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RECENT EXPERIMENTAL RESULTS OF THE ACCELERATOR DRIVEN SYSTEM WITH A SUB-CRITICAL NUCLEAR REACTOR (ADS) PROGRAM

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Abstract

A series of studies on the accelerator driven system (ADS) has been carried out since 2009 at KURNS. In these studies, Kyoto University Critical Assembly (KUCA) has been used as sub-critical system connected with the proton beam line from FFAG accelerator facility (Fig. 1). A profile of accelerator facility and experimental results, including the first evidence of the transmutation of minor actinides at ADS, will be presented.

INTRODUCTION

Disposal of spent fuel generated after light water reactor (LWR) operation is an urgent worldwide issue that must be addressed. For instance in Japan, approximately 17,000 tons of spent fuel is stored as of April 2014. Twenty tons of spent fuel is generated with operation of a 1 GWe class LWR for one year. If we assume that 15% of electricity demand in Japan (forecast for 2030) is to be covered by nuclear power, 20 units of this class of LWRs (20 GWe) will be required, and 400 tons of spent fuel will be generated annually. One ton of spent fuel contains 1 kg of minor actinides (MAs). That is, if a group of LWRs generating the electric power of 20 GWe is operated for one year, 400 kg of MA will be generated.

Some MAs have an extremely long half-life. For instance, ^{237}Np has over 2 million years. It takes about 10,000 years to reduce the potential toxicity of ingestion of high-level radioactive waste from spent fuel containing MAs to the same extent as natural uranium. This fact makes it difficult to dispose high-level radioactive waste. With accelerator driven system (ADS) described in this report, long-lived MAs in spent fuel can be converted into stable or short-lived nuclei, and the potential toxicity decay time can be reduced from 10,000 years to a few hundred years. Therefore, ADS research and development, which greatly contributes to the disposal of spent fuel, is extremely significant from this social background.

ACCELERATOR DRIVEN SYSTEM

An accelerator driven system is composed of a nuclear reactor facility and an accelerator facility. It sustains a nuclear fission chain reaction induced by spallation neutrons obtained by irradiation of a heavy metal target using a high energy proton beam from the accelerator. The nuclear reactor plays a role of neutron booster which amplifies the neutron flux from the target.

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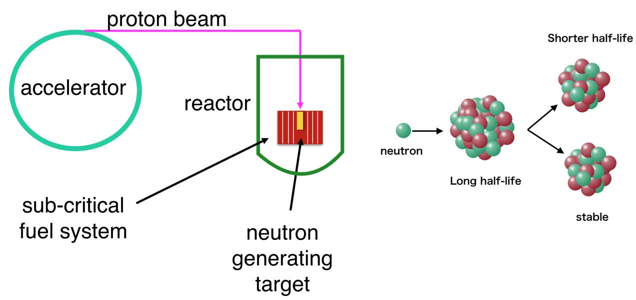

Figure 1: Concept of ADS.

In resent years,the ADS 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 reactor operation in a critical state, the fraction of the MAs in the fuel system is limited as a few percent. On the other hand, in the ADS, MA can be loaded up to some 30 % because the fuel system is operated in a sub-critical state, in which more stable chain reaction can be obtained.

EXPERIMENTAL FACILITY FOR ADS STUDIES AT KURNS

At the Institute for Integrated Radiation and Nuclear Science, Kyoto University (KURNS), basic experimental studies on the ADS have been started since 2009 using a research reactor Kyoto University Critical Assembly (KUCA) [2]. A fixed field alternating gradient (FFAG) synchrotron has been constructed to deliver high energy proton beams to the KUCA. In these studies, the KUCA is used as a sub-critical reactor and the FFAG accelerator is used as a proton driver.

KUCA

The research reactor KUCA has been designed for precise study on reactor physics. It is a thermal reactor. Its typical output power is on the order of 10 W even in a critical state. It consists of 3 cores: A-Core, B-Core and C-Core. Polyethylene is used as moderators and reflectors of neutrons in A-Core and B-Core while H_2O is used in C-Core. For the ADS experiments, A-Core is used in a sub-critical state.

The A-Core accepts both 100-MeV proton beams from FFAG MAIN RING and 300-keV deuteron beams from a Cockcroft–Walton accelerator. The 100-MeV protons hitting heavy-metal targets such as W or Pb-Bi induce spallation neutrons, while the 300-keV deuterons hitting the Lithium

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OPERATION STATUS AND UPGRADING OF CYCLOTRON IN LANZHOU

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Abstract

IMP operates the Heavy Ion Research Facility in Lanzhou (HIRFL), which consists of the Sector Focusing Cyclotron, the Separated Sector Cyclotron, the Cooler Storage Ring, and a number of experimental terminals. The HIRFL is mainly used in fundamental research of nuclear physics, atomic physics, irradiation material and biology, and accelerator technology. This paper mainly introduces the operation status and upgrading of HIRFL. So far, HIRFL achieves all-ion acceleration from proton to uranium. In addition, in order to improve the efficiency of HIRFL, we will build two new Linac injectors for SSC and CSR, respectively.

INTRODUCTION

HIRFL (Heavy Ion Research Facility in Lanzhou) is the major facility of national laboratory of heavy ion accelerators. It is one of the national laboratories of China, which focused on nuclear physics, atomic physics and heavy ion related application and cross-disciplinary researches. As shown in Fig. 1. HIRFL consists of the ECR (Electron Cyclotron Resonance) ion sources, the Sector Focus Cyclotron (SFC), the Separated Sector Cyclotron (SSC) and the Cooler Storage Ring (CSR). SFC is a k = 69 and SSC is a k = 450. The CSR is a double cooler-storage-ring system consisting of a main ring (CSRm), an experimental ring (CSRe), and a radioactive beam line (RIBLL2). Presently, the heavy ion beams with an energy range of 1(U) – 10(C) MeV/u could be provided by the SFC and 10(U) – 100(C) MeV/u by the SFC + SSC.

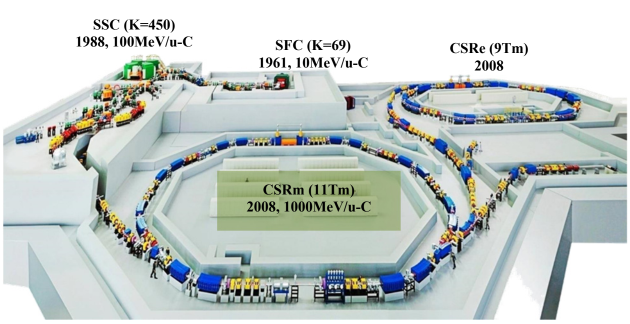

Figure 1: Present layout of the HIRFL.

OPERATION STATUS OF HIRFL

The machine combination operation modes of the HIRFL are SFC, SFC+SSC, SFC+CSRm and SFC +CSRm+CSRe. The time distribution of HIRFL operation consists preparation of machine, beam commissioning, the target beam and failure during the target beam. As shown in Fig. 2, HIRFL is operated about 7500 h during the last 5 years, the target beam time exceeds 70% of the total operating time. Average proportion of faults in each system during the five-year is shown in Fig. 3.

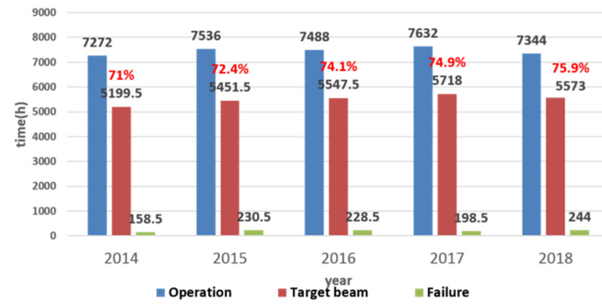

Figure 2: Operation time of the HIRFL.

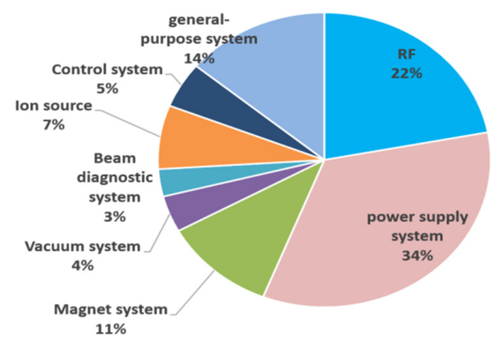

Figure 3: Average failure ratio of the accelerator subsystem during the recent five years.

The element types accelerated by HIRFL shown in Fig. 4, and 25 kinds of beams are provided annually. In the past five years, 61 kinds of new beams with different ions, different charge states and different energies have been produced. Typical ions accelerated by the HIRFL are listed in Table 1.

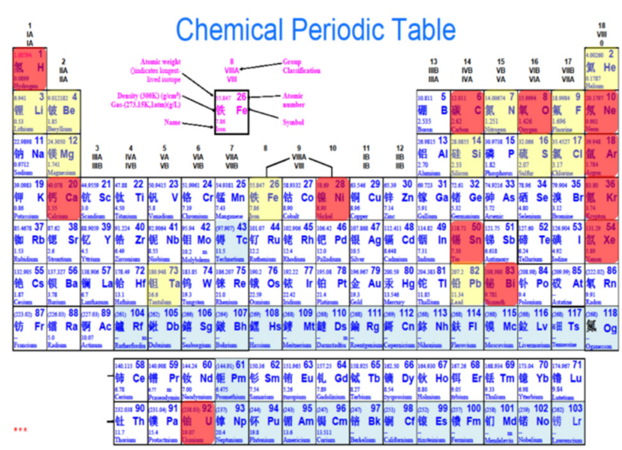

Figure 4: The element species provided by the HIRFL.

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STATUS REPORT ON GANIL AND UPGRADE OF SPIRAL1

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Abstract

The GANIL facility (Grand Accélérateur National d'Ions Lourds) at Caen is dedicated for acceleration of heavy ion beams 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 since 2001. New demands from the physics community motivated the upgrade of this facility in order to extend the range of post-accelerated radioactive ions. A 2 MEuro project allowed the profound modification of the facility and the commissioning was achieved in 2017. The status of this facility and the last results will be presented. The review of the cyclotron operation from 2001 to 2019 will be presented as well.

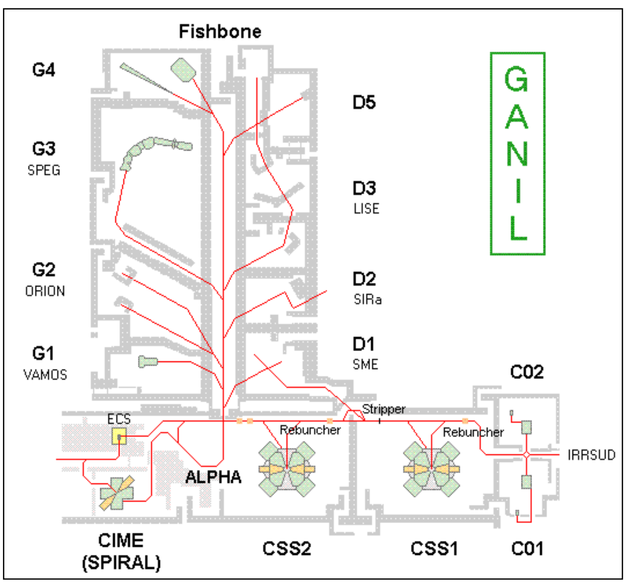

Figure 1: GANIL Layout.

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 (<1 MeV/A)0.
2. A charge state among the ion distribution after the ion stripping foil downstream CSS1 is sent to atomic physics, biology and solid states physics line D1 (4 - 13 MeV/A).
3. A high-energy beam out of CSS2 is transported to experimental areas (< 95 MeV/A), for nuclear physics and previous applications.
4. Finally, stable beams from SPIRAL1 source can be sent to LIRAT (< 10 keV/q) or post-accelerated by CIME and used for testing detector for example.

During radioactive beam production with SPIRAL1, the two first cases are still possible, 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.

2001-2019 GANIL OPERATION STATUS

Since 2001 (Fig. 2), more than 56000 hours of pilot beam time has been delivered by GANIL to physics, which correspond to 93% of scheduled experiments.

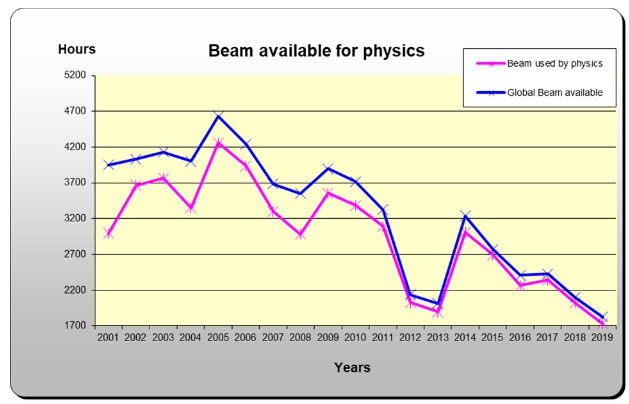

Figure 2: Beam time for physics.

In 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 shrinking to devote more human resources to the project SPIRAL2, in particular 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 19 years. 67.8% of beam time is dedicated to Physics and 12.6% for machine tuning.

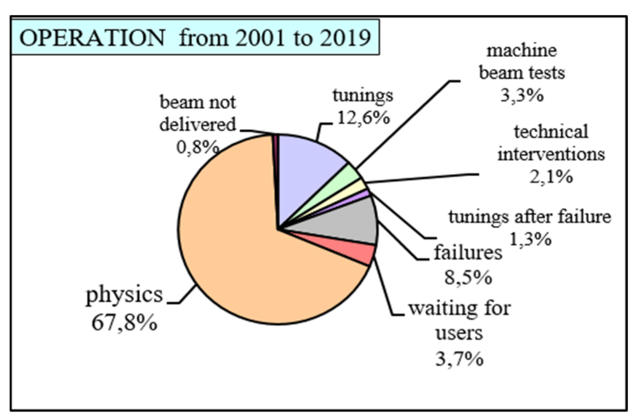

Figure 3: Statistic Running.

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RECENT PROGRESS IN RIKEN RI BEAM FACTORY

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Abstract

Recent efforts at the RIKEN RI Beam Factory (RIBF) are aimed at increasing the beam intensity for very heavy ions such as xenon and uranium. This paper presents upgrade programs carried out over the past few years, including modifications of the RF cavities of the RIKEN Ring Cyclotron and improvements of the charge stripper. The current performance of the RIBF accelerators and future plans to further increase the beam intensity are also presented.

OVERVIEW OF RIBF

The Radioactive Isotope Beam Factory (RIBF) at RIKEN is a cyclotron-based accelerator facility that uses fragmentation or fission reactions of intense heavy-ion beams to produce intense RI beams over the whole atomic mass range [1, 2]. The RIBF started beam delivery in 2007, after the commissioning of the three ring cyclotrons, fRC, IRC, and SRC, that were constructed to boost the energies of the beams accelerated by the RIKEN Ring Cyclotron (RRC), shown in Fig. 1. The main specifications of the four ring cyclotrons are summarized in Table 1. There are currently three injectors, AVF, RILAC, and RILAC2, that provide a wide variety of heavy-ion beams, as described below.

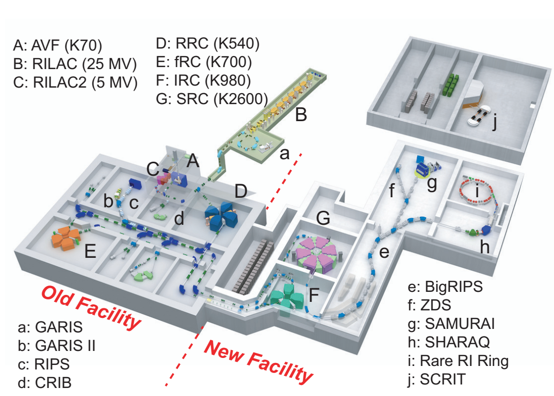

Figure 1: Schematic drawing of the RIKEN RI Beam Factory (RIBF). The accelerators (A–G) and experimental devices (a–j) are presented.

The scientific goals of the RIBF include establishing a new and comprehensive way of describing nuclei and improving the understanding of the synthesis of heavy elements in the universe. As shown in Fig. 1, distinctive experimental devices have been set up in the new facility, as well as in the old facility, which mainly uses the beams from the RRC.

We are also promoting applications of heavy-ion beams to various research fields, such as nuclear chemistry and biological science, using the heavy ion beams from RILAC, AVF, RRC, and IRC.

Table 1: Specifications of the RIBF Ring Cyclotrons

	RRC	fRC	IRC	SRC
Sectors	4	4	4	6
K [MeV]	540	700	980	2600
R_{inj} [cm]	89	156	278	356
R_{ext} [cm]	356	330	415	536
Weight [t]	2400	1300	2900	8300
Trim coils/ main coil	26	10	20	4 (SC) + 22 (NC)
RF system	2	2 + FT	2 + FT	4 + FT
Freq. [MHz]	18–38	54.75	18–38	18–38

One of the most important features of the RIBF accelerator system is the ability to accelerate all ions from hydrogen to uranium to 70% of the speed of light. To make this possible, three acceleration modes are used in the RIBF accelerators, as shown in Fig. 2.

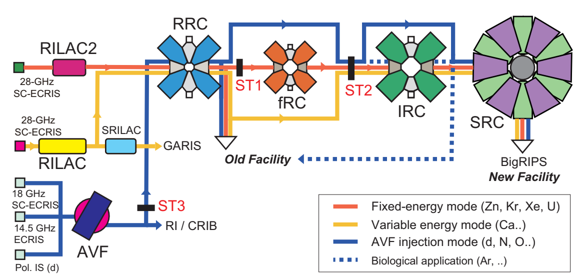

Figure 2: Accelerator chain of the RIBF. The three injectors, RILAC2, RILAC, and the AVF cyclotron, are followed by four booster cyclotrons, the RIKEN Ring Cyclotron (RRC), fixed-frequency Ring Cyclotron (fRC), Intermediate-stage Ring Cyclotron (IRC), and Superconducting Ring Cyclotron (SRC). The charge strippers are indicated by labels in red text (ST1–ST3). The superconducting linac booster, SRILAC, is under construction [3].

The first mode is a fixed-energy mode, originally intended for accelerating very heavy ions such as xenon and uranium. This mode uses the RILAC2 injector with a powerful 28-GHz superconducting ECR ion source, and boosts the beam energy up to 345 MeV/u with the four booster ring cyclotrons (RRC, fRC, IRC, SRC). Two charge strippers are used for the

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PROGRESS WITH A NEW RADIOISOTOPE PRODUCTION FACILITY AND CONSTRUCTION OF RADIOACTIVE BEAM FACILITY AT iTHEMBA LABS

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Abstract

With the termination of the neutron and proton therapy programs at iThemba LABS, the use of the Separated Sector Cyclotron (SSC) has now shifted to nuclear physics research with both stable and radioactive ion beams, as well as biomedical research. A dedicated isotope production facility with a commercial 70 MeV H-minus cyclotron has been approved and both the cyclotron and isotope production target stations will be housed in the vaults that were previously used for the therapy programs. The status of this new facility will be reported. In the future the SSC will mostly be used for nuclear physics research, as well as the production of isotopes that cannot be produced with the 70 MeV H-minus cyclotron. At present the production of the α-emitting radionuclide Astatine (^{211}At) with a 28 MeV alpha beam is being investigated. Progress with the construction of a facility for production of radioactive beams will be discussed. There will also be reports on development work on the ECR ion sources and progress with implementation of an EPICS control system.

DEDICATED 70 MeV CYCLOTRON FOR ISOTOPE PRODUCTION

The initial idea to simultaneously produce radioisotopes and radioactive ion beams with a dedicated 70 MeV H-minus cyclotron was discarded due to a number of reasons as explained in [1]. A feasibility study has shown that a very cost effective, dedicated isotope production facility can be constructed at iThemba LABS by making use of the existing infrastructure, which became available when iThemba LABS discontinued proton and neutron therapy. The layout of the proposed facility is shown in Fig. 1. There will be two isotope production vaults (Fig. 1, vaults A and B) with two bombardment stations in each. The 70 MeV H-minus cyclotron will be housed in a separate vault (Fig. 1, vault C) located between the two isotope production vaults. The irradiated targets will be transported via a rail transport system, through new labyrinths that will be connected to existing labyrinths, to the existing hot cells. Detailed FLUKA calculations have been done for the different vaults and labyrinths to ensure that all the radiation safety requirements will be met.

With a dedicated isotope production facility available, the bulk production of isotopes with the SSC will end. In future the SSC will then mainly be used for nuclear physics research and the development of new radioisotopes that cannot be produced with the dedicated isotope production facility, such as the alpha emitter ^{211}At.

Following approval of the project by the Board of the National Research Foundation, a contract for the manufacturing, delivery and installation of the 70 MeV cyclotron and associated beamlines has recently been signed after an open tender process. The 70 MeV H-minus cyclotron is capable of delivering two 375 µA beams simultaneously from two extraction ports placed 180 degrees apart. The consulting engineers for the design, development and construction of the required infrastructure have also been appointed. The infrastructure of the 70 MeV project will be completely separated from the infrastructure of the existing SSC facility to ensure that the new facility can operate independently from the SSC facility.

The time schedule for completion of this project is 3 years. The cyclotron and beamlines will be delivered within 2 years after contract signature. During this time, the infrastructure and the modifications to the 3 vaults will be completed and the 4 target stations will be designed, built and installed. Commissioning of the new equipment will take place during the third year.

ISOTOPE PRODUCTION TARGET STATIONS

The current plan is to build four new target stations that will receive beam from the 70 MeV cyclotron. They will be similar in design to the existing horizontal-beam target station (HBTS or Elephant) at iThemba LABS, but with thicker local radiation shields and several other smaller modifications and improvements. These target stations will be identical in all respects except for the aperture of the entrance collimator, which can have different sizes on different stations. During bombardment, a target will be completely surrounded by a composite radiation shield, consisting of an inner iron layer, a borated paraffin wax middle layer and a lead outer layer. This local shielding will reduce the neutron flux into the vault by about three orders of magnitude and reduce the thickness of the concrete shielding required for the vault significantly. More details on the station design can be found in [2]. Target transfer between a station and an electric rail transport system will be facilitated by a robot arm. All target handing, including the connection of cooling water, will be done by remote control.

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DESIGN AND COMMISSIONING OF RF SYSTEM FOR SC200 CYCLOTRON

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Abstract

The SC200 proton therapy superconducting cyclotron is currently under construction by ASIPP (Hefei, China) and JINR (Dubna, Russia). The RF (Radio Frequency) system which provides an accelerating electric field for the particles, has been designed and tested in a high-power commissioning. The RF system consists of RF cavity, Low-level RF control system, RF source, transmission network and so on. The main performances of RF cavity meet design and use requirements in the cold test. The RF cavity achieved an unload Q factor of 5200 at the resonant frequency of 91.5 MHz, 65 kV (Center), ~115 kV (Extraction) accelerating voltage and coupling state of S11 < - 30 dB. The low-level RF (LLRF) system has been tested with an amplitude stability of < 0.2% and a phase stability of < 0.1 °C in the high-power commissioning. What's more, the cavity has already operated in a ~50 kW continuous wave state after 4 weeks RF conditioning. Some risks have been exposed at higher power test, but related solutions and improvements have been developed. In future work, the target of RF system is effective operation under the overall assembly of cyclotron after further optimization and RF conditioning.

INTRODUCTION

The SC200 proton therapy superconducting cyclotron is currently under construction by ASIPP (Hefei, China) and JINR (Dubna, Russia). The RF system which provides an accelerating electric field for the particles, has been designed and tested in a high-power commissioning. The key components of RF system are Low-level RF control system, RF source, transmission network, which will be discussed in following paragraphs [1, 2]. The assembled RF system in commissioning stage is shown in Fig. 1.

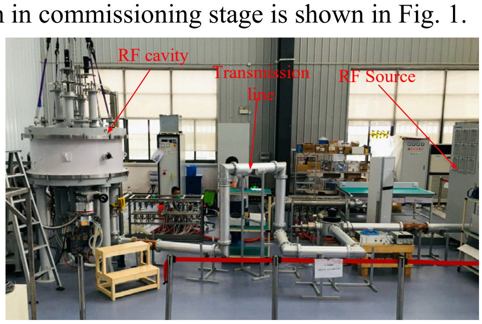

Figure 1: Assembled RF system in commissioning stage.

A high-power commissioning has been performed for the cavity. RF conditioning contributes to improve the performance RF cavity, so as to achieve high power feeding in cavity. Temperature record and X-ray calibration have also made for RF cavity to verify its performance. Moreover, some improvements have been done for cavity to solve related problems.

DESIGN OF RF SYSTEM

The RF system mainly consists of RF cavity, Low-level RF control system, RF source, transmission network. The RF source provides power to RF cavity through 6-inch coaxial transmission line under the control of Low-level RF control system. The RF cavity consists of Dee, Liner, Stems, Trimmers and coupling looping. The layout of RF cavity is shown in Fig. 2. Some optimizations have been made on the cavity based on the original physical model. Therefore, the Dee is optimized to a gradient shape with lighter weight. The inside of Dee has enough space for water cooling pipes. The design and manufacture of water - cooling paths on the rectangular Stem become easy. The new design also provides strong support for Dee to reduce the risk of deformation. The disc of trimmer and Dee form an equivalent capacitance, which is tuned by moving the trimmer up and down. In order to reduce the influence of high temperature under high power, water cooling pipes are also arranged on the outside of the cavity.

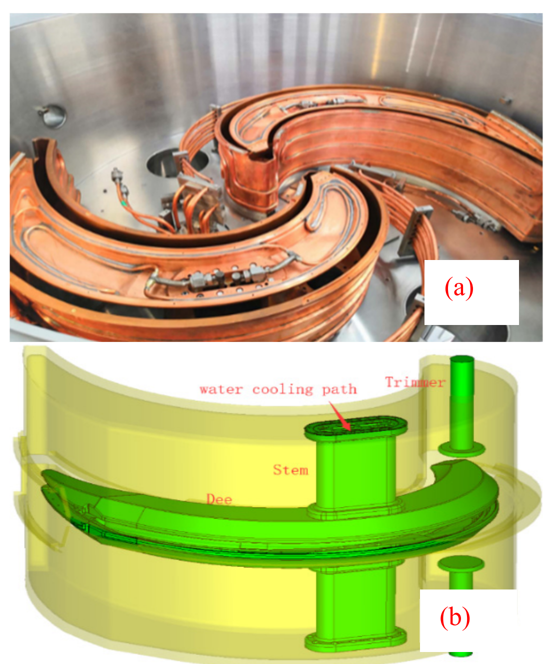

Figure 2: Layout of RF cavity. ((a) is half cavity with up and down symmetry, (b) is half cavity with left and right symmetry).

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RECENT PROGRESS ON ION SOURCE OF SC200 CYCLOTRON

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Abstract

A 200 MeV compact superconducting cyclotron, named SC200, for proton therapy is under development by collaboration of ASIPP (Hefei, China) and JINR (Dubna, Russia). The ion source is a significant subsystem of the cyclotron. A hot cathode internal ion source has been designed and tested for SC200 cyclotron. The ion source has been successfully arc discharged on the test bench. The extracted beam current has been measured over 100 µA and filament lifetime of ion source exceeded 100 h, which indicated that the ion source meets the design requirements. The stability of the filament under strong magnetic field has also been tested and the differences between the two kinds of filament are compared.

INTRODUCTION

Per end of 2018 more than 220000 patients have been treated worldwide with Particle Therapy. About 190000 have been treated with protons, about 28000 with C-ions and about 3500 with He, pions and other ions. Proton therapy delivers radiation to tumor tissue in a much more confined way than conventional photon therapy thus allowing the radiation oncologist to use a greater dose while still minimizing side effects. Proton beam therapy uses special machines, a cyclotron and synchrotron being the most common, to generate and accelerate protons to speeds up to 60 percent the speed of light and energies of up to 250 million electron volts. These high-energy protons are steered by magnets toward the treatment room, and then to the specific part of the body being treated. In some older proton machines, additional pieces of equipment are needed to modify the range of the protons and the shape of the beam. Newer facilities make similar adjustments by fine tuning the energy of the beam and the magnetic fields which guide their path ("pencil beam scanning" or "scanning beam"). These modifications guide the proton beam to precise locations in the body where they deliver the energy needed to destroy tumor cells. The SC200 superconducting cyclotron for hadron therapy is under development by collaboration of ASIPP (Hefei, China) and JINR (Dubna, Russia) [1]. Superconducting cyclotron SC200 will provide acceleration of protons up to 200 MeV with maximum beam current of 400 nA in 2020. Internal ion source of PIG type will be used. The Penning ion source is perfectly suitable for the accelerator, as the structure of it is simple, compact, and discharging-efficient. The penning ion source produces plasma by heating cathode which will release thermoelectron. Under the effect of arc voltage electric field, the accelerated electron will collide hydrogen, then produces plasma. The proton of plasma will be extracted and then be accelerated to form proton beam [2].

EXPERIMENTAL PROCEDURES

We established a test bed to carry out experiment so as to verify the proper functioning of ion source. The structure is shown as below Fig. 1. It includes six sections: magnet system, vacuum system, water cooling system, power system, data-collecting system and gas injection system. The magnet system consists of magnet power, coils and yoke. It can generate uniform magnet field with the maximum strength of 1 T around the arc chamber of ion source [3]. The beam extraction depends on the negative high voltage on the electrode. The beam extraction electrode was fixed outside the ion source by ceramic insulation, and the gap between the electrode and the ion source is kept at approximately 2 mm. The extraction electrode slit size is 4.3 mm × 1 mm with a 1 mm thickness. Because of space limitation, a bent copper block replaces the Faraday cup to collect the extracted ion beam. Such a system enables us to measure total amount of ion current extracted from the plasma chamber of the ion source. On this ion source test bench, a lot of ion source performance tests have been done, including the selection of ion source discharge parameters, the relationship between ion source discharge capacity and gas flow, arc voltage and other factors.

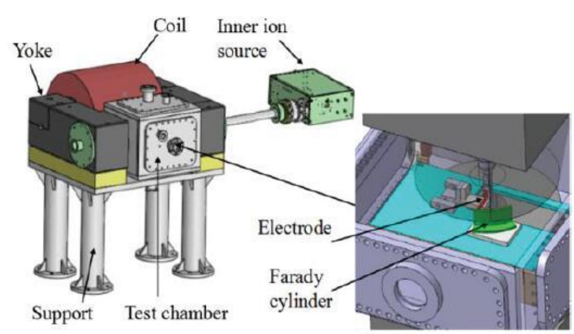

Figure 1: The components of the ion source test bench.

In order to verify that the filament can also maintain good performance in the central region of the SC200 cyclotron, we went to the high magnetic field laboratory of the Chinese Academy of Science and carried out repeated experiments under the 3T magnetic field generated by their equipment. The specific conditions of the device are shown in Fig. 2.

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OPTIMAL DESIGN AND FLUID-SOLID COUPLING THERMAL ANALYSIS OF SC200 SUPERCONDUCTING PROTON CYCLOTRON ELECTROSTATIC DEFLECTOR

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Abstract

In recent years, the study of proton therapy equipment has received increasing attention in China. Hefei CAS Ion Medical and Technical Devices Co., Ltd. (HFCIM) is developing a proton medical device based on the superconducting proton cyclotron. The electrostatic deflector (ESD) is the key extraction component of the SC200 superconducting cyclotron, which uses a high-intensity electric field to bend the beam from the track. The fierce interaction between the proton beam and the deflector septum, causes a great loss of beam and unwanted excess heat accumulation and radiation. In order to minimize the risk of damage caused by the proton beam loss, the fluid solid-thermal coupling analysis of the deflector was performed by applying computational fluid dynamics (CFD) on ANSYS. The maximum temperatures of the septum in various cases of the cooling water speed, the septum thickness and material have been investigated respectively. The result based on analysis provide a valuable reference for the further optimization on the material selection and structural design for ESD.

INTRODUCTION

In modern society, the incidence of cancer has increased year by year. Proton therapy is becoming one of the main methods of cancer treatment because the proton beam provides superior dose distribution at several anatomical sites [1]. In recent years, proton therapy has received increasing attention in China and has made progress on a number of key technologies. Against this background, HFCIM is developing a proton medical device based on superconducting proton cyclotron (SC200). The extracted proton beam energy is designed to be 200 MeV and the beam current is higher than 400 nA. The proton beam extraction uses a precessional extraction method. The electrostatic deflector (ESD) is the first extraction element in the extraction system of the SC200 superconducting cyclotron, which uses a high-intensity electric field to strip the beam from the orbit.

Figure 1 shows the diagram of SC200 extraction system. In a cyclotron, the beam may be deposited at the extraction radius due to the extremely small turn separation. ESD cannot peel off the last turn without affecting the internal turns and the beam loss is much less, which is very difficult. Therefore, the thickness of the septum must be as thin as possible, and the specification range is 0.1 - 0.5 mm. The deposited beam energy is the most important risk of destroying ESD, and its performance directly affects the beam parameters. This paper mainly discusses the structural design and fluid-solid coupling thermal analysis of electrostatic deflector, and provides a valuable reference for further optimization.

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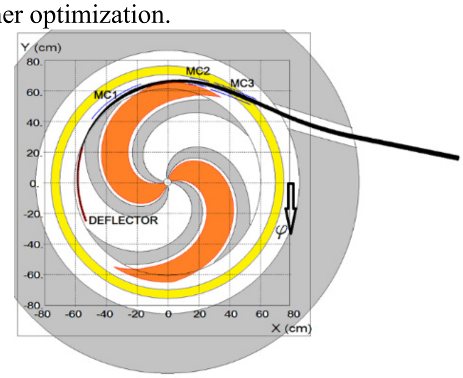

Figure 1: Schematic diagram of SC200 extraction system.

DESIGN AND SIMULATION

Simulation Model

The main structure of the electrostatic deflector is shown in Fig. 2. The septum is an integration design that is directly attached to the housing and has a thickness of only 0.1 mm. The outer surface of the septum is grooved, and the cooling water pipe is brazed in the groove to achieve the best cooling effect.

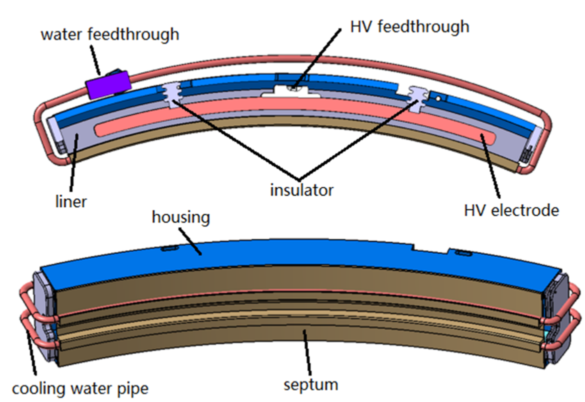

Figure 2: Main structure of ESD.

It is assumed that the beam loss rate at the entrance of the electrostatic deflector is 60%, which means that the

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BEAM DYNAMICS SIMULATION OF THE EXTRACTION FOR A SUPERCONDUCTING CYCLOTRON SC240*

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Abstract

In order to diversify the company's cyclotron, a design study has been carried out on a 240 MeV superconducting cyclotron SC240 for proton therapy, which is based on our experience in design of SC200. In order to increase turn separation and extraction efficiency, resonant precessional extraction method is employed in the extraction system. A first harmonic field consistent with the Gaussian distribution is added to introduce beam precessional motion. Its effects on phase space evolution and turn separation increase is studied by a high efficiency beam dynamics simulation code. According to the study, its amplitude and phase have been optimized to meet the requirements of extraction beam dynamics. Based on beam dynamics simulation, the parameters of extraction system elements (two electrostatic deflectors and six magnetic channels) are chosen. Besides, the effects of sectors spiral direction on beam extraction are studied. Extraction efficiencies and beam parameters have been calculated.

INTRODUCTION

In order to diversify the proton therapy cyclotron product series, ASIPP (Institute of Plasma Physics, Chinese Academy of Sciences) starts designing a superconducting cyclotron to extract 244 MeV, 500 nA proton beam [1]. The main parameters of SC240 cyclotron are listed in Table 1. In order to increase extraction efficiency and decrease the voltage of deflectors as much as possible, the proposed extraction method is resonance extraction [2].

BEAM PRECESSION DESIGN

Working Diagram

Figures 1 and 2 show that Qr drops quickly in extraction region. The beam will cross $Qr = 1$ resonance line when energy reaches 241 MeV. A first harmonic field bump will be added near $Qr = 1$ to increase coherent radial oscillation to generate big turn separation at entrance of first deflector.

Sector Spiral Direction

Before setting about designing the first harmonic field bump, we should choose an optimal sector spiral direction. As shown in Fig. 3, there are two different sector spiral direction: Case 1: beam moves in the direction of the sector spiral, and the position of entrance of first deflector is $\varphi = 44°$; Case2: beam moves against the direction of the sector spiral, and the position of entrance of first deflector is $\varphi = 91°$. We did beam precession simulation in extraction region under the 2 cases above with same amplitude of first harmonic field bump and optimal bump phase. The simulation conditions and results are shown in Fig. 4. The simulation shows that the extraction radius of case 1 is about 1.5 cm bigger than case 2.

Table 1: The Main Parameters of the Cyclotron SC240

Parameter	Value
Extracted beam energy	244 MeV
Extraction radius	80.88 cm
Extraction mechanism	Resonance crossing and precessional motion
Spiral angle (maximum)	71°
Pole radius	84 cm
Outer radius of yoke	160 cm
Hill/valley gap	5 cm/60 cm
Central field/Extraction field	2.39/3.01 T
Coil cross section	dx82×dy115 mm^2
Current density	62.56 A/mm^2
Number of cavity	4
RF frequency	72.79 MHz
Harmonic mode	2
Cavity voltage	~100 kV

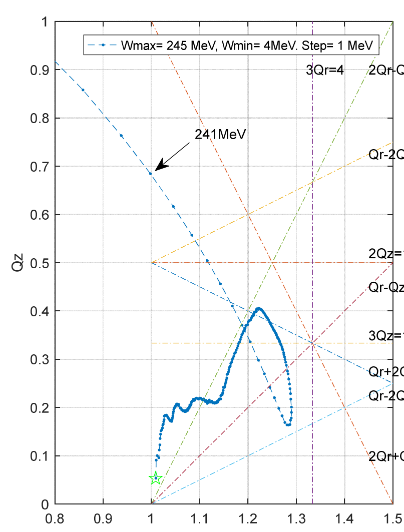

Figure 1: Working diagram of SC240 cyclotron.

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THE DESIGN AND SIMULATION ON THE EXTRACTION SYSTEM FOR CYCIAE-50

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Abstract

A 50 MeV H^- compact cyclotron as a proton irradiation facility is under construction at China Institute of Atomic Energy (CYCIAE-50). The proton beam with the energy of 30 MeV to 50 MeV and the current of 10 μA will be extracted by a single stripping extraction system. In order to reduce the beam loss, the combination magnet is fixed inside the magnetism yoke. The positions of stripping points for the different extraction energy are calculated and the extracted beam trajectories after stripping foil are simulated in detail in this paper. The extracted beam distribution after stripping foil and the extracted beam characters will be studied in this paper. The beam parameters after extraction will be given by the extracting orbit simulation. The design on the whole stripping extraction system has been finished and will be presented in this paper.

INTRODUCTION

China Institute of Atomic Energy (CIAE) has been devoted to the development of the technologies on proton cyclotrons with high intensity and medium & high energy superconductive proton cyclotrons since 1958, when the first cyclotron had been built at CIAE [1]. CIAE has successively built a series of high intensity beam proton cyclotron with different energy ranges of 10 - 100 MeV [2-5]. For 100 MeV H^- cyclotron at CIAE (CYCIAE-100), more than 1 mA beam has been used on the internal target and maximum proton beam current of 520 μA was used on the power target last year [6, 7]. In order to study the radiation damage to spacecraft materials and devices induced single-particle effects in the space radiation environment, a 50 MeV H^- compact cyclotron as a proton irradiation facility is under construction at CIAE (CYCIAE-50).

CYCIAE-50 consists of a 50 MeV proton cyclotron, two beam lines and two radiation effect simulation experimental target station. The 50 MeV proton cyclotron is a compact cyclotron with the proton beam energy from 30 - 50 MeV, and the beam intensity is from 10 nA to 10 μA. The cyclotron is about 3.2 m in diameter, 3.5 m in total height and 80 t in total weight. The proton beam will be extracted by a single movable stripping extraction system. In order to reduce the beam loss, the combination magnet is fixed inside the magnetism yoke. The extracted proton energy can be extracted continuously by changing the stripping position in the radial direction under the fixed magnetic field and RF frequency. A single stripping probe with a piece of carbon foil will be inserted radially from the main magnet pole. The proton beams with the energy range of 30 - 50 MeV will be extracted by charge exchange with stripping foil and then be transported into the crossing point in a combination magnet center separately under the fixed main magnetic field. The combination magnet is fixed between the adjacent yokes of main magnet in the direction of valley region. The difference of stripping extraction system between CYCIAE-50 and CYCIAE-100 is only single stripping probe is chosen and no foil changing system is used for CYCIAE-50 due to the much lower extracted beam current of 10 μA.

The extracted beam optic trajectories are studied in detail in this paper. To keep all the proton beams with various energies transported through the same crossing point in the combination magnet, the stripping probe can be moved in the radial direction and rotated in the angular direction. The positions of stripping points for the different extraction energy are calculated. The extracted beam trajectories after stripping foil and the extracted beam distribution on the stripping foil are simulated in detail in this paper. The design on the combination magnet will be given in this paper too.

THE POSITIONS OF COMBINATION MAGNET AND STRIPPING FOIL

The positions of the stripping points and the combination magnet are chosen by calculating the extraction trajectories of extracted proton beams after stripping foil for different energy with the code CYCTR, which is developed by CIAE [8]. The main magnetic field used to calculate the extraction trajectories is assumed to have midplane symmetry. The extracted beam energy is chosen by the corresponding static equilibrium orbit, which is calculated with the code CYCIOP [9].

For CYCIAE-50, the radius of magnet pole is 1.0 m and the combination magnet will be set at the position of ($R = 1.75$ m, $\theta = 100°$). Figure 1 shows the position of combination magnet and the extracted beam trajectories from the stripping foil to the combination magnet center for different energies. The red lines are the equilibrium orbits. Table 1 shows the positions of stripping foil with the extraction energy between 20 MeV and 50 MeV. The stripping probe is inserted in the radial direction from the main magnet pole and proton beam will be extracted from the direction of valley. The stripping foil is at ($R = 0.9374$ m, $\theta = 58°$) for 50 MeV and ($R = 0.7399$ m, $\theta = 56°$) for 30 MeV. So, the stripping probe needs to be

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THE DESIGN AND CALCULATION ON THE INJECTION AND CENTRAL REGION FOR CYCIAE-50

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Abstract

A 50 MeV cyclotron is being built at China Institute of Atomic Energy (CYCIAE-50). CYCIAE-50 is a compact H^- cyclotron with the proton beam energy of 30 MeV to 50 MeV and the beam current of 10 μA. A multi-cusp H^- ion source with the beam current of 5 mA will be used for this machine. The design on the injection and central region of CYAIAE-50 has been finished. The way of matching the beam from ion source to central region and the design of central region will be present in this paper. In addition, some significant problems in central region will be discussed, including radial alignment, axial focusing, longitudinal focusing, etc.

INTRODUCTION

A compact H^- cyclotron, CYCIAE-50, is being constructed for Space Science and Applied Research (CSSAR). H^- beams are injected through a spiral deflector with the energy of 30 keV, and extracted by a stripping foil in the range 30 - 50 MeV with the current of 10 μA. There are four straight pole sectors in CYCIAE-50 and the magnetic field in central region is 0.9 T. Forth harmonic acceleration is adopted with two 50 kV, 65.5 MHz cavities in the valleys.

A 30 keV, 5 mA external H^- multi-cusp ion source is adopted, which is the same as the case of CYCIAE-100 [1]. The injection system is very simple design. The H^- beam from the ion source enters the spiral inflector in the center region only through a solenoid. The ion source and the injection beamline are being manufactured. The design procedure and results of central region, spiral inflector and injection line are displayed in this paper.

CENTRAL REGION DESIGN

The following problems should be concerned for the central region designs:

- Central region must fit the structures of RF cavities and shimming bars.
- Beams should pass through electrodes from their center line.
- Good axial focussing and radial centering.

CYCLONE is a particle tracking code especially fitting the calculation in central region. The magnet field is got from finite element method program [2] and the 3D electric potential map can be obtained from code of RELAX3D [3]. When we design central region, we usually adjust electrode structure and sometimes shimming bars if necessary.

The process of central region design is shown as follows:

- According to the magnetic field, RF cavities, shimming bars and injection energy, the central region will be designed, partly referring to the design of cyclotrons at CIAE [4-8].
- Finding the reference particle in accelerating region by orbit tracking, who needs the least turn to be accelerated to 50 MeV and has the least amplitude of radial oscillation.
- Tracking reference particle backwards to injection point, by which optimizing electrode structure.
- Tracking multiparticle from injection to extraction and optimizing electrode structure until getting a good beam dynamical result.

The Electrode structure, electric field distribution and particles' trajectory in central region are shown in Fig. 1. Central rays within ±20° phase width is tracked, whose phase history is shown in Fig. 2 and radial misalignment is shown in Fig. 3. It needs 272 turns for the reference particle from 30 keV to 50 MeV and less than 279 turns for particles within ±20° phase width. As shown in Fig. 2, the 40° phase width is compressed to 25° in central region. The amplitudes of radial oscillation around static equilibrium orbit (SEO) are less than 1.5 mm.

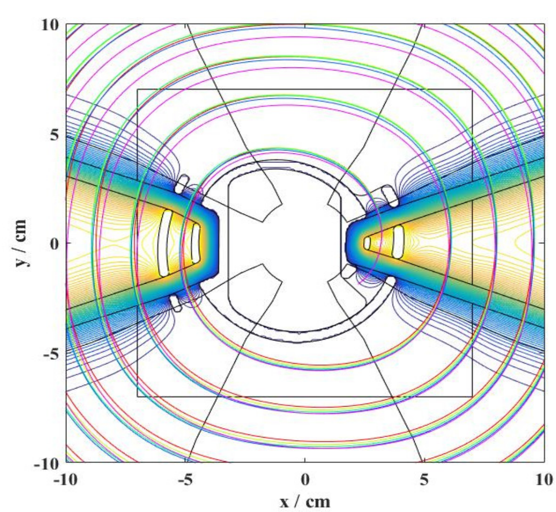

Figure 1: Electrode structure, electric field and particles' trajectory in central region.

The vertical focussing includes magnetic focussing and electric focussing. Vertical electric focussing plays an important role at low energy, which depends on electrode structure and the phase of particles [9].

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MECHANICAL DESIGN OF BEAM LINES FOR 230 MeV SC CYCLOTRON AT CIAE

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Abstract

A 230MeV SC cyclotron (CYCIAE-230) is under construction at CIAE, which can extract 230MeV proton beam for proton therapy. To develop the proton beam transfer system which used in the field of proton therapy, the mechanical design of proton beam lines based on the CYCIAE-230 has been finished at CIAE. The proton beam transfer system includes the beam lines, beam dump, gantry, nozzle, couch, image guidance system, etc. Two beam lines are designed at CIAE this moment. One is for the nozzle system, the other is for the beam dump. The beam lines include four systems: the energy selection system (ESS), the beam transportation systems (BTS), gantry system, and beam dump. The beam lines are very compact in order to match the beam optics and the space limitation. The gantry can be rotated ±180°. The collimation of beam lines is very important to get the better beam quality for the proton therapy. There are several key components in beam lines, such as magnets, energy degrader, beam diagnostics components, vacuum components, etc. The designed mechanical tolerance of the magnets is limited less than 0.1 mm. There are at least four targets on each magnet for collimation and all the components can be adjusted in three dimensions. The magnets are being manufactured now. The mechanical design of proton beam lines based on the CYCIAE-230 will be presented in this paper.

INTRODUCTION

To build a healthy China, improving cancer 5-year survival rate is one of the most important actions. In China, the deaths caused by cancer are 2.5 million, and the new cancer cases are 3.5 million each year [1]. Proton therapy is an effective way for the cancer treatment. More than 4 million cancer patients in China will be beneficial from proton therapy each year.

To meet urgent needs for proton therapy, one of the technology innovation plan in "Dragon 2020 — major medical equipment - medical cyclotron key technology and engineering research" had launched by China National Nuclear Corporation (CNNC) [2]. In this project, a 230 MeV compact superconducting cyclotron is developing at China Institute of Atomic Energy (CIAE) to extract 230 MeV proton beam [3]. Beam lines for the 230 MeV SC cyclotron to transport the beam to the nozzle system and to the beam dump are under construction at the same time.

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The whole project consists of a 230 MeV SC cyclotron (CYCIAE-230), the energy selection system (ESS), the beam transportation systems (BTS), a gantry and a beam dump, as shown in the Fig. 1 [4].

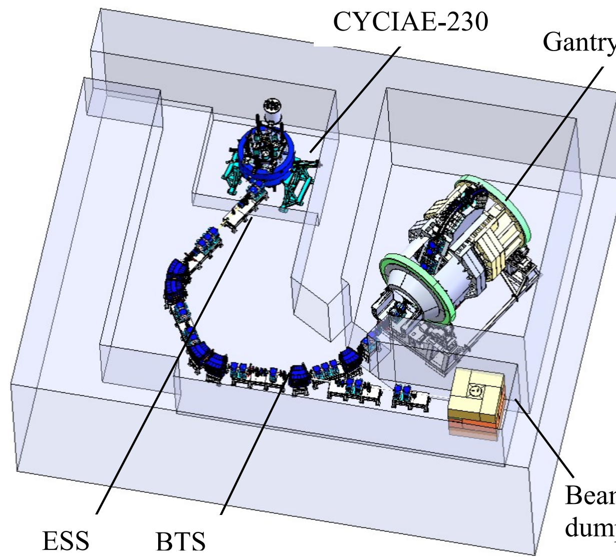

Figure 1: Layout of CYCIAE-230 and beam lines.

The beam line is about 47 m long. The ESS is 5.2 m long. The BTS is 19.8 m long, which is the longest system in beam lines. The beam line on gantry is 13.5 m long and the beam line to beam dump is 8.5 m long.

BEAM LINES ON GROUND

The beam lines on ground divided into three parts, include ESS, BTS and the beam line to beam dump. The height of the beam on ground is 1.25 m, all of the components in beam lines on ground are designed to meet this requirement.

There are trenches at both sides of the beam lines on ground. Along the beam direction, cables are put into the left trench and water pipes are put into the right trench. All of the components are designed to meet this layout. The mechanical specifications of the components in beam lines on ground are listed in Table 1.

There are many components in ESS, one of the most important component is the energy degrader. The energy degrader is used to adjust the proton energy, which can fit to the depth of the tumor [5]. To test the performance of the degrader, two types of degrader had been made. The shape of the two degraders are wedge and circle, as shown in the Fig. 2. The energy distribution of the circular degrader is

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A 50 MeV PROTON BEAM LINE DESIGN

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Abstract

The cyclotron center at the China Institute of Atomic Energ (CIAE) is now developing a medium-energy proton irradiation device that provides a proton beam with an energy range of 30 MeV to 50 MeV to simulate a space proton radiation environment, which has a significant impact on spacecraft. A beam transport line is designed for irradiation effect study based on this 50 MeV compact cyclotron, which requires continuous adjustment of the beam energy and the beam spot on the target requires high uniformity. The proton beam extracted from the cyclotron is adjusted to the energy required by using the degrader and the energy selected system, then the proton beam will be transported to the target. In order to obtain uniform large-diameter beam spot on the target, a wobbling magnet is installed on the beam line to uniformly sweep the proton beam on the target and finally obtain the proton beam with energy of 10 MeV-50 MeV, current of 10 μA and beam spot of 20 cm*20 cm on the target.

INTRODUCTION

Protons are the main components of the space radiation environment, causing radiation damage to spacecraft materials and devices, as well as induced single-particle effects, which seriously threaten satellite safety, especially the scientific satellite payload is more sensitive to damage caused by space protons. The Research Center of Cyclotron in China Institute of Atomic Energy (CIAE) has designed a medium-energy proton irradiation device, which is mainly composed of a 50 MeV proton cyclotron, a beam transport line and an experimental terminal. The center has already developed several compact cyclotrons and proton beam lines [1-4].

The 50 MeV cyclotron is designed as a compact structure that extracts protons from 30 MeV to 50 MeV, with a lower energy range, a degrader is provided on the beam line to reduce beam energy to 10 MeV. For irradiation effect study in this case, the energy dispersion required is small so the energy selected system is necessary.

A wobbling magnet is installed a few meters in front of the target to provide a magnetic field with periodic rotation changes, which make the beam spot uniformly sweep on the target.

The layout of the beam line and element design is shown in this paper.

LAYOUT OF THE 50 MeV PROTON BEAM TRANSFER SYSTEM

The layout of the 50 MeV irradiation dedicated proton beam transport system is shown in Fig. 1. Since the proton energy extracted by the cyclotron is adjustable in the range of 30 MeV~50 MeV, a combination magnet is placed inside the yoke which will combine proton beams with different energies to one beam line. The diagnostic box is including faraday cup (FC), fluorescent target (SS) and the beam profile monitor (BPM), which are used to measure the beam intensity and the beam profile; D1 is the degrader, which can reduce the beam energy extracted from the cyclotron to a lowest energy 10 MeV by using different thicknesses of graphite; C is a collimator; B1 and B2 are two 45° bending magnets that deflect the proton beam by 90°, and these two bending magnet and the collimators can select proton energy to reduce energy dispersion; Q is a quadrupoles for proton beam focusing; SXY is steering magnet for correcting the particle center; T is the vacuum pump for obtaining the vacuum of the pipe; W is the wobbling magnet that provide a magnetic field with periodic rotation changes. This magnetic field causes the beam on the target to periodically rotate and scan to improve the uniformity and the size of the beam spot on the target [5].

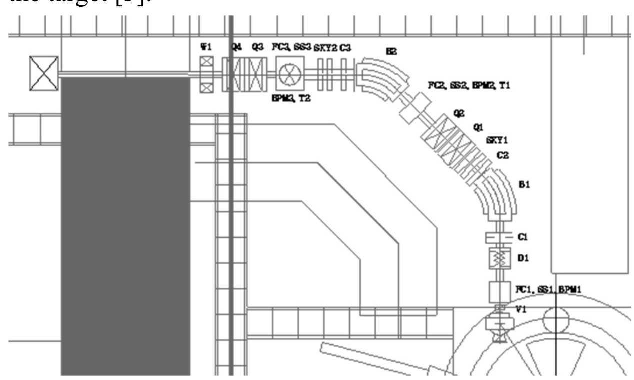

Figure 1: The layout of the 50 MeV beam transfer system.

The total length of the beam line is about 12 m, the inner diameter of the beam pipe is Φ78 mm, and the material is aluminium. The optics and the magnets design will be given in detail.

OPTICS RESULTS

The 50 MeV compact proton cyclotron uses a stripping method to extract the proton beam with the energy range 30 MeV~50 MeV, the maximum beam intensity is 10 μA, and the minimum intensity is 10 nA. The beam with different energy after the stripping foil is transported through the combination magnet into the same beam pipe. The initial input parameters for the optical matching are the σ matrix of the beam on the stripping film provided by the extraction system (calculated by using the COMA program) and the beam transfer matrix of the stripping foil to the exit of the combination magnet (by using GOBLIN and STRAPUBC). The optical matching of the beam line

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MAGNETIC FIELD MEASUREMENT AND SHIMMING FOR A MEDICAL COMPACT CYCLOTRON

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Abstract

A compact cyclotron is developed by Cyclotron Research and Design Center at China Institute of Atomic Energy (CIAE) to extract 14 MeV proton beam for medical radioisotopes production, so as to meet the market demands of early diagnosis of malignant tumors, cardiovascular and cerebrovascular diseases. Owing to the small size and limited space of small medical cyclotrons, critical requirements are imposed on magnetic field measurement. For this reason, a magnetic field measurement system, with high-precision and high-stability, suitable for small cyclotrons is adopted and then an efficient magnetic field shimming method is used, which greatly reduces the construction period. It provides a strong guarantee for the stable operation of medical small cyclotrons.

INTRODUCTION

The Cyclotron Research and Design Center at China Institute of Atomic Energy developed a 14 MeV medical cyclotron for boron neutron capture therapy (BNCT). The main magnet of the cyclotron adopts a compact size, and the diameter is 1 m. Four straight sectors are adopted and the harmonic number is 4 in the cyclotron. The gap between the magnetic poles is between 23 mm and 26 mm, and the beam current is 1 mA. For the above characteristics of the BNCT cyclotron, a fully automated magnetic field measurement system for the magnetic field mapping and shimming is adopted.

DESIGN OF THE MAGNETIC FIELD MAPPING INSTRUMENT

Principally it should be ensured that the components of the field mapping system placed inside the accelerator are non-magnetic and the eddy current is not obvious during the movement of the system. Hall probe is used for measuring the magnetic field ranging from 400 G to 20 kG with the calibrated precision of 10^{-4} which means the field measurement errors is less than 2 G. The measuring arm can rotate freely clockwise and counterclockwise around the central axis of the accelerator with the angular positioning precision of 20 s. The Hall probe on the measuring arm can move in the radial direction with the range from -2 cm to 50 cm based on the center of the cyclotron and the radial positioning precision reaches 0.1 mm. The period of the magnetic field measuring is less than 8 hrs for one mapping in which the radial interval is 1 cm and the angular interval is 1° [1]. The random error and system error are shown in Table 1.

Table 1: Parameters of Measuring Precision

Random Error	Value
Magnetic field measuring error/Gs	2
Radial measuring error/mm	0.1
Radial positioning error/mm	0.1
Angle measuring error/s	12
Angle positioning error/s	20
System Error	**Value**
Measuring arm horizontal error/mm	0.1
Measuring arm axial error/mm	0.2
Center shaft tilt error/deg	0.2

MECHANICAL STRUCTURE

The main mechanical structure is mainly composed of the support rail, the measuring arm, the Hall probe base, the angular rotating component, the radial driving component, and the center shaft component [2]. The support rail adopts aluminum alloy material, which is the support of the measuring arm with two rounds of balls supporting between to reduce the resistance during the movement. The angular rotating component built-in circular grating drives the arm rotation via the central shaft. Both ends of the Hall probe base are connected to the transmission rope, and the radial movement is driven by the radial drive component, and the radial position is indirectly determined according to the rotation angle of the rope wheel. The mechanical structure is shown in Fig. 1.

CONTROL MODULE

The radial motion controller sends the analog signal to the servo motor driver to drive the motor according to the position reference and feedback. In the angular direction, the controller drives the stepping motor by calculating the output count pulse to realize open loop control. Indirect closed-loop control is implemented by a software algorithm according to the position signal fed back by the

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MECHANICAL MODIFICATIONS OF THE MEDIAN PLANE FOR THE 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. Recently a significant upgrade has been proposed to increase the light ion beam intensity by means of extraction by stripping. For the implementation of the new extraction mode, many relevant modifications are needed in the median plane. The biggest upgrade action is the replacement of the present superconducting magnet with a new one, compatible with the beam trajectory and envelope in the extraction by stripping. The extraction by stripping mode implies the installation of two stripper systems, one in a hill and the other in a valley, that allow to extract all the ions requested by the users. Finally, since the present electrostatic extraction mode will be maintained, several relevant mechanical issues have to be faced when switching from one extraction mode to the other one, the location of one electrostatic deflector being the same as the stripper system. The focus of this paper will be the presentation of the different mechanical features involved in the upgrade.

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]. To reach our aim, it is necessary to design a stripper device, to be implemented when the Electrostatic deflector is not used and removed. To achieve fast extraction trajectories when we use the extraction by stripping, compatible with simulation studies, it is necessary to design a new extraction channel that overlaps geometrically with the tubes of the electrostatic deflectors movements, increasing the complications of the two setup functioning. These features cause the definition of a new median plane and the redesign of some components of the CS.

MEDIAN PLANE REDEFINITION

To satisfy all the extraction by stripping equipment, the median plane of the CS will be modified (Fig. 1).

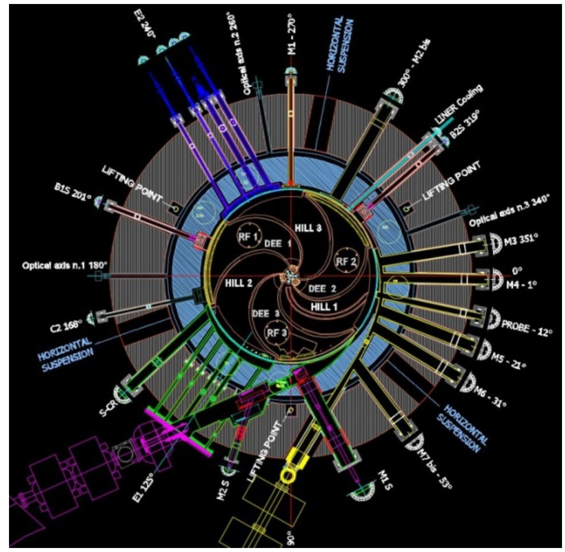

Figure 1: The new median plane.

Due to the new extraction channel, it has been necessary to optimise the position of the three lifting points and of the three horizontal suspensions of the vacuum chamber [2]. The design of the new extraction channel must allow the arrangement of two new magnetic channels, M1S and M2S, in addition to those already existing in the cyclotron, to locally reduce the magnetic field and focus the beam in the radial direction. These new magnetic channels have interferences with the electrostatic extraction mode. The M1S shaft collides with the actual extraction channel and so to solve that, the shaft has a suitable gap to permit the beam trajectory of the electrostatic extraction mode. The M2S channel has an interference with one of the electrostatic deflector handlings; therefore, we designed the new extraction channel to make the M2S channel and the electrostatic deflector setting compatible. The M1S and M2S are made of three iron bars, that need of a housing to contain them and a shaft, connected with the housing, that allows to modulate their position, for our selected ions. For the two magnetic channels, the geometrical dimensions and the resultant forces of the iron bars are different.

For both magnetic channels, the resultant forces are tilted in relation to the penetrations axis, we implemented mechanical simulations by means of Comsol Multiphysics, a FEM (Finite Element Method) software. To obtain acceptable stress and strain values for the two housings and shafts, we optimized the mechanical design and the choice of the materials. Moreover, for the extraction by stripping, two identical compensation bars, B1S and B2S

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3D MAGNETIC OPTIMIZATION OF THE NEW EXTRACTION CHANNEL FOR THE LNS SUPERCONDUCTING CYCLOTRON

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Abstract

The upgrade of the Superconducting Cyclotron operating at INFN-LNS is the main objective of the general upgrade of the LNS facility, consisting in the enhancement of light-medium ion beam intensity. To overcome the present maximum power of 100 W of the beam extracted by electrostatic deflector and achieve a beam power as high as 10 kW, the implementation of the extraction by stripping method has been proposed. Intense ion beams with mass in the range 10 to 40 amu (^{12}C, ^{18}O, ^{20}Ne, ^{40}Ar) in the energy range of interest (15-70 MeV/u) will be delivered to the NUMEN experiment, as well as used for production of in-flight radioactive beams. The present work consists in the optimization of the magnetic channels needed to limit the radial and axial beam envelopes. The design of the magnetic channels has been accomplished by fully three-dimensional magneto-static simulations using Comsol Multiphysics and a custom transport code developed in Matlab along the last year at INFN-LNS. The effect of a magnetic shielding structure in the extraction channel is presented, together with the possibility of producing a magnetic gradient from an asymmetric coil.

INTRODUCTION

A custom transport code was developed at INFN-LNS to support the design of different parts of the extraction by stripping system. In particular stripping foil area, extraction channel geometry and magnetic channels. The tool is fully three dimensional and starting from the measured middle-plane magnetic field map deduce the three-dimensional magnetic field map in the acceleration region of the cyclotron. The stationary beam envelope in the radial and vertical phase-space diagrams are found for all the beams of interest. An example of what called auto-ellipses is shown in Fig. 1 in the case of $^{18}O^{6+}$ at 45.6 AMeV, nominal beam condition considered in all this paper for comparison reason.

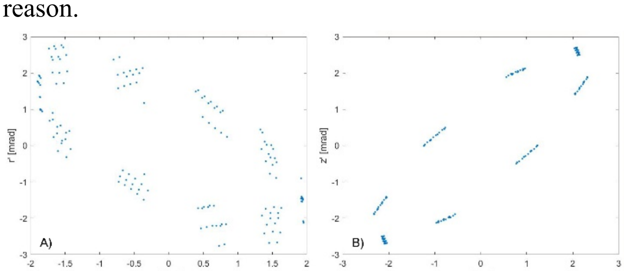

Figure 1: Auto-ellipse beam particle distributions of $^{18}O^{6+}$ at 45.6 AMeV, A) radial phase-space diagram, B) vertical phase-space diagram.

The size of the beam envelope was chosen to be close to the normalized beam emittance of 1π·mm·mrad for 99% of the beam envelope, value estimated for our accelerated beam. The stationary beam envelope along a full turn was also calculated, and the intersection with the stripping foil region (shown in red in Fig. 2) were saved every approximately 0.03 degree. The showed magnetic field map is a merge between measured map in the acceleration region, and the remaining part coming from a fully 3D magnetic model of the entire cyclotron joke and superconductive coils. Acceleration region was not extracted from the 3D simulation because of missing trimmer coil in the simulation model. The black contour of Fig. 2 marks the walls of the vacuum chamber. If the beam trajectory crosses this black contour the code mark the particle as lost. In the centre of the cyclotron a black circle represents a beam forbidden area in correspondence of the central region.

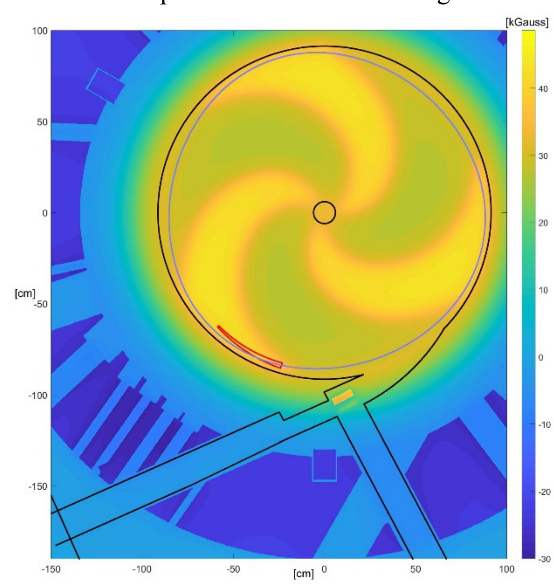

Figure 2: Magnetic field map of the cyclotron with vacuum region delimited by black line, foil region in red and stationary trajectory in blue.

After, the beam is fully stripped by the stripping foil the trajectory changes drastically. By selecting carefully, the stripping foil location it is possible to drive the deflected beam through the new extraction channel. Figure 3 shows the fully stripped trajectory in blue. Immediately after the cyclotron joke there are red dots representing hit of lost particles. Figure 4 shows the behaviour of the stripped beam by showing in light blue the magnetic field along the central particle trajectory. In black the number of remaining particles divided by two (for graphical reason). Then the beam envelope is represented showing the maximum distance between the central particle and the farther beam

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VERTICAL FOCUSSING WITH A FIELD GRADIENT SPIRAL INFLECTOR

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Abstract

Traditional spiral inflectors suffer from vertical defocussing, leading to beam loss. In this study the electrode shape of an inflector is modified to intentionally produce transverse electric field gradients along the beam path, which have a significant influence on the optics. This is done by placing the traditionally parallel electrodes at an angle relative to each other in the transverse plane, creating a quadrupole field on the central path. Varying the electrode angle along the path length creates an alternating-gradient effect. The electrode entrance and exit faces are also shaped to create quadrupoles inside the fringe field. By numerical optimisation a design with good vertical focussing is obtained. Experiments show a roughly 100% improvement in transmission in cases where the buncher is turned off. However, high losses at extraction are observed with the buncher turned on, due to RF-phase spread introduced by longitudinal defocussing in the inflector. This results in an improvement of only 20% during normal cyclotron operation, and shows that an inflector should ideally focus vertically and longitudinally at the same time. Ongoing work to achieve such combined focussing is briefly described.

INTRODUCTION

Spiral inflectors based on the Belmont-Pabot [1] design are known to have very good transmission, but suffer from vertical defocussing, which can lead to beam loss in the inner region of the cyclotron [2]. This undesired vertical behaviour is illustrated in Fig. 1, where the beam passing through the C-inflector of the Solid-Pole-Cyclotron 2 (SPC2) [3] at iThemba LABS is modelled in TOSCA [4]. A substantial portion of the beam strikes the vertical slits downstream from the inflector, or is lost vertically on the puller electrode.

Solutions to the vertical defocussing problem implemented in the past include the addition of an electrostatic or magnetic quadrupole behind the inflector, but this requires additional space in the cramped inner region [5], and does not prevent emittance blow-up in the inflector itself. Another solution proposed at Dubna, is to give the electrodes a V-shape to create focussing electric fields, similar to the vertical direction of a spherical electrostatic bend [2]. In this article a design is introduced that involves shaping the inflector electrodes to create quadrupole electric fields in the transverse plane, and varying their strengths along the path length, to create an effect similar to strong focussing.

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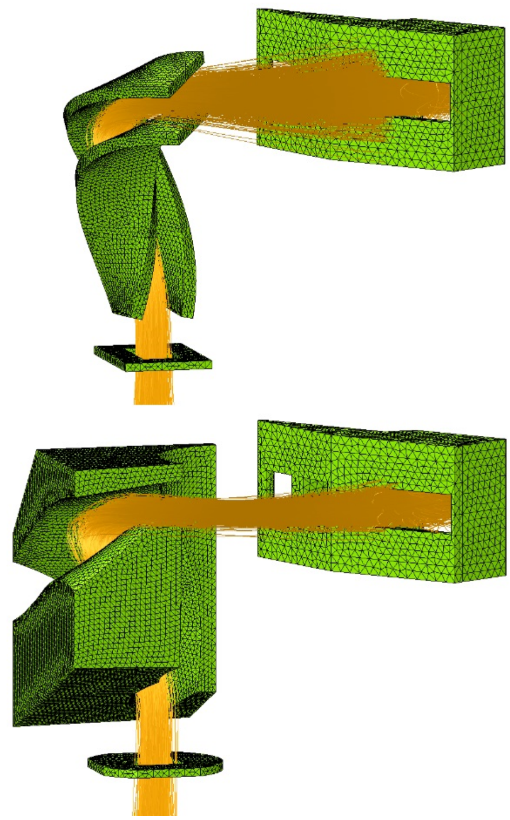

Figure 1: Beam passing through the inflector and striking the vertical slit in an ordinary spiral inflector (top), and in a field gradient inflector with vertical focussing (bottom).

ELECTRIC FIELD GRADIENTS

The traditional spiral inflector design by Belmont and Pabot specifies the electric field on the central trajectory, but places no constraints on the field gradients. Since the first order optics of the device depends on these gradients, it might be possible to control the focussing of an inflector by selecting appropriate electric field gradients.

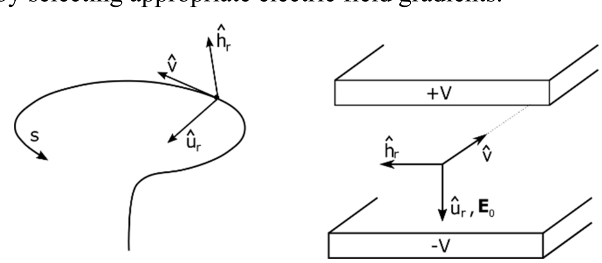

Figure 2: Standard inflector coordinate system (left) and the positioning of the electrodes to create the central field $\boldsymbol{E_0}$ (right).

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RESEARCH ON METALLIC ION BEAM PRODUCTION WITH ELECTRON CYCLOTRON RESONANCE ION SOURCES

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Abstract

Many experiments in nuclear physics request the production of metallic ion beams. All elements from Lithium up to Uranium are of interest and most of them are required as a specific isotope which demands commonly enriched materials. Depending on the material properties, beams of rare isotopes can be produced from solid materials or solid compounds. In this report the results of experiments carried out under a collaboration of JINR and iThemba LABS on the production of metallic ions from Electron Cyclotron Resonance (ECR) Ion Sources using resistive oven evaporation, Metal Ions from VOlatile Compounds (MIVOC) method and sputtering technique will be presented.

INTRODUCTION

Several methods for the production of ions from solid materials have been developed. Solid materials can be evaporated from a resistor or inductive oven inserted into a source chamber [1, 2]. Refractory metals can be sputtered by plasma ions [3] or inserted into plasma with subsequent heating by energetic plasma electrons ("insertion technique") [4, 5]. Another way of producing ions of solids is to feed plasma of an organometallic compound using the MIVOC method [6]. The selection of the best method to feed solids into ECR ion sources strongly depends on specific properties of materials.

OVEN EXPERIMENTS

Development of the oven evaporation method for production of ions of solids for FLNR JINR ECR ion sources was stimulated by the requirements of production of intense ^{48}Ca beam, which is the key ingredient in the experiments on synthesizing of new heavy nuclei.

To solve this problem, a new method for the solid material feed into the ECR source was developed. The combination of a micro oven with a hot tantalum liner inside the discharge chamber allowed the production of intense beams of ions of metals with relatively low evaporation temperature (Li, Mg, Ca, Bi) [7]. This development allowed long-term experiments on synthesis of super heavy elements during last 20 years and led to discovery of new super heavy elements with Z = 113–118 [8].

The experience of FLNR ECR ion source group was successfully applied in a collaboration of JINR and iThemba LABS on the production of metallic ions from ECR ion sources at iThemba LABS.

The experiments on production of ions of solids by oven evaporation method were performed with the GTS2 ECR ion source [9]. The layout of the beam line used for the experiments is shown in Fig. 1. In all experiments the source was operated with 14 GHz frequency.

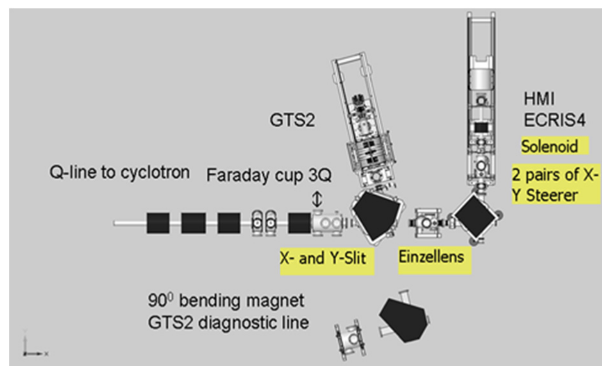

Figure 1: Experimental layout for the oven and MIVOC experiments.

The GTS2 ECR ion source is equipped with two ports through which electrically heated ovens can be introduced into the plasma chamber. The oven used for the measurements was designed and manufactured by the ion source group at FLNR. The design is based on the micro oven [10], which has been successfully used for several years for the production of ^{48}Ca and Li ion beams. The present design of the oven allows using a crucible with an inner volume of 480 mm^3, which is about 6 times more than that of the original design. The calibration for the oven inner temperature as a function of the oven electrical heating power is shown in Fig. 2. The oven was mechanically and electrically connected to the oven support of the GTS2. The oven is positioned inside the plasma chamber in a way that the tip of the oven has a distance of 30 mm to the bias disc. In addition, a liner made from 0.1 mm stainless steel sheet was installed inside the plasma chamber. The liner has folds on both ends to keep it in 1 mm distance to the plasma chamber wall to reduce the thermal contact. This results in a higher temperature of the liner by means of microwave and plasma heating thereby preventing the condensation of the oven material.

The beam extracted from GTS2 was either analysed with Faraday cup 3Q behind the 104°-bending magnet in the Q-line or with Faraday cup Q2 in the diagnostic beam line behind the 90°-bending magnet (see Fig. 1).

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SIMULATION OF THE AXIAL INJECTION BEAM LINE OF DC140 CYCLOTRON OF FLNR JINR

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Abstract

Flerov Laboratory of Nuclear Reaction of Joint Institute for Nuclear Research carries out the works under creating of FLNR JINR Irradiation Facility based on the cyclotron DC140. The facility is intended for SEE testing of microchip, for production of track membranes and for solving of applied physics problems. The main systems of DC140 are based on the DC72 cyclotron ones that now are under reconstruction. The DC140 cyclotron is intended for acceleration of heavy ions with mass-to-charge ratio A/Z within interval from 5 to 5.5 up to two fixed energies 2.124 and 4.8 MeV per unit mass. The intensity of the accelerated ions will be about 1 pμA for light ions (A<86) and about 0.1 pμA for heavier ions (A>132). The injection into cyclotron will be realized from the external room temperature 18 GHz ECR ion source. The simulation of the axial injection system of the cyclotron is presented in this report.

INTRODUCTION

Flerov Laboratory of Nuclear Reaction of Joint Institute for Nuclear Research carries out the works under the creating of Irradiation Facility based on the DC140 cyclotron. The DC140 will be a reconstruction of the DC72 cyclotron [1, 2]. Table 1 presents the main parameters of DC140 cyclotron

Table 1: DC140 Cyclotron Main Parameters

Pole (Extraction) Radius, m	**1.3 (1.18)**	
Magnetic field, T	1.415 to 1.546	
Number of sectors	4	
RF frequency, MHz	8.632	
Harmonic number	2	3
Energy, MeV/u	4.8	2.124
A/*Z* range	5.0 to 5.5	7.577 to 8.25
RF voltage, kV	60	
Number of Dees	2	
Ion extraction method	electrostatic deflector	
Deflector voltage, kV	70	

The irradiation facility will be used for Single Event Effect (SEE) testing of microchips by means of ion beams (^{16}O, ^{20}Ne, ^{40}Ar, ^{56}Fe, $^{84,86}Kr$, ^{132}Xe, ^{197}Au and ^{209}Bi) with energy of 4.8 MeV per unit mass and having mass-to-charge ratio *A*/*Z* in the range from 5.0 to 5.5.

Besides the research works on radiation physics, radiation resistance of materials and the production of track membranes will be carrying out by using the ion beams with energy of about 2.124 MeV per unit mass and A/Z ratio in the range from 7.577 to 8.25.

The working diagram of DC140 cyclotron is shown in Fig. 1. The acceleration of ion beam in the cyclotron will be performed at constant frequency f = 8.632 MHz of the RF-accelerating system for two different harmonic numbers h. The harmonic number $h = 2$ corresponds to the ion beam energy $W = 4.8$ MeV/u and value h = 3 corresponds to $W = 2.124$ MeV/u. The intensity of the accelerated ions will be about 1 pμA for light ions ($A \le 86$) and about 0.1 pμA for heavier ions ($A \ge 132$).

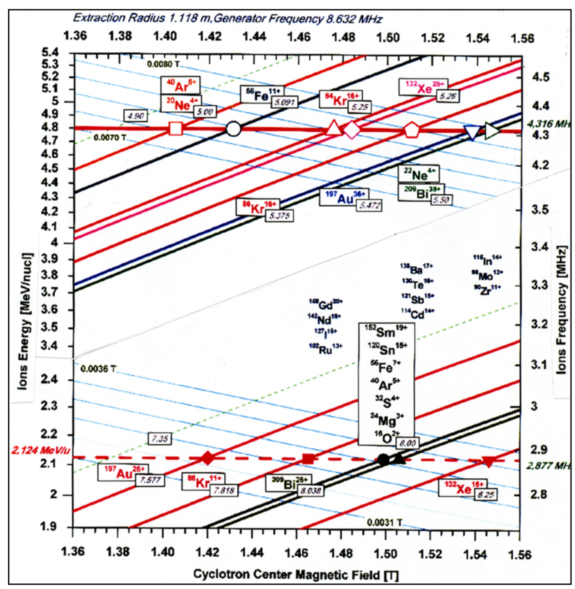

Figure 1: Working diagram of DC140 cyclotron.

The axial injection system of DC140 cyclotron will be adapted from the existing DC72 cyclotron one [3].

This report presents the simulation of the beam dynamic in the axial injection beam line of DC140 cyclotron. The simulation was carried out by means of MCIB04 program code [4].

ECR ION SOURCE

The ion beams are produced in superconducting ECR ion source DECRIS-SC designed in Flerov Lab of JINR [5]. The working frequency DECRIS-SC is equal to 18 GHz. It is able to produce the beams of ion from ^{22}Ne to ^{209}Bi. The ion beam currents at the source exit sufficient for the facility operation are contained in Table 2.

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THE RESULTS OF MAGNETIC FIELD FORMATION AND COMMISSIONING OF HEAVY-ION ISOCHRONOUS CYCLOTRON DC280

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Abstract

The DC280 cyclotron is the new accelerator of FLNR Super Heavy Elements Factory. It was commissioned in the beginner of 2019. DC280 is intended for production of high intensity, up to 10 pmkA, beams of heavy ions with mass to charge ratio A/Z = 4 - 7. The wide range of accelerated ions from Helium to Uranium and smooth variation of extracted beam energy in the range W = 4 to 8 MeV/nucl. are provided by varying of the level of main magnetic field from 0.64 T to 1.32 T. The DC280 magnetic field was formed in a good conformity with results of computer modelling. In spite of the commissioning of cyclotron still is in progress, the first experiments gave the intensity 1.35 pmkA of $84Kr^{14+}$ and 10 pmkA of $12C^{2+}$. At the present work the results of calculations, magnetic field measurements and first experiments are presented.

INTRODUCTION

The main feature of new DC280 cyclotron is a wide range of operational modes and a high intensity of accelerated beams [1].

The cyclotron can accelerate heavy ions from Helium to Uranium with mass to charge ratio of A/Z = 4 – 7. The extracted energy of the beams can be smoothly varied in the range of W = 4 – 8 MeV/nucl. by changing of main magnetic field level and shape. The main challenge of DC280 magnetic system formation is covering all possible operational modes with minimal power consumption. According to the working diagram, Fig. 1, the magnetic field level should be varied in the wide range from 0.64 T to 1.32 T. In parallel, the isochronous radial growth of average magnetic field should be varied from 30 Gs to 100 Gs. For that, the 11 radial and 4 pairs of harmonic correcting coils are utilized and provide the needed operational correction.

DC280 is a compact type cyclotron. It has H-shape main magnet with 4-meter pole diameter, Table 1. Four pairs of straight, 45-degrees sectors form the variation of magnetic field, that keeps betatron frequencies in the ranges $1.005 < Qr < 1.02$ and $0.2 < Qz < 0.3$. The isochronous magnetic field is formed by variation of sectors height from the pole side. The sectors surfaces from median plane side stay flat. It decreases the sensitivity of replay function and, as a result, decreases the requirement to accuracy of sector shaping. DC280 magnet was manufactured and assembled with designed accuracy. Table 1 presents some important parameters with accuracies that were measured after assembling.

For DC280 magnetic field formation the original magnetometer was created. As a result of mapping and final formation, the magnetic field was formed in a good agreement with results of computer modelling. The first harmonic amplitude was decreased to about 1 Gs.

The first experiments have shown the efficiency of beam transmission from the inner radiuses until deflector has reached up to 90%.

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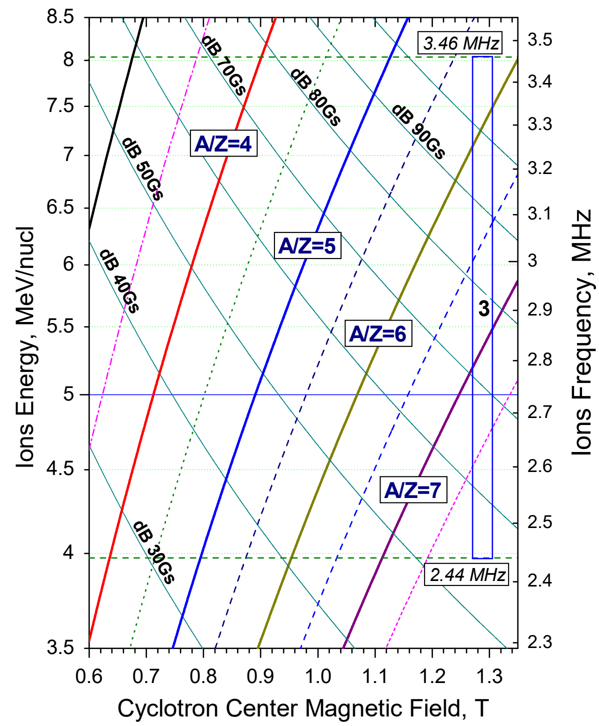

Figure 1: DC-280 Working diagram.

Table 1: Main Parameters of DC-280 Cyclotron Magnet

Parameter	Value
Main magnet size, mm	8760x4080x4840
Pole, mm	4000
Pole to pole gap, mm	500, accuracy ±0.2
Sector to sector gap, mm	208, accuracy ±0.17
Poles axis centering, mm	accuracy 0.53
Sector angular extent (spirality)	45° (0°)
Main magnet power, kWt	280
Correcting coils power, kWt	18

MAPPING SYSTEM

For final magnetic field formation, the DC280 mapping system was created [2]. The mapping system is based on 14 Hall probes and measures the magnetic field in a polar coordinate system with accuracy 10^{-4}. The Hall probes are placed on the plank with radial distance of 160 mm one to another. The plank is moved radially with a step of 10 mm

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SIMULATION OF THE BEAM EXTRACTION SYSTEM OF DC140 CYCLOTRON OF FLNR JINR

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Abstract

Flerov Laboratory of Nuclear Reaction of Joint Institute for Nuclear Research carries out the works under creating FLNR JINR Irradiation Facility based on the cyclotron DC140. The facility is intended for SEE testing of microchip, for production of track membranes and for solving of applied physics problems. The main systems of DC140 are based on the DC72 cyclotron ones that now are under reconstruction. The DC140 cyclotron is intended for acceleration of heavy ions with mass-to-charge ratio *A/Z* within interval from 5 to 5.5 up to two fixed energies 2.136 and 4.8 MeV per unit mass. The intensity of the accelerated ions will be about 1 pμA for light ions (*A*<86) and about 0.1 pμA for heavier ions (*A*>132). The beam extraction system consists of electrostatic deflector and two magnetic channels. The simulation of the extraction system of the cyclotron is presented in this report. The extracted beams characteristics outside the cyclotron, that will serve as initial conditions for the design of experimental beam lines of FLNR JINR IF are determined.

INTRODUCTION

Flerov Laboratory of Nuclear Reaction of Joint Institute for Nuclear Research carries out the works under the creating of Irradiation Facility based on the DC140 cyclotron. The DC140 will be a reconstruction of the DC72 cyclotron [1, 2]. Table 1 presents the main parameters of DC140 cyclotron.

Table 1: DC140 Cyclotron Main Parameters

Parameter	Value	
Pole (extraction) radius, m	1.3 (1.18)	
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RF voltage, kV	60	
Number of Dees	2	
Ion extraction method	electrostatic deflector	
Deflector voltage, kV	70	

The irradiation facility will be used for Single Event Effect (SEE) testing of microchips by means of ion beams (^{16}O, ^{20}Ne, ^{40}Ar, ^{56}Fe, ^{84,86}Kr, ^{132}Xe, ^{197}Au and ^{209}Bi) with energy of 4.8 MeV per unit mass and having mass-to-charge ratio *A*/*Z* in the range from 5.0 to 5.5.

Besides the research works on radiation physics, radiation resistance of materials and the production of track membranes will be carrying out by using the ion beams with energy of about 2.124 MeV per unit mass and *A/Z* ratio in the range from 7.577 to 8.25.

The working diagram of DC140 cyclotron is presented in report MOP019 at this conference [3]. The acceleration of ion beam in the cyclotron will be performed at constant frequency f = 8.632 MHz of the RF-accelerating system for two different harmonic numbers h. The harmonic number h = 2 corresponds to the ion beam energy W = 4.8 MeV/u and value h = 3 corresponds to W = 2.124 MeV/u. The intensity of the accelerated ions will be about 1 pμA for light ions (A ≤ 86) and about 0.1 pμA for heavier ions (A ≥ 132).

The extraction system of DC140 cyclotron differs from DC72 cyclotron one, based on extraction by stripping foil [4], and consists of electrostatic deflector and two magnetic channels. The first is the passive channel placed in the region of strong magnetic field of the cyclotron. The second is permanent magnet channel placed in the region of low level magnetic field.

This report presents the simulation of the $^{209}Bi^{38+}$ ion beam dynamic in the extraction beam line of DC140 cyclotron.

CYCLOTRON MAGNETIC FIELD

The magnetic field of DC140 cyclotron within the project range is formed by variation of the currents in the main and in ten correcting coils. Radial distribution of the magnetic fields for acceleration of $^{209}Bi^{38+}$ ions up to energy W = 4.8 MeV/u is shown in Fig. 1 [5].

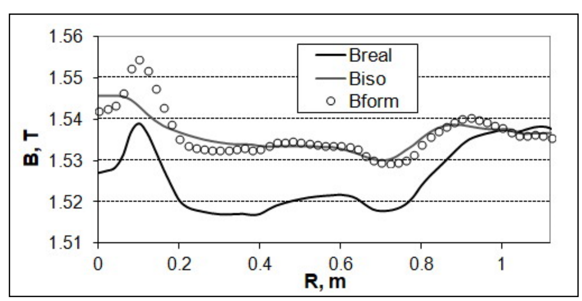

Figure 1: Magnetic fields for acceleration of $^{209}Bi^{38+}$ ions. Breal – magnetic field formed by main coils ; Biso – isocronous magnetic field ; Bform – magnetic field formed by main and correcting coils.

For the other kind of ions, the form of magnetic field is similar to the considering case.

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SIMULATION OF BEAM EXTRACTION FROM TR24 CYCLOTRON AT IPHC

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Abstract

The CYRCé (CYclotron pour la ReCherche et l'Enseignement) TR24 cyclotron is used at IPHC (Institut Pluridisciplinaire Hubert Curien) for the production of radio-isotopes for diagnostics, medical treatments and fundamental research in radiobiology. The TR24 cyclotron produced and commercialized by ACSI delivers a 16-25 MeV proton beam with intensity from few nA up to 500 µA. The TR24 is a compact isochronous cyclotron with normal-conducting magnet and stripper foil for the beam extraction. The calculation model for OPERA 3D program code is described. The magnetic field map in the working region of the cyclotron is generated. The beam characteristics outside the cyclotron, that will serve as initial conditions for the design of future beam lines are determined.

INTRODUCTION

The study of beam extraction from TR24 [1] cyclotron is mandatory for the design of the future beam lines and the specification of the performances in regard of the different applications. The simulation of the ion trajectories for different azimuthal positions of the stripper, the influence of energy dispersion taking into account the 3D cyclotron fringe field and field of the combo magnet will help us to define the reference orbit, the best beam extraction and the optimal settings of the optical elements.

MAIN PARAMETERS OF PROBLEM

H^- ion beam is produced in the CUSP ion source [2] with kinetic energy of 30 keV The beam emittance is strongly dependent on beam current.

For H^- ion beam currents equal to 5 mA the initial beam emittance is equal to 50 π·mm·mrad. The main parameters of the TR24 cyclotron and H- ion beam are indicated in Table 1.

CYCLOTRON MAGNETIC FIELD

The main magnet of TR24 compact cyclotron is intended to produce the isochronous magnetic field with the level of 1.36 T at the cyclotron centre. Magnet has 170 x 170 x 110 cm closed yoke with pole diameter of 120 cm. Four azimuthally-profiled sectors provide the isochronous acceleration and focusing of the H^- beam up to the extraction radius of about 51 cm.

For analysis of the extraction efficiency and beam characteristics along the extraction trajectory a 3D computer model of the cyclotron magnet was created. Magnetic field calculations were performed with TOSCA OPERA 3D. The calculated average magnetic field and flutter distributions along cyclotron radius are presented in Fig. 1.

Table 1: Cyclotron and H^- Beam Parameters

Parameter	Value
Center magnetic field, T	1.36
RF frequency, MHz	85.085
Harmonic number	4
Dee voltage, kV	50
Number of dee	2
Maximum extraction radius, cm	51
Charge	-1
Mass number	1
Maximum current, mA	5
Injection energy, keV	30
Extraction energy, MeV	18-24
Injected Beam emittance, π·mm·mrad	50

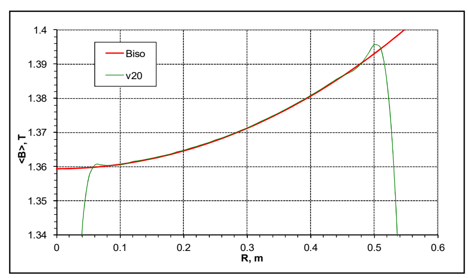

Figure 1: Isochronous (red line) and simulated (green line) average magnetic field.

The results of calculations are used for trajectory analysis of the extracted beam from the last orbits to the object point in the beam transporting line placed beyond the cyclotron at the entrance of the combo magnet at radius of 132 cm. The median plane distribution of the inner magnetic field, the field in the yoke and the field outside magnet up to 150 cm from cyclotron center is shown in Fig. 2.

CLOSED AND EXTRACTION ORBITS

In contrast to [3], closed orbits exist for the entire range of output energies without any correction of the average magnetic field.

The closed and extraction orbits for extraction energy W_{ex} range (Table 1) are shown in Fig. 3.

The main parameters of the closed orbits for various values of the extraction energy W_{ex} at extraction point are shown in Figs. 4-5.

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PROJECT OF A NOVEL MULTI-ORBITAL BEAM BUNCHING AND EXTRACTION FROM THE U-120M CYCLOTRON

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Abstract

We introduce the bunching system for a time structure control of the U-120M cyclotron beam. The system is based on a unique pulsed vertical deflection of the selected final orbits of the internal accelerated beam of the H⁻ ions to an extractor-stripper (a thin carbon foil positioned below the cyclotron median plane). A set of home-made programs have been developed for simulations and parameters determination of the system. Results of some simulations (i.e. dimensions of the deflection system, parameters of the pulsed high voltage power supply, position of the stripper, beam trajectories, beam parameters, beam losses, Be target position etc.) are presented. The system will be used for fast neutron generation and consequently for spectrometric measurement of neutron energy by the time of flight (TOF) method. The system will provide beam bunch interval up to 2000 ns range of a defined beam time structure (up to beam bunch period to beam bunch width ratio min 100).

INTRODUCTION

Motivation

For wide range of applications and advanced technological systems (i.e. nuclear power reactors, accelerator driven systems (ADS), fusion technology) neutron induced reactions play irreplaceable role. The data for neutronic calculations is based on transport codes with evaluated data libraries, supported by measurements and experimental tests of reaction models. Proposed chopping system supplies pulsed proton beam of the cyclotron U-120M which in connection with the Be target provide necessary tool for precise measurement of angle/energy-dependent cross-sections by neutron TOF method. Planned facility will be complementary with the parameters of the European TOF facilities (nTOF CERN, GELINA Geel, NFS Ganil [1]). The NPI has a long-term experience with the design, manufacture and operation of targets for production of fast neutrons and their use in various projects and experiments [2]. Study and project of the TOF system [3] on the new cyclotron TR-24 (repetition frequency 85 MHz/pulse width 2.3 ns) which was based on the double deflection (sinusoidal and pulsed) was not implemented also due to very strict requirements for the parameters of deflection voltage. For that reason, we focused on the design and implementation of the TOF system on the cyclotron U-120M (26 MHz/5 ns).

Beam Pulse Parameters

For the fast neutron generation, the maximum H⁻/proton beam energy (i.e. 36 MeV) of the cyclotron U-120M was chosen. In this case the width of the beam pulse should be approx. 5 ns (FVHM) and period of approx. 40 ns. The required beam pulse width to beam pulse period should be approx. 1/100. The proportion of unwanted or parasitic pulses extracted between working pulses should not exceed 1 %.

PROPOSED SOLUTION AND DESIGN

We were inspired by the system implemented in 60 s on the cyclotron in Karlsruhe [4]. Internal vertical H⁻ beam deflection we combined with the stripping extraction method. The beam of accelerated, H⁻ ions is directed after vertical deflection to the stripping foil and extracted to an external Be target located outside the acceleration chamber. In order to solve this task, the program of simulation of acceleration and extraction of beams on the cyclotron U- 120M – Durycnm18 [5] was extended by additional modules. Due to the narrow aperture (20 mm) inside the 180° Dee the accelerated beam is shifted above the regular median plane using the built-in correction coil of the cyclotron.

This vertical beam shift provides more space for vertical deflection of the beam in working pulses. The beam accumulated between the working pulses in the range of radii 47–50 cm is vertically deflected by the two-section deflector to the stripping foil and extracted to the short beam line with Be target at the end. Bunching system layout is demonstrated in the Fig. 1.

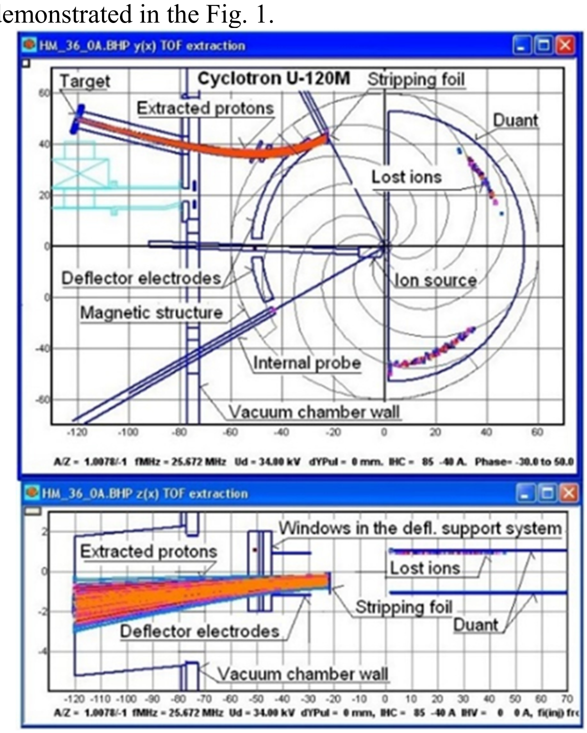

Figure 1: TOF extraction system arrangement.

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SYNCHRONIZATION AND HIGH SPEED HIGH VOLTAGE SWITCHER FOR PULSE BUNCHING SYSTEM OF THE CYCLOTRON U–120M

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Abstract

Pulse bunching system for neutron time of flight (TOF) measurements on the cyclotron U-120M exploits a unique pulsed vertical deflection of the selected final orbits of the internal accelerated beam of the H^- ions to an extractor-stripper. This system is described in details on an individual poster of this conference. A key device is the pulse high voltage (HV) power supply (HV switcher) which is supplying the deflector and elevates H^- ions in defined time structure to an extractor-stripper. The developed HV switcher is based on the SiC MOSFET transistors. It can provide HV pulses with the following pulse parameters: amplitude up to 13 kV, front edge less than 20 ns, flat top 20 ns, back edge less than 20 ns and repetition frequency up to several hundred of kHz. We have also developed the pulse synchronization with the cyclotron RF (25 MHz), which enables to set up front edge of bunching pulses within 2π with accuracy 80 ps. Human-machine interface is based on SCADA software Reliance and PLC Tecomat Foxtrot.

INTRODUCTION

U-120M Cyclotron

The U-120M cyclotron was originally designed as an accelerator of light positive ions (A/Z = 1–2.8) with the maximum energy up to tens of MeV. Since the early 1990s, the cyclotron has undergone major upgrade in terms of acceleration of negative ions H^-, D^- in order to increase external beam intensities [1].

The cyclotron is equipped with a beam line system for the transport of the accelerated and extracted ions to the experimental and target facilities. This system includes also a short beam line for the transport of ions extracted from negative regimes [2].

Protons can by used for neutron production (deuterons and ^{3}He particles were tested as well) for ToF, and are extracted from the beam using the stripping foil. The proton beam is directed to the target installed at the end of the beam pipe. In the negative ion mode of acceleration, the protons resp. deuterons with energies of 6–36 MeV resp. 10–20 MeV with good beam current stability are obtained and used for neutron production at the suitable targets. An average beam current for neutron production is usually 10–15 μA [2].

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Time Structure of the Cyclotron Beam

The cyclotron radiofrequency (RF) system is not operated at the continuous wave regime. In order to protect the RF accelerating system against discharges and to control the beam current, the RF frequency is modulated by a dedicated 150 Hz macropulsed signal. A duty cycle of the corresponding 6.67 ms signal period is adjustable and determines a time interval in-between the macropulses filled with proton bunches. For the lowest RF (≈10 MHz), the duty cycle can reach rather high values of about 65 %. On the other hand, for the highest RF (≈25 MHz) the maximum duty cycle is limited to 25 %. The cyclotron radiofrequency depends on required output beam energy [3].

Time Structure of the Buncher

For measured of neutron energy by the TOF method the required beam pulse width to beam pulse period should by lower than 1/400. The proportion of unwanted or parasitic pulses extracted between working pulses should not exceed 1 %.

We assume to use 25 MHz cyclotron RF. The period of the bunches is therefore t_{acc} = 39 ns and bunch duration is approximately t_b = 6.5 ns. Principle of the proposed bunching system of the cyclotron U-120M is shown in the Fig. 1. The deflection system consist of two parts with total length of 742 mm. The time of flight of the 36 MeV proton bunch through deflection system is t_{flight} = 11.1 ns.

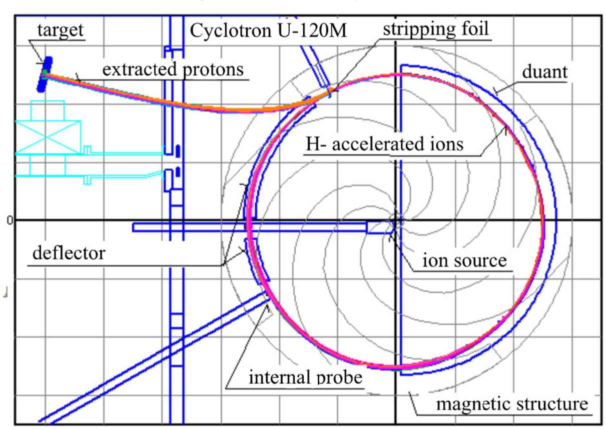

Figure 1: Schematic diagram of U-120M cyclotron with deflection and extraction system.

In the Fig. 2. is shown necessary time structure of pulsed deflection voltage U_{def} for trouble-free beam deflection. Amplitude of the voltage is 10 kV.

Flat top of deflection pulse have to be minimally $t_{ft} = t_b + t_{flight}$. So, t_{ft} = 17.6 ns. The time for switch on or switch off is $t_{switch} = t_{acc} - t_{ft}$. Thus, maximum possible time

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DEVELOPMENT OF A REPLACEMENT FOR THE LONG RADIAL PROBE IN THE RING CYCLOTRON

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Abstract

The long radial probe in PSI's Ring cyclotron delivers a radial pattern of all but the first few turns. In recent years, the measurement has been plagued by artefacts and mechanical problems. We report here on the development of a replacement, which should also provide a more flexible basis for extended measurement capabilities.

INTRODUCTION

In 1993 the actual long radial probe RRL1 was installed in the ring cyclotron [1]. It replaced a multi-finger probe operated since 1974 [2], which covered the turns from 110 MeV to 590 MeV at low beam currents.

The almost 3 m long probe is parked in a separately supported chamber connected to an 'intermediate sector' between two of the eight sector magnets. When moved by a wire rope into the cyclotron (Fig. 1), the forks upper and lower trolleys have to transfer from outer to inner rails over a gap of ~5 cm required by the vacuum valve. By using a 33 um vertical carbon fibre, the radial profile of all but ~6 innermost turns can be measured at full beam current up to 2.4 mA. The probe wire is biased to +60 V in order to suppress thermionic electrons at lower beam energies [3] and to decrease artefacts. From 2002 - 2009, upper and lower fingers from 100 µm SiC, extending vertically until 1 mm from the midplane, were installed to get vertical information at beam currents up to 500 µA.

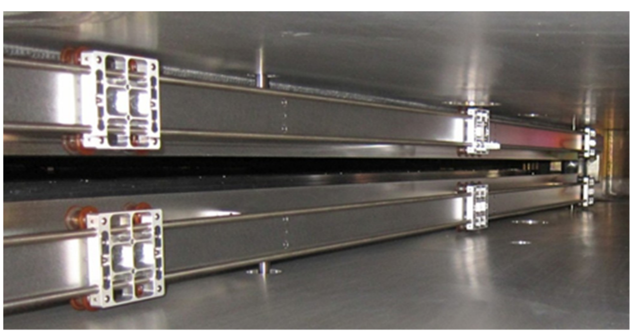

Figure 1: Actual probe fully inserted. The last trolley to the left (not shown) which combines upper and lower arm of the fork stays in the outer chamber. Some of the seven fixtures of the rails are visible.

The probe has delivered nice results. However, two problems are impeding the probe signal. Since the installation of the more powerful RF cavities until 2008, artefacts attributed to plasma clouds [4] occur frequently and are often dominant (Fig. 2). A repetition of a probe measurement often leads to a gradual decrease of the disturbance. Possibly charging of surfaces at the probe and its surroundings plays also a role here.

Since 2014, we observe a severe noise, occurring only with beam and outside a certain machine radius, with this radius being smaller for the foregoing inward than for the outward movement and changing over time. The reason is not identified, plasma may again be a candidate. In addition, there is a problem affecting the probe movement. At venting and pumping of the cyclotron, the overdetermined mounting of each rail at several points at the vacuum chamber results in relative movements between these rails and also with respect to the rails in the external chamber. To prevent the probe to be stuck, the rails must be positioned accordingly, which requires a tedious adjustment, for which a reproducible procedure has not been found. This has to be repeated every time the intermediate sector has moved, which happens, e.g., at a change of the Indium or double O-ring sealed adapter flange towards the downstream magnet chamber.

We also learned that the internal low-noise signal cables, which are useful to minimize microphonic noise at cable bending during probe movement, are badly outgassing softeners. Hence, a replacement of the ageing internal probe cables may improve the noise problem, but in exchange may contribute to the plasma-related problems, for which the exact mechanisms are not known.

Two years ago we started the development of a replacement for RRL1. Besides solving the actual problems, it should also provide a more flexible platform for extended measurement capabilities as a phase probe or diagonal wires [1] to get information on the vertical beam profile.

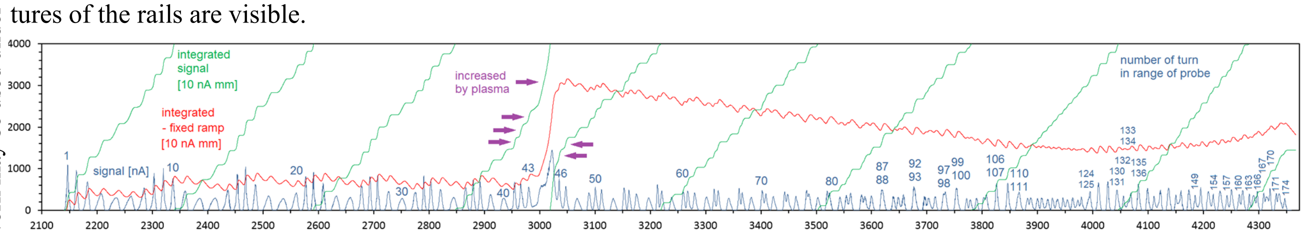

Figure 2: A nicer example of a measurement taken at a beam current of 2200 µA. It is affected by plasma only in a narrow range. A day later, the maximum disturbance was 30 times larger and affected many more turns. With the beam switched off but RF still on, the artefact from the plasma cloud decays within seconds.

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FAST RECHARGING OF ELECTROSTATIC INJECTION AND EXTRACTION SEPTA AFTER BREAKDOWN

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Abstract

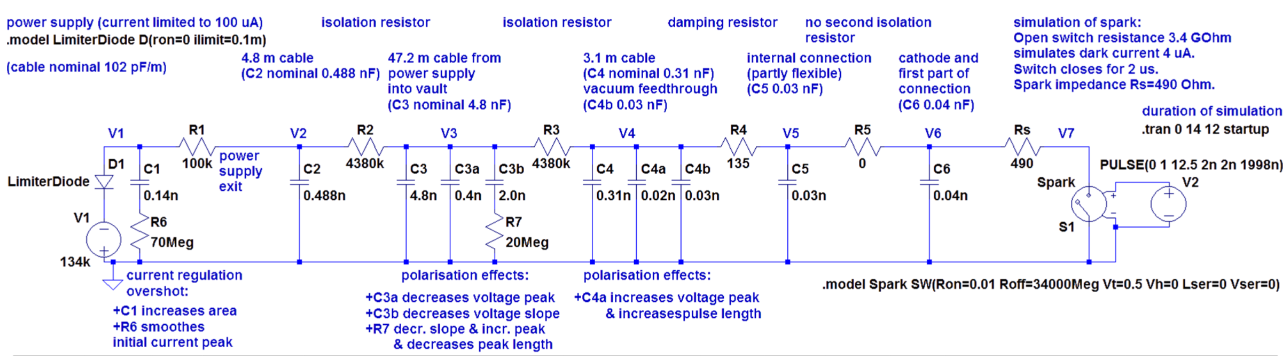
We propose to recharge an electrostatic injection or extraction septum in a high-power cyclotron fast enough to omit the need for switching off the beam at a high voltage breakdown.

INTRODUCTION

In the Ring cyclotron, a proton beam of up to 2.4 mA is injected and extracted with the help of electrostatic septa [1]. Depending on tuning status, conditioning, actual problems and actual beam current, 5 to 300 short beam trips occur per day, from which ~1/10 include high voltage (HV) breakdowns in these septa. However, we do not know whether the breakdown is the reason or a consequence of beam switch off and related interlocks of loss monitors indicating errant beam. Anyhow, then the beam is switched off and ramped up again in about half a minute. This already amounts to a large fraction of the unscheduled downtime of the accelerator [2]. Some 5% of the experiments at the subsequent spallation source SINQ, as 2D or 3D imaging of processes, suffer from information loss due to these interruptions [3]. Also, the frequent beam switch-off and corresponding thermal cycling may accelerate the ageing of the SINQ target [4]. As a remedy for that fraction of beam trips, which are caused by a septum, we propose a recharging of the septum within 1 ms, which would allow to keep the beam running, being lost only for this short time. The amount of uncontrolled beam loss and the needed reaction times for surveillance is comparable to the switching of the full beam between beam lines routinely performed for the operation of the ultra-cold neutron source UCN [5]. Furthermore, for interlocks caused by other transients, detected, e.g., by loss monitors, a fast recharge of the septa may also allow to keep the beam running, if the causes decay correspondingly fast. The required fast surveillance will be eased by the new generation of loss monitor read-out electronic under preparation [6].

ACTUAL SETUP

The electrical (Fig. 1) and mechanical (Fig. 2) setup is discussed in the context of the injection septum EIC. The HV supply located outside the vault is connected to the septum via a long HV cable, a CERN type [7] external isolation resistor, a vacuum feedthrough, an in-vacuum damping resistor and a flexible connection to the cathode, which allows the mechanical adjustment of the septum during operation. A breakdown nearly fully discharges septum and short cable to isolation resistor, but not the long cable, since the discharge cannot be maintained with a low current. The exchange of charge already stored in the long cable and the power supply takes ~8 ms and recharges the cathode already to ~93% of the nominal 134 kV. Then the power supply delivers a charging current, typically limited to 100 µA, for ~0.6 s. With most breakdowns, a standard load curve is precisely reproduced (Fig. 3). During loading, the beam is already switched off due to beam losses or the low-voltage indication of the HV supply. Occasionally, multiple breakdowns occur (Fig. 4), or deeper breakdowns, which are also likely to be "assembled" by consecutive, but not resolved sparks. We also see switch off due to low-voltage indication resulting from overly increased dark current induced by operation of the nearby radial probe RRL [8].



HV supply cur limit	R3	R4	R5	Rs		V2max	V3max	V4max	I1max	I2max	I3max	I4max	I5max	Ismax	V6 deficit after 1 ms	V6 deficit <1 kV after	HV supply in cur limit for
100 uA	4.38 MΩ	135 Ω	0 Ω	490 Ω	actual operation	-126.2 kV	-125.2 kV	~0 kV	168 uA	937 uA	31 mA	178 A	-	266 A	82 kV	511 ms	559 ms
500 uA	4.38 MΩ	135 Ω	0 Ω	490 Ω	increased current limit	-128.3 kV	-125.5 kV	~0 kV	553 uA	1.16 mA	31 mA	173 A	-	266 A	82 kV	107 ms	79 ms
500 uA	350 kΩ	135 Ω	0 Ω	490 Ω	lower Risol	-127.9 kV	-124.0 kV	~0 kV	561 uA	2.0 mA	382 mA	173 A	-	266 A	10.2 kV	105 ms	80 ms
500 uA	350 kΩ	1 MΩ	0 Ω	1200 Ω	plus 2nd Risol (instead Rdamp)	-134.0 kV	-132.3 kV	-122.3 kV	370 uA	370 uA	32 mA	134mA	-	111 A	1.8 kV	13 ms	-
500 uA	350 kΩ	135 Ω	1 MΩ	1600 Ω	plus 2nd Risol (new)	-134.0 kV	-133.0 kV	-125.8 kV	217 uA	217 uA	23 mA	123 mA	134 mA	83 A	1.05 kV	1.1 ms	-
100 uA	350 kΩ	135 Ω	1 MΩ	1600 Ω	plus 2nd Risol (new)	-133.6 kV	-133.0 kV	-125.8 kV	109 uA	201 uA	23 mA	123 mA	134 mA	83 A	1.05 kV	1.1 ms	29 ms

Figure 1: Present electrical circuit. Rs chosen to approximate calculated curves in Fig. 5 by V6. Its value corresponds to arc resistance at passing 75 kV. C4b, C5, C6 estimated from geometry. Simulation results are given for variants as well.

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DESIGN OF 5.8 MHz RF ELECTRODE FOR AMS CYCLOTRON

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Abstract

Accelerator Mass Spectrometry (AMS) is a powerful method for separating isotopes, and electrostatic tandem accelerators are widely used for AMS. Sungkyunkwan University is developing AMS that can be used in a smaller space based on cyclotron. Unlike conventional cyclotrons used in PET or proton therapy, cyclotron-based AMS provides high turn number and high resolution. In this study, we proposed a cavity with a frequency of 5.8 MHz and an accelerating voltage of 300 V to accelerate the particles in the cyclotron. The proposed cavity was designed as an electrode and verified by CST Microwave studio.

INTRODUCTION

AMS has been developing rapidly since the 1980s. As a new application of accelerators, AMS has been widely applied in archeology, earth and planetary science, materials and environmental sciences. Especially AMS has a bright future in biomedical applications.

In general, the accelerator used in the AMS system is an electrostatic accelerator Tandem. This is because tandem accelerators are electrostatically accelerated and can be applied to a wide variety of particles, regardless of their weight.

Cyclotrons can be used to separate particles on their own. so cyclotron is suitable for use in AMS systems. This can benefit greatly from the size and cost of AMS systems compared to tandem accelerators. However, cyclotrons can only be used for specifically targeted particles and have a major weakness in resolution and sample acquisition which are key variables in AMS systems.

Sungkyunkwan University has developed a cyclotron-based AMS system targeting carbon which is the most widely used particle in AMS systems. The cyclotrons were developed with a focus on particle classification which is a key variable of AMS rather than acceleration efficiency which is an important variable of the accelerator. In order to improve the resolution, a design with a high turn number and a high Harmonic number was carried out and artificial intelligence was applied to have high accuracy at a low sample acquisition number. The final specifications are as follows.

In this study, we describe a cavity in the cyclotron's components that accelerates particles. The cavity is designed and impedance matched through the RF circuit, verified by CST MICROWAVE STUDIO.

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DESIGN FEATURE

The resolution of cyclotron is as follows:

$$\text{Resolution} = \pi h n$$

Where h is the harmonic number and n is the number of turns. According to the equation, the higher the harmonic number and the number of turns the greater the resolution. Cyclotrons induce the movement of particles through the magnetic field of the electromagnet and accelerate the particles through the electric field of the cavity. Because it affects each other, the electromagnet and the cavity are designed to have one side design first, and the other side design according to the design side first.

In this study, the design of the electromagnet was carried out and the cavity was designed according to the design of the electromagnet. The requirements are shown in Table 1.

Table 1: Specification of AMS Cyclotron

Specification	Value	Unit
E	200	keV
R_{in} / R_{ext}	138 / 453.6	mm
Mass Resolution	5000	
Turn number	159	
Dee voltage	300	V
Frequency	5.8	MHz
E_{in}	25	keV
Dee angle	20	°
Number of Dees	2	

By default, the size of the cavity is proportional to the wavelength of the frequency. The larger the band of frequencies used, the shorter the wavelength of the frequency. So the size of the cavity is usually smaller. At 5.8 MHz, the wavelength is approximately 51724 mm. The types of cavities commonly used in cyclotrons are λ/4 and λ/2 resonators. In this case, 12931 mm for the λ/4 type and 25862 mm for the λ/2 type are required. The acceleration section of the particle required in Table 1 is very different from 138 mm to 453.6 mm.

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DESIGN AND MANUFACTURE OF 10 kW, 83.2 MHz 4-WAY POWER COMBINER FOR SOLID STATE AMPLIFIER

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Abstract

The purpose of this study is to improve the insertion loss of a 20 kW solid-state RF power amplifier and the power coupling efficiency by reducing reflected power. For this purpose, a power combiner, which is a core component of a solid-state RF power amplifier, was designed and fabricated. The 4-way power combiner employs the Wilkinson type, which has excellent power coupling efficiency and isolation, and operates at 83.2 MHz. This paper covers the design and cold test results.

INTRODUCTION

RF amplifiers for particle accelerators require high frequency, power and phase stability. Depending on the type of particle accelerator, the power requirement is 10 kW to 2 MW or more for continuous sources and a maximum of 150 MW for pulse sources.

These high frequency, power and phase safety requirements have led to the use of tube amplifiers as the source of particle accelerators. Tube amplifiers include Tetrode amplifiers, Inductive output tubes, Klystrons, Magnetrons and Gyrotrons. Tube amplifiers have been used as a power source for particle accelerators because they can supply frequencies up to 10 GHz and power up to 100 MW. Recently, however, limitations of tube amplifiers have begun to emerge. All tube amplifiers have the same problem, and typical problems include heat loss, voltage breakdown, output window failure, and multipactor discharge. Semiconductor amplifiers have emerged to solve impedance problems during beam loading and reflection problems during multipacing.

In the case of a semiconductor amplifier, the output power of a single amplifier is lower than that of a tube amplifier, but when sufficient power cannot be obtained, the output of several amplifiers can be combined to achieve a target output. In addition, semiconductor amplifiers have low voltage requirements and low maintenance costs. The cost of amplifiers (including replacement preamplifiers) in the total operating cost of a particle accelerator system is quite high. Therefore, the maintenance cost of a semiconductor amplifier with low voltage requirements is much lower than that of a tube amplifier because the power efficiency of an RF amplifier determines the power consumption and the power consumption soon determines the operating cost. In addition, the semiconductor amplifier is modularized, so that the failure of a single amplifier unit does not affect the whole system, and it is easy to find the fault part, so that maintenance is easy and cost is low. In the future, as the efficiency of MOSFETs, a key component of semiconductor amplifiers, increases, the amount of power available for output is expected to increase.

However, semiconductor amplifiers still have a lower maximum output power than tube amplifiers and have some disadvantages. Semiconductor amplifiers require a compact system that has high RF power per unit volume due to low acceleration efficiency per unit volume. In addition, the LDMOS device, a key component of the semiconductor amplifier, is sensitive to increased junction temperature, requiring a heat sink design with good thermal management efficiency.

There is also a problem of lowering power coupling efficiency due to unbalance of amplitude and phase. The semiconductor amplifier combines the power of single amplifier units to achieve the target power. When single amplifier units have different powers and phases and ignore them and combine them, there is a risk of damage to the equipment due to the reflected power generated by the phase and power difference. To solve this problem, amplitude and phase trimmers have been developed and individual PA phase adjustments have been used to compensate for phase imbalance, but no perfect solution has yet emerged. In this paper, we designed a power combiner that increases the power coupling efficiency and minimizes the reflection power to solve the problem of power coupling efficiency degradation due to the amplitude and phase imbalance of semiconductor amplifiers.

DESIGN FEATURE

The most suitable type for power combiners that must combine large powers of 10 kW is Gysel power combiners. Gysel power combiners are superior to Wilkinson power combiners in terms of thermal endurance and power handling, making them suitable for high power applications.

However, the proposed 4-way power combiner has the goal of improving insertion loss and reflected power. The advantages of Gysel power combiners, thermal endurance and power handling, have no direct impact on insertion loss and improved return power. Therefore, Wilkinson power combiner, which has low loss type, is more suitable for the target than Gysel power combiner. In addition, the

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RF MEASUREMENT OF SKKUCY-10 RF CAVITY FOR IMPEDANCE MATCHING

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Abstract

The 10 MeV cyclotron was designed for next version in Sungkyunkwan University, after the SKKUCY-9 had developed for medical application for PET. The RF cavity, which generates the electric field in cyclotron, was designed based on a half-wavelength resonator and optimized to improve the unloaded quality factor (Q_0). The design specifications of RF cavity were resonance frequency 83.2 MHz, Q_0 5830 and Dee voltage 40 kV with geometrical values resonator length 560 mm, Dee angle 35° and Stem radius 16 mm. The RF cavity of the SKKUCY-10 was fabricated and installed inside the electromagnet, and RF characteristics were measured with a network analyzer. The RF coupling coefficient and characteristic impedance for desired condition were selected at 1.08 and 52 Ω, respectively. The RF coupling coefficient and characteristic impedance were measured 0.8-1.2, 52-49 Ω according to temperature as 15-21°C. The power coupler was checked for optimization of RF coupling coefficient and characteristic impedance, and the results show good agreement with simulated and measured data.

INTRODUCTION

RF cavity generates electric field with resonant frequency in cyclotron and is developed based on coaxial resonator to improve RF power efficiency according to electric field [1]. Cyclotrons aimed at producing radio tracers have been developed as isochronous magnets with azimuthally varying magnetic fields, and fix frequency RF cavities with constant dee voltages [2].

An isochronous cyclotron using fixed frequency has developed to optimize the magnetic field to satisfy the synchronous phase of charged particles by equilibrium-orbit. However, due to the thermal and beam loading effect at cyclotron operation, the RF coupling state and the dee voltage variation can occur inside the RF cavity. To overcome this, the capacitive type fine tuner, the amplitude of the RF amplifier, and the phase control are applied to keep the stable condition of the RF cavity, which are regulation of dee voltage, resonant frequency and RF critical coupling state [3].

The medical AVF cyclotron (named SKKUCY-10) is developing for 10 MeV proton at Sungkyunkwan university, and the RF system based on half-wavelength coaxial resonator was designed to have 83.2 MHz resonant frequency and 50 Ω characteristic impedance [4].

In this paper, the RF coupling state and characteristic impedance was analyzed with considerations of thermal and beam loading effect. The initial conditions of temperature and beam power were assumed based on the specification of SKKUCY-10, and the RF coupling coefficient and characteristic impedance were calculated by simulation code. In addition, the RF coupling coefficient and characteristic impedance were measured according to environment temperature in RF system, and compared with simulation results.

METHODS AND MATERIALS

The RF cavity, capacitive power coupler and fine tuner structure of the 10 MeV cyclotron are shown in Fig. 1. The power coupler is designed as a 50 Ω, 3.125 inch standard coaxial rigid line, and the inner conductor of the rigid line is coupled by capacitance adjacent to the side of the dee. The fine tuner consists of an electrically grounded plate and movement motor. The plate is coupled by capacitance adjacent to the side of the dee, and the plate diameter was designed to be 50 mm to compensate for wide variations in the RF cavity.

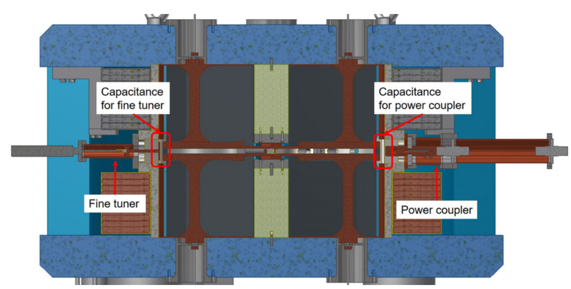

Figure 1: Power coupler and fine tuner for SKKUCY-10.

In the RF system of SKKUCY-10, the power coupler was considered with impedance matching as 50 Ω to satisfy critical coupling state, and the RF specification is shown in Table 1. The fine tuner was designed to have a tuning range of ±0.5 MHz with 83.2 MHz, and the RF coupling coefficient was optimized to 1.03 when the coupler gap distance is 18.7 mm.

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DESIGN OF HIGH SENSITIVE MAGNET AND BEAM DYNAMICS FOR AMS CYCLOTRON

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Abstract

To produce a Carbon 14 for Accelerator Mass Spectrometry (AMS), AMS Cyclotron magnet was designed. For AMS system, Cyclotron magnet has been required high mass resolution. In order to realize high mass resolution, the phase error is designed within ±10 and the mass resolution was 5000. Cyclotron electromagnet was designed with a mass resolution of 5000, a harmonic number of 10, a center magnetic field of 0.5332 T, a maximum energy of 200 keV, a minimum turn separation of 1.2 mm. and a size of 1580 mm × 800 mm. We used CST particle studio and Cyclone for beam dynamics simulation of this cyclotron magnet. This paper describes AMS cyclotron magnet and beam dynamics design.

INTRODUCTION

Design of high sensitive magnet and beam dynamics study of AMS Cyclotron magnet was started in 2017 May at Sungkyunkwan University. The main purpose of AMS Cyclotron is accelerator mass spectrometry for medical purpose. Accelerated Carbon-14 beam can be used for mass spectrometry [1, 2].

This paper presents a design of high sensitive magnet and beam dynamics for AMS cyclotron. A magnet of AMS cyclotron is made of DT-4 steel with 10^{th} harmonics. The main parameters of magnet are decided by 200 keV Carbon-14 beam. These main parameters are relation with size of magnet, power consumption, beam parameters. The accelerators for AMS system require high mass resolution.

DESIGN AND SYSTEM DESCRIPTION

The design process of cyclotron magnet is shown in Fig. 1. The main design parameter is decided at initial calculation. The maximum beam energy, dimension of cyclotron magnet size is the part of main design parameters. From the initial calculation, maximum energy of Carbon-14 beam is decided from the magnetic rigidity. The extraction radius set as 453.6 mm and central magnetic field is set to 0.5332 T so RF frequency is 5.8 MHz when the 10^{th} harmonic is used. The approximate 3D modelling of the electromagnet was performed based on calculated main design parameters. The magnetic field of the 3D model of the electromagnet is analysed using TOSCA. After that, the phase error is calculated using the CYCLONE code and the reference field is designed using the phase error

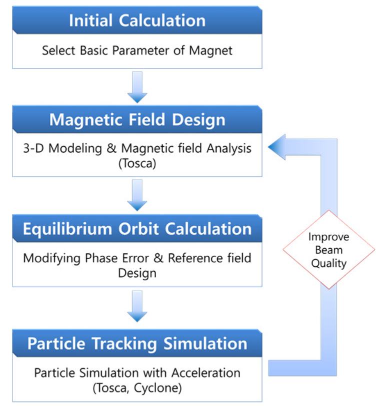

Figure 1: Cyclotron design process.

The designed magnetic field result from TOSCA were imported into CYCLONE. CYCLONE code calculates equilibrium orbit, phase error, single particle trajectory, tunes of designed magnetic field. The magnetic field error between reference field and designed field has calculated by using

$$\frac{\Delta B(r)}{B(r)} = \gamma^2(r)\frac{\Delta f_p(r)}{f_p(r)}. \tag{1}$$

The magnetic field was modified by magnetic field error from Eq. (1) [3]. The magnetic field error between reference field and designed field should be less than 10 Gauss for get high quality of Carbon-14 beam (Fig. 2).

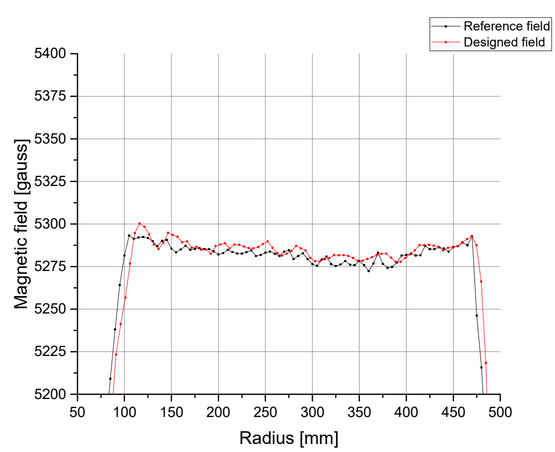

Figure 2: Magnetic field design.

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CONTROL SYSTEM IN 10 MeV CYCLOTRON BASED ON IoT

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Abstract

Many The Internet of Things is one of the new most advanced technologies in the world. One of the applications of this technology is using it in places where remote control is preferred or it needs to control various processes at different times throughout the day. The cyclotron accelerator is one such system in which the start-up process until radio medicine production requires continuous monitoring and inspection. In this research, we have tried to use the internet of things technology in the process of cyclotron control system specially in fine tuning section.

INTRODUCTION

Every process needs control and monitoring to properly execute and monitor performance. The purpose of the cyclotron accelerator control system is to do the same. System control will also prevent possible damage and facilitate troubleshooting.

In the past, the cyclotron control system was fully hardware designed by relays and then wired. The major drawback of this method was that, if there was a change in the control system, the hardware and wiring of the relays would also have to be changed. This increased the cost and time. Relay systems also had a slower operating speed and were much more difficult to troubleshoot due to wired communication.

With the advent of intelligent control devices and the use of a series of programmable tools and software that operate intelligently, the above issues have been resolved, as well as with the benefits of smaller system dimensions and the possibility to exchange information with other systems, causes that using the Internet of Things for ease of communication.

Our 10 MV cyclotron is comprised of several components including: magnet, RF system, vacuum system, cooling section and ion source. Each of these parts contains components that must be carefully monitored by accurate sensors during the process, and if necessary, automatically assigned the commands to these parts. As a result, it is better to have all of its subsystems intelligently controlled and monitor in order to sustain the cyclotron accelerator performance. All of these subsystems are controlled by programable components and have a communication through the IoT protocols. In this research, we have tried to use the internet of things technology in the process of cyclotron control system specially in fine tuning section.

CYCLOTRONS

As mentioned, the cyclotron accelerator is composed of various components, including ion sources, magnets, cavities, and the vacuum system. When the charged particles leave the ion source, they travel through the space between the poles and accelerate as they pass through the cavity. What drives the charged particles in this device is a variable electric field generated by the cavity. And what holds the particles in a circular path is the force of the magnetic field. Thus, the particle is accelerated through the electric field and driven by the magnetic field, both focal and in a circular path, after being injected into the middle plane and positioned in the appropriate rotation plane. Finally, the particle is extracted by a stripper in a radius of proper energy [1].

Accelerators are used in the medical field to produce diagnostic radio-medicine, radiotherapy, and rapid neutron production for the treatment of cancers. The 10 MeV cyclotron was designed to produce FDG radio-medicine for PET spectroscopy.

INTERNET OF THINGS (IoT)

IoT technology is the creation of a global network of uniquely addressable objects based on a standard communication protocol. Active involvement of "objects" in commerce, information gathering and processing processes while being able to interact with each other and with the environment, with the ability to transmit information and to respond automatically to natural or physical events by performing a process or without direct human intervention in many industries can be helpful.

Not long after the idea of the IoT was developed by Kevin Ashton, who pointed to factors such as increasing data volume in the world, the importance of controlling objects, human limitations, time, speed and accuracy. But in various industries and everyday life is expanding rapidly.

In the IoT structure, the human structural system is inspired by the way that equipment and sensors play the same role as the human five senses and wireless cellular networks, local area networks, data storage and processing security, and transactional and analytical systems, replaces the brain. As a result, the system consists of three main parts: sensors, communications and protocols, and data processing.

In each application, the sensors are characterized by what is appropriate for that control system. In the selection of sensors, the type of sensor and the its accuracy should be specified and taken into account.

For the cyclotron, these sensors include pick up probes for feedback from the RF field inside the cavity, directional coupler outputs to investigate the rate of return wave at the beginning of the tuning system, tuner capacitor location, phase and frequency of the RF signal from the LLRF section, temperature and Pressure sensors, output beam flow, etc. [2].

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BEAM STRIPPING INTERACTIONS IMPLEMENTED IN CYCLOTRONS WITH OPAL SIMULATION CODE

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Abstract

Beam transmission optimization and losses characterization, where beam stripping interactions are a key issue, play an important role in the design and operation of compact cyclotrons. A beam stripping model has been implemented in the three-dimensional object-oriented parallel code OPAL-CYCL, a flavor of the OPAL framework. The model includes Monte Carlo methods for interaction with residual gas and dissociation by electromagnetic stripping. The model has been verified with theoretical models and it has been applied to the AMIT cyclotron according to design conditions.

INTRODUCTION

Compact cyclotrons are one of the most versatile accelerators involved in radioisotope production employed in PET scans as diagnostic tools in hospitals. Due to short lifetimes of some radioisotopes, it is recommended that the accelerator facility is located inside the hospital, thus the compactness is a relevant factor. Hence, superconducting magnets can be used to increase the magnetic field, minimizing the acceleration region and consequently reducing the overall cyclotron size. An internal ion source must be considered as well. However, technical complications arise in the design and manufacturing processes. Given the worsening of the vacuum due to the internal source, combined with the limited space of acceleration region and the amount of components in the accelerator, the vacuum conditions could be a considerable source of losses, even more in the case of H^- beams. As a consequence, beam current will be reduced, as well as the efficiency and radioisotope production. Additionally it could increase the activation of the machine. Thus, optimization of beam transmission as well as minimization of activation associated with lost particles, is of great importance in compact cyclotrons. Specifically, it is essential to study the effect of some residual physics phenomena, as the interaction of the beam with residual gas and electromagnetic stripping. In this paper a general beam stripping model is presented being integrated into the particle accelerator framework OPAL [1]. It allows a more realistic description of the beam dynamics and a characterization of the losses.

AMIT CYCLOTRON

A compact cyclotron is being developed as part of the AMIT project, aimed at the production of single doses of ^{18}F and ^{11}C radioisotopes. The AMIT cyclotron has been designed to improve the size and cost efficiency limitations through a careful study of the electromagnetic design [2] and the beam dynamics [3]. The machine aims to produce a 10 μA beam of 8.5 MeV protons. It is a Lawrence type cyclotron with weak focusing. It employs two superconducting coils in a Helmholtz arrangement and magnetic iron yoke to provide the 4 T magnetic field and a 180° Dee attached to the RF cavity, with a 60 kV accelerating peak voltage imposed by the non RF-particle isochronism, to accelerate H^- ions produced by a cold cathode Penning Ion Source, and with stripping mechanism for beam extraction. The superconducting magnet [4] of NbTi has a warm iron configuration, where only the coils are kept cold inside a common cryostat. It is cooled down with two-phase helium, circulating in a closed circuit and recondensed externally.

Figure 1: General arrangement of the AMIT cyclotron.

BEAM STRIPPING

H^- ions have become increasingly popular in cyclotrons due to high efficiency extraction process. However, the second electron of this type of hydrogen has a low bounding energy (0.75419 (2) eV [5]). Therefore, the electron has a high probability of being stripped by interaction with residual gas or with electromagnetic field, increasing beam losses. Other types of ions, or even neutral particles, are also affected, although with less probability. The processes are classified according to the charge state of the particle, $\sigma_{qq'}$, where q represents the charge state before and q' after the process. The processes to be considered in case of H^- are single- or double-electron-detachment (σ_{-10} or σ_{-11}). Regarding protons, the process available is electron capture.

Assuming that particles are normally incident on a homogeneous medium and that they are subjected to a process with a mean free path λ between interactions, the probability density function for the interaction of a particle after travelling a distance x is [6]:

$$F(x) = \frac{1}{\lambda} \cdot e^{-x/\lambda} \tag{1}$$

where $F(x)dx$ is the probability of having an interaction between x and $x+dx$. Hence, the probability of an interaction

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EXTRACTION BEAM ORBIT OF A 250 MeV SUPERCONDUCTING CYCLOTRON*

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Abstract

A superconducting cyclotron based on proton therapy facility is being developed at Huazhong university of science and technology (HUST). Due to the compact size of the main magnet, the beam orbits at the extraction region are distributed densely, which creates difficulties for beam extraction leading to severe beam loss. In order to deal with these challenges, the orbit precession method has been employed in the extraction system design. In this paper, we introduce a method of employing a first harmonic field near the $\nu_r = 1$ resonance where the beam energy is about 248 MeV to adjust the amplitude of beam orbit oscillation. The optimum amplitude and phase of the first harmonic field are designed to obtain a large turn separation in the extraction region. Three different ways of generating the first harmonic field are compared for optimization.

INTRODUCTION

As a kind of radiotherapy, proton therapy is becoming increasingly more accepted, which is preferred for most tumors due to minimal damage to healthy tissues and precise local dose control. Proton therapy is considered to be the most effective radiotherapy for cancer, with a cure rate of 80% [1].

The superconducting cyclotron HUST-SCC250 based on proton therapy facility has excellent advantages of economy and compactness, but it also complicates the electromagnetic structure. The orbit separation at the extraction region is usually smaller than the beam size, which makes the extraction efficiency very low. Resonant extraction denotes the focusing oscillation is coherently excited, thus enhancing the distance between successive turns and facilitating extraction of the beam.

In this paper, particle tracking code CYCLOPS is used to analyze the magnetic field and find the location of $\nu_r = 1$ resonance, where the first harmonic covering a radial range of 2 cm is introduced to increase the turn separation [2]. In order to find the appropriate phase of the first harmonic field, the particles are tracked by CYCLONE code so that the amplitude of the field is determined to be 12 Gs, and the phase is 20°~45°. Finally, there are three ways to create the first harmonic field.

* The work is supported by the National Nature Science Foundation of China (11775087).
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STATIC ORBIT PROPERTIES ANALYSIS

The static equilibrium orbit (SEO) characteristics of the given magnetic field maps plays an important role in the study of cyclotron extraction orbit. The level of isochronism of the field is represented by the difference of the nominal rf angular frequency ω_0 and the revolution angular frequency of particle along the SEO ω, which is given as $(\omega_0 / \omega - 1)$. Figure 1 shows the evolution of the isochronism from low energy of 5 MeV to the extracted beam energy of 252.6 MeV, which is calculated with an energy step of 0.4 MeV.

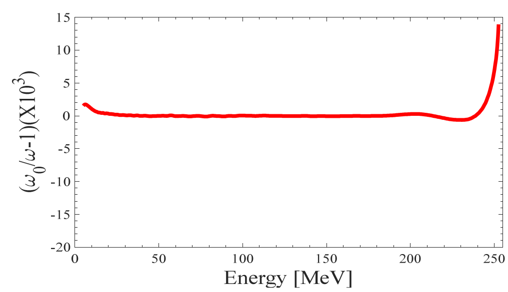

Figure 1: The isochronism parameter $(\omega_0 / \omega - 1)$ vs. energy.

The isochronism of the given magnetic, which varies around zero over the energy range, provides essential information for calculating the phase shift by the well-known phase-energy equation:

$$\Delta(\sin\phi) = \sin\phi_f - \sin\phi_i = \frac{2\pi h}{\Delta E}\int_{E_i}^{E_f}\left(\frac{\omega_0}{\omega} - 1\right)dE \qquad (1)$$

where h is the rf harmonic number, ΔE is the energy gain per turn. Figure 2 shows the results calculated with h = 2 and ΔE = 0.4 MeV/Turn.

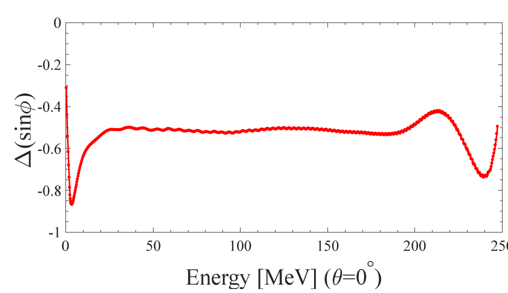

Figure 2: The phase shift $\Delta(\sin\phi)$ vs. energy.

The initial phase $\phi_1 = 32.8^\circ$ is chosen such that the integral of $\sin\phi$ over the whole energy range equals to zero, so

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THE MAGNETIC FIELD DESIGN OF CYCLOTRON AT IMP

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Abstract

A cyclotron magnet is studied at Institute of Modern Physics, Chinese Academy of Sciences (IMP, CAS), and the whole system include one main magnet and other magnetic gradient correctors, which is used to accelerate the Kr^{26+} beam. The structure of superconducting coils and room-temperature iron core are adopted for the main magnet. This paper describes the magnetic field design of the cyclotron, and several shimming methods are used to meet the isochronous magnetic field of Kr^{26+} beam, including pole face shimming method and side shimming method. The final optimization results show that the error between simulation and theory value is small. In addition, the magnet structure is also described.

INTRODUCTION

At present, the activities on the development of isochronous cyclotron are carried out at IMPCAS (Fig. 1). This project includes cyclotron and several beam lines, which intended for obtaining the Kr^{26+} beam to produce nuclear track membrane. The cyclotron magnet has the pole diameter size of 1.64 m and provides the maximum magnetic fields 2.8 T between sectors. Its main parameter is shown in Table 1.

Table1: Main Parameters of the Cyclotron

Parameter	Value
Maximum energy [MeV]	10
Beam species	$^{86}Kr^{26+}$
Number of sectors	4
Ion source	outer
Hill angle [°]	56
Valley angle [°]	34
Max. average Mag. field [T]	2
Harmonic number	4
Magnet aperture [mm]	50-80

The main magnet has a round yoke, four pairs of straight-line sectors. In this paper, we introduce the main magnet with particular emphasis on the isochronous mangetic field design. In addition, we would ensure the cyclotron magnet structure of accordance with the magnetic field calculation.

MAGNETIC FIELD DESIGN AND OPTIMIZATION

The shape of the magnet yoke is optimized by OPERA- 3D magnetic field calculation [1], The OPERA-3D program was used to calculate the three-dimensional field. In the Modeller, the 1/16 model is created according to the symmetry of the magnetic field. Figure 1 shows the geometry of the cyclotron model by the OPERA. Consider with the vacuum and RF systems, there are four holes at the valley centre was designed. Figure 2 shows the radial magnetic field along the “hill” median line at the centre plane. We have been able to obtain a reasonable isochronous magnetic field by some optimization methods.

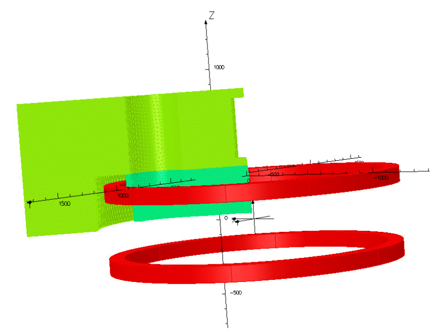

Figure 1: OPERA 3D model.

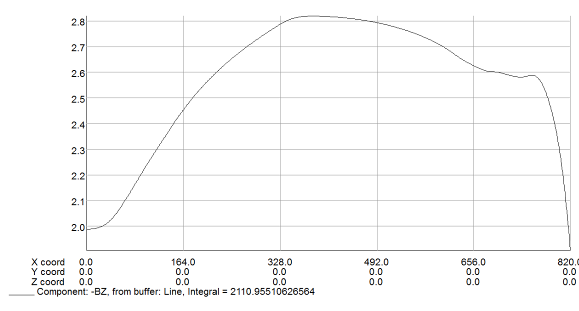

Figure 2: Radial magnetic field distribution.

By successive approximation, cylinder side is optimized as the final shape. In addition, to avoid the rapidly decreasing field in the center region and at the final radius, two special shimming shapes are adopted in these two areas. The optimization structure of sector is shown in Fig. 3. The comparison between the calculation and theory is shown in the Fig. 4, the result shows the deviation does not exceed 10 Gauss over a large area.

In addition, horizontal and vertical focusing frequencies are also obtained from the equilibrium orbit calculation. Generally, we hope the focusing frequency away from the resonances, especially the vertical focusing frequency. Figure 5 shows the two focusing frequencies, the vertical focusing frequency is below 0.5 except some points in final radius [2].

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A PATHWAY TO ACCELERATE ION BEAMS TO 3 GeV WITH A K140 CYCLOTRON*

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Abstract

The capabilities of the K140, 88-Inch Cyclotron at Lawrence Berkeley National Laboratory (LBNL) have been significantly enhanced through the addition of three successive generations of electron cyclotron resonance ion sources (ECRISs). These ion sources have helped the 88-Inch Cyclotron to evolve from a light-ion accelerator to one that has accelerated over half of the naturally-occurring elements in the periodic table, and in particular has accelerated ultra-high charge state heavy ions, such as xenon and uranium. Recently, with $^{124}Xe^{49+}$ ions injected from the superconducting ECRIS VENUS, the 88-Inch Cyclotron reached a new peak extracted kinetic energy of ~2.6 GeV. This is approximately a fifteen-fold energy increase over what this K140 cyclotron could achieve when it started operation almost six decades ago. A next-generation ECRIS, MARS-D, is under development and will further raise the extracted beam energy from the cyclotron. It is anticipated that the higher charge state ions produced by MARS-D will result in the 88-Inch Cyclotron accelerating ions in excess of 3 GeV for use by the radiation effects testing community. This paper will present and discuss the development of the MARS-D ECRIS and the 88-Inch Cyclotron's recent and possible future achievements.

INTRODUCTION

The K140, 88-Inch Cyclotron at Lawrence Berkeley National Laboratory (LBNL) has, in its nearly six decades of service, evolved from a light ion accelerator to one that has successfully accelerated ions ranging in mass from protons to the heaviest naturally-occurring element, uranium [1, 2]. The enhancement of this cyclotron's capabilities has continued through the addition of three successive generations of Electron Cyclotron Resonance Ion Sources (ECRISs). To date the 88-Inch Cyclotron has accelerated the 49 elements indicated in Fig. 1, which represents more than half of the naturally occurring elements including quite a number of their isotopes.

The wide range of ions capable of being accelerated by the 88-Inch Cyclotron has led to its use for a diverse range of applications, such as nuclear chemistry, syntheses of super heavy isotopes, nuclear structure, neutron beams for isotope breeding, space effects testing, etc. The very first single event effects (SEE) tests in the world were conducted using beams from LBNL's 88-Inch Cyclotron by the Aerospace Corporation in 1979 [3]. The combined versatility of the ECRIS, coupled with flexibilities in both the 88-Inch Cyclotron's magnetic field and accelerating frequency, allowed for the development of a number of "cocktail beams" in the mid-1980s where a collection of ions with very similar mass-to-charge ratios are injected into the cyclotron simultaneously and by employing small accelerating frequency changes, single ion species are fully accelerated and extracted [1, 4]. This capability led to the establishment of the Berkeley Accelerator Space Effects (BASE) Facility operating in conjunction with the 88-Inch Cyclotron to provide beams of heavy ions, protons, and neutrons for radiation effects testing. The continued advancement of different generations of ECRIS has led to great enhancement of both ion energy and variety enabling the BASE Facility continue to be at the forefront of radiation effects testing.

Though older, 88-Inch Cyclotron has not yet reached its full potential and the proposed ion source discussed below could push this accelerator to new heights. A brief introduction to ECRISs is given, followed by a description of how advancements in ECR technology at LBNL have enhanced the capabilities of the 88-Inch Cyclotron. Finally, a case is made the novel design of a next-generation ECRIS at LBNL may present the easiest path to the 88-Inch Cyclotron producing 3 GeV ion beams.

ECR ION SOURCE BASICS

The production of multiply-charged ions via ECR ion source was first reported by Geller at GANIL in 1972. This ion source uses a superposition of axial solenoids and a radial multipole (typically a sextupole) to confine a plasma in a magnetic field where that increases in all directions from the source center, i.e., a minimum-B field. Microwaves are injected into the source chamber at frequencies that allow for resonant electron heating on closed shells of constant magnetic field. These energetic electrons ionize neutrals and ions in a step-wise fashion.

The ionizing electrons are more energetic and are more likely to ionize if their source lifetime is long, therefore better plasma confinement leads to both higher currents and higher charge states. Geller developed semi-empirical scaling laws [5] predicting that extracted ion currents will increase as the square of both the injected microwave frequency and the confining magnetic field ($I_q \propto f^2 \propto B^2$). These scaling laws have continued to hold for three generations of ECRIS development, and it is expected that source performance will continue to improve with increased confining magnetic field.

ECRIS development since its invention has shown that

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UPGRADE OF THE PSI INJECTOR 2 CYCLOTRON

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Abstract

The high intensity proton accelerator facility at Paul Scherrer Institute (PSI) is capable of providing beam currents of up to 2.4 mA at a kinetic energy of 590 MeV. PSI is following an upgrade plan to further increase the beam power and to further minimize proton losses. Up to now, this has mainly been achieved by the installation of high gradient copper resonators in the Ring cyclotron and the installation of more powerful RF-amplifiers. Currently, PSI follows a similar approach for the Injector 2 cyclotron providing 72 MeV protons for the injection into the 590 MeV Ring cyclotron. In order to increase the turn separation in the injector cyclotron which results in lower relative beam losses, the two 150 MHz resonators operated in accelerating mode are replaced with two 50 MHz Aluminum resonators providing higher acceleration voltage. This paper describes the status of the upgrade, i.e., the replacement of the first resonator and related hardware.

INTRODUCTION

The Injector 2 cyclotron was commissioned in the 1984. The rf system consists of the Resonators 1 & 3, which are 50 MHz double cap cavities for the main acceleration. In addition, the injector is equipped with two flat top Resonators 2 & 4 operated at a frequency of 150 MHz, initially to provide a broad phase acceptance. However, it was later discovered that space charge forces lead to a Vortex motion of the particles and thus a self-focusing of the bunches [1]. It turned out that changing the phase of the Resonators 2 & 4 by 180 degrees and thus providing additional energy gain per turn leads to even lower proton losses in the cyclotron. In this configuration during several shifts of 8 hours the operation of the Injector 2 cyclotron at 2.4 mA was demonstrated.

To further increase the beam current to 3 mA and consolidate the rf system, an upgrade program of the Injector 2 rf system was started [2, 3]. This upgrade is as well essential for the amplifier chains because some of the tetrodes used in the amplifiers up to 10 kW are not anymore available on the market.

THE NEW RF SYSTEM

In the new rf system the Resonators 2 & 4 will be replaced by 50 MHz single gap cavities with a higher voltage and a field distribution with the peak shifted toward the outer radius of the Injector 2. This will lead to an even higher energy gain per turn and a better turn separation at the extraction. The gap voltage of the old and new cavities is compared in Fig. 1. Because of the change in the frequency from 150 MHz to 50 MHz, the old analog LLRF system and the amplifiers need to be replaced.

In a second phase the 50 MHz LLRF system and the amplifiers for the Resonators 1 & 3 will be as well renewed.

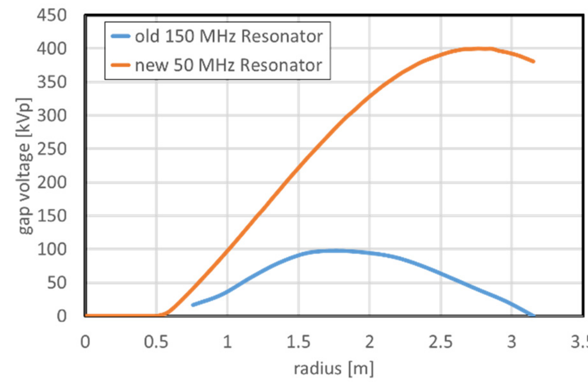

Figure 1: Gap voltage of Resonators 2 & 4.

The New 50 MHz Resonator

The rf volume of the new Resonator has an 8 shape in the cross section. On both sides there are two wings which serve as vacuum chamber towards the sector magnets (see Fig. 2). Within this space diagnostic elements and in the Resonator 4 the extraction magnets AXA/AXB are installed.

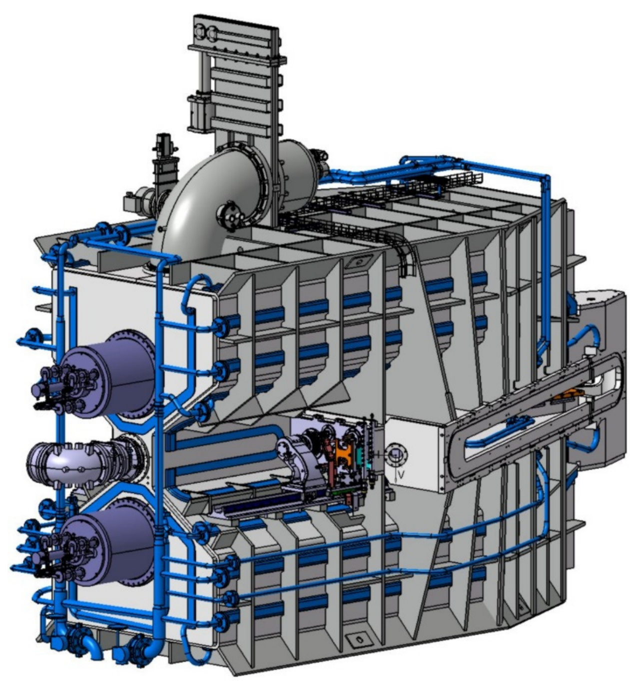

Figure 2: Isometric view of Resonator 4 with tuner, coupling loop in the front and vacuum pump on the top.

The new Resonators were made of Aluminum allowing using the existing cooling infrastructure of the Resonators 1 & 3. Both resonators were designed at Paul Scherrer Institute (PSI) and manufactured in France by the company SDMS. Some key parameters are listed in Table 1.

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NOVEL IRRADIATION METHODS FOR THERANOSTIC RADIOISOTOPE PRODUCTION WITH SOLID TARGETS AT THE BERN MEDICAL CYCLOTRON*

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Abstract

The production of medical radioisotopes for theranostics is essential for the development of personalized nuclear medicine. Among them, radiometals can be used to label proteins and peptides and their supply in quantity and quality for clinical applications represents a challenge. A research program is ongoing at the Bern medical cyclotron, where a solid target station with a pneumatic delivery system is in operation. To bombard isotope-enriched materials in form of compressed powders, a specific target coin was realized. To assess the activity at EoB, a system based on a CZT detector was developed. For an optimized production yield with the required radio nuclide purity, precise knowledge of the cross-sections and of the beam energy is crucial. Specific methods were developed to assess these quantities. To further enhance the capabilities of solid target stations at medical cyclotrons, a novel irradiation system based on an ultra-compact ~50 cm long beam line and a two-dimensional beam monitoring detector is under development to bombard targets down to few mg and few mm diameter. The first results on the production of ^{68}Ga, ^{64}Cu, ^{43}Sc, ^{44}Sc and ^{47}Sc are presented.

INTRODUCTION

The availability of novel medical radioisotopes is a key issue for advances in nuclear medicine. Of particular interest are the so-called theranostic pairs, which consist of one radionuclide used for diagnostics (β^+ or γ emitter for PET or SPECT) and one for therapy (β^-, Auger or α emitter for radio-immunotherapy). The two radionuclides must have very similar or identical chemical properties, as in the case of isotopes of the same element. They can be used to label the same biomolecules that, once injected into the patient's body, undergo the same metabolic processes. In this way, they allow treating the disease and, at the same time, assessing their uptake and following the evolution of the therapy by means of medical imaging. Along this line, radiometals can be bound to proteins and peptides and a few of their isotopes form the most promising pairs , such as ^{43,44}Sc/^{47}Sc and ^{61,64}Cu/^{67}Cu.

The availability of these radionuclides represents the bottle-neck for the development of theranostics in nuclear medicine. To solve this problem, the large number (> 1000 worldwide) of compact medical cyclotrons [1] could be exploited to produce the diagnostic partner of the pair and, in some cases, also the therapeutic one. Being designed to produce ^{18}F, which is presently the main PET radioisotope, medical cyclotrons provide proton beams of low energy (about 20 MeV) and relatively high intensity (>100 µA). For the production of radiometals, very rare and expensive isotope enriched materials have to be bombarded. They are often available in form of powder and, to obtain high yields, the use of a solid target station represents the best solution. Solid target stations for compact medical cyclotrons are rare. They are designed to irradiate target coins on which the enriched material is electroplated, a methodology that is not suitable for the production of several radiometals. For the bombardment of compressed materials in form of powder and to irradiate solid targets of small dimensions (about 6 mm diameter or less) novel irradiation instruments and methods have to be conceived and developed.

We report here about some of the developments and results obtained in the framework of the research programs ongoing at the cyclotron laboratory in operation at the Bern University Hospital [2, 3]. This facility is based on an IBA Cyclone 18/18 medical cyclotron (18 MeV proton beams, max. 150 µA extracted current, 8 out ports), which is used for routine production of ^{18}F during the night and for multidisciplinary research activities during the day. For the last purpose, it is equipped with a 6 m long Beam Transport Line (BTL) bringing the proton beam to a second bunker with independent access. Although uncommon for a hospital-based facility, this solution was fundamental to obtain the results reported in this paper.

SOLID TARGET DEVELOPMENTS AND FIRST RESULTS

To pursue our research program on novel medical radioisotopes, an IBA Nirta Solid target station was installed in one of the out ports of the cyclotron together with a pneumatic solid target transfer system (STTS) by TEMA Sinergie. The STTS was customised in such a way that the shuttle containing the irradiated target can be sent either to one hot cell in the nearby GMP radio-pharmacy or to a receiving

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THE USE OF PSI's IP2 BEAM LINE TOWARDS EXOTIC RADIONUCLIDE DEVELOPMENT AND ITS APPLICATION TOWARDS PROOF-OF-PRINCIPLE PRECLINICAL AND CLINICAL STUDIES

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Abstract

Paul Scherrer Institute (PSI) runs a High Intensity Proton Accelerator (HIPA) facility, where a maximum of 100 μA protons is gleaned from high intensity 72 MeV protons from Injector 2, a separated sector cyclotron, into the IP2 target station. These protons irradiate various targets towards the production of exotic radionuclides intended for medical purposes.

Many radiometals in use today are for the diagnosis of disease, with the most popular means of detection being Positron Emission Tomography. These positron emitters are easily produced at low proton energies using medical cyclotrons, however, developments at these facilities are lacking. The fixed 72 MeV proton beam is degraded at IP2 using niobium to provide the desired energy to irradiate targets to produce the likes of ^{44}Sc, ^{43}Sc, ^{64}Cu and ^{165}Er. Once developed, these proofs-of-principle are then put into practice at partner facilities.

Target holders and degraders require development to optimize irradiation conditions and target cooling. Various options are explored, with pros and cons taken into consideration based on calculations and simulations.

INTRODUCTION

Paul Scherrer Institute (PSI), Switzerland's premier research facility, runs a High Intensity Proton Accelerator (HIPA) amenity as part of its Large Facilities, where three accelerators are connected in series to increase proton beam energy. A Cockroft-Walton accelerator accelerates protons at 870 keV to the Injector II separated sector cyclotron, where the protons are accelerated to 72 MeV at an intensity of ~2.5 mA to the Ring cyclotron. The Ring cyclotron accelerates the protons further to 590 MeV, which is then sent down the beam line to various experimental vaults, before the remainder of the beam is collected in a Pb beam dump, which serves as a neutron spallation source for the Swiss Neutron Source (SINQ) [1].

Along the beam line between Injector II and the Ring cyclotron, the Radionuclide Development/production irradiation station (known as IP2) currently gleans ~50 μA protons from Injector 2, by means of a beam splitter, into the IP2 target station (Fig.1). These protons irradiate various targets towards the production of exotic radionuclides intended for medical purposes.

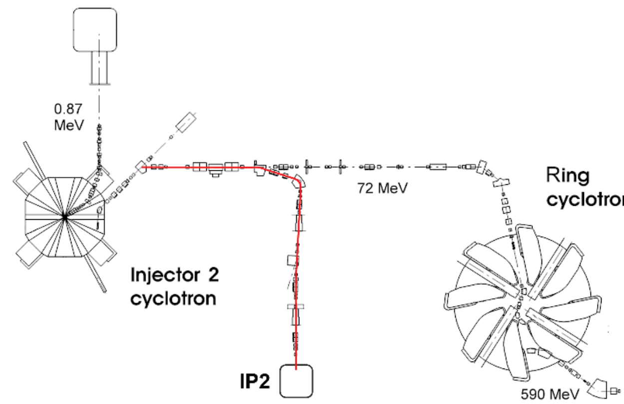

Figure 1: The beam transfer from the Cockroft Walton accelerator via the Injector II cyclotron to the Ring cyclotron. The red line indicates the 72 MeV beam gleaned from Injector II to IP2. Figure adapted from [2].

Many radiometals currently used in nuclear medicine are for the diagnosis of disease, with the most popular means of detection being Positron Emission Tomography (PET). These positron emitters are easily produced at low proton energies using medical cyclotrons, however, development using such facilities are rare.

The irradiation station at IP2 is used for ~9 months of the year and, as a result, cannot be considered for use in any commercial setting. The system is still put to good use, however, towards the development of novel, non-standard radiometals. The station was used to produce the likes of ^{18}F [3] and ^{124}I [4] in a novel way by utilizing its higher beam energy, as well as ^{67}Cu [5], ^{82}Sr and ^{68}Ge, but these activities were halted over a decade ago. As the use of PET increased in popularity for the diagnosis of cancer, the strategy of the station's use was adjusted to meet the growing demand for positron-emitting radionuclides.

Positron-emitting radionuclides are popular, too, because they can easily be produced at medical cyclotrons (with an installed solid target station) utilizing the (p,n) nuclear reaction in the vicinity of 13 MeV protons. To apply this to the revised strategy of IP2's use, it was necessary to degrade from 72 MeV to the desired energy of the radiometal to be produced. Once developed, these proofs-of-principle can then be put into practice at partner facilities.

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CHARACTERIZATION OF NEUTRON LEAKAGE FIELD COMING FROM ^{18}O(p,n)^{18}F REACTION IN PET PRODUCTION CYCLOTRON

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Abstract

The paper shows a new method for characterization of the secondary neutron field quantities, specifically a neutron spectrum leaking from ^{18}O enriched H_2O XL cylindrical target in IBA Cyclone 18/9 in the energy range of 1–15 MeV. This leakage spectrum is measured by stilbene scintillation detector in different places. The neutron spectra are evaluated from the measured proton recoil spectra using deconvolution through maximum likelihood estimation. A leakage neutron field is not only an interesting option for irradiation experiments due to a quite high flux, but also for a validation of high energy threshold reactions due to a relatively high average energy. The measured neutron spectra were compared with calculations in MCNP6 model by using TENDL-2017, FENDL-3, and default MCNP6 model calculations. TENDL-2017 and FENDL-3 libraries results differ significantly in the shape of the neutron spectrum for energies above 10 MeV while MCNP6 gives incorrect angular distributions. Activation measurements of the different neutron induced reactions support the characterization. The ^{18}F production yield is in a good agreement with TENDL-2017 proton library calculation within a respective uncertainties. The shape of the measured spectrum is also compared with the calculations with TALYS-1.9 using the different models.

INTRODUCTION

All experiments were performed using IBA Cyclone 18/9 accelerator (18 MeV for H$^-$, 9 MeV for D$^-$ particle) which is located in UJV cyclotron laboratory. The most common radioisotope product of the facility is 2-fluoro-2-deoxy-D-glucose (FDG) labeled by ^{18}F which origins from ^{18}O(p,n)^{18}F reaction. Furthermore, it has the capacity to produce the other positron-emitting medical isotopes such as ^{11}C, ^{13}N, ^{15}O. The cyclotron is surrounded by a 4 m wide and 5.75 m long ferroconcrete shielding bunker as a biological shielding. The accelerator has 2 m in diameter and is centered to the shorter side and the same distance from the side wall.

Measurements were performed during irradiation (by 18 MeV protons) of 2.7 ml ^{18}O enriched water (minimal content of 98%). The water is placed in a niobium pin which is sealed by a Havar foil. Accelerator window is covered by a Ti foil. The current, generated by the proton beam on the target, was approximately 75 µA in case of the activation experiments, while it was 0.92 µA in the case of neutron spectra measurements near target. The current was approximately 80 µA in the case of neutron and gamma spectra measured further from the target.

EXPERIMENTAL AND CALCULATION METHODS

The 10×10 mm stilbene scintillation detector was used for measuring neutron leakage spectra in the range of 1.0–14 MeV in the steps of 100 keV. Energy calibration was tested at LVR-15 reactor in Research centre Rez by means of a silicon filtered beam [1]. The efficiency calibration employs a measurement using a pure ^{252}Cf neutron source. This upgraded two-parameter spectrometric system NGA-01 [2, 3] is fully digitized and is now able to process up to 500 000 impulse responses per second. Pulse shape discrimination unit is used to distinguish the type of the detected particle by analyzing the pulse shape, while particle energy is evaluated from the integral of the whole response (energy integral). The pulse shape discrimination value is computed by the field-programmable gate array using an integration method which uses the comparison of the area delimited by part of a trailing edge of the measured response with the area delimited by the whole response. Then the neutron spectra are evaluated from the acquired recoiled proton spectra by means of deconvolution using Maximum Likelihood Estimation [4]. The substantial sources of uncertainty in the measurement were: an energy calibration uncertainty of 3–5%, an uncertainty in the efficiency crystal calibration factor 2.1%, and an uncertainty in the total emission of the neutron ^{252}Cf source 1.3%. Total measurement uncertainty, including statistical uncertainty and dispersion between measurements, is between approximately 2.4%–15% in the measured region.

In the case of activation experiments, the experimental reaction rates were derived from the gamma activities of irradiated samples. Irradiated samples were measured by means of a well-defined HPGe detector with verified geometry and efficiency calibration, for more details see [5]. The reaction rates were derived using the following formula:

$$q = C(T_m)\frac{\lambda \times k}{\epsilon \eta N}\frac{1}{1-e^{-\lambda T_m}}\frac{1}{e^{\lambda \Delta T}}\frac{1}{1-e^{\lambda T_{ir}}}, \qquad (1)$$

where: q is the experimental reaction rate per atom per second, N is the number of target isotope nuclei, η is the detector efficiency, ϵ is gamma branching ratio, λ is the decay constant, ΔT is the time between the end of irradiation

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JINR PROJECTS OF CYCLOTRON FOR PROTON THERAPY

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Abstract

The physical design of the compact superconducting cyclotron SC230 (91.5 MHz) has been performed. The cyclotron can deliver up to 230 MeV beam for proton therapy and medical and biological research. As the cyclotron will have a relatively small magnet field, it is possible to use both superconducting and resistive coil. Besides a superconducting cyclotron we simulate design of the cyclotron with a conventional copper water-cooled coil.

INTRODUCTION

Since 2016 the project of SC200 superconducting cyclotron for hadron therapy has been jointly developed by JINR and ASIPP (Hefei, China) [1]. The production of the cyclotron faced a lot of engineering challenges which are mainly aroused due to high magnetic field of the accelerator.

Recent developments of superconducting cyclotrons for proton therapy, such as SC200, Pronova [2], Sumitomo 230 MeV [3] share similar parameters that define the structure of the cyclotron. All projects are four-sector cyclotrons with ~3 T central field. Such parameters were chosen in pursuit of compact dimensions. None of those cyclotrons are yet in operation. It was, therefore, decided to rethink some design decisions after careful analysis of SC200, other projects and operating cyclotrons for proton therapy.

There are two most successful accelerators in the proton therapy: Varian Proscan [4], design proposal by H. Blosser et al. in 1993, and C235 (IBA Belgian) [5]. Both cyclotrons have much smaller central field, 2.4 and 1.7 T. First of all, we increased the pole of the cyclotron in order to decrease mean magnetic field to about 1.5 T in the center. Corresponding RF frequency for this value of the magnetic field is about 90 MHz at 4th harmonics operation mode. As the cyclotron will have a relatively small magnet field, it is possible to use both superconducting and resistive coil. Both solutions have their pros and cons. Earlier [6] we reported design of the SC230 cyclotron with superconducting coil. Its parameters are recapitulated in Table 1.

SC-230 CYCLOTRON

Computer Simulations of the Magnet

Simulations were performed in CST studio [7] in the parametrized model of the magnet (see Fig. 1) created in Autodesk Fusion 360. The dimensions of the yoke (see Fig. 2) were chosen to restrict the magnetic stray field in the range of 200 - 300 G just outside accelerator, providing full saturation of the iron poles and yoke. Average magnetic field and flutter from CST simulation are presented in Fig. 3.

Betatron tunes calculated with CYCLOPS-like code are presented in Fig. 4.

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Table 1: Parameters of the Cyclotron SC230

Parameter	Value
Magnet type	Compact, SC coil, warm yoke
Ion source	PIG
Final energy, MeV	230
Pole radius, mm	1350
Mean mag. field (center), T	1.5
Dimensions (height×diameter), m	1.7 × 4
Weight, tonnes	130
Hill/Valley gap, mm	50/700
A·Turn number	170 000
RF frequency, MHz	91.5
Harmonic number	4
Number of RF cavities	4
Voltage, center/extraction kV	35/90
RF power, kW	40
Number of turns	600
Beam intensity, μA	1.0
Extraction type	ESD

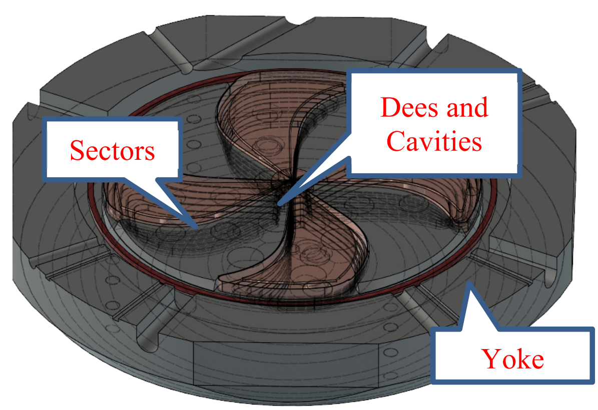

Figure 1: Layout of the cyclotron's 3D computer model (magnet and accelerating system).

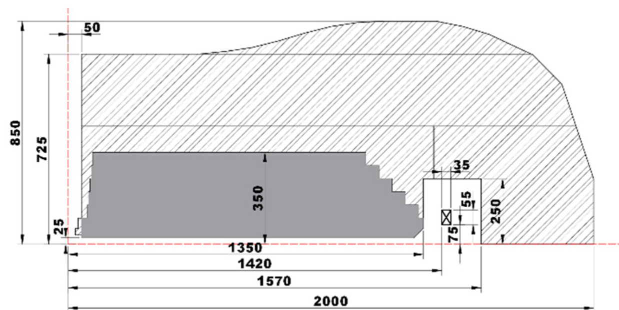

Figure 2: SC230 magnet yoke and SC coil general dimensions.

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MRI-GUIDED-PT: INTEGRATING AN MRI IN A PROTON THERAPY SYSTEM

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Abstract

Integration of magnetic resonance imaging (MRI) in proton therapy (PT) has the potential to improve tumor-targeting precision. However, it is technically challenging to integrate an MRI scanner at the beam isocenter of a PT system due to space constraints and electromagnetic interactions between the two systems. We present a concept for the mechanical integration of a 0.5 T MRI scanner (MR-Open, ASG Superconductors) into a PT gantry (ProteusONE, IBA). Finite element modelling (FEM) simulations are used to assess the perturbation of several of the gantry's elements on the homogeneity of the scanner's static magnetic field. Results show that only the perturbations by the bending magnet are significant and to be taken into account during treatment planning and dose delivery.

INTRODUCTION

Image guidance in conventional PT systems is provided by X-ray or (cone-beam) CT systems. Better image guidance and adaptive therapies for several tumor sites can be achieved by changing to MRI guidance. The first benefit of MRI is the absence of ionizing radiation dose: an advantage in for example paediatric cases and an enabler for continuous imaging. Daily adaptations of the treatment plan and organ motion visualization in for example the abdomen or the thorax become feasible. Secondly, MRI provides unparalleled soft-tissue contrast, enabling margin reduction in the treatment planning and potentially hypo-fractionation. For more information and an overview of the subject the reader is referred to [1].

Challenges

Before an MRI-guided-PT system can be designed there are several technical challenges to overcome. We mention the four most pressing issues. Firstly, there is the problem how to mechanically integrate the two large complex devices. Secondly, there is the mutual magnetic interference to be taken into account: the perturbation of the image quality by the PT system and the perturbation of the beam quality by the MRI's magnetic fields. Thirdly, there is the integration of a Faraday cage to shield the MRI from surrounding RF sources and it needs to be confirmed that the MRI receiver coils function correctly in or near the beam path, without altering the beam properties. Finally, methods for dosimetry in the presence of a magnetic field need to be established. All of this, and more, requires adjustment of the treatment workflow for a synchronized operation of both the imaging and the treatment equipment.

Scope of Proceedings

In these proceedings we discuss the mechanical integration of an MRI scanner on a PT gantry and an FEM study to assess the perturbation of the gantry's elements on the homogeneity of the MRI scanner's magnetic field.

A PT gantry comprises strong magnets mounted on heavy, ferromagnetic, iron support structures. These can be detrimental to the B-field homogeneity of an MRI scanner. Two possible sources of perturbation are studied. Firstly, the gantry rotation: Moving ferromagnetic objects can cause a change in the B-field. Secondly, the magnetic fringe field of the 60° bending magnet on the gantry: This last magnet on the gantry is closest to the MRI scanner and has a field that varies with beam energy.

Further Research

To test the technical feasibility, a first experimental setup was realized at the PT center in Dresden, combining a 0.22 T open MRI scanner with a static proton beam line. For more information, the reader is referred to [2].

MECHANICAL INTEGRATION

A 0.5 T open MRI scanner is the preferred choice for the integration with an IBA ProteusONE system [3]. The scanner's design would be based on that of the MR-Open manufactured by ASG Superconductors [4], see Fig. 1.

The low field strength scanner is foreseen to provide a good contrast-to-noise ratio and adequate image resolution [5]. At the same time, the liquid helium free scanner is based on a dry-cooled, superconducting magnet and has a large opening for patients between the magnet coils.

By modifying the C-shaped yoke of the MR-Open to a closed yoke, the integration of the MR on the PT system is foreseen as shown in Fig. 2. The beam exiting from the gantry to the isocenter is parallel to the B-field of the MRI

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ON-LINE DYNAMIC BEAM INTENSITY CONTROL IN A PROTON THERAPY CYCLOTRON*

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Abstract

Modern proton therapy facilities use the pencil beam scanning (PBS) technique for the treatment of tumours: the beam is scanned through the tumour volume sequentially, i.e. stopping the beam at each position in the tumour for the amount of time necessary to deliver the prescribed dose for that position, and then moving to the next position (dose-driven delivery). This technique guarantees robustness against fluctuations in the beam current. Modern cyclotrons however offer very stable beam currents, and allow regulating the beam intensity online to match the requested intensity vs. time profile of the beam ('time-driven' delivery). To realise time-driven delivery at the COMET cyclotron at the Paul Scherrer Institute (PSI), we have designed a beam intensity controller which is able to partially compensate for the non-linearity and the delay introduced by the physical limitations of the beam line elements and its drivers; this is particularly important when trying to achieve a very fast modulation of the beam, as required by clinical plans. Experimental results have shown good performance for most current clinical scenarios, and we are investigating more advanced solutions for higher dose rates scenarios.

INTRODUCTION

Proton therapy (PT) is a radiation therapy technique which established itself recently as treatment of choice of many tumours, particularly paediatrics [1]. Modern PT facilities use the pencil beam scanning technique (PBS) for the treatment of deep-seated tumours, because it provides better tissue sparing and less neutron contamination than other delivery techniques, such as passive scattering. In PBS, the beam is moved sequentially through the target volume, and stopped at each point through the volume for the amount of time needed to deliver the amount of protons defined by the treatment plan (therefore is also called 'discrete scanning'). About 75% of all PT facilities feature a cyclotron [2], as this technology offers high intensities and a very reliable beam current output, which are both advantageous to keep treatment times within predefined limits (about 2 Gy/minute needed to irradiate a 1-liter volume). Despite this excellent timing performance, PBS is currently mostly used to treat static tumours (for example, brain tumours) and in some cases used to treat tumours with limited periodical motion due to respiration, such as lung or liver, with or without motion mitigation strategies. This is due to the fact that the reciprocal/independent motion of the beam and the target cause an interference pattern in the resulting dose distribution, that worsens the delivered dose distribution (the so-called the interplay effect) and makes in the end the treatment ineffective. PBS can be used to treat such tumours only in combination with motion mitigation techniques [3], to ensure the dose degradation remains within acceptable limits.

At PSI, in the clinical treatment unit Gantry 2, we are investigating a new delivery technique, continuous line scanning (CLS), which offers substantially lower treatment times and better dose conformity of moving targets treatments, particularly when combined with motion mitigation. In recent papers [4, 5] we compared it with the two main discrete scanning techniques used for PBS, the so-called spot scanning [6] and raster scanning [7], showing that CLS brings clear advantage over the other techniques for liver tumours treated with motion mitigation.

One of the keys of CLS performance is its high flexibility and speed in the dose modulation, which is achieved by both quickly adapting the beam transverse scanning speed as well as beam intensity to what is specified for the treatment. This however requires fast intensity changes to be performed already at the cyclotron. Though the PSI COMET cyclotron is designed to match such a requirement, achieving a reliable intensity control that also meets the stringent safety requirements for patient routine treatments represent a challenge not fully considered at the time of design. We have preliminarily reported [8] a first attempt at designing a beam intensity controller for this application, and the challenges of the final design and implementation [9]. After summarising the main challenges and the characteristics of our design, we will report in this paper the experimental validation of the implemented solution.

BEAM INTENSITY CONTROL AT THE PSI PROTON THERAPY CYCLOTRON

The COMET Cyclotron at PSI and its Intensity Regulation

The COMET cyclotron (ACCEL/Varian) [10] provides a beam of 250 MeV to the treatment rooms at PSI. The beam energy is then lowered to what needed for the treatments in a degrader and energy selection section placed downstream. The beam intensity is defined at the cyclotron and gets considerably lowered when passing through the energy selection system. For keeping the beam delivery efficiency high, stable beam currents and a high cyclotron output are of utmost importance.

Inside the cyclotron, the beam is extracted from a cold-cathod-type proton source by a puller, and then accelerated

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INTEGRATION OF EtherCAT HARDWARE INTO THE EPICS BASED DISTRIBUTED CONTROL SYSTEM AT iThemba LABS

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Abstract

iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) has, over the past 30 years, carried out several upgrades to its control electronics and software. This culminated in the adoption of EPICS as the de-facto distributed control system at the lab. In order to meet the changing technology and user requirements, iThemba LABS adopted EtherCAT as its new industrial communication standard. Building on an open EtherCAT master implementation and prior community development, iThemba LABS has successfully integrated a variety of EtherCAT hardware into its EPICS control system (Fig. 1). This paper presents the open source software toolchain that has been developed and is used at iThemba LABS and showcases several hardware installations at the facility and abroad. Community involvement and future plans for this initiative are also presented.

Figure 1: 19-inch rack mountable EtherCAT enclosures designed at iThemba LABS.

INTRODUCTION

iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) is a multidisciplinary facility conducting research in subatomic physics, material research, radiobiology, and the research and development of unique radioisotopes for nuclear medicine and industrial applications. The facility operates and maintains a number of accelerators, the largest of these a K=200 separated sector cyclotron can accelerate protons to energies of 200 MeV. The control systems of these machines have been continually upgraded over the last 30 years in order to keep equipment failure to a minimum and to enhance technical capabilities.

Evolution of the iThemba LABS Control Architecture

The original control system was developed in the late 1970s around a few mini-computers with the control electronics and instrumentation interfaced via CAMAC. This system was then upgraded in the early 1990s to a distributed PC-based system running OS/2 and communication over Ethernet LAN. An in-house “simple” interface (SABUS) was also developed to supersede the ageing CAMAC bus and an assortment of I/O cards were developed to gradually replace the existing CAMAC modules.

With the OS/2 operating system no longer being supported by IBM, the decision was made in the late 2000s to migrate the control system onto the EPICS platform. The SABUS hardware interface was retained on account of robustness, noise-immunity and the large amount of re-cabling that would have to be done if this was changed. The various EPICS client user interfaces were developed in MEDM and Qt. By the mid-2010s about 60% of the control hardware was under EPICS control using SABUS cards to control power supplies, stepper motors, pneumatic actuators, all aspects of the vacuum, slits and scanner systems [1–3].

Migration to EtherCAT

The long design cycles involved in developing custom in-house SABUS cards resulted in a number of legacy OS/2 CAMAC systems still remaining. CAMAC hardware was becoming increasingly difficult to find and the rapid rate of obsolescence of modern electronic components meant that the in-house SABUS cards had to be periodically redesigned. In light of these challenges, and after an investigation of various industrial bus technologies, iThemba LABS adopted EtherCAT as its new industrial communication bus in 2015 due to its high-speed performance, existing integration with EPICS and wide selection of commercial off-the-shelf hardware.

SOFTWARE STACK

EtherCAT is an open real-time Ethernet fieldbus developed by Beckhoff (Verl, Germany) and maintained by the EtherCAT Technology Group (ETG) [4]. The EtherCAT topology employs a master/slave principle, where the master node (typically the control system) sends Ethernet frames to the slave nodes, the slave nodes then extract data from and insert data into these frames with a few nanoseconds delay. Each EtherCAT slave includes a controller with a Fieldbus Memory Management Unit (FMMU). The FMMU allows the mapping of logical addresses in the Ethernet frame to physical ones within the slave modules. The registers in each slave that can be mapped by the FMMUs are known as either Process Data Objects (PDOs) or Service Data Objects (SDOs).

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THREE YEARS OPERATION OF CYCIAE-100

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Abstract

The 100 MeV high intensity proton cyclotron (hereinafter referred to as CYCIAE-100) developed by China Institute of Atomic Energy is a multi-purpose variable energy AVF cyclotron for nuclear fundamental research and nuclear technology application. Its design specifications are: energy from 75 to 100 MeV continuously adjustable, beam intensity 200 μA, beam current can be extracted in both directions. The first physics experiment was carried out in November 2016 right after the national acceptance. By June 2019, we completed the construction of multiple experimental terminals for CYCIAE-100, such as single-event effect experimental terminal, ISOL experimental terminal, and white-light neutron experimental terminal. Several typical physics experiments of CYCIAE-100 have been carried out. Such as: The physics experiment of CYCIA-100 driving ISOL device to generate radioactive nuclear beam, white light neutron experiment, SiC and SRAM proton irradiation experiments, calibration experiment of high-energy proton electron total dose detector probe, and proton irradiation damage effect experiment of photoelectric devices. At present, the beam time for beam development of CYCIAE-100 is about 5000 hours, providing effective beam time for more than 3000 hours for many users at home and abroad, and the other beam time for beam development. This paper introduces the operation of CYCIAE-100 in the past three years, as well as the construction of experimental beam lines and terminals and typical experiments carried out.

CONSTRUCTION OF BEAMLINES AND EXPERIMENTAL TERMINALS

At the beginning of the design, the CYCIAE-100 had multiple beam lines and experimental terminals. Further, due to lack of funds and other factors, construction of some beam lines and experimental terminals were not completed when the accelerator was first beamed out in 2014. Then, as the accelerator gradually putting into the operation and while carrying out physical experiments, the construction of some beam lines and experimental terminals were also gradually carried out [1]. By July 2019, we completed the construction of multiple experimental terminals for CYCIAE-100, such as single-event effect experimental terminal, ISOL experimental terminal, and white-light neutron experimental terminal.

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Single-event Effect Beam Line and Experimental Terminal

The single-event effect beam line and experimental terminal are located on the east side of the physical experiment hall. They are mainly used to carry out experiments on single-event effect and anti-radiation reinforcement of aerospace devices. Figure 1 shows the single-event effect beam line and the experimental terminal. The proton beams are transmitted along the south to the common beam line, after they are extracted from CYCIAE-100. Then, after the proton beams are deflected by the southward switching magnet, they enter the single-event effect beam line. At present, a large number of experiments about single-particle effects and radiation-resistant reinforcement have been carried out at the experimental terminal.

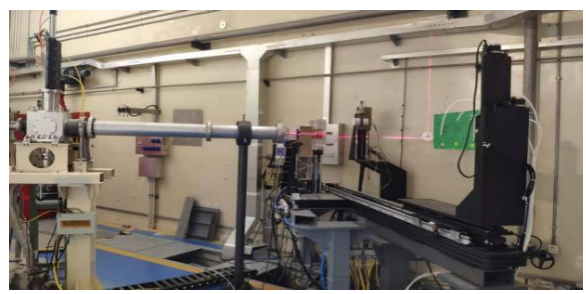

Figure 1: Beam line and experimental terminal of single-event effect.

Construction of ISOL Beam Line and Experimental Terminal

The ISOL beam line and experimental terminal are one of the important components in the HI-13 Tandem Accelerator Upgrade Project. The ISOL experimental terminal uses the proton beams generated by CYCIAE-100 to bombard the target material to produce medium- and short-lived radionuclides. Subsequently, the neutral radionuclide atoms generated in the target are converted into charged particles, and the required radioactive nuclear beams are sorted by a magnetic analyzer and accelerated up to 300 keV. A new set of superconducting post-accelerators and existing HI-13 tandem accelerators can further accelerate ions. The proton beams generated by CYCIAE-100 are transmitted through the north common beam line, pass through the northward switching magnet, enter the ISOL beam line, and are transmitted to the ISOL target chamber. The proton beams interact with the selected target material to generate the desired radioactive nucleus. The radionuclide atoms diffuse out from the target and enter the ion source ionization chamber to be ionized.

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THE INJECTION AND CHOPPER-BASED SYSTEM AT ARRONAX C70XP CYCLOTRON

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Abstract

The multi-particle cyclotron of the Arronax Public Interest Group (GIP) is used to perform irradiation up to hundreds of µA on various experiments and targets. To support low and high average intensity usage and adapt the beam time structure required for high peak intensity operation and experiments such as pulsed experiments studies, it has been devised a pulsing system in the injection of the cyclotron. This system combines the use of a chopper, low frequency switch, and a control system based on the new extended EPICS network. This paper details the pulsing system adopted at Arronax, updates and results for various intensity experimental studies performed with alpha and proton beams. Updated work on the simulation of the injection is also shown, specifically towards high intensity future irradiation.

INTRODUCTION

The Arronax cyclotron has been performing irradiation for 9 years delivering beams with intensities ranging over several orders of magnitudes. Typically for experimental studies, the average intensity is below one µA, while highest intensity irradiation for radio-isotope production can be at least up to 350 µA for proton and 20 µA for alpha in a single beamline. The cyclotron provides bunches interspaced by 32.84 ns (RF frequency = 30.45 MHz) translating into 7.8×10^7 particles per bunch for protons. To conform to the needs of the users for the range of beam intensities, several techniques are being employed based on the tuning of the source and the various magnet elements throughout the accelerator and specifically in the injection.

Additionally, a new chopper-based system located in the injection has been added and its characteristics and impact on the beam are being investigated in order to extend its use for high intensity operations.

CONCEPT AND LAYOUT

The pulsing chopper based system is designed to provide a variable number of trains of bunches to users from an initial continuous bunch structure, typical of cyclotrons. The present prototype design and functioning system allows thus to modify train duration and repetition. It is detailed in [1] as well as the first results at low intensity and the monitoring system that is being used.

The chopper system allows to bend away bunches at low energy (~40 keV for protons and 20 keV for other particles) in the injection. Its main components are:

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- Two parallel copper plates within the beampipe
- A High Voltage (HV) switch (Behlke type) located outside the beampipe and closed (<30 cm) to the plates.
- Control electronics and a Raspberry Pi3 server within an EPICS network environment.
- A Control System Studio-based (CSS) interface with a simple visualisation terminal.

At the present time, the CSS interface gives operators the possibilities to manually modify the duration, repetition and number of trains that the experimenters require.

The control electronics located outside the cyclotron vault serves as a counting board for the number of RF buckets, a trigger for the desired state (closed/open) of the switch and a mirror trigger for experimental use.

When the HV switch is closed, 3.3 kV is applied to the plates, ejecting bunches to the injection beampipe wall.

EXPECTED CAPACITIES

At low intensity, the resulting trains have been checked using a light detector and have indicated rise and fall times of the order of a few microseconds [1]. An extended scan over the repetition frequency and train duration has been performed and has shown the potential usage from 10 Hz to 50 kHz with trains from 164 ns up to the continuous case.

A relatively good linearity has been obtained for duration above a few hundreds of ns and with repetition below 10 kHz. With this configuration at Arronax, Fig. 1 illustrates the average intensity <I> required for protons to reach, in a single train, dosimetry level of 33 Gy/s at the plateau before the Bragg peak as a function of the train duration. The figure indicates that a 6.4 ms train at <I> = 500 nA can reach the considered dosimetry level, and 320 µs at <I> = 10 µA.

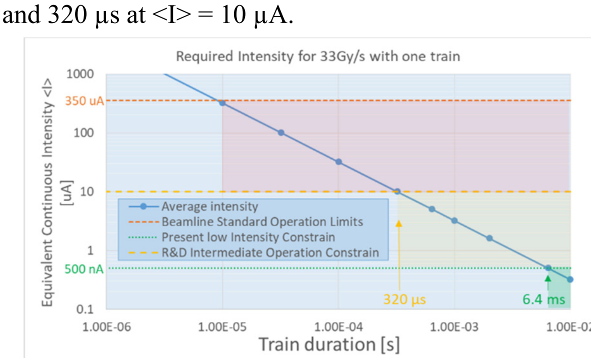

Figure 1: Avg. intensity as a function of the train duration to reach a dosimetry of 33 Gy/s at the Bragg peak plateau.

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OPERATIONAL EXPERIENCE IN THE TREATMENT OF OCULAR MELANOMAS WITH A NEW DIGITAL LOW-LEVEL RF CONTROL SYSTEM

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Abstract

Ocular melanomas have been treated for the last 20 years at the Helmholtz-Zentrum Berlin in collaboration with the Charité – Universitätsmedizin Berlin. However, parts of the initial control system electronics date back to the 1970s, when the machine was installed. Facing a critical shortage of legacy and obsolete components and with the down-time due to failures in the electronics on the increase, a decision was made to install the digital low-level RF control system, developed by iThemba LABS, on our k=132 cyclotron. A short description of the installation and commissioning process, which occurred in April 2017, and the experiences of the first two years of operation with the new digital low-level RF control system is presented.

INTRODUCTION

The HZB cyclotron with its two 30 kW RF amplifiers was built 45 years ago [1]. Over time some components of the whole cyclotron have been renewed, rebuilt or optimized. Especially in the high frequency systems, the 1 kW tube driver amplifiers were replaced by 2 kW semiconductor amplifiers, the system frequency generator was replaced by a network compatible device and various analogue displays were replaced by digital displays.

However, many components in both the low level and high level system of the RF are still from the early days. The two RF amplifiers in the high level system are still in their original condition, with the exception of minor optimizations, and are very robust. Spare parts for the amplifiers are available or can be made by ourselves. Some main components like e.g. the 100 kW amplifier tubes are still manufactured. Failures in the high level systems occur mainly due to leaks and defects in the water cooling system, and can be fixed by replacing or repairing the unit. The electronic modules in the low level systems were constructed using the wire wrap technology common at the time (Fig. 1), which is relatively compact despite the large number of components, but makes repair and maintenance more difficult. With the increasing age of the electronic modules, contact problems and wire breaks on the wire wrap cards occurred in addition to defective components.

Since various built-in special high frequency components and high-level logic ICs are no longer available, repairs were made even more difficult by increasingly scarce spare parts. Due to these problems and the desire for a better overview and diagnosis of the RF parameters, it was decided to replace the complete low level control of the two RF systems. An in-house development was rejected due to lack of personnel and time, and adaptable ready-made solutions were sought.

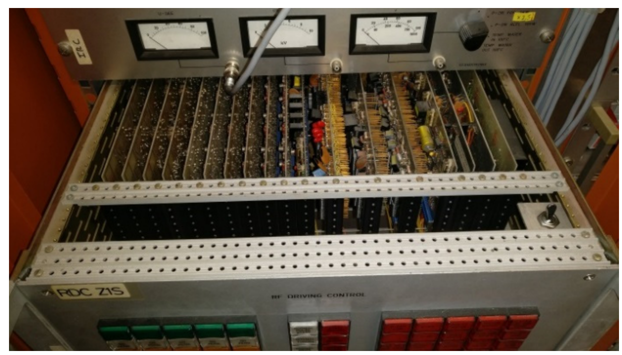

Figure 1: Old low level RF control system.

The digital low level RF (LLRF) control system newly developed and built by W. Duckitt at iThemba LABS [2] in Cape Town South Africa seemed to be suitable to replace the low level electronics of the RF systems at the HZB cyclotron. At this time in 2015, the digital LLRF control system was already successfully used with both injector cyclotrons SPC1 and SPC2 at iThemba LABS and the installation at the main cyclotron SSC and various buncher systems were planned. In October 2015, after clarification of the adaptability of the system and the technical implementation at the HZB cyclotron, it was decided to use the LLRF control system from iThemba LABS on both our RF systems.

PREPARATIONS AND INSTALLATION

From the beginning of 2016 to May 2017, all preparations, conversions and necessary measurements and tests were carried out in addition to normal accelerator operation during the maintenance periods. iThemba LABS built five LLRF control system modules for the HZB cyclotron and delivered them in March 2017. Two of the modules are planned for the north and south system at the cyclotron, one module serves as reference oscillator and two modules are intended as reserve or in the future for the buncher at the accelerator. For a synchronized operation of the modules, a distribution of the reference frequency and a 10 MHz clock signal had to be prepared using existing RF splitters. Since the installation of the LLRF control system had to take place without disturbing the accel-

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THE CYCLOTRON TR-FLEX AT THE CENTER FOR RADIOPHARMACEUTICAL CANCER RESEARCH AT HELMHOLTZ-ZENTRUM DRESDEN-ROSSENDORF

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Abstract

The new Center for Radiopharmaceutical Cancer Research was established at Helmholtz-Zentrum Dresden-Rossendorf e.V. to centralize the main units: a high current proton cyclotron, a radiopharmaceutical production – GMP unit including quality control, laboratories for PET-radiochemistry, chemical laboratories, laboratories for biochemical investigation, laboratories for small animal imaging and an animal keeping facility.

The cyclotron TR-Flex was put into operation in 2017 and it is equipped with two extraction ports. Both are movable to adjust the energy of the extracted proton beam in the range from 15 MeV up to 30 MeV. One extraction port is coupled with a combination magnet and two beam lines. A [^{123}I]-iodine gas target station is installed at the first beam line and a four-port target selector is installed at the end of beamline two. The second extraction port has no beamlines but is equipped with a four-port target selector. Two [^{18}F]- water targets, one [^{18}F]F_2 gas target, one [^{11}C]CH_4 gas target, one [^{11}C]CO_2 gas target, one 30° and one 90° solid state target are mounted on two target selectors.

In our contribution we report our experience of the new cyclotron TR-Flex during the first two operation years. Typical beam parameters, saturation yields and the reliability of the TR-Flex are presented. Furthermore we describe the new home-built Radionuclide Distribution System.

INTRODUCTION

Radiopharmaceutical research and the production of radiopharmaceuticals have a long history at the Research Center in Rossendorf. The production of radiopharmaceuticals started in 1958. The basis were a nuclear research reactor (10 MW) and the Cyclotron U-120 (Leningrad). A broad scale of radiolabeled products based on ^{14}C, ^{131}I, ^{123}I, ^{32}P, ^{75}Se, ^{67}Ga, ^{85}Sr, ^{111}In, ^{211}At and fission radionuclides such as ^{90}Sr/ ^{90}Y, ^{99}Mo were provided. Furthermore, the Research Center was the second producer of fission ^{99}Mo/ ^{99m}Tc-generators with an amount of 20 TBq ^{99}Mo per week. A wide-spread research to ^{99m}Tc coordination chemistry and radiopharmacology and ^{99m}Tc-kits was established including a wide range of labelled compounds for human use.

The Cyclotron U-120, Leningrad (1958 - 1999) was used for routine production of ^{67}Ga, ^{85}Sr, ^{111}In, ^{123}I, ^{211}At and the corresponding labelled compounds for human use. The start for research for PET was in 1982. The first [^{18}F]FDG (electrophil) production was in 1983.

1997 marked the official opening of Rossendorf PET-Center for research and application including the manufacturing authorization for PET drugs. The marketing authorization includes [^{18}F]FDG (GlucoRos), [^{18}F]Fluoride (NaFRos) and [^{18}F]FDOPA (DOPARos). Furthermore, there are 15 different radiopharmaceuticals available on demand.

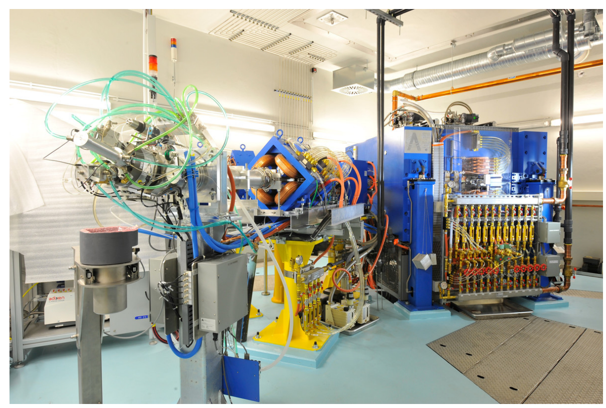

Figure 1: The TR-Flex cyclotron at the HZDR. The beamline 1B with a 4-port target selector is shown in the foreground. The second 4-port target selector is at the opposite side of the Cyclotron. Picture: HZDR/Frank Bierstedt

The former cyclotron of the HZDR, an IBA Cyclone 18/9, was put in operation in autumn 1996. After 18 years of routine operation comprehensive upgrades would have to be necessary to fulfill the new demands in the second decade of the 21th century. On the other hand HZDR could not forego the RN production with the Cyclone 18/9 during the ZRT building phase. Thus, HZDR decided to install a new cyclotron with higher ion energy and higher ion bean current.

THE TR-FLEX CYCLOTRON

The TR-Flex cyclotron, shown in Fig. 1, from Advanced Cyclotron Systems Inc. (ACSI, Canada) [1] was put into operation in 2017. The cyclotron is equipped with two extraction ports. Both extraction foils are radially movable to adjust the energy of the extracted proton beam in the range of 15 MeV up to 30 MeV. Two beamlines are connected behind a combo magnet on the extraction port 1. Two 4 port

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CYCLOTRON CAVITY POLLUTION RECOVERY

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Abstract

In a cyclotron, RF cavities are usually among the most reliable subsystems, provided minimal care and maintenance. Nevertheless, several parameters may affect cavity performance after several years of operation. To name a few typical causes of degradation: decreasing vacuum quality, various gas loads or gas qualities triggering adverse effects, deposition of highly emissive material on the cavity due to overheating of components like pass-through connectors, accidental use of chemicals or not-suited greases. The cavity status can be monitored but, in the worst cases, the RF tuning may become difficult and it is important to apply methods in order to recover a better cavity Q-factor. In this paper, cases of cavity pollution will be shown, their potential root causes discussed and some recovery methods described.

INTRODUCTION

RF Cavities, Equivalent Circuit and Power Characterization

RF cavities are a key subsystem of cyclotrons. They create the necessary electric field required to accelerate charged particles. The RF system of a cyclotron can be seen as a RLC circuit that resonates at the pulsation $\omega_{res} = \frac{1}{\sqrt{LC}}$.

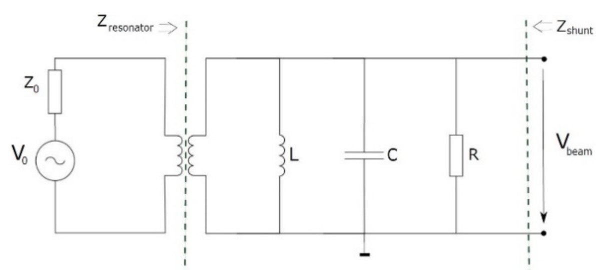

Figure 1: RLC equivalent circuit of a RF system. Adapted from F. Caspers [1].

The inductor and capacitor represent a lossless resonator, while the resistor characterizes the losses of the circuit. Equation (1) gives the impedance seen by the beam, called the shunt impedance, and at resonance it is equal to the ohmic resistor.

$$Z(\omega) = \frac{1}{\frac{1}{R}+j\omega C+\frac{1}{j\omega L}} \text{ and } Z(\omega_{res}) = R \quad . \quad (1)$$

The average dissipated power is defined as the power emitted by Joule losses. Therefore, for a constant accelerating voltage, the higher the shunt impedance, the lower the dissipated power.

$$P = \frac{V_{max}^2}{2R} \quad . \quad (2)$$

The challenge faced by cyclotron users is therefore the following: tune the system to work at resonance and limit the power dissipated by the cavities by maximizing the shunt impedance. In order to understand the parameters involved in this challenge, we need to introduce the cavity scaling laws given by Eqs. (3) and (4) and the skin depth depicting the surface thickness where most of the RF current flows (8):

$$\frac{R}{Q} = const \quad , \quad (3)$$

$$Q * \frac{\delta}{\lambda} = const \quad , \quad (4)$$

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu}} \quad , \quad (5)$$

where Q is the quality factor of the RF system, $\frac{R}{Q}$ is called the characteristic or geometric impedance, δ is the skin depth, σ is the electric conductivity and μ is the magnetic permeability.

From these relationships, we can conclude that if the skin depth of the cavity increases (by decreasing the conductivity at the same resonance frequency) the Q factor must decrease, and so does the shunt impedance. The power dissipated rises, for a set voltage.

This phenomenon can be also understood by introducing the surface resistance of the RF cavity:

$$R_{surf} = \frac{1}{\sigma\delta} = \sqrt{\frac{\omega\mu}{2\sigma}} \quad . \quad (6)$$

And the power dissipated in the cavity walls due to ohmic heating is given by [2]:

$$P = \frac{1}{2} R_{surf} \int |H|^2 dS \quad , \quad (7)$$

where H is the magnetic field [A/m] induced by the RF electric field.

Increasing the skin depth (by decreasing the conductivity at the same resonance frequency) increases the surface resistance seen by the current and therefore also increases the power dissipated. The shunt impedance and the surface resistance behave thus inversely.

In the equivalent RLC model described in Fig. 1, R is the resistor across which the voltage driving the beam is generated. It represents the losses of the resonator for that given voltage. The surface resistance describes the losses due to the ohmic heating as well, but from an electric and magnetic field point of view. The oscillating electric field creates in turn an oscillating magnetic field, inducing cur-

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BUNCHER FOR THE OPTIMIZATION OF THE INJECTION OF A 70 MeV CYCLOTRON

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Abstract

The design of an injection buncher for the 70 MeV cyclotron in use at Laboratori Nazionali di Legnaro (LNL) labs of INFN is under way. This buncher is to be installed between the ion source and the injection, to match the injected beam to the acceptance angle of the cyclotron's injection.

The planned design is a 3/2 beta-lambda double-gap driven with one or two harmonics of the 56 MHz cyclotron's frequency.

Remotely-driven variable capacitors will be used for easy tuning of the matching box from the control system.

The mechanical layout and simulations will be presented.

DESIGN OF THE BUNCHER

The injection buncher for the 70 MeV cyclotron at Laboratori Nazionali di Legnaro (LNL) of INFN is on design stage since a while, due to the commitment of the cyclotron's team to other activities. Nevertheless, slowly but constantly the design is being carried out by the team.

Relatively to older presentations [1, 2], the mechanical design is reconsidered and implemented in stability and accuracy. Beam dynamics simulations have been started, and the results are shown here. A chopper is also being considered.

GENERAL LAYOUT

The buncher will be installed along the injection line, between the multi-casp H^- ion source and the central region, in a dedicated vacuum box, placed between two focusing solenoids. The vacuum box can be isolated from the ion source and the cyclotron closing two gate valves, placed before and after the position of the buncher. The ion source provides up to 10 mA of DC current at 40 keV. The frequency of the buncher will of course be the same as the radiofrequency (RF) of the cyclotron, e.g. 56 MHz. The length of the buncher is calculated upon the $\frac{3}{2}\beta\lambda$, that is 73.995 mm, where $\beta\lambda$ is the distance covered by the ions accelerated by the source during one RF cycle.

Mechanical Layout

To improve the beam dynamics, the ground electrodes should be not too short. Two different configurations have been studied: a $\frac{3}{2}\beta\lambda$ buncher that has a longer drift tube, and a $\frac{1}{2}\beta\lambda$, that allows longer ground electrodes.

It is not possible to have long ground electrodes and long drift tube at the same time, due to the limited longitudinal dimensions: the two gate valves are placed at short distances before and after the position of the buncher.

The $\frac{3}{2}\beta\lambda$ and the $\frac{1}{2}\beta\lambda$ configurations have both been calculated and compared.

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The $\frac{3}{2}\beta\lambda$ buncher This configuration allows the use of two separate electrodes for the injection of two different harmonics of the radiofrequency power.

Using the $\frac{3}{2}\beta\lambda$ configuration, and 5 mm between the RF electrode (the drift tube) and the ground (GND) electrodes, the length of the drift tube will be of 69 mm, and the total length of the whole buncher is 119 mm, with 20 mm of GND electrode's length.

To determine the inner diameter of the buncher we remind that it must be as small as possible, with respect to the diameter of the beam, to increase the transit time factor [3,4].

The dimensions of the $\frac{3}{2}\beta\lambda$ configuration are specified in Table 1.

Table 1: Dimensions of the $\frac{3}{2}\beta\lambda$ Buncher: Drift Tube and Ground (GND) Electrodes

Element	**Length (mm)**	**Diameter (int/ext)**
GND1	20	40/50
Gap1	5	-/-
Drift tube	69	40/50
Gap2	5	-/-
GND2	20	40/50

The rendering of the new design of the $\frac{3}{2}\beta\lambda$ can be seen in the following Fig. 1.

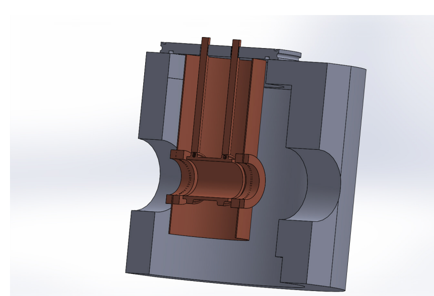

Figure 1: Rendering of the section of the buncher. The ground electrodes will be screwed with the external screen. Two electrodes are foreseen to feed the RF power to the buncher, at one ore two harmonics.

The Fig. 2 shows the calculation of the electric potential in the plane cutting the buncher along ts axis, where the Fig. 3 shows the detail of the potential along the axis of the drift tube.

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UPGRADE OF THE CENTRAL REGION OF THE SUPERCONDUCTING CYCLOTRON AT INFN-LNS

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Abstract

The Superconducting Cyclotron (CS) at INFN-LNS is regularly operated with beam power up to 100 W. The present efforts in upgrading the cyclotron are directed towards an increase of beam power up to 10 kW for ions with mass number A≤40 and energies between 15 and 70 AMeV by means of increase of beam intensity. Moreover, a beam energy resolution of 0.1% is requested by the NUMEN project at INFN-LNS. We plan to achieve high beam power by increasing the efficiency of the injection and extraction processes. The current extraction efficiency is lower than 60%. We expect to increase it to a value close to 100% by extracting the specific ion beams by stripping and no longer by electrostatic deflectors. A spiral inflector is used to inject onto the median plane the ion beams produced by the two ECR ion sources. Including the effect of a drift buncher placed in the axial injection line, the current injection efficiency is about 15%. The study of an upgraded CS central region is ongoing at INFN-LNS. First results of simulation study aimed to increase the injection efficiency are presented.

INTRODUCTION

The Superconducting Cyclotron at INFN-LNS in Catania, known as CS, has about 25 years track-record of accelerating ion beams to support the nuclear physics community of the laboratory. Furthermore, it is also used for the treatment of ocular melanoma by proton beam.

It is a multi-particle variable energy cyclotron with a wide operating diagram. The CS accelerates ions with charge-to-mass ratio Q/A in the interval 0.1 - 0.5. For any Q/A, the maximum energy per nucleon is determined by either the bending limit $E/A = 800 \cdot (Q/A)^2$ or the vertical focusing limit $E/A = 200 \cdot Q/A$.

The CS is very compact with a pole radius of 90 cm. The isochronous magnetic field in the range 2.2 – 4.8 T is produced by two superconducting main coils, three fully-saturated iron pole sectors and twenty trim coils wound around each hill [1]. Three RF-cavities provide the accelerating voltage for the beams and operate in the frequency range 15 - 48 MHz in harmonic mode 2. Ion beams, generated by two ECR ion sources, are axially injected.

The extraction system consists of two electrostatic deflectors placed on consecutive hills and eigth passive magnetic focusing channels [2]. The extraction by electrostatic deflectors limits the maximum beam intensity because of losses and induced heat-load on the septum of the first device. The current extraction efficiency is lower than 60% and the maximum beam power that the CS can deliver is about 100 W [3]. The constraint on the maximum beam intensity prevents to inject in the cyclotron high current, although the ion sources are able of high performance.

The cyclotron will be under an upgrade process in the near future to increase the beam intensity. High beam intensity is required by the NUMEN project at INFN-LNS [4]. It aims at accessing experimental-driven information on nuclear matrix elements involved in the half-life of neutrinoless double beta decay, by high-accuracy measurements of cross section of heavy ion induced double charge exchange reactions. The project requires mainly beams of carbon, oxygen and neon with intensity up to $10^{13} - 10^{14}$ pps. The required energies for these beams are in the range 15 - 70 AMeV, which corresponds to a beam power in the range 1 - 10 kW. Furthermore, a good beam energy resolution (~1/1000) is required.

In order to deliver high beam intensity, it is planned to increase the overall efficiency, including beam injection, acceleration and extraction processes.

The extraction by stripping for ions with A ≤ 40 has been proposed. It will allow to inject into the cyclotron, accelerate and to extract beam current higher than the actual one. According to data in Ref. [5], for the ion beams and energies required by NUMEN, the percentage of fully-stripped ions after the stripping process is higher than 99%. Consequently, an extraction efficiency close to 100% is expected. The implementation of the stripping extraction is not trivial because it requires substantial changes in the cyclotron [6].

The improvement of the injection efficiency is another important aspect of the CS upgrade project to achieve the desired high beam intensity. The overall efficiency is strongly constrained by the NUMEN requirement on the energy spread. Therefore, the evaluation of the energy spread of the extracted beam is essential.

THE EXISTING CS CENTRAL REGION

During the first four years of operation, the CS worked as a booster of the 15 MV Tandem at INFN-LNS [7]. Since the year 2000, the machine works in stand-alone mode.

A spiral inflector is used for 90° bending of ion beams from the vertical direction into the cyclotron median plane. It has a bending radius A of 27 mm and the so-called tilt-parameter k' is zero. The electrode distance d is 6 mm and the aspect-ratio s/d is 2. The inflector is surrounded by a copper housing to isolate the device from the RF-fields driving the CS. A copper collimator with a circular aperture of 6 mm diameter is placed before the device entrance to protect the inflector electrodes from the ion hits.

The CS central region is composed of a set of electrodes attached to the dees and dummy-dees. Pillars crossing the

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UPGRADE OF THE FAST NEUTRON BEAM VAULT AT iTHEMBA LABS TO A METROLOGY FACILITY

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Abstract

Quasi-monoenergetic neutron beams are typically produced at the iThemba LABS fast neutron beam facility by the ^{7}Li(p,xn) or ^{9}Be(p,xn) reactions. With the proton beams available from the separated sector cyclotron, the neutron energy range from about 30 MeV to 200 MeV can be covered almost continuously. The facility first became operational in the late 1980s. The fast neutron beam facility at iThemba LABS has been designated by the National Metrology Institute of South Africa (NMISA) as an entity responsible for providing traceability for the medium and high-energy neutron measurements in South Africa. As a result, the facility is undergoing a major upgrade and development in order for it to meet the requirements for a medium and high-energy neutron metrology facility. As part of the ongoing upgrade, Monte Carlo (MC) simulations aimed at benchmarking the experimental data are ongoing.

INTRODUCTION

iThemba LABS (Laboratory for Accelerator-Based Sciences) is one of the few facilities in the world that can provide quasi-monoenergetic neutron beams in the energy range of up to 200 MeV [1]. Quasi-monoenergetic neutron beams that range from about 30 MeV to 200 MeV are produced in the D-line experimental vault (Fig. 1) via the ^{7}Li(p,xn) or ^{10}Be(p,xn) reactions [2] for varying thicknesses of Li and Be targets, using proton beams available from the separated sector cyclotron (SSC). The iThemba LABS neutron beam facility has been designated by the National Metrology Institute of South Africa (NMISA) as an entity responsible for providing traceability for the medium and high-energy neutron measurements in South Africa. Thus, the facility is intended to be recognised and supported by the international neutron physics and metrology communities for calibrations of neutron detectors and radiation protection dosemeters; including those with a strong sensitivity to epithermal and thermal neutrons such as survey meters. Moreover, cross-section measurements of neutron-induced reactions in the medium and high-energy region (with as low uncertainties as possible) will be performed. In this regard, the neutron beam facility at iThemba LABS is undergoing a major upgrade and development in order for it to meet the requirements for a medium and high-energy neutron metrology facility.

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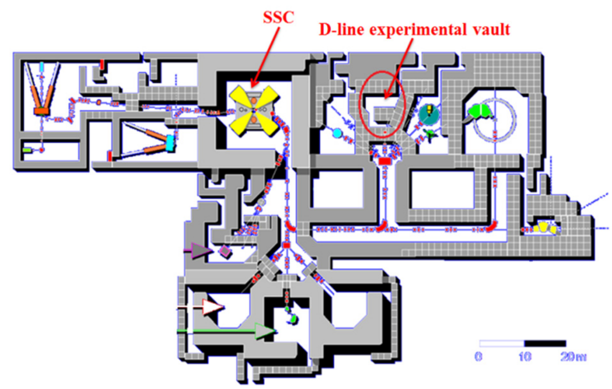

Figure 1: Layout of the iThemba LABS facility showing the location of SSC and the D-line experimental vault.

An ISO-accreditation of the facility will provide it the ability to participate in international key-comparison studies in the area of neutron metrology for medium to high-energy neutrons.

iTHEMBA LABS NEUTRON BEAM FACILITY

At the iThemba LABS neutron beam facility, neutron production targets (Li or Be) are mounted on a target ladder (Fig. 2, label 1) that has four positions, with one permanently occupied by a quartz viewer. At beam currents of a few nanoAmpere (nA), the position of the beam spot can be monitored using the quartz viewer. Out of the three other positions, one is left empty for background target runs while the remaining two are dedicated for neutron production targets. The target ladder is operated remotely. The proton beam is deflected into the beam dump after passing the target. At this point, the Faraday cup that is positioned in the proton beam dump is used to measure the beam charge. The neutron production area of the neutron beam facility at iThemba LABS is separated from the experimental area by an iron shielding wall with collimators at 0°, 4°, 8°, 12° and 16° neutron emission angles (Fig. 2). The collimator channels have rectangular cross sections of about (5 × 5) cm^2. Optimized neutron beam collimator inserts with conical shapes are required in order to improve the uniformity of the beam profile throughout the irradiated target.

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DEFLECTING SYSTEM UPGRADE INITIAL SIMULATIONS FOR 37 MeV CYCLOTRON AT NPI REZ

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Abstract

NPI Rez U-120M multi-particle variable energy cyclotron system for positive ions extraction consists of three electrostatic deflectors, one active magnetic channel and an electromagnetic bump exciter. The deflectors transmission ratio for deuterons, alpha particles and Helium 3 ions is rather low, usually about 10 %, for protons it is far below 5 %. Based on an experience from other cyclotron laboratories, the general concept of the extraction system has been modified and the last two electrostatic deflectors were replaced with two magnetic channels. In the early stage of the upgrade, simulations were performed for protons at 28 MeV and Helium 3 ions at 44 MeV with and without the magnetic bump exciter. The extraction efficiency and beam losses along the extraction path are evaluated. The presented modified extraction system simulations suggest promising results. The total transmission ratio of the deflecting system has increased significantly, allowing work to continue and expect a positive final result.

ACTUAL SITUATION OVERVIEW

The isochronous cyclotron U-120M is a four sector machine with a pole diameter 120 cm, 18 trim coils. It is in operation from 1977. Initially it was built in JINR as a positive ions accelerator, an option for negative ions was enabled circa 15 years later. Complete list of accelerated ions with their maximal energies is specified in Table 1. For both ion polarities an internal cold cathode Penning type ion source is used. The negative ions are extracted using a stripping foil with efficiency close to 100 %.

The extraction of positive ions is rather problematic and requires a significant improvement. There are two main issues related to the low extraction ratio. Firstly, it is the low extracted beam current, but usually this can be compensated by a prolonged irradiation time. Secondly, it is very high activation of the cyclotron equipment, especially the extraction elements, which prevents an efficient maintenace.

Table 1: Possible positive ions with their energy ranges and maximal internal currents at the U-120M cyclotron.

Particle	Energy range	Maximal current int.
protons	6 – 37 MeV	200 µA
deuterons	7 – 20 MeV	80 µA
α	12 – 40 MeV	40 µA
$^3He^{2+}$	17 – 54 MeV	20 µA

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Extraction System Concept

The original concept of the extraction system described in [1] is shown in Fig. 1. The system had consisted of an electrostatic first harmonic exciter (EE) and an electrostatic compensator (EC), three electrostatic deflectors (ESD) and one magnetic channel after ESD III (not in figure). Extraction efficiency of this configuration was close to 40 %. After the compensator part failed, the electrostatic exciter was replaced by a magnetic bump coil. This change was made in about 1980 and the extraction efficiency had dropped significantly.

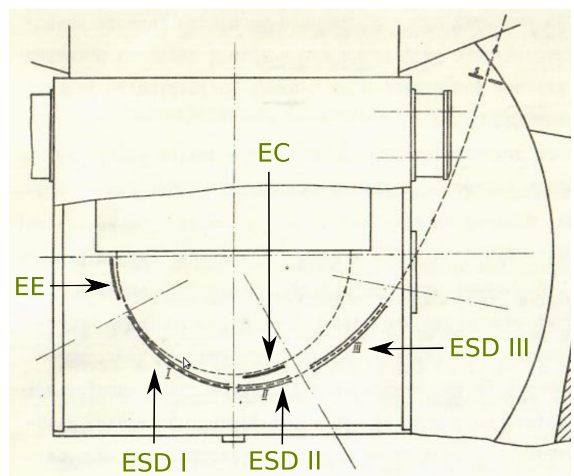

Figure 1: The original concept of the extraction system [1].

Electrostatic Deflectors

The system consists of three ESD's located at azimuths 120°, 182° and 215°. Septum of the first electrostatic deflector is placed near extraction radius 510 mm where ν_r is still ~1.03.

The original intention was that the electrostatic deflectors would also have vertical beam focusing properties. This resulted in their rather complicated shape (see Fig. 2). Moreover the first ESD is divided into a part for the beam deflection and a part for the beam deflection and vertical focusing. The nontrivial shape of the septums and electrodes are responsible for a part of the high extraction losses. Second part is due high radial beam dispersion, as the beam passes all three deflectors without any kind of radial focusing.

Magnetic Field Bumper

The beam is extracted by a Brute force method as the $\nu_r = 1$ region is crossed very fast [2]. The magnetic bump coil is a dipole magnet with the center at azimuth 98°, 12°

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NEW CENTRING BEAM MONITOR FOR HIGH POWER PROTON BEAM ROTATING TARGET

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Abstract

The high intensity proton accelerator (HIPA) at the Paul Scherrer Institute (PSI) delivers 590 MeV c.w. proton beam with currents of up to 2.4 mA, i.e., 1.4 MW beam power. For experiments of nuclear and material research the beam is directed to the 4 or 6 cm graphite 1 Hz rotating target (Target E). Centring the beam on the target is an important task for the operation and has safety issues in case of beam misalignment. Transmission monitoring has been the standard method to optimize the beam position on the target, though not very sensitive. A new method is currently being tested that provides a more sensitive off-axis detection. It is based on the detection of beam intensity modulation from the milled grooves at the target edge. This paper presents the concept and preliminary experimental results that can be obtained with this method.

INTRODUCTION

At the 1.4 MW high intensity proton accelerator facilities (HIPA) at Paul Scherrer Institute (PSI), the proton beam is accelerated from a Cockcroft-Walton source followed by two cyclotrons: the so-called Injector 2 cyclotron accelerating the beam from 870 keV to 72 MeV and the so-called Ring cyclotron accelerating it to 590 MeV. The beam is then directed through 2 meson graphite targets (Target M and E) to the spallation neutron source SINQ [1]. The energy deposit on Target E is 20 kW mA^{-1} with a beam 2-sigma width of 1.5 mm in the horizontal direction and 1.7 mm in the vertical direction.

The correct centring of the beam on the Target E is important since the rim of the wheel is only 6 mm wide. Missing partly the target would not only reduce the meson production rate but also leads to a pencil beam hitting the SINQ target window, which could not withstand such power densities.

Transmission minimization has been the standard method to center the beam position on the Target. The transmission is the ratio of the beam current measured after and before the target. For this method, a beam position scan is performed to identify the range and the optimum position corresponding to the minimum transmission. This is however an indirect measurement and is not very sensitive.

The new method currently being tested allows a more sensitive detection of off-axis beam conditions. The method is based on the detection of beam current modulations induced by grooves milled at the target rim. Evidence of these modulations is indicative of off-axis beam conditions, the modulation amplitude giving some information about how far off-axis the beam is located.

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EXPERIMENTAL SETUP

The Grooved Target

The Target-E for this experiment is shown in Fig. 1. The tests took place in the summer 2019 during 2 months, the target then had to be replaced due to bearing problems.

Figure 1: The Target-E used for the experiment.

The 60 mm wide rim of the target is divided into 12 segments. Between the segments a 1 mm wide gap allows for thermal expansions as well as dimensional changes due to irradiation.

The grooves on each segments are easily visible in Fig. 2. The spaces between each groove have been calculated so that, for a target rotating at 1 Hz, a beam current modulation at either 114 Hz (left off-axis) or 138 Hz (right off-axis) will be measured. These two frequencies have been chosen so that they are located exactly between two harmonics of the 12 Hz signal generated from the target blades.

Four groove milling depths were tested on this target: 0.3, 0.5, 0.7 and 0.9 mm on groups of 3 elements distributed equally to investigate the sensitivity of the detection and the possible physical defects. One groove on each side was milled deeper (1 mm) to act as an absolute marker (see Fig. 2).

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MANUFACTURING AND COMMISSIONING OF CYCLOTRONS IN A SERIES PRODUCTION AT VARIAN

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Abstract

On 16th of March 2019 Varian celebrated the 10th anniversary of first patient treatment in the Munich Proton Center.

Since the first cyclotron installation, 22 cyclotrons have successfully been manufactured, commissioned, and tested in Troisdorf production.

A better understanding of the cyclotron mechanisms and physics allowed for significant faster commissioning lead times without changing the hardware setup substantially.

Essential improvements in area of qualification of magnetic field configuration, RF conditioning, and beam commissioning are presented.

KEY PERFORMANCE INDICATORS

Varian's superconducting AC250 cyclotron delivers proton beams with a fixed energy of 250 MeV with beam currents of up to 800 nA. This compact cyclotron is a four-sector cyclotron operating at an RF frequency of approx. 72 MHz, which is the second harmonic of the orbital frequency, see [1] and [2] for more key parameters of the cyclotron.

During the last years, several improvements were introduced in the phase of production and factory commissioning of the cyclotron. This allowed an increased number of fully commissioned cyclotrons, which were tested and optimized to the medical specifications needed for clinical operation, especially with respect to extraction efficiency as well as beam shape and stability.

After the superconducting coil is cooled down to liquid helium temperature of 4.2 K the magnetic is excited for the first time followed by the field mapping process. By using a pre-shimmed cyclotron, i.e. omitting several shimming / field mapping iterations, the number of field maps could be reduced significantly. During the commissioning of the first cyclotrons, several iterations were performed, i.e. the magnetic field configuration was optimized incrementally by adjustments of the shimming pattern. Afterwards the magnetic field was mapped. Starting with cyclotron #7 (C7), the number of shimming iterations and corresponding field maps was gradually decreased towards a pre-shimming first time used with cyclotron #15, see Fig. 1. This means, that a default shimming pattern is used for each cyclotron and the magnetic field configuration is only verified via field mapping.

Although test criteria (e.g. extraction efficiency, max. beam intensity, and beam position stability) have simultaneously become more elaborate and strict over the past years, improvements of the test processes as well as hardware changes result in a significant reduction of needed working hours for RF and beam commissioning as well, see Fig. 2. Details of the improvements will be described in the following section.

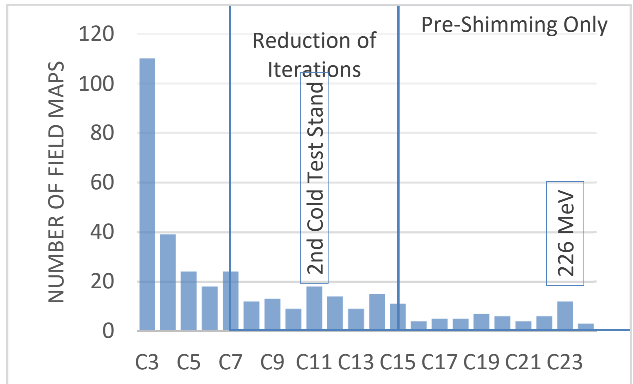

Figure 1: Number of collected field maps for different projects (indicated by C followed by integer).

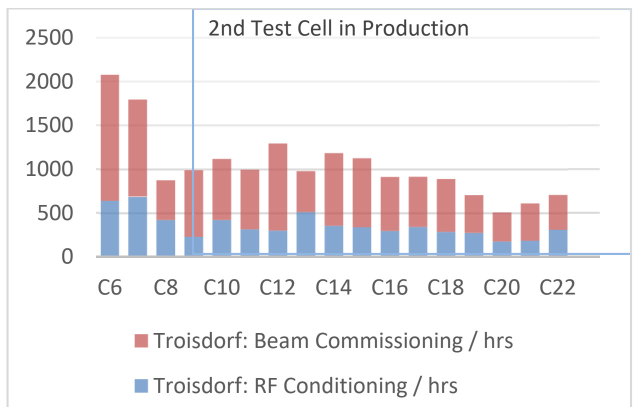

Figure 2: Used working hours for RF and beam commissioning in the Troisdorf cyclotron test cells.

IMPROVEMENTS

Several hardware changes were introduced with the goal to make commissioning processes faster, more reliable, and reproducible. During beam commissioning, a so-called foil irradiation is performed several times. After each beam characterization and optimization iteration, beam width and position are checked via the irradiation of radiation sensitive foils. These foils are attached to the entrance and exit of the extraction deflectors and focusing bars. Figure 3 shows a schematic overview of the cyclotron and the position of the different extraction elements.

Instead of pasting the foil pieces directly to the respective component, foil frames and holders were designed for easier and more reliable installation of the foils.

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RECENT EXTENSIONS OF JULIC FOR HBS INVESTIGATIONS

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Abstract

At the Forschungszentrum Jülich (FZJ) the energy variable cyclotron JULIC is used as injector of the Cooler Synchrotron (COSY) and for low to medium current irradiations of different types. Recently a new target station was set up and is mainly used for tests of new target materials, neutron target development and neutron yield investigations with high power proton or deuteron beam in perspective of a high brilliance accelerator based neutron source (HBS) with the Jülich Centre for Neutron Science (JCNS). Beside this, ToF-experiments are performed to investigate and optimize the pulsing structure for HBS. The target station is installed inside an Experimental area close to the cyclotron bunker, offering space for complex detector and component setups for nuclear and neutron related experiments. It is used for other purposes like electronic or detector tests and irradiation as well. This report briefly summarizes the history of JULIC and the activities for its future perspectives.

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 hadron physics program at the Cooler Synchrotron COSY exploits the internal experimental setups PAX, KOALA and the PANDA Cluster-Jet Target Development. The Jülich Electric Dipole Moment Investigation project (JEDI) [3] profits from the availability of polarized beams from the injector cyclotron and the unique capabilities and experiences at the COSY facility. The extracted beam is used for the PANDA experiment, detector tests and for high-energy irradiation in the area of the finished TOF experiment. The JESSICA and Big Karl-Experiment areas are also used with extracted beam for other FAIR related detector tests and developments like CBM, e.g., Fig. 1 presents the layout of the COSY facility with the JULIC cyclotron and the experimental areas.

The COSY accelerator facility [4], operated by the Institute for Nuclear Physics at the Forschungszentrum Jülich, 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 behaviour of hadrons in an energy range that resides between the nuclear and the high energy regime. Operation of the cyclotron JULIC started 1968 and it provides mainly 45 MeV H^- respectively 76 MeV D^- with beam currents up to ~10 µA.

Within the framework of the High Brilliance neutron Source project [5], Jülich is developing a scalable pulsed accelerator-based neutron source capable to support the large scale facilities and provide an efficient network of small and medium neutron sources throughout Europa.

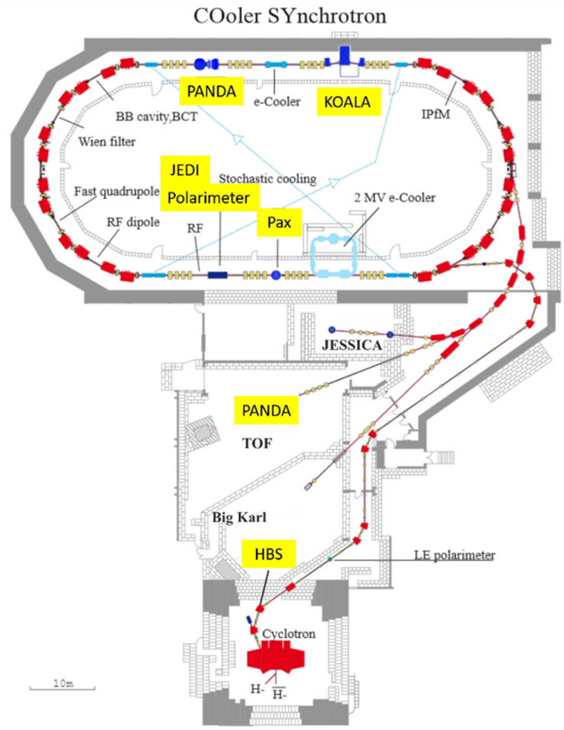

Figure 1: Layout of the COSY facility with the new beam-line from the cyclotron into the Big Karl Experiment area

The HBS JULIC Neutron Platform is going to be installed at the Big Karl experimental area aside the JULIC cyclotron providing experimental space for the development, testing and operation of components of pulsed accelerator based neutron sources within the HBS project together with the Jülich Centre for Neutron Science. Figure 2 shows the planned experimental setup in Big Karl-area.

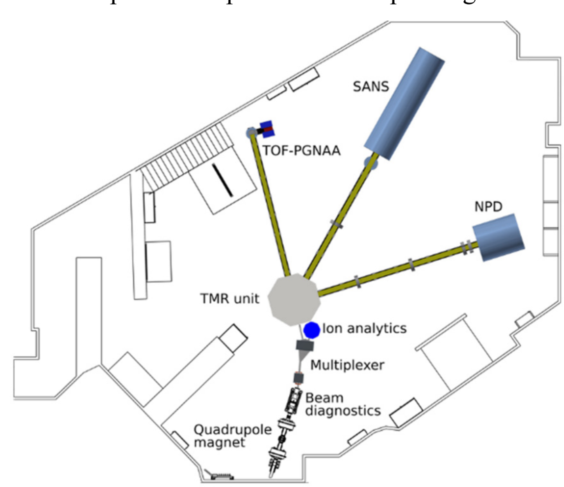

Figure 2: Planned experimental setup in Big Karl area.

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BEAM PROPERTIES AT THE EXPERIMENTAL TARGET STATION OF THE PROTON THERAPY IN BERLIN

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Abstract

Beside the therapy station for ocular tumours, we have an experimental area for irradiations with protons and other ions either in air or in vacuum. The beam spot can be focused to a diameter of 1 mm in air. For larger homogeneous irradiated areas, we can use beam scanning with up to10 nA spot current. If scanning is not possible due to experimental needs, scattering foils are used.

For protons, the energy can be set to a mono-energetic beam of 68 MeV or to spread-out Bragg peaks with a mechanical range shifter. Very quick energy changes are achieved by absorber plates to reduce the energy.

THE EXPERIMENTAL AREA

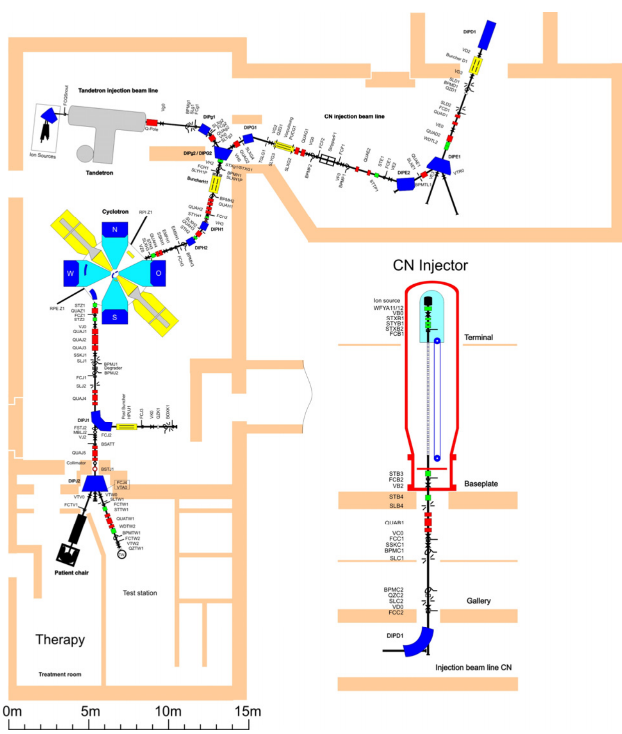

Figure 1: Layout of the accelerators and target stations.

The experimental area is located just beside the installation for the treatment of ocular tumours (Fig. 1). Thus, the beam as used for therapy can be brought to the target station in short time by switching the last dipole magnet in the beamline. The standard therapy beam is a quasi-DC 68 MeV proton beam with a beam size of 40 mm in diameter and a very homogenous beam profile (see Fig. 5). The beamline in the experimental area also permits to focus the beam down to a diameter of 1 mm.

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As from beam time to beam time slight changes in the settings of the beam line were needed to obtain the same beam position on target, the beam line settings were recalculated: Instead of a focal point between two quadrupole triplets the beam is now kept parallel at this position. With this setting, only tiny adjustments are needed on the last elements in the beamline to compensate slight differences when extracting the beam from the cyclotron.

Different settings for experiments are possible: The beam can be extracted in air via a thin Kapton foil and the samples to be irradiated are mounted on a xy table with a stroke of 50 cm and a positioning precision of 0.1 mm. The maximum weight for the samples is 50 kg. Large and sensitive objects can be irradiated: The largest sample was a painting with a size of 1 m × 1.4 m. Behind the xy table is a 2 m long optical bench. This is used mainly for irradiations in vacuum in order to avoid scattering of the beam in air.

The samples are aligned on the beam line axis with the help of an adjusted Laser system. The proton intensity is measured on-line using an ionisation chamber of PTW Freiburg. Radiation safety limits the quasi-DC proton beam intensity to about 10 nA in the experimental area. For most experiments this is largely sufficient.

BEAM SIZE ADAPTATION

The two-dimensional distribution of the beam is measured using a CCD camera with an x-ray converter foil (Sensicam QE from PCOAG). The resolution of the camera is 50 µm per pixel. For a quick determination of the beam spot, films are used.

Widening of the Beam Using a Scanning System

For higher proton intensities and passive irradiations a scanning system may be used. The scanning system consists of two scanners: a 21 cm long y-scanner, 5 cm distance, and a 21 cm long x-scanner. Settings of the power supplies for the scanning system is done with a LabView code.

This code also corrects for influences of the scanning frequency on the current of the power supplies and for the geometric differences due to the fact that the scanners are in different positions on the beam axis. To define the irradiation field, the user can choose between various functions, repetition rates, and distances of the scan lines. The user also has to define the shape of the beam spot, which was determined using a quartz, a film or the CCD camera. The dose distribution for the chosen parameters is then simulated and visualised. Figure 2 shows in the top row two different shapes of a focused beam. Identical settings

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TOWARDS FLASH PROTON IRRADIATION AT HZB

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Abstract

The HZB cyclotron has been providing protons for eye-tumor treatment for more than 20 years. While it has been very successful using conventional dose rates (15-20 Gy/min), recent studies indicate that rapid irradiation with very high dose rates (FLASH) might be equally efficient against tumors but less harmful to healthy tissues. The flexible operation schemes of the HZB cyclotron can provide beams with variable intensities and time structures, covering a wide unexplored regime within the FLASH requirements (>40 Gy/s in <500 ms). This paper presents the results of the first FLASH beam production at HZB towards the establishment of an in-vivo clinical irradiation in the future.

INTRODUCTION

The cyclotron of Helmholtz-Zentrum Berlin (HZB) in Germany has been providing protons for the treatment of ocular tumors to more than 3600 patients since 1998, with a local tumor control of 96% five years after the treatment [1]. However, according to recent studies, side effects to healthy nearby tissues may be significantly reduced by using high dose-rate FLASH irradiation [2].

In short, the FLASH scheme utilizes much higher dose rates in much shorter irradiation times compared to conventional radiotherapy — regardless of the type of radiation being used. With its exact specifications not yet universally acknowledged, most studies categorize an irradiation of more than 40 Gy/s within 500 ms or less into the FLASH regime. Under these conditions, the normal cells appear to experience an equivalent dose of ~70% with respect to the dose received by the tumorous cells (1.4 dose-modifying factor), sparing thus selectively healthy tissues from radiation damage and enabling higher dose delivery to the tumor [3]. The underlying biological mechanism as well as the optimal irradiation parameters are still under investigation.

Different institutes worldwide are currently trying to test this new radiotherapy concept and prove its potential benefits. The first application to a human was recently conducted on a skin tumor using a 5.6 MV electron linac, which generated 15 Gy in 90 ms, delivered in 10 pulses of 1 µs each with a 100 Hz repetition rate [4]. Experiments with protons are also under preparation to be applied to small animals using a clinical system [5].

The HZB cyclotron, originally designed for ion experiments requiring various intensities and time structures, is nowadays an ideal machine for testing a broad unexplored regime of the FLASH radiotherapy — even in-vivo. Towards this direction, this paper demonstrates the first FLASH proton-beam production at HZB, the currently feasible parameters and finally the short- and mid-term plans of applying ocular proton irradiation on mice using the FLASH scheme for the first time.

MACHINE AND EXPERIMENTAL SETUP

The HZB cyclotron can be operated with two different types of injectors:

- A Tandetron (tandem accelerator), abbreviated as *TT*, which is routinely used for the medical operation due to its increased stability,
- a Van-de-Graaff accelerator, abbreviated as *CN*, which provides bunched beams of higher intensity and is equipped with a fast kicker (pulser) to selectively guide bunches within a specified time window into the cyclotron.

For the standard machine settings, the proton beam extracted from the cyclotron has a kinetic energy of 68 MeV, a repetition rate of 20 MHz and a bunch duration in the order of 5 ns when using the TT injector, or down to 1 ns when using the CN injector. These timescales are negligibly short for radiotherapy — even that of FLASH — meaning that the delivered beam is considered as approximately continuous (quasi-DC). Nevertheless, a pulsing scheme with a time window of at least 50 ns and a repetition rate of up to 2 MHz can be applied when using the CN injector. Regarding the average beam current at the end of the beamline, around 40 nA can be reached with the TT and 10 times more with the CN.

Considering the future plan of irradiating eyes of mice, whose tumors are typically located in a depth of 5 mm from the eye's front surface, a reduced proton energy will be needed at the irradiation target. Therefore, a 16 mm-thick aluminum plate was used as a range shifter between the exit port of the accelerator beamline and the target. In order to block the scattered protons downstream and irradiate only the desired area of the target (a circular field of ~9 mm diameter for mouse eyes), a holder for interchangeable round collimators of different diameter was placed in between. An Advanced Markus® ionization chamber [6], which is indicated for measuring high dose rates, was installed at the target position. A photo of this experimental setup can be seen in Fig. 1. Before and after measuring the dose rate, the dose monitor was replaced by a 12-bit CCD camera to capture the transverse profile of the beam with a resolution of 1280 × 1024 pixels and a scaling of 48 ± 2 µm/pixel.

The above setup was used to measure the delivered dose rate, range (Bragg-peak) and transverse distribution of the quasi-DC proton beam at the target for each injector.

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STATUS OF A 70 MeV CYCLOTRON SYSTEM FOR ISOL DRIVER OF RARE ISOTOPE SCIENCE PROJECT IN KOREA*

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Abstract

A 70 MeV H^- cyclotron commercially available for medical isotope production will be used as an ISOL driver for rare isotope science project in Korea. The cyclotron is scheduled to be installed in 2021 for beam commissioning in the following year. In fact the building to house the cyclotron is currently almost complete so that the cyclotron system newly contracted needs to fit into the existing building, which brings some challenges in equipment installation and adaptation to utilities. Two beam lines to transport high-current proton beams into ISOL targets have been designed and are described along with other issues associated with the interface of the ISOL system.

INTRODUCTION

A 70 MeV cyclotron system was contracted with a company in May 2017 to be used as the driver of the ISOL system for rare isotope science project (RISP) in Korea [1, 2] and a building to house the system has been constructed since 2017. However, the contract was broken in early 2019 while the building is near completion. A new contract was made with IBA in July 2019 after reviewing the building interface and the design of ISOL beam lines. It was then mutually confirmed no major modification of the present building is needed to accommodate the cyclotron system of IBA [3].

The major parameters of cyclotron are listed in Table 1. The cyclotron size is slightly smaller than the previous one so that minor modifications are sufficient for installation. The primary use of cyclotron will be to provide ISOL target with proton beams in a diameter of 2-5 cm. with a beam power up to 10 kW for RISP. A wobbler magnet will be installed in the cyclotron vault and then the drift length to the target is over 8 m, which may cause some instability of the beam spot at the target.

Table 1: Main Cyclotron Parameters

Item	Value
Beam energy range	30 – 70 MeV
Max. beam current	0.75 mA
Extraction port number	2
Weight	140 tons
Beam size at ISOL target	20-50 mm

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BUILDING INTERFACE

Construction of the cyclotron building is nearly completed in 2019 with its design fit for the cyclotron of BEST Cyclotron Systems, Inc. [4, 5]. Hence, the building design was checked before the new contract was made whether any major modification of the current building is needed such as new penetration holes on the walls designed for radiation shielding, but no significant work was found.

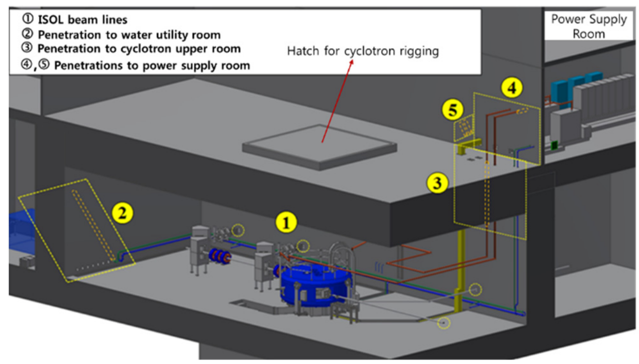

Figure 1: Penetration holes and a hatch in the cyclotron vault and in the upper room. The vault is located in B1. In ④ there are holes for rf transmission line of the final amplifier located in the power supply room, which is not needed for the IBA cyclotron.

The cyclotron will be rigged and installed through the hatch shown in Fig. 1 with one or two cranes anchored outside of the building. Also shown in Fig. 1 are utility connections through the shielding walls, which are grouped into four depending on their usage as denoted. A major difference in cyclotron component is that the final RF amplifier is directly attached to the cyclotron dee rather than placed in the power supply room. Hence, two high-power transmission lines of over 10 m long and their penetration holes are saved.

In the current building, there is no crane inside the vault so that it is expected to have some difficulty during installation and maintenance later. To relieve this issue we plan to install a simple jib crane near the cyclotron, which can also cover some beam line components.

The cyclotron pit was constructed to accommodate the ion source and injection beam line located under the cyclotron, but the IBA system has them on the top of the cyclotron. The lower space will be utilized to house some components such as for vacuum, so it is actually thought to be useful.

The beam loss inside the cyclotron and along the beam line is expected to be less than the loss used for the design of shielding walls. At the maximum current of 750 μA,

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MUON CYCLOTRON FOR TRANSMISSION MUON MICROSCOPE

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Abstract

A transmission muon microscope is an unprecedented tool which enables its users to reconstruct 3D image of samples such as a living cell. Muons can gain penetrative power as their energy increase, though electrons above 1 MeV start to trigger electromagnetic showers and protons above 1 GeV cause nuclear reactions. Muons accelerated up to about 5 MeV are able to penetrate a living cell (~10 µm), which is impossible with ultra-high voltage (1 MeV) electron microscopes. In order to accelerate muons, efficient acceleration is necessary because the lifetime of muons is only 2.2 µm.

In addition, it is important to accelerate muons without increasing their energy dispersion. Cyclotron with a flat-top acceleration system is the best suited for the transmission muon microscope and is being developed at the J-PARC muon facility (MUSE). In this paper, the transmission muon microscope project and the development of the muon cyclotron will be presented.

INTRODUCTION

Muons at muon beam facilities are generated from pion decays, and these pions are produced via nuclear reactions of a proton beam in a muon production target. The conventional muon beams have been utilized for varieties of sciences such as magnetism study using the µSR (muon spin rotation) technique, non-destructive element analysis from muonic x-ray using a negative muon beam, and so on. However, the beam size of a conventional muon beam is relatively wide ($O(10)$ mm). Development of a high-intensity muon microbeam will open a unprecedented research area using muon microscope (a transmission muon microscope and scanning muon microscope), therefore it is a very important milestone in muon science and materials research.

A high intensity muon beam, so-called "surface muon" beam (4 MeV), is obtained from positive pion decays near the surface of a muon production target, but its energy spread is large (~10 %), which is determined by a momentum bite of bending magnets in the muon beamline. The large energy spread makes it impossible to obtain a muon microbeam due to chromatic aberration. Therefore, we re-accelerate ultra-slow muons to produce a high-intensity muon microbeam. At the J-PARC muon facility (MUSE) [1], ultra-slow muons are generated by laser ionization of a muonium (Mu, a bound state of μ^+ and e^-) [2]. Since muoniums are emitted from a hot tungsten target (2000 K), the initial energy of ultra-slow muons is cooled down to 0.2 eV. We plan to re-accelerate ultra-slow muons up to 5 MeV while keeping its energy spread less than 500 eV ($\Delta E/E = O(10^{-5})$), and then the beam is focused to a muon microbeam using a superconducting lens. The novel positive muon microbeam can be used for a transmission muon microscope. The penetrative power of muons enables us to obtain image of thick sample, such as a living cell (~10 µm).

An AVF cyclotron with a flat-top RF system is adopted to re-accelerate muons. Cyclotron's efficient acceleration is inevitable because the lifetime of a muon is only 2.2 µs. A flat-top RF system is also necessary not to increase energy spread. Ultra-slow muons are first accelerated electrostatically up to 30 keV and then injected into the muon cyclotron and accelerated up to 5 MeV. The muon intensity is about 10^4 /pulse with a repetition rate of 25 Hz. The beam parameters are summarized in Table 1.

Table 1: Beam Parameters

Particle	Positive muon μ^+
Mass	m_μ = 105.6 MeV/c^2
Lifetime	τ_μ = 2.2 µs
Injection	
Number of particles	10^4 /pulse
Repetition rate	25 Hz
Kinetic energy	30 keV
Pulse width	200 ps
Emittance (1σ)	1 π mm mrad
Extraction	
Kinetic energy	5 MeV
Energy width ($\Delta E/E$)	$O(10^{-5})$
Emittance (1σ)	0.1 π mm mrad

BASIC DESIGN OF MUON CYCLOTRON

Toward the installation of the muon cyclotron in FY2020, detailed design of the muon cyclotron has been almost finished and its fabrication is on-going simultaneously. Figure 1 is a schematic of our muon cyclotron. The external structure of the cyclotron is inherited from the HM-10 cyclotron of the Sumitomo Heavy Industries, Ltd., but the internal design is quite different. Major changes are as follows:

- Built-in ion source → external injection,
- installation of a flat-top RF cavity,
- increase of gaps between poles to extract the muon beam.

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FEASIBILITY STUDY FOR CONVERTING THE CS-30 INTO A VARIABLE ENERGY CYCLOTRON FOR ISOTOPE PRODUCTION USING THE INTERNAL TARGET SYSTEM*

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Abstract

This paper reports a method to reduce the beam energy of the CS-30 cyclotron from 26.5 down to 10 MeV using the internal target system in CS-30 cyclotrons for isotopes production. Irradiations of solid targets, in this type of cyclotrons, take place when the target is positioned horizontally inside the cyclotron tank. In its final position, the target plate interrupts the beam from completing its orbit and nuclear reactions take place. Calculations are made to determine the beam energy as a function of radius. Verification of the new method was achieved by producing pure Ga-68 at an energy level of 11.5 MeV.

INTRODUCTION

Production of radioisotopes by CS-30 cyclotron at KFSHRC started in 1982 with seven targets, each positioned at the end of a beamline. In addition to these seven beamlines, it is also possible in this type of cyclotron to irradiate a solid target internally. A special ISO-RABBIT mechanical system connects the cyclotron with one of the hot cells to receive the target before irradiation and deliver it after irradiation. The internal target is located inside the cyclotron tank at the edge of the pole where the proton has gained full energy of 26.5 MeV [1]. Table 1 illustrates the specification of the CS-30 cyclotron [2].

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. In positive ion machines, the mechanism is more complicated, consisting of an electrostatic deflector (which has two parts: a septum. 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 [3-6].

Figure 1 illustrates the internal target mechanism of a CS-30 cyclotron, which holds the target plate (to be irradiated) in final position at the edge of the pole where the proton energy is 26.5 MeV.

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Table 1: Main Specification of CS30

Parameter	Value
Proton Energy	26.5 MeV
Deuteron Energy	15.0 MeV
He-3 Energy	38.0 MeV
He-4 Energy	30.0 MeV
External Beam Power	2000 W
Pole Diameter	38 inch
Weight	22 t
Number of Dees	2
Acceleration mode	fundamental
Voltage Gain Per Turn	100 kV

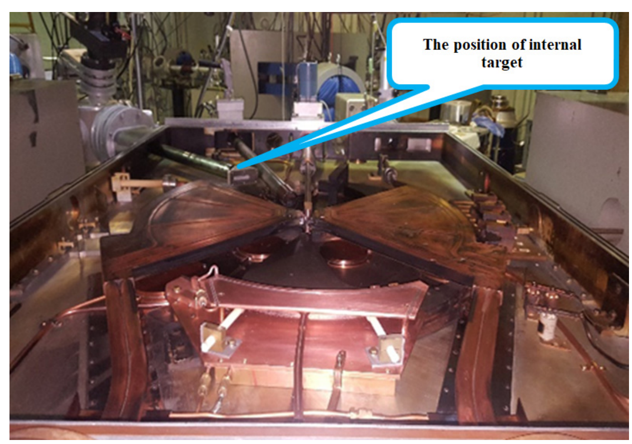

Figure 1: The normal position of the internal target during irradiation at 26.5 MeV.

This paper reports the possibility of reducing the cyclotron energy from 26.5 down to 10 MeV by moving the internal target mechanical system toward the central region of the cyclotron. The low energy beam, then, can be used to produce low energy-produced isotopes such as Ga-68 (produced at 11.5 MeV).

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EMBEDDED LOCAL CONTROLLER FOR THE CS-30 CYCLOTRON*

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Abstract

The Embedded Local Controller is used for upgrading the old CS-30 cyclotron control system at King Faisal Specialist Hospital and Research Centre. It is installed inside the cyclotron vault and connected to the control room using CAN serial bus. This is to avoid adding more wires from cyclotron vault to the outside, because there is no room for extra wires in the feed through conduits. The system is carefully designed to be fault tolerant so that it can run in a radiation environment without failure. Details of the design and field test results are presented.

INTRODUCTION

Production of radioisotopes by CS-30 cyclotron at KFSHRC started in 1982 with seven targets, each positioned at the end of a beamline. In addition to these seven beamlines, it is also possible in this type of cyclotron to irradiate a solid target internally. A special ISO-RABBIT mechanical system connects the cyclotron with one of the hot cells to receive the target before irradiation and deliver it after irradiation. The internal target is located inside the cyclotron tank at the edge of the pole where the proton has gained full energy of 26.5 MeV [1, 2]. Table 1 illustrates the specification of the CS30 cyclotron

In our attempts to upgrade the control system of our old CS-30 cyclotron, we always face the wiring problem. The wiring channels are full of heavy gauge wires and there is no room to add more wires for our upgrade. This raised the need to add a part of this upgrade locally inside the cyclotron vault, and motivated us to design our robust embedded controller to use inside cyclotron vault. Cyclotron local controller is placed inside cyclotron vault to overcome the wiring problem, therefore, it is subjected to a high ionizing and non-ionizing radiation, and must be carefully designed to guarantee reliable operation for a long time [3].

A prototype of the system was produced and as a first try, it is used as a cyclotron vacuum system controller. It has been placed under actual field-testing for more than a year without any failure.

SYSTEM OVERVIEW

The control system consists of backplane, controller board, optional signal conditioning board, and power supply, all placed inside a 19”, 3U sub-rack (see Fig. 1). Figure 2 shows that system is placed inside the cyclotron vault and connected to the remote user interface computer though CAN serial bus.

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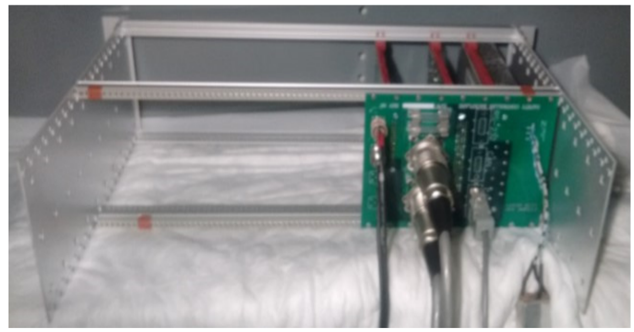

Figure 1: Embedded local controller system.

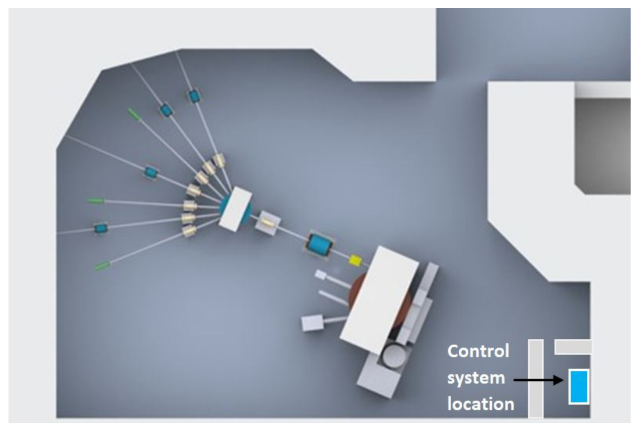

Figure 2: Control system location inside cyclotron vault.

CONTROLLER BOARD DESCRIPTION

Figure 3 shows the PCB of the controller and block diagram of this board is shown in Fig. 4. This board has all sub-circuits that allow it to be high reliability standalone controller. At the top is TMS570LS0432 safety microcontroller (Texas Instruments) that has many features, which make it very robust in the radiation environment [4]. There is a digital I/O sub-circuit, with 16 lines output (24 V, 0.5 A), 24 lines input (24 V), and four high-speed inputs (24 V) that can be used as quadrature encoder input. Additionally, there is an analogy I/O sub-circuit, with 8 analogy inputs (programmable range) and 8 analogy outputs (programmable rage). In addition, there are two CAN ports, one isolated and the other non-isolated, and one isolated RS-232 port. All sub-circuits power supplies are protected and can be on/off controlled, and can be monitored through the microcontroller, this feature is crucial to monitor current variation due to the effect of radiation.

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BREMSSTRAHLUNG PHOTONS EMISSION IN 28-GHz ELECTRON CYCLOTRON RESONANCE PLASMA

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Abstract

Radial measurements of bremsstrahlung photons show high-energy intensity beyond a critical energy from electron cyclotron resonance (ECR) heating and its nature is not well understood so far. For the first time we have measured the bremsstrahlung photons energy intensity from 28-GHz ECR ion source at Busan Center of KBSI. Three round type NaI(Tl) detectors were used to measure the bremsstrahlung photons emitted at the center of the ECRIS at the same time. Another NaI(Tl) detector was placed downstream from the ECR ion source for monitoring photon intensity. The ECR ion source was operated at Radiofrequency (RF) power of 1 kW to extract ^{16}O beam with a dominant fraction of O^{3+}. Bremsstrahlung photons energy spectra were measured at the center of the ECR ion source. We studied possible systematic uncertainties from different characteristics among the three NaI(Tl) detectors by repeating measurements alternatively. Geant4 simulation was performed to take the geometrical acceptance and energy-dependent detection efficiency into account due to large non-uniformity in the material budget. We extracted true bremsstrahlung energy spectra from the 28-GHz ECR ion source using the inverse-matrix unfolding method. The unfolding method was based on a full geometry Geant4 model of the ECR ion source. The high energy intensities of the bremsstrahlung photons at the center of the ECRIS were explained by the internal structure and shape of ECR plasma.

INTRODUCTION

An electron cyclotron resonance ion source (ECRIS) is one of the most used ion source types for high charge state heavy ion production [1]. Most electron cyclotron resonance (ECR) ion source including Korea Basic Science Institute (KBSI), rely on the superposition of solenoid and hexapole magnetic fields for plasma confinement [2]. The ECR plasma state depends on various operation conditions such as radiofrequency (RF) power, the pressure of the injected gas and the solenoid coil current. Also, ECR on sources are usually built for a specific maximum resonance frequency, e.g 28 GHz [3]. The ECR plasma used in this study is 28 GHz was developed as injector equipment for the heavy ion linear accelerator at the KBSI.

In ECR radio frequency microwaves heat plasma electrons in order to provide ionization of neutral gases. As a result of ECR heating very high electron energies are produced which can generates a large amount of bremsstrahlung photons [1,4]. Two process in the ECR plasma lead to the emission of bremsstrahlung radiations in the form of x-rays. First bremsstrahlung is created by electron-ion collisions within the plasma volume. The second process is when electrons are lost from the plasma, collide with the plasma chamber wall and radiate bremsstrahlung due to their sudden deceleration [1,5].

The produced bremsstrahlung photons deposits energy in the structure of ion sources and turns out to be substantial heat load to the cryostat in the case of superconducting ECR ion sources [4,6]. The cryogenic system can remove only a limited amount of the heat from the cryostat. If more heat is added to the system than can be removed, the temperature of the liquid helium rises and can cause the superconducting coils to quench [2].

Bremsstrahlung photons produced in ECR ion source have been made since late 1960s [7]. Nevertheless, many of these experiments used to measure the bremsstrahlung photons in only one direction, axially using one or two detectors but under different conditions. However, since the bremsstrahlung photons emitted from the ECR is expected to be anisotropic due to various effects [5]. This paper presents the first measurements results of the bremsstrahlung photons energy intensity at the center of the ECR ion source at three azimuthal angles.

EXPERIMENTAL SETUP

The data that is presented in this paper was carried out to measure bremsstrahlung photons energy intensity from 28 GHz superconducting ECR ion source of the compact linear accelerator facility at Korea Basic Science Institute (KBSI), cyclotron research centre.

ECR ion source developed at KBSI is composed of a six racetrack hexapole coils and three mirror solenoid magnets [8]. The axial magnetic field is about 3.6 T at the beam injection area and 2.2 T at the extraction region, respectively. A radial magnetic field of 2.1 T can also be achieved on the plasma chamber wall. A higher current density NbTi wire was selected for winding of sextupole magnet. The inner face of the 5 cm thick solenoid coil is placed at a distance of 44 cm from the beam axis. The 10 cm thick iron shielding structure is 120 cm wide, 122 cm high and 170 cm long [9].

The experiment setup to measure bremsstrahlung photons spectra in this study is totally different from previous experiment conducted by other researchers. Photon energy spectra were measured using three round type NaI(TI) detectors as shown in Fig. 1 facing the edge of ECRIS at the center of the ECR ion source.

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A 15-20 MeV/NUCLEON ISO-CYCLOTRON FOR SECURITY AND RADIOISOTOPE PRODUCTION*

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Abstract

Cargo inspection systems exploit the broad bremsstrahlung spectrum from a 6 - 10 MeV, low-duty cycle electron accelerator which in the presence of significant backgrounds presents challenges in image and material identification. An alternative approach is to use ions which can excite nuclear states either directly, or through generation of secondary high-energy signature gammas which are produced from nuclear interactions in a target. RadiaBeam is designing a compact sector isocyclotron ~1.2 - 1.5 m extraction radius, with high-gradient cavities to accelerate multi-ion species up to 15 - 20 MeV/u, respectively, with large turn-to turn, centimeter-level separation for low-loss extraction without lossy foil stripping. A strong-focusing radial field profile will be optimized in a separated-sector format for control over machine tune simultaneous with isochronous orbit requirements for high-current (~0.5 mA) operation. Innovation in injection will be introduced to replace the high-loss central region. Non-security applications of the cyclotron include medical isotope production, ion radiobiology, as well as material science research and ion instrumentation development.

INTRODUCTION

In cargo scanning for Special nuclear material (SNM), detection can be performed by either passive or active interrogation. The approach proposed here is an active, accelerator-based interrogation systems based on an ion accelerator capable of 15 - 20 MeV/nucleon.

Commercially-available accelerator-based security inspection systems generally exploit the broad bremsstrahlung spectrum generated using a 6 - 10 MeV, pulsed, low-duty cycle electron accelerator (i.e. linac or betatron) which in the presence of significant backgrounds presents difficulties in image and material identification which can make precise analysis challenging [1, 2]. An alternative approach is to use low energy (10 - 20 MeV/u) ions, which can excite nuclear states either directly, or through generation of secondary high-energy signature gammas produced from nuclear interactions in a target [3]. In the presence of nuclear materials, a beam of ions or secondary gammas will excite characteristic nuclear states which can be selectively identified by an appropriate detector array via spectral absorption or emissions eliminating the broad bremsstrahlung photon background that can avalanche a detector. The multiple monoenergetic gammas can be used in transmission to differentiate materials based on density and Z. Further, the Continuous Wave (CW) beam proposed here is well matched to detector systems in both collection and response times, facilitating low-dose scans and/or a much higher gamma ray energy spectrum for signature nuclear state excitation and applying established gamma-ray spectroscopy techniques. The idea is to use low energy nuclear reactions to produce mononenergetic gammas to improve the measurement of average density and Z; improving identification of lead and uranium, for example.

Designing for a charge to mass of ½ as proposed in Table 1 would allow either protons in the form of H_2+ or deuteron beams to be accelerated, for example, and delivered using the same system with deuterons adding neutron scanning capability. Another active detection approach which uses a CW accelerator for interrogation relies on measurement of delayed radiation [4] from induced photofission uniquely identifying SNM. What is unique to beam in a CW accelerator is that it can be triggered/inhibited on an RF timescale (~25 to 50 ns) through RF control systems, optimally tailoring to detection and maximizing signal to noise ratio by controlling both the strength and duration of the delayed radiation.

Table 1: Preliminary Accelerator Parameters for Q/A = ½

Parameter	Value
Accelerated Ions	H_2^+ (p), deuterons, He, B, Li, C, O, Ne, Si
Sectors	4
Extraction Energy	15-20 MeV/u
Injection Energy	0.5-1 MeV/u
Peak Current (avg)	0.5-1 mA (CW)
Inject/Extract Radius	0.1 / 1.3-1.5m
Field @ extraction	1.3T
Acceleration	400 kV/turn (2 cavities)
RF frequency	~40 MHz (8^{th} harmonic)

The high-current machine under design (Table 1) is also ideal for producing radioisotopes with many applications in medicine, biology, physics, chemistry, agriculture, national security and environmental and materials science. The most direct benefits are realized in medical diagnosis and therapy – expanding the availability of key or currently rare isotopes domestically is considered a high, even critical priority. One medical application is Radioimmunotherapy (RIT), a promising, new modality that selectively delivers radionuclides that emit α-particles, β-particles, or Auger electrons to tumours. The isotope group of the Nuclear Science Advisory Committee (NSAC), recognizing the gap between production and demand of α-particle-

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REINFORCEMENT LEARNING BASED RF CONTROL SYSTEM FOR ACCELERATOR MASS SPECTROMETRY

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Abstract

Accelerator Mass Spectrometry (AMS) is a powerful method for separating rare isotopes and electrostatic type tandem accelerators have been widely used. At SungKyunKwan University, we are developing AMS that can be used in a small space with higher resolution based on cyclotron. In contrast to the cyclotron used in conventional PET or proton therapy, the cyclotron-based AMS is characterized by high turn number and low dee voltage for high resolution. It is designed to accelerate not only ^{14}C but also ^{13}C or ^{12}C. The AMS cyclotron RF control model has nonlinear characteristics due to the variable beam loading effect of the acceleration of various particles and injected sample amounts. In this work, we proposed an AMS RF control system based on reinforcement learning. The proposed reinforcement learning finds the target control value in response to the environment through the learning process. We have designed a reinforcement learning based controller with RF system as an environment and verified the reinforcement learning based controller designed through the modelled cavity.

INTRODUCTION

Accelerator mass spectrometry is an instrument for analysing the mass of radioactive isotopes. It accelerates various ions such as ^{10}Be, ^{14}C, ^{28}Al, ^{38}Cl, ^{41}Ca, and ^{129}I and it is used in clinical experiments. AMS has higher resolution than conventional Mass Spectrometry. For general mass spectrometry, it has 10 - 12 parts per trillion (ppt) level sensitivity, but for accelerator mass spectrometer it has a high sensitivity of 10 - 15 ppt and tandem accelerators type AMS has been widely developed. However, cyclotron-based AMS is still under study because of its potential for miniaturization and efficiency compared to existing tandem accelerators [1, 2].

Unlike conventional cyclotron used for PET or proton therapy, AMS cyclotron has relatively low voltage and high rotation number for resolution. There is also the feature of accelerating various kinds of particles. This feature leads to non-linearity in control and interferes with performing precise beam and RF control. The external environment of the accelerator is continuously changed according to the type of particles and the quantity of the incident sample. In order to solve such a problem, it is inappropriate as a control system based on the existing linear section.

Reinforcement learning is one of the methods of machine learning such as Supervised Learning and unsupervised learning. It is a way to improve the behaviour through reward based on mutual relation of environment. Reinforcement learning does not require prior knowledge of the environment and is used for robots and games because it guarantees learning and adaptability [3].

In this work, reinforcement learning based RF control system was developed. From the viewpoint of reinforcement learning structure, we can redefine the controller as an agent and the cyclotron control variable as environment and to interconnect environment between agent, state, action and reward should be defined as shown in Fig. 1.

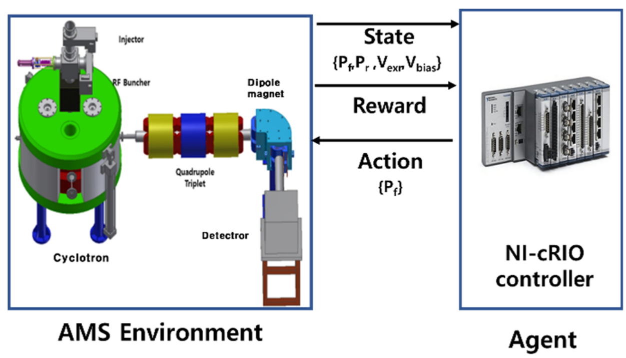

Figure 1: Reinforcement Learning based AMS control block diagram.

SYSTEM DESIGN

In AMS RF cavity, the electric field from rf source can be calculated by following formula.

$$E_{PK} = \kappa_e \sqrt{P_t} \ ,$$

where κ_e is coefficient which is determined using computer code and P_t is transmitted power. P_t is changed by cavity coupling coefficient and resonant-frequency mismatch and is related to beam loading effect and reflected power. Those parameters are used to describe state as follows:

$$\{P_f, P_r, V_{exr}, V_{bias}\} \quad ,$$

where P_f is forward power from rf source, P_r is reflected power and V_{exr}, V_{bias} is extraction and biases voltage, which effect injection beam quality from ion source, respectively.

To measure forward and reflected power, ZFBDC20-61HP+ bi directional coupler was installed between cavity and RF amp and NI-cRio was communicated with ion source process controller station. The action space for the RF controller can be expressed by:

$$A = \{a| -\Delta f, 0, \Delta f\} \ ,$$

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DESIGN AND CONSTRUCTION PROGRESS OF CYCLOTRON BASED PROTON IRRADIATION FACILITY FOR SPACE SCIENCE

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Abstract

The proton irradiation facility for space science research and application consists of a 50 MeV proton cyclotron, two beam lines and two radiation effect simulation experimental target stations. And the shielding plant facilities is constructed at the same time. The equipment provided by CIAE mainly includes a 50 MeV proton cyclotron, beam transport lines and experimental terminals, as well as dose monitoring and installation equipment. The 50 MeV proton cyclotron CYCIAE-50 is a compact, negative hydrogen ion cyclotron with the proton beam energy from 30 - 50 MeV, and the beam intensity is from 10 nA to 10 uA. The CYCIAE-50 is about 3.2 m in diameter, 3.5 m in total height and 80 t in total weight. The magnet of the cyclotron is a compact AVF structure electromagnet at room temperature with 30 kW exciting power. The diameter of the pole is 2 m, the outer diameter of the yoke is 3.2 m, and the height of magnet is 1.5 m. The cyclotron uses an external multi-cusp H^- ion source. The H^- beam from the ion source is injected into the center region through the axial injection beamline. Then the H^- beam is injected into the accelerating orbit by the spiral inflector. The cyclotron frequency is about 16 MHz. The RF system of the cyclotron is a pair of $\lambda/2$ cavities driven by a 23 kW transmitter. The fourth harmonic accelerating frequency is about 65 MHz. The proton beam is extracted by a single movable stripping carbon foil and the stripping extraction efficiency is more than 99%. The CYCIAE-50 has now been designed in detail, and its main components, such as the main magnets and RF cavities, are being manufactured in the factories in China.

This paper introduces the design and construction progress of the proton irradiation facility based on a 50 MeV cyclotron. The proton irradiation facility for space science is oriented to space proton radiation environment simulation. The proton radiation has an important influence on the spacecraft, and the energy of more than half of the protons in the space is no more than 50 MeV. The Proton Irradiation Facility could provide proton beam with energy range of 30-50 MeV, and beam density in the range of $5 \times 10^5 \sim 5 \times 10^9$ p·cm^{-2}·s^{-1}. It is suitable for the ground simulation test of displacement damage of optoelectronic devices, as well as the proton single particle effect ground simulation test of deep submicron devices and nanodevices. It provides technical support for the development of scientific satellite load and optoelectronic devices. Compared with the large accelerator facility, the proton irradiation facility based on the compact cyclotron is a type of space proton radiation environment simulation device with high performance and lower price. The layout diagram of the proton irradiation facility for space science is shown in Fig. 1. The proton beam from the cyclotron passes through two 45° deflection magnets and the energy selection system. At the experimental hall, there are two experimental beam lines for different proton radiation effects.

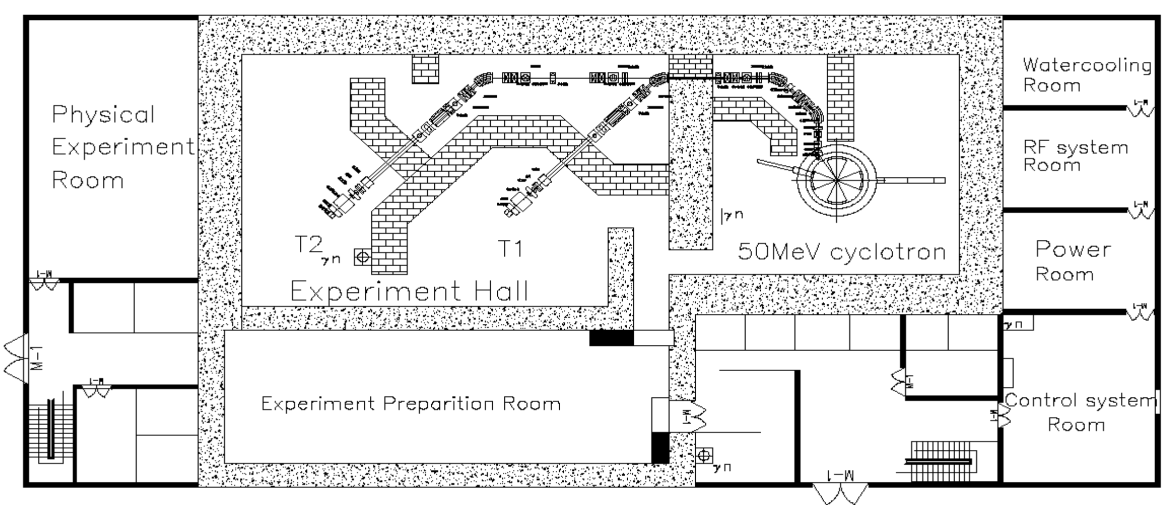

Figure 1: Layout of the proton irradiation facility based on 50 MeV cyclotron.

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CONCEPT OF 15 MeV CYCLOTRON FOR MEDICAL ISOTOPES PRODUCTION

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Abstract

The purpose of this article is to show the prospects of cyclotrons with resistive coils and prove that even in such a well-established field there is still room for innovation. The concept of a 15 MeV cyclotron accelerating H^- ions with a current of up to 1 mA is presented. The design features significantly lower weight and power consumption compared to the majority of existing cyclotrons of the same energy.

INTRODUCTION

Cyclotrons are widely used, delivering 10 - 70 MeV proton (mostly) beams for medical isotopes production such as PET, SPECT isotopes and 200 - 250MeV proton beams for hadron therapy. The modern trend is to apply superconducting coils to increase magnetic field strength of the cyclotron in order to make the accelerator more compact, and thus reduce the overall cost of the cyclotron setup. Nowadays superconducting cyclotrons and synchrocyclotrons are successfully operating not just for proton therapy (Varian Proscan [1], S2C2 (IBA) [2], Mevion [3]) but also for isotope production (Ionetix [4]). Some of them appeared quite recently, and some work for years and have proved their effectiveness.

However, the author believes that at least at the low-energy area there is still room for improvements of the resistive-coil machines.

To summarize, here are the reasons why the author believes that cyclotrons with resistive coils are still a good choice for medical applications:

- There are opportunities for optimization, examples are presented further in the paper.
- Compared to superconducting cyclotrons, power consumption and dimensions are not necessarily higher, but in some cases could be lower, as cryocoolers consume power, and also occupy space around the magnet.
- Low magnet field is easier to shim, the isochronizing requirements are lower.

A NEW 15 MeV CYCLOTRON RC3/6

Usually, cyclotrons dedicated for isotope production accelerate H^- ions to get use from extraction by stripping on the foil. Extraction by stripping has about 100% efficiency, low energy H^- ions has only one disadvantage, high vacuum is required.

Concept RC3/6

The cyclotron needs to be compact, cheap, reliable and to have a low power consumption. Concept RC3/6 lead us to more efficient design of the cyclotron than typical four-sector accelerator. What is the essence and specific feature of the concept 3/6? The three-sector cyclotron operating at the 6 harmonic mode of acceleration allows to have an effective magnetic system due to wide sectors providing higher mean field and narrow valleys sufficient for placing resonators corresponding to 6th harmonic of acceleration (see Figure 1). The sectors of the magnet are 90° azimuthal width, and valleys are about 30 degrees. In such case the 6th harmonic mode is optimal for acceleration and the resonance frequency must be 128 MHz for magnetic field equal to 1.4 T.

Such configuration is beneficial for both magnet and RF design, as the magnet, while having necessary average magnet field is being very efficient (has small number of A·turns), high frequency RF system is very compact and power-efficient.

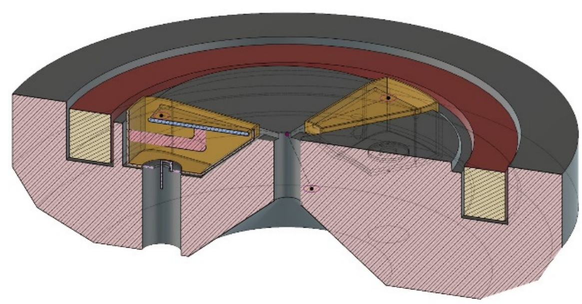

Figure 1: Layout of the 3D computer model of the cyclotron.

Table 1. Parameters of the Cyclotron

Magnet Type	Resistive
Ion source	external
Final energy [MeV]	15
Final radius [mm]	370
Mean Magn. field [T]	1.4
Dimensions (height×diameter) [mm²]	720 × 1420
Weight [kg]	6500
Hill/Valley field [T]	1.8/0.4
Hill/Valley gap [mm]	25/300
A*Turn number	17 000
Magnet power consumption [kW]	1.5
RF frequency [MHz]	128
Harmonic number	6
Voltage [kV]	20
RF power [kW]	4
Turn number	120
Beam intensity [μA]	Up to 1000
Extraction type	stripping foil

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STUDY OF MERIT RING FOR INTENSE SECONDARY PARTICLE PRODUCTION

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Abstract

An intense negative muon source MERIT (Multiplex Energy Recovery Internal Target) for the nuclear transformation to mitigate the long-lived fission products from nuclear plants have been proposed. For the purpose of proof-of-principle of MERIT scheme, a FFA (Fixed Field Alternating focusing) ring has been developed. In this paper, the results of study for proof-of-principle experiment on MERIT scheme will be reported.

INTRODUCTION

Recently, nuclear transmutation with negative muons has been conceived as one of the ways to mitigate the radioactive nuclear wastes such as long lived fission products (LLFPs) [1]. In muonic atom, which is formed by trapping negative muon, the atomic nucleus absorbs a negative muon with large probability (95%) [2], if the atomic number Z is more than 30 and then, it transforms to stable nucleus by beta decay and the emission of several neutrons. For example, long lived cesium isotope ^{135}Cs ($\tau_{1/2}$=2.3 million years) which is produced from the nuclear power plant in burning out one ton of enriched the nuclear fuel including 3% of ^{235}U can be transformed to non-radioactive Xe isotopes within about five years, if the yield of negative muon is $10^{16}\mu^-$/s.

Negative muons decayed from negative pions are efficiently produced by the nucleon-nucleon interactions with high energy hadron beam using the target nucleus containing neutrons. In order to generate negative muons effectively, MERIT (Multiplex Energy Recovery Internal Target) scheme has been proposed. The principle of the MERIT scheme is shown in Fig. 1. Contrary to the original ERIT scheme [3,4], the transverse emittance growth caused by multiple scattering is rather modest since a primary hadron beam energy is relatively high. On the other hand, the longitudinal emittance growth rate becomes large. The wedge-shaped target placed at the dispersive orbit could reduce this effect and also the injection beam energy becomes lower, which could cure the load of the injector.

The characteristics of the MERIT scheme are shown as follows.

- Energy recovery and ionization cooling;
- CW operation with fixed RF frequency beam acceleration and storage;
- Negative pion production using internal thin target;

There are a couple of difficulties in negative pion production. One is the energy loss of the projectile proton by ionization of target. The efficiency of negative pion production drops until the particle energy reaches the threshold energy of pion production at about 250 MeV/u. Another problem is the absorption of negative pions in the solid target. The absorption cross section of negative pions with the target nucleus is so large that a thinner target must be used. Thus, a high beam current and a thin target are both essential to improve the efficiency in negative muon production.

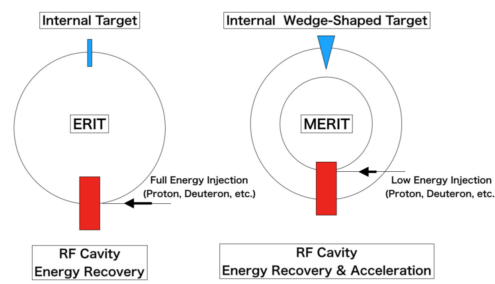

Figure 1: Schematic diagram of ERIT and MERIT scheme.

In MERIT scheme, the fixed RF frequency acceleration makes a cw beam operation with low energy beam injection. Negative pion production using a thin target has advantages for reducing the negative pion loss in the target and keeping high reaction rate with energy recovering and cooling by RF re-acceleration.

To prove a principle of MERIT scheme, in particular, on the fixed RF frequency beam acceleration and storage with a wedge type of thin internal target, a scaling type of FFA ring, the name is MERIT-PoP (Proof-of-Principle) ring has been developed with remodeling the FFA-ERIT ring [3,4], which was built at the Institute for Integrated Radiation and Nuclear Science in Kyoto University (KURNS). As preparation for the experimental study on MERIT scheme, beam study on the closed orbit distortion (COD) correction and measurement of betatron tune of the MERIT-PoP ring was carried out [5]. In this paper, study for the PoP experiment on MERIT scheme using the MERIT-PoP ring is reported.

MERIT-POP RING

The MERIT-PoP ring has been developed with several modifications of existing the FFA-ERIT proton ring. A semi-isochronous acceleration in the scaling FFA is useful for the fixed RF frequency acceleration [6], where it is essential to keep a slippage factor(η) close to zero. In case of the scaling FFA, η depends only on the field index k and Lorentz factor

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DEVELOPMENT OF A CENTER REGION FOR NEW SUMITOMO CYCLOTRON

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Abstract

We Sumitomo Heavy Industries, Ltd. have been newly developing an AVF cyclotron which employs the superconducting magnet. This cyclotron purposes medical use, especially proton therapy fields and is most compact and high intensity among AVF cyclotrons which can accelerate to the energy for proton therapy. In this paper we report and focus on its center region. The center region consists of an ion source, a beam shaper, RF electrodes and two functional pair of centering coils that use Bz 1st harmonic (C-H coils). These components were finished manufacturing and await the component test after the assembly.

INTRODUCTION

This cyclotron is a compact cyclotron which has a 2.8 m diameter and 1.7 m height yoke, thus also that center region becomes compact and is equipped into a tiny space of it within about 0.2 m diameter [1]. Figure 1 shows external view of a whole center region. There are many small components in the center region and these components will be introduced in the following sections.

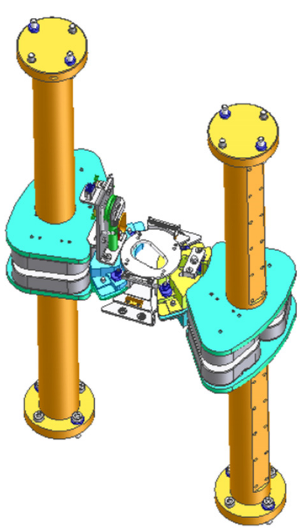

Figure 1: 3D schema of a whole center region.

COMPONENTS OF CENTER REGION

Ion Source

The PIG ion source with hot cathode is applied and located at the center of the cyclotron as an internal ion source. The structure of the ion source is classic and simple PIG ion source because of tiny space of the center region. An anti-cathode which is set against the filament and floating on the ground reflects thermal electron. As this cyclotron has 3.0 T magnetic field, the filament heated by current receives the Lorentz force strongly. It may be a problem that this force deforms the filament. To avoid the deformation, AC current heating is newly introduced into this ion source. This method made application of hot cathode PIG ion source under high magnetic field possible.

The performance of this ion source have been confirmed on our test bench (Fig. 2). The performance test was conducted under the condition that 3.2 T magnet field and static extraction. The H^+ beam current was measured about 300 µA at most (Fig. 3) [2].

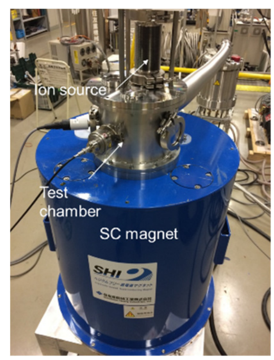

Figure 2: Test bench of ion source.

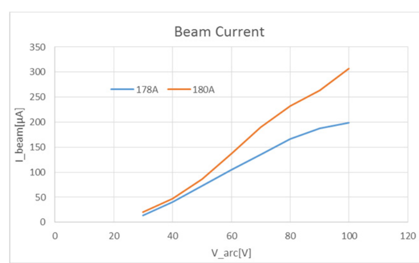

Figure 3: Extracted beam current on the test bench. This shows arc voltage vs extracted beam current in case of two type of filament current.

In case of hot cathode type PIG ion sources, filaments are supplies and must be exchanged periodically. As the mechanical driving system which evacuate the ion source from the cyclotron without broking vacuum is equipped under the cyclotron, a maintenance of ion source is possible to be performed easily and rapidly.

Dee and Counter Dee Electrode

The extraction of the proton beam from the ion source is conducted with RF electric field made by the dee electrode. The voltage of 50 kV is loaded between the puller and the ion source and the beam is extracted to accelerated orbits. Extracted beams turn around 15 mm radius and RF field

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OPTICAL DESIGN OF AVF WEAK-FOCUSING ACCELERATOR

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Abstract

A trend in proton beam therapy systems is downsizing their footprints. A larger main magnetic field for the downsizing, however, requires a septum magnet to generate a larger magnetic field for beam extraction. In order to relax the specification of the septum magnet, we consider an azimuthally varying field (AVF) weak-focusing accelerator. The magnetic fields of its hills and valleys can be designed while maintaining the average magnetic fields over the design orbits. Thus, by locating the septum magnet near one of the valleys, the specification is relaxed while keeping the footprint of the accelerator. In this study, we show an optical design of an AVF weak-focusing accelerator with cotangential orbits. The magnetic field in the valleys is smaller than the average magnetic field over the maximum energy orbit by 0.2 T. We evaluate gradient magnetic fields required for beam extraction and find the possibility of variable energy extraction by the static gradient fields.

INTRODUCTION

A trend in proton beam therapy (PBT) systems is downsizing their footprints. We have proposed a compact accelerator for PBT with cotangential orbits [1, 2]. Figure 1 shows a schematic of the accelerator. Its concept is to achieve both compactness and variable energy extraction. For compactness, a superconducting magnet which generates a weak-focusing magnetic field of approximately 4-5 T and an RF cavity which can modulate its frequency are applied. For variable energy extraction, the orbits are not concentric but cotangential like the classical microtron, and an RF kicker and gradient fields (generated by a peeler and a regenerator) are combined. Due to the characteristic orbit configuration, there is small turn separation region on one side, where the RF kicker is installed. Each orbit between 70 MeV and 235 MeV passes through the RF kicker. By turning on the RF kicker, the beam trajectory is moved toward the outside of the circulating region. The beam moved by the RF kicker is eventually affected by the gradient magnetic fields generated by the peeler and the regenerator. The gradient magnetic fields bring about 2/2 resonance, and the beam arrives at the entrance of the extraction channel. Along the extraction channel, septum magnetic fields are applied to extract the beam from the accelerator.

A larger main magnetic field requires septum magnets to generate larger magnetic fields for extraction. Since the proposed accelerator is designed to extract low energy (approximately of 70 MeV) beams, it requires the septum magnets to generate even larger magnetic fields compared with cyclotrons and synchrocyclotrons. Among the septum magnets, the first septum magnet, which is located at the entrance of the extraction channel, is under the severest conditions. Hence, we considered a new idea to relax the specification of the first septum magnet.

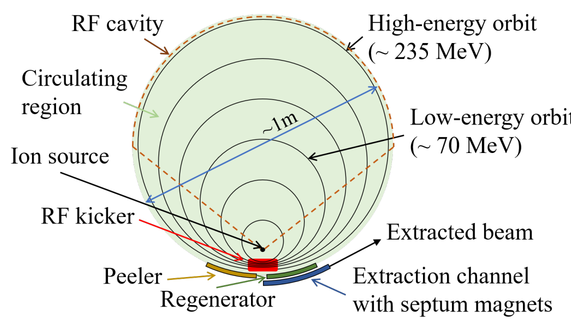

Figure 1: Schematic of compact accelerator.

AVF WEAK-FOCUSING ACCELERATOR

We denote the fringe magnetic field at the entrance of the extraction channel by B_f, and the first septum magnetic field by $-\delta B$. Then the curvature radius of the beam at the entrance is given by

$$\rho(K) = \frac{\sqrt{K(K + 2E_0)}}{cq\left(B_f - \delta B\right)}, \tag{1}$$

where c denotes the speed of light, and q, E_0, and K denote charge, rest energy, and kinetic energy of the beam, respectively. We denote the maximum kinetic energy and the average main magnetic field over the maximum kinetic energy orbit by K_M and B_M, respectively. In order to extract the beam with its energy of K, $\rho(K)$ has to be larger than ρ_M, where ρ_M is given by

$$\rho_M = \frac{\sqrt{K_M(K_M + 2E_0)}}{cqB_M}. \tag{2}$$

If B_f is reduced, δB is also reduced while $\rho(K)$ maintained. The easiest approach to reduce B_f is to reduce B_M. However, if B_M is reduced, not only B_f is reduced, but also ρ_M is increased, indicating a larger footprint of the accelerator and larger $\rho(K)$ for extraction. Hence for relaxing the specification of the first septum magnet, B_f should be reduced without reducing B_M. To satisfy this condition, we consider an azimuthally varying field (AVF) weak-focusing accelerator. By locating the extraction channel near one of the valleys, B_f at the extraction channel is reduced while B_M maintained.

The AVF field is normally applied to cyclotrons to satisfy both isochronism and stable betatron motion. Since isochronism requires a magnetic field to increase with radius, the average magnetic fields of usual AVF cyclotrons increase

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COMPACT COTANGENTIAL ORBIT ACCELERATOR FOR PROTON THERAPY

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Abstract

A new type accelerator is being developed for the next generation particle therapy system. This accelerator utilizes a weak focusing DC magnetic field and a frequency modulated RF acceleration. Since a superconducting magnet is applicable to the main magnet, the accelerator can be compact. The accelerator characteristically has cotangential orbits to form an orbit-concentrated region. A beam is extracted from the region by using a new extraction method with the transverse RF kicker, peeler and regenerator magnetic fields. In this method an extracted beam energy can be controlled by applied time of the acceleration RF voltage without using an energy selection system (ESS). Intensity and pulse width of the extracted beam can be controlled by a voltage and/or a frequency pattern of the RF kicker.

INTRODUCTION

Currently, a cyclotron type accelerator (AVF cyclotron, synchrocyclotron) and a synchrotron are provided to practical use of particle therapy.

Since a superconducting magnet is applicable to a cyclotron type accelerator with a DC main magnetic field, it is a merit to be able to downsize the accelerator. However, it is necessary to install an ESS outside the accelerator in order to obtain various desired beam energy levels for treatments. A degrader in an ESS generates unnecessary radiation and reduces beam utilization efficiency. There is also a problem of fragmentation that makes it difficult to apply the cyclotron type accelerator to uses other than proton therapy.

On the other hand, a synchrotron has a merit to extract a variable energy beam without the ESS. In addition, transverse RF-driven slow extraction technology [1] has made it possible to control both the position and the intensity of the extracted beam with high accuracy. Thus, a synchrotron is advantageous for scanning irradiation. However, since the synchrotron requires an AC main magnetic field, it is difficult to adopt the superconducting magnet as a means to achieve a smaller body.

The cotangential orbit accelerator that combines the merits of both a cyclotron type accelerator and a synchrotron has been proposed as a next-generation accelerator for particle beam therapy [2]. This new accelerator uses the DC main magnetic field and the frequency-modulated RF acceleration. The accelerator body can also be downsized by applying the superconducting magnet. It is more nortable that a variable energy beam can be extracted without the ESS by the new method. The accelerator can be applied to both proton and heavy ion beam therapies. In particular, the result of the conceptual design study on the accelerator for proton therapy is described in this paper. The main specifications of the accelerator are listed in Table 1.

Table 1: Margin Specifications

Parameter	Value
Diameter of yoke	2.7 m
Total weight	60 t
Magnetic field	4.0 T at injection point, 3.94 T at max. energy orbit
Main coil	NbTi cable, conductive cooling
Magnetomotive force of main coil	1.8 MA
Harmonic number	1
RF frequency	61.0 ~ 48.5 MHz
RF voltage, required power	10 kV, 30 kW
Extracted beam energy	70 MeV to 225 MeV without degrader
Extraction method	Slow extraction, RF kicker + peeler regenerator
Pulse repetition rate	< 500 Hz

DISTRIBUTION OF ORBITS

The orbits are decentered as shown in Fig. 1 (a) to create the orbit-concentrated region with the radial width of about 10 mm. This region is located at orbits from 70 MeV to 225 MeV, and that corresponds to the extraction energy range needed for treatment. There are two reasons for forming the orbit-concentrated region.

- Extracting the beam from the orbit-concentrated region allows for reduction of the required radial displacement from the equilibrium orbit for each beam within the extraction energy range.
- Installing the RF kicker on the orbit-concentrated region makes it easier to apply the transverse RF electric field to each beam within the extraction energy range.

These two points are essential to realize the new extraction method. Figure 1 (b) shows the ideal main magnetic field distribution on the midplane that realizes such an orbital arrangement. The tune diagram is shown in Fig. 2. It has been confirmed that there is sufficient horizontal and vertical acceptance based on results of a tracking analysis with the ideal main magnetic field distribution [3].

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REVIEW AND CURRENT STATUS OF THE 70 MeV HIGH INTESITY PROTON CYCLOTRON AT LNL

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Abstract

In 2017 the new cyclotron has been successfully commissioned and started the operation at Laboratori Nazionali di Legnaro (LNL) of INFN. The cyclotron is the proton driver foreseen for the Selective Production of Exotic Species (SPES) project, providing the high power beam for radioactive ion beams (RIBs) production by the ISOL technique. The SPES facility is today under construction and first low energy RIBs are expected to be available in 2021. The facility has been designed in order to exploit the versatility of the cyclotron in terms of wide range of energy and beam current extracted: 35 - 70 MeV energy and 20 nA - 500 µA of average current. Moreover, the possibility to extract at the same time two proton beams allows to share these both for experimental physics session and applications. In particular, at LNL a collaboration between private company and public institution will lead to a profitable synergy in R&D of new radioisotopes and the related production. In the session the results of the commissioning and the operation of cyclotron will be presented as well as the description of the SPES facility together with its potentiality in nuclear physics research and applications.

SPES PROJECT STATUS

The SPES project [1] is developing in the international framework of the new facilities producing radioactive ion beams for experiments exploring the frontiers of nuclear physics. It will mostly provide neutron-rich exotic beams, through the production of fission fragments by the interaction of high power proton beam (8 kW) with UCx targets. The neutron rich exotic ions produced by the above direct reaction, will be selected in mass with a very high resolution on the order of 1/20000 and then, once the charge breeding process increases the charge to mass ratio, the ions are accelerated with ALPI linac booster up the energy of 10 MeV/amu (A~130).

SPES project is developing in several branches spreading from fundamental research to applications and interdisciplinary physics. The complexity of the project has required to separate it in four phases with the aim to provide a multipurpose facility:

- α-phase: construction of main building and installation and commissioning of the high intensity accelerator delivering the high power proton beams.
- β-phase: installation and commissioning of Radioactive Ion Beams (RIB) facility. It consists on ISOL targets, low energy beam transport lines, beam cooling device and High Resolution Mass Separator (HRMS), charge breeding system, new RFQ injector and re-acceleration.
- γ-phase: installation and commissioning of equipment and laboratories for production and R&D of radioisotopes for medical applications.
- δ-phase: realization of experimental hall for the production of neutrons beam by interaction of high intensity protons with heavy and light targets.

The SPES project entered in the construction phase in 2010 with the assignment of the tender for the cyclotron supply to Best Cyclotron System Inc. (BCSI) Canadian company.

The α-phase has been accomplished out at the end of 2017: the main building has been constructed and principal plants, services and auxiliary systems were supplied in order to allow the first operation of the accelerator. The cyclotron has been installed in 2015 and finally commissioned in 2017. From mid-2018, in the SPES building several activities have started in order to complete the services (electrics, hydraulics, thermo-mechanics) and the infrastructures (laboratories, finishing of irradiation rooms, additional shielding) necessary to carry out the β-γ-δ phases.

Certainly the β-phase is the most complex and articulated of the project. It includes not only the realization of the items described above but also additional works to provide a significant upgrade of the actual ALPI superconducting linac (cryogenics system, controls, etc..) in order to improve both the performance and reliability. The works related this phase are still ongoing: the ISOL target station is ready to be installed in the dedicated bunker and the low energy beam transport line components are under construction. The beam cooler device is being realized in collaboration with LPC of CNRS at Caen (France). The HRMS design has been completed and the tender for the construction will be launched in few months. The charge breeder has been installed and ready for the commissioning with stable beams. The resistive RFQ to be used as new injector for ALPI booster is under construction. The main schedule foresees the commissioning at low energy of the first beam extracted from ISOL target in 2021. The completion of the SPES commissioning with RIBs at fully energy is expected in 2023.

The γ and δ phases are related to the applications of high intensity proton beam extracted from the cyclotron.

The γ-phase foresees the setting-up of 3 bunkers dedicated to the production of innovative radioisotopes for diagnostics and therapy in medical environment. One low intensity irradiation area is being prepared for nuclear cross-section measurements. Moreover, the laboratories for chemical treatment of the produced radionuclides and for special targets preparation will be equipped. The project funded for this purpose is LARAMED [2].

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STATUS OF THE HZB CYCLOTRON

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Abstract

For more than 20 years eye tumours are treated in collaboration with the Charité – Universitätsmedizin Berlin. The close co-operation between Charité and HZB permits joint interdisciplinary research. Irradiations with either a sharp, well focused or a broad beam, either in vacuum or in air are possible. In addition, a ^{60}Co-source for γ-irradiations is available. Experiments now comprise dosimetry, detector comparisons, and ambulant mouse irradiations. Furthermore, radiation hardness tests on detectors, CCD-cameras and other electronics are performed.

In order to improve the beam diagnosis between the 2 MV injector Tandetron and the cyclotron a harp has been installed, leading to new beam line calculations for the injection line.

ACCELERATORS AND OPERATION

The k=130 cyclotron of HZB is served by two injectors: a 6 MV Van-de-Graaf and a 2 MV Tandetron (see Fig. 1 in [1]). The Tandetron is our usual injector for therapy, delivering an extremely stable beam. The Van-de-Graff injector is used as backup, for rare gas beams, and if a beam with a different time structure is required.

The standard beam is a 68 MeV quasi-DC broad proton beam. For experiments, time structures vary from quasi-DC to single pulses with a pulse width of less than 1 ns. The beam spot may be 50 mm in diameter with a homogenous distribution or may be focused to less than 1 mm.

Operation of the accelerator complex went smoothly. As the scheduled beam time is only little more than one week in two shift mode per month, major break-downs have an enormous effect on the relative down time, e.g. the high downtime in 2015 was due to faulty operation during run-up of the cyclotron. With exception of 2015, the relative down-time of the accelerator was below 5%. Furthermore, as can be seen in Fig. 1, most of the downtime occurs during the start-up phase of the accelerator complex. Since 2011 the Tandetron is our usual injector for therapy, improving the downtime. The main cause for down-time is the cyclotron. Here, the installation of the new low-level RF control [2] reduced the RF faults. 10% of the down-time is due to cuts in the electricity supply.

BEAM UTILIZATION

By far most of the beam time (85%) is delivered for therapy. The experimental use of the beam time is: accelerator development 8%, medical physics and dosimetry 5%, and radiation hardness tests about 2%.

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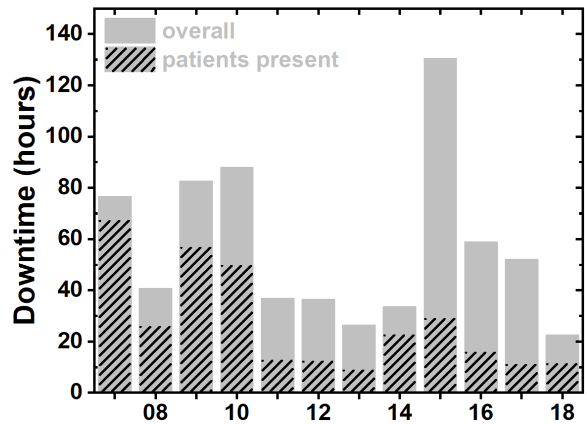

Figure 1: Downtime in hours for the past years. With exception of 2015, the relative downtime was below 5%.

Therapy of Ocular Melanomas

We now look back to more than 20 years of accelerator operation for proton therapy. Overall, more than 3500 patients have been treated. For the past ten years, nearly 220 patients have been irradiated each year in a routine workflow. Special cases were children, pregnant and breast-feeding patients.

In Tables 1 and 2 the clinical results of different radiation types used for the treatment of ocular melanomas of different centres as well as of Charité are shown. Compared to other radiation techniques, protons provide an excellent tumour control of 96% after 5 years as well as a very good eye retention rate.

Table 1: Tumour Control after 5 Years

Radiation	Others	Charité
^{106}Ru [3,4]	91%	ca. 92%
^{125}I [3]	91%	
Protons[3,5,6]	96%	ca. 96%
LINAC (SRT) [3,7]	94%	
Cyberknife (SRS) [8,9]	73%	

Table 2: Eye Retention Rate after 5 Years

Radiation	Others	Charité
^{106}Ru [10,4]	91%	ca. 92%
^{125}I [11]	91%	
Protons[5,12,6]	96%	ca. 96%
LINAC (SRT) [7]	94%	
Cyberknife (SRS) [8,9]	73%	

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AGOR STATUS REPORT

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Abstract

The operations of the superconducting cyclotron AGOR over the past years will be reviewed. Reliability issues encountered after nearly 25 years of operation and mitigation measures to warrant reliable operation for the coming decade will be discussed.

The research performed with AGOR has significantly shifted from fundamental physics to radiation biology and medical radiation physics, both in collaboration with the Groningen Proton Therapy Center, and radiation hardness studies. The radiation biology research will be substantially expanded in the coming years with a new beam line for image guided preclinical research. For this research new dose delivery modalities including scanning, spatial fractionation and very high dose rates are developed. In addition, a new program has been started on the production of exotic nuclei, for which a new superconducting solenoid fragment separator will be developed.

For the radiation hardness testing a cocktail beam at 30 MeV/amu with several ion species up to Xe has been developed and is now routinely delivered for experiments. A cocktail at 15 MeV/amu up to Bi is under development.

INTRODUCTION

The superconducting AGOR cyclotron, built by a French-Dutch collaboration in the period 1987 – 1994, has, after being transferred from Orsay (France), been operational in Groningen since the beginning of 1996. It can deliver beams of all elements, as is illustrated in the operating diagram in Fig. 1. The upper limit on the beam energy is determined by K_{bend} = 600 MeV and K_{foc} = 200 MeV; the lower limit by the lowest RF-frequency of 24 MHz and the location of the $\nu_r + 2\nu_z = 3$ resonance. The dots in the figure indicate the beams delivered for experiments over the years.

In the period 1996 – 2013 the beams delivered have mainly been used for research in nuclear physics (light ions) and on fundamental symmetries (heavy ions). Since 2014 the emphasis has shifted towards biomedical research, detector development and radiation hardness testing.

OPERATION

The cyclotron is operated 120 hours per week for about 26 weeks per year, which still meets current demand. From a technical perspective it is feasible to operate the cyclotron about 40 weeks per year; this would require additional operating staff to be recruited and trained.

With the shift from fundamental physics to radiation biology and physics and technology of particle therapy the number of individual experiments has significantly increased while their duration has strongly decreased from several days to typically 16 hours. It regularly happens that the cyclotron has to deliver a different beam every day of the week.

Over the past few years proton beams have been provided for over 80 % of the beam time, accelerated either as protons ($E_p \geq 120$ MeV) or as molecular hydrogen ($40 \leq E_p \leq 90$ MeV). The remainder of the beam time helium, carbon and oxygen beams with energies in the range 30 – 90 MeV/amu have been provided.

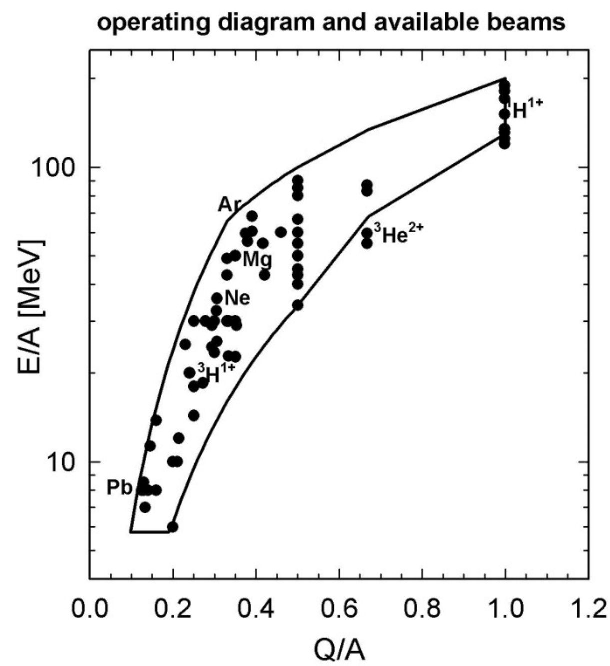

Figure 1: Operating diagram of the AGOR cyclotron.

RELIABILITY ISSUES

After nearly 25 years of operation reliability issues start to appear on certain sub-systems of the accelerator. These are to a large extent related to availability of spare parts and components and, for the control system, incompatibility with current hardware and standards for communication. In addition, wear and tear necessitates replacement of certain components.

Control System

The central control system of the AGOR accelerator facility is based on the commercial Vsystem software package [2]. We have recently ported the system from the 32-bit to the 64-bit version in order to maintain compatibility with modern hardware. Depending on the specific requirements local control is performed by PLC's (vacuum, cryogenics, cooling) and locally developed microprocessor-based systems communicating over BITBUS (power supplies, beam diagnostics). Both suffer from obsoles-

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STATUS OF THE CYCLOTRON FACILITY AT RESEARCH CENTER FOR NUCLEAR PHYSICS

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Abstract

Research Center for Nuclear Physics (RCNP), Osaka University operates a K140 AVF cyclotron and a K400 ring cyclotron. We promote the nuclear physics, accelerator physics and related scientific fields using its unique beams. From 2018, the RCNP started the Research Center of Subatomic Sciences as the International Joint Usage/Research Center in Japan. It enables more efficient support for the researches using the resources of the RCNP facility. We have carried out the stable operation until Feb. 2019 when the 2 years of shutdown period starts for the upgrade works. We have been carrying out a program of the upgrade of the K140 AVF cyclotron. We aim at 10 times higher intensity for the proton beam than before and further stability of the operation. We also carried out the upgrade of the cyclotron building and related facilities to handle beams with higher intensity. The upgrade works are planned to be completed in the beginning of 2021. These upgrades are the most important programs to reinforce the function of the newly established center.

INTRODUCTION

Research Center for Nuclear Physics (RCNP), Osaka University operates a K140 AVF cyclotron which was completed in 1973 and a K400 ring cyclotron which was completed in 1992 and promotes the nuclear physics, accelerator physics, and related scientific fields since its foundation in 1971. Several kinds of the electron cyclotron resonance ion sources and a low energy beam transport system provide various ion beams including polarized proton and deuteron beams for injection to the K140 AVF cyclotron. The K140 AVF cyclotron have been used for providing medium energy beams to the experimental station and for injecting the beams to the K400 ring cyclotron. The K400 ring cyclotron accelerates protons up to 420 MeV at the maximum and other ions with their charge number Q and mass number A up to $400(Q/A)^2$ MeV. Precision of the beam energy is uniquely high ($\Delta E/E \sim 10^{-4}$) and it is taken advantage of in the precise measurement of the nuclear energy structures combined with the distortion matched beamline [1] and the world's most precise spectrometer Grand Raiden [2]. The proton beams with energy of 396 MeV is used for the production of secondary beams of muons as described in the later section and neutrons. The neutron beam with a broad energy spectrum is called as the white neutron beam which approximates the energy spectrum of cosmic ray neutrons on the ground level [3]. It is used for the test of the radiation-induced soft errors of semiconductor integrated circuits mainly by the industrial researchers. The middle energy beams are mainly used for the production of radioactive isotopes (RIs). We allied with 5 accelerator facilities in Japan and have provided short-lived RIs which are difficult to be commercially purchased. The accelerator building and the structure inside with the cyclotrons, spectrometers and the beam lines are shown in Fig. 1.

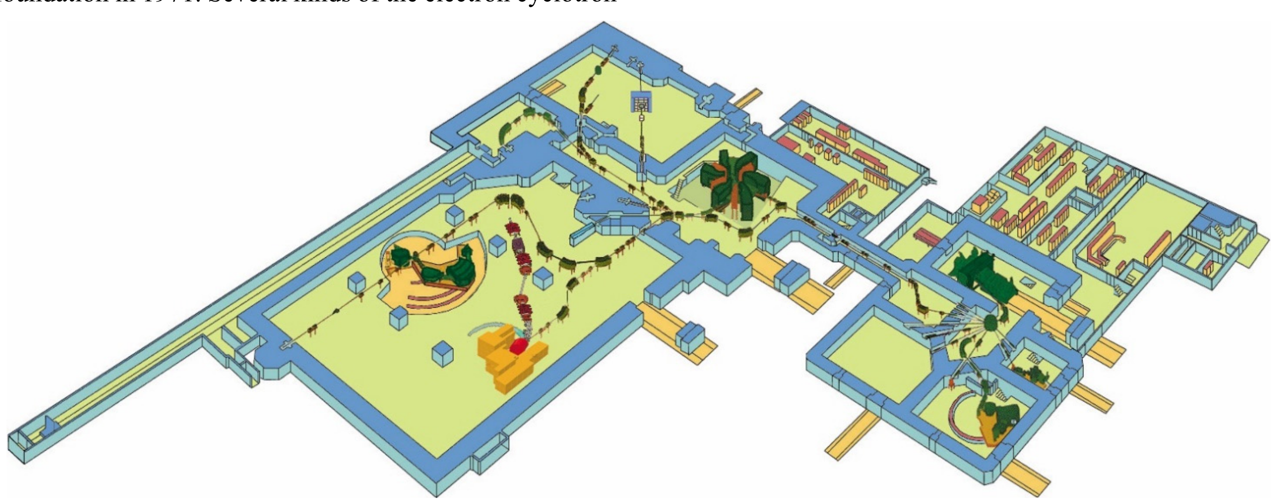

Figure 1: A birds-eye view of the RCNP cyclotron facility.

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THE DEVELOPMENTS OF THE RF SYSTEM RELATED TO THE K-800 SUPERCONDUCTING CYCLOTRON UPGRADE*

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Abstract

The K-800 superconducting cyclotron has been in operation at Laboratori Nazionali del Sud for almost 25 years. It has been subjected to continuous upgrades and modifications since 1994: the RF couplers have been redesigned, the new dees have been changed from aluminium to copper, as has the new central region from radial to axial injection of the beam, the hybrid configuration solid state - tube of the power amplifiers, the digital LLRF, etc. The next scheduled important upgrade of the Cyclotron mainly consists in a new extraction beam line able to support the increase of the beam current intensity. The accelerated beam will be extracted in two ways: by stripper and by electrostatic deflector and, consequently, one of the most important features of the new upgrade is the new cryostat. Further upgrades and refurbishments of the other main parts of the cyclotron, such as a new liner, the modification of the RF cavities and dees, the refurbishment of HLRF-LLRF, the insertion of the stripper extraction system, to name but a few, are in progress, too. This work focuses on the RF system upgrade.

INTRODUCTION

The LNS Superconducting cyclotron has been operating at LNS since 1995. The original design was thought up to produce beams for nuclear physic experiments in the range of a few dozen watts. In the initial configuration, the cyclotron was a booster of the 16 MV Tandem. The injection was radial and the Tandem and Cyclotron operated together as a coupled accelerator system. The introduction of the axial injection and the redesign of the central region means the cyclotron has been a stand-alone accelerator since 2000. The two accelerators, Tandem and Cyclotron, have been operating independently for the last 19 years. In the meanwhile, the cyclotron's good results with the axial injection were a sort of flywheel to develop, through the EXCYT project, the production of radioactive ion beams on a thick target with the ISOL technique [1]. However, the limitation, in terms of maximum output power (<150 Watts) of our extraction system due to some intrinsic constraints and efficiency around 50 - 60% of the electrostatic deflector (ED), became quite clear. Yet the strong interest, in terms of demand, for high intensive beams is still valid. A new important project, in fact, has requested this kind of beam. The project, called NUMEN (NUclear Matrix Elements for Neutrinoless double beta decay), proposes an innovative technique to measure the nuclear matrix that is of relevant interest for the double β decay without neutrino emission. This ambitious technique needs beams of $^{12}C^{4+}$ $^{18}O^{6+}$ $^{20}Ne^{4+}$ mainly, with a maximum beam current intensity of 10^{14} pps, which means a cyclotron beam power between 1 and 10 kW. This is more or less 10 - 100 times the present maximum beam power of 100 W. In any case, some preliminary experimental results, obtained at the INFN-LNS with the present version of the superconducting cyclotron, have provided an encouraging indication of the capability of the proposed technique to access relevant quantitative information for NUMEN [2]. Another facility, strongly interested in high intensive beams, using the inflight technique to produce RIBs is FRIBs@LNS (in Flight Radioactive Ion BeamS at LNS), already installed at LNS, allows one to carry out nuclear physics experiments investigating the properties of short-lived nuclear species. The maximum power delivered with the upgraded Superconducting Cyclotron, suggests a specific study to design, a proper beam line with a new fragment separator, named FRAISE (FRAgment Inflight SEparator) too [3].

MAIN MODIFICATIONS

The main difference between the present configuration of the cyclotron and the future upgraded one, is the introduction of a second extraction technique by stripping. In this way the extraction efficiency is enough to achieve the high intensity requests. The new median plane of the cyclotron with both extraction channels, by stripper and through electrostatic deflector (E.D.), is shown in Fig. 1.

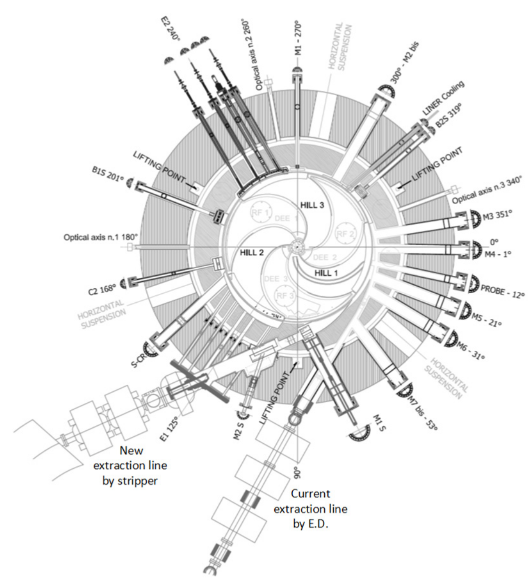

Figure 1: Median plane of the upgraded cyclotron.

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STATUS OF FFAS (MODELLING AND EXISTING/PLANNED MACHINES)

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Abstract

Since their rebirth two decades ago, great progress has been made in Fixed Field alternating gradient Accelerator (FFA) design, with different optical concepts and technological developments. Several machines have been built, and others are planned. The talk will review the recent progress around the world.

INTRODUCTION

A Fixed Field alternating gradient Accelerator (FFA) is defined as a circular particle accelerator, with a static guide field, like cyclotrons, and focusing and defocusing elements alternated to provide a strong focusing similar to modern synchrotrons. This principle is not new and came shortly after the discovery of the alternating gradient focusing [1] in the 1950s, in Japan [2], in USSR [3] and USA [4, 5], independently. Electron models were built shortly after its discovery by the Midwestern Universities Research Association (MURA) group [6–8] in the USA, but after it closed in 1967, FFA development was paused for about 40 years. If cyclotrons benefitted from the spiral geometry developed with FFAs [4, 5], pulsed synchrotrons, more suitable to reach the energy frontier, were favoured over FFAs for high energy physics. However, the importance of the beam power over the final energy has been growing recently, since intense sources of secondary particles from high-power proton beams are now a priority in several fields. An FFA would be a good candidate for such proton drivers since it can indeed reach relativistic energies, contrary to cyclotrons, and fixed field gives the possibility for higher repetition rates and at a more energy efficient operation than in Rapid Cycling Synchrotrons (RCS).

Since the rebirth of the FFAs twenty years ago, several machines have been designed and built in Japan [9–13], and in the UK [14], with several of them still in activity, like the ADS complex [15] and the MERIT experiment [16] at Kyoto University and the 150-MeV ring at Kyushu University [17]. Several machines are planned for the near future or being commissioned at the moment. At CERN, the nuSTORM project aims to study neutrino interactions with a muon-decay racetrack ring composed of FFA magnets [18]. In the USA, to demonstrate the feasibility of the use of FFA arcs in the eRHIC project [19], the Cornell-BNL Energy recovery linac Test Accelerator (CBETA) is under commissioning [20, 21]. In the UK, a major upgrade of the ISIS synchrotron is currently under study [22] and the FFA option is under consideration. A test ring is planned at RAL to demonstrate the capability of the FFA to deliver a high-power and short pulse proton beam for spallation neutrons [23].

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Several simulation codes are now available to model FFAs. Since the beam orbit in an FFA moves spatially with momentum, synchrotron simulation codes, which assume a central orbit independent of momentum, are unsuitable for studying FFAs. However, cyclotron codes and more generally static field codes including OPAL [24], Zgoubi [25], SCODE, MUON1 and FIXFIELD among others are now used to design FFAs. The first three integrate space charge to study high intensity effects.

FFAs are usually designed with an increasing radius, but excursion can be also done in the vertical direction. It has been first proposed in 1955 [27] as an “electron cyclotron”. It has been rediscovered recently [28]. Vertical FFA (vFFA) could be an asset when it comes to accelerate ultra-relativistic particles, because of its quasi-isochronicity. This arrangement has several other advantages. First, it results in an orbit radius independent of momentum, like synchrotrons. Second, the horizontal dispersion function and the momentum compaction factor are zero, with infinite transition energy. Third, the scaling property is separated from the geometrical arrangement of the lattice footprint. In principle, the ring could have any shape and it would still be possible to maintain a scaling property as long as the vertical magnetic field satisfies the design shape of scaling magnets. Finally, a rectangular shape for the main magnets and the coil geometry is simpler compared to the spiral magnet of horizontal FFA.

This paper will present the new concepts in terms of lattice first for the horizontal excursion FFA, and then for the vertical excursion FFA.

HORIZONTAL EXCURSION FFA

DF Spiral

To keep the linearised transverse motion equations independent of momentum, the vertical component in the horizontal mid-plane of the magnetic field B_z varies with radius r according to the so-called scaling law, following

$$B_z = B_0 \left(\frac{r}{r_0}\right)^k \mathscr{F}\left(\theta - \ln\frac{r}{r_0}\tan\zeta\right), \qquad (1)$$

with k the constant geometrical field index, r_0 the reference radius r_0, B_0 the field at that radius, ζ the constant logarithmic spiral angle and $\mathscr{F}$ an arbitrary fringe field fall-off function.

There are two types of zero-chromatic horizontal FFA, the radial type (case where $\zeta = 0$) and the spiral type. In the radial sector FFA, the alternating gradient is achieved with reverse bend magnets, while designing a lattice with logarithmic spiral FFA magnets gives a constant edge focussing independent of the beam momentum. Spiral FFAs thus have a smaller circumference than radial sector FFAs,

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FACTORS INFLUENCING THE VORTEX EFFECT IN HIGH-INTENSITY CYCLOTRONS

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Abstract

We discuss factors that have potential influence on the space charge induced vortex motion of particles within high intensity bunches (curling of bunches, Gordon 1969) in isochronous cyclotrons. The influence of the phase slip due to deviations from strict isochronism determines if the bunches of a specific turn are above, below or at "transition", and hence whether stable vortex motion of the bunches is possible at all. Secondly there are possible longitudinal and transverse effects of rf acceleration, the former depending on the bunch phase ("bunching" or "debunching"), the latter depending on the gradient of the accelerating voltage. High accelerating voltages in the first turns call the applicability of adiabatic approximations and analytic methods into question. The influence of the rf acceleration is expected to be significant only at low beam energy, i.e. should have small or even negligible effect beyond the central region of compact machines.

INTRODUCTION

Due to their operation principle, isochronous cyclotrons provide no longitudinal focusing of particles within a bunch. In case of high beam intensity, the natural expectation would be that the presence of the space charge force has a defocusing effect in all directions. However, as explained by Gordon and others [1–8], the space charge force combines with the cyclotron specific coupling between longitudinal and transverse motion thus leading to a parasitic effective longitudinal focusing. This effective focusing was confirmed by bunch shape measurements in the PSI Injector II cyclotron [6,9,10] and allows to operate this machine at high intensities without flattop resonators. The phase of the former flattop resonators has been reversed in order to increase the energy gain per turn.

Because of the inherent nonlinearity and complexity of the problem, a full analytical treatment has not been found to date. Here we refer to a linear approximation that has been suggested [7, 8] and used to understand the phenomenon in general. In Ref. [8] the linear model is used to develop a numerical code that allows to determine conditions for beam matching. This simple linear model effectively approximates the cyclotron by a constant focusing channel (CFC), and allows to derive some conclusions concerning the stability of the vortex effect. These conclusions have been compared with numerical studies using the particle-in-cell (PIC) code OPAL [11, 12]. The numerical simulations revealed that Gaussian beams which fulfill the linear matching conditions, are indeed (meta-) stable, but only under appropriate boundary conditions [8, 13]. Significant deviations from isochronism (strong phase excursions), for instance, are able to drive the beam out of the region of stability and may cause strong halo formation [13]. Here we present some results concerning effects of the acceleration voltage. These effects are expected to be important at low beam energy, i.e. during beam formation in the central region of the cyclotron.

CENTRAL REGION

A typical simplifying assumption used in previous studies is that of adiabatic acceleration, i.e. that the energy gain per turn (or per Dee gap) is small compared to the considered beam energy. This assumption is known to be questionable

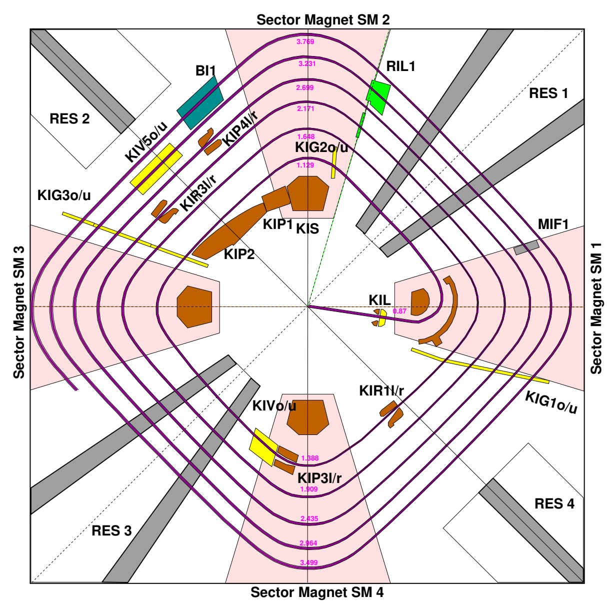

Figure 1: Layout of the central region of Injector 2.

in the first turns of Injector 2 (see Fig. 1): the DC beam of a Cockcroft-Walton preaccelerator passes a buncher before it is guided by an axial injection line towards the median plane. The injected beam energy is 870 keV, but the energy gain in the first resonator is of order ≈ 350 keV, and hence too large to safely presume adiabaticity.

We performed OPAL simulations of the acceleration of 2 mA beam for 3 different acceleration voltages with an initial distribution matched to a closed 1 MeV orbit in Injector 2. A too high accelerating voltage severely disturbs the vortex effect and leads to deformed bunches with increased halo formation as shown in Fig. 2. Figure 3 shows the number or particles versus distance from the bunch center and the corresponding integral. These results provide evidence that even in the case of well-matched beam injection, non-adiabatic acceleration causes halo formation and thus requires appro-

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BDSIM SIMULATION OF THE COMPLETE RADIONUCLIDE PRODUCTION BEAM LINE FROM BEAM SPLITTER TO TARGET STATION AT THE PSI CYCLOTRON FACILITY

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Abstract

The beam line for radionuclide production at the PSI Cyclotron Facility starts with an electrostatic beam splitter, which peels protons of a few tens of microamperes from the main beam around two milliamperes. The peeled beam is guided to a target station for the production of a variety of radionuclides. Beam Delivery Simulation (BDSIM), a Geant4 based simulation tool, enables the simulation of not only beam transportation through optics elements like dipoles and quadrupoles, but also particle passage through components like collimators and degraders. Furthermore, BDSIM facilitates user-built element with its accompanying electromagnetic field, which is essential for the modelling of the first element of the beam line, the beam splitter. With a model, including all elements from the beam splitter to the target, BDSIM simulation delivers a better description of the beam along the complete line, for example, beam profile, beam transmission, energy spectrum, as well as power deposit, which is of importance not only for present operation, but also for further development.

INTRODUCTION

The beam line for radionuclide production at the PSI Cyclotron Facility starts with an electrostatic beam splitter [1]. The splitter peels a beam of a few tens of microamperes from the main 72 MeV beam up to 2.4 mA intensity. The peeled beam gets a horizontal kick from the electrostatic field of the beam splitter, which creates a clearance more than 40 mm at the entrance of a septum magnet 3.395 m downstream. The peeled beam is then bent 17.5° away from the main beam, after passing the septum magnet, and is thereafter guided by the beam line to a target station for the production of a variety of radionuclides. The splitter is essential for the beam transportation. However, the splitter has so far been excluded from beam optics calculations, for example the envelope fit applying the program TRANSPORT [2]. The beam splitter is not a conventional beam transportation element. It is made of special materials, has a peculiar geometric form, and is accompanied with a 3D electrostatic field, while the beam transportation is correlated with all of these factors. It is therefore difficult to be defined by a conventional beam optics program, such as TRANSPORT or MADX.

Beam Delivery Simulation (BDSIM), a Geant4 based simulation tool, enables the simulation of not only beam transportation through optics elements like dipoles and quadrupoles, but also particle passage through components like collimators and degraders. Furthermore, BDSIM facilitates user-built elements in a wide range of geometrical forms and of practically any material. Importantly, an electromagnetic field can be attached to such a user-built element [3-5]. With a model, including all elements from the splitter to the target, BDSIM simulation delivers a better description of the beam along the complete line, for example, beam profiles at certain places, beam transmission through a degrader, power deposit on a component, as well as energy spectrum upon reaching the target. This is of importance not only for present operation, but also for further development.

SIMULATION

Electrostatic Field Analysis

The electrostatic field of the beam splitter is simulated with the program ANSYS. Figure 1 shows a quarter of the geometrical model of the splitter, as it is symmetrical about both horizontal and vertical middle planes. The septum consists of 117 tungsten strips 0.05 mm thick and 2 mm wide. The strips are tensioned onto a C-shaped structure with a 4-mm distance between the neighbouring strips, which gives a total length of 698 mm along the beam direction.

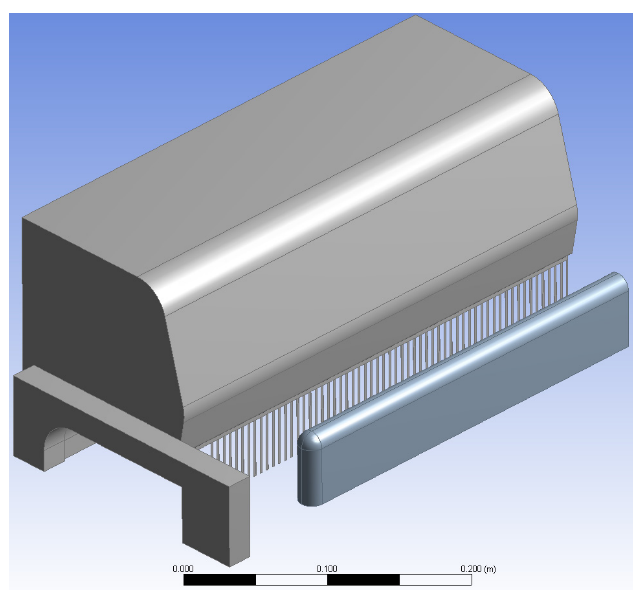

Figure 1: Geometrical model of beam splitter.

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CONCEPTUAL DESIGN OF CENTRAL REGION FOR HIGH-TEMPERATURE SUPERCONDUCTING SKELETON CYCLOTRON (HTS-SC)

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Abstract

A compact high-current accelerator is highly desirable for short and effective Boron Neutron Capture Therapy (BNCT) as well as radioisotopes production in a hospital environment. In accordance with this, a compact high-temperature superconducting skeleton cyclotron (HTS-SC) was proposed. HTS-SC is an air-core K-80 cyclotron with a relatively small extraction radius of 40 cm for a 50 MeV H^+ and 40 MeV D^+ beam. Owing to its compactness, a relatively high central magnetic field (>2.4 T) remains as a significant challenge for high current injection. This work describes a preliminary study of the injection using a spiral inflector and the central region design of the HTS-SC. Besides, the transverse beam dynamics are also discussed in order to investigate the upper limit of injection current.

INTRODUCTION

Since the first cyclotron developed by E.O. Lawrence and M. S. Livingston [1], it has been widely applied in various scientific researches and applications. In accordance with the advancement of high-temperature superconducting (HTS) tapes since these decades, the performance of a HTS cyclotron had also improved greatly to be more compact and efficient in producing high-energy or high-intensity beam with a lower power consumption. Following this trend, many works around the world have adopted HTS cyclotrons in various medical applications. However, most of them are relatively bulkier and of low-intensity (<100 μA), as they are mostly used to produce radioisotopes [2, 3]. In order to improve the versatility of HTS cyclotrons for direct therapeutic applications such as particle therapy or BNCT, beams of higher intensity are necessary. Therefore, this work wishes to propose a HTS skeleton cyclotron (HTS-SC) to produce a high-intensity beam for the previously proposed accelerator-based multi-port BNCT (AB-mBNCT) system, which can deliver multiple treatments at the same time [4], as well as the production of medical radioisotopes. Figure 1 shows the schematic of the applications of HTS-SC.

The proposed HTS-SC is an air-core (i.e. meaning of "skeleton") K-80 cyclotron with a small extraction radius of 40 cm for multiple-ion beams. It consists of 3 sector coils (SC) with a maximum spiral angle of 40°, 1 circular main coil (MC) of 60 cm radius and 7 small trim coils (TC) of radius varying from 5 cm to 45 cm. Owing to its compactness, a relatively high central magnetic field of about 2.4 T is required for a 50 MeV H+ beam. The radio frequency system consists of two 90° Dee locating directly opposite to each other, presently operating at a frequency from 34.5 MHz to 75 MHz with a maximum voltage of about 80 kV. Besides, an external injection system is required for the proposed HTS-SC in order to produce a high-intensity beam. As a part of the study of HTS-SC, this work will discuss about the conceptual design of its central region and its corresponding injection using a spiral inflector. As the space-charge effect is very important for a high-intensity beam at low energy, the transverse beam dynamics from the entrance of the inflector until several tenths of turns in the cyclotron are also discussed in order to investigate the upper limit of the injection current.

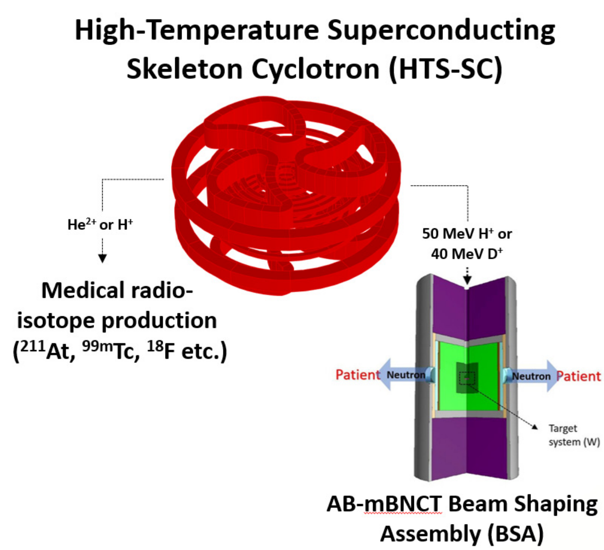

Figure 1: Schematic of the proposed HTS-SC and its application for AB-mBNCT as well as radioisotope production.

MATERIAL AND METHOD

Magnetic Field Distribution

The magnetic field distribution was calculated using the finite element magnetostatic (FEM) code TOSCA. The isochronous field is first estimated using Eq. (1).

$$< B(\overline{r}) > = \frac{B_0}{\sqrt{1-\beta(\overline{r})^2}} \quad (1)$$

After that, a better isochronous field was optimized by utilizing the orbital frequency obtained from OPAL (Object Oriented Parallel Accelerator Library) code developed by PSI [5]. The radial dependence of average magnetic field after optimization of isochronism is shown in Fig. 2.

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PRECISE MODELLING AND LARGE SCALE MULTIOBJECTIVE OPTIMIZATION OF CYCLOTRONS

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SYNOPSIS

This contribution gives a summary of an invited presentation delivered at this conference.

The usage of numerical models to study the evolution of particle beams is an essential step in the design process of particle accelerators. However, uncertainties of input quantities such as beam energy and magnetic field lead to simulation results that do not fully agree with measurements. Hence the machine will behave differently compared to the simulations. In case of cyclotrons such discrepancies affect the overall turn pattern or alter the number of turns. Inaccuracies at the PSI Ring cyclotron that may harm the isochronicity are compensated by 18 trim coils. Trim coils are often absent in simulations or their implementation is simplistic. A realistic trim coil model within the simulation framework OPAL has been investigated. It was used to match the turn pattern of the PSI Ring (see Fig. 1). Due to the high-dimensional search space consisting of 48 simulation input parameters and 182 objectives (i.e. turns) simulation and measurement cannot be matched in a straightforward manner. Instead, an evolutionary multi-objective optimisation with more than 8000 simulations per iteration together with a local search approach was applied that reduced the maximum error to 4.5 mm over all 182 turns (see Table 1 and Figs. 2 and 3).

The results of this study have recently been published in their entirety in [1], to which the reader is further referred.

Table 1: Maximum absolute error (l_∞-norm), mean absolute error (MAE) and the mean squared error (MSE) of the best individual of the optimizer and local search compared to the measurement. In both cases the maximum error is at turn 2.

Method	**l_∞-norm** (mm)	**MAE** (mm)	**MSE** (mm^2)
optimizer	6.4	2.0	6.3
local search	4.5	1.4	3.4

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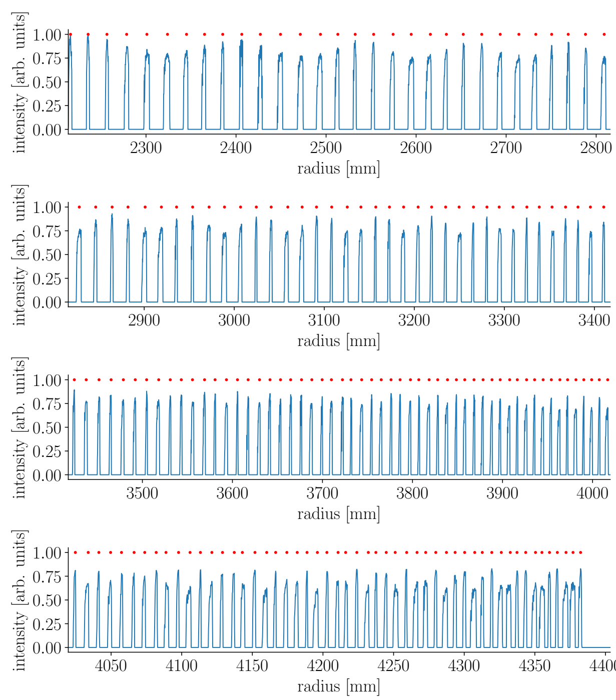

Figure 1: Histogram of the probe RRL measurement. The intensity is normalized. The red dots mark detected peaks.

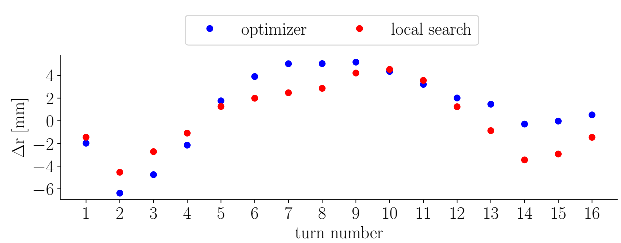

Figure 2: Error of the turn radius at RRI2 between measurement and simulation of the best individual obtained by multi-objective optimization and local search.

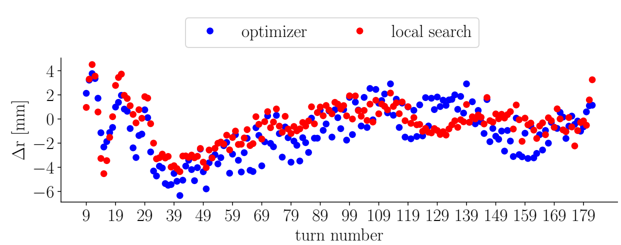

Figure 3: Error of the turn radius at RRL between measurement and simulation of the best individual obtained by multi-objective optimization and local search.

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REACT AUTOMATION STUDIO: A NEW FACE TO CONTROL LARGE SCIENTIFIC EQUIPMENT

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Abstract

A new software platform to enable the control of large scientific equipment through EPICS has been designed. The system implements a modern tool chain with a React front-end and a PyEpics back-end as a progressive web application. This enables efficient and responsive cross platform and cross device operation. A general overview of React Automation Studio as well as the system architecture, implementation at iThemba LABS, community involvement and future plans for the system is presented.

INTRODUCTION

Mobile phone and tablet technology have driven the need for cross platform and cross device applications that deliver an instantaneous user experience.

We were eager to be a part of this technical revolution, yet the tools available to us in the EPICS [1] open source community could not enable us to develop mobile based user interfaces (UI) for EPICS.

Having upgraded many of our systems to EPICS [1–4, 6] control and having developed several state-of-the-art EPICS-EtherCAT [1–3, 6, 7] control systems with Control Systems Studio (CS-Studio) [2, 3, 5, 6] operator UIs, we were poised with the problem of converting the remaining software systems for the rest of the facility to a similar standard.

We chose however to first investigate an alternative that involved creating a progressive web application (PWA) [8] framework for EPICS. The fruits of this investigation have led to the first release of a software framework to allow real-time, cross platform and cross device responsive UI creation for EPICS. This framework has been called React Automation Studio.

A general overview of React Automation Studio as well as the system architecture, implementation at iThemba LABS, community involvement and future plans for the system is presented in the sections below.

SYSTEM REQUIREMENTS

The goal of this first release was to a develop a containerised system consisting of a back-end to serve EPICS variables to a PWA front-end that could run cross platform and cross device.

For the back-end it was critical to incorporate user authentication and authorisation, whilst ensuring that it would not be necessary to manually declare process variables that needed to be served to the client. In other words the client must request the variables needed, and the back-end server should dynamically connect and relay the process variable meta and live data to the client.

For the client, the goal was to place a data connection wrapper on freely available React components and to build in the features for macro replacement of variable and system names. This was to allow for the creation of reusable operator interfaces to implement alarm handling and to add in diagnostic ability such as a probe interface where further information about the process variable is displayed.

Finally, the system should be sufficiently documented with use cases, examples and a front-end implementation guide.

Each of the goals have been achieved and the system overview is given below.

SYSTEM OVERVIEW

React Automation Studio has been containerised with Docker [9] and version controlled as a mono-repository using Git [10].

Each of the Docker containers are deployed as micro services and environment variables can be configured to deploy the system on different ports, to enable user authentication and authorisation or to serve the application on a unique URL or on the localhost. Separate Docker commands exist to load the development and production versions. These containerised environments allow for the precise versioning of packages used and prevents deployment dependency issues.

The software stack for React Automation Studio is shown in Fig. 1 and an overview of the system components are outlined below:

pvServer

We needed to develop a back-end server to relay the process variable (PV) data to the client. We initially evaluated a JavaScript back-end using a JavaScript EPICS channel access (CA) module, but we found the support and development to be limited and it also faced stability issues.

The chosen alternative is a Python [11] back-end which uses the well supported and well maintained PyEpics [12] CA module.

The resulting micro-service is the Python process variable server (pvServer). It is layered on the Flask [13] and Flask-Socket-IO [14] web application frameworks to serve the EPICS process variables to clients.

Communication between clients and the pvServer occurs between the data connection wrapper in the client components and the pvServer as follows:

The client initially makes a Socket-IO [15] connection to the pvServer. Depending on whether or not authentication is enabled the client will first be authenticated, and then the data connection wrapper will emit Socket-IO events to the pvServer requesting access to the EPICS variable.

Depending on the clients access rights, access is either denied or the socket connection is placed in a Socket-IO room

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REVIEW OF HIGH POWER CYCLOTRONS AND THEIR APPLICATIONS

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Abstract

An incomplete review of existing machines and of present new projects of high power cyclotrons is here presented. Both high energy and low/medium energy cyclotrons will be described. Specific requests for different fields of applications are also discussed.

INTRODUCTION

It is from the early years of the Eighties that the cyclotron community has proposed challenging cyclotrons to produce intense beams of kaons, antiprotons, neutrinos and other particles [1, 2] or to be used to drive subcritical reactors [3]. Unfortunately, up to now the cyclotron community was not able to get funds for none of these projects intended to surpass the performances of the TRIUMF and PSI cyclotrons. The main technical problems related to the construction of these projects are here discussed. Fortunately, the creativity of our community is again alive and new projects and ideas flourished.

HIGH INTENSITY LOW-MEDIUM ENERGY CYCLOTRONS

Low energy cyclotrons (15-30 MeV) are mainly used to produce radioisotopes, producing beams with intensity in the range 0.1-1 mA. But in the latest years the 30 MeV cyclotrons have also been used to drive BNCT facilities [4], and the perspective is towards increasing of this application, whose request is a beam current increase up to 2 mA or more.

The 70 MeV cyclotrons, supplied by IBA and BEST companies, are mainly used for the production of medical radioisotopes and their declared maximum intensity is about 1 mA. The wide range of energy of extracted beams varying from 35-70 MeV with the possibility to deliver two beams simultaneously make this kind of accelerator very flexible in use and particularly suitable to be employed as driver for multipurpose facilities. The SPES facility at LNL (Italy) [5] has already carried out the commissioning of the C70 cyclotron which will provide high power beams for nuclear research and radioisotopes R&D and in next future both RISP (Daejeon, Korea) [6] and iThemba (Cape Town, South Africa) laboratories will be equipped with cyclotrons with such performances.

The above energy range and current are appropriate to produce radioisotopes but an increase in the beam current would allow to increase the production rate for the present medical isotopes and also could open the opportunity to produce radioisotopes with small production cross sections or long half-lives.

The perspective to produce the ^{68}Ge/^{68}Ga generator for imaging diagnostic, through the reactions ^{71}Ga(p,4n)^{68}Ge and ^{69}Ga(p,2n)^{68}Ge, is very appealing to replace the usual ^{99}Mo/^{99m}Tc generator. Indeed, the half-life of the ^{68}Ge parent is of about 270 days while the lifetime of ^{99}Mo is only of 66 hours. Moreover, the half-life of the ^{68}Ga is just 68 minutes versus the 6 hours of the ^{99m}Tc.

Another interesting new radioisotope is ^{225}Ac, produced through the reaction ^{226}Ra(p,2n)^{225}Ac. This is a four alpha particles emitter and it is a wonderful tool for targeted radiotherapy. To produce efficiently this radioisotope it is convenient to use a proton beam with energy higher than 50 MeV and current in excess of 3-5 mA. This trend is confirmed by the new project TR100 [7] and by the interest of PSI to develop a dedicated beam line to the radionuclide production [8].

Another viable way to produce ^{225}Ac is bombarding Thorium target with a proton beam of about 450 MeV, as recently tested at TRIUMF [9].

Bombarding ^{232}Th by a proton beam with energy higher than 50 MeV is also a way to produce ^{213}Bi, another radioisotope that decays producing four alpha, also this is very appealing for radiotherapy.

An alternative production method to produce ^{213}Bi is through the reaction α+^{232}Th as presently investigated at GANIL [10]. Bombarding ^{232}Th with alpha particles allows to produce many different alpha emitters like ^{212}Pb, ^{213}Bi, ^{225}Ra, ^{225}Ac. The energy of the alpha beam must be higher than 50 MeV. These energies and the high current for α beam are not achievable with the present commercial cyclotrons but are in the energy range of the proposed IsoDAR cyclotron [11].

THE ISODAR CYCLOTRON

The IsoDAR compact cyclotron will be able to deliver up to 5 mA of H_2^+ beam with a maximum energy of 60 MeV/amu [11]. This cyclotron was designed to drive the experiment for sterile neutrino research [12] and as first stage of the cascade cyclotrons to perform the DAEδALUS experiment [13]. This cyclotron could also be used to accelerate He beam up to 240 MeV with intensity of about 1 mA (120 kW of beam power). The possible use of the IsoDAR cyclotron to produce huge amounts of medical radioisotopes for diagnostic and therapy, using both the high intensity proton beam and the He beam, are well described in a recent paper [14].

The large pole diameter of IsoDAR and the use of 4 RF cavities allow to extract the beam with high efficiency using the electrostatic deflector. For the extraction of protons also the stripping of H_2^+ molecule can be used. The feasibility to use a stripper foil with an intensity of 1.7 mA was tested with the 72 MeV proton beam at PSI [15].

The most serious problem to accelerate the high current beam is related to injection. The relatively low velocity and

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PRODUCTION OF 70 MeV PROTON BEAM IN A SUPERCONDUCTING CYCLOTRON

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Abstract

Production of 70 MeV proton beams with help of a cyclotron-type facility is one of highly requested tasks presently. Such beams are used for medical applications including direct tumor irradiation and also for production of medical isotopes. The applications mentioned above dictate corresponding requirements imposed on the beam quality and intensity. For proton therapy treatment it is sufficient to have 300 to 600 nA output beam current with rather strict tolerance on the transverse beam quality. On the other hand, for the isotope production the major requirement is high enough beam intensity (hundreds μA) with less demanding beam quality. Nowadays, for production of the proton beams in the energy range considered cyclotrons with resistive coil weighting ~140 to 200 t are mostly used. In these cyclotrons two extraction methods – with electrostatic deflector and with stripping foils – can provide somewhat different quality of the output beam. In given report a possibility of using a superconducting cyclotron instead of room-temperature one is considered. To this end, acceleration of various ions was investigated with analysis of the main facility parameters and resulting output beams.

INTRODUCTION

Nowadays, the majority of cyclotrons intended for production of proton beams with energy about 70 MeV have rather low magnetic field in range of 1 to1.4 T [1-2]. As a result, the facility has footprint of 4 to 6 m and weight above 140 t. Application of higher level of magnetic field for such machines based on superconductive technology permits designing of accelerator with substantially lower size and weight. But application of high magnetic fields introduces some limitations in the cyclotron design. For example, acceleration of H^- ions in the selected energy range becomes practically impossible in high magnetic field due to massive particle losses by Lorentz stripping. On contrary, in room-temperature machines acceleration of H^- ions are widely used that provides a highly effective particle extraction near 100% by stripping foils with a possibility of some energy variation of the output beam. So, in the superconducting cyclotrons either protons or H_2^+ ions can be used for acceleration. The latter has a strong enough coupling of outside electron with the nucleon to stay stable even in considered high magnetic field of the facility. In case of protons an application of an electrostatic deflector for particles extraction leads to somewhat lower extraction efficiency and fixed energy of the output beam. On the other hand, for extraction of accelerated H_2^+ ions a stripping foil can be used. This will increase the output proton beam intensity twice compared to the internal H_2^+ beam current: each H_2^+ ion generates 2 protons downstream the stripping foil. The price in this case would be essentially bigger size of the facility compared to the cyclotron for proton acceleration with the same central magnetic field.

The goal of present work is investigation of various variants of superconducting cyclotrons for production of proton with output energy about 70 MeV in terms of their main technical parameters and extracted beam characteristics. Comparison of obtained parameters with that for existing commercial cyclotrons is also included. The highly realistic computer modelling of the proposed accelerators was performed with usage of spatial distributions of the facility electromagnetic fields and careful beam dynamics analysis.

PROTON CYCLOTRON

The 70 MeV cyclotron for acceleration of ions with charge to mass ratio 1 has K-value 70 MeV. So, in the paper we adopt K70 as a name for the machine. For protons the main limitation for the magnetic field level relates to the possibility of the practical realization of the machine central region. Calculations show that for magnetic field above 2.9 T it will be highly problematic to design the required center structure since it is almost impossible to install the spiral inflector infrastructure in the region: there is no room for potential connections to the inflector electrodes. The inflector diameter together with its RF shield is less than 25 mm for 2.9 T central magnetic field. The cyclotron magnetic system has 4-fold structure based on spiral sectors (Fig. 1). The valley axial gap 450 mm permits placement of 2 spiral RF cavities operating on the 2nd harmonic with frequency 88 MHz. The peak dee voltage of 30 kV is limited by consumption power in the system. The axial gap between the sectors reduces from 30 mm in the central region to 22 mm at the final radius. Parameters of the superconducting coil and required space around it for placement of the cryostat were selected looking at similar configurations of the successfully operating cyclotrons. The engineering current density in the coil is 75 A/mm^2 as result of this approach. The obtained eventually magnetic field distribution provides a sufficient axial focusing of the beam with axial betatron frequency being above 0.2 in the whole radial range (but the very center). The resulting diameter of the cyclotron is less than 2 m and its weight ~18 t.

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CONCEPTUAL DESIGN OF TR100+: AN INNOVATIVE SUPERCONDUCTING CYCLOTRON FOR COMMERCIAL ISOTOPES PRODUCTION*

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Abstract

Utilizing dedicated cyclotrons to produce medical isotopes is an arising technology in hospitals across Canada. An excellent example is that in Jan. 2015, the CycloMed99 team, led by TRIUMF, demonstrated a breakthrough in producing the world's most highly used medical isotope, Tc-99 m, on existing medical cyclotrons. Now we propose to design an innovative H_2^+ superconducting cyclotron TR100+ for the production of commercially valuable radioisotopes. This project will be aiming at proton energy of 70 – 150 MeV and proton current of ~800 µA, since (i) cyclotron in this energy range is not developed world-wide; (ii) in this energy range numerous highly interested and increasingly demanded radionuclides can be produced, e.g. Sr-82 and Ac-225. Our machine shall be designed to accelerate H_2^+, by injection from external ion source and extraction by stripping. This shall allow to extract proton beam of variable energies with very high extraction efficiency, thus allow to reduce activation caused by beam losses. The basic parameters of our machine and simulations of stripping extraction will be presented in this paper.

OVERVIEW

There are two main types of commercial medical cyclotrons [1]: (i) those for medical isotope production, and (ii) those for proton therapy. The former are typically high-current low-energy (1 mA, 7 – 30 MeV) H^- machines, while the latter are low-current high-energy (1 µA, 200 – 400 MeV) proton machines. There are several well-established vendors [1] in each of these markets: ACSI, GE, Varian, IBA, Siemens, Sumitomo and Still River; and emerging players such as BEST and CIAE (China). From this overview it becomes apparent that 7 – 30 MeV and 200 – 250 MeV medical cyclotrons are well covered in the market by multiple strong players.

However, contrastingly, the 70 – 150 MeV range is not well represented; there being only few outliers at 70 and 100 MeV: the Best Cyclotrons 70P (in Legnaro, Italy) [2], the IBA C70 (in Nantes, France) [3], and CYCIAE-100 in Beijing [4]. All these are accelerating H^- to extract protons by stripping, in which a dominant factor limiting the beam intensity is the beam losses due to the electromagnetic stripping of the second electron during acceleration. To reduce activation of the accelerator system, caused by the resulting beam spills, the losses have to be kept low. This requires the magnetic field to be lower, the higher the machine energy, which in turn leads to the larger magnet size. Since the cost of the cyclotron rises with magnet size, the commercial H^- cyclotron balances acceptable losses versus size, ending up at a compromised energy of ~70 MeV [5].

Another option is to use protons directly, without stripping. But this extraction method requires well separated turns, which is achieved with a large radius of the machine and a high accelerating voltage, making the cyclotron very expensive. Proton machines for the therapy (up to ~1 µA extraction) can hardly reach an extraction efficiency above 80% [6, 7]. If they were for high current, they would not be able to run, because too much beam would get lost at extraction, exacerbating the neutron production and machine activation problem.

To overcome these limitations and reliably deliver high current (≥500 µA) proton beam on target, we intend to accelerate H_2^+, two protons bound by a single electron, with a binding energy much larger than the H^- case. This implies that a much higher magnetic field can be used in a compact cyclotron with significantly reduced magnet size and consequently lower costs.

In this energy range up to 150 MeV, numerous highly interested and increasingly demanded radio-nuclides can be produced, either as parent nuclei for generator use, or directly as an active pharmaceutical ingredient. For example, the two isotopes Actinium-225 and Bismuth-213 are anticipated to drive radiopharmaceutical developments for the researches of cancers (Melanoma, Prostate and Pancreatic) conducted at BCCA in Canada, and to expand in the world leading radionuclide imaging program. Another example, the isotope Strontium-82 (Sr-82) is used exclusively to manufacture the generators of Rubidium-82, which is the most convenient Position Emission Tomography (PET) agent in myocardial perfusion imaging. Over the last years, the demand for the Sr-82 from pharmaceutical industry has been growing, and such a demand is anticipated to continue to grow for the next 20 years. Other commercially relevant medical isotopes that can be produced from proton beams in the energy range 70 – 150 MeV include At-211, Ti-45 and Ra-223. With additional development, access to isotopes such as Ra-224, Pb-212 and Bi-212 will be possible. To date, virtually all Sr-82 is produced at large research facilities which are primarily used for scientific researches, and in most cases is partially subsidized. Using dedicated cyclotrons to produce medical isotopes is an arising technology in hospitals across the world.

Commercial superconducting (SC) cyclotrons are becoming ever more compact due to the introduction of successive

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DEVELOPMENT OF A TRANSPARENT PROFILER BASED ON SECONDARY ELECTRONS EMISSION FOR CHARGED PARTICLE BEAMS

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Abstract

The PEPITES[1] project aims at realizing an operational prototype of an ultra-thin, radiation-resistant profiler able to permanently operate on mid-energy (O (100 MeV)) charged particle accelerators. Initially motivated by the needs of protontherapy, the proposed development may have a range of applications that is well beyond the foreseen framework.

INTRODUCTION

Beam profiling during patient treatment in hadrontherapy requires ultra-thin monitors to preserve the high beam quality. For detectors upstream in the line, a material budget as low as ~15 µm water-equivalent is needed. Besides, the current trend of dose escalation to treat highly resistant tumors implies challenging requirements to the monitor in terms of radiation hardness and dynamic range.

To fulfil these requirements, PEPITES, a new type of transparent beam profiler (< 10 µm water-equivalent thickness (WET)) is under development. It will equip the beam line of the ARRONAX cyclotron [1] and will be used daily to monitor the beam during radiobiological and preclinical experiments [2]. The profiler will measure the lateral beam shape in a broad range of energy (15-70 MeV) and a wide range of intensity (100 fA-10 nA), for alpha, proton and deuteron particles.

PRINCIPLES

PEPITES uses secondary electron emission (SEE) for the signal as it requires only a minimal thickness of material (~10 nm); very linear, it also offers a great dynamic. The SEE yield is proportional to the dE/dx of the beam particles [3, 4] and is independent of the beam intensity up to current far beyond expected needs both for medical use and radiobiology needs. The lateral beam profile is sampled using segmented electrodes, constructed by thin film methods. Gold strips, as thin as the electrical conductivity allows (50 nm), are deposited on an as thin as possible insulating substrate which, in contrast with conventional systems like ionization chambers, are free from mechanical constraints and can be as thin as achievable. Aromatic polyimides (PI), such as Kapton® or CP1™, are chosen as polymer substrate due to their insulating properties and resistance to radiation [5]. When crossing the gold, the beam ejects the electrons by SEE, the current thus formed in each strip allows the sampling.

The thinness of the monitor disturbs very little the incident beam, which can then be delivered to the patient while keeping the profiler in the line, ensuring continuous monitoring. Also, it makes the energy deposit very small allowing the monitor to tolerate higher currents than existing systems without suffering from overheating problems. Besides, the absence of mechanical efforts on the membranes makes radiation damages of less consequence than with classical systems like ionization chambers allowing to extend the operation duration of the system.

Prototype Layout

The layout of the prototype is shown in Fig. 1. It will consist of four electrodes: two segmented cathodes each facing an anode (with a 15 mm gap) biased at 100V to ensure the collection of secondary electrons emitted by the strips. The four electrodes are made of 50 nm thick gold deposited by chemical vapor phase on polymer membranes: 32 strips for cathodes and fully metallized anodes. The membranes are made of 1.5 µm thick CP1™, a colorless polyimide developed by the NeXolve company [6]. Initially developed for solar sails, its availability in very small thickness and the presence of aromatic cycles in its structure, thus making it extremely resistant to radiation, make it an element of choice for the construction of the detector.

The profiler is divided into two mechanically independent blocks for the measurements of the beam position and lateral shape in the two directions (X and Y). The signals from the strips can be rather low as resulting from SEE (about 10% yield) and spreading of the beam over the strips. A dedicated low-noise Application Specific Integrated Circuit (ASIC) chip being developed at CEA

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SHE FACTORY: CYCLOTRON FACILITY FOR SUPER HEAVY ELEMENTS RESEARCH

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Abstract

The synthesis of heavy and the heaviest elements and the study of their nuclear and chemical properties are of highest priority in the basic research programme of the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research in Dubna (FLNR JINR). The synthesis of super heavy elements (SHE) with atomic numbers 113-118 has been achieved in the ^{48}Ca-induced reactions. The seventh period of the Periodic Table has been completed. In accordance with the development program, the first in the world SHE Factory was built at the Laboratory on the basis of the new DC280 cyclotron which was commissioned in 2019. DC280 has to provide intensities up to 10 pμA for ions with atomic masses over 50. The main task of the Factory is the synthesis of new chemical elements with atomic numbers 119 and higher, as well as a detailed study of the nuclear and chemical properties of previously discovered super heavy elements. The Factory are being equipped with target materials, new separators and detectors for the study of the nuclear, atomic and chemical properties of the new elements.

INTRODUCTION

Since 1998 priority experiments on synthesis of new superheavy elements (SHE) with atomic numbers of 114-118 in reactions of ^{48}Ca ions with actinide targets (^{242,244}Pu, ^{243}Am, ^{245,248}Cm, ^{249}Bk, ^{249}Cf) have been carried out at the FLNR JINR on the U400 accelerating complex. Over 50 new isotopes of elements 104 to 118 with maximum neutron excess were for the first time produced and their decay properties were determined in these investigations. The International Unions of pure and applied physics (IUPAP) and chemistry (IUPAC) recognized the priority of Dubna in the discovery of elements 114-118. The seventh period of the Periodic Table has been completed. The discovery of the new domain (island) of stability and the very fact of existence of SHE have posed a number of new questions associated with fundamental properties of nuclear matter. Can even heavier nuclei exist? Is the “Island of Stability” of SHE the last one on the Chart of the Nuclides? Can the superheavy nuclei be formed in the process of nucleosynthesis like those stable and long-lived nuclei in the groups of Pt, Pb, and U-Th found in Nature? What is the limit of Mendeleev’s Table? How much are the chemical properties of SHE similar to those of their lighter homologues? Direct synthesis of elements with Z > 118 in fusion reactions means using projectiles heavier than Ca, since the capability of high-flux reactors to produce target material is limited to Cf isotopes. It is expected that production cross sections of nuclei with Z = 120 in the reaction ^{54}Cr+^{248}Cm and nuclei with Z = 119 via ^{50}Ti+^{249}Bk will be about ten times lower than those of production of ^{294}Og in experiments with ^{48}Ca. For more detailed studying nuclear - physical and chemical properties of SHE it is necessary significantly increasing efficiency of experiments [1]. For the solution of this task the first in the world Factory of superheavy elements (SHE Factory) was created at the FLNR JINR in 2019.

Figure 1: Building of SHE Factory.

SHE FACTORY

Creation of the SHE Factory was associated with developing the FLNR experimental basis in several directions. These directions are:

- creation of the new powerful accelerator of stable and long-living isotopes with mass range A = 4-238 with intensity up to 10 pμA for A ≤ 50 and energy up to 8 MeV/nucleon;
- construction of a new experimental building and infrastructure for placing the accelerator with five channels for transportation of beams to 3 experimental halls (total area up to 1000 m^2), equipped with systems of shielding and control matching the class two of operations with radioactive materials;
- development of new separating channels, development of new detection modules for the study of nuclear, atomic, and chemical properties of new elements;
- production of new target materials and development of techniques of making targets with high thermal and radiation stability;
- development of a base for research with intense ion beam in related fields of science and technology.

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FIRST BEAMS PRODUCED BY THE TEXAS A&M UNIVERSITY RADIOACTIVE-BEAM UPGRADE*

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Abstract

The first test beams of radioactive ions produced by the ion-guide-on-line (IGOL) system coupled to an electron-cyclotron-resonance ion source for charge-breeding (CB-ECRIS) have been accelerated to high energy by the Texas A&M K500 cyclotron. The radioactive ions were produced by energetic protons, provided by the K150 cyclotron, impinging on foil targets. Low charge-state ions were then swept by a flow of helium gas into an rf-only sextupole ion-guide (SPIG) which transported them into the plasma of the CB-ECRIS. The K500 cyclotron and beam-line transport were tuned with analog beam before tuning the radioactive beam.

INTRODUCTION

Reference [1] gives a complete description of the Texas A&M upgrade. As part of the upgrade the K150 cyclotron has been re-commissioned to use as a driver for the production of radioactive ions. The method is to first stop radioactive products from beam-target collisions and transport them as low-charge-state ions using the IGOL technique. This technique was pioneered and continues to be developed at the University of Jyväskylä Cyclotron Laboratory [2]. Using this technique, a light-ion guide (LIG) is being developed where reaction products result from energetic, light-ion beams (p, d, ^{3}He, or α) impinging on a foil target. These products remain as 1+ ions and can be injected into CB-ECRIS for charge-breeding to higher charge states. A low-energy beam of ions of one selected high charge-state is then transported to the K500 superconducting cyclotron for acceleration to high energy. Figure 1 illustrates the scheme where protons and deuterons result from stripped accelerated negative ions. The high-energy radioactive beam is transported from the K500 to a detector station for analysis. Eventually the radioactive beams will be used for experiments.

LIGHT ION GUIDE AND SPIG

For LIG an energetic beam of light ions impinges on a thin foil target to produce radioactive products (via (p, n) for example) that then exit the target to encounter a rapid flow of helium gas. The products are mainly in the ionized state, and in the helium this ionization is reduced to the 1+ charge-state, taking advantage of the unfavorable energetics of neutralization of 1+ heavy ions colliding with neutral helium. The flow of helium through the target cell ushers the 1+ ions through an orifice into a highly pumped region where a large fraction of the helium is pumped away. Originally the ions were guided by a small electric field through an aperture in a skimmer electrode after which they could be accelerated to form a low energy (~10 kV) beam.

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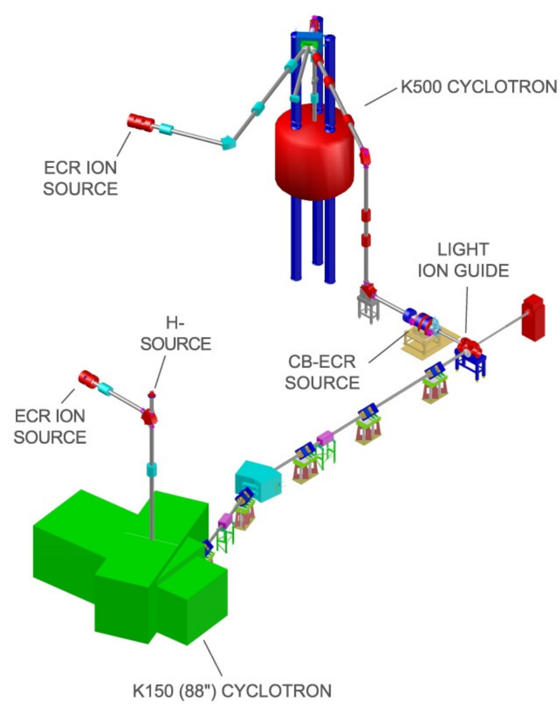

Figure 1: Simplified layout of the Texas A&M light-ion-guide scheme.

One disadvantage of the skimmer is that the ions can encounter a significant pressure of helium in the acceleration region which introduces an energy spread in the beam. In order to counter this, a system was introduced where before acceleration the thermalized ions travel along a SPIG through a sequence of pumping baffles before being accelerated [3]. References [4, 5] detail the development of the SPIG which consists of a parallel array, usually sextupolar, of conducting rods or vanes with low-power, high-frequency rf impressed. The rods are alternately phased by 180° so that rf fields of parabolically increasing intensity are set up in the interior of the sextupole. Ions travel through the channel between the rods contained by the rf fields while a larger fraction of the helium is pumped away. In reference 3 it is shown that ions accelerated by some initial voltage of several

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DESIGN OF ACCELERATOR MASS SPECTROMETER BASED ON CYCLOTRON

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Abstract

In this paper, we present a cyclotron accelerator mass spectrometry system based on artificial intelligence. Cyclotron based AMS system are consist of cyclotron, ion source, RF buncher, dipole magnet and triplet quadrupole, detector. This Cyclotron based AMS system optimized the detection efficiency of 14C$^-$ particles through artificial intelligence algorithms. Cyclotron was designed with a mass resolution of 5000, AVF electromagnet with 4 sectors. RF system was designed as RLC circuit consisting of Dee of which angle is 20 degrees. The stripping method was used of extraction. The ion source of AMS uses Cs sputtering source with Einzel lens and RF buncher. In this system, AI algorithm is applied to the detection and analysis algorithm through artificial neural network development to overcome the mass resolution time and precision by 14C$^-$ sample number. The AMS has been designed and detailed hardware production is underway, and the system will be integrated in 2020 to carry out the mass decomposition experiment.

INTRODUCTION

In accelerator mass spectrometry, tandem accelerator is mainly used. Sungkyunkwan University developed cyclotron-based AMS cyclotron see Fig. 1. The advantage of the cyclotron-based AMS system is reducing the size and cost of the entire system. because cyclotron itself acts to separate the particles [1].

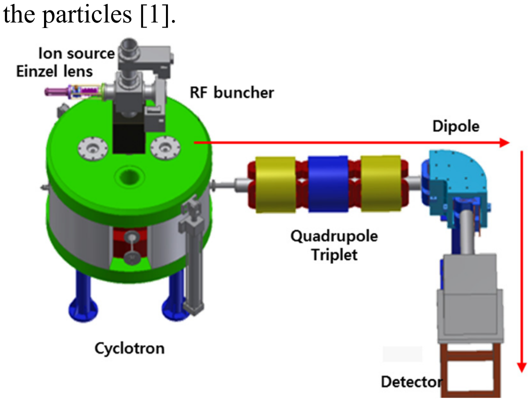

Figure 1: 3D drawings of Accelerator Mass Spectrometry based on cyclotron.

The tandem type accelerator is an electrostatic type, and the finally discharged particles are DC type. In the case of cyclotron, the electric field of RF emits the emissive particles in AC form. So Relatively fewer samples than static AMS. To solve this problem, we add artificial intelligence to increase the accuracy of the analysis.

The 3D drawing of cyclotron for AMS is shown in Fig. 2 and specification table of AMS cyclotron is shown as Table 1. This cyclotron is for accelerating carbon-14 beam.

DESIGN AND SYSTEM DESCRIPTION

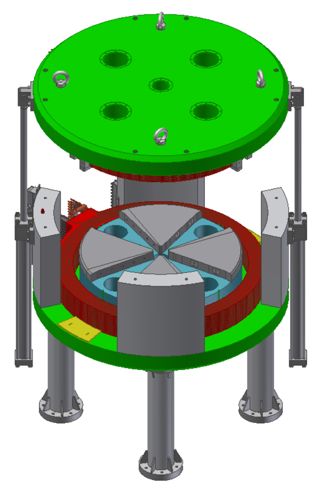

Figure 2: 3D drawings of cyclotron for AMS.

Table 1: AMS Cyclotron Magnet Specification

Parameter	Value
Maximum energy	200 keV
Beam species	Carbon-14 negative
Ion source	Cs sputtering
Number of sectors	4
Hill angle	60°
Valley angle	40°
Pole radius	0.510 m
Extraction radius	0.453 m
Hill / Valley gap	0.25
Harmonic number	10
Radio frequency	5.8 MHz
Radial tune	~ 1.01
Vertical tune	0.4
B-field (min., max.)	0.137, 0.687 T

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3D PRINTING FOR HIGH VACUUM APPLICATIONS

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Abstract

The 3D printing technology has made the leap from a home-based private practice to industrial manufacturing. Due to the increasing reliability of printers and increasing material diversity, especially in the metal sector, double-digit percentage growth rates are possible in the future.

This thesis deals with the manufacturing of parts made by 3D printing for high vacuum application. Different components are printed and examined for their vacuum compatibility.

As shown furthermore, conventionally made standard components can be vacuum tight welded to printed parts. This enables a cost-effective production with more complex components, such as a vacuum chamber. In addition, functional components can already be realized in the manufacturing process. The integration of a system of flow channels directly into the wall of a chamber is just one example. Thus, such a chamber can be heated during evacuation and effectively cooled in later operation.

INTRODUCTION

There is almost nothing left today that cannot be created by 3D printers. This doesn't only apply to the private sector, but increasingly also to the industrial environment.

The reason for this is the growing reliability of the process. Industrial 3D printers are fully automated machines that today can produce more cheaply, more reliably, and faster. Table 1 shows growth rates of 13 - 23% per year, with a market volume of 22.5 billion euros in 2030 [1].

Table 1: Compound Annual Growth Rate

Business	CAGR until 2030	Market Vol. 2015 in Billion €	Market Vol. 2030 in Billion €
Aerospace	23%	0.43	9.59
Medicine	23%	0.26	5.59
Automotive	15%	0.34	2.61
Industry	14%	0.44	2.98
Retail Trade	13%	0.30	1.89

Advantages of 3D printing

The 3D printing technology allows a lot of freedom in the design. In addition, the geometry of the component can be optimized so that a significant weight saving is possible and the part still meets the requirements of the strength. This topology optimization leads to a lightweight design of the parts, which is particularly important in the aerospace industry. In addition, compared to the milling out of the solid, a significant material savings is achieved here because no superfluous material (with the exception of any support structures) must be removed and and nearly no waste material is produced during production.

Since no moldings and other tools are necessary for the production of 3D printed components, there are no further costs. Another advantage results from the possibility of adding hollow and lattice structures, which can be used for the integration of a cooling system.

The fact that, apart from plastic, more and more materials are available, especially metals such as stainless steel, aluminum, titanium or similar and open new areas of application for 3D printing. Thus, in the present thesis, the application of this method in vacuum technology is examined.

Vacuums

When talking about vacuum technology, one has to specify the term vacuum more precisely (e.g., Fig. 1) because the different pressure ranges [2] place different demands on equipment and materials.

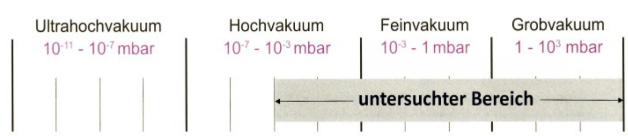

Figure 1: Pressure ranges.

This work is limited to the area of high vacuum. The limitation is due to the simple handling of the components and the existing pumping station, with which a minimum of 10^{-5} mbar is not undercut.

PRINTING OF THE COMPONENTS

LaserCUSING

The components investigated in this thesis were made of stainless steel 1.4404 using the process named LaserCUSING® patented by Concept Laser.

LaserCUSING® is an additive process in which components based on CAD data are produced layer by layer from the finest metal powder. The powdered metal is directly melted by a laser, which moves off the component cross-section. As a result of the subsequent cooling, the material solidifies. After a layer has been produced in this way, the building platform is lowered, a new layer of powder is applied and generated analogously to the next component cross-section. The structure of the part thus takes place layer by layer with a layer thickness of 15-500 microns.

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PHYSICS AND TECHNOLOGY OF COMPACT PLASMA TRAPS*

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Abstract

ECR Ion Sources are deemed to be among the most performing ion sources feeding particle accelerators, cyclotrons in particular. Improvements of their performances strictly depend on the knowledge of plasma physics in compact magnetic traps. The paper will comment on the results obtained by the INFN-LNS team and international collaborators by means of a multi-diagnostics setup able to monitor the evolution in space and time of several plasma parameters, simultaneously with beam extraction and analysis in the LEBT, in single vs. double frequency operations, including the RF power and magnetic field scalings, and exploring regimes dominated by plasma turbulence. The results are relevant for the operations of existing ion sources and for the design of new ones. Compact magnetic traps fashioned in a similar way of ECRISs can be considered as an experimental environment by itself: we are exploring this opportunity relying to the in-plasma measurements of radionuclides lifetimes (in particular, beta-decaying elements): CosmoChronometers or nuclei involved in the s-process nucleosynthesis are among the case studies, opening new perspectives in the nuclear astrophysics field.

INTRODUCTION

This paper describes the complex setup of diagnostics tools supported and developed in the frame of INFN-LNS activities on ion sources along the years. Efforts about diagnostics for ECR Ion Sources by other groups in the world are also mentioned. Plasma diagnostics have been developed in the ECRIS community for measuring plasma density and temperatures in a space and time resolved way, thus investigating the spatial structure of the plasma and its temporal behaviour, in stable and turbulent regimes. Precise measurements of parameters are crucial to correlate plasma vs. beam properties. Also in the perspective to use ECR ion traps for studying nuclear β-decays, thus correlating eventual variation of the lifetime to the plasma properties, plasma diagnostics play a fundamental role. The relevance on R&D for new diagnostics tools in ECR ion sources is witnessed by a plenty of publications [1-11].

DIAGNOSTICS TOOLBOX AT INFN-LNS

INFN has supported along the years the efforts of LNS R&D group on plasma based ion sources in the design and implementation of advanced diagnostics techniques, under the experiments HELIOS, RDH and VESPRI and, last, in the frame of PANDORA Feasibility Study. Of the list below, it is worth mentioning the A3 technique (the X-ray pin-hole camera) that has allowed to characterize the plasma morphology and to perform space resolved spectroscopy (thus evidencing the local displacement of electrons at different energies, as well as of plasma ions highlighted by fluorescence lines emission) versus the main tuning parameters such as the pumping wave frequency and the strength of the confining magnetic field. A summary of the diagnostics tools now composing the “arsenal” (described in details in [10, 11]) available or under design/installation at INFN-LNS is here presented, grouping them in four cathegories according to ther property of the plasma that we want to measure:

A. Warm & Hot electrons Temperature
 - A1 – Continuous and characteristic X radiation E<30 keV measured by SDD detectors;
 - A2 – Hard X-rays (E>50 keV, up to hundreds keV) by large volume HpGe detectors;
 - A3 –X-rays (1<E<20 keV) pin-hole camera with high energy resolution (around 150 eV) for space resolved X-ray spectroscopy;

B. Cold Electron Temp. & Density
 - B1 – Space Resolved Optical Emission Spectroscopy (space resolution less than 100 μm and spectral resolution of about 10^{-2} nm in the range 200-900 nm;)
 - B2 – Line integrated density measurement through microwave interferometry;
 - B3 – Faraday-rotation diagnostics (horn antennas coupled to Orthomode Transducer for polarimetry);

C. Ion Temperature
 - C1 – Measurement of X-ray fluorescence lines broadening through high resolution) X-ray spectroscopy, by using doubly curved crystals coupled to polycapillars;
 - C2 – Space resolved measurements are possibile with a Polycapillar+doubly-curved-crystal+CCD (X-ray sensitive) camera in a “pin-hole method” scenario;

D. On-line Charge State Distribution (CSD)
 - D1 – Space Resolved Optical Emission Spectroscopy:
 - D2 – X-ray fluorescence lines shift through high resolution); X-ray spectroscopy (curved crystals + polycapillar);
 - D3 – Space resolved measurements: Polycapillar+doubly-curved-crystal+CCD (X-ray sensitive) camera in a “pin-hole method” scenario;

A rendered view of the several diagnostics is illustrated in Fig. 1.

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CENTRAL REGION UPGRADE FOR THE JYVÄSKYLÄ K130 CYCLOTRON

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Abstract

The Jyväskylä K130 cyclotron has been in operation for more than 25 years providing beams from H to Au with energies ranging from 1 to 80 MeV/u for nuclear physics research and applications. At the typical energies around 5 MeV/u used for the nuclear physics program the injection voltage used is about 10 kV. The low voltage limits the beam intensity especially from the 18 GHz ECRIS HIISI. To increase the beam intensities the central region of the K130 cyclotron is being upgraded by increasing the injection voltage by a factor of 2. The new central region with spiral inflectors for harmonics 1–3 has been designed. The new central region shows better transmission in simulations than the original one for all harmonics and especially for h=2 typically used for nuclear physics. The engineering design for the new central region is being done.

INTRODUCTION

The Jyväskylä K130 cyclotron [1] is a normal conducting multi-particle multi-energy accelerator that has been in operation since 1992. The cyclotron has been used for more than 160 000 hours providing beams from H to Au with energies ranging from 1 to 80 MeV/u. Currently about 3/4 of the running time is used for nuclear physics research and 1/4 for industrial applications. The main application is space electronics irradiation testing, which is done by accelerating ion beam cocktails at 9.3 Mev/u and 16.2 MeV/u [2], while the majority of the heavy ion beams for the nuclear physics program are run at energies close to 5 MeV/u.

The typical injection voltage used for nuclear physics beams is around 10 kV. Such a low voltage limits the available accelerated beam intensity due to several effects. The beams produced by electron cyclotron resonance ion sources (ECRIS) have a strong divergence due to the magnetic field of the ion source and especially when tuned for medium charge states and high intensities, also the space charge effects will limit the beam intensity available for acceleration. Also, typical normalized rms-emittance of a beam produced by modern ECRIS is about 0.1 mm mrad [3], which equates to about a geometric envelope emittance of 200 π.mm.mrad for Ar^{8+} accelerated with 10 kV injection voltage, assuming a KV-distribution. As the K130 cyclotron has an acceptance of 100 π mm mrad part of the beam is obviously lost. All of these effects can be mitigated by increasing the injection voltage. Using the recently commissioned 18 GHz ECRIS HIISI [4–6] at Jyväskylä it has been observed that produced beam intensities of medium charge states such as Ar^{8+} double as source voltage increases from 10 kV to 20 kV. Therefore, a project has been initiated to redesign and upgrade the central region of the K130 by increasing the injection voltage by a factor 2.

PLAN FOR REDESIGN

The K130 has a broad operation range by being able to accelerate particles with two 78° dees with 10–21 MHz RF at a maximum of 50 kV using harmonic modes h =1–3. Injection of beams is done axially using separate spiral inflectors for each of the three harmonic modes. The inflectors can be switched through the axial bore using an automatic changer. The inflector housing is fixed and common to all harmonic modes. Each of the harmonic modes has a fixed design orbit leading to a well-centered acceleration. The injection voltage therefore scales as

$$U_{\mathrm{inj}} = \frac{q}{2m} B_0^2 r_{\mathrm{inj}}^2, \qquad (1)$$

where q and m are the particle charge and mass, B_0 is the cyclotron magnetic flux density on axis and r_{inj} is the injection radius. The dee voltage V_{dee} scales linearly with U_{inj} for a fixed design orbit. Only slight centering errors of < 5 mm can be corrected using harmonic coils.

For the upgrade of the central region the fixed design orbits and injection radii are redefined. The original injection radii 13.1, 18.8 and 18.8 mm for harmonic modes 1, 2 and 3 respectively [7] are replaced by 18.5, 26.6 and 26.6 mm – i.e. the radii are multiplied by $\sqrt{2}$. The proportionality constant between V_{dee} and U_{inj} was halved to keep the number of turns in the accelerator almost constant. The magnetic design of the machine was left as originally designed with a 20° integrated phase slip at the central field bump and isochronous field elsewhere until the extraction.

DESIGN PROCESS

The new central region was designed using IBA tracking code AOC [8], which numerically integrates the equations of motion in static magnetic fields and RF electric fields. The 3D magnetic fields were produced using first order expansion of 2D maps measured in the end of 1980s when the cyclotron was built. The electric fields were constructed assuming that $\vec{E}(\vec{r},t) = \vec{E}'(\vec{r})\cos(t)$, where $\vec{E}'(\vec{r})$ is a static electric field computed by Vector Fields Opera [9] and imported to AOC on a set of regular grids in cylindrical coordinates.

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AN IMPROVED CONCEPT FOR SELF-EXTRACTION CYCLOTRONS

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Abstract

A study is made for an improved concept of self-extraction in low and medium energy cyclotrons to be used for production of medical isotopes. The prototype of the self-extracting cyclotron was realized around the year 2001. From this machine, currents higher than 1 mA were extracted and transported to a Pd-103 production target. However, at the higher intensities, the extraction efficiency was dropping to about 70-75%, and the extracted emittance was rather poor, leading to additional losses in the beamline. Several improvements of the original concept are proposed: i) the beam coherent oscillation (as needed for good extraction) is no longer generated with harmonic coils, but is obtained from a significant off-centring of the ion source, ii) the cyclotron magnet has perfect 2-fold symmetry, allowing the placement of two internal sources and dual extraction on two opposite hill sectors, iii) a substantial improvement of the magnetic profile of the hill sectors. Simulations show an extraction efficiency up to almost 93% and emittances at least a factor 3 lower as compared to the original design. The new magnetic design is shown, and results of beam simulation are discussed.

THE PROTOTYPE

The principle of self-extraction is known already for almost 20 years [1]. During extraction, the beam crosses the region of decreasing magnetic field near the pole edge. In existing isochronous cyclotrons, the pole gap usually is large, leading to a gradual radial field fall-off and resulting in a loss of isochronism and ultimate deceleration of the beam. An extraction system is needed to transfer the beam from the limit of isochronous acceleration to the limit of radial focusing. Self-extraction is based on creating a sharp transition from the isochronous to the instable region such that the latter can be reached before falling out of RF accelerating resonance and such that the beam can escape spontaneously from the cyclotron. The prototype (Figure 1) was realized by IBA in the beginning of this century [2].

The cyclotron has unconventional features with respect to typical commercial machines. The pole gap decreases quasi-elliptically towards larger radii. The pole on which the beam is extracted, is radially longer than the others and in it, a groove is machined. This creates a field shape with a sharp dip that acts like a septum and at the same time provides optics for the extracted beam. In order to maximize the extraction, harmonic coils are used to enhance the turn separation at the entrance of the extraction path. A permanent magnet gradient corrector, is placed immediately at the exit of the pole to provide radial focusing to the diverging beam. The small part of the beam, which is not properly

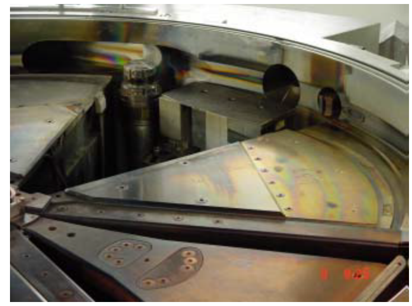

Figure 1: The extraction path in the prototype, showing the groove in the long pole, the gradient corrector and the beam separator. The harmonic coils are placed underneath aluminium pole covers.

extracted, is intercepted on a beam stop (the beam separator) that is placed immediately at the pole exit, in between the circulating and the extracted beam. This beam separator (BS) is designed for low activation and high thermal load. The prototype successfull extracted beams almost up to 2 mA. However, rather poor beam quality was observed and also the extraction efficiency was limited to about 80% at low intensities and about 70% to 75% at higher intensities. This drop (partly) relates to an increase of the dee-voltage ripple resulting from the noisy PIG-source and beam-loading. Although encouraging, the prototype was not yet good enough for industrial applications. The measured beam-quality and extraction efficiency at low intensities agreed quite well with simulations.

Table 1: Cyclotron Main Design Parameters

Cyclotron Type	**Compact Isochronous**
particle	proton
injection	dual internal PIG-source
extraction radius/energy	52 cm; 14 MeV
rotational symmetry	2-fold (quasi 4)
B_{ave} and B_{max}	1.15 T; 1.9 T
quasi-elliptical gap	16 mm < g < 40 mm
minumum gap at extraction	18 mm
pole radius short/long	54 cm/57 cm
number of dees/angle	2; 36°
RF frequency/mode	69.1 MHz; h = 4
dee-voltage	55 kV
available RF power	200 kW

IMPROVEMENTS OF THE DESIGN

Table 1 shows the main design parameters of the cyclotron. Several improvements of the prototype are proposed [3]: i) The groove is replaced by a plateau. This lowers the strong magnetic sextupole component in the extraction path and

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A NEW SOLUTION FOR COST EFFECTIVE, HIGH AVERAGE POWER (2 GeV, 6 MW) PROTON ACCELERATOR AND ITS R&D ACTIVITIES*

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Abstract

Due to the successful construction of a 435-ton magnet for CYCIAE-100, it has been proved that the gradient adjustment of magnetic field along radius can effectively enhance the vertical focusing during the isochronous acceleration. This key technology was applied to the general design of a 2 GeV CW proton accelerator, the energy limitation of the isochronous machine is increased from ~1 GeV to 2 GeV, by our contribution of the beam dynamics study for high energy isochronous FFAG.

This paper will introduce CIAE's engineering experience of precision magnet, beam dynamics by single particle tracking and the advantages of beam dynamics simulation based on large-scale parallel computing. The cost-effective solution for such a 2 GeV high power circular accelerator complex will be presented in detail after the brief introduction about the high power proton beam production by the CYCIAE-100.

INTRODUCTION

The 100 MeV compact cyclotron, CYCIAE-100 was approved formally to start the construction in 2011[1], and the first proton beam was extracted on July 4, 2014. In 2017, the 200 μA proton beam development was conducted, and in 2018, the production of high power beam from 20 kW to 52 kW had been delivered successfully to the beam dump, which was quantitatively predicted ten years ago [2]. After about 8 years of construction, installation, beam commissioning and operation, various proton beam intensities from 2 pA to 520 μA can be provided for users for different applications. The Fig. 1 shows the 520 μA beam with the bunching effect of about 1.6 at the high current operation. The beam was measured by the beam dump at the end of the beam line for isotope production.

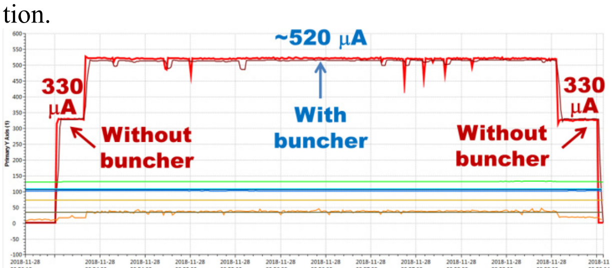

Figure 1: The 52 kW CW Proton Beam Production.

During the construction of the 435-ton large-scale precision magnet for CYCIAE-100, we noticed that the 2nd order pole profile adjustment of magnetic field gradient along radius can effectively enhance the vertical focusing from the energy of 70 MeV to 100 MeV for such a AVF cyclotron [3]. This technology is also applied to pole profiles of the F & D magnets by two 3rd order functions respectively for the general design of a 2 GeV CW proton accelerator, which is using the 800 MeV cyclotron as an injector [4].

GENERAL CONSIDERATIONS IN OVERALL DESIGN OF 2 GEV CW FFAG

There are three different types of constructed accelerators for high power proton beam production: the cyclotron, LINAC and RC synchrotron. The average power of the accelerators currently is from 0.2 MW to 1.4 MW. The proton accelerator with highest beam power under construction is the ESS's SC LINAC, with a beam power of 5 MW [5]. The FermiLab researcher reported the energy efficiency of the three operational accelerators with the highest beam power in the world [6]. The energy efficiency of the PSI cyclotron is about 3 times of the other types. In order to develop high average beam power, high power efficiency and high cost effective proton machine, the isochronous accelerator is a good technical route, if it can break through the energy limitation of 1 GeV, which is presented by Dr. Y. Ishi [7]. Based on the basic FFAG idea, the research for a new solution for cost effective, high average power, 2 GeV proton accelerator was first proposed at CIAE in 2013. Combining the engineering experiences on large radial range varying gradient magnet in CYCIAE-100 and the strong focusing in FFAG, we achieve isochronous acceleration up to 2 GeV. The overall design has been basically completed after several years of research, simulation and optimization. It is a fix frequency, CW FFAG accelerator. Its layout with 100 MeV pre-injector, 800 MeV injector and 10 FDF cell CW FFAG is shown in Fig. 2, and the main parameters in Table 1.

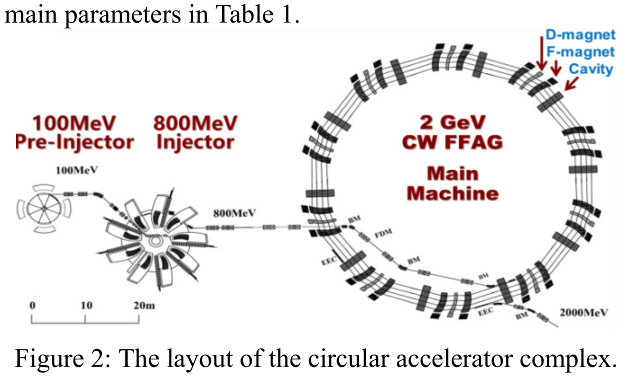

Figure 2: The layout of the circular accelerator complex.

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CURRENT STATUS OF SUMITOMO'S SUPERCONDUCTING CYCLOTRON DEVELOPMENT FOR PROTON THERAPY

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Abstract

Sumitomo Heavy Industries, Ltd. is developing a compact superconducting isochronous 230 MeV cyclotron for proton therapy. It is designed to produce 1000 nA proton beams for high dose rate cancer treatment.

The cyclotron magnet, which includes a liquid-helium-free cryostat, has been fabricated and the magnetic field has been measured. Magnetic field distribution and parameters such as horizontal and vertical tunes agreed well with the original design. A 120 kW solid-state RF system is being tested. Other components such as the ion source and electrostatic deflector are being fabricated. After the testing of individual components, they will be assembled and beam testing will be scheduled at a new test site.

INTRODUCTION

Sumitomo Heavy Industries, Ltd. developed a normal conducting AVF proton cyclotron P235 in the 1990s [1]. Today, several P235 cyclotrons are in operation for cancer treatment.

In 2012, the basic design of a superconducting (SC) cyclotron [2] was established to reduce the size and cost of the system. The narrow pole-gap design makes the size smaller than existing isochronous cyclotrons for this purpose. Two h = 2 cavities and one supplementary h = 4 cavity are used to obtain large turn separation at the electrostatic deflector (ESD).

SC cyclotron components have been fabricated and tested since 2017. Figure 1 shows the magnet assembled in 2018. In the following sections, the current status of cyclotron component development and beam dynamics are discussed.

Figure 1: Superconducting cyclotron magnet. Diameter of the yoke is 2.8 m.

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The detailed design started in 2015 [3]. The updated design parameters are listed in Table 1. Some parameters such as beam current have been changed to meet high dose rate therapy requirements. The supplementary h = 4 cavity has been removed to further reduce costs. To achieve turn separation with low acceleration voltage, a precessional extraction scheme was adopted.

Table 1: Main Design Parameters of the SC Cyclotron

Description	Parameter	Unit
Particle species	Proton	
Energy	>230	MeV
Beam current (max.)	1000	nA
RMS emittance	~ 1	π mm.mrad
RMS momentum spread	<0.1%	
Extraction efficiency	>70%	
Extraction radius	0.6	m
Average magnetic field	3.1–3.9	T
Yoke size	ϕ2.8 m × 1.7	m
Yoke weight	65 t	t
Coil material	NbTi/Cu	
Stored energy	5.1	MJ
Magnetic induction	9.7×10^5	AT/coil
Main coil current	442	A
Coil cooling time	14	days
Field ramp up time	<1.5	h
Quench recovery time	<24	h
RF frequency	95.2	MHz
Harmonic number	2	
Dee voltage	50–75	kV
RF wall loss	<120	kW

CYCLOTRON COMPONENTS

Cryogenic System

The cryostat [4], as shown in Fig. 2, was fabricated in 2018. Two NbTi coils are supported by four horizontal and four vertical structures. The coils are conduction cooled by four 4 K Gifford–McMahon cryocoolers (RDE-412). After the cryostat was assembled in the yoke, its performance was tested. The cooling time of the coils from room temperature to 4.2 K was 14 days, as shown in Fig. 3. Ramp-up time from 0 A to 488 A was 1.5 h. Quench protection of SC coils was done by a 1.1 Ω dump resistor. To date, we

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ENERGY REDUCTION OF VARIAN'S ProBeam 250 MeV CYCLOTRON TO 226 MeV

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Abstract

With its superconducting 250 MeV isochronous proton cyclotron AC250, Varian uses a powerful accelerator for the ProBeam particle therapy systems. However, data from clinical operation has shown that the vast majority of treatments is only making use of proton ranges of less than 30 cm WET (water equivalent thickness), i.e. beam energy of 218 MeV at the patient. This led to a decision at Varian in Dec 2018 to conduct a redesign program with the goal to reduce extraction energy of the ProBeam cyclotron to 226 MeV. We present beam dynamics simulations for the AC226 beam acceleration and extraction. They actually show that only a reduced main coil current and adapted magnetic shimming process, as well as a slightly lower RF frequency is needed for re-tune. Furthermore, results indicate that a similar performance as compared to the AC250 can be expected. A first of its kind (FOIK) AC226 cyclotron is built by seamless integration into Varian's production process. The magnetic field measurement and shimming is completed, in-house RF and beam commissioning is planned for autumn 2019. We report on the status of the FOIK machine.

ProBeam CYCLOTRON

Varian's Proton Solutions (VPS) business unit provides with its superconducting isochronous proton cyclotron AC250 a powerful accelerator for the ProBeam proton therapy platform. With a fixed extraction energy of 250 MeV and extracted beam currents of up to 800 nA, this cyclotron drives proton therapy centers worldwide, many of them already in clinical operation, others currently in an installation and commissioning phase.

Design details of this cyclotron and factory testing including RF and beam commissioning were already reported in [1, 2]. The current status of VPS cyclotron series production is presented in [3].

ENERGY REDUCTION TO 226 MeV

Motivation

During the last decade, analysis of clinical cases has shown that the vast majority of treatments is only making use of proton ranges of less than 30 cm WET (water equivalent thickness), which corresponds to a beam energy of 218 MeV at the patient. Taking into account energy losses and necessary energy degradation of a few MeV from cyclotron exit to gantry isocenter, the corresponding beam extraction energy is 226 MeV. Consequently, the current 250 MeV ProBeam cyclotron is somewhat overdesigned in terms of beam energy, leading to potentially higher building cost for the customer, esp. due to more stringent shielding requirements.

Furthermore, in either case an energy degrader installed behind the cyclotron extraction must be used which lowers the beam energy by moving graphite wedges into the beam path. The energy degradation also leads to significant, needless reduction of beam intensity. This effect can be minimized when the cyclotron generates a lower energy beam already by design, which then results in a lower requirement for the extracted beam current to be provided by the cyclotron.

Therefore, VPS decided in December 2018 to redesign the ProBeam AC250 cyclotron for 226 MeV extraction.

Basic Concept

To achieve a fast integration of the new AC226 machine in VPS's ongoing production, the changes must be as limited as possible. VPS therefore decided not to change the extraction radius of the cyclotron of 816 mm (radius of the septum of the first extraction deflector ED1). Then the extraction of 226 MeV protons requires a lower magnetic field[1] B_{extr} of 2.82 T at 816 mm. Accordingly, the magnetic field[2] B_0 at the cyclotron center needs to be reduced and determines a slightly lower revolution frequency which finally results in change of the 2nd harmonic RF frequency f_{RF} from 72.8 MHz to 70.3 MHz. Since the RF acceleration voltage (roughly 80 kV in the center) is not changed, the mean number of turns until the protons reach extraction radius is decreased to about 580. A comparison of relevant cyclotron parameters for 226 MeV and 250 MeV machines is summarized in Table 1.

Table 1: ProBeam Cyclotron Key Parameters 226 MeV vs. 250 MeV

Parameter	226 MeV	250 MeV
R_{extr}	816 mm	816 mm
B_{extr}	2.82 T	2.98 T
${}^2B_0$	2.27 T	2.35 T
I_{coil}	~148 A	~162 A
f_{RF}	70.3 MHz	72.8 MHz
# turns	~580	~650

In practice, adaption and isochronism of the shape of the averaged magnetic field from cyclotron center to extraction can be achieved by reducing the excitation current I_{coil} of the superconducting main coil and by a proper modification of the magnetic shimming of the iron poles.

[1] Azimuthally averaged magnetic field.
[2] $B_0 = B_{\mathrm{extr}} / \gamma$.

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CYCLOTRONS BASED FACILITIES FOR SINGLE EVENT EFFECTS TESTING OF SPACECRAFT ELECTRONICS

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I. V. Kalagin, S. V. Mitrofanov, JINR, Dubna, Russia

Abstract

Space radiation is the main factor limiting the operation time of the onboard equipment of the spacecraft due to the radiation effects occurring in the electronic components. With a decrease in the size of semiconductor structures, the sensitivity to the effects of individual nuclear particles increases and hitting one such particle can cause an upset or even failure of a component or system as a whole. Since the phenomenon occurs due to the impact of a separate particle, these radiation effects are called Single Event Effects (SEE). To be sure that the electronic component is operational in space, ground tests are necessary. SEE tests are carried out on test facilities that allow accelerating heavy ions from C to Bi to energies from 3 to a few dozen MeV/A. Cyclotrons are best suited for this purpose. In this paper, the installations created by request of ISDE based on the cyclotrons of FLNR JINR are described.

INTRODUCTION TO THE SEE TESTING

Space ionizing radiation consists of Earth's radiation belts, galactic cosmic rays and solar energetic particles. Their effect results in different effects in semiconductor microelectronic components. Figure 1 shows the variety of cosmic radiation, its composition and the types of radiation effects it induce.

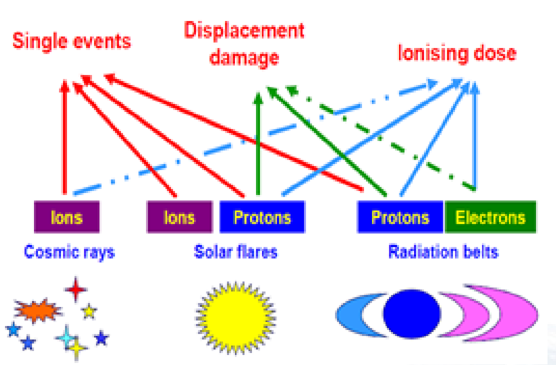

Figure 1: Types of space radiation.

The physical mechanism of interaction between a semiconductor structure and a heavy ion and a proton is illustrated in Fig. 2. The ion induces direct ionization while the proton induces secondary ionization due to knocking out atoms of the semiconductor material.

In the figures below you can see examples of the electronic components failure as a result of heavy ions exposure.

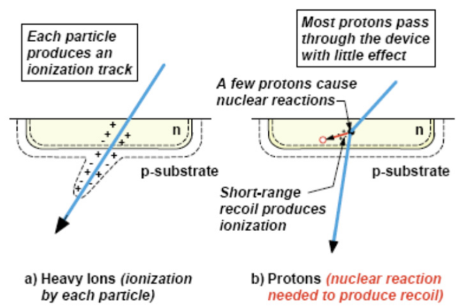

Figure 2: Mechanism for heavy ion and proton SEU effect.

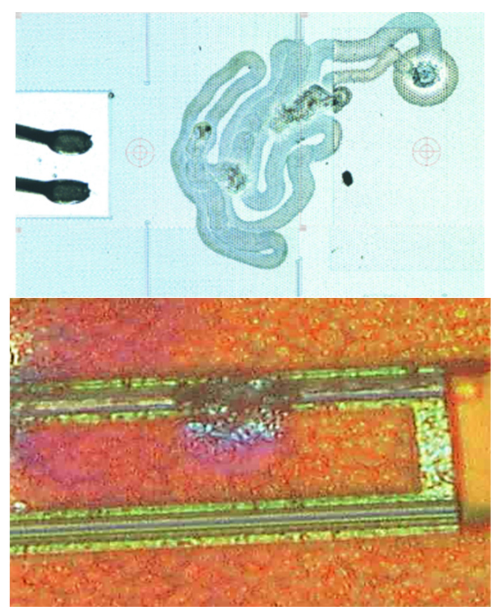

Figure 3: Examples of electronic components failure.

Table 1 represents a classification of heavy ion induced single event effects.

SEE testing is carried out with: Ion accelerator (dominating), Proton accelerator, Laser simulator (result calibration on the ion or proton accelerators is necessary!).

Guidelines using for SEE testing: "Methods of high energetic protons and heavy ions radiation testing of digital VLSI ICs performed on charged particles accelerators", "Methods of high energetic protons and heavy ions radiation testing of analog and mixed ICs performed on charged particles accelerators", "Methods of high energetic protons and heavy ions radiation testing of power MOSFETs performed on charged particles accelerators", "Methods of ICs radiation hardness characteristics calculation in the results of heavy ion facility direct experiments".

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DESIGNING CYCLOTRONS AND FIXED FIELD ACCELERATORS FROM THEIR ORBITS*

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Abstract

The transverse motion of particles in fixed field accelerators with mid-plane symmetry is entirely determined by the properties of the closed orbits. In this study I exploit this property to produce a variety of isochronous magnetic distributions. All the results presented in this paper are verified using CYCLOPS simulations.

INTRODUCTION

The transverse tunes of separated sector cyclotrons, and other fixed-field accelerators, can be estimated "on the back of an envelope" using the hard-edge approximation and the concatenation of drift-edge-bend-edge-drift transfer matrices, see for instance Refs. [1–4]. In this paper, I try to go a little further by presenting a way to calculate exactly the transverse tune from the non-hard-edge shape of the closed orbits. The only approximation is that the magnetic field presents a mid-plane symmetry.

The first section is a review of the derivation of the Hamiltonian for linear motion in a magnet with median plane symmetry [5]. The second section is dedicated to derive the relations between the parameters of this Hamiltonian and the geometry of the closed orbit. In the third section, I present examples of isochronous field distributions, and verify my calculations using CYCLOPS. My intention is to show that it is possible to design a cyclotron starting from its orbits, rather than from its field.

In the last section I present an example of application of this method to a non-isochronous fixed field accelerator.

LINEAR MOTION HAMILTONIAN

Let's consider a charged particle with mass m and charge q travelling in empty space on a closed orbit, under the sole influence of a static magnetic field. Let's also assume that the closed orbit is contained in a plane. Let $\rho(s)$ be the curvature of the closed orbit, and (x, y, s) be the Frenet-Serret coordinates around it. Let the plane of the orbit be the $y = 0$ plane, and let the magnetic field be everywhere normal to this plane:

$$(\nabla \times \mathbf{A})(0,0,s) = \begin{pmatrix} 0 \\ B_0(s) \\ 0 \end{pmatrix}, \quad (1)$$

where $B_0(s) = B(0,0,s)$. The vector potential should also satisfy the absence of source along the orbit, which is:

$$(\nabla \times \nabla \times \mathbf{A})(0,0,s) = \mathbf{0}\,. \quad (2)$$

Using the definition of the curl operator in the planar Frenet-Serret system:

$$\nabla \times \mathbf{A} = \left(\frac{1}{h}\frac{\partial A_s}{\partial y} - \frac{\partial A_y}{\partial s}, \frac{\partial A_x}{\partial s} - \frac{1}{h}\frac{\partial A_s}{\partial x}, \frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y} \right),$$
$$h = 1 + x/\rho, \quad (3)$$

and considering a vector potential in the form of a truncated power series about the equilibrium orbit [6], we find by inspection that the following vector potential

$$\begin{aligned} A_x &= 0, \\ A_y &= \frac{\partial B}{\partial s} xy, \\ A_s &= -\frac{B}{2\rho}\left(x^2(1+n) + y^2 n\right) - xB, \end{aligned} \quad (4)$$

satisfies Eq. (1). It also satisfies Eq. (2) provided that:

$$n = -\frac{\rho}{B_0}\left.\frac{\partial B}{\partial x}\right|_{x=y=0}, \quad (5)$$

which is the standard definition of the magnetic field index.

Let's now consider the Courant-Snyder Hamiltonian [6] $H(x, P_x, y, P_y, t, -E; s) =$

$$qA_s - \left(1+\frac{x}{\rho}\right)\sqrt{\frac{E^2}{c^2} - m^2c^2 - (P_x - qA_x)^2 - (P_y - qA_y)^2}, \quad (6)$$

where E, P_x, P_y and t are, respectively, the particle's total energy, transverse canonical momenta, and time of flight. For the longitudinal coordinates to be, like the transverse ones, deviations for the reference particle's coordinates, we proceed to the canonical transformation $(t, -E) \rightarrow (z = s - \beta ct,\ \Delta P = \frac{\Delta E}{\beta c})$ using a generating function of the second kind:

$$F_2(t, \Delta P) = \left(\frac{s}{\beta c} - t\right)(E_0 + \beta c \Delta P)\,. \quad (7)$$

where the constants βc and E_0 are, respectively, the reference particle velocity and total energy. The new Hamiltonian is obtained by adding $\frac{\partial F_2}{\partial s} = \frac{E_0}{\beta c} + \Delta P$ to the old one.[1]

Without changing the dynamics, we scale all the momenta by the constant reference particle's momentum $P = \frac{1}{c}\sqrt{E_0^2 - m^2c^4}$. The scaled momenta become:

$$\begin{aligned} p_x &= P_x/P, \\ p_y &= P_y/P, \\ p_z &= \Delta P/P, \\ h &= H/P\,. \end{aligned} \quad (8)$$

Expanding the resulting Hamiltonian to second order in x, y, z, p_x, p_y, and p_z, we find that all first order terms vanish

* TRIUMF receives funding via a contribution agreement with the National Research Council of Canada.
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[1] One can verify that the partial derivative of F_2 w.r.t. the old position t gives the old momentum $-E$. The new position z is obtained from the partial derivative of F_2 w.r.t. the new momentum ΔP.

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FLNR JINR ACCELERATOR COMPLEX FOR APPLIED PHYSICS RESEARCHES: STATE-OF-THE-ART AND FUTURE

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Abstract

The main activities of FLNR, following its name -- are related to fundamental science, but, in parallel, plenty of efforts are paid for practical applications. Certain amount of beam time every year is spent for applied science experiments on FLNR accelerator complex. The main directions are: the production of the heterogeneous micro - and nano-structured materials; testing of electronic components (avionics and space electronics) for radiation hardness; ion-implantation nanotechnology and radiation materials science. Status of all these activities, its modern trends and needs will be reported. Basing on FLNR long term experience in these fields and aiming to improve the instrumentation for users, FLNR accelerator department announce the design study for a new cyclotron, DC140, which will be dedicated machine for applied researches in FLNR. Following the user's requirements, DC140 should accelerate the heavy ions with mass-to-charge ratio A/Z of the range from 5 to 8 up to fixed energies 2 and 4.8 MeV per unit mass. The first outlook of DC140 parameters, its features, layout of its casemate and general overview of the new FLNR facility for applied science is presented.

INTRODUCTION

The main point is that for applied science people use powerful machines which were created and developed to solve the wide range of fundamental research. The usage of 'science' accelerators for such activities is connected which high cost of beam time and difficulty to meet quick changes of user's requirements. Also, there is a "time lack" problem when application begins to demand the beam time more than accelerator centre could provide to it in parallel with its scientific plan's realization. Usually, it means that all technical "bugs" and methodological questions were successfully fixed and answered, and users requesting the time as much as they could. That's why Flerov Laboratory of Nuclear Reaction of Joint Institute for Nuclear Research starts the Design Study of the dedicated applied science facility based on the new DC130 cyclotron. The irradiation facility will be used mainly for the following applications: creation and development of track membranes (nuclear filters) and the heavy ion induced modification of materials; activation analysis, applied radiochemistry and production of high purity isotopes; ion-implantation nanotechnology and radiation materials science; testing of electronic components (avionics and space electronics) for radiation hardness.

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RADIATION MATERIAL SCIENCE

Characterization and monitoring of structural defects enhanced by ~100 MeV heavy ions in nuclear ceramics represents an important issue. Besides many intriguing fundamental science questions, these experiments may be of considerable practical value in view of such pressing problems such as radiation stability of inert matrix fuel hosts and coated fuel particles. Materials to be employed as inert matrices for transmuting of minor actinides by means of nuclear reactions should obviously present suitable characteristics as hosts for the actinides and as targets for the irradiation in a reactor. A key parameter to be considered is the resistance to radiation damage due to neutron exposure, gamma and beta radiation, self-irradiation from alpha decay, and fission fragments. Structural modifications induced by fission products, i.e. atoms with a mass ranging from 80 to 155 and an energy of about 100 MeV, still remain uncertain because the effects cannot be investigated using classical low-energy ion implanters. To date, only limited data concerning the microstructural response of non-fertile ceramics to ion irradiation of fission energy are available and external bombardment with energetic ions offers a unique opportunity to simulate fission fragment-induced damage.

The main objective of ongoing projects in radiation material science in FLNR is to determine the radiation tolerance of several oxides, carbide and nitride based ceramics (MgO, Al_2O_3, ZrN, SiC, Si_3N_4, A_lN), considered as candidates for inert matrix fuel hosts, irradiated with high-energy heavy ions, simulating fission fragments impact. Our central objectives are:

a) To study the structural changes and mechanical stresses induced by swift heavy ions as function of ion fluence, irradiation temperature and ionizing energy loss;
b) To elucidate the dense ionization effect on pre-existing defect structures in irradiated materials;
c) To compare the radiation stability of nanocrystalline and bulk ceramics.

TRACK – ETCHING MEMBRANE

In the 1970s, advances in heavy-ion accelerator technology resulted in the idea to replace the fission fragment irradiation with bombardment by high energy, multiply charged ions. The advantages of the accelerator irradiation method are the following: (i) there is no radioactive contamination of the irradiated material because the ion energy is normally below the Coulomb barrier; (ii) all of the bombarding particles are identical; (iii) the ions have a

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3D RADIO FREQUENCY SIMULATION OF THE INFN-LNS SUPERCONDUCTING CYCLOTRON

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Abstract

An upgrade plan of the Superconducting Cyclotron operating at INFN-LNS is ongoing. In this paper, a 3D numerical model of the Cyclotron radio frequency cavity is presented. Simulations include the coaxial sliding shorts, liner vacuum chamber, coupler, trimming capacitor and the Dees structures. CST microwave studio software has been used for numerical computation. RF simulations are mandatory also in order to analyze the field in the beam region and evaluate the impact of different Dees geometry and eventual field asymmetries. Moreover, 3D COMSOL Multiphysics simulations have been carried out in order to couple the electromagnetic field solution to a custom beam-dynamics code developed in Matlab as a future plan. Time evolution of accelerated beam and electromagnetic field make also possible to verify the magnetic field synchronization. Experimental validation of the developed model will be also presented.

INTRODUCTION

The INFN-LNS Superconducting Cyclotron (SC) is a three sector compact machine with a wide operating range, able to accelerate heavy ions with values of q/A from 0.1 to 0.5 to energy from 2 to 100 AMeV [1]. The SC has been in operation for more than 20 years for nuclear physics experiments, which require low intensity beams. Up to now the maximum beam power has been limited to 100 W due to the beam dissipation on the electrostatic deflectors. To fulfill the request of users aiming to study rare processes in Nuclear Physics [2, 3], 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 [4–6]. The feasibility of extraction by stripping through an optimized extraction channel with an increased transverse section has been studied in [7–9]. In the meantime, the RF system has gone through many improvements for more reliable operation of the cyclotron [10, 11]. Moreover, the vertical gap between the dees 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 [12]. This paper describes a numerical study of the RF cavity of the INFN-LNS SC, especially focused on the eventual vertical asymmetry at the dee gap. RF driven-field simulations allow to investigate the fundamental accelerating mode and eventual RF leakages and asymmetries [13–16].

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RF NUMERICAL MODEL VS EXPERIMENTAL RESULTS

The 3D model was created by using Autodesk Inventor [17] to provide a proper geometry with the actual dimensions to the 3D commercial electromagnetic simulators, CST Microwave Studio [18] and COMSOL multiphysics [19]. In particular, COMSOL could be used connected to a MATLAB-developed beam dynamics code [8]. In Fig. 1 the overall geometry of the simulated model of RF cavity of the LNS SC it is shown: the dee stems, the trimmer, the coupler and the dees have been included into the simulation. Figure 2 shows the CST MWS simulated 3D Electric field distribution vector (left) and intensity (right). The RF Cavity has a capacitive coupled power input, while, on the other side of cyclotron, cavity has a tuner. Both the components are controlled by external motor for tuning of the cavity matching and frequency. For COMSOL simulations (see Fig. 3), we added an external lateral volume in correspondence of the dee plane to the previous geometry, in order to simulate the "accelerating" electric field for the beam-dynamics code.

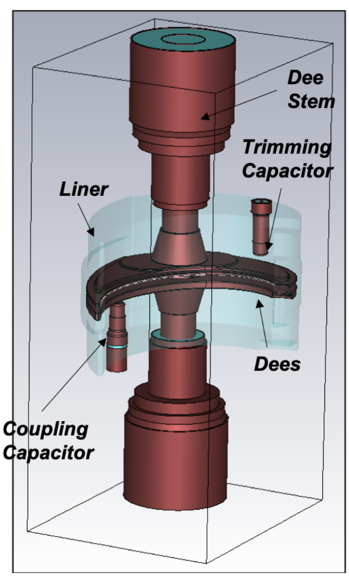

Figure 1: Overall geometry of the simulated model of RF cavity of the LNS Superconducting Cyclotron (SC).

As experimental validation of the developed model we performed driven RF simulation by varying the coupler and trimmer position. Figure 4 shows that a good impedance matching (in terms of $|S_{11}|$) can be obtained by moving the coupler towards the dee-plane. The comparison between the numerical results of Fig. 4 and the experimental results