OPERATIONAL EXPERIENCE AND UPGRADE PLANS OF THE RIBF ACCELERATOR COMPLEX

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Abstract

The Radioactive Isotope Beam Factory (RIBF) is a cyclotron-based accelerator facility for nuclear science, completed at the end of 2006. RIBF can produce the most intense RI beams using fragmentation or fission of high speed heavy ion beams. Continuous efforts since the first beam have increased the beam intensity and achieved stable operation. 49.8 pnA (3×10^{11} /s) of uranium ion beam was extracted from the final accelerator SRC with energy of 345 MeV/u in 2016, which is currently the world record. For further expansion of the scientific opportunity, an upgrade program has been proposed to increase the intensity of uranium ion beam by a factor greater than twenty. The program includes two components. The first component is increasing space charge limit of the beam intensity in the low-energy ring cyclotron (RRC) by replacing the existing resonators with newer ones to achieve higher accelerating voltage. The second component is skipping the first stripper, which requires an increase in the magnetic rigidity of the ring cyclotron just after the first stripper (FRC). The new ring cyclotron will consist of six-sector magnets with four rf-resonators to maintain approximately 15 mm of turn separation, which is similar to that in the present FRC, the K-value of which is 2200 MeV. A conceptual design of the new cyclotron is ongoing. Certain issues to realize the intensity upgrade are also under discussion.

INTRODUCTION TO RI BEAM FACTORY

The Radioactive Ion Beam Factory (RIBF) is a cyclotron-based accelerator facility that uses fragmentation or fission of heavy ion beams to produce intense RI beams over the whole atomic range [1]. The purposes of the RIBF are to explore the inaccessible region of nuclear chart, to discover the properties of nuclei far from stability, and to advance knowledge in nuclear physics, nuclear astrophysics, and applications of rare isotopes for society. The RIBF facility consists of four cyclotron rings (RRC [2], FRC [3], IRC [4], and SRC [5]) with three injectors, including two linacs (RILAC [6,7] and RILAC2 [8]) and one AVF cyclotron (AVF) [9]. Cascades of the cyclotrons can provide heavy ion beams from H_2^+ to uranium ion at more than 70% of the speed of light to efficiently produce RI beams. Three acceleration modes are available, as shown in Fig. 1. The first mode is used mainly for mid-heavy ions, such as Ca, Ar, and Zn. The second mode is used for light ions, such as O and N. The third mode is used for very heavy ions such, as Xe and U. Table 1 lists the specifications of the four ring cyclotron of RIBF. RRC has been operating since 1986. FRC and IRC have similar structures to that of RRC. The K-value per weight is listed in the table, which clearly shows that FRC is a very compact machine compared to the other cyclotrons. We can see that SRC is the most challenging machine to obtain an acceleration voltage of 640 MV for uranium acceleration up to energy of 345 MeV/u. The design and construction of the RIBF accelerators started from 1997 and we obtained the first beam at the end of 2006.

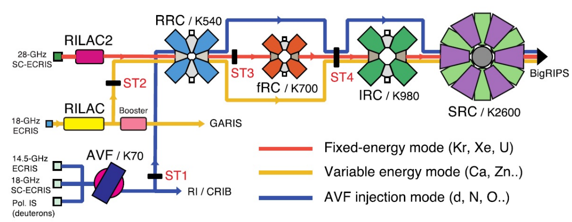

Figure 1: Acceleration modes for RIBF facility.

OPERATION FOR TEN YEARS

Operations for about ten years since the first beam have been very successful. Our continuous efforts have increased beam intensity, especially of very heavy ions, such as Xe and U, as shown in Fig. 2. The maximum beam intensity of uranium ion is 50 pnA, which is the world record. The beam availability has been significantly improved, exceeding 90% since 2014.

A 28 GHz ECR ion source using superconducting solenoids and sextuple magnets was constructed because powerful ion sources are essentially required to increase the uranium beam intensity [10, 11]. The operation of this ion source on the beam line started from 2011 with the new injector linac (RILAC2). Currently, approximately 150 eμA of U^{35+} can be stably extracted with uranium metal sputtering. A high-temperature oven for uranium ions is also under development.

Charge strippers are important devices to increase the intensity of uranium beam because they have a high risk of bottleneck problems owing to fragility against high-power

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UPGRADE OF THE LNS SUPERCONDUCTING CYCLOTRON FOR BEAM POWER HIGHER THAN 2-5 kW

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Abstract

The LNS Superconducting Cyclotron has been in operation for more than 20 years. A wide range of ion species from Hydrogen to Lead, with energy in the range 10 to 80 AMeV, have been delivered to users. Up to now the maximum beam power has been limited to 100 W due to the beam dissipation on the electrostatic deflectors.

To fulfil the demand of users aiming to study rare processes in Nuclear Physics, the beam power has to be increased up to 2÷10 kW for ions with mass lower than 40 a.m.u., and extracted by stripping. This development has to maintain the present performances of the machine, i.e. the existing extraction mode for all the ion species allowed by the operating diagram.

To perform the extraction by stripping, a significant refurbishing operation of the Cyclotron is needed, including a new cryostat with new superconducting coils, a new extraction channel with a 60 mm vertical gap, additional penetrations to host new magnetic channels and new compensation bars.

Moreover, the vertical gap of the acceleration chamber is planned to be increased from the present 24 mm up to 30 mm by renewing the existing liners and trim coils.

A general description of the refurbishing project is presented.

INTRODUCTION

The LNS Superconducting Cyclotron (CS), designed by the Milano Group headed by F. Resmini, has been in operation since 1995 [1]. The CS was designed to be operated as a booster of a Tandem accelerator and to deliver beams for nuclear physics experiments mainly. The usual beam power stays around few tens of Watts.

After the year 2000, the CS was equipped with a central region to operate in stand-alone mode. Ion beams are now produced by ECR ion sources and injected into the cyclotron through the axial hole using a spiral inflector. The success of axial injection operation stimulated the development of the EXCYT project to produce radioactive ion beams on a thick target with the ISOL technique [2].

To operate the EXCYT project we pushed the CS to the maximum beam current, but it became clear that despite our efforts, the extraction system and in particular the two electrostatic deflectors (ED) were not able to deliver beam currents more than 150 W. This limit was mainly due to the extraction efficiency of the CS that stays around 50-60% and to the constraints of our ED. Although it is water cooled, can work with a maximum beam loss of 100 W. Recently some nuclear physicists proposed to use the magnetic spectrometer with large solid angle and large momentum acceptance "MAGNEX" to measure the nuclear matrix that is of relevant interest for the double β decay without neutrino emission [3,4]. This experiment, called NUMEN, needs mainly beams of Carbon, Oxygen and Neon with intensity up to 10^{14} pps. The required energies are in the range 15÷70 AMeV, which corresponds to a beam power in the range 1÷10 kW.

According to this relevant scientific interest, the management of LNS-INFN approved a program to upgrade the CS. This upgrade will be relevant also for experiments that use radioactive ion beams produced by in-flight fragmentation. In particular, a new dedicated beam line for the production and selection of the radioactive ion beams is under design. Moreover, the availability of light ion beams with medium power opens the opportunity also to produce radioisotopes of medical interest.

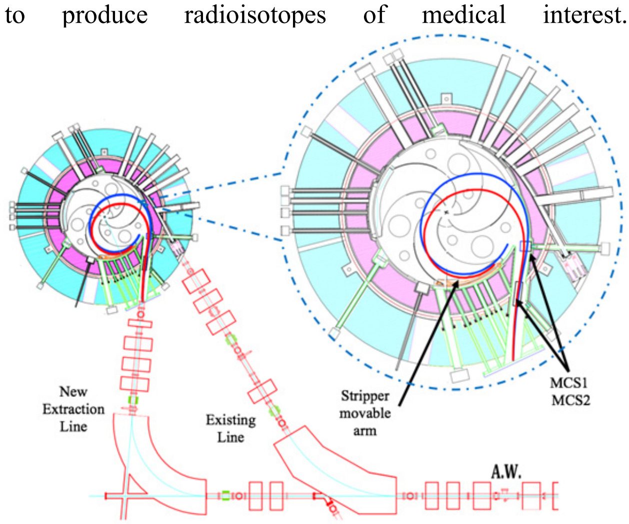

Figure 1: Layout of the Superconducting Cyclotron with the existing and the new extraction beam lines. Two extraction trajectories, in red and blue, are also shown.

MAIN MODIFICATIONS

The extraction of 1÷10 kW beams is not feasible using the ED nor through the existing extraction channel. Indeed, the existing extraction channel allows to extract beams with a transversal size not larger than 8 mm, and this magnetic channel has no thermal shields to dissipate the beam power coming from haloes. So a solution based on extraction by stripping has been investigated [5]. According to Fig. 1, the ion beams are accelerated with a charge state q=Z-1÷Z-3 and after crossing a stripper foil the ions become fully stripped. The use of a stripper foil, placed at a proper position, allows the beam trajectory to escape from the region of the cyclotron pole and to come out through the new extraction channel. This extraction mode is currently used in the cyclotron of FLEROV laboratory [6]. The energies of our beams are enough high,

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IN MEMORIAM: MICHAEL K. CRADDOCK*

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Abstract

Michael K. Craddock, TRIUMF accelerator physicist and UBC professor, died on 11 November, 2015 after a brief illness. Michael left the UK to join the UBC Nuclear Physics group in 1966, just at the time a new accelerator to replace the aging Van de Graaff was under consideration. He was a leading member of the founding team that decided on a 500 MeV H^- cyclotron and directed the beam dynamics design of the cyclotron to first beam in December 1974. With the cyclotron running at full intensity he moved his interest to higher energies and led the accelerator physics team in the design of the 30 GeV KAON Factory (1982-1994). After retirement from UBC in 2001 he moved his research interest to FFAGs.

INTRODUCTION

Michael Craddock was born on 15 April in Portsmouth, UK and received his early education there. He then attended Oxford University for his Bachelor's and Master's degrees in mathematics and physics in 1957 and 1961 and became a scientific officer at what was then the Rutherford High Energy Physics laboratory (RHEL) working on the 50 MeV proton linear accelerator (PLA) (see Fig. 1).

In parallel he pursued a D. Phil in nuclear physics at Oxford which he obtained in 1964. His thesis topic was "The Nuclear Interactions of High Energy Particles" under the supervision of D. Roaf and R. Hanna. The work involved developing a polarized source, beam polarimeter and cryogenic target for studying proton-He4 elastic scattering at 22 and 29 MeV. As an indication of his future thoroughness in research the thesis contains 14 pages of references. In 1966 Michael joined the Physics Department at the University of British Columbia, later with a joint appointment at TRIUMF, and was TRIUMF's leading beam physicist throughout his career.

Michael with a training in mathematics loved equations and his early note books are filled with formula relating to polarized proton sources, equations of charge at particle motion in magnetic and electric fields etc. He passed this approach on to his many graduate students and beam dynamics team, although eventually embraced computing simulations but usually they were carried out by others. He excelled in writing research papers – the references present only a small subset of his published papers, and was particularly interested in the history of accelerator developments. At the Cyclotron Conference in Lanzhou in 2010 he presented a paper on "Eighty Years of Cyclotrons" [1]. His last scientific article was a history of accelerator science and technology in Canada which was completed by Robert Laxdal and recently published [2].

Michael was a strong supporter of the international accelerator community beginning as the program chair for the 1972 Cyclotron conference in Vancouver, conference chairman for the 1985 and 1997 Particle Accelerator Conferences and also the 1992 Cyclotron conference. He was a valued member of the international organizing committees and scientific advisory boards for these conferences. He gave the after dinner address to the 1992 conference on "Proper and Improper Accelerators – In praise of Cyclotrons and their Builders".

At TRIUMF Michael was the head of the Beam Dynamics group or the Accelerator Research Division for much of his career and was instrumental in training a new generation of beam physicists. Some of these individuals are identified in the references and acknowledgements. (For 29 years he was TRIUMF's correspondent to the *CERN Courier*.)

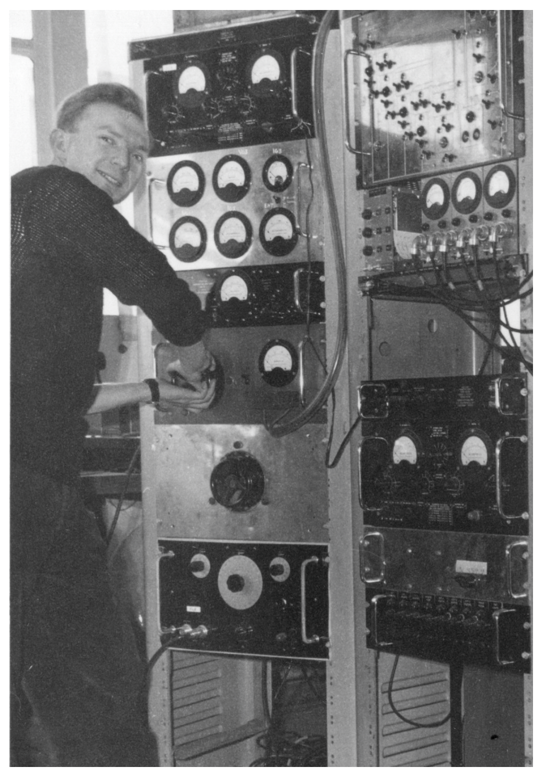

Figure 1: Michael Craddock at the controls of the Rutherford Laboratory PLA in 1964.

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CYCLOTRON TECHNOLOGY AND BEAM DYNAMICS FOR MICROBEAM APPLICATIONS

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Abstract

We have been improving a beam quality of the TIARA cyclotron to form a heavy-ion microbeam with a spot size about 1 μm. An energy spread ΔE/E of the beam on the order of 10^{-4} is required for eliminating chromatic aberrations in the focusing magnets. A flat-top acceleration system using the fifth-harmonic frequency was installed in the cyclotron to reduce the energy spread. In addition, a magnetic field stabilization system, an acceleration phase control technique and a new central region were developed to provide the microbeam stably for beam users. A cocktail beam acceleration technique was introduced to quickly change the microbeam to the other one, and a few microbeams can be used in a beam time.

INTRODUCTION

Takasaki Ion accelerators for Advanced Radiation Application (TIARA) facility of the National Institutes for Quantum and Radiological Science and Technology (QST) was constructed to provide high-energy ion beams mainly for research in biotechnology and materials science. QST [1] was newly established in April 2016 by merging the National Institute of Radiological Sciences (NIRS) with a few research institutes of the Japan Atomic Energy Agency (JAEA).

An AVF cyclotron with a *K*-value of 110 [2] and three electrostatic accelerators are installed in TIARA, and ion beams with wide ranges of energy and ion species are available. A microbeam with a spot size about 1 μm is a powerful tool to analyze and/or irradiate a microscopic area. At TIARA, microbeam applications such as in-air Particle Induced X-ray Emission (PIXE) analysis and Proton Beam Writing (PBW) are carried out by focusing ion beams accelerated by the electrostatic accelerators [3]. On the other hand, in a vertical beam line of the cyclotron hundreds MeV heavy-ion microbeam irradiation to living cells is carried out by using micro collimators for elucidation of cellular radiation response [4]. However, spot size of the microbeam is larger than that of the electrostatic accelerator's one due to fabrication limit of the collimator and scattered ions at the edge of the collimator. In addition, targeting speed is too slow since a targeting point is adjusted by moving a mechanical sample stage. To form a microbeam with a spot size about 1 μm, a microbeam formation system using quadrupole magnets with a beam scanner was installed in the other vertical beam line of the cyclotron.

To form such a microbeam using the focusing magnet, an energy spread Δ*E*/*E* of the ion beam must be reduced to the order of 10^{-4} for eliminating chromatic aberrations in the focusing magnet. However, the energy spread of the cyclotron beam is typically on the order of 10^{-3} while that of the electrostatic accelerator on the order of 10^{-4}. A flat-top (FT) acceleration system using a fifth-harmonic frequency was developed to reduce the energy spread. In addition, cyclotron technologies such as magnetic field stabilization system and beam phase control techniques were introduced to ensure the effect of the FT acceleration. In this paper, we briefly describe the above cyclotron development, and also mention a technique to quickly change ion species of the microbeam and recent microbeam development of a 320 MeV $^{12}C^{6+}$.

MICROBEAM FORMATION AND SINGLE-ION HIT CONTROL SYSTEM

Figure 1 shows the system of the focusing microbeam formation and single-ion hit, which means irradiating a targeted point with a high-energy ion one by one. Details of the microbeam formation system [5] are shown in Fig. 2. The system consists of quadruplet quadrupole magnets, a pair of micro slits, a pair of divergence angle defining slits, and so on. The beam shifter upstream the micro slits matches the incident beam trajectory with the microbeam line axis. Magnification factors of the focusing system for *x* and *y* directions are equally 1/5. The 90° bending magnet doesn't have a role as an energy analyser; therefore reduction of the energy spread of the incident beam is indispensable condition. The targeting point is determined by the electrostatic beam scanner. Ions pene-

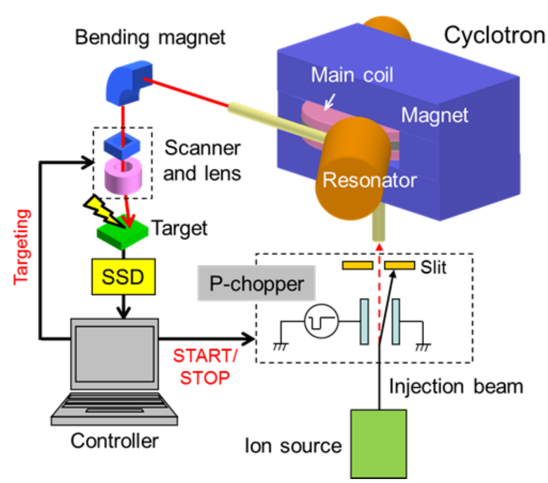

Figure 1: Layout of equipment for microbeam formation and single-ion hit control system at the TIARA cyclotron facility.

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SIMULATION AND DETECTION OF THE HELICAL ION-PATHS IN A SMALL CYCLOTRON

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Abstract

The small cyclotron COLUMBUS, which was developed in high school Ernestinum Coburg in cooperation with the Institute of Research of Jülich and the University of Applied Sciences of Coburg, is a particle accelerator for education and teaching purposes.

Since its installation, the cyclotron has been continuously upgraded and is now part of the newly created Student Research Centre of the University of Coburg.

In the cyclotron hydrogen ions are accelerated and their positions recorded after a few revolutions by a Faraday cup, which is moved by a linear translator in radial direction across the trajectories of the ions.

This thesis presents a MATLAB simulation of the orbits of the accelerated hydrogen-ions. In contrast to the simpler common school model that approximates the tracks in the acceleration gap by straight tracks, the presented simulation considers the deflection of the ions by the magnetic field in the acceleration gap. So a more realistic picture of the paths can be drawn, which will help to adjust the cyclotron and explore the initial orbits of the ions in detail.

INTRODUCTION

The COLUMBUS project began in 2012 and was first presented at the Cyclotrons 2013 in Vancouver [1]. At this time, however, no jet operation was possible. The first beam was detected in April 2014.

As part of a master's thesis a linear translator was developed in order to move the detector, a Faraday-cup in a radial direction behind the dummy dee. In addition to the registered ions the corresponding x-position of the cup is measured, too [2].

To give students a clear picture of the acceleration processes of the ions in the cyclotron, the ion trajectories are calculated and then visualized in a diagram. This allows qualitative and later quantitative predictions of experiments.

THE STRUCTURE OF THE SIMULATION

As shown in Fig. 1 the simulation consists of three sections, the input-layer, the simulation-layer and the presentation-layer.

The Input-Layer

The input-layer incorporates three groups of parameters which define the ions, the experiment and the geometry of the cyclotron. So the simulation can be easily adapted to different situations.

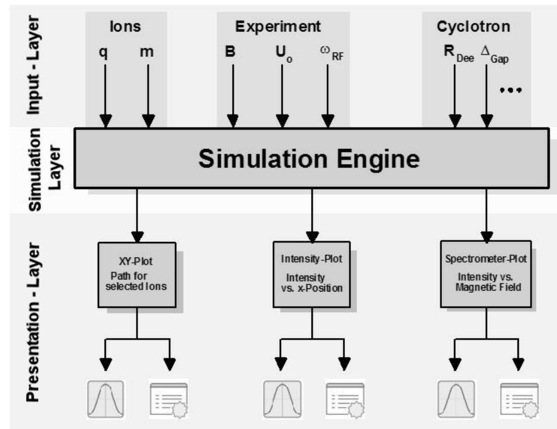

Figure 1: Structure of the Simulation.

The Simulation-Layer

In this layer there is the Simulation Engine, a MATLAB program which calculates all variables such as the positions, the velocity, the radius and the cyclotron-frequency ω_{ZF} of the ions during the acceleration process.

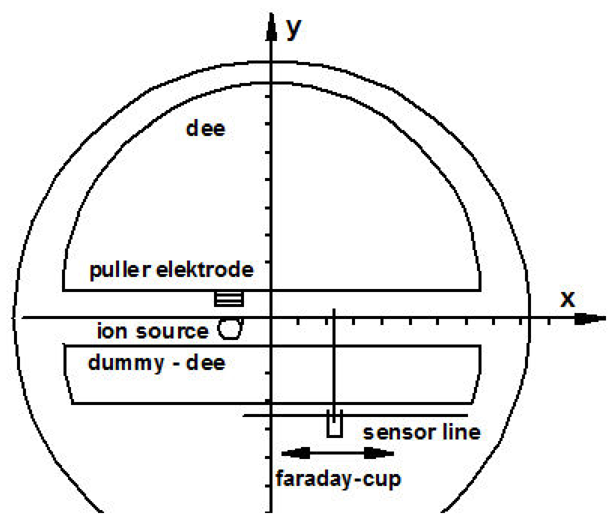

Figure 2: Cartesian coordinate system of the Cyclotron.

For this purpose a coordinate system has been introduced, which has its origin (0, 0, 0) in the center of the vacuum chamber, i.e. Fig. 2. The magnetic field is directed parallel to the z-axis of the coordinate system. The plain z = 0, parallel to the chamber bottom, represents the plain of the path of the accelerated ion beam. The ion source is located at position (-15, 5, 0) (all figures in mm), a Faraday-cup as an ion detector moves along the line y = -31 mm, the so-called sensor-line. This line ex-

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RADIATION DAMAGE OF COMPONENTS IN THE ENVIRONMENT OF HIGH-POWER PROTON ACCELERATORS

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Abstract

At high power accelerators, radiation damage becomes an issue particularly for components which are hit directly by the beam, like targets and collimators. Protons and secondary particles change the microscopic (lattice) structure of the materials, which macroscopically affects physical and mechanical properties. Examples are the decrease of thermal conductivity and ductility as well as dimensional changes. However, the prediction of these damage effects and their evolution in this harsh environment is highly complex as they strongly depend on parameters such as the irradiation temperature of the material, and the energy and type of particle inducing the damage. The so-called term "displacements per atom" (DPA) is an attempt to quantify the amount of radiation induced damage and to compare the micro- and macroscopic effects of radiation damage caused by different particles at different energies.

In this report, the basics for understanding of the mechanisms of radiation damage will be explained. The definition and determination of DPA and its limitations will be discussed. Measurements and examples of the impact of radiation damage on accelerator components will be presented.

INTRODUCTION

The change in material properties due to damage to the lattice structure, which sometimes leads to the failure of components, is called radiation damage. It is a threat particularly to components at loss points in high-power accelerators. These components include targets, beam dumps, and highly exposed collimators. There is renewed interest in the topic of radiation damage owing to new projects and initiatives which require high-power accelerators, and therefore materials which will withstand high power sufficiently long. One such project is the European Spallation Source (ESS), which is being built in Lund, Sweden [1] with a rotating wheel target composed of tantalum cladded tungsten bars irradiated with 5 MW of 2.5 GeV protons. The Facility for Rare Ion Beams (FRIB) is being built at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. This facility will deliver heavy ions with extremely high power densities of 20–60 MW/cm^3 [2]. The Daedalus project is an initiative at MIT with the aim of studying CP violation [3]. For this purpose, a neutrino beam shall be produced by three cyclotrons, each delivering a proton beam with energy of about 800 MeV. The planned beam power on target are foreseen to be 1, 2, and 5 MW for the first, second, and third cyclotron, respectively. At PSI, a 1.3 MW proton beam is routinely available, which constitutes the most intense steady state proton source in the world at present. Higher powers of up to 1.8 MW are envisaged for the future.

For all these projects, it is essential to know how long the heavily irradiated components can be operated safely. In addition, improvement of the lifetime of components needs knowledge about the underlying mechanism of radiation damage and its relation to the changes in material properties. One problem is that components cannot be tested under the same conditions as experienced during operation. Therefore, the correlations between data obtained under different conditions need to be understood.

Prominent macroscopic effects on structural materials caused by radiation damage are the following:

- Hardening, which leads to a loss of ductility;
- Embrittlement, which leads to fast crack propagation;
- Growth and swelling, which lead to dimensional changes of components and can also induce additional mechanical stress;
- increased corrosion rates, in particular in contact with fluids;
- irradiation creep, which leads to deformation of components;
- Phase transformations in the material or segregation of alloying elements, which leads to changes in several mechanical and physical properties.

Besides changes of structural mechanical properties physical properties change as well. Particularly serious is the steep decrease of the thermal conductivity for components, which need to be heavily cooled due to the energy deposition of proton beams. Design studies rely on prediction of the temperature distribution in a component and thus on the knowledge of the thermal conductivity of the material. The consequence is that the component might reach higher temperatures than foreseen, which could lead to the failure of the component.

In pulsed sources, components in addition undergo thermal cycles, causing fatigue. Cracks may occur, which could lead to failure of the component. This phenomenon might be also influenced and accelerated by radiation due to additional hardening and embrittlement. Sometimes, a phenomenon attributed to radiation damage, might in fact be caused by other effects like e.g. rapid heating or pitting.

In the following, some examples of observed radiation damage will be given. In preparation for the above-mentioned FRIB, several objects were studied at NSCL with respect to radiation damage due to heavy ions. For this purpose, a 580 mg/cm^2 tungsten foil, which corresponds to a thickness of 0.03 cm, was irradiated with 76Ge30+ ions at 130 MeV/nucleon. After irradiation of

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DESIGN OF THE ENERGY SELECTION SYSTEM FOR PROTON THERAPY BASED ON GEANT4*

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Abstract

Huazhong University of Science and Technology (HUST) has planned to build a proton therapy facility based on an isochronous superconducting cyclotron. The 250 MeV/500 nA proton beam is extracted from a superconducting cyclotron. To modulate beam energy, an energy selection system is essential in the beamline. The simulation based on Geant4 has been performed for the energy selection system and its result will be discussed in this paper. This paper introduces the variation rules of the beam parameters including the beam energy, beam emittance, energy spread and transmission. The degrader's gap and the twiss parameter are proven to be effective ways to reduce the emittance after degrader.

INTRODUCTION

Huazhong University of Science and Technology (HUST) has proposed to construct a proton therapy facility, which includes two rotating gantries and one fixed beam treatment room [1,2]. To modulate the proton beam energy for treatment, an energy selection system (ESS) is located in the beam-line. The beam energy can be modulated by the interactions between the energetic particles and the degrader's material. The ionization process with the electrons, the multiple Coulomb scattering with the nucleus and the nuclear reaction are the mainly components of the interactions, which will contribute to the energy degradation, the emittance growth and the secondary particles' production.

The energy selection system consists of an energy degrader, a set of collimators, and a double bend achromatic (DBA) section with an energy selection slit. An overview of the conceptual layout is shown in Fig. 1, and the main parameters of the beam are listed in Table 1. The energy degrader is aimed at the energy modulation by controlling the thickness of the degrader. The emittance collimators are designed to suppress the beam emittance significantly increased in the degrader. And the energy slit in DBA section is used to limit the energy spread.

This paper mainly describes the variation rules of the beam parameters including the beam energy, beam emittance, energy spread and transmission. And furthermore, the degrader's gap and the twiss parameter are illustrated to be effective ways to reduce the emittance after degrader.

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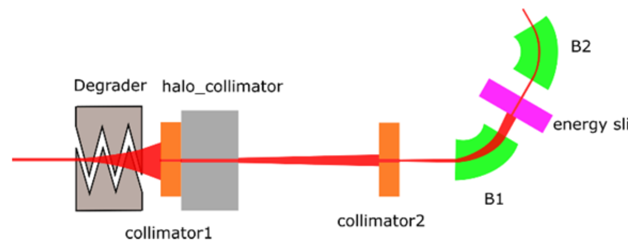

Figure1: Overview of the energy selection system (ESS).

Table 1: Main parameters of the beam

Location	Parameter	Design value
Before ESS	Energy	250MeV
	Current	500nA
	Emittance	5 π mm · mrad
	Energy spread	0.5%
After ESS	Energy range	70~250MeV
	Transmission	0.2%
	Emittance	5 π mm · mrad
	Energy spread	±0.5%

THEORY AND SIMULATION

To simulate the passage of particles through matter, the model of ESS is built in Geant4 [3].Geant4 toolkit consists of many kinds of physical package. For example, the QBBC physical package is effective tool for the simulation of interactions between 250 MeV proton and the material. The detailed model parameters are presented in Table 2 [4]. Therefore, the beam parameters can be obtained from the simulation result.

Table 2: Model parameters of ESS

Object	Material	Central position (mm)	Length (mm)
Degrader	Graphite	0	200
Col1	Copper	167.5	35
Halo_col	Graphite	300	60
Col2	Copper	1187.5	35

Energy Selection

Energy degrading is the main purpose of the energy selection system based on the Bethe-Bloch formula [5] shown in Eq. (1).

$$-\left(\frac{\mathrm{dE}}{\mathrm{dx}}\right)=4\pi \mathrm{N}_a r_e^2 m_e c^2 z^2 \left(\frac{Z}{A}\right)\left(\frac{1}{\beta^2}\right)\left[\ln\left(\frac{2m_e c^2\gamma^2\beta^2}{I}\right)-\beta^2-\frac{\delta}{2}\right]. \quad (1)$$

DESIGN STUDY OF THE 250 MeV ISOCHRONOUS SUPERCONDUCTING CYCLOTRON MAGNET*

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Abstract

Superconducting cyclotron is an optimum choice to deliver high quality continuous wave (CW) proton beams for proton therapy with its compactness and power saving. Field isochronism and tune optimization are the two crucial factors of cyclotrons during the magnet design. This paper is concentrated on the superconducting magnet design, mainly including the spiral magnet, isochronous field and the tune optimization. The main parameters and some features of the machine will be presented.

INTRODUCTION

Today, cancer is a leading cause of death worldwide especially in industrial countries. Its treatment still presents a real challenge. In China, the survival and cure rate for cancer patients is lower than 15%. It is reported that the number of new cancer cases and deaths will reach 15 million or even more in 2020 [1].

As a method of radiation therapy, proton therapy has attracted widespread attention in recent years. Proton beams have the characteristic Bragg peak in their depth-dose distribution compared to traditional X-ray. Hence, proton therapy is preferable for most types of tumors due to accurate local dose control and minimum damage to the healthy tissues surrounding at the target tumor. Approximately more than 50,000 cancer patients have been treated with proton beams and Proton therapy is recognized as the most effective radiation therapy method for cancers with very high cure rate of 80% [2][3].

There are two main categories of accelerators that are currently used for proton therapy, synchrotrons and cyclotrons, which can accelerate protons up to energies of 230-250 MeV. With the Superconducting technology developed, a superconducting isochronous cyclotron is the best choice for it has great advantages of compactness and economy, saving costs for construction and operation.

For isochronous cyclotrons with fixed RF frequency, the field isochronism is important, which means the azimuthal average magnetic field should be increased to keep the same gyration frequency of the accelerating beam when the beam energy changes. What is more, the axial beam tune due to the field changes is also important and difficult to avoid the axial instabilities, especially the vertical tune is very low. The sectors should be shaped with a suitable geometry which can meet both the two requirements. It is an iterative procedure by matching the sector angle width and the spiral angle to find the shape of the magnet that provides the required magnetic field.

* Work supported by National Natural Science Foundation of China, with grant No.11375068.
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A 250 MeV isochronous superconducting cyclotron (SCC-250) was proposed in HUST for the purpose of proton therapy [4]. This paper mainly focused on the superconducting magnet design ignoring the central region design, including the spiral magnet, isochronous field, and tune optimization. Some special extraction considerations in the demonstrated model are discussed. The main parameters and some features of the machine are presented.

OVERALL DESIGN OF THE MAGNET

A fourfold symmetric compact magnetic structure has been chosen to produce the required azimuthal varying magnetic field. The superconducting coils can product much higher magnetic field and the magnet radius can be much smaller. It is not difficult to reach 4-5 T, but this will make extraction design more challenging due to a smaller accelerated turn separation. Meanwhile, the formation of the isochronous field using a flat pole gap becomes challenging. In our case, the maximum magnetic field flux intensity is about 3.9 T, with the azimuthal average field 3.1 T.

Based on the parameters of extraction energy (250 MeV) and the extraction field *Bext*, the other main parameters, like: the pole diameter, injection field, total ampere turns, hill and valley gap can be determined using simple analytical calculation [5], which define the initial layout of the cyclotron magnet.

In order to ensure the axial stability of the beam during acceleration, it is necessary to shape the edges of the sectors as spirals. The matrix method was applied for approximate description of the dynamic of the beam inside the cyclotron to define the initial spiral angle, and the initial maximum spiral angle in the extraction is about 70 degrees.

The design of the yoke is performed taking account of two parameters: 1) the avoidance of saturation in the yoke; 2) the fringing field shape near the cyclotron. A value of the yoke radius $Ryoke = 2 \cdot Rpole$ should be a conservative choice. Based on the considerations above, the main parameters of the magnet can be determined and are listed in Table 1. Based on the parameters in Table 1, the 1/4 magnet model simulated by TOSCA [6] is shown in Figure 1.

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MAGNET OPTIMIZATION AND BEAM DYNAMIC CALCULATION OF THE 18 MeV CYCLOTRON BY TOSCA AND CYCLONE CODES

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Abstract

Designing and manufacturing of the 18 MeV cyclotron has been started for producing H^- for applications in Positron Emission Tomography (PET) radioisotopes at Amirkabir University Of Technology. Up to this point, there were 2 steps in magnet design: Initial design and optimization processes. The AVF structure with hill and valley was selected for getting strong axial focusing in magnet design and achieving up to 18 MeV energy for the particle. After finishing the initial design, optimization process in magnet design was started for achieving the best coincidence in magnetic field.

Checking the beam dynamic of the particle is one of the most important and necessary steps after magnet simulation. The phenomenon which confirms simulated magnet validity is obtaining reasonable particle trajectory. This paper focused on the optimization process in magnet design and simulation of the beam dynamic. Some results which ensure a particle can be accelerated up to 18 MeV energy, are presented. All magnetic field calculation in whole magnet was calculated by OPERA-3D (TOSCA) code. Also beam dynamic analysis by applying magnetic field data from the magnet simulation was done in CYCLONE code.

INTRODUCTION

The 18 MeV cyclotron magnet was designed with CST code and the STP file was uploaded in TOSCA code [1]. So all magnet calculations were done in TOSC code. The material of the magnet was considered steel-1010. The magnetic field curve versus radius before applying optimization process is shown in Fig. 1.

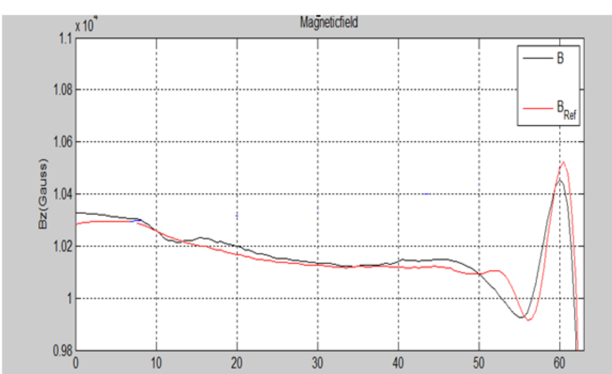

Figure 1: Average magnetic field versus radius before optimization process.

As shown in Fig. 1, B_{ref} (red curve) is the ideal magnetic field and the black one is the simulated magnetic field. Before applying the optimization method, there is not acceptable coincidence between two curves. So optimization process was started.

OPTIMIZATION METHODS

In magnet design, there are some methods which can be used for achieving best results. The methods which were used in optimization process are changing ampere-turn up to 58000, decreasing the gap between poles as a function of radius and shimming of pole edges [2].

Shimming of Pole Edges

At first, in initial design, horizontal shimming was used. In this way achievement to best result in magnetic field was difficult. So in the optimization process shimming of pole edges was changed to vertical form. In vertical shape, some of the pole points were selected and their heights were changed. Also triangle magnet shapes were added the end of the poles for increasing magnetic field at the end of the curve.

Figure 2 shows all used shimming methods in magnet design.

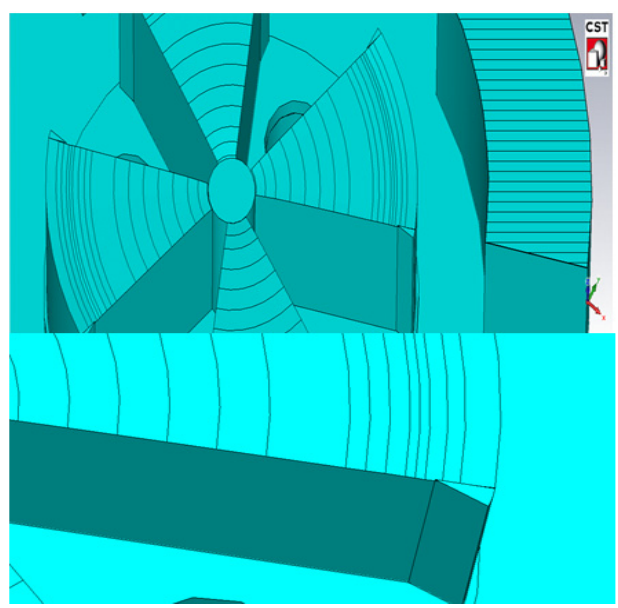

Figure 2: Shimming of pole edges.

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EQUIVALENT CIRCUIT MODEL OF CYCLOTRON RF SYSTEM

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Abstract

Cyclotron cavity modelled via electromagnetic circuits in the desired frequency. The design performed according to resonator basis and also cyclotron acceleration requirements with ADS software and compared to simulations made by the CST microwave studio. The scattering parameters obtained for main resonators of the cyclotron and Dee parts as a diaphragm for each of cavity sections and also for the whole structure. All the characteristics modelled and calculated by the electromagnetic rules and theory of resonators from circuit model. Then it analysed with numerical methods for benchmarking. Finally, it shows that the circuit model able to modelled accurately the cyclotron cavity and especially it can estimate precisely the structure parameters without any time consuming numerical method simulations.

INTRODUCTION

A particle accelerator is a machine that uses electromagnetic fields to propel charged particles to nearly light speed and to contain them in well-defined beams [1]. One kind of accelerators is oscillating field accelerators, which use radio frequency electromagnetic fields to accelerate particles, and circumvent the breakdown problem. Also circular accelerators partition to several types such as; Cyclotrons, Synchrocyclotrons and isochronous cyclotrons, Betatrons and etc. [2].

Cyclotron which is our discussion about, are accelerators in which particles are propelled in spiral paths by the use of a constant magnetic field. This accelerator was invented for the first time by Ernest O. Lawrence in 1932 [3]. The cyclotron was one of the earliest types of particle accelerators, and is still used as the first stage of some large multi-stage particle accelerators. It makes use of the magnetic force on a moving charge to bend moving charges in a semicircular path between accelerations by an applied electric field. The applied electric field accelerates electrons between the "Dees" of the magnetic field region. The field is reversed at the cyclotron frequency to accelerate the electrons back across the gap [4]. One of the main parts of the cyclotron is the RF cavity. In this paper we have proposed the circuit model to consider the cyclotron RF cavity response to analyze its behavior in resonance frequency.

CYCLOTRON ACCELERATORS

The cyclotron principle involves using an electric field to accelerate charged particles across a gap between two "D-shaped" magnetic field regions. The magnetic field accelerates the particles in a semicircle, during which time the electric field is reversed in polarity to accelerate the charge particle again as it moves across the gap in the opposite direction. In this way a moderate electric field can accelerate charges to a higher energy [4]. Cyclotron includes some different sections that is illustrated in block diagram of Fig. 1 which the RF cavity is one of the main parts.

RF CAVITY STRUCTURE

With regard to the overall structure of the cyclotron accelerators been described above, its different parts are illustrated in Fig. 2. The main part of such a device is a resonator which provides resonance at considered frequency. Resonator structures are different. The oscillations in a resonator can be either electromagnetic or mechanical [5]. In the cyclotron accelerator, the cavity resonator is used. Due to the low resistance of their conductive walls, cavity resonators have very high quality factors; that is their bandwidth is very narrow. Thus, they can act as narrow band-pass filters [5]. The different cavity designs are depending on the specifications and geometric layout of a cyclotron [6].

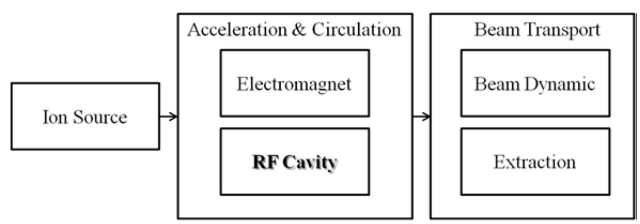

Figure 1: Brief block diagram of the cyclotron accelerator.

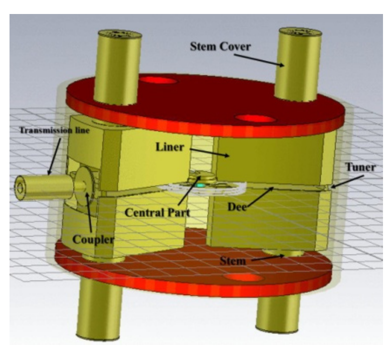

Figure 2: Overall structure of the RF cavity.

Therefore, a coaxial resonator in fixed frequency, double gap and superconducting can be suitable for this application. But as mentioned, the cyclotron, because of the conditions governing the charged particle rotation, requires a region in the center of the resonator to get energy to the particles through an electric field. As a result, in the center, it has to be a horizontal plate, called Dees, with a certain angle that generate the electric field, between the

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DESIGN OF THE FAST SCANNING MAGNETS FOR HUST PROTON THERAPY FACILITY*

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Abstract

For implementation of proton therapy, Huazhong University of Science and Technology has planned to construct a 250 MeV/500 nA superconducting cyclotron for proton therapy. In the beam-line, the scanning system spreads out the proton beam on the target according to the complex tumor shape by two magnets for horizontal and vertical scanning independently. As dipole magnets are excited by alternating currents and the maximum repetition rate is up to 100 Hz, the eddy currents are expected to be large. This paper introduces the design of these two scanning magnets and analyzes the eddy current effect. Slits in the end pole are proven to be an effective way to reduce the eddy current. Different directions, distributions and width sizes of slits are simulated and compared to determine the slits arrangement. At last, the maximum temperature of the optimized scanning magnets reaches the temperature requirements.

INTRODUCTION

Nowadays, particle therapy becomes a more effective method for radiation cancer treatment than traditional X-rays or gamma rays treatment. Huazhong University of Science and Technology(HUST) has proposed to construct a proton therapy facility based on a superconducting cyclotron in 2014 and this project is founded in 2016 [1]. In this project, we plan to build two rotating gantries and one fixed beam treatment room [2]. The energy of the proton beam ranges from 70 MeV to 250 MeV, corresponding to the range in water from 4 cm to 38 cm, and it can be modulated via the energy selection system(ESS) in the beam-line [3]. For active scanning method, a scanning magnet system is located at the end of beam line and precisely controls the beam position to spread out the proton beam on the tumor target. The scanning range at the iso-center is 30 cm×30 cm.

This paper mainly describes the design of two scanning magnets and analyzes the eddy current effect of AC dipole magnets.

SCANNING MAGNETS

The scanning magnet system is a core component of the active scanning system, which consists of two orthogonal H-type dipole magnets (SMX and SMY). The layout of the rotating gantry is shown in Fig. 1 and the main parameters of these two scanning magnets are list in Table 1 . To achieve the fast beam scanning at the iso-center and decrease the radius and cost of the gantry, the length of SAD(Source to Axis Distance) is 2.8 m. The distances from SMX and SMY to the iso-center are chosen as 2.85 m and 2.37 m. The maximum deflection angle is determined by the maximum magnetic rigidity 2.43 T·m, corresponding to 250 MeV proton beam. In the gantry, SMY is located after SMX, indicating that SMY should have a larger gap and pole width than SMX. According to the simulation of beam trajectory, the gap and pole width of SMX and SMY are determined. As for the power supply, these two dipole magnets are excited by alternating currents and the repetition frequencies are 100 Hz and 40 Hz, determined by the target scanning speed 60 m/s in x direction and 24 m/s in y direction. This requires the maximum current ramping speed to be up to 228 kA/s and the maximum magnetic field gradient to be 208 T/s.

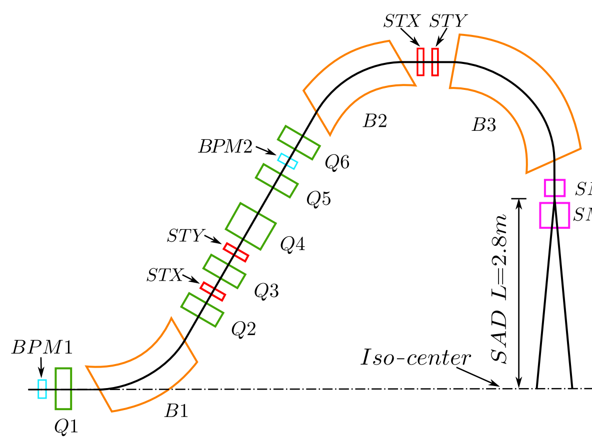

Figure 1: The layout of the rotating gantry and the illustration of the SAD length.

Table 1: Main Parameters of Scanning Magnets

Parameter	Units	SMX	SMY
Max Deflection Angle	mrad	55	65
Magnet Gap	mm	40	90
Magnet Pole Width	mm	90	160
Max Field Strength	T	0.52	0.39
Number of coil turn	Turns/pole	15	18
Coil Inductance	mH/coil	0.3325	0.605
Coil Resistance	mOhm/coil	2.21	2.74
Repetition Frequency	Hz	100	40

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PHYSICAL DESIGN OF EXTERNAL TWO-STAGE BEAM CHOPPING SYSTEM ON THE TR 24 CYCLOTRON

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Abstract

We briefly introduce a new Cyclotron Laboratory of the Nuclear Physics Institute (NPI) of the Czech Academy of Sciences with the new cyclotron TR 24 which was commissioned in October 2015. One of the planned uses of TR 24 beams is a generation of high-intense fast neutrons fluxes with implementation of a chopping system for spectrometric measurements of neutron energy by the Time-of-Flight (TOF) method. For this purpose, physical design of a new ion-optical beam line was completed as well as comprehensive study of an external fast chopping system on this beam line. A set of home-made programs DtofDeflect has been developed for this system consisting of the first chopper powered by sinusoidal voltage and the second chopper powered by pulse voltage. The programs allow to find the optimum geometric and voltage parameters of the system by the means of mathematical simulations. The chopping system can provide the external 24 MeV proton beam with 2.3 ns pulse length at a repetition period of 236 ns in order to comply with the required pulse length to the repetition period ratio of 1 : 100.

INTRODUCTION

In 2011 it was decided to modernize an experimental basis of the NPI to supplement the original accelerator – isochronous cyclotron U-120M [1] (commissioned in 1977), with a new compact accelerator, which would take over some applications and extend experimental possibilities with its parameters. A good compromise solution between the required new cyclotron parameters (maximum beam energy at maximum beam current) and available funds was the purchase of the cyclotron TR 24 (24 MeV/300 μA) [2] of the Canadian company Advanced Cyclotron Systems, Inc. (ACSI). Research program of the TR 24 will be focused on production of established and novel medical radionuclides (e.g. ^{44}Ti, ^{67}Cu, ^{89}Zr and ^{68}Ga), and to feasibility study of implementing direct production of ^{99m}Tc via (p,2n) reaction as an viable alternative to reactor-produced generator ^{99}Mo/^{99m}Tc. Regarding the long-term experience with generation of fast neutron fields [3] on the cyclotron U-120M, the further important research program will be dedicated to experiments associated with the generation of high fast neutron fluxes. Physical design of the chopping system for spectrometric neutron TOF measurements fulfils one of the potential utilization of the TR 24 beam and defines conditions of its feasibility.

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NEW CYCLOTRON LABORATORY

The TR 24 cyclotron forms a core of the new laboratories built instead of a decommissioned (2012) Van de Graaf generator (VdG). The project started in 11/2012 and site acceptance test of the TR 24 was completed in 10/2015.

Figure 1: Old VdG and new cyclotron buildings.

Reconstruction of the VdG building covered design of the cyclotron layout and its shielding within the given ground plan. The cyclotron hall and hall for TOF system are located in the basement, the control room in the first floor above the cyclotron. Due to the space limitations, big care was devoted to minimizing thickness of the ceiling and the walls. Detailed simulations based on the MCNPX code resulted in reducing their thickness to 1.8 and 2.0 m, respectively, including the shapes of cable conduits and ventilation pipes. This solution required precise composition of heavy concrete with the density greater than 3 t/m^3. Effective cyclotron cooling and air-conditioning systems which include also air-conditioning for the radiochemical labs and the 6-floor building were designed so that more than 50% of thermal power produced by the cyclotron can be recuperated and utilized for heating of the building.

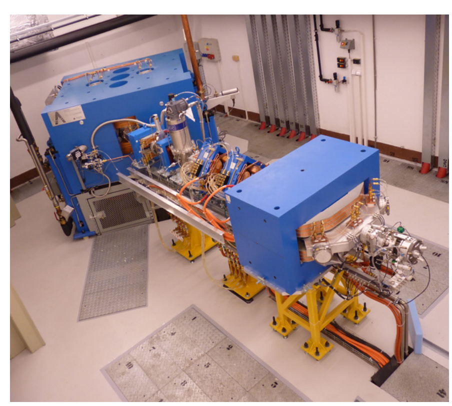

Figure 2: Cyclotron TR 24 with the beam line.

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DEVELOPED NUMERICAL CODE BASED ON THE EFFECTS OF SPACE CHARGE IN CENTRAL REGION OF 10 MeV CYCLOTRON

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Abstract

To study of space charge effects in 10 MeV cyclotron of Amirkabir University of Technology the C++ code is developed. This cyclotron is designed to accelerate H- up to10 MeV energy. The important components of cyclotron that effect on calculations of space charge include four sector magnets, 2 RF cavities with 71 MHz frequency and internal PIG ion source. Equations of motion and effects of charged particles in electromagnetic field of accelerator are integrated in C++ code. The conventional method, 4-order Runge-Kutta, is used to solve the equations. The results of calculations show space charge effects of beam particles on each other in accelerating process.

INTRODUCTION

The purpose of manufacturing 10 MeV Amirkabir University of Technology produced Fluor-18. The cyclotron contains some component to produce an electric field, magnetic field and injection particle. Component of central region shows in Fig. 1. Beam injection by an internal ion source PIG [1] was carried out. H- Beam with zero kinetic energy produced by the ion source, these particles by the puller that located at a certain distance from the ion source were pulled out due to potential difference between these two points. The primary particles begin to move and primary energy particles from this method will be provided [2]. Voltage of Dummy Dees and pullers are zero and 42 keV respectively, particles that accelerated in a first step and don't have any collection with a body of cyclotron now again accelerated. Continues acceleration of particles performed by a potential difference between the central part of the liner and central part of Dee's. Due to the beam dynamic depended to the early turns, set of electric and magnetic field geometry and initial condition of particle is very important. If the central region was not properly designed, couldn't be expected that particles extracted from cyclotron.

Numerical code was written in C++ program that used the conventional Rung-Kutta method and initial condition of particles and electric and magnetic distribution to calculate the trajectory of space charge effect of particles.

The method that used in this code is of effect of summing up the Coulomb's electric field of particles on one particle. That means effect of electric field of particles on the particle that located near them is considered.

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THE METHOD OF CALCULATING OF THE BEAM TRAJECTORY SPACE CHARGE

A code for calculation of particle trajectory in the central region of cyclotron, written by using C ++ language. Electric and magnetic field calculated by OPERA-3D-TOSCA.

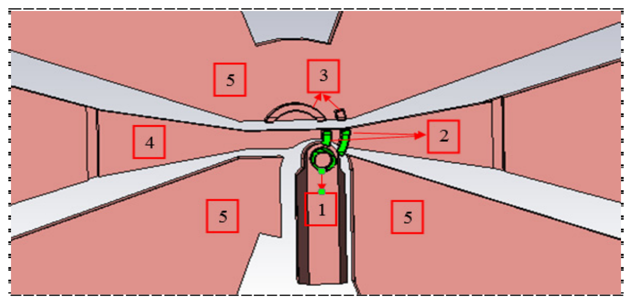

Figure 1: Geometry of electric field in central region 1) head of ion source 2) pullers 3) dummy Dee's 4) central part of Dee 5) central part of liner.

Results of TOSCA extracted and imported in to C++ code. C++ code calculated equation of motion according to the electric and magnetic field data's and initial condition that determined. Equation of motion that used in C++ code followed equation 1, 2, 3 [3].

$$\frac{d\vec{r}}{dt} = \frac{\vec{p}}{m\gamma} \quad (1)$$

$$\frac{d\vec{p}}{dt} = q(\vec{E}\cos\omega t + \frac{d\vec{r}}{dt} \times \vec{B}) \quad (2)$$

$$\frac{dW}{dt} = \vec{F}.\vec{\vartheta} = \frac{d\vec{p}}{dt}.\frac{d\vec{r}}{dt} \quad (3)$$

Above equations are used in Cartesian coordinate(x,y,z), where B(B_x, B_y, B_z), E(E_x, E_y, E_z) are magnetic and electric fields respectively. In this code magnetic field that created from beam current is not considered but electric field of that considered. So the electric field is as follows:

$$E_{(x,y,z)} = \varepsilon^{RF}_{(x,y,z)} + \varepsilon^{SC}_{(x,y,z)} \quad (4)$$

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SPES CYCLOTRON BEAMLINES

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Abstract

The SPES (Selective Production of Exotic Species) facility purposes are the production of radioactive beams (RIBs) by ISOL technique, the production and the research on innovative radioisotopes and experiments with high intensity neutron beams.

For these reasons, the 70p cyclotron, designed by BEST Cyclotron Systems Inc. (BCSI), has been installed at Laboratori Nazionali di Legnaro (LNL): it is a machine able to produce a beam current up to 700 µA shared into two extraction channels. Beams at the energy values of 35 MeV, 50 MeV and 70 MeV have to be transported to the experimental areas with specific properties and minimizing the beam losses. Here, the main features of the needed beamlines are described.

BEAMLINES OF THE SPES PROJECT

The core of the SPES project is the 70p cyclotron, a 4 sectors machine with room temperature coils, designed to accelerate H^- ions. The extraction by stripping method allows the beam current sharing into two extraction channels: it is possible to carry out simultaneously the production of radioactive ions and other applications [1].

Figure 1 shows the layout of the underground floor of the SPES building. The central vault (A1) houses the 70p cyclotron and it is surrounded by different experimental areas: in particular, there are three bunkers shielded for receiving high power beam (up to 50 kW). Figure 1 reports the beamline for the beam transport to the ISOL target (L1), which was designed by BCSI [2], and the beamlines L3b-L3c and L2, dedicated to the SPES applications. The beamline L1 is actually operational and, with the second extraction channel, it is included in the commissioning of the 70p cyclotron. As concern the other beamlines, the main properties of the achieved solutions are here described: these beamlines have the same initial elements of the beamline L1, from the combo magnet at the cyclotron extraction to the first switching magnet; the new designs have to take into account this fixed part and the preliminary results related to the first machine operations. The main requirement for each configuration is the minimization of the beam losses along the beam path: the allowable limit is 1%.

BEAM TRANSPORT TO ISOL AREA

The beamline to the ISOL area was installed in the vault in May 2015. The beamline design was completed to satisfy all the requirements needed for the ISOL facility, that is, a final RMS spot size around 4 mm. For the cyclotron commissioning by using the beam dumper designed by LNL SPES target team [3], new tunes of the 4 couples of quadrupoles were required, in order to increase the RMS spot size in the range 8 – 12 mm and, then, to optimize the power distribution in the inner surfaces of the device. A summary of the simulation results is reported in Table 1, for the minimum and the maximum values of the RMS spot size: the beam losses are less than the required limit.

Table 1: Simulation Results of the L1 Beamline Tunes

Energy [MeV]	35		50		70	
RMS spot [mm]	8	11	8	11	8	11
Q1 [T/m]	4.99	4.99	6.31	6.31	5.06	4.91
Q2 [T/m]	-5.41	-5.41	-6.69	-6.69	-6.68	-7.66
Q3 [T/m]	-4.35	-4.30	-5.25	-5.15	-5.45	-5.56
Q4 [T/m]	3.05	3.19	3.81	3.81	3.20	3.72
Q5 [T/m]	3.60	3.87	4.51	4.98	5.82	6.84
Q6 [T/m]	-5.06	-5.01	-6.24	-6.52	-7.25	-8.41
Q7 [T/m]	-4.04	-3.81	-4.64	-4.31	-5.90	-4.99
Q8 [T/m]	3.13	2.65	3.34	2.97	4.38	3.35
Losses [%]	0.12	0.22	0	0.19	0.02	0.1

Up to now, the L1 beamline has been fully tested only by using 70 MeV beam and the 4-jaw collimators placed just after the combo magnet have been used to reduce the beam halo. Furthermore, the wobbler system placed just before the A6 bunker entrance has been activated in order to get a uniform beam distribution and to avoid thermal stresses of the beam dumper. These effects have to be included in the complete study of the performance of the L1 beamline and are useful data for the improvement of the design of the new beamlines.

RADIOISOTOPE PRODUCTION

LARAMED (LAboratorio per la Produzione di RAdionuclidi per la MEDicina) is the proposal of LNL for the production of innovative radiopharmaceutical and conventional radionuclides [4]. The beamlines L3b and L3c, which satisfy the requirements described in table 2, share all the elements in A1 hall, then a 45 deg switching magnet is used to bend the beam in the low current experimental area.

Table 2: Main Features of the LARAMED Beamlines

	L3b	**L3c**
Energy range	35 – 70 MeV	35 -70 MeV
Average current	300 µA	< 1 µA
Beam spot size (RMS sigma)	3 mm	3 – 4 mm
Optic layout	3 quad doublets	1 switching magnet, 2 quad doublets

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AN AIR IONIZATION CHAMBER SIMULATION USING MONTE CARLO METHOD*

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Abstract

The CYCIAE-100 cyclotron with proton beam 200uA/100MeV and several beamlines have been developed at China Institute of Atomic Energy (CIAE) [1]. In order to protect the machine from excessive radiation activation, an uncontrolled loss criterion of 1uA is specified. Calculation for radiation shielding shows that high neutron and gamma are produced under this condition. To measure the high energy gamma -ray (about 2 MeV) [2] during machine running and void damage by the prompt radiation, an air ionization chamber is designed to fulfil this goal. A Geant4 program is developed to simulate the energy response of detectors; the EM filed data is also taken into consideration in the program. The simulation results indicate that the energy response linearity satisfies the requirement of the project specification.

INTRODUCTION

The Beijing Radioactive of Ion beam Facility (BRIF) Project has been built at CIAE. BRIF is consist of CYCIAE-100 proton cyclotron, ISOL, existing HI-13 Tandem, and super conducting linac(Tandem's booster). It is used for nuclear physics, proton therapy, materials science and application of nuclear technology etc. [3]. The driving accelerator, a 100MeV H- cyclotron, will provide high intensity stable proton beam from 75MeV to 100MeV up to 200uA. During the commissioning and operation, for the sake of beam loss, high energy neutron and photon will generate, which are harmful to staff's health and the reliability of cyclotron devices. In order to measure the actual radiation dose at real time and evaluate its hazard, a set of radiation dose monitoring system is necessary. We investigate the dose monitoring system of similar accelerators. According to the characteristics of the radiation field brought by the cyclotron, a radiation monitoring system has been constructed.

The monitoring system includes neutron detectors and γ detectors. The Monte-Carlo simulation results for shielding calculation illustrated that the energy of photon distribute from several keV to 10 MeV, the average energy is about 2 MeV yet. The maximum ambient dose equivalent rate is no more than 1Sv/h in the plane of beam transfer during beam delivering at the inner side of the wall of cyclotron vault and experiment hall. It is necessary to development a γ detector with high reliability that can work under above mentioned condition.

In consideration of the wide energy distribution of the photon, the energy response of detectors should have good linearity up to 10 MeV, furthermore working under high flux of neutron and photon, the detectors should have simple structure and less electronics to be maintained. For the reasons mentioned above, Air ionization chambers are very suitable compared with other detectors for the 100 MeV cyclotron radiation monitoring system. In order to study the characteristics of the energy response and determine the optimum size of the components of the chamber, A Geant4 code is programmed to achieve this goal; meanwhile Maxwell 3D is applied to evaluated the electrostatic electric field in the chamber.

SIMULATION TOOLS AND MODEL

Simulation Tools

There are two tools served mainly in this work, Geant4 and Maxwell 3D. The capacitance is important to the design of the preamplifier, moreover the electrostatic field distribution will influence the transit time of electron and ions generated by photon with air significantly. The Maxwell three-dimension (3D) is a set of powerful EM field simulation software; it can precisely solve different EM issue using finite element method. Geant4 is an open source framework, which can be used to simulation the interaction and transport process of particles in materials. Geant4 is widely employed in high energy physics, medical physics, detector studies, etc. [4], which is developed by CERN. It's also a huge Monte Carlo development toolkit. The data of physics models are represented as object oriented in Geant4. All the processes are built in, so the users can accomplish the whole simulation independent of external program.

The Geant4 framework provides toolkits to simulate the EM interactive processes; user can develop programs that emulate electron and photon interaction with different materials, meanwhile Geant4 provide several evaluated data library such as EPDL97, EEDL, EADL, NDL etc.

Detector Structure and Material

The main structure of the air ionization chamber can be sphere or cylinder. The sphere chamber has the most optimum performance of angular response to isometric radiation field. Due to the ionization chambers is installed at the same plane of beam, the cylinder structure is chosen according to our design, and this structure is easy to fabricate also. The sketch of the detector is shown in Figure 1. There are two parts consist in the detector, the air ionization chamber is located at upper cylinder, while the electronics circuit is seated at the bottom of the detector. The outer shell is made of metal to protect the chamber and the electronics circuit.

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PHYSICAL DESIGN OF THE EXTRACTION TRIM-RODS IN A 230 MeV SUPERCONDUCTING CYCLOTRON*

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Abstract

In order to increase turn separation and accordingly extraction efficiency in a superconducting cyclotron CYCIAE-230, a first harmonic bump is required to introduce beam processional motion. Eight trim-rods of variable position are employed at the extraction region to generate the desirable field bump. The amplitude and phase of first harmonics can be adjusted by changing the position of trim-rods to meet the requirements of extraction beam dynamics. However, its side effect on the isochronous field in acceleration region is inevitable. Therefore, the rest positions of trim-rods need to be determined and the re-shimming procedure of main magnet model needs to be implemented interactively. The effects of trim-rods and its influence on the isochronous field in a new model will be presented.

INTRODUCTION

CYCIAE-230, a superconducting cyclotron aims for proton therapy, is under design and construction at China Institute of Atomic Energy [1,2]. Beam dynamics and processional extraction design of CYCIAE-230 are studied for years. First harmonic bump is the source of procession in the extraction region, it could be generated from trim-coils as our former machine [3], but trim-rod field is more predictable and stable in the saturated pole region, and trim-rod method is proved effective in field shimming [4] and field excitation [5]. Extraction efficiency is the key parameter of extraction system, which related to radial oscillation amplitude, turn separation of particle motion and septum width of deflector. Trim-rods which located at the central line of each pole introduce first harmonic bump to provide enough processional motion and turn separation with the help of $\nu_r = 1$ resonance. In former extraction design stage, we adopted ideal Gaussian first harmonic field bump with fixed phase [6]. But real trim-rod field distribution should be employed for a precise result. And real field has effect on main magnet isochronous field which can be analysing by same model.

In this paper, two main magnet models, a 90 degree folded and a 360 degree one, are introduced. Trim-rod field is studied in detail with the 90 degree model, and the procedure of eight trim-rod position design to provide first harmonic bump with certain amplitude and phase is accomplished. Trim-rod field of 90 degree and 360 degree model with the same trim-rod position are compared. And finally, real trim-rod field effect on the isochronous field and the re-shimming results are presented.

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MAIN MAGNET AND TRIM-ROD MODEL

As the spiral sector pole model of CYCIAE-230 is complicated in trim-rod design, a straight sector pole model is used instead for simplicity. A 90 degree sector model (Fig. 1) is used in preliminary design to analyse the physical properties of trim-rod field and a full 360 degree model is used to determinate final trim rods parameters. The pole angle width and spiral angle had been well designed to get isochronous field and working diagram.

The extraction trim-rods are rod shaped with diameter of 30 mm and length of about 80 cm, located at the central line of each pole with radius 79 cm. Trim-rods are driven by electric motors separately. When a trim-rod is elevated, an air-rod is generated inside the pole, leading to a field bump which decrease main magnet field locally. First harmonic field with amplitude less than 10 Gauss and arbitrary phase can be achieved by positioning eight trim-rods. For simplicity, the trim-rods are replaced by square rods with same cross section area in models.

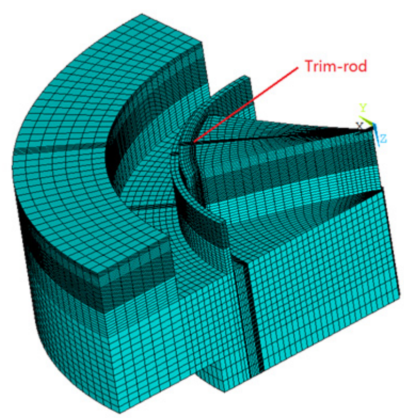

Figure 1: 90 degree straight sector model.

TRIM-ROD POSITION DESIGN

Main task of trim-rods physical design is to determine the height of each air-rod and the rest position of trim-rods. Design process is based on 90 degree sector model and the requirements of extraction beam dynamics. The oscillation amplitude at extraction point is mainly dependent on the amplitude and phase of the first harmonic bump, the FWHM of amplitude radial distribution $B_1(r)$ also has accumulative effect on oscillation amplitude, but the FWHM is hard to adjust.

It had been tested that first harmonic bump with following parameters reaches the highest extraction efficiency: 2.74 Gauss amplitude at 79 cm, 337 degree phase and the Gaussian fit of $B_1(r)$ has $\sigma = 6$ cm, and second harmonic amplitude should be less than 1 Gauss to minimize the effect of second order resonance. About 10% change of

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INVESTIGATION OF MINIMIZED CONSUMPTION POWER ABOUT 10 MeV CYCLOTRON FOR ACCELERATION OF NEGATIVE HYDROGEN

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Abstract

SKKUCY-10 cyclotron with 10 MeV particle energy was designed with purpose of production about fluorodeoxyglucose (FDG). Design strategy was maximization of accelerating voltage in order to secure the turn separation. Magnet had deep valley type, RF cavity had four stems and one RF power coupler. There was internal ion source for compact design of cyclotron. Specification of cyclotron was analysed by simulating particle dynamics for central region and whole system. AVF cyclotron had 83.2 MHz of radio frequency, 1.36 T of average magnetic field, 40 kV of main accelerating voltage. Phase slip between RF and beam was less than 15 degrees, minimum turn separation was over 2 mm. Specifications of both single beam analysis of reference particle and multi-beam analysis of bunch of particles were calculated by using Cyclone v8.4 and CST-Particle studio codes.

INTRODUCTION

Cyclotron was one of main device to product medical radio isotopes such as ^{18}F, ^{13}N, ^{11}C, ^{15}O for PET and ^{64}Cu, ^{67}Ga, ^{99m}Tc, ^{123}I for SPECT and so on [1]. Since fluorodeoxyglucose(FDG) was useful for diagnosis of cancer by using positron emission tomography machine, cyclotron was started to developed rapidly for production of ^{18}F isotope. Production yield of ^{18}F was studied with many nuclear reaction, there were optimal condition, acceleration energy, type of particle. Main process was also discovered (p, n) reaction at ^{18}O liquid target with few MeV energy level.

Design strategy of cyclotron was affected by user, medical physicist and researcher of radio isotope, and cyclotron market. Most cyclotron was distinguished by accelerating energy. One of design goal is compact size or high current with low energy for production of medical isotope with 7~20 MeV, another is high efficiency with 30~100 MeV for research field. There also be higher energy 100, 250 MeV cyclotron in order to apply the proton therapy or production of neutron [1- 3].

Cyclotron of ^{18}F production was developed to maximize the beam current with optimal energy 9~11 MeV. Low energy cyclotron usually had sector focus magnet typed pan cake and internal penning ionization gauge ion source. There are two types low energy cyclotron, one is used 4 stems dee and deep valley magnet, other is 2 stems dee and shallow valley magnet [4, 5]. Deep valley design was known that it has advantage of increasing characteristic of vertical focus. It was affected to decrease the beam losses inside cyclotron, to maximize the emission current at the target. One of main limitation of emission current is performance of internal ion source, it is depended on number of particle in the plasma region inside of chimney. So there was high current cyclotron used two internal ion source in order to increase the emission current [6].

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DESIGN OF MAIN STRUCTURE

Cyclotron focused production of ^{18}F isotope was designed for acceleration of negative hydrogen ion with 10 MeV peak energy. Main strategy of design was maximization of beam current keeping the small size of cyclotron. Design of cyclotron was performed by progressing four steps. First one is selected radio frequency 83.2 MHz, fourth harmonics considered specification of RF power, size of magnet and coil power.

Design Concept

Cyclotron for 10 MeV was consisted of sector focus magnet, coils, half wavelength resonator, PIG internal ion source and vacuum chamber. Scheme of structure was represented in Fig. 1, it is shown cross section view according to beam plane (z = 0). Magnet has 8 hills and shim bar, four side yokes, RF system was consisted of four dees and four liners, one power coupler and fine tuner. Vacuum chamber was positioned between coil and hill, one PIG ion source connected with chamber.

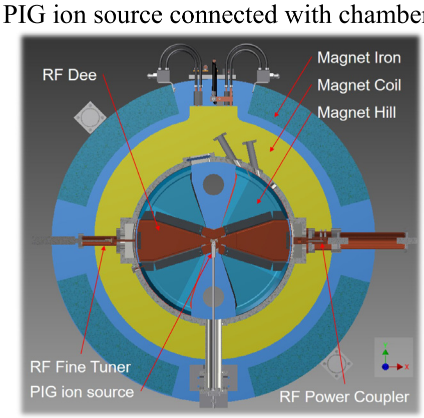

Figure 1: Cross section view of 10 MeV cyclotron.

Main parameter of cyclotron structure was listed up at Table 1. There were four sectors in the magnet iron, pole radius was 750 mm. When radio frequency is 83.2 MHz, isochronous radius for 10 MeV is calculated about 335

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SIMULATION CODE DEVELOPMENT FOR HIGH-POWER CYCLOTRON*

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Abstract

A high power cyclotron is a good candidate as a driver of the accelerator driven system for the transmutation of long lived nuclear wastes. In this work, a simulation code has been developed for describing the beam dynamics in the high power cyclotron. By including higher order terms in transverse transfer matrix and space charge effects, we expect to describe the beam motion more accurately. The present code can describe equivalent orbit at each energy, calculate the tunes, and also perform multi-particle tracking. We report the initial results of the code for the simulation of a 13 MeV cyclotron. Lastly, an upgrade plan is discussed to add more features and to increase calculating efficiency.

INTRODUCTION

In Korea, nuclear energy occupies about 40 percent of the electric power production. It can be a solution to the energy problem that we are facing these days before commercializing nuclear fusion energy. But one of the difficulties is that expanding nuclear power plant as the nuclear power is dangerous when natural disaster occurs, thus, high-level radioactive waste that has a half-life of a few hundred thousand years is created. To transmute from high-level radioactive waste to short-lived radioisotope, development of high power cyclotron which is part of ADS (Accelerator Driven System) is very desirable.

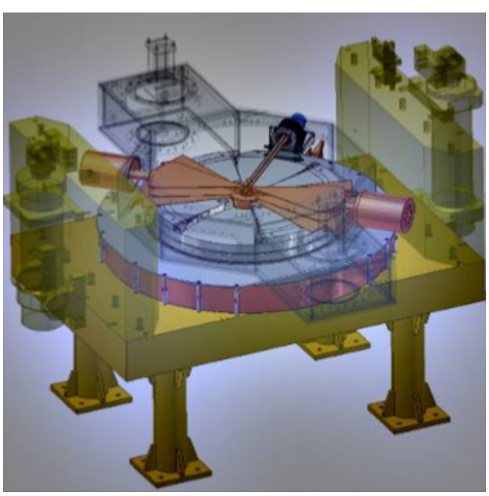

Figure 1: 13 MeV cyclotron.

As benchmark study for the simulation code, we simulate beam dynamics in KIRAMS 13 MeV Cyclotron (Fig. 1). The KIRAMS 13 MeV Cyclotron has four sector magnets and a RF cavity where it has its frequency of 77.3 MHz, Ion sources are producing proton beam and the beam current is 80 μA. The EO Code (Equilibrium Orbit Code) including beam tracking function is written by Matlab to demonstrate equilibrium orbit of multi-particle beam. This code uses Runge-Kutta Gill method to solve integration of the canonical equations of motion. This code does not yet include acceleration effect, but the conventional way of adding small energy is adopted. So the present code can describe equilibrium orbit at each energy level, and we can analyze various physical parameters such as equilibrium orbit, phase space, phase error, betatron tune, resonances and Twiss parameters.

In the future, we will add acceleration effect and algorithm of space charge effect in EO Code.

BEAM TRACKING

The magnetic field distribution (Fig. 2) is designed by OPERA-3D.

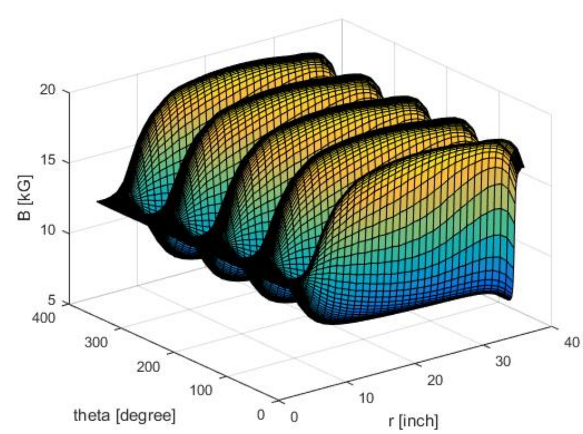

Figure 2: Magnetic field distribution with respect to r and θ.

The characteristic of EO Code is based on the integration of the canonical equations of motion [1]. EO Code uses Runge-Kutta Gill method to calculate differential equations of motion. EO Code consists of several steps. First, this program calculates equations of motion which are r, p_r, x and p_x as a function of θ. Second, this program checks whether closed orbit is made or not. If closed orbit is not made, the program increases r and p_r of particle and iterates to find closed orbit of particle. If a closed orbit is made, the program then calculates the equations of mo-

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NUMERICAL ORBIT TRACKING IN 3D THROUGH THE INJECTOR CYCLOTRON FOR HEAVY IONS AT iTHEMBA LABS

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Abstract

The electric and magnetic fields of the second injector cyclotron (SPC2) [1] were modelled in 3D with finite element methods, using OPERA-3d [2], in an effort to determine the cause of the relative poor 5% beam transmission through the machine in the 8-turn mode. Simulation of the particle motion was done using machine operational parameters for acceleration of a $^{20}Ne^{3+}$ beam.

Using TOSCA [2], an isochronous magnetic field was calculated from a complete cyclotron magnet model and the electrostatic field distribution from a dee electrode model. The SOPRANO-EV [2] modelling of the RF resonance conditions of the resonators provided radial electric field profiles in the acceleration gaps.

A command line program was developed to combine the information of the three models and implement time-dependent control of the electrostatic fields during the particle tracking.

In addition, based on calculated data from OPERA-3D, the parallel particle-in-cell code OPAL-CYCL [3, 4] was used to calculate a particle orbit for comparison.

SIMULATION MODELS AND CONTROL

General

The SPC2 pre-accelerates heavy ion beams before injection into the separated sector cyclotron. The beam from one of the two external ion sources is axially injected upwards and bent into the median plane of SPC2 through a spiral inflector. It is a solid pole cyclotron with 4 radial magnet sectors and 8 trim coils. The electric fields in the 4 acceleration gaps are provided by two horizontal λ/4 coaxial resonators with 90° dees that operate in the frequency range 8.6 MHz to 26 MHz [5].

Simulating the 8-turn orbit mode in SPC2 requires cyclotron settings such that a particle crosses 34 acceleration gaps before reaching the electrostatic extraction channel (EEC), followed by another acceleration gap crossing before exiting the machine. The horizontal width of the EEC gap at the entrance is 14 mm and its radial centre position is adjustable between 456 and 470 mm.

The calculations reported here are based on known operational conditions for a $^{20}Ne^{3+}$ beam with an extraction energy of 3.81 MeV, for acceleration at a harmonic number of 6 and peak dee voltage of 37.4 kV at 12.16 MHz. The spiral inflector voltage and ion source extraction voltages are 4.3 kV and 13.37 kV, respectively.

The magnetic flux density in the centre is 0.88 T.

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Cyclotron Magnet Model

The finite element model of the SPC2 magnet includes all geometrical detail of the steel and coils, together with the axial hole in the yoke that, amongst others, contains solenoids and steerer magnets in the lower half of the yoke. The known magnetic material characteristics of the iron are used in the simulation.

The same magnet model was used to build a database that is used to predict the coil currents required for isochronous magnetic fields at different particle energies [6].

The lower pole geometry of the magnet and coils are shown in Fig. 1.

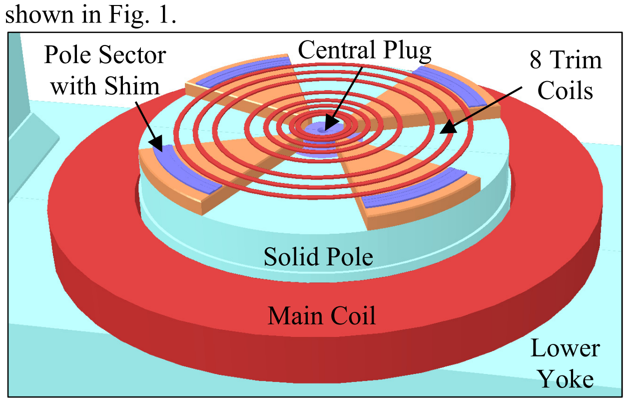

Figure 1: The lower half of the magnet pole geometry, including 4 pole sectors, shims and coils.

Acceleration Electrode Model

In order to obtain the fields in the acceleration gaps under RF conditions, the electric field profile in each acceleration gap was calculated with a model for each of the two RF resonators, using the eigenvalue solver of SOPRANO. The model shown in Fig. 2 includes the dees, dummy dees, puller, capacitors, short-circuit plates and central region, but without the inflector. The calculated normalized field values are shown in Fig. 3.

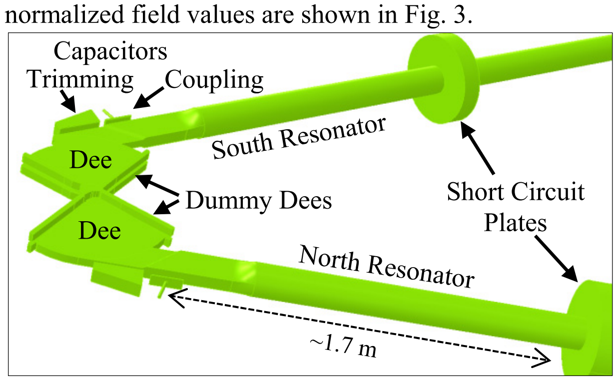

Figure 2: Model of the RF resonators without the outer conductors.

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INJECTION LINE STUDIES FOR THE SPC2 CYCLOTRON AT ITHEMBA LABS

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Abstract

The transmission efficiency of some ion beams through the second solid-pole injector cyclotron (SPC2) at iThemba LABS requires improvement. In order to understand the beam optics in the injection line, and match the beam to the acceptance of the cyclotron, the beam envelope behaviour from the beginning of the vertical injection-line to SPC2 was investigated with different simulation programs. The transverse effects were taken into account by the beam transport codes TRANSOPTR and TRANSPORT, while the multi-particle simulation code OPAL was used to include space-charge effects. Simulations of the effect of an additional buncher, operating at the second harmonic, on the transmission of the beam through the cyclotron were made.

INTRODUCTION

A K=8 MeV second solid-pole injector cyclotron at iThemba LABS, shown in Fig. 1, is used to pre-accelerate light and heavy ions, as well as polarized protons, before injection into the separated-sector cyclotron (SSC) for final acceleration [1]. The beams are mainly used for nuclear physics experiments. To accelerate both light and heavy ions, SPC2 was designed to utilize three constant orbit patterns. Depending on the final energy required and type of ion species to be accelerated, ions make 8, 16, or 32 turns before extraction. The transmission efficiency for the 8 turn pattern, however, requires improvement.

Figure 1: A photograph of SPC2.

The beams from the ion sources, which are situated in the SPC2 vault basement, are injected axially into the cyclotron. The DC beam is bunched using a double-gap buncher operating at the fundamental frequency before being deflected onto the median plane of the cyclotron with a spiral inflector. The beam is bunched in order to increase the number of ions that can be accelerated within the phase acceptance of the cyclotron.

In an attempt to improve the transmission efficiency of SPC2, beam dynamics simulations studies of the vertical beam line were performed using three codes. For the transverse optics of the beam along the injection line the beam transport code TRANSPORT [2] was used. The second-order beam transport code TRANSOPTR [3] was used because of its capability to include an arbitrary matrix for the spiral inflector. The Object Oriented Parallel Library (OPAL) code [4], which includes 3D space-charge effects, was utilized to investigate the bunching efficiency of an additional buncher, operating at the second harmonic, on the number of ions that can be grouped within the phase acceptance of SPC2.

TRANSVERSE OPTICS

Beams of heavy ions produced by the electron cyclotron resonance (ECR) ion sources are deflected into the vertical beam line using a 90^0 dipole magnet. The vertical beam line, shown in Fig. 2, consists of two triplets (Q1–Q6) and two solenoids magnets (SL1 and SL2). Also available are steering magnets that steer the beam in both X and Y directions [5].

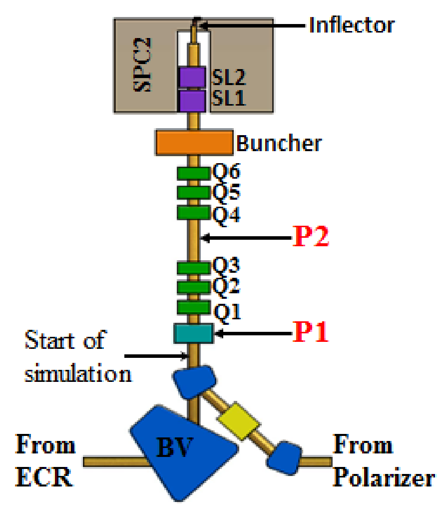

Figure 2: The axial beam line leading into the median plane of SPC2.

It is assumed that the deflection of the beam from the horizontal beam line into the vertical beam line is axisymmetric. Thus, for the present study only the beam dynamics through the vertical beam line was investigated. In the current study $^{20}Ne^{3+}$ ions with an energy of 48.50 keV were considered. The initial phase space parameters

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FAST SCANNING BEAMLINE DESIGN APPLIED TO PROTON THERAPY SYSTEM BASED ON SUPERCONDUCTING CYCLOTRONS*

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Abstract

Proton therapy is recognized as one of the most effective radiation therapy method for cancers. The superconducting cyclotron becomes an optimum choice for delivering high quality CW proton beam with features including compactness, low power consuming and higher extraction efficiency. This paper introduces design considerations of the beamline with fast scanning features for proton therapy system based on superconducting cyclotrons. The beam optics, the energy selection system (ESS) and the gantry beamline will be described.

INTRODUCTION

HUST Proton Therapy Facility is a 5 years (2016-2020) Major State Research & Development Program supported by MOST (Ministry of Science and Technology, China). This is a collaborative project with teams from HUST, CIAE (China Institute of Atomic Energy), Tongji Hospital and Xiehe hospital affiliated to HUST. The main purposes of this project includes 1) R&D of a proton therapy facility based on isochronous superconducting cyclotron, with two 360 degrees gantry rooms and one fixed beam line treatment room; 2) Installation and commissioning in the International Medical Center of HUST; 3) Clinical experiments for CFDA. The main specifications are listed in Table.1.

Table 1: Main Specifications of HUST PT Facility

Parameter	Specification
Beam energy from the cyclotron	250 MeV
ESS energy range	70-250 MeV
Energy modulation time per step	≤ 150ms
Gantry rotation range	±180 degree
Positioning precision at Iso-center	≤0.5mm
Max. dose rate	3Gy/L/min
Field size	30cm×30cm

This paper mainly introduces design and considerations of the beamline. Since the cyclotron is designed to provide 250MeV fixed energy proton beam, ESS must be used to modulate beam energy in range of 70-250 MeV. Pencil beam scanning will be employed for fast and accurate treatment, with the main mode of spot scanning.

OVERALL CONSIDERATIONS OF BEAMLINE

Figure 1 shows the layout of the beamline. The degrader is placed at the downstream of the cyclotron, for better radiation control of neutrons. A DBA (double bend achromatic section) is followed with the degrader, with an energy select slit. For the gantry beamline, a downstream scanning scheme is chosen to avoid construction of large aperture 90 degrees dipole which is required in upstream scanning. Another cons is the linear dependency between the beam position and the scanning magnet current relieves difficulty of the therapy planning. To avoid the dose accumulation on skins due to un-parallel beam, the SAD (source-axis distance) is designed to around 2.8 m.

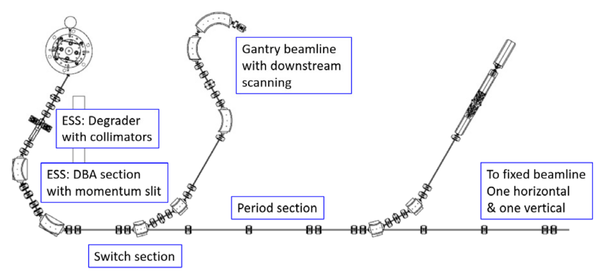

Figure 1: Layout of the beamline (correction magnets and beam diagnostics are hidden).

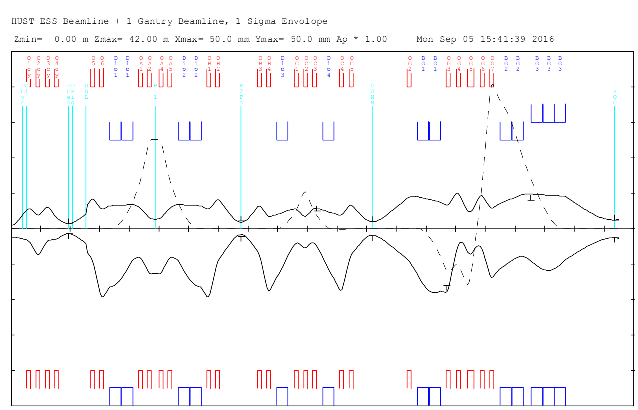

Figure 2: 1 sigma beam envelope for the main beamline including ESS and gantry beamline.

Figure 2 shows the 1 sigma beam envelope of the beamline using Transport code [1]. Main optics consideration about the beamline are:

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PRODUCTION OF F-18 AND TC-99M RADIONUCLIDES USING AN 11-MEV PROTON-ACCELERATING CYCLOTRON*

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Abstract

An 11-MeV proton-accelerating cyclotron has been employed to produce F-18 and Tc-99m radionuclides. In this report, F-18 radionuclide was produced from enriched-water ($H_2{}^{18}O$) target whereas Tc-99m was generated from natural molybdenum trioxide (MoO_3) target. Two recoiled radioactive impurities such as Co-56 and Ag-110m are identified in the F-18 solution whereas N-13 was recognized as an impurity in the Tc-99m production. The Co-56 radionuclidic impurity is presumably sputtered off the havar window in the target system whereas Ag-110m is originally from a silver body housing the enriched water target which is generated by secondary neutron irradiated Ag-109. In addition, N-13 impurity found in the post-irradiated MoO_3 target occurs presumably via (p,α) nuclear reaction.

INTRODUCTION

Positron and gamma ray emitting radionuclides such as F-18 and Tc-99m have been used for medical imaging of tumors, cancers and other metabolism-related diseases via the-so-called Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT) [1-4]. In Indonesia, F-18 radionuclide has been routinely produced using an 11-MeV cyclotron at Dharmais Cancer Hospital [5], whereas cyclotron-produced Tc-99m is still under investigation. Previous research suggested that radionuclidic impurities such as Co-56 and Ag-110m radionuclides were identified in the post-irradiated enriched water target, though it did not quantify the radioactivities. Further studies are, therefore, required to better understand the amount of impurities and their dependence on the proton beam doses.

In terms of technetium-99m, it has been reported that the most widely used radionuclide in nuclear medicine has experienced shortages lately [6-7] since production of the gamma emitting radioisotope has been mostly carried out using nuclear reactors while the rate of new nuclear reactor establishments is slowing down and the number of aging reactors is increasing. An alternative method of producing Tc-99m using cyclotrons has been proposed elsewhere [8] to tackle the shortage issues. Medium energy protons in the range of 8 – 18 MeV have been suggested to irradiate molybdenum (Mo) targets [9], either natural or enriched Mo to obtain high specific activity of Tc-99m, though enriched Mo-100 is preferred for better yields [10].

* Work supported by TWAS, BATAN and NCC
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In this paper, production of F-18 radionuclide at different integrated proton beam currents or doses is discussed and dependence of impurity intensities on proton beam current is also presented. Moreover, preliminary result of Tc-99m production using an 11-MeV cyclotron is also highlighted in this report.

EXPERIMENTAL METHOD

The 11 MeV Cyclotron

The cyclotron employed in this investigation is a typical Eclipse Radioisotope Delivery System (RDS) 111 cyclotron located at the National Cancer Center (NCC), Dharmais Cancer Hospital in Jakarta, Indonesia, which has been described elsewhere [5]. The cyclotron accelerates 11-MeV protons at a beam current of up to 60 μA, though in this investigation the maximum proton beam employed in the target irradiation is between 20 and 30 μA, depending on the targets of interest, while the irradiation time varied between 15 and 60 minutes.

The Target Systems

The target vessel/body for F-18 production comprises of a silver body/tube and is separated from the beam window by another 50 μm thick Havar foil, which has been described elsewhere [5]. During proton bombardment, havar foil is expected to be activated via (p,n) nuclear reaction, thus the proton-generated radionuclides could potentially contaminate the enriched water target should they recoil off the havar window.

In Tc-99m production, the target system consists of an aluminum tube housing a target holder where the target is placed in, as can be seen in Figure 1. During the target irradiation, the target system was cooled by Helium and water coolant to avoid excessive heat while the temperature was monitored throughout the irradiation procedure.

Production and Analysis of F-18

Fixed energy proton beams of 11 MeV was bombarded into 1.8 mL enriched-water target ($H_2{}^{18}O$). The experiment was conducted at variable proton beam currents between 10 and 30 μA.hr. At the end of the bombardment, F-18 yields and radionuclide impurities were analyzed shortly following an hour cooling period using a portable gamma ray spectrometer. The spectrometer consists of a NaI(Tl) detector coupled to a portable pocket Multi Channel Analyzer (MCA).

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STUDY OF THE BEAM EXTRACTION FROM SUPERCONDUCTING CYCLOTRON SC200

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Abstract

According to the agreement between the Institute of Plasma Physics of the Chinese Academy of Sciences (ASIPP) in Hefei, China, and the Joint Institute for Nuclear Research (JINR), in Dubna, Russia, the project of superconducting isochronous cyclotron for proton therapy SC200 is under development at both sites. The cyclotron will provide acceleration of protons up to 200 MeV with maximum beam current of ~1 μA.

Extraction system of the beam consists of electrostatic deflector and two passive magnetic channels. Electric field strength in deflector does not exceed 170 kV/cm, gradients of magnetic field in channels are in a range of 2-4 kG/cm. Both channels focus the beam in horizontal plane. Axial focusing of the beam is provided by edge magnetic field of the cyclotron.

Results of the beam tracking inside extraction system are presented. Efficiency of the beam extraction was estimated for different amplitudes of the betatron oscillations in the accelerated beam.

WORKING DIAGRAM OF CYCLOTRON

Different 3D codes have been used [1] in order to find acceptable geometry of the cyclotron magnetic system. Main purpose was to provide the working diagram without crossing of the most dangerous resonances such as $2Q_z=1$ and $Q_r-Q_z=1$. Many of the magnetic field maps computed by the different codes had large nonlinearities especially at edge region where a sector gap was rather small (<2 cm). These nonlinearities led to a waving of the betatron tunes and multiple crossing of the resonances. The most linear field map was obtained by the CST code [2].Figure 1 shows the working diagram of the cyclotron calculated on the base of this map. To get this diagram, the average magnetic field of the map was substituted by isochronous one. Resulting field map that correspond to presented diagram was applied for simulation of the beam acceleration up to deflector entrance.

One can see that the working point crosses the resonance $Q_r-Q_z=1$ at the very end of acceleration. This condition forced us to locate the deflector before full crossing of the resonance and implement extraction of the beam. The results are discussed below. The possibility that avoids crossing of this resonance is expected by means of special correctors during real shaping of the magnetic field.

Simulation of the beam acceleration shows that crossing of the $3Q_r=4$structural resonance is not dangerous. Increase in the radial amplitudes is acceptable.

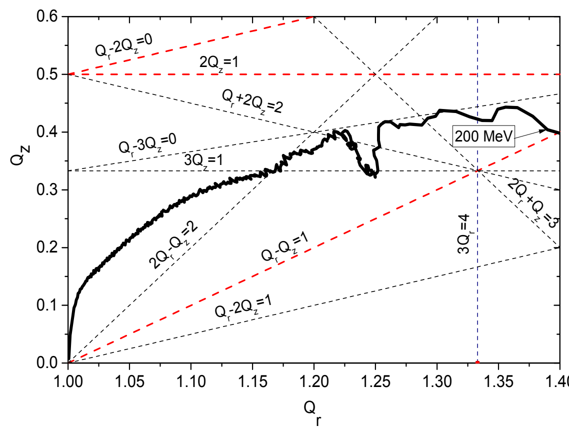

Figure 1: Working diagram of the SC200 cyclotron.

BEAM PARAMETERS AT DEFLECTOR ENTRANCE

There are two different ways to enlarge radial gain enhancement at deflector entrance, resonance and not resonance. The 1-st one was used in VARIAN C250 cyclotron [3], the 2-nd one in IBA C235 [4]. And the 2-nd will be applied in our cyclotron. In this scheme of extraction, the radial gain enhancement is mainly provided by radial betatron motion at Q_r~1.2-1.3. If amplitude of incoherent radial oscillations in accelerated beam comprises 3-5 mm then the radial width of the beam at deflector entrance is of about 2-3 mm. Not more than 10% of this value is provided by energy gain per turn, and the main part is connected with betatron motion.

In order to get the beam parameters at deflector, a bunch of 1000 protons was accelerated from the energy of 80 MeV. Initial parameters of protons were matched with the cyclotron acceptance at this energy for different amplitudes of radial oscillations in the range of 2-5 mm. Amplitude of axial oscillations was equal to 2.5 mm.

Different types of proton losses were estimated:

- axial, due to impact of the $Q_r-Q_z=1$coupling resonance;
- on a tip of septum, assuming 0.1 mm its thickness;
- on external side of the septum looking on the accelerated beam.

Different septum thickness along its length has been studied, constant 0.1 mm or linear increased up to 1-2 mm.

* Work supported by the funding of CN-RU cooperation cyclotron design
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THE ISOLPHARM PROJECT FOR THE PRODUCTION OF HIGH SPECIFIC ACTIVITY RADIONUCLIDES FOR MEDICAL APPLICATIONS*

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Abstract

ISOLPHARM is a branch of the INFN-LNL SPES project, aimed at the production of radioisotopes for medical applications according to the ISOL technique. Such an innovative method will allow to produce carrier-free radionuclides, useful to obtain radiopharmaceuticals with very high specific activities. In this context a primary proton beam, extracted from a cyclotron will directly impinge a target, where the produced isotopes are extracted and accelerated, and finally, after mass separation, only the desired nuclei are deposed on a secondary target.

This work is focused in the design and study of the aforementioned production targets for a selected set of isotopes, in particular for ^{64}Cu, ^{89}Sr, ^{90}Y, ^{125}I and ^{131}I. ^{64}Cu will be produced impinging Ni targets, otherwise the SPES UC_x target is planned to be used. Different target configurations are being studied by means of the Monte Carlo based code FLUKA for the isotope production calculation and the Finite Element Method based software ANSYS ® for the temperature level evaluation.

An appropriate secondary target substrate for implanting the produced isotopes is under study.

INTRODUCTION

SPES (Selective Production of Exotic Species) is a project aiming at the construction of an ISOL facility (Isotope Separation On-Line) at INFN-LNL (Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Legnaro) for the production of radioactive ion beams of neutron rich nuclei with high purity, with mass ranging between 80 and 160 amu [1].

In this framework the ISOLPHARM project is devoted to the application of the SPES technologies for the production of innovative radiopharmaceuticals.

Radiopharmaceuticals are drugs capable of delivering a predefined dose of radiation to a biological target tissue for diagnostic or therapeutic purpose. They are usually composed by a “radioactive core” and a “carrier system” that allows to deposit radiation selectively onto the malignant tissue avoiding the compromising of healthy cells.

Since the ISOL technique allows the on-line production of high intensity and high quality radioactive ion beams [2], it might be an efficient way to produce radionuclides for radiopharmaceuticals with specific activity close to its theoretical value. The higher is the specific activity, the more effective is the radionuclide for the radiolabeling of compounds.

ISOLPHARM project will mainly deal with two aspects: the isotope production according to the ISOL technique and the radioPHARMaceuticals labelling with the produced nuclei, after the radionuclide purification.

Radionuclides will be produced by impinging a dedicated target with a primary proton beam extracted from SPES cyclotron (up to 70 MeV 350 μA). The production target will be held at high temperature (up to 2200-2300°C), thus allowing the migration of the produced nuclei towards the ion source thanks to the diffusion and effusion processes [1]. After ionization a radioactive ion beam will be extracted with a potential difference up to 40kV. Mass separation will provide the desired single-mass nuclide beam which will be deposed in an appropriate collection target. Since the collected isotopes are characterized by a single mass number, the subsequent chemical separation will provide the desired single isotope for the radiopharmaceuticals labelling. After pharmaceutical processes high specific activity drugs will be available for diagnosis and therapy (Fig. 1).

The radioisotopes interesting from a radiopharmaceutical point of view are: ^{89}Sr, ^{90}Y, ^{125}I, ^{131}I, ^{133}Xe [3, 4, 5, 6, 7], which can be produced through fission using the SPES uranium carbide target, and ^{64}Cu [8] produced through spallation on a dedicated nickel target. Different production target configurations are described in this work.

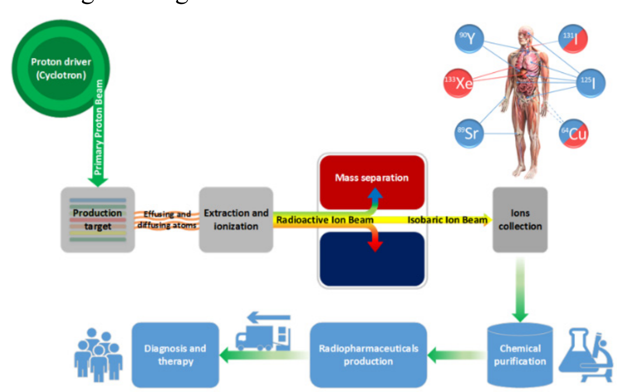

Figure 1: Overview of the ISOLPHARM project, grey balloons concern the isotope production aspects, blue balloons deal with the chemical and pharmaceutical aspects. On the top right are indicated the first planned isotopes for radiopharmaceutical labelling.

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BEAM OPTICS CONSIDERATIONS FOR ISOTOPE PRODUCTION AT THE PSI CYCLOTRON FACILITY

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Abstract

The isotope production beam line starts at the electrostatic beam splitter, which peels off a beam of a few tens of µA from a main beam of high intensity up to 2.4 mA. The beam optics has to ensure that the beam on target will be in right size. Due to the parasitic nature of the beam line, the beam optics also has to get along with the tuning of the main beam, especially in the sections upstream of the beam splitter. Aiming at a reliable and efficient isotope production, the beam optics is monitored for each irradiation session. The operational experience together with further development is presented.

BEAM LINE

The isotope production beam line starts at the electrostatic beam splitter EXT and ends at the target station as illustrated in Figure 1, where the important beam optics elements, namely the bending magnets, the steering magnets and the quadrupoles, are marked blue, orange and red, respectively. The length of the beam line is approximately 22 m.

The splitter EXT peels off a beam of a few tens of µA from the main beam coming from the 72 MeV Injector II cyclotron. The intensity of the peeled beam is regulated through adjusting the position of the splitter with respect to the main beam by a control loop [1].

The beam for the isotope production is deflected around 0.6° by the electrostatic field, whereas the main beam passes through a field-free region. A separation more than 40 mm may be created at the entrance of the septum magnet AYA, about 4 m downstream of the splitter EXT. The magnet AYA bends the peeled beam 17.5° further away from the main beam.

The beam energy may be reduced from 72 MeV to 40 MeV by inserting the graphite degrader DYD into the beam line. The degrader DYD locates in front of the quadrupole QYA6.

The beam position is controlled by the beam centering program through adjusting the strength of steering magnets according to the actual beam positions measured by the beam position monitors named as MYS*N* in Figure 1. Here *N* is an integer number with odd and even representing horizontal and vertical position, respectively. The measured beam positions are stored automatically into the database.

The beam profiles are measured by the beam profile monitors named MYP*N* in Figure 1. Here *N* is also an integer number with odd and even representing horizontal and vertical profile, respectively. The profile scan may be carried out with a single monitor or a group of preselected monitors. The profile measurement and the database registration are performed not automatically, but on demand.

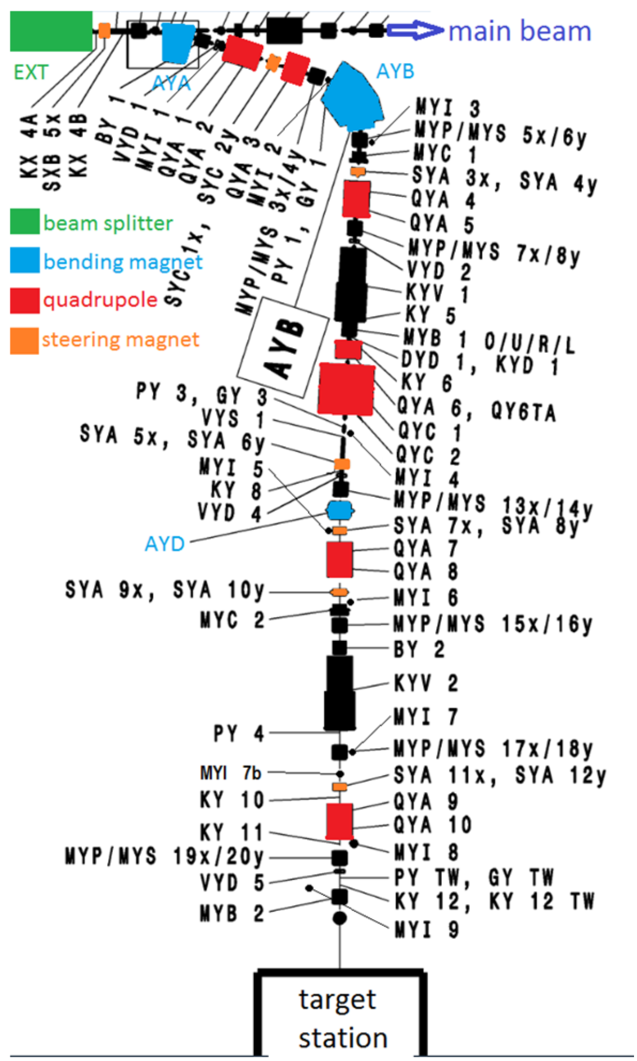

Figure 1: Isotope production beam line.

BEAM OPTICS

The beam line has to guide the beam of desired size onto the target. The challenge to the beam optics comes firstly from the fact that the required beam size differs significantly from one isotope production to another. For example, the diameter of $^{44}CaCO_3$(graphite) target for ^{44}Sc production is around 6 mm which requires a beam of 2σ less than 5 mm, while ^{64}Ni(Au) target for ^{64}Cu production requires a beam of 2σ greater than 7 mm. The difficulty arises also from the fact that the beam size on target cannot be measured in situ in real-time. The profile monitor next to the target is one meter away. The other difficulty arises from the parasitic nature of the beam line. As a

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ACTIVITIES FOR ISOTOPE SAMPLE PRODUCTION AND RADIATION EFFECT TESTS AT JULIC/COSY JÜLICH

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Abstract

At the Forschungszentrum Jülich (FZJ) the intermediate energy cyclotron JULIC, used as injector of the Cooler Synchrotron (COSY), and at the COSY itself, over the last years, have been enabled to perform low to medium current irradiations. Main task is to support the FZJ radionuclide research programme of INM-5, by developing, adapting and optimizing the irradiation facilities. The INM-5 target holders were implemented via an adapter section to the external target station of JULIC to obtain reliable irradiations with 45 MeV protons and 76 MeV deuterons, both for nuclear reaction cross section measurements and medical radionuclide production. For testing of radiation effects, displacement damage (DD) and single event effects (SEE), with energetic protons for electronics used in space and accelerators the beam can be extracted to a dedicated test stand, e.g. used by Fraunhofer INT. To provide these possibilities at higher energies up to 2.5 GeV as well one external beamline of the cooler synchrotron COSY is going to be equipped with a new irradiation vacuum chamber to separate the irradiation zone from the COSY-vacuum system and adaption for the dosimetry systems are done. Different dosimetry systems (PTW® Farmer ionization chambers, PTW® Bragg Peak chambers, Gafchromic® Dose sensitive foils) are available to monitor and control the ongoing irradiation. This report briefly summarizes the relevant technical activities.

INTRODUCTION

The Institute for Nuclear Physics (IKP) [1] is focusing on the tasks given by the Helmholtz Association (HGF). This comprises the design and preparations for the High Energy Storage Ring (HESR) of FAIR [2] with the PANDA experiment. The on-going hadron physics program at the Cooler Synchrotron COSY exploits the internal experimental set-up PAX. The extracted beam is used for the PANDA experiment, detector tests and also for high energy irradiation in the area of the finished TOF experiment. IKP is part of the section “Forces And Matter Experiments” (FAME) at the Jülich-Aachen Research Alliance (JARA). This joins scientists and engineers from RWTH Aachen and Forschungszentrum Jülich for experiments, theory and technical developments for anti-matter (AMS) and electric dipole moment experiments (EDM). The institute is member of the HGF project Accelerator Research Development (ARD) and pursues research on various accelerator components. The future project Jülich Electric Dipole Moment Investigation (JEDI) [3] will profit from the availability of polarized beams from the injector cyclotron and the unique capabilities and experiences at the COSY facility.

CYCLOTRON OPERATION

The COSY accelerator facility [4, 5], operated by the Institute for Nuclear Physics (IKP) at the Forschungszentrum Jülich GmbH, consists of the injector cyclotron JULIC and the Cooler Synchrotron COSY. Both accelerators are originally dedicated to fundamental research in the field of hadron, particle, and nuclear physics, to study the properties and behavior of hadrons in an energy range that resides between the nuclear and the high energy regime.

The cyclotron JULIC provides 45 MeV H^- respectively 76 MeV D^- with max. beam currents of ~10 μA. Operation of the cyclotron started 1968 and beside the Nuclear Physics experiments a small amount of the available beam time was used for irradiation. In the beginning the irradiations were performed with internal targets inside the cyclotron. But since the implementation of the target holders of the INM-5 at the external target station of JULIC via an adapter section [6], reliable irradiations can be done both for nuclear reaction cross section measurements and medical radionuclide production. In the case of the deuterons, the emphasis is on cross section measurements because the data base for many of the deuteron-induced reactions is weak. The proton beam, on the other hand, is mainly used for the production of the important β^+ emitter ^{73}Se via the $^{75}As(p,3n)$-reaction over the energy range of $E_P = 40 \rightarrow 30$ MeV at beam currents of a few micro amps. A view of the adapter at the end of the beam line is given in Fig. 1.

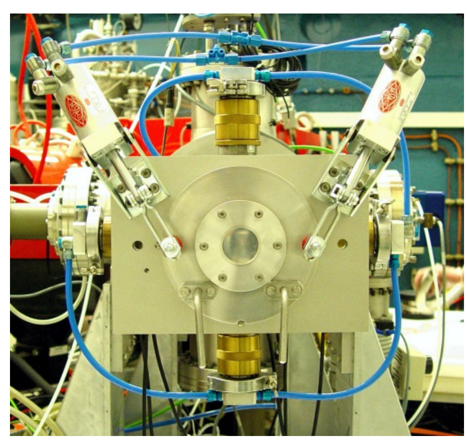

Figure 1: Head of adapter section at the external JULIC beam line.

For the last 15 years Fraunhofer INT with IKP have been operating a dedicated radiation effects test facility at an external beam line of the JULIC cyclotron [7], which can be seen in Fig. 2. Since the tests are performed in air,

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A DIAMOND DETECTOR TEST BENCH TO ASSESS THE S2C2 BEAM CHARACTERISTICS

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Abstract

During the assembly and initial start-up of the superconducting synchro-cyclotron (S2C2) in the manufacturing hall at Ion Beam Applications (IBA), some key properties of the extracted beam have to be validated. A new setup was developed to assess the beam direction out of the S2C2, the beam energy variation as a function of main coil current and main coil position, and the time structure of the beam. In the future, the setup will be extended with an emittance slit. The beam detector in this setup is a sensitive "poly-crystalline diamond detector" (pCVD), which requires small amounts of beam from which a maximum amount of information can be extracted. The high sensitivity and versatility of the detector are important aspects in order to limit the activation of the S2C2 during in-factory beam tests.

INTRODUCTION

The activation of the S2C2 during in-factory beam tests has to be limited to an absolute minimum to facilitate the transport of the accelerator to the installation site. Therefore, a sensitive and versatile detector is needed to extract as much information as possible at a minimum beam intensity. Therefore, a new setup was developed which measures the beam direction, size and divergence and the beam energy variation with main coil current and horizontal main coil position.

THE EXPERIMENTAL SETUP

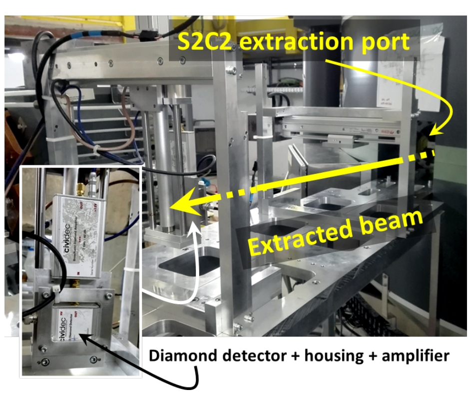

Figure 1: The diamond detector setup installed on a table directly connected on the exit port of the S2C2. The support of the diamond detector can be moved to fixed distances from the exit port and the detector itself can move continuously both horizontally and vertically in the beam. An additional support is foreseen to install an emittance slit.

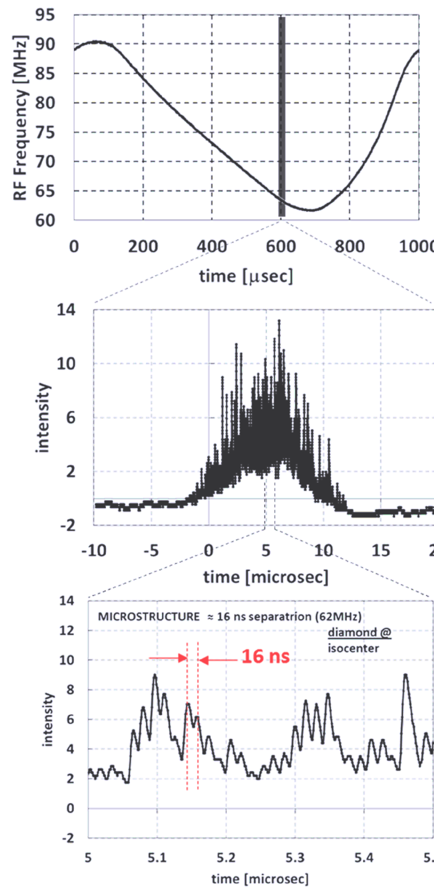

Figure 2: (top) 1 period of the RF frequency sweep in the S2C2. Extraction of the beam happens around 63 MHz. (middle) The diamond detector signal. (bottom) A zoom on the diamond detector signal. Individual proton bunches on the RF wave are visible. The bunches come out at a frequency of 63 MHz, or with a periodicity of 16 ns.

The beam detector is a "poly-crystalline diamond detector" (pCVD, see [1]) with an active surface of $10\,mm^2 \times 10\,mm^2$ and a thickness of 500 mm. Protons of 230 MeV loose about 400 keV in the detector. This detector is typically used as beam loss monitor or for time-of-flight measurements. In our case, the good timing properties (sharp rising time and fast fall-time) and its high sensitivity make it an excellent detector to measure small intensity pulses from the S2C2. Figure 1 shows the full setup, installed on the exit port of the S2C2. A support structure, carrying the diamond detector, can be installed at fixed distances from the exit port. The detector itself is scanned continuously both horizontally as vertically in the beam path. A second support structure is foreseen to install an emittance slit.

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STUDY OF GEANT4 SIMULATION FOR CYCLOTRON RADIOISOTOPE PRODUCTION IN VARIOUS TARGET SIZE

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Abstract

The application of radioisotopes in medical radiology is essential for diagnosis and treatment of cancer. The fabrication of radioisotopes has main factors that maximize the fabrication yield and minimize the costs. An effective method to solve this problem is that the usage of Monte Carlo simulations before experimental procedure [1]. This paper studies the simulation and presents cyclotron models for the energy 13 MeV with moderate beam intensity are used for production of 11C, 13N, 15O, and 18F isotopes widely applied in positron emission tomography [1]. TR-13 cyclotrons with high beam intensity are available on the market for production of most medical and industrial isotopes. In this work, the physical and technical parameters of different models are compared. Overall, this confirms the applicability of Monte-Carlo to simulate radionuclide production at 13 MeV proton beam energy.

INTRODUCTION

Compact cyclotron is normally used to produce for short-term lived radioisotopes, especially using applications for positron emission tomography (PET) [1, 2]. These kind of machines accelerate protons and also produce four positron emitters that are carbon-11, nitrogen-13, oxygen-15 and fluorine-18. The four positron emitters are easily produced by the low-energy and nuclear reactions. Normally, the methods of productions about these emitters use gas and liquid targets for employing. In addition, many medical cyclotrons are adopted both two target systems, which are generally attached directly to cyclotron. It is suitable to produce radioisotopes by using targets systems, however it didn't be optimized sufficiently about thickness with materials [2].

In this study, the Monte-Carlo simulation code Geant4 is used for optimization of target thickness as well as target materials that role as a critical assessing the yield for isotope production of system. It is a typically calculation tool that suggests particle tracking and interaction with mass. And also, it can provide wide range of applications, which is target design, calorimetry, activation and dose rate measurement. To get results harmoniously, we set out to use Geant4 to calculate following hadronic reactions for nuclear and particle physics for carbon-11, nitrogen-13, oxygen-15 and fluorine-18.

DESIGN AND SYSTEM DESCRIPTION

Geant4 is open source code, which is Monte Carlo toolkit for the tracking particles through matter. It is often used that applicate physics and medical field with various area. This simulation tool is suitable for evaluation of irradiation of target system with a large data driven physics models [1].

The simulation model is the target system of the SKKUCY-13 cyclotron. The geometry is based on a simple drawing of the system. The target system is made of cylindrical shape target chamber and target body that can modulate the energy of the beam and a target at the end of the fixed chamber. Fig.1 shows the geometry for simulation to calculate radioisotopes production. The target is made for optimization of target shapes which allows the selection of the thickness. The proton beam line passes through the tube with foil before hitting the target. This schematic drawing geometry model is generated to calculate for target configurations with adopted various thickness system.

Figure 1: Geometry for radioisotope production target system.

In this paper, a further investigation has been performed via the low-energy (p, n) and (p, α) nuclear reactions cross section values for energies at 13 MeV using the TENDL library [1, 3].

To calculate the cross section values, several simulations were run using different chamber thickness and a thin 11C, 13N, 15O and 18F target in target chamber, so the energy would remain approximately constant while the proton would travel through the target. To achieve reasonable computing time, sensitive volume (the target chamber) was defined to track particles in the regions of interest. On average, around 10000 events were necessary to achieve good precision. This represents around one hour of simulation on a general purpose processor.

RESULTS AND DISCUSSIONS

The isotope number of reactions relative to ^{11}C, ^{13}N, ^{15}O and ^{18}F production were also compared to theoretical results of P. W. Schmor et al [4]. The relative simulated

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TEST PRODUCTION OF Ti-44 USING RFT-30 CYCLOTRON

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Abstract

RFT-30 30 MeV cyclotron has been developed for the production of radioisotopes and their applications. Fluorine-18, which is a widely-used positron emitter, has been produced regularly since 2015. In addition, research on the production of generator radioisotopes has been performed using this cyclotron. A generator means a device used to extract the positron-emitting daughter radioisotope from a source of the decaying parent radioisotope such as ^{44}Ti and ^{68}Ge.

In this research, Sc targets were proton-irradiated in order to produce ^{44}Ti. Gamma spectra of irradiated targets were measured to confirm the production of Ti-44.

INTRODUCTION

Cyclotron-based production of generator radioisotopes has been researched for several tens of years [1,2]. A generator concept is a device that contains a parent radioisotope (RI) with relatively long half-life. A positron-emitting daughter RI can be extracted from it and used for its application. The generator can enable continuous research of positron emitter applications for a sufficiently long time without daily-production of RI using a cyclotron.

In Korea Atomic Energy Research Institute (KAERI), the production of RIs such as ^{44}Ti for Ti/Sc generator and ^{68}Ge for Ge/Ga generator has been researched recently using RFT-30 30 MeV cyclotron. Here, we present a test and actual production of ^{44}Ti via proton irradiation of Scandium (Sc) targets. Sc targets were proton-irradiated, and then, characterized using gamma spectroscopy to confirm the production of ^{44}Ti.

EXPERIMENTAL

Sc disks with a diameter of 50 mm and a thickness of 0.5 mm (Sc 99.5%, Goodfellow, England) were used as irradiation targets. Sc disks were installed at the end of the beam-line (Fig. 1), and then irradiated with a proton beam generated form a RFT-30 cyclotron at Advanced Radiation Technology Institute of KAERI. The irradiation process was carried out with water cooling in a vacuum chamber. The energy of the proton beam was ~30 MeV, and total doses were 12 and 1750 μAh. The average beam current was 10 and 30 μA, respectively.

Gamma spectrum of proton-irradiated Sc disks was measured with multi-channel analyzer (MCA).

RESULTS AND DISCUSSION

Main nuclear reaction which can be induced by the proton irradiation of Sc is ^{45}Sc(p, 2n)^{44}Ti. ^{44}Ti nuclei are created by the direct (p, 2n) reaction and ^{44}Sc nuclei are produced by following β^+ decay with a half-life of 59.1 year.

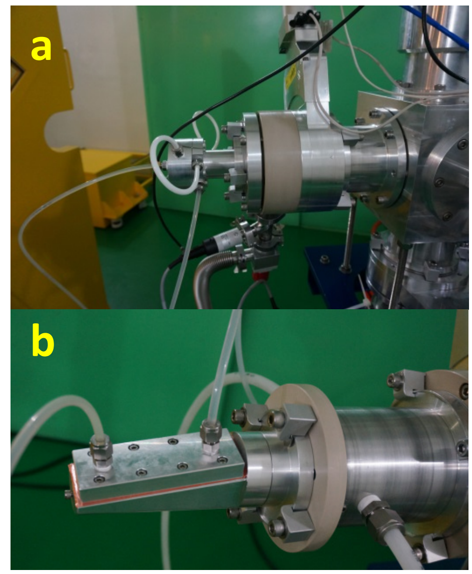

Figure 1: Installation of targets at the end of a beam-line: test target (a) and inclined target for actual production (b).

For the test production, Au-coated Sc disk was proton-irradiated. Au coating was introduced to prevent the corrosion of Sc by the cooling water. Gamma spectrum of an irradiated Sc target is shown in Figure 2. Irradiated Sc with Au coating showed several peaks centered at 67.87, 78.32, 1237 keV, emitted from ^{44}Ti. This result indicated that ^{44}Ti was successfully produced. The appearance of a peak centered at 511.0 keV, corresponding to the annihilation of β+, also proves the production of positron-emitting radioisotopes.

Some other peaks corresponding to ^{44}Sc (1157 keV) which is a daughter radioisotope of ^{44}Ti, and ^{197}Hg (268.7 keV) which is produced from Au coating are also appeared.

However, it was found that Sc target was severely damaged by the proton beam because of high beam current density. In order to resolve this problem, we fabricated and installed inclined target system (Fig. 1b). If we used inclined target, the irradiated area is greatly increased so that we can lower the beam current density. In addition, the penetration length is also increased so that much more nuclear reactions can be induced. The inclined target was proton-irradiated with a dose of 1750 μAh and separation of ^{44}Ti is under processing.

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SIMULATION OF OPTIMUM THICKNESS AND CONFIGURATION OF 10 MeV CYCLOTRON SHIELD

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Abstract

Baby Cyclotrons that made in Self-shield type have been employed for use in Medical centers for the diagnosis of cancer diseases by positron emission tomography (PET) system. Conceptual design studies and construction of a 10 MeV cyclotron have been done at the Amirkabir University of Technology. Here in we have done a discussion on simulation of gamma and neutron dose rates at a distance of one meter outside of the cyclotron shielding. This shield consist of Lead, polyethylene (10% B) layers from inside to outside respectively. With increasing the thickness of lead and polyethylene we will see a decrease in the gamma and neutron dose which received by the water phantom at a distance of one meter outside from the surface of the shield of the cyclotron. Note that the gamma and neutron dose at the beginning (without any shielding) was on the order of several thousand μSv per hour that by achieve to a certain amount of thickness of the shield, the dose was reduced to below of the limited level. In this study, the MCNPX Code has been used. In MCNPX Code that used the variance reduction techniques for decreasing relative errors of calculation which was a good method for this case study.

INTRODUCTION

With the development of cyclotron in the 1930s, radioisotopes have been produced for medicine, industry, agriculture and research significantly [1]. Cyclotron accelerators have many applications in the industrial and medical fields.

Today, fluorine is used in radiopharmaceuticals and plays an essential part in the oncology. The cyclotron accelerator is applied in medicine to produce radioisotopes for PET device using for the detection of cancerous diseases. PET is one of the ways to determine the physiological and chemical processes in the body by a quantitative method. Some radioisotopes produced by Cyclotron are ^{11}C, ^{15}O, ^{14}N, and ^{18}F which their half-lives are 20, 2, 10, and 110 minutes respectively. Operation of accelerators will produce gamma and neutron radiation. These radiations can have damaging effects to accelerator operator and those referring to accelerators department. In order to reduce the effects of this radiation, there are different ways that must comply with the principle of ALARA. One of these ways is using of a radiation shield. Depending on the kind of application, the type of radiation shielding will be important. In determining the type of radiation shield, the location and atmosphere dedicated to the cyclotron room is effective.

If the large space will be available, the cyclotron vault model can be used. Because cyclotrons have medical applications and are often used in medical centers and hospitals, there is space limitation for it. On the other hand, since short half-life radioisotopes are produced (approximately 2 hours), it is required to use them in a cyclotron nearby. These items create a situation that a self-Shield is used for radiation shielding.

WORK METHOD

In this study, we simulate a self-shield type for protection. In fact, instead of cyclotron room, a shield that attached to the cyclotron is used. It can be used anywhere. Because of producing gamma and neutron radiation in the cyclotron accelerator, each of them require their appropriate shielding. In this situation, combined shield is needed. For gamma-ray, high atomic number materials such as lead shielding are used. And for neutron radiation, low atomic number materials such as concrete, polyethylene and boron that is neutron capture also, lithium and cadmium are used.

Neutron absorption cross section of these materials are several thousands Barn [2]. This order of number is good for absorbing neutrons.

Although cadmium has a higher neutron absorption cross section than the other two materials, but it leads to strong secondary gamma-ray production and therefore, that is required to utilize thicker layer of lead for attenuation of gamma rays which is not appropriate. So it is better to use boron and lithium [3]. In this study that is based on a 10MeV cyclotron accelerator, Negative hydrogen ion beam has a current of 150 Aμ and is accelerated to 10MeV. In this model, particles are accelerated horizontally. The outer dimensions of the accelerator, which includes its height and diameter, are 1767 mm and 1760 mm respectively. Conceptual design studies and construction of a 10 MeV cyclotron have been done at the Amirkabir University of Technology [4].

Target of cyclotron is usually considered as the main source of radiation. In fact, more than 90% of radiation comes from the target, although there are reactions with other components of the cyclotron, such as the collision of proton beams and secondary radiation with the accelerator body.

A cylindrical target of 1.5 mm height, 1.2 mm inner diameter, and 3 mm outer diameter has been studied. The thickness of cylinder base, which calculated with SRIM code is 1μm and it is bombarded by proton beams. Target foil is regarded neodymium. To produce FDG, target

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COUPLING OF CYCLOTRONS TO LINACS FOR MEDICAL APPLICATIONS

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Abstract

Cyclotron and Linac technologies cover the vast majority of accelerator solutions applied to medicine. Cyclotrons with beams of H^+/H^- around 20 MeV are found for radioisotope production and cyclotrons with beams up to 250 MeV are widely used for protontherapy. Linacs are present in every medium-sized hospital with electron beams up to 20 MeV for radiotherapy and radioimaging. They have also recently become available as commercial products for protontherapy. The coupling of these two strong technologies enables to expand the capabilities of cyclotrons by using linacs as boosters. This opens the way to innovative accelerator systems allowing both radioisotope production and ion beam therapy (cyclinacs), new treatment techniques (high energy protontherapy) and new imaging techniques (proton radiography). This paper provides an overview of the technical challenges linked to coupling cyclotrons to linacs and the various solutions at hand.

INTRODUCTION

Cyclotrons

A list of all existing research and commercial cyclotrons is regularly compiled [1]. The vast majority of cyclotrons have a medical purpose as producers of radioisotopes for medical imaging and therapy. The typical primary beams of H^+/H^- ions are accelerated by normal conducting isochronous cyclotrons with kinetic energies up to 30 MeV. Compared to other accelerator technologies, cyclotrons benefit from their compactness, reliability and efficiency. Nowadays, normal conducting cyclotrons also represent the workhorse in protontherapy [2] with H^+ beams in the 235-250 MeV range. Recently, also superconducting isochronous and synchro-cyclotrons enter the protontherapy world as commercial solutions and their numbers are rapidly increasing.

Linacs

The vast majority of modern radiotherapy apparata is based on 3 GHz electron linacs, which are normal conducting copper standing-wave structures providing electron beams up to 20 MeV. They are so compact (1-2 m length) and light that they are mounted on rotating systems to irradiate the tumors from all possible angles.

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TERA Foundation

For more than 20 years, the TERA foundation has played an active role in the development of accelerator and detector technologies employed in the field of hadrontherapy. Its outputs and staff are, among others, at the core of the Proton Ion Medical Machine Study [3], the CNAO Foundation [4], which has built and operates the Italian hadrontherapy center in Pavia and the company ADAM S.A. (Switzerland), which commercializes protontherapy centers based on linacs. In the field of detectors, TERA developed the Proton Range Telescope [5] installed at CNAO and the BISE (Beam Imaging with Secondary Electrons) [6] detector installed at the 18 MeV cyclotron of Swan Isotopen AG.

TERA's present activities focus on designing novel gantries that make full use of the special properties of the beams produced by hadron linacs, and also research and development in the technologies of linacs for carbon (and helium) ion acceleration [7]. In collaboration with CERN, two lines of development are pursued: a system made of an RFQ followed by three linac structures (called "*all-linac solution*") and the combination of a cyclotron and a linac, a so-called "cyclinac". This combination allows enhancing the advantages of both accelerator types and opens new possibilities in therapy and imaging for radiotherapy centers (ex-novo or based on existing cyclotrons). The main innovations of all the proposed linac systems are the rapid energy variation (at rates in the range 100-400 Hz), the small transverse emittances of the beams and the cost-effectiveness. The related research activities concern pulsed ion sources, high-gradient high-frequency linacs, new concepts for beamlines and gantries, beam tracking tools and full-scale Monte Carlo simulations from the source to the patient.

CYCLINACS

General

The use of linacs for therapy has the advantage of allowing a fast (within a few ms) modulation of the beam output energy. This is a unique feature of a cyclinac, since protontherapy cyclotron systems use degraders for energy variation in the timescale of 100-1000 ms and the synchrotron systems vary the beam energy from cycle to cycle in timescales of 1-2 s. Additionally, the linac beam has a very small transverse emittance (around 0.3 μm rms, normalized) which allows to reduce the aperture (and cost) of the high energy beam transfer line magnets.

On the other hand, there are some technical challenges linked to the design of cyclinacs and corresponding beam-

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A MULTI-LEAF FARADAY CUP ESPECIALLY FOR PROTON THERAPY OF OCULAR TUMORS

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Abstract

For radiation therapy with protons knowing the beam range with high accuracy is crucial. The Multi-leaf Faraday Cup (MLFC) allows a quick and precise range measurement of the full radiation field in air. In the field of eye tumor therapy an accuracy in the submillimeter regime is required. We present an MLFC with 47 channels which can be read out simultaniuosly. Each channel consists of a 10 µm copper foil, connected to an ammeter, next to a 25 µm kapton foil. An automated preabsorber system allows range measurements in different energy regions. The achievable relative resolution of 50 µm in water meets the desired accuracy for eye tumor therapy. Furthermore is is possible to gain information about the dose distribution in water for quality assurance measurements.

MOTIVATION

Over the past years radiation therapy with protons has become a very important tool in cancer treatment. Since 1998 a collaboration of the Charité Universitätsmedizin and the Helmholtz-Zentrum Berlin (HZB) provides a treatment facility for eye cancer. Ocular tumors especially benefit from the superior dose distribution of protons. This distribution known as the Bragg-Peak provides the highest dose just before the end of the finite range in tissue (see Fig. 1).

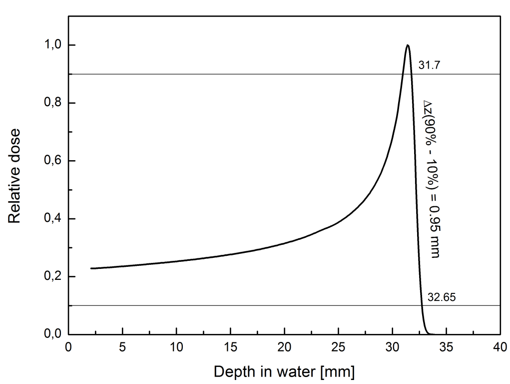

Figure 1: Typical single Bragg Peak (SBP) of the HZB cyclotron with 0.95 mm distal dose fall off (90 - 10 %).

That way it is possible to deliver the maximum dose only to the target volume and spare critical tissues highly sensitive to radiation. At our facility this leads to a local tumor control of 96 % after 5 years. The human eye is a very small organ (with a volume of 6 – 7 cm^3) and contains of several critical structures crucial for the sight, e.g. the optical nerve or the macula. When treating melanomas located close to those structures a very precise positioning of the target volume and a precise knowledge of the proton range is required.

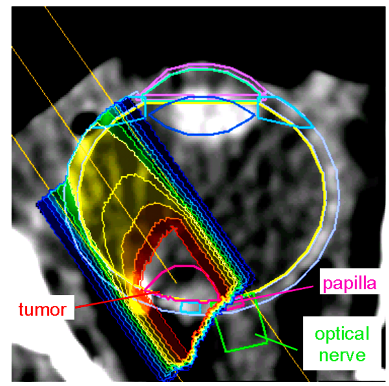

Figure 2: Planned radiation field with marked critical structures and the tumor.

At our facility we achieve a distal dose fall off (the distance between 90 and 10 percent of the maximum dose) of less than 1 mm (Fig. 1). This is also a reason why the range measurement needs to be accomplished with a resolution of 0.1 mm. During quality assurance this is usually done by measuring the dose distribution in a water phantom. The measurements are very time consuming and therefore it would be a great advantage to use a device which enables quick and precise range measurements.

METHODS AND MATERIAL

MLFC

A Multi-Leaf Faraday Cup (MLFC) is a well-suited device for a quick and precise range measurement. It is a stack of alternating conductor and insulator plates. Each conducting plate is connected to ground potential via an ammeter. Incoming protons stop in a certain plate and add positive charges which create a current by pulling electrons from the ground. Thus the differential fluence (and therefore the range) of a proton beam can be measured.

By determining the needed plate thickness and number a MLFC can be set to meet the eye tumor therapy requirements. It furthermore enables measurements of the full radiation field in air.

Our device consists of 47 copper foils with a thickness of 10 µm, which equals approx. 50 µm water equivalent. As insulator we use Kapton foils of 25 µm thickness corresponding to approx. 32 µm water.

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OFFLINE TESTS WITH THE NSCL CYCLOTRON GAS STOPPER*

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Abstract

Rare isotopes are produced at the National Superconducting Cyclotron Laboratory NSCL by projectile fragmentation at energies of ≈100 MeV/u. The NSCL has successfully used linear gas stopping cells for more than a decade to decelerate projectile fragments to the keV range; first for experiments at low-energy and more recently for reacceleration.

A novel reverse-cyclotron has been constructed by the NSCL based on a superconducting sectored-cyclotron magnet and LN_2-cooled He gas to confine and slow down the fragments. Efficient stopping is predicted even for light ions that are difficult to thermalize in linear gas cells. The thermalized ions are transported to the center by a radial RF-carpet system, extracted through the yoke with an ion conveyor and accelerated to <60 keV for delivery to users.

Measured field profiles have confirmed field calculations. The cryogenic beam-stopping chamber has been installed inside the magnet. The RF ion-guiding components have been tested successfully offline and are being prepared for low-energy ion-transport tests inside the magnet.

INTRODUCTION

The NSCL facility uses fast projectile fragmentation to provide rare-isotope beams (RIB) for a broad range of research. The production method is chemically unselective and allows the production of isotopes far from the valley of stability as evidenced by the more than 900 RIBs delivered to users at NSCL so far. While most of the beams have been provided at the production energies on the order of 100 MeV/u, beams are increasingly requested at rest or at energies of a few MeV/u.

Linear gas stopping cells have been used for more than a decade at NSCL to slow down the beam to the keV-energy range. These 'stopped beams' are delivered to NSCL's low-energy experimental area, i.e. the Penning-trap mass spectrometer LEBIT [1] and the laser spectroscopy setup BECOLA [2] as well as the re-accelerator ReA [3].

The linear gas stopping cells use solid degraders to slow down the incoming beam to an energy that can be dissipated in helium gas at a pressure of ≈100 mbar to a bar and over a typical length of a meter. While a higher pressure allows for efficient stopping in more compact cells, recent installations favor larger sizes to reduce ionization per volume and use lower pressure to benefit from efficient RF ion guiding techniques for fast ion extraction [4], [5].

Extreme purity of the stopping gas is required to prevent charge-exchange of stopped ions with contaminants and other reactions, which can lead to loss of ions and/or unwanted molecular ions. In order to provide cleaner beams, the latest generation of gas stopping cells, including a new cell currently under development at NSCL, use cryogenic cooling to freeze out contaminants.

Most of the fragments provided as stopped beams at NSCL so far had masses of ≈40 u and higher, which allowed for efficient stopping in NSCL's currently operational 1.2 m long ≈80 mbar stopping cell [6].

Slowing down energetic *light* ions with solid degraders and low-pressure gas can induce several meters of range straggling and prevent efficient stopping in gas cells of practicable size or with extraction times comparable to nuclear lifetimes. Demand for stopped light-ion beams at NSCL has been on the rise, in particular since reaction studies with RIBs at the reaccelerator ReA have become possible. Even more interest has been voiced as significantly higher beam rates are expected with the primary beam upgrade in the FRIB (Facility for Rare Iostope Beams) era. The cyclotron gas stopper will be one of several complementary stopping options, built to specifically address the demand for light ions: It provides extreme stopping length as the beam is injected into stable orbits of a cyclotron magnet. Following energy degradation to an appropriate magnetic rigidity, the beam continues in an inward-spiraling motion as it slows down in the presence of buffer gas.

The concept of a gas-filled cyclotron-type magnet has been used to slow down and trap exotic light particles at LEAR/CERN [7], it was considered for the slowing-down of light ions such as Be^+ [8] and developed for a wider application by our group [9]–[11].

CYCLOTRON GAS STOPPER CONCEPT

Figure 1 illustrates the concept of the cyclotron stopper. The high-energy beam delivered from NSCL's A1900 fragment separator enters the gas-filled stopping chamber through a penetration in the return yoke of a three-sectored cyclotron-type magnet. After ≈ 1/4 turn and at a radius of about 0.9 m, the beam passes through a solid degrader, which reduces the beam rigidity to 1.6 Tm and puts the beam on a stable orbit. At this point, the beam is nearly fully stripped. The presence of the helium gas causes the beam to lose energy and pick up electrons. In average, the rigidity of the

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CHALLENGES IN FAST BEAM CURRENT CONTROL INSIDE THE CYCLOTRON FOR FAST BEAM DELIVERY IN PROTON THERAPY*

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Abstract

The COMET cyclotron at PSI has been successfully used to treat patients with static tumours using the spot scanning technique, i.e. sequentially irradiating different positions inside the tumour volume. Irradiation time for each position ranges from micro- to milliseconds, with total treatment duration of about a minute. For some tumours (e.g. lung) physiological motion (e.g. respiration) interferes with the scanning motion of the beam, lowering treatment quality. For such mobile tumours, we are developing a new technique called continuous line scanning (CLS), aiming at reducing treatment time by more than 50%. In CLS, dose rate should stabilize (within few percent) within tenths of a millisecond. We thus implemented a first prototype for fast, real-time beam control: a PID controller sets the internal electrostatic vertical deflector of the accelerator, regulating the beam current output based on the instantaneous current measured just before the patient and the knowledge of the transmission from the accelerator to the patient. In pre-clinical experiments, we achieved good control of the global dose delivered; open issues will be tackled in the next version of the controller.

INTRODUCTION

Proton therapy step-and-shoot scanning techniques, like spot scanning [1] or raster scanning [2], have been remarkably successful in treating static tumours such as those located in the brain or in the spine [3]. The intrinsic dynamic of the scanned pencil beam, moving sequentially through the tumour volume in all three dimensions, is however a disadvantage when treating tumours moving periodically (due to respiration, like lung or liver): the interference between scanning beam motion and tumour motion [4–6] can deform the dose distribution up to a clinically unacceptable level (so-called 'interplay effect'). To reduce this effect, motion mitigation techniques have been proposed. One example is rescanning [7, 8], a technique which foresees delivering the same plan several times, each time with a reduced dose, to a moving target, in this way averaging out the interference pattern between the scanning beam motion and the target motion. Though promising, motion mitigation techniques are not widely used, since they lengthen irradiation time, lowering patient comfort and throughput. Only a handful of centres worldwide offer such treatments.

Moving away from the step-and-shoot approach could potentially provide the fast, efficient irradiation suitable for motion mitigation. In this context, at PSI Gantry 2 we are developing a new irradiation technique called continuous line scanning (CLS) [9]. CLS paints an arbitrary dose distribution in the tumour volume by continuously changing the beam current and position within an energy (=depth) layer. We have shown [10, 11] that this technique can achieve dose distributions comparable to spot scanning, but reduce the treatment time by more than 50%, depending on the irradiation conditions and the motion mitigation strategy used [12].

One of the main differences between the standard pencil beam scanning delivery techniques and CLS is the way the beam moves from one position to the next during irradiation. In dose-driven techniques like spot and raster scanning the beam moves to the next position after the full dose prescribed for the current position has been delivered. This makes them robust with respect to beam instabilities, as they can compensate such effects by shortening or lengthening the time spent at a certain position; for this reason, such techniques are standard in clinical centres. Our proposed CLS implementation is instead time-driven, meaning the treatment control system (TCS) changes the values of the actuators controlling beam position and current according to a time table; this potentially makes the irradiation faster than dose-driven systems, as CLS does not rely on integrated signals to move from one position to the next. However, this poses stronger requirements on the precision of beam delivery and on the reaction time to beam instabilities, in order to avoid deformation of the resulting dose distribution.

In this document, we report about the challenges of such a system concerning beam current control, and the solution we designed for future clinical application.

FAST CURRENT CONTROL AT THE PROSCAN FACILITY

Beam Current Control in the COMET Cyclotron

The COMET [13] (ACCEL/Varian) cyclotron accelerates the proton beam used for patient treatment at Gantry 2 to an energy of 250 MeV. The beam is extracted from the proton source using a negatively charged puller, and is then accelerated passing through 4 dees. The proton source is kept at stable extraction conditions; the beam current is modulated as required by the treatments by stopping part of the protons inside the cyclotron using collimators.

Fast current changes are achieved using an internal electrostatic deflector (so-called vertical deflector, VD), which deflects the beam towards collimators built in one

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NEW TIME STRUCTURES AVAILABLE AT THE HZB CYCLOTRON

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Abstract

While most of the beam time of the cyclotron is used for proton therapy of ocular melanomas, an increasing amount of beam time is used for experiments. In response to a growing demand on time structures a new pulse suppressor was developed.

The set-up of the pulse suppressor, measurements on the time structures for various beams and examples of their experimental use will be presented.

INTRODUCTION

About 90% of the beam time of the cyclotron is used for proton therapy of ocular melanomas. However, there is an increasing amount of beam time for experiments. While most of these experiments can be performed with the quasi DC-time structure of the beam from the cyclotron, there is a demand for pulsed beams with a huge variety of time structures.

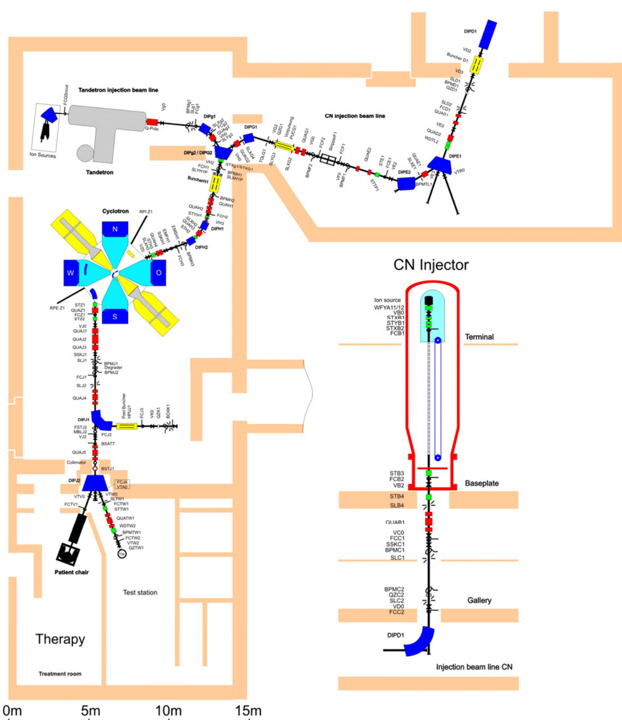

Figure 1: Layout of the accelerator. The yellow marked items influence the time structure of the beam.

Originally the accelerator complex was developed for heavy ions, as it is reflected in its first name VICKSI (*Van-de-Graaff Isochron-Zyklotron Kombination für schwere Ionen* – Van-de-Graaff Isochronous-Cyclotron combination for heavy ions) [1]. This reflects on the design of the pick-ups and the phase probes as well as the design of the bunchers and pulse suppressors. In order to analyse the time structure, we have developed a special pick-up, now permanently installed in the extraction line [2].

Figure 1 shows the actual layout of the facility with the devices influencing the time structure marked in yellow. While the Tandetron-cyclotron combination provides an extremely stable quasi DC beam, there exists no possibility to influence the time structure of the beam, as the last buncher in front of the cyclotron was designed for heavier ions with a charge to mass ratio between 1/2 and 1/8. Time structures can be achieved only using the 6 MV Van-de-Graaff as injector. A first buncher is situated in its terminal. Two bunchers and a pulse suppressor are located in the injection beam line. A second pulse suppressor on the extraction line after the 90° analysing magnet was used to get rid of parasitic pulses.

As mentioned above, for light ions we can use only the buncher in the high-voltage terminal and the first one in the beam line. Due to the lower time-focussing, the transmission through the cyclotron is only 50% compared to 100% achievable with heavy ions and the use of all bunchers. The pulse width of the beam is 1 ns for 68 MeV protons compared to 0.3 ns for heavy ions.

The limited transmission through the cyclotron is not a problem, as the requested beam intensities are far below 1 µA (DC equivalent). However, the limitations in the existing pulse suppressor yielded maximum repetition rates of 75 kHz for protons due to the necessary high voltages.

SINGLE TURN EXTRACTION

For proton therapy it is not relevant if single turn extraction is achieved. Figure 2 shows the pick-up signal of the extracted 68 MeV proton beam with a DC injection. The distances of the pulses are 50 ns, corresponding to the 20 MHz cyclotron RF and the pulse width is about 5 ns. Reflections on the cables are the reason for the multiple peaks about 5 ns after the first signal.

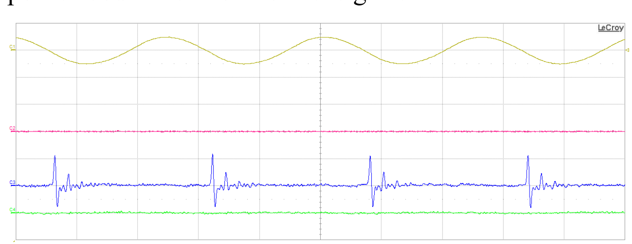

Figure 2: Pick-up signal of 68 MeV extracted proton beam (blue) with DC injection and cyclotron RF (yellow).

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RECENT IMPROVEMENTS IN BEAM DELIVERY WITH THE TRIUMF'S 500 MeV CYCLOTRON.*

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Abstract

TRIUMF's 500 MeV H- Cyclotron, despite its 44 years age is under continuous development. Many aspects of beam delivery have been improved over the last few years. Regular 3-week cusp source filament exchange cycle has advanced to multi-months due to greatly improved filament life time. Fine source tuning allowed beam intensity rise in support of routine extraction of 300 µA of protons. The injection line model has been fully correlated with online measurements that enabled its tuning and matching to the emittance defining slits and the cyclotron entrance. Cyclotron routinely produces 3 simultaneous high intensity beams (~100 µA each). Multiple techniques have been developed to maintain extracted beams intensity stability within +/- 1%. Record extraction foil life times in excess of 500 mA-hours have been demonstrated with highly-oriented pyrolytic graphite foil material and improvements in foil holder. Beam rastering on ISOL target allowed higher yields. A single user extraction at 100 MeV was achieved by applying phase slip and deceleration inside the cyclotron.

ION SOURCE AND INJECTION LINE

A powerful test stand for H- ion source development has been built in 2012. An intense cusp source filament study carried on over a couple of years. Resulting choice of filament material and shape allowed a breakthrough in the filament life time. Regular filament change was based on a 3 weeks cycle. Recently deployed filament survived 9 weeks, when it failed prematurely for a reason unrelated to its deterioration. Presently projected filament life expectancy is about 4 months. Figure 1 shows filament current drop in time; each peak corresponds to a filament replacement.

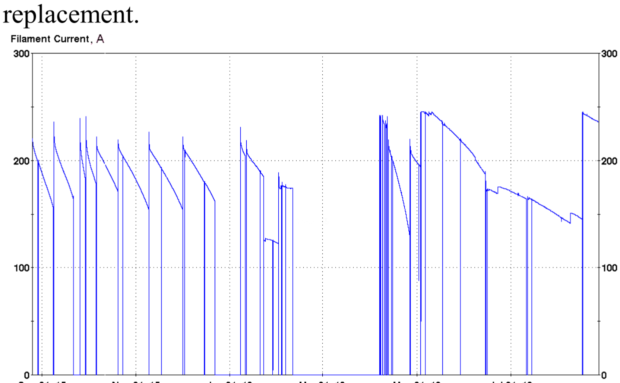

Figure 1: H- source filament current evolution.

In 2014 the ion source showed a very peculiar instability. It manifested itself as a strong dependence of beam steering at the output of the optics box on beam pulser setting (see Fig. 2). An assessment revealed an insulating coating layer on the electrostatic steering plate that was previously a grounded counterpart of the pulser deflecting plate. Electrical charge accumulated on the insulating layer was responsible for changing electrical field within steerer/deflector that caused uncontrollable beam steerinig. The problem was resolved by replacing aluminum plates with stainless steel ones.

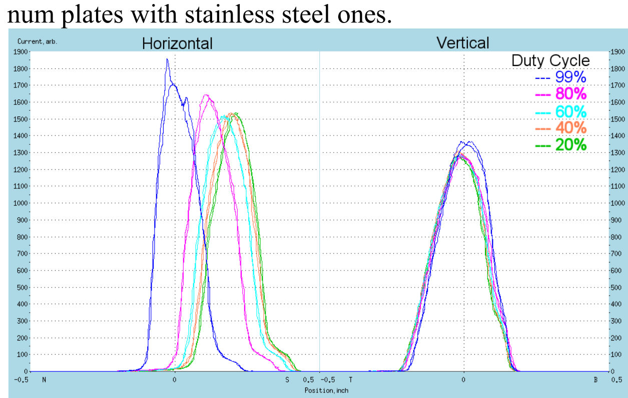

Figure 2: Beam horizontal steering vs duty cycle.

For a long time there was no clear understanding of the beam asymmetry at the exit of the source acceleration column. An OPERA model of an electrostatic steerer [1] offered an explanation to this issue: when circular apertures are used in conjunction with parallel plates and the plates have a net bias, the assembly acts partially as a quadrupole. There are two ways to avoid this effect: balancing the opposite polarity bias on the plates so the median plane becomes at ground potential or making a rectangular slot apertures of same orientation as the plates.

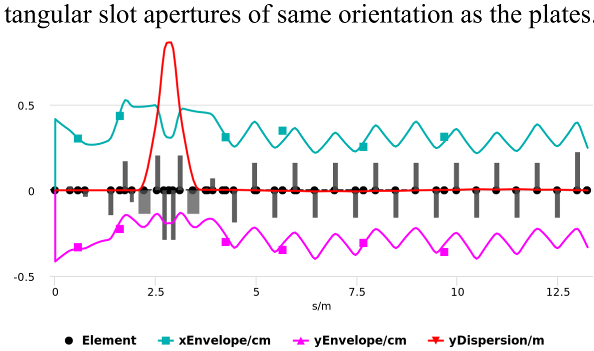

Figure 3: Beam envelope trough 1/3 of injection line; squares represent beam size at profile monitors.

Removing the quadrupole effect from the otherwise symmetrical section of beam optics allowed development of the accurate model of beam optics from the source down to the cyclotron entrance. This effort culminated by introduction of a High Level Application (HLA) that models the whole injection line. It uses online data from 5 profile monitors and live settings of the optics to reconstruct beam parameters and produces a new optics setting

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UPDATED PHYSICS DESIGN OF THE DAEδALUS AND IsoDAR COUPLED CYCLOTRONS FOR HIGH INTENSITY H_2^+ BEAM PRODUCTION*

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on behalf of the DAEδALUS Collaboration.

Abstract

The Decay-At-rest Experiment for δ_{CP} violation At a Laboratory for Underground Science (DAEδALUS) and the Isotope Decay-At-Rest experiment (IsoDAR) are proposed experiments to search for CP violation in the neutrino sector, and "sterile" neutrinos, respectively. In order to be decisive within 5 years, the neutrino flux and, consequently, the driver beam current (produced by chained cyclotrons) must be high. H_2^+ was chosen as primary beam ion in order to reduce the electrical current and thus space charge. This has the added advantage of allowing for stripping extraction at the exit of the DAEδALUS Superconducting Ring Cyclotron (DSRC). The primary beam current is higher than current cyclotrons have demonstrated which has led to a substantial R&D effort of our collaboration in the last years. We present the results of this research, including tests of prototypes and highly realistic beam simulations, which led to the latest physics-based design. The presented results suggest that it is feasible, albeit challenging, to accelerate 5 mA of H_2^+ to 60 MeV/amu in a compact cyclotron and boost it to 800 MeV/amu in the DSRC with clean extraction in both cases.

INTRODUCTION

Physics Motivation

The standard model of particle physics includes three so-called "flavors" of neutrinos: ν_e, ν_μ, and ν_τ, and their respective anti-particles. These particles can change flavor (neutrino oscillations), a process that can be described using a mixing matrix. This necessarily means that neutrinos must have a small mass [1]. In addition, some experiments aimed at measuring these oscillations in more detail have shown anomalies that led to the postulation of so-called "sterile" neutrinos which would take part in the oscillation, but, contrary to the three known flavors, do not interact through the weak force [2]. Another important question is whether the three neutrino model can give rise to a CP-violating phase δ_{CP} [3], which might explain the matter-antimatter asymmetry in the universe today. DAEδALUS [4, 5] and IsoDAR [6] are proposed experiments to search for CP violation in the neutrino sector, and sterile neutrinos, respectively. In the following, we will give a brief overview of the facilities and identify and discuss the most critical aspects.

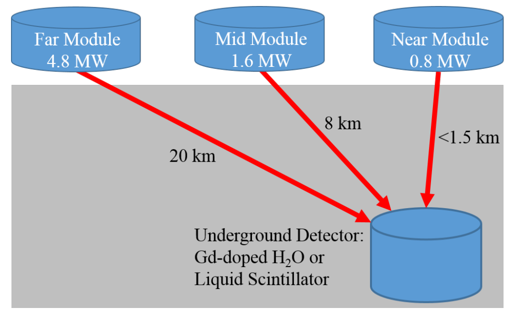

Figure 1: Schematic of the layout of DAEδALUS accelerator modules. The powers at the respective modules, are average values based on a 20% duty cycle.

Facilities Overview

In the DAEδALUS concept (described in detail in [4, 5]), three accelerator modules are placed at distances 1.5, 8, and 20 km from a large detector (see Figure 1). As the neutrino oscillation probability depends on L/E, the ratio of neutrino energy to the distance traveled [1], this scheme can work as follows: The near module constrains the flux, the mid module constrains the rise of the probability wave and the far module measures the oscillation maximum. Each of these modules consist of one or more chains of cyclotrons, as depicted in Figure 2. The neutrino distribution from the production target is more or less isotropic, which means the number of produced neutrinos needs to increase with distance if one wants to keep statistics up. Hence the higher power of the far site which will be reached by using several modules. In this way, DAEδALUS can be used to measure a δ_{CP} dependent maximum of the oscillation curve. Figure 2 shows schematically the main parts of DAEδALUS:

1. Ion source
2. Low Energy Beam Transport (LEBT)
3. DAEδALUS Injector Cyclotron (DIC)
4. Medium Energy Beam Transport (MEBT)
5. DAEδALUS Superconducting Ring Cyclotron (DSRC)
6. High Energy Beam Transport (HEBT)
7. Neutrino production target

As DAEδALUS is a big project, it makes sense to look for a staged approach and physics that can be done with only part of it. In this case using only the DIC and replacing the DSRC with a different production target comes to mind. This is IsoDAR, a search for sterile neutrinos. Here the primary H_2^+ beam at 60 MeV/amu is used to produce $\bar{\nu}_e$ through isotope-decay-at-rest. In both experiments, the primary ion beam

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A NOVEL USE OF FFAGS IN ERLS - IN COLLIDERS: ERHIC, LHEC AND A PROTOTYPE AT CORNELL UNIVERSITY*

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Abstract

We propose a novel use of Non Scaling Fixed Field Alternating Gradient beam line (NS-FFAG) to replace multiple beam lines in existing Energy Recovery Linacs (ERLs) (4-pass at Novosibirsk, ERL of CEBAF, ERL at KEK, etc.) with NS-FFAG beam lines connected with spreaders and combiners to the linac. We present two designs for the Electron Ion Colliders one at CERN-LHeC and one at Brookhaven National Laboratory-eRHIC to be placed in the tunnel of the existing Relativistic Heavy Ion Collider (RHIC) called eRHIC. The proof of principle electron accelerator with the NS-FFAG arcs is to be built at Cornell University Wilson Hall where there are already available injector, superconducting linac accelerator and the dump. There are very new developments in the NS-FFAG design never accomplished before: arc-to straight adiabatic matching with merged multiple orbits into one, permanent magnet design for the arc and straights with ability of four times in energy, etc.

INTRODUCTION

There are many ways for accelerating particles in the non-relativistic region: the neutron generators or for Accelerator Driven Subcritical System (ADS) and they could be the superconducting linacs, fast cycling synchrotrons, superconducting cyclotrons, FFAG's etc. The isochronous circular accelerator, where the beam arrives for all energies at the same time to the RF and operates in the CW mode is very advantageous. A preferred solution is a straight superconducting linac but it requires large power, long length and it is very expensive. Cyclotrons might be the preferred solution. This presentation shows examples of savings in the linac lengths in relativistic electrons acceleration for the LHeC, eRHIC, and an ERL at Cornell University (eRHIC prototype) with isochronous condition. It is not suggested that this solution could be applied for non-relativistic particles but it provides an input for new possibilities in this case. The energy recovery in all three examples is possible as the electron time of flight during acceleration is properly adjusted on the top of the RF sinusoidal wave, while during the deceleration or energy recovery it is shifted close to the minimum of the RF wave. There are multiple advantages in using ERL's in the electron ion colliders: electrons are colliding only once with hadrons, due to energy recovery the enormous power of the electron beam is brought down to the dump with initial very low energy and with the overall linac efficiency very close to 100%.

Electron Energy Colliders LHeC and eRHIC

The electron ion collider LHeC goal is to study of deep inelastic scattering (DIS) into unknown areas of physics and kinematics. "The physics program also includes electron-deuteron and electron-ion scattering in a (Q^2, 1/x) range extended by four orders of magnitude as compared to previous lepton-nucleus DIS experiments for novel investigations of neutron's and nuclear structure, the initial conditions of Quark-Gluon Plasma formation and further quantum chromo-dynamic phenomena"[1].

LHeC:

The LHeC collider will collide 60 GeV maximum energy electrons with 7 TeV protons or heavy ions. The LHeC collider main parameters are shown in Table 1.

Table 1: Beam Parameters LHeC

	Protons	Electrons
Energy (GeV)	7000	60
γ	7460	11740
$\varepsilon_{x,y}$ (nm)	0.4	0.43
Beam	>430 mA	6.4 mA

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ACCELERATION OF POLARIZED DEUTERON BEAMS WITH RIBF CYCLOTRONS

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Abstract

We have recently performed experiments with polarized deuteron beams at the Radioactive Isotope Beam Factory (RIBF). Tensor- and vector-polarized deuterons were produced using the RIKEN polarized ion source (PIS) [1], which is an atomic-beam-type ion source equipped with an electron cyclotron resonance (ECR) ionizer, and were accelerated to 190 MeV/u, 250 MeV/u, and 300 MeV/u with a cyclotron cascade. To measure the various spin observables, the spin orientation of the deuteron beams was freely directed by using a Wien filter. The advantage of this method is that since the velocity of the deuteron is low the size of a magnet required for the spin rotation is very compact. On the other hand it is crucial to realize strict single-turn extraction for each cyclotron because the cyclotron magnetic field causes precession of the deuteron spin resulting in a deviation between its spin orientation and the beam propagation direction. This paper describes the acceleration of the polarized deuteron beams by the RIBF accelerators and the method to confirm single-turn extraction.

INTRODUCTION

The mission of the Radioactive Isotope Beam Factory (RIBF) accelerator complex is to expand the availability of rare isotope beams. The RIBF accelerator complex was designed to provide various heavy ions with energies of up to 400 MeV/u. The versatility of the primary beams is one of the key advantages of RIBF. The acceleration mode is chosen according to the species, energies, and required intensities. Until now, 345 MeV/u beams of ^{48}Ca and ^{70}Zn, 320 MeV/u beam of α and 345 MeV/u beams of ^{78}Kr, ^{124}Xe, and ^{238}U, have been produced at RIBF using the RIKEN heavy-ion linac (RILAC) injector [2] in variable-energy mode and the RILAC2 injector [3] in fixed-energy mode, respectively. In addition, light ions d (190, 250, 300 MeV/u), ^{12}C, ^{14}N,^{16}O (250 MeV/u), and ^{18}O (230, 250, 294, 345 MeV/u) have been accelerated using the light-ion mode of the azimuthal varying field (AVF) cyclotron as an injector to the RIKEN ring cyclotron (RRC) and superconducting ring cyclotron (SRC), as shown in Fig. 1. While RIBF can provide intense heavy-ion beams for the production of radioactive isotope beams, light-ion beams are also available for physics experiments requiring high precision. Among them, a polarized deuteron beam with an intermediate energy of 100–300 MeV/u is one of the most powerful probes to study spin-dependent interactions, such as three-body-force of nucleon interactions [4]. Required turn purity was more than 99% for these experiments.

POLARIZED DEUTERON BEAMS

Production of Polarized Deuteron Beams

The RIKEN polarized ion source (PIS) is an atomic-beam-type ion source. It is a copy of one developed at Triangle University Nuclear Laboratory (TUNL) [5], and was modified at the Indiana University Cyclotron Facility (IUCF) [6].

A schematic illustration of RIKEN PIS is shown in Fig. 2. First, D_2 gas produced from heavy water in a water electrolyzer is dissociated and formed into atomic beams in a dis-

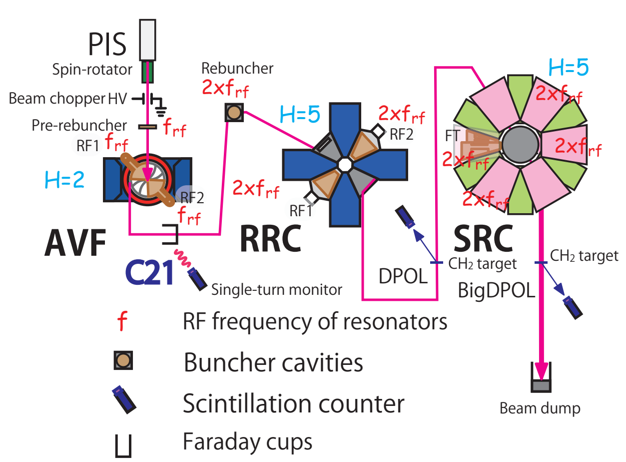

Figure 1: Setup of accelerators and monitors for polarized deuteron acceleration utilizing azimuthally varying field (AVF) cyclotron, RIKEN ring cyclotron (RRC) and superconducting ring cyclotron (SRC).

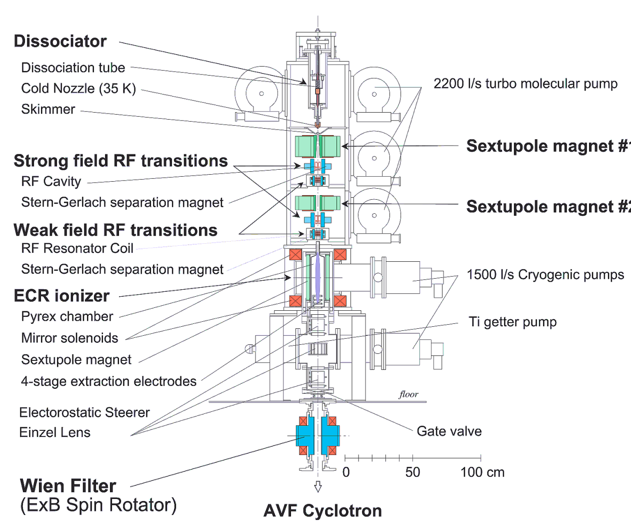

Figure 2: Schematic illustration of RIKEN polarized ion source.

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100 MeV H$^-$ CYCLOTRON DEVELOPMENT AND 800 MeV PROTON CYCLOTRON PROPOSAL*

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on behalf of the BRIF Project Team

Abstract

Since the last cyclotron conference in Vancouver, significant milestones have been achieved on the BRIF (Beijing Radioactive-Ion Beam Facility) project. On July 4, 2014 the first 100MeV proton beam was extracted from the H- compact cyclotron. The cyclotron passed beam stability test with beam current of 25 µA for about 9 hours operation. In the year of 2015, the first radioactive ion beam of K-38 was produced by the ISOL system, and the beam current on the internal target of the 100 MeV cyclotron was increased to 720 µA. In the year of 2016, the cyclotron was scheduled to provide 1000 hours beam time for proton irradiation experiment, single-particle effects study and proof-of-principle trial on the proton radiography technology. It is also planned to build a specific beam line for proton therapy demonstration on the 100 MeV machine. In this talk, I will also introduce our new proposal of an 800 MeV, room temperature separate-sector proton cyclotron, which is proposed to provide 3~4 MW proton beam for versatile applications, such as neutron and neutrino physics, proton radiography and nuclear waste treatment.

INTRODUCTION

The Cyclotron Laboratory at China Institute of Atomic Energy (CIAE) has been devoting to cyclotron development and related applications since it was established in 1956 [1]. An 100 MeV high intensity H-cyclotron, CYCIAE-100, is being built at CIAE. The machine is selected as the driving accelerator for the Beijing Radioactive Ion-beam Facility (BRIF). Figure 1 shows the layout of this project. The energy range of extracted proton beam for CYCIAE-100 can be adjusted continuously from 75 MeV to 100 MeV and 200 - 500 µA CW beam will be provided at the initial stage [2]. The first beam of CYCIAE-100 was extracted on July 4, 2014 [3], the operation stability have been improved and beam current have been increased gradually. On May 4, 2015, the first radioactive ion beam of $^{38}K^+$ was produced by bombarding CaO target by the 100 MeV proton beam. The effort for mA beam is continuing and 1135 µA beam was got on the internal target in June of this year.

In this paper, the beam commissoning progress and subsystem improvment of the 100 MeV H$^-$ cyclotron since last cyclotron conference in Vancouver will be presented, including the multi-cusp source, buncher, matching from the energy of the injected beam, vertical beam line and central region, beam loading of the RF system and instrumentation for beam diagnostics etc. In addition, this paper also introduces the recent conceptual design progress of the pre-study of an 800 MeV, 3-4 MW separate-sector proton cyclotron, referred to as CYCIAE-800 [4], which is aimed to provide high power proton beam for various applications, such as neutron and neutrino physics, proton radiography and nuclear data measurement and ADS system.

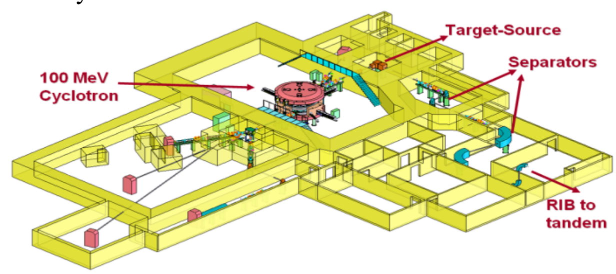

Figure 1: The layout of the BRIF project.

BEAM COMMISSIONING

By the end of 2013, all the sub-systems of CYCIAE-100, including the main magnet, the main coil, the rf system, the vacuum system, the injection system, the ion source, the diagnosis and extraction units, the lifting system and the power supply systems, were installed and assembled on site. Figure 2 shows the photograph of the cyclotron, which was taken at the time all the subsystems were installed on site. The construction of CYCIAE-100 takes the advantages of both high precision typically seen in AVF cyclotrons and strong focusing in separated sector cyclotrons. The main parameters for CYCIAE-100 are presented in Ref. [5].

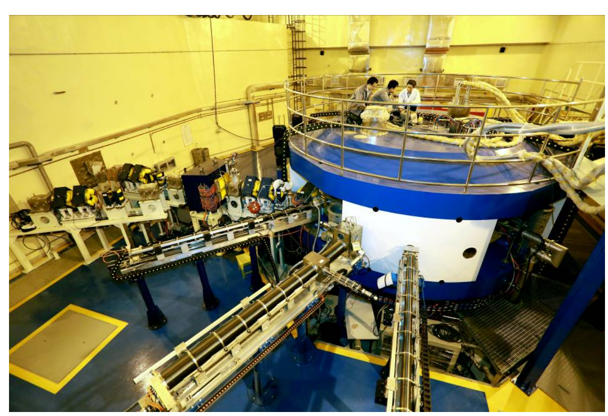

Figure 2: The 100 MeV compact cyclotron.

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CHARGE STRIPPER RING FOR CYCLOTRON CASCADE

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Abstract

In the multi-stage acceleration of heavy ions such as the acceleration at the RIKEN RI beam factory (RIBF), the electron stripping process with charge strippers is an inevitable process for the efficient acceleration. The efficiencies, however, for the charge-state conversion of very heavy ions are not so high with common charge strippers in the acceleration up to the energy around hundreds MeV/u. The total efficiency of two charge strippers for 238U acceleration at the RIBF is only 6%. It is a bottleneck for the intensity upgrade. In the present study, we designed high-efficient charge stripper rings which have applicability to the RIBF.

INTRODUCTION

In a multi-stage acceleration of heavy ions, the electron stripping of the ions with charge strippers is an essential process for efficient acceleration. When one accelerates the very heavy ion beams, such as uranium ions, up to several hundred MeV/u, it is not possible to provide full strip beams with conventional strippers. Charge state of the beams after the stripper has a distribution following the physical law. The intensity of ions should be reduced significantly in exchange for the efficient acceleration.

In the uranium acceleration at the RIKEN RI beam factory (RIBF) [1], the charge state is converted twice and the total conversion efficiency is only 6%. The low conversion efficiency is an important bottleneck to generate a high-intensity uranium beam. Such beams are strongly desired in the world because they can provide a huge breakthrough for exploring the new domain of the nuclear chart.

The FRIB project, one of the next generation heavy ion facilities in the USA [2], is planning to use the multi-charge acceleration technique. In this scheme, the beams with five charge states are accelerated and transported at the same time in the superconducting linear accelerator. Unfortunately, this technique is not applicable for the acceleration with ring-type accelerators, such as a cyclotron.

In this paper, we propose and discuss charge stripper rings which can be available as an efficient stripper in a multi-stage accelerator complex involves circular rings such as the RIBF.

URANIUM ACCELERATION AT RIBF

The acceleration scheme of ^{238}U beams at the RIBF is shown in Fig. 1. $^{238}U^{35+}$ beams extracted from the 28-GHz superconducting ECR ion source [3] is accelerated with an injector RILAC2 [4] and four ring cyclotrons (RRC, fRC, IRC, SRC) up to the energy of 345 MeV/u.

The charge state is converted twice at the energies of 10.8MeV/u and 51 MeV/u, respectively. The first stripper based on the He gas [5,6] converts the charge state from 35+ to 64+ with the conversion efficiency of about 20%. The second stripper of rotating carbon disk stripper [7] converts from 64+ to 86+ with the efficiency about 30%.

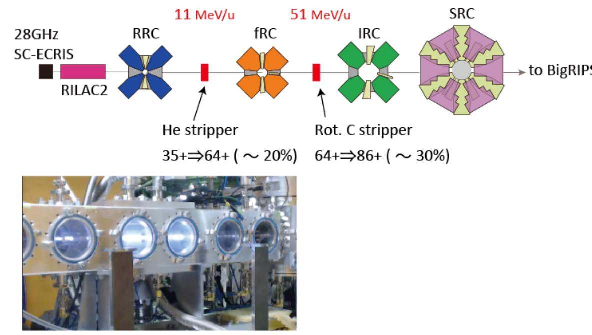

Figure 1: Acceleration scheme of ^{238}U ion beams at the RIBF.

A simple way to increase the low total conversion efficiency is to remove the first stripper and to improve the fRC to accept U^{35+} beams (K value is approximately 2200). In a design of a conventional normal conducting ring cyclotron, the new fRC should be a very huge and heavy cyclotron comparable with the SRC, the largest cyclotron in the world [8]. Although it is a sure way to improve the present intensity of uranium beams, we require further optimization of the design for the new fRC.

CONCEPT OF STRIPPER RING

We propose here the new concept of an efficient stripper ring as shown in Fig. 2. As a conventional scheme at the RIBF, $^{238}U^{35+}$ beams coming at the frequency 18.25 MHz are injected to the first stripper and only $^{238}U^{64+}$ beams (20% of the injected beams) are passed through the subsequent selection dipole magnet. The others are dumped inside the magnet.

On the other hand, in the new scheme, the beams other than the selected charge state are circulated recovering the energies and re-entered to the stripper. The beams with the selected charge state are extracted continuously, repeating this circulation process.

Assuming the conversion efficiency $\varepsilon_0 = 0.2$ is unchanged, the total conversion efficiency after the n-times circulation is given by $\epsilon_n = 1-(1-\epsilon_0)^n$. Ideally, the conversion efficiency becomes 3 times higher than the initial efficiency ε_0 after the 3 times circulation. The bunch structure of the extracted beams must be preserved to match to the acceleration condition of the subsequent cyclotrons.

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EXTRACTION BY STRIPPING IN THE INFN-LNS SUPERCONDUCTING CYCLOTRON: STUDY OF THE EXTRACTION TRAJECTORIES

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Abstract

The INFN-LNS Superconducting Cyclotron will be upgraded to allow for the extraction by stripping for ion beams with masses below 40 amu. By choosing properly the position of the stripper, it is possible to convoy the trajectories of the selected representative ion beams across a new extraction channel (E.C.).

Here we report the design study for the new E.C. and the simulations of the beam envelopes for a set of ions to find out the parameters of the magnetic channels necessary to focus and to steer the beams through the new extraction line. Two new compensation bars have been designed to compensate the first harmonic contribution of the new magnetic channels. The results of these simulations will be also presented.

INTRODUCTION

The INFN-LNS Superconducting Cyclotron (CS), designed over thirty years ago, is an isochronous three-sector compact accelerator with a wide operating diagram: ion species from H to Pb are accelerated with energy in the range 10-80 AMeV.

The beam extraction system, composed of two electrostatic deflectors followed by a set of magnetic channels, does not allow to achieve a beam power exceeding 100 W, due to the power dissipation on the electrostatic deflectors.

The stripping extraction is a valid alternative to increase the extracted beam power up to 2-10 kW for the ion species with mass less than 40 amu. A preliminary study demonstrated its feasibility [1] if a new extraction channel (E.C.) is drilled. Indeed, the extraction by stripping through the existing extraction channel for the ions of interest is less convenient because a wider clearance is required to allow intense ion beams pass through. Furthermore, the quadrupole component for the magnetic channels varies in a range of values wider than those necessary for the new extraction channel.

In Fig. 1 the median plane of the CS with the existing and the new extraction channels is shown together with the trajectories of two selected ions.

Thanks to high beam power, the INFN-LNS users will be also able to make researches on low cross section processes in nuclear physics. In particular, a high beam power is required by the NUMEN experiment, which proposes to measure the element of the nuclear matrix in the neutrino-less double beta decay using double charge exchange reactions [2,3], and the production of radioactive ion beams by in-flight fragmentation technique will also be enhanced [4].

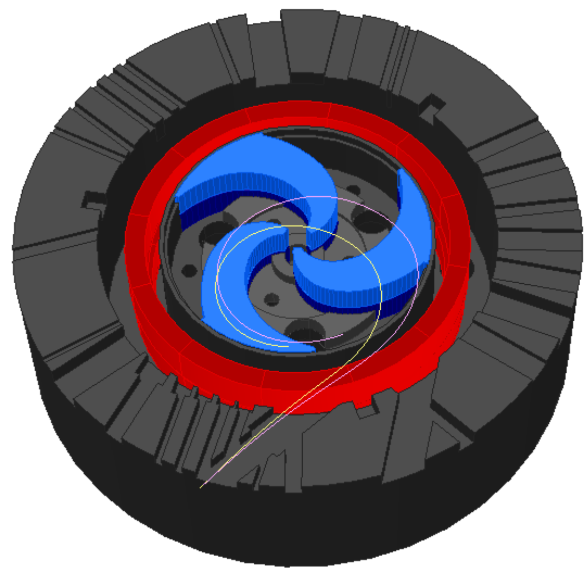

Figure 1: Extraction trajectories of some studied ions through the new extraction channel.

To accomplish the stripping extraction, a significant upgrade of the CS will be necessary, mainly because a new cryostat with new superconducting coils [5] is mandatory to have a larger vertical gap in the extraction line and additional penetrations are necessary to host new magnetic channels and new compensation bars. A general description of the CS upgrade operations is presented in ref. [6]. In addition, the existing extraction mode will be maintained to satisfy the demand of ion beams in a wide mass and energy range by the INFN-LNS community.

STUDY OF THE STRIPPING EXTRACTION

The ion species considered in the present study of the stripping extraction are ^{12}C, ^{18}O, ^{20}Ne accelerated with charge state q=Z-1 or Z-2 or Z-3 at energies in the range 15÷70 AMeV.

We assumed that all these ions of interest, at energies higher than 15 AMeV, are fully stripped of their electrons after crossing the stripper foil [7].

After the change of the charge state, the trajectory of each ion has a strong first harmonic precession and this could bring the beams to come out from the cyclotron field.

The study of the stripping extraction has been performed mainly through two codes, GENSPE and

COLD CATHODE ION SOURCE FOR IBA CYCLONE®230

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Abstract

At IBA, we use a P.I.G. floating cathode ion source for injection in the CYCLONE®230 cyclotron. The purpose of the project is to investigate how the present ion source could be replaced by a P.I.G. cold cathodes one with a longer lifetime. Experiments described in this article were done on a dedicated test setup to benchmark the different modes. A new chimney design has been developed to test cold cathode mode in CYCLONE®230 without any other mechanical modifications.

INTRODUCTION

The floating cathode source uses a tantalum filament which needs to be replaced typically every 5 to 7 days. Cold cathodes ion sources are already used in other IBA cyclotrons and allow a much longer period between two maintenance operations. H^+ cold cathode ion source has been developed with AIMA for the new synchro-cyclotron. Pulses are very short (few µs) during capture process in the synchrocyclotron, but much longer pulses (few ms) are produced in the isochronous CYCLONE®230 cyclotron.

TEST CAMPAIGN

The test bench developed with AIMA for the synchro-cyclotron source five years ago was modified to allow vertical insertion of the CYCLONE®230 source shaft in the same setup. The 1.7 Tesla large aperture magnet (see Fig. 1) and all the equipment were installed on an elevated platform, so the ion source can be vertically inserted in the vacuum box (see Fig. 2).

Figure 1: 1.7T test magnet and the vacuum system at AIMA.

*philippe.cailliau@iba-group.com

Figure 2: CYCLONE® 230 source arm mounted on a dedicated insertion system underneath test magnet.

The three measurement plates collecting the different ion species and the puller electrode are at DC high voltage (15kV). The ion source is at ground potential. All these elements are located in a vacuum chamber as shown in Fig. 3.

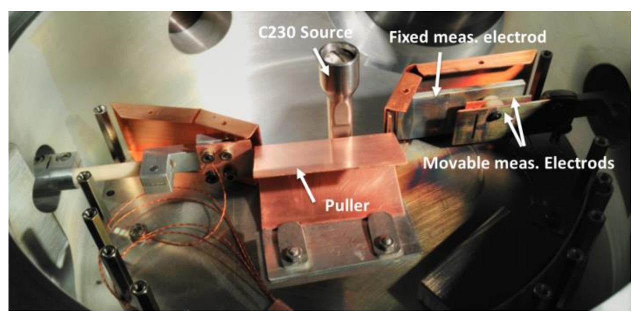

Figure 3: Test bench vacuum chamber, high voltage top plate removed. One can observe the chimney, the puller and measurement electrodes.

Arc and filament power supplies are standard CYCLONE®230 equipment. In floating cathode mode, we operate at arc voltage (Varc) below 200V. Since the cold cathode mode requires at least 800V to light up a plasma, the arc power supply was modified to generate pulses up to 500V and an additional 1 kV commercial DC power supply was connected in series.

FLOATING CATHODE SOURCE BASELINE

The first experiment consisted in recording a baseline of the actual floating cathode ion source on the test bench. The aim is characterising the source performances as function of parameters of its own design, i.e. independently of the isochronous machine central region environment. The extraction gap has been minimized for 15 kV extraction voltage and fixed on the setup.

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EXTRACTION SYSTEM DESIGN FOR THE NEW IBA CYCLOTRON FOR PET RADIOISOTOPE PRODUCTION

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Abstract

At IBA, we have designed, constructed, tested and industrialized an innovative isochronous cyclotron for PET isotope production. The design has been optimized for cost-effectiveness, compactness, ease of maintenance and high performances, with a particular emphasis on its application and market. Multiple target stations can be placed around the vacuum chamber. An innovative extraction method (patent applications pending) has been designed which allows to obtain the same extracted beam sizes and properties on the target window independent of the target number. This is achieved by proper design and shaping of the magnet poles. This magnetic design is discussed together with beam dynamics simulations and beam extraction tests on the first machine.

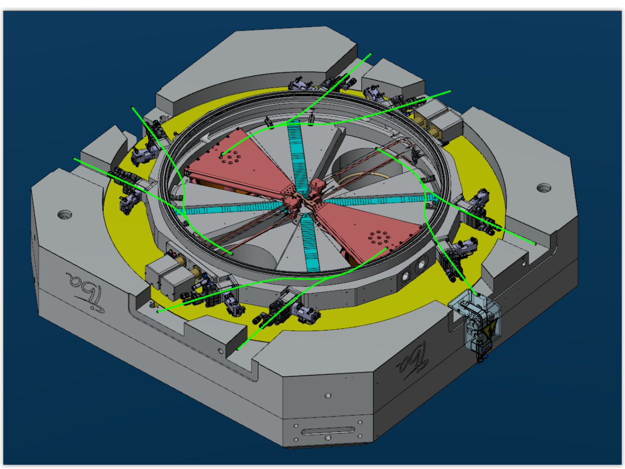

Figure 1: View on the upper half of the CYCLONE®KIUBE. In grey is shown the magnetic iron including the return yoke and the four poles. The pole-inserts (in blue) are used to shim the isochronous field. Further shown is the main coil (yellow), the accelerating structure (red) and the 8 target stations mounted on the vacuum chamber. The extracted orbits are shown in green.

INTRODUCTION

Modern medical radioisotope production cyclotrons often accelerate negatively charged ions such as H^- and/or D^-, because this allows for an easy way of extraction: the beam passes a thin stripper foil which removes the two electrons attached to the ion, resulting in an instantaneous change of sign of the orbit local radius of curvature such that the particles are directed towards the exit of the pole region. The method has several advantages: i) the very simple extraction device, ii) 100% extraction efficiency, iii) the possibility for simultaneous dual beam extraction, iv) the possibility to place several targets around the machine and and v) good beam optics. This technique is also used in the well-known IBA CYCLONE®18/9 [1]. This cyclotron accelerates H^- to 18 MeV and D^- to 9 MeV. In recent years, the need for D^- has gradually decreased and therefore IBA decided to design the CYCLONE®KIUBE [2,3] as a new PET cyclotron accelerating only H^-. In this new machine we re-visited the extraction design to implement possible improvements. Figure 1 shows a view on the upper half of this new cyclotron.

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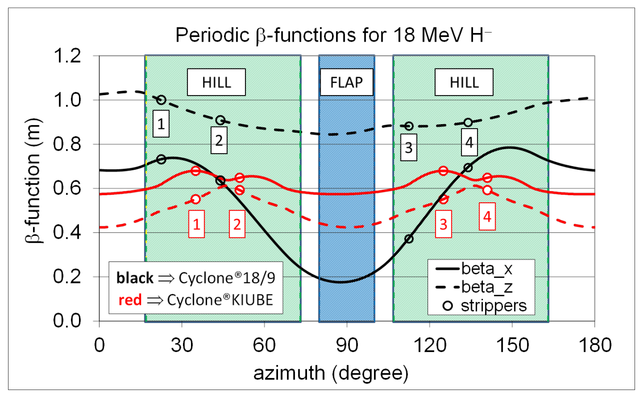

Figure 2: Periodic horizontal (solid) and vertical (dashed) β-functions along the 18 MeV closed orbit. The red curves correspond with the CYCLONE®KIUBE. For comparison, the same curves are given for the CYCLONE®18/9 [1]

EXTRACTION DESIGN

A maximum of 8 targets can be placed around the cyclotron vacuum chamber for isotope production. For the new extraction design we looked for an optical solution such that the beam sizes on these targets i) are more or less independent of the target position and ii) have a more or less circular shape. In the CYCLONE®18/9 the switch of the isochronous magnetic field shape from D^- to H^-, is done by two movable iron inserts (the flaps), placed in two opposite valleys. In the H^- mode, these flaps are moved close to the median plane and there introduce a considerable 2nd harmonic magnetic field component. This makes that the extracted beam optics towards the targets is quite different for extraction on the pole upstream or the pole downstream of the flap-valley.

The linear beam optics can be conveniently represented with the beta-function Twiss-parameter. The beam size X

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MAGNET DESIGN OF THE NEW IBA CYCLOTRON FOR PET RADIO-ISOTOPE PRODUCTION

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Abstract

An innovative isochronous cyclotron for PET isotope production has been designed, constructed, tested and industrialized at Ion Beam Applications (IBA) [1]. The design has been optimized for cost-effectiveness, compactness, ease of maintenance and high performance,which are key elements considering its application in the dedicated market. This cyclotron (patent application pending) produces 18 MeV protons and the cyclotron is called the **Cyclone® KIUBE**. Compared to the previous 18 MeV proton and 9 MeV deuteron machine from IBA, the Cyclone®18/9, the gap between the poles has been reduced from 30 mm to 24 mm and the method of pole shimming to obtain an isochronous magnetic field has been reviewed thoroughly. In early 2016, the first prototype Cyclone® KIUBE was successfully commissioned at the IBA factory and the measured proton beam intensity outperformed the Cyclone® 18/9.

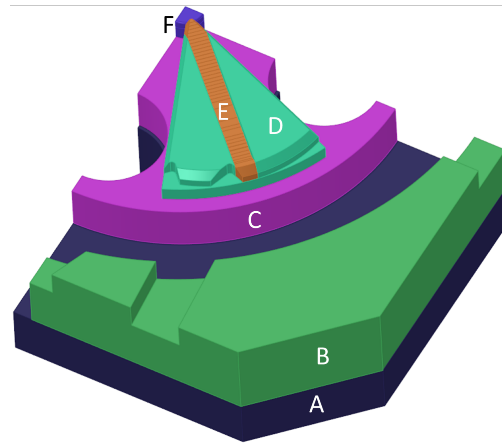

Figure 1: The magnetic circuit, including (A) the return yoke, (B) lateral return yoke, (C) sector, (D) the pole, (E) the pole insert and (F) the central plug.

MAGNET DESIGN

The magnetic design of the Cyclone® KIUBE was performed with the OPERA-3D code in combination with IBA's in-house beam dynamic codes. One symmetry period of the 4-fold symmetric Cyclone® KIUBE is shown in Fig. 1, where the (lateral) return yoke, the pole, the pole inserts (patent application pending) and sectors are indicated. The Cyclone® KIUBE fits a rectangular cuboid of 1740x1740x860 mm^3. The vertical gap between the pole faces has been reduced by 6 mm in the Cyclone® KIUBE, compared to the Cyclone® 18/9. This minor reduction allows to reduce the total current and power consumption and the overall size and weight of the cyclotron. The pole azimuthal length has been reduced from 55 degrees to 45 degrees. In this way, the valleys become wider and the pumping hole in the valley can be made bigger. It increases the pumping efficiency and improves the vacuum level. As such, beam losses of the H^- ions can be reduced and the transmission efficiency can be increased. The position of the pumping holes is shown in Fig. 2. The vacuum chamber is located between the coil and the outer radius of the pole. The cut corners of the square cyclotron are filled at two opposite locations by the yoke lifting system, whereas the remaining two opposing corners are left free for auxiliary equipment. Two small openings in the lateral return yoke are present for the coil cooling and electrical connections. These holes break the four-fold symmetry of the complete cyclotron, but do not introduce large second harmonic imperfections, as will be shown in Fig. 6. The larger iron volume of the lateral return yoke next to the poles promotes the magnetic flux passage, thereby creating a sufficiently large flutter in the median plane.

A view on the pole is shown in Fig. 3. A "groove" is present in the center of the pole to accomodate the pole insert (see next paragraph). Two stripping extraction systems per pole give the possibility to install 8 targets in the different extraction ports (4) in the lateral return yoke.

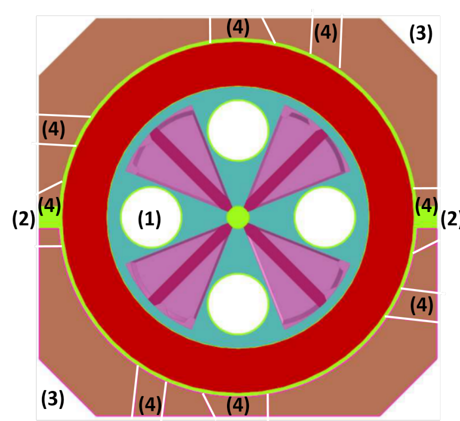

Figure 2: A top view on the Cyclone® KIUBE. 1/ the four pumping holes in the valleys, 2/ the coil electrical and cooling ports, 3/ the yoke lifting system and 4/ the extraction ports.

POLE INSERTS

The pole inserts in the Cyclone® KIUBE are the novel approach to the traditional pole edge milling (used in the Cyclone®18/9) during the magnetic mapping of the

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INSTALLATION AND COMMISSIONING OF THE Cyclone®70P: Zevacor PROJECT

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Abstract

In October 2013, IBA sold its first Cyclone®70p, extracted 70 MeV proton machine to Zevacor Pharma, Indianapolis, IN, USA.

This brand new machine combine the advantages of the design of the Cyclone®30 HC (1,5mA extracted beam) and the Cyclone®70 XP (multi-particle). Moreover, this high energy cyclotron has been optimized for H^- ions acceleration, activation reduction and long term beam production.

The installation will be used for high power and long term irradiations of rubidium Rb targets to produce strontium ^{82}Sr generator applied in the field of cardiac imaging.

From cyclotron to beam lines and up to the target station, all subsystems have been reviewed to reach highest level of quality, reduce the activation (by the use of low activation material and reduction of beam losses) and finally optimized the maintenance.

For that delivery, the machine will be equipped with 6 beam transport lines and 2 solid target station units.

In June 2015, about 21 months after contract signature, the IBA Factory Acceptance Tests have been successfully performed in Belgium and the machine was shipped to Indianapolis, IN, USA to be installed in Customer factory cyclotron vault.

RIGGING AND INSTALLATION

In September 2015, the Cyclone® 70P and auxiliary equipment have been successfully rigged (inserted) into the various vaults (see Figs. 1-3).

This 140 tons cyclotron and its surrounding equipment reached their final position in a few days allowing the installation start up.

The installation has been started according to ambitious schedule (3 months in advance of the contractual planning) thanks to a very good collaboration with the Customer during the whole building construction.

COMMISIONING

The Cyclone® 70P for Zevacor Pharma (Figs. 4-6)is delivering 70 MeV proton beam to up to 6 target vaults.

All those vaults (cyclotron and targets) have typically 4m concrete walls to shield it.

The beam is extracted thanks to stripper shaft (variable energy from 30 to 70 MeV) through 2 switching magnets located on each side of the cyclotron to the beam lines.

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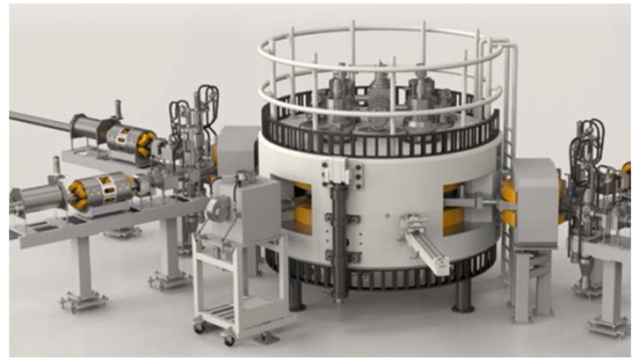

Figure 1: Cyclone® 70P general overview.

Figure 2: Cyclone® 70P rigging in Indianapolis.

Figure 3: Cyclone® 70P in vault in Indianapolis.

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DESIGN OF THE Cyclone® 70 P

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Abstract

The IBA Cyclone® 70 P is a high intensity 70 MeV proton-only cyclotron dedicated to the production of radioisotopes for PET generators and SPECT. The nominal power of the extracted beam goes above 50kW (750µA@70MeV). The proton-only cyclotron was developed based on the previous experience of the multi-particle Cyclone® 70 XP running in Nantes, France.

Numerical tools have been extensively used to optimize the magnetic field, to avoid potentially harmful resonances during acceleration and improve the acceleration efficiency of the cyclotron. In addition, electromagnetic and mechanical calculations permitted to obtain a low dissipated power and electromechanically robust design of the RF system. The vacuum computations have permitted to optimize the beam transmission, the placement and type of cryopumps.

This new development of Cyclone® 70 P was the initial part of the successfully finished IBA project also presented during this conference [1].

MAGNET DESIGN

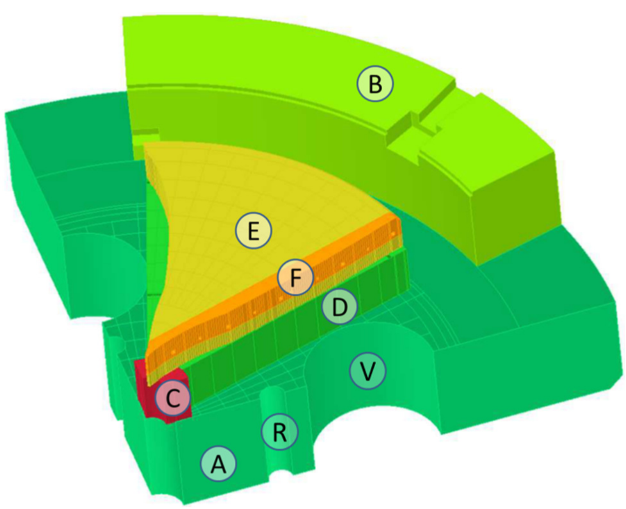

Figure 1: Cyclone® 70 P – lower (or upper) one period of the four-fold rotational symmetry.

The Cyclone® 70 P magnet, Figure 1, consists of: top (bottom) return yoke (A) having diameter of 3820 mm. The lateral return yoke (B) closes the magnet of 1700 mm high. The central plug (C) and the sector (D) create the base for the pole (E) with the outer radius of 1240 mm.

The removable pole edge (F) attached to the, stair-like, lateral pole edge is iteratively milled during mapping process to obtain the isochronous magnetic field for accelerated H^- ions.

The total iron weight is about 108 tons and the resistive coils add next 4 tons.

The cyclotron vacuum chamber and the coil fill the space between the outer radii of the pole and sector and the inner radius of the lateral return yoke.

The vertical gap between poles and between removable pole edges is constant 40 mm and more than 40k Ampere-turns are necessary to reach the required field level in the median plane.

Two ports are located in each valley. The vacuum pumping port (V) diameter is large (520 mm). The dee stem, the dee cooling tubes pass through the small diameter (100 mm) port (R).

The shape of the second lateral pole edge is fixed and its small spiralization helps to obtain higher vertical tune ν_z and to avoid dangerous resonances.

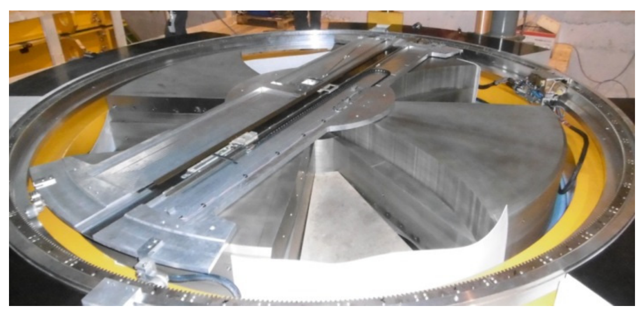

Figure 2: The lower half of the Cyclone® 70 P and the mapping system.

The new mapping system, Figure 2, measuring the magnetic field axial component in the cyclotron median plane on any chosen radial and azimuthal grid was also developed in this project.

The mapping system is supported by the cyclotron lateral return yoke and allows magnetic field measurements practically to the radius where magnetic field values are close to zero between resistive coils.

The magnetic field of the cyclotron model was used to determine the central region geometry. The measured field was used for the crosscheck and the optimization of the spiral inflector of the axial injection system.

The same fields have been used to find positions of the strippers to extract 30-70 MeV protons and to determine the position of the port in the lateral return yoke where the extraction system shaft passes and pivots.

Magnetic field values for radii beyond the outer coil radius, necessary for extraction calculations, have been taken from the calculated models.

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COMMISSIONING AND TESTING OF THE FIRST IBA S2C2

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Abstract

The first unit of the IBA superconducting synchrocyclotron (S2C2), used in the Proteus®ONE compact proton therapy solution, has been installed and commissioned in Nice. In this communication, we will present some selected results of the commissioning with the main focus on the accelerator aspects, showing the influence of machine parameters on beam properties like stability, energy and intensity, which are key elements in proton therapy applications.

THE PROTEUS®ONE LAYOUT

Figure 1 shows the S2C2, installed at the testing facilities in Louvain-la-Neuve (Belgium), and the layout of the compact gantry, which is attached to the S2C2. Together, they constitute the main components of the Proteus®ONE proton therapy system. More information on the S2C2 characteristics can be found in [1]. The compact gantry is described in [2]. A main feature of the compact gantry is the integration of the energy selectrion system (ESS) in the gantry itself (see Fig. 1). At the end of the ESS, the dispersion is maximized and a slit is present to select the needed proton energy.

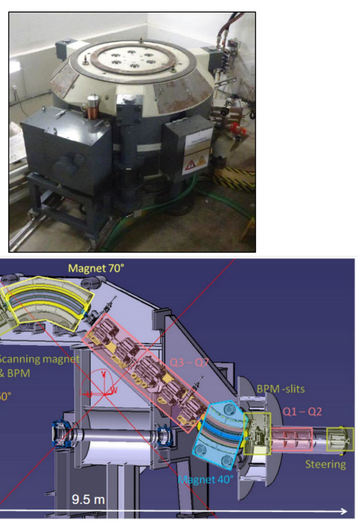

Figure 1: (Top) The S2C2 installed at the testing facilities. (Bottom) the compact gantry layout. The S2C2 and the compact gantry constitute the Proteus®ONE system.

THE S2C2 TIMING

Figure 2 shows the timing properties of the S2C2. The green line shows the source arc current feedback (pulsed cold cathode source), the red line shows the RF frequency sweep

Table 1: S2C2/Proteus®ONE Main Properties and Key Figures

Nominal beam energy	230 MeV
Max. clinical charge at isocenter	4.5 pC
Energy spread at nominal energy	≈400 keV
Pulse repetition rate	1 kHz
Pulse duration	10 μs
RF frequency range	60-90 MHz

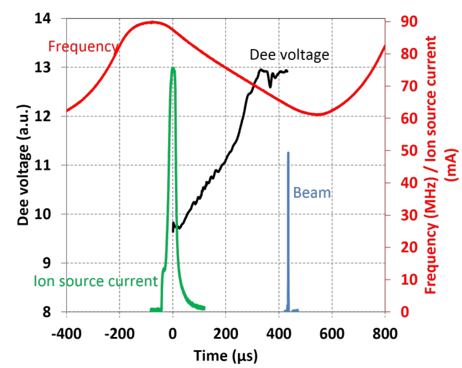

Figure 2: Timing properties of the S2C2 in the Proteus®ONE system: the source timing, dee voltage regulation, RF frequency sweep and the beam signal.

(periodicity of 1 ms) and the black line shows the dee voltage profile during acceleration. The blue line is the measured beam signal induced on a senstive diamond probe [3]. These timings are repeated at a frequency of 1 kHz, which is the periodicity of the RF frequency sweeps.

EMITTANCE

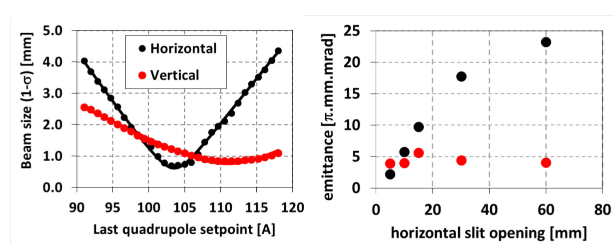

Figure 3: (Left) the horizontal and vertical beam spot size on the degrader position (≈2.0 m after the S2C2 exit port) (Right) the evolution of the horizontal and vertical emittance as a function of a horizontal slit, installed prior to the degrader.

Figure 3 shows the measured beam size on the position of the energy degrader, 2 m downstream from the S2C2 exit port. Two quadrupoles and a horizontal slit are positioned

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THE USE OF GRAPHENE AS STRIPPER FOILS IN SIEMENS ECLIPSE CYCLOTRONS

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Abstract

This paper presents the results of an experimental study for the use of graphene foils as an extractor (stripper) foil in the 11-MeV Siemens Eclipse Cyclotron. The main advantage of graphene foils compared with carbon is very high thermal conductivity. The graphene also has significant mechanical strength for atomically thin carbon layers. The life time of these foils is more than 16,000 µA*H. The graphene foils showed a significant increase in the transmission factor (the ratio of the beam current on the stripper foil to the current on the target), which was approximately more 90%. The technology in fabricating these graphene foils is shown. The pros and cons of using the graphene material as a stripper foil in cyclotrons are analysed.

INTRODUCTION

The use of stripper foils in the cyclotrons with negative hydrogen ions allows for easy output of the proton beam from the cyclotron into the target [1]. The 11-MeV Eclipse Cyclotron [2] uses this approach for the production of medical isotopes. The standard stripper foils based on carbon materials are widely used for these goals. The discovery of graphene [3] and the unique properties of graphene have created a large interest in this material as a stripper foil compared to the standard graphite and carbon foils. The main difference is the thermal conductivity of graphene which is up to 20 times higher than that of polycrystalline graphite. This gave interest for the application of graphene as a stripper foil in accelerators of charged particles and especially in commercial cyclotrons, such as the Eclipse cyclotron. The preliminary application of graphene foils from Applied Nanotech [4] as a stripper foil shows the main advantages of this material in comparison with the standard carbon and graphite foils. The main focus of this study was to determine the lifetime of stripper foils and to understand any cyclotron operating performance improvements. One the main questions was to characterize the radiation damage of graphene under irradiation by negative hydrogen ions with a kinetic energy of 11 MeV and current up to 100µA.

THE TECHNOLOGY OF FABRICATION FOR GRAPHENE FOILS

The technology for the fabrication of graphene foils is described in more detail in [5]. The foil fabrication method is based on the controlled reduction of graphene oxide by hydrazine with addition of ammonia in an aqueous dispersion. The dispersion of graphene oxide with loading of 0.5% wt. in water was obtained from Angstron Materials. The dispersion was reduced for 4 hours at 95°C and then cooled down to room temperature. The thickness of graphene foils was controlled by using a calculated volume of graphene dispersion knowing the loading of graphene. A commercially available stainless steel filter holder was used to make graphene foils by pressure filtration. The diameter of the fabricated foils was 13 cm. The filter holder allowed increasing the differential pressure across the filter. A compressed air line with a pressure regulator was connected to the filter holder to pressurize the air space above the graphene dispersion. Pressure up to 300 kPa was used to filter the dispersion. Commercially available polymer filter membranes with a diameter of 142 mm were used for the filtration. After filtration, graphene foils still on the filter membrane were removed from the filter holder and peeled off the filter membrane to obtain free-standing graphene foils. The described process can be adapted to fabricate foils with a wide range of foil thickness and using different isotopes of carbon.

EXPERIMENT

The experiments with graphene foils with a thickness of about 3µm (0.5mg/cm^2) were conducted on four Siemens Eclipse cyclotrons. The graphene foils were installed on the carousels of the Eclipse cyclotron. The general picture of the graphene material is shown in Figure 1.

a) b)

Figure 1: General view of graphene foils: a) fabricated foil; b) graphene cross section.

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DIAGNOSTIC TOOL AND INSTRUMENTATION FOR HANDLING 50 KW BEAM POWER

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Abstract

The SPES facility entered the commissioning phase and the 70 MeV cyclotron is delivering the proton beams at the maximum power permitted. The INFN team has developed additional beam instrumentation in order to stop the particles at different power allowing the tuning of the beamline and to check the particles losses during the transport. In particular, a beam dumper able to stop up to 55 kW beam power has been constructed and tested as well as the beam loss monitor system by INFN team. Here we present the status of the beam instrumentations supplied by INFN and the results achieved during the test with the beam.

INTRODUCTION

For the SPES facility at Laboratori Nazionali Legnaro of INFN in Italy a 70 MeV proton cyclotron has been installed and is being commissioned. To safely verify the capability of the machine, and correctly tune both cyclotron and beam line, several diagnostic have been developed and installed. Among them most relevant are Faraday cups (FC) for low power (up to 1 kW) beam, a more powerful beam dumper (BD) to stop the full power (700 μA, 70 MeV, i. e. 49 kW) beam and ionization chambers beam loss monitors, divided into four sectors to be able to highlight misalignment of the beam on the beam line. The general layout of the cyclotron vault is shown in Fig. 1.

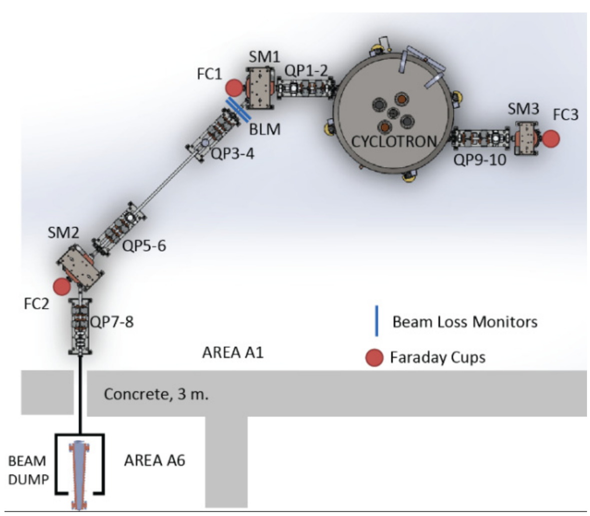

Figure 1: General layout of the cyclotron vault, showing the cyclotron, the main diagnostics and the focusing quadrupoles (QP).

LOW POWER FARADAY CUPS

Two low power water-cooled (closed-circuit) Faraday cups (FC) have been installed. They are able to withstand and measure up to 1kW:

- 14 μA, 70 MeV
- 28 μA, 35 MeV

The temperature of the FCs are measured with Pt1K sensors, current is measured directly through a current amplifier, and 50 mm Pb shielding wrap the FCs to allow access to the cyclotron vault. The FCs are made of oxygen-free high conductivity (OFHC) copper. The thickness of the copper at the impact walls span from a minimum of 8 mm, were the cooling water flows, to a maximum of 24 mm. The FCs were simulated using Comsol software, using as a cooling medium water, 3 litres/min, at 20 °C inlet temperature. The thermal power simulated is a cylinder with depth of 7.09 mm, with Gaussian power distribution (with σ = 5mm) with cylindrical symmetry, as shown in Fig. 2.

The simulated temperature profile on the symmetry axis is at 500 W incident power is shown in Fig. 3. The beam is arriving from the right side. The curves refer to different elapsed times since start of the beam.

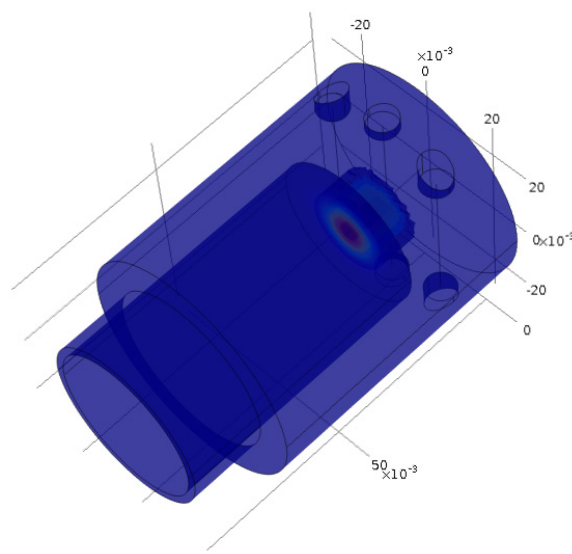

Figure 2: In blue the simulated FC volume, in red at its centre the thermal load of gaussian profile.

A NEW CONCEPT OF HIGH CURRENT POWER SUPPLY FOR THE MAIN CYCLOTRON MAGNET AT TRIUMF*

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Abstract

A sophisticated power supply was studied and designed to supply a high current to the main magnet of the TRIUMF cyclotron. The power supply will be operated with a current up to 20000 A in DC mode. It has been designed using a modular approach, with a 12-pulse input rectifier and two DC link which feeds sixteen DC/DC chopper modules in parallel connection.

The conceived power supply integrates a sophisticated control and a precise current measurement chain developed at CERN for the Large Hadron Collider (LHC).

This paper presents the solution described in the design report, the choice of the main purchased components which will lead to a final assembly and test before the end of 2016.

CONVERTER TOPOLOGY

The main components are:

- Input Circuit Breakers and Pre-charge Circuit.
- Two Rectifier Transformers.
- Two Main Rectifier stages (with fuses).
- Two passive RLC Filters downstream from each Main Rectifier stage.
- Output stage composed of 16 switching IGBT modules operating in parallel.
- Freewheeling diodes across the output bars.

The main input contactor/breaker (MCB) is realized by a motorized circuit breaker, which provides manual and remote ON/OFF functionality to the power supply.

The ground breaker is located at the input of the power supply: it is a manual switch with a keyed lock-out feature which allows the output of the breaker to be connected to ground only when the main input contactor/breaker is open.

To limit the inrush current during the start-up of the power supply a pre-charge resistive branch is used, remotely enabled via an auxiliary contactor.

The input stage realizes a 12-pulse topology through two three-phase transformers, phase-shifted by 30 degrees.

The two rectifier stages, each composed of a rectifier bridge plus a damped LC filter, realize two separated DC-links for the downstream chopper modules. Each DC-link provides the input for the following switching stage, each composed of eight chopper modules operating in parallel.

All the switching modules have an output filter inductor, and converge on a damped capacitive filter, placed at the output of the power supply.

*TRIUMF receives federal funding via contribution agreement through the National Research Council of Canada.

A free-wheeling diode (realized with 3 devices in parallel) is located across the output bus bars to correctly discharge the energy stored in the magnet when the power supply turns off.

Technical Specifications

A list of main technical specifications for the power supply is presented in Table 1.

Table 1: Main ratings of the power supply

PARAMETER	VALUE
Output Current/Voltage	20000 A / 80 V
Output Power	1600 kW
Mode of operation	DC
Regulation Mode	Constant Current
Topology	IGBT based buck converter
Equivalent Output Switching Frequency	16 x 10 kHz = 160 kHz (10 kHz for each module and 8 PWM carriers phase-shifted)
Absolute Accuracy	±1 part in 10^4
Current Ripple	±2 ppm of 20 kA for the range 17 kA to 20 kA
Short Term Stability (5 min) @ max I_{OUT}	≤ 2 ppm of 20 kA
Long Term Stability (8 hour) @ max I_{OUT}	≤ 5 ppm of 20 kA
Power Factor	≥ 0.96
THDin	Typical of a 12-pulse rectifier stage
AC Input	3ϕ, 3-wire, 800 VAC
Cooling	Air and Water cooling
Footprint	20.7 x 8.4 feet

Chopper Modules

The output stage is a chopper converter that consists of 16 modules in parallel. Each module has three IGBTs in parallel with the same PWM and every IGBT has its own inductor (see Fig. 1). The switching frequency is exactly 10 kHz and the power of each module is up to 100 kW.

The 16 modules are controlled with a phase-shift to increase the effective switching frequency to 160 kHz and thus reduce the ripple in the output current.

Layout

The power supply is composed of five cubicles (max dimensions per cubicle 2500x1500 mm) plus an air-conditioned control cabinet (see Fig. 2).

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DEVELOPMENTS OF ION SOURCES, LEBT AND INJECTION SYSTEMS FOR CYCLOTRONS AT RCNP

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Abstract

Several developments for cyclotrons at Research Center for Nuclear Physics (RCNP) Osaka University have been carried recently in order to improve the high intense ions in MeV region.

The additional glazer lens on axial injection of AVF cyclotron has been installed to improve the beam transmission to inflector of AVF cyclotron. Additional buncher for the heavy ion injection like Xe beam which requires high voltage bunching in comparison with the proton case also has been installed. Extension of baffle slits on injection line of Ring Cyclotron also has been done to extend the flexibility of injection orbit. Modification of low energy beam transport (LEBT) from ion sources to AVF injection axis including the development of real time emittance monitors also has been carried. This new fast emittance monitor realizes the more efficient tuning of ion source beam which should be matched to acceptance of cyclotron.

INJECTION AXIS OF AVF CYCLOTRON

To improve the beam current accelerated by AVF cyclotron, two components have been installed on the injection axis of AVF cyclotron. Those are additional buncher and glaser lens.

Buncher

To improve the beam current of heavy ion, especially of Xe, additional buncher has been installed on injection axis. In Fig. 1, existing buncher is shown by “b” and located 2550mm above median plane (MP) of AVF. This existing one makes saw wave by RF combining with 1x, 2x and 3x harmonics and maximum saw voltage is +-600V. This buncher can bunch lighter ion which has small m/q and is accelerated with higher frequency, but the voltage or distance from median plane are not enough for heavy ion like Xe. So additional new buncher is installed to help to improve beam current in combination with existing one. This new buncher makes saw wave by charge-discharge circuit with maxmum voltage of 0~+1200 V at 2 MHz operation, 0~+600 V at 6 MHz and 0~+200 V at 20 MHz. The installation position is 4600 mm above the median plane as shown in Fig. 3 by “a”.

The beam test has been done for several ions. For the proton with acceleration frequency of 9.32 MHz, the optimized beam current at extraction of AVF cyclotron is 4.1µA with existing buncher only, 0.57µA without any buncher, 3.5µA with new one only, and 5.0µA with both bunchers. For the $^{12}C^{5+}$ case with 10.2 MHz RF, the optimized beam current at extraction of AVF cyclotron is 400 nA with existing buncher only, 175 nA without any buncher, 550 nA with new one only, and 760 nA with both bunchers. These show that new buncher works well especially for heavier ion with combination with existing one.

Glaser Lens

To improve the efficiency of AVF injection, additional glaser lens has also been installed. Previously the injection axis has only 3 glasers shown as d, e and f in Fig. 1, it was hard to deliver the beam through the region of 0~2000 mm above the median plane where the beam pipe size is narrow of 57 mm in diameter and only the beam with the size up to 5 mm at the iris slit shown by “g” in Fig. 3 can be delivered. So new additional glaser is installed at the position of “c” shown in Fig. 1. With this new additional glaser, now the beam with the size of 10 mm at the iris slit can be delivered.

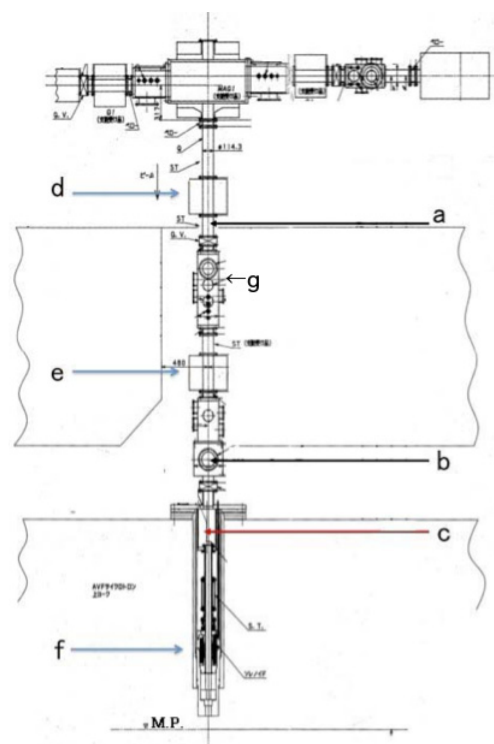

Figure 1: Schematic side view of injection axis of AVF Cyclotron. a: new buncher, b: existing buncher, c: new glaser, d~f: existing glaser, g: iris slit.

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HIGH ACCURACY CYCLOTRON BEAM ENERGY MEASUREMENT USING CROSS-CORRELATION METHOD

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Abstract

This paper propose a method to measure the proton beam energy of the CS-30 cyclotron by using two fast current transformer (FCT) and accurately estimate THE TIME OF FLIGHT (TOF) using windowed cross-correlation method. Currently available techniques use pulse width or edge delay measurement to get the TOF. However, the accuracy of these methods are limited by sampling rate, signal level, noise, and distortion. By using Cross-Correlation and interpolation, we can get a fractional delay measurement, and the system works with low level signals (low beam current) and it is robust in the presence of noise and distortion.

INTRODUCTION

The CS-30 cyclotron is 30-inch AVF cyclotron requires a high energy gain per turn and a fixed frequency RF system. It was assembled and tested at TCC in USA before being shipped to Saudi Arabia [1-3]. The CS-30 can accelerate four different particles with different energy levels. Table 1 gives more details about the CS30 specifications and Figure 1 is a photo of the accelerator and its vault.

Beam energy is very important parameters in beam diagnostic process either for radioisotope production or proton therapy. Cyclotrons is known to produce bunches of protons with nanosecond duration and repetition frequency the same as the RF of the Dee voltage. Beam energy can be estimated using Time of Flight (TOF) method while using either single pickup or dual pickups and the pickup can be capacitive or inductive [4, 5]. In single pickup, ToF is estimated by measuring the pulse width of the pickup output and in dual pickups ToF is estimated by measuring the delay between the two waveforms output from the pickups. The two pickups of inductive type is the method of choice in this paper; in this case ToF is obtained by measuring the delay between the two waveforms output from two fast current transformer (FCT) separated by a suitable distance. The FCT converts the beam current bunches into voltage pulses waveform that can be acquired using Analog to Digital Converter (ADC) and send to the PC for digital signal processing.

Delay measurement usually done using edge to edge delay measurement [4, 5], in this case the accuracy is limited by the ADC sampling rate, signal level, noise, and distortion. However, the proposed method calculates the cross-correlation of the two FCT outputs and interpolates the result to get the time of the peak value, which represents the delay between the two waveforms. In this case the delay accuracy is a fraction of the sampling rate which means very high accuracy and the system works with low level signals (low beam current) and high noise levels. Further accuracy improvement is obtained by measuring the temperature and compensate for dimensions change of the FCT fixture due to thermal expansion.

Table 1: Main Specifications of CS-30 [2]

Parameter	Value
Proton Energy	26.2 MeV
Deuteron Energy	15.0 MeV
Helium-3 Energy	38.0 MeV
Helium-4 Energy	30.0 MeV
External Beam Power	2000 Watts
Pole Diameter	38 inch
Number of Sectors	3
Weight	22 T
Number of Dees	2
Acceleration Mode	Fundamental
Voltage Gain per Turn	100 kV

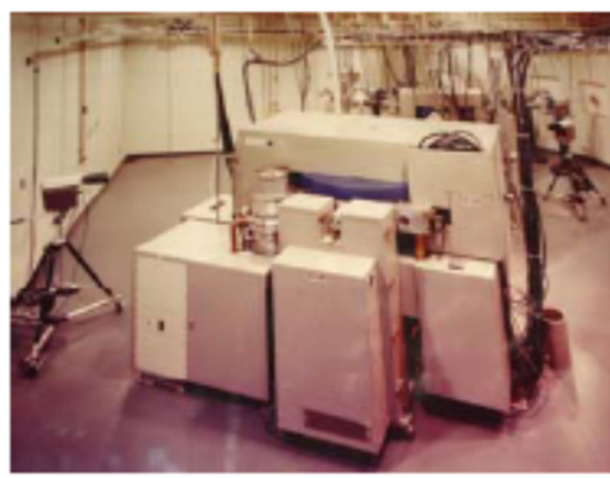

Figure 1: A Photo of the CS30 Cyclotron.

TIME OF FLIGHT (TOF) BASED ENERGY MEASUREMENT

For fast proton, the relativistic kinetic energy E_k can be calculated from [6]:

$$E_k = mc^2(\gamma - 1) \tag{1}$$

where:

$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}} \tag{2}$$

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MAGNETIC FIELD MEASUREMENT SYSTEM OF CS-30 CYCLOTRON

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Abstract

The magnetic field of the CS-30 Cyclotron at King Faisal Specialist Hospital and Research Centre (KFSHRC) has been measured using Hall probe-based mapping system. Although the CS-30 Cyclotron was under full operation for 3 decades, yet, it was crucial to evaluate the stability of beam orbits and also to study the low extraction efficiency, particularly after stripping the cyclotron coils and its three sectors. The rational for stripping magnetic component was to replace the pole tip seal underneath the frame.

The Hall probe was mounted on a high precision X - Y stage, which was driven by three stepping motors, two motors for Y - axis and a motor for X - axis. The 3MH5 digital Tesla-meter is a high performance magnetic field measuring instrument, based on the Hall Effect magnetic field to voltage transducer. It has digital data correction to provide 0.01% accuracy and it provides the possibility of automatic data acquisition via USB port of our computer.

In this paper, a Hall probe mapping system and the results of the magnetic measurement of the CS-30 magnet are described.

INTRODUCTION

The CS-30 cyclotron at King Faisal Specialist Hospital and Research Center (KFSHRC) has been operating since 1982 for production of radioisotopes, such as ^{18}F and ^{15}O for positron emission tomography applications [1].

Some cyclotrons, including the CS-30 at KFSHRC, contain sets of harmonic coils, also called trim coils, arranged to supply a weak field that acts as a magnetic pump and enhances the main magnetic field in the central region and in the extraction region. Depending on the polarity of the electric current applied to those coils, they can generate a positive field, enhancing the main magnetic field, or a negative one (in the opposite direction) which weakens the main field slightly.

Additionally, cyclotrons have an extraction system, comprising the equipment that extracts the beam from the accelerated region to the main beamline of the cyclotron. In negative ion cyclotrons (whose accelerated particles are negative ions), this is done by stripping electrons from the negative ions using carbon foils [2]. In positive ion machines, the mechanism is more complicated, consisting of an electrostatic deflector (which has two parts: a septum made of tungsten, held at zero potential, and a high voltage electrode) and a magnetic channel to eliminate the magnetic field effect of the extracted beam. On the last rotation, particles experience a strong electric field capable of modifying slightly the trajectory of their orbit.

The magnetic field of CS-30 magnet was measured using the Hall mapping method described in [2-6]. For measurement of cyclotron magnets, the Hall probe mapping system at many laboratories use the polar coordinate system [2-4]. It is mounted on a high precision x–y stage, which is driven by a stepping motor at end of the Hall probe carrier, and maps the magnetic field in the polar coordinates. The system used the **'flying mode'** field-mapping method in which the data acquisition is made while the Hall probe moves [4]. The requirements of the field measurement system for CS-30 are listed in Table 1.

Table 1: Specifications of the Mapping System

System specifications &Unit	Value
X scan capability (mm)	1000
Y scan capability (mm)	1000
Mechanical resolution (μm)	1
Range of magnetic field (T)	2
Relative error for $\langle B(r)\rangle$-measurement (%)	0.01

HALL MAPPING SYSTEM

The teslameter and Hall probe have been used widely to measure the magnetic fields of cyclotrons. The 3MH5 digital teslameter is a high performance magnetic field measuring instrument, based on the Hall effect magnetic field-to-voltage transducer (Hall probe). It has digital data correction to provide 0.01% accuracy and it provides the possibility of automatic data acquisition via a USB port. The Hall probe is mounted on a high precision X-Y stage driven by three stepping motors, one for the x-axis and two for the y-axis. The stepping motors are run by a 3-axis stepper controller/driver (TMCM-3110). Time resolution of the x-axis and y-axis can reach up to 25 and 34 μm respectively. The time resolution of the Hall probe is 100 ms; however, measurements were taken every 200 ms. The Hall probe has a built-in temperature sensor to compensate for variation in temperature.

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THE ASSEMBLY AND ADJUSTMENT OF THE SECOND STRIPPING PROBE SYSTEM FOR CYCIAE-100

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Abstract

A 100 MeV H- compact cyclotron is under construction at China Institute of Atomic Energy (CYCIAE-100). The proton beams ranging from 75 MeV - 100 MeV with 200 μA beam intensity will be extracted in dual opposite direction by charge exchange stripping devices. The stripping probe system is the key part of extraction system for CYCIAE-100. The first stripping extraction system was installed in 2014 and it has satisfied all kinds of requirements for the proton beam extraction. The first 100MeV proton beam was got on July 4, 2014 and the beam current was stably maintained at above 25 μA for about 9 hours on July 25, 2014. The first RIB with ISOL system driven by 100 MeV proton beam was generated in 2015. The second stripping system was installed in 2015 after the assembly and adjustment. The beam commissioning based on the second stripping system will be finished and the extracted proton beam parameters will be measured in detail in this year.

INTRODUCTION

A 100 MeV H- compact cyclotron is under constructed in China Institute of Atomic Energy (CYCIAE-100) [1-3]. The machine is selected as the driving accelerator for the Beijing Radioactive Ion-beam Facility (BRIF). 75 MeV - 100 MeV proton beams with 200 μA - 500 μA beam intensity will be extracted in dual opposite direction by charge exchange stripping devices [3]. In total 7 target stations will be built based on CYCIAE-100 for the fundamental and applied researches. For CYCIAE-100, the diameter of main magnet is 6160mm, corresponding to 4000mm for the magnet pole. The magnet is 2820mm high with a total weight of 435 tons. The quality factor of the two rf resonators reach 9500, which is highest value among the existing compact cyclotrons in the world. Two identical 100 kW RF amplifiers have been adopted to drive two cavities independently. In order to reduce the beam losses caused by residual gas stripping process, a high-speed cryo-panel system is utilized to raise the vacuum to $5*10^{-8}$ torr level. By the end of 2013, all the sub-systems of the cyclotron are installed and assembled on site. The first stripping extraction system was installed in 2014 and it has satisfied all kinds of requirements for the proton beam extraction. The first 100MeV proton beam was got on July 4, 2014 [4] and the beam current was stably maintained at above 25 μA for about 9 hours on July 25, 2014. The first RIB with ISOL system driven by 100 MeV proton beam was generated in 2015. The operation stability have been improved and beam current have been increased gradually. 720 μA beam was got on the internal target at the beginning of this year. The effort for mA beam is continuing and 1135 μA beam was got on the internal target in June of this year [5]. Figure1 is the fresh photo of the cyclotron and its beam line.

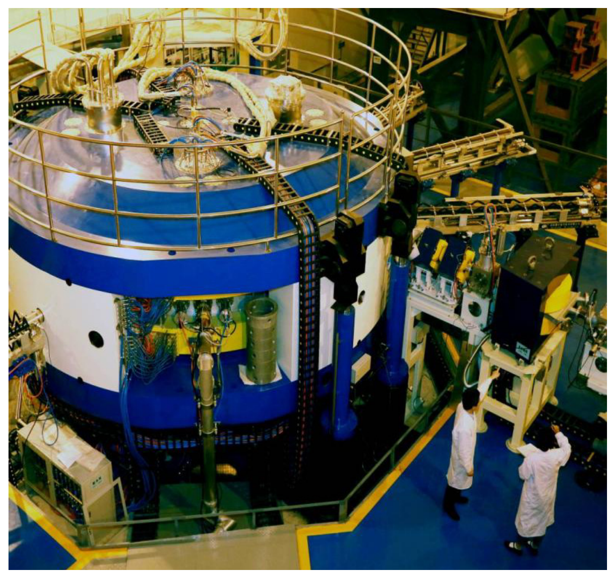

Figure 1: The 100 MeV compact cyclotron.

The second stripping system was installed in 2015 after the assembly and adjustment. After the debugging, the stripping probe system can work very well. The movement precision is better than 0.1mm and the precision of azimuthal movement is better than 0.01 degree, which satisfies the design requirement. The beam commissioning based on the second stripping system will be finished and the extracted proton beam parameters will be measured in detail in this year.

THE DESIGN AND CONSTRUCTION OF STRIPPING PROBE SYSTEM

The stripping probe system is the key part of extraction system for CYCIAE-100. Two stripping probes with carbon foil are inserted radially in the opposite direction from the main magnet pole and the obtained two proton beams by charge exchange after stripping foil are

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THE CONTROL SYSTEM DEDICATED FOR BEAM LINE OF PROTON RADIOGRAPHY TEST-STAND ON A 100 MeV CYCLOTRON CYCIAE-100*

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Abstract

This paper outlines the design of the control system for beam line ofproton radiography on 100 MeV cyclotron CYCIAE-100. The project proposed by the China Institute of Atomic Energy (CIAE). For high intensity operation, a dedicated controls system and stabilized operation environment are preferable. In order to satisfy the requirements of this proton radiography control system, we have built a complex control system which contains PLC controller, MOXA controller, IOC and EPICS system. In this paper, the designing, constructing and commissioning of the proton radiography control system will be described.

INTRODUCTION

CYCIAE-100 100MeV H- compact cyclotron is the main component of HI-13 tandem upgrade project. It can provide the proton beam of 70-100 MeV with beam current of 200-500 μA. CYCIAE-100 consists of some subsystem such as main magnet system, RF system, main vacuum system, beam detection system, control system and so on. The control system is an important subsystem which main function is to carry out the devices of CYCIAE-100 automation control.The first beam of CYCIAE-100 was extracted on July 4, 2015 [1]. In previous work, we have completed the main magnet system and vacuum system. With the improve of system stability, in June of 2016, 1135 μAbeam was got on the internal target.

Nowadays, proton radiography is a main tool for providing a development direction for advanced hydrotesting research. For x-ray radiography, its advantages are simplicity and relatively low cost of the facilities, the main element of which is an electron accelerator. But x-ray with high penetrating power passing through an object engender photon showers which result in background noise in the recorded image. In thick objects, the photon noise can completely conceal the useful image. Proton radiography does not have these problems. In terms of penetrating power, protons significantly surpass x-rays. In 2014, the low energy proton radiography system utilizes a 11MeV proton beam to radiograph thin static objects, which developed at CAEP [2].

OVERALL DESIGN

Proton radiography requires a particular magnetic lens system to provide a point-to-point imaging from the object to the image. The design detail is described in Ref. [3]. For the above reason, the beam precise control must to take into account at the beginning of the control system design. In the beam line of proton radiography there are many subsystems, such as magnet power system, vacuum system, water cooling system, beam detection system and stripping probe system. Considering for a lot of signals to be control, we use the SIMEMENS S7 series Programmable Logic Controller (PLC) controller which CPU model are S7-400, S7-300 and ET-200. Because of the SIMEMENS S7 series have exceptional stability. The MOXA controller is used to receive analog feedback signals. The Experimental Physics and Industrial Control System (EPICS) [4] is the like a bridge connects the Input/Output Controller (IOC) and the Operator Interface (IOC) which stored in the INSPUR server. The structure of proton radiography control system is shown in Figure 1.

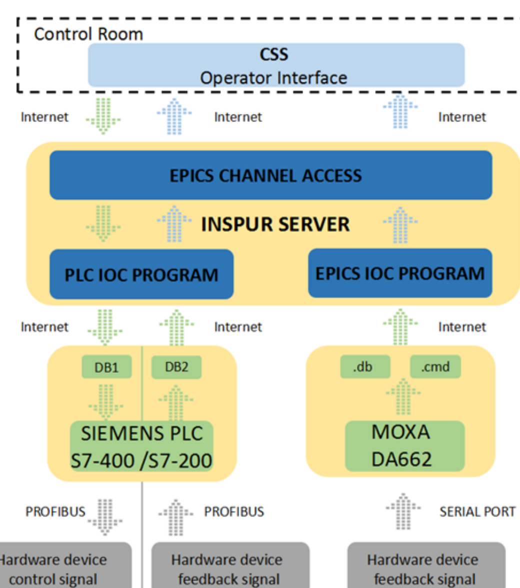

Figure 1: The structure of proton radiography control system.

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THE HIGH QUALITY WATER COOLING SYSTEM FOR A 100 MeV CYCLOTRON*

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Abstract

A high quality water cooling system with total heat power dissipation of 500 kW has been built and successfully used for a 100 MeV high intensity Cyclotron. The main features of this system are high water quality with specific conductivity bellow 0.5 µS/cm, high cooling water temperature stability better than ±0.1 ℃ for long time operation，and much electric power-saving in comparing with classical design. For some special usages, such as high beam power target and vacuum helium compressor, they all are well treated and reasonably separated from the main cooling system. There are totally 108 distributed water branches corresponding to different sub-equipments of the cyclotron. The water cooling system is under automatic control with PLC, the operation status and all parameters can be remotely monitored from the control room. All of the involved equipments can be switched on/off by one key, no on-duty staff is needed at normal conditions. This system has been put into commissioning for two years and proved successful and reliable.

INTRODUCTION

Beijing Radioactive Ion-beam Facility (BRIF) has been built at China Institute of Atomic Energy (CIAE). As a key component of BRIF project, CYCIAE-100 provides a 75 MeV – 100 MeV, 200 µA– 500 µA proton beam [1,2]. The main part of heat power dissipation coming from different equipments of the cyclotron should be taken away by water cooling system, which is totalling about 500 kW. There are some special requirements, such as high beam power target with strong radioactivity and vacuum helium compressor requiring ultra-low temperature cooling water. Besides, the main magnet power supply and RF system require cooling water have higher temperature stability to maintain their high specifications, external ion source locating at 40 kV high level require the cooling water of low conductivity. All of the special requirements should be considered in the general design of the water cooling system.

Unique climate of Beijing is another factor of considerations for the water cooling system design. The four-seasons are clear and there is a much difference in temperature between summer and winter, usually above 50 . Fully take the advantage of the natural environments of Beijing could save much electric power and decrease the operation cost during the continuous run terms.

GENERAL DESIGN

Based on the requirements of the 100 MeV cyclotron, the cooling water system was generally designed with one main system and two sub-systems. The main system is used for the most part of equipments of the cyclotron, and the two sub-systems are used for hot targets and vacuum helium compressor respectively.

The key parts of the main system are located in the recycling water supply room and the cooling devices including a large scale of heat dissipation tower and 10 cryo-generators are located outside nearby. A specially designed water storage tank with a separator inside is used for internal and external recycling water simultaneously. The de-ionized water production and water quality improving devices are built online to keep the cooling water always in good conditions. The cooling water delivered to the RF power generators, RF cavities, main magnet coils, ion-source, beam lines and so on through different water tubes and distributed branches.

There are totally 108 distributed water branches corresponding to different sub-equipments of the cyclotron. At each branch, there are one water flow switch for safe inter-lock, one flow meter for monitoring, one temperature sensor for remote diagnostics.

The cooling water used for the high power targets is supplied by a dependant water loop located in the radioactive-protective room, which has heat exchange with the main cooling system but physically separated from it to avoid any pollute of the main cooling water.

The cooling water of 15 ℃ required by vacuum helium compressor is provided with another separated water cooling system, because it is much different in temperature from the main cooling water of about 25 ℃.

The general diagram of water cooling system is shown in Fig. 1.

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PRELIMINARY DESIGN OF RF SYSTEM FOR SC200 SUPERCONDUCTING CYCLOTRON

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Abstract

The SC200 is a compact superconducting cyclotron, which is designed under the collaboration of ASIPP (Hefei, China)-JINR (Dubna, Russia), for proton therapy. The protons are accelerated to 200 MeV with maximum beam current of ~500 nA. The very high mean magnetic field of 2.9 T-3.5 T (center-extraction) challenges the design of radio frequency (RF) system because of the restricted space. The orbital frequency of the protons is ~45 MHz according to the magnetic field and beam dynamics. The RF system is supposed to operate at 2rd harmonic of ~90 MHz. Two RF cavities located at the valley of the magnet have been adopted. The preliminary design of RF system, which consists of active tuning, coupling and so on, is presented. The computation and simulation showed good results to ensure the RF cavities operating at the 2rd harmonic and the proper variation of acceleration voltage versus radius.

INTRODUCTION

The SC200 superconducting proton cyclotron is designed under the collaboration of ASIPP and JINR for proton therapy. The RF cavity is the critical and complex component of SC200. The RF cavity works as a resonator to generate necessary voltage between Dee gaps to accelerate protons continuously. The half-wavelength coaxial resonant cavity has been adopted in SC200. It is mainly composed of stem, Dee, coupling loop, tunable shorted terminal, cavity, as shown in Fig. 1.

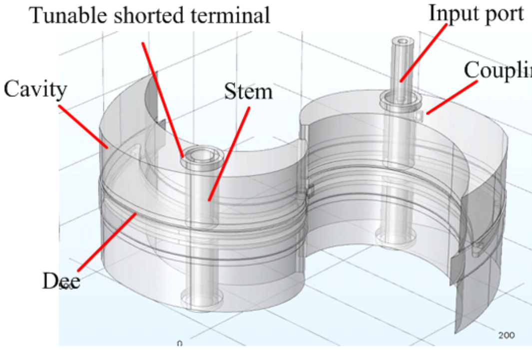

Figure 1: RF cavity structure.

According to the physical design requirements of SC200 Superconducting Proton Cyclotron [1-3] the main technical parameters of RF cavity are described in Table 1.

Table 1: Technical Parameters of SC200 RF Cavity

Parameter	Value
Frequency	90 MHz(2 harmonic)
Cavity number	2
Source power	~100 kW
Cavity type	λ/2 coaxial
Accelerate voltage	60 kV(Center)~ 120 kV(Extraction)
Dee azimuthal extension	40°
Dee Cavity azimuthal extension	50°

Due to the high magnetic field of cyclotron, the compact structure has challenged the requirements of RF design. First, the resonance frequency and correct voltage distribution have to fit the requirements of acceleration, especially in the central region and extraction region. What's more, the proper coupling and tuning method should be found to cover possible working frequency. Finally, the operation stability and thermal consideration need to be taken into account.

ACCELERATION

Resonance frequency (f) and quality factor (Q value) are the important characteristic parameters to describe the performance of the resonant cavity (RF cavity). Table 2 shows the simulation results from different codes, respectively. The simulation results show good agreement.

The eigen-frequency of ~90 MHz has been found with correct voltage distribution along the radius of Dee, as shown in Fig. 2. The Q value has been estimated with and without the surface loss of cavity. The typical value of Q is ~7000 which is reasonable and acceptable. The Q value (~4500) has decreased as the surface of cavity was set up to loss material (copper).

Table 2: Eigen Mode Analysis Results

Software	f (MHz)	Q (without loss of cavity)	Q (with loss of cavity)
CST	90.6	7230	4590
HFSS	89.6	6880	\
COMSOL	89.46	\	4067

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NEURAL NETWORK BASED GENERALIZED PREDICTIVE CONTROL FOR RFT-30 CYCLOTRON SYSTEM

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Abstract

Beamline tuning is time consuming and difficult work in accelerator system. In this work, we propose a neural generalized predictive control (NGPC) approach for the RFT-30 cyclotron beamline. The proposed approach performs system identification with the NN model and finds the control parameters for the beamline. Performance results show that the proposed approach helps to predict optimal parameters without real experiments with the accelerator.

INTRODUCTION

Beamline tuning is an important and critical issue in the accelerator control. The control is to manipulate the devices of the system in order to make the accelerator be the desired state. The operators should control the accelerator system to obtain the desired output. Especially, beam tuning is a difficult task for the accelerator. Beamline tuning is to manipulate the control parameters of beamline to obtain the desired beam shape. For the beam tuning, the operators should manipulate the parameters based on the measured information during the operation. Beamline tuning requires human resources and is time consuming works since the accelerator is very non-linear and highly complex.

Researches using the neural network have been proposed for the beam tuning. In SLAC, artificial intelligence (AI) technique has been proposed for accelerator control [1]. The approach utilizes the feedback control approach based on the neural network. The approach trains the neural network with the beamline emulator and then controls the steering magnets of the beamline. Another approach has been proposed for the control of the ion source of the RFT-30 cyclotron [2]. The approach trains the ion source model using the neural network and then finds the optimal parameters to obtain the desired ion source current.

In this work, we propose a neural network based generalized predictive control (NGPC) approach for the RFT-30 cyclotron beamline. First, the proposed approach constructs the beamline model by using the NN based system identification procedure. Next, the model predictive control (MPC) approach is used for finding the optimal parameters for the beamline tuning. The proposed approach can reduce the beam tuning time and enables effective beamline tuing. Moreover, combined with other control approach, it enables beam auto-tuning and control automation.

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CONTROL PROBLEM OF RFT-30 CYCLOTRON BEAMLINE

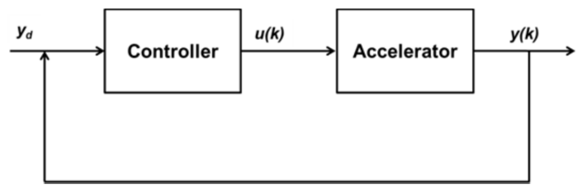

Figure 1: Overview of the accelerator feedback control.

Control means to manipulate the input signals to obtain the desired output signals. Figure 1 shows the accelerator feedback control system. Assume that $y(k) \in R^m$ is m-dimensional plant (i.e., accelerator) output and $u(k) \in R^n$ is n-dimensional control input, and reference target y_d is a control objective. The controller receives the error $e(k) = y_d - y(k)$ and then decides the control input $u(k)$. Control problem is defined as minimizing the error $e(k)$ between the reference target y_d and the plant output $y(k)$.

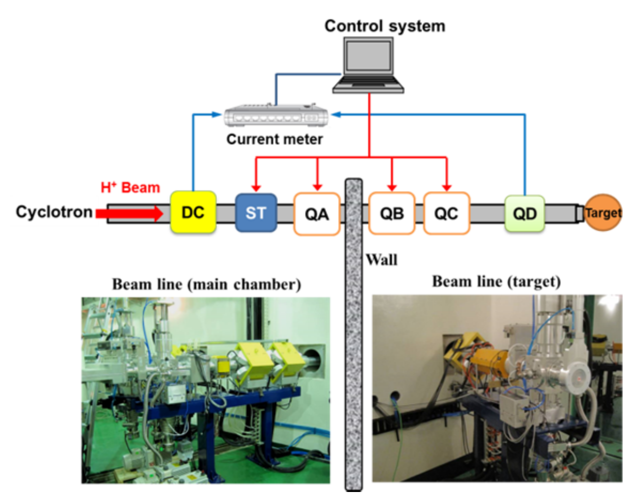

Figure 2: Overview of the RFT-30 cyclotron beamline.

Figure 2 shows the beamline system of the RFT-30 cyclotron. The RFT-30 cyclotron is a 30 MeV proton accelerator for radioisotope (RI) production and research. The RFT-30 is composed of four beamlines which are used for transmitting the proton beam to a target system. As shown in Fig.2, each beamline is composed of drum collimator (DC), steering magnet (ST), quadrupole magnet (QA, QB, QC), quadrant (QD), and vault/target faradaycup (FC). Steering magnet controls the center position of the proton

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PLC CONTROL SYSTEM FOR VACUUM AND 20 kW RF AMPLIFER

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Abstract

Since 2015, the Sungkyunkwan University has been upgrade 10 MeV cyclotron (SKKUCY-10) prototype for producing radio isotopes. For stable and robust cyclotron operation, local controller is main issue. Especially, RF and Vacuum is main part for control system and each sub system fault result in damage to the other sub systems. To solve those problem, we integrate RF amplifier and vacuum local controller by LS PLC (Programmable Logic Controllers). Integrated Interlock event is also processed at one controller. This paper describe system requirement for RF amplifier and vacuum and discuss the detailed design and software development by PLC programming at SKKUCY -10.

INTRODUCTION

Robust and reliable SKKUCY-10 control system is required to operate stably cyclotron for produce radioisotopes. During several year, Sungkyunkwan University has been develop and test SKKUCY-10 prototype control system. SKKUCY-10 controller has one Compact-RIO main controller and several local controllers that include magnet, RF and Ion source hardware [1]. SKKUCY-10 main control system was implemented to realize supervisory Control and Data Acquisition (SCADA). At operating by main controller, RF AMP and vacuum subsystem faults and sequence error sometime result in critical damage to other subsystem such as RF power generation at low vacuum level. To solve those problem, we replace RF and vacuum local controller to one integrated PLC. Developed PLC controller was implemented based on RF, vacuum system requirement and operation sequence.

SYSTEM REQUIREMENT

Figure 1 show the scheme of RF and vacuum system. Integrated vacuum and RF control system require to operate and monitor all hardware. It also require interlock function to protect each machines from damage during operating cyclotron. To fulfil requirement of controller each SKKUCY-10 RF and vacuum system analysis was implemented and based on analysis, interlock mechanism was developed.

RF AMP Requirement

SKKUCY-10 three-stage RF amplifier consist of pre-amplifier, intermediate power amp (IPA) and Power amp (PA). Through tree-stage RF amplifier, RF power is amplified to 20 KW. In SKKUCY-10 RF amplifier, 350V IPA and 7500V PA Vacuum tube anode power supply were required [2]. Heating for Electron emission from cathode was considerable for warming-up procedures. At least 120 second filament warming-up time was set for stable vacuum tube performance. RF amplifier interlock is also considerable parameter for protection from high voltage. Overload parameter from each cathode current and VSWR value is used for major Interlock parameter for amplifier.

VACUUM Requirement

Dual vacuum pump architecture is main properties of SKKUCY-10 vacuum system. Dual vacuum make it possible to decrease time to reach high vacuum level (10^{-6} Torr) and also machine fault probability. Two diffusion pump and two rotary pump are connected through magnet valley holes. At initial step to make vacuum state, rotary pump are used. Using Rotary pump, 10^{-2} Torr Vacuum level can be reached. After reached those low vacuum level, diffusion pump are operated. Vacuum level mainly determine state of vacuum system. According to vacuum level and pump states, roughing, foreline and gate valve are operated.

Interlock

In order to machine protection and personal safety, each system interlock conditions and system interaction during high power RF test were considered. Table 1 show RF and vacuum signal and condition for interlock.

Table 1: Signal and Condition for Interlock

Value	condition	Event
VSWR OVELOAD	PA over Voltage	RF oscillator off
IPA&PA OVERLOAD	IPA & PA Cathode over current	RF oscillator, &PA off
PA Water flow status	Flow rate	RF oscillator , HV off
PA air cooling status	Contact switch off	RF oscillator , HV off
Pump status 1&2	False	RF oscillator off
Vacuum status	Vacuum level	RF oscillator off
EMERGENCY STOP	Ture	HV off

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DEVELOPMENT OF MAGNETIC FIELD INSTRUMENTATION FOR 10 MeV CYCLOTRON

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Abstract

To produce a radio isotope for Positron Emission Tomography (PET), 10 MeV compact Cyclotron was installed at Sungkyunkwan University. This cyclotron had been produced 10 MeV proton beam. For this cyclotron magnet, the magnetic field measurement instrumentation was being developed. The hall probe sensor was used for field measurement. This hall probe sensor moves radial direction and angular direction by mechanically. The Magnetic field measurement instrumentation measures the field in the range of 5 mm for radial direction and 1 degree for angular direction. Magnetic field was measured with and without cooling. Magnetic field was carried with 4 Gauss without cooling and 0.1 Gauss with cooling. Our developed magnetic field measurement instrumentation has 0.1 Gauss of an error and 0.01 Gauss of resolution over 9 hours.

INTRODUCTION

The SKKUCY-10 Cyclotron at the Sungkyunkwan University was been developed since 2015 for production of proton beam. 10 MeV proton beam can produce radioisotopes for positron emission tomography (PET) imaging. To produce 10 MeV proton beam, magnetic field was modified by calculated magnetic field error. The magnetic field error between isochronous field and designed field should be less than 15 Gauss to get high quality of proton beam [1, 3].

This paper presents a development of magnetic field measurement instrumentation for compact cyclotron. The Hall probe sensor can measure ~3 T range, 0.01 Gauss resolution [2]. Specification of hall probe sensor was shown as Table 1.

The coil of the electromagnet creates heat and it interrupt the magnetic field while cyclotron operating. Also the unexpected vibrations of magnetic field measurement instrumentation cause measurement errors. These kinds of errors had been fixed by taking data processing and the operation methods of the measurement system.

Magnetic field measurement instrumentation measures the field in the range of 5 mm for radial direction, and 1 degree for angular direction. Field measurement program is based on LABVIEW. It can monitor the field intensity synchronously, and it is utilized for full field mapping of 10 MeV cyclotron.

DESIGN AND SYSTEM DESCRIPTION

The specification of hall probe sensor was shown as Table 1. The magnetic field range of SKKUCY-10 cyclotron was 0.33 T to 2.17 T and operating temperature was around 50°C. This hall probe sensor was expected high accuracy of measurement.

Table 1: Specification table of hall sensor probe [2]

Parameters	Values
Field measurement range	~ 3 T
Field measurement resolution	0.001 ~ 0.01 Gauss
Temperature Range	-20 °C ~ 60°C
Temperature stability	± 10ppm of reading/°C
Accuracy at 25°C	± 0.01%

3D model of magnetic field measurement instrumentation for 10 MeV cyclotron are given in Fig. 1. The hall sensor probe was on the bracket ①. It will rotate mid-plane of magnet. The step motor ② was installed at valley, which is connected with rotation jig using by tension belt. The Rotation plate ③ prevent the rotation jig form tilting when magnetic field measurement instrumentation operates. The hall probe sensor had been moved by spur gear ④ and ratchet gear ⑤ along the radial direction. The Linear guide ⑥ supports hall probe sensor.

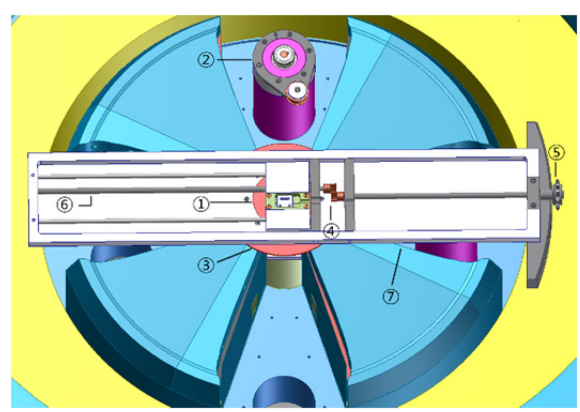

Figure 1: 3D Model of Magnetic Field Measurement Instrumentation. ① : Step motor, ② : Hall Probe Sensor bracket, ③ : Rotation Plate, ④ : Spur Gear, ⑤ : Ratchet Gear, ⑥ : Linear Guide, ⑦ : Rotation jig.

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METHODS OF COMPENSATION OF THE BEAM VERTICAL DIVERGENCE AT THE EXIT OF SPIRAL INFLECTOR IN CYCLOTRONS

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Abstract

While the axial injection into the cyclotron, the beam is turned from axial direction into median plane by means of inflector. Commonly used type of inflector is an electrostatic spiral inflector. The spiral inflector is easy to handle and has a good beam transmission factor. On the other hand, the negative feature of spiral inflector is the beam vertical divergence at its exit. It leads to increasing of beam vertical dimension and aperture losses at the first orbits. The methods of compensation of the beam vertical divergence at the inflector exit are considered at present report. These methods are used at FLNR JINR cyclotrons and give good results in transmission factor, beam quality and operation modes.

INTRODUCTION

The axial injection systems of FLNR cyclotrons (U400, U400M, IC100, DC280) are equipped by spiral inflectors. The calculations and exploitation experience show the aperture losses in the cyclotron centre because of the beam vertical divergence at the inflector exit. It not only worsens the beam intensity and quality, but decreases the inflector operation time.

The beam vertical divergence at the inflector exit appears because the ions, shifted from the central ion trajectory, have the different length of the paths inside the inflector and so spend a different time in the inflector electric field. It leads to the difference in the rotation angles of the ions. The ions with initial shifting towards the cyclotron centre, -h start position at the Figure 1, have a smallest length of the path and receive incomplete rotation angles, less then 90^o. And vice versa, the ions with +h shifting at the start position receive rotation angle more then 90^o. The farther ion is shifted from the central trajectory, the more this angular difference.

The calculations have shown that this effect is stronger for the ions, shifted along the transverse, median axis h at the inflector entrance and not so actual for shifting in vertical, u axis direction.

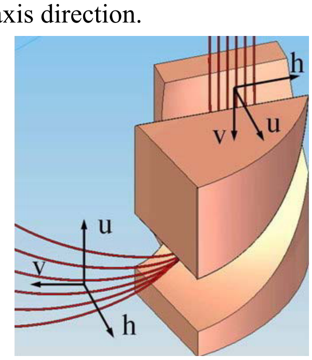

Figure 1: The computer model of spiral inflector and trajectories of ions with initial shifting along axis h.

The beam behaviour at the inflector exit was investigated by calculations and experiments for U400 cyclotron. It was found that the beam after inflection has a strong vertical divergence, that leads to aperture losses at the inflector box and dees noses, Figure 2. The experimental beam track was received on thermo-sensitive film at the first accelerating gap window. This situation is typical for cyclotrons, equipped with spiral inflector.

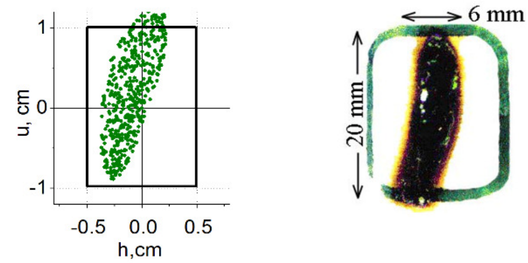

Figure 2: The calculation and experimental results - beam track at U400 first accelerating gap window.

There are some methods of decreasing of the beam vertical divergence after spiral inflector. Usually to produce vertical focusing of the beam, the additional correcting element is placed between the inflector exit and the first accelerating gap. Such element could be either the passive magnetic channel [1] or the electrostatic quadrupole lens [2]. Unfortunately, the additional correcting elements need special place for installation at the cyclotron centre and it could be a problem especially for compact cyclotrons. Another method, used at FLNR cyclotrons, is a special form of the inflector electrodes, which produces the electric field with focusing effect [3].

PASSIVE MAGNETIC CHANNEL

First efforts to solve the problem of beam vertical divergence after inflector were undertaken for U400 cyclotron. Because the very intensive physical program, about 7000h/year and a short cyclotron maintains time, the installation of passive magnetic channel was chosen [4]. It took not much time and reconstruction efforts. The iron pieces of channel were installed inside inflector box, which could be easily extracted from vacuum chamber.

Passive magnetic channel provides the local gradient of the magnetic field about 4kGs/cm along 25mm of the beam path between the inflector exit and the first accelerating gap. At this distance, the beam is focused vertically and is defocused horizontally. The horizontal divergence is not strong because, as a rule, the beam at the spiral inflector exit has a constriction point in horizontal, h axis direction. Because a very intensive energy growth, provided by 4 dees with 130kV of RF, the accelerated beam don't “feel” magnetic field perturbation beyond the magnetic channel.

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AXIAL INJECTION CHANNEL OF IPHC CYCLOTRON TR24 AND POSSIBILITY OF ION BEAM BUNCHING

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Abstract

The CYRCé cyclotron (CYclotron pour la ReCherche et l'Enseignement) is used at IPHC (Institut Pluridisciplinaire Hubert Curien) for the production of radio-isotopes for diagnostics and medical treatments. The TR24 cyclotron produced and commercialized by ACSI (Canada) delivers a 16-25 MeV proton beam with intensity from few nA up to 500 microA. The axial injection and bunching of the H- ion beam by means of multi harmonic buncher is considered in this report. The buncher may be installed in the axial injection beam line of the cyclotron. The use of a grid-less multi-harmonic buncher increases the accelerated beam current and gives an opportunity for new proton beam applications. The main parameters of the sinusoidal (one-harmonic) and multi-harmonic bunchers are evaluated.

INTRODUCTION

The beam transport and bunching of the **H⁻** ion beam by means of multi-harmonic buncher which may be installed in the axial injection beam line of the TR24 [1] cyclotron is considered. Using a buncher will give an opportunity to increase the accelerated beam current. The results of the simulation in the first order of the beam optics are given in this report. The simulation of beam transport was carried out by means of 3D version of MCIB04 program code based on momentum method [2].

BEAM LINE LAYOUT

The scheme of the beam line and the approximate length of the optical elements are shown in Fig.1. This scheme was the basis for simulation of the dynamics of the ion beam.

H⁻ ION BEAM PARAMETERS

H⁻ ion beam is produced in the CUSP ion source [3] with kinetic energy of 30 keV. The beam emittance is strongly dependent on beam current. For H- ion beam currents varying from 1 mA to 5 mA the initial beam diameter is equal to 10 mm and the normalized beam emittance is changing within range 0.1÷0.4 π mm×mrad. The main parameters of the **H⁻** ion beam used in the simulation are contained in Table 1.

Table 1: **H⁻** Beam Parameters

Parameter/notation	Value	Unit
Charge/ Z	1	
Mass number/ A	1	
Kinetic energy/ W	30	keV
Beam diameter/ d	10	mm
Beam geometric emittance / ε	50 π	mm×mrad
Ion beam current/ I	5	mA
Neutralization factor/ f	0.95	

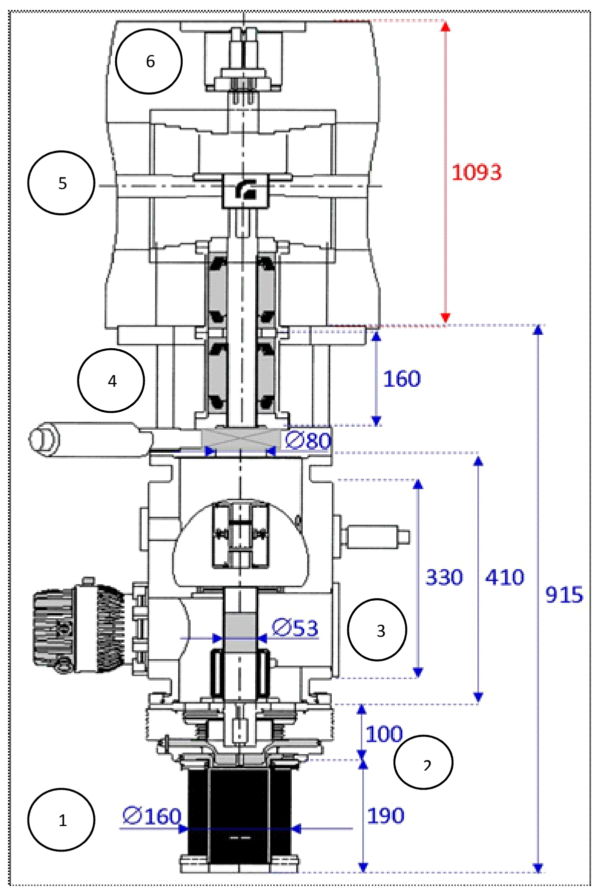

Figure 1: Axial injection beam line of TR24 cyclotron. 1 - CUSP ion source; 2 - extraction electrodes; 3 - EM steering (H/V); 4 - EM quad doublet; 5 - ES deflection; 6 - cyclotron.

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THE DESIGN OF THE MEDICAL CYCLOTRON RF CAVITY*

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Abstract

In the cyclotron, RF system as an essential component provides energy for the ions is accelerated. However, the RF cavity is the most important equipment which produced the accelerating field. According to the physical requirements, RF cavity, the resonant frequency of that is 31.02 MHz, was designed in the paper.

THE RF CAVITY DESIGN AND SIMULATION WITH CST

On the basis of the physical design requirements, the relevant physical parameters of the RF cavity have been given, as shown in Table. 1.

Table 1: Basic Parameter of the Cavity

Name	Results
Resonant Frequency	31.02
Dee Voltage	60-70KV
Dee Angle	33°
Extraction Radius	750mm
Injection Radius	35mm
Phase Stability	≤±1o
Amplitude Stability	≤5×10-4
Frequency Stability	≤1×10-6

The Structural Design of the Cavity

The cyclotron RF cavity adopts half-wave resonant structure, which of the accelerate gap is 8mm. Its structure diagram is shown in Fig. 1.

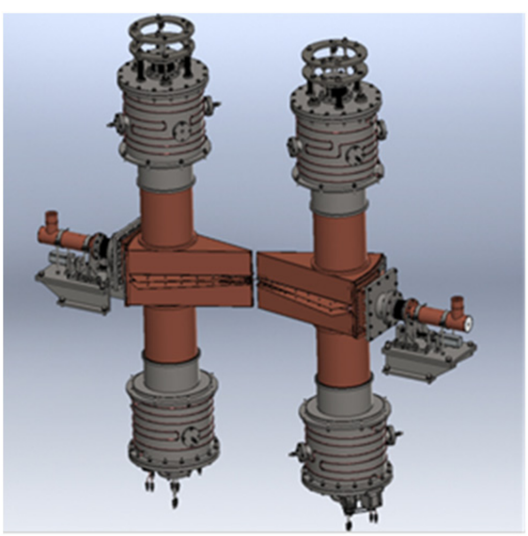

Figure 1: The cavity structure.

Simulation with CST

According to the structure parameter, the three-dimensional model is founded with CST. The simulation results show that the resonant frequency is 30.95 MHz, Q value is 7400 and power loss is 20 kW. The field distribution is shown in Fig. 2.

According to the structure parameter, the three-dimensional model is founded with CST. The simulation results show that the resonant frequency is 30.95 MHz, Q value is 7400 and power loss is 20 kW. The Field distribution is shown in Fig. 2.

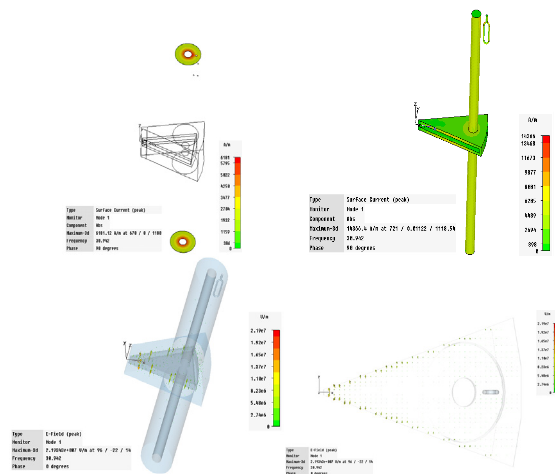

Figure 2: Electric-magnetic field and surface current distribution.

The tuning mode of the resonant cavity includes coarse-tune with short-plate and fine-tuning. The height of the short plate influences the frequency and Q value of the cavity. The curve is shown in the Fig. 3.

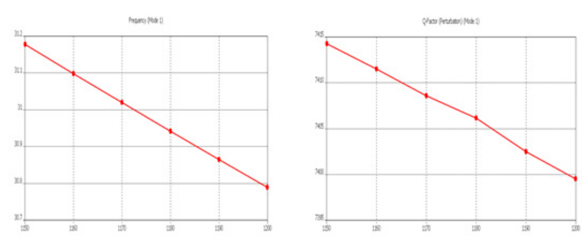

Figure 3: The change curve of the Q value and frequency.

MEASUREMENT RESULT OF THE CAVITY

Finally, the measured and commissioning results are shown in Table 1. The system has been operational for about 2 years. The system is stable and reliable.

* Work supported by IMP
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COMPACT MEDICAL CYCLOTRONS AND THEIR USE FOR RADIOISOTOPE PRODUCTION AND MULTI-DISCIPLINARY RESEARCH

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Abstract

Compact medical cyclotrons are conceived for radioisotope production in a hospital-based environment. Their design in terms of field shape, stability and radio-frequency (RF) is aimed at obtaining high intensity (>150 µA) beams at kinetic energies of the order of 20 MeV. To guarantee high performances, an optimization procedure during the commissioning phase is crucial as well as a regular preventive maintenance. Beyond radioisotope production, these accelerators can be the heart of a multi-disciplinary research facility once access to the beam area and beams down to the pA range are possible. The first requirement can be achieved by means of an external beam transport line, which leads the beam to a second bunker with independent access. Currents down to the pA range can be obtained by specific ion source, RF and magnetic field tuning procedures, opening the way to nuclear and detector physics, radiation protection, radiation bio-physics and ion beam analysis developments. On the basis of the experience gained with the cyclotron at the Bern University Hospital, the accelerator physics aspects of compact medical cyclotrons are discussed together with their scientific potential.

INTRODUCTION

Cyclotrons are fundamental tools in modern medicine. They are employed to treat cancer by particle teletherapy [1, 2] and to produce radiolabelled compounds for diagnostic imaging and metabolic therapy [3, 4].

In the last years, a remarkable scientific and technological progress led to the development of several commercial medical cyclotrons. They presently represent reliable and affordable solutions to fulfill the needs of research laboratories, radio-pharmaceutical companies and healthcare institutions. In this process, the interplay among academia and industry has been crucial and the majority of the cyclotrons and of the related equipment on the market is the result of spin-off endeavors.

Medical cyclotrons can be schematically classified in five categories on the basis of their main characteristics: the energy and the intensity of the accelerated beams. As reported in Table 1, proton therapy cyclotrons feature the largest energy and the lowest intensity. They can be based on conventional or on superconducting technology. Their problematics are different with respect to the machines designed for radioisotope production [2] and will not be discussed here. Some research laboratories have recently installed 70 MeV cyclotrons which can be used for the production of specific radioisotopes (ex. ^{82}Sr for ^{82}Rb generators) and for research activities. These accelerators can provide beams of different energy and accelerate also alphas or deuterons. Along this line, 30 MeV cyclotrons are installed in research laboratories or in radiopharmaceutical companies producing Single Photon Emission Tomography (SPECT) radioisotopes (^{131}I in particular). Both 70 and 30 MeV cyclotrons require a large infrastructure and are therefore quite rare. The most common medical cyclotrons feature a beam energy in the range 15-25 MeV and are excellent tools to produce ^{18}F ($T_{1/2}$=110 minutes), the most common and requested radioisotope for Positron Emission Tomography (PET). These accelerators are compact, cost effective and can be installed in a hospital-based facility. There are more than 300 cyclotrons of this kind in operation and their number is continuously increasing [3]. For simplicity, I will refer to them as compact medical cyclotrons and they will be discussed in detail throughout this paper. Other commercial medical cyclotrons feature smaller beam energies and are often devoted to the production of only one PET radioisotope in limited quantities. They will not be further discussed.

Compact medical cyclotrons usually run during the night or early in the morning to produce short-lived radioisotopes for PET imaging. They are available during daytime and their beams could in principle be used for multi-disciplinary research. To exploit their valuable science potential, specific conditions must be fulfilled. Since daily radioisotope production induces high residual radioactivity, the cyclotron bunker is accessible only for very short periods which are

Figure 1: The compact medical PET cyclotron and its research beam line installed at the Bern University Hospital.

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STUDIES AND UPGRADES ON THE C70 CYCLOTRON ARRONAX

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Abstract

The multi-particle cyclotron C70 Arronax is fully running since 2010 and its RF run time has increased up to 4400 hours in 2015. The accelerator is used for a wide variety of experiments (physics cross-sections, radiolysis, radiobiology) and radio-isotope productions. This requires runs with 7 orders of intensity range from a few pA up to 350 µA and a large range of particles energy.

Machine and beamline studies are continuously needed. For example magnet intensity scan inside the cyclotron and in the beamlines, respectively with compensation coils and the quadrupoles have been done. These scans caracterise performances of the machine and help both operations and mitigation of particle losses. Additionally beam loss monitors and control systems are being devised to support further the high intensity and precision requirements on the runs. Also a pulsed train alpha beam system located in the injection has been designed. The proof of principle with a dedicated run has been performed.

The results of the machine studies and status of these developments are presented in this paper.

INTRODUCTION

The cyclotron Arronax [1] (Accelerator for Research in Radiochemistry and Oncology at Nantes Atlantique), running since 2010, the year of its commissioning, has started in 2011 its hands-on phase [2]. Arronax has gradually increased the number of hours it uses the cyclotron.

The cyclotron delivers beams separately in six vaults surrounding the main cyclotron vault [3]. Five of the vaults are used for high intensity beams and the sixth one, beamline for experiments, is dedicated to low and ultra-low intensity (<100 electric pA).

The priority list for production of radio-isotopes covers both isotopes for imaging and therapy. It includes, but not exclusively, ^{82}Sr, ^{64}Cu, ^{211}At and ^{166}Ho. ^{211}At requires an energy degrader that has been installed in one of the beamline and as for ^{166}Ho, a neutronic activator is in use, all at intensities above 10µA.

RANGE OF OPERATION

The cyclotron provides four types of positively charged particles (proton, alpha, deuterons, HH+) which intensity and energy can be modified according to the experimental needs. Figure 1 shows a map of the operation range for each particle at intensity from a few nA up to 100s of µA on the target with energies from 32 MeV up to 70.3 MeV for protons. Protons and deuterons have the widest energy range mainly due to cross-section measurements being performed at Arronax on numerous physics production channels [4]. Several runs with protons for ^{82}SR production have started in 2016 at 150µA on target, extending the production capacities at Arronax.

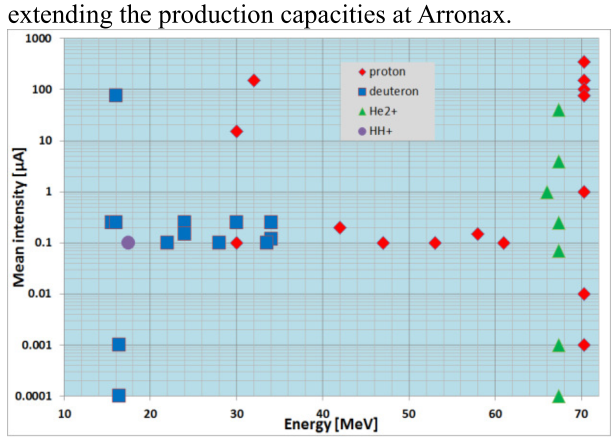

Figure 1: The operation range for the C70 Arronax with the 4 particles in use.

THE MACHINE OPERATION

The use of the cyclotron, here expressed in term of number of RF hours, has increased over the years up to 4400h in 2015 as shown in Fig.2, being limited mostly by manpower. Each year includes 4 main preventive maintenances that are performed over a week. Also, a Computerized Maintenance Management System (CMMS) – MaintiMedia from Tribofilm, is in place since 2015, to support the general maintenance follow-ups.

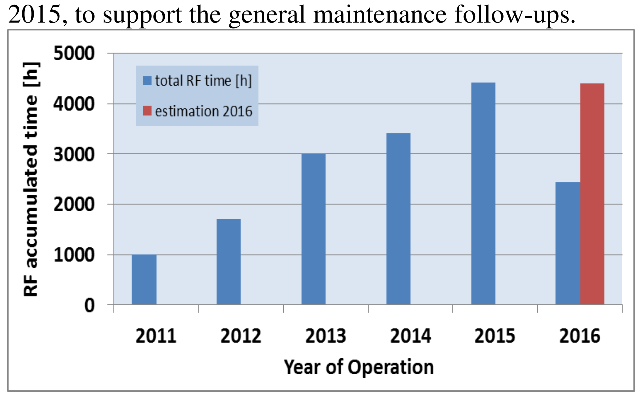

Figure 2: RF accumulated time per year since 2011 and as of august for 2016 and estimation for this year.

The settings on the machine parameters at the beginning of a run are systematically adjusted to increase

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DEVELOPMENT OF THE CYCLONE® KIUBE: A COMPACT, HIGH PERFORMANCE AND SELF-SHIELDED CYCLOTRON FOR RADIOISOTOPE PRODUCTION

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Abstract

About 15 months ago, at IBA, we have launched the design, construction, tests and industrialization of an innovative isochronous cyclotron for PET isotope production (patent applications pending). The design has been optimized for cost effectiveness, compactness, ease of maintenance, activation reduction and high performances, with a particular emphasis on its application on market. Multiple target stations can be placed around the vacuum chamber. An innovative extraction method (patent applications pending) has been designed which allows to obtain the same extracted beam sizes and properties on the target window independent of the target position.

INTRODUCTION

This isochronous cyclotron for PET radioisotope production produces fixed energy 18MeV proton beam and is called the **Cyclone® KIUBE**, Figure 1.

Today, three versions are available producing 100μA, 150μA and 180μA on target and the option with self-shielding is also available.

Figure 1: CYCLONE® KIUBE.

DESIGN

General Layout

The Cyclone® KIUBE, Figure 2, is a new concept starting from scratch. All the subsystems have been redesigned and optimized for high power beam production and reduced maintenance. During the study phase, all the teams have been largely challenged to meet requirements and systematic tools as TRIZ methods have been used.

First of all, the magnet system [1] has been designed to reduce the machine footprint, to make the access to all the sub-components easier and simplify the self-shielding concept. The median plan height has been modified to ensure an easy access to all the cyclotron components for maintenance.

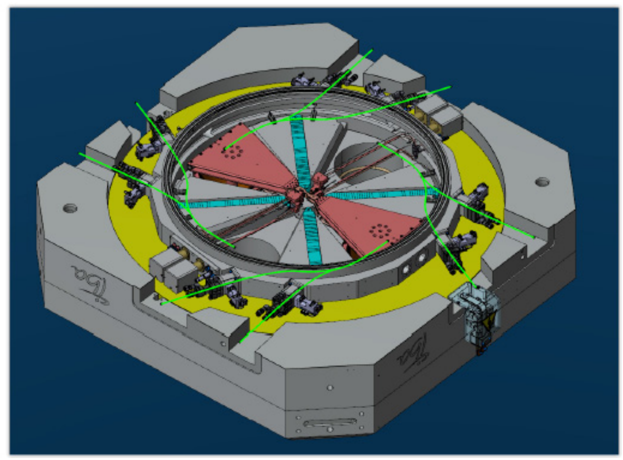

Figure 2: Magnet and extraction general overview.

The pole shape has been optimized [2] to ensure the same beam quality (shape and intensity) on the 8 targets surrounding the machine. The Figure 3 presents the top view of the pole with two gradient corrector cuts.

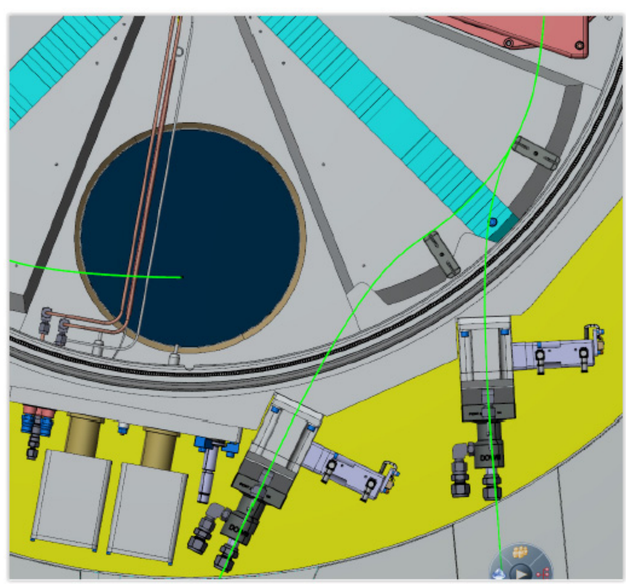

Figure 3: Two extraction systems per pole.

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BEST 70P CYCLOTRON COMMISSIONING AT INFN LN LEGNARO

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Abstract

Best Cyclotron Systems Inc (BCSI) has designed and manufactured a 70 MeV compact cyclotron for radioisotope production and research applications. The cyclotron has been built at the Best Theratronics facility in Ottawa, Canada for the INFN-LNL laboratory in Legnaro, Italy. The cyclotron has an external negative hydrogen ion source, four radial sectors with two separated dees in opposite valleys, cryogenic vacuum system and simultaneous beam extraction on opposite lines. The beam intensity is 700 microamperes with variable extraction energy between 35 and 70 MeV. The beam commissioning performances at the customer site are reported.

BEAM COMISSIONING

The cyclotron and beam line equipment has been installed and commissioned at INFN LN Legnaro and the *Factory Acceptance Test* (FAT) has been successfully repeated before proceeding with high energy beam acceleration.

1 MeV Acceleration

The cyclotron is equipped with a low energy beam intercepting probe located at the 1 MeV radius. The probe is used to optimise the beam transport through the *Low Energy Beam Transport (*LEBT) line and characterise the beam injection efficiency and acceleration to 1 MeV. A complete characterisation up to 1 MeV has been done and reported [1] as part of the FAT.

Beam intensity and stability parameters have been confirmed to better values as shown in Table 1.

Table 1: Beam at 1 MeV Probe

Parameter	Value
Beam current	900 µA
Ion source current	8.5 mA (max. 15 mA)
Injection efficiency	10.3%.
Beam ripple	±1% of the average value stability better than 5 µA

High Energy Acceleration

Beam acceleration to high energy was scheduled in several steps to ensure that beam tuning on target was optimum while maintaining the beam losses to a minimum. The beam line layout as shown in Fig. 1 allowed us to install multiple low power Faraday cups at the exit of each beam line switching magnet in addition to the high power beam dump of 50 kW (INFN supply) installed in target vault A6. Tests on Faraday cups were conducted at low beam currents of 3 to 20 µA single and double beam extraction. Beam delivery operation and tunes were verified and optimised at 100 µA beam current on the beam dump.

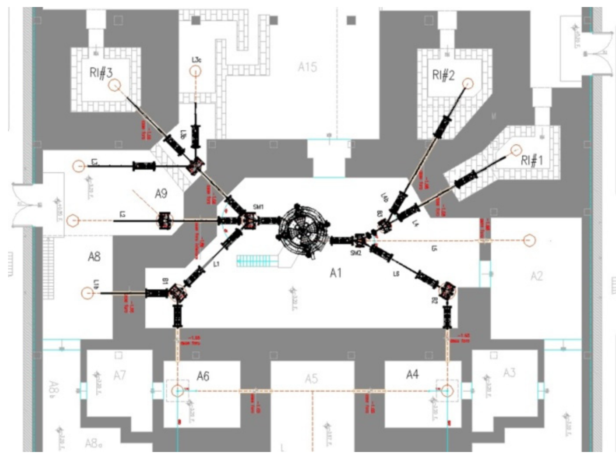

Figure 1: Beam line layout.

Beam Profile Measurement

Two helical wire beam scanners per beam line were installed to characterise the beam profile during the tuning process. Scans have been done up to maximum beam current by closely monitoring the power dissipation on the wire (increased rotation speed at higher beam powers). Figure 2 shows the beam profile (peak voltage) for wobbler off and on status versus x axis position.

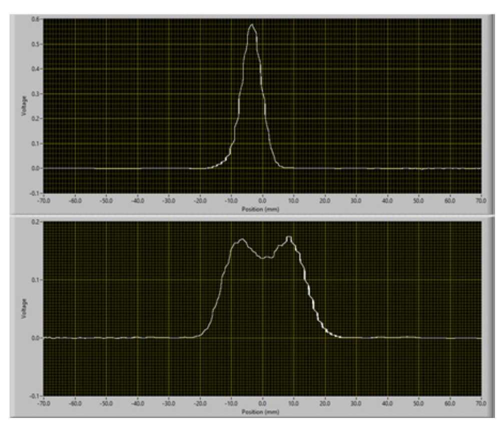

Figure 2: Beam profile (V), wobbler off/on versus x axis position.

Pulsed Beam

Two methods of pulsing the beam intensity were considered: amplitude and phase modulation. In either case the modulated parameter was switched between values:

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SOME EXAMPLES OF RECENT PROGRESS OF BEAM-DYNAMICS STUDIES FOR CYCLOTRONS

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Abstract

Two subjects are highlighted. The first is the problem of high space charge effects in cyclotrons. The second is the the progress in development of tools and simulations for industrial and medical cyclotrons at IBA.

INTRODUCTION

This paper reviews examples of recent progress in beam dynamics studies for cyclotrons. The paper is not extensive, but rather follows developments of two subjects during the past years and tries to add an educational accent. The first is the problem of high space charge. This subject is at this moment very important, in view of possible applications of (compact) cyclotrons for ADS, or for generating high fluxes of neutrinos for experiments such as IsoDAR or Daeδalus (see this conference [1]). Examples are given of the increased understanding based on (semi-)analytical models and of the latest developments and achievements based on numerical simulations. The second subject is the progress in simulations for industrial and medical accelerators as has been achieved at our company during the last years.

SPACE CHARGE IN CYCLOTRONS

One can distinguish roughly three types of intensity limiting space charge effects in cyclotrons: i) the problem of beam blowup due to the weak vertical focusing in the cyclotron center, ii) the problem of loss of turn separation due to space charge induced energy spread and iii) the problem of space-charge induced halo for poorly matched beams.

Space Charge Effects in the Cyclotron Center

This paragraph refers to papers of Rick Baartman, Thomas Planche and Yi-Nong Rao [2–5]. In the central region of a (compact) cyclotron, the azimuthal magnetic field variation falls quickly to zero and Tterefore the magnetic vertical focusing becomes very weak. The beam current is limited by the space charge vertical defocusing and the resulting vertical losses on the central region.

The incoherent vertical tune shift inversely depends on the kinetic energy of the particle. Thus increasing the injection energy helps to increase the current limit. This is done for example at PSI (870 keV) and at Triumf (300 keV). A drawback is that losses at these higher injection energies can already be harmful. Furthermore such high injection energies can not be done in smaller machine. For compact cyclotrons, one has to rely on the weak electric focusing of the RF gaps.

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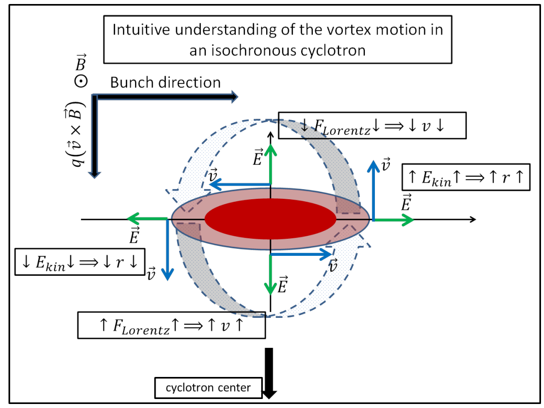

Figure 1: Intuitive understanding of the vortex motion

This focusing is RF-phase dependent. The bunch-center must cross the gap on the falling RF slope . This means that the head of the bunch experiences weaker focusing than the tail. By this, space charge causes progressive loss of the bunch head [2]. When using a (spiral) inflector, the beam needs to be strongly compressed in three dimensions (by bunching and transverse focusing). The beam at the inflector exit is therefore strongly mismatched with respect to the weak vertical focusing. The complicated spiral inflector optics strongly correlates the 6D phase space. Both effects result in strong emittance growth [5].

Loss of Turn-Separation Due to Space Charge

This paragraph refers for some part to a nice overview paper of Rick Baartman [6] in the 2013 Vancouver cyclotron conference. In an isochronous cyclotron, the space charge effect induces a vortex motion and an increase of energy spread in the bunch. An intuitive understanding of the this is obtained from Fig. 1. Here the bunch is moving clockwise from left to right. Due to the outward directed space charge force, the leading particles gain energy. In an isochronous cyclotron they can only move to higher radius. Trailing particles loose energy and move to lower radius. The radially exterior particles experience a reduction of centripetal force and fall behind in phase. The opposite happens for the interior particles.

The bunch density shows an effect of macroscopic rotation (vortex). If the the space charge equipotential curves would be similar to that of the ellipse and the space charge force would remain perfectly linear, then the elliptical bunch-shape would be conserved. Generally this is not the case and the bunch starts to deform (spiralize) such that the outer part of the bunch will rotate slower than the core.

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SIMULATION OF THE BEAM DYNAMICS IN THE AXIAL INJECTION BEAM LINE OF FLNR JINR DC280 CYCLOTRON

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Abstract

DC280 is novel cyclotron which is created i the FLNR JINR. This cyclotron allows accelerating the ions of elements from Helium to Uranium with the mass to charge ratio in the range of 4 – 7.5 providing ion currents up to 10 pμA. The simulation of ion beam dynamics in the high voltage axial injection beam line of DC280 cyclotron is presented. One part of the injection system is placed at the High Voltage Platform and other part is in the grounded yoke of the DC-280 magnet. The 3D electromagnetic field maps of the focusing solenoids, analyzing magnet, accelerating tube and spherical electrostatic deflector are used during this simulation. The calculated efficiency of ion beam transportation is equal to 100%.

INTRODUCTION

The DC-280 [1] injection system has to provide ion beam transport from the ECR-ion source to the cyclotron centre and capturing into acceleration more than 70 % of ions with the mass to charge ratio of A/Z=4÷7.5 [2].

The experience of operation of FLNR cyclotrons demonstrates the substantial dependence of the efficiency of injection on the beam current for ions with energies of about 15 keV per unit charge. At the ion beam currents of 10 μA the efficiency of capture into acceleration reaches 50÷60 % while for the ion currents of 80÷150 μA it decreases down to 30÷35%. This effect may be explained by increasing of the beam emittance at high level of the microwave power in the ECR ion source and influence of the space charge on bunching of the ion beam. To improve the injection efficiency due to decreasing of both the emittance and the influence of space charge the injection energy has to be increased.

The axial injection system of the DC-280 cyclotron has two pieces of High Voltage Platforms (HVP). The maximal voltage on the HVP is 75 kV. Every HVP is equipped by an ECR ion source with injection voltage of 25 kV, the focusing elements (solenoids) and the magnets for ion separation. The high voltage accelerating tube is installed at the edge of the HVP to increase the ion energy (up to 100×Z keV in maximum). The acceleration in high voltage accelerating tube allows decreasing the ion beam emittance in about 1.5 times. The beam is matched at the entrance of the acceleration tube by means of the electrostatic lens.

For rotation of the ion beam onto vertical axis the spherical electrostatic deflector is used. To increase the efficiency of acceleration the multi-harmonic buncher is used. It is placed in the vertical part of the channel just after the electrostatic deflector. The buncher is working at 1, 2 and 3 harmonics of the RF system of the cyclotron. The ion beam emittance is matched with the acceptance of the spiral inflector by two solenoids installed at the vertical part of the beam line.

The numerical simulation of the ion beam dynamics in the axial injection channel has been performed by using the 3D electromagnetic field maps of the ECR ion source, solenoidal lenses, analyzing magnet [3], electrostatic lenses, accelerating tube and spherical electrostatic deflector [4]. All calculations have been done with the help of MCIB04 program code [5].

BEAM LINE ELEMENTS

Scheme of the axial injection channel is shown in Fig. 1

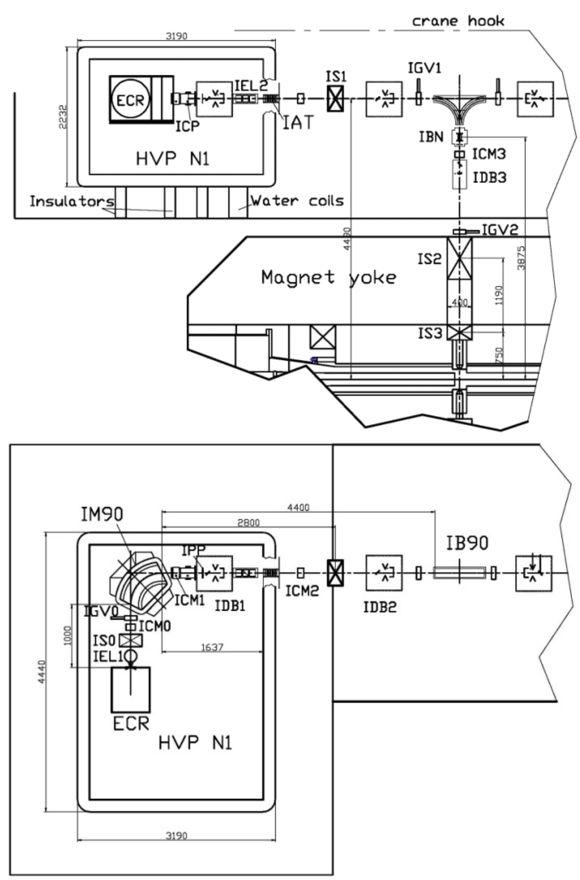

Figure 1: Scheme of axial injection channel. HVP – High Voltage Platform; ECR – ECR ion source; IS0-3 – solenoids; IM90 – analyzing magnet; IEL1,2 – electrostatic lenses; IAT – acceleration tube; IB90 – spherical electrostatic deflector; IBN – multi-harmonic buncher; IDB1-3 – diagnostic box.

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SPACE-CHARGE SIMULATION OF TRIUMF 500 MeV CYCLOTRON*

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Abstract

We present a method to improve computation efficiency of space charge simulations in cyclotrons. This method is particularly efficient for simulating long bunches where length is large compared to both transverse size and turn separation. We show results of application to space charge effects in the TRIUMF 500 MeV cyclotron.

INTRODUCTION

The TRIUMF 500 MeV cyclotron accelerates H^- ions, and uses charge exchange extraction. No turn separation is required for extraction, which allows a very large phase acceptance of this machine (about 60°) [1]. Bunches are very long, and have a very large energy spread between the head and the tail (see for instance Fig. 8). Each bunch therefore occupies a large and slim volume in real space. Solving Poisson equation in a PIC code over such a large volume would require a significant computation time.

In addition, at high energy the turn separation is several times smaller than the radial beam size even for an infinitesimal phase slice. It is therefore essential to take into account the effect of many overlapping neighbouring turns. The multibunch calculation used in `OPAL` [2], is most appropriate when bunch length and width are comparable, but in the TRIUMF case, the bunch length can be 400 times its width.

To overcome these difficulties, we use periodic boundary conditions in the radial direction. This trick, originally proposed by Pozdeyev as a possible way to improve his code `CYCO` [3, 4], is presented in Ref. [5]. The radial dimension of the box inside which Poisson's equation is solved is equal to the turn separation. Particles of the bunch that fall out of this box are returned to the box assuming radial periodicity (see Fig. 1). In fact, these particles appear to belong to the neighbouring turns. The charge density in this 3D box is divided onto slices cut along the y direction (see Fig. 1). To take into account the image charge, we use "metallic" boundary conditions in the vertical direction; to simulate the effect of neighbouring turns, we use periodic boundary conditions in the radial direction.

We have implemented such a 3-D Poisson's equation solver into a piece of code that we call `tricycle`

Poisson Solver Test

To test our Poisson's equation solver we compute the electric potential from a static sphere of charge constituted of 10^6 randomly distributed macro-particles; results are shown in Fig. 2.

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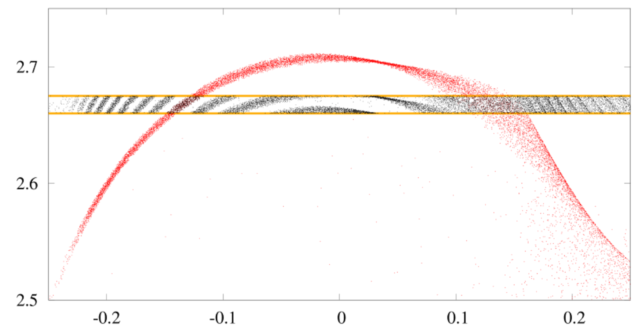

Figure 1: Beam folding applied to accelerated turn #100 of TRIUMF. The original particle distribution is shown in red (in top view). The folded beam in show in black. The yellow line materializes the edge of the box inside which Poisson's equation is solved; perodic boundary condition is applied along those two sides. Coordinates are in metres.

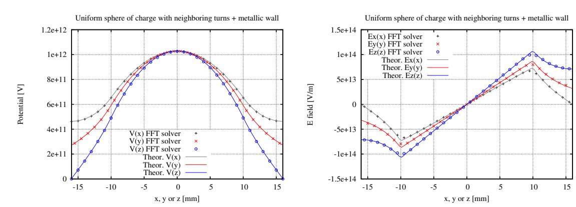

Figure 2: Electrostatic potential (left) and electric field (right) from a uniform sphere of charge; the dots presents results from `tricycle` with a $32 \times 32 \times 32$ size PIC grid; solid lines are from theory. Note the three different boundary conditions in x, y, and z: periodic (neighbouring turns), open, and metallic (potential=0), respectively.

The theoretical electrostatic potential from a uniform sphere of charge with such boundary conditions writes:

$$V(x,y,z) = \sum_{i_x=-\infty}^{+\infty} \sum_{i_z=-\infty}^{+\infty} (-1)^{i_z} f(x - i_x \Delta x, y, z - i_z \Delta z) \quad (1)$$

where Δz is the vertical gap of the vacuum chamber, Δx the turn separation (x here is along the radial direction), and $f(x,y,z)$ is derived from Gauss's law:

$$f(x,y,z) = \begin{cases} \dfrac{Q}{\epsilon_0 4\pi r} & r \geq R\,, \\[2ex] \dfrac{Q}{\epsilon_0 8\pi R}\left(3 - \dfrac{r^2}{R^2}\right) & r < R\,, \end{cases} \quad (2)$$

where $r = \sqrt{x^2 + y^2 + z^2}$, R is the radius of the sphere, and ϵ_0 is the vacuum permitivity.

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A NEW DIGITAL LOW-LEVEL RF CONTROL SYSTEM FOR CYCLOTRONS

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Abstract

Stable control of amplitude and phase of the radio frequency (RF) system is critical to the operation of cyclotrons. It directly influences system performance, operability, reliability and beam quality. iThemba LABS operates 13 RF systems between 8 and 81 MHz and at power levels of 50 W to 150 kW. A critical drive has been to replace the 30 year old analog RF control system with modern technology. To this effect a new generic digital low-level RF control system has been designed. The system is field programmable gate array (FPGA) based and is capable of synthesizing RF signals between 5 and 100 MHz in steps of 1 μHz. It can achieve a closed-loop amplitude stability of greater than 1/10000 and a closed-loop phase stability of less than 0.01º. Furthermore, the system is fully integrated with the Experimental Physics and Industrial Control System (EPICS) and all system and diagnostic parameters are available to the Control System Studio clients. Three prototypes of the system have been in operation since November 2014. A general analysis of RF control systems as well as the methodology of design, implementation, operational performance and future plans for the system is presented.

INTRODUCTION

iThemba LABS is a multi-disciplinary cyclotron research facility situated in South Africa. It operates 13 RF systems between 8 and 81 MHz and at power levels of 50 W to 150 kW to deliver particle beams for nuclear physics experiments, radiotherapy and the production of radioisotopes.

A critical drive has been to replace the 30 year old legacy analog RF control system with modern technology. To this effect a new generic digital low-level RF control system has been designed.

CURRENT STATE OF TECHNOLOGY

Continuing rapid advances in Field Programmable Gate Arrays (FPGA), digital signal processing (DSP), high speed digital to analog converters (DAC) and high speed analog to digital converters (ADC) have made it feasible to develop state of the art digital RF control systems [1,2].

For example, PEFP have developed a digital low level RF (DLLRF) system for a linac accelerator [2]. They achieved 1% amplitude and 1˚ phase stability using a mixture of analog and digital hardware.

INFN LNS developed a DLLRF system for their cyclotrons utilizing direct digital synthesis ICs from Analog Devices [3]. This approach achieved a phase stability of 0.1˚.

In a joint project, JAERI and KEK achieved a 0.2% amplitude stability utilizing a mixture of analog and digital hardware for a linac accelerator [4].

A similar study demonstrated that it is possible to measure an RF signal with a phase accuracy of 0.05˚ and an amplitude accuracy of 0.02% using high-speed ADCs and FPGAs [5].

Finally, LEPP achieved 0.02˚ phase and 0.01% amplitude stability when applying their DLLRF to their linac system [6].

These advances demonstrate that DLLRF control systems can produce an RF signal with an amplitude stability that can rival or exceed that of analog systems.

METHODOLOGY OF DESIGN

In our DLLRF control system design particular attention was paid to direct digital synthesis (DDS) techniques, the performance and capabilities of high speed DACs, ADCs and DSP techniques used for demodulation of RF signals.

We set out to achieve 0.01% amplitude and 0.01˚ phase resolution over an operating frequency of 5 to 100 MHz. A market analysis revealed suitable DACs to achieve this, but it also highlighted that there were no ADCs available that could achieve true 16 bit amplitude resolution between 5 and 100 MHz.

Our solution was to use a heterodyning approach and mix the RF signal down to an intermediate frequency (IF) that is sampled with an appropriate ADC [7].

State of the art digital designs utilize in-phase and quadrature (I/Q) demodulation to extract phase and amplitude information [1, 2, 4, 7]. Integrated circuit devices have been developed for telecommunications applications to determine I/Q components [8]. These devices, however, do not operate over our full frequency range and cannot detect phase deviations below 0.2˚. Hence these devices are not suitable for our purposes.

The solution was to develop hardware utilizing FPGAs. The FPGA-based solution offered a highly customizable development platform which was an excellent base for experimenting with hardware design and the optimization of techniques and algorithms. A Xilinx Spartan 6 FPGA was chosen in our final implementation. The design and performance of the production version of the new DLLRF control system is discussed in the following sections.

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HYBRID CONFIGURATION, SOLID STATE–TUBE, REVAMPS AN OBSOLETE TUBE AMPLIFIER FOR THE INFN K-800 SUPERCONDUCTING CYCLOTRON*

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Abstract

An insertion of a solid state amplifier is substituting the obsolete first stage of a full tube RF power amplifier. The amplifier is based on two tube stages. The first, equipped by a tetrode, the RS1054, was being manufactured by Thales until some years ago. Some spare parts have been ordered but not enough to guarantee smooth cyclotron operation for the next few years. It was necessary to come up with a new solution. We were basically at a crossroad: replace the first stage with another tube still in production or change the technology from tube to solid state. A study, from market research to the technology point of view was carried out and the final decision was to use a solid state stage as an innovative solution for this kind of power vs frequency range of operation. The prototype of this hybrid amplifier has been in operation with our cyclotron since January 2015. The details of these decisions, the description of the modified amplifier (solid state – tube) and the successful results of this hybrid configuration will be shown in this presentation.

RF AMPLIFIERS STORICAL OVERVIEW

The RF power amplifiers are made by two tetrode stages driven by solid state commercial amplifiers. The drivers are class A, wideband, 50 dB gain and a maximum out power of 200 W. The RF power amplifier can deliver a maximum power of 75 kW, the total gain between 1st and 2nd stage is about 30 dB. The first stage is wideband, based on the tetrode RS1054L by Thales, in ground-cathode configuration, air-forced cooling. The second stage is a narrow band stage, common grid configured, based on 4CW100000E by CPI, water cooled.

Figure 1: RF amplifiers and the 1st – 2nd stages view.

The three RF power amplifier cabinets with the internal view of the final stage are shown in Fig. 1. The tuning system for all the frequency range (15-50 MHz) is automatic. This amplification system was made, under technical specification by our Institute, at the end of 1980s. Since the commissioning of the Superconducting Cyclotron, 1994, the amplifiers have been operating, related to the RF power stages, without significant changes or upgrade. The robust and classical electrical design of the amplifiers has ensured, more or less, an uninterruptable operation, for the last 30 years. Figure 2 shows a simple block diagram of the RF system, with drivers and final amplifiers [1].

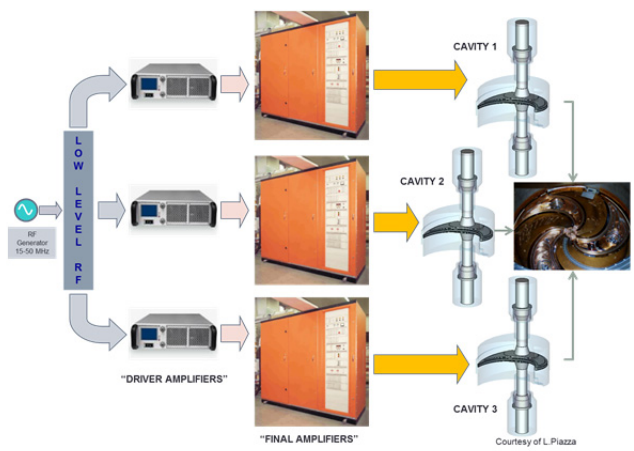

Figure 2: Block diagram of the RF system.

The total gain between drivers and final amplifiers is approximately around 80 dB. The distribution is about 50 dB for the driver and 30 dB for the final amplifier. The final is divided between 14 and 16 dB respectively for the 1st and 2nd stages. Despite the cost of the two tetrodes, in terms of spare parts, has greatly increased in the last decade, we decided to continue operating with this configuration. But some expedients was adopted. For example, we optimized the main parameters of the amplifiers, to reduce the maximum output power from 75 kW to 30 kW, enough for our cyclotron performance and as result, the average life span of the tetrodes was increased. We decided to refurbish the exhausted tetrodes, instead of buying new ones, reducing the cost by a third, and the reconstructed tetrode, can be considered like new. Unfortunately, this refurbished technique can be done only for the second stage, the 4CW100000E by CPI, while for the first stage, the RS1054L by Thales, it was not available. Apparently, the type, hardware and geometry of the tetrode itself made the rebuilding of the Thales tetrode almost impossible [2, 3].

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DESIGN AND SIMULATION OF CAVITY FOR 18 MeV CYCLOTRONS

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Abstract

RF system is the key part of the cyclotron and cavity is the key part of RF systems. The basic parameters of cavity design are the resonant frequency, Dee voltage, RF phase and RF power. Proper operation of the cavity depends on the suitable voltage distribution in accelerating gap, phase stability in the cavity and as well as optimal scattering parameters. In this simulation using CST MWS, different parts of the cavity such as Stem and Dee are optimized to achieve optimum dimensions for the desired resonant frequency, Dee voltage and RF power. Main properties of the designed cavity are resonant frequency at 64.3 MHz, Dee voltage of 45 kV and RF power of 11 kW.

INTRODUCTION

IRANCYC-18 is an 18 MeV compact low energy cyclotron for short life medical isotope production. The RF system is designed to accelerate 150 μA of H− ions to 18 MeV. The RF specifications are shown in Table 1.

Table 1: Main RF Specifications

Parameter	Value
Resonant Frequency	64.3 MHz
Harmonic Number	4
Dee Voltage	45 kV
Resonant Mode	λ/4
Matching Impedance	50 Ω
Material	OFHC copper
Number of Dee	2
Dee angle	44

The RF system is composed of λ/4 delta cavities housed inside the valleys of the magnet, power amplifiers, power switch, directional coupler, transmission lines, coupling and tuning capacitors and low level control circuits. Block diagram of RF system is shown in Fig. 1. RF power has been capacitively coupled into the cavity by rigid coaxial line, also a tuning capacitor is used to adjust the cavity frequency.

DESIGN ITEMS

The Operating frequency of resonant cavity is 64.3 MHz. This cavity works at fourth harmonic [1]. In the design of the cavity, the main parts are Dee, Stem and central region. Angle and width of the Dee and the gap between the Dee and Liner as accelerating region are the points that in the design should be considered. The suitable angle and width of Dee is calculated on the basis of Eq. (1) [2]. Also the distance of the accelerating gap can be calculated on the basis of electric field and required voltage as well as considering the Kilpatrick's criterion.

$$\Delta E_k = V_{dee}.N.q.\sin\left(\frac{h.\alpha}{2}\right) \quad (1)$$

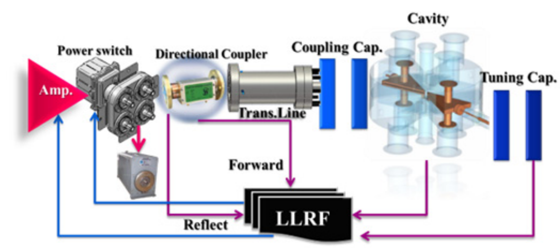

Figure 1: Block diagram of RF system.

Another important part of the cavity is Stem that with regard to the capacitive role of Dee, Stem have an inductive role of cavity circuit. The structure of Stem is like a coaxial line that can play three roles in the design:

1. Inductive's role of Stem can change the resonant frequency [3]
2. Shunt impedance of the cavity structure has direct relation to Stem dimensions and therefore with cavity losses.
3. Displacement of Stem along the accelerating gap can change the voltage distribution along the accelerating gap [4].

CST MWS software has been chosen for design and simulation. CST STUDIO SUITE is a general-purpose electromagnetic simulator based on the Finite Integration Technique (FIT), unlike most numerical methods, FIT discretizes the following integral form of Maxwell's equations rather than the differential one [5]. Geometry designed in this software which has been shown in Fig. 2.

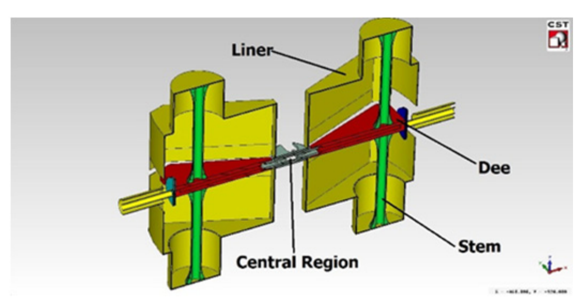

Figure 2: Designed geometry in CST MWS.

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A COUPLED CYCLOTRON SOLUTION FOR CARBON IONS ACCELERATION

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Abstract

A concept of coupled cyclotrons for acceleration of carbon ions (charge 6+) to 400 MeV/nucleon by a separated sector cyclotron consisting of six sector magnets with superconducting coils is proposed. Injection to the machine will be provided by a compact 70 MeV/nucleon cyclotron. The accelerator complex is intended for setting up a radiation therapy facility employing carbon ions. The advantages of the dual cyclotron design are typical of cyclotron-based solutions. The first design studies of the sector magnet of the main cyclotron (magnetic field increases from 4.2 T to 6.5 T, RF frequency 73.56 MHz, RF mode 6) show that it is feasible with acceptable beam dynamics. The accelerator has a relatively compact size (outer diameter of 8 m) and can be an alternative to synchrotrons.

INTRODUCTION

Development of accelerators for producing carbon beams with the energy of 400–450 MeV/nucleon for hadron therapy appears to be an increasingly important issue today. The existing facilities for producing these beams are mainly based on synchrotrons. It seems interesting to use isochronous cyclotrons instead, as is the case in proton therapy. However, the developed designs of compact superconducting cyclotrons have some disadvantages in addition to their advantages [1]. An alternative solution can be a facility based on a superconducting sector cyclotron justified in detail in [2]. The design of this facility should comply with a number of conditions. First, the size and weight of the accelerator must be as small as possible, which makes it expedient to use the maximum high magnetic field. Second, the injection energy should be low enough for the injector to be of tolerable size. Third, the magnetic system design should be feasible, that is, the parameters of the superconducting coil (engineering current density, acting forces) should be adequate and the space between the sectors should be large enough to accommodate accelerating elements, inject a beam, etc. [3]. A separate task is to develop a system such that both maintains isochronism of the magnetic field and allows beam acceleration with a minimum number of resonance crossings.

INJECTION SYSTEM

The injection energy is chosen to be 70 MeV/nucleon because the accelerator with this final energy can be also used to accelerate H_2^+ ions. Their subsequent stripping allows obtaining protons of the appropriate energy suitable for medical applications. This cyclotron can be used for treating eye melanomas and also for producing radioisotopes.

A compact superconducting cyclotron seems to be the most optimal option. The magnetic rigidity of 70-MeV/nucleon C^{6+} ions is about that of 250-MeV protons in the Varian cyclotron [4]. So, some technical solutions of the Varian machine can be applicable to the injector. The use of an external carbon ion source limits the central magnetic field to a maximum of 3.0 T because of performing injection through a spiral inflector. Another constraint comes from the necessity to have the same RF frequency in the injector and in the booster machines, which also governs the central magnetic field in the injector. The optimum solution is a cyclotron with a central field of 2.4 T operating at the fourth harmonic of the accelerating field. The magnetic field is formed by four spiral sector shims. With an acceptable spiral angle of 50°, the external diameter of the accelerator will be no larger than 3 m and the weight will be about 90 t.

The system for injection in the main cyclotron consists of four magnetic channels and an electrostatic deflector (Fig. 1).

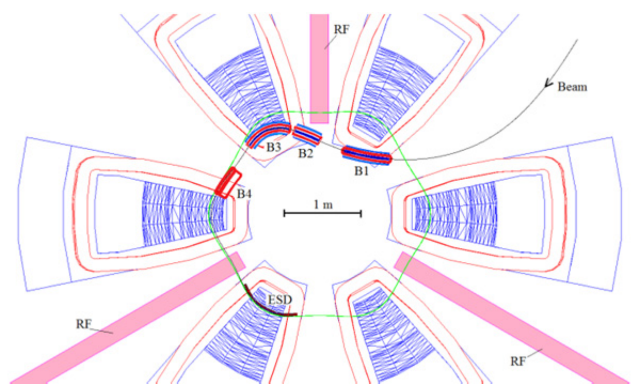

Figure 1: Injection system

The central fields in the channels are 1.2, 1.4, 1.4, and 0.8 T. The fourth magnetic channel comprises a septum. The strength of the electric field on the electrostatic deflector (ESD) is 80–90 kV/cm and can be slightly varied to ensure good beam centering.

As far as possible, the channels are arranged in the region of the magnetic field with a large gradient. The channel structure made such as to provide increasing or decreasing magnetic fields allows compensating for the negative effect of the main field on the transverse emittance of the beam. The axial distance between the coils with their cryostats in the beam injection region is

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NEW DEVELOPMENTS AT iTHEMBA LABS

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Abstract

iThemba LABS has been in operation for more than 30 years and is now at a stage at which refurbishment and – in some cases – replacement of the infrastructure and critical components is required. The replacement and refurbishment of the cooling system, which include the cooling towers and chillers, the 4.4-MVA uninterruptable power supply batteries and other critical components, are discussed. Progress with a facility for low-energy radioactive ion beams will be reported on. A proposal to remove radioisotope production from the separated sector cyclotron (SSC) and the production of the future radioisotopes with a commercial 70-MeV cyclotron to make more beam time available for nuclear physics research with the SSC will also be discussed. Developments on our electron cyclotron resonance ion sources, the PIG ion source and low-level digital RF control system have also been carried out. Good progress with integration of the existing control system to an EPICS control system has been made. The adoption of EtherCAT as our new industrial communication standard has enabled integration with much off-the-shelf motion, actuator and general interface hardware.

BEAM STATISTICS

The SSC's performance over the past six years is shown in Table 1. The increase in the number of interruptions can be expected as the facility has now been in operation for 30 years. The time lost due to interruptions has increased to more than 10% for some years. This is at the upper limit of what can be tolerated for medical applications. There was an increase in the beam time lost due to power failures. The facility has run without the Uninterruptable Power Supply (UPS) for more than two years, i.e. since early 2013. The average number of power interruptions without the UPS was about 3 per month. This meant that the various subsystems of the accelerators were prone to power failures, which resulted in increased downtime. Another factor which accounts for the increased downtime is interruptions relating to various radio-frequency (RF) systems of the accelerators. Many of these interruptions were due to power amplifiers. A project was initiated to build spare RF amplifiers for the injector cyclotrons and bunchers and refurbish the power amplifiers of the SSC. All the low-level RF control systems will be replaced during the next 2 years. To reduce the unscheduled interruptions to about 5% of scheduled beam time, the rate of refurbishment and replacement of the infrastructure has been increased.

Table 1: Operational Statistics of the SSC for the past 6 Years

Year	Beam supplied as		% of scheduled beam time for	
	% of total time	% of scheduled time	Energy changes	Interruptions
2010	67.6	82.18	5.2	7.3
2011	68.9	85.91	5.4	4.8
2012	69.9	82.04	6.1	7.9
2013	63.0	81.17	6.2	10.7
2014	67.3	80.81	5.4	8.1
2015	64.1	77.69	5.6	10.8

INFRASTRUCTURE REFURBISHMENT

A number of infrastructure refurbishment projects have been initiated recently. Two of the larger projects are the replacement of the batteries of the 4-MVA uninterruptable power supply and the chillers of the central cooling plant. Both these projects will make a valuable contribution to sustainable stable operation of the facility.

Cooling Towers and Chiller Upgrade

The accelerator complex utilizes a central cooling plant for all the cooling requirements. The heart of the system comprises four water-cooled chillers, seven cooling towers and associated pumps supplying chilled water at 6°C with a capacity of 4.4 MW. The chillers are operated in parallel and switched in on demand as the heat load increases. Since installation in 1982 the system has performed well, but has become inefficient and troublesome to maintain. During 2011 the cooling towers have been replaced and subsequently funds have been approved to replace the chillers and pumps during 2016. An extended mid-year maintenance period of 2 months has been scheduled to allow the work to be completed. As part of the upgrade a new programmable logic controller (PLC) and building management system (BMS) will also be installed. The new equipment will not only be more reliable, but will also offer a sustainable energy saving due to the high Coefficient of Performance (COP) of the modern technology chiller units.

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DEVELOPMENT OF FLNR JINR HEAVY IONS ACCELERATOR COMPLEX (DRIBs III)

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Abstract

The status of the FLNR JINR cyclotrons and plans of their modernization are presented. At present time, three isochronous cyclotrons: U400, U400M and IC100 are under operation at the JINR FLNR. The new isochronous DC-280 cyclotron is being created at the FLNR JINR for the new Super Heavy Element Factory.

INTRODUCTION

The Flerov Laboratory of Nuclear Reactions of Joint Institute for Nuclear Research (FLNR JINR) scientific program on heavy ion physics consists of experiments on synthesis of heavy and exotic nuclei using ion beams of stable and radioactive isotopes and studies of nuclear reactions, acceleration technology and applied research.

Presently, the FLNR JINR has four cyclotrons of heavy ions: U400, U400M, IC100, that provide performance of the basic and applied researches. Total annual operating time of the U400 and U400M cyclotrons is more than 10000 for many years (Fig. 1). The old U200 cyclotron is out of operation now.

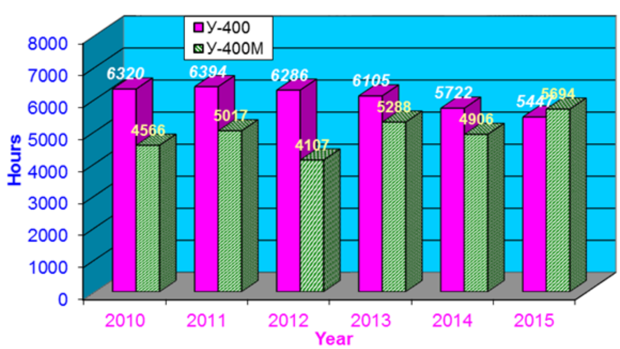

Figure 1: U400 and U400M operation in 2010-2015.

At present time the project of Super Heavy Element Factory is being performed at the FLNR JINR [1]. The project implies design and creation of the new DC280 cyclotron which has to provide intensities of ion beams with middle atomic masses (A~50) up to 10 pμA. The FLNR JINR facilities are shown in Fig. 2.

U400 CYCLOTRON

The isochronous U400 cyclotron has been in operation since 1978 [2]. The cyclotron produces ion beams of atomic masses 4-209 with energies of 3-29 MeV/nucleon. The main parameters of the U-400 are presented in Table 1. About 66% of the total time has been used for acceleration of $^{48}Ca^{5+}$ ions on the U400 cyclotron for synthesis of superheavy elements. New prospects for the synthesis of superheavy elements may appear to be connected with the usage of the intense beam of neutron-rich ^{50}Ti. The beam of ^{50}Ti ions has been accelerated into the U400 cyclotron. The extracted beam intensity of the of ^{50}Ti ions was about 0.5 pμA [3].

In 2014 the cyclotron was equipped by a dedicated channel for SEE testing of electronic components for ROSCOSMOS [4].

The U400 modernization is planned. The aims of the modernization are increasing the total acceleration efficiency and possibility to vary ion energy fluently at factor 5 for every mass to charge ratio (A/Z). The width of ion energy region will be 0.8-27 MeV/nucleon. The project of U400 modernization intends decreasing the magnetic field level at the cyclotron center from 1.93-2.1T to 0.8-1.8T, see Tab.1 (U400R). The axial injection and ion extraction systems will be changed. For the ion extraction both the stripping foil and the deflector methods are considered. Moreover, the project intends changing the U400 vacuum, RF and power supply systems. The expected ion beam intensities will be at least 2.5 times more than U400 ones [5].

Table 1: Comparative Parameters of U400 and U400R

	U400	**U400R**
Parameters	**Value/Name**	
Magnet weight	2100 t.	2100 t.
Magnet power	850 kW	200 kW
RF system power	100 kW	100 kW
Magnetic field level	1.93-2.1 T	0.8-1.8 T
The A/Z range	5-12	4-12
The frequency range	5.42-12.2 MHz	6.5-12.5 MHz
Harmonic modes	2	2-6
The max extraction radius	1.72 m	1.8 m
Vacuum level	$(1\text{-}5)\cdot 10^{-7}$ Torr	$(1\text{-}2)\cdot 10^{-7}$ Torr
Ion extraction method	Stripping foil	Stripping foil Deflector
Number of ion extraction directions	2	2

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STATUS OF THE TEXAS A&M UNIVERSITY CYCLOTRON INSTITUTE*

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Abstract

Both the K500 superconducting cyclotron and the older K150 (88") conventional cyclotron at the Texas A&M University Cyclotron Institute are in constant use for both experimental physics and chemistry as well as for customer-based, radiation-effects testing. In addition, an upgrade program using the K150 as a driver for the production of radioactive beams to then be accelerated to intermediate energies by the K500 Cyclotron is ongoing. Both a light-ion guide and a heavy-ion guide are being developed for this purpose. The status of the cyclotrons and of the associated electron-cyclotron-resonance ion sources (ECRIS) and the H-minus ion source used on the K150 as well as the status of the upgrade are presented.

INTRODUCTION

The Texas A&M K500 superconducting cyclotron was commissioned in 1988, while the Texas A&M K150 cyclotron (formerly the 88") was recommissioned in 2007. Beams are injected into each cyclotron by dedicated ECR ion sources, while a negative hydrogen/deuterium source injects into the K150, as well. Figures 1 and 2 are representations of the beams run by the K500 and K150, respectively. Figure 3 demonstrates the division of K500 time in the last three years devoted to nuclear physics and nuclear chemistry (8684 hrs.) and to outside use (9567 hrs.), mainly consisting of computer-chip single-event-effects (SEE) testing by a variety of satellite and avionic concerns. In addition, there is an ongoing effort to develop a K500+K150 radioactive-beam capability which will supplement the radioactive beams provided by the momentum-achromat-recoil spectrometer (MARS) [1].

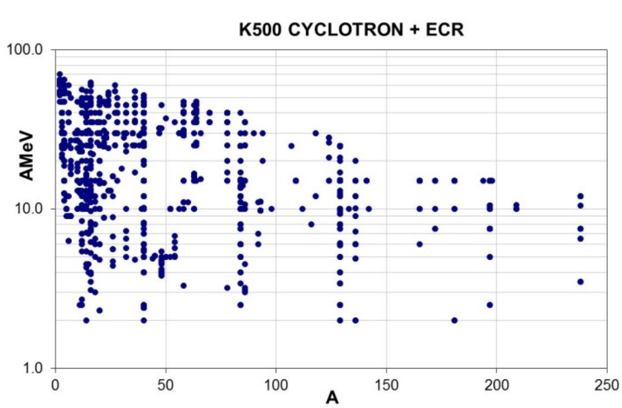

Figure 1: Beams run to date by the K500.

*Work supported by U. S. Dept of Energy Grant DE-FG02-93ER40773

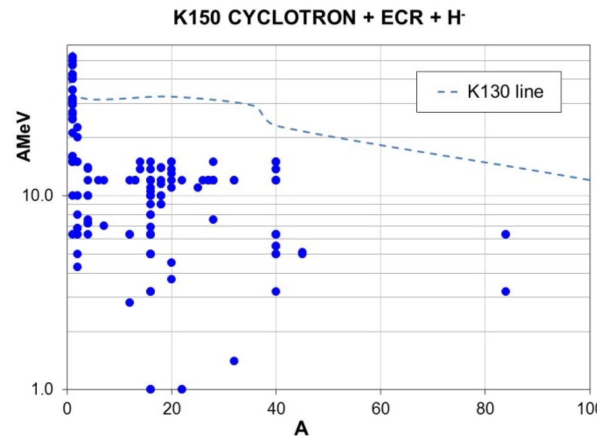

Figure 2: Beams run to date by the K150.

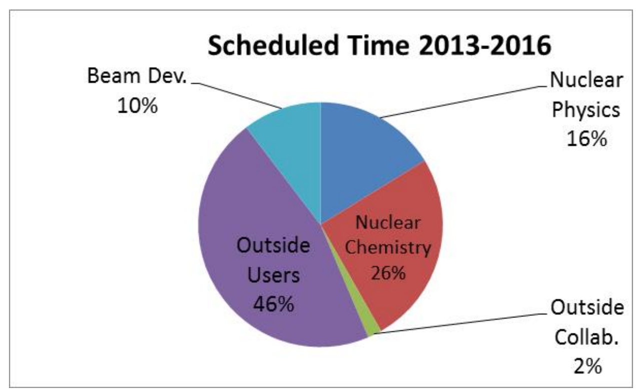

Figure 3: Division of K500 scheduled time.

CYCLOTRONS

The K500 and its injector 6.4 GHz ECRIS (ECR1) continue to operate well, averaging 6212 hours per year of beam-on-target over the last three years. The central inflector was replaced recently with a new one with electrodes fabricated from aluminum. The older tantalum electrodes showed considerable wear from heavy-ion sputtering.

The K150 has just recently come into extensive use although it still suffers from poor vacuum (3 X 10^{-6} torr) since the installed cryopanel remains unconnected to a coolant supply. As previously reported [2] K150 beams are tuned using the trim-coil program CYDE with field maps generated by TOSCA. An analysis of the field by TOSCA with the rectangular yoke included does not yield an appreciable first harmonic in the acceleration region, but both the middle-radius harmonic coils, valley coils 3 and 4, are extensively used for tuning in addition to the central and extraction harmonic coils, valley coils 1 and 5.

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THE S2C2: FROM SOURCE TO EXTRACTION

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Abstract

The superconducting synchro-cyclotron (S2C2) is the new compact 230 MeV proton cyclotron which will be used in the ProteusONE® proton therapy solution by Ion Beam Applications (IBA). Apart from being the first constructed superconducting cyclotron at IBA, the S2C2 is also the first synchro-cyclotron at IBA. In order to study the beam dynamics in this type of accelerator, new computational tools had to be developed which deal with the much larger number of turns compared to IBA's isochronous cyclotrons, the characteristic longitudinal capture in the central region and the regenerative extraction mechanism. This contribution is structured in four parts. In a first part, the general properties of the S2C2 are discussed (magnetic field, RF frequency, tune, ...). The three following parts discuss in detail the injection, acceleration and extraction.

GENERAL PROPERTIES

The S2C2 is a weak focusing cyclotron with a central field of 5.75 T. The average field as a function of radius is shown in Fig. 1(top). The bottom panel of Fig. 1 shows the

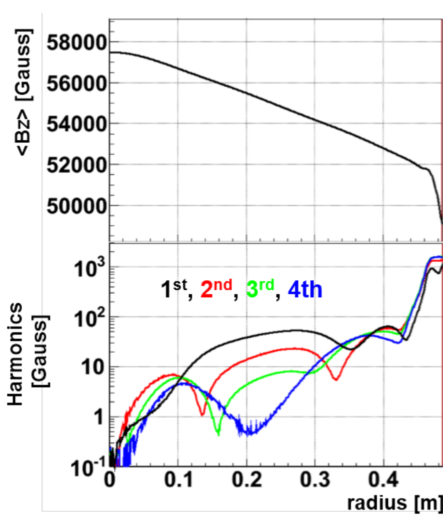

Figure 1: Average magnetic field (top) and first four harmonic components of the magnetic field (bottom) as a function of radius.

first four harmonic components. The first harmonic dominates between the center and 40 cm, whereas all harmonics rise drastically beyond 45 cm due to the presence of the extraction elements, which induce a localized field bump of 1 Tesla. The horizontal and vertical tunes (ν_r and $2\nu_z$) of

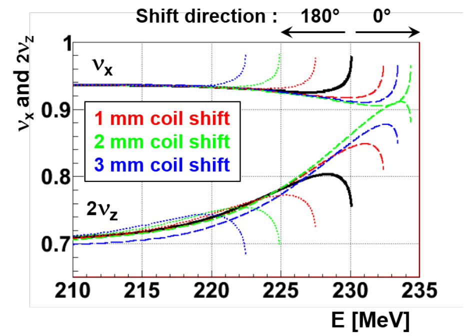

Figure 2: The horizontal tune (ν_r) and twice the vertical tune ($2\nu_z$) as a function of energy for different main coil positions. Black = nominal position, dashed colored = shift away from the regenerator, dotted colored = shift towards the regenrator.

the S2C2 are shown in Fig. 2 as a function of energy and for different horizontal positions of the superconducting main coil. As can be seen, the Walkinshaw resonance (ν_r=$2\nu_z$) is crossed when the coil is shifted by >2mm away from the regenerator. The precise horizontal main coil positioning is crucial to avoid the Walkinshaw resonance and determines the extracted beam energy (when ν_r=1).

The RF frequency varies from around 90 to 60 MHz, covering the injection and extraction frequencies at 87.6 and 63.2 MHz, resp. One full RF frequency cycle (1 ms) is shown Fig. 3.

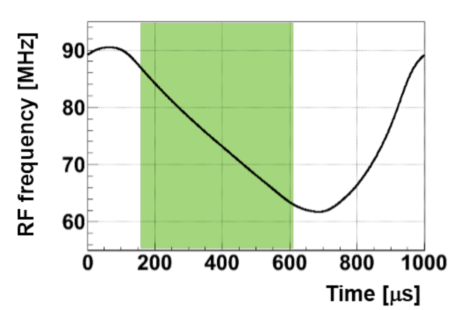

Figure 3: One period (1 ms) in the RF frequency cycle. The acceleration period is indicated in green and lasts about 450 µs.

Figure 4 shows a magnetic field map in the median plane and the position of the regenerator, the septum, the extraction channel and the yoke penetrations for the three horizontal tie rods.

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THE IONETIX ION-12SC COMPACT SUPERCONDUCTING CYCLOTRON FOR PRODUCTION OF MEDICAL ISOTOPES

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Abstract

A 12.5 MeV, 25 μA, proton compact superconducting cyclotron for medical isotope production has been produced. The machine is initially aimed at producing 13N ammonia for Positron Emission Tomography (PET) cardiology applications. With an ultra-compact size and cost-effective price point, this system offers clinicians unprecedented access to the preferred radiopharmaceutical isotope for cardiac PET imaging. A systems approach that carefully balanced the subsystem requirements coupled to precise beam dynamics calculations was followed. The system is designed to irradiate a liquid target internal to the cyclotron and to minimize the unnecessary radiation. The scientific design of the machine has been described elsewhere.[1] The overall engineering, construction, commissioning, and experience at the first customer site will be described here.

INTRODUCTION

An ultra-compact, 12.5 MeV, proton, isochronous, sector focused, superconducting cyclotron for medical isotope production has been produced and large scale manufacturing is being ramped up. The cyclotron is designed to be auto-tuned and does not require a skilled dedicated operating or maintenance staff. As shown in Figure 1, the first installation on the customer site occurred on January 30, 2016 at the University of Michigan followed by the first production of N13 on February 28, 2016. The machine features a patented cold steel yoke and pole design [2] in conjunction with warm iron logarithmically spiralled focusing sectors. Initially a batch of three machines have been manufactured and tested, and three additional machines are under construction in a production facility currently capable of producing up to 32 machines per year.

Table 1: Cyclotron Parameters

Parameter	Value
ION Source	PIG, Cold Cathode
Central Magnetic Field	4.5 T
Number of Sectors	3
RF Frequency	68 MHz
Peak Dee Voltage	≤ 20 KV
Final Energy	12.5 MeV
Maximum Beam Intensity	25 μA
Installed Weight	~ 2.3 tons

The cyclotron will be discussed in terms of five systems consisting of 1) Magnet, 2) RF, 3) Ion Source, 4) Target, and 5) Controls & Instrumentation. Since this is a commercial project, details of the engineering will be described at a conceptual level.

Figure 1: Beta Installation at the University of Michigan.

SUPERCONDUCTING MAGNET

Figure 2 shows the structure of the superconducting magnet. It is a conduction cooled, cryogen free design cooled by a single PT-415 pulse tube cryo-cooler. It requires approximately two days to evacuate the cryo-vessel to below 10 mTorr followed by approximately ten days to fully cool it to operating values. The magnet is normally left continuously charged in persistence mode and requires approximately five hours to charge or discharge. The cold steel design simplifies the magnet design while also eliminating tune drift due to steel temperature fluctuations.[2] Although the conduction cooled cold steel magnet simplifies the design and improves stability, this comes at a cost of significantly increasing design complexity and tolerances while also decreasing the available space for other systems. This design requires a systems approach to ensure that one system component (e. g. beam dynamics, median plane spacing, etc.) is not overly optimised with the unintended detriment to another (e.g. RF, target, etc.).

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DEVELOPMENT OF HTS MAGNETS FOR ACCELERATORS

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Abstract

At RCNP, we have been developing magnets utilizing first generation HTS wires for this decade. HTS materials have advantages over LTS materials. Magnets can be operated at 20 K or higher temperature and cooled by cryo-coolers. The cooling structure becomes simpler and the cooling power of a cooler is higher. Owing to a large margin in operating temperature, it is possible to excite HTS magnets by AC or pulsed currents without quenching. After successful tests of proto type models, two magnets have been fabricated for practical use. Their design and operational performance of two models and the switching dipole magnet are discussed.

INTRODUCTION

High critical temperature superconductor (HTS) materials were discovered in 1986 for the first time [1]. Since then, new HTS materials have been developed to achieve higher critical temperature. At present, two kinds of wires are commercially available having length over several hundred meters. They are based on Bi-2223 (the first generation wire) and REBCO (the second generation wire). Although HTS wires have several advantages over low critical temperature superconducting (LTS) wires, application studies of HTS wires have been limited so far. We have been developing magnets by applying the first generation wires for more than 10 years at the Research Center for Nuclear Physics (RCNP) of Osaka University.

Three model magnets were fabricated; a mirror coil for an ECR ion source [2], two sets of race track coils for a scanning magnet [3], and a 3T super-ferric dipole magnet having a negative curvature [4]. They were excited with AC and pulse currents as well as DC currents and their performance was investigated. After successful performance tests of proto type models, two magnets have been fabricated for practical use. A cylindrical magnet generates a magnetic field higher than 3.5 T at the center to polarized 210 neV ultra cold neutrons [5]. A switching dipole magnet is excited by pulse currents in order to deliver accelerated beams to two target stations by time sharing.

MODEL MAGNETS

Air core magnets were fabricated and measured AC losses were compared to simulations. A two-dimensional scanning magnet was designed to model a compact system for the cancer treatment [3]. The magnet was designed to deflect 230 MeV protons by 80 mrd in both the horizontal(x) and vertical (y) directions as shown in Fig. 1. The iso center is at 1.25 m from the magnet and the irradiation field is 200 mm by 200 mm.

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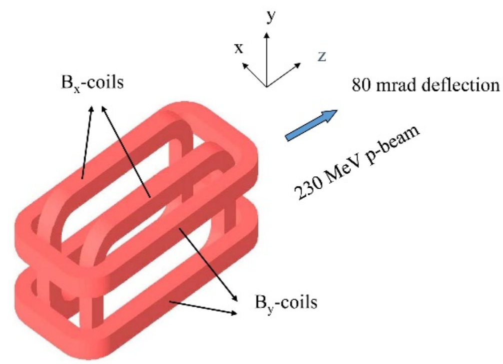

Figure 1. A schematic layout of the scanning magnet. They generate the horizontal (B_x) and vertical (B_y) field.

The magnet consists of two sets of two racetrack shaped coils. Specifications of coils are summarized in Table 1. Three double pancakes are stacked to form one coil. 9 mm thick brass cooling plates are inserted between pancakes. Figure 4 shows an assembled B_x coil which is vacum impregrated by epoxy resin. Detailed structure of coil is described in ref. [3]. The HTS tape was supplied by American Superconductor Corporation. The Ic of the tape was measured at 77 K in a 10 m pitch before winding and was between 125 and 140 A corresponding to an electric field amplitude of 1 μV/cm.. The Ic of the each pancake and stacked coil were measured in a liquid N_2 bath and were 56-62 and 40-43 A, respectively. Two single-stage GM refrigerators are used to cool coils and thermal shields separately. An AL330 of CRYOMECH, Inc. is used to cool coils and it has a cooling capacity of 45 W at the desined operating temperature 20 K. From the temperature dependence of the Ic ($B_\perp$) characteristics of the tape, Ic is estimated to be 260 A.

Table 1: Specifications of Coils of the Scanning Magnet.

Inner size	B_x: 150 mm x 300 mm B_y: 150 mm x 380 mm
Cross-section	30 mm x 30 mm
Separation	70 mm
Maximum field at the center	0.6 T
HTS tape length/coil	B_x: 420 m, B_y: 460 m
Number of turns/coil	420 turns
Stacking/coil	3 Double pancakes
Inductance/coil	B_x: 75 mH, B_y: 92 mH

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STATUS OF HYDROGEN ION SOURCES AT PKU*

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Abstract

Cyclotrons are quite often to be used to accelerate different hydrogen ion beams with high intensity for different purposes around the world. At Peking University (PKU), special efforts were paid on developing compact 2.45 GHz microwave driven ion sources with permanent magnets to generate high intensity H^+, H_2^+, H_3^+ and H^- ion beams as well as other ion beams. For the positive ion beam, we can easily produce a 130 mA hydrogen ion beam with H^+ fraction higher than 92% with a PKU standard ϕ100 mm × 100 mm 2.45 GHz ECR ion source. Also we have got 42 mA H_2^+ beam and 20 mA H_3^+ beam with a specifically designed 2.45 GHz ECR ion source under different operation condition. The fractions of H_2^+ and H_3^+ are higher than 50% within the mixed hydrogen ion beams for each case. Recently, a Cs-free volume H^- source based on 2.45 GHz microwave was developed successfully in our lab. It can generate 45 mA H^- beam with duty factor of 10% and a 29 mA beam at CW mode at 35 keV. Its operation duty factor can vary from 1% to 100%. The power efficiency is about 29 mA/kW in CW mode and 21 mA/kW in 10% (100 Hz/1 ms) pulsed mode. A 300 hours 50 keV/50 mA CW proton beam continuous operation with no beam trip demonstrated that PKU 2.45 GHz ECR ion source has high stability and reliability. Details of these sources will be presented in the paper.

INTRODUCTION

Cyclotrons are wildly used in fundamental physics research, medical therapy, radioisotopes production etc. In principle, cyclotrons can accelerate various ions from hydrogen to uranium. Among numerous ions, hydrogen ions (H^+, H^-) are most commonly to be accelerated by cyclotrons. For example, about 10 mA CW H^+ ion beam was injected into the Cockcroft-Walton pre-accelerator of the 590 MeV cyclotron at PSI, which was one of the most powerful cyclotron around the world. [1] Moreover, negative hydrogen ion (H^-) was also very popular as it could be stripped as H^+ at the extraction area of cyclotron so that very high extraction efficiency could be achieved by using charge-exchange extraction method. [2] At TRIUMF, about 15 mA CW H^- ions were needed to inject into a TR30 cyclotron. [3] Otherwise, for some medical cyclotrons, several mA H^- ions extracted from ion source were required for isotope production. [4]

Nowadays, high current high power facility is an important trend for cyclotrons. But accompanying with the increasing of beam current, the space charge effect caused by repulsive force between particles leads to strong beam loss in cyclotron. To solve this problem, it is proposed to accelerate H_2^+ or H_3^+ ions, which have much lower generalized perveance, and then strip them at the export of cyclotron to get H^+. [5] The DAEδALUS project is an example on this idea. [6, 7] DAEδALUS accelerator will produce 800 MeV H^+ with a beam current of 10 mA. This current already exceeds the limitation of present cyclotrons and is unacceptable for the machine. To reduce the space charge effect and achieve the extracted current from the cyclotron, H_2^+ ion beam will be used to take place of H^+.

2.45 GHz microwave driven ion source has the reputation for its high current, low emmitance, long lifetime and high stability. [8] It can operate in pulsed and CW mode. At PKU, high current ion sources driven by 2.45 GHz microwave has been developed for several decades. [9] Single charged ions such as H^+, O^+, N^+, Ar^+, D^+ etc. can already be generated by the ion source. In addition, H_2^+, H_3^+ and H^- ions were also extracted from this kind of ion source by modifying the structure and adjusting operation parameters. [10, 11] Up to now, the 2.45 GHz microwave ion source at PKU has been utilized by the Separated Function Radio Frequency Quadrupole (SFRFQ) project, [12] the Peking University Neutron Imaging FaciliTY (PKUNIFTY) project, [13] Coupled RFQ & SFRFQ, [14] Dialectical Wall Accelerator (DWA) [15] and the Xi'an Proton Application Facility (XiPAF) [16]. During the operation of these facilities, the ion sources developed at PKU have already shown very good performance and stability. More details of hydrogen ion sources at PKU will be reported in this paper.

PROTON ION SOURCE

The standard structure of the microwave ion source at PKU is shown Fig. 1. [13] It is a very compact ion source with an outer diameter of 10 cm and a length of 10 cm, and its weight is lower than 5 kg. The magnetic field is generated by three NdFeB permanent magnetic rings. Microwave generated by magnetron is injected into the ion source through a circulator, a three-stub tuner, a directional coupler, a dc-break waveguide and a standard BJ26 rectangular waveguide. A three-layer Al_2O_3 microwave window is used here to couple the microwave with plasma chamber, and a protective BN disc is mounted to prevent the bombardments of electrons. The extraction system is composed of three electrodes: plasma electrode, screening electrode and ground electrode. The diameter of the beam emission aperture is ϕ6 mm.

Many efforts were carried out to improve the beam current, beam quality, proton fraction as well as source stability and reliability. Up to now, a 130 mA H^+ beam with proton fraction of 92% was extracted at 50 kV from

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DEVELOPMENT AND VALIDATION OF A FAST CRYOCOOLER MAINTENANCE SYSTEM

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Abstract

At IBA, we have been developing and testing new systems to simplify cryocooler maintenance at a minimal cost (material, interruption of service). A local heating system has been designed to heat-up both stages of a cryocooler to room temperature while keeping the cold mass at a low temperature. The heating system has to fulfill severe requirements such as high power density, compatibility with vacuum and low temperature, and easy operation. The whole system has been designed and tested in a dedicated test bench and then duplicated onto a full-size superconducting coil. It has been extensively tested under different conditions to prove that the heating system is robust and reliable and has no impact on the superconducting coil performances.

INTRODUCTION

The basic principle of the developed system for maintenance relies on a patent that dates back to the 90's [1]. It consists in performing a quick local heating of the cryocoolers to room temperature while keeping the cold mass as cold as possible. This method, also known as cold swap, requires that the cryogenic system and the heating system can support the mechanical stress induced by the large temperature gradient that will occur during the heating operation.

A preliminary study had demonstrated that the required heating power to reach room temperature in our superconducting coil in 20 minutes was 1kW for a cryocooler second stage and 500W for a first stage [2]. Given the available space in the cryostat, high power density resistors are required. They also have to be vacuum and cryogenics compatible and be robust and reliable over more than 20 years. Finally, the heat load due to all the wiring must be compatible with the available cooling power.

DEDICATED TEST BENCH

A dedicated test bench has been designed and used to test the different components of the heating system (Fig. 1). The turbo pump allows to reach a good vacuum level in the chamber in 3 h. A small aluminium thermal mass has been attached to the second stage of a Sumitomo RDK415D2 cryocooler (Fig. 2) and it takes another 4 h to reach the final temperature of 6.3 K without the use of any superinsulation. Each stage cryohead was equipped with one Cernox and one Pt100 per stage to monitor the temperature. Several vacuum feedthroughs allow us to monitor each stage temperature and also to control and monitor separately each heater resistor. A LabVIEW™ program has been developed to record the temperatures, pressure and also to control the two power supplies for the first and second stage separately.

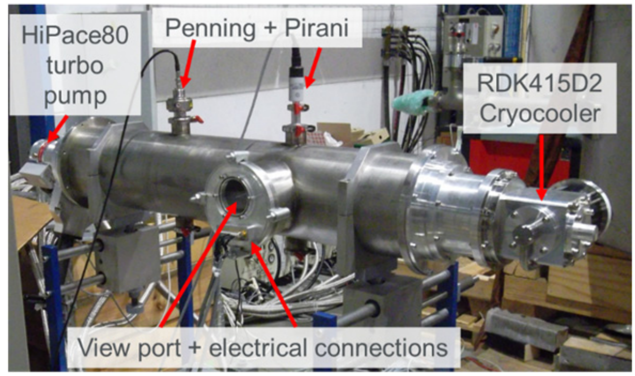

Figure 1: Dedicated test bench.

This test bench allows us to iterate rapidly on the design of the heaters and their wiring to make them robust, safe and reliable. The heating resistors have been tested extensively for vacuum and cryogenic compatibility, reliability after several tens of cycles between 4 K and room temperature. Destructive tests were also performed to check the robustness of the resistors and their safe operation condition. Thermal anchoring of all the wiring was also very important to avoid local hot spot and reduce the heat load to the second stage where only a few watts are available at 4 K. The full heating system (for 1st and 2nd stage) for a single cryocooler head has been designed, tested and validated on this test bench.

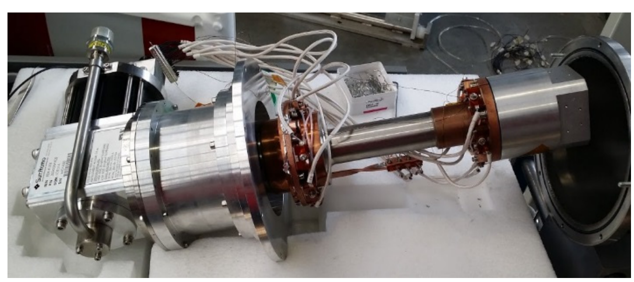

Figure 2: 1st and 2nd stage heating system.

INTEGRATION IN A SUPERCONDUCTING COIL

Proof of Concept of the Cold Swap Maintenance

As soon as the heating system was validated, it was reproduced for the four cryoheads of a R&D superconducting coil. The objective was to validate the required heating power and to evaluate the maximum temperature reached by the cold mass and hence the subsequent cooling time.

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PLANNING CONSIDERATIONS FOR RADIOISOTOPE PRODUCTION CYCLOTRON PROJECTS - REGULATORY FEEDBACK

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Abstract

Over the last ten years, there has been a significant increase in projects to build, operate or upgrade cyclotrons in Canada. This is largely driven by their increased use for the production of radioisotopes.

The Canadian Nuclear Safety Commission regulates the use of nuclear energy and materials to protect health, safety, security and the environment in Canada. Its mandate includes the oversight of particle accelerators. The CNSC regulates the full life cycle of such facilities, with regulatory oversight though construction, commissioning, operation, and decommissioning activities.

This paper outlines common practices for such projects, highlighting the particular aspects that should be considered in the early stages of project planning and providing examples of best practices and challenges that, if properly addressed, help ensure continued safe operation of the facility through its entire life cycle.

The paper discusses the necessary elements of effective planning for such projects, touching on layout and space considerations; workload projection and maximum research capacity; shielding penetrations; cooling water circuit activity; storage of active components; management of radioactive waste from cyclotron and processing labs; construction and commissioning project management; integration of equipment safety systems and building safety systems; nuclear ventilation and filtration options; and strategies for staffing and training.

INTRODUCTION

The Canadian Nuclear Safety Commission (CNSC) regulates the use of nuclear energy and materials to protect health, safety, security and the environment in Canada. Construction, commissioning, operating or decommissioning a radioisotope production cyclotron facility requires a licence from the CNSC [1]. The applicant provides to the CNSC, at each licensing phase, information to demonstrate that safety aspects have been covered in the project and to convince the regulator that no undue risk is introduced by conducting the proposed activity [2, 3].

Experience has shown that prudent design with careful consideration of safety at the very early stage of the project as well as along with the evolution of the project is vital to the overall safe operation of the facility. Deficiencies in the design are often difficult to fix or costly. The following are examples of safety considerations which could be easy to miss by the proponents especially at the early stages of the project.

LAYOUT AND SPACE

A radioisotope production cyclotron facility is more than merely a vault to host the machine and a control room. The footprint needed for the processing and servicing areas is large. For medical institutions which are often located in dense urban areas, the available space is an issue. The layout should allow to host all the required equipment and to permit the implementation of all contamination controls. Also, it should allow easy and safe movement of the workers and materials within the facility and to and from the facility.

WORKLOAD PROJECTION AND MAXIMUM PRODUCTION CAPACITY

Nowadays, there are many cyclotron designs available commercially with increasing beam currents and energy. For conventional isotope supply such as PET isotopes, the machine beam current doesn't need to be very high. A single target machine with 150 µA beam current on target would probably be sufficient to supply a reasonably large demographic area. The research programs associated with new projects are often less defined in the beginning and the needs for beam current, the number of beamlines, and hours of operation, are hard to predict.

The safety implications are two folds; first, the proponent should establish a safety envelop for the maximum parameters they want to design the facility against. This safety envelope will be used to design the shielding required for the target areas and/or the cyclotron bunker. It will also, define the maximum radioactivity that will be present in the target which must be confined at all time. This is used to assess the consequences of target failures and any release to the facility or the environment in case of an accident.

Second; since in practice, the urgency and needs is what drives the progress of the project, it often happens that the proponent is keen on proceeding with a partial operation of the facility such as the clinical isotope part but is not ready for the more advanced research on other parts of the facility. The CNSC may permit approval of the project in phases, i.e., allowing limited operation of the facility. However, this requires a rigorous quality assurance program and change control to clearly define the various phases of the project and what is allowed and what is not allowed at any given time.

SHIELDING PENETRATIONS

Cyclotron bunkers are normally built with thick concrete walls. Penetrations are needed for various purposes such as product transfer, electrical, control, cooling water circuits and ventilation. Also, the facility may have under the floor service channels passing through walls. Penetra-

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OPERATION AND MAINTENANCE OF RF SYSTEM OF 520 MeV TRIUMF CYCLOTRON*

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Abstract

1 MW CW 23 MHz RF system of the TRIUMF 520 MeV Cyclotron has been in operation for over 40 years. Continuous development of the RF power amplifiers, the waveguide system and of the measurement and protection devices provides reliable operation and improves the performance of the RF System. In this article, operation and maintenance procedure of this RF system are analyzed and recent as well as future upgrades are being analyzed and discussed. In particular, we discuss the improvements of the transmission line's VSWR monitor and their effect on the protection of the RF system against RF breakdowns and sparks. We discuss the new version of input circuit that was installed, tested and is currently used in the final stage of RF power amplifier. We analyze various schematics and configurations of the Intermediate Power Amplifier (IPA) to be used in the future. The thermo-condition improvements of the Dee voltage probe's rectifiers are described.

INTRODUCTION

TRIUMF 520 MeV Cyclotron's high power RF system consists of three main parts – the 1.8 MW CW RF amplifier, the transmission line (TL) and the resonator [1]. The TL itself is composed of two coaxial lines with wave impedances of 50 and 30 ohm. The second part of the TL has three capacitor stations that match 50 ohm impedance of the TL's first part with the coupling loop port of the resonator that is at TL's terminus.

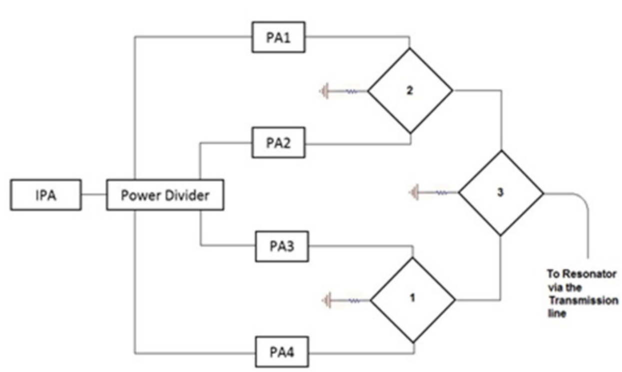

Figure 1: RF System of the 520 MeV cyclotron.

*TRIUMF receives federal funding via a contribution agreement through the National Research Council of Canada.

TRANSMISSION LINE RESONATOR OPERATION AND SPARK PROTECTION

Instability in the RF system's operation appears when there are sparks, electrical breakdowns and multipactor discharge in the resonator. The VSWR monitor is used to protect the RF system. This monitor turns off the RF system, if the reflected power in one of the 12 channels exceeds a specified threshold value. The RF control system analyses the rate of Dee voltage drop, classifies the events and then tries to recover the system. The follow up analysis of where sparks and electrical breakdowns took place is done using an oscilloscope. The oscilloscope operates in stand-by mode otherwise. An example of a typical signal pattern that illustrates a spark inside the resonator is presented in Fig. 2.

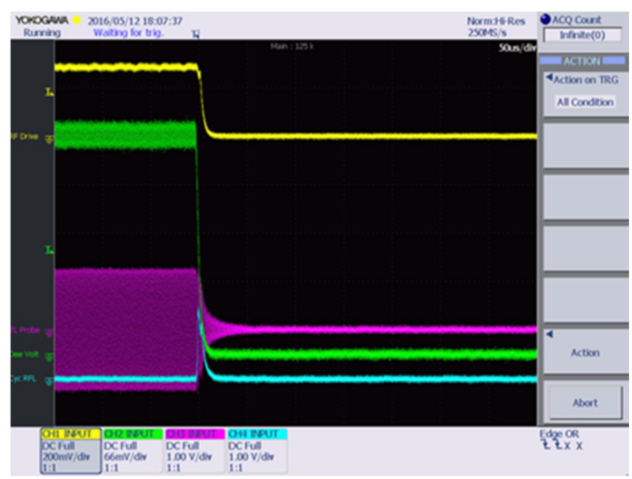

Figure 2: Resonator RF signals following a spark, when drive is OFF (yellow – drive amplitude, green – Dee voltage, pink – RF signal, blue – rectified voltage of the reflected signal).

The rate of Dee voltage drop allows to determine, whether this spark happened inside the resonator or inside the TL and how large the spark was. The RF control system has sensors to determine the Dee voltage drop and if zero Dee voltage is detected. If either case is detected the RF control system generates the signal to turn OFF the RF drive and to determine the time when RF system's recovery should be attempted.

However, if these sensors didn't respond properly or responded with some delay, the standing beat wave in the TL could reach double amplitude of the original signal (see Fig. 3). As a result, some parts of the TL such as matching capacitors, the water feedthrough or the TL conductors and insulators could be damaged.

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STATUS OF THE COSY/JÜLICH INJECTOR CYCLOTRON JULIC

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Abstract

The accelerator facility COSY/Jülich is based upon availability and performance of the isochronous Jülich Light Ion Cyclotron (JULIC) as pre-accelerator of the 3.7 GeV/c COoler SYnchrotron (COSY). From 1993 to 2014 JULIC provides in 24/7 operation for more than 6500 hours/year polarized or unpolarized negatively charged light ions for COSY experiments in the field of fundamental research in hadron, particle and nuclear physics. The cyclotron has reached in spring 2016 in total about 285000 hours of operation since commissioning in 1968. The on-going program at the facility foresees increasing usage as a test facility for accelerator research and detector development for realization of the Facility for Antiproton an Ion Research (FAIR), and other novel experiments on the road map of the Helmholtz Association and international collaborations. In parallel the COSY beam and the cyclotron beam are also used for irradiation and nuclide production for fundamental research purposes. For that purpose the irradiation capabilities and diagnostic tools have been upgraded in the last years. Experience with special rf devices and pulsed ion sources for JULIC enables the development of dedicated tools for experiments and other accelerators, e. g. a pulsed 100 keV source for protons and negative ions for the ELENA project at CERN.

INTRODUCTION

The Institute for Nuclear Physics (IKP) [1] is focusing on the tasks given by the Helmholtz Association (HGF). This comprises the design and preparations for the High Energy Storage Ring (HESR) of FAIR [2] with the PANDA experiment. The on-going hadron physics program at the Cooler Synchrotron COSY exploits the internal experimental set-up PAX. The extracted beam is used for the PANDA experiment and also for high energy irradiation in the area of the finished TOF experiment. IKP is part of the new section "Forces And Matter Experiments" (FAME) at the Jülich-Aachen Research Alliance (JARA). This joins scientists and engineers from RWTH Aachen and Forschungszentrum Jülich for experiments, theory and technical developments for anti-matter (AMS) and electric dipole moment experiments (EDM). The institute is member of the new HGF project Accelerator Research Development (ARD) and pursues research on various accelerator components. The future project Jülich Electric Dipole Moment Investigation (JEDI) [3] will profit from the availability of polarized beams from the injector cyclotron and the unique capabilities and experiences at the COSY facility.

CYCLOTRON OPERATION

Since 1968 the Cyclotron JULIC (see Fig. 1) has been operational and provided overall more than 285000 hours availability for experiments and beam development [4-6]. The fraction of the run time since start of commissioning as COSY's injector in 1992 is shown in Fig. 2. In the first 4 years on H_2^+-beams were used for the stripping injection into the synchrotron ring. Two negative ion sources provide beam for routine unpolarized operation [7]. A source of the charge exchange type provides polarized particles beam.

Figure 1: The isochronous cyclotron JULIC.

About 98% of the scheduled beam time could be provided for experiments. Excluded were short events, like sparks, which are recovered automatically by rf control computer or by operator's reaction. The most common reasons for these events were power drops, shortage in water cooling and failures in the rf subsystem. The time for septum exchanges has substantially decreased after essential improvements have been done.

Cyclotron Maintenance

The Cyclotron is in use since end of 1968. Most of the systems for injection and acceleration were improved and refurbished between 1980 and 1992. A new rf generator has been installed in 1992. Wear-out symptoms have been observed, analysed and fixed during the last decade. The vacuum system and its control system have been upgraded with respect to oil-free operation. The central adjustable air-line tuner has been replaced in 2007.

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BEAM INTENSITY MODULATION CAPABILITIES OF VARIAN'S PROBEAM® ISOCHRONOUS CYCLOTRON

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Abstract

Varian's ProBeam® 250 MeV superconducting proton cyclotron is an isochronous cyclotron for radiological applications using pencil beam scanning mode and provides continuous beam (at its fundamental frequency of 72 MHz). In its clinical operation mode, up to 800 nA of proton beam are specified and routinely extracted. Even more can be extracted in technical mode. The cold cathode Penning ion source provides enough protons to reach this current, and a layer-to-layer intensity modulation of the scanned beam is realized with an internal electrostatic deflector, which is used to vary the extracted beam current between maximum and zero. However, for research applications there is sometimes the request for higher flexibility, in particular for higher possible beam intensities and faster beam intensity modulation. In order to explore capabilities of the machine for such research modes, experimental investigations have been performed: Pulsed beams with repetition rates of up to 2 kHz and variable pulse lengths down to 4 µs as well as peak currents during pulse of up to 30 µA are in the accessible range with only changes at power supply level.

STANDARD OPERATION MODE

The ProBeam cyclotron delivers up to 800 nA proton beam in clinical operation. Protons are generated in the internal cold cathode Penning ion source, which is running continuously and allows varying the beam current via setting of the internal discharge current. The relation between both is found to be linear in the typically used internal discharge range (80 to 280 mA). The source parameters typically need adjustment only once at the start of each treatment day, and in general need little tuning along cathode life time to compensate for the normal wear of these parts.

Fast beam intensity modulations during treatment are possible via an internal electrostatic deflector. This deflector is designed for switching frequencies up to 2 kHz and switching times from one stable deflection level to another within less than 100 µs. This time scale for precise switching is determined by ringing, which is caused by the electrical properties of the voltage supply line from power supply to cyclotron. Beam blocking voltage level, however, can be exceeded permanently within only 3 µs.

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MODIFICATIONS

Generation of high intensity proton beams for experimental operation is possible via modifications on power supply level and considering the general constraint that the average extracted proton current should not exceed approx. 1 µA for machine safety reasons.

From this follows directly: A pulsed beam operation is necessary to limit the average current. In particular, a pulsed operation of the ion source supports this operation mode by allowing much higher short term internal discharge currents (thus extracted beam currents), that would not be stable in continuous operation mode of the source. In the following section, such a pulsed mode of the ProBeam's ion source is characterized.

Change to Pulsed Ion Source Mode

An additional electrical module (one standard 19" rack slot) was installed at the ion source power supply. It basically consists of a capacitor which is constantly charged by the power supply, and a wave form generator controlled high voltage switch, as well as means for current and voltage diagnostics. An extensive parameter scan has been performed at a dedicated ion source test stand [1] at *Paul Scherrer Institut* (PSI) and the dependencies on pulse rate, duty, applied discharge voltage, and hydrogen gas pressure within the source have been evaluated. Although absolute numbers for the extracted beam at this test stand and extracted beam at the cyclotron may not be compared directly, the general scaling behaviour might well be. Results are shown in Figure 1 and Figure 2. Due to the source operation at the test stand at lower magnetic field (approx. 1 T) higher internal source pressures and lower internal discharge currents are used compared to the ProBeam cyclotron.

Several general characteristics could be observed and are in accordance to the expectations in this operation mode:

- Stable operation at much higher peak discharge currents during pulses compared to continuous mode is possible.
- Towards high duty factors the behaviour approaches the continuous mode.
- Shortest pulse lengths result in highest average currents during pulse.
- Higher voltage leads to higher currents.
- Lower H_2 gas pressure is also beneficial for higher currents.

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RECENT ION SOURCE DEVELOPMENTS FOR VARIAN'S PROBEAM® CYCLOTRON

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Abstract

The cold cathode Penning ionization gauge (PIG) type proton source of the Varian's ProBeam® 250 MeV superconducting isochronous cyclotron suffers from the usual cathode/chimney erosion during operation. Furthermore, a relatively high hydrogen gas flow is needed to generate a proton beam in the µA range, which induces conditions for RF operation below optimum. In the quest to increase cathode/chimney life time and thereby directly extend service intervals, thus reducing the total cost of ownership, several experimental investigations have been performed at a dedicated test bench at Paul Scherrer Institut (PSI), Switzerland, including material studies, a detailed operation analysis and switching to a hot cathode design.

THE ION SOURCE TEST STAND

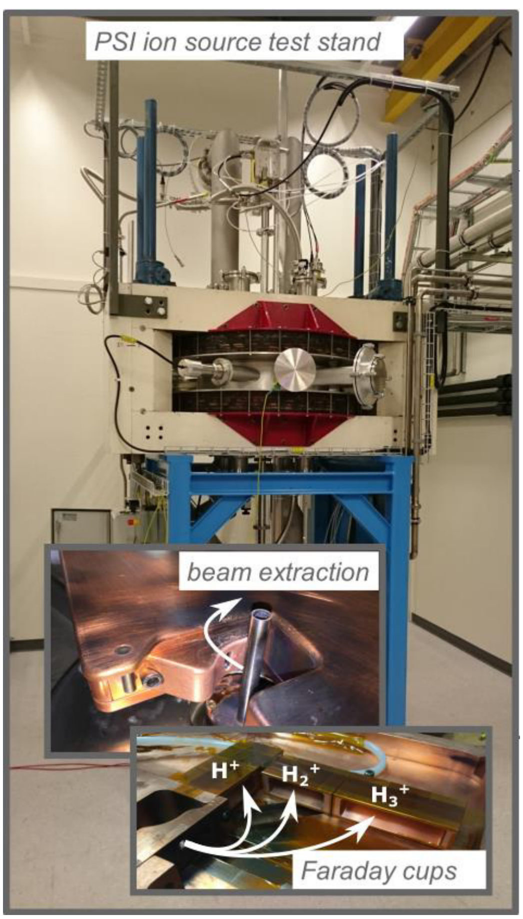

Figure 1: Picture of the test stand. Inserts show beam extraction from source and diagnostic setup.

The dedicated ion source test stand used for this work is located at PSI, Switzerland. A picture of the setup shown in Figure 1. It provides up to 1.4 T central magnetic field, extraction from ion source with typically -30 kV voltage, and ion species separating diagnostics (Faraday cups).

The ProBeam ion source can be operated and its performance experimentally investigated. The main difference to the situation in the ProBeam cyclotron is the lower magnetic field as provided by the test stand's normal conducting magnet. This reduces the confinement of the charged particles in the source plasma and results in higher necessary internal gas pressures, which are achieved by higher hydrogen gas flow rates into the source. While the source in the ProBeam cyclotron is typically run with 1 to 2 sccm hydrogen gas flow, the test stand is operated in the range of 8 to 16 sccm. This difference has to be considered when comparing the results presented here to the situation in the ProBeam cyclotron.

The second difference to the ProBeam cyclotron is the DC extraction at typically -30 kV at the test stand. This does not affect the internal source operation, and has only an influence on the absolute values of the extracted current.

THE COLD CATHODE ION SOURCE

To sustain the internal source plasma, the cold cathode Penning ion source relies on secondary electron emission induced by ions hitting the cathodes. The (only slightly ionized) hydrogen plasma contains mainly H^+ and H_2^+ ions, which have only low secondary electron emission yields (range: 0.2 to 0.5) at the typically used cathode potentials in the range of -1 to -1.8 kV. A stable discharge between few and up to about 300 mA is possible. A schematic of such a source is shown in Figure 2.

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DEVELOPMENT OF CONTROL SYSTEM FOR 10 MeV CYCLOTRON*

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Abstract

AmirKabir University of Technology is developing a 10 MeV cyclotron to produce radio isotopes. In order to operate the cyclotron stably, all sub-systems in the cyclotron are controlled and monitored consistently. The control system has been developed based on PLC and the operation is monitored by HMI permanently. Also, the control console located in the control room, provides data logging and controlling different steps of operation by the operator. In addition, the system can be remotely accessed over the network to monitor the status of cyclotron easily. The configuration of the control system for 10 MeV cyclotron will be presented in this paper.

OVERVIEW OF 10 MeV CYCLOTRON

The cyclotron accelerates the negative hydrogen particle to produce radioisotopes, and a couple of sub-systems make the particle acceleration possible. The cyclotron consists of cooling system, vacuum system, magnet system, ion source system, and RF system.

In order to accelerate the particle stably, it is necessary to fix the temperature and humidity of the environment. In addition, the order of vacuum inside cyclotron should be under 1×10^{-6} mbar. A double-stage high-vacuum system has been installed to improve the vacuum state. The cyclotron includes a panning ion gauge (PIG) type ion source for generating negative hydrogen from plasma by the use of arc power supply outside of cyclotron. The electromagnet field made by both RF system and magnet system accelerates the negative hydrogen for the desired energy level. The RF system is composed of two parts which are RF resonator and RF amplifier. The RF amplifier provides the high power RF signals to RF cavity to increase the dee voltage up to 50kV for electric field inside the cyclotron. The electric field is regulated by RF tuner. The average magnetic field is 1.71 T generated by about 143A coil current from magnet power supply (MPS) [1].

CONTROL SYSTEM DESIGN

The control system has access to each sub-system, and monitors the status of each device. In addition, the control system should set the proper parameters depending on the monitoring data from sub-systems, and prevent from the emergency situation occurred during the operation sequence of cyclotron. Therefore, we have carried out a requirement analysis starting from the system specification, and then designed the control system considering capability, expandability and accessibility to achieve high reliability and safety for the system [2].

The architecture of the control system consists of two parts; a host computer and a main control system (PLC). The main control system gathers the status signals of all sub-systems and supervises the whole cyclotron, comprehensively. Many parameters used in main control system, are shared with the host computer, so an operator can control the cyclotron through the host computer [3]. Each of sub-systems have a sub-program and interlock functions in PLC to protect them from unexpected damages. The primary specifications of 10 MeV cyclotron are shown in Table 1.

Table 1: Specifications of 10 MeV Cyclotron

System	Parameter	Specification
Magnet	Max/Min magnetic field	0.26/1.83 T
Ion source	Type	PIG
	H2 gas flow rate	0 ~ 10 SCCM
	Beam current	100 μA
RF	Frequency	71 MHz
	Dee voltage	50 kV
	Power	15 kV
Vacuum	Level of vacuum	1×10^{-6} mbar
Cooling	Water Temp.	20 ºC
	Water Resistivity	> 10 MΩ

Cooling System Control

The cooling system is a basis system with vacuum system for beam acceleration of cyclotron. The important parameters of cooling system are water temperature, resistivity, pressure, and flow. Therefore, the parameters are controlled in real time and consistently by different controllers which are installed in the chiller. PLC controls and monitors the status of cooling system by output analogue signals (4~20 mA) of chiller's controllers.

Vacuum System Control

The developing cyclotron has initial vacuum state (about 1×10^{-2} mbar) by using rotary pump, and then makes the high vacuum state (about 1×10^{-6} mbar) by using turbo-molecular pump. There are many valves such like roughing valve, fore-line valve, and main valve, between each vacuum pump and chamber. The vacuum level is measured by pirani and penning gauges. PLC receives the monitoring signals of vacuum status from gauges and controls the vacuum pumps and valves, simultaneously.

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MECHANICAL ASPECTS OF THE LNS SUPERCONDUCTING CYCLOTRON UPGRADE

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Abstract

The Superconducting Cyclotron (CS) is a three sectors compact accelerator with a wide operating diagram, capable of accelerating heavy ions with q/A from 0.1 to 0.5 up to energies from 2 to 100 MeV/u. The proposed upgrade to increase the light ion beam intensity by means of extraction by stripping implies many modifications of the median plane. The main activities of the mechanical upgrade are: the actuation of the new magnetic channels for the extraction by stripping and the realization of the two extraction modes, by stripping and by electrostatic deflection. For the magnetic channels and compensating iron bars, we are studying the problems of mechanical handling. To obtain the two extraction modes, we are trying to design a new set that allows for the exchange of two devices: electrostatic deflectors and stripper with its magnetic channels for stripping extraction.

INTRODUCTION

The Superconducting Cyclotron (CS) is an accelerator which was designed for low intensity beams, whose main limitations to extract high beam power are the two electrostatic deflectors. The goal of the upgrade is to make extraction by stripping possible, interchanging the stripper with one of the two electrostatic deflectors, to achieve high power beams for the set of beams of interest and, at the same time, to maintain the versatility of the CS [1]. The detailed study of the beam dynamics along the stripping trajectory, for various ions at different energies, has led to the need for a new extraction channel. The interference of this channel with the electrostatic deflector handling, is the start of our study of the technical implications on the CS median plane.

RESULTS ON THE STRIPPING EXTRACTION

A study about beam dynamics of the stripping extraction, was necessary to compute stripping extraction for every ion and energy whatever the charge state of the accelerating particle is [2]. The results of this study are reported in another paper presented at this conference and are summarized in (Fig. 1).

The optimization of the different particles and energy trajectories allow us to have a common extraction point, for the purpose of making easier the design of the new extraction channel.

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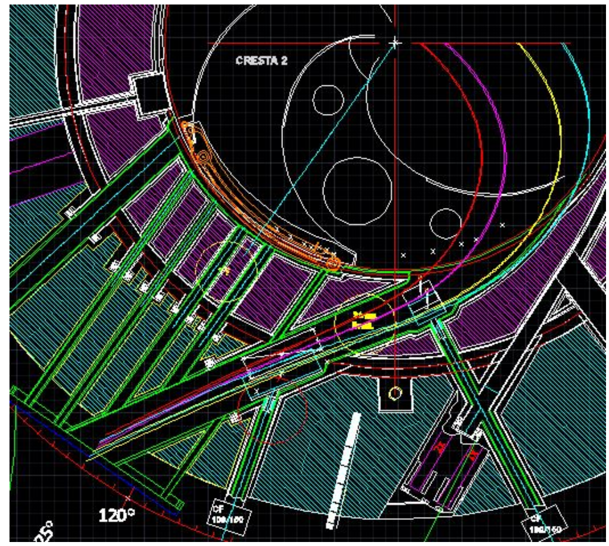

Figure 1: The different particle trajectories after the stripper crossing.

MECHANICAL ASPECTS

The fundamental mechanical aspects of the extraction by stripping, concern the modifications of the median plane of the CS (Fig. 2). Due to the design of the new extraction channel, there is the necessity of moving one of the lifting points of the vacuum chamber (from 107° to 90°). This forced us to rotate the position of the three horizontal suspensions (from 96°, 216°, 336° to 41°, 161°, 281°) because in the 90°-110° area, there is not enough space to allocate both the lifting point and the horizontal suspension. The new lifting points positions are 90°, 210°, 330°. The 41° and 281° horizontal suspensions caused respectively the suppression of the M7 and M2 magnetic channels, which were designed as part of the electrostatic extraction equipment but have never been used in the real life. Moreover the radial penetration for the beam injection was removed. Furthermore for the new extraction by stripping, a study has been done for the design of the magnetic channels. Able to reduce locally the magnetic field and to focus the beam in the radial direction, as a result of this study, two magnetic channels, M1S and M2S, are necessary: they are made up of three iron bars that we have to block inside a steel housing to avoid their movements. Through the simulations, we obtained the force values in the three directions and their range on the median plane for every ions. About the channel M1S, the resultant force is of about 9 KN, towards the CS centre. There is no need to remove it except in emergency case from the inner side of the CS. Its mechanical handling, for the necessary movement, had an interference with the old extraction channel (Fig. 3).

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STATUS AND UPGRADE OF THE CRYOGENIC PLANT OF THE LNS SUPERCONDUCTING CYCLOTRON AFTER 25 YEARS OF OPERATION*

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Abstract

The Superconducting Cyclotron (CS) is a compact accelerator with three sectors with a wide operating diagram, capable of accelerating heavy ions with values q/A from 0.1 to 0.5 up to energies from 10 to 80 MeV/u. An upgrade of the CS superconducting magnet is in progress to extend the capability of the machine to high intensity beam facilities.

In this paper we describe the status of CS Cryostat and its Cryogenic Plant after 25 years of continuous operations at 4.2 K with the exception of the stop of about one year for the tenth test and the stop for restoring of the liquefier and the main issues happened during that long time. We describe the last complex and demanding procedure for the revamping of the He liquefier, its ancillary parts, other cryogenic parts of the CS, with special attention about the Piping and Instrumentation, gas analysis, Heat Exchangers, LN_2 transfer lines, Human-Machine Interface, vacuum system for thermal isolation, GHe recovery system and the optimization for the consumption of electrical power.

In conclusion we describe some hypothesis about the future upgrade of the Cryogenic system and the new Cryostat of the CS, in special way we analyse an approach to redefine the interconnection, piping boundary line and cryogenic diagnostic.

INTRODUCTION

The solution for the actual cryostat has been evaluated and the final decision was to include the superconducting coils in the helium bath. This solution, in principle, has then determined a macroscopic structural of practically forced cryostat.

DESCRIPTION

Below we will illustrate in detail the structure of the Superconducting Cyclotron and the relative plant. A detailed description of the cryogenic system can be found elsewhere [1].

Cryostat

The total of the actual cryostat is shown in Fig. 1. The entire complex is made of AISI 316L. It has an internal diameter of 1980 mm and an outer diameter a 2720 mm, with a height of 1740 mm for a total weight of approximately 4000 kg. The coils are realized with the system of the "double pancakes", stacked and subsequently and preloaded when in position. The coils inside the helium vessel are fixed to the annular structure (Median Plane).

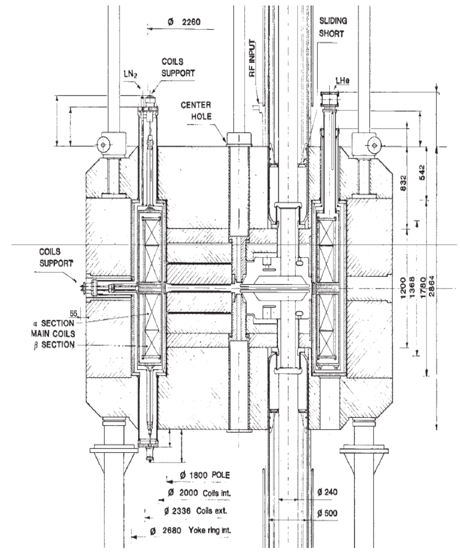

Figure 1: CS scheme.

Under the action of the weight, it is discharged on the inner wall in the case of the lower coil, and the maximum force of repulsion between the coils of 60 tons, the specific voltage stress applied to the tie rods is less than 20 kg/mm^2, and this force of container of helium, the latter with a thickness of 10 mm reduces the tensile stress at only 0.7 kg/mm^2.

The Median Plane has a thickness of 300 mm, corresponding to the separation between the coils. In it, three radial openings with an axial dimension of 200 mm are formed, which allow the passage of the beams and the housing of electrostatic and magnetic deflectors channels. The helium container is suspended from the vacuum chamber by means of vertical tie rods which therefore must withstand the total weight of the container and of the coils and the magnetic forces resulting from any asymmetry of the magnetic field.

An assessment of these forces in the event of a possible inaccuracy of mounting tolerable, up to about 0.5 mm, provides negligible values with respect to the weight of the complex coil-container of helium. The helium vessel has a weight of about 18,000 kg. There are 3 “upper” vertical tie rods made in titanium alloy (6% Al and 4% V) with a diameter of 18 mm immersed in the cold mass. Each of them in theory could support the total force applied to the structure (Fig. 1). Moreover there are 3 lower tie rods with a diameter of 6 mm to block the structure.

As you can see from Fig. 1, the tie rods have the task of supporting the entire structure, while the three lower links keep the coils in a fixed position.

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IMPROVEMENT OF THE NIRS-930 CYCLOTRON FOR TARGETED RADIONUCLIDE THERAPY

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Abstract

In recent years, the production of radionuclides for Targeted Radionuclide Therapy (TRT) with the NIRS-930 cyclotron has been one of the most important activities in National Institutes for Quantum and Radiological Science and Technology (QST, NIRS).

In the production of ^{211}At, for example, a target material with low melting point is irradiated with a high intensity helium ion beam. A vertical beam line has the advantage in irradiation with low-melting-point target. Therefore, a vertical beam line has been modified for the production of radionuclides. This line was used for neutron source with beryllium target.

The beam intensity and beam energy are important parameters for the effective production of radionuclides for TRT. In order to increase beam intensity, the acceleration phase and injection energy have been optimized by measuring beam phase. The beam energy has been measured by TOF and adjusted by tuning the acceleration frequency. Those studies and improvement are reported.

INTRODUCTION

The NIRS-930 cyclotron was installed in 1974 for a fast neutron therapy and production of radionuclide [1]. The fast neutron therapy was terminated in 1994. At present, the NIRS-930 cyclotron is mainly used for production of radionuclides. Other purposes of the NIRS-930 cyclotron are research of physics, developments of particle detectors in space, research of biology, and so on.

Recently, the TRT has been one of the most important activities in NIRS, QST. Therefore, production of alpha emitter radionuclides for TRT is increased. The operation time for production of radionuclide at the NIRS-930 cyclotron is shown in Fig. 1. In recent five years, the operation time of helium ion beam is increasing. In 2015, the operation time of helium ion beam was increased to 479 hours, which was higher than that of proton beam and was more than 50% of that for production of radionuclides.

VERTICAL BEAM PORT

A layout of NIRS cyclotron facility is shown in Fig. 2. The HM-18 cyclotron is only used for production of PET-radiopharmaceuticals. The NIRS-930 cyclotron has 10 beam ports, and 5 beam ports of them are exclusively used for radionuclide production. The C-1 and C-2 beam ports are used for production of PET-radiopharmaceuticals. The C-4 beam port is used for production of metal radionuclides such as ^{62}Zn/^{62}Cu for SPECT. The C-9 and C-3 are vertical irradiation ports. The C-9 beam port is used for production of radionuclides with a low-melting-point solid target such as 124I and 76Br [2]. The C-3 beam port was used for fast neutron therapy, and this beam port has been modified for radionuclides production recently. This beam line has wobbler magnets for avoiding heat concentration on a target [3].

In order to produce radionuclides for TRT, the target material with low melting point is irradiated with a high intensity beam. Because an irradiation face doesn't change even if the target melts, the vertical beam port has the advantage in irradiation with low-melting-point target. Therefore, the radionuclides for TRT is produced using these two vertical irradiation ports. ^{211}At has been produced for TRT using the C-9 beam port [4].

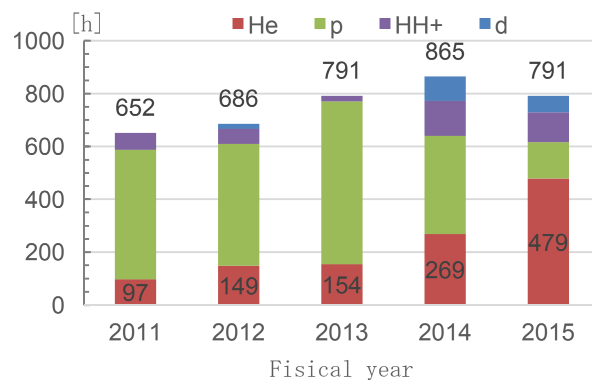

Figure 1: The operation time for production of radionuclide.

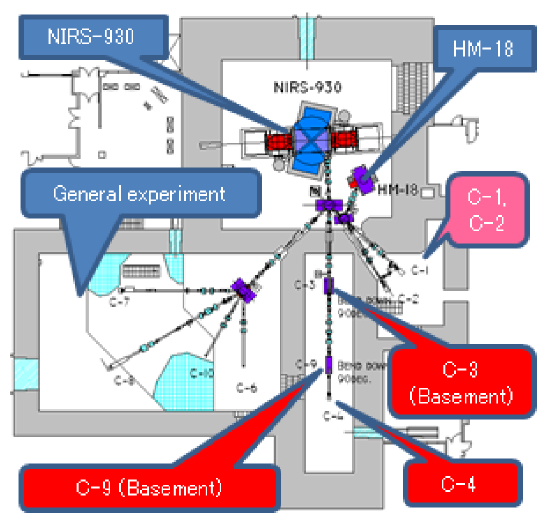

Figure 2: Layout of the NIRS-930 cyclotron. C-3: Radionuclides production using heat damageable targets; C-9: Radionuclides production ^{124}I, ^{76}Br, etc; C-4: Radionuclides production for SPECT; C-1, C-2: Production of PET-radiopharmaceuticals.

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STUDY ON ENERGY UPGRADE AND BEAM TRANSMISSION EFFICIENCIES FOR RIKEN K-70 AVF CYCLOTRON

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Abstract

The central region of the RIKEN AVF cyclotron was modified in order to increase the beam energy of protons and M/Q = 2 ions, and acceleration tests were performed. Before the modification, we investigated the injection acceptance in the modified structure of the central region. In the acceleration tests, the energy of protons was successfully increased from 14 MeV to 30 MeV in the acceleration harmonics 1 (H = 1) operation. On the other hand, in the conventional acceleration harmonics 2 (H = 2) operation, the transmission efficiencies were lower than those before the modification.

INTRODUCTION

The RIKEN AVF cyclotron [1] was commissioned in 1989 and is used as a stand-alone machine and an injector for the RIKEN ring cyclotron. Its K-value is 70 MeV, and the maximum extraction energies to date are 14 MeV for protons and 12.5 MeV/u for M/Q= 2 ions. This cyclotron has been operated jointly by RIKEN and the Center for Nuclear Study, the University of Tokyo. The operation time was 2900 h in 2014, and the information regarding its operation is described in Ref. 2.

Figure 1 shows the acceleration performance of the AVF cyclotron. The maximum magnetic field is 1.76 T. The RF frequency ranges 12–24 MHz and the nominal dee voltage is 50 kV. Until 2009, the operational region had been limited to the yellow area, but in order to increase the beam energies to meet the demands from users for nuclear physics and radioisotope production, the modification of the central region of the cyclotron was designed by Vorozhtsov et al. [3] and was executed in the summer of 2009. As a result, the operational region has been expanded to the blue area in Fig. 1, while the extraction energies have increased to 12 MeV/u from 9 MeV/u for M/Q = 2 ions. After this modification, in order to further increase the extraction energy (to 30 MeV for protons), they also designed another structure with a smaller RF shield by changing the support structure of the inflector. Figure 2 shows the superimposed plan views of the central region. One is for the existing structure (S1) modified in 2009, and the other is for the tested structure (S2), in which the RF shield was made smaller. The region accelerated in the structure S2 is expanded to the green area in Fig. 2. Using the structure S1 or S2, light ions such as protons can be accelerated in the acceleration harmonics 1 (H = 1). The displacement between H = 1 and 2 in the blue and green areas is caused by an acceleration phase-shift from the peak of the dee voltage for H = 1 acceleration. In the H = 1 operation, protons can be accelerated up to 20 MeV for S1 and 30 MeV for S2. An acceleration test of 20 MeV protons was executed in the existing S1 structure in July 2016. Moreover, in August, we changed the central region from the existing structure S1 to the structure S2, and performed the acceleration tests. In the tests, in addition to the acceleration of 20 and 30 MeV protons, the H = 2 acceleration test was also performed to check whether the transmission efficiencies through the cyclotron deteriorated.

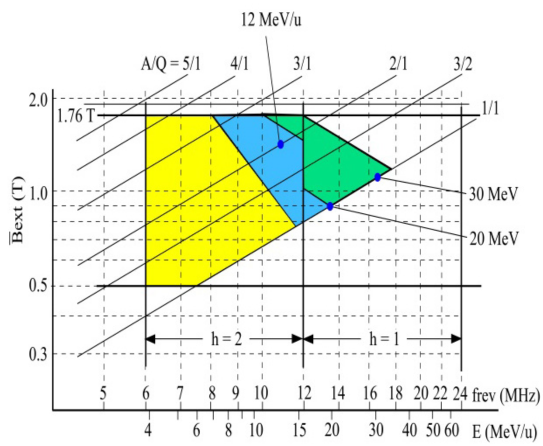

Figure 1: Acceleration performance of the AVF cyclotron. The yellow, blue, and green areas correspond to the original (before 2009), existing, and currently-tested geometries, respectively.

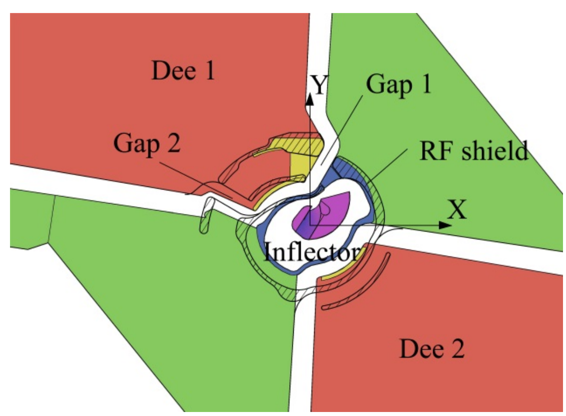

Figure 2: Existing and tested geometries of the central region. The shaded area indicates the existing geometry.

TRACKING SIMULATION

Before modifying the central region with the structure S2 and performing tests, we re-studied the influence on shows a computer model used for the calculation of the the injection acceptance by tracking calculations. Figure 3

DESIGN OF RF PICK-UP FOR THE CYCLOTRON

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Abstract

The radio-frequency (RF) pick-up for RFT-30 cyclotron which was located in the Korea Atomic Energy Research Institute (KAERI) was designed by Sungkyunkwan University in Korea. This paper covers proper position of RF pick-up and things to consider when designing. Our RF pick-up antenna is designed for RFT-30, but approach to design process can be used any RF pick-up antenna design. This paper provide some tendency graph according to position of RF pick-up.

INTRODUCTION

Recently cyclotron is used many research field such as nuclear reactions, nuclear physics, radioisotope applications, life science and so on. Various field needs variable performance of beam. Reliable output beam is necessary to get good results [1].

Cyclotron is a kind of particle accelerator. RF cavity is a component of cyclotron, which accept electromagnetic field from RF source and serves accelerating field to particles.

There are some problems when RF power input to RF cavity, such as inputting power variation or mismatched impedance. Sometimes device should be stopped operating because of these problems. It is possible to solve these problem that using RF pick-up. Because RF pick-up accept electromagnetic signal in real time. The signal of RF pick-up is applied to cyclotron control system, it is possible to safe driving. Our RF pick-up design is going to use RFT-30 and RF pick-up used in RF system, so Table.1 is contained. Simulation results were performed by CST microwave studio [2].

Table 1: Specification of RFT - 30 Cyclotron RF System [3]

Parameter	Value
RF frequency	64.05 MHz
Number of Dees	2
Dee angular width	39 deg
RF amplifier power	50 kW
Number of Harmonics	4

SIMULATION PROCEDURE

RF pick-up is measuring resonance signals in RF cavity, such as resonance frequency. In this work, we can find RF cavity quality factor, impedance matching status and so on by using these signals.

RF pick-up is same principle to RF power coupler. However role of two things are different. Purpose of RF coupler is transportation of RF power from RF generator to RF cavity, whereas purpose of RF pick-up antenna is measuring electric field in excited RF cavity by RF power. RF pick-up is connected with a measuring instrument directly. So, in design of RF pick-up, we must consider status of measuring instrument such as maximum acceptance power.

It would be significant to take the appropriate location of the RF pick-up and not to affect the performance of the RF cavity when designing the RF pick-up. The appropriate position represents to get RF power supplement that should not exceed the measurement limitation of the network analyser.

Prior to starting the design, coupling type must be determined.

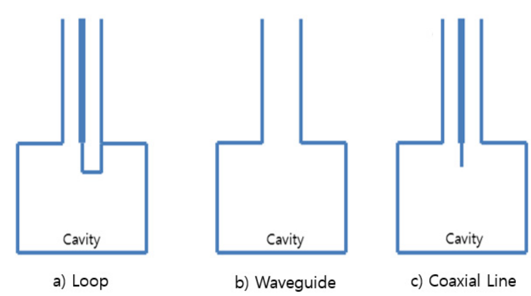

Figure 1: Different types of RF power coupler.

There are 3 types of RF power coupler are shown in Fig. 1. If magnetic field passing through the loop, induced current is generated. This current becomes pick-up signal at loop type coupler. Waveguide type is directly connected to RF cavity and waveguide performs a RF pick-up, coaxial line type usually is used in electric field.

ANALYSIS OF THE PLASMA CHARACTERISTICS FOR BEAM CURRENT OPTIMIZATION FOR TR-13 CYCLOTRON ION SOURCE

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Abstract

There is a TR-13 cyclotron that extracts energy of 13 MeV protons which is located in Sungkyunkwan University. The researchers in this laboratory were eager to improve the technical problems of the components and finally optimize the beam profile. The finally extracted beam current is critically depends on the initially extracted beam from the Ion Source Injection System (ISIS). The ISIS is composed of several electrical instruments. The voltage or current which is applied to these components can affect the finally extracted beam profile. However, the original values for the input voltage or current is almost fixed to special values that had been written in the operation manual. It means that the bad condition of this cyclotron cannot be matched for these values which had been conducted in the best condition of the operation. So, by using the programmable logic controller (PLC), it is possible to use varying inputs in various conditions, and the beam current is able to be stabilized much better than applying the constant input values. Finally, this paper would show the tendency of the plasma generation in terms of modulating the applying input values which occurs inside the ion source chamber. It represents the plasma characteristics that critically influence the beam current.

INTRODUCTION

TR-13 cyclotron is originally manufactured from TRIUMF company in Canada. IT accelerator engineering centre in Sungkyunkwan University tried to manage this cyclotron's for engineering research.

One of the most significant factors for the performance of the accelerator is the extracted beam current. The beam current depends on lots of background environments such as the vacuum level, stability of the input/output power, or gas injection and so on. And also the firstly extracted beam from the ion source chamber can be the primary points for intensifying the finally extracted beam current. Since the last beam profile is strongly affected by the initially extracted beam from the ion source, the beam flows in the ion source injection system should be considered weightily. The ion source injection system consists of ion source, steering magnets, quadruple magnets, inflector, etc. Though, the plasma generation can be the systemic function for the whole structure of the ion source injection system [1, 2].

In the ion source chamber, negative hydrogen ion generating reaction is performed under several conditions. The simple procedures follows: hydrogen gas injection, electron emission form the high current filament, arc discharge between hydrogen gas and the electrons, plasma region displacement, ion beam extraction. Within these procedures, the operator can manipulate many conditions in the ion source chamber. Briefly, the negative hydrogen ion beam generation is dependent to vacuum level, arc discharge, electron emission, plasma potential, and extraction voltage which is able to be controlled by PLC system. Thus, this paper will represents the feature inside the ion source chamber on the part of plasma characteristics [4].

EXPERIMENTS

Experiments with variety of conditions had been conducted, and it shows many specific tendencies. Every electronical devices are remotely controlled by PLC unit.

Mass flow controller (MFC) in this system is a device that control the flowing amount of the neutral hydrogen gas that coming from the gas source to the ion source chamber. It can decide the vacuum level in the ion source chamber and thus the amount of the hydrogen particles to be reacted with electrons can be controlled [3].
The controlling range of the hydrogen has injection is 0~10 SCCM and the whole range is covered for the experiments.

Figure 1 features the operation of the power supplies (Arc P/S, Filament P/S, Plasma P/S) within the condition of arc voltage : 100V, arc current : 2A, plasma potential : 3.1V), without injecting the hydrogen gas. In the experiments, only the arc current ,the plasma potential, steering magnet and the extraction lens voltage had been changed. The arc current is decided by the amount of the generated plasma, and plasma potential corresponds to the displacement of the plasma region in the ion source chamber. And they determine the total amount of the extracted beam. The plasma current and the extractor lens current of each situations had been observed in this experiment. Conclusively, the graphs show that in order to increase the beam current extracted from the ion source, the extractor lens current should not reach to saturation level earlier.

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BEAM BASED CALIBRATION MEASUREMENTS AT THE PSI CYCLOTRON FACILITY

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Abstract

The PSI high intensity proton accelerator (HIPA) facility consists of a Cockcroft-Walton accelerator and two cyclotrons, INJECTOR 2 and the Ring machine (see Fig. 1). It is in operation since four decades [1]. Though the design details of the original machine are well documented, a considerable number of changes have been made to various components in the course of time. Moreover some measurements like magnetic field mappings or the survey of central region collimators can only be done in the construction and/or assembly phase, either for mechanical reasons, due to restrictions of time schedule or due to the activation of components. Further development of the facility requires precise beam dynamics models (for instance with OPAL [2]) which in turn requires an accurate machine description.

INTRODUCTION

An effective method to test the consistency of the data used to model the machine is based on the combination of beam tracking simulations and beam based measurements. We present some results of such beam based alignment and calibration measurements that have been made during beam development shifts with INJECTOR 2. They allows to cross-check collimator positions, Dee voltage distribution, turn patterns, beam energy and trim coil field profiles using measurements of radial probes, phase pickups and profile monitors. A sensible reconstruction of cyclotron parameters starts

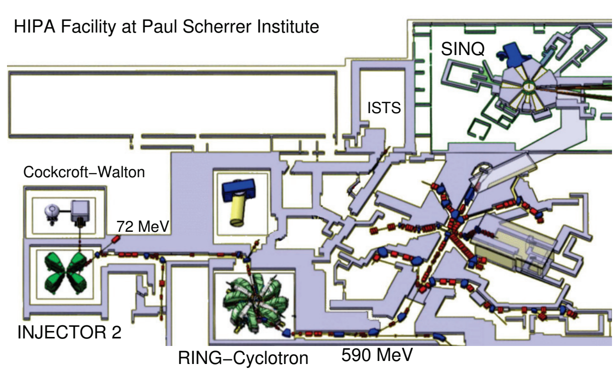

Figure 1: High Intensity Proton Accelerator (HIPA) Facility at PSI. The Cockcroft Walton delivers typically 10 – 12 mA protons DC. After the formation of bunches by two bunchers in the injection line of INJECTOR 2, the beam is accelerated to 72 MeV and transported to the RING cyclotron. The 590 MeV proton beam of maximal 2.4 mA is used to produce pions, muons using carbon targets and neutrons by spallation in the swiss neutron source SINQ.

with the RF-frequency ω_{rf}, the parameter which is usually well-known or easy to measure. Based on the frequency it is possible to determine the average magnetic field as seen by the beam, provided that some kind of phase measurement is available. The PSI INJECTOR II for instance is equipped with 8 phase probes (MIF1-MIF8) required for the adjustment of the isochronism. The long radial probe (RIL1) can be used to localize the turns at the azimuth of the probe. The radius gains allow to reconstruct the energy gain as a function of radius. The energy gain per radius gain of the cyclotron is given by

$$\frac{dE}{dR}(R) = \frac{E\,\gamma\,(\gamma+1)}{R}\,, \tag{1}$$

which can be crosschecked also with computed equilibrium orbit data. Then the energy gain per turn is

$$\frac{dE}{dn}(R) = \frac{dE}{dR}(R)\,\frac{\Delta R}{\Delta n}(R)\,. \tag{2}$$

Measurements with the long radial probe (RIL1) have been performed during a beam development shift in 2015. For this calibration measurement, the buncher located in front of INJECTOR II in the 870 kV injection line was switched off in order to ensure a beam of well-known and sharp energy. We picked the peak positions of RIL1-0005Y15.SDDS, shown together with RIL1-0002Y15.SDDS in Fig. 2. The PSI INJECTOR 2 is specifically well-suited for such measurements, as the phase curve of the beam is almost flat such that the radius gain can be directly used to compute the Dee voltage. Once frequency, dee voltage and field are resonably well known, it is possible to use the beam position measurements of the long probe RIL1 to match the starting conditions of tracking computation to the position data.

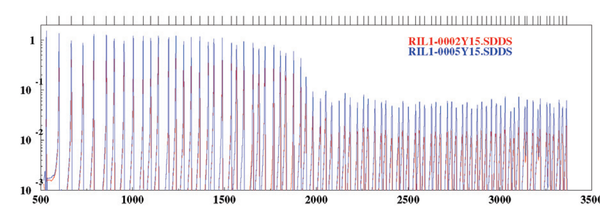

Figure 2: Measured raw data of the long radial probe RIL1 (INJECTOR II) and the beam positions. From turn number and extraction energy, one can directly compute the *average* energy gain per turn.

Figure 3 shows the resulting energy gain as derived from the RIL1 beam position measurements. The energy gain matches well to historical data of the resonator voltage profiles. The turn-by-turn analysis of the radius gain is shown in Fig. 4. Though we find a wide range between injection and extraction where the turn pattern is in excellent agreement with the simulated orbit, the agreement is less convincing in the more critical areas of injection and extraction, respectively. We hope that we can achieve further improvements

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AUTOMATED DOCUMENTATION OF TUNES IN THE BEAM LINES OF THE COMET CYCLOTRON

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Abstract

The proton beam from the COMET cyclotron can be transported to three gantries and two horizontal lines [1]. The beam energy is adjusted by a variable degrader. For each branch several "tunes" are defined, each listing the previously evaluated magnet, degrader and collimator settings for a certain beam energy [2]. The beam quality at the end stations is routinely checked meticulously in the frame of treatment quality assurance [3]. Independently of this, software has been developed (in the frame of the machine control system) to collect, for series of tunes, all available information on the beam and on the machine settings in the active beam line. Routinely used, this allows a close observation of the stability and reproducibility of the machine and keeps ready consistent data sets for detailed studies. This tool can also be used to collect, in a short space of time, extensive data for beam dynamics simulations with OPAL [4] or optimisation procedures based thereon [5], to verify the beam line performance after changes to hardware or software, or to check the functionality of the beam diagnostics. The data set characterising a single tune is organised systematically, allowing to share data viewers with standard beam diagnostics.

ENVIRONMENT

In the PROSCAN beam lines, beam profiles are measured by multi-strip ionisation chambers (MSIC) and the beam energy by multi-leaf Faraday cups (MLFC) [6]. The channels of a single monitor can be read out simultaneously to reduce the effect of beam noise. The signals of current, halo and loss monitors and from slits, stoppers and collimators can also be read out. Monitors and stoppers are inserted into the beam by compressed air actuators. All these parameters as well as all actual machine parameters and settings in the database [7] can be accessed or, if possible, set via EPICS. Information on the tune settings can be read from tune files or interpolated from tune tables [8]. MATLAB is permanently running on a 64-bit Linux-PC in order to get short start-up times [7]. A MATLAB-EPICS interface is available [9].

MEASUREMENT SOFTWARE

A MATLAB program allows to set a tune and the beam current (in the right order and adapted to transmission, in order to prevent overcurrent at the end station), to change predefined machine settings (to modify the tune), to measure statically (i.e. after settling of the tune) predefined monitors, to log predefined machine parameters, to store the tune settings and changes (Fig. 1). For each measured tune, a tune data file with a MATLAB structure (Fig. 2) is stored, containing all the information well organized and accessible. Predefined script files can be loaded to do this for sequences of tunes. In addition, for each sequence a protocol file is generated, listing the measured tunes with modifications.

Within a tune measurement, drive movements and measurements are sequenced effectively and controlled (to e.g. make sure that the monitor movements are finished before a measurement starts or to stop the sequence in case of unexpected behaviour). This allows to perform the sequences reliably and much faster than it would be possible 'by hand'. E.g. the measurement of a tune from COMET to Gantry 3 entrance takes a minute (38 profiles, 1 MLFC, 162 signals from diagnostics or machine parameters, transients).

The program can run compiled or not compiled. For test purposes, options can be chosen to not move drives or set tunes or set beam current or open first stopper. This allows testing without mastership of the facility (when these actions are reserved for other users) or a dry run without feeding beam into the lines.

Measurement of Transients

The electronics reading out the monitors can measure waveforms of profiles or of individual signals. Up to 4095 samples with a minimum time step of 0.2 ms can be taken. (For larger time steps, the signal is integrated.) This allows to observe profiles or other signals also during the transition from one tune to the next (Fig. 3, Fig. 2 lower part). Of course with the limitation that only one beam-destroying monitor can be used at a time. At least the beam current after the cyclotron is measured in this way for each tune data file, in order to document the beam current fluctuations caused by the ion source [10].

AUXILIARY SOFTWARE

The measurement software already roughly depicts profiles in the GUI to allow the user to see if the sequence is running correctly.

A post-processing routine evaluates for a batch of tune data files the transient profiles, adds the results to the data structure and stores it in new files. Due to the large number of profiles, this step is too time-consuming to do it already during the measurement sequence.

A simple viewer allows to load a tune data file and to depict the information on the static measurement (evaluated profiles, MLFC, tune details, logged parameters, comments, error messages). Another viewer depicts the transient measurements (Fig. 3).

These routines again are written in MATLAB, allowing a simple reading of tune data files. To make the data available to OPAL, a simple batch routine is used to export text files.

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SUPPRESSION OF RF RADIATION ORIGINATING FROM THE FLATTOP CAVITY IN THE PSI RING CYCLOTRON

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Abstract

In the PSI Ring cyclotron, protons are accelerated from 72 MeV to 590 MeV. In several upgrade programs, the beam current was increased from the initial design value of 100 µA up to 2.4 mA. The rf-system of this separated sector cyclotron consists of 4 copper cavities running at 50 MHz for the main acceleration. For the purpose of increasing the phase acceptance of the Ring, an aluminum flattop cavity is operated at a gap voltage of 555 kVp at the 3rd harmonic frequency.

As a result of the progressively increased flattop voltage, this cavity was pushed toward its mechanical and electrical limits. As a consequence, rf-power is leaking into the cyclotron's vacuum space and is causing several problems. A visible effect was the formation of plasma in the vacuum chamber [1].

In the last shutdown, an attempt was made to reduce the radiated rf-power. On the vacuum sealing between the flattop cavity and sector magnet 6, a shim was installed which reduces the gap for the beam from 60 mm to 25 mm in height. Results of this intervention will be presented and compared with finite element model simulations.

INTRODUCTION

The flattop cavity in the Ring cyclotron is located between Sector Magnet 6 (SM6) and Sector Magnet 7 (SM7) as shown in Fig. 1. AS2 and AS3 are rf-radiation probes.

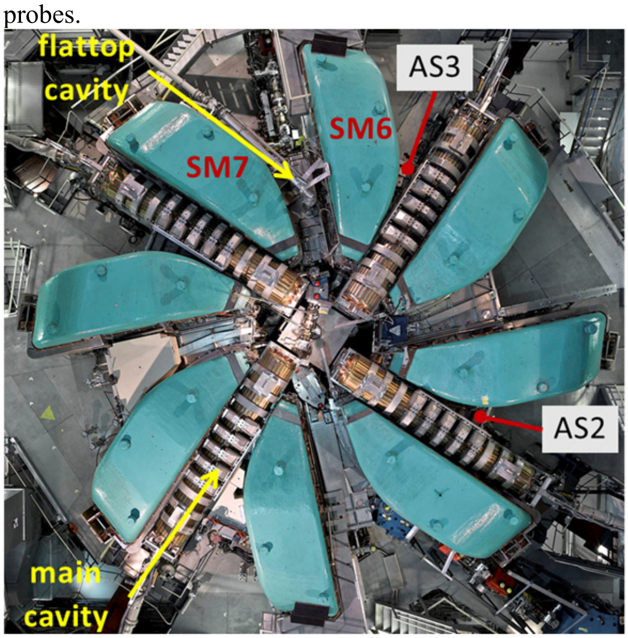

Figure 1: The PSI Ring cyclotron.

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The FT cavity is directly attached to the vacuum chamber on the SM7 side by an O-ring. However, an expandable sealing (see Fig. 4) is installed between the cavity and SM6. This expandable sealing is an O-shaped bellow made of aluminum, holding an O-ring on both sides. For a vacuum tight connection it is pressurized by air to 0.7 Bar. For installation in the machine, the expandable sealing is shrunk by applying vacuum. This sealing has a vertical gap size of 60 mm.

Simulations showed that the radiated power of the flattop cavity could be reduced, by adding a metal shim (25 mm vertical gap size, 102 mm length) outside the cavity into the beam aperture from 11.9 kW to 3.3 kW. This is a reduction of 8.6 kW or 75% [2].

It turned out to be difficult to add such a shim on the flattop cavity towards SM7 because a mechanical support holding the shim is needed. Additionally, for the installation of such a shim the cavity would have to be taken out of the ring cyclotron.

A much easier way to install a shim was to reduce the gap in the expandable vacuum sealing on the SM6 side of the flattop cavity. Figure 2 shows a cross section of flattop cavity, expandable vacuum sealing with shim, and vacuum chamber of sector magnet.

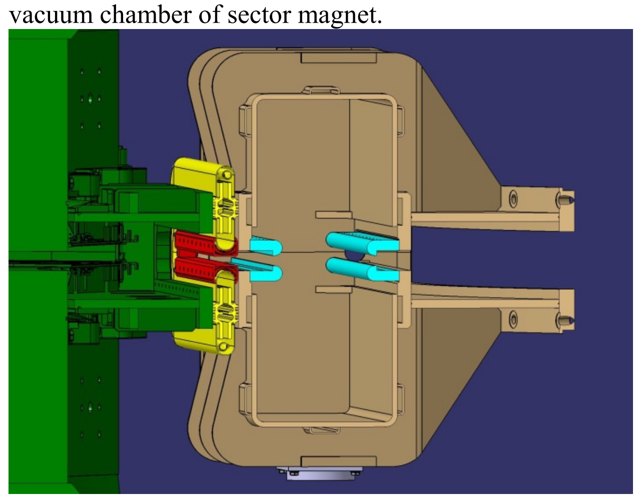

Figure 2: Cross section of flattop cavity (beige) with electrodes (cyan), expandable vacuum sealing (yellow) with shim (red) and vacuum chamber of sector magnet 6 (green).

SHIM

The design of the new shim was straight forward. The gap size should be lowered to 25 mm and the maximum length is given by the space between SM6 and flattop cavity such that the sealing could still be installed. We decided to use an aluminum sheet of 4 mm thickness which is formed into a U-shape (see Fig. 3). The expand-

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OPERATIONAL STATUS OF THE UNIVERSITY OF WASHINGTON MEDICAL CYCLOTRON FACILITY

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Abstract

The University of Washington Medical Cyclotron Facility (UWMCF) is built around a Scanditronix MC50 compact cyclotron that was commissioned in 1984 and has been in continual use since. Its primary use is in the production of 50.5 MeV protons for fast neutron therapy. While this proton energy is too low for clinical proton therapy, it is ideal for proton therapy research in small animal models. In addition to the protons used for fast neutron therapy and proton therapy research, the MC50 is able to accelerate other particles at variable energies. This makes it useful for medical isotope research, including isotopes such as ^{211}At, ^{186}Re, and ^{117m}Sn that are being developed to target and treat metastatic disease at the cellular level.

The original accelerator and therapy control systems were run on a DEC PDP-11 with a custom centralized I/O system built around the Z80 processor and chipset. Over the last 10 years we have continually been upgrading the controls while remaining operational, moving to a distributed system developed with the open source Experimental Physics and Industrial Control System (EPICS) toolkit.

INTRODUCTION

In '78-'79 the National Cancer Institute (NCI) awarded contracts to 4 institutions to construct, develop, and operate state-of-the-art fast neutron therapy facilities: University of Washington (UW), Fox-Chase Cancer Center (FCCC), M.D. Anderson (MDA), and University of California, Los Angeles (UCLA). Of these four facilities, the UW fast neutron therapy program is the only one still in existence. The longevity of the UW facility can be ascribed to a commitment from physician and faculty leadership, an exceptional maintenance and upgrade program, and the fact that the facility was designed with the flexibility to support a variety of research programs. The UWMCF was built around a Scanditronix MC50 cyclotron that can produce 28-50.5 MeV protons, 13.6-23.8 MeV deuterons, and 27-47.3 MeV alphas and in addition to producing beam for fast neutron therapy, it also produces beam for medical isotope production, proton therapy research, and radiation effects testing.

OPERATIONS AND MAINTENANCE

The cyclotron facility was built inside the UW Medical Center (UWMC). At the end of construction and commissioning, ownership, operation, and all documentation was turned over to the UW. This model is quite different than most of the modern proton therapy facilities where operation and maintenance are done under service contracts by the accelerator manufacturers. This model has allowed the UW to develop in-house expertise and provided the freedom to modify and upgrade the facility to support changing research needs. The facility is maintained by an in-house engineering/physics group of 5.5 full time employees. The facility operates Tuesday-Friday 7:30 am - 4:30 pm, and is shut down for maintenance on Mondays. There are no planned maintenance shutdowns beyond the Mondays and facility downtime has averaged less than 1.5% over the last 20 years.

The Medical Cyclotron Facility is operated as a cost center within the UW and the service it sells is beam time. The facility is entirely reliant on the business it generates for income and is not allowed to operate with a surplus or deficit. If it does it must adjust its reimbursement rate based on projected usage and operating cost estimates. The primary customer is the UWMC. They pay for beam time required for patient treatments and account for roughly 90% of the income. The remaining income comes from grant based research (isotope and proton therapy research) and commercial users (isotope production and radiation effects testing).

RECENT UPGRADES

The original accelerator and therapy control systems were based on a centralized PDP11/23 control computer and Z80 based I/O devices. For the last 10 years there has been a concerted effort to upgrade the control system to a distributed PC system using the Experimental Physics and Industrial Control Systems (EPICS) toolkit. At this point the new therapy control system has been developed and commissioned, and the accelerator control system has been upgraded with the exception of the RF subsystem, which will be completed soon. One major change to the new therapy control system is the inclusion of a Digital Imaging and Communications in Medicine (DICOM) server to allow for the standardized transfer of treatment plans.

FAST NEUTRON THERAPY

The fast neutron therapy beam is generated by focusing protons (65-75 μA) on a 10.5 mm thick beryllium target housed in a rotating gantry. The neutron beam is flattened with a tungsten flattening filter downstream of the beryllium target, and can then be modified with one of three onboard tungsten wedge filters (30deg.-45deg.-60deg.) to create a wedged profile. The neutron beam is finally collimated with a 40-leaf steel/polyethylene multi-leaf collimator. The standard therapy dose rate is 60 cGy/min at d-max (1.7 cm) for a 10.3x10.0 cm field.

We have recently developed a Monte Carlo model of our neutron therapy beam using MCNPX. The model developed allows us to simulate percent depth dose, lateral dose profiles, and neutron fluence. Preliminary results are in good accordance with measured values. [1]

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MAGNETIC SYSTEM FOR SC200 SUPERCONDUCTING CYCLOTRON FOR PROTON THERAPY

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Abstract

The superconducting cyclotron SC200 for proton therapy that is under design by ASIPP (Hefei, China) and JINR (Dubna, Russia) will be able to accelerate protons to the energy 200 MeV with the maximum beam current of 1 μA. A conceptual design study with 3D codes for the superconducting cyclotron magnet has been carried out during 2015-16 at ASIPP and JINR. The main design considerations are reviewed. The results obtained by numerical field computation for a suitable choice of design parameters are presented. Results of numerical calculations are the basis for technical design of SC200 cyclotron.

CYCLOTRON OVERVIEW AND ITS PARAMETERS

In order to respond to the increasing interest in Russia and China for proton therapy, JINR and ASIPP have started the development of a dedicated proton therapy facility in frame of the China-Russia joint research center on superconducting protons accelerator. The center has been founded in Hefei, east China's Anhui province recently. The research center, co-built by the Joint Institute for Nuclear Research of Russia and Institute of Plasma Physics of Chinese Academy of Sciences, aims at developing SC200 - China's first compact superconducting cyclotron for medical application - within three years. SC200 will be used for accurate treatment of cancer. The systems and components related to SC200 is expected to be manufactured by the Institute of Plasma Physics by 2017 and both parties will jointly assemble these systems and components and complete the whole project by 2018.

The main SC200 cyclotron design characteristics:

- Compact design similar to the lot existing cyclotrons
- Fixed energy, fixed field and fixed RF frequency
- Bending limit W=200 MeV
- Accelerated particles: protons
- Superconducting coils enclosed in cryostat, all other parts are warm
- Injection by PIG ion source
- Extraction with an electrostatic deflector and passive magnetic channels

MAGNETIC SYSTEM SIMULATION

The preliminary choice of the magnetic system parameters was provided by 2D codes (POISSON [1] and OPERA-2D [2]). At this stage the basic magnet system sizes and sectors gap parameters were estimated. The optimization of the spiral sectors parameters and final choice for magnet design has been done by TOSCA, the magneto-static module of OPERA-3D, 3D code ANSOFT MAXWELL [3] and CST code [4].

At the each step of the magnet optimization the simulated magnetic field maps were analysed by the beam dynamic codes and the beam extraction procedure was studied too.

The SC200 cyclotron model view is shown in Fig. 1. The magnetic field map calculated in the median plane of the cyclotron is shown in Fig. 2.

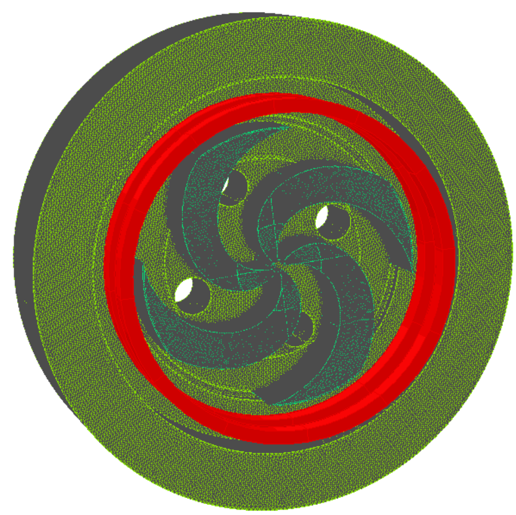

Figure 1: Layout of the TOSCA model for SC200 cyclotron.

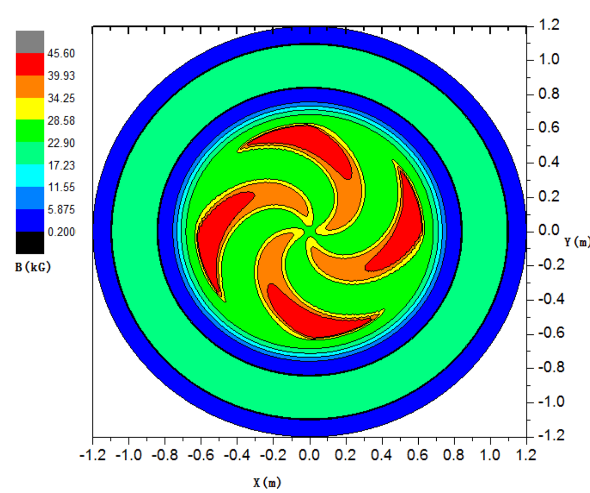

Figure 2: Contour plot of median plane magnetic field.

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STATUS OF THE ISOL CYCLOTRON SYSTEM IN RISP*

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Abstract

An ISOL system has been developed for providing neutron-rich RI beam to multi-disciplinary users by Rare Isotope Science Project (RISP) of the Institute for Basic Science (IBS) in Korea. The ISOL system is composed of proton driver, target/ion source station, mass separator, charge breeder, and A/q separator. A selected beam of interest is then injected into re-accelerator, which is a superconducting linac. A 70 MeV proton cyclotron was chosen as the proton driver to induce direct fission of UCx target. The final goal of beam power on target is 70 kW, which will be achieved gradually from 10 kW during post-RISP. Recently, commercial H^- compact cyclotrons and high-intensity cyclotrons have been considered for its extension of multi-purpose uses. In this paper, the specifications of the cyclotrons along with concerned issues and the status of our procurement plan will be presented.

INTRODUCTION

RISP was launched to develop RAON, the name of the heavy-ion accelerator, in 2011. The RAON can utilize both the Isotope Separation On-Line (ISOL) and In-flight Fragmentation (IF) to produce rare isotopes for multi-disciplinary uses (see Fig. 1). The RAON is composed of a driver linac, an IF system, an ISOL system, a post-accelerator, high-energy experiment facility I&II, a very-low-energy experiment facility, and a low-energy experiment facility. The driver linac has two superconducting ECR ion sources, a LEBT, a RFQ, a MEBT, a low-energy superconducting linac (SCL1), a charge stripper, and a high-energy superconducting linac (SCL2). The IF system is employed of an IF target, a pre-separator, and a main separator. The driver linac can accelerate heavy ions up to an energy of 200 MeV/u with a maximum beam power of 400 kW. The ISOL system consists of a 70 MeV proton cyclotron, a target/ion source, a mass separator, a charge breeder, and an A/q separator followed by a post-accelerator system. Not only the IF system and the ISOL system operates independently but also the beam from the ISOL system can be injected via the post-accelerator and SCL2 to IF system for more exotic rare isotopes. The conceptual design and technical design studies on RAON accelerator systems have been conducted since 2012. RISP will be accomplished by the end of 2021.

ISOL system will use a proton cyclotron system as a proton driver and UCx targets to produce neutron-rich (n-rich) isotopes. The final goal is direct fission of ^{238}U by 70 kW proton beam. A 70 MeV proton cyclotron and high-

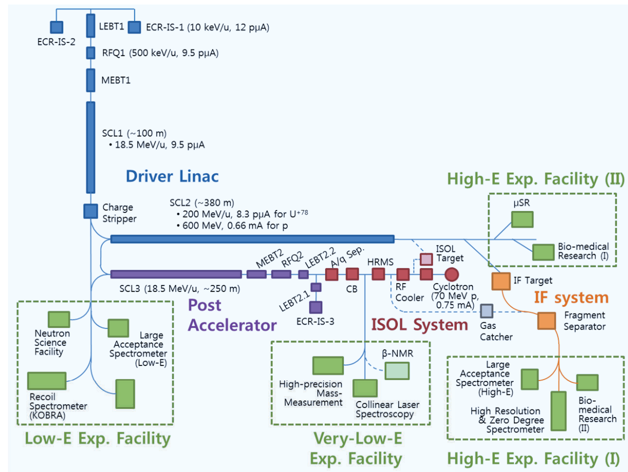

Figure 1: Conceptual diagram of the RAON.

intensity deuteron cyclotrons have been considered to produce more than 70 kW proton beam. Cost, fabrication time, and feasibility aspects were taken into account to choose a suitable cyclotron for RISP.

MAIN ISSUES

The operating plan of the cyclotron is to continuously supply the 70 kW proton beam on the UCx target uniformly over 300 hours for n-rich isotopes. Carbon stripper foil's lifetime, thermal control system of the UCx target, and beam losses inside a cyclotron are critical issues to satisfy the operating plan. The lifetime of a carbon stripper foil is about 20 000 μAh for 100 μg/cm² [1, 2]. It is not possible to meet the beam operating time by one carbon foil when the beam current is 1 mA. Applying a multiple foil extraction system with at least 15 foils is introduced, the required operating time can be achieved. However, the beam stop during foil replacement is unavoidable. In this situation, the thermal control of the UCx target and quick foil-exchange systems are necessary to maintain specific temperature of the target. In addition, radio activation inside a cyclotron is concerned about maintenance due to the beam losses by Lorentz stripping and vacuum dissociation during acceleration and extraction [3]. Even several percentage of beam losses at 70 kW can cause high radio-activation in a cyclotron. High vacuum pressure and/or high Dee voltage are needed to minimize the beam losses.

CANDIDATES FOR AN ISOL DRIVER

A High-intensity cyclotron such as the PSI injector II cyclotron was debated at the beginning of the RISP. PSI injector II is a separated sector cyclotron and can accelerator the proton up to 72 MeV with 2.5 mA. A 70 MeV proton cyclotron was reviewed by ISOL group at the conceptual

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DESIGN OF A BEAMLINE FROM CYRCé FOR RADIOBIOLOGICAL EXPERIMENTS

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Abstract

The PRECy project (Platform for Radiobiological Experiments from CYRCé) foresees the use of a 16-25 MeV energy proton beam produced by the recently installed TR24 cyclotron at the Institut Pluridisciplinaire Hubert Curien (IPHC) of Strasbourg for biological tissues irradiation. One of the exit ports of the cyclotron will be used for this application along with a combination magnet. The platform will consist of up to 3 or 5 experimental stations linked to beamlines in a dedicated 15 m x 13 m area next to the cyclotron vault. One of the beamlines will receive proton beams of a few cm diameter at intensities up to 100 nA. The status of the design of the first beam line is presented. The characterization of the proton beam parameters has been performed using the quad scan method. TraceWin and COSY Infinity codes allowed simulating the beam envelopes and defining the electromagnetic equipment that will compose the beamline.

INTRODUCTION

In October 2013, the Institut Pluridisciplinaire Hubert Curien (IPHC/CNRS) of Strasbourg inaugurated its brand new circular accelerator manufactured by ACSI (CAN) [1]. This cyclotron, called CYRCé (*Cyclotron pour la Recherche et l'Enseignement*), works at energies between 16 and 25 MeV for intensities up to 500 µA (Fig. 1).

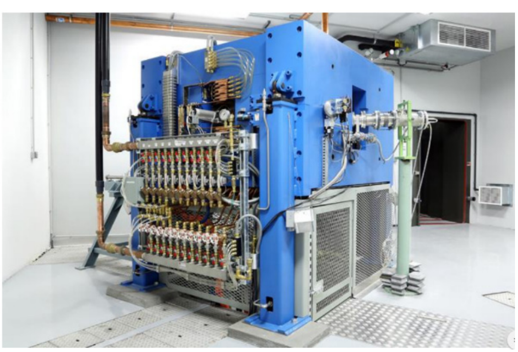

Figure 1: Picture of CYRCé in the casemate.

The accelerator mainly delivers ^{18}F and ^{64}Cu radioelement but also ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{124}I, ^{64}Cu, ^{68}Ge, ^{76}Br, ^{89}Zr for positron emission tomography (PET) and ^{123}I, ^{111}In, ^{67}Ga, ^{57}Co, ^{99}mTc for single-photon emission computed tomography (SPECT).

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PRECy

A Multi-Phase Project

The PRECy project aims at developing a platform for radiobiological studies from CYRCé. They will be performed for a better understanding of the RBE (Relative Biological Effectiveness) *in vitro* and *in vivo* in small animals (mice) and the study of combination treatment with chemotherapy and proton therapy. The project is divided into two phases over the years 2015 - 2020:

- Phase I (2015-2017): Extraction and Transport of 25 MeV proton beams, out of the existing casemate, to the experimental low energy stations dedicated to *in vitro* studies of the interaction of protons with the cells. By slowing down the beam, it will be possible to cover a range of energy ranging from a few hundred keV to 25 MeV and allow experimental measurements of the RBE on cell cultures and more fundamentally on the molecules constituting the living. The goal is to better understand the effects of the dose deposition at low linear energy transfer (LET) where biological effects are most important.
- Phase II (2018-2020): Extraction, acceleration of protons up to 70 MeV and beam transport to the experimental halls of high energy radiation biology for the *in vivo* study (small animal). The acceleration system should allow to vary the energy of the beam and scanning a surface to enable a dose deposition in a volume (tumor) defined.

At low energy (Phase I), it will be possible to measure the biological effects *in vitro* at the Bragg peak (at the level of the tumor) and *in vivo* in subcutaneous tumors implanted in small animals. The post accelerating protons up to 70 MeV (Phase II) will allow measuring biological effects at low linear transfer, upstream of the Bragg peak (before the tumor) and thus to study the effects of radiation on healthy tissues crossed during treatments. In addition, this power increase will work *in vivo* orthotropic tumors.

rpPET Beamline

rpPET is a joined collaboration between IPHC and the Paul Strauss Centre [2] which started in 2015 for a period of 36 months. It consists in studying the relationship between the physical dose and biological effects in a proton therapy in mice by Positron Emission Tomography.

The rpPET beamline is entirely located inside the casemate and is composed of collimators, Faraday cups and of a steerer.

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STATUS OF THE DC-280 CYCLOTRON PROJECT

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Abstract

The current status of the project of the DC-280 cyclotron is presented. The DC-280 will be the basic facility of the Super Heavy Element Factory which is being created at the FLNR JINR. The main parts of the DC-280 are already made. In according to FLNR plans the cyclotron has to be assembled in the period from 2016 to 2017. The cyclotron commissioning will be in the end of 2017.

INTRODUCTION

The DC-280 cyclotron designed at the Flerov Laboratory of Nuclear Reaction of the Joint Institute for Nuclear Research in Dubna (FLNR, JINR, Dubna) is intended for carrying out fundamental and applied investigations with ions from He to U (masses from A = 2 up to 238) produced by ECR sources. The DC-280 will be the basic facility of the Super Heavy Element Factory (SHEF) that is being created at the FLNR. The energy of the ions extracted from the cyclotron may vary from 4 up to 8 MeV/amu. The expected ion beam intensity at DC-280 extraction is 10 pμA for ions with masses up to 50 [1]. The main parameters of the DC-280 cyclotron specified in Table 1.

Table 1: Main Parameters of the DC-280

Parameter	Value
Injecting beam potential	Up to 100 kV
Pole diameter	4 m
A/Z range of accelerated ions	4-7.5
Magnetic field	0.6-1.35 T
K factor	280
Gap between plugs	400 mm
Valley/hill gap	500/208 mm/mm
Magnet weight	1100 t
Magnet power	300 kW
Dee voltage	2x130 kV
RF power consumption	2x30 kW
Flat-top dee voltage	2x13 kV
Flat-top power consumption	2x2 kW
Beam orbit separation	10-16 mm
Radial beam bunch size	3 mm
Electrostatic deflector length	1300 mm
Electrostatic deflector voltage	80 kV
Magnetic channel length	900 mm
Magnetic channel gradient	4.6-8.4 T/m
Efficiency of beam transfer	>50%
Total accelerating potential	up to ~ 40 MV

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The DC-280 (Fig. 1) will be equipped with high voltage injection system. The system will consist of two high voltage (HV) platforms with ECR sources. The injection has to provide effective ion transportation from the ECR-ion source to the cyclotron center [2]. To produce required ions, two types of ECR ion sources will be created at the FLNR: the DECRIS-PM source with permanent magnets [3] and a superconducting ECR one.

The DC-280 will be the isochronous cyclotron with four pairs of focusing sectors. For ion acceleration, two main 40° dees and two flat-top 20°dees will be used [4]. The expected beam parameters are listed in Table 2.

Table 2: Expected Beam Parameters of the DC-280

Ion	Ion energy [MeV/amu]	Intensity [pps]
^{7}Li	4	1×10^{14}
^{18}O	8	1×10^{14}
^{40}Ar	5	1×10^{14}
^{48}Ca	5	6×10^{13}
^{54}Cr	5	2×10^{13}
^{58}Fe	5	1×10^{13}
^{84,86}Kr	5	2×10^{12}
^{136}Xe	5	1×10^{12}
^{238}U	7	5×10^{10}

Figure 1: Layout of the DC-280 in the SHEF building (see Fig. 2).

The cyclotron ion beam extraction system the will be equipped with an electrostatic deflector and a passive focusing magnetic channel (Table 1).

To transport accelerated ion beams to experimental setups five beam lines will be utilized. All the beam lines will have the common switching magnet. The experimental hall will be divided into three separated parts that have to be radiation shielded. The total experimental area will be about 1000 m^2 [5].

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KURRI FFAG'S FUTURE PROJECT AS ADSR PROTON DRIVER

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Abstract

The accelerator complex using FFAG synchrotrons at KURRI has been operated for the ADSR experiments connecting the 100 MeV proton beam line with the research reactor facility so called KUCA since 2009. Fruitful results have been produced for the reactor physics using various configurations of the nuclear fuel core and variations of the neutron production target. Since higher energy beams such as 300 – 500 MeV are desired for the further study of the ADSR system, we are investigating the energy upgrade possibility of the accelerator complex. One of the candidates is to construct a new FFAG ring which adopts continuous acceleration with fixed frequency (serpentine acceleration) outside of the existing.These higher energy beams can be used for neutron or muon production experiments as well as ADSR study.

INTRODUCTION

An Accelerator Driven Sub-critical Reactor (ADSR[1]) is a hybrid system which is composed of a nuclear reactor facility and an accelerator facility.It sustains a nuclear fission chain reaction induced by a large amount of spallation neutron obtained by irradiation of a heavy metal target using high energy proton beams generated by accelerators. The nuclear reactor plays the role of neutron booster which amplifies the neutron flux from the target.

These days, especially after the severe nuclear accident in Fukushima Japan, the ADSR is paid attention not only as an energy production facility but as a device which transmutes long-lived radioactive materials such as the minor actinide (MA) to other materials whose lifetimes are much shorter than the original ones [1]. In the nuclear fuel cycle, MAs can be processed in a fast breeder. But in terms of the stability of the critical operation, the fraction of the MAs in the fuel system is limited as a few percent. On the other hand, in the ADSR, MA can be loaded up to some 30 % because the fuel system is operated as sub-critical.

At the Kyoto University Research Reactor Institute (KURRI), basic experimental studies about the ADSR have been started since 2009 using a one of research reactors Kyoto University Critical Assembly (KUCA) [2]. In these studies, the KUCA has been operated in the sub-critical mode and FFAG accelerators has been used as a proton driver. In this report, an overview of the FFAG accelerator complex, a current status of the usage of beams and discussion of possible upgrades of it will be presented.

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[1] Sometimes it is also referred as ADS which stands simply for Accelerator Driven System.

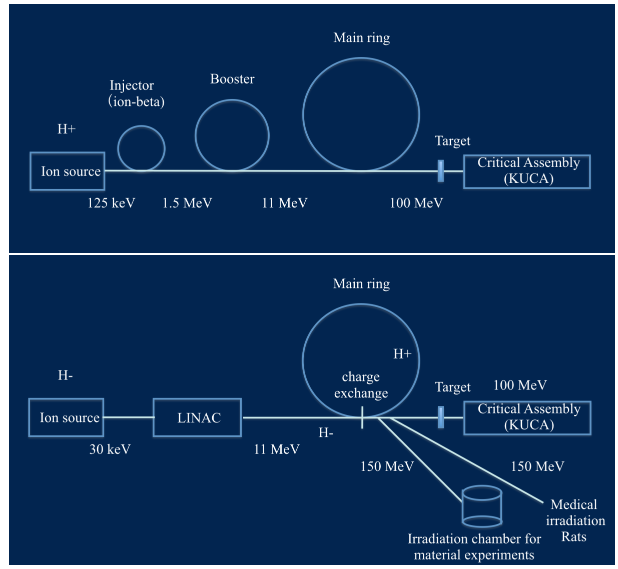

Figure 1: The schematic diagram of the FFAG Accelerator Complex. The upper is the original configuration, the lower is the upgraded one. The injector system composed of the Injector (ion-beta) and the Booster has been replaced by the H^- linac.

OVERVIEW OF THE FFAG ACCELERATOR COMPLEX AT KURRI

The schematic diagram of the KURRI-FFAG accelerator complex is shown in Fig. 1. The complex used to have 3 FFAG rings: the ion-beta, the booster and the main ring. All three rings adopt an FFAG focusing scheme [3]. However, the original injector system, which was composed of the ion-beta and the booster has been replaced by the 11 MeV H^- linac in order to increase the beam intensity. Table 1 shows the basic parameters of the complex. Figure 2 is an overview of the complex. The main ring has 2 extraction energies: 100 MeV for the ADSR experiments and 150MeV for other irradiation experiments.

The new injector system consists of 3 linacs RFQ, DTL1 and DTL2. It was adopted as an injector of the ERIT ring [4]. The injection beam line is shown in Fig. 3. The H^- beams are injected into the FFAG main ring through a charge stripping foil made of carbon. In this injection scheme, no pulse device is used. Even orbit merging magnets are not necessary because the H^- beams are merged into the circulating beam inside the main magnet of the main ring as shown in Fig. 4. The beam current extracted from the main ring has been increased by a factor of 10 because of this replacement.

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COMPACT SUPERCONDUCTING CYCLOTRON SC200 FOR PROTON THERAPY

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Abstract

The SC200 superconducting cyclotron for hadron therapy is under development by collaboration of ASIPP (Hefei, China) and JINR (Dubna, Russia). Superconducting cyclotron SC200 will provide acceleration of protons up to 200 MeV with maximum beam current of 1 μA in 2017-2018. We plan to manufacture in China two cyclotrons: one will operate in Hefei cyclotron medical center the other will replace Phasotron in Medico-technical center JINR Dubna and will be used for cancer therapy by protons. Now we present results of simulation of magnetic, accelerating and extraction systems. The cyclotron is very compact and light, the estimate total weight is about 35 tons and extraction radius is 60 cm. We have performed simulations of all systems of the SC200 cyclotron and specified the main parameters of the accelerator. Average magnetic field of the cyclotron is up to 3.5 T and the particle revolution frequency is about 45 MHz, these parameters increases the requirements for the accuracy of all simulations.

INTRODUCTION

The Medico-technical complex (MTC) JINR annually treated at the proton beam more than 100 people. For treatment MTC uses proton beam with energy up to 200 MeV specializing mainly on treatment of head localizations.

The 200 MeV final energy has been chosen for SC200 cyclotron based on the experience of work of the MTC JINR and statistics for necessary depth of treatment provided by HIMAC (Japan) concerning the treated patients from 1995 to 2001 [1].

The proton beam with energy 200 MeV can irradiate all of the tumor localizations with a maximum depth of 25 cm. SC200 cyclotron will also be used for eye melanoma treatment at energies 60-70 MeV after degrading beam energy. Degrading the 200 MeV energy to 60-70 MeV would provide better beam quality compared to degrading from conventional energy 250 MeV.

Taking into account the fact, that the size and cost of the cyclotron are approximately determined by the maximum proton energy, it was decided to limit the maximum proton energy to 200 MeV.

SC200 is an isochronous superconducting compact cyclotron. Superconducting coils will be enclosed in cryostat, all other parts are warm. Internal ion source of PIG type will be used. It is a fixed field, fixed RF frequency and fixed 200 MeV extracted energy proton cyclotron. Extraction will be organized with an electrostatic deflector and magnetic channels. For proton acceleration we are planning to use 2 accelerating RF cavities, operating on the 2nd harmonic mode.

MAGNET SYSTEM OF CYCLOTRON SC-200

The design of the SC200 magnetic system is described in details in [2]. Most accurate results of simulations were received in the parametrized model of the magnet (see Fig. 1) created in CST studio. Change of parameters automatically changes computer model. In addition, sector geometry can be replaced by importing from Matlab. Results of simulations are exporting to Matlab for analyzing by conventional CYCLOPS-like code or for particle acceleration in 3D fields. So we had powerful model to change quickly a number of parameters of the magnet in order to receive isochronous field with suitable betatron frequencies.

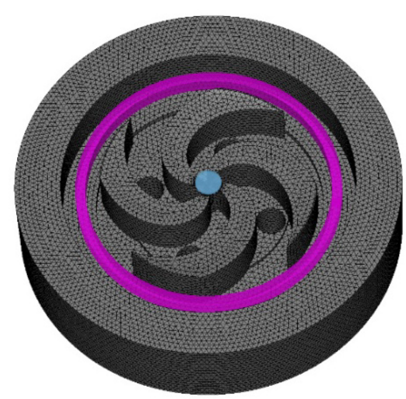

Figure 1: 3D meshed model of the magnet, central “plug” (steel cylinder connecting the sectors) is 4cm in diameter.

Isochronism of the average field was reached by decreasing of the sector width correspondently to orbital frequencies in closed orbits. Initially azimuth width of sector was equal 40 degrees. Azimuthal width of sector against radius which provide isochronous field is shown in Fig. 2. Maximal cut of the sector width will reach 18 mm. Orbital frequencies of the final average field (Fig. 3) are presented in Fig. 4. From Fig. 4 we can estimate that difference between mean field and isochronous is about 1-2 G in accelerating region. We would like to notice that all results were received with not very big number of mesh cells about 4 millions.

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HIGH INTENSITY AND OTHER WORLD WIDE DEVELOPMENTS IN FFAG ACCELERATORS

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Abstract

Here I present an overview of developments in Fixed Field Alternating Gradient accelerators, focusing on high intensity hadron accelerator designs. I will detail progress in studies of space charge effects and simulation, experimental characterisation of a 150 MeV proton FFAG at KURRI in Japan, experimental optimisation of FFAGs and novel FFAG developments for future applications.

INTRODUCTION

Fixed field Alternating Gradient (FFAG) accelerators combine strong focusing optics like a synchrotron with a fixed magnetic field like a cyclotron. Unlike a synchrotron, the magnetic field experienced by the particles is designed to vary with radius, rather than time. In the original types of FFAG invented in the 1950's and '60's, the vertical component of the magnetic field B_y varies with radius R according to the 'scaling law' according to

$$B_y = B_0(\frac{R}{R_0})^k, \tag{1}$$

with field index k, reference radius R_0 and field at that radius B_0. In the radial sector FFAG the alternating gradient is achieved with opposite sign 'F' and 'D' magnets, whereas in the case of the spiral sector FFAG, the polarity does not change but a spiral angle is used to gain additional focusing.

A revival of interest since the 1990s has seen a number of FFAGs constructed, including scaling and linear non-scaling variants for protons [1, 2] and electrons [3] respectively. Since this time, the range of FFAG designs has rapidly diversified and there are now designs with non-linear field profiles and non-radial edge angles, racetrack shapes or super-periodic structures, dispersion suppression sections, vertical orbit movement and other innovations. While it would be impossible to give an exhaustive review of such developments here, I will highlight examples to direct the reader toward the general direction of travel in this constantly evolving field.

In recent years, the focus of the community has started to shift away from basic proof-of-principle designs and further toward designing FFAG accelerators for real world applications. This has led to a significant amount of novel development in the field, for example, through recent work towards recirculating FFAG arcs for the eRHIC project.

In the high intensity direction, work is underway to establish design principles for high intensity FFAG accelerators for applications including radioisotope production, neutron spallation sources and accelerator driven systems (ADS). This has highlighted the need to establish a better understanding of the limitations of these machines with high bunch charge. From 2013 an international collaboration between institutes in Japan, UK and USA has been formed to use an existing scaling proton FFAG accelerator at Kyoto University Research Reactor Institute (KURRI) in Japan to work toward exploring the high intensity regime in FFAG accelerators. Experimental campaigns have thus far been aimed at characterising this machine in detail. At the same time, a detailed simulation and code development programme is underway, highlighting the complexities of benchmarking observed FFAG dynamics to simulation models, particularly when imperfections exist in the machine.

Alongside this new direction, FFAG accelerators are considered to be a promising option for medical applications at lower intensity due to their capability of high repetition rate and variable energy extraction operation with no limitation on top energy. Detailed concepts of FFAGs for proton and ion therapy have now been developed taking into consideration the desire for proton tomography capability. As this field moves toward optimised accelerators with rapid variable energy extraction, the FFAG concept is particularly promising for beam-lines and gantries with large energy acceptance over the entire treatment range while maintaining a fixed magnetic field. This and other potential applications will be discussed in the latter section.

TOWARD HIGH INTENSITY

General Features of FFAGs for High Intensity

Fixed field accelerators which employ DC magnets lend themselves naturally to high power operation, as the repetition rate of the machine can be increased above the 50-60 Hz of rapid cycling synchrotrons up to 100 or 200 kHz, dependent only on the rf system. If the magnets are superconducting or permanent magnets, the energy efficiency may be improved over existing machines which employ rapidly ramped, resistive magnets.

In this regime, we have to differentiate between high power beams and high intensity beams. In a cycled machine such as a synchrotron, a beam with high power requires a very high intensity and very high peak current, whereas for a CW machine a very high power can be achieved with relatively low peak current. The peak current determines the space charge tune shift and the main beam dynamics issues to be addressed.

In the FFAG community ideas are being developed for CW cyclotron-like machines which maintain strong focusing to higher energies using edge angles and arbitrary field profile with radius [4–6]. Concepts which introduce additional degrees of freedom to the orbit shape or movement, such

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HEAT TRANSFER STUDIES OF THE IRANCYC-10 MAGNET AND ITS EFFECTS ON THE ISOCHRONOUS MAGNETIC FIELD

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Abstract

In magnets for cyclotron, one of the prominent problems is difference between simulation and feasible operations. By considering more factors in simulation these difference can be reduced. Thermal effect and heat transfer is one phenomenon which can change favourite features of the magnets. IRANCYC-10 is a compact AVF cyclotron which is in manufacturing phase at AmirKabir University of Technology. In IRANCYC-10 heat transfer studies have been done for RF cavity, RF transmission line and PIG ion source. In this paper, accurate simulation of heat transfer and magnetic field have been done. Also thermal effects on isochronous magnetic field for IRANCYC-10 is investigated. For heat transfer and CFD simulations, Ansys CFX and for magnetic simulation Opera 3D Tosca have been used. The initiate magnet ampere-turn in simulation is 45201 and water mass flow rate for magnet system is considered 53 lit/min.

INTRODUCTION

IRANCYC- 10 is a 10 MeV cyclotron for accelerating of H^- in FDG production which is under manufacturing phase at AmirKabir University of technology [1] IRANCYC-10 exclusively has been designed for FDG production in hospital. Heat transfer and thermal analysis has been done for RF cavity, RF transmission line and PIG ion source [2], [3] and [4] in IRANCYC-10. In this project heat transfer and temperature raise for coil of the IRANCYC-10 has been simulated. As one of the main parts of this machine, AVF magnet have been designed by opera 3D Tosca. AISI 1010 is used for this magnet [5]. In Table 1 and Figure 1 relevant parameters of the magnet and magnetic field mapping can be seen.

Table 1: Relevant Parameters

Parameter	Value
Pole radius	45 cm
Maximum Magnetic field in main plan	1.78 T
Initiate Ampere turn	45201
Number of coil pancakes	18
Material of the coil	OFHC Copper (C 10100)

This magnet had been designed by Opera 3D Tosca and it was optimized as much as possible. On the other hand there is always difference between simulation and feasible problems and this difference create time-consuming tuning of the machine. One of the major reasons for the discrepancy between the simulation and operation in magnet of the cyclotrons, is temperature raise of the coils. In operation when the coil start to heat and raise temperature in fact it can effect OFHC copper conductivity. So other parameters of the magnet can change and isochronous field will be effected. Heat transfer study and optimized cooling system is essential in order to reduce inconsistency between magnetic field and isochronous field. In these coils it is almost impossible to eliminate the heat effects on the magnets even with the cooling system so it should be diminished and compensated if it is significant. This study is useful in cyclotron tuning phase.

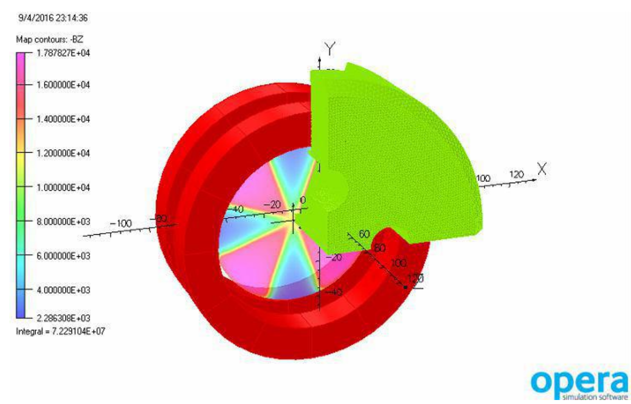

Figure 1: Magnetic field mapping.

COOLING CHARACTERISTICS

The coil of IRANCYC- 10 made of 18 pancakes in Figure 2 one pancake is shown. The main reason is less pressure drop of the cooling water. In this coil like other conventional coils in AVF cyclotrons, hollow conductors has been used. The dimension of this hollow conductor is rectangle (10*10 mm) and its hollow is circle (5.7 mm diameter). In order to avoid erosion and other mechanical problems in OFHC copper, the maximum velocity of the water should be less than 2.43 m/s [6]. So the maximum mass flow rate of each hollow conductor can be calculated by Eq. (1):

$$\dot{m} = \rho \times V \times A \ . \qquad (1)$$

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RECIRCULATING ELECTRON BEAM PHOTO-CONVERTER FOR RARE ISOTOPE PRODUCTION*

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Abstract

The TRIUMF 50 MeV electron linac has the potential to drive cw beams of up to 0.5 MW to the ARIEL photo-fission facility for rare isotope science. Due to the cooling requirements, the use of a thick Bremsstrahlung target for electron to photon conversion is a difficult technical challenge in this intensity regime. Here we present a different concept in which electrons are injected into a small storage ring where they make multiple passes through a thin internal photo-conversion target, eventually depositing their remaining energy in a central core absorber which can be independently cooled. We discuss design requirements and propose a set of design parameters for the Fixed Field Alternating Gradient (FFAG) ring. Using particle simulation models, we estimate various beam properties, and electron loss control.

INTRODUCTION

In 1999 W.T. Diamond published a paper [1] stressing the possibility of producing high yields of neutron-rich radioactive ions, using a high power electron beam from an e-linac as the driver accelerator for a Radioactive Ion Beam (RIB) facility. The electron beam could be scanned over a large area of a high Z Bremsstrahlung-production target. This would significantly reduce the power density on the Bremsstrahlung-production target and on the isotope-production target. A big advantage is that, such a facility would come at low cost, compared with other beam accelerators.

As a result during the following decade a couple of laboratories around the world tried to capitalize on this idea. At Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research in Dubna, Russia, a 50 MeV compact accelerator of the microtron type MT-25 [2] was built and the first experimental results were published in 2002 [3]. From IPN Orsay, in France, the results of the ALTO facility [4] based on a linear accelerator at 50 MeV were published in 2008. Both facilities chose a low power regime of operation of 500 W of electron beam power. ARIEL (the Advanced Rare IsotopE Laboratory) started at TRIUMF in 2010, first with the e-linac design, fabrication and installation. This first phase was complete in 2014, followed by the start-up of the electron target station design, and other concomitant projects and accelerator energy upgrades. The challenging aspect of ARIEL is to design and build a target station capable of dissipating up to 500 kW (50 MeV, 10 mA) of electron beam power.

In this paper we name the Bremsstrahlung production target, the converter and the isotope production target, the target.

Figure 1 shows experiment results from Dubna [3]. This graph shows that only the photons at energy around 10-20 MeV induce fission reactions by exciting the Giant Dipole Resonance (GDR) of the ^{238}U nucleus. The overlapping area on Figure 1 of the GDR and the γ-quanta spectrum contains the photons of interest. The power carried by photons with energies above 3 MeV will cause thermal loads onto the converter and target. Since this is an intrinsic property of the production of photonuclear reactions, it cannot be reduced without lowering the production of radioisotopes in the target.

The low energy photons undergo photoelectric absorption (between 1 keV and 1.5 MeV) and Rayleigh scattering (below 100 keV) depositing their energy in matter. On the high-energy side, photons contribute to Compton scattering (significant up to 10 MeV) and pair production (starting at 1.022 MeV and growing for increasing photon energies), which impacts the heating up of the converter and the target, without producing any fission reactions.

An ideal configuration would have only the intrinsic power of the produced Bremsstrahlung brought to interaction with the target, with neither charged particles (electrons and positrons) nor low energy photons reaching the target.

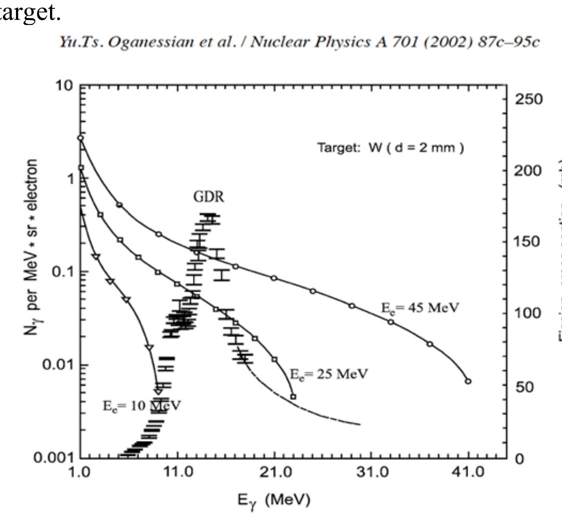

Figure 1: The γ-quanta spectrum (left scale) produced by electrons with various energies. The experimental points (right scale) correspond to the ^{238}U photo-fission cross-section [3, 5].

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SINGLE STAGE CYCLOTRON FOR AN ADS

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Abstract

In order to cope with the challenge of an ADS demonstrator, the accelerator is required to deliver a beam driving power in the range of 5 to 10 MWatt. Therefore it is mandatory to propose an accelerator design able to address highly demanding criteria which are a challenge for high power accelerator designers.

Taking into account the outstanding performances of the PSI ring cyclotrons, it is clear that cyclotrons are competitive challengers to high power linacs. The preliminary design studies of two options of a Single Stage Cyclotron Driver show that this concept could bring attractive solutions in term of reliability, cost effectiveness and power efficiency.

Some critical aspects of these designs which make use of the reverse valley magnetic field concept will be discussed in this paper.

THE PIONEERS OF HIGH POWER CYCLOTRONS

The requirements for ADS open different technical solutions for the driver accelerator. This reminds « the Meson factory race » in the 1970's where two rather different cyclotron designs were proposed in the same energy domain (500 to 600 MeV) to produce mesons.

These two large cyclotrons, the Swiss SIN [1] (today PSI) and the Canadian TRIUMF [2] were designed for 100 μA beam intensities which were very challenging in the 70's.

These two cyclotron facilities are based on rather different concepts.

THE PSI H+ TWO STAGES CYCLOTRON

The PSI has proved the soundness of large separated magnet spiral sectors (8) concept with 4 powerful large single gap RF λ/2 cavities delivering up to 600 KV peak voltage at the running-in. This design imposed a two stages cyclotron with a 72 MeV injector cyclotron (Figure 1). The cyclotrons operate with a high extraction efficiency based on the "single turn operation mode".

Since 1974 an outstanding intensity improvement program has been carried out. In 1984 the Philips compact isochronous injector has been replaced by a four separated sectors injector with an external 870 KeV injection line. In order to reduce the number of turns in the booster ring cyclotron, new copper resonators have been installed in 2008, resulting in a higher energy gain per turn. Since the very beginning the extracted beam intensity has been raised by a factor 20 and today the PSI cyclotron chain is delivering a 2.2 mA-590 MeV beam [3] with a 5.10^{-4} beam losses on the septum of the booster deflector.

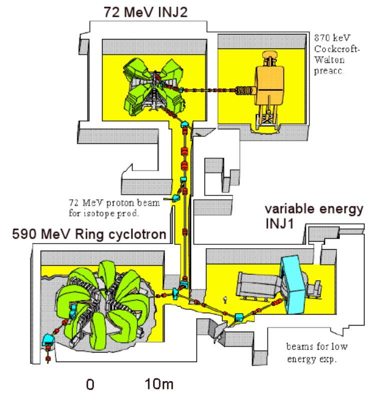

Figure 1: The layout of the two stages PSI cyclotron chain. INJ2 is the four separated sectors cyclotron superseding the old INJ1 compact cyclotron.

THE TRIUMF H- SINGLE STAGE CYCLOTRON

The TRIUMF design is the pioneer of a "single stage" acceleration up to 525 MeV exploiting the negative H- ion acceleration with two simultaneous extracted beams at 100 % extraction efficiency.

The relativistic electromagnetic stripping effect of the H- ions (the second electron is weekly bounded, 0.754 eV) requires a low magnetic field. Therefore the size of the machine is large (extraction radius 6.9 m, total iron weight of the magnet 2500 tons), the maximum B-field in the sector median plane being close to 6.1 kGauss. Besides a strong spiral is needed to achieve the vertical focusing (maximum spiral angle close to 70 deg.). As shown on the Figure 2, the acceleration is achieved by an unusual RF system made of λ/4 large resonators resulting in a single « Dee-gap » providing a 400 KeV peak energy gain per turn. The resonators are fed by a 1.8 MWatt RF Amplifier chain. The injection is external and axial from a 300 KeV injection line. The stripping extraction works in the "overlapping turns" extraction mode.

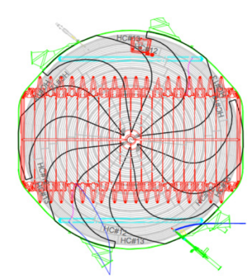

Figure 2: The TRIUMF 6 sectors single stage cyclotron with the RF resonators in red.

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STATUS OF THE HIGH INTENSITY BEAM FACILITY AT LNL-INFN

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Abstract

In 2016 the SPES (Selective Production of Exotic Species) project [1] has entered in the commissioning phase at Laboratori Nazionali di Legnaro (LNL) with the first operations of the proton driver accelerator. The project, whose main goal is the research in nuclear physics with Radioactive Beams (RIBs), has foreseen the construction of a new building hosting the accelerator able to deliver protons up the energy of 70 MeV and 50kW of beam power to be used as a primary beam for the ISOL source and for a production beam for other applications. The new facility design has been expanded and upgraded for taking advantage of the dual simultaneous extraction of beams from the Cyclotron in order to provide a multipurpose high intensity irradiation facility. Today the new facility is partially installed and the Cyclotron supplied by Best Cyclotron System Inc (BCSI) company [2] with the related beam transport lines are under commissioning. The status of the commissioning of the high power accelerator and the capabilities of the facility as multipurpose high intensity proton beam laboratory will be presented.

INTRODUCTION

SPES project aims to provide high intensity and high quality beams of neutron-rich nuclei to perform forefront research in nuclear structure, reaction dynamics and interdisciplinary fields like medical, biological and material sciences. The production of exotic nuclei is based on ISOL technique providing low energy secondary beams that will be isotopically selected by a High Resolution Mass Spectrometer, then ionized by a breeding process, and finally re-accelerated by the actual ALPI machine operating at LNL. The primary beam is provided by a cyclotron able to accelerate H^- ion up to the energy of 70 MeV and 700 μA of average current. The protons are extracted by the stripping of H^- at different energies varying from 35 to 70 MeV. The main advantage of the H^- acceleration is the possibility to extract simultaneously two proton beams by sharing the total current available. Since only 200 μA current is needed for the production of radioactive ions, the remnant current is available for other applications. For that reason an independent area of SPES facility has been built and equipped in order to deliver proton beams for multipurpose applications in parallel sessions with RIBs production. Up to 10 experimental stations are foreseen to be irradiated by proton beams and three of those are put into bunkers shielded for receiving high power beam (up to 50 kW).

FACILITY DESCRITPION

SPES building has been thought to accommodate the cyclotron, the beam transport lines and the target stations for RIBs productions. In addition, several target areas are arranged around the area A1, where the cyclotron is placed. Figure 2 shows the overall layout of the underground level of the new facility.

Two main extraction beamlines come from the cyclotron, then by means of two switching magnets (SM1 and SM2) the beam may be guided up to 6 beamlines (3 for each SM) that allow to get directly the target stations or to reach additional switching dipoles. Finally, up to 10 target stations can be supplied by the beam.

The actual configuration foresees a single complete beamline (BL1) up to A6 area where a 50 kW beam dumper was installed and the first section of the second extraction line including the switching magnet (SM2).

The 70 MeV Cyclotron

The driver of SPES project is a resistive cyclotron able to deliver two simultaneous proton beams with energy varying within 35 and 70 MeV and 700 μA total current.

The cyclotron and the beamline (see Fig. 1) have been supplied and installed by BCSI on 2015. The cyclotron is a 4 straight sectors machine, accelerating H^- ion that are extracted by the stripping process to get the proton beams. In order to minimize losses due to the Lorentz stripping during the acceleration, the cyclotron operates with a peak magnetic field of 1.6 T. The extraction radius is about 1300 mm and total weight is 160 tons.

Figure 1: Picture of actual installation at SPES building of LNL.

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STABLE AND EXOTIC BEAMS PRODUCED AT GANIL

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Abstract

The GANIL facility (Grand Accélérateur National d'Ions Lourds) at Caen produces and accelerates stable ion beams since 1982 for nuclear physics, atomic physics, and radiobiology and material irradiation. Nowadays, an intense exotic beam is produced by the Isotope Separation On-Line method at the SPIRAL1 facility (being upgraded to extend the range of post-accelerated radioactive ions) or by fragmentation using LISE spectrometer. The review of the operation from 2001 to 2016 will be presented, with a focus on last year achievements and difficulties.

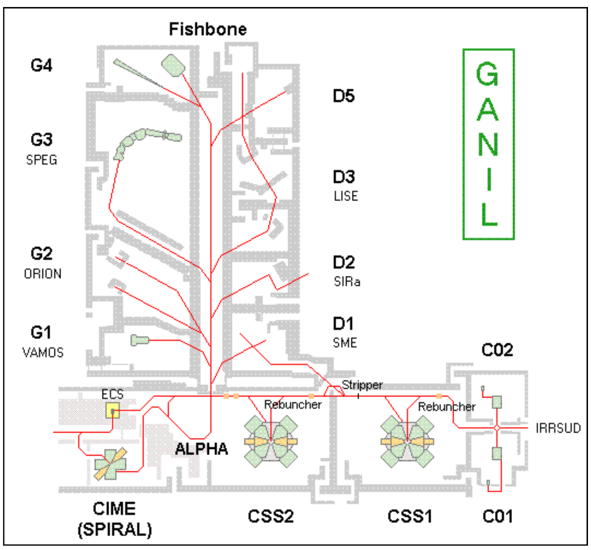

Figure 1: GANIL layout.

OPERATION REVIEW

Multi-beam delivery is routinely done at GANIL using its 5 existing cyclotrons (Fig. 1):

1. Beams from C01 or C02 are sent to an irradiation beam line IRRSUD (<1MeV/A).
2. A charge state of the ion distribution after the ion stripping foil downstream CSS1 is sent to atomic physics, biology and solid states physics line D1 (4-13MeV/A).
3. A high-energy beam out of CSS2 is transported to experimental areas (<95MeV/A), for nuclear physics and previous applications.
4. Finally, stable beams from SPIRAL1 source can be sent to LIRAT (<10keV/q) or post-accelerated by CIME and used for testing detector for example.

During radioactive beam production with SPIRAL1, the combinations are reduced to the two first (cases 1, 2), CSS2 beam is sent toward the SPIRAL1 target, and radioactive beam is sent to the experimental areas.

In addition, Ion sources are available in "hall D" building for atomic physics at very low energy.

2001-2016 GANIL OPERATION STATUS

Since 2001 (Fig. 2), more than 50172 hours of pilot beam time has been delivered by GANIL to physics, which correspond to 88.6 % of scheduled experiments.

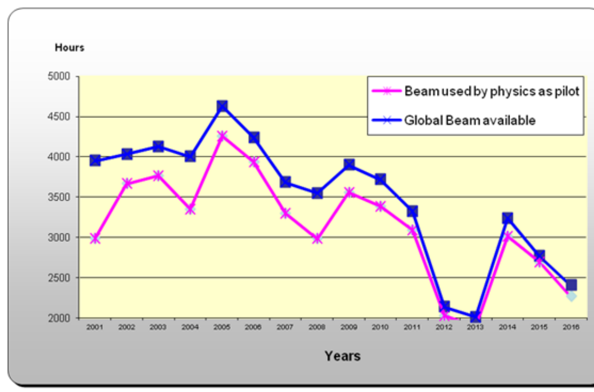

Figure 2: Beam time available for physics over 16 years.

On average, the number of beams delivered per year has increased until 2010. Owing to the construction and assembly of the new SPIRAL2 accelerator and upgrade of SPIRAL1, the running time has been shrinked to devote more human ressources to the project SPIRAL2, in particulier in 2012 and 2013 with only 2000 hours of experiments time (instead of 3500 hours per years).

Figure 3 shows the statistic running of the machine over 15 years. 67.2 % of beam time is dedicated to Physics and 12.4% for machine tuning.

In 2015 (March to July), the pilot beam time was 78%, the failure rate is only 8%. On the other hand, the SME and IRRSUD operation were decreased by several water leaks.

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PROTON RADIOGRAPHY EXPERIMENT BASED ON A 100 MeV PROTON CYCLOTRON*

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Abstract

A proof-of-principle test-stand for proton radiography is under construction at China Institute of Atomic Energy (CIAE). This test-stand will utilize the 100 MeV proton beam provided by the compact cyclotron CYCIAE-100, which has been built in the year of 2014, to radiograph thin static objects. The assembling of the test-stand components is finished by now. We will carry out the first proton radiography experiment in this July and hopefully we can get the first image before the opening of this conference. In this paper, the designing, constructing and commissioning of the proton radiography system will be described.

INTRODUCTION

Proton radiography is a new scatheless diagnostic tool providing a potential development direction for advanced hydrotesting research. In comparison with flash radiography, proton radiography has higher penetrating power, higher detection efficiency, less scattered background, inherent multi-pulse capability, more exact material identification and large standoff distance between test objects and detectors. Proton radiography was firstly used for dynamic experiments on a proton energy 800 MeV linear accelerator facility at the Los Alamos National Laboratory [1]. Proton radiography on static objects with a single pulse and energy to 24 GeV was carried out at the the Brookhaven National Laboratory in the year of 2011 [2]. In 2014, a low energy proton radiography system was developed at Chinese Academy of Engineering Physics, which utilizes a 11 MeV proton beam to radiograph thin static objects [3].

As a driving accelerator for Beijing Radioactive Ion-beam Facility (BRIF), a 100 MeV H- compact cyclotron, normally referred to as CYCIAE-100, was constructed to provide the proton beam of 70-100 MeV with beam current of 200 μA [4]. The first beam of CYCIAE-100 was extracted on July 4, 2014 [5]. The operation stability have been improved and beam current have been increased gradually. 720 μA beam was got on the internal target at the beginning of 2016. The effort for mA beam is continuing and 1135 μA beam was got on the internal target in June of 2016. This cyclotron can provide two proton beams simultaneously for the ion source of the Isotope Separation On-Line system (ISOL) and experimental instrument in the experiment hall, as is shown in Figure 1. In the experiment hall, a switching magnet guides the beam to different beam lines. It is scheduled to build a low energy proof-of-principle test-stand for proton radiography based on the down-left beam line.

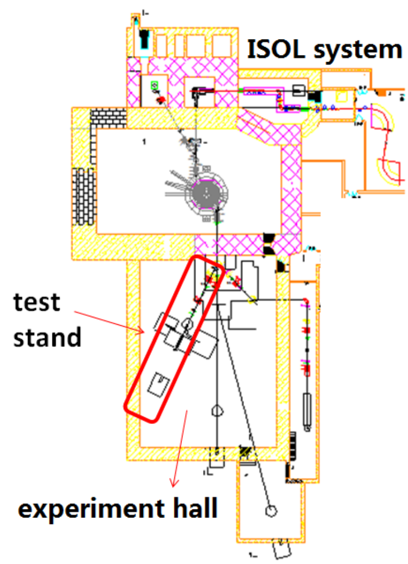

Figure 1: Layout of the BRIF facility.

BEAM LINE DESIGN

Proton radiography requires a particular magnetic lens system to provide a point-to-point imaging from the object to the image. Zumbro, Mottershead and Morris suggested a type of lens, normally referred to as Zumbro lens, whose first-order transfer matrix is the ***-I*** matrix, which means means the matrix element $R_{12} = R_{34} = 0$ [6]. The Zumbro lens has a Fourier plane at the mid-plane of the lens, where the position of a particle is determined by its initial angle only and is independent of its initial position (angle sorting), as is shown in Figure 2. The particles of large MCS angle in a matched beam can be removed through a transverse collimator at the Fourier plane. To form a Fourier plane, the incident particle's transverse displacement / and angle deviation along beam direction /' must be strongly correlated and comply with the following formula:

$$\omega \equiv /'/ = T_{116}/T_{126} \quad (1)$$

where T_{116} and T_{126} represents the second order chromatic aberrations of the Zumbro lens in TRANSPORT notation [7]. This means the matched beam emittance should equal zero, as is shown in Figure 3 (left).

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