FRONTIER TECHNOLOGIES AND FUTURE DIRECTIONS IN HIGH INTENSITY ISOL RIB PRODUCTION*

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Abstract

The future frontier of the ISOL technique is to increase the intensity of the RIB beams. In the ISOL technique several ways to increase substantially the production of rare isotope beam. The most expedient one is to increase the incident beam. Increasing the overall release efficiency and ionization efficiency are the other two easiest ways to increase the overall RIB intensity.

Now with the TRIUMF/ISAC facility the ISOL RIB facility can operate routinely up to 50 kW, this is 100 μA on target. But, the driver beam intensity cannot increase without considering the radiation damage issues and the challenge to the ion source itself where ionization efficiency is dramatically affected by target out-gazing.

The other technology challenge for the ISOL technique is the target material itself. The main concern is the capability of the target material to sustain high power density deposited by the driver beam. Refractory metals foil target are suitable but nevertheless very limited in the available species we can produce with those targets. We have developed composite target at ISAC that increases the overall target thermal conductivity in order to be able to operate carbide and oxide at full beam intensity for the carbide and at 30 kW for the oxide targets, respectively. The other solution is to use two-step target where the driver beam impinges a converter, which is decoupled from the ISOL target.

INTRODUCTION

The production of Rare Isotope Beam (RIB) is quite a challenge mainly due to fact that the most interesting rare isotopes are the one that lied close to the limit of stability both on the neutron rich and deficient side and most of the time very have short half-life. Making it difficult to make them using techniques such as chemical or mass separation off-line. In the On-Line Isotope Separation (ISOL) method, the isotopes are produced by nuclear reactions in a thick target that is closely coupled to the ion source, allowing them to be quickly turned into an ion beam that can be mass analyzed and transport efficiently to experiments.

The main challenge comes from the fact that the reaction products stop in the bulk of the target and the atoms have to be released efficiently out of the target container before we can make an ion beam. The steps for producing RIB from the ISOL method are:

- A high energy beam impinging onto a thick target material enclosed in a target container, which is directly coupled to an ion source,
- The isotopes are produced in nuclear reactions and come to rest embedded in the target material,
- The rare atoms have to diffuse through the target material grain or foil lattice to the surface, diffusion process,
- The rare atoms have to effuse, meaning bounce around until it reaches the exit hole of the target container leading to the ion source. Each time the rare atom has to desorb from the surface, effusion process,
- The rare atoms has to be ionized and extracted to form an ion beam, ionization process,
- The beam is mass analyzed and transported to the experiment.

The challenge is to optimize each step if to produce an intense, pure ISOL RIB.

The frontier technologies in ISOL RIB production are to achieve higher RIB intensity of nearly all isotopes, especially in the extreme neutron rich area of the nuclear chart. There are several paths to achieve higher RIB intensity,

- Increase of the driver beam intensity on target,
- Improve the release efficiencies out of the ISOL target, especially for the refractory species,
- Improve the ionization efficiency and
- Efficient high charge state breeding.

Increasing the driver intensity will lead directly to higher ISOL RIB intensity, but to do so we need to improve the target material and the target container for higher power deposition, section 1 and 2 describes the advance in target material fabrication and target container at ISAC. Section 3 describes the attempt to improve the release of radioactive isotope from thick target and section 4 describes the advance in the ion source technology to improve the beam purity from Resonant Ionization Laser Ion Source and plasma ion sources, electron impact and cyclotron resonances ion sources. Finally, section 5 describes the future project under construction and the next generation of ISOL target station.

ISOL RIB PRODUCTION

To reach higher ISOL RIB one can increase the incident driver beam on target. This can only be achieved at the condition that the target material and the target container are capable of sustaining reliably the power deposition by the driver beam. Firstly, the target material has to have a thermal conductivity high enough to release the power deposited inside the target material to the target container. Secondly, the target container has to be capable of dissipating the heat from the target material to the

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THE FRIB PROJECT – ACCELERATOR CHALLENGES AND PROGRESS*

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Abstract

The Facility for Rare Isotope Beams, a new national user facility funded by the U.S. Department of Energy Office of Science to be constructed and operated by MSU, is currently being designed to provide intense beams of rare isotopes to better understand the nuclear physics, nuclear astrophysics, fundamental interactions, and industrial and medical applications. The FRIB driver linac can accelerate all stable isotopes to energies beyond 200 MeV/u at beam powers up to 400 kW. Key technical R&D programs include low-β CW SRF cryomodules and highly efficient charge stripping using a liquid lithium film. Accelerator-physics challenges include acceleration of multiple charge states of beams to meet beam-on-target requirements, efficient production and acceleration of intense heavy-ion beams from low energies, accommodation of multiple charge stripping scenarios and ion species, designs for both baseline in-flight fragmentation and ISOL upgrade options, and design considerations of machine availability, tunability, reliability, maintainability, and upgradability.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB), baselined as a 7-year, US$680 million construction project, is to be built at the Michigan State University under a corporate agreement with the US DOE [1]. FRIB driver accelerator is designed to accelerate all stable ions to energies above 200 MeV/u with beam power on the target up to 400 kW (Table 1). After production and fragment separation, the rare isotope beams can also be stopped, or stopped and then reaccelerated. The fast, stopped, and reaccelerated rare isotope beams serve a vast range of scientific users in the fields of nuclear physics and applications.

As shown in Figure 1, the driver accelerator consists of Electron Cyclotron Resonance (ECR) ion sources, a low energy beam transport containing a pre-buncher and electrostatic deflectors for machine protection, a Radiofrequency Quadrupole (RFQ) linac, linac segment 1 (with Quarter-wave Resonators (QWR) of β=0.041 and 0.085) accelerating the beam up to 20 MeV/u where the beam is stripped to higher charge states, linac segments 2 and 3 (with Half-wave Resonators (HWR) of β=0.29 and 0.53) accelerating the beam above 200 MeV/u, folding segments to confine the footprint and facilitate beam collimation, and a beam delivery system to transport to the target a tightly focused beam. The reaccelerator (ReA) consists of similar β=0.041 and 0.085 accelerating structures [2].

Table 1: FRIB driver accelerator primary parameters.

Parameter	Value	Unit
Primary beam ion species	H to ^{238}U	
Beam kinetic energy on target	> 200	MeV/u
Maximum beam power on target	400	kW
Macropulse duty factor	100	%
Beam current on target (^{238}U)	0.7	emA
Beam radius on target (90%)	0.5	mm
Driver linac beam-path length	517	m
Average uncontrolled beam loss	< 1	W/m

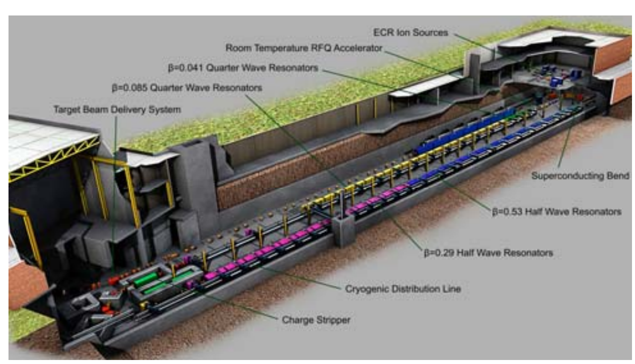

Figure 1: Layout of the FRIB driver accelerator.

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DESIGN STUDY OF IN-FLIGHT FRAGMENT SEPARATOR FOR RARE ISOTOPE SCIENCE PROJECT IN KOREA

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Abstract

A heavy-ion accelerator complex has been designed for rare isotope beam production utilizing both in-flight fragmentation and ISOL methods in Korea. The project had been planned with conceptual design efforts, and was officially launched in January this year. The driver accelerator is a superconducting linac with a beam power of 400 kW. The uranium beam for projectile fragmentation is to be accelerated to 200 MeV/u. The in-flight fragment separator can be divided into pre and main separators. The target system and beam dump to handle the full beam power are located in the front part of the pre-separator. Radiation transport and shielding have been studied using PHITS and MCNPX. Beam optics design performed in the previous conceptual study is being further optimized. The separator will be composed of superconducting quadrupole magnets and conventional dipole magnets. Prototyping of the superconducting magnets is planned.

INTRODUCTION

The rare isotope science project (RISP) was initiated in Korea this year to establish a radioisotope beam facility. The facility will use both in-flight fragmentation (IF) and ISOL methods to produce rare isotope beams. A superconducting linear accelerator with the maximum beam power of 400 kW will drive the IF system, and an H^- cyclotron of 70 kW will be used for ISOL. The uranium beam of 200 MeV/u is a main beam for IF.

A schematic configuration of the facility is shown in Fig. 1 [1]. The separator is divided into pre and main stages. The shape of pre-separator is close to S as the two dipole magnets bend the beam in the opposite direction while the shape of main separator is C using four dipole magnets. Beam optics of different configurations of pre-separator has been studied in the aspect of removing unwanted beams. The basic beam optics design of main separator is currently thought to be kept the same as the one previously designed [1], and we are trying to refine the pre-separator design.

The pre-separator includes a target and beam dump system to separate the isotope beam of interest so that the primary and unwanted isotope beams are dumped into water-cooled shielding structure in a localized area, where remote handling devices are employed. The pre-separator should be well isolated from downstream components. The radiation shielding, damage and heat deposit have been calculated using PHITS [2] and MCNPX [3]. The entire separator is located at the same vertical level in the current design.

The separator consists of large-aperture superconducting quadrupole magnets for large angular and momentum acceptance, which operate at 4 K, and conventional dipole magnets with the maximum magnetic rigidity of 8 T·m. In the front end of pre-separator, superconducting magnets utilizing high-Tc superconductor are considered to avoid large cryogenic loads at 4 K. We will prototype both low-temperature and high-Tc superconducting magnets, and will be tested in a cryostat with cryo-coolers installed.

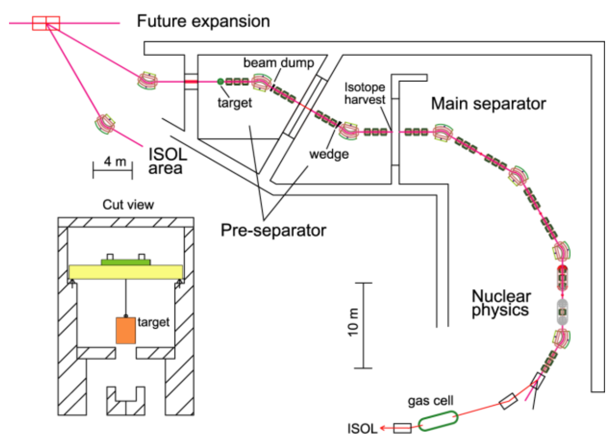

Figure 1: Conceptual layout of the in-flight fragment separator facility.

BEAM OPTICS DESIGN OF PRE-SEPARATOR

An array of magnetic elements of the pre-separator, which employs four dipoles in C-shape, is shown in Fig. 2 together with beam trajectories in the transverse planes. The calculations were performed using COSY Infinity [4]. The locations of beam dump, radiation shielding wall and a wedge are indicated. Momentum dispersion at the beam dump is enlarged compared to the S-shape pre-separator case using two dipole magnets. However, beam is vertically not focused at the wedge, which can cause additional momentum spread.

A result of beam optics calculation using TURTLE [5] is shown in Fig. 3 for the case of four dipole magnets in C-shape. Beam emittance is 4 π•mm·mrad assuming a Gaussian beam distribution, and momentum dispersion of the beam is ±5%. The beam distributions at the locations of beam dump and wedge show the beam spreads by momentum dispersion.

DESIGN AND STATUS OF THE SUPER SEPARATOR SPECTROMETER FOR THE GANIL SPIRAL2 PROJECT

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Abstract

The Super Separator Spectrometer (S3) is a device designed for experiments with the very high intensity stable heavy ion beams of the superconducting linear accelerator of the SPIRAL2 Project at GANIL. S3 is designed to combine high acceptance, a high degree of primary beam rejection, and high mass resolving power to enable new opportunities in several physics domains, e.g. super-heavy and very-heavy nuclei, spectroscopy at and beyond the dripline, isomers and ground state properties, multi-nucleon transfer and deep-inelastic reactions. The spectrometer comprises 8 large aperture multipole triplets (7 superconducting and 1 open-sided room temperature), 3 magnetic dipoles, and 1 electrostatic dipole arranged as a momentum achromat followed by a mass separator. A summary of the beam-optical simulations and the status of the main spectrometer components will be presented with special emphasis on the design of the superconducting multipole triplets.

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ARGONNE IN-FLIGHT RADIOACTIVE ION SEPARATOR*

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Abstract

The Argonne In-flight Radioactive Ion Separator (AIRIS) is a new device that is being designed as a part of proposed future upgrade of the ATLAS facility at Argonne. AIRIS is a large recoil separator for the in-flight radioactive beam that will provide at least 10 times more collection efficiency than the existing system. In combination with other proposed ATLAS upgrades it will provide a 2 orders of magnitude gain in the intensity for the in-flight produced secondary beams compared to the existing facility. The resulting unprecedented intensities for the recoil beam open new opportunities in several physics domains, e.g.: gamma ray spectroscopy after secondary reactions, reactions for rp-, γp-, αp- processes and CNO cycle. The proposed design for the AIRIS device is based on four multipole magnets and four dipole magnets arranged in a so called broadband spectrometer configuration. This arrangement will be followed by two RF cavities to provide further selection. The advantages of such a design as well as key device parameters will be discussed in detail. We will also demonstrate the performance of the device for few representative reaction cases that can be studied using AIRIS.

INTRODUCTION

ATLAS at Argonne is undergoing an efficiency and intensity upgrade. The proposed upgrade is being done in two stages, details are presented in [1, 2, 3]. One of the upgrades being proposed in the second stage of the upgrade is the installation of a large recoil separator for the in-flight radioactive beam program resulting in a better separation of the desired rare isotope beam from the primary production beam. The schematic layout of the proposed device, the **A**rgonne **I**n-flight **R**adioactive **I**on **S**eparator (**AIRIS**), is shown in Fig. 1. AIRIS, along with other intensity and efficiency upgrades, will result in two orders of magnitude increase in the intensity of the in-flight rare isotope beams, and the availability of higher energies also augments the range of rare ions that can be produced with this technique. The physics that is proposed to be studied includes nuclear structure studies and study of nuclear astrophysics processes. This paper summarizes the current status of design studies for AIRIS.

AIRIS DESIGN

AIRIS design is comprised of a magnetic chicane that is preceded by a target station and followed by a RF sweeper and a superconducting debuncher section, as shown in Fig. 1. The selection of recoil beams of interest will be done by appropriately placing slits and beam blockers at the central image of the magnetic chicane. Further selection will happen along the second half of the chicane and at the end slit placed at the final image. Further purification of the recoil beam will be done in the RF sweeper where the tail of the primary beam whose rigidity overlaps with the recoil beam are separated in time and can easily be separated. Finally the recoil beam will go through the debuncher section that will reduce the energy spread and will allow efficient beam transport to experimental stations.

It is a design goal for AIRIS to work for recoil beams of up to 1Tm. It is envisioned that up to 1 pμA stable beams will be used and will require development of new suitable production targets based on rotating target wheels or liquid oil films. The recoil beam will have angular spread of $\pm$ 50 mrad in X and Y, momentum spread of $\pm 5\%$ and have beam spots of $\pm$5 mm x $\pm$5 mm.

Table 1 summarizes key parameters for the AIRIS device.

Table 1: AIRIS parameters

Parameter	Units	Value
Magnetic chicane length	m	5.87
Dispersion at the central image per percent of kinetic energy deviation	mm	1.2
Angular acceptance	mrad	50
Minimum drift space	cm	15
Multipole parameters		
Number of multipole magnets		4
Half aperture	cm	10
Multipole magnet length	cm	20
Maximum quadrupole poletip field	T	1.5
Maximum sextupole poletip field	T	0.05
Dipole parameters		
Number of dipoles		4
Maximum dipole field	T	1
Dipole bend angle	deg	22.5
Dipole radius of curvature	m	1
Dipole half gap	cm	5
Debuncher parameters		
Maximum Debuncher cavity field	MV/m	4
Debuncher frequency	MHz	72
Debuncher length	cm	10
Debuncher half aperture	cm	2

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RARE-ISOTOPE BEAM FACILITIES IN ASIA

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Abstract

Growing activities in the rare-isotpe beam (RIB) facilities in Asian countries are reviewed herein. The status of and planned developments are presented for several RIB facilities in Japan, China, India, and Korea.

INTRODUCTION

Recent research fields of the nuclear physics are widely spread on the nuclear chart. Studies in these fields require the use of a wide variety of rare-isotope beams (RIBs); the ion species, intensity, and quality of the RIBs strongly depend on the scientific objectives of the study. In other words, the accelerator technologies required for rare-isotope studies need to fulfill diverse requirements. These requirements cannot be fulfilled by a single RIB facility. Therefore, a number of facilities that are complementary to each other have either been constructed or are being planned worldwide[1, 2].

In Asian countries, the number of activities at RIB facilities is rapidly growing. This paper presents a brief review of the present status and future plans of several RIB facilities that are located in Japan, China, India, and Korea.

JAPAN

RIKEN RIBF

The RIKEN Radioactive-Isotope Beam Factory (RIBF)[3], which was started in 2006, is based on the in-flight fragmentation scheme. Figure 1 shows a schematic layout of RIBF. The main accelerator of RIBF is the superconducting ring cyclotron (SRC)[4]. In 2010, a new injector known as RILAC2 was commissioned, which is dedicatedly used for the acceleration of very heavy ions such as xenon and uranium[5]. While this acceleration mode is being used at RIBF, the original linac injector can be used independently, for the production of super-heavy elements, for instance.

Figure 2 shows a schematic drawing of the RILAC2 injector. It accelerates heavy ions with M/q < 7, that are produced by a 28-GHz superconducting ECR ion source, up to 680 keV/u with an RFQ and three DTLs. The accelerated beams are injected into the RIKEN Ring Cyclotron (RRC: K = 540 MeV) without charge-stripping. A major portion of the rf system of RILAC2 operates at a fixed frequency of 36.5 MHz, where the maximum power consumption of each rf resonator is designed to be below 20 kW. It has been operating very stably since the beam commissioning.

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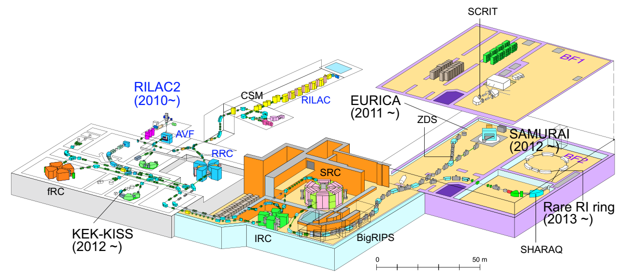

Figure 1: Layout of the RIKEN RIBF.

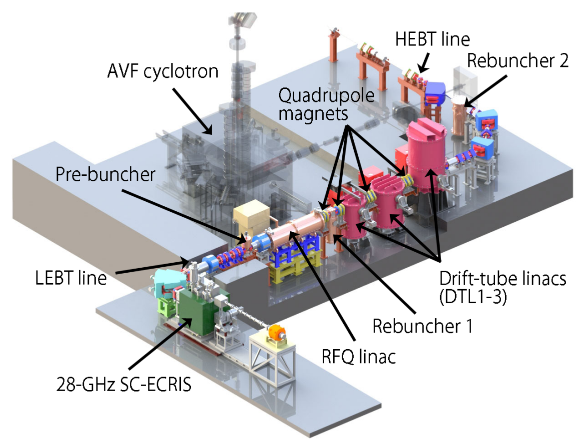

Figure 2: Schematic drawing of RILAC2 injector.

The evolution of maximum beam intensities for beams accelerated at RIBF is summarized in Fig. 3. Owing to the continuous efforts, the intensities are gradually becoming improved[6, 7]. It should be noted that the intensities of light ions such as deuterons and ^{18}O have already reached 1 pμA. On the other hand, the maximum currents in the RILAC2 injection mode are 3.5 pnA for ^{238}U, 15 pnA for ^{124}Xe; the heavy-ion intensities remain to be improved.

One of the major obstacles in increasing the intensity of uranium and xenon beams is the limited lifetime of the carbon-foil strippers currently used. In order to overcome this difficulty, a gas-stripper system employing helium is being developed[8, 9]. An actual structure of the stripper has already been constructed based on several test results, and the beam commissioning has recently been started. A drawback of the gas stripper is that the available charge state becomes smaller compared to that obtained in the carbon-foil stripper. Therefore, the magnet power supplies of the fRC cyclotron have been upgraded in order to accommodate the lower charge states. Acceleration tests with the

PROGRESS AND PLANS FOR HIGH MASS BEAM DELIVERY AT TRIUMF*

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Abstract

ISAC is a TRIUMF facility for the production and post-acceleration of radioactive ion beams (RIB). The RIBs are produced in two target stations using a 500 MeV proton of up to 100 μA of beam current. The produced radioactive species are then ionized and extracted up to 60 kV. The ions of interest are mass selected and transported to either the low energy experimental area or to the post-accelerators. The first stage of acceleration is accomplished via an RFQ followed by a DTL; at this medium stage the energy ranges between 0.15 MeV/u and 1.8 MeV/u for a mass to charge ratio range between $3 \leq A/q \leq 7$. The second stage of the acceleration is achieved with a 40 MV superconducting linac for a final energy up to 18 MeV/u. High mass (greater than 30) beams need multiple charges to be accepted by the RFQ. The single charge ions out of the target source are charge bred using an ECR charge state booster. The breeding process generates a significant amount of background contamination that masks the desired ions inside a mixed ‘cocktail beam. Such a cocktail needs to be cleaned of contaminants to be useful for the experiments. An unprecedented effort is going on at TRIUMF trying to clean the high mass cocktail beams using the accelerator chain as filter. The progress and future plans of the project will be presented in this paper.

INTRODUCTION

The ISAC facility at TRIUMF, represented in Fig. 1, produces, post-accelerates and delivers radioactive ion beams (RIB) using the isotope separation on line (ISOL) method.

A general scheme for this type of facility sees an accelerator, the driver, accelerates light projectiles, the primary beam, toward a thick target. The light projectiles, protons or light ions, break the target nuclei producing neutral radioactive isotopes. These neutral atoms diffuse into a source where they are ionized and extracted at source potential. In general the ISOL method produces high quality emittances but the complicated and relatively slow process reduces the possibility of extracting isotopes with few ms half-lives. The radioactive ions are magnetically separated and if necessary post accelerated to reach the final energy requested.

The singly charged RIB produced in the ISAC target ion source can be either used by the low energy experimental station with an energy up to 60 keV (extraction voltage) or post accelerated to the medium and high energy experiments. In order to inject ion beams with mass greater than 30 in the post accelerators we have to further strip the singly charged to reduce the mass to charge ratio to value ≤ 7. The charge state is boosted by means of an electron cyclotron resonance (ECR) source located downstream of the mass separator that select the RIB coming from the target.

The charge state booster ionized non only the RIB but also any other element present in its ionization chamber and immediate surrounding. Such elements belong either to the background residual gas or to the materials that constitute the vacuum chamber itself. These undesired element ionization generates a background current of orders of magnitude higher with respect to the radioactive species. This background makes extremely challenging identifying and selecting the RIB.

TRIUMF Accelerator division in collaboration with Science division (high mass task force) is engaged in an effort to develop a toolkit for such challenging charge bred beams. This toolkit includes separation and filtration techniques as well as software and diagnostic aids to plan and streamline the beam tuning and delivery.

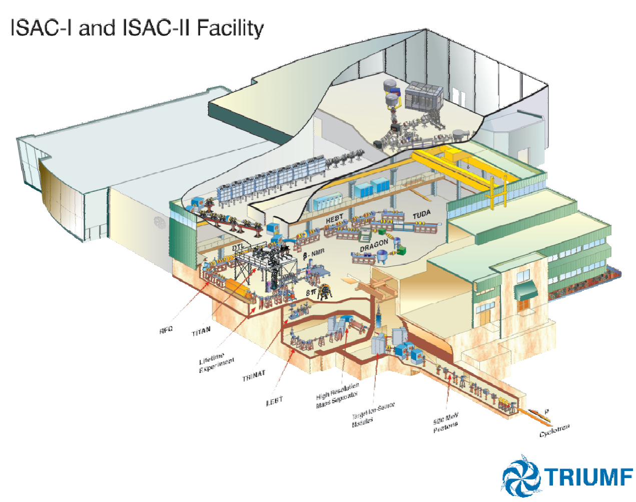

Figure 1: Overview of the ISAC facility at TRIUMF.

THE ISAC FACILITY

The ISAC facility has the highest power (50 kW) driver proton beam. The plain overview of the facility is represented in Fig. 2. The target stations, mass separator and charge breeder are located in the well shielded ISAC basement (see shaded area in Fig. 2). The target stations are inside a vault to contain radiation in a confined area. Different target materials are available for the production target including silicon carbide, tantalum, uranium carbide and niobium. Two target configurations are available: low and

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PROGRESS OF THE SPIRAL2 PROJECT

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Abstract

The SPIRAL2 facility will extend the possibilities offered at GANIL to heavier radioactive beams, with much higher intensities : it will provide intense beams of neutron-rich exotic nuclei created by the ISOL production method. The extracted exotic beam will be used either in a new low energy experimental area called DESIR, or accelerated by the existing SPIRAL 1 cyclotron (CIME. The intense primary stable beams (deuterons, protons, light and heavy ions) will also be used at various energies for nuclear physics, as well as for neutron-based research and multidisciplinary research, in dedicated caves called S3 and NFS. During year 2008, the decision has been taken to build the SPIRAL2 machine in two phases: - first phase including the driver accelerator and its associated new experimental areas (S3 and NFS caves), - second phase including the RIB production part, with the low energy RIB experimental hall called DESIR, and the connection to the GANIL existing facility for post-acceleration by the existing CIME cyclotron. The SPIRAL2 facility is now in its construction phase, with the objective of obtaining the first beams for physics during year 2014 with the first phase.

CONTRIBUTION NOT RECEIVED

OPERATIONAL CONSIDERATIONS FOR FUTURE MULTI-USER RIB FACILITIES*

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Abstract

Like other radioactive ion beam facilities, the ISAC facility at TRIUMF is capable of serving only a single RIB user at a time. With the construction of ARIEL, the Advanced Rare-Isotope Laboratory, ISAC will gain a second RIB production front end and the ability to serve multiple users simultaneously. This will introduce significant new complexity to operations and beam delivery at ISAC and place additional constraints on experimental scheduling and personnel requirements. These constraints will have to be taken into consideration when planning the operation of the combined ARIEL and ISAC facilities in order to maximize the benefits associated with having multiple RIB production facilities.

INTRODUCTION

ISAC, the Isotope Separator and Accelerator facility at TRIUMF, is a high-power ISOL-type rare-isotope beam (RIB) facility [1,2]. RIB production is driven by 480—520 MeV protons from TRIUMF's main cyclotron at currents of up to 100 µA. An artist's rendering of the facility is shown in Fig. 1 with the proton beamline visible at lower right. As ISAC has only a single driver and mass separator, only one RIB can be produced at any one time. This limits the amount of RIB that can be delivered to experiments to ~2500—3000 hours/year.

To increase the amount of RIB available to experiments, a new facility, the Advanced Rare Isotope Laboratory (ARIEL) [3], is currently under construction. In its initial phase, ARIEL will comprise a 10-mA, 50-MeV superconducting electron linac, target station(s), mass separators and low-energy beam transport to the existing ISAC experimental beamlines (Fig. 2). The e-linac will serve as a driver for RIB production by photofission and other photon-induced reactions. With ISAC, this will allow the simultaneous delivery of two RIB, doubling the number of hours of RIB available to experiments. Plans for the future expansion of ARIEL include a second high-current proton beamline to complement that already driving RIB production at ISAC and the ability to deliver three RIB simultaneously.

The move from single-user to multi-user operation brings with it a number of challenges. Many of these are technical in nature and beyond the scope of this paper. From an operations and beam delivery standpoint, however, there are still significant challenges to be addressed, in particular because of the impact that multi-user operation will have on both experiment scheduling and personnel requirements.

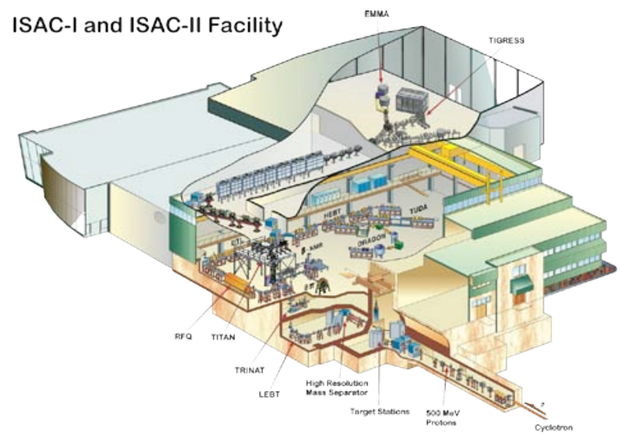

Figure 1: The ISAC facility at TRIUMF.

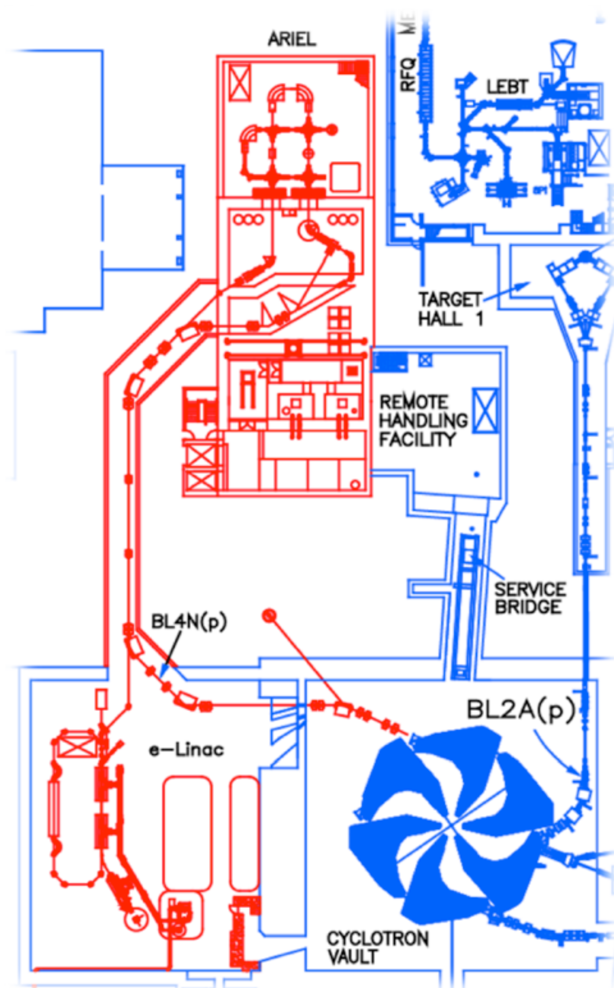

Figure 2: Beamline layout of the Advanced Rare Isotope Laboratory, showing its location relative to existing TRIUMF facilities. ISAC is at top right.

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COMMISSIONING EXPERIENCE WITH CARIBU

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Abstract

The Californium Rare Ion Breeder Upgrade (CARIBU) of the ATLAS superconducting linac facility aims at providing low-energy and reaccelerated neutron-rich radioactive beams to address key nuclear physics and astrophysics questions. These beams are obtained from fission fragments of a Cf-252 source, thermalized and collected into a low-energy particle beam by a helium gas catcher, mass analyzed by an isobar separator, and charge bred with an ECR ion source to higher charge states for acceleration in ATLAS. The facility has ramped up operation from an initial 2.5 mCi source to the present 55 mCi source. A 500 mCi source has been produced at Oak Ridge National Laboratory and is expected to be ready for installation in mid-2012. Low-energy mass separated radioactive beams have been extracted, charge bred with a 10% efficiency, reaccelerated to 6 MeV/u, and delivered to GAMMASPHERE for beta decay studies. The Canadian Penning Trap (CPT) mass spectrometer has been relocated to the CARIBU low-energy beam line. Mass measurements on over 60 neutron-rich nuclei have already been performed and additional measurements are underway. In addition, a new tape station for beta decay studies has just been commissioned.

THE CARIBU FACILITY

Science is driving the development of ever more capable radioactive beam facilities. While present day facilities (REX-ISOLDE, TRIUMF, TRIAC, ANL) can deliver particle intensities in the 10^4 to 10^8 pps range, future facilities (FRIB, HIE ISOLDE, SPES, SPIRAL2, EURISOL) will deliver beams in the 10^{10} to 10^{13} pps regime. However, these are large costly projects which have a long timeline from conception to full operation. In the United States, the Facility for Rare Ion Beams (FRIB) [1] will be the flagship radioactive beam facility producing a wide array of beams via in flight fragmentation, but the facility is not expected to be fully functional until 2021. In the interim, the CARIBU facility [2] (Fig. 1) will provide beams of radioactive nuclei albeit with a more limited reach and intensity but also at a substantially reduced cost and project footprint. CARIBU will utilize fission fragments from ^{252}Cf to provide nuclei which will be thermalized in a helium gas-catcher, mass separated and injected into an ECR charge breeder (ECRCB) to raise their charge state for subsequent acceleration in the ATLAS superconducting linear accelerator. The facility also encompasses a low-energy experimental area for mass measurements and decay studies.

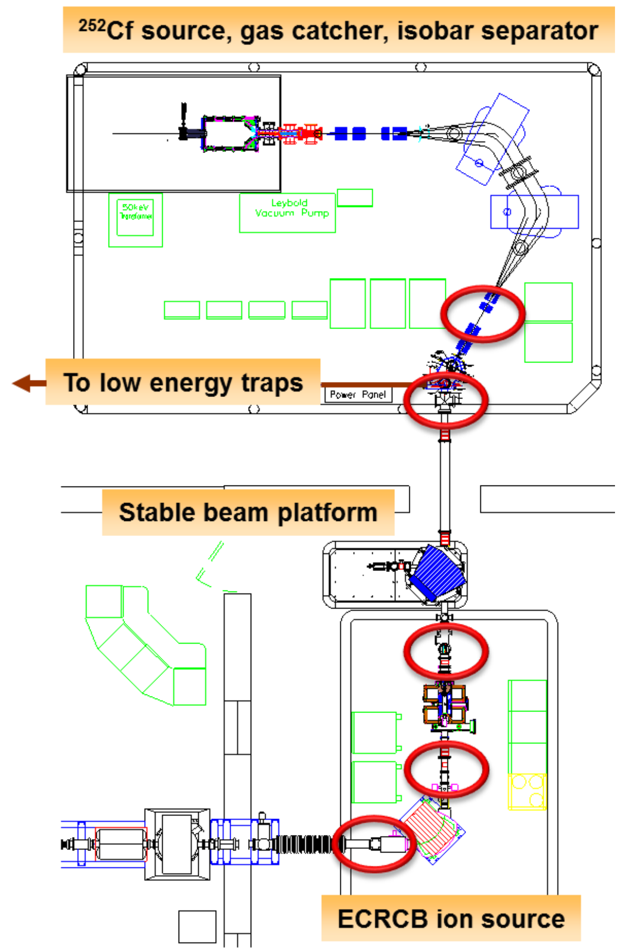

Figure 1: Overview of CARIBU facility and ECR charge breeder. The locations of surface barrier detectors used for radioactive beam tuning are marked with red ovals.

Californium Source

A ^{252}Cf fission source is used to produce the neutron-rich nuclei with a fission fragment distribution peaked in regions of interest that are not well populated by uranium fission. With a 2.6 year half-life and a 3.1% fission branch, ^{252}Cf has a relatively long source lifetime and thus minimizes the need for source replacement. The source is stored in a heavily shielded cask assembly which attaches to the helium gas catcher/RFQ ion guide system. In its final configuration, CARIBU will utilize a 1Ci ^{252}Cf source, but facility commissioning took place with a 55 mCi source. This served as a test of the shielding integrity and allowed for safe equipment modifications.

GANIL OPERATION STATUS AND UPGRADE OF SPIRAL1

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Abstract

The GANIL facility (Caen, France) is dedicated to the acceleration of heavy ion beams for nuclear physics, atomic physics, radiobiology and material irradiation. The production of stable and radioactive ion beams for nuclear physics studies represents the main part of the activity. The exotic beams are produced by the Isotope Separation On-Line method with SPIRAL1 facility. It is running since 2001, producing and post-accelerating radioactive ion beams. The review of the operation from 2001 to 2011 is presented. Because of the physicist demands, the facility is about to be improved with the project Upgrade SPIRAL1. The goal of the project is to extend the range of post-accelerated exotic beams available. The upgrade of the "Système de Production d'Ions Radioactifs en Ligne" phase I (SPIRAL1) is in progress and should be ready by 2015.

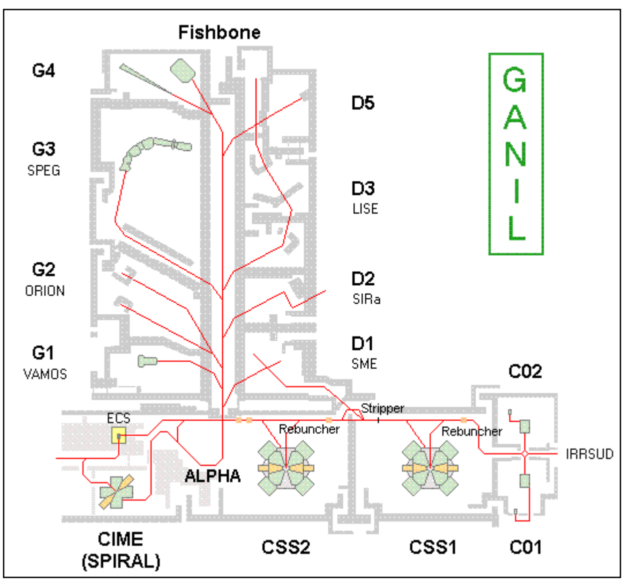

Figure 1: GANIL layout.

OPERATION REVIEW

Multi-beam delivery is routinely done at GANIL using its 5 existing cyclotrons. Up to five experiments can be ran simultaneously in different rooms with stable beams (Figure **1**):

- Beams from C01 or C02 are sent to an irradiation beam line IRRSUD (<1MeV/u).
- A charge state of the ion distribution after the ion stripping downstream CSS1 is sent to atomic physics, biology and solid states physics line D1 (4-13MeV/u).
- A high-energy beam out of CSS2 is transported to experimental areas (<95MeV/u).
- An auxiliary experiments shares the previous CSS2 beam (10% of the pilot experiment time)
- Finally, stable beams from SPIRAL1 source can be sent to LIRAT (<34keV/A) or post-accelerated by CIME and given to detector tests for example.

During radioactive beam production with SPIRAL1, the combination are reduced to the four first and with radioactive beam sent to the 2 last experimental areas mentioned.

2001-2009 GANIL OPERATION STATUS

Since 2001 (Figure 2), more than 38280 hours of beam time has been delivered by GANIL to physics. A third of this time is given to SPIRAL1. The total beam time for physics (tuning and maintenance excluded) is on the average around 3400 hours a year.

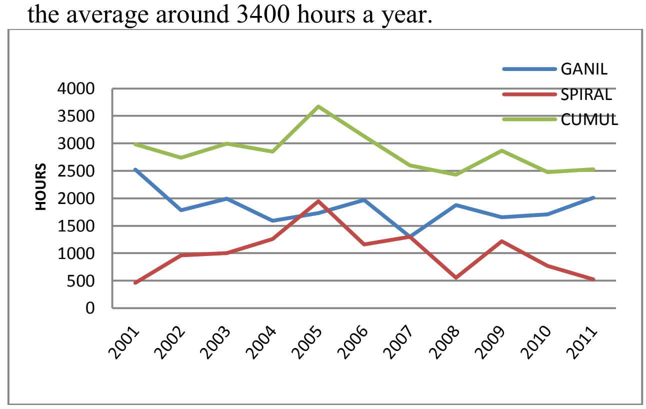

Figure 2: Beam time repartition between SPIRAL and GANIL beams over 11 years.

The number of beam delivered per year (Figure 3) has increased until 2010. Owing to the arrival of SPIRAL2, the running time has been reduced to devote more ressources to the project.

THE RIB DYNAMICS OF THE SPIRAL 2 TRANSFER LINE

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Abstract

The design of the SPIRAL 2 RIB extraction and mass analysis is the result of previous experiences at GANIL (SIRa) and SPIRAL and concerns the ISOL process [1]. The layout presents different beam sections of optical interest starting after the target ion source (TIS) with a conventional Einzel lens, a 1 T solenoid, a triplet of magnetic quadrupoles and a magnetic dipole for the mass analysis. The down-stream 1+ ions transfer line to the users is designed following a conservative solution composed of emittance limitation, homothetic betatron matching, passive and symmetrical optical lattices (point to point and unitary transport) as well as beam instrumentation enabling the control of the losses (pepperpots, slits, beam profilers, Faraday cup, etc.). This contribution will mainly focus on the description of the beam line, its characteristics and on some side effects which have to be taken into account in order to match the beam properly during the operations.

INTRODUCTION

The SPIRAL 2 Project

The SPIRAL2 project is based on a multi-beam driver for both ISOL and low-energy in-flight RIB production. A superconducting light/heavy-ion linear accelerator capable of accelerating 5 mA deuterons up to 40 MeV and 1 mA heavy ions up to 14.5 MeV/u is used to feed both thick and thin targets. The intense RIBs are produced by several reaction mechanisms (fusion, fission, transfer, etc.) and technical methods (ISOL, recoil spectrometers, etc.). The production of high intensity RIBs of neutron-rich nuclei will be based on fission of a uranium target induced by neutrons, obtained from a deuteron beam impinging on a graphite converter (up to 10^{14} fissions/s) or by direct irradiation with a deuteron, ^{3}He or ^{4}He beam. The post acceleration of RIBs in the SPIRAL2 project is provided by the existing CIME cyclotron, which is well adapted for separation and acceleration of ions in the energy range from about 3 to 10 MeV/u for masses A~100-150. SPIRAL2 beams, both before and after acceleration, can be used in the present experimental area of GANIL [2].

The RIB Lines

The RIBs have a relatively large beam emittance, therefore a dedicated beam transport system is built to extract, separate and transport the desired single-charged ion 1+ beam. The beam lines are designed to accept a transverse geometric emittance of 80 π mm.mrad, in horizontal and vertical planes. Most of the contaminants must be suppressed by means of slits, collimators and magnetic analysis. This is the role of the Beam Production Zone (ZPF), see top part of Figure 1. The beam lines must connect different areas of the SPIRAL 2 project (identification station IBE, low energy experiments area DESIR, N+ multi-charged ion beam line leading to the existing GANIL facility). This is the role of the Beam Transport Zone, see bottom part of Figure 1. In order to achieve all the requirements a structure divided into “stages” or “sections” has been developed. The different sections are described in the following. All the ion-optical simulations except for the high current beam calculations have been performed with the TraceWin code [3].

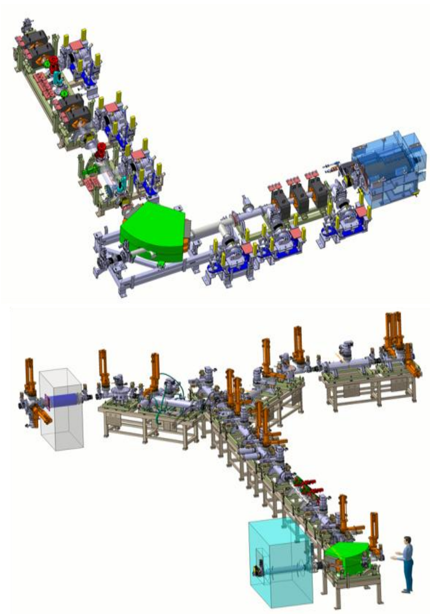

Figure 1: 3D view of the Beam Production Zone (top) and Beam Transport Zone (bottom) of the SPIRAL2 1+ lines.

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THE DARMSTADT MULTI-FREQUENCY DIGITAL LOW LEVEL RF SYSTEM IN PULSED APPLICATION*

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Abstract

Triggered by the need to control the superconducting cavities of the S-DALINAC, the development of a digital low level RF control system was started several years ago. The chosen design proved to be very flexible since other frequencies than the original 3 GHz may be adapted easily: The system converts the RF signal coming from the cavity (e. g. 3 GHz) down to the base band using a hardware I/Q demodulator. The base band signals are digitized by ADCs and fed into a FPGA where the control algorithm is implemented. The resulting signals are I/Q modulated before they are sent back to the cavity. Meanwhile, this system has been successfully operated on 3 GHz, 6 GHz and 325 MHz cavities, on normal and superconducting cavities as well as in cw or pulsed mode. This contribution will focus on the 325 MHz version built to control a pulsed prototype test stand for the p-LINAC at FAIR and possible extensions to even lower frequencies. We will present the architecture of the RF control system as well as results obtained during operation.

INTRODUCTION

The S-DALINAC is an 130MeV recirculating electron linac that is operated in CW mode [1]. It uses superconducting niobium cavities at 2K with a loaded Q of $3\cdot 10^7$ for acceleration. Their 20 cell design and the high operating frequency of 3GHz make them very susceptible for microphonics. Designing and improving the Low-Level RF System therefore was and is one major research activity [2,3].

In addition to the superconducting cavities, room-temperature chopper and buncher cavities are operated. As the new polarized electron injector has been assembled in the accelerator hall [4] the need for a harmonic system arose: Its bunching system consists of a chopper cavity and a 3 GHz as well as a 6 GHz harmonic buncher. Currently, our RF control system has to deal with different loaded quality factors (Q_L) ranging from some 5000 to $3\cdot 10^7$ as well as with different operating frequencies. Due to its modular design, reflected in the hardware design as well as in the control algorithm (being programmed into an FPGA) the system was adapted to the needs of proton Linac currently under design ats GSI/ FAIR [5]. This normal conducting drift tube linac comprises 12 crossed-bar H-mode cavities (CH cavities) that are operated at 325.224MHz in pulsed mode, requiring some major changes in the RF control, described lateron. The cavities are fed with RF pulses of 200 µs length at a maximum repetition rate of 4 Hz [6]. The beam pulse length is 36 µs, representing a significant beam load of approx. 80 %. Based on beam dynamics calculations, the field stability requirements were set to 0.1 % and .5°.

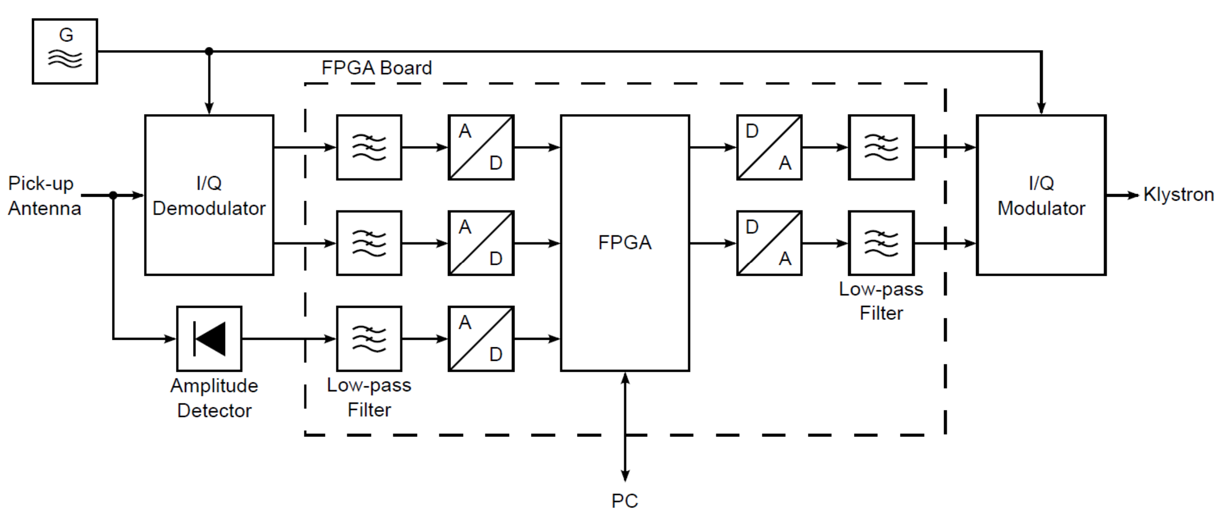

Figure 1: Overview of the hardware components of the rf control system. The (frequency dependant) modulator and demodulator are located on the rf board whereas the FPGA board only contains the signal processing hardware. The control algorithm itself is programmed into the FPGA, allowing SEL and GDS operation.

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CONTROL AND INFORMATION SYSTEM FOR BARC-TIFR SUPERCONDUCTING LINAC BOOSTER

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Abstract

Superconducting LINAC booster is modular machine which consists of 7 cryomodules each consisting four quarter wave resonators and one superbuncher module. The control system is a mixed distributed control system. Geometrical distributed system architecture has been followed for RF control. RF control has four local nodes(RF LCS) each nodes catering to two cryostat. Two additional nodes are made for beam line system and cryogenics distribution system, making it a systematic distribution system. The system is developed on Linux operating system but the software is portable on Linux and Microsoft windows. The software is developed in two layers namely scanner and operator interface. Scanners interacts with the interface hardware. All scanners are developed in JAVA , which is very challenging job looking towards the feature of JAVA. Various issues regarding this were closely investigated and solved to overcome the deficiency of JAVA .A micro-controller based board has been developed for cryogenics line distribution system. Different subsystems of the control system has been developed independently. A complete integration of the system will be completed before December 2012.

CONTROL SYSTEM ARCHITECTURE

LINAC is a booster to existing 14 MV Pelletron accelerator and built as moduler structure[1]. LINAC Booster's layout is given in fig 1.

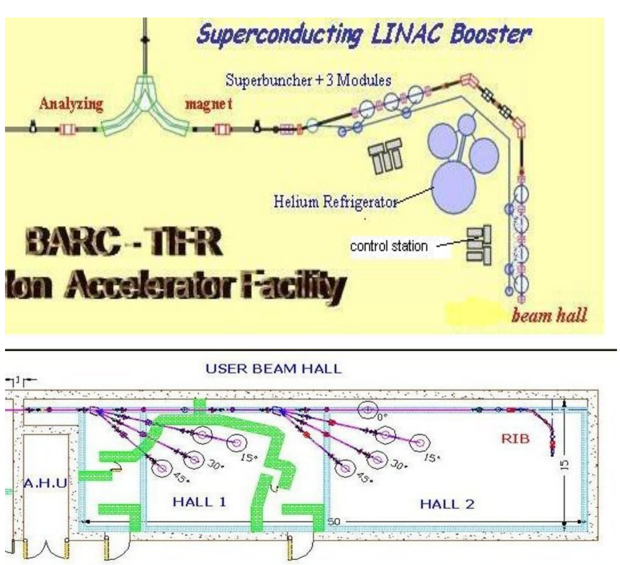

Figure 1: LINAC booster Layout.

LINAC can be divide in two half LIN1 and LIN2 . LIN1 consisting of three cryomodules for accelerating cavities , one cryomodule with single Superbuncher cavity and achromatic bending section. LIN2 consisting of four cryomodules with accelerating cavity.

LINAC control system follows the LINAC moduler structure and gemetric distributed control system has been selected for RF control with four nodes for RF control each node (RF LCS) is connected to each two nearby cryomodules. One node has been put for Beam line devices which include focussing magnets , bending magnets and Beam diagnostics devices . One node has been dedicated for Cryogenics distribution system. Each nodes are totally independent to each other which makes it possible to operate the system even when pelletron beam without further acceleration from LINAC have to be transported to beam hall. All nodes are interconnected to each other using Ethernet Link as filed bus. All control nodes LCS (Local Control stations) are located in accelerator hall. In main control room two PCs known as MCS (Main Control Station) are connected via Ethernet for interaction with the control system(fig 2) .

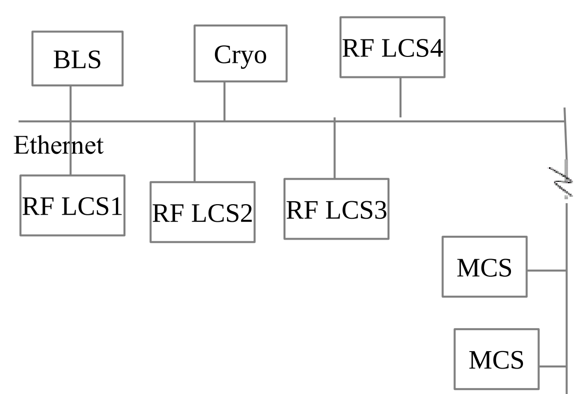

Figure 2: LINAC booster Layout.

A multilayer Hardware architecture has been followed each RF node consists of a CAMAC crate at Front Equipment Interface unit. CAMAC crates (fig3). CAMAC crates have an in house developed Ethernet based crate controller though the crates can be accessed from any PC connected in the network , its accesses has been limited to a single PC at Device interface unit . Device interface unit PC is connected. Communication between different LCSs and MCS is through Device Interface unit PC.

EXTENSION OF SUPERCONDUCTING LINAC OPERATION TO LIGHTER BEAMS

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Abstract

The Pelletron LINAC Facility, Mumbai is a major centre for heavy ion accelerator based research in India. The superconducting linear accelerator, indigenously developed to boost the energy of heavy ion beams delivered by the Pelletron accelerator, has been operational since July, 2007. The Liquid Helium Refrigeration plant for the LINAC has been upgraded to enhance the refrigeration capacity to ~450 Watts at 4.5K without LN_2 pre-cool, from the earlier capacity of ~300 Watts. All beam lines in new user halls have been commissioned and new experimental setups have been added. Several experiments have been carried out using beams of ^{12}C, ^{16}O, ^{19}F, ^{28}Si, ^{31}P. The superconducting lead on Copper QWR cavity used in the LINAC is designed for β=0.1 and hence it is difficult to accelerate lighter beams. Due to growing interest in studying Li induced reactions on fissile targets at energies higher than 55 MeV, we have recently accelerated ^{7}Li beam using four cryostat modules. Starting with 40 MeV ^{7}Li beam from the Pelletron, 56 MeV beam was successfully delivered at target station for a test experiment.

INTRODUCTION

The Pelletron LINAC Facility at TIFR, Mumbai, comprising the 14 MV Pelletron (commissioned in 1989) and the superconducting LINAC booster (operational since 2007) [1,2] caters to a variety of experiments in Nuclear Physics, Atomic Physics, Condensed Matter Physics, Material Science, Radiochemistry, Accelerator Mass Spectroscopy, etc. The Pelletron serves both as a standalone accelerator and as an injector to the superconducting LINAC booster. Several modifications have been made to improve the performance of accelerator.

The Liquid Helium Refrigeration plant for the LINAC has been upgraded to enhance the refrigeration capacity to ~450 Watts at 4.5K without LN_2 pre-cool, from the earlier capacity of ~300 Watts. A vacuum jacketed liquid nitrogen transport line from the Low Temperature Facility (LTF) to LINAC accelerator and user halls (~200 m long) has been installed to provide continuous supply of liquid nitrogen.

New micro-controller based instrumentation and interface has been developed for control and monitor of the cryogenic parameters, beam diagnostics and beam transport devices. The operator Graphical User Interface (GUI) in the control room has been suitably enhanced, which communicates with the remote devices via individually addressable 16-port Ethernet to RS232 serial switch [3]. A digital implementation of the Low-Level RF controller based on a self-excited loop (SEL) with phase and amplitude feedback has been developed and successfully tested on a single superconducting cavity [4]. This paper describes some of the recent developments.

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CRYOGENICS

The Linac utilizes a custom-built liquid helium refrigerator Linde TCF50S, installed in 1999. It was originally rated for a refrigeration power of 300 Watts at 4.5 K, which could be further enhanced by a maximum of 150 W with LN_2 pre-cool. The two-phase helium at 4.5 K produced at the JT stage in the refrigerator is delivered to the LINAC through a cryogenic distribution system at a supply pressure of 1.6 bara. The phase separation is achieved in the individual cryostat, typically at a pressure of 1.35 bara. The cold helium gas (4.5 K) is returned to the helium refrigerator at a pressure of 1.20 bara. The observed pressure drops in the distribution network and the mass flows have been modelled to estimate the overall thermodynamic efficiency of the system. Due to the elevated delivery pressure of the cryogen to the LINAC, the effective total available cooling power reduces to ~260 Watts. For the whole system without RF power, the estimated heat load is ~140 W. Therefore, the net available cooling power for RF load is only ~120 W, which is not adequate to power up all the accelerating cavities. Hence, during the accelerator operation, the refrigerator was used with partial liquid nitrogen pre-cooling. In order to eliminate the use of liquid Nitrogen pre-cooling, the plant has been upgraded to deliver ~450 W at 4.5 K. This has been done by replacing the original compressor having a flow rate of 62g/s by a new one having a capacity of 79g/s. Also, two turbines in the cold box have been replaced by more efficient versions and all the valve seats in the plant were changed to adapt to the higher mass flow rate. The upgraded plant has been fully tested and commissioned. The cryogenic system was found to be very stable during the accelerator operation with full RF load. The helium gas recovery system has been augmented with an additional recovery compressor and a 30 m^3 gas bag, to provide to total capacity of 60 m^3. This is expected to significantly reduce the helium gas

PROGRESS ON THE RFQ BEAM COOLER DESIGN FOR SPES PROJECT

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Abstract

The SPES project is the new Radioactive Ion Beam facility under construction at Laboratori Nazionali of Legnaro, Italy. In this framework, a study of a new RFQ beam cooler device is in progress in order to improve the beam quality in terms of transverse emittance and energy spread. The electromagnetic design of the RFQ section and the electrostatic layout of the injection and extraction regions have been done. The beam dynamics study is going on by means of dedicated codes which allow to take into account the interaction of the ions with the buffer gas needed to cool the beams. The preliminary design of the device started in 2011 by V Committee of INFN in the framework of the REGATA experiment. Both beam dynamics study and the electromagnetic design are presented in this work together with the experimental set up to investigate the sustainability of high voltages at low He pressure.

INTRODUCTION

The experiments with radioactive beams require beams of high purity while the methodology ISOL (Isotope Separator On Line), used to produce them is isotopically unselective. Actually the output beam from the first mass selection (resolution 1/200) is constituted by all the radioisotopes with charge +1 and with almost the same mass number. In order to separate the radioisotope of interest from the contaminants, which may have intensities orders of magnitude higher a further mass selection, is required. This mass selection is carried out by High Resolution Mass Spectrometers (HRMS) whose capacity of selection (1/20000), without loss of transmission, depends on the emittance of the incoming beam. A lower emittance has the further advantage of reducing the beam transport losses and, moreover, makes easier the detection of radioisotopes and increases the accuracy of the measurement of their properties.

The devices used to reduce the emittance of low energy (a few tens of keV) radioactive beams are called buffer gas-filled Radio Frequency Quadrupoles (RFQ) cooler [1]. Many devices of this type have been successfully used up to now to reduce the beam emittance of low current (a few pnA) ion beams. However, the increased beam current intensity (up to 1μA) of the new generation ISOL facilities such as for example SPIRAL2, asks for new technological challenges for their fulfilment [2,3].

BEAM COOLER CONCEPT

In a RFQ cooler, a quadrupolar electric field, generated by two pairs of electrodes placed at distance $2r_o$, oscillating in phase opposition at frequency $\omega/2\pi$ and at amplitude voltage V_{rf} , provides a potential well which can confine the motion of a particle of charge e and mass m. It can be shown that the particle motion is stable when the Mathieu parameter q, given by:

$$q = \frac{4eV_{rf}}{m\omega^2 r_0^2} \qquad (1)$$

satisfies the conditions $0< q<1$.

For q values within this range, the particle motion in the quadrupole is, in first approximation, the sum of two predominant motions, the micromotion, which is the particle oscillation at the frequency of applied electric field, and the macromotion, which is due to the effect of the potential well created by the quadrupolar RF field configuration. The micromotion amplitude is attenuated approaching the axis of the quadrupole, according to the decrease of the electric field. It is then amplified when the ion moves away from the axis. This type of motion is always revitalized by the electric field applied to the electrodes.

As a first approximation (for values of q less than 0.5), the frequency of the macromotion is related to that of the micromotion by the relation

$$\omega_M = \frac{q}{2\sqrt{2}}\omega \qquad (2)$$

It may likewise be shown that, the amplitude of the macromotion oscillation exceeds of a factor *2/q* the maximum micromotion amplitude. The ion then performs a wide oscillations at macromotion frequency, that are perturbed by micromotion. The amplitude of the macromotion movement is reduced in presence of dissipative processes, as collision with gas molecules present in the RFQ structure. The ion exchanges part of its energy with the gas molecule in the impact. It can be shown that, in average, the ion loses energy only if the gas molecule has an atomic weight lower than the ion ones [4]. It is also important that the buffer gas is neutral and inert in order to not remove beam ions by chemical reactions or charge exchange processes. The energy loss increases with the number of collisions, which is proportional to gas pressure. A gas inlet in the structure makes the process more efficient. The overall effect of the collisions is to introduce a viscous force which slows the ion until it reaches a constant drift speed. The introduction of this force in the equation of motion reduces the amplitude and lowers the frequency of the macromotion oscillation. The effect of the gas is therefore to reduce both transverse size and speed of the beam so to decrease its transverse emittance.

PERFORMANCE OF ALPI NEW MEDIUM BETA RESONATORS

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Abstract

All the Nb sputtered medium β cavities installed up to 2011 in ALPI were produced by upgrading of old previously Pb plated substrates. For the first time this year we had the opportunity to test on line four 160 MHz, β=0.11 QWRs which were designed and built in order to be Nb sputtered. These resonators were built in between 2007 and 2008 and they were tested at low fields (up to 3 MV/m) just after their production, when they showed Q_0 values exceeding $1x10^9$. They were then stored for about three years in plastic bags and they were installed in ALPI only this year. The on line tests showed Q_0 values reduced of about a factor five with respect to the ones measured in laboratory. It is the first time we could pick out a Q deterioration caused by storage in air, probably because we previously had the possibility to install the cavities in the on line cryostats within some weeks from the time of cavity production.

So far we have not recognized any Q–degradation, both when the sputtered cavities were maintained in vacuum for many years and also when they were open to air for a few weeks for cryostat maintenance. This time, as it had happened in the maintenance of cryostat CR19 housing high β resonators, we could instead improve the Q-curves by high pressure rinsing the resonators and by making a better rf contact between the cavity and its bottom plate.

INTRODUCTION

A large number of Nb on Cu sputtered cavities are in operation in ALPI since many years [1]. They are Quarter Wave Resonators (QWRs) operating at 160 MHz. Eight high β (β=0.13) and 44 medium β (β=0.11) units are used for beam acceleration. In ALPI there are also further 16, 80 MHz, low β, bulk Nb accelerating QWRs [2]. All these resonators are housed in cryostats containing four cavities each. Further 4Nb/Cu+2Pb/Cu QWRs, two per cryostat, are used for beam bunching.

The four high β cavities presently installed in cryostat CR20 are on line since 1998. Their substrates were designed and built in order to be sputtered and their on line performance exceeds 6 MV/m @ 7 W in average [3]. The remaining four high β resonators, have the same inner shape, but they have a different construction technology [4]. They had been housed in the cryostat CR20 in between 1995 and 1997; in 2001, after being re-sputtered, they were moved into the cryostat CR19. Their maintenance, in 2010, produced a substantial improvement in performance, as described later in this paper. Up to the last year all the installed accelerating medium β resonators were obtained by sputtering old substrates previously lead plated [5]. The cavity renewing process started at the end of 1998 and was completed by 2004 [6]. The cavity upgrading practically doubled their averaged operational accelerating field (4.8 MV/m a @ 7W), but the drawbacks of old substrates did not allow to reach the results obtained in high β resonators [6].

Between 2007 and 2009 we built and tested in laboratory four new medium β cavities properly designed to be sputtered, but only this year we had the possibility to test them on line [7].

THE NEW MEDIUM BETA CAVITY

The new medium β cavity has a shape similar to the ALPI high β resonators: a rounded shorting plate links the inner and the outer conductors. The first, 60 mm in diameter, ends in an hemisphere, the latter, which has an inner radius of 90 mm, extends about 70 mm beyond the inner conductor.

The necessary reduction of optimum β with respect to the high β cavity, is achieved by the plastic deformation of the outer conductor which, around the beam axis, is protruded toward the inner cavity side. The beam ports are external to the cavity body and are screwed to the outer conductor without any gasket. Both the original beam port design and the rounded shorting plate allow smooth connection surfaces where a better sputtered film can be obtained. The cavity shares the cryostat vacuum. Figures 1 and 2 show the new medium β substrate before chemical treatment.

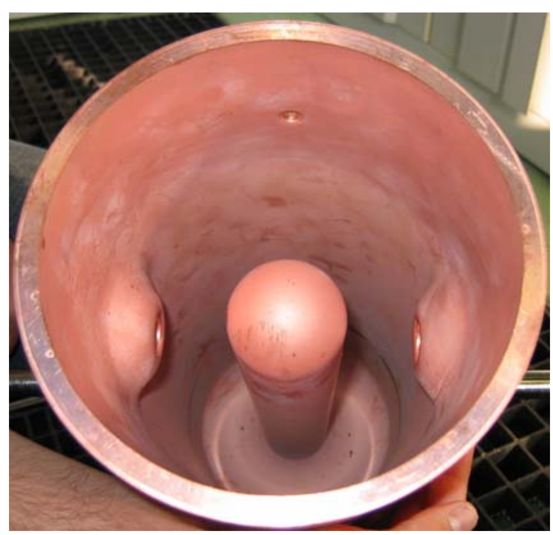

Figure 1: The inside of new medium β substrate before chemica treatment.

DAMAGE SITUATION OF THE 12UD PELLETRON TANDEM ACCELERATOR AT THE UNIVERSITY OF TSUKUBA BY THE GREAT EAST JAPAN EARTHQUAKE

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Abstract

The 12UD Pelletron tandem accelerator at the University of Tsukuba suffered serious damage from the Great East Japan Earthquake on 11 March 2011. On the day, the 12UD Pelletron tandem accelerator was in operation at 8 MV. A main tank of the 12 UD Pelletron tandem accelerator located from downstairs 4th floor to 7th floor was strongly shaken by the shock of the earthquake. All high voltage accelerating columns fell down in the accelerator tank. A situation of the damage and a post-quake reconstruction project of the Tandem Accelerator Facility at the University of Tsukuba are reported.

INTRODUCTION

The 12 UD Pelletron tandem accelerator was manufactured by National Electrostatic Corp. (NEC), USA and was installed at the University of Tsukuba, Tandem Accelerator Complex (UTTAC) in 1975 [1]. A maximum terminal voltage of 12 MV is available for various ion beam applications [2]. By the Great East Japan Earthquake on 11 March 2011, the 12UD Pelletron tandem accelerator suffered serious damages. The 9.0-magnitude earthquake hit the east Japan area. Many accelerator facilities were damaged by this earthquake [3]. A maximum acceleration was 371.7 cm/s^2 (gal) with the duration time of 300 s that registered by the Kyoshin-Net (NIED) [4] at the site of the University of Tsukuba. On the day, 12UD Pelletron tandem accelerator was in operation at 8 MV for ^{41}Ca trial measurements by AMS. The electricity supply went out during the earthquake. The blackout lasted for 4 days, and we had to continuously stop the electric power for 2 days for hazard avoidance. We could not access our facility for the first week because of many aftershocks. Fortunately, there were no casualties by this earthquake in the facility. The 1 MV Tandetron accelerator at the facility did not have any serious damage because of its T type hard structure and it has worked properly after the earthquake.

DAMAGE OF THE 12UD PELLETRON TANDEM ACCELERATOR

Fig.1 shows a cross-section drawing of the 12UD Pelletron tandem accelerator facility which is a vertical type. A main tank of the 12 UD Pelletron tandem accelerator is located from downstairs 4th floor to 7th floor in the accelerator tower. Fig. 2 shows a plane view of the 1st floor with two experimental rooms.

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Accelerator Tank

The accelerator tank was strongly shaken by the shock of the earthquake. Three shock prevention devices for the accelerator tank at the 7th floor were pushed out with breaking anchor bolts of 1 inch in diameter as shown in Fig. 3. Weight supports and jacks at the 4th floor were moved as nearly taken off as shown in Fig. 4. All high voltage accelerating columns fell down in the accelerator tank. Fig. 5 shows the downed accelerating column in the tank at the bottom. Structures of the terminal shell and columns inside the tank were completely collapsed.

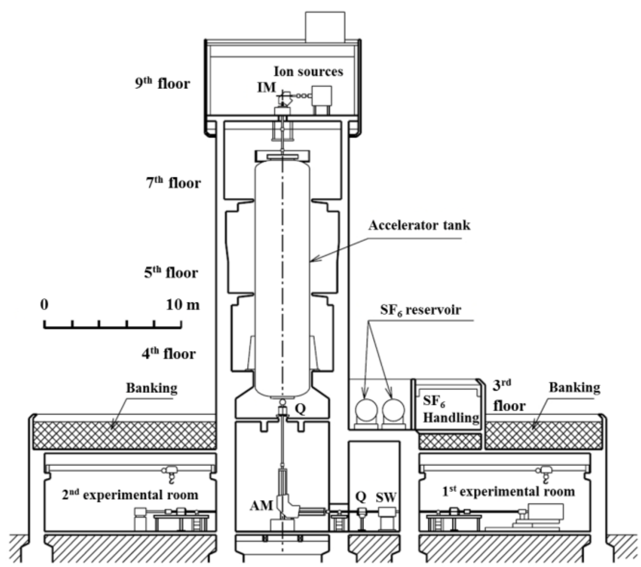

Figure 1: Layout of the 12UD Pelletron tandem accelerator facility at the University of Tsukuba.

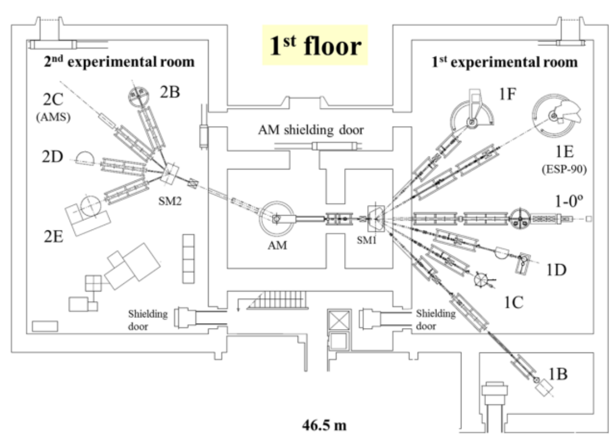

Figure 2: A plane view of the 1st floor at the facility.

LONGITUDINAL BEAM MOTION IN THE KEK DIGITAL ACCELERATOR: TRACKING SIMULATION AND EXPERIMENTAL RESULTS

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Abstract

Beam commissioning in the KEK Digital Accelerator, which is a small scale induction synchrotron (IS), has been conducted since the middle of 2011. Longitudinal beam motion in the induction synchrotron, utilizing induction cells (IC) for acceleration and confinement, is characterized as barrier bucket acceleration. A tracking code has been developed to understand the longitudinal motion affected by longitudinal space charge forces, considering programmed settings of confinement and acceleration voltage. This code, in which the trigger control scenario is fully implemented, calculates temporal evolution of momentum and phase of macro-particles. Beam commissioning results without acceleration and confinement are compared with simulation results.

INTRODUCTION

The induction synchrotron concept for accelerating charged particles, was introduced by K.Takayama and his colleagues in 2000[1] and demonstrated using the KEK 12 GeV synchrotron[2] at High Energy Research Organization (KEK). Later this idea had been adapted to the booster ring, which is a rapid cycle synchrotron. For this purpose, necessary modifications and upgrades had been conducted over 3 years. Now it is officially called the KEK Digital Accelerator(KEK-DA). Its details are described in reference [3]. In addition, the ideas and basics behind the KEK-DA are well explained in K.Takayama's text book [4], and the latest status will be presented in this conference.

In this paper, after a short introduction of the KEK-DA system with its layout, the model used to describe the longitudinal motion including longitudinal space charge forces will be discussed. Then the commissioning results and simulation results are shown to be well consistent with each other. Through extensive studies, it turns out that the momentum distribution in the longitudinal phase space is mainly determined by electric fields of the Einzel lenz chopper [5] where several μs-long beam is chopped out of a 5 ms-long beam pulse extracted from the ECRIS. The simulations shows that this initial momentum distribution evolves through the low energy beam transport line from the ECRIS to the ring and the beam arrives at the ring with bump profiles both on the beam bunch head and tail. This property in the pulse profile have been observed in the experiment. Further more experiments and simulation works have pursued how the profile evolves in the ring. The simulation will manifest what role space charge forces take in the temporal evolution of the phase space distribution, comparing with experimental data.

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OUTLINE OF KEK-DA

The KEK-DA complex consists of many subsystems just as other accelerator facilities. Fig.1 shows an overview of KEK-DA.

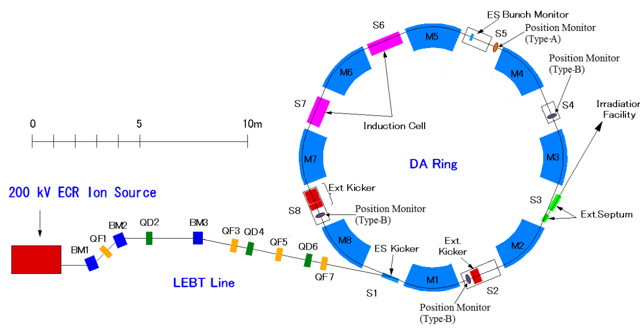

Figure 1: Layout of KEK-DA.

For the present beam commissioning, He^{1+} beam is extracted from an Electron Cyclotron Resonance Ion Source(ECRIS)[6] and chopped by the Einzel lens chopper to be several μs beam bunch. The beam bunch is then accelerated to 200 keV by a post-acceleration column installed right after the chopper and guided through Low Energy Transport Line(LEBT). Electrostatic Kicker, installed at one of the drift section (S1 in Fig.1) of the ring, is used to kick the beam bunch on the ring orbit. 8 combined function magnets are installed in the ring to bend the beam and confine it transversely. Induction cells are installed at S6 and S7 section to provide longitudinal confinement and acceleration for the beam bunch. These induction cells are driven by switching power supply [3] powered by DC power supply. Trigger of pulse voltages for acceleration and confinement are fully controlled by the digital control system consisting of the FPGA and DSP[7] A combination of several extraction kickers and septum magnets is used for beam extraction.

FEEDBACK OF SLOW EXTRACTION IN CSRM*

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Abstract

The transverse tune of the beam in the synchrotron will fluctuate due to the quadrupole current ripple, which lead the spill ripple through the variation of the separatrices area. In order to reduce the ripple of the spill, a pair of fast response quadrupole (FQ) is adopted to compensate the tune ripple caused by other quadrupoles. After using the FQ feedback, the amplitude of the spill ripple within 800Hz has been reduced to 1/10 times from the normal mode. This method will be used in the HITFiL (Heavy Ion Therapy Facility in Lanzhou).

INTRODUCTION

The CSRm [1] is the main cooler storage ring in the national laboratory of heavy ion accelerators in China. The slow extraction [2] has been realized in CSRm in June 2008. In order to suppress the spill ripple which modulated by the quadrupole power ripple, a group of fast response quadrupole has been adopted in the synchrotron. The spill structure is improved greatly compare with the normal mode.

THE MECHANISM OF SLOW EXTRACTION

The RF-Knock Out [3] slow extraction method is adopted in CSRm. The work point of the synchrotron has be set to near the 1/3 resonant line, then the phase space is divided into 2 parts by resonant sextupoles. The particle is stable until it reaches the unstable area by transverse RF. The emittance of the stable area is described as [4]:

$$E_{stable} = 48\sqrt{3}\pi \frac{q^2}{S^2} \qquad (1)$$

Where, $q = Q_x - Q_{res}$ is the difference between the particle tune and the resonant tune. In ideal situation the q keep constant during the extraction process, actually, the current of the quadrupoles will fluctuated with the external power grid. The tune of the particle which lies on the strength of the quadrupoles in the synchrotron will fluctuated, i.e., the q will fluctuated with the external power grid, which cause the stable area fluctuating. Since the emittance of the beam increased smoothly, the stable area fluctuation will bring the spill ripple. If the emittance growth rate is less than the fluctuation of the stable area, the spill will appear discontinuity [4].

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THE NORMAL MODE OF SLOW EXTRACTION IN CSRM

Status of Normal Mode

Figure 1 shows the experiment result of normal mode in CSRm. The duration of the extraction time is set as 5 seconds. As one can seen in the figure,

- the spill ripple is large, and there is no beam extraction in the later part; The spill is not continuous but a series linear peak;
- The spill ripple in 50Hz and its harmonic under 250Hz is visible;

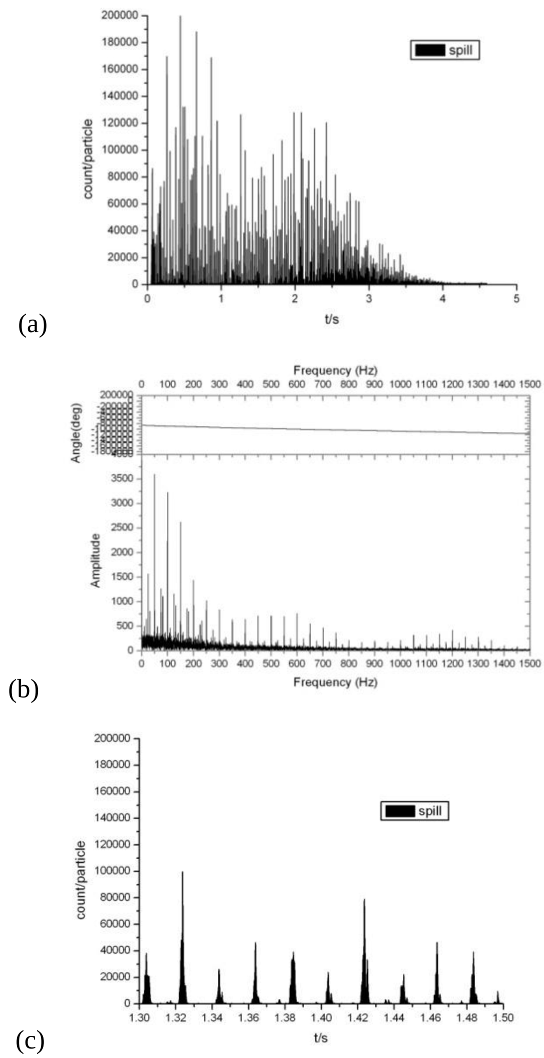

Figure 1: Spill in normal mode (sample rate is 10 kHz). (a) Structure of one spill, (b) The FFT of one spill, (c) Detailed spill structure in 1.3s-1.5s.

MULTIPHYSICS AND PRESSURE CODE ANALYSIS FOR QUARTER WAVE β=0.085 AND HALF WAVE β=0.29 RESONATORS*

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Abstract

The driver linac design for the Facility for Rare Isotope Beams (*FRIB*) at Michigan State University (*MSU*) makes use of four optimized superconducting radio frequency (*RF*) resonators to accelerate exotic ions to 200 MeV/μ. The RF resonators were optimized using computer simulations for all expected physical encounters and corresponding electrical resonant frequency changes. Principal guidance from the ASME boiler and pressure vessel code (BPVC) were applied.

INTRODUCTION

The FRIB, a new national user facility funded by the U.S. Department of Energy Office of Science to be constructed and operated by MSU, is currently being designed to provide intense beams of rare isotopes to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society. The FRIB driver accelerator can accelerate all stable isotopes to energies beyond 200 MeV/u at beam powers up to 400 kW [1]. FRIB uses two *80.5 MHz λ/4* quarter wavelength resonators (*QWR*) operate at $\beta_{opt} = v/c = 0.041$ and *0.085* and two *322 MHz λ/2* half wavelength resonators (*HWR*) operate at $\beta_{opt} = 0.29$ and *0.53*; Figure 1.

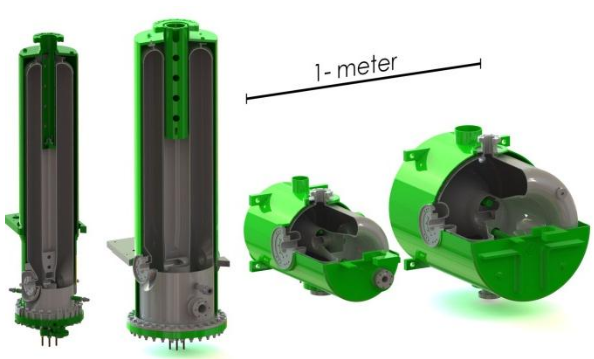

Figure 1: The FRIB Resonators. From left to right: 80.5 MHz β = 0.041, 80.5 MHz β = 0.085, 322 MHz, β = 0.29, 322 MHz β = 0.53.

INTEGRATED ANALYSIS APPROACH

Project requirements state resonator designs must satisfy BPVC. The analysis for the 80.5 MHz β = 0.041 has been completed and was presented at SRF2009 [2]. For the remaining 3 resonators, the first step of the analysis was to validate the design using equivalence of the ASME Section VIII, Division 2. This analysis[3] yields pressure capability for 300K and 2K. Table 1 displays the material allowable stresses as established by ASME code, and the Table 2 displays the stress states that exist during the pressurization of the helium vessel. P_m is the general membrane stress allowable, P_l is the local membrane stress allowable, and $P_l + P_b$ is the local plus the bending stress allowable.

Table 1: Resonator Material Properties [4], [5], [6]

Material	Temp (K)	Elastic Modulus (GPa)	Yield Strength (MPa)
Niobium RRR250	295	103.0	38
Niobium RRR250	4	104.0	372
Niobium-45 Titanium	295	62.1	475
Niobium-45 Titanium	4	68.2	680
Grade 2 Titanium	295	106.9	275
Grade 2 Titanium	4	118.8	560

Table 2: Resonator Stress Allowable [4], [5], [6]

Material	Temp (K)	Pm (MPa)	Pl (MPa)	Pl + Pb (MPa)
Niobium RRR250	295	25	38	38
Niobium RRR250	4	248	372	372
Niobium-45 Titanium	295	226	340	340
Niobium-45 Titanium	4	450	680	680
Grade 2 Titanium	295	143	214	214
Grade 2 Titanium	4	375	560	560

The second step verified the resonator tuning sensitivity, tuning range, and tuning force. The simulation was also used to determine maximum stresses in the resonator and stiffen the resonator as needed to achieve the required tuning range.

The next step of the integrated approach was to determine the resonators helium pressure sensitivity. If the pressure sensitivity was found to be too high, stiffeners were added accordingly.

The final step of the integrated analysis was to compute the Lorentz Force Detuning (LFD). The LFD value was compared to the target goal and if too high design changes were necessary.

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SIMULATION OF ELECTRON AND ION DYNAMICS IN AN EBIS*

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Abstract

To model the dynamics and charge state distribution (CSD) of the ions in an Electron Beam Ion Source (EBIS), a time-dependent, self-consist particle-in-cell Monte Carlo code (EBIS-PIC) has been developed by FAR-TECH, Inc. The energetic background electron beam is modelled by PBGUNS by dividing the long beam path into several segments to resolve the big length-to-radius spatial scaling problem. The injected primary ions and ionized neutral gas ions are tracked using Monte Carlo method which includes the ionization, charge-exchange and Coulomb collisions with the electron beam. The potential well is calculated by solving the Poisson equation each time step. EBIS-PIC calculates the spatial and velocity space distributions and the evolution of the charge state distribution of trapped ions in EBIS devices operating in fast or slow trapping mode. The physical model of EBIS-PIC and the simulations of the experiments on the Test EBIS at BNL are described. The results are in good agreement with the experimental measurements.

INTRODUCTION

In an EBIS, a high current electron beam created by an electron gun is compressed to high density as it enters a strong solenoidal magnetic field (Figure 1). The beam is stopped by an electron collector after passing through a series of drift tubes and exiting the solenoid. The injected primary ions are confined in the radial direction by the potential well created by the space charge of the electrons, and in the axial direction by positive potential barriers on the drift tubes at the two ends of the device. Ions are then ionized to high charge states by electron impact and extracted as the output beam. EBIS are one of the best candidates for producing highly charged radioactive ions.

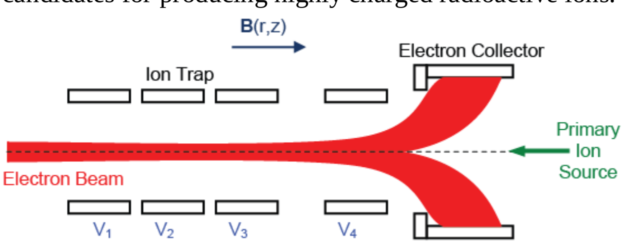

Figure 1: Diagram of EBIS device. The electron beam travels to the right until stopped by the electron collector. The primary ion source is to the right of the collector.

FAR-TECH has developed a numerical tool, EBIS-PIC, to simulate ion dynamics and charge breeding in an EBIS. The tool has modules to model various physics in the EBIS. The initial electron beam is simulated by PBGUNS [1] by dividing the beam path into several segments. The injected primary ions and ions from neutral gas are tracked using a time dependent Monte Carlo method which includes Coulomb collisions and ionizations with background electron beam and charge exchange with neutrals. The electrostatic potential is updated by solving Poisson's equation. The EBIS-PIC has been used to simulate Cs 1+ charge breeding experiments on Test EBIS [2, 3] at BNL. The basic parameters of Test EBIS are listed in Table 1. We use the Test EBIS as an example device to illustrate the simulation of electron beam and ions.

Table 1: Operation Parameters of Test EBIS

Parameter	Value
Trap length	0.7 m
Drift tube radius	1.5 cm
Max magnetic field	5 T
Drift tube voltages	12, 6, 9 kV
Ion Specie	Cs
Ion Current	15 μA
Ion Energy	9kV
Pressure	5×10^{-10} Torr

ELECTRON BEAM MOELING

In EBIS operation, the electron beam propagates several meters from the cathode to collector through drift tubes. The length to radius ratio could be from 200 to 1000. To resolve such big spatial scaling issue, the electron beam is simulated by PBGUNS in several regions to increase accuracy. The PBGUNS code uses relaxation techniques to solve the Poisson's Equation for the potentials on a large, rectangular array of squares, alternately computing potentials and trajectories. It is modified to be able to perform the simulation of the long electron beam path in sections with different grid settings to achieve required accuracy. The sectional simulations were linked continually from the gun to the collector by passing the beam conditions, including the radial distribution of beam energy, angle and spin velocities, and ensuring a steady state in all the sections.

A full electron beam simulation for Test EBIS was performed in 4 regions with their boundaries shown in Figure 2b as vertical dashed lines. The steady state electron beam (shown in Figure 2b) travels ~ 3 meters from the gun to the electron collector in the magnetic field shown in Figure 2a. The electrostatic potential along

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TANDEM EBIS*

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Abstract

A method to increase the ion beam intensity of RHIC EBIS by extending its ion trap into magnetic field of an additional superconducting solenoid is described. The strong axial support of the cold masses in these solenoids is required to place them on a common axis close to each other. Such configuration of solenoids allows to produce a long EBIS with a single electron gun, electron collector and injection system. Preliminary calculations of magnetic forces, magnetic field and potential distributions are presented along with proposed structure of the ion traps.

INTRODUCTION

RHIC EBIS supplies the RHIC accelerating facility with highly charged ions from He2+ to U39+. The design of this ion source and its main components can be found in [1-9] and the results of its experimental study and commissioning on RHIC accelerating facility can be found in [10-13]. The total ion charge, which can be accumulated in the ion trap of the Electron Beam Ion Source (EBIS) is limited by the charge of the electrons within the axial ion trap. Usually some factors like an insufficient ion injection, not full axial trapping, and contamination of the trap with the residual gas ions result in a reduction of the accumulated charge of working ions below this maximum value. For electron current 10.0 A, electron energy 20 keV, and the trap length 1.5 m the project value of the RHIC EBIS ion capacity is 177 nC or $1.1 \cdot 10^{12}$ el. ch. with the charge of working ions constituting 50% of the electron charge. It has been experimentally proven that the extension of the ion trap beyond the limits of the uniform magnetic field results in an increased accumulated ion charge at a cost of some reduction of the effective electron beam density [14]. No disruption of the EBIS operation has been observed. The reduction of the effective current density of the ion trap extended into a low magnetic field area requires some longer confinement time to produce the required charge state of the working ion specie compare to a trap with uniform magnetic field.

THE CONCEPT OF TANDEM EBIS

One way to increase the intensity of the extracted ion beam from EBIS is an axial extension of the ion trap, making it longer. The capacity of the ion trap is proportional to the length of the trap if the radial depth of the potential well remains the same in any axial position of the trap. The extension of the ion trap requires an additional area with an acceptable value of the magnetic field, which is concentric with the existing one. Extending the magnetic field by building a longer superconducting solenoid or placing two solenoids in the same cryostat seem not practical. It is proposed to use an additional superconducting solenoid of the same length and a “warm” inner diameter (ID) as the existing one to extend the magnetic structure and the ion trap of the existing RHIC EBIS creating a longer Tandem EBIS (Fig. 1) with a single electron gun, a single electron collector and a common vacuum system. For the presented geometry the preliminary PerMag simulations give the value of the minimum magnetic field in a gap between two solenoids of 2.1 kGs for magnetic field in the center of each of two superconducting solenoids 4.8 T. This value of minimum magnetic field is quite sufficient for the electron beam transmission in the transition region between both magnets.

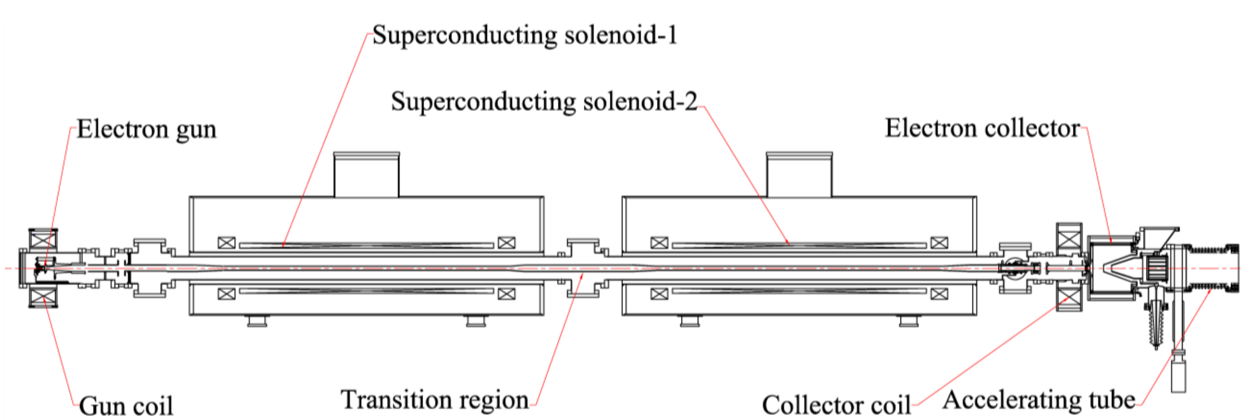

Fig. 1. Schematic of the Tandem EBIS.

*Work supported under the auspices of the US Department of Energy and the National Aeronautics and Space Administration.
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HEAVY ION ACCELERATOR DEVELOPMENT AT IUAC DELHI

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Abstract

Inter University Accelerator Centre has been involved in the development of heavy ion accelerators, ion sources, beam lines and experimental facilities for providing various heavy ion beams in a wide energy range varying from a few tens of keV to hundreds of MeV for experiments by more than four hundred research groups from all over India and abroad. A large vertical Pelletron electrostatic tandem accelerator capable of achieving terminal voltage up to 16MV has been in operational for more than a couple of decades. Superconducting niobium linac booster accelerating modules having eight niobium quarter wave resonators each have been developed and used. A high temperature superconducting electron cyclotron resonance ion source (HTS-ECRIS) was designed, fabricated and installed. It is in regular operation for production of highly charged ion beams for alternate high current injector (HCI) system consisting of radio frequency quadrupole and drift tube Linacs. Details of developments of various heavy ion beam facilities and experimental systems at IUAC will be presented.

CONTRIBUTION NOT RECEIVED

A COST-EFFECTIVE ENERGY UPGRADE OF THE ALPI LINAC AT INFN-LEGNARO*

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Abstract

The ALPI SC linac at INFN-LNL is being constantly upgraded in terms of maximum beam energy (E_f) and current, made available for experiments. Presently, a liquid-N cooling scheme is being applied to the RF power couplers of the 16 full Nb resonators, to keep them locked at 5 MV/m, vs. present 3 MV/m. A further upgrade of the 44 "medium beta section" cavities, changing the cavity Cu substrates, was prototyped and is reported at this conference: however it is not fully funded yet and is extremely time-consuming. A cost-effective E_f upgrade is proposed here: to move 2 SC buncher cryostats, which house a single working SC QWR but were designed for 4, at the end of ALPI, equipping them with 4 Nb/Cu QWRs each (new bunchers would either be NC QWRs or a single SC cavity cryostat). The contribution of these cryostats to E_f would be extremely effective: e.g. a E_f~10 MeV/A (I_{beam}≥ 1 pnA) Pb beam, a very attractive tool for the nuclear physics community, is achievable. A being performed upgrade of ALPI cryoplant, expected to increase the refrigeration capability by ~25%, makes this change possible today. Details of this solution, as well as its limits, will be presented and discussed

INTRODUCTION

The heavy ion accelerator complex at INFN-LNL is based on the superconducting (SC) linac ALPI, which may be alternatively fed by the 15 MV XTU Tandem or by the SC injector PIAVE (V_{eq} = 8 MV), based on superconducting RFQs. For masses heavier than A ~ 100 the use of the Tandem tends to become unpractical due to the limited life-time of the terminal stripper foils and PIAVE is left as the only option.

At present, for masses beyond A~150, the maximum available energy with PIAVE-ALPI ranges between 7,5 and 8,5 MeV/A. In addition, the development of new heavy mass ions with the ECR ion source is not always straightforward nor particularly swift, having to be carried out only in those periods when the accelerators are not delivering beams to users (30% of the year time, without considering the time necessary for periodic maintenance), since an ECR test bench is not available.

The quest for the heaviest masses is indeed increasing: a large fraction of the proposed experiments at INFN-LNL aims at populating neutron-rich nuclei via multinucleon transfer or deep inelastic reactions with stable beams, as an alternative tool to fragmentation or the use of exotic beams. With very heavy stable projectiles (e.g. Pb), one could populate, in particular, nuclei in the regions of shell closures N=82 or N=126, which are beyond reach, incidentally, with fission or fragmentation.

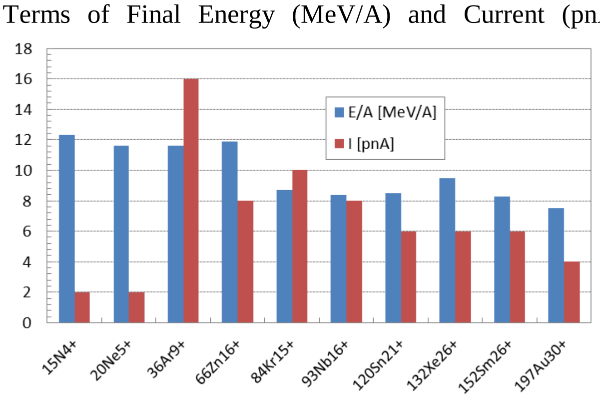
This quest determines the need to increase the final energy of PIAVE-ALPI, so as to go beyond the Coulomb barrier for nuclear reactions involving heavy projectiles and targets. For the Pb-onto-Pb case, for instance, the requested energy is 9,5÷10 MeV/A.

The paper deals with the status of beam developments with the PIAVE-ALPI linac; covers the recent and present upgrades in the SC QWR performance; describes the being performed upgrade of the cryoplant which, for the first time, gives that minimum redundancy in refrigeration power which makes it possible to add two cryostats with accelerating cavities at the end of ALPI. The reuse of the two "bunching" cryostats CRB2 and CRB4 as "accelerating" ones is finally discussed, together with proposal for new bunching units in their place.

BEAM DEVELOPMENTS WITH THE ECR ION SOURCE

Albeit affected by the limited time left available by nuclear physics experiments, the development of new beam species with the ECR ion source made some progress lately. The original Alice ion source was replaced in 2008 by a Supernanogan type ECRIS (Pantechnik), a source which – though not being top rated in terms of performance - was particularly suitable for use on the PIAVE HV platform thanks to its whole-permanent-magnet structure. Beams of noble gases were tested and made available pretty soon (Ar, Kr, Xe), together with a number of species which had already been developed by the company itself (Ag, Ta, Au).

Table 1: Present Performance of PIAVE-ALPI Beams, in Terms of Final Energy (MeV/A) and Current (pnA)



THE COMPACT PULSED HADRON SOURCE STATUS*

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Abstract

The Compact Pulsed Hadron Source (CPHS) at the Tsinghua University in Beijing, China has been reported in this paper. CPHS consists of a proton linac, a neutron target station, and a small-angle neutron scattering instrument, a neutron imaging/radiology station, and a proton irradiation station. The proton linac accelerator part is composed of a ECR ion source, LEBT section, a RFQ accelerator, a DTL linac and a HEBT. Up to now, the IS/LEBT and the RFQ have ready. The first phase of the CPHS construction is scheduled to complete 3MeV proton beam on the target in the end of 2012.

INTRODUCTION

In 2010 June, Tsinghua University, in order to respond the increasing demand in China of accelerator-based neutron and proton experimental platforms for basic researches and technological developments, startup a project of building a Hadron Application and Technology Complex (HATC) which begins with a relatively small and moderate-power facility but later expandable. The initial phase of the HATC is called the Compact Pulsed Hadron Source (CPHS)[1]. The missions of CPHS are education student & staff training; instrumentation and R&D; neutron instrumentation tests; limited-scale science discovery & applications with neutron imaging & scattering instruments. It will be completed as soon as possible in 3 years.

CPHS consists of a proton linac (13 MeV, 16 kW, peak current 50 mA, 0.5 ms pulse width at 50 Hz), a neutron target station, a small-angle neutron scattering instrument, a neutron imaging/radiology station, and a proton irradiation station. The initial phase of the CPHS construction is scheduled to complete in the end of 2012.

The accelerator consists of a ECR ion source, LEBT section, a RFQ accelerator, a DTL linac and a HEBT. ECR ion source will give up to 60mA at 50keV proton beam with proton ration large than 85%, and 0.02 πcm mrad normalized rms-emittance. A very short length of LEBT(less than 1.3m) will be used to matching the beam from ion source to the RFQ entrance. A 3 meters long of RFQ accelerate the proton to 3MeV. No MEBT will be requirement in this project. The Drift Tube Linac with permanent magnets focusing lens will accept the proton beam direct from RFQ. A 4.3 meters length of DTL with 43 cells will accelerate the beam up to 13MeV and the HEBT section will transport the proton beam from output of DTL to the Be target inside with 3.5cmX3.5cm uniform distribution. The main parameters of CPHS are listed in Table 1. Figure 1 shows the CPHS facility layout.

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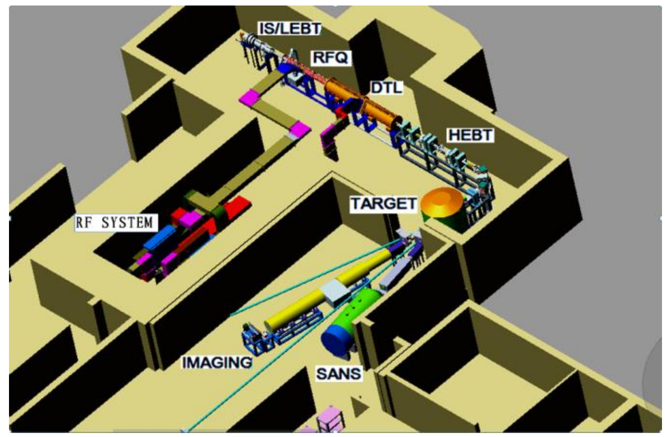

Figure 1: CPHS main facility layout.

Table 1: CPHS primary design parameters.

Species	proton
Proton power on target （kW）	16
Proton energy （MeV）	13
Average beam current（ mA）	1.25
Pulse repetition rate（ Hz）	50
Protons per pulse	1.56×10^{14}
Pulse length （ms）	0.5
Peak beam current（ mA）	50
Target material	Be
Moderator type	H_2O (300K), CH_4 (20K)

IS & LEBT

The proton beam is produced from the electron cyclotron resonance (ECR) proton source (2.45 GHz, 1.5 kW) and transported through the LEBT. The H_2 plasma is restricted by an axial magnetic field shaped by the source body of an all-permanent-magnet (NdFeB rings) design. The 50 keV pulsed beam of 0.5 ms length is extracted by a four-electrode system. The 1.3 m long LEBT consists

DEVELOPMENT OF NRA SYSTEM FOR A 1.7 MV TANDEM ACCELERATOR

- HUMAN RESOURCE DEVELOPMENT PROGRAM FOR NUCLEAR ENGINEERING, THE UNIVERSITY OF TOKYO -

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The University of Tokyo

Abstract

Extremely high sensitivity has been required in the measurement of light elements for the frontier materials science. Ion beam analysis can meet this. We have developed a new NRA system. The system shown successfully its performance by the demonstrative experiment in which fluorine profiles in TiO2 substrate were clearly obtained using 19F (p, αγ)16O reaction.

This system was applied for the student experiment. The newly developed NRA system has great potential for the frontier research.

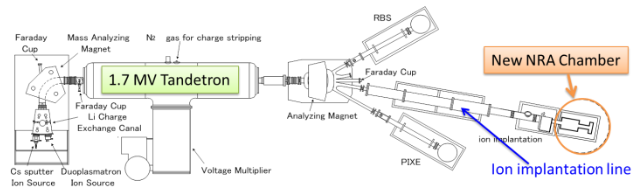

Figure 1: Schematic illustration of the RAPID.

INTRODUCTION

The 1.7MV tandem accelerator (Rutherford Backscattering Spectroscopic Analyzer with Particle Induced X-ray Emission and Ion Implantation Device, RAPID) at the University of Tokyo has been used for various research projects and educational studies since its installation in 1994. Additively, it has been used for the educational purpose recently. Model experiments with ion beam analysis are very helpful for students to understand ion-material interaction which is the foundation of nuclear engineering and materials processing.

Several developments and modifications have also done for new research including, for example, a low level ion irradiation system [1]. In the fall of 2011, we were newly developed a NRA (Nuclear Reaction Analysis) system in order to respond to the recent demand for the sensitive quantification of light elements (H, N, O, F, etc). The performance of new NRA system were demonstrated using 19F (p, αγ)16O reaction. This demonstration was so simple to understand that this model experiment immediately arranged to a student experiment program. The program was used as a part of "Human resource development program for nuclear engineering" proceeded by our department. The new NRA system has great potential for the frontier research for the materials science and functional material process engineering.

DEVELOPMENT OF NEW NRA SYSTEM

Figure 1 shows the schematic illustration of the 1.7MV tandem accelerator RAPID. RAPID has three beam lines: RBS&ERDA, PIXE and Ion implantation course.

The angle of Ion implantation line is fixed at -7° to the central axis of the accelerator to eliminate neutral particles. NRA detection system was newly developed at the end of the ion implantation line.

Outline of New NRA System

Figure 2 shows the layout of new NRA system. The new NRA chamber consists of the main chamber, the sample insertion port and a vacuum pump. The Gamma ray induced by proton beam is detected with a 4 inch bismuth germanate scintillation detector. The BGO detector put in perpendicular to the direction of proton beam travel. The NRA system has several features as follows:

1) Chamber design for high counting efficiency.
2) Effective electron suppression.
3) Effective avoidance against charge-up by using fine copper mesh.

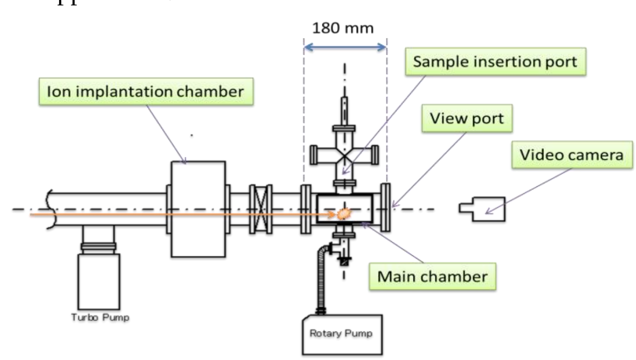

Figure 2: Layout of new NRA system.

Main Chamber

Figure 3 shows the top view of the main chamber. The special feature is a deeply scooped duct to make the BGO detector being close to the reaction position. Electron suppressor electrode is put in front of the target. The shape of the suppressor is specially designed to suppress secondary electrons effectively. By this design, large effective solid angle for the detector is realized.

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NEW DEVELOPMENTS AT THE TANDEM ACCELERATORS LABORATORY AT IFIN-HH

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Abstract

The upgrade of the 9 MV Tandem accelerator at IFIN-HH started in 2006. Remarkable work was done in the last 6 years that can be seen in the improved performance and reliability of the machine. Using original preparation techniques, some new beam species were tested for the first time in our laboratory. This opened the door to new experiments. A major improvement for the laboratory is the installation of 1 MV Tandetron accelerator dedicated to ultra-sensitive accelerator mass spectrometry (AMS) measurements of ^{14}C, ^{10}Be, ^{26}Al and ^{129}I, and 3 MV Tandetron accelerator dedicated to ion beam analysis (IBA). The main directions of the research activity in the laboratory will be shortly presented.

INTRODUCTION

The Bucharest FN Tandem accelerator was commissioned in 1973. The accelerator was produced by High Voltage Electrostatic Corporation - HVEC USA. The first upgrade of the machine was done in 1983 when a new negative Cs sputtering ion source was installed [1] and the maximum accelerating voltage on the terminal was increased from 7.5 to 9 MV by installing new accelerating tubes with stainless steel elements and inclined field and introducing of SF_6 into the insulating gas mixture. In 1977 the accelerator column was destroyed and in 1986 it was partially damaged by two major earthquakes.. Following these two events a second major upgrade was done, thus the earthquake protection system was installed [2].

Starting with 2006 a major upgrade program is ongoing. The upgrade works from 2006 to 2009, which include the installation of the pelletron charging system, a new sputtering ion source, a dedicated sputter ion source for AMS measurements, installation of titanium, spiraled field accelerator tubes, a lithium charge exchange alpha source, nanosecond pulsing system, new power supplies for the major ion optics elements, and refurbishment of the vacuum system were already reported in Ref. [3].

Nevertheless the upgrade program of our main accelerator continued and other two major experimental facilities are already installed. The upgrade of the electrical system of the main ion optic elements on the tandem accelerator continued with renewal of the power supplies of the beam deflection elements. The old stabilization system of the accelerator functioning since 1973 was also replaced with an in house version, improving the stability of the accelerated beam. The alpha source installed in 2006 was upgraded to a more stable and reliable version. In order to ease the operation of the main power supplies of the bipolar magnets and beam deflectors, automated control system of the power supplies was realized. One important improvement of the accelerator is the installation of a new gas transfer system (made by DILO [4]). Compared with the old system using oil vacuum pumps and compressor, the new system is a state-of-the-art system specially customized to work with our machine. The new gas plant will improve the quality of insulating gas due to its oil free pumps and compressors and will diminish the gas losses at each transfer to an acceptable level. For the safety of the stripping foils and for protecting the accelerating tubes of accidental migration of carbon stripping foils inside them, a fast closing valve [5] was installed on the high energy section after the analyzing magnet. With this occasion, all the beam lines were replaced before and after the analyzing magnet with new beam lines having vacuum treated surfaces, thus improving the vacuum in that area.

One of the most important achievements for the research studies done at the tandem accelerator in this period were the new delivered beams that opened the possibility for new physics experiments in fields of basic and applied research.

Starting with 2010 two new HVE Tandetron accelerators [6] were installed in IFIN-HH with the support of an infrastructure grant [7] funded by the National Authority for Scientific Research [8]. The 1 MV Tandetron accelerator, along with its chemistry laboratory is dedicated for ultra-sensitive accelerator mass spectrometry measurements of C, Be, Al and I elements. The 3 MV machine, presently under commissioning, is dedicated for ion beam analysis techniques. Both machines are aimed to continue the long tradition in the applied physics research, currently being done at the 9 MV tandem accelerator.

MAIN UPGRADES OF THE 9 MV FN PELLETRON TANDEM ACCELERATOR

Upgrade of the Beam Steering System Power Supplies

The beam deflection system of the accelerator is an important part in the operating procedure. The beam quality and stability was often affected by the defective operation

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TERMINAL VOLTAGE STABILIZATION OF PELLETRON TANDEM ACCELERATOR

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Abstract

An NEC terminal voltage stabiliser TPS-6.0, based on conventional corona control, has been installed and investigated on the ANU 14UD tandem accelerator. The fluctuations in the charge transport of the electrostatic pelletron generator and their correlation with mechanical oscillations of the chains and terminal voltage ripple have been analysed. Emphasis during commissioning is placed on the components of the two-loop feedback system and on the application of this system to production of high energy-resolution beams. The relationship between transfer functions for the two loops required for optimum operation is discussed. This system produces the beam position at the image slit of the 90° energy-analysing magnet with long-term stability equivalent to a 3.9 kV FWHM fluctuation of the terminal voltage. The concept of novel fast control loop utilizing the high-frequency component from the image slits to control the voltage of the last gap of high-energy acceleration tube is described.

INTRODUCTION

A variety of nuclear physics experiments require the minimum energy spread of particle beams. High-energy resolution is also required for the need in beam position stability at applications of ion beam analyses. Several methods have been employed to achieve beam energy resolutions of $\Delta E/E = 10^{-4}$ to 10^{-5} in the electrostatic accelerators. In small machines with a terminal voltage below 5 MV, the stabilization system can be implemented by controlling the up-charging voltage [1]. The modulation of the amplitude of down-charge has a more rapid effect on the terminal voltage than corresponding changes in up-charge. The Daresbury 30 MV tandem has used the laddertron down-charge with the response speed limited to 0.06 s delay [2]. Burger *et al.* refer to the stable periodic pattern of the acceleration voltage fluctuations and have introduced "predictive fluctuation compensation" [3]. A TUNL system has implemented the terminal collector filter circuit for charging system [4]. The potential of the terminal can be controlled by varying the current load [1]. A fast response variation is achieved by modulating the electron beam from a gun at a base of the tube.

Since the weak components of the control loop are the signal delay characterizing the corona transfer function and the response of down-charge or variable load systems, a more direct energy-affecting element with fast response is desirable. The components for the application of the corrective voltages are the ion source, the terminal or the stripper, the high energy end of the accelerator and the target. Reference [1] describes a terminal ripple reduction system consisting of a capacitive liner along the tank wall facing the terminal, to which a terminal correction voltage derived from a capacitive pick-up or slit current signal is applied. Modulating the terminal stripper is another alternative [5]. The energy of the particles at the terminal is high enough so that a few kV energy modulation does not affect the optics. At a number of laboratories, various techniques such as time of flight, data gating, energy sorting and target potential modulation are being used to improve the energy resolution.

We will describe an energy feedback system yielding high-resolution particle beams, which has been developed for the ANU Heavy Ion Accelerator Facility (HIAF). This system utilizes two principal feedback mechanisms. The standard feedback loop employs a correction signal derived from summing the signal from capacitive pickoff plates (CPO) with a slit difference signal or a generating voltmeter (GVM). This signal is applied to the control grid of a high voltage triode 6BK4 connected to corona points mounted inside the tank. The maximum cut-off control frequency is below 10 Hz because of the transit time for electrons from the corona points to the terminal. Since information about higher frequency beam energy variations is present in the slit difference signal, the correction voltage is generated and applied to the last gap of the high-energy acceleration tube. This new method has the same advantage as modulation of terminal stripper. However it is much simpler since the control element is located at ground potential. The fast correction loop has not been implemented yet and is at R&D stage. In this paper, we will describe elements of both systems, its application for the production of high-resolution particle beams and some measurements of system performance.

DESCRIPTION OF THE HIAF VOLTAGE CONTROL SYSTEM

The GVM signal is only capable of showing relatively slow voltage variations (<1 Hz) due to the dc filtering of the ac signal generated as the grounded rotating vane alternately covers and uncovers the stator plates connected to the GVM amplifier. The momentum analysed currents intercepted by the control slits at the image position are fed into two matched low-noise logarithmic pre-amplifiers. The slit signals are coupled to the pre-amplifier by short 2 m coaxial cables. The

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LINAC EXPERIENCE IN THE FIRST TWO YEARS OF OPERATION @ CNAO (CENTRO NAZIONALE ADROTERAPIA ONCOLOGICA)

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Abstract

CNAO is the first medical accelerator facility for deep hadrontherapy with protons and carbon ions in Italy. The LINAC injector at CNAO, entirely built by the GSI and Frankfurt University collaboration, is equal to the HIT LINAC working in the hadrontherapy centre of Heidelberg, Germany [3]. It includes a four-rods type RFQ structure accelerating up to 400 keV/u and an IH structure to increase the energy up to 7 MeV/u. Such LINAC works as injector in a 78 m circumference synchrotron where the protons and carbon beams reach respectively 250 MeV/u and 400 MeV/u. The LINAC commissioning was performed during 2009 and from beginning of 2011 it entered into routine and continuous operation (24hrs, 7days). First patient was treated in September 2011. Maintenance periods are foreseen three times per year. Different diagnostic elements are installed along the injection line, like profile grids, faraday cups, current transformers, capacitive pick-ups. The principal parameters are daily monitored, like output energy by means of online not destructive ToF measurements, cavities voltage, cavities RF forward power and beam current transmission. No major faults were observed in the first two years of operation. LINAC beam energy is stable within 0.02 MeV/u on a typical value of 7.17 MeV/u. The relation between LINAC extraction and synchrotron injection is under investigation. This paper summarizes the monitoring issues (i.e. reproducibility of settings and beam parameters as well as long term stability measures) on the CNAO LINAC during daily patient treatments and outlines the measurements performed in the initial commissioning compared within actual status.

THE CNAO MACHINE

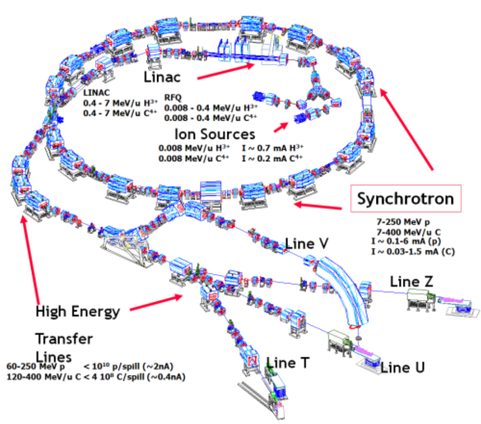

Figure 1: Sketch of the CNAO machine complex.

CNAO machine is depicted in Fig.1.

Particles originate from one of the two Electron Cyclotron Resonance (ECR) sources, producing either C^{4+} or H^{3+} ions, at 8keV/u; they travel along the LEBT line and the LINAC reaching 7MeV/u energy and pass through the Medium Energy Beam Transfer (MEBT) line where a debuncher cavity is placed in order to reduce the beam energy dispersion. Then particles are accelerated in a 25m diameter synchrotron and, finally, are extracted into one of the four extraction lines, delivering either C^{6+} or proton beam to one of the three treatment rooms.

Extraction energy depends on treatment requirements: the deeper is the tumour to be irradiated, the higher is the required energy. Extraction energy can vary from 120 to 400MeV/u for Carbon ions and from 60 to 250MeV/u for protons. Extraction process is of the order of one second.

Actually beam maximum intensity at patient is $5 \cdot 10^9$ and $1 \cdot 10^8$ particles/s per spill, for protons and Carbon ions respectively. It can be reduced up to a factor 10, by inserting pepper-pot filters in the MEBT line and extracting the beam with spills over a longer extraction time.

THE CNAO MEDICAL EXPERIENCE

From September 2011, 21 patients were treated with protons with an average of 6 patient/day and 35 treatment sessions/patient [1]. Each session is done by two different fields with different irradiation angles for a total of about 10-15 minutes of beam irradiation. The selected cases are principally chordoma (16 patients) and chondrosarcoma (5 patients) tumours in the head-neck (13 patients) or pelvis (8 patients) districts.

For head and neck tumors, solid mask, bite block, infrared-reflecting markers are used for patients fixing into couch. For pelvis tumors, the patient is fixed by means thermoplastic body mask. The dose uniformity is within the requested limit of ± 2.5%.

Today all the 148 foreseen energies are applied for treatments, one room is used with proton beams and with a fixed spot size of 1 cm using a couch for patient positioning.

During next year it will be possible to work all the three rooms, including the vertical line, with variable spot size of proton and carbon ions; in the treatment room both chair and couch for patient positioning will be available.

THE LINAC INJECTOR

The layout of the CNAO injector includes two ECR ion sources and the LEBT [5]. A particularity of the CNAO

PHYSICAL DESIGN OF THE SPES FACILITY

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Abstract

SPES (Selective Production of Exotic Species) is the Italian project for a rare isotope beam (RIB) facility based on a cyclotron as primary accelerator and on the existing superconducting linac ALPI as post accelerator. The cyclotron, energy up to 70 MeV and total current of 0.75 mA, shared on two exits, is in construction in the industry. The production of neutron-rich radioactive nuclei, with ISOL technique, employs the proton induced fission on a direct target of UCx; the fission rate expected with a proton beam of 40 MeV and 0.2 mA, is 10^13 fissions/s. The main goal of physical design of the SPES facility is to provide an accelerator system to perform forefront research in nuclear physics by studying nuclei far from stability, in particular neutron-rich radioactive nuclei with masses in the range of 9–160.

The final RIB energy on the experimental target will be up to 10 MeV/A for A = 130, with an intensity in the range of 10^7–10^9 pps.

INTRODUCTION

The SPES strategy is to develop a facility for Nuclear Physics research together with a facility for applied Physics based on the same technology and infrastructure.

SPES [1] is designed to provide neutron-rich radioactive nuclear beams (RIB) of final energies in the order of 10 MeV/A for nuclei in the A= 9-160 mass region. The radioactive ions will be produced with the ISOL technique using the proton induced fission on a Direct Target of UCx [2] and subsequently reaccelerated using the PIAVE-ALPI accelerator complex [3]. A Uranium fission rate of 10^13 fission/s is foreseen.

A Cyclotron with a maximum current of 0.750 mA rowing two exit ports will be used as proton driver accelerator with variable energy (30-70 MeV).

Two proton beams can be operated at the same time sharing the total current of 0.750 mA. To reach a fission rate of 10^13 fission/s a proton beam current of 200 µA (40MeV) is needed; the second beam, up to 500 µA 70MeV, will be devoted to applications; mainly neutron production for material research and study of new isotopes for medical applications.

The expected rate of fast neutrons is estimated to be 10^14 n/s at the target output using a Pb target (mean energy 1MeV).

The ISOL technique for radioactive beam production is based on a driver accelerator which induces nuclear reactions inside a thick target. The reaction products are extracted from the target by thermal process, ionized 1+, isotopically selected, ionized n+ and injected into a re-accelerator. In order to produce neutron-rich isotopes it is mandatory to perform fission reactions in Uranium or other actinide targets using protons, deuterons, neutrons or gammas. The SPES choice is to use a proton beam to induce fission on a UCx target (Direct Target).

Fig. 1 shows schematically the SPES main elements located at underground level, a second floor at ground level hosting laboratories and services is not shown.

The driver is the proton cyclotron delivering beam on different targets. Two production ISOL targets are planned to be installed. The production target and the first mass selection element will be housed in a high radiation bunker. Before the High Resolution Mass Spectrometer (HRMS) a cryopanel will be installed to prevent the beam line to be contaminated by radioactive gasses and a RFQ cooler to reduce the input emittance of the HRMS. After passing through the HRMS, the selected isotopes will be stopped inside the Charge Breeder and extracted with increased charge (n+). A final mass selector will be installed before reaching the PIAVE-ALPI accelerator, to clean the beam from the contaminations introduced by the Charge Breeder itself.

Two facilities for applied physics are planned: a neutron facility that make use of the proton beam to produce neutrons and an irradiation facility for production and study of radioisotopes for medical use.

KEK DIGITAL ACCELERATOR AND RECENT BEAM COMMISSIONING RESULT*

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Leo Kwee Wah, Graduate University of Advanced Studies, Hayama, Kanagawa Japan
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Abstract

The early beam commissioning of the KEK digital accelerator, which consists of novel accelerator components such as a permanent magnet x-band ECRIS, an Einzel lens longitudinal chopper, an electrostatic injection kicker, and induction acceleration devices, is reported here. Performance of the Einzel lens longitudinal chopper is described. Results of beam commissioning, such as the beam orbit correction, barrier bucket bunch capture, and induction acceleration are described.

INTRODUCTION

The KEK digital accelerator (DA) is a small-scale induction synchrotron (IS) without a high-energy injector [1]. The concept of an IS was experimentally demonstrated in 2006 [2] by utilizing the KEK 12 GeV PS. Instead of an RF cavity, an induction cell is employed as the acceleration device. It is simply a one-to-one transformer, which is energized by a switching power supply generating pulse voltage. Two types of induction cells for acceleration and confinement are employed. It is a crucial point of the IS that voltage timing is controlled by a gate signal of solid-state switching elements based on bunch signals detected at the bunch monitor. This operational performance enables acceleration of ions from extremely low velocities, and is the reason why the DA does not require a high-energy injector. It is understood from these properties that the DA is capable of accelerating any species of ion, regardless of possible charge state.

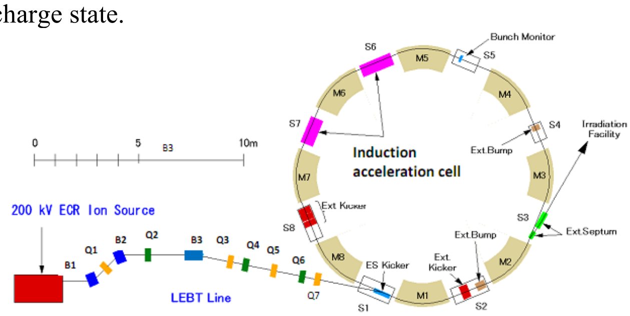

Figure 1: Outline of the KEK Digital Accelerator.

In the KEK DA, schematically shown in Fig. 1, a 5 msec long ion beam is created in the electron cyclotron resonance ion source (ECRIS) and chopped by the newly developed Einzel lens chopper in 5 μsec and post-accelerated in the acceleration column attached with the 200 kV high-voltage terminal (HVT), after which it propagates through the low-energy beam transport line (LEBT) to be injected into the ring with the electrostatic injection kicker. The electrostatic kicker voltage is turned off before the injected beam pulse completes a single turn in the DA ring, which is a rapid-cycle synchrotron. The injected beam is captured with a pair of barrier voltage pulses and accelerated with pulse voltages, the pulse length and amplitude of which are controlled in digital. He1+ ions beam commissioning in the KEK-DA is described here.

MACHINE

Permanent Magnet ECRIS [3]

The ECRIS is embedded on the DC 200 kV high voltage platform. In order to minimize the consumed electric power and avoid troublesome of water cooling on the high voltage platform, the permanent magnet ECRIS being operated in the pulse-mode (10 Hz and 2-5 msec) has been developed. This ECRIS driven by a 9.35 GHz TWT with a maximum output power of 750 W is capable of producing from hydrogen ion to Argon ion, which are extracted at 10-14 kV. The HVT including the Einzel lens chopper and the post-acceleration column is schematically shown in Fig.2.

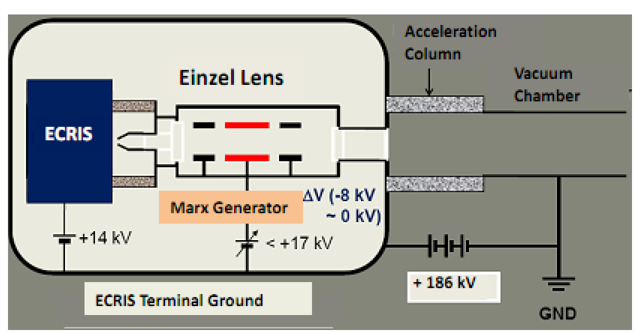

Figure 2: Schematic of the HVT and its contents.

Einzel Lens Chopper[4]

As stated in the above introductive part, the revolution time-period of ions in the KEK-DA is around 10 μsec. The single-turn injection scheme requires a pulse length

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LASER ABLATION OF SOLIDS INTO AN ELECTRON CYCLOTRON RESONANCE ION SOURCES FOR ACCELERATOR MASS SPECTROSCOPY

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Abstract

A project using accelerator mass spectrometry (AMS) is underway at the ATLAS facility to measure the atom densities of transmutation products present in samples irradiated in the Advanced Test Reactor at INL. These atom densities will be used to infer effective actinide neutron capture cross-sections ranging from thorium to californium isotopes different neutron energy spectra relevant to advanced fuel cycles. This project will require the measurement of many samples with high precision and accuracy. The AMS technique at ATLAS is based on production of highly-charged positive ions in an ECRIS followed by injection into a linear accelerator. We use a picosecond laser to ablate the actinide material into the ion source. We expect that the laser ablation technique will have higher efficiency and lower chamber contamination than sputtering or oven evaporation thus reducing 'cross talk' between samples. In addition a multi-sample holder/changer is part of the project to allow for a quick change between samples. The results of off-line ablation tests and first results of a beam generated by the laser coupled to the ECR are discussed as well as the overall project schedule.

INTRODUCTION

Advanced nuclear fuel cycles are currently under evaluation in order to assess their potential to cope with new requirements of radioactive waste minimization, optimization of resource utilization and reduced risk of proliferation. This assessment should account for several key features of the fuel cycle, as of irradiated fuel processing, innovative fuel development and fabrication, waste characterization and disposal. In some cases, the impact of nuclear data and of their associated uncertainties can be crucial in order to assess further exploration. The need for accurate data has been pointed out in recent studies devoted to Generation-IV systems, see e.g. [1]. The very high mass actinides can play a significant role in the feasibility assessment of innovative fuel cycles. As an example, the potential build-up of ^{252}Cf when recycling all transuranics in a light water reactor, leads to increased neutron emissions that could impact the fuel fabrication process [2]. As a consequence, the poorly known nuclear data of higher mass transuranics need to be significantly improved.

At present, most evaluated data files provide some information on these isotopes, but up to now, there has been little emphasis on the quality of these data and very little reliable uncertainty estimations have been provided. This situation is due to the difficulty to make both integral and differential cross section measurements for these isotopes.

The MANTRA (Measurements of Actinides Neutrons Transmission Rates with Accelerator mass spectroscopy) project objectives are to obtain valuable integral information about neutron cross sections for actinides that are important for advanced nuclear fuel cycles. The proposed work takes advantage of two experimental facilities: the neutron irradiation capabilities of the Advanced Test Reactor (ATR) at the Idaho National Laboratory and the Accelerator Mass Spectrometry (AMS) capabilities of the Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory [3].

In this paper we will concentrate on the requirements of the AMS program and the novel aspects, namely the laser ablation and the multi-sample changer, that are implemented at the ECR ion source to carry out this research project. The requirements placed on the AMS measurements to be performed at ATLAS are quite challenging. These challenges include high-precision isotope ratio measurements, minimization of cross-talk between samples, efficient use of milligram samples, and the processing of an unprecedented number of samples for a facility as complex as ATLAS. Unique element (Z) identification is desirable, but is not expected to be possible except for specific cases.

The measurement configuration for ATLAS uses the ECR-II ion source [4], significantly modified as discussed below, as the source of ions. After acceleration and deceleration (increasing the accelerator m/q resolution but keeping the ion energy within acceptance range of analytical elements) in the ATLAS linac to approximately 1 MeV/u, the actinide ions of interest are counted in the focal plane of the Fragment Mass Analyzer (FMA) [5].

EXPERIENCES AND LESSONS LEARNED AT CARIBU WITH AN OPEN 252CF SOURCE

S.I. Baker, J.P. Greene, A. Levand, R.C. Pardo, G. Savard, R.C. Vondrasek, L.W. Weber [ANL, Argonne, USA]

Abstract

The CARIBU (the CAlifornium Rare Ion Breeder Upgrade) project at ATLAS is based on the creation of beams of neutron-rich nuclei produced as fission fragments from the 3% fission branch that occurs naturally in the decay of Cf-252. These fission fragments are thermalized in ultrapure helium gas and turned into a charged beam for use by the ATLAS accelerator or 'stopped' beam experiments. This requires a very thin source, electroplated on a stainless steel or platinum backing so that the fission fragments escape into the helium gas and are efficiently thermalized and collected into an ion beam. The information learned from the successive use of two sources with strengths of 2 mCi and 100 mCi has now prepared us for the installation in mid-summer of a 500 mCi source recently produced by Oak Ridge National Laboratory. This paper will describe the radiological monitoring system and our experience with the two weak "open" sources which have exercised and tested our radiological controls, emissions monitors, and procedures for the CARIBU facility and the source transfer area.

CONTRIBUTION NOT RECEIVED

ADVANCED ACCELERATOR TECHNOLOGY ASPECTS FOR HADRONTHERAPY

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Abstract

Nowadays cancer can be considered as one of the wide spread diseases all around the world. About 50% of the patients are successfully cured and in 40% of these cases radiotherapy is the applied treatment modality. Radiation beams are produced by particle accelerators and about 30% of the 17500 particle accelerators running in the world are devoted to radiotherapy.

Classical radiotherapy employs photons and electrons that damage the diseased cells but irradiate also the healthy ones. A better conformation of the dose to the tumour and an increasing sparing of the healthy tissues is obtained using hadrontherapy, a high-precision radiotherapy exploiting the depth-dose deposition characteristics of hadronic particles.

The first hadrontherapy treatments have been performed in particle physics research centers clinically adapted; nowadays there are dedicated facilities designed and built as hadrontherapy clinical centres. The realization of machines for hadrontherapy is more challenging than standard radiotherapy: while many hospitals have a device for classical radiotherapy, hadrontherapy needs a dedicated complex with the needed technology for the hadron acceleration.

This paper will give an overview on the existing hadrontherapy centres presenting the technology that is applied in the hadrontherapy world.

HADRONTHERAPY RATIONALE

Cancer is one of the major world health problems: about 7 million people are known to die each year because of this disease. Cancer is the hysterical and irregular growth and propagation of a cluster of cells. Radiotherapy technique is based on the principle of using ionizing particles to damage the DNA of the cancer cells in order to first block their ability to regenerate and finally to cause their death.

As soon after their discovery in 1895, X-Rays have been used with medical purposes for the treatment of ill tissues. From these first completely empirical tests, radiotherapy has evolved a lot becoming an important tool in medicine and one of most exploited technique in the fight against cancer: about 40% of cancer patients are cured by radiotherapy, either alone (25%) or in combination with other techniques like surgery or chemotherapy. Nowadays among the 17500 accelerators running in the world, 50% are for medical use and more than 8000 are only for radiotherapy purposes.

Standard radiotherapy uses photons and electrons that deposit the maximum of their energy near the beam entrance and a significant part of energy also after the tumour target. As a consequence not only the tumour cells are damaged but also the healthy ones. Recently several techniques are employed to confine this problem: computer-aided optimization of the treatment plans (Intensity Modulated Radiation Therapy) allows to reach a better dose conformity irradiating from several directions and using collimators to transversally shaping the tumor. Anyway also considering the recent improvements, the depth dose deposition characteristics of the standard particles represent a great limitation and disadvantage in the radiotherapy field.

Hadrontherapy is the answer to this problem. Indeed it is based on the use of hadrons (the hadrons we are talking about are protons and heavy ions) whose Bragg curve is characterized by a narrow peak that occurs distant from beam entrance: this gives a good dose localization with low dose at the entrance and at the exit of tumour target. This effect is well shown in Fig. 1.

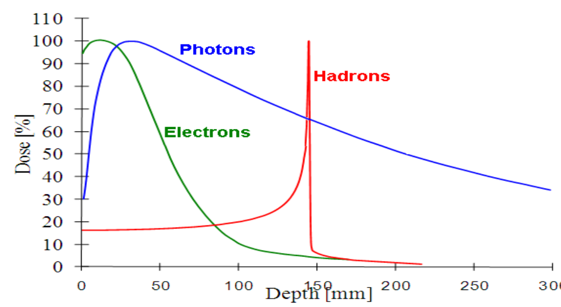

Figure 1: Bragg peaks in the case of photons, electrons and hadrons

This allows to shape the radiation field not only transversally but also longitudinally using several Bragg peaks at different penetration depths that create the so called SOPB (Spread Out Bragg Peak). In other words hadrontherapy is a high precision kind of radiotherapy. The hadrons mostly exploited are protons and carbon ions. Some figures of merit that allow to understand the advantages of hadrontherapy are the Linear Energy Transfer [1] (LET, whose value along the particle path describes the Bragg curve), the Relative Biological Effectiveness (RBE) [2], i.e. the ratio between the photon and ions doses to produce the same biological effect, the Oxygen Enhancement Ratio (OER) [3], i.e. the dose to produce a biological effect in the absence of oxygen to the dose to produce the same effect in oxygen presence. For Cobalt gamma rays the maximum LET is about 10 keV/μm, for protons it is approximated 100 keV/μm while for heavier ions it may reach 1000 keV/μm presenting a high value in the Bragg peak region and a low one at the beam entrance. The proton RBE is about 1 while ions heavier than helium have a RBE greater than 3 at the Bragg peak and about 1 in the entry channel. The photon OER is about 3 while it decreases when LET is greater than 100 keV/μm approaching to unit at 300

FOCUSING OF INTENSE HEAVY ION BEAMS WITH PLASMA LENSES

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Abstract

Gabor lenses are a special type of plasma lens using a stable confined electron cloud for beam focusing. The electrons provide space charge neutralization of the beam traveling through the lens volume. At the same time a radial symmetric electrostatic self field focuses the beam mass independently. It is possible to control the density and distribution of the confined electrons providing variable focusing strength and moderate emittance growth of the beam. The knowledge of the behavior of the electron column inside this lens type is essential to understand the impact on beam transport. Therefore several diagnostic tools were developed to measure the electron cloud properties with and without ion beam propagation through Gabor lenses. Based on experimental results a new Gabor plasma lens has been designed for focusing heavy ion beams. A comparison of this lens type and a superconducting solenoid is planned at the low energy transport section of the GSI - High Current Test Injector (HOSTI).

CONTRIBUTION NOT RECEIVED

ELECTRON BEAM ION SOURCES, TRAPS, AND STRINGS: VERSATILE DEVICES TO MEET THE HIGH CHARGE STATE ION NEEDS OF MODERN FACILITIES

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Abstract

Electron beam ion sources (EBIS) and its variants such as the electron beam ion trap (EBIT) and electron string ion source (ESIS) have been selected to provide highly charged ions for several atomic and nuclear physics facilities. Since the capture and breeding can be short and highly efficient, EBIST devices are increasingly being chosen for trapping and/or reacceleration of radioactive beams. The sources can range from petite to grand, using electron beams from ~1mA to 10A or more. They often serve accelerators and beam lines in large laboratories but they can be self contained laboratories where experiments are made in situ. We will discuss the basic principles as well as applications of these sources at various facilities around the world. Some emphasis will be placed on the recently commissioned RHIC EBIS source which is now providing beams for both high energy physics at the relativistic heavy ion collider as well as the NASA space radiation laboratory at BNL.

CONTRIBUTION NOT RECEIVED

COMMISSIONING OF CARIBU EBIS CHARGE BREEDER SUB-SYSTEMS*

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Abstract

A high-efficiency charge breeder based on an Electron Beam Ion Source (EBIS) to increase the intensity and improve the purity of accelerated neutron-rich radioactive ion beams is being developed by the ANL Physics Division. The design of the CARIBU EBIS charge breeder is complete and manufacturing of the components and sub-systems is in progress. Two key elements of the breeder - a 6-Tesla superconducting solenoid and a high-perveance electron gun were recently delivered and successfully commissioned. The current status of the ANL EBIS development and commissioning results of different EBIS sub-systems will be presented.

INTRODUCTION

The Californium Rare Isotope Breeder Upgrade (CARIBU) for the Argonne National Laboratory Argonne Tandem Linac Accelerator System (ATLAS) has been recently commissioned. In its full capacity, the CARIBU facility will use fission fragments from a 1 Curie (Ci) ^{252}Cf source [1]. The ions are thermalized and collected into a low-energy ion beam by a helium gas catcher, mass selected by an isobar separator, and charge bred to higher charge states for acceleration in ATLAS. To reach energies E/A ~ 10 MeV/u, one should inject ions with a charge-to-mass ratio (q/A) ≥ 1/7 into the ATLAS. In the first stage, the existing Electron Cyclotron Resonance (ECR) ion source is used as a charge breeder [2]. The maximum intensity of radioactive ion beams at the output of the gas catcher for a 1 Curie ^{252}Cf source will not exceed 10^7 ions per second. A charge breeder (CB) based on an Electron Beam Ion Source (EBIS) has significant advantages over the ECR option for ion beam intensities up to about 10^9 ions per second, providing higher efficiency, shorter breeding times and significantly better purity of highly charged radioactive ion beams for further acceleration. The EBIS CB project for CARIBU is heavily utilizing state-of-the-art EBIS technology recently developed at Brookhaven National Laboratory [3]. However, the parameters of the electron gun, potential distribution in the ion trap region, electron collector and injection/extraction lines are substantially modified to obtain the highest acceptance and breeding efficiency of low intensity rare isotope beams which is expected to be higher than 20%. Special attention was paid to the vacuum system because the vacuum inside the EBIS trap will define the purity of charge-bred radioactive ion beams.

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DESIGN OF CARIBU EBIS CHARGE BREEDER

In this section the main features of the CARIBU EBIS design will be highlighted. The main parameters of the CARIBU EBIS CB are presented in Table 1.

Table 1: Main parameters of CARIBU EBIS CB

Parameter	Low current e-gun	High current e-gun
Superconducting solenoid: length/field	1 m/6 T	1 m/6 T
Diameter of IrCe thermionic cathode	1.6 mm	4 mm
Electron beam current	0.2 A	2 A
Electron beam energy	~ 2 keV	~ 5 keV
Electron beam diameter in the trap	~ 230 μm	~ 580 μm
Electron beam current density in the trap	~ 480 A/cm^2	~ 750 A/cm^2
Ion trap length	0.5 m	0.5 m
Trap capacity (in elementary charges)	~ $4 \cdot 10^{10}$	~ $2 \cdot 10^{11}$

Two e-guns were developed and built for the breeder: a high-current (2 A) and a low-current (0.2 A) e-gun. The low-current e-gun will be used to study the possibility of higher breeding efficiency for shell closures with lower electron beam energies.

Prior to installation into the CARIBU-ATLAS beam line, the breeder will be commissioned off-line and breeding efficiency will be optimized by injecting a pulsed ion beam generated by a surface ionization Cs^+ ion source. Setup for off-line commissioning of the breeder is presented in Fig. 1.

Scintillator-based pepper-pot emittance meters [7] developed at ANL and Faraday cups will be installed at several locations along the injection and extraction lines to measure emittance and current of injected and extracted ion beams.

Eleven drift tubes are used to transport the electron beam from the EBIS e-gun to the collector entrance. All drift tubes have longitudinal slots to facilitate pumping of the ion trap volume (Figures 2 and 3).

DREEBIT EBIS/T FOR APPLICATIONS IN ACCELERATOR PHYSICS

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Abstract

Electron Beam Ion Sources and Traps (EBIS/T) provide light up to heavy ions of low up to high charge states for various applications in accelerator physics such as medical particle therapy and charge breeding. Beside the well-known but quiet costly superconducting EBIS/T type systems compact and permanent magnet-operated EBIS/T from the DREEBIT GmbH are available, favorable for low-budget projects. Moreover, the "flagship" of the DREEBIT ion source family, the superconducting EBIS-SC features operating parameters comparable to the complex and expensive systems in the EBIS/T community.

HIGHLY CHARGED IONS

Properties

Highly charged ions yield interesting properties, in particular for accelerator physics. They feature a very efficient acceleration potential since the kinetic energy gain increases linearly with the charge state for electrostatic accelerator and even quadratically with the charge state for circular accelerators. Furthermore, the potential energy of highly charged ions leads to high power deposition into surfaces connected with higher secondary particle emission at ion solid interactions.

Production

However, the production of highly charged ions (HCIs) has led to different technological approaches, such as ion stripping in ion accelerator structures, ECR ion sources, laser ion sources and Electron Beam Ion Sources/Traps (EBIS/T). Beside the mentioned technologies EBIS/T systems have proved as reliable and stable working sources of HCIs of the highest charge states.

EBIS/T

EBIS/T ionize initially neutrals and low charged ions in magnetically compressed high-dense electron beams up to high and very high charge states. Already small amounts of bare uranium ions have been produced.
Normally, such EBIS/T facilities feature special, sophisticated and complex laboratory installations of the superconducting ion source type.
There are only two suppliers in the world offering commercial EBIS/T systems. One of them is the DREEBIT GmbH Dresden (Germany) marketing a whole family of EBIS/T systems.

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The room-temperature Dresden EBIS/T with permanent magnets feature operating parameters which suit most of the user requirements at by far lower initial as well as maintenance costs (see Fig. 1). In addition, in order to satisfy the need for increased ion output, a liquid helium free superconducting EBIS (Dresden EBIS-SC) with closed-cycle refrigerator technology is available complementing the ion source portfolio of the company (see Fig. 2).

USER-SPECIFIC ION IRRADIATION FACILITY

Based on its ion source knowledge the DREEBIT GmbH has designed and comissioned several customer-specific ion irradition facilities equipped with Dresden EBIS/T systems (see Fig. 3). The facilities are complemented with the necessary ion optics and ion diagnostics such as Einzel lenses, deflectors, quadrupol beam bender, accel/decel lens systems, Wien filter, Pepper-Pot-Emittance Meter, Retarding-Field Analyzer, Faraday cups. Individual target chamber and target transfer systems. In dependence on the user need different configurations of ion sources and beamline equipment as mentioned above have been accomplished.

Figure 1: Room-Temperature EBIS/T.

APPLICATIONS

EBIS/T systems have been succesfully operated in low energy beamlines so far. In order to extend the application potential investigations on charge breeding as well as in medical particle therapy have been done.

ELECTRON AND ION BEAM DYNAMICS IN THE CARIBU EBIS CHARGE BREEDER

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Abstract

An Electron Beam Ion Source (EBIS) is being built to charge breed ion beams from the Californium Rare Isotope Breeder Upgrade (CARIBU) for acceleration in the Argonne Tandem Linear Accelerator System (ATLAS) at Argonne National Laboratory (ANL). The overall efficiency of the source and charge breeder system is important since CARIBU will produce many low intensity radioactive ion species. Simulations of the electron and ion beam dynamics have been used to determine the system's expected performance. The details of these simulations and results will be presented.

CONTRIBUTION NOT RECEIVED

ECRIS LATEST DEVELOPMENTS

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Abstract

The production of intense beams of highly charged ions (HCI) is one of the most relevant challenge for the future accelerator facilities. Electron Cyclotron Resonance Ion Sources (ECRIS) are nowadays the most powerful devices able to feed accelerators with HCI in a reliable and efficient way. The reliability of frontier solutions for magnets and the increased costs for microwave generators make scaling to larger frequency not viable. Any further improvement of ECRIS output currents and average charge state requires a deep understanding of electron and ion dynamics in the plasma. In the past 20 years different teams have been working in the forefront of ion source developments with both experimental and theoretical activities, proposing different solutions to improve the production rate. The paper will discuss the most recent technological developments in the field, worldwide, together with the modeling issues of non-classical evidences like sensitivity of Electron Energy Distribution Function to the magnetic field detuning, influence of plasma turbulences on electron heating and ion confinement, coupling between electron and ion dynamics and relative impact on the formed ion beam.

CONTRIBUTION NOT RECEIVED

PRODUCTION 72 MHZ β=0.077 SUPERCONDUCTING QUARTER-WAVE CAVITIES FOR ATLAS

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Abstract

A total of eight 72 MHz β=0.077 superconducting quarter-wave cavities have recently been completed at Argonne National Laboratory. Seven of these will installed into the ATLAS superconducting heavy-ion linac as part of a beam intensity upgrade, with one remaining for the purposes of continuing to push the performance limits in these structures. Cavities were fabricated using techniques adapted the worldwide effort push niobium cavities close to the material limits. Key developments include the use of electropolishing on the complete helium-jacketed cavity. Wire EDM has been used instead of traditional niobium machining in order to minimize performance limiting defects near the weld seams. Hydrogen degassing at 600C after electropolishing has also been performed. Initial test results show practical acceleration at 4 Kelvin with cavity voltages, Vacc>3 MV/cavity and at 2 Kelvin with Bpeak>120 mT and Vacc>5 MV/cavity.

CONTRIBUTION NOT RECEIVED

STATUS OF THE HIE-ISOLDE PROJECT AT CERN

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Abstract

The HIE-ISOLDE project represents a major upgrade of the ISOLDE nuclear facility with a mandate to significantly improve the quality and increase the intensity and energy of radioactive nuclear beams produced at CERN. The project will expand the experimental nuclear physics programme at ISOLDE by focusing on an upgrade of the existing Radioactive ion beam EXperiment (REX) linac with a 40 MV superconducting linac comprising thirty-two niobium-on-copper sputter-coated quarter-wave resonators housed in six cryomodules. The new linac will raise the energy of post-accelerated beams from 3 MeV/u to over 10 MeV/u. The upgrade will be staged to first deliver beam energies of 5.5 MeV/u using two high-β cryomodules placed downstream of REX, before the energy variable section of the existing linac is replaced with two low-β cryomodules and two additional high-β cryomodules are installed to attain over 10 MeV/u with full energy variability above 0.45 MeV/u. An overview of the project including a status summary of the different R&D activities and the schedule will outlined.

INTRODUCTION

The High Intensity and Energy (HIE) ISOLDE project [1] aims at several important upgrades of the present ISOLDE radioactive beam facility at CERN. The main focus lies in the energy upgrade of the post-accelerated radionuclide beams from 3 MeV/u up to over 10 MeV/u through the addition of superconducting (SC) quarter-wave resonators (QWRs) operating at 101.28 MHz. This will open the possibility of many new types of experiments including transfer reactions throughout the nuclear chart.

The project also includes a design study that aims at improving the target and front-end part of ISOLDE to fully benefit from upgrades of the existing CERN proton injectors, e.g. LINAC4 and upgrade in energy of the PS Booster. This improvement combined with upgrades to the RILIS laser ion source and the radiofrequency quadrupole (RFQ) cooler and buncher (ISCOOL) will lead to an increase of radioactive beam intensities of up to an order of magnitude. The beam emittance will be improved with the implementation of ISCOOL placed after a pre-separator but before a new High-Resolution Separator (HRS). The new HRS, based on the latest magnet technology, will have sufficient mass resolution to permit isobaric separation. ISCOOL will also permit a tailoring of the time structure of the beam, removing the dependence on the proton beam time structure and diffusion-effusion properties of the target and ion source units. Highly charged ions will be provided for REX and other users through an improved low energy stage of REX-ISOLDE and a possible installation of an upgraded Electron Beam Ion Source (EBIS) charge breeder.

The linac upgrade will be staged in order to deliver higher beam energies to the experiments as soon as possible, with future upgrade stages ensuring a wide range of energy variability and providing an optional ∼100 ns bunch spacing. The first stage of the upgrade involves the design, construction, installation and commissioning of two cryomodules downstream of REX, the existing post-accelerator. These cryomodules will each house five high-β (β_g = 10.3%) SC cavities and one SC solenoid. Extra cryomodules will be added to the beam line in a modular fashion until all six cryomodules, including two cryomodules housing six low-β (β_g = 6.3%) SC cavities and two SC solenoids, are online. The upgrade will be completed with a final stage that will see the linac extended in order to make room to pre-bunch the beam into the existing RFQ accelerator at a sub-harmonic frequency below 101.28 MHz, allowing the bunch spacing to be increased without significant loss in transmission; time-of-flight particle detection will then be viable at the experiments. Also foreseen is a beam chopper to reject the background of populated satellite bunches either side of the main sub-harmonic beam pulses. The staged installation of the linac is shown schematically in Figure 1. The pre-

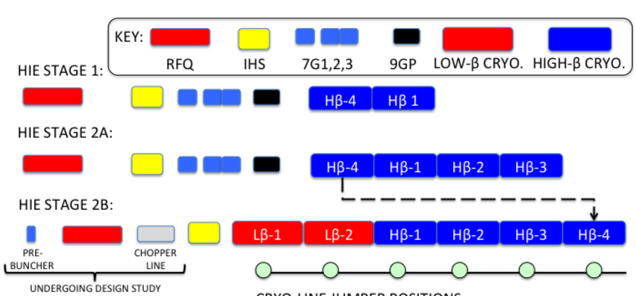

Figure 1: A schematic of the staged installation of the HIE-ISOLDE linac (Existing REX structures: RFQ, IHS: 20-gap IH-structure, 7GX: 7-gap split-ring cavities, 9GP: 9-gap IH-structure).

THE SC CW LINAC DEMONSTRATOR – 1ST TEST OF AN SC CH-CAVITY WITH HEAVY IONS

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Abstract

The superconducting (sc) continuous wave (cw) LINAC Demonstrator is a collaboration project between GSI, the Helmholtz Institute Mainz (HIM), and the Institute for Applied Physics (IAP) at the Goethe University Frankfurt. The aim is a full performance test of a 217 MHz sc Crossbar H-mode (CH) cavity, which provides gradients of 5.1 MV/m at a total length of 0.69 m. In addition the Demonstrator comprises two 9.3 Tesla sc solenoids. The configuration of a CH-cavity embedded by two sc solenoids is taken from a conceptual layout of a new sc cw LINAC with nine CH-cavities and seven solenoids. Such an accelerator is highly desired by a broad community of users requesting heavy ion beam energies in the Coulomb barrier range. A successful test of such an sc multigap structure is an important milestone towards the proposed cw-LINAC.

THE SC CH-CAVITY

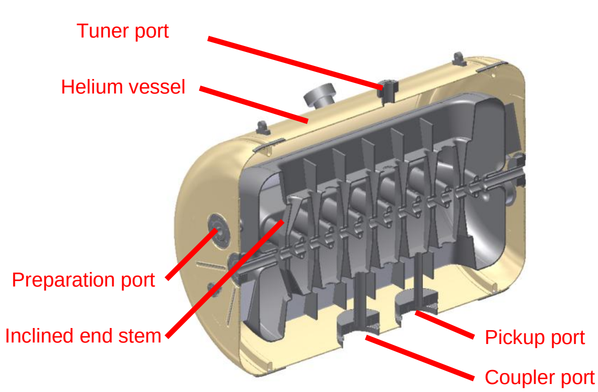

Figure 1: The 217 MHz sc CH-cavity.

The sc CH-cavity is the key component of the Demonstrator project. Four sc CH-cavity types were and are developed at the IAP so far:

(1) A first prototype of a 360 MHz sc CH-cavity (β=0.1, 19 gaps) was tested at the IAP successfully. In vertical rf-tests maximum gradients of up to 7 MV/m at Q_0-values between 10^8 and 10^9 were achieved [1, 2].
(2) The delivery of a 325 MHz sc CH-cavity (β=0.16, 7 gaps) is imminent [3]. The site acceptance test at RI, Germany is in progress. First rf-tests at room temperature were successful.
(3) The cavity designed for the cw-LINAC Demonstrator project (β=0.06, 15 gaps) is operated at 217 MHz (fig.1). Its general parameters are listed in table 1.
(4) The cold part layout of the 17 MeV injector of the MYRRHA (Multi-purpose hybrid research reactor for high-tech applications) project should comprise 176 MHz cavities [4].

THE SC CW LINAC DEMONSTRATOR

Although the results of the warm and cold rf-tests of the 360 MHz cavity at the IAP were very promising, for a proof-of-principle on the sc CH-cavities tests under real operational conditions must be passed. That is the aim of the Demonstrator project. At the GSI High Charge Injector (HLI) a 217 MHz sc CH-cavity should be operated with heavy ion beam.

The project is financed by HIM mainly and is supported by the Accelerator Research & Development (ARD) program of the Helmholtzgemeinschaft (HGF).

Table 1: General parameters of the sc CH-Cavity designed for the cw-LINAC Demonstrator.

β		0.059
max A/Q		6
Frequency	MHz	217
Gap number		15
Total length	mm	690
Cavity Diameter	mm	409
Gap length	mm	40.8
Aperture	mm	20
Effective gap voltage	kV	225
Voltage gain	MV	2.97
Accelerating gradient	MV/m	5.1

COMMISSIONING AND OPERATION OF SUPERCONDUCTING LINAC AT IUAC DELHI

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Abstract

The major part of the superconducting (SC) linac at IUAC has been operational for the past few years and the last accelerating module is in the final stage of completion. At present the superbuncher (SB), the first two linac accelerating modules and the re-buncher (RB) are operational and ion beams in the mass range ^{12}C to ^{107}Ag from Pelletron accelerator have been further accelerated and delivered to conduct scheduled physics experiments. A method of random phase focusing to select the accelerating phase of the resonators between 70° and 110° has been successfully tried to reduce the time width of the beam bunch delivered for experiments. Presently, to improve the accelerating fields of the linac resonators in phase locked condition, enhancement of the microphonics damping efficiency with bigger diameter SS-balls, testing of an alternate tuning mechanism based on Piezo Crystal and improvement of the cooling efficiency of the drive coupler are being tried out. The outcomes of all these experiments are being implemented on the resonators of the last cryostat which is under commissioning stage.

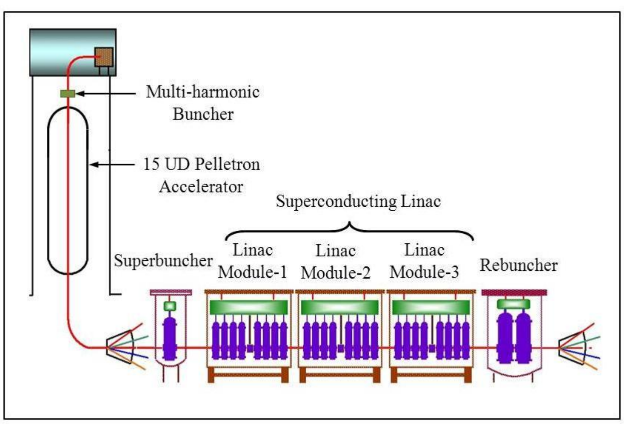

Figure 1: Schematic layout of Pelletron and Linac. The figure is not to scale.

INTRODUCTION

The Pelletron accelerator of IUAC has been delivering ion beams for experiments since early nineties in the energy range of few tens to few hundreds of MeV [1]. A Superconducting Linear Accelerator (Linac) was chosen to augment the energy of the ions from the existing Pelletron accelerator. The linac was designed to have a superbuncher cryostat having a single niobium Quarter Wave Resonator (QWR) followed by three accelerating modules, each containing eight QWRs and a rebuncher cryostat housing two QWRs. The complete layout of the Pelletron and linac is given in figure 1. The prototype niobium resonator and the first batch of twelve resonators were built by IUAC in collaboration with Argonne National Laboratory [2]. The remaining resonators for module 2 and 3 are indigenously fabricated using the in-house facilities of electron beam welding, high vacuum annealing furnace and surface preparation laboratory [3]. Eight indigenous resonators were installed in the second module and different beams were accelerated through the first two linac accelerating modules with the help of superbuncher and rebuncher. At present the fabrication work for the remaining resonators to be installed in the last linac module is in the final stage.

BEAM ACCELERATION THROUGH THE FIRST TWO LINAC MODULES

The beam acceleration in the mass range of ^{12}C to ^{107}Ag by the first accelerating module with the help of SB and RB resonators are being carried out since last few years [4,5,6]. Recently, the second accelerating module became operational and during this test, beams were accelerated by the sixteen resonators of module 1 and 2. The accelerating field obtained at ~6 watts of power and the phase locked fields at the time of beam acceleration are shown in figures 2 and 3. During linac operation, it was observed that for many resonators, there was a substantial reduction between the phase locked fields and the accelerating fields obtained at 6 watts of input power. A number of steps have been taken to tackle this problem and these are presented in next section.

At the time of operation of the first two linac modules, three beam species from Pelletron accelerator were further accelerated through linac. The final beam was delivered for several months in the beam line of Hybrid Recoil Mass Analyser (HYRA) and National Array of Neutron Detector (NAND) to conduct Nuclear Physics experiment. The beam and their final energies are presented in Table-1.

DESIGN STUDIES FOR A NEW HEAVY ION INJECTOR LINAC FOR FAIR

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Abstract

As the GSI UNILAC started operation in 1975, it will be more than 40 years old when the commissioning of the future Facility for Antiproton and Ion Research (FAIR) at GSI will start. To assure reliable operation for FAIR and to provide beams for a variety of experiments, three separate linacs were proposed and are under development: 1.) A dedicated 70 MeV proton linac will serve as injector for the FAIR pbar physics program. 2.) To deliver high-intensity heavy-ion beams for FAIR, the existing post-stripper linac at the UNILAC should be replaced by a new high energy heavy-ion linac with short beam pulses, low pulse repetition rate, and fixed end energy. 3.) A new superconducting cw heavy-ion linac behind the upgraded high charge state injector HLI shall provide ion beams with high duty cycle and adjustable energy in the MeV/u region for the super-heavy element program as well as for further UNILAC experiments. A conceptual design study for the second machine – a new heavy-ion linac injector for FAIR – using 108 MHz IH-type drift tube structures is presented, including a proposal to increase the ion charge states for synchrotron injection as well as a linac beam energy upgrade using 325 MHz CH structures.

INTRODUCTION

The Facility for Antiproton and Ion Research (FAIR) presently under development at GSI in Darmstadt (Fig. 1) will provide worldwide unique accelerator and experimental facilities allowing for a large variety of forefront research in physics and applied science. The FAIR accelerators will increase the intensity of primary proton and heavy ion beams available for experiments and for the production of secondary beams by up to two orders of magnitude with respect to the existing GSI facility [1]. Besides the realisation of the challenging FAIR SIS100 synchrotron, various upgrades of the UNILAC linear accelerator (Fig. 2) and of the SIS18 synchrotron play a key role to achieve the FAIR design intensities, since the existing GSI accelerators will serve as injection chain for FAIR [2–7]. As major design parameters, 15 emA U^{28+} beams at 11.4 MeV/u [2] and 70 mA proton beams at 70 MeV are required for SIS18 injection.

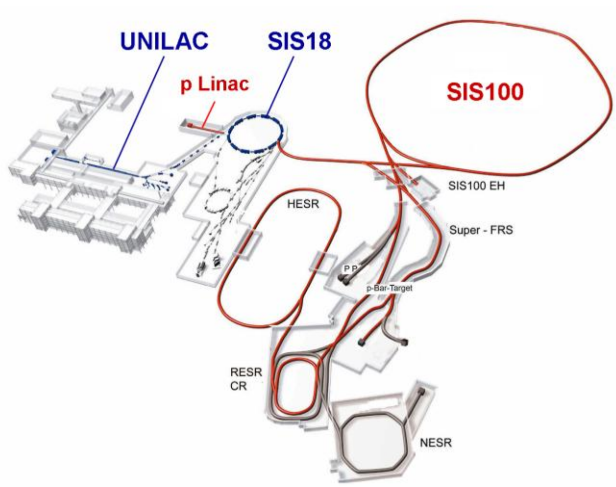

Figure 1: Sketch of the FAIR facility [1]. The existing GSI accelerators (indicated in blue) with the UNILAC heavy-ion linac and the SIS18 synchrotron will serve as injection chain for the new SIS100.

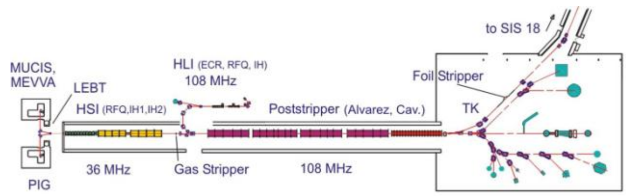

Figure 2: Layout of the present heavy-ion UNILAC accelerator at GSI and low-energy experimental area.

Present Linac Constraints and Proposals

For high current operation of the UNILAC [2], the 36 MHz High Current Injector (HSI) [8] – comprising a 120 keV/u IH-RFQ and two IH-DTL tanks – accelerates ion beams up to U^{4+} ($A/q \leq 59.5$) to 1.4 MeV/u (pre-stripper linac). After the gas stripper and the charge separation section, further acceleration to 11.4 MeV/u for synchrotron injection is provided by the 108 MHz post-stripper linac ($A/q \leq 8.5$), consisting of five Alvarez DTL cavities and ten single gap resonators for fine tuning of the linac end energy.

High magnetic rigidity of the ion beams and high beam currents as needed for FAIR injection require very strong electric and magnetic fields for acceleration and focusing along the linac within short beam pulses and at low repetition rate and duty cycle.

On the other hand – contradictory to the requirements for the FAIR injector – experiments using low-energy beams in the MeV/u region behind the UNILAC, like the super-heavy element (SHE) program as well as material research, biophysics, and plasma physics experiments, are demanding ion beams with up to 100 % duty factor, resulting in very high average rf power requirements along the linac. These experiments are currently limited by the maximum duty cycle of the UNILAC of 25 % [9].

Moreover, the focusing magnets along the present post-stripper linac can be operated only in DC mode, which makes the machine inefficient in terms of short pulse operation and represents a major flexibility limitation since the focusing fields cannot be adapted to the varying needs when different ion beams have to be accelerated from pulse to pulse (diverse ion species, magnetic rigidities, and beam currents).

HEAVY ION SUPERCONDUCTING LINACS: STATUS AND UPGRADE PROJECTS

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Abstract

We observe that there is an increase in the demand, by the scientific community, for accelerated CW ion beams which can be efficiently provided by SC ion linacs. This demand can be categorized into two areas: existing and new facilities. Existing facilities are being refurbished and upgraded for higher energies and beam intensities. Several new projects are under development or construction worldwide. Recently, development of new SC ion linacs has started in China, Korea and Spain. In this talk I will briefly review both the upgrade and new SC ion linac projects with a primary focus on the advances in heavy-ion linac technologies achieved at ANL in connection with the efficiency and intensity upgrade of ATLAS.

CONTRIBUTION NOT RECEIVED

OVERVIEW OF THE RISP SUPERCONDUCTING LINAC

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Abstract

The Rare Isotope Science Project (RISP) got launched December 2011 which consists of In-Flight Fragmentation Facility and ISOL facility, providing uniques research opportunities in broad range of sciences. The superonducting driver linac can accelerate up to 200 MeV/u for uranium beam and up to 600 MeV for proton beam. The ISOL post linac which is also a superconducting linac. Design parameters and choices are presented.

CONTRIBUTION NOT RECEIVED

STATUS AND UPGRADE PROJECT OF HIRFL

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Abstract

Heavy Ion Research Facility at Lanzhou is a heavy ion accelerator complex for nuclear, atomic, and biology application research activities. It is the biggest heavy ion accelerator facility in China, consisting two cyclotrons in series as injector and two cooling storage rings (CSRm and CSRe) as main synclotron and experimental spectrum separately. The species from P to U were accelerated in the machine, And the maximum energy is 1 GeV/u for C. The experimetal teminals are on meterial, biology, canser therapy, SHE, RIB, mass measurement, inner target, and so on. To improve beam intensity and available beam time, a linear injectors SSC-LINAC were proposed in 2009. It consists a 4-rod RFQ and 4 IH-DTL tanks. The RFQ, IH-DTL, and 60 kW solid state amplifier for SSC-LINAC are tested priliminaryly. The operation status and progress of upgrade projects of HIRFL are presented in the paper.

CONTRIBUTION NOT RECEIVED

NEW DEVELOPMENTS IN LOW-Z GAS STRIPPER SYSTEM AT RIKEN RADIOACTIVE ISOTOPE BEAM FACTORY (RIBF)

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Abstract

The RIKEN radioisotope beam factory (RIBF) has been successfully operated for more than five years as the first next-generation exotic beam facility after the extraction of the first beam at the end of 2006. Continual development efforts in these five years have led to improved performance of the accelerators, thereby leading to increase in the intensity of the various heavy-ion beams that have been produced. Furthermore, the operation of a new 28-GHz superconducting electron cyclotron resonance (ECR) ion source and a new injector linac was started from October 2011 to overcome the difficulty in increasing the uranium beam intensity that is currently far below our goal of 1 pμA (6×10^{12} particles/s). However, the most serious problem, which is the design and implementation of a charge stripper for high-power uranium beams, has thus far remained unsolved, despite extensive R&D studies on strippers using large foils mounted on a rotating cylinder and the study of a N_2 gas stripper. A gas stripper is free from problems related to lifetime issues and uniformity in stripper thickness, although the equilibrium charge state in such a stripper is considerably lower than that in a carbon foil stripper owing to the absence of the density effect. These merits of gas strippers have motivated us to develop a low-Z gas stripper to achieve a higher equilibrium charge state even in gases, by virtue of suppression of the electron capture process in low-Z gas. In this light, we carried out the following R&D programs. The first one included the measurement of the electron-loss and electron-capture cross sections of uranium ions in He gas to extract the equilibrium charge state. The second study obtained measurements of charge distributions and energy spreads using thick layers of windowless He gas targets. The results of these studies were satisfactory, and it was decided to practically construct the proposed machine for He gas stripping. We constructed and installed the new He gas stripper for the operation of an uranium beam in January 2012. Tests using uranium beams are in progress before the the uranium beam series, which is scheduled for the coming autumn 2012.

INTRODUCTION

RI Beam Factory

The RIKEN Nishina Center for Accelerator-Based Science constructed the RadioIsotope Beam Factory (RIBF) [1] with the aim of realizing a next-generation facility that

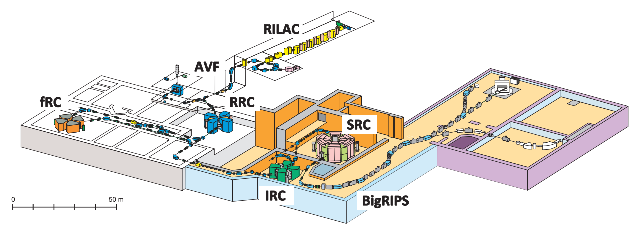

Figure 1: Bird's eye view of RI Beam Factory.

can produce the most intense RI beams in the world at energies of several hundred mega-electronvolts per nucleon over the entire range of atomic masses. The RIBF facility includes an accelerator complex that can accelerate ions over the entire range of masses and deliver 80-kW uranium beams at an energy of 345 MeV/u. Figure 1 shows a bird's eye view of the RIBF. The section on the left indicates the old facility that was completed in 1990. Many experiments have been carried out with light-ion RI beams using the four-sector K540-MeV RIKEN ring cyclotron (RRC) with two injectors, the RIKEN linear accelerator (RILAC), and the AVF cyclotron. The feasibility of conducting such light-ion experiments is enabled by the fact that the RRC can accelerate relatively light ions up to 100 MeV/u, which is the value of the lower limit for RI beam production. In order to expand the mass range for RI beam production up to that of uranium, three ring cyclotrons, the fixed-frequency ring cyclotron (fRC), the intermediate-stage ring cyclotron (IRC), and the superconducting ring cyclotron (SRC) were designed and constructed as energy boosters for the RRC.

The design and construction of the RIBF accelerators was begun in 1997, and the accelerator building was completed at the end of March 2003. In November 2005, an important milestone was reached; the superconducting sector magnets for the SRC were successfully excited at the maximum field level. The first beam was obtained on December 28, 2006 [2]. Many improvements have since been carried out to increase the beam intensity and to commission new beam species to meet the requirements of different experiments. Furthermore, the operation of the new injection system that consists of a 28-GHz superconducting ECR ion source (SC-ECRIS) [3] and a linac (RILAC2) [4] was started in October 2011 to overcome the difficulty in increasing the uranium beam intensity, whose current value is far below our goal of 1 pμA (6×10^{12} particles/s) [5]. The SC-ECRIS was designed to have a large plasma vol-

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NEW DESIGN FOR THE SARAF PHASE II LINAC

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Abstract

We have developed a new design for the 40 MeV/u - 5 mA proton/deuteron SARAF Phase-II Linac. It includes a RFQ, room-temperature bunchers and two types of SC cavities. The new design is based on highly optimized ring-shaped HWR structures operating at 176 MHz, the same frequency as the current SARAF Phase-I linac. We will first present the optimized design of all the components from the RFQ to the SC cavities, then the proposed linac layout, and finally the results of end-to-end beam dynamics simulations including machine errors, realistic corrections and beam loss analysis.

CONTRIBUTION NOT RECEIVED

DESIGN STUDY FOR FRONT-END SYSTEM AT RARE ISOTOPE SCIENCE PROJECT

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Abstract

Heavy ion beams of 400 kW and 70 kW are generated at the RISP by in-flight and ISOL methods, respectively. Front-end system for the in-flight at the RISP consists of two 28 GHz superconducting ECR-IS with 10 keV/u, a LEBT with two 90 degree bends and two bunchers with 40.625 MHz, a RFQ with 81.25 MHz and 300 keV/u, and a MEBT with two re-bunchers. The front-end system design studies have been performed to optimize the beam and accelerator parameters to meet the required design goals. For this, we performed front-end simulations with two-charge state beams and present the design performance and results of the beam dynamics.

INTRODUCTION

RISP (Rare Isotope Science Project) is designed to accelerate the ions from proton to uranium for 400 kW in-flight system. The accelerator can be segmented into front-end accelerator and superconducting linear accelerator. The front-end includes two ECR ion sources, low energy beam transport (LEBT), radio frequency quadrupole (RFQ) and medium energy beam transport (MEBT). ECR ion source generates various charge states of ions from proton to uranium. LEBT delivers these ion beams to the RFQ efficiently. Bunching at the LEBT is considered by two bunchers. RFQ accelerates the uranium beam up to 300 keV/u. The MEBT matches the beam from the RFQ to the superconducting linac. Fig. 1 shows the layout for the front-end system. We show the design results in the front-end system.

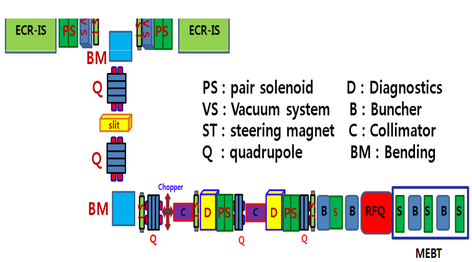

Figure 1: Layout of the front-end system for the drive linac.

ECR ION SOURCE

The goal of the design of the ECR-IS is to produce various ions with 10 keV/u of the kinetic energy and normalized rms emittance of 0.1 πmm-mrad. Two ECR ion sources are considered for the RISP, as shown in Fig. 1. Superconducting magnets and RF source of 28 GHz are used and the main design parameters from the two R&D groups of KAERI and KBSI are summarized in Table 1[1]. The design of the superconducting magnets is the most important part of the ECR ion source design. The feature of KAERI model is to use five solenoids for adjusting ECR zone efficiently. On the other hand, the step winding technique for sextupole coils is the KBSI's idea to build the ECR ion source compactly.

For the superconducting magnets, 4 K cryogenic system has to be prepared. The ECR ion source needs more than 10 W cooling powers at 4 K during the operation because X-rays from the plasma chamber could be an extra heat load to the cryostat. Reducing the X-rays, therefore, is also a key design factor for the ECR ion source. A tantalum is used as a radiation shielding material. Dual frequency operation improves the overall performance so that considering an extra 18 GHz RF source can be a good choice to achieve high charge states and high current ions. Additionally, a high temperature (2000 ^oC) oven for solid isotopes and a high voltage platform of 70 kV for heavy ions are necessary.

Table 1: Main parameters of the ECR-IS.

	KAERI	**KBSI**
Frequency(GHz)	28	28
RF power (kW)	10	10
Chamber diameter(mm)	150	150
Chamber material	Al	Al
Mirror length(mm)	500	500
External voltage(kV)	30	30
SC wire	NbTi	NbTi (OK35,38)
Number of solenoid	5	3
Sextupole winding type	Saddle	Race track
$B_{inj}(T)$	4.2	3.6
$B_{ext}(T)$	2.2	2.1
$B_r(T)$	3	2.2
$B_{min}(T)$	0.3-0.8	0.4-0.8

LEBT

The LEBT consists of two 90 degree bends and quadrupoles for achromatic optics, solenoids for beam matching with ECR-IS and RFQ, two bunchers, steering magnets, collimation systems and diagnostics. Fig. 2 shows designed optics and beam envelopes for the LEBT beam line that is optimized by TRANSPORT code. The

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DEVELOPMENT OF THE INTENSITY AND QUALITY OF THE HEAVY ION BEAMS AT GSI

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Abstract

For injection into the future FAIR SIS100 synchrotron the GSI linear accelerator UNILAC and synchrotron SIS18 have to provide $1.5{\cdot}10^{11}$ p/spill for the reference U^{28+} beam. The MEVVA ion source extracts 37 emA of U^{4+} beam. For improved transmission in the front end accelerator the RFQ vanes were revised and exchanged. A new ion source terminal with direct beam injection into the RFQ is calculated and partly realized for loss free beam transport to the RFQ. To improve the quality of the space charge dominated beam in the DFFD periodic focussing Alvarez section a transversal 4th order resonance was investigated by simulations and experimentally. The multi turn beam injection into the SIS18 requires emittances below $\beta\gamma\varepsilon x/\beta\gamma\varepsilon y = 0.8/2.5$ µm. This suggests introducing a new concept for emittance transfer by solenoidal stripping. A set-up for experimental proof of principle will be installed at the foil stripper. The SIS18 has been equipped with NEG-coated chambers for all magnets and the injection septum. Newly installed ion catchers improve especially the dynamic vacuum pressure. The effect on progress in beam quality development and intensity will be reported.

INTRODUCTION

For the reference ion U^{28+} the UNILAC has to inject $2{\cdot}10^{11}$ particles per 60 µs into the SIS18. This again injects four batches of $1.5{\cdot}10^{11}$ particles each into the future FAIR SIS100 synchrotron [1] with a repetition rate of 2.7 Hz to fill it finally with $6{\cdot}10^{11}$ particles for acceleration up to 2.7 GeV/u for radioactive beam production. Alternatively SIS100 accelerates intense proton beams up to 30 GeV for pbar-production.

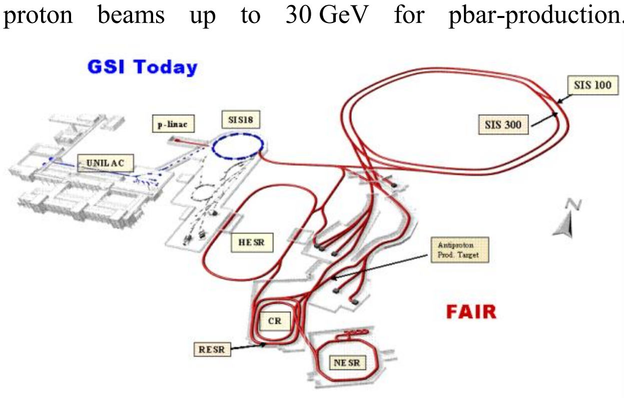

Fig. 1: The existing GSI accelerators UNILAC and SIS18 and the future accelerator facility FAIR.

This booster operation of the SIS18 [2] is the most challenging case concerning beam intensity, repetition rate, and dynamic vacuum challenges. Heavy ion beams of energies up to 30 GeV/u will be provided by the FAIR synchrotron SIS300, using higher charge states and a slower cycling rate. SIS300 can also serve as a stretcher for the production of radioactive beams, which will be injected, cooled, and stored in a system of rings with internal targets and in-ring experiments (Fig. 1).

GSI uses heavy ion sources of e.g. MUCIS or MEVVA type which generate for a whole string of low charged ions beams of sufficient intensity. As the UNILAC was originally not designed for space charge dominated beams different measures are necessary to reduce beam losses and improve beam quality.

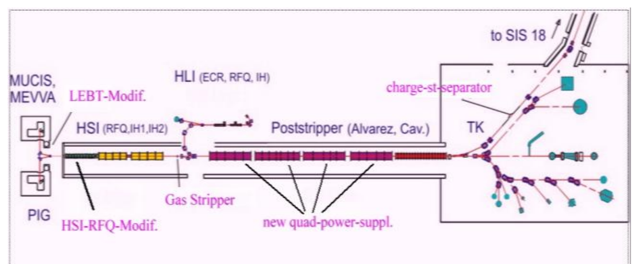

Fig. 2: Schematic overview of the UNILAC, experimental area, transfer channel to SIS, and locations of upgrades.

The scheme of the UNILAC is presented in Fig. 2. The prestripper accelerator HSI (high current injector) comprises a 36 MHz RFQ and two IH-type drift tube DTLs for final energy of 1.4 MeV/u, suited for ions with mass to charge ratios up to 65. A gas stripper increases the charge states, e.g. U^{4+} delivered by the MEVVA source is stripped to U^{28+}. Five 108 MHz Alvarez DTLs accelerate the ions up to 11.4 MeV/u. Finally a chain of ten single gap resonators allows exact adjusting of any energy between 3.6 and 12.4 MeV/u. A second injector HLI (high charge state injector) with an ECR source injects directly into the post stripper section. Finally, up to three different ion species can be accelerated interchangeably to different energies. Different experiments in any mixture on basis of a 50 Hz pulse-to-pulse switching mode can be accomplished. The transfer channel to SIS18 includes a foil stripper for another charge state increase and is also suitable for 4 Hz pulse-to-pulse operation of beams from different ion species passing through different stripping foils.

The SIS18 rigidity is 18 Tm with warm magnets of 1.8 T maximum field strength. The present ramp power is limited to 4 T/s. This allows a repetition rate of ~ 1 Hz only. The ring includes 12 double dipole magnets with

THE HITRAP DECELERATOR AND BEAM INSTRUMENTATION

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Abstract

A linear decelerator is being commissioned for heavy, highly-charged ions (HCI) at GSI in Darmstadt/Germany. HCI with only one or few electrons are interesting systems for many different experiments as for instance precision tests of the theory of quantum electrodynamics (QED). In order to transform heavy HCI produced at 400 MeV/u to stored and cooled HCI at low energy the linear decelerator facility HITRAP has been setup behind the experimental storage ring (ESR). The ions are decelerated in the ESR from 400 to 4 MeV/u, cooled and extracted. The ions are then matched to an interdigital H-type structure (IH) using a double drift buncher, decelerated from 4 to 0.5 MeV/u in the IH, and then down to 6 keV/u in a 4-rod radio frequency quadrupole (RFQ). To detect and analyze the weak and sparse ion bunches a new type of energy analyzing detector has been developed along with improvements of other standard beam instrumentation. One million highly charged ions have been decelerated with the IH from 400 MeV/u to about 0.5 MeV/u per cycle. The RFQ has shown in off-line tests to decelerate ions, however, the measured longitudinal acceptance does not fit the properties of the ion beam decelerated in the IH. This requires a refined design, which is underway.

INTRODUCTION

Heavy, highly-charged ions, as for instance U^{91+} or even the bare U^{92+}, are well suited for cutting edge experiments in atomic, nuclear and solid state physics [1]. They are simple but come along with a very strong electric field due to the heavy nucleus and hence the large amount of positive charge enclosed in the small nuclear volume. This suits perfectly well to test quantum electrodynamics (QED) theory at the strong-field limit. Quantities that can be calculated with high precision and which are at the same time sensitive to the investigated QED effects are the g-factor of the bound electron, the electron binding energies of the innermost electrons or the hyperfine splitting of the electronic levels. To be decisive, those measurements require the same high precision as the calculations. For this, the ions have to be stored and cooled in a well defined environment at very low energy. This is possible in a Penning trap by electron and resistive cooling to about 4K [2]. The observation of the stored particles will then allow for mass measurements at the ppt level, corresponding to a determination of the electron binding energies with eV precision. Similarily, the bound-state g-factor can be determined with a precision that even tests our knowledge of fundamental constants like the mass of the electron. Laser excitation of the transition energies between hyperfine levels will become feasible several hundred times more precise than presently [3].

Heavy, highly-charged ions are very instable systems when in close contact with electrons since a huge potential energy is concentrated in a very small volume. When those HCI at very low energy come close to neutral matter relaxation processes happen very fast and give snapshot-like insight into the dynamics and correlation of the electrons in the neutral collision partner. If energy and position are well defined the exchange of multiple charges can be studied by a complete analysis of the kinematics of all involved particles. For that, highly-charged ions are accumulated in a Penning trap and cooled. After ejection a well defined ion beam will be targeted to a cold sample of neutral atoms and the products will be investigated by a reaction microscope [4]. Two different target types will be applied for HITRAP experiments: a pulsed gas target [5] and a magneto optical trap [6].

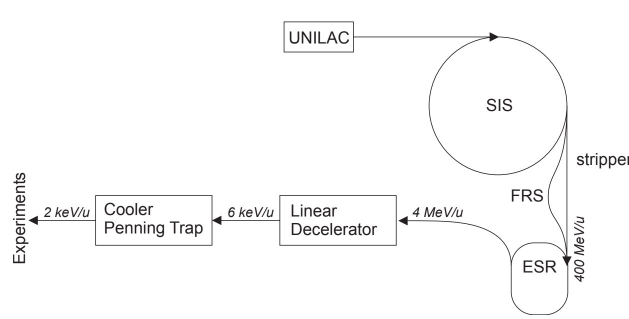

Figure 1: The HITRAP facility at the GSI accelerator complex. UNILAC stands for Universal Linear Accelerator, SIS is the heavy ion synchrotron and ESR is the Experimental Storage Ring. The beam from the SIS can be sent directly into the ESR of fragmented by nuclear reactions and then analyzed and separated in the Fragment Separator (FRS)

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