PROGRESS ON THE HIE-ISOLDE FACILITY

Y. Kadi, M.J. Garcia Borge, W. Venturini Delsolaro, N. Delruelle, J.A. Ferreira, J.C. Gayde, G. Kautzmann, M. Martino, J.A. Rodriguez, E. Siesling, L. Valdarno, CERN, Geneva, Switzerland

Abstract

After 20 years of successful ISOLDE operation at the PS-Booster [1], a major upgrade of the facility, the HIE-ISOLDE (High Intensity and Energy ISOLDE) project was launched in 2010. It is divided into three parts; a staged upgrade of the REX post-accelerator to increase the beam energy from 3.3 MeV/u to 10 MeV/u using a superconducting linac [2], an evaluation of the critical issues associated with an increase in proton-beam intensity and a machine design for an improvement in RIB quality. The latter two will be addressed within the HIE-ISOLDE Design Study [3]. This paper aims to provide an overview of the present status of the overall project by giving an insight to the infrastructure modifications, installation and tests of the HEBT lines as well as progress on the commissioning of the SC linac. Plans for the second phase of the project will be highlighted.

INTRODUCTION

The present schedule foresees to deliver beams up to 4.2 MeV/u for the heaviest species this autumn with a single high-beta cryomodule. A second cryomodule will be installed during the winter shutdown 2015/2016 bringing the energy to 5.5 MeV/u for all the radionuclides available at ISOLDE. This will complete phase 1, making Coulomb excitation studies possible up to A/q=4.5. A second phase will consist in adding two more high-beta cryomodules during the winter shutdown 2016/2017, thus doubling the available accelerating voltage. Finally, in phase 3, two low-beta cryomodules would be installed, replacing some normal conducting structures of the present REX-ISOLDE. This will allow varying continuously the energy between 0.45 and 10 MeV/u together with an improved beam quality. A detailed description of the optics and beam dynamics design choices for the linac can be found in [4].

As we write, installation of the HIE-ISOLDE technical infrastructure has been completed with minor disruptions to the parallel running of the Low-Energy physics programs at the ISOLDE facility. The SC linac as well as the HEBT lines have been installed and tested.

This paper offers a snapshot of the main activities as the commissioning of the HIE-ISOLDE linac with beam is in progress.

TECHNICAL INFRASTRUCTURE

The long shutdown of the CERN accelerators in 2013-2014 was used to upgrade the general infrastructure of the existing ISOLDE facility. All the services are by now fully operational.

The overhauled ALEPH compressor units/cold box together with the new cryogenic distribution line (Fig. 1) have been commissioned and supplying LHe at 4.5K since June 2015 [5].

Figure 1: Cryogenic distribution line feeding the SC linac with liquid He at 4.5K.

In the ISOLDE experimental hall, Controls, DC and RF cables with a total length of more than 65 kilometres have been installed and power supplies, beam instrumentation and vacuum equipment racks are in place and operational.

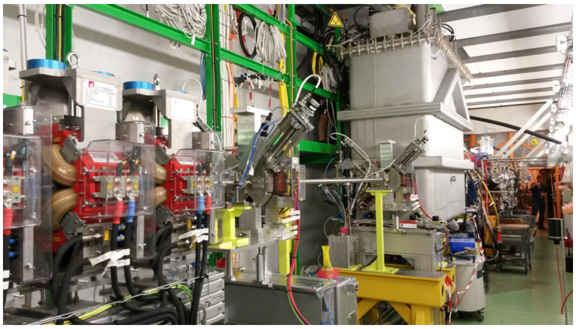

Figure 2: Cryomodule 1 and the first part of the straight section downstream of the superconducting (SC) linac inside the shielding tunnel.

The first high-beta cryomodule (CM1) was transported to the HIE-ISOLDE linac tunnel in May (Fig. 2) and after a dense installation campaign, CM1 was ready for cryogenic cool-down a month later. The installation and commissioning of the second high-beta cryomodule (CM2) is scheduled for the first quarter of 2016.

Subsystems such as cryogenic instrumentation, vacuum controls, RF interlocks, fire and oxygen deficiency alarms have all been tested.

Elements of the SC linac and the first two High-Energy Beam Transfer lines (XT01 and XT02) have all been installed (Fig. 3). The quadrupole, H/V corrector and dipole magnets and associated beam diagnostic boxes have all been tested and commissioned. The first two experiments (Miniball and the Scattering chamber) are being installed in view of the first physics run this coming Fall.

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FRIB ACCELERATOR: DESIGN AND CONSTRUCTION STATUS*

J. Wei[#1], H. Ao[1], N. Bultman[1], F. Casagrande[1], C. Compton[1], L. Dalesio[1], K. Davidson[1], K. Dixon[2], B. Durickovic[1], A. Facco[1,4], F. Feyzi[1], V. Ganni[2], A. Ganshyn[1], P. Gibson[1], T. Glasmacher[1], W. Hartung[1], L. Hodges[1], L. Hoff[1], K. Holland[1], H.-C. Hseuh[1,6], A. Hussain[1], M. Ikegami[1], S. Jones[1], M. Kelly[3], K. Kranz[1], R.E. Laxdal[1,5], S. Lidia[1], S. Lund[1], G. Machicoane[1], F. Marti[1], S. Miller[1], D. Morris[1], J. Nolen[1,3], P. Ostroumov[3], S. Peng[1], J. Popielarski[1], L. Popielarski[1], E. Pozdeyev[1], T. Russo[1], K. Saito[1], G. Shen[1], S. Stanley[1], M. Wiseman[2], T. Xu[1], Y. Yamazaki[1]

[1] Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824 USA
[2] Thomas Jefferson National Laboratory, Newport News, VA 23606 USA
[3] Physics Division, Argonne National Laboratory, Argonne, IL 60439 USA
[4] INFN - Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy
[5] TRIUMF, Vancouver, Canada
[6] Brookhaven National Laboratory, Upton, NY 11973 USA

Abstract

With an average beam power approximately two to three orders of magnitude higher than operating heavy-ion facilities, the Facility for Rare Isotope Beams (FRIB) stands at the power frontier of the accelerator family. This report summarizes the current design and construction status.

INTRODUCTION

In August 2014, the Department of Energy's Office of Science approved Critical Decision-3b (CD-3b), Approve Start of Technical Construction, one year after approving CD-2 (Approve Performance Baseline) and CD-3a (Approve Start of Civil Construction and Long Lead Procurements) for the FRIB construction project (Fig. 1). The total project cost for FRIB is \$730M, of which \$635.5M is provided by DOE and \$94.5M is provided by Michigan State University (MSU). The project will be completed by 2022. "When completed, FRIB will provide access to completely uncharted territory at the limits of nuclear stability, revolutionizing our understanding of the structure of nuclei as well as the origin of the elements and related astrophysical processes" [1].

FRIB will be a new national user facility for nuclear science. Under construction on campus and operated by MSU, FRIB will provide intense beams of rare isotopes (that is, short-lived nuclei not normally found on Earth). FRIB will enable scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society.

In creating this new one-of-a-kind facility, FRIB builds upon the expertise and achievements of the National Superconducting Cyclotron Laboratory (NSCL), a National Science Foundation (NSF) user facility at MSU. Since 2001, NSCL's coupled cyclotron facility, one of the world's most powerful rare isotope user facilities, has been conducting experiments on rare isotopes. Since 2014, the re-accelerator (ReA3), consisting of a radio-frequency quadrupole (RFQ) and a superconducting radio-frequency (SRF) linac, was constructed and commissioned to accelerate beams of rare isotopes. The FRIB project scope consists of a high-power driver accelerator, a high-power target, and fragment separators.

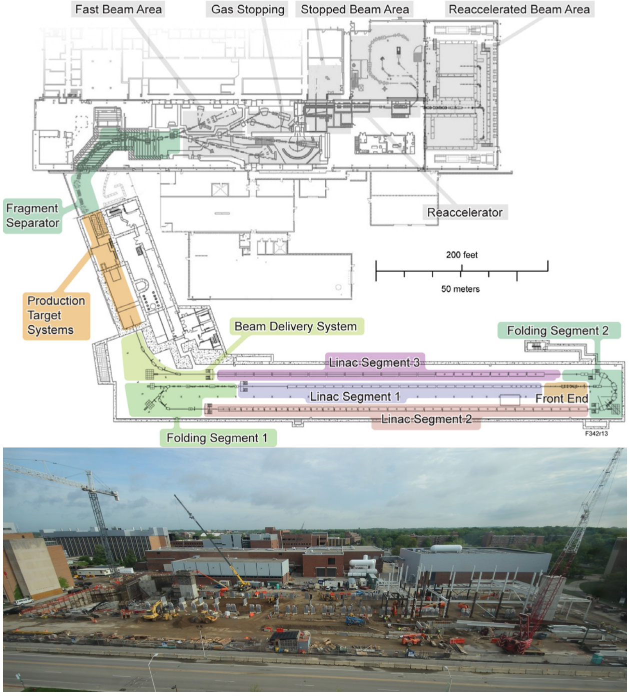

Figure 1: Layout of the FRIB driver accelerator, target and fragment separator (colored areas) and existing infrastructure (top); photograph showing FRIB civil construction (bottom).

The FRIB driver accelerator is designed to accelerate all stable ions to energies >200 MeV/u with beam power on the target up to 400 kW (Table 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

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#wei@frib.msu.edu

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REVIEW OF HEAVY-ION CYCLOTRONS

N. Fukunishi[#], RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama, Japan

Abstract

The basic features of heavy-ion cyclotrons are briefly summarized and various activities concerning heavy-ion cyclotron facilities worldwide are reviewed with an emphasis on important achievements and recent upgrades.

INTRODUCTION

Livingston reported that the 37-inch Berkeley cyclotron first accelerated a carbon beam up to 50 MeV in 1940 [1]. Seventy-five years have passed, and dramatic augmentations of beam energy, intensity, and ion species have been obtained for heavy-ion cyclotrons. Bending indices (K_B) for heavy-ion cyclotrons commissioned after 1980 and those commissioned before 1980 but currently working are plotted in Fig. 1 by year of commissioning. The bending limit of cyclotron energy is given by $E/A = K_B \times (q/A)^2$, where E, q, and A are the total kinetic energy, charge state, and mass number, respectively. These data are based on the "List of Cyclotrons" compiled in 2005 [2] and include newly commissioned cyclotrons and recent developments reported at subsequent international cyclotron conferences.

Many heavy-ion cyclotrons were commissioned from 1980 to 2000. Two major trends are innovation in compact superconducting (SC) cyclotrons and the introduction of separate-sector (SS) cyclotrons for heavy ions. Conventional Thomas-type cyclotrons have also been continuously commissioned. Most of the cyclotrons shown in Fig. 1 have undergone upgrades since their commissioning. In this review, these heavy-ion cyclotrons are classified into three groups according to their type. Their basic features are briefly summarized and important achievements so far and recent (up to 2013 or 2014) upgrades are described. Note that some important activities such as those related to heavy-ion cyclotrons dedicated to medical uses, innovative design studies, and novel applications are not included in order to remain within the paper's space limitations and the author's area of expertise.

COMPACT CYCLOTRONS

More than 20 compact cyclotrons are currently in operation, some of which are listed in Table 1. All of them are Thomas-type cyclotrons [3]. The bending indices (K_B) of the compact cyclotrons shown in Fig. 1 range from 10 to 625 MeV, but cyclotrons with K_B of 100–200 MeV are widely used for stand-alone operations. The isochronous magnetic field is formed by a set of magnet poles with an azimuthally varying gap and a set of main and trim coils. Conventional dee electrodes are used for acceleration with typical voltages ranging from 50 to 100 kV. These cyclotrons are now equipped with electron cyclotron resonance (ECR) ion sources and beams are axially injected. Beam extraction is performed by the electrostatic deflector (ESD) or charge-stripping technique.

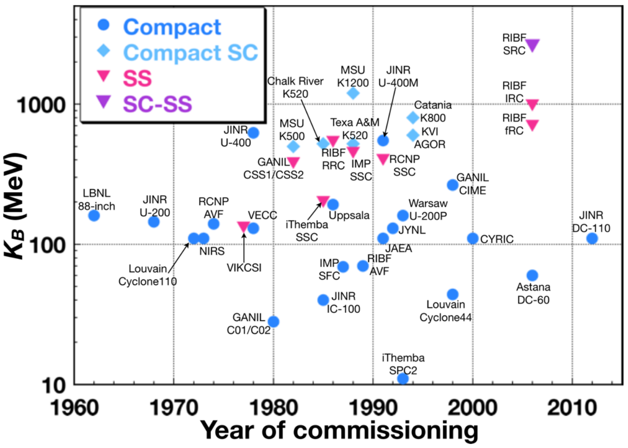

Figure 1: Heavy-ion cyclotrons.

University of Jyväskylä (JYFL)

The main accelerator at JYFL is the K130 cyclotron [4] constructed by Scanditronix. Since its commissioning in 1992, the cyclotron has been used for both nuclear physics and applications. The latter includes testing space electronics and producing medical isotopes and nano-filters. The annual use of K130 has exceeded 6000 h for more than 15 years [5]. To meet increasing demands, a new compact cyclotron (MCC30/15) producing high-intensity 30-MeV H^- and 15-MeV D^- beams was introduced in 2009 [6], and the building facilities were expanded. JYFL has demonstrated that a medium-scale isochronous cyclotron combined with original and sophisticated experimental techniques can make important contributions to nuclear physics studies.

Lawrence Berkeley National Laboratory (LBNL)

The historically famous 88-inch cyclotron at LBNL commissioned in 1962 serves highly charged ions like Xe^{43+} for microchip testing and medium-charge-state high-intensity beams (^{48}Ca) for nuclear physics experiments [7] thanks to its powerful ECR ion sources, AECR-U and VENUS. Super-heavy element research demands higher-intensity ^{48}Ca beams, so the low-energy part of the facility was modified to reduce the space charge effect. Specifically, the extraction voltage of the AECR-U ion source was increased from 14 to 25 kV, which is comparable to that of VENUS. The axial injection line was also modified to manage 25-kV

[#] fukunisi@ribf.riken.jp

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HISTORY OF SOLID DISK IMPROVEMENT FOR ROTATING CHARGE STRIPPER

H. Hasebe, H. Okuno, H. Kuboki, H. Imao, N. Fukunishi, M. Kase, and O.Kamigaito
Nishina Center for Accelerator-Based Science, RIKEN
2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Abstract

In 2007, we installed a rotating disk stripper device in the final charge stripper section for acceleration of U beam. At first, we selected a carbon disk stripper. However, the quality of the beam after it passed through the stripper was unusable because of the non-uniform thickness and unexpected low density of the stripper. In 2012, the rotating stripper using a Be-disk successfully realized the stable U beam operation. However, the thermal load of the increasing beam intensity caused deformation of the Be-disk even after a short irradiation period. In 2015, highly oriented graphite sheets of high density were used as the disk stripper, which had the longest lifetime. The graphite sheet exhibited improved stripping and transmission efficiencies.

INTRODUCTION

A charge stripper is an essential device used to strip U beams to produce the high-charge state of U^{86+} at 50 MeV/nucleon before acceleration by a subsequent cyclotron at the RIKEN RI Beam Factory (RIBF). A 17-$mg \cdot cm^{-2}$ thick static-type carbon foil (C-foil) was used as the stripper at the RIBF because of its high melting point. As the intensity of the U beam was expected to increase, a rotating carbon disk (C-disk) stripper device was constructed in 2006[1]. A C-disk of diameter 120 mm was installed and tested in 2007. However, the C-disk could not be used as the stripper because of its non-uniform thickness and unexpected low density. Other C-disks, which were commercially available or originally fabricated, were tested, but none met our requirements. Therefore, until 2011, the only alternative was to use polycrystalline graphite foils fabricated by Arizona Company[2]. These foils were used as the static-type C-foil stripper and needed to be replaced every time their lifetime was over in order to accomplish the U beam time. However, the lifetime of these static C-foils decreased to 9 h as the beam intensity increased. Hence, providing stable U beams was difficult.

BERYLLIUM DISK STRIPPER

In October 2012, other materials were tested as alternatives to C-disks: low-density C [2], Ti [3], and Be [3]. Each disk had a thickness of 19 $mg \cdot cm^{-2}$. A U^{64+} beam at 50 MeV/nucleon was irradiated on the C/Ti/Be disk at rotating speeds ranging from 300 to 1000 rpm. The charge states at the peak were 82+ and 86+ for the Ti- and Be-disk, respectively. The charge distribution of Be was almost the same as that obtained for the static C-foil. Therefore, Be-disk could be used instead of the C-foil stripper. The charge distribution of the C-disk could not be obtained because of non-uniformity in its thickness.

The Be-disk was used during the beam-time operation from November to December, 2012. We successfully delivered a stable U beam during the long-term operation. Totally 1.18×10^{18} U particles were irradiated on the Be-disk over a period of 37 days[4]. The number of irradiated particles and the disk conditions are summarized in Table 1 along with other disks described below. The first Be-disk is denoted as Disk 1 in Table 1. For Disk 1, the emittance of the beam increased after the stripper exceeded the accepted levels for subsequent cyclotrons because of the non-flatness of the disk. To obtain flatter disks, we fabricated a Be-disk that was subjected to diamond polishing (Disk 2) in March 2013[5]. In addition, the disk thickness was reduced from 0.1 mm (19 $mg \cdot cm^{-2}$) to 0.085 mm (16 $mg \cdot cm^{-2}$), which was suited for the injection energy of the subsequent cyclotron. Therefore, transmission efficiencies of the downstream cyclotrons were improved. The Be-disk seemed still usable after irradiation with 9.29×10^{17} U particles during the 30-day beam-time operation[6]. Therefore, the Disk 2 was used again for the U beam-time operation in March 2014. Although the disk was already distorted, it survived for 21 days more. During the beam time of 51 days (including the 30 days in 2013) as mentioned in Table 1, a total of 1.68×10^{18} U particles was irradiated on the disk. Figure 1 shows the photographs of the Be-disks before (left) and after usage (right). As shown in Figure 1 (Disk 2), many cracks were observed along the beam irradiation traces, and the beam transmission efficiency decreased as well, thus, indicating that the lifetime of the disk was over. The Be-disk was replaced with a new disk (Disk 3), which was identical to Disk 2 (0.085-mm-thick, diamond polished), for the remaining beam time. In addition, a total of 8.83×10^{17} U particles was irradiated on the new Be-disk over a period of 17 days. The beam transmission efficiency was improved owing to the diamond polish. However, as the upstream beam intensity increased, the thermal load increased from 90 W to 230 W, resulting in deformation of the disk. In October 2014, we introduced a Be-disk with a special design (Disk 4) to reduce the thermal deformation. Because of this improvement, Disk 4 survived even after the 20-day U beam time with radiation of approximately 9×10^{17} U particles. The main changes were as follows. 1) The outer diameter of the disk was changed from 120 mm to 110 mm; 2) Small cuts

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GANIL OPERATION STATUS AND NEW RANGE OF POST-ACCELERATED EXOTIC BEAMS

O. Kamalou1), J. Angot2), O. Bajeat1), F. Chautard1), P. Delahaye1), M. Dubois1), T. Lamy2),
L. Maunoury1), G. Normand1), A. Savalle1)
1) GANIL, Grand Accélérateur National d'Ions Lourds, CEA-DSM/CNRS-IN2P3, Bvd H. Becquerel, BP 55027 14076 Caen cedex 5, France
2) LPSC - Université Grenoble Alpes - CNRS/IN2P3, 53 rue des Martyrs, F-38026 Grenoble cedex, France

Abstract

The GANIL facility (Grand Accélérateur National d'Ions Lourds) at Caen produces and accelerates stable ion beams since 1982 for nuclear physics, atomic physics, radiobiology and material irradiation. The range of stable beam intensity available at GANIL extends from very low intensity (< 109 pps) to high beam intensity (~2.1013 pps). The review of the operation from 2001 to 2015 is presented. One of the methods to produce exotic beam at GANIL, is the Isotope Separation On-Line method with SPIRAL1 facility. It is running since 2001, producing and post-accelerating radioactive ion beams mainly from gaseous elements. Due to the physicists demands for new radioactive nuclei, the facility is being improved in the framework of the project "Upgrade SPIRAL1". The goal of the project is to extend the mass range of post-accelerated as well as low energy exotic beams using devoted 1+ Target Ion Source System associated with a charge breeder. The latest results of the charge breeder tests and the status of the upgrade will be presented.

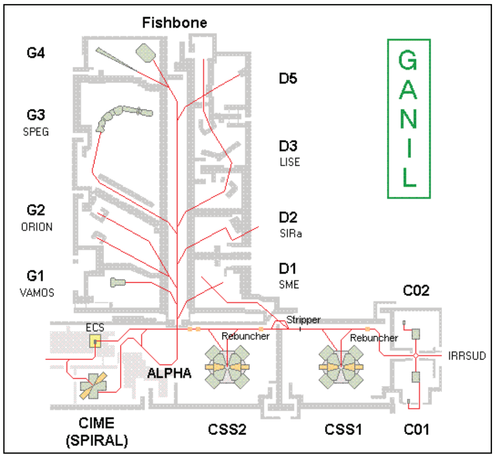

Figure 1: GANIL layout.

OPERATION REVIEW

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

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

During radioactive beam production with SPIRAL1, the combinations are reduced to the four first (cases 1, 2, 3, 4) and radioactive beam is sent to the experimental areas.

2001-2015 GANIL OPERATION STATUS

Since 2001 (Fig. 2), more than 71400 hours of beam time has been delivered by GANIL to physics, which correspond to 88.6 % of scheduled experiments.

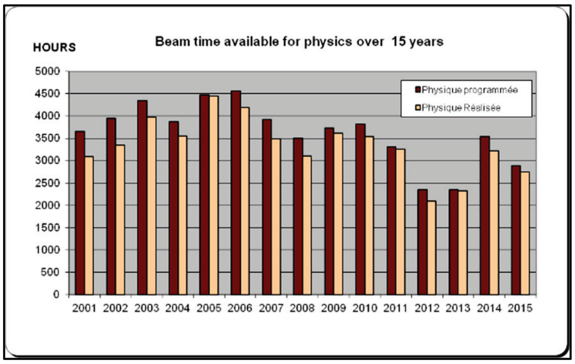

Figure 2: Beam time available for physics over 15 years.

In average, the number of beams delivered per year has increased until 2010. Owing to the construction and assembly of the new SPIRAL2 accelerator, the running time has been shrinked to devote more human ressources to the project, in particulier in 2012 and 2013 with only 2000 hours of running time (instead of 3500 hours per years).

Figure 3 shows the statistic running of the machine over 14 years. As we can see, 67 % of beam time is dedicated to Physics and 12.5% for machine tuning.

PROPOSAL TO INCREASE THE EXTRACTED BEAM POWER FROM THE LNS-INFN SUPERCONDUCTING CYCLOTRON

A. Calanna[1], L. Calabretta[1], D. Rifuggiato[1], G. Cuttone[1], G. D'Agostino[1], A.D. Russo[1],
A. Radovinsky[2]
1) INFN-LNS, Catania, Italy 2) PSFC T&ED MIT, Cambridge, MA 02139, USA

Abstract

The LNS Superconducting Cyclotron, CS, is an isochronous 3-sector compact machine with a wide mass-energy range of heavy ions: beams from protons to lead from 10 to 80 AMeV have been delivered for the past 20 years. However, the extracted current density does not exceed the tenth of enA, corresponding to a beam power of 100 W. Recently, the demand to increase the beam intensity of light ion of a factor 10 to 100 was posed by nuclear physicists. A feasibility study proved a new mode of extraction by stripping would allow for an extraction efficiency of 99% and consequently a high intensity provided by the cyclotron. Here the design of the actual central region as well as the feasibility study of the new extraction for this range of ions is presented. It emerges that the present cryostat is not compatible with the new extraction geometry; therefore, a new cryostat has to replace the present one.

INTRODUCTION

The goal of the study presented is to investigate the possible gain on the extracted beam power from the CS.

Two approaches were chosen. At first, we studied the feasibility of a new mode of extraction from the cyclotron that could radically improve the beam power on target. Today, two electrostatic deflectors and a set of magnetic channels perform the beam extraction. The extraction efficiency is low since almost the 50% of the accelerated beam is lost on the first electrostatic deflector. When a beam power of 100 watt is extracted, the same power is dissipated in the electrostatic deflector septum. Going beyond this value produces serious instabilities in the voltage holding. Extraction by stripping for light ions, with A<20, within the range of 15-70 MeV/amu should guarantee an extraction efficiency of 99% or more because the probability to have q=Z after the stripper foil is >99% for this range of ions and energies [1]. This can increase the maximum beam intensities up to a factor 10-100, to reach beam power values of few kW.

Furthermore, a parallel study started to design a new dedicated central region optimized for these ions and energies. The new central region will be operated with the RF cavity voltages higher of a factor two respect to the present one. Like the existing central region, it will be working in the so-called constant orbit mode, which means the cavity voltage to accelerate the beam scales with the beam energy. Now, a 3D model of the actual central region has been created and the first tracking orbits have been performed thanks to the peculiarity of OPERA 3D, which allows the combination of magneto-static and modulated electric fields. A sketch of the CS actual central region is shown in Fig. 1.

The NUMEN experiment, which proposes to measure the element of nuclear matrix using double charge exchange reactions [2, 3], is the main reason to increase the beam power. However, many other experiments, currently accomplished at LNS, will take advantage from this upgrade. These experiments make use of radioactive ions beam produced with fragmentation in-flight technique at FRIBS@LNS [4]. Production of radioisotopes of medical interest can be considered too.

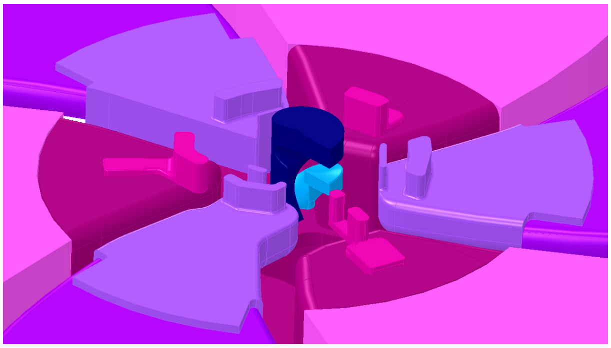

Figure 1: Drawing of the CS actual central region.

The present extraction mode will be maintained, which means the CS will provide all the beams accelerated up to date since there is a huge demand for these beams. For this reason, after the upgrade, the beams will be extracted from the CS with both extraction modes: extraction by stripping and extraction by electrostatic deflectors.

RESULTS OF THE FEASIBILITY STUDY FOR THE STRIPPING EXTRACTION

Since the CS is an operating cyclotron, measured maps are available. From them, we created 3D maps of the field in the gap between the poles solving the Maxwell's equations. Then we imported them on the Post- Processor module of OPERA 3D to have the field on the whole gap and to track particle trajectories. In this way, on one hand we created a new modern tool to reproduce all beam dynamics features that have been computed during the past 20 years with two old codes developed initially at MSU by Gordon [5], GENSPE and ESTRAZ. On the other hand, this new tool allows to easily visualize single

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DESIGN OF A SECTOR MAGNET FOR HIGH TEMPERATURE SUPERCONDUCTING INJECTOR CYCLOTRON

Keita Kamakura*, K. Hatanaka, M. Fukuda, T. Yorita, H. Ueda, K. Shimada,
S. Morinobu, T. Saito, K. Nagayama, H. Tamura, Y. Yasuda, RCNP, Osaka University
10-1, Mihogaoka, Ibaraki, Osaka, Japan

Abstract

We propose a separated sector cyclotron (SSC) using high temperature superconducting (HTS) magnet for a next generation cyclotron. From its stability and low operating cost, HTS cyclotrons are expected to apply for accelerator-driven subcritical reactors or beam cancer treatment systems. On the other hand, we still have a variety of issues and challenges to implement them. As a first step, we are planning to develop an HTS cyclotron as an injector for K400 ring cyclotron at RCNP. It will be the first attempt in the world. This plan will improve beam intensity in our facility and also contribute to component developments for the next generation cyclotron. The most serious issues are development of large-size HTS magnets that can be used in SSC. One-meter-size HTS dipole magnet is made for testing. Now we are going to exam the magnet and evaluate the characteristics of large HTS magnets. The result of the test will be incorporated with the sector magnet design. Moreover, we have been working on conceptual design of the new injector, developed magnetic field and orbit analysis programs. In this session, the current status of designing HTS injector cyclotron at RCNP will be discussed.

CURRENT STATUS OF RCNP

At RCNP, K140 AVF cyclotron and K400 ring cyclotron are used to accelerate various ion species from proton to Xe (Figure 1). Those beams are used for nuclear physics experiments, neutron irradiation, isotope production, etc.

One of the most important features of our facility is the precise nuclear measurement with high energy resolution beam and Grand Raiden Spectrometer. It makes us possible to achieve resolution shown in formula (1).

$$\frac{\Delta E}{E} \sim \frac{12.8\ \mathrm{keV}}{295\ \mathrm{MeV}} \sim 4.3 \times 10^{-5} \qquad (1)$$

Beam intensity of the precise beam is about few nA.

For secondary beam production, intensity limit of primary proton beam is 1.1 μA which is not that high.

NEW INJECTOR PROJECT

Currently, we are planning to upgrade our facility by increasing the beam current up to 10 times of present values. One crucial factor of our problem is the low transmission of AVF injector cyclotron. So we decided to implement a new separated sector cyclotron as injector, as shown in Figure 2.

Conceptual Design

Considering requirements from the K400 ring cyclotron downstream, we finished a conceptual design on the new injector cyclotron [1].

For heavier ion acceleration, K value is raised up to 200 MeV. Maximum magnetic field is 1.7 T. It can be generated by normal conductor, but we decided to apply HTS coils for technological development.

Motivations for HTS Cyclotron

High temperature superconductors have several advantages over normal conductors and low temperature superconductors, which are:

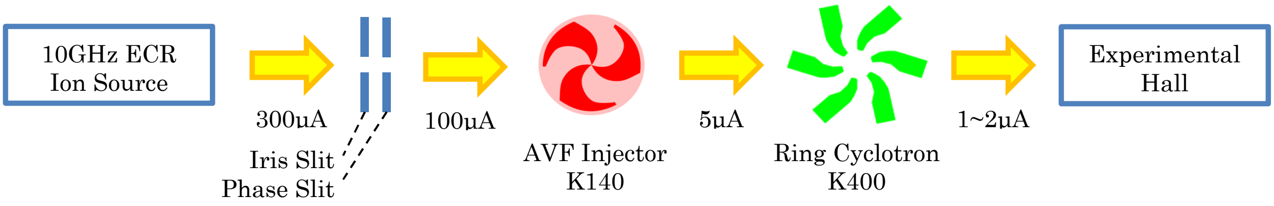

Figure 1: One example of proton acceleration in current RCNP cyclotron cascade.

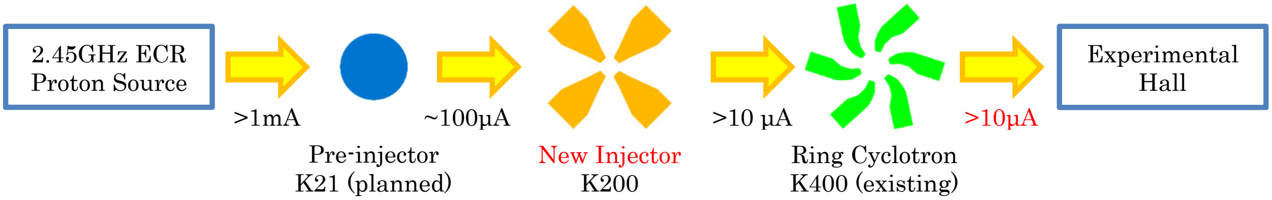

Figure 2: One example of proton acceleration in current RCNP cyclotron cascade.

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* keita@rcnp.osaka-u.ac.jp

INJECTION AND ACCELERATION OF INTENSE HEAVY ION BEAMS IN JINR NEW CYCLOTRON DC280

G. Gulbekian, I. Ivanenko, N. Kazarinov, E. Samsonov, JINR, Dubna, 141980, Russia

Abstract

At the present time the activities on creation of the new heavy-ion isochronous cyclotron DC280 are carried out at Joint Institute for Nuclear Research. The isochronous cyclotron DC-280 will produce accelerated beam of ions with A/Z= 4 - 7 to energy W= 4 – 8 MeV/n and intensity up to 10 pμA (for 48Ca). The goal for DC-280 accelerator complex is more then 40 % beam transfer efficiency. To achieve high-intensity ion beam, the cyclotron is equipped with high-voltage, up to 80 kV, injection line and independent Flat-Top RF system. To decrease the aperture losses at centre region the electrostatic quadruple lens will be installed between inflector and first accelerating gap. The paper presents the results of simulation of beam injection and acceleration.

INTRODUCTION

One of the basic scientific programs which are carried out in the FLNR JINR is synthesis of new elements which requires intensive beams of heavy ions. At present time the isochronous cyclotron U-400, which is in operation since 1978, is capable of providing long term experiments on 48Ca beams with an intensity of 1 pμA. Its operation time is more than 6000 hours per year. To enhance the efficiency of experiments it is necessary to obtain accelerated ion beams with the following parameters:

Ion energy 4÷8 MeV/n
Ion masses 10÷238
Beam intensity (up to A=50) 10 pμA
Beam emittance less 30 π mm mrad

These parameters formed the base for the new isochronous cyclotron DC-280 [1]. The basic technical solutions to realize new project are shown in Table 1.

Table 1: DC-280 Cyclotron - Basic Technical Solutions

Parameter DC280	Goals
1. High injecting beam energy (up to 100 keV/Z)	Decreasing space charge factor. Decreasing beam emittance.
2. High gap in the centre	Space for a long spiral inflector
3. Low magnetic field	Large starting radius. Good orbit separation. Low deflector voltage
4. High acceleration rate	Good orbit separation.
5. Flat-top system	High capture. Beam quality.

The new cyclotron complex provides an opportunity of carrying out physical and chemical research using radioactive targets, such as U, Pu, Am, Cm, Bk. The layout of the cyclotron assembling is shown in Figure 1.

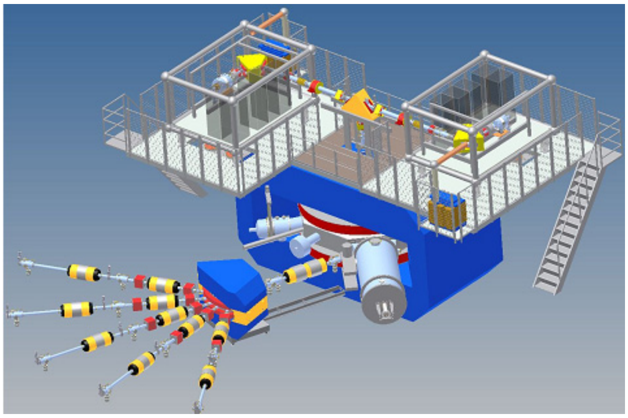

Figure 1: The layout of the DC-280 cyclotron.

Now the most of new cyclotron complex elements have been manufactured and the project is at the stage of laboratory building construction.

THE AXIAL INJECTION SYSTEM

The DC-280 injection system has to provide ion transition from the ECR-ion source to the cyclotron centre and capturing into acceleration more than 70 % of ions with the atomic mass to charge ratio of A/Z=4÷8 [2]. The experience in operation of FLNR cyclotrons demonstrates that at ion energies of 15 keV/Z the injection efficiency essentially depends on the ion beam current. At the ion beam currents of 80÷150 eμA the efficiency of capture into acceleration reaches 30÷35 %, but for the ion currents less than 10 eμA increasing of the efficiency to 50÷60 % has been observed. The reason of it may be the decreasing of the ion beam space charge effect and decreasing the beam emittance, especially at low level of the microwave power in the ECR source. To improve the injection efficiency we will increase the injection energy up to 100 keV/Z, since the emittance and the space charge effects have to be decreased.

The high-voltage axial injection of the DC-280 will consist of two high voltage platforms, HVP. The maximal voltage on the HVP will be 75 kV. Every HVP will be equipped with an ECR ion source with injection voltage 25 kV, a focusing elements and a magnet for ion separation and analyzing. The high voltage accelerating tube will be installed at the edge of the HVP to increase the ion energy.

Two types of ECR ion sources will be used: the DECRIS-PM source with permanent magnets and the DECRIS-SC superconducting one. The first ECR ion source has to produce high intensities (15÷20 pμA) of ions with medium masses (for example, $^{48}Ca^{7+,8+}$), the

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STATUS OF THE ACCULINNA-2 RIB FRAGMENT SEPARATOR

W. Beeckman, S. Antoine, P. Bocher, M. Cavellier, O. Cosson, F. Forest, N. Huttin, P. Jehanno,
P. Jivkov, C. Kellener, A. Kreiss, J.L. Lancelot, M.J. Leray, X. Milpied, R. Riedinger, O. Tasset,
SIGMAPHI, Vannes, France
A.S. Fomichev, L.V. Grigorenko, V.I. Kazacha, S.A. Krupko, S.V. Stepantsov, G.M. Ter-Akopian
on behalf of the ACCULINNA-2 collaboration, Flerov Laboratory of Nuclear Reactions,
JINR, RU-141980 Dubna, Russia

Abstract

Operated since 1996, the ACCULINNA RIB fragment separator has provided scientific results recognized by the nuclear physics community. In 2008 it was decided to build a new separator, ACCULINNA-2 which should deliver RIBs produced with 35-60 A MeV primary heavy-ion beams with $3 \leq Z \leq 36$. It is optimized for large RIB intensities and high precision studies of direct reactions populating nuclear systems near and beyond the drip lines through sophisticated correlation experiments [1].

Late 2011, SIGMAPHI got a global contract for optics check, design, fabrication, installation and alignment of the complete ACCULINNA-2. It includes magnets, vacuum and PS for about 40 magnets, from small correctors to 1-6 tons quads, 14 tons dipoles and 6- and 8-poles. We describe the evolution of the project, from functional needs to working system. Thanks to the early involvement of the industrial partner, the collaborative spirit and the freedom of tradeoff between magnet, PS and vacuum chamber, the final product meets all and even exceeds most requirements while meeting industrial needs for standardization.

The next step of the upgrade, a zero-angle spectrometer is also reported.

INTRODUCTION

FLNR JINR ACCULINNA-2 does not compete with large RIB facilities but rather complement them in a **cost effective** solution, delivering **high intensity RIBs** in the **lowest energy range** accessible to in-flight separators shown in Table 1.

Table 1: Characteristics of in-flight separators. ΔΩ and Δp/p are angular and momentum acceptances, Rp/Δp is the first-order momentum resolution for 1mm size object.

	ACC / ACC-2 FLNR JINR	**RIPS / BigRIPS RIKEN**	**A1900 MSU**	**FRS / SuperFRS GSI**	**LISE3 GANIL**
ΔΩ [msr]	0.9 / 5.8	5.0 / 8.0	8	0.32 / 5.0	1
Δp/p [%]	±2.5 / ±3.0	±3.0 / 6.0	±5.5	±2.0 / 5.0	±5.0
Rp/Δp	1000 / 2000	1500 / 3300	2915	8600 / 3050	2200
Bρ [Tm]	3.2 / 3.9	5.76 / 9.0	6	18 / 18	3.2 – 4.3
Length [m]	21 / 38	27 / 77	35	74 / 140	19 (42)
E [AmeV]	10÷40 / 6÷60	50÷90 / 350	110÷160	220÷1000 / 1500	40÷80
Additional RIB Filter	No / RF-kicker	RF-kicker / S-form	S-form & RF-kicker	S-form / Preseparator	Wien filter

As shown in Fig. 1, its structure is very comparable to that of RIPS in RIKEN [2] with a separation accomplished by means of dipole-wedge-dipole selection. High intensity, DC mode primary beam of U-400M cyclotron hits the solid beryllium, rotated liquid-cooled production target. Normal conducting magnets including 6- and 8-poles are used. The low intensity secondary part of separator is placed outside the accelerator closed area providing good background conditions in the experimental area.

The reader is referred to [3] for the expected beams, sources, instrumentation and planned experimental program and [4] for further reading on the facility.

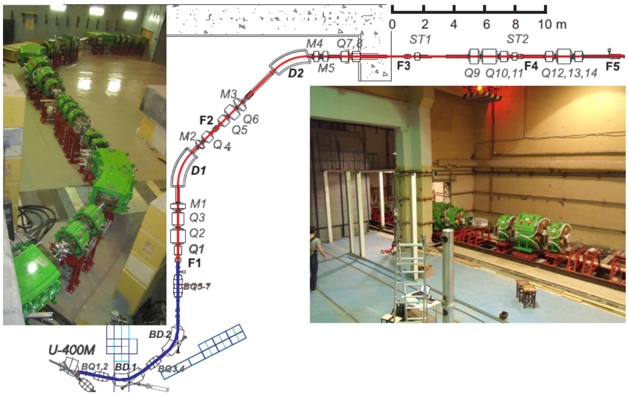

Figure 1: General layout and Room1 magnets, from primary line (blue) dipole BD1 to secondary line (red) quad Q8 (left) and Room2 Q10 to Q14 (right).

OPTIMIZATION

The scope of responsibility for SIGMAPHI was:

1. Optics check and « challenging »
2. All magnets – full electromagnetic calculations, mechanical design and fabrication
3. All power supplies, choice and fabrication
4. All vacuum, pressure calculations, layout, fabrication
5. Installation of all hardware
6. Alignment

Being in control of the 4 first items gives full freedom for an **optimized design** leading to an **energetically efficient** and **cost effective** facility, a too rare, although very interesting opportunity.

Indeed, the usual practice for labs is to have separate contracts for magnets, PS and vacuum, on the basis of *technical* specifications rather than *functional* ones. Every individual supplier is given very little room for change or improvement and must manage to achieve the cost goal

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BEAM ALIGNMENT PROCEDURE FOR SCANNED ION-BEAM THERAPY

Y. Saraya#[1], E. Takeshita[2], T. Furukawa[1], Y. Hara[1], K. Mizushima[1], N. Saotome[1], R. Tansho[1],
T. Shirai[1] and K. Noda[1]
[1]National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage-ku, Chiba 263-8555, Japan
[2]Kanagawa Cancer Center Hospital, 2-3-2 Nakao, Asahi-ku, Yokohama 241-8515, Japan

Abstract

It's important to control the beam position for the 3D pencil-beam scanning because the position accuracy of the beam has a serious matter on the alignment of the irradiation field. In order to suppress this matter, we have been developed a simple procedure for the beamline tuning. The fluctuation of the beam position is tuned with the steering magnets and bending magnets with monitoring the beam positions using the fluorescent screen monitors. After the tuning, the beam position at the isocenter is checked on the verification system which is consists of the screen monitor and the acrylic phantom. These adjustments are iterated until the deviation for all energies of the beam are within 0.5 mm. We had been performed the beam commissioning using our procedure in Kanagawa Cancer Center.

INTRODUCTION

Heavy-ion beams such as carbon-ion beams are superior in terms of high dose localization and biological effect around the Bragg peak. Three-dimensional (3D) pencil-beam scanning is an ideal irradiation technique to use these fundamental advantages [1]. In 3D pencil-beam scanning, extremely precise dose distribution could be deliver to the tumour since beams interact only with a low material budget in the beamline. Misalignment of the beam position at the patient position causes discrepancy between irradiated dose distribution and prescribed dose distribution. The difference of dose distribution increases unwanted dose to normal tissue. Thus, beam adjustment is important, periodically check of beam position is necessary. We have been developed a simple procedure for beam adjustment.

Adjustment of the beam transfer line is performed by steering beam position to the central orbit. There is difference between central orbit and the reference axis in the treatment room. The reference axis is defined with the acrylic phantom that steel sphere is embedded. The reference axis is called isocenter. Coordinate axes of the CT image and X-ray image are adjusted to the isocenter as well as beam position. All devices concerning patient setup have to be adjusted against the isocenter in order to deliver accurate dose distribution to the tumour. In this paper, we report our beam alignment procedure which we applied to beam transfer line in Kanagawa Cancer Center.

A compact dissemination treatment system of carbon-ion therapy had been constructed at Kanagawa Cancer Center. The carbon-ion scanning system which is designed by National Institute of Radiological Sciences had been installed. We are undertaking the commissioning to start treatment in December this year.

BEAM ALIGNMENT METHOD

A layout of high energy beam transfer line in Kanagawa Cancer Center is shown in Fig.1. Carbon-ion beams extracted from the synchrotron are transported to four treatment rooms. Two treatment rooms have a horizontal beamline, other two rooms have horizontal and vertical beamlines. In the beam transfer line, some fluorescent screen monitors (SCN) are installed for monitoring beam position and profile. Center of a beam profile is moved to central position at each screen monitor.

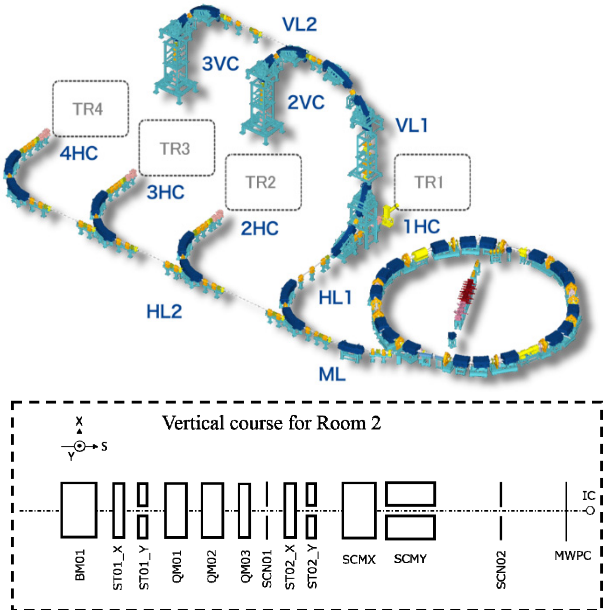

Figure 1: A layout of high energy beam transfer line in Kanagawa Cancer Center. The beamlines are composed of the horizontal and vertical beamlines. A figure surrounded with dotted line is configuration of magnets and SCN on the vertical beamline for Room 2.

In our beam alignment method, we basically steer the beam position using steering magnets. If deflection angle of steering magnet is large, beam position is steered with bending magnet. Since beam duct aperture is most narrow at the bending magnet for deflecting the beam toward upstairs or downstairs, beam adjustment of vertical beam line is performed before the adjustment of horizontal beam line. If the beam position is tuned at upstream SCN,

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#y_saraya@nirs.go.jp

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A NOVEL METHOD OF BEAM SCANNING OVER A LARGE SAMPLE AREA AT PLF, MUMBAI

C. Rozario, S. Pal*, J.N. Karande,
Pelletron Linac Facility, TIFR, Mumbai, India- 400005
V. Nanal, R.G. Pillay
Dept. of Nuclear and Atomic Physics, TIFR, Mumbai, India - 400005

Abstract

Many applications require uniform irradiation with heavy ion beams and special electric/magnetic devices are employed to scan the beam over the desired target area. We report a novel method of beam scanning using a magnetic steerer in the beam line. Indigenously developed magnetic steerers, comprising a pair of coils with sine-cosine winding, are installed in beam lines at PLF (Mumbai) for correcting the X-Y position of beam. This steerer is adapted to work as a scanner by employing a microcontroller and an interface unit for constant current bipolar power supply. A triangular waveform is applied to control the excitation current for scanning the beam simultaneously in both horizontal (X) and vertical (Y) planes. A programme generates a raster pattern governed by a pre-settable number of X sweeps for each Y sweep. The dwell time at each of X-Y position was adjusted considering the time constant arising due to the inductance of the steerer. Multiple raster scans were used to produce uniform irradiation over the sample. The scanner has been successfully employed for uniform irradiation of GaAs substrate for photoconductive THz applications using ^{12}C beam.

INTRODUCTION

The Pelletron LINAC Facility (PLF), Mumbai is a major centre for heavy ion accelerator based research in India. The Pelletron (14MV) was commissioned in 1989 and the superconducting LINAC booster employing Pb plated QWRs was added in 2007 [1, 2]. Several experimental facilities have been established at this centre to pursue research in nuclear, atomic, condensed matter physics, interdisciplinary areas and applications. For R&D in materials for science applications, the uniform irradiation of high-energy, intense ion beams over a large area is required. It is therefore, desirable to design and develop a relatively simple and inexpensive beam scanner. There are various methods for making uniform irradiation with a well focused pencil like narrow beam over a large area. Some of them involve simply broadening the spatial profile of the beam by defocusing, or scattering, while others employ special electric/magnetic devices for moving the beam over desired sample area. The defocusing method, although simple, can not yield a uniform irradiation over a large area and lacks good reproducibility of dose distribution. The scattering method using double scattering foils and occluding ring [3, 4] results in loss of particle energy and in beam intensity due to the scattering foils. Raster scanning with electromagnetic device is very useful for heavy ions as it does not involve scattering or energy loss. The present paper describes a novel method of beam scanning using a magnetic steerer in the beam line.

SCANNING SYSTEM

The beam scanning system is required to provide beam deflection in both horizontal (X) and vertical (Y) direction. The magnets in the scanning system must have sufficient rigidity to generate the required deflection at the target and should have fast ramping speed to ensure uniform intensity in desired area even for small doses. Moreover, the accuracy and reproducibility are highly essential for preparation of multiple samples. Indigenously developed magnetic steerers, are installed in beam lines for correcting the X-Y position of beam. This steerer is adapted to work as a scanner by employing a microcontroller and an interface unit for constant current bipolar power supply. The steerer consists of standard 36 slotted motor-stator housing with two independent pairs of sine and cosine windings, which produces a homogeneous field in the X and Y directions over a large volume. The vacuum chamber is cylindrical in shape with ~10 cm diameter and ~15 cm long. The sine-cosine winding pairs are connected in parallel to reduce the effective coil inductance. The field is found to be homogeneous (better than 1 %) in central region of 50 mm radius over an effective length of ~ 9 cm. Each doublet coil can take a maximum current of 10 A, which gives a $B_{max} = 0.5$ T along the axis of the steerer. The inductance of the coil is 50 µH and time constant is 15 µsec. Figure 1 shows a photograph of steerer magnet and schematic of the beam scanning system.

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*sanjoy.pal@tifr.res.in

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NEW HIGH-ENERGY BEAM TRANSPORT LINE DEDICATED TO BIOLOGICAL APPLICATIONS IN RIKEN RI BEAM FACTORY

N. Fukunishi[#], M. Fujimaki, M. Komiyama, K. Kumagai, T. Maie, Y. Watanabe, T. Hirano, T.Abe
Nishina Center for Accelerator-based Science, RIKEN, 2-1 Hirosawa, Wako, Saitama, Japan

Abstract

The existing beam transport system of the RIKEN RI Beam Factory has been extended to deliver higher energy beams to the existing irradiation port for biological applications in order to breed seaweed using an ion-beam breeding technique widely used for flowers and crops. The maximum magnetic rigidity of the new branch beam line is 4.4 T-m. As a result, a 160-MeV/nucleon argon beam is available for seaweed breeding experiments. The new beam line was commissioned in January 2015 and we confirm that the design specifications have been met.

INTRODUCTION

Heavy-ion beams are widely used for biological applications thanks to their high biological effectiveness. The RIKEN Nishina Center has used energetic heavy ions as an effective tool inducing mutations of flowers, crops, and microbes [1]. Selective breeding is conducted from irradiated samples and many commercially useful plants have been produced. The beams used in these experiments are 135-MeV/nucleon carbon, nitrogen and neon beams, a 95-MeV/nucleon argon beam and a 90-MeV/nucleon iron beam. These are obtained from the RIKEN Ring Cyclotron commissioned in 1986 [2]. Linear Energy Transfer (LET) is proportional to the second power of the ion's charge for the ions having the same velocity. Hence we can control damage to the sample by changing ion species. The LET dependence of biological effects has been demonstrated by modern genetic analysis in which the pattern of gene deletion was shown to differ among ion species [3].

The difference between our method and cancer therapy is that the Bragg peak region is not used because too much damage leads to a low survival rate of irradiated samples and would be less effective for obtaining useful new breeds. Using the Bragg peak region would also create a further difficulty. In these breeding experiments, the LET-dependence of the mutation effectiveness should be precisely determined to develop a database, essential for efficient breeding. But an ion's LET changes greatly within the sample irradiated if we use the Bragg peak region of the ion. The only exception is the irradiation of very thin samples, but these are not always available.

The effectiveness of ion-beam breeding has been established for a wide variety of plants. Based on this success, a new project has started, in which ion-beam breeding is applied to seaweeds, such as wakame (*Undaria pinnatifida*) and kombu (*Saccharina japonica*). Wakame is a special product of the Tohoku region in Japan, which was seriously damaged by a big earthquake in 2011. In applying this technique to seaweed, heavier ions, such as argon and iron, were expected to be more effective than lighter ions; but these ions do not have sufficient energies to form nearly flat LET distributions. To solve this problem, we decided to use a higher-energy cyclotron: the Intermediate-stage Ring Cyclotron (IRC) [4]. The bending limit of the IRC is 980 MeV, much higher than that of the RRC (540 MeV). The maximum beam energy of the IRC for medium-heavy ions is 160 MeV/nucleon, also much higher than the 95 MeV/nucleon of the RRC. This energy upgrade results in a nearly 3-fold increase of the ion range in the assumed experiments with argon ions. However, the existing beam delivery system of the RIBF cannot deliver a beam extracted from the IRC to the existing irradiation port where a fully automated irradiation system is installed [1]. Hence, the existing beam delivery system has been extended to meet this demand.

HIGH-ENERGY BEAM LINE

Beam Line Description

The relevant part of the RIBF beam delivery system is shown in Fig. 1. A beam extracted from the IRC is deflected by the DAKR dipole magnet in order to separate the beam from the existing SRC-injection line. The SRC (Superconducting Ring Cyclotron) is the final-stage accelerator of the RIBF. The section from IRC extraction to DMR2 makes the dispersive IRC beam doubly achromatic. The beam is bent up by DMR3 and bent down by DMR4 to shift the beam vertically by 3 m to compensate for the floor level difference. Here, the beam is doubly achromatic in the vertical direction. The section from DMR5 to DMR6 forms an achromatic bending system of 90°. The section from DMR7 and DMR8 is also doubly achromatic. After that, the beam line is joined to the existing beam delivery fishbone at the DMA1. The section from just after the DMR2 to DMR6 is not newly constructed but uses the existing IRC bypassing beam line in reverse. The IRC bypassing beam line was constructed to inject a beam accelerated by the RRC directly into the SRC, skipping the IRC, in order to perform light-ion experiments, especially polarized deuteron experiments. Faraday cups are added to the IRC bypassing beam line to adapt it for the present purpose.

The ion optical design was made by using TRANSPORT code. The maximum magnetic rigidity was 4.4 T-m, slightly smaller than the maximum magnetic rigidity of the IRC (4.57 T-m). The beam envelopes

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[#] fukunisi@ribf.riken.jp

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PROPOSAL FOR A HIGH POWER DEUTERON CYCLOTRON AT RISP

A. Adelmann[1], J.R. Alonso[2], L. Calabretta[3],A. Calanna[3], D. Campo[4], J. Yang[5], J.W. Kim[6], S. Jeong[6]
[1]PSI, Villigen, Switzerland, [2]MIT, USA
[3]INFN-LNS, Catania, Italy, [4]INFN-LNL, Legnaro, Italy
[5]CIAE, Beijing, China, [6]RISP, Daejeon, Korea

Abstract

We are proposing a compact isochronous cyclotron able to accelerate a high intensity beam with q/A 0.5 up to the final energy of 60 MeV/A. When accelerating H_2^+, it can be used as a driver for a high-intensity anti-neutrino source, as in the IsoDAR experiment. We believe that this type of cyclotron source placed near a neutrino detector, like Reno_50 or KamLAND would give impressive sensitivity to sterile neutrino searches and to electroweak measurements using neutrino-electron scattering. Here we present the idea of a modified IsoDAR cyclotron as the primary accelerator to drive the ISOL system of Rare Isotope Science Project (RISP) at Daejeon (Korea). The IsoDAR cyclotron is able to accelerate any ion with charge to mass ratio q/A=0.5 so deuterons or fully stripped light ions can be accelerated with high beam current and delivered to the production target for radioactive ions of RISP.

INTRODUCTION

The IsoDAR neutrino source [1] consists of a (q/A=0.5) cyclotron delivering 60 MeV protons to a ^{9}Be target. IsoDAR can use the same cyclotron design as the injector cyclotron for the two-cyclotron system for the 800 MeV DAEδALUS experiment [1, 2].

This paper describes a design study of the IsoDAR cyclotron [3], the features of this accelerator and the possible uses in other research fields. In particular, we are exploring the use of the IsoDAR cyclotron to accelerate a deuteron beam up to an energy of 40 MeV/A to fulfill the requests of RISP (the Rare Isotope Science Project) in Daejon, Korea. In particular, RISP is evaluating the advantage of using a high power deuteron beam to strike a target converter producing an intense neutron flux to irradiate a target of ^{238}U. The rare isotopes produced by the neutron-induced fission are then analyzed and reaccelerated. A modified IsoDAR cyclotron could not only deliver a proton beam through the acceleration of the H_2^+, but also fully-stripped light ions like carbon and oxygen. These different projectiles allow the use of the most convenient target-beam combination to produce different radioactive species. Here we focus on how the IsoDAR cyclotron can satisfy the needs of RISP.

ISODAR CYCLOTRON FEATURES

The cyclotron designed for the IsoDAR experiment is very similar to the one designed for DAEδALUS injector. It is a 4 sector normal conducting machine able to provide H_2^+ beams, and more generally, beams with q/A=0.5 up to an energy of 60 MeV/A. Several reasons have convinced the IsoDAR collaboration that H_2^+ was the right ion to accelerate.

The binding energy of the electron in H_2^+ is 2.75 eV, this eliminates the Lorentz stripping problem. The acceleration of a molecular beam like H_2^+ needs a better vacuum, of the order of 10^{-5} Pa, to minimize the interaction with the residual gas. This vacuum level is within the range of existing machines.

Furthermore, H_2^+ acceleration reduces space-charge effects. A simple way to see this is to note that for every two protons injected at the center, there is only +1 electric charge. Thus, we have 5 mA of H_2^+ while we provide 10 mA of protons to the target.

Table 1: Details of the IsoDAR Cyclotron Design

Design element	Design value	Design element	Design value
E_{max}	60 MeV/A	E_{inj}	35A keV
R_{ext}	1.99m	R_{inj}	55 mm
<B> @R_{ext}	1.16 T	<B> @R_{inj}	0.97 T
Sectors	4	Hill width	25.5° - 36.5°
Valley gap	1.8 m	Pole gap	80-100 mm
Outer diameter	6.2 m	Full height	2.7 m
Cavities	4	Cavity type	λ/2 double gap
Harmonic	4th	frequency	32.8 MHz
Acc. Voltage	70 – 240 kV	Power /cavity	310 kW
ΔE/turn	1.7 MeV	Turns	95
ΔE/turn @R_{ext}	<20 mm	ΔR/turn @R_{inj}	>56 mm
Coil size	200x250 mm^2	Current density	3.617 A/mm^2
Iron weight	450 tons	Vacuum	<10^{-7} mbar
Beam Injection	By spiral inflector	Beam Extraction	electrostatic deflector

A measure of the space charge effect is the generalized perveance K [4]:

$$K = \frac{qI}{2\pi\epsilon_0 m\gamma^3\beta^3}$$

where: q and m are the charge and mass of the particle, β and γ are the usual relativistic parameters, ε_0 is the vacuum permittivity, and I is the beam current.

PROGRESS ON THE UPGRADE FOR TRT AT NIRS CYCLOTRON FACILITY

S. Hojo[#], T. Wakui, K. Katagiri, K. Nagatsu, H. Suzuki, M. Nakao,A. Sugiura, and A. Noda
NIRS, Anagawa 4-9-1, Inage, Chiba, JAPAN

Abstract

The cyclotron facility at National Institute of Radiological Sciences (NIRS) includes two cyclotrons, a NIRS-930 cyclotron (Thomson-CSF, Kb=110 MeV and Kf=90 MeV) and a small cyclotron HM-18 (Sumitomo-Heavy-Industry) [1]. The NIRS-930 cyclotron has been used for radionuclide production, nuclear physics, detector development and so on, since the first beam in 1973. The HM-18 has been used for radionuclide production for PET since 1994.

In recent years, the production of radionuclides for Targeted Radionuclide Therapy (TRT) by using NIRS-930 has been one of the most important activities in NIRS. Since demand of radionuclide users on beam intensity is growing, we have launched to upgrade the cyclotron facility, such as installation of multi-harmonic beam buncher in NIRS-930 and a reinforcement of nuclear ventilation system in a cave.

Progress on the upgrade for TRT at the cyclotron facility and status of the NIRS cyclotrons are to be presented in this report.

INTRODUCTION

The NIRS-930 cyclotron has been mainly operated to produce radionuclides. The system layout of NIRS-930 facility is shown in Fig. 1. This facility has 10 beam ports, and 4 beam ports of them are exclusively used for radionuclide production. The C-1 and C-2 beam port are used for production of radionuclides for PET. The C-4 beam port is used for production of metal radionuclides such as ^{62}Zn/^{62}Cu for SPECT. The C-9 beam port is used for production of radionuclides with a low-melting-point solid target such as ^{124}I and ^{76}Br [2]. In addition to these 4 beam ports, renewal of the C-3 beam port is in progress for radionuclides production. This beam line has wobbler magnets for avoiding heat concentration on a target [3]. Radionuclide production using this beam port will be started in January, 2015.

The ratio of operation times of NIRS-930 in fiscal year 2014 is shown in Fig. 2. The radionuclide production account for 49% of the operation times, and its related operation, namely beam tuning and machine studies to make a suitable beam, was 21%. Thus, almost 70% of whole operation time was shared for the purpose of radionuclides production.

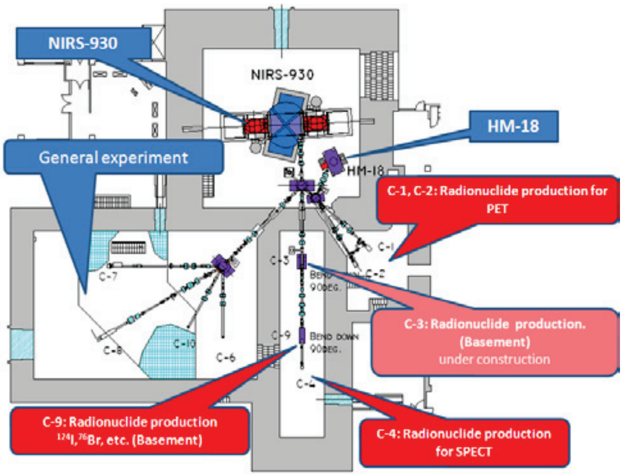

Figure 1: The system layout of the NIRS-930 facility.

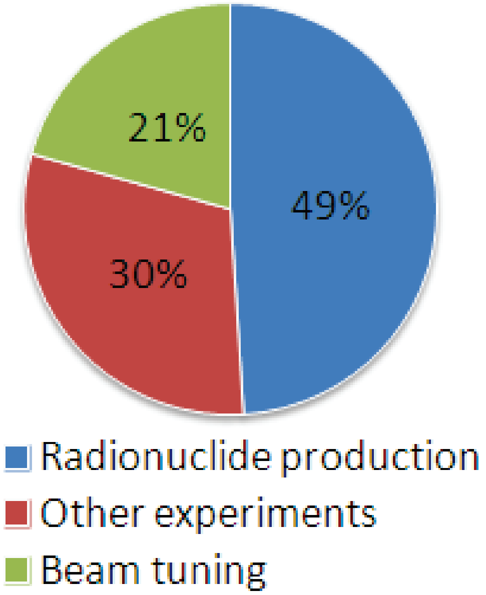

Figure 2: The ratio of operation times of NIRS-930 in fiscal year 2014.

CURRENT STATE OF RADIONUCLIDE PRODUCTION USING NIRS-930

In the past, radionuclide produced using NIRS-930 was mainly used for molecular imaging such as PET and SPECT. In recent years, production techniques of radionuclides such as ^{211}At, ^{186}Re, ^{64}Cu, and ^{67}Cu have been developed and applied for studies of TRT at NIRS.

A list of radionuclide produced NIRS-930 is shown in Table 1 with reactions and beams. The highest beam power is 600 W at 30 MeV proton 20 eμA.

[#] s_hojo@nirs.go.jp

THE MULTI PARTICLE SIMULATION FOR THE CYCLOTRON NIRS-930

M. Nakao#, S. Hojo, K. Katagiri, A. Noda, K. Noda, A. Sugiura, T. Wakui, NIRS, Chiba, Japan
V. Smirnov, S. Vorozhtsov, JINR, Dubna, Moscow, Russia
A. Goto, Yamagata University, Yamagata, Japan

Abstract

Simulation for the cyclotron NIRS-930 of many particles considering space charge effect has been performed and results are compared with experiment. NIRS-930 is used for producing radionuclide used as nuclear medicine and for providing beam for physical and biological experiment. To increase the yield of radionuclides, they need to increase beam intensity of cyclotron. For such a purpose, computer simulation using a code SNOP has been performed. The simulation of proton with 30 MeV of extraction energy with harmonic number of 1 was already performed and well simulated RF phase and extraction efficiency. Then we tried to apply SNOP to 18 MeV protons with harmonic 2. The bunch length of injection beam changes injection and extraction efficiency. This indicates optimizing buncher improves the efficiency. We optimized electric deflector and magnetic channel in order to maximize extraction efficiency. We show the phase space plot to visualize the improvement of efficiency. We intend to apply the parameters suggested by the simulation to actual cyclotron operation to improve beam intensity and quality.

INTRODUCTION

Simulation studies about the cyclotron NIRS-930 [1] (Thomson-CSF, K_b=110 MeV, K_f=90 MeV) have been carried out aiming to understand the beam behavior for increasing beam intensity. If we assume negative ion injection, beam intensity could become more than double. But it needs large scale upgrade of target and shielding. So we hope to improve the injection, acceleration and extraction efficiency to increase beam intensity.

We need to know what causes the beam loss though we can detect the lost beam current only at the probe experimentally. Therefore beam simulation study of the purpose of identifying the beam loss point and find parameters of cyclotron elements which can realize high efficiency.

SIMULATION METHOD

Simulation Program SNOP

Simulation program SNOP [2,3] simulates particle orbit from beam injection to extraction with the electric fields of the inflector, the Dee electrodes and the deflector; the magnetic fields of the main coils, the trim coils and the harmonic coils and the magnetic channel which were calculated by OPERA-3d [4]. The particle orbit was derived continuously from the beginnig point to the lost point (or successfully extracted), dividing to the regions of injection (inflector), acceleration, and extraction internally of the program. The particle orbit was solved by the fourth order Runge-Kutta method. The space charge effect was taken into account both by particle to particle method and by particle in cell (PIC) method using FFT and Poisson boundary. Results of both methods are compared and parameters such as time and space division are determined considering the consistency of the both methods.

Modeling of NIRS-930

Figure 1 shows the calculation model of the NIRS-930. The beam from the ion source sit on the cyclotron yoke is guided by a bending magnet and comes into the central part of cyclotron. The inflector injects the beam with the use of static electric field. NIRS-930 has 4 spiral sectors. Main coil, 12 pairs of trim coils, 4 injection harmonic coils and 4 extraction harmonic coils are utilized to form magnetic field of accelerating region. The beam is accelerated by the RF electric field by the dee electrode whose central angle is 86°. The extraction radius is 920 mm and there are an electrostatic deflector, a magnetic channel and a gradient corrector for beam extraction.

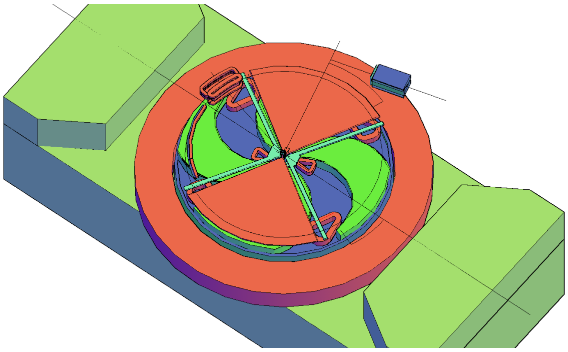

Figure 1: The half cut model of the cyclotron NIRS-930.

INJECTION AND EXTRACTION EFFICIENCY DEPENDENCE ON BUNCH LENGTH

Changing the RF phase difference of buncher and dee electrodes, the efficiency of injection and extraction depends on particle amount in phase acceptance varies. The experimental result is shown in Fig. 2. Injected beam intensity was measured by main probe inserted to the position of the radius of 10 cm and extracted beam intensity was measured by faraday cup at beam line just after extraction form cyclotron. The maximum extraction efficiency was 28 % and which was more than twice higher

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RIKEN RING CYCLOTRON (RRC)

Yutaka Watanabe, Masayuki Kase, Masaki Fujimaki, Nobuhisa Fukunishi, Eiji Ikezawa,
Osamu Kamigaito, Keiko Kumagai, Takeshi Maie, Jun-ichi Ohnishi, Kazutaka Ohzeki,
Hiroki Okuno, Naruhiko Sakamoto, Kenji Suda, Shu Watanabe, Kazunari Yamada
RIKEN Nishina Center, Wako, Saitama, Japan
Seiji Fukuzawa, Makoto Hamanaka, Shigeru Ishikawa, Kiyoshi Kobayashi,
Ryo Koyama, Takeshi Nakamura, Minoru Nishida, Makoto Nishimura,
Junsho Shibata, Noritoshi Tsukiori, Kazuyoshi Yadomi
SHI Accelerator Service Ltd., Tokyo, Japan

Abstract

The RIKEN Ring Cyclotron (RRC) has operated stably for over 28 years and has supplied many types of heavy-ion beams for various experiments. The RRC has three types of injectors: the azimuthal varying field (AVF) cyclotron for comparatively light ions, the variable-frequency RIKEN heavy-ion linac (RILAC), and the RIKEN heavy-ion linac 2 (RILAC2) for high intensities of very heavy ions, such as those of U and Xe. Many accelerator combinations are possible, although the RRC should act as the first energy booster in any acceleration mode. The total operation time of the RRC is usually more than 3000 h/year. Recently, however, frequent malfunctions caused by age-related deterioration and beam loss, such as a layer short of main coils and vacuum leaks at feed-through, cooling water pipes, extraction devices, a bellows and so on, have been occurring at the RRC. The present status of the RRC is presented in this paper.

INTRODUCTION

Although the RIKEN Ring Cyclotron (RRC) began operation in 1986, it still plays an essential role as the first energy booster in the Radioactive Isotope Beam Factory (RIBF) accelerator complex. The RIBF was built by 2007 to expand the scope of research on heavier nuclei, thus building upon previous work on light unstable nuclei. The RIBF uses a combination of three injectors, RRC, three new cyclotrons (fRC, fixed-frequency Ring Cyclotron; IRC, Intermediate-stage Ring Cyclotron; and SRC, Superconducting Ring Cyclotron), and the RIKEN projectile fragment separator [1]. Using the RIBF, we aim to produce the most intense radioactive isotope beams in the world, with intensities of up to 1 pμA and including isotopes of all atomic masses. Stable operation of highly intense beams has been gradually realized at the RIBF. However, frequent malfunctions have recently occurred at the RRC due to age-related deterioration and beam loss. Some components have been repaired, and others have been replaced, but these issues remain serious and have not yet been solved. The operation of and problems with the RRC are as follows.

Table 1: RIBF Operating Statistics from August 2014 to July 2015.

Beam particle	Energy (MeV/u)	Acceleration mode	Actual beam current (pnA)	Beam tuning time (h)	Actual beam time (h)	Availability (%)
12C	70	AVF-RRC	350.0	28.4	36.0	100.0
12C	135		393.2	149.5	47.0	100.0
40Ar	95		76.5	169.5	32.0	100.0
56Fe	90		6.3	108.8	21.0	100.0
84Kr	70		5.6	72.8	121.0	100.0
86Kr	36	RILAC-RRC	8.8	41.3	12.0	100.0
48Ca	63		235.3	39.5	104.3	95.4
136Xe	10.75	RILAC2-RRC	405.0	90.3	106.0	109.4
238U	10.75		2500.0	110.2	48.0	100.0
40Ar	160	AVF-RRC-IRC	1.6	136.7	48.0	100.0
pol.d	190	AVF-RRC-SRC	290.0	77.1	123.9	105.6
48Ca	345	RILAC-RRC -IRC-SRC	530.0	175.6	492.2	96.3
78Kr	345	RILAC2-RRC -fRC-IRC-SRC	486.1	143.5	732.0	90.1
238U(1st)	345		27.9	261.8	532.1	94.2
238U(2nd)	345		31.4	214.6	553.0	91.5
238U(3rd)	345		39.5	87.2	252.0	99.5
			Total	1907	3260	

RRC OPERATION

The operation of the RRC from August 2014 to July 2015, including that of the fRC, IRC, and SRC, was published previously [2]. A list of the beams accelerated by these cyclotrons during this period is presented in Table 1. As shown, seven acceleration modes have employed the RRC, including an AVF-RRC-IRC mode for biological experiments that was first used in the winter of 2015. The actual beam service time during which the RRC was used, excluding beam tuning time, was 3260 h in the past year. The beam availability [1], defined as the ratio of actual beam service time to scheduled beam service time, was more than 90 %. Although there was downtime due to hardware trouble in 2011, this beam availability has recently increased each year [1-3]. The total yearly operation time of the RRC, including beam

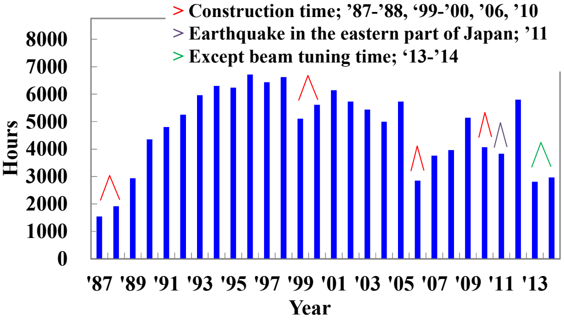

Figure 1: Total yearly operation time of RRC.

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ynabe@riken.jp

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DEVELOPMENT OF LOW-ENERGY HEAVY-ION BEAMS BY THE RIKEN AVF CYCLOTRON AND HYPER ECR ION SOURCE OF CNS

Y. Kotaka#, Y. Ohshiro, S. Watanabe, H. Yamaguchi, N. Imai,
S. Shimoura, Center for Nuclear Study, University of Tokyo, Wako, Saitama, Japan
M. Kase, S. Kubono, Riken Nishina Center, RIKEN, Wako, Saitama, Japan
K. Hatanaka, Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka, Japan
A. Goto, Yamagata University, Yamagata, Yamagata, Japan
H. Muto, Center of General Education, Tokyo University of Science, Chino, Nagano, Japan

Abstract

The first of three categories of the upgrade of RIKEN AVF cyclotron is to expand a variety of metal ion beams using Hyper ECR ion source. The non-axial rod method, multi-hole micro-oven method and plasma spectroscopy was developed. The second is to increase acceleration energy. By the beam simulation, the center region was renovated and $^4He^{2+}$ 12.5 MeV/u ion beam can be available. The third is to increase beam intensity. For injection, a pepper-pot emittance monitor is developed for the purpose of measuring a four-dimensional phase space distribution. For extraction, flat top system was developed. Using a faraday cup installed at the exit of deflector, the extraction efficiency is improved. For the transmission efficiency from AVF cyclotron to CNS RI Beam separator, the redesign of beam transport system is planned.

INTRODUCTION

RIKEN AVF cyclotron was built in 1989. This original design is the following. RF frequency range is 12-24 MHz. The acceleration harmonics is 2. Maximal RF voltage is 50 kV. Average magnetic field range at the extraction is 0.5-1.76 T. K-value is 70.

The upgrade of AVF cyclotron has been conducted since 2000 by a collaboration of the Center for Nuclear Study (CNS) of the University of Tokyo and RIKEN Nishina Center to meet the request of CNS RI Beam separator (CRIB) which can produce the low energy RI beam to study nuclear astrophysics [1].

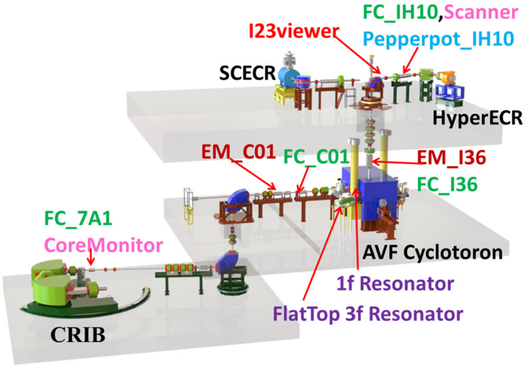

Figure 1: The schematic view of Hyper ECRIS, AVF cyclotron and CRIB with beam transport line.

We have three categories of the upgrades. One is to expand a variety of ion species. Two is to expand the region of available acceleration energy. Three is to increase beam intensity. Each will be in the following.

Besides, nondestructive beam monitors, Scanner [2] and Core Monitor [3], were developed to see stability.

Figure 1 shows the location of AVF cyclotron, Hyper ECR ion source (ECRIS), CRIB and the several diagnostics.

EXPAND ION SPECIES

We have developed two methods for feeding vapor of solid materials into the plasma by ECRIS in order to expand the ion species as well as increasing the beam intensity stably [4]. One is the non-axial rod method applied for CaO, SiO_2 and FeO, operating up to 2600 degrees. Since the tip of the material rod is placed near the wall of plasma chamber, the constant vapor rate of material is obtained. Two is the multi-hole micro-oven method applied for P_2O_5, Li, and S, operating up to 800 degrees. We can control the vapor rate with the number of holes of crucible. The beam intensities extracted from the ECRIS are listed in Table 1 together with melting point.

Table 1: Solid Ion Species Ionized by Hyper ECRIS

Ion Species	Beam Intensities (eμA)	Charged Material	m.p. (°C)
$^{6,7}Li^{2+}$	200→280	Li pure metal (Oven)	180
$^{6,7}Li^{3+}$	34→75	Li pure metal (Oven)	180
$^{10}B^{4+}$	50	$B_{10}H_{14}$ (^{10}B-99.9,MIVOC)	99
$^{11}B^{4+}$	50	$B_{10}H_{14}$ (MIVOC)	99
$^{24}Mg^{8+}$	30→45	Mg pure metal (Oven)	650
$^{28}Si^{9+}$	32→35	SiO_2 (Rod)	1500
$^{31}P^{9+}$	29	P_2O_5 (Oven)	563
$^{32}S^{9+}$	47	S grain (Oven)	119
$^{40}Ca^{12+}$	25	CaO (Rod)	2572
$^{56}Fe^{15+}$	7→15	FeO (Rod)	1420
$^{58}Ni^{15+}$	13	$C_{10}H_{10}Ni$ (MIVOC)	173
$^{59}Co^{15+}$	7→20	Co pure metal (Rod)	1493
$^{87}Rb^{20+}$	1.2	RbCl (Oven)	682

Plasma spectroscopy has been developed in order to separate the desired ion species from the same m/q ion species in the plasma. The method is to observe the light intensity of the desired ion species by a grating monochromator. We confirmed the relation between the light intensity of an optical line spectrum of $^6Li^{3+}$ and its beam intensity measured by the faraday cup (FC) located at the exit of AVF cyclotron. Therefore, we can apply the light intensity to the beam intensity [5]. By this method, the tuning efficiency of ECRIS has been improved.

#kotaka@cns.s.u-tokyo.ac.jp

PHASE BUNCHING IN THE CENTRAL REGION OF THE JAEA AVF CYCLOTRON FOR HEAVY-ION ACCELERATION IN THE THIRD-HARMONIC MODE

N. Miyawaki[#], S. Kurashima, H. Kashiwagi, S. Okumura, JAEA, Gunma, Japan
M. Fukuda, Osaka University, Osaka, Japan

Abstract

Phase bunching realized in the central region of the JAEA AVF cyclotron for heavy ion acceleration in the third-harmonic mode (*h* = 3) was evaluated using both calculations with a simplified geometric trajectory model and measurements of internal beam phase distributions. The phase bunching effect for *h* = 3 was compared with that for *h* = 2, where the geometric condition of the central region differs from that for the former. Both of the measurements of internal beam phase distributions without the buncher and the calculations with the model have shown that the phase bunching effect for *h* = 3 was equivalent to that for *h* = 2 when a beam buncher was not used before the acceleration. In the measurement using the buncher, the phase width in the case of *h* = 3 was larger than that of *h* = 2. In order to enhance of the phase bunching for *h* = 3, it is necessary to modify the geometric condition of the central region and to increase the ratio of a peak dee-voltage to an extraction voltage of an ion source, which is one of the parameters determining the phase bunching performance, with a suitable injected beam distribution in the radial phase space.

INTRODUCTION

The azimuthally varying field (AVF) cyclotron with a K number of 110 MeV at the Japan Atomic Energy Agency (JAEA) is widely utilized for research in radiochemistry, biotechnology and materials science as well as nuclear physics and the production of radioisotopes [1]. In order to produce a variety of heavy ion beams in a wide range of energy, the cyclotron is operated with three acceleration harmonic modes of *h* = 1, 2 and 3, which is defined as $f_{\mathrm{rf}} / f_{\mathrm{particle}}$, a ratio of the rf frequency to the orbital one. Heavy ions up to osmium ions are produced by four normal conducting electron cyclotron resonance (ECR) ion sources.

Recently, the cyclotron was upgraded for the advanced ion beam applications using a microbeam [2] and a single-pulse beam [3]. In the microbeam formation, an energy spread of the order of 10−4 is required to reduce the influence of chromatic aberrations caused in the focusing lenses. A flat-top acceleration system was developed to minimize energy spread of an ion beam [4], and the central region of the cyclotron was remodelled to minimize the beam phase width [5]. For production of the single-pulse beam, specific techniques to optimize the acceleration phase [6] and to stabilize the magnetic field [7] are needed to enhance the controllability of the beam pules number extracted from the cyclotron [3].

The remodelled central region generates the phase bunching effects in the acceleration harmonic mode of *h* = 2 and 3. Phase bunching originates in energy-gain modulation produced in a rising-slope region of an acceleration-voltage waveform at the first acceleration gap, and minimizes the beam phase width at the second acceleration gap. We elucidated the mechanism of phase bunching by a simplified geometric trajectory model [8]. The beam phase correlations between the first and the second acceleration gap obtained by the geometric trajectory model for three acceleration harmonics in the JAEA AVF cyclotron were consistent with the correlations between the initial beam phase and the beam phase at 100 turns analysed by the orbit simulation [9]. Moreover, the phase bunching performance in the central region of the cyclotron was evaluated by measurement of the beam phase distributions. The correlations between the buncher phase and the measured internal phase distribution for *h* = 1 and 2 were consistent with the calculated results obtained by the geometric trajectory model [10]. However, the phase bunching effect for *h* = 3 in the central region, where the geometric condition of *h* = 2 is different, was not evaluated yet.

In this paper, we described the calculation and the measurement of the phase bunching for *h* = 3 in the JAEA AVF cyclotron, and the comparison of the phase bunching effect for *h* = 3 with that for *h* = 2.

CALCULATION OF PHASE BUNCHING BY GEOMETRIC TRAJECTORY MODEL

The phase bunching performance was evaluated with the correlation between the initial phase difference $\Delta\phi$ and the phase difference $\Delta\phi$S at the second acceleration gap by the geometric trajectory model in homogeneous magnetic field, as indicated by the following equation,

$$\Delta\phi_S = \Delta\phi + h\left(\theta_E + \Delta r'\right) + h\cdot\sin^{-1}\left[\begin{array}{l}\dfrac{\sqrt{1-V_R\sin\phi_P}+\Delta r}{\sqrt{1-V_R\sin\left(\phi_P+\Delta\phi\right)}}\sin\theta_P \\ -\sin\left(\theta_E+\Delta r'+\theta_P\right)\end{array}\right], \qquad (1)$$

where θ_P is a span angle from the first to the second acceleration gap, θ_E is the angle between the straight line of the acceleration gap passing through the cyclotron center and the line perpendicular to the particle emitting direction, V_R is the ratio of a peak dee-voltage to an extraction voltage of an ion source in units of MV, Δr and Δr' are the position difference and emission angle difference from the reference particle, respectively and ϕ_P

[#] miyawaki.nobumasa@jaea.go.jp

STATUS REPORT OF THE OPERATION OF THE RIKEN AVF CYCLOTRON

K. Suda*, M. Fujimaki, N. Fukunishi, T. Kageyama, O. Kamigaito, M. Kase, M. Komiyama,
K. Kumagai, T. Maie, M. Nagase, T. Nagatomo, T. Nakagawa, H. Okuno, N. Sakamoto,
A. Uchiyama, T. Watanabe, Y. Watanabe, K. Yamada,
RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama, Japan
T. Nakamura, S. Fukuzawa, M. Hamanaka, S. Ishikawa, K. Kobayashi, R. Koyama, M. Nishida,
M. Nishimura, J. Shibata, N. Tsukiori, K. Yadomi,
SHI Accelerator Service Ltd., Shinagawa, Tokyo, Japan
Y. Kotaka, Y. Ohshiro, S. Yamaka,
Center for Nuclear Study, University of Tokyo, Wako, Saitama, Japan

Abstract

The RIKEN AVF cyclotron has been operating 26 years as an injector for the RIKEN ring cyclotron. The AVF cyclotron also provides low energy ion beams for the CNS Radio-Isotope Beam separator (CRIB) of the Center for Nuclear Study (CNS), the University of Tokyo, as well as to produce RIs for commercial use. The operating time is more than 2,000 hours per year.

INTRODUCTION

The RIKEN AVF cyclotron (AVF, K=70 MeV) [1] was constructed as an injector for the RIKEN Ring Cyclotron (RRC, K=540 MeV) [2]. In the AVF-RRC acceleration mode, ions from H^{2+} to ^{87}Rb are accelerated by AVF up to 3.78 to 7 MeV/u, and are further accelerated by RRC up to 65 to 135 MeV/u. They are provided to experimental course of RIKEN Accelerator Research Facility (RARF).

Since 1991, it was started to provide low energy heavy ion beams as a stand alone accelerator (AVF standalone mode). In the AVF standalone mode, various ions from proton (A/Q=1) to ^{42}Ca (A/Q=3.5) are accelerated up to 3.41 to 12.5 MeV/u (14 MeV for proton). The beams are provided for experiments of nuclear physics with CRIB (E7A course) [3], for student experiments (E7B course) and for production of Radioactive Isotopes (C03 course), as shown in Fig 1.

Since 2009, the AVF was started to be used as an injector of light ions for the RI-Beam Factory (RIBF) [4, 5]. In the light-ion mode of RIBF, the AVF Cyclotron has provided polarized deuteron, ^{14}N, ^{18}O, etc., so far. The beams further accelerated by RRC and Superconducting Ring Cyclotron (SRC, K=2600 MeV) [6] are provided for experiments of RIBF.

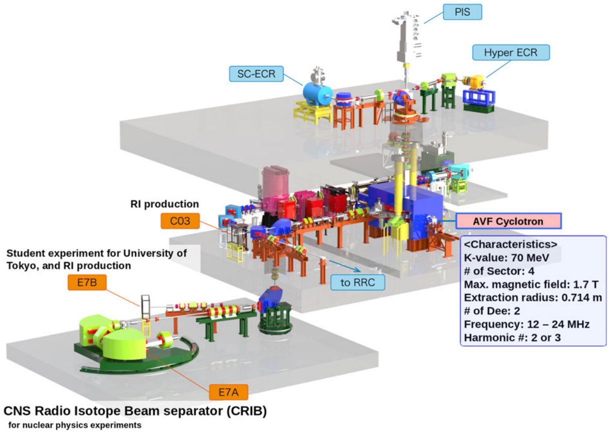

Figure 1: Overall view of the RIKEN AVF cyclotron with ion sources, and beam courses of the AVF standalone operation.

Three external ion sources (HYPER-ECR, SC-ECR, and Polarized deuteron) are available. One of the ion sources are selected to be used depending on the requirement of nuclear species (metal, gas). The beam time schedule is decided by considering the development and preparing time of ion sources, so that the nuclear species can be changed in a short time as much as possible.

We will report the operating status of AVF (beam energies and species, operation statistics, troubles, and maintenance work) for the period from August 2014 to July 2015.

ACCELERATED BEAMS

Figure 2 shows energy per nucleon versus mass number for all kinds of beams accelerated by the AVF cyclotron. The species accelerated before August 2014 are shown by open solid circles. In this period, in the AVF standalone mode, two kinds of beams ($^4He^{2+}$ at 7.5 and 10.0 MeV/u) were extracted for the first time (red solid circles). The other eight beams in this mode are shown by red open circles. In the AVF-RRC mode, $^{40}Ar^{11+}$ accelerated up to 3.78 MeV/u was extracted for the first time (blue solid circles). The other six beams in this mode are shown by blue open circles. In the RIBF mode, polarized deuteron at 3.97 MeV/u was extracted (a green open circle). Accelerated beams in this period for these acceleration modes are summarized in Table 1.

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* ksuda@ribf.riken.jp

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IMPROVEMENT OF MASS-TO-CHARGE RATIO RESOLUTION OF THE JAEA AVF CYCLOTRON USING A BEAM CHOPPING SYSTEM

S. Kurashima[#], N. Miyawaki, H. Kashiwagi, JAEA, Gunma, Japan
M. Fukuda, Osaka University, Osaka, Japan

Abstract

A mass-to-charge ratio (*M*/*Q*) resolution of the JAEA cyclotron is about 3,300 and this high-resolution enables us to quickly change the ion species by a cocktail beam acceleration technique. To further improve the *M*/*Q* resolution, a new technique is being developed by combining the cocktail beam acceleration and beam chopping techniques. The beam chopping system consists of a pre-beam kicker installed in the beam injection line and a post-beam kicker downstream of the cyclotron. This new technique is able to separate beam bunches from a pulse train of the ion beam including impurity ion species. As a result, we succeeded to completely separate the 125 MeV $^{20}Ne^{5+}$ and the 100 MeV $^{16}O^{4+}$ beams, that was quite difficult using previous techniques. The *M*/*Q* resolution of the cyclotron has been significantly improved to 25,000 at present.

INTRODUCTION

An AVF cyclotron with a *K*-value of 110 MeV was constructed at TIARA (Takasaki Ion accelerators for Advanced Radiation Application) facility of the Japan Atomic Energy Agency (JAEA) to provide high-energy ion beams mainly for research in biotechnology and materials science [1]. Various kinds of beam irradiation techniques such as a heavy-ion microbeam formation and a large-area uniform irradiation were developed for beam users.

A cocktail beam acceleration technique [2,3] was also developed for quick change of the ion species extracted from the cyclotron. In this technique, a cocktail of ions having almost identical mass-to-charge ratio (*M*/*Q*), produced in an ion source, is injected into the cyclotron. The cyclotron can separate an ion species from others since the cyclotron has another aspect as a high-performance mass spectrometer. Change of the ion species completes within about ten minutes by adjusting an acceleration frequency and changing a feeding gas of the ion source if necessary. However, the cocktail of ions such as $^{16}O^{4+}$ and $^{20}Ne^{5+}$ was not available since the *M*/*Q* resolution of the cyclotron was inadequate to separate them. To improve the *M*/*Q* resolution, a new technique has been developed by combining the cocktail beam acceleration and a beam chopping techniques.

In this paper, we briefly describe theories of the cocktail beam acceleration and the unique method to improve the *M*/*Q* resolution, and show some experimental results.

COCKTAIL BEAM ACCELERATION

A radio frequency f_{RF} of an acceleration voltage generated on a pair of dee electrode is expressed as

$$f_{RF} = hf_{ion} = \frac{h}{2\pi}\frac{eQ}{uM}B\,, \qquad (1)$$

where h is an acceleration harmonics defined by the ratio of f_{RF} to the orbital frequency of the ion f_{ion}, e elementary electric charge, Q charge state of the ion, u atomic mass unit, M mass of the ion in u, B magnetic field for isochronism. A beam bunch of the ion is repeatedly accelerated at a fixed phase of the rf voltage under good isochronous field, and is extracted from the cyclotron through an electrostatic deflector and a magnetic channel. When other ion species with a slight difference of the mass-to-charge ratio $\Delta(M/Q)$ is injected into the cyclotron, shift of the acceleration phase $\Delta\phi$ after N revolutions is given by

$$\Delta\phi = 2\pi hN\frac{\Delta(M/Q)}{(M/Q)}\,. \qquad (2)$$

Table 1 shows a list of ion species with the $M/Q \approx 4$, and here, we assume that $^{12}C^{3+}$, $^{16}O^{4+}$ and $^{20}Ne^{5+}$ beams are simultaneously injected into the cyclotron tuned to accelerate them up to 6.25 MeV/u. When the acceleration frequency f_{RF} is adjusted for $^{16}O^{4+}$ beam the acceleration phase of $^{20}Ne^{5+}$ advances and that of $^{12}C^{3+}$ lags gradually. The $\Delta\phi$ of $^{12}C^{3+}$ is much larger since the *M*/*Q* difference from $^{16}O^{4+}$ is about 5 times as large as that of $^{20}Ne^{5+}$, as shown in Fig. 1. The design values of the total number of revolutions are 550, 265 and 210 for the acceleration harmonics h = 1, 2 and 3, respectively. The impurity ion species cannot be extracted from the cyclotron when the energy gain of the beam bunch reaches deceleration region or decreases considerably after hundreds of revolutions. As a result, only one ion species is extracted. The ion species can be changed quickly by adjusting f_{RF} corresponding to the *M*/*Q* difference. This is the principle

Table 1: List of ion species with the $M/Q \approx 4$. Beam energy is 6.25 MeV/u for all ion species (h = 2).

Ion	M/Q	$\Delta(M/Q)/(M/Q)$	f_{RF} (MHz)
$^{4}He^{1+}$	4.00205		11.9079
		6.501×10^{-4}	
$^{12}C^{3+}$	3.99945		11.9156
		3.176×10^{-4}	
$^{16}O^{4+}$	3.99818		11.9194
		6.003×10^{-5}	
$^{20}Ne^{5+}$	3.99794		11.9201
		5.230×10^{-4}	
$^{36}Ar^{9+}$	3.99585		11.9264
		4.004×10^{-5}	
$^{40}Ar^{10+}$	3.99569		11.9268

[#] E-mail: kurashima.satoshi@jaea.go.jp

ELECTROSTATIC DEFLECTOR OF THE CYCLOTRON DC-280 AXIAL INJECTION CHANNEL

N.Kazarinov#, I.Ivanenko, FLNR, JINR, Dubna, Russia

Abstract

The spherical electrostatic deflector will be used in the axial injection channel of the DC-280 cyclotron for rotation of the ion beam onto vertical axis. The results of the simulation of beam dynamics in the deflector based on 3D electrical field map are discussed in this report. The results of simulation of the ion beam transport in the axial injection beam line of the cyclotron are presented also.

INTRODUCTION

The isochronous heavy-ion cyclotron DC-280 is a basic part of the Super Heavy Element Facility – the new accelerator complex of Joint Institute for Nuclear Research [1,2]. The DC-280 cyclotron will produce high-intensity beam of accelerated ions in the range from helium to uranium. The maximum design value of a current of ion beams will be 10 pmcA and the maximum kinetic energy will be 8 MeV/u.

In this report the design of the spherical electrostatic deflector of high voltage injection system [2, 3] of DC-280 cyclotron is presented. Using the electrostatic deflector is explained both weight reduction and lower power of the power supply system in comparison with the bending magnet. The design is based on three-dimensional calculation of the electric field carried out by using OPERA 3D program code [4].

The 3D macro-particle beam dynamic simulation in the deflector was done in the curvilinear coordinates system connected with reference orbit, defined for computational field map. This simulation was carried out by using MCIB04 program code [5].

3D PHYSICAL MODEL OF DEFLECTOR

3D physical model of electrostatic deflector is shown in Fig. 1.

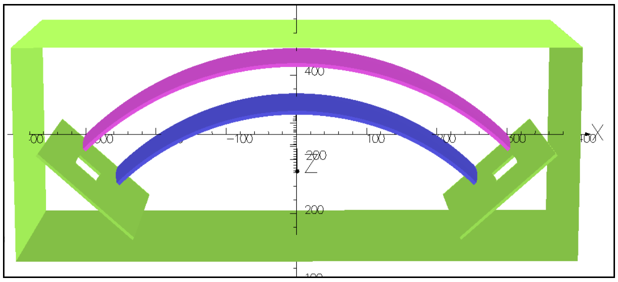

Figure 1: Physical model of deflector.

Bender consists of two electrodes under the potentials U_1 (blue colour), U_2 (red colour) and three ground electrodes (green colour). The design bending radius R=40 cm, the gap between the electrodes d = 6 cm, the horizontal width of the electrodes h = 16 cm. The electric field map consists of two distributions $\Phi_{1,2}(\vec{r})$ corresponding to the following combinations of voltages at the electrodes (U_1=-10kV,U_2=0) and (U_1=0,U_2=10kV). The resulting field map of the deflector $\Phi(\vec{r})$ is a superposition of these distributions:

$$\Phi(\vec{r}) = \left[U_2\Phi_2(\vec{r}) - U_1\Phi_1(\vec{r})\right]\times 10^{-4} \qquad (1)$$

The distributions of the components $E_{X,Y}$ of the electric field along the designed orbit of the deflector are shown in Fig.2.

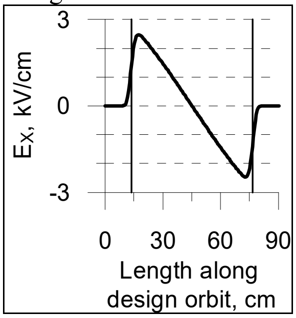

Figure 2a: E_X component of electric field.

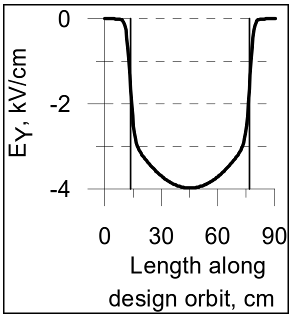

Figure 2b: E_Y component of electric field.

CALCULATED EQUILIBRIUM ORBIT

The calculated equilibrium (solid line) and design (dashed line) orbits are shown in Fig.3a. Deviation Δ between calculated and designed orbits is shown in Fig.3b. In the non-relativistic approximation, the equilibrium orbit in the deflector does not depend on the mass-to-charge ratio A/Z of the ion.

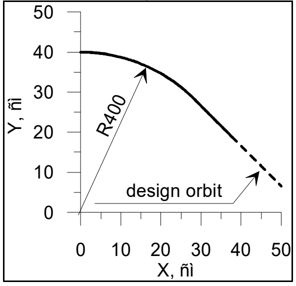

Figure 3a: Deflector orbits.

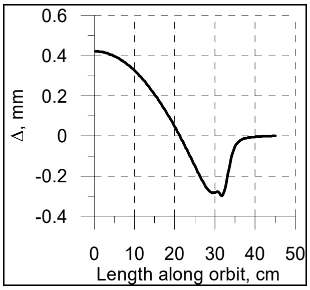

Figure 3b: Deviation Δ.

The particle motion at the equilibrium orbit of the deflector is completely determined by two functions – the curvature of the orbit $K_0(s)$ and "friction coefficient" $\Lambda_0(s)$:

#nyk@lnr.jinr.ru

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COOLING STACKING INJECTION IN NICA BOOSTER

E. Syresin, Joint Institute for Nuclear Research, Russia

Abstract

The multi cycling injection from the linear accelerator to the NICA booster is planned to use for storage of Au^{31+} ions at energy 3.1 MeV/u. The intensity of the stored ions is increased by 3-5 times at injection intensity of $5\cdot10^8$-10^9 ppp. The intensity of the stored beam is higher by one order of magnitude comparing with injection intensity of 10^8 ppp. The maximal intensity is restricted by the incoherent diffusion heating of the stack and the ion life time. The simulations of the cooling stacking injection were performed by BETACOL code. The coherent instability can be developed at a high ion intensity in presence of the electron cooling. The increment of instability essentially depends on the choice of the working point.

INTRODUCTION

The Nuclotron-based Ion Collider fAcility (NICA) [1] is a new accelerator complex is under construction at Joint Institute of Nuclear Research aimed to provide collider experiments with heavy ions up to gold at maximum energy at center of mass of $\sqrt{s} \sim 11$ GeV/u.

The complex NICA consists of three superconducting accelerators: booster, acting synchrotron-Nuclotron and collider which provides average luminosity of $10^{27}cm^{-2}s^{-1}$.

The collider NICA is proposed for study of baryon interaction in the hot and dense quark-gluon matter and search of mixed phase of that matter. The planed experiments will realize in colliding ion-ion beams.

The main goals of booster are connected with of $4\cdot10^9$ ppp gold ions Au^{31+} and its acceleration up energy of 600 MeV/u which is required for stripping of ion charge state Au^{79+}. Booster synchrotron has maximum magnetic rigidity of 25 Tm and the circumference of about 215 m. The Booster is equipped with an electron cooling system that allows to provide cooling of the ion beam in the energy range from the injection energy up to 100 MeV/u.

The multi cycling cooling stacking injection is planned to increase the stored ion intensity in booster NICA at injection energy of 3.1 MeV/u. The injection from the electron linac is repeated with frequency of 10 Hz. The intensity of gold ion beam at linac exit is equal to 10^8-10^9 ppp. The vacuum pressure in booster is $5\cdot10^{-11}$ mbar that corresponds to the ion life time of 3-5 sec at injection energy of 3.1 MeV/u. The average ion flax is the key booster characteristic, it is equal to $R=N/\tau$, where N is number of stored ions, τ is time duration of booster cycle. Average ion flax is equal to $R=2\cdot10^8$ sec^{-1} at number of stored ions $N=10^9$ ppp and time duration of booster cycle of $\tau=5$ sec.

The rms beam emittance $\varepsilon_{x,y}=\sigma_{x,y}^2/\beta_{x,y}$ at exit of the linear accelerator is equal to $\varepsilon_x/\varepsilon_y=3$ $\pi\cdot$mm$\cdot$mrad, here $\sigma_{x,y}$ – rms transverse beam size, $\beta_{x,y}$ is the beta function in injection area. The horizontal acceptance for stored stack ions is equal to $\varepsilon_{ac}=10$ $\pi\cdot$mm$\cdot$mrad. The equilibrium stack orbit is displaced relatively to the septum on a distance $(\beta_{inj}\varepsilon_{ac})^{1/2}$, where β_{inj} is the horizontal beta function in injection area. The bump of equilibrium orbit is displaced at single turn injection on a distance $2\sigma_x=2(\beta_{inj}\varepsilon_x)^{1/2}$. The angle spread of injected beam is equal to $(\varepsilon_x/\beta_{inj})^{1/2}$. The initial horizontal beam emittance corresponds to $\varepsilon_{inj-x}=2\varepsilon_x+(\varepsilon_x\varepsilon_{ac})^{1/2}=11{,}5$ $\pi\cdot$mm$\cdot$mrad in the booster.

The simulation of multi cycling cooling stacking injection were performed by the BETACOOL code [2] for gold ions Au^{31+}. The electron beam current is equal to 0.1 A, the beam has uniform density at radius less than 2 cm. The length of electron cooling section is equal to 1,94 m.

The efficiency of electron cooling is equal to ratio of amplitude of second injection pulse to amplitude of first injection pulse (Fig.1). The efficiency of electron cooling is equal to 40% at injection repetition frequency of 10 Hz. The maximal ion stored intensity corresponds to $4.6\cdot10^9$ ppp at injection intensity of 10^9 ppp and ion life time of 4.4 sec.

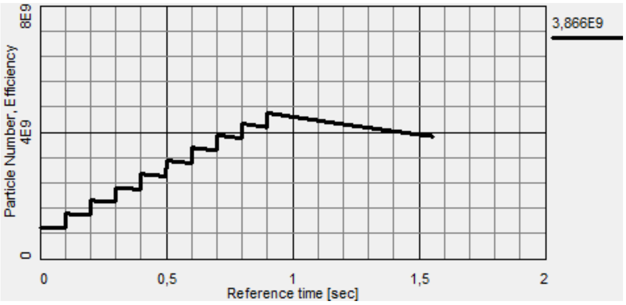

Figure 1: Dependence of stored ion intensity on time at 10 cycle injection.

The average ion flax is equal to $R=7.6\cdot10^8$ sec^{-1} at an number of stored ions of $N=4.6\cdot10^9$ ppp and time duration of booster cycle of $\tau=6$ sec. Cooling stacking injection increases by 3.8 times the average flax in comparison with single turn one cycle injection.

The maximal stack ion intensity is restricted by several effects: the incoherent stack noise, the instability of cooled ion stack and the ion life time at interaction ions with residual gas atoms and molecules.

The emittance of cooled ion stack is defined by number of stored ions N_{st} and betatron tune shift ΔQ

$$\varepsilon_v=(r_pZ^2N)/(4\pi A\beta^2\gamma^3\Delta Q),$$

COHERENT SYNCHRO-BETA COUPLING IN THE KEK DIGITAL ACCELERATOR

T. Monma^{A,B)}, K. Takayama^{A,B,C,D)}, T. Yoshimoto^{A,B)}, Liu Xigguang^{A,B)}
^{A)}Tokyo Institute of Technology, Nagatsuda, Kanagawa, Japan
^{B)}High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan
^{C)}The Graduate University for Advanced Studies (SOKENDAI), Hayama, Kanagawa, Japan
^{D)}Tokyo City University, Tamadsutsumi, Tokyo, Japan

Abstract

The KEK Digital Accelerator is a small-scale fast cycling induction synchrotron, where induction pulse voltages discretely accelerate heavy ion beam. Its voltage height V_{out} is constant due to a technical restriction and does not correspond to the required acceleration voltage per turn $V_n=\rho C_0[dB/dt]$ at the n-th turn. The induction acceleration system is triggered when $\Sigma\ V_n\ \text{-}\delta\Sigma\ V_{out}. > V_{out}$ (δ=1 when acceleration voltage is supplied. δ=0 when acceleration voltage is not supplied). Consequently, a perturbation on the betatron oscillation induced by a discrete change of the equilibrium orbit becomes notably large. A size of this perturbation is quantitatively estimated by means of numerical simulation and is compared with the experimental result.

INTRODUCTION

The KEK Digital Accelerator (DA) [1,2] is a small-scale fast-cycling induction synchrotron that does not require a high-energy injector (see Fig. 1). The induction acceleration system shown in Fig. 2 was developed to demonstrate the induction synchrotron concept in 2006 using the KEK 12-GeV proton synchrotron [3], which is a typical slow-cycling synchrotron. There are two basic technical issues for induction acceleration in the KEK-DA.

1. An induction cell is employed as the acceleration device, which is simply a one-to-one pulse transformer energized by a switching power supply (SPS) generating pulse voltage pulses. The SPS is connected to the DC voltage power supply. The output voltage height for acceleration, V_{acc}, is necessarily determined by the setting voltage of the DC power supply, which is fixed to a constant value in the range from 0.3 kV to 2.0 kV per cell within the acceleration cycle.
2. The KEK-DA ring does not have dispersion-free regions. The induction acceleration cells are placed at the region where the size of the momentum dispersion function is 1.4 m.

Since the guiding magnetic fields of the KEK-DA are excited sinusoidally, an ideal profile of V_{acc} is of half sine shape as shown in Fig. 3. The ideal profile of V_{acc} is not realized because of the technical reason 1.

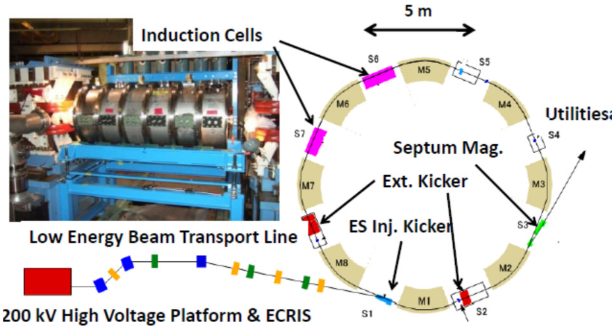

Figure 1: Schematic view of the KEK-DA.

In the early and late stages of acceleration, the required acceleration voltage is lower than the fixed output voltage of the induction cell. Thus, the pulse density of the acceleration voltage must be controlled. This is actually carried out in the following way. Gate trigger of the solid-state switching elements employed in the SPS is generated when the integrated required acceleration voltage V_{req} reaches V_{acc} of the induction cell, resulting in the production of V_{acc} at the induction cell. This method has been called "pulse density control" since its proposal [4].

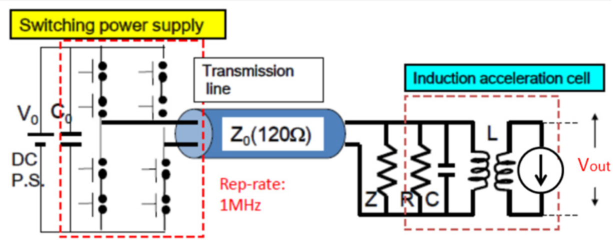

Figure 2: Equivalent circuit for the induction acceleration system, where the induction cell with a matching resistor is connected to the SPS through a 120 Ω transmission line.

The individual equilibrium orbit $D(s)\Delta p/p$ of particles changes gradually associated with ramping of the guiding magnet until the acceleration voltage is generated. The equilibrium orbit of an assumed particle located at the bunch center should return to position zero after acceleration voltage generation. The oscillation amplitude and phase of the betatron motion of an individual particle, however, simultaneously change, because the actual orbit $x(s)=x_\beta(s)+D(s)\Delta p/p$, which is a deviation from the ideal orbit, never changes at the acceleration gap position. If momentum dispersion function vector ($D(s)$, $D'(s)$) at the

SUPER-BUNCH INDUCTION ACCELERATION SCHEME IN THE KEK DIGITAL ACCELERATOR

T.Yoshimoto[#,1,2], X. Liu[1,2] T. Adachi[2,4],T.Kawakubo[2], H. Kobayashi[2,3], S.Takano[2], E.Kadokura[2], K.Okamura[2], and K.Takayama[1,2,3,4]
[1]Tokyo Institute of Technology, Nagatsuta, Kanagawa, Japan
[2]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan
[3]Tokyo City University, Todoroki, Tokyo, Japan
[4]The Graduate University for Advanced Studies, Hayama, Kanagawa, Japan

Abstract

KEK Digital Accelerator (KEK-DA) [1] is a fast cycling induction synchrotron with induction cells driven by switching power supplies (SPS). The rectangular pulse voltages are precisely controlled by a field-programmable gate array (FPGA). One of our next missions for the KEK-DA is to demonstrate super-bunch (very long beam) acceleration technique in which the beam occupies over half of the ring at injection [2]. For that, power supplies for the SPS have to be upgraded from fixed voltage to time-varying voltage to provide beam-required acceleration. This is effective to suppress the blow-up of the longitudinal emittance and ensures the super-bunch acceleration stably.

INTRODUCTION

The concept of induction synchrotron was originally invented by Takayama and Kishiro in 2000 [2] and then a super-bunch hadron collider was proposed in 2002 [3]. The proof-of-principle experiment for induction synchrotron was successfully performed in the KEK 12GeV PS synchrotron in 2007 [4]. After that, the same group developed the KEK-DA, a small prototype of fast cycling induction synchrotron, which was converted from the old PS 500MeV booster ring. With this machine, the wide-band acceleration as a novel scheme of induction synchrotron was demonstrated [5], in which the revolution frequency can be increased by a factor of more than 10 in one acceleration cycle.

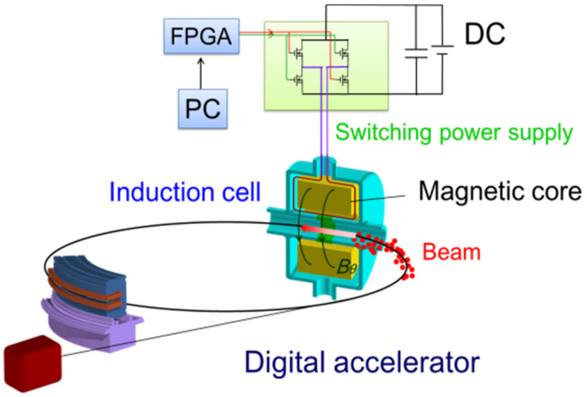

Figure 1: The Overview of the KEK-DA.

The schematic view of the KEK-DA is shown in Fig. 1. Heavy ion beams are produced in the electron cyclotron resonance ion source (ECRIS) and accelerated by the extraction voltage of 200 kV. Then, they are directly injected into the ring by the electrostatic injection kicker. The timings of the acceleration pulses are precisely controlled by a FPGA. The optimization of the timing is made following the ramping magnetic flux density of the bending magnets $B(t)$ [6].

In the current setup of the KEK-DA, fixed DC power supplies provide acceleration voltages for induction cells as shown in Fig. 1. It is difficult to give the acceleration voltages precisely following the required acceleration voltage per turn $V(t)$ ($= \rho C_0 dB(t)/dt$) that is necessary for the curvature radius of the ion in the bending magnet ρ and the circumference of the beam orbit C_0. In order to avoid the discrepancy, the acceleration voltage has to be generated intermittently as they correspond with the required acceleration voltage equivalently. The detailed discussion was already reported in other places [5, 7]. Although the present scheme can achieve the wide-band acceleration, it generates some synchro-beta coupling in horizontal direction and longitudinal emittance blow-up at the initial acceleration stage. In such a way to reduce both effects, an upgrade plan with time-varying DC power supply is considered in the next section. Furthermore, this plan can be adapted to super-bunch acceleration scheme.

ACCELERATION SCHEME

In induction acceleration, confinement and acceleration voltage can be generated independently as shown in Fig. 2. Two sets of confinement voltages produce a beam bucket with the length of one third of a beam revolution period at every turn. The height and width of the positive pulse are the same as the negative pulse. On the other hand, the required acceleration voltage changes continuously in the whole acceleration period. The positive pulse height is the half of the negative one, whereas the positive width is twice of the negative one to prevent magnetic cores of induction cells from saturation. This means that the acceleration pulse is asymmetric different from other existing accelerators.

#yoshimo@post.kek.jp

A RACETRACK-SHAPE FIXED FIELD INDUCTION ACCELERATOR FOR GIANT CLUSTER IONS

K. Takayama[1,2,3,4)], A. Adachi[1,3)], M. Wake[1)], K. Okamura[1,3)], and Y. Iwata[5)]

[1)]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan
[2)]Tokyo Institute of Technology, Nagatsuda, Kanagawa, Japan
[3)]The Graduate University for Advanced Studies, Hayama, Kanagawa, Japan
[4)]Tokyo City University, Tamadsutsumi, Tokyo, Japan
[5)]National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibarali, Japan

Abstract

Recently the racetrack-shape fixed field induction accelerator (RAFFIA) has been proposed as a unique driver to obtain high energy giant cluster ions [1]. Its essential properties are introduced here. The first realistic model under designing is described.

INTRODUCTION

Since the first proposal of the RAFFIA it has attracted interests of the related society developing applications of giant cluster ions such as C-60. So far a single-end electrostatic accelerator has been the typical diver for giant cluster ions. Achievable energy there is limited to around 50 keV/nucleon. A synchrotron or cyclotron may be suitable to obtain higher energy. However, the restriction on the frequency band-width of acceleration RFs requires an expensive and extremely large scale injector. It is a better choice to employ induction acceleration [2] instead of RF acceleration in order to avoid this restriction. As a matter of fact, the synchrotron employing induction acceleration has been demonstrated both in a slow-cycling mode [3] and fast-cycling mode [4] at KEK.

The racetrack-shape fixed field induction accelerator given in Reference 1, which looks like a microtron, seems to be much suitable to accelerate giant cluster ions with an extremely large mass to charge ratio, *A/Q,* to high energy in a limited site space for the accelerator, because a large magnetic rigidity is expected with the 90 degrees bending magnet.

Not only C-60 but also another attractive giant cluster atom with super lattice structure such as Si-108 [5] is available now. High charge–state ion sources for C-60 or Si-108 are under development. Integrating these cluster ion sources with the RAFFIA, we can realize a unique giant cluster ion driver.

ESSENTIAL PROPERIES OF THE RAFFIA

The schematic layout of the RAFFIA is shown in Fig. 1. The ring consists of 4 bending magnets of 90 degrees and 8 pairs of doublet Q magnet occupying the two long straight sections. The injection device and extraction region are placed in the upper straight section. The former is a 20 kV electrostatic injection kicker, which is the same as that being operated in the KEK digital accelerator [4]. There are several choices for the latter. A conventional extraction system consisting of extraction kickers and septum magnets is among them. Meanwhile, the lower straight section is occupied by the induction acceleration cells.

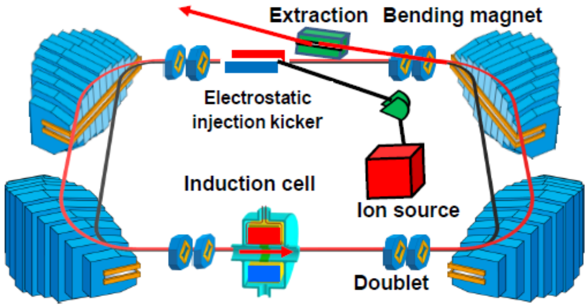

Figure 1: Layout of the RAFFIA with initial orbit (black) and the last orbit just (red).

Energy gain per nucleon in the RAFFIA is rather small, less than *(Q/A)*x50 keV. This means a large number of revolution in the machine. Orbit stability in the transverse direction is mostly crucial. In Reference 1 the reverse field strip in the open front of the bending magnet and negative gradient on the median plane are introduced to improve the vertical focusing(see Fig. 2). It turns out that the introduced focusing effects leads to the sufficient stability for both directions with a help of optimized time-

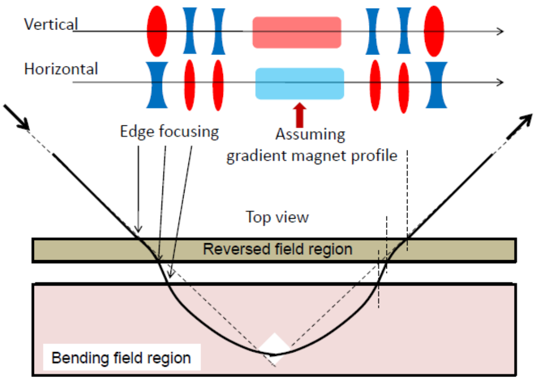

Figure 2: Properties of focusing/defocusing on the median plane.

NUCLOTRON AT JINR: OPERATION EXPERIENCE AND RECENT DEVELOPMENT

N. Agapov, O. Brovko, A. Butenko, E.E. Donets, E.D. Donets, A. Eliseev, V. Fimushkin, A. Govorov, E. Ivanov, V. Karpinsky, V. Kekelidze, H. Khodzhibagiyan, A. Kovalenko, V. Mikhailov, V. Monchinsky, S. Romanov, V.Slepnev, A.Sidorin, A. Smirnov, E. Syresin, G. Trubnikov, V. Volkov

JINR, Dubna, Moscow Region, Russia

Abstract

The results of 20 years of operation and development of the first superconducting synchrotron based on 2T cold iron fast cycling SC-magnets are presented. The Nuclotron technology of superconducting magnetic system for the NICA facility at JINR and for FAIR project will be used.

INTRODUCTION

The Nuclotron accelerator complex at Laboratory for High Energy Physics is the basic facility of JINR for generation of proton, polarized deuteron (also neutron/proton) and multicharged ion (nuclear) beams in energy range up to 6 GeV/amu. The Nuclotron was built during 1987-92. This accelerator based on the unique technology of superconducting magnetic system [1]. All design, tests and assembling works were carried out at the LHEP. Production of the structural cryomagnetic elements was done by the JINR workshops.

The Nuclotron accelerator complex (Fig. 1) consists of

- set of ion sources,
- Linac LU-20,
- 45 T·m SC synchrotron Nuclotron,
- 1000 m^2 experimental hall,
- beam transport lines,
- liquid He plant.

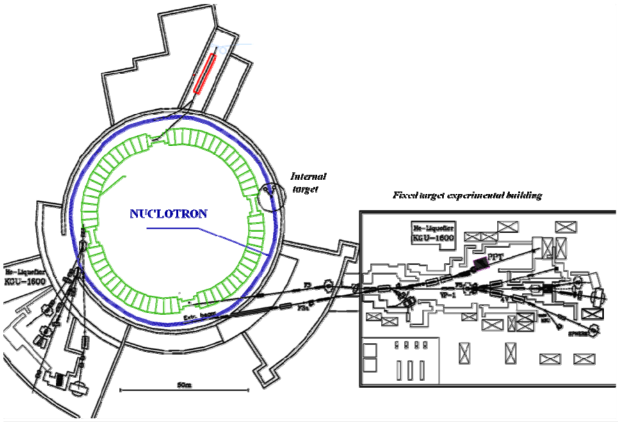

Figure 1: The Nuclotron accelerator complex.

The complex used presently for fixed target experiments on extracted beams and experiments with internal target. The program includes experimental studies on relativistic nuclear physics, spin physics in few body nuclear systems (with polarized deuterons) and physics of flavours. At the same time, the Nuclotron beams are used for research in radiobiology and applied research.

In the nearest future the Nuclotron technology of superconducting magnetic system will be used for new accelerators of the NICA facility under creation at JINR [2].

OPERATION

51 runs of the Nuclotron operation were performed since March 1993. Main result of the Nuclotron development during this period is stable and reliable operation of all the systems proving beam quality required for users. The operational time is about 2000 hours per year optimized in accordance with the JINR topical plans accounting the plan of the NICA construction. For more efficient usage of the beam time, the regime with two parallel users is realized routinely: experiment with internal target at the first plateau and beam extraction at the second one. Different types of the ion beams are delivered for the experiments (Table 1).

Table 1: Nuclotron and Beam Parameters

Nuclotron parameter	Project	Status (2015)
Max. main. field, T	2	2 (1.85 routine)
B-field ramp, T/s	1	0.8
Accelerated particles	p–U, d↑	p, d-Xe
Max. energy, GeV/u	12 (p), 5.9 (d) 4.5(^{197}Au^{79+})	5.9 (d, ^{12}C), 1.5 (^{124}Xe^{42+}, ^{40}Ar^{16+})
Intensity, ions/cycle	10^{11} (p,d) 10^9 (A> 100)	d $2\text{-}5{\cdot}10^{10}$ ^{124}Xe^{24+} $1{\cdot}10^4$ ^{12}C $2{\cdot}10^9$ ^{40}Ar^{18+} $2{\cdot}10^5$ ^{7}Li^{3+} $3{\cdot}10^9$

Increase of the beam intensity and widening of the ion species are related with construction of three new ion sources: SPI (Source of Polarized Ions), LIS (Laser Ion Source), Krion-6T (ESIS type heavy ion source). New powerful Nd-YAG laser was tested for the carbon beam generation during the run #48. For the first time Krion-6T

PARTICLE TRACKING SIMULATION WITH SPACE CHARGE EFFECTS FOR AN INDUCTION SYNCHROTRON AND PRELIMINARY APPLICATION TO THE KEK DIGITAL ACCELERATOR

X. Liu#
Tokyo Institute of Technology, Nagatsuda, Kanagawa, Japan
High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan

Abstract

In order to study the beam behaviour of the induction synchrotron which features low energy injection, a dedicated particle tracking simulation code with a 2.5D space charge field solver, which takes into account of the boundary condition, has been developed. The beam dynamics included in this code are discussed and simulation results assuming parameters of the KEK Digital Accelerator are presented. This code will help to understand the various features of the beam behaviour in the present beam commissioning and serve as a tool for the design of the future induction synchrotrons.

INTRODUCTION

The concept of induction synchrotron has been raised around 2000 by K. Takayama and J. Kishiro [1]. This concept has been experimentally confirmed in 2006 with the former KEK Proton Synchrotron (PS) [2]. After that, the booster for the KEK-PS has been modified to the present KEK Digital Accelerator [3]. The beam commissioning has been started since the middle of 2011 and the recent experimental studies can be seen in [4] and [5]. Though the longitudinal motion has been discussed in [6] and the longitudinal space charge field has been studied with simulation in [7], the 3D particle tracking simulation with the space charge has not been done yet.

In this paper, a 2.5D "slice-by-slice" scheme and the space charge solver with a boundary matrix method will be discussed. The justification of this solver is also described. Preliminary results of its application to the KEK-DA will be briefly shown.

SCHEME DESIGN

The following vector is chosen to represent the information of a macro particle in the simulation:

$$\vec{x} = (x, xp, y, yp, z, dpp) \qquad (1)$$

where (x, xp) and (y, yp) are the positions in the horizontal and vertical phase space respectively, and $(z, \Delta p/p)$ is the longitudinal phase space. Here $z = s - \beta_0 c \cdot dt$ ($\beta_0 = v_0 / c$, v_0 is the velocity of the reference particle and c is the light speed) is the particle's longitudinal distance and $\Delta p / p$ is the momentum deviation from the referential particle.

For particle tracking without the space charge from s_0 to s_1 along the beam orbit of the referential particle, the change of particle information defined in Eq. (1) is given by,

$$\vec{x}_{s_1} = M_{s_0 \to s_1} . \vec{x}_{s_0} \qquad (2)$$

where M is a 6×6 transfer matrix from s_0 to s_1. In order to include the space charge and keep the simplicity of Eq. (2), the single kick approximation is used [8],

$$x(s) \xrightarrow{K_{sc}} x(s)' \xrightarrow{M} x(s + \Delta s) \qquad (3)$$

where K_{sc} is the kick due to space charge forces and $\Delta s = s_2 - s_1$. K_{sc} can be expressed with the space charge induced field [9]

$$\vec{x}_{sc} = (0, \frac{\Delta s \cdot Qe}{\gamma_0^2 p_0 \beta_0 c} E_x, 0, \frac{\Delta s \cdot Qe}{\gamma_0^2 p_0 \beta_0 c} E_y, 0, \frac{\Delta s \cdot Qe}{\beta_0^2 E_{total}} E_z) \qquad (4)$$

Here we assume that during a very small step size of Δs, the change of the space charge field caused from a change of the beam distribution is ignorable. In Eq.(4), (E_x, E_y, E_z) is the electric field in the beam frame, Q is the charge state of the particle, e is the unit electron charge, $\gamma_0 = 1/\sqrt{1-\beta_0^2}$, p_0 is the momentum and E_{total} is the total energy of the reference particle. The magnetic field due to moving beam is considered by including $1/\gamma_0^2$.

2.5D SPACE CHARGE SOLVER

A "slice-by-slice" scheme is chosen to solve the space charge field induced by the beam. In this scheme, the particle distribution will be longitudinally divided into k slices as seen in Fig. 1. Each slice will be meshed into $m \times n$ grids. Thus, there will be $m \times n \times k$ boxes in the 3D space.

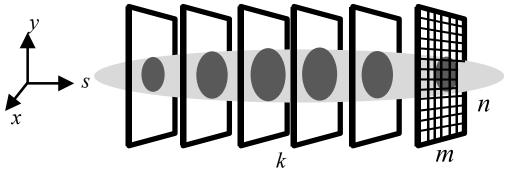

Figure 1: 2.5D slice-by-slice scheme.

The charge of the macro particles will be assigned to closest grid points (eight points for each macro particle) with the Particle-In-Cell (PIC) method, in which the

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#liuxg@post.kek.jp

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BEAM CONFINEMENT DYNAMICS IN A BARRIER BUCKET

*Masatake Hirose $^{A,B)}$, Ken Takayama$^{A,B,C,D)}$, Takashi Yoshimoto $^{B,C)}$, Liu Xiggung $^{B,C)}$
$^{A)}$Tokyo City University, Tamatsutsumi, Setagaya, Tokyo, Japan
$^{B)}$High Energy Accelerator Research Organization (KEK), Tsukua, Ibaraki, Japan
$^{C)}$Tokyo Institute of Technology, Nagatsuda, Yokohama, Kanagawa, Japan
$^{D)}$The Graduate University for Advanced Studies (SOKENDAI), Hayama, Kanagawa, Japan

Abstract

In an induction synchrotron such as the KEK digital accelerator, the barrier voltage pulse with almost rectangular shape is generated in an induction cell of a 1-to-1 pulse transformer driven by the switching power supply. Its peak amplitude and pulse length are flexibly changed but the rising/falling time is uniquely determined by a combination of the circuit parameters including characteristics of the employed solid-state switching element. Behavior of particles captured in the barrier bucket is quite various, depending on the barrier voltage shape. This paper systematically discuss about the phenomenology of beam dynamics for the barrier bucket and compare numerical simulations with the experimental results obtained in the KEK digital accelerator.

INTRODUCTION

Beam handling using the barrier bucket has been initiated by Jim Griffin of Fermilab in 1983, where the barrier voltage was obtained by superimposing multiple harmonic RFs[1]. The stability region in the phase space that the barrier voltage made came to be called an isolated bucket, However, it is hard to realize almost square pulse in a high-Q cavity, because, a large number of harmonics are needed. This technique has evolved since then [2]. The barrier voltage was realized in the low-Q cavity where necessary number of harmonic waves for square pulse formation is reduced. By feeding the harmonic waves amplified by a semiconductor amplifier to the cavity, the beam handling using the barrier bucket was demonstrated [3].

On the other hand, in an induction synchrotron such as the KEK digital accelerator, the barrier voltage pulse with an almost rectangular shape is generated in an induction cell of a 1-to-1 pulse transformer driven by a switching power supply (SPS). Such an induction acceleration technique is equivalent to the RF acceleration. The induction acceleration has been successfully demonstrated in the slow-cycling and fast-cycling synchrotrons in KEK [4, 5]. The KEK digital accelerator is a fast-cycling induction synchrotron, which is shown in Fig. 1. The experiment of beam handling by the barrier bucket has been extensively conducted in the KEK digital accelerator.

The barrier voltage shown in Fig. 2 is generated by the induction acceleration system shown in Fig. 3. Pulse height V_{bb} of the barrier voltage is uniquely determined by setting the voltage of the DC power supply. Pulse length t_f and barrier pulse duration T are determined by setting of timings ($t1$, $t2$, $t3$, $t4$), which manages the On/Off operation of the switching elements of the SPS. It is controlled by a program installed in Fields Programmed Gate Array (FPGA). Rising and falling times of the voltage pulse, t_{rise} and t_{off} are determined by the intrinsic nature of the switching power supply including the circuit parameters and characteristics of the solid-state switching device. It is about 30 nsec in this case.

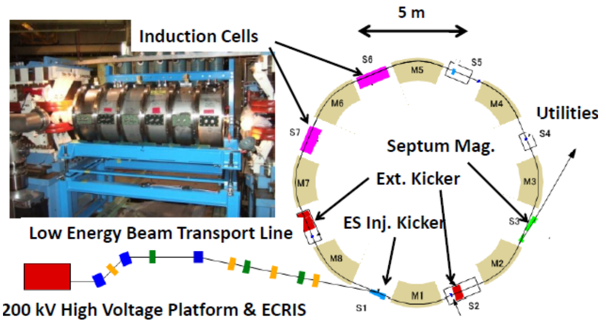

Figure 1: Schematic view of the KEK Digital Accelerator.

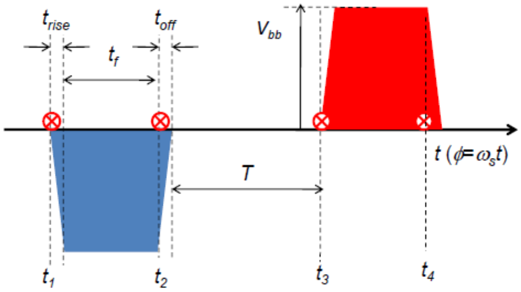

Figure 2: Barrier voltage pulses.

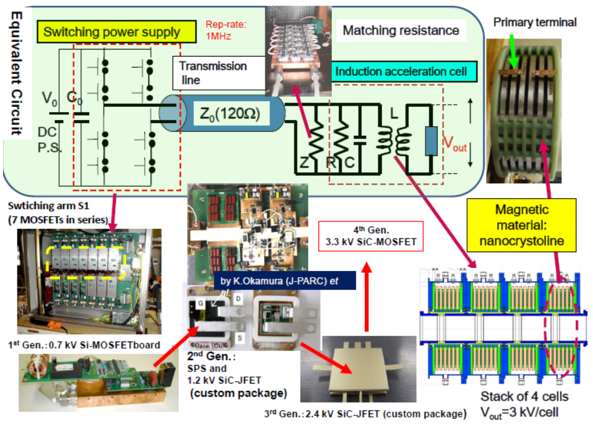

Figure 3: Equivalent circuit for the induction acceleration system.

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masatake@post.kek.jp

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PERFORMANCE OF A FAST KICKER MAGNET FOR RARE-RI RING

H. Miura[A], Y. Abe[B], Z. Ge[B], K. Hiraishi[C], Y. Ichikawa[C], I. Kato[A],
T. Moriguchi[C], D. Nagae[B], S. Naimi[B], T. Nishimura[A], S. Omika[A], A. Ozawa[C],
F. Suzaki[A,B], S. Suzuki[A], T.Suzuki[B], N.Tadano[A], Y. Tajiri[C], Y. Takeuchi[A],
T. Uesaka[B], M. Wakasugi[B], T. Yamaguchi[A], and Y. Yamaguchi[B]
[A]Saitama University, [B]RIKEN Nishina Center, [C]University of Tsukuba

Abstract

To inject rare isotopes individually into the storage ring, Rare-RI Ring, recently constructed at RIBF, a fast kicker magnet was developed. The developed kicker magnet is distributed constant twin type. The shape of magnetic field is essential for the individual injection, and the timing property is given by the inductance and capacitance components of the kicker. Based on detailed simulations of the equivalent electronic circuit of the kicker, we optimized the electrodes and ferrite cores of the kicker. In June 2015, we carried out the first commissioning of Rare-RI Ring using ^{78}Kr^{36+} beam with an energy of 168 MeV/nucleon. We succeeded in injection and ejection particle-by-particle by using the developed kicker system.

INTORODUCTION

The Rare-RI Ring is an isochronous storage ring developed to measure the masses of rare isotopes with a precision in the order of 10^{-6} [1]. The rare isotopes are randomly produced as secondary beams by in-flight fission or fragmentation of an intense DC beam from the RIBF accelerator complex, and their yields are as small as 1 events/day. Therefore, we apply the individual injection method to perform mass measurements of rare RI efficiently.

The individual injection method consists of fast kicker magnet with the RI beam self-trigger system [2]. The trigger pulse for the kicker is generated by a particle detector installed upstream of the beam line at F3, and is sent to the kicker system by a fast coaxial cable (see Fig. 1). The most important is that magnetic field is quickly excited before rare RI of interest arrives at the ring. The kicker should have a fast rising time and also a fast falling time for injected rare RI to be stored in the central orbit of the ring.

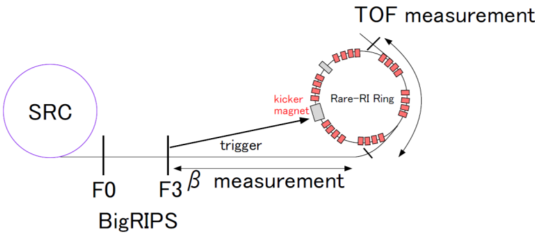

Figure 1: Schematic of the beam line of the Rare-RI ring facility.

DEVELOPMENT OF KICKER MAGNET

The developed kicker magnet is distributed constant twin type. The kicker magnet is equivalent to an electronic circuit that is π type *LC* circuit. To achieve the impedance $Z = 12.5\ \Omega$, the parameters of inductance $L = 70$ nH and capacitance $C = 230$ pF were designed. The inductance is given by the shape of ferrite cores, and the capacitance is given by the distance between high-voltage and ground electrode of the kicker. Figure 2 shows a photograph of the prototype kicker magnet.

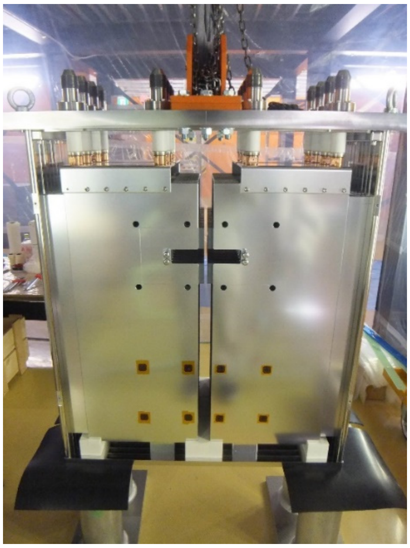

Figure 2: Prototype kicker magnet.

First, we optimized the parameter for one side of the kicker magnet (left or right electrode shown in Fig. 2). As the result, the parameter are $L = 120$ nH and $C = 280$ pF. Figure 3 shows a comparison of the simulation result and experimental data. The agreement is satisfactory.

However, the current pulse shape of the both side kicker magnet (full system) was different from that of one side kicker magnet, because of mutual inductance between both ferrite, as shown in Fig. 4. Based on the result of one side kicker magnet and the simulations, the mutual inductance was estimated to be $M = 30$ nH. The result was well reproduced by the simulation, as shown in Fig. 4. However, a tail component around 800 ns in the pulse shape still remains as shown in Fig. 4. The tail component of magnetic field disturbs the trajectory of particle stored in the ring.

PERFORMANCE OF A RESONANT SCHOTTKY PICK-UP IN THE COMMISSIONING OF RARE-RI RING

F. Suzaki*, Y. Abe, Z. Ge, D. Nagae, S. Naimi, T. Uesaka, T. Watanabe, M. Wakasugi, K. Yamada,
Y. Yamaguchi, J. Zenihiro, Y. Yano, RIKEN, Wako, Japan
I. Kato, H. Miura, T. Nishimura, S. Omika, T. Suzuki, N. Tadano, Y. Takeuchi, T. Yamaguchi,
Saitama University, Saitama, Japan
K. Hiraishi, Y. Ichikawa, T. Moriguchi, A. Ozawa, S. Suzuki, Y. Tajiri,
University of Tsukuba, Tsukuba, Japan

Abstract

Rare-RI Ring was constructed at RIKEN RIBF for precise isochronous mass spectrometry of unstable nuclei. In June 2015, we performed the first commissioning of the ring using ^{78}Kr beam with the energy of 168 MeV/nucleon. We successfully carried out the individual injection which is one of the characteristics of the ring, and also we succeeded in the storage of ^{78}Kr ions for a few seconds.

We evaluated the performance of the resonant Schottky pick-up which was installed in the Rare-RI Ring. The purpose of the resonant Schottky pick-up is a monitor for tuning of the isochronous field in the ring. The resonant Schottky pick-up detected single ^{78}Kr ions, where the frequency resolution was 1.29×10^{-6} (FWHM). The resolution is in the same order of the required isochronicity. The sensitivity and resolution of the resonant Schottky pick-up are sufficient for the tuning of isochronous optics.

INTRODUCTION

Determining masses of extremely neutron-rich nuclei is important for study of nuclear structure and nucleosynthesis. Such unstable nuclei which locate far from β-stability line are short lived and rare, so here we call such nuclei rare RIs. In order to measure masses of rare RIs precisely, Rare-RI Ring was constructed at RIBF [1, 2]. Because rare RIs are randomly produced by nuclear reactions with intense primary beam from the cyclotron complex, only one rare RI is injected into the ring by using the individual injection with the fast kicker system.

We employ the isochronous mass spectrometry method. For high precision of the masses ($\Delta m/m \sim 10^{-6}$), we require to tune the isochronous field in the order of 10^{-6}. As a monitor for the tuning, we adopt a resonant Schottky pick-up. The resonant Schottky pick-up was designed by the systematic 3D electromagnetic simulations with Micro Wave Studio [3], and was tested offline before installation in the ring [4]. From Schottky spectra, we obtain the revolution frequency information of circulating ions. The momentum change of a stored ion causes the frequency change in the Schottky spectrum, so the isochronicity indicates no change in frequency, despite momentum change of the stored ion. The resonant Schottky pick-up is required to have high sensitivity such that it can detect a single ion with sufficient resolution. In the present study, we evaluated the performance of the resonant Schottky pick-up in the commissioning.

RESONANT SCHOTTKY PICK-UP

The resonant Schottky pick-up consists of a pillbox-type resonant cavity and ceramic gap. The resonant cavity is made of aluminum with outer diameter, length, and inner diameter of 750, 200, and 320 mm, respectively. Figure 1 is the photographs of the resonant Schottky pick-up. When the beam pass through the resonant Schottky pick-up, an electromagnetic field is induced in the cavity. The change of magnetic flux in the induced electromagnetic field is detected by a pick-up loop. The coupling factor of the pick-up loop was optimized to be one. By adjusting the position of two tuners, the resonance frequency is changed in the range of 173 ± 1.5 MHz.

We performed an offline test of the resonant Schottky pick-up with a network analyzer. We determined the shunt impedance R_{sh} with the bead method. As the result, we acquired basic quantities of the resonant cavity: the resonance frequency $f_{\mathrm{res}} = 171.43$ MHz, $R_{\mathrm{sh}} = 161\ k\Omega$ and unloaded quality factor $Q_0 = 1880$.

ONLINE RESULT AT COMMISSIONING

The first commissioning of Rare-RI Ring using ^{78}Kr beam with the energy of 168 MeV/nucleon was carried out

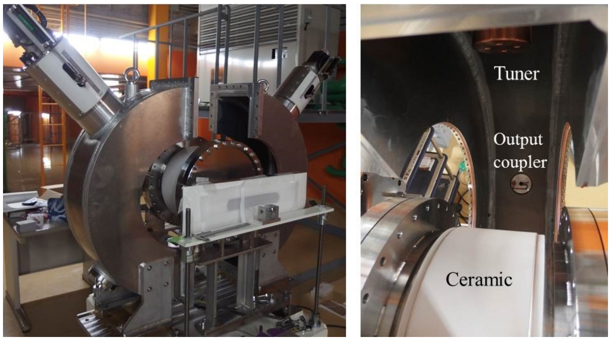

Figure 1: (Left): The resonant Schottky pick-up divided in half. The Schottky pick-up has a pillbox-type resonant cavity. (Right): Inside of the resonant cavity. In the upper part, a tuner for fine tuning the resonance frequency is shown. In the lower part, a pick-up loop for detecting the induced magnetic flux is shown.

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* suzaki@ribf.riken.jp

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SI-THYRISTOR MATRIX ARRAY DRIVEN ELECTROSTATIC INJECTION KICKER FOR THE KEK DIGITAL ACCELERATOR AND BEAM DYNAMICS ANALYSIS OF INJECTION

H. Kobayashi#1,2, X. Liu2,3, T. Kawakubo2, and T. Adachi2,4

1Tokyo City University, Setagaya, Tokyo, Japan
2High Energy Accelerator Research Organization/Accelerator Laboratory (KEK), Tsukuba, Japan
3Tokyo Institute of Technology, Nagatsuda, Japan
4The Graduate University for Advanced Studies (SOKENDAI), Hayama, Kanagawa, Japan

Abstract

The electrostatic (ES) kicker is used for heavy ion beam injection [1] into the KEK digital accelerator (DA) ring [2]. A voltage of 20 kV, which must be immediately turned off after injection, is put across the electrostatic electrodes before injection so as to deflect the injected beam on the ring orbit. The SI-Thyristor Matrix Array (SI-Thy MA) as a turning off switching device has been developed to replace the conventional thyratron [3]. The long ringing in the turn-off voltage affects on longitudinal motions of the injected beam bunch. Its careful analysis is discussed here.

INTRODUCTION

Voltage ringing continues for about 3.5 μs after switching on of the SI-Thy MA as shown in Fig. 1. It is apparently longer than that of the thyratron. This is caused by intrinsic natures of the SI-Thy MA. Details of the newly developed SI-Thy MA were reported in Reference 3. Fortunately, such relatively longer ringing time duration does not become any actual problem even in the case of hydrogen ion of A/Q=1, because its revolution time of 6 μs is much longer than the ringing time duration . The ringing in voltage vibrates in time with damping. The oscillation period is about 550 ns.

Since its operation we have noticed interesting phenomena related to this voltage ringing. Creation and annihilation of micro-bunches as seen in Fig. 2 are among them. In order to investigate such ringing effects on the beam dynamics, extensive injection experiments were conducted. From the experiment adjusting the kicker discharge timing, the ringing was known to be responsible for perturbations on the circulating beam bunch. As a result, it turned out that the residual electric fields generated at an entrance and the exit of the ES-kicker, originating from the ringing voltage affects on the longitudinal beam dynamics. In addition, it has been observed that the creation of microstructure strongly depends on a beam intensity.

The physics model that explains the direct ringing effect is shown in Fig. 3. The ES-kicker region is 1 m long, and the transit time (τ) necessary for a particle to pass the region is about 330 ns. It is clear that the net effect of the residual voltage remains in the energy gain of a particle during passing the injection kicker.

For the purpose to fully understand the longitudinal beam dynamics in the early stage just after injection, the simulation program has been developed, which takes account of the longitudinal space charge effect and wake fields in an isolated impedance with the oscillation frequency close to the microstructure. The observation point is shown in Fig. 3. φ and E in the Figure denote the phase and the energy of the macro-particles at the observed point.

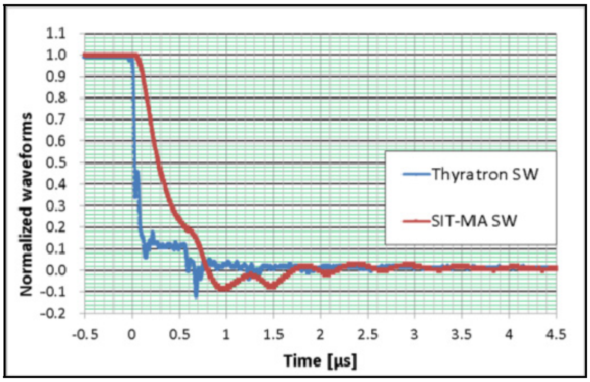

Figure 1: ES-Kicker voltage waveforms for both switches.

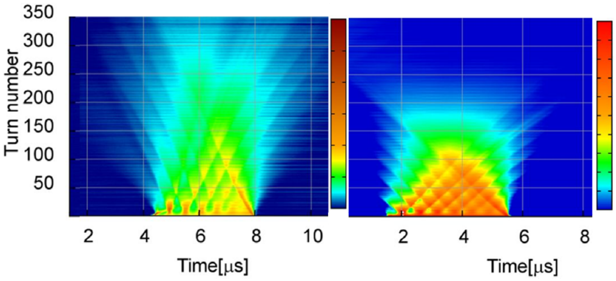

Figure 2: Temporal evolution of the injected bunch for 40 μA (experiment: left) and 100 μA (experiment: right), the line density is projected on the 2D time space, the time within a single revolution (the horizontal direction) and time from the injection (the vertical direction).

[#] khiroshi@post.kek.jp

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RECENT UPDATES ON THE RIKEN RI BEAM FACTORY CONTROL SYSTEM

M. Komiyama, M. Fujimaki, N. Fukunishi, K. Kumagai, A. Uchiyama,
RIKEN Nishina Center, Wako, Saitama, Japan
T. Nakamura, SHI Accelerator Service, Ltd., Shinagawa, Tokyo, Japan

Abstract

RIKEN Radioactive Isotope Beam Factory (RIBF) is a cyclotron-based heavy-ion accelerator facility for producing unstable nuclei and studying their properties. Following the first beam extraction from a superconducting ring cyclotron, the final-stage accelerator of RIBF, in 2006, several types of extensions and updates have been performed in the RIBF control system as well as the accelerators and their components. In this paper, we will present two latest updates of the RIBF control system. One is the upgrade of the existing beam interlock system in order to adapt to the increase in the types of experiments performed in RIBF recently. The other is the development of two types of successors that are designed to be compatible with the existing controllers for magnet power supplies.

INTRODUCTION

Overview of RIBF Accelerator Complex

RIKEN Radioactive Isotope Beam Factory (RIBF) is a multistage accelerator complex, which consists of two heavy-ion linacs and five heavy-ion cyclotrons including the world's first superconducting ring cyclotron (SRC); several acceleration modes can be made available by selecting a combination of the accelerators depending on the purpose of the experiment [1]. The RIBF accelerator research facility consists of the old facility, which was commissioned in 1986, and the newly constructed one (new facility), which was commissioned in 2006. At the old facility, various types of experiments such as biological irradiation are performed using the RIKEN ring cyclotron (RRC) [2]. The new facility was constructed in the downstream of the old facility and has added new dimensions to the facility's capability. Three new cyclotrons were constructed in the downstream of the RRC to accelerate beams with energies of several hundreds of MeV/nucleon over the entire range of atomic masses. In May 2015, a 345-MeV/nucleon ^{238}U beam of 39.5 pnA was successfully extracted from the SRC. A high-power heavy-ion beam extracted from the SRC is transported to the superconducting radioactive isotope beam separator, BigRIPS [3]. At the BigRIPS, various types of RI beams are produced, separated, and identified in an event-by-event mode. The tagged RI beams are delivered to experimental setups placed downstream of the BigRIPS.

Overview of the RIBF Control System

Figure1 shows the overview of the RIBF control system. The components of the RIBF accelerator complex, such as magnet power supplies, beam diagnostic devices, and vacuum systems, are controlled using the experimental physics and industrial control system (EPICS) [4]. In addition, there are several control systems, such as a system for radio frequency (RF) and ion source, that are not integrated into the EPICS-based system. The RIBF accelerator complex is operated under the control of the EPICS-based and the non-EPICS-based control systems [5].

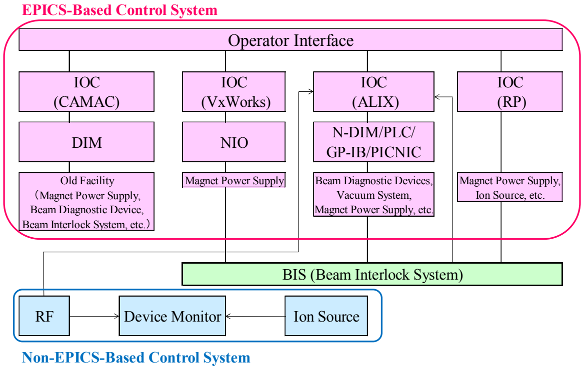

Figure 1: Overview of RIBF Control System.

There are two kinds of interlock systems in the RIBF facility, which are independent of the above-mentioned control systems. One is a radiation safety interlock system for human protection, HIS [6], and the other is a beam interlock system (BIS) to protect the hardware of the RIBF accelerator complex from significant beam losses for high-power heavy-ion beams [7]. The BIS stops a beam within 10-15 ms after detection of any interlock signal. For realizing the specification, after the BIS detects an interlock signal, it sends the signal to a beam chopper placed at the exit of the ion source. In addition, the BIS sends a signal to the closest Faraday cup located upstream of the trouble point to be set into a beam transport line. Although in the latter process, approximately 1 s is required to complete the movement of the Faraday cup, which is determined by mechanical limitations, this function is effective to ensure redundancy of the safety mechanism. At present, the BIS stops a beam within 10-15 ms in average. Many interlock signals such as failure signals are transported to the BIS sent from RF systems used in cyclotrons, magnet power supplies, vacuum gate valves in the beam transport lines, and beam

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* misaki@riken.jp

A FAST, COMPACT PARTICLE DETECTOR FOR TUNING RADIOACTIVE BEAMS AT ATLAS*

C.A. Dickerson[#], B. DiGiovine, C. Hoffman, L. Y. Lin, R.C. Pardo, K.E. Rehm, G. Savard
ANL, Argonne, IL 60439, USA
C. Deibel, J. Lai, D. Santiago-Gonzalez, LSU, Baton Rouge, LA 70803, USA

Abstract

Radioactive ion beams (RIB) at the Argonne Tandem Linear Accelerator System (ATLAS) are produced either from the in-flight method at 5-15 MeV/u for A < 30, or via reacceleration of fission fragments from the CAlifornium Rare Isotope Breeder Upgrade (CARIBU) at 4-10 MeV/u for 80 < A < 160. These RIB are typically accompanied by contaminant beams >100x more intense. The goal of this work is to develop a fast (>10^5 pps), compact (retractable from the beam line) particle detector capable of A and Z identification to enable accelerator optimization on the exact species of interest. The detector should have an energy resolution of ≤5% and be resistant to radiation damage. A gas ionization chamber supplemented with an inorganic scintillator was chosen as the basic conceptual design. GSO:Ce was chosen as the primary candidate scintillator due to a demonstrated energy resolution of ~3% for 15 MeV/u He and less irradiation induced performance degradation than other candidate materials.

INTRODUCTION

At the Argonne Tandem Linear Accelerator System (ATLAS) we are developing a fast, compact particle detector to aid the tuning of low intensity beam constituents with relatively high intensity (>100x) contaminants. These conditions are regularly encountered during radioactive ion beam production via the in-flight method, or when charge breeding fission fragments from the CAlifornium Rare Isotope Breeder Upgrade (CARIBU). Presently silicon barrier detectors (SBD) are used for mass identification via total energy measurements. However, the total acceptable SBD rate is limited to ~1000 pps, so the signal rate from any minority constituents 100x less intense is typically much too slow to enable meaningful accelerator optimization. In addition, SBDs can tolerate a very limited integrated flux before their performance deteriorates.

The in-flight method of RIB production at ATLAS generally produces beams of interest with energies 5–15 MeV/u and masses less than 30 AMU, while reaccelerated fission fragments from CARIBU, 80 < A < 160, are typically accelerated to energies of 4–10 MeV/u. Our goal is to achieve ~5% energy resolution at a total rate of 10^5 pps over these energy and mass ranges without significant performance degradation after extended use.

The detector will combine a gas ionization chamber with an inorganic scintillator to generate ΔE and residual E signals and enable the identification of both the Z and the A of the beam constituents. This configuration allows the needed compactness to retract the assembly from the beam path. The conceptual design of the detector and considerations for the selection of the scintillator, photoelectric device, and counting gas are presented in this paper.

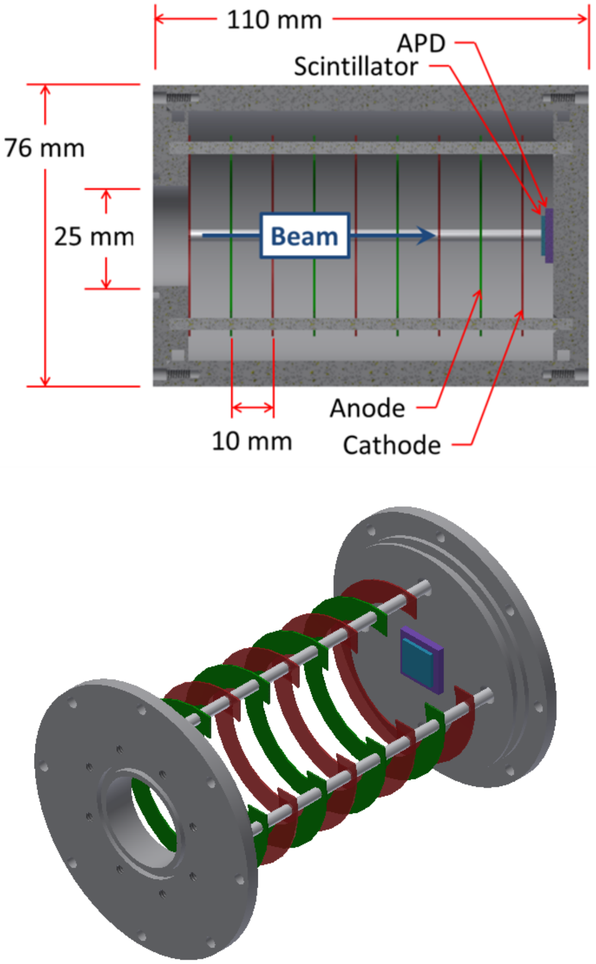

Figure 1: (Upper) A cross section showing the general layout and dimensions of the detector configuration. (Lower) A view of the detector with the vacuum tube removed and the electrodes cut away for clarity.

DESIGN

A hybrid of a gas ionization chamber (IC) supplemented with a scintillator was the chosen conceptual design, shown in Fig. 1. Both the gas and scintillator are fast,

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[#] cdickerson@anl.gov

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STATUS AND UPGRADES OF HIRFL*

Y.J. Yuan#, L.T. Sun, J.C. Yang, X.J. Yin, L.J. Mao, J.X. Wu, X.W. Ma, X.H. Zhang, D.Q. Gao, R.S. Mao, Z. Xu, W. Zhang, J. Meng, L.Z. Ma, P. Li, J.W. Xia, H.W. Zhao IMP/CAS, Lanzhou, China
Y.R. Lu, K. Zhu, G. Liu, State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
S. Litvinov, Y. Litvinov, M. Steck, F. Nolden, GSI, Darmstadt, Germany
V. Parkhomchuk, BINP SB RAS, Russia

Abstract

The Heavy Ion Research Facility at Lanzhou (HIRFL) is the only one large scale heavy ion accelerator complex that uses cyclotron (SFC and SSC) as injector, synchrotron (CSRm) for accumulation and post acceleration, storage ring (CSRe) for in-ring experiments in Asia. To reach the increasing requirements from nuclear physics, atomic physics, interdisciplinary science and their applications, many upgrading plans were launched or scheduled. The present status and recent upgrading plans of HIRFL will be introduced in this paper. For the upgrading plans, the development of new linac injector for HIRFL and the plans to improve the performance of experiments will be discussed in detail.

INTRODUCTION

HIRFL is the only one large scale heavy ion accelerator complex that uses cyclotron (SFC and SSC) as injector, synchrotron (CSRm) for accumulation and post acceleration, storage ring (CSRe) for in-ring experiments in Asia[1-5]. The layout of HIRFL is shown in Fig.1. For CSRm, both multi-turn injection and charge exchange injection methods are used with strong support from cross-section-variable electron cooling during beam accumulation; and both fast and slow extracted[6] beams are available for experiments and transmission to CSRe.

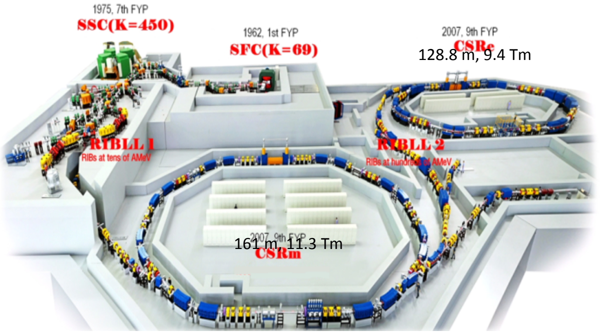

Figure 1: Layout of HIRFL

The operation time is 7,272 h in 2014, while beam time for experiments counts 5,199.5 h. The distribution of operation time is shown in Fig.2. The distribution of experiment time among researches is shown in Fig.3.

In 2014, about 25 kinds of ions, with different charge states and energies, were provided by HIRFL accelerator complex (See Table 1). Among them about 10 beams were provided for the 1st time (green background), 6 beams (marked by *) were supplies for ring experiments.

Table 1: Typical Beams Supplied in 2014

No.	SFC			SSC	
	Ion	Energy MeV/u	Current eμA	Energy MeV/u	Current eμA
1*	$^{78}Kr^{19+/28+}$	4	4.2		
2	H_2^+	10	4		
3	$^{40}Ar^{11+}$	4.8	3.2		
4*	$^{16}O^{6+}$	7	8.5		
5	$^{12}C^{4+/6+}$	7	2.3	80.55	0.17
6	$^{40}Ar^{12+/17+}$	6.17	5	70	0.45
7	$^{16}O^{6+/8+}$	6.17	5.9	70	0.45
8	$^{12}C^{4+/6+}$	5.361	2.8	60	0.24
9	$^{209}Bi^{31+}$	0.911	0.6	9.5	0.04
10	$^{58}Ni^{19+/25+}$	6.17	1.2	70	0.07
11	$^{32}S^{9+}$	3.9	1.7		
12	$^{40}Ar^{9+/15+}$	2.794	3	30	0.05
13	$^{20}Ne^{7+}$	6.17	3.8		
14	$^{16}O^{6+}$	7.5	2		
15	$^{22}Ne^{8+}$	7.5	2.2		
16	$^{86}Kr^{17+/26+}$	2.345	4.5	25	0.13
17	$^{12}C^{4+/6+}$	4.906	5	54.5	0.35
18*	$^{36}Ar^{15+}$	8.5	1.9		
19	$^{14}N^{4+}$	4.5	2.8		
20	$^{40}Ca^{12+}$	5	2		
21*	$^{12}C^{3+}$	4.2	5		
22*	$^{12}C^{4+}$	7	10		
23	$^{40}Ca^{12+}$	4.825	2		
24	$^{209}Bi^{31+}$	0.911	0.3	9.5	0.01
25*	$^{58}Ni^{19+}$	6.3	1.2		

*For ring experiments

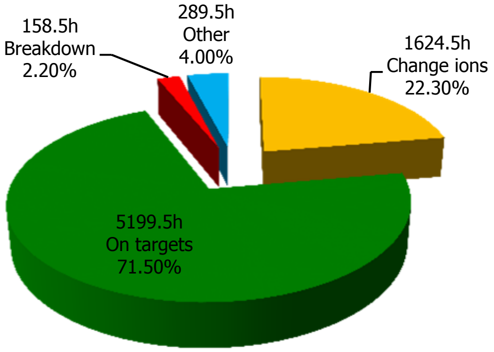

Figure 2: Distribution of operation time

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#yuanyj@impcas.ac.cn

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BEAM LOSS IN THE LOW ENERGY ION RING (LEIR) IN THE LIGHT OF THE LHC INJECTOR UPGRADE FOR IONS (LIU-IONS)

M. Bodendorfer, M.E. Angoletta, J. Axensalva, D. Manglunki, S. Pasinelli
CERN, Geneva, Switzerland

Abstract

For the LHC injector upgrade for Ions (LIU Ions), the Low Energy Ion Ring (LEIR) is requested to deliver twice the intensity per extraction compared to the last Pb^{54+} ion run in 2013 [1]. As the number of injected ions has been increased into LEIR, a fast loss is observed during the RF-capture of the electron cooled ion beam, and this loss today leads to an effective saturation of the available ion intensity at extraction.

Based on chromaticity measurements with Pb^{54+} beam in LEIR with bunched beam and during acceleration in February 2013 [2], we suspected the chromaticity of the LEIR machine to be wrong in the vertical plane. To investigate the stationary behavior of the LEIR machine, we have developed a new method to measure the machine chromaticity on the low energy flat bottom of LEIR during a single cycle, where the ion beam is un-bunched and coasting. The new method controls the ion beam momentum by the LEIR electron cooler beam rather than the LEIR RF-system. The new method uses the LEIR Schottky system to measure the applied momentum change rather than the radial beam position offset in dispersive regions. The existing tune measurement system is used to measure the tune in the same way as in the classic way involving the RF-system and bunched ion beam. The new method allows a single-cycle-chromaticity measurement of coasting and un-bunched beam with high accuracy and no dependency of cycle-to-cycle machine variation.

INTRODUCTION

LEIR has accumulated, cooled and stacked ion beams of Oxygen (O^{4+}), Lead (Pb^{54+}) and Argon (Ar^{11+}). For LIU, LEIR is requested to deliver 1.6×10^9 ions in 2 bunches, which is 50% more intensity compared to the last Pb^{54+} ion run in 2013. The number of injected lead ions into LEIR has been increased during several machine development studies (MDs) in late 2012 and early 2013. Total intensities of up to 1.8×10^9 lead ions have been observed during the coasting beam phase before RF capture. An ion beam loss is then observed during and after the RF-capture. Today, this loss leads to an effective saturation of the available ion intensity at extraction. Fig.1 shows a typical Pb^{54+} NOMINAL cycle as it is used for LHC injections. Fig.2 shows that with two bunches per extraction up to 5.9×10^8 ions per bunch have been measured.

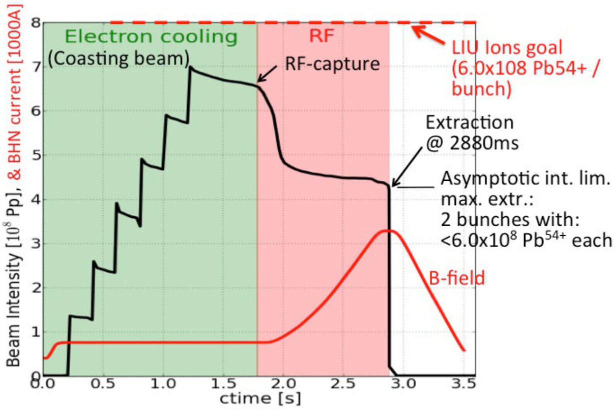

Figure 1: A typical LEIR NOMINAL cycle, 3.6s in length with main magnet current, proportional to particle momentum in red and ion beam intensity in black versus cycle time.

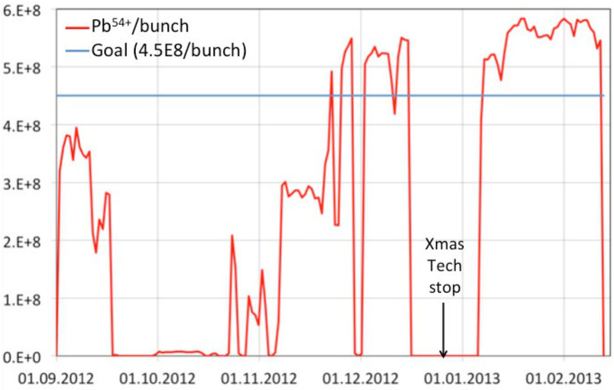

Figure 2: Extracted ions per bunch from LEIR from September 1st 2012 until February 1st 2013. The intensity goal of the LHC ion run for LEIR was 4.5×10^8 ions per bunch, which was achieved in January 2013.

However, with respect to the LIU Ions beam parameter goals, the extracted beam intensity, which was achieved during the last ion run in early 2013, is not sufficient. In fact, 8×10^8 ions per bunch are required for LIU Ions [1].

BEAM LOSS SYMPTOMS IN 2013

The LEIR Pb^{54+} low energy beam loss has been analysed in the past [2, 3]. The chromaticity of LEIR with Pb^{54+} was measured to be positive in the vertical plane (Fig.3) in February 2013, and as such, was found to be inconsistent with the machine design [4] and beam stability needs, both requiring at first order negative chromaticity for the horizontal plane and for the vertical plane.

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THE CRYOGENIC STORAGE RING CSR

M. Grieser, A. Becker, K. Blaum, C. Breitenfeldt, F. Fellenberger, S. George, J. Göck, F. Grussie,
R. von Hahn, P. Herwig, J. Karthein, C. Krantz, H. Kreckel, S. Kumar, J. Lion,
S. Lohmann, C. Meyer, P. M. Mishra, O. Novotný, A. P. O'Connor, R. Repnow,
S. Saurabh, C. D. Schröter, D. Schwalm, S. Vogel, A. Wolf
MPI für Kernphysik, Heidelberg, Germany
S. Schippers, K. Spruck, Institut für Atom- und Molekülphysik, Universität Gießen, Germany
D. Zajfman, Weizmann Institute of Science, Rehovot, Israel

Abstract

The CSR is a cryogenic electrostatic storage ring located at MPI for Nuclear Physics in Heidelberg. The CSR is designed to perform experiments on ions stored in a low thermal radiation field (≈ 10 K) and in ultra high vacuum conditions. The experimental vacuum system of the CSR, together with all ion optical elements, is entirely housed in a cryostat. On March 17, 2014 a 50 keV Ar^+-beam, delivered from the new electrostatic ion accelerator platform was successfully injected and stored in the CSR at room temperature. The ion beam storage was an important mile stone in verifying the optical design and high-voltage stability. In spring 2015, the complete CSR was cooled to an average temperature below 10 K and first experiments with stored atomic and molecular ions have been successfully performed. We discuss the layout and first operation with a focus on ion beam diagnostics.

Figure 1: The cryogenic storage ring CSR with 35 m circumference.

INTRODUCTION

The CSR shown on Fig. 1, is a fully electrostatic storage ring used to store atomic, molecular and cluster ion beams [1] in the energy range of q·(20-300) keV, where *q* is the charge state of the ions. The whole storage ring can be cooled down to temperatures of only a few Kelvin where the stored molecular ion beams reach their lowest quantum states. This very low temperature also creates an extremely high vacuum. In fact, observations in the first cryogenic operation indicate residual gas densities below 20 molecules/cm^3. Cooling all ion optics and the vacuum enclosure to 10 K also provides the benefit of a uniquely low level of blackbody radiation in studies with molecular ion beams. In March 2014, to demonstrate the functionality of the CSR, a 50 keV $^{40}Ar^+$ beam was stored for hundred of turns in the ring under room temperature conditions. The complete storage ring was not yet cooled or baked-out at this time, a vacuum in the 10^{-7} mbar range was obtained, limiting the storage life times for singly charged ions to the order of a few milliseconds. In 2015, the storage ring was cooled down to an average temperature below 10 K. At this temperature lifetimes for singly charged ions up to 2500 s have been achieved. A detailed report of the first cryogenic operation of the storage ring will be given in an upcoming publication.

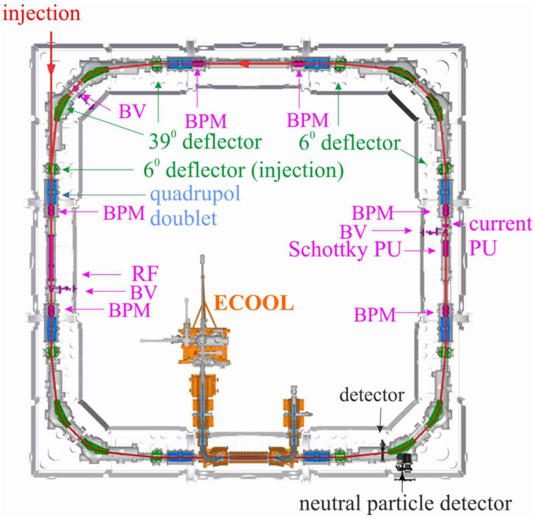

Figure 2: Layout of the cryogenic storage ring CSR. The diagnostics are marked in purple color, it means: BPM-horizontal and vertical beam position monitor, BV-beam viewer, PU- pick-up, RF-rf-system.

LAYOUT

The circumference of the storage ring is approximately 35 m. The beam optical elements consist of two quadrupole families, 6° deflectors to separate the ion beam from neutral reaction products and 39° deflectors (Fig. 2). In the current configuration it is possible to merge the ion beam with laser beams. The remaining experimental straight sections will contain an electron cooler and a reaction microscope for reaction dynamics investigations, respectively. The last remaining linear section is uniquely reserved for beam diagnostics, which contains a beam viewer for the first turn

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THE RARE-RI RING AT RIKEN RI BEAM FACTORY

Y. Yamaguchi*, Y. Abe and Rare-RI Ring Collaborators, RIKEN Nishina Center, Wako, Japan

Abstract

The Rare-RI Ring is an isochronous storage ring to measure masses of short-lived rare nuclei by using relative TOF measurement method. The expected precision of the measured mass is of the order of ppm.

We examined the basic performance of the devices, i.e. injection line, septum magnets, dipole magnets with trim-coils, and fast-kicker system by using α-source in 2014. We demonstrated that trim-coils, which are fixed on the dipole magnets of the ring, can adjust the isochronous condition of the ring. An α-particle was injected into the ring individually by using self-trigger mechanism and was extracted from the ring several turns after the injection.

In June 2015, a commissioning run using a ^{78}Kr beam was performed and basic performances of the Rare-RI Ring were verified. We succeeded in injecting a particle, which was randomly produced from a DC beam using cyclotrons, into the ring individually with the fast-kicker system, and in extracting the particle from the ring less than 1 ms after the injection with same kicker system. We measured time-of-flight (TOF) of the ^{78}Kr particles between the entrance and the exit of the ring to check the isochronism. Through the first-order adjustment with trim-coils, the isochronism on the 10-ppm order was achieved for the momentum spread of ±0.2%. Higher-order adjustment employed in future will lead us to the isochronism on the order of ppm. In addition, we confirmed that a resonant Schottky pick-up successfully acquired the frequency information of one particle in storage mode.

In this paper, the technical aspects of the Rare-RI Ring and the preliminary results of the beam commissioning will be described.

INTRODUCTION

Systematic mass measurements, especially for neutron-rich exotic nuclei very far from the stability, are essential for solving the r-process path. However, nuclei in such regions have very short half-lives and have a very low production rate even with the powerful accelerator complex in RI Beam Factory, therefore, very fast and sensitive apparatus is needed. To this end, we have proposed a unique apparatus, the so called "Rare-RI Ring" about 10 years ago [1], to precisely measure masses of such rare-RIs.

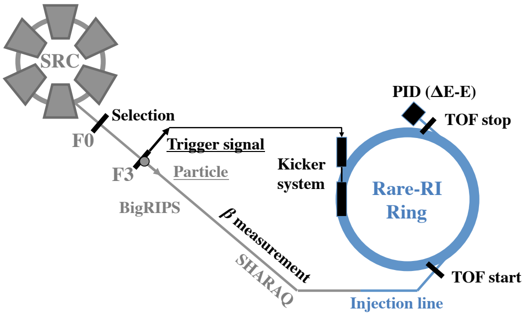

Figure 1: Conceptual design of mass measurement with the Rare-RI Ring located after the SHARAQ spectrometer.

Figure 1 shows the conceptual design of mass measurement by using the Rare-RI Ring. When a produced secondary particle passes through the timing detector at F3 of the BigRIPS separator [2], a trigger signal is generated. The trigger signal is transmitted to a fast-kicker system via a high speed coaxial tube. Kicker magnets are then immediately excited by thyratrons. In the meanwhile, the particle goes through the BigRIPS separator, the SHARAQ spectrometer [3], and an injection line. The particle that arrives at the entrance of the ring is injected into an equilibrium orbit of the ring using septum and kicker magnets. After the particle revolves in the ring about 700 μs, it is extracted using another septum and the same kicker magnets to measure TOF. In addition, it is identified by ΔE-E detectors after extraction. The revolution time of the particle is measured with an precision of better than 10^{-6} under the precise isochronous condition. The β measurement is necessary to correct a revolution time of non-isochronous condition particles. In addition to the short measurement time, this method enables us to measure the mass of even one particle which is suited to measure masses in the r-process region. The mass measurement principle details can be found in Ref. [4].

THE RARE-RI RING

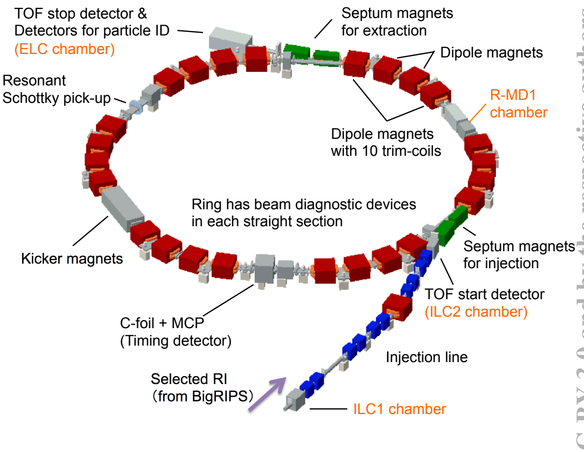

Figure 2: Components of Rare-RI Ring.

Figure 2 shows the components of the Rare-RI Ring. Injection line consists of five quadrupole doublets and one

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[*] yamaguch@ribf.riken.jp

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JINR SUPERCONDUCTING SYNCHROTRON FOR HADRON THERAPY

E.M. Syresin, V.A. Mihailov, N.A. Morozov, A.V. Tuzikov
Joint Institute for Nuclear Research, Dubna, Russia

Abstract

The medical carbon synchrotron at maximal ion energy of 400 MeV/u was developed in JINR. The project goal is accumulation of the superconducting technology at construction of the carbon synchrotron with a circumference of 69.6 m on basis of the Nuclotron type magnet elements. For injection of the carbon ions it is proposed to use IH linac of C4+ at energy 4 MeV/n. The superconducting gantry is developed for patient treatment. The gantry consists of two 67.5° and one 900 bending sections, each including two similar dipole magnets of a low aperture (about 120 mm). Such gantries are intended for multiple raster scanning with a wide carbon beam and the technique of layer wise irradiation with a spread out Bragg peak of several mm.

INTRODUCTION

Hadron therapy with beams of heavy nuclear particles (protons and carbon ions) is the most efficient radiation oncology treatment. Hadron therapy in Russia can offer substantial advantages for treatment to 50000 patients per year. Carbon ion therapy is particularly efficient for patients with radioresistant tumors. A project of the medical superconducting synchrotron dedicated for the carbon therapy has been designed in JINR (Fig.1).

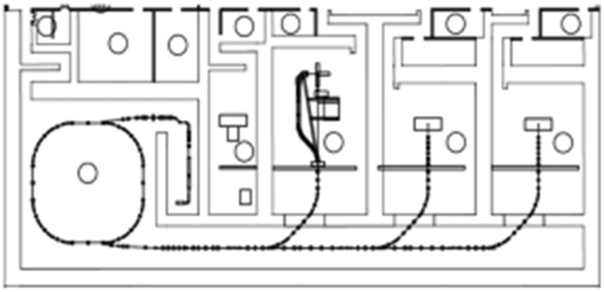

Figure 1: Layout of JINR accelerating equipment based on superconducting synchrotron for center of ion therapy.

The perimeter of the superconducting synchrotron in this complex is 70 m. The magnetic system of the synchrotron consists of four superperiods. The distribution of carbon ions with energy from140 MeV/u to 400 MeV/u from synchrotron into three medical booths is implemented in the transport channel.

The basis of this medical accelerator is the superconducting JINR synchrotron – Nuclotron [1,2]. The Nuclotron type straight dipole magnets [2] were adopted for the optic of the medical synchrotron and beam delivery system. The superconducting magnets permit to reduce the accelerator electrical consumption, the size and weight of the accelerator. Especially the superconducting technology is important at design of the carbon gantry. A superconducting gantry was developed for tumor treatment.

INJECTION

The superconducting electron string ion source [3] is planed to use for $^{12}C^{4+}$ injection in the carbon linac. The compact IH linac [4] will apply as synchrotron injector.

The injection channel consists from two sections: the discharge section, where accelerated in IH linac ions C^{4+} are discharged to ions C^{6+}, and the section of injection of ions C^{6+} in the synchrotron.

CARBON SYNCHROTRON

The basic parameters of the carbon synchrotron [5] are given in Table 1. The FODO structure (Fig.2) is more preferable for injection and extraction schemes and corrections of the closed orbit distortions. The synchrotron magnetic system (Table 2) consists of 4 superperiods, which involves 8 straight dipole magnets, 8 quadrupole lenses and multipole correctors. The maximum magnetic field in dipole magnets corresponds to 1.8 T. The beam and the synchrotron structure dynamic characteristics are given in Table 3.

Table 1: Basic Parameters of Carbon Synchrotron

Injection/maximal energy	4/400 MeV/u
Injection magnetic rigidity/ maximal	0.59/ 6.36T·m
Circumference	69.6 м
Column limit of intensity at injection	10^{10} p/cycle
Betatron tune shift	0.03
Revolution time at injection	2.37 µs
Number of turns at injection	20
Injection efficiency	50 %
Time of synchrotron acceleration	0.5 s
Slow extraction time	(0.5 -10) s
Energy of extracted beam	(140 – 400) MeV/u
Extraction efficiency	96%
Critical energy	3.1 GeV/u

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FIRST SIMULATION RESULTS OF HEAVY-ION ACCELERATION IN THE RCS OF J-PARC

P.K. Saha*, H. Harada, M. Kinsho, M. Yamamoto and H. Sako
J-PARC Center, KEK & JAEA, Tokai-mura, Naka-gun, Ibaraki-ken, Japan

Abstract

We present first space charge simulation results of heavy-ion (HI) acceleration in the 3-GeV Rapid Cycling Synchrotron (RCS) of Japan Proton Accelerator Research Complex (J-PARC). RCS is 1 MW proton beam power source for the Material and Life Science Experimental Facility (MLF) as well as an injector for the Main Ring (MR). Recently, importance of heavy-ion (HI) physics program in J-PARC are being intensively discussed for studying so-called QCD phase structures at high baryon density by using slowly extracted HI beam of 1-20 AGeV in the MR. Although detail accelerator scheme to adapt HI has not yet been fixed, in this work we studied possibilities of U^{86+} acceleration in the RCS by using ORBIT 3-D simulation code. The simulation results show that a more than $1{\times}10^{11}$ of U^{86+} ions per pulse can be accelerated in the RCS without any significant beam losses. That gives a total of $4{\times}10^{11}$ ions for each MR cycle and sufficiently meets experimental requirements concerning primary beam intensity.

INTRODUCTION

Japan Proton Accelerator Research Complex (J-PARC) has 3 proton accelerators and several experimental facilities that make use of high intensity proton beams [1]. The accelerator facility comprises a 400 MeV H^- Linac, a 3-GeV Rapid Cycling Synchrotron (RCS) and a 50-GeV (30-GeV at present) Main Ring synchrotron (MR) [2]. Major experimental facilities are Material and Life Science Experimental Facility (MLF), Hadron Experimental Facility (HD), Neutrino Experimental Facility (NU) and also an Accelerator Driven Transmutation Experimental Facility (TEF).

The importance of heavy-ion (HI) physics program in J-PARC is being intensively discussed recently, which consists of low and high energy programs [3]. The high energy program aims to explore QCD phase structures at nearly one order higher baryon density as compared to the normal nuclear density (ρ_0). The aim is to use slowly extracted HI beam from the MR with kinetic energy 1~20 AGeV. In order to reach baryon density as high as possible, the U+U system is considered by bombarding more than $1{\times}10^{10}$ U ions per cycle (a few sec) on a fixed U target. On the other hand, advantages of studying strangeness physics produced by HI collisions are also being discussed. The J-PARC energy gives maximum hypenuclear production due to coalescence of high density baryons [4].

However, there exist many issues and challenges to adapt a new HI accelerator scheme in the specifically designed and already running high intensity proton machines. Other than space and budget one big issue is not to interfere any existing or planned programs that make use of proton beams.

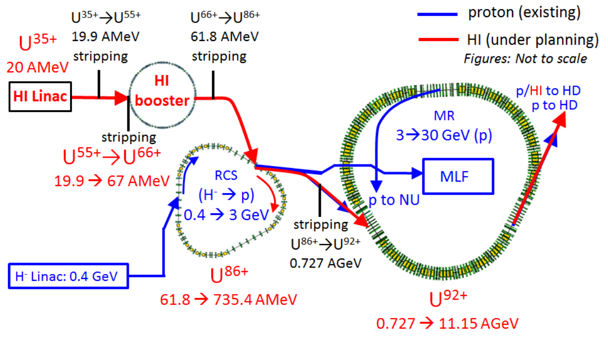

Figure 1: A preliminary scheme for HI acceleration (yet unofficial) to adapt in the existing J-PARC proton facilities.

Figure 1 shows a preliminary HI accelerator scheme (guided by red arrows), added to the existing J-PARC proton accelerators and facilities (guided by blue arrows). The first approach is to use existing RCS and also the MR, where a HI Linac followed by a smaller HI booster ring have to be constructed. There exist many advantages if RCS and the MR can be successfully utilized for accelerating HI to the required energy. Proton beam powers in both machines are approaching to the design goal, while RCS has already demonstrated 1-MW equivalent beam acceleration in early 2015 [5]. The measured beam losses were as low as less than 0.2% and were mostly due to the foil-beam interaction during more than 300 turns H^- change-exchange injection. The beam dynamics issues are well understood, resulting a well beam loss mitigation even at 1 MW, which can be successfully applied for discussing HI beam dynamics issues and realistic measures.

While HI accelerator scheme and how it can be connected to J-PARC facility are under planning, we have investigated the possibilities of HI acceleration in the RCS. The numerical simulation results are presented in this paper.

HI SCHEME IN THE RCS

Figure 2 shows a layout of the RCS. The proton beam energy at injection and extraction are 0.4 and 3 GeV, respectively. The extracted beam is simultaneously delivered to the MLF and MR at a repetition rate of 25 Hz. A new HI injection system is considered to be added at the end of RCS extraction straight section. The uranium ions having 86+ charge states (U^{86+}) will be injected for a single turn from the upstream new HI booster. The injection system can be thus very simple and straightforward, which may not require a large space. However, injection energy of HI has to be

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[*] E-mail address: saha.pranab@j-parc.jp

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COMMISSIONING OF HEAVY-ION TREATMENT FACILITY I-ROCK IN KANAGAWA

E. Takeshita[#], S. Minohara, Y. Kusano, S. Yamada
Kanagawa Cancer Center, Kanagawa, Japan
T. Furukawa, K. Mizushima, Y. Hara, N. Saotome, R. Tansho, Y. Saraya, K. Noda
National Institute of Radiological Sciences, Chiba, Japan

Abstract

As part of the Kanagawa "Challenge-10-years strategy to cancer" it was decided in March 2005 to establish a carbon-ion therapy system at the Kanagawa Cancer Center (KCC). From around 2009, the basic design and the foundational planning of the facility were considered and in January 2012 a contract was made with the Toshiba Corp. In December of the same year, the construction of the main building for the acceleration and treatment devices was started and completed in October 2014. Currently, the KCC is in a commissioning phase with the aim to start treatment in December of this year. Various treatments for cancer, which include the present photon LINAC for the radiation therapy, will be provided to patients in cooperation with our cancer center hospital. In addition, we will combine a compact dissemination treatment system of carbon-ion therapy to the pencil beam 3D scanning technique designed by the National Institute of Radiological Sciences (NIRS). The treatment experience with the carbon-ion scanning technique will be the second in the country following NIRS. In this paper, we report on the progress of the beam commissioning at KCC.

INTRODUCTION

The carbon-ion therapy facility of the KCC, which is called "Ion-beam Radiation Oncology Center in Kanagawa (i-ROCK)", has been introduced with concepts for cancer treatment as described below. At first, we aim to provide the most suitable treatment, which includes the existing photon LINAC for the radiation therapy, to any patient in cooperation with our hospital organization. The facility for carbon therapy has been constructed, focusing the cancer treatment on "Quality of Life (QOL)".

The general layout and schedule of the i-ROCK project was considered with its original specifications from around 2009. In January 2012, an agreement with the Toshiba Corp. was made to introduce and install the carbon-ion therapy system. The construction of the facility building was started from December 2010 by the Kajima Corp. and was completed in October 2014. The equipment of the treatment system was delivered from May 2014. At present, various commissionings have been performed to start first treatment in December 2015.

SPECIFICATIONS

The original specifications of the facility used for the treatment follow that of the compact dissemination treatment system of carbon-ion therapy [1] designed and developed by the NIRS. This system was already used for the cancer treatment in Gunma University and SAGA HIMAT achieving good results while each facility vendor was different. One of the main features in i-ROCK is the combined installation with a 3D pencil beam scanning system [2] developed by NIRS and the compact dissemination treatment system of carbon-ion therapy. The main specifications are indicated in Table 1.

Table1: Specifications of i-ROCK

Item	Basic specifications
Ion	C^{6+}
Energy	140～400 MeV/u (variable)
max. Field	20×20 cm^2
max. Dose rate	2 Gy/min
Beam intensity	~1.2×10^9 pps (variable)
Irradiation type	Scanning Extended scanning
Treatment room	Horizontal: 2 rooms Horizontal/Vertical: 2rooms

In order to use efficiently use the pencil beam delivered from the synchrotron accelerator, the treatment room set up contains 4 (Horizontal/Vertical x 2 rooms, Horizontal x 2 rooms, 6 ports for total of 4 rooms). Generally, more than one treatment room per accelerator was set up in the present facility because during treatment time more than 80 % is spent on the positioning of the patient by the X-ray imaging system. However for our facility, it is a little bit different. We considered with the ration of the treated tumor in Kanagawa and the treatment protocol for the carbon therapy to fix the number of the treatment room. With these considerations, our facility can accept 880

[#] takeshita.e@kcch.jp

DEVELOPMENT OF A LIQUID LITHIUM CHARGE STRIPPER FOR FRIB*

F. Marti#, P. Guetschow, FRIB, East Lansing, MI, USA
Y. Momozaki, J. A. Nolen, C. B. Reed, ANL, Argonne, IL 60439, USA

Abstract

The Facility for Rare Isotope Beams (FRIB) being built at Michigan State University for the US Department of Energy (DOE) will deliver heavy ion beams with beam power of 400 kW. SRF cavities accelerate the ions to energies above 200 MeV/u. At energies of 16-20 MeV/u a charge stripper increases the charge state just before the first bend in the linac (a second bend is located downstream). Due to the high power deposition on the stripping media and radiation damage solid strippers are not practical. The baseline design selected a liquid lithium film stripper. This stripper has been developed in collaboration with Argonne National Laboratory (ANL). A stripper module is being built at MSU with an estimated completion date of December 2015. We plan to operate the stripper outside the FRIB tunnel for 18 months to learn the reliability and stability issues before final installation in the accelerator.

INTRODUCTION

Michigan State University was charged by the Office of Science of the DOE of the US to design and build the Facility for Rare Isotope Beams (FRIB) at the end of 2008. The facility is funded by the Office of Nuclear Physics with contributions and cost share from Michigan State University. The goal of the facility is the production of rare isotopes produced by the in-flight separation method. This method provides fast development time for any isotope and allows short lived isotopes of any element to be available.

One of the main components of the facility is a driver linac capable of producing beams of ions from the low mass region up to U at energies above 200 MeV/u and with a total beam power on target of 400 kW [1, 2]. The linac is folded in three segments running parallel to each other with two 180 degree bends in between. After the first linac segment and before the first bend a charge stripper is located to increase the Q/A of heavy ions by more than a factor two.

This paper describes the design and construction of the liquid lithium charge stripper and the extensive experimental work done up to now.

WHY LITHIUM?

As described previously [3], liquid lithium was selected as the baseline design for the FRIB charge stripper because traditional solid carbon strippers have very limited lifetime under heavy ion bombardment [4]. There is no solid lattice that can be damaged by the high energy deposition and the flowing liquid takes away the heat deposited by the beam on the stripping media. The use of lithium was initially proposed by the ANL group at the time of the Rare Isotope Accelerator (RIA) R&D [5]. Lithium has several properties that make it the preferred liquid metal for this application.

The vapour pressure of lithium at its melting temperature (186 C) is quite low (~ 10^{-7} Pa). If we compare with Hg for example, mercury has a vapour pressure of ~ 10^{-1} Pa at room temperature and when heated by the beam it will be even higher.

The heat capacity of lithium is quite high (~ 4.2 J/g/C at 200 C) meaning that it will have a limited temperature increase when exposed to the beam, and its boiling point (1336 C at 1 bar) is much higher than the melting point.

The major drawback of lithium is its pyrophoricity. [6] It will burn in oxygen and nitrogen producing caustic fumes (oxide and nitride). Contact of molten alkali metal with concrete will cause spalling of the concrete and spattering of the metal. Special precautions must be taken to avoid any contact of the lithium with water or humid air.

EXPERIMENTAL WORK

Production of the Lithium Film

The film thickness required to achieve near equilibrium charge state is of the order of 10 µm. We need the film to move fast through the beam to take the heat away. Speeds of close to 50 m/s are necessary. The initial ANL experiments [7] created a high velocity jet of liquid lithium by pressurizing a tank with argon gas that contained the liquid and pushing the lithium through a small diameter nozzle. This high velocity jet impinged on a flat plate that created the thin film, about 9 mm wide as illustrated in Fig. 1.

The original experiments proved the feasibility of creating the lithium film using pressurized liquid at temperatures around 200 C.

Stability and Thickness Measurements

In 2009 a collaboration was established between FRIB and ANL to continue the experimental work at ANL with the objective of measuring the thickness and stability of the lithium film.

A limitation on these experiments was that the flow of lithium could be maintained for less than 30 minutes because the liquid would flow from the supply tank to the

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#marti@frib.msu.edu

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UPGRADE OF THE UNILAC FOR FAIR

L. Groening[1], S. Mickat[1], A. Adonin[1], W. Barth[1,3], X. Du[1], Ch.E. Düllmann[1,3,4], H. Hähnel[2],
R. Hollinger[1], E. Jäger[1], M.S. Kaiser[1], U. Ratzinger[2], A. Rubin[1], P. Scharrer[1,3,4], B. Schlitt[1],
G. Schreiber[1], A. Seibel[1,2], R. Tiede[2], H. Vormann[1], C. Xiao[1], C. Zhang[1]
[1]GSI, D-64291 Darmstadt, Germany
[2]Goethe University of Frankfurt, D-60438 Frankfurt, Germany
[3]Helmholtz Institute Mainz, Mainz, Germany
[4]Johannes Gutenberg-University, Mainz, Germany

Abstract

The UNIversal Linear Accelerator (UNILAC) at GSI serves as injector for all ion species from protons to uranium since four decades. Its 108 MHz Alvarez type DTL providing acceleration from 1.4 MeV/u to 11.4 MeV/u has suffered from material fatigue. The DTL will be replaced by a completely new section with almost same design parameters, i.e. pulsed current of up to 15 mA of $^{238}U^{28+}$ at 11.4 MeV/u. A dedicated source terminal & LEBT for operation with $^{238}U^{4+}$ is currently constructed. The uranium source needs to be upgraded in order to provide increased beam brilliances and for operation at 2.7 Hz.

INTRODUCTION

GSI is currently constructing the Facility for Ion and Antiproton Research (FAIR) [1]. It aims at provision of 3×10^{11}/s uranium ions at 1.5 GeV/u. Due to its high rigidity uranium imposes the highest challenges to the accelerator chain wrt fields and machine protection. Additionally, a total of 4×10^{12}/s cooled anti-protons are to be delivered. The complete accelerator chain is depicted in Fig. 1. The existing UNIversal Linear ACcelerator UNILAC will provide all primary ions but protons. A dedicated proton linac is currently under design and construction [2]. In order to deal with the FAIR requirements in the upcoming decades the UNILAC needs a considerable upgrade.

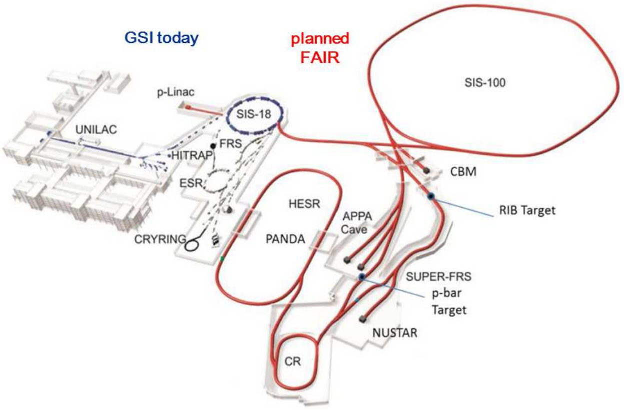

Figure 1: Facility for Anti proton and Ion Research (FAIR) under construction at GSI.

The existing UNILAC (Fig. 2) together with the subsequent synchrotron SIS18 serves as injector for FAIR. The UNILAC has three ion source terminals that can be operated in pulse-to-pulse switching mode at 50 Hz. One terminal is equipped with an ECR source providing highly charged ions. Another terminal houses a Penning source providing low intensity beams at intermediate charge states. The third terminal is dedicated to provision of intense beams of low-charged ions. It can be equipped with various source types as MUCIS and CHORDIS for light to intermediate-mass ions for instance. Intense heavy ion beams are produced in a MEVVA or VARIS source at 2.2 keV/u. Beams are bunched and pre-accelerated to 120 keV/u along a 9 m long RFQ operated at 36 MHz. Afterwards two IH-cavities provide for acceleration to 1.4 MeV/u. For uranium the highest particle numbers are obtained by using the charge state $^{238}U^{4+}$. After the IH-DTL the acceleration efficiency is increased by passing the beam through a gaseous stripper which delivers a mean charge state of $^{238}U^{28+}$ at its exit. This increase of charge state is at the expense of intrinsic particle loss as prior to 2014 about 87% of the uranium ions are stripped to a charge state different from 28+. After dispersive selection of the desired charge state the beam is matched to the subsequent post stripper Alvarez DTL. The latter is operated at 108 MHz and comprises five tanks. Its exit beam energy is 11.4 MeV/u being the injection energy for the synchrotron SIS18. The UNILAC design parameters are listed in Table 1. The age of the UNILAC together with the requirement to provide reliable and intense beams for the upcoming FAIR era calls for a revision of the UNILAC. In the following the planned upgrade activities are described.

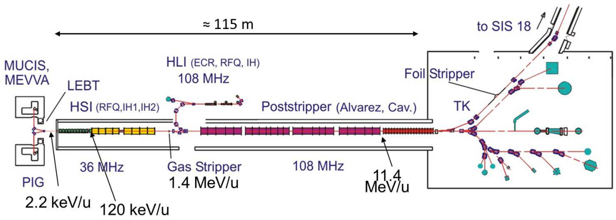

Figure 2: The UNIversal Linear ACcelerator (UNILAC) at GSI.

SOURCE, LEBT, MEBT, AND RFQ

In order to provide the mean uranium intensity required for FAIR the source has to be operated with a repetition rate of 2.7 Hz. Although this target has been reached for lead

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A PULSED GAS STRIPPER FOR STRIPPING OF HIGH-INTENSITY, HEAVY-ION BEAMS AT 1.4 MeV/u AT THE GSI UNILAC

P. Scharrer[1,2,3], W. Barth[1], M. Bevcic[2], Ch. E. Düllmann[1,2,3], L. Groening[2],
K.P. Horn[2], E. Jäger[2], J. Khuyagbaatar[1], J. Krier[2], A. Yakushev[2]

[1]Helmholtz-Institut Mainz, 55099 Mainz, Germany
[2]GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[3]Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany

Abstract

The GSI UNILAC in combination with SIS18 will serve as a high-current, heavy-ion injector for the future FAIR. It has to meet high demands in terms of beam brilliance at a low duty factor (100 µs beam pulse length, 2.7 Hz repetition rate). An advanced 1.4 MeV/u gas stripper setup has been developed, aiming at an enhanced yield into the required charge states. The setup delivers short, high-density gas pulses in synchronization with the beam pulse. This provides an increased gas density at a reduced gas load for the differential pumping system. In recent measurements, high-intensity, heavy-ion beams of U^{4+} were successfully stripped and separated for the desired charge state. The modified stripper setup, as well as major results, are presented, including a comparison to the present gas stripper based on a N_2 gas-jet. The stripping efficiency into the desired 28^+ charge state was significantly increased by up to 60 % using a hydrogen stripper target while the beam quality remained similar.

INTRODUCTION

The UNIversal Linear ACcelerator (UNILAC) will serve as part of an injector system for the Facility for Antiproton and Ion Research (FAIR), currently under construction at GSI in Darmstadt, Germany. A key projectile for FAIR is the heavy ion ^{238}U [1]. To meet the beam requirements for FAIR, an upgrade program of the UNILAC has started to increase the delivered uranium beam intensities. The aim is to deliver short-pulsed, high-current, high-intensity U^{28+} beams with a repetition rate of 2.7 Hz to the subsequent SIS18 accelerator.

In the UNILAC, a gas stripper is used to increase the charge state of the beam ions at an energy of 1.4 MeV/u. Currently, the gas stripper operates with a super-sonic N_2-jet as a target, created by a laval nozzle with a back-pressure of up to 0.45 MPa [2]. To be able to deliver the desired beam parameters for FAIR-injection, an upgrade program of the gas stripper is ongoing, aiming at increasing the stripping efficiency into the U^{28+} charge state. Improving the performance of the gas stripper for uranium operation has proved difficult in the past, predominantly because of the high gas load for the differential pumping system using the continuous gas-jet [3].

A new approach was tested by applying a pulsed gas injection to the existing stripper setup, using a newly developed setup replacing the laval nozzle. The aim is to temporally increase the gas density in the interaction zone of the gas stripper just when a beam pulse is passing. The reduction of the gas load allows increased gas densities, which enables the practical use of other promising gases as stripper targets by providing the conditions to reach equilibrated charge-state distributions.

In first measurements in February 2014, the functionality of the pulsed gas cell was tested. At the end of 2014, another measurement series was conducted using a wide range of different gases to test the stripping performance for uranium beams and to increase the stripping efficiency into U^{28+}.

HEAVY-ION STRIPPER OPERATION

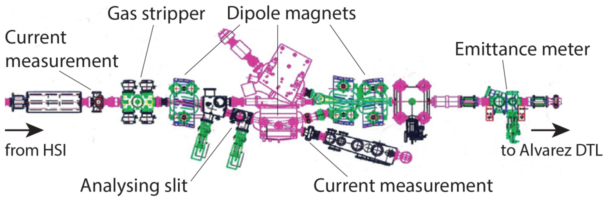

Figure 1: Layout of the UNILAC gas stripper section between the HSI and the Alvarez DTL.

In the UNILAC, the ion beams are delivered by three different ion sources in a time sharing mode. For the production of heavy ions like ^{238}U, a new Vacuum ARc Ion Source [4] is used. The prepared ion beams are delivered to the High Current Injector (HSI) [5]. The HSI comprises of a combination of a Radio Frequency Quadrupole structure (RFQ) and an interdigital H-structure drift tube linac (DTL), and accelerates the ion beams up to 1.4 MeV/u. Behind the HSI, the ion beams are focused onto a charge-analysing slit behind the gas stripper by two quadrupole doublets. The UNILAC stripper section is shown in Fig. 1. In the gas stripper, the charge state of the beam ions is increased by charge-changing processes occurring in the collisions between beam ions and neutral gas particles. Behind the stripper, the beam ions are separated by their charge state using a system of three dipole magnets. To select a charge state for further acceleration, an analysing slit is used behind the first dipole magnet at a deflection angle of 15°.

With the existing N_2-jet stripper, the stripping efficiency into the U^{28+} charge state at maximum back-pressure of

ADVANCES OF THE SPIRAL 2 PROJECT

J-M. Lagniel, GANIL, Caen, France
for and with the SPIRAL 2 Team

Abstract

The first phase of the SPIRAL 2 project dealing with the high-power superconducting linac and the two experimental areas called Neutron for Science (NFS) and Super Separator Spectrometer (S3) is well advanced. The building and conventional facilities are now ready and the project has entered in a phase during which the linac components are successively installed and commissioned (the first beam was produced in December 2014). After having briefly recalled the project scope and parameters, the constraints linked to the safety rules and the way the installation and commissioning are done will be explained. The next steps which are the DESIR low-energy experimental area and the q/A = 1/7 heavy ion second injector will be also presented.

SPIRAL 2 STATUS

The agreement giving the start of the SPIRAL 2 project [1] [2] was signed in September 2006 by the French state, Basse-Normandy region, department of Calvados, town of Caen, urban community of Caen-la-Mer, CNRS and CEA. Fig. 1 gives a 3D view of the building; the construction of which started in December 2010. With more than 100 rooms the total surface is 7,200 m^2 consisting of 4 floors and 2 basement levels.

Most of the conventional facility equipment and some parts of the accelerator (parts of the ion sources, RFQ cavity, magnets and cryomodule supports…) were installed before the end of the construction of the building (September 2014). Ref. [3] describes the integration of the accelerator processes, construction of the building and process connections.

Fig. 2 gives an overview of the accelerator, beam lines and experimental halls at the -2 level (- 9.50 m underground). The large free space at the north of the two source rooms is reserved for the future installation of a new injector (source and RFQ) able to inject Q/A up to 1/7 heavy ions in the superconducting LINAC. One can also notice that the building has been built in such a way that a LINAC extension at higher energy and/or the installation of new experimental areas are possible.

Proton/Deuteron Source and LEBT

The SPIRAL 2 proton/deuteron source is a 2.45 GHz ECR source which uses permanent magnets, it is designed to produce 5 mA 20 keV proton and 40 keV deuteron beams in CW or pulsed modes.

This source and associated low energy beam transfer line have been constructed by the CEA/IRFU team and successfully tested at Saclay [4]. This work was completed in July 2012. Reliability and stability were improved; emittance was measured and optimized versus space-charge compensation measurements.

The source and beam line have then been dismantled and transported to the GANIL site.

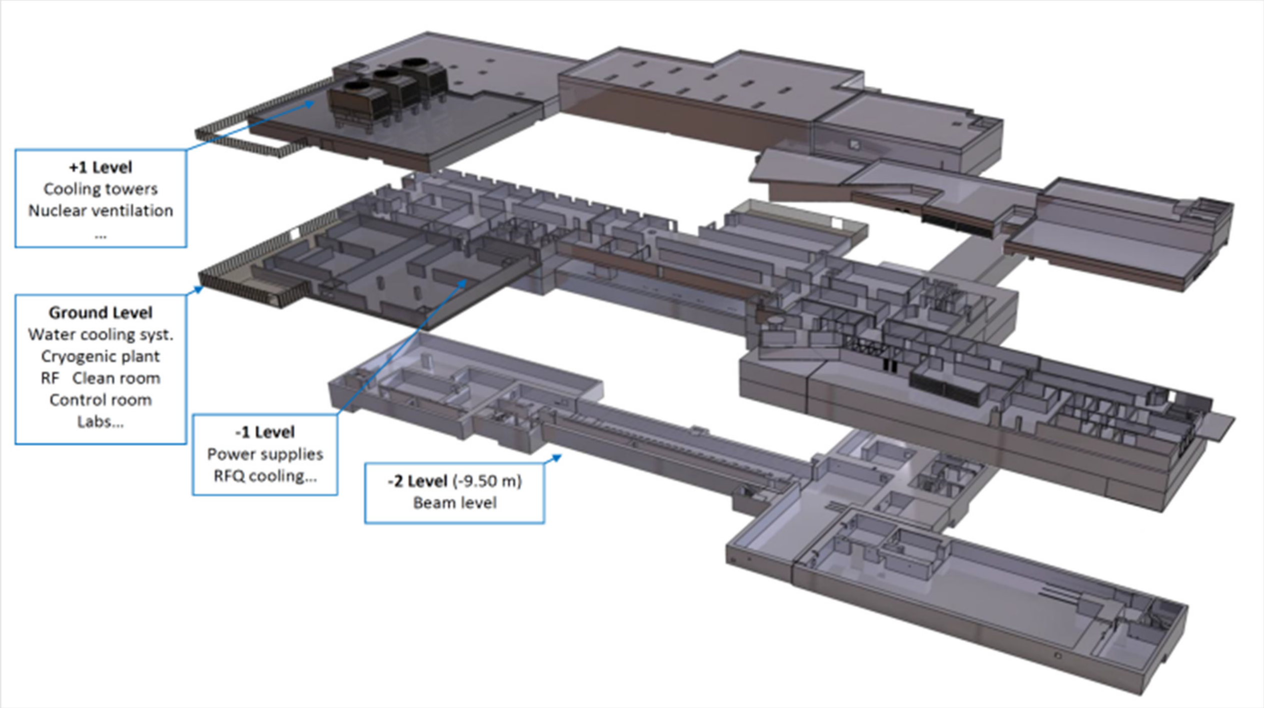

Figure 1: 3D view of the SPIRAL 2 building.

SPIRAL2 PROJECT: INTEGRATION OF THE ACCELERATOR PROCESSES, CONSTRUCTION OF THE BUILDINGS AND PROCESS CONNECTIONS

P. Anger, P. Bisson, O. Danna, X. Hulin, JM. Lagniel, F. Perocheau, E. Petit, L. Roupsard
GANIL Laboratory, Caen, France

Abstract

The GANIL SPIRAL 2 Project is based on the construction of a superconducting ion CW LINAC (up to 5 mA - 40 MeV deuteron and 33 MeV proton beams, up to 1 mA - 14.5 MeV/u heavy ion beams) with two experimental areas named S3 (“Super Separator Spectrometer” for very heavy and super heavy element production) and NFS (“Neutron For Science”).

The building studies as well as the accelerator and experimental equipment integration started in 2009. The ground breaking started at the end of 2010. The integration task of the different equipments into the buildings is managed by a trade-oriented integration unit gathering the accelerator integration team, the building prime contractor and a dedicated contracting assistant. All work packages are synthesized at the same time using 3D models. 3D tools are used to carry out integration, synthesis, process connections and the preparation of the future assembly.

Since 2014, the buildings and process connections are received and the accelerator installation is well advanced.

This contribution will describe these 3D tools, the building construction, the process connection status and our experience feedback.

INTRODUCTION

Officially approved in May 2005, the GANIL SPIRAL2 radioactive ion beam facility (Figure 1) was launched in July 2005, with the participation of many French laboratories (CEA, CNRS) and international partners. In 2008, the decision was taken to build the SPIRAL2 complex in two phases: A first one including the accelerator, the Neutron-based research area (NFS) and the Super Separator Spectrometer (S3), and a second one including the RIB production process and building, and the low energy RIB experimental hall called DESIR [1][2][3].

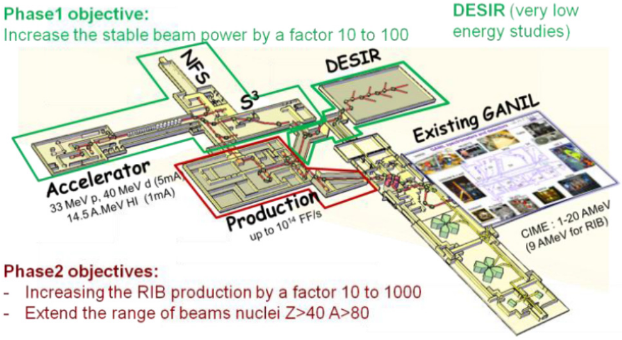

Figure 1: SPIRAL2 project layout, with experimental areas and connexion to the existing GANIL.

In October 2013, due to budget restrictions, the RIB production part was postponed, and DESIR was planned as a continuation of the first phase.

The first phase SPIRAL2 facility is now built, the installation and connecting tasks are in progress, with the aim of obtaining the first beam for physics (NFS) in 2016 [2][4].

DEFINITION OF THE NEEDS AND PRELIMINARY DESIGN

After the implementation of the Product Breakdown Structure (PBS), a global detailed specification was carried out to define the needs for each room of the building in terms of surface, mechanical stress for the floor, general servitudes to accommodate the accelerator and the experimental processes as well as for all the technical rooms receiving cryogenic, command control, RF power, vacuum systems.... The infrastructure needs (electricity, water cooling, nuclear ventilation, air conditioning, handling systems…) were also defined at that time.

These detailed specifications were used by the building prime contractor to make the building drafts and, in a second time, the preliminary design then the detailed design, with a cost estimate and control at each step.

The SPIRAL2 team took the decision to design the entire project with 3D tools due to the high degree of complexity of the processes and the very high level of the integration including connecting pipes and cables trays. We also wanted to be able to guarantee our ability to install, set up and maintain the equipments. For this 3D work the challenge comes from the fact that the same level of study is required for the building and conventional facilities, processes (ion sources, beam lines, RFQ, SC Linac and associated equipments) and for the process connections. A contracting assistant fully dedicated to these missions of 3D synthesis and 3D integration joined the SPIRAL 2 team in 2009.

The first difficulty was to define whole large reservations (floor or wall opening >1 m^2) for the infrastructure and process distributions in the concrete during the preliminary design phase. This request was due to obtain the authorization to build the facility taking into account the earthquake holding and the depth of the wall for the biological constraints.

The distribution principle was confirmed taking into account the position of electrical cabinets, the cable trays, fluid and RF distributions. The integration of all equipments (processes and infrastructure) was finally

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THE PROJECT SPES AT LEGNARO NATIONAL LABORATORIES

M. Comunian, A. Pisent, A. Palmieri, L. Ferrari INFN-LNL, Legnaro, Italy
L. Bellan, INFN-LNL, Legnaro, Italy. Department of Physics and Astronomy, University of Padova, Padova, Italy.
A. D. Russo, INFN-LNS, Catania, Italy
B. Chalykh, ITEP, Moscow, Russia

Abstract

At LNL INFN is under construction a Rare Isotope Facility (SPES) based on a 35-70 MeV proton cyclotron, able to deliver two beams with a total current up to 0.5 mA, an ISOL fission target station and an existing ALPI superconducting accelerator as a post accelerator (up to 10 MeV/u for A/q=7). In this paper, some highlights are presented: the isotope separation part (low, medium and high-resolution classes), some highlights of the mechanical and RF aspects of the RFQ and the end to end simulation (from the charge breeder to the end of ALPI). High selectivity and high transmission for a beam of a very low intensity, plus the specific challenges related to the use of ALPI (with a reduced longitudinal acceptance) and related to the specific lay out led to specific and common problems which have been solved during the design stage.

INTRODUCTION

SPES, acronym of Selective Production of Exotic Species, is a CW radioactive ion beam facility under construction at LNL INFN in Italy. It will produce and accelerate neutron-rich radioactive ions, in order to perform nuclear physics experiments, which will require beams above Coulomb barrier.

The main functional steps of the facility are shown in Fig.1: the primary beam delivered by the cyclotron, the beam from the fission target (as an example, up to 10^{13} particle/s of ^{132}Sn), the beam cooler, the separators, the charge breeder and the accelerator (the existing ALPI with a new RFQ injector). The use of the continuous beam from the +1 source, which can use different configuration types LIS, PIS, SIS, maximizes the RNB efficiency but need a CW post accelerator (RFQ and ALPI). The beam is prepared for the post-accelerator stage with a charge breeder device (an ECR that woks in continuous). The energy on the transfer lines are determined by the chosen RFQ input energy (5.7 keV/u); for this reason, all the devices where the beam is approximately stopped (production target, charge breeder and RFQ cooler) lay at a voltage proportional to the ratio A/q. The charge state range (3.5<A/q<7) is bounded by the RFQ field level for the upper limit and by the minimum voltage on q=1 transport line.

METHOD FOR SIMULATIONS

The main software used for the simulations is TraceWin [1] a 3D multiparticle tracker, capable of field map usage. In such a way, the quarter-wave cavities of the linac ALPI were simulated via field-maps in order to take into account all nonlinear order effects. Due to that, the TraceWin code is capable to set all beam line for the runs of the LNL installed accelerators [2].

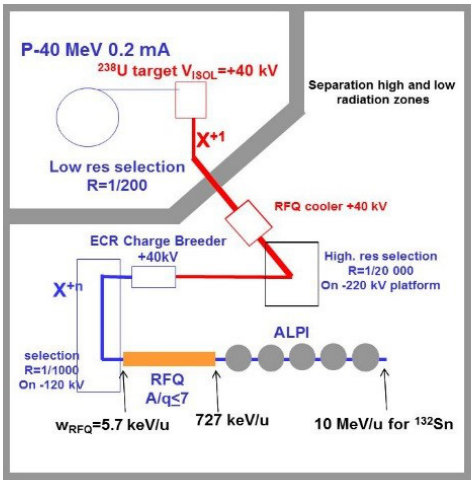

Figure 1: functional scheme of the SPES facility. There are two main areas: the 1+ line and the n+ line, where 1+ and n+ indicates the beam charge state.

THE SEPARATION STAGES

The general layout of the SPES facility is presented in Fig. 2.

The reference beam for the beam dynamics simulations is chosen to be the ^{132}Sn, extracted at 40 kV at the end of the target extraction system. It has been chosen a q=19 after the charge breeder i.e. A/q= 6.9, in such a way to test the maximum required electromagnetic fields of the line elements of the facility.

There are three normalized rms emittance regimes: after the target, it is chosen to be $\varepsilon_{n,rms}$=0.007 mm mrad, with an equivalent geometric emittance at 99% of $\varepsilon_{geo,99\%}$= 80.18 mm mrad. Then, the beam cooler prepares the beam to the HRMS stage, reducing the emittance down by a factor 5. After the CB, the emittance for the BD calculation is assumed to be $\varepsilon_{n,rms}$=0.1 mm mrad. As far as the longitudinal phase space is concerned, a uniform distribution between ±20 eV (reduced to ±1 eV

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THE SPES RIB PRODUCTION COMPLEX

A. Andrighetto, M. Ballan, E. Boratto, F. Borgna, S. Corradetti, M. Manzolaro, A. Monetti,
A. Mozzi, D. Scarpa, R. Silingardi, M. Rossignoli, G. Vivian, G. Bisoffi and G. Prete,
INFN, Laboratori di Legnaro, Italy
M. Guerzoni, A. Margotti, INFN Sezione di Bologna, Bologna, Italy
R. Oboe, Dipartimento di Tecnica e Gestione dei Sistemi Industriali dell'Università di Padova,
Vicenza, Italy
G. Meneghetti, Dipartimento di Ingegneria Industriale dell'Università di Padova, Padova, Italy
M. Ferrari, A. Zenoni, Dipartimento di Ingegneria Meccanica e Industriale, Università degli Studi di
Brescia, Italy

Abstract

SPES [1] is a second-generation ISOL RIB facility [2] of the National Institute of Nuclear Physics (INFN laboratory, Legnaro, Italy) actually in construction phase. The main goal is to provide intense neutron-rich Radioactive Ion Beams directly impinging a UC_x target with a proton beam of 40 MeV and current up to 0.2 mA. The production target follows an innovative approach which consists in a target configuration able to keep high the number of fissions, up to 10^{13} per second, low power deposition and fast release of the produced isotopes. The exotic isotopes generated in the target are then ionized, mass separated and re-accelerated by the ALPI [3] superconducting LINAC at energies of 10 AMeV and higher, for masses in the region of A=130 amu, with an expected rate on the secondary target up to 10^9 particles per second In this work, we will present the recent results on the R&D activities regarding the SPES RIB production complex (see Fig.1).

THE SPES FACILITY

The radioactive ions will be produced with the ISOL technique using the proton-induced fission of uranium contained in the UC_x [4] direct target and subsequently reaccelerated using the PIAVE-ALPI accelerator complex. The Best C70 cyclotron with a maximum current of 0.8 mA rows two exit ports those will be used as a primary proton beam driver, with variable energy (30-70 MeV). The cyclotron is able to accelerate H-beam, provided by an external multi-cusp ion source, up to the energy of 70 MeV. Since the stripping process does the proton extraction, the final energy varies within 35-70 MeV. Two independent extraction channels placed at 180° one with respect to the other, provide the simultaneous delivery of two beams. In order to reach an in-target uranium fission rate of 10^{13} fission/s, a proton beam current of 200 μA (40 MeV) is necessary; the second beam, up to 500 μA and 70 MeV, will be devoted both to neutron production for material research and to research on new isotopes for medical applications. 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 (diffusion-effusion), ionized, mass separated and injected into a re-accelerator. The first mass selection is performed by a Wien Filter with 1/100 mass resolution, installed just after the first electrostatic quadrupole triplet inside the production bunker with the aim to confine the larger part of radioactivity inside the high shielded area. The transfer line toward ALPI is equipped with several beam handling systems to purify the beam. A Beam Cooler and a High Resolution Mass Separator (HRMS) with 1/20000 mass resolution will be installed inside the new building. Before the injection in the ALPI superconducting LINAC it is necessary an increase of the charge state from 1 + to n +. This is performed by means of a ECR Charge Breeder. The linear accelerator ALPI, with a range between about 0.04 and 0.2 and CW operation, represents an ideal re-accelerator for the radioactive beams.

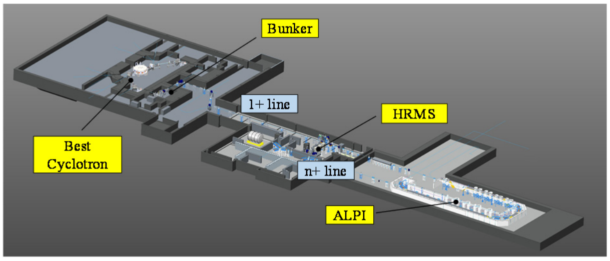

Figure 1: SPES facility. In the image, we can observe the location of cyclotron, production bunker, the path of 1+ line and n+ line toward ALPI, with the HRMS system in the middle.

THE TARGET SOURCE UNIT

In the ISOL facilities, the production target with the ion source constitutes the central component, which are capable to convert the primary beam into a radioactive ion beam. In particular, the reference version of the SPES production target is made of 7 UC_x [5] co-axial disks. These disks have diameter and thickness of 40 and 1 mm, respectively, and are impinged by a 40 MeV 0.2 mA proton beam, thus generating approximately 10^{13} fissions per second. In the SPES project, the primary proton beam is stopped in the target, dissipating its power and generating

SUPERCONDUCTING CAVITY CRYOMODULES FOR HEAVY-ION ACCELERATORS AT ARGONNE*

Z.A. Conway, A. Barcikowski, G.L. Cherry, S.M. Gerbick, B.M. Guilfoyle, C.S. Hopper,
M.J. Kedzie, M.P. Kelly, S.-h. Kim, S.W.T. MacDonald, B. Mustapha, P.N Ostroumov and
T.C. Reid, ANL, Argonne, IL 60439, USA

Abstract

Over one year ago the ATLAS Efficiency and Intensity Upgrade (EIU) was finished. A major portion of this upgrade was the installation of a new superconducting cryomodule for the acceleration of $\beta = 0.077$ heavy-ion beams. The EIU cryomodule is capable of supplying a voltage gain greater than 17.5 MV with a total cryogenic load of 45 W to 4.5 K, 12 W static and 33 W dynamic. This unit is comprised of seven 72.75 MHz quarter-wave resonators and four 9 T solenoids. This presentation will review the technology advances that resulted in exceptional operational performance of the EIU cryomodule and the ongoing development work for a new eight-cavity beta = 0.11 half-wave cryomodule.

INTRODUCTION

Low-beta ($\beta = v/c < 0.5$) cryomodules occupy a significant portion of the length of proton/heavy ion accelerators. Two recent examples of this are: (1) The proposed 800 MeV booster linac for the Fermilab Proton Improvement Project-II (PIP-II) with low-beta cryomodules occupying 30% of its length which house 59 of the 116 SC cavities [1]. (2) The Michigan State University 200 MeV/u Facility for Rare Isotope Beams (FRIB) ~300 m driver linac where 100% of the cryomodules house low-beta co-axially loaded SC cavities [2]. The accelerator real-estate length occupied by the low-β cryomodules is a strong incentive to make them efficient and high performance.

At Argonne we installed a heavy-ion cryomodule capable of achieving high accelerating voltages with small cryogenic loads which has been in operation for over a year [3]. This cryomodule houses 7 72.75 MHz quarter-wave resonators (QWRs) optimized for the acceleration of beta = 0.077 ions and 4 9 T solenoids. In this paper we first discuss the measured thermal loads. This is followed by a comparison of the results to the previous split-ring cryomodule performance. Finally, a few concluding remarks are made.

The new QWR cryomodule was first cooled to 4.5 K in December 2013 and has been in full-time use supporting ATLAS operations since March 2014. This has given us ample time to characterize the cryomodule performance and the results presented here represent the highest measured thermal-load; e.g., with all cavities operating at 2.5 MV.

QWR CRYOMODULE

Cryomodule cold-mass hanging from the lid is shown in Figure 1. The EIU cryomodule is a modified version of our previous box-type cryomodule which has been in operation since 2009 [4]. Argonne box cryomodules implement current state-of-the-art techniques developed for electron accelerators such as separate cavity and insulating vacuum systems, surface processing and clean handling to achieve and preserve record single-cavity test performance [3, 5], and a design which enables the clean assembly to be complete and hermetically sealed prior to installing the “dirty” subsystems of the cryomodule. The cryomodule structure has been described in great detail in [6].

The cryomodule 4.5 K cryogenic system is gravity fed where each of the 7 QWR and 4 solenoids is attached to a common helium distribution manifold. All penetrations through the cryomodule 80 K thermal shield are baffled or covered such that the solid angle for room temperature surfaces viewing 4.5 K surfaces is minimal (a few square inches for the entire cryomodule) and much of the reflective path between room temperature and 4.5 K is coated with high-infrared-emissivity blackened surfaces [7]. Further reducing the 4.5 K heat load are the low-emissivity 80 K and 4.5 K surfaces which are either aluminized mylar or electropolished stainless steel. Finally, all of the connections to 4.5 K are very low-conductivity. This is accomplished by using very thin stainless steel walls (e.g., the beam-line gates valves and the helium manifold safety pressure relief) or by taking advantage of the acoustic impedance mis-match between titanium and stainless steel at low temperature to increase the contact impedance between these materials (e.g., the cold-mass hangers). The calculated 4.5 K static thermal load is 15 W where the major contributors are: 5 W from 80 K to 4.5 K radiation; 4 W from the helium manifold (with 1.5 W from the solenoid current lead feedthrough and 1 W from the safety pressure relief port); 3 W from the power couplers; and the remainder comes from several <1 W sources which are the beam-line gates valves, the cold-mass hangers, the cavity cool-down lines and the slow-tuner gas lines. We measured the 4.5 K static thermal load with two different methods: (1) The cryomodule helium system was sealed and the rate of

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#zconway@anl.gov

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STATUS AND OPERATION OF THE ATLAS SUPERCONDUCTING ACCELERATOR*

M. R. Hendricks, R.C. Pardo, A. Krupa, ANL, Argonne, IL 60439, USA

Abstract

ATLAS (the Argonne Tandem Linac Accelerator System) is a super conducting heavy ion accelerator which can accelerate nearly all stable, and some unstable, isotopes between protons and uranium with a charge to mass range of 1/1 to 1/7. The maximum energy ranges of these accelerated ions are 7-17 MeV per nucleon with intensities ranging from a few thousand ions/second to microampere currents. On average ATLAS delivers a different ion species and energy each week to one of six target areas. ATLAS currently operates 24 hours a day, 7 days per week, and at least 40 weeks per year. Topics discussed will be how we handle day to day operation of the facility including start up, reusing old accelerator configurations for new experiments (scaling), tuning for in-flight produced radioactive beams, troubleshooting problems, and maintenance.

THE ATLAS FACILITY

ATLAS is the worlds' first superconducting heavy ion accelerator [1]. From its origins in 1978 until now it has consistently pushed new boundaries for stable low energy ion beam production. Located at Argonne National Laboratory outside of Chicago, Illinois in the United States, ATLAS has been delivering beams consisting of stable isotopes between protons through uranium for 37 years. The facility (Fig. 1) has two ion sources, an ECR source for multipurpose use and a charge breeding source coupled to the CARIBU radioactive ion source [2]. Once ions are produced they are accelerated through a maximum of 50 superconducting RF resonators which can give beam energies of 10-20 MeV/A depending on the atomic mass of the ion. Typical beam currents of 5-500 electrical nanoamps to target are common. However, the facility has demonstrated 35 electrical micoamps through the first linear accelerating section. While the facility can accelerate ions in a mass range between protons and uranium, in 2014 the facility accelerated 29 unique ions species. Of those 29 species, 5 species delivered to target were radioactive ion beams (RIB). Two of the 5 species were from CARIBU, and 3 were produced in-flight from accelerated stable beam.

Staffing and Operations

The facility operates 24 hours a day, 7 days a week. Relying on a total staff of 21 full time employees, divided into the following specialities and full time employees: physicists (2), operations (8), ion source (2), control system (2), cryogenic (2), mechanical (2), and electronic (3).

New experiments are scheduled, on average, once a week and involve reconfiguring all elements of the accelerator. Two methods exist for this reconfiguration, either using an old saved configuration from a previous experiment, or by establishing a new configuration. The largest advantage to using an old saved configured is the amount of time saved versus establishing a new accelerator configuration. Even though a new configuration takes more time to create, it typically achieves the best beam quality. Depending on requirements for different experiments, it may take 8-24 hours to establish the accelerator and be delivering the requested ion species, energy, and intensity to target.

Accelerator configurations are saved via an offline computer. These saved configurations create a library of configurations which can be leveraged in future experiments. These configurations are scaled when applicable to future experiments. Resonators are scaled by the mass to charge ratio, but limited to approximately ±15% of the saved configuration's mass to charge ratio. This limit is driven by the lack of linearity when setting resonator phase and amplitude beyond this percentage. Magnetic devices are scaled based on the magnetic rigidity. The ability to scale accelerator configurations is critical for setup and delivering CARIBU beams, as well as for performing accelerator mass spectroscopy.

Facility Upgrades

The accelerator has undergone several improvements in the past 6 years, which have greatly benefited its operation and performance. In 2009 the last cryostat of the accelerator containing 1978 era RF resonators was replaced with a new cryostat containing, at that time, state of the art quarter wave resonators (QWR) [3]. These QWR had more than twice the voltage potential, a world record at the time, than the previous resonators. This cryostat had additional improvements as well, such as separating the cavity and cryostat vacuum spaces. Separating the vacuum spaces is motivated by the desire to keep the QWR RF surfaces as clean as possible. This cleanliness is import to maintaining cavity performance and is also a challenge to preserve. Since introduction there has been no degradation of quality or potential gradients for the QWR.

In 2011 a room temperature radio frequency quadrouple (RFQ) [4] was installed at the beginning of the accelerator. Since an RFQ maintains beam emittance, beam transmission through the first accelerating section, the PII Linac, improved to over 80%, instead of 60%, as was achievable under the previous configuration.

The most recent upgrade to the facility was a reconfiguration of the BOOSTER linac, including the

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INTEGRATING THE TRACK BEAM SIMULATION CODE TO IMPROVE ATLAS OPERATIONS*

C.A. Dickerson#, B. Mustapha, C.E. Peters, ANL, Argonne, IL 60439, USA

Abstract

At the Argonne Tandem Linear Accelerator System (ATLAS) we are integrating TRACK, three dimensional particle tracking software that numerically integrates the equations of motion, into the accelerator control system. ATLAS delivers a variety of ions (1 – 238 AMU) at various energies (1 – 15 MeV/u) to multiple targets. By comparing simulated and observed performance, model driven operations will improve the understanding of the facility, reduce tune times, and improve the beam quality for these diverse operating conditions. This paper will describe the work to interface TRACK with the real-time accelerator control system, and the results of simulations used to characterize and configure the accelerator.

INTRODUCTION

Accelerator operations at ATLAS need to be flexible and versatile to accommodate the variety of operating configurations. ATLAS operates two sources to six target lines, as shown in Fig. 1. Experiments are changed 1-2 times per week. Ion species range from protons to ^{238}U, and energies from 0.5 to >15 MeV/u. In addition to stable beam delivery, radioactive ion beams (RIB) can be produced via the in-flight method or by reaccelerating fission fragments from the CARIBU [1] source. RIB delivery poses a particularly difficult challenge since the RIB intensities are typically much too low <10^6 pps to monitor using conventional Faraday cups and wire scanners. For these cases the accelerator is first configured for a pilot beam of sufficient intensity then scaled to match the rigidity of RIB. While a compact particle detector is being developed to aid the tuning of low intensity beams at ATLAS [2], these situations could benefit particularly from component settings accurately predicted using simulation software.

To improve the efficiency and reliability of ATLAS operations, the beam tracking software TRACK [3] is being interfaced with the ATLAS control system. The goals of this effort are to identify regions of significant beam loss and areas of distortion which then lead to significant loss, and to reduce the setup time for accelerator configuration and optimization. Besides displaying beam characteristics for real time configurations, the simulations will be able to predict component fields for previously unencountered situations and configurations – when new equipment requires a reconfiguration, or during in-flight radioactive ion beam production when the 6D beam distribution changes dramatically at the production target. The graphics outputs of the simulations, which show the evolution of the beam through the accelerator (Fig. 2), will be a great training aid for operations staff and experimenters, and finally a more accurate understanding and model of the machine will evolve as the differences between the expected and observed accelerator performance are investigated.

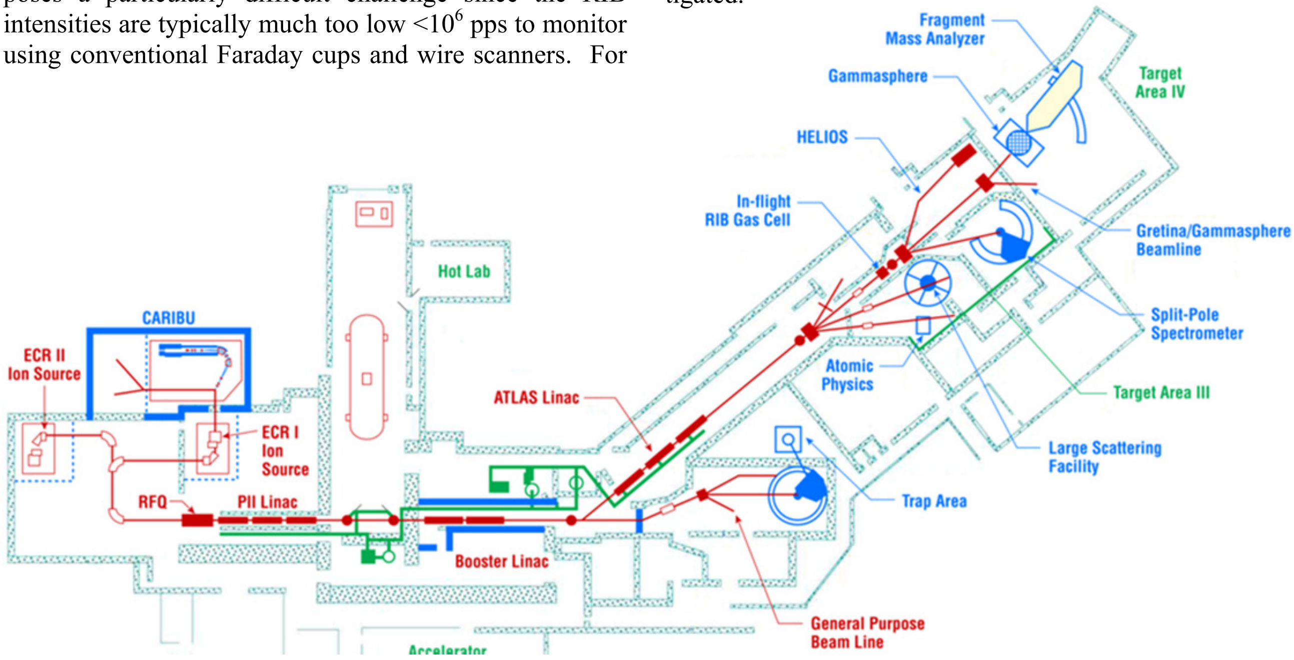

Figure 1: The ATLAS accelerator layout.

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#cdickerson@anl.gov

THE ATLAS INTENSITY UPGRADE: PROJECT OVERVIEW AND ONLINE OPERATING EXPERIENCE*

R.C. Pardo, A. Barcikowski, Z. Conway, C. Dickerson, M. Hendricks, M. P. Kelly,
S.H. Kim, Y. Luo, S. MacDonald, B. Mustapha, P. Ostroumov, C. Peters,
M. Power, R. Scott, S. Sharamentov, R. Vondrasek, G. Zinkann
Physics Division, Argonne National Laboratory, IL 60439 USA

Abstract

ATLAS, the world's first accelerator to use RF superconductivity for ion acceleration, has undergone a major facility upgrade with the goals of significantly increased stable-beam current for experiments and improved transmission for all beams. The dominant components of the upgrade are a) new CW-RFQ to replace the first three low-β resonators, b) a new cryostat of seven β=0.077 quarter-wave resonators demonstrating world-record accelerating fields, c) an improved cryogenics system, and d) the retirement of the original tandem injector. This latest upgrade followed closely on the earlier development of a cryostat of β=0.14 quarter-wave resonators. The reconfigured ATLAS system has been in operation for over one year and its performance after the upgrade will be presented.

INTRODUCTION

ATLAS (the Argonne Tandem Linac Accelerator System) is the world's first superconducting accelerator for ions. ATLAS began as a proof-of-principle project in the early 1970s to demonstrate that a superconducting resonator's field amplitude and phase could be controlled with sufficient precision to enable the acceleration of ions [1]. In order to continue to meet current requirements of the experimental program, ATLAS has been continuously upgraded to provide the tools necessary to remain at the forefront of nuclear science.

A key component in ATLAS's continuing success has been the constant improvements to the facility including the evolution of best practices in constructing and operating superconducting resonators as well as new techniques for ECR ion source operation. Those developments are seen in the different classes of resonators that have been developed at Argonne and the new techniques in superconducting RF (SRF) technology that have been applied and the world best performance of the CARIBU ECR charge breeder ion source. From the split-ring resonator which was capable of approximately 3 MV/m accelerating field, to the quarter-wave resonators used in the Positive Ion Injector section of ATLAS installed in the early 1990s, and now to the fully helium immersed; pure niobium quarter-wave resonators used in an energy upgrade of the facility in 2009 as well as the most recent new upgrade to the center (Booster) section of ATLAS in 2014, one sees a continuing progression of state-of-the-art SRF technology now culminating in routine accelerating fields of up 8 MV/m.

This paper describes the overall facility operating performance and goals achieved in three major improvement projects going back to 2009. The goals of these projects are to improve the linac performance by increasing the maximum available beam current and improving the overall beam transmission and efficiency in order to increase beam currents for radioactive beams and high current stable beam operations.

PROJECTS OVERVIEW

In the last 6 years, the ATLAS accelerator has undergone a number of improvements that are aimed at addressing the current and future needs of the nuclear science community. These changes to the ATLAS accelerator have provided significant performance improvements in both accelerating fields and beam transmission. Thus four major accelerator improvement activities have been implemented at ATLAS in the past few years:

1. A new cryostat of seven quarter-wave (β=0.14) resonators has been installed as the last ATLAS cryostat restoring the maximum beam energy to approximately 21 MeV/u for the lightest ions and approximately 10 MeV/u for unstripped ^{238}U.
2. A new, room-temperature CW radio frequency quadrupole (RFQ) linac has been installed as the first accelerating resonator in the linac. It replaces three of the original, very low-velocity, superconducting resonators of the Positive Ion Injector (PII) Linac. This project has improved the overall bunching efficiency so that approximately 80% of the DC source current can be captured into a high-quality beam for acceleration through ATLAS.
3. A second new cryostat of seven quarter-wave (β=0.077) resonators has been constructed to replace three cryostats of split-ring resonators in the middle section (booster) of the ATLAS linac. These resonators are achieving world-record accelerating field performance for low-beta resonators, and reducing the total resonator count in the linac (from 64 to 51) while maintaining the total accelerating voltage. The center portion of the original ATLAS cryogenic system has been completely rebuilt, the beam optics in the center section of the ATLAS accelerator was redesigned and improved, and new shielding was installed to accommodate the higher intensity stable beams that are now available.

The ATLAS facility floor plan and identification of the location of these projects is shown in Figure 1.

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THE ISAC-II LINAC PERFORMANCE*

M. Marchetto, S. Kiy, R.E. Laxdal, Y. Ma, O. Shelbaya, Z. Yao, V. Zvyagintsev
TRIUMF, Vancouver, Canada

Abstract

The ISAC-II superconducting linac is operating for almost a decade. The linac first installation includes twenty cavities housed in five cryomodules. The Phase II linac upgrade consisted of the addition of twenty cavities housed in three cryomodules. The upgrade brings the linac to a nominal 40 MV of effective accelerating gradient according to the design specification. Moreover the upgrade was the first step to qualify a Canadian vendor (PAVAC) for the production of bulk niobium superconducting cavities. Each cryomodule includes bulk niobium quarter wave resonators and a 9 T superconducting solenoid for transverse focusing. The linac features a single vacuum space. Over the years the linac has experienced vacuum incidents and high power rf cable failures in vacuum that were addressed during maintenance. In a recent maintenance program cavities from a single cryomodule were removed and chemically etched to improve performance. Future cavity treatments are in the plan but they are restricted by the priority of the scientific program. The author will present the status of the linac performance and future development plans. Reliability and availability of the linac will be discussed, metrics that will be come even more important with the advent of ARIEL.

INTRODUCTION

The Isotope Separation and ACceleation (ISAC) facility at TRIUMF produces radioactive ion beams (RIB) (see Fig. 1).

The RIBs are produced using the isotope separation on line (ISOL) method [1] where an accelerator, the driver, produces light projectiles, the primary beam, that impinge on 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. 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 produced radioactive ions are magnetically separated and sent to an experimental station. ISAC counts fifteen experimental stations distributed in three experimental areas characterized by different energy ranges: low, medium and high. In the high energy experimental area the beam is boosted by the ISAC-II superconducting linac.

Presently only a single RIB is available and can be sent to one of the fifteen stations at the time. The future ARIEL facility is going to increment the RIB availability to three ion beams that can be sent simultaneously to three different experimental stations.

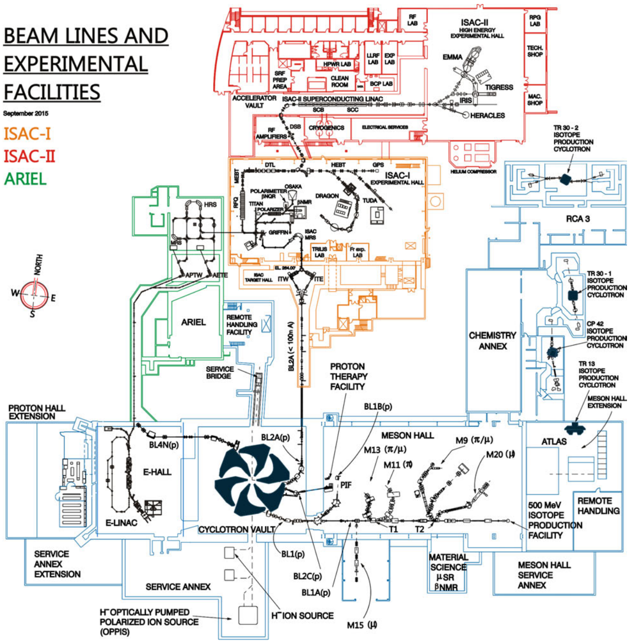

Figure 1: The TRIUMF site with the ISAC-I (red), ISAC-II (orange) and ARIEL (green) facilities.

ISAC OVERVIEW

ISAC uses the TRIUMF cyclotron as driver to accelerate protons at 500 MeV up to 100 μA of current. This is presently the highest power (up to 50 kW) driver beam for an ISOL facility. It allows to produce the most intense RIB of certain species like ^{11}Li for which yield of $2.2 \cdot 10^4$ s^{-1} has been achieved.

The overview of the ISAC facility is represented in Fig. 2 where the three experimental areas are highlighted.

Driver

The TRIUMF cyclotron accelerates H$^-$ ions up to an intensity of 300 μA to a maximum energy of 500 MeV. The H$^-$ are then stripped and protons are presently extracted in three different beam lines at different energies, one of which is dedicated for the ISAC radioactive beam production.

The simultaneous extraction of multiple beams with stable delivery is challenging. Nevertheless a 90% availability of the proton beam for the ISAC facility is regularly achieved.

The capability of multiple extractions can be expanded by refurbishing a fourth existing extraction beam line giving two simultaneous proton beams for RIB production [2] as represented in Fig. 3. This possibility together with an upgrade of the cyclotron [3] is key to the future ARIEL facility.

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PROGRESS ON SUPERCONDUCTING LINAC FOR THE RAON HEAVY ION ACCELERATOR

H. J. Kim* reprenting the RAON, IBS, Daejeon, Korea

Abstract

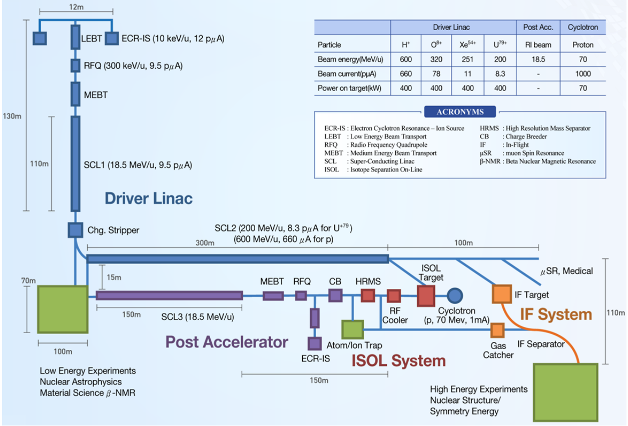
The RISP (Rare Isotope Science Project) has been proposed as a multi-purpose accelerator facility for providing beams of exotic rare isotopes of various energies. It can deliver ions from proton to uranium. Proton and uranium ions are accelerated upto 600 MeV and 200 MeV/u respectively. The facility consists of three superconducting linacs of which superconducting cavities are independently phased. Requirement of the linac design is especially high for acceleration of multiple charge beams. In this paper, we present the RISP linac design, the prototyping of superconducting cavity and cryomodule.

INTRODUCTION

The RISP accelerator has been planned to study heavy ions in nuclear, material and medical science at the Institute for Basic Science (IBS). It can deliver ions from protons to uranium atoms with a final beam energy, for example, 200 MeV/u for uranium and 600 MeV for protons, and with a beam current range from 8.3 pμA (uranium) to 660 pμA (protons) [1, 2]. The facility consists of three superconducting linacs of which superconducting cavities are independently phased and operating at three different frequencies, namely, 81.25, 162.5 and 325 MHz.

SUPERCONDUCTING LINAC

Lattice Design



	Driver Linac				Post Acc.	Cyclotron
Particle	H^+	O^{8+}	Xe^{54+}	U^{79+}	RI beam	Proton
Beam energy(MeV/u)	600	320	251	200	18.5	70
Beam current(pμA)	660	78	11	8.3	-	1000
Power on target(kW)	400	400	400	400	-	70

ACRONYMS

ECR-IS : Electron Cyclotron Resonance – Ion Source
LEBT : Low Energy Beam Transport
RFQ : Radio Frequency Quadrupole
MEBT : Medium Energy Beam Transport
SCL : Super-Conducting Linac
ISOL : Isotope Separation On-Line
HRMS : High Resolution Mass Separator
CB : Charge Breeder
IF : In-Flight
μSR : muon Spin Resonance
β-NMR : Beta Nuclear Magnetic Resonance

Figure 1: Layout of the RISP accelerator.

The configuration of the accelerator facility within the RISP is shown in Fig. 1. An injector system accelerates a heavy ion beam to 500 keV/u and creates the desired bunch structure for injection into the superconducting linac. The injector system comprises an electron cyclotron resonance ion source, a low-energy beam transport, a radio-frequency quadrupole, and a medium-energy beam transport. The superconducting driver linac accelerates the beam to 200 MeV/u. The driver linac is divided into three different sections, as shown in Fig. 2: a low-energy superconducting linac (SCL1), a charge stripper section (CSS) and a high-energy superconducting linac (SCL2). The SCL1 accelerates the beam to 18.5 MeV/u. The SCL1 uses two different families of superconducting resonators, i.e., a quarter wave resonator (QWR) and a half wave resonator (HWR). The SCL11 consists of 22 QWRs whose geometrical β is 0.047 and 22 qudruopole doublets. The resonance frequency of the QWR is 81.25 MHz. The cryomodule of the SCL11 hosts one superconducting cavity. The SCL12 consists of 102 HWRs whose geometrical β is 0.12 and 62 quadrupole doublets. The resonance frequency of the HWR is 162.5 MHz. This segment has two families of cryomodules: one type of cryomodule hosts two superconducting cavities, and the other hosts four superconducting cavities. The CSS accepts beams at 18.5 MeV/u. The charge stripper strips electrons from the heavy-ion beams to enhance the acceleration efficiency in the high-energy linac section. The charge stripping section consists of normal conducting quadrupoles and room-temperature 45-degree bending magnets. The quadrupole magnets provide adequate transverse focusing and beam matching to the SCL2, and the bending magnet provides momentum dispersion for charge selection. The SCL2 accepts a beam at 18.5 MeV/u and accelerates it to 200 MeV/u. The SCL2 uses two types of single spoke resonators, i.e., SSR1 and SSR2. The SCL2 consists of the SCL21 and the SCL22, each with geometric β 0.30, resonance-frequency 325-MHz SSR and a geometric β 0.51, resonance-frequency 325-MHz SSR. The single-spoke-resonator type is chosen mainly because it can have a larger bore radius compared with the half-wave-resonator type, which is very important for reducing the uncontrolled beam loss in the high-energy linac section. The numbers of cavities in the SCL21 and the SCL22 is 69 and 138 respectively. The cryomodules of the SCL21 and SCL22 host 3 and 6 cavities, respectively. The SCL2 provides a beam into the in-flight fragmentation (IF) system via a high-energy beam transport (HEBT).

The post accelerator (SCL3) is designed to accelerate the rare isotopes produced in the ISOL (Isotope Separation On-Line) system. The SCL3 is, in principle, a duplicate of the driver linac up to low energy linear accelerator. The accelerated rare isotope beams are reaccelerated in the SCL2. Hence, the RISP accelerator provides a large number of rare isotopes with high intensity and with various beam energies.

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* hjkim@ibs.re.kr

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STATUS AND PERSPECTIVES OF THE CW UPGRADE OF THE UNILAC HLI AT GSI

P. Gerhard*, L. Groening, W. Hartmann, S. Mickat, K. Tinschert, H. Vormann, K.-O. Voss
GSI, Darmstadt, Germany

Abstract

The High Charge State Injector (HochLadungsInjektor) HLI was commissioned in 1991 [1]. It was the first linac comprising of a Radio Frequency Quadrupole RFQ and an Interdigital H-Type cavity IH. For more than twenty years, it successfully provided essential heavy ion beams with high duty cycle for several lighthouse experiments and developments at GSI. Among them are the Super Heavy Element Research SHE, namely the experiments SHIP, TASCA, SHIPTRAP, and the heavy ion cancer therapy. Three out of the six transuranium elements found at GSI were discovered with ion beams from the HLI [2]. The ever increasing demand for beam intensity was met by the proposal of a SuperConducting Continuous Wave sc cw-Linac. As the HLI will serve as an injector for this new accelerator, a cw upgrade for the HLI was developed.

THE ORIGINAL HLI

The High Charge State Injector (see Fig. 1, and Table 1) is equipped with a Compacte A Plusieurs Résonances Ionisantes Cyclotron Electroniques (CAPRICE) ion source and a high resolution 135° spectrometer; the source was recently upgraded to slightly higher magnetic fields of 1.4 T.

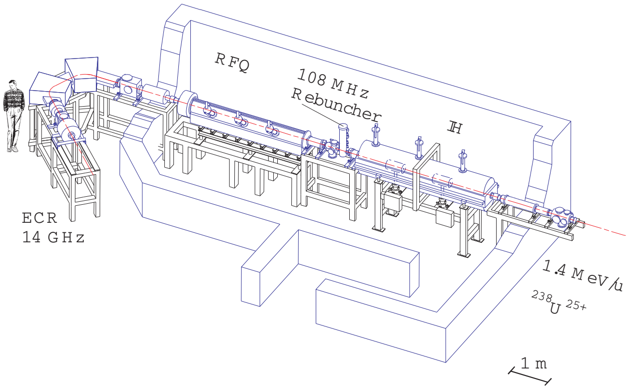

Figure 1: Overview of the HLI.

Behind the spectrometer the beam is matched to a 4-rod RFQ, which accelerates the ions from 2.5 to 300 keV/u. This is followed by a MEBT, which includes a magnetic quadrupole triplet and a doublet as well as a $\lambda/4$-buncher for transversal and longitudinal matching of the beam to the following IH cavity. The IH accelerates the beam to the final energy of 1.4 MeV/u. The beam is then transported to the UNIversal Linear ACcelerator UNILAC through a 180° bend (not shown in Fig. 1). A second $\lambda/4$-buncher provides for proper matching to the first Alvarez tank.

Table 1: Basic Parameters of the HLI

Property	Value
Mass resolution /(Δm/m)	$3 \cdot 10^{-3}$
Beam intensity /pnA	$\leq$1
A/z 50% d.c. (cw)	$\leq$8.5 (6.0)
Injection energy /(keV/u)	2.5
Extraction energy /(MeV/u)	1.4
RF Frequency /MHz	108.408
Design emittance /(π·mm·mrad)	1.5 (norm.)
Total length /m	10.8

The HLI was originally designed for a duty cycle (dc) of 50% and a pulse repetition rate of 50 Hz. Most of the magnets are operated at constant current, as it was not planned accelerating different ions in parallel. Thus, the HLI can be operated with cw beam as far as the magnets are concerned, but most other devices, like beam diagnostics, and the control system are designed for pulsed operation only.

The ECR ion source is ideal for stable, long lasting beams. Due to its low material consumption, rare isotope beams can be produced very efficiently. This has made the HLI the prominent injector for medium heavy ions requested by experiments at the Coulomb barrier up to now.

CURRENT STATUS AND CW UPGRADE

With no major changes, the HLI was in routine operation and successfully providing beams for coulomb barrier experiments and injection into the heavy ion synchrotron SIS for nearly 20 years. Nevertheless, the demand for higher (average) beam intensities grew with time, and two strategies were proposed to deal with this demand: An upgrade of the source to directly increase the beam current, and an upgrade of the whole accelerator to move from pulsed to cw operation, thereby raising the duty cycle and the average beam intensity by another factor of four.

MS-ECRIS

About ten years ago, an international project was started to develop a high performance ion source using the concept of electron cyclotron resonance. This source was called MS-ECRIS [3]. It was intended to install it as a second source in front of a new LEBT branch at the HLI. Key feature of the source was a strong confinement by higher magnetic fields, produced by sc magnet coils. The aim was to reach higher charge states and at the same time deliver more ions to the accelerator. In 2007, the magnet system was tested for the first time, and quenches occurred when both coils were

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[*] p.gerhard@gsi.de

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CHARGE BREEDING EXPERIENCES WITH ECR AND EBIS FOR CARIBU

Richard Vondrasek[#], A. Barcikowski, C.A. Dickerson, P.N. Ostroumov,
R. Pardo, A. Perry, G. Savard, R. Scott, S.I. Sharamentov
Physics Division, Argonne National Laboratory, Lemont, IL 60439, USA

Abstract

The efficient and rapid production of a high-quality, pure beam of highly charged ions is at the heart of any radioactive ion beam facility. An ECR charge breeder, as part of the Californium Rare Ion Breeder Upgrade (CARIBU) program at Argonne National Laboratory, was developed to fulfil this role. The charge breeding efficiency and high charge state production of the source are at the forefront of ECR charge breeders, but its overall performance as part of the accelerator system is limited by a pervasive stable ion background and relatively long breeding times. Steps have been taken to reduce the level of background contamination but have met with limited success. As such, an EBIS charge breeder has been developed and is now running in an off-line configuration. It has already demonstrated good breeding efficiencies, shorter residence times, and reduced background, and it is scheduled to replace the ECR charge breeder in late 2015. The resultant change in duty cycle and time structure necessitates changes to the overall facility operation. The experiences with these breeders – their strengths and their weaknesses - will be discussed.

CARIBU FACILITY

The CAlifornium Rare Isotope Breeder Upgrade (CARIBU)[1] provides radioactive beams to the Argonne Tandem Linac Accelerator System (ATLAS). The fission fragments are produced not by an ISOL facility but instead by a 1.3 Ci ^{252}Cf fission source. The Cf source is located inside a large-volume RF/DC helium gas catcher [2] which thermalizes the fission products and extracts them rapidly to form a low-energy beam of 1+ or 2+ ions from which the isotopes of interest are selected via a high-resolution magnetic separator. The beam is transported to either a low-energy area which includes a Penning trap and tape station or to an ECR source where the beam is charge bred for subsequent acceleration in the ATLAS linac.

The ECR breeder has been delivering charge bred radioactive species to the ATLAS experimental program for several years and in the last year has provided more than 81 days of beam. While its charge breeding efficiency and high charge state production have been at the forefront of ECR charge breeding, its overall performance as a part of the accelerator system has been hindered by the pervasive background present in ECR ion sources.

As such, an EBIS charge breeder is replacing the ECR in late 2015. The EBIS has a lower level of beam contamination than an ECR and exhibits improved charge breeding efficiency and faster breeding times [3, 4].

ECR CHARGE BREEDER

The ANL ECR breeder [5] is a room temperature source, and the plasma is excited with two RF frequencies – a 10.44 GHz klystron and an 11-13 GHz traveling wave tube amplifier (TWTA). It has an open hexapole structure providing good pumping to the plasma chamber region resulting in a base plasma chamber pressure of 2x10^{-8} mbar. The open structure also allows the RF and support gas to be introduced radially into the plasma chamber. This scheme eliminates the need for cut-outs in the field shaping iron to accept the RF waveguides and results in a highly symmetric axial magnetic field where the ions enter the plasma. This differs from other ECR breeders presently in existence which are closed hexapole devices with axial RF injection. The 1+ ions are introduced into the plasma through a grounded high-purity aluminum tube mounted on a linear motion stage. The stage has a 30 mm range of travel, and thus the deceleration point of the 1+ ions can be adjusted on-line without disturbing the source conditions. The source is designed to operate at a 50 kV potential although it typically operates at 36 kV. The source has produced beams primarily in the mid-mass regime but has also exhibited good performance for low mass beams such as sodium and potassium (see Table 1).

Table 1: Summary of Charge Breeding Performance for Both Stable Ions and CARIBU Provided Radioactive Ions

Ion	Half-life (s)	Efficiency (%)	A/Q
$^{23}\text{Na}^{7+}$		10.1	3.29
$^{39}\text{K}^{10+}$		17.9	3.90
$^{84}\text{Kr}^{17+}$		15.6	4.94
$^{85}\text{Rb}^{19+}$		13.7	4.47
$^{110}\text{Ru}^{22+}$	11.6	11.8	5.00
$^{135}\text{Te}^{26+}$	19.0	5.0	5.19
$^{129}\text{Xe}^{25+}$		13.4	5.16
$^{132}\text{Xe}^{27+}$		14.1	4.89
$^{133}\text{Cs}^{26+}$		14.7	5.11
$^{133}\text{Cs}^{27+}$		13.5	4.93
$^{141}\text{Cs}^{27+}$	24.8	12.3	5.22
$^{142}\text{Cs}^{27+}$	1.69	7.3	5.26
$^{143}\text{Cs}^{27+}$	1.79	11.7	5.30
$^{143}\text{Ba}^{27+}$	14.3	14.7	5.30
$^{144}\text{Ba}^{28+}$	11.5	14.3	5.14
$^{146}\text{Ba}^{28+}$	2.22	13.3	5.21

Charge Breeder Enhancements

The performance of the ANL ECR charge breeder can be attributed to several aspects: the open hexapole which

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[#] vondrasek@anl.gov

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STATUS REPORT ON THE OPERATION OF THE RIBF RING CYCLOTRONS

K. Ozeki#, T. Dantsuka, M. Fujimaki, T. Fujinawa, N. Fukunishi, H. Hasebe, Y. Higurashi,
E. Ikezawa, H. Imao, T. Kageyama, O. Kamigaito, M. Kase, M. Kidera, M. Komiyama,
K. Kumagai, T. Maie, M. Nagase, T. Nagatomo, T. Nakagawa, M. Nakamura, J. Ohnishi,
H. Okuno, N. Sakamoto, K. Suda, A. Uchiyama, S. Watanabe, T. Watanabe, Y. Watanabe,
K. Yamada, H. Yamasawa, RIKEN Nishina Center, Wako, Japan
S. Fukuzawa, M. Hamanaka, S. Ishikawa, K. Kobayashi, R. Koyama, T. Nakamura, M. Nishida,
M. Nishimura, J. Shibata, N. Tsukiori, K. Yadomi, SHI Accelerator Service Ltd., Tokyo, Japan
Y. Kotaka, CNS, University of Tokyo, Saitama, Japan

Abstract

Operating status of four ring cyclotrons (RRC, fRC, IRC, SRC) from August 2014 to July 2015 is reported. We are engaging in the improvements and adjustments for increasing beam intensities year after year, and maintenances for the stabilization of beam supply. In these contributions, we will report the past performances of accelerated beams, statistics of operational and tuning time on corresponding period, as well as failures and copings with them.

INTRODUCTION

At RIKEN Nishina Center, the Radioactive Isotope Beam Factory (RIBF) [1] consists of four ring cyclotrons and three injectors. The four ring cyclotrons are: the RIKEN ring cyclotron (RRC) [2], which was commissioned in 1986; fixed-frequency ring cyclotron (fRC) [3], which was commissioned in 2006; intermediate stage ring cyclotron (IRC) [4]; and superconducting ring cyclotron (SRC) [5]. The three injectors are: the RIKEN heavy ion linear accelerator (RILAC) [6], RILAC2 [7], and AVF cyclotron (hereafter, AVF) [8,9]. The list of nuclei accelerated in the RIBF so far is shown in Fig. 1. Several acceleration modes are available through selection of a combination of accelerators. All ions from hydrogen to uranium can be accelerated up to 345 MeV/u (400 MeV/u for *A*/*Z*~2). There are three types of acceleration modes corresponding to each injector, which use the SRC. The beam extracted from the RRC can also be used at the experimental laboratories in the old facility. In addition, high-energy light ions recently became available at the biological irradiation laboratory in the old facility (E5B), which were accelerated using AVF, RRC, and IRC and then transported back to the old facility. Figure 2 shows the examples of energy attained at each stage in multiple-stage acceleration for each acceleration mode using SRC and IRC. The solid line shows the fixed-frequency mode, in which RILAC2 is used as the injector and all the ring cyclotrons are connected in series. The dashed line represents the variable-frequency mode, in which RILAC is used as the injector. The dotted line denotes the light-ion mode, in which AVF is used as the injector [10]. The dashed-dotted line shows a mode, which utilizes the newly installed IRC-E5 beam line. In this contribution, the status of the ring cyclotron system in the RIBF from August 2014 to July 2015 is reported.

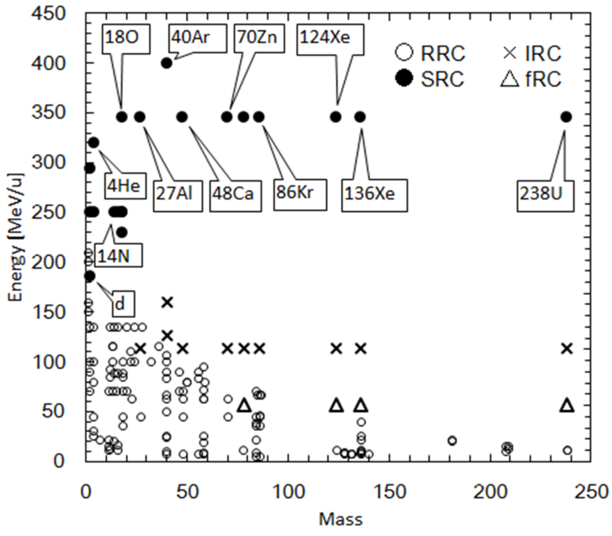

Figure 1: List of nuclei accelerated in the RIBF so far.

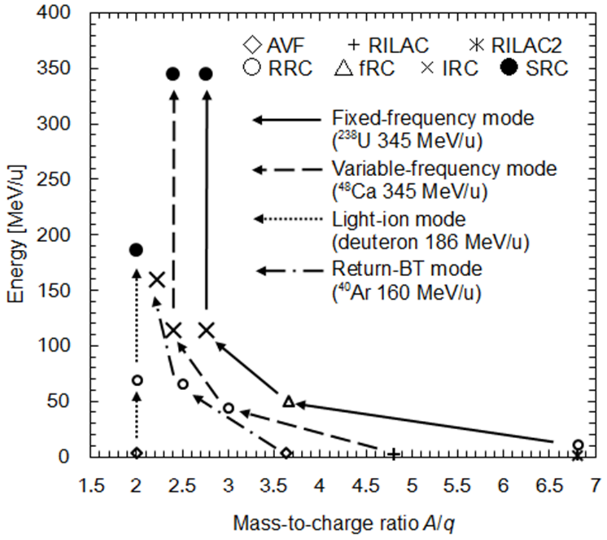

Figure 2: Transitions of energy and mass-to-charge ratio of accelerated nuclei in each acceleration mode in the RIBF.

#k_ozeki@riken.jp

ELECTRON-BEAM-DRIVEN RI SEPARATOR FOR SCRIT AT RIKEN RI BEAM FACTORY

T. Ohnishi*, S. Ichikawa, and M. Wakasugi
RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama, Japan

Abstract

Electron-beam-driven RI separator for SCRIT (ERIS) was constructed for the SCRIT (Self-Confinement RI Target) electron scattering facility at RIKEN RI Beam Factory. It is employed to produce low-energy, high-quality, and high-intensity RI beams used for the electron scattering of unstable nuclei. For RI production, ERIS uses the photofission of uranium driven by an electron beam, and the estimated production rate of fission products is 2.2×10^{11} fissions/s with 30-g uranium and a 1-kW electron beam. The RI production in ERIS was started at 2013. After several improvements of production target and ion source, the rate of ^{132}Sn was achieved to 2.6×10^{5} atoms/s with 15-g uranium and a 10-W electron beam. Further studies in ERIS are in progress to supply intense RI beams stably for the electron scattering with RI.

INTRODUCTION

Electron scattering is an unambiguous probing method to study the nuclear structure because of the well-known interaction and no internal structure of electron [1]. Thus, electron scattering has been applied to the study of stable nuclei for many years. As for short-lived unstable nuclei, it has not been applied due to the difficulty of preparing unstable nuclei target. To overcome this problem and realize electron scattering of short-lived nuclei, a novel target forming technique, named as SCRIT(Self-Confinement RI Target) [2], was proposed. SCRIT harnesses the ion trapping phenomenon in an electron storage ring. The validity and performance of SCRIT was already demonstrated [3,4]. Based on this successful achievement, the SCRIT electron scattering facility [5] was constructed at RIKEN RI Beam factory, and it has been operated from 2009.

Electron-beam-driven RI separator for SCRIT (ERIS) [6] is constructed as an online isotope separator (ISOL) system which is dedicated to produce a radioactive isotope (RI) beam for the SCRIT facility. In ERIS, the photofission of uranium driven by the electron beam is used for the RI production, because this reaction is effective for producing more neutron-rich isotopes around the tin region compared with other fission reactions [7]. This region is the first target of our project, and ^{132}Sn, especially, is an important nucleus in the study of unstable nuclei owing to its double magic number structure. After the commissioning of the beam line of ERIS, the RI production was started from 2013, and ^{132}Sn was clearly observed in the first attempt [6].

In this paper, we introduce ERIS briefly, and report the recent progress of the production target and the RI production.

EXPERIMENTAL SETUP OF ERIS

Figure 1 shows the schematic layout of ERIS. ERIS consists of a production target, a forced electron beam induced arc discharge (FEBIAD) type ion source, and a beam analyzing transport line. Produced RIs are transported to the SCRIT device installed inside the electron storage ring. Details of the components of ERIS and the result of the commissioning are described in Ref. [6].

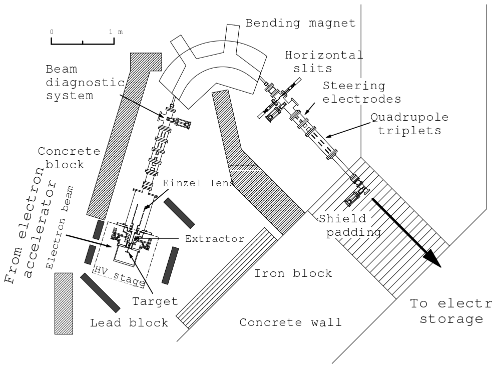

Figure 1: Schematic layout of ERIS. ERIS is surrounded with a concrete wall 2 m in thickness and local shields in the form of concrete, iron, and lead blocks are also installed.

The production target is installed inside a graphite container, which is 21 mm in inner diameter and 60 mm in inner length. This container is surrounded with a tantalum heater, and it is connected to the ion source by the transfer tube. For fast effusion and diffusion, all components are heated up to around 2000 °C. Figure 2 shows a tantalum heater and its setting.

In ERIS, the FEBIAD type ion source is used, because of its applicability to a wide range of elements and its stable operability with high ionization efficiency. The basic design of the ion source is based on CERN ISOLDE [8] and HRIBF [9] at Oak Ridge National Laboratory. Details of the ion source including the electrical connections is described in Ref [6]. This ion source is placed on a high-voltage stage (<50kV) for acceleration.

The beam transport line consists of an einzel lens, a doublet and a triplet electrostatic quadrupoles, four steering electrodes, and a 120° bending magnet with radius of 0.8 m. The diameters of the apertures of the einzel lens and the quadrupole electrodes are 120 and 40 mm, respectively. The maximum magnetic rigidity of the bending magnet is

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[*] oonishi@ribf.riken.jp

ACCELERATION SCHEME OF RADIOACTIVE ION BEAM WITH HIMAC AND ITS INJECTOR LINAC

Akira Noda#, Satoru Hojo, Ken Katagiri, Masao Nakao, Etsuo Noda, Koji Noda, Akinori Sugiura,
Kazutoshi Suzuki, Takashi Wakui , NIRS, Inage, Chiba, 263-8555, Japan
Manfred Grieser, MPI-K, 69117, Heidelberg, Germany

Abstract

At the National Institute of Sciences (NIRS), cancer therapy with the use of a carbon beam has been successfully applied since 1994 by using 'HIMAC' (Heavy Ion Medical Accelerator in Chiba). Recently the number of treated patients has been increased to nearly 1000 per year. For the purpose of real-time verification of the irradiation distribution in the patient's body during a heavy ion cancer treatment, the capability of the so-called "Open PET" with a radioactive $^{11}C^{6+}$ ion beam has been proposed[1] and projectile fragment ^{11}C ion beams, already has been tried to be applied[2], but the beam intensity was rather poor, about 10^5 pps, and a good S/N ratio had not been attained[1]. Therefore to remedy this situation, the acceleration of radioactive ions created by the "Target Fragment" scheme, where beams from the cyclotron irradiate a target, has been proposed[3]. In the present paper, in connection with recent developments[4], an acceleration scheme of secondary produced radioactive ^{11}C ion beams with HIMAC and its injector is investigated.

INTRODUCTION

Radiation cancer therapy utilizing heavy ions has increased its importance by a steady increase of the treatment numbers in addition to the fact that it is improving the "Quality of Life" of the patients. Up to now the irradiated region by heavy ion beams has been estimated with a preparatory irradiation into a water phantom and by using computer simulation. However, recent innovations of imaging technology might enable a direct detection of the irradiation area during the real therapy treatment with the use of an "OPEN PET"[1]. For such purpose, it is inevitable to provide enough ions ($>10^7$ pps) to the irradiation port of HIMAC for attaining a good S/N ratio.

Up to now, radioactive ion beams of ^{11}C, produced by projectile fragmentation of stable ^{12}C ion beams have been created[2] and transferred to the secondary beam port of HIMAC for the purpose of visualization of the beam stopping point. Its intensity, however, was rather limitted (less than 10^5 pps) and it is not strong enough for real clinical usage.

In order to attain enough intensity of a radioactive ^{11}C ion beam, a scheme utilizing target fragments, produced by high intensity proton beam irradiation with the use of the cyclotron; NIRS HM18, has been considered[3], which is a similar scheme used at ISOLDE of CERN[5] , although the energy region of the primary proton beam is much lower. Originally a N_2 gas target has been proposed using a $^{14}N(p, \alpha)^{11}C$ reaction[6]. The collection efficiency of molecules containing radioactive ^{11}C ions, however, is rather limited with the use of a N_2 gas target, because separation of the huge amount of the impurity N_2 gas is a serious problem to provide the ^{11}C molecules to the 1+ ion source under vacuum condition, which is different from radioactive drug generation case. Therefore a new scheme using a solid $NaBH_4$ target for $^{11}B(p,n)$ ^{11}C reaction is utilized where the ^{11}C gas can be ionized and efficiently collected[4].

RADIOACTIVE ISOTOPE PRODUCTION

Radionuclide Production with Cyclotrons at NIRS

At NIRS since its establishment, various knowledge and experiences have been accumulated concerning treatment and imaging with the use of radioactivity. Recently more than 200 radiopharmaceuticals have been developed and been globally utilized for diagnostic imaging. Reflecting the rapid progress of imaging and medical treatment utilizing radio-pharmaceuticals, Targeted Radionuclide Therapy (TRT) has been also investigated and basic experiments with animals have been applied using α-particle with high LET (Linear Energy Transfer) or radioisotopes with Auger electron emission. In table 1 and table 2, lists of radionuclides produced by

Table 1: Ion Beams from the NIRS930 Cyclotron and their Created Radionuclides

Beam Particle	Radionuclide
Proton	^{89}Zr
	^{11}C
	$^{62}Zn/^{62}Cu$
	^{68}Ge
	^{67}Cu
H_2^+	^{64}Cu
	^{124}I
Deuteron	^{177}Lu
Helium	^{67}Cu
	^{43}Sc
	^{47}Sc
	^{74}As
	^{155}Tb
	^{186}Re
	^{211}At
	^{28}Mg

Table 2: Ion Beams from HM-18 Cyclotron and their Created Radionuclides

Beam Particle	Radionuclide
Proton	^{11}C
	^{13}N
	^{18}F
Deuteron	^{15}O

#a_noda@nirs.go.jo

PUSHING THE INTENSITY ENVELOPE AT THE ATLAS LINAC*

B. Mustapha#, C. Dickerson, P. Ostroumov, R. Pardo, M. Hendricks, R. Scott and G. Zinkann
ANL, Argonne, IL 60439, USA

Abstract

The ATLAS linac at Argonne National Laboratory has recently been upgraded for higher beam intensity and transport efficiency. A new 60 MHz RFQ replacing the first few cavities of the Positive Ion Injector (PII) section and a new superconducting module replaced three old cryomodules of split-ring resonators in the Booster section of the linac. Following the installation of the new RFQ, we performed a high-intensity run using a $^{40}Ar^{8+}$ beam. A beam current of 7 pμA was successfully injected and accelerated in the RFQ and PII section of the linac to an energy of 1.5 MeV/u. The results of this run are presented and the limitations to reach higher currents are discussed. A second run is planned to try to push the beam current higher and farther into the Booster and ATLAS sections of the linac. Finally, a future intensity upgrade plan, motivated by the inflight production of radioactive beams using the AIRIS separator and the proposed multi-user upgrade with potential stable beam applications is presented and discussed. The ultimate goal of this upgrade plan is to reach 10 pμA or higher for most beams at the full ATLAS energy.

THE RECENT ATLAS UPGRADE AND IMPROUVEMENT IN BEAM CHARACTERISTICS

The Argonne Tandem Linear Accelerator System (ATLAS) was the first superconducting linac for ion beams in the world [1]. It has been operating and delivering ion beams for over thirty years at different capacities. Over the same period, ATLAS has undergone several upgrades [2]. The most recent is the Efficiency and Intensity upgrade [3].

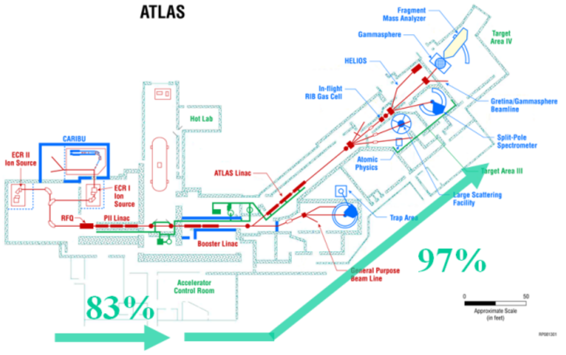

Figure 1: ATLAS layout after the recent Intensity and Efficiency Upgrade showing typical beam transmission through the different linac sections.

The Efficiency and Intensity upgrade consisted of a new RFQ [4] and a new superconducting module [5]. The RFQ replaced the first three superconducting cavities of the Positive Ion Injector (PII) to avoid deterioration of the beam quality due to fast acceleration of low energy beams. The RFQ uses the existing multi-harmonic buncher (MHB) as a pre-buncher. Two notable features of the ATLAS RFQ are trapezoidal modulations in the accelerating section and a compact output matcher to produce an axially-symmetric beam for direct beam injection into the PII which uses solenoidal focusing [6]. The new cryomodule replaced three old modules with split-ring resonators [7]. The split-ring cavities steer the beam resulting in beam loss and the subsequent quench of solenoids. The new cryomodule is made of 7 quarter-wave resonators (QWR) and 4 superconducting solenoids. The QWRs were designed and built with steering correction [8]. The new module should be able to accelerate 10 to 100 times higher intensity stable beams without significant beam loss.

Both the new RFQ and cryomodule have been successfully commissioned and are now being used for routine ATLAS operations. The improved beam quality from the RFQ, both transverse and longitudinal, has increased the transmission by 50 to 100% for all beams accelerated in ATLAS [9]. The overall transmission is now routinely over 80%, which is dictated by the MHB used to produce a small longitudinal emittance for more efficient beam transport and acceleration in ATLAS [10]. Figure 1 shows the current layout of ATLAS after the recent intensity and efficiency upgrade.

HIGH INTENSITY RUN AT ATLAS

A high-intensity run was performed at ATLAS in February 2014, just before the installation of the new cryomodule. The goal of this run was to inject and accelerate 10 pμA of a heavy-ion beam through the RFQ+PII section of ATLAS.

An ~ 120 eμA $^{40}Ar^{8+}$ beam was produced at the ECR-2 ion source. The LEBT, RFQ and PII were first tuned with low current beam using attenuators to control the beam intensity and collimating slits to control the beam emittance. A transmission of 80% or more through the RFQ+PII is essential. A lower transmission would mean a substantial beam loss that will prevent ramping up the beam current. The beam intensity was increased by gradually removing beam attenuators, opening slits and adjusting the gas in the ECR. The final results were: 72 eμA injected into the RFQ+PII section with 58 eμA transmitted and accelerated (consistent with the simulated MHB-RFQ transmission) to the full 1.5 MeV/u energy. That is a 7.2 pμA $^{40}Ar^{8+}$ beam, which is a significant

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#brahim@anl.gov

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OPTIMIZATION DESIGN OF THE RFQ TRAPEZOIDAL ELECTRODE

Li Chenxing[#], He Yuan, Wang Zhijun, Institute of Modern Physics, CAS, Lanzhou, China

Abstract

In order to reduce the length of a deuteron beam RFQ, trapezoidal modulation is used in the last 3-meter-long section. Because there is no existing tested design procedure fitting for designing this type of unconventional structure, a VBA code used for designing trapezoidal modulation RFQ electrode was developed. VBA is an effective and efficient tool for completing repetitive work. So it can be used to design repetitive analogous cells of electrode of RFQ or DTL or other periodic acceleration structures. By using this VBA code, cell length and the exit energy can be obtained accurately. The feasibility and accuracy of this method have been validated by beam dynamics simulation.

INTRODUCTION

The conventional method to design RF cavities such as RFQ or DTL can be divided into three steps [1]. First, generate the basic parameters of acceleration cells. Second, model and optimize the cavity structure. Third, evaluate the beam performance by beam dynamics simulation using the RF field generated from the RF simulation done in the second step. To achieve a reasonable solution, iterations of these three steps will be necessary. It is predictable that the repetitive work will occupy the most time of the design. The electric field in the RF cavities such as RFQ or DTL is concentrated mainly in small regions near the electrode gaps. This makes it feasible to design the local regions where the electric field concentrated independently by using 3D electrostatic codes such as CST EM Studio [2].

The secondary development based on VBA (Visual Basic for Applications) has been extensively utilized in mechanical design. The design efficiency can be improved and the design period can be shortened due to the repetitive work in the design procedure can be completed by computer code. By means of the VBA in CST, the automated design and optimization of RFQ electrode or DTL tubes using CST EM Studio can be achieved. Based on CST EM Studio, a VBA code that aims to optimization of longitudinal structure of RFQ electrodes and DTL tubes has been developed. By utilizing this code, the design of the trapezoidal modulation electrode of the last 3-m-long section of a deuteron beam RFQ has been done.

DEUTERON BEAM RFQ DESIGN

The main design parameters for the deuteron beam RFQ are listed in table 1. The RFQ will consist of five identical ~ 105 cm long segments. Figure 1 shows the full five-segment engineering model.

Table 1: The Main Parameters for the Deuteron Beam RFQ

Parameter/Feature	Value
Input Energy	20 keV/u
Output Energy	1.7 MeV/u
Frequency	162.5 MHz
Vane Voltage	65 kV
Average Aperture Radius	4.8 mm
Length	5.25 m
Bunching	Internal

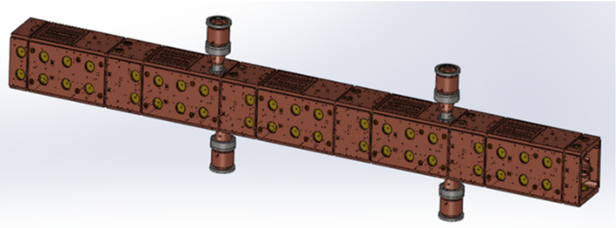

Figure 1: 3D model of the deuteron beam RFQ.

In order to increase the acceleration efficiency of the RFQ, the trapezoidal modulation electrode is introduced in this RFQ. The first 2 m section of the electrode is sinusoidal and the last 3.25 m section of the electrode is trapezoidal. As the design result, the energy at the exit is nearly 1.7 MeV/u. The first 2 m section is designed by the code DESRFQ [3]. Because there's no ready-made code to design the unconventional structure of the trapezoidal modulation electrode, a VBA code based on CST EM Studio has been developed for the design of the trapezoidal modulation electrode.

THE DESIGN OF ELECTRODE WITH TRAPEZOIDAL MODULATION

The idea utilizing trapezoidal modulation electrode to increase the acceleration efficiency was initially actualized by the IHEP-Protvino group [4] and also has been implemented in ATLAS RFQ [5]. Figure 2 shows the longitudinal section of one cell trapezoidal modulation RFQ electrode and the 3D model. It can be seen that each cell of the trapezoidal modulation RFQ electrode is comprised of two flat parts and one sinusoidal transition part between them. The proportion of the flat parts in the cell length is represented by k. The electrostatic simulation can be done when the 3D model is generated. Figure 3 shows the axial component of the electrostatic field for different proportions of the flat parts. As expected, the maximum of the axial component of the electrostatic field increase as the proportion enlarges

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[#] lichenxing@impcas.ac.cn

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THE QUALITY ASSURANCE AND ACCEPTANCE SYSTEM OF NIOBIUM MATERIAL FOR RAON CAVITIES

Mijoung Joung#, Yoochul Jung, Hyungjin Kim, IBS, Deajeon, Korea

Abstract

The QAAS (Quality Assurance and Acceptance System) of superconducting material for RAON's cavities has been set up. The subject was selected by how the part is affected by RF (Radio Frequency) in the cavity operation at cryo-temperature. The QAAS consist of property analysis and checking the surface condition. Each step has criteria its own to pass the assurance and acceptance system. The method to analyze the properties and to inspect the niobium surface was described. The certificates were classified by RRR values of Nb pieces due to distribution of RRR value. The Nb properties slightly different by RRR values, so we will set a bunch of niobium pieces for one specific cavity with Nb pieces having similar RRR value.

INTRODUCTION

The high quality material is needed to make a high performance resonator. The niobium is widely used as superconducting material for SRF (Superconducting Radio Frequency) cavity and the niobium surface condition is one of the important factors to determine the cavity performance because the surface resistance is related to the energy of the cavity and the surface resistance depending on material quality and surface condition. There are two aspects about quality control of material. One is to control the material's chemical, mechanical, electrical and optical properties. The other is that to control the niobium surface. Many other institutes carry out the checking the properties and surface inspection using various methods before doing machining [1-5]. The material properties are determined at the production stage by project demands, so it is necessary to verify the properties by sampling. In case of surface checking, it is necessary step for mass production. However, it is practically impossible to inspect all of the niobium because of the time limitation and man power. For this reason, the subject for inspection was selected by considering RF (Radio Frequency) effect. The parts where the highest electric and magnetic field is exerted was selected and it is called as RDP (Radio frequency Dominant Part). It will be explained about the kind of inspection, inspection process, subject selection, the criteria of acceptance and the inspection and measurement method. Also the certificates of Nb provided by the ATI metallurgy were classified.

QAAS OF NIOBIUM FOR RAON

QAAS (Quality Assurance and Acceptance System) will be introduced in this section.

The Type of Niobium and the Subject Selection

There are three types of niobium for RAON's cavity.

- Big sheet (635*1200 mm, 3t)
  (600*800 mm, 3t)
  (450*600 mm, 5t)
- Cut set (specific size corresponding to the part, 3t)
- Rod or Tube (Φ 60, 3t)

Big sheet is used for cavity prototype and extra sheet. Cut set is a bunch of Nb pieces which were cut by a required size of each cavity part with extra margin. The rod or tube of Nb is for beam port. And big sheet has two types of grade, which are RRR (Residual Resistivity Ratio) 300 and RRR 50 (Reactor grade). And it has different thickness which are 3mm and 5mm. The RRR 50 grade sheet is only used for supporting structure such as ribs for upper part or doubler of beam port cup. All of Nb cut set and Nb rod have 3mm thickness.

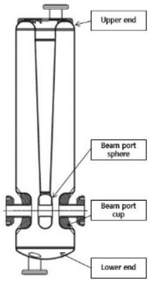

Figure 1: QWR cross section.

Figure 1 shows the RDPs (Radio frequency Dominant Part) which are strongly affected by RF field in the cross section of QWR (Quarter Wave Resonator). In case of QWR, upper, lower and beam tube parts are RF dominant part. The RISP (Rare Isotope Science Project) will make four kinds of the cavities which are QWR, HWR (Half Wave Resonator and two kinds of SSRs (Single Spoke Resonators).

Whole Process

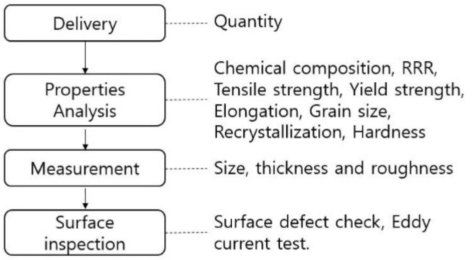

Figure 2: Whole process of QAAS.

#mijoung@ibs.re.kr

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STUDY OF ELECTRODE CONFIGURATION OF THE FOUR BEAM IH-RFQ LINAC

Shota Ikeda, Tatsunori Shibuya,
Graduate School of Science and Engineering, Tokyo Institute of Technology, Tokyo, Japan
Noriyosu Hayashizaki,
Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Tokyo, Japan

Abstract

The multi-beam acceleration method, which is technique for accelerating low energy, high intensity, heavy ion beams by accelerating multiple beams to decreasing the space charge effect, and integrating these beams by a beam funneling system [1]. Working towards the commercialization of this method, at the Tokyo Institute of Technology we have been developing a 4 beam IH-RFQ linac. As part of the design work for the 4 beam IH-RFQ linac, we evaluated the cell parameters of the RFQ electrodes using a RFQ design code and a beam dynamics simulation code. Also, we evaluated the RF properties of several electrode layouts using a three dimensional electromagnetic simulation code. This paper reports on the results.

INTRODUCTION

The multi-beam acceleration method utilizes multiple beams to decreasing the space charge effect, then integrates these beams by a beam funneling system. The space charge effect has a property that is inversely proportional to the square of beam velocity and proportional to the beam current. Therefore, low-energy (from keV/u to several MeV/u) high-intensity (over 10 mA) heavy ion beam acceleration is the most severe condition.

We have been developing a 4 beam IH-RFQ linac shown in Figure 1, which consists of sixteen RFQ electrodes (4x4 set) and the stem electrodes installed alternately on upper and lower ridge electrodes. The RF electromagnetic field is stimulated by the TE111 mode. The electric field and magnetic flux distribution in a 4 beam IH-RFQ linac is shown in Figure 2. The RFQ electric field is generated by induced current through the ridge electrodes and the stem electrodes.

The electrical capacitance of the 4 beam IH-RFQ linac is large compared with that of a single beam type, because there of the large volume of the stem electrodes and the 4 set RFQ electrodes in the cavity. Therefore the resonance frequency of the 4 beam IH-RFQ linac is lower than that of a single beam type.

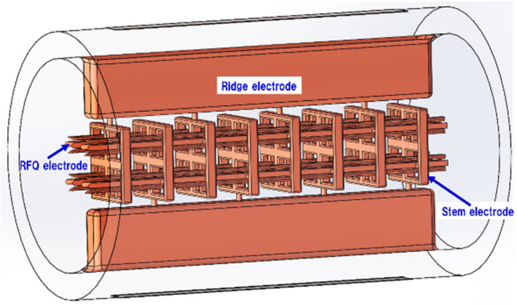


Figure 1: Configuration of the 4 beam IH-RFQ linac.

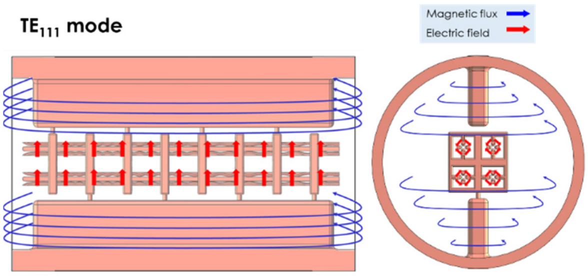
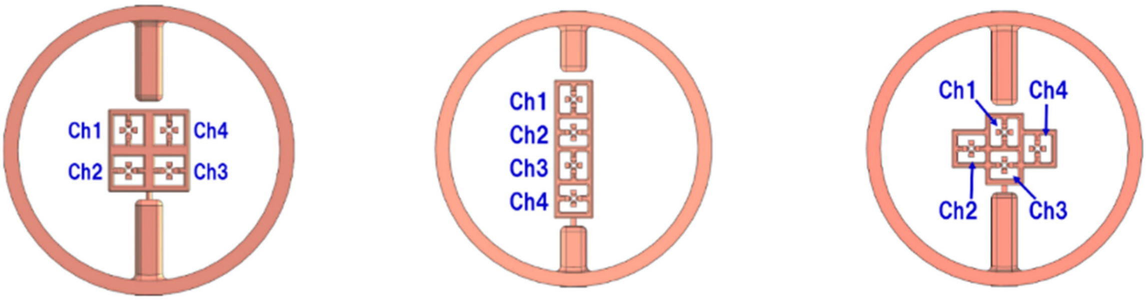


Figure 2: Electric field and magnetic flux distribution.



Layout 1 Layout 2 Layout 3

Figure 3: Electrode layouts of the 4 beam IH-RFQ linac.

LINAC OPTIONS FOR THE ION INJECTOR OF MEIC*

J. Guo#, Y. Zhang
Thomas Jefferson national Accelerator Facility, Newport News, VA 23606 USA

Abstract

In the current baseline design of the Medium-energy Electron-Ion Collider (MEIC) proposed by Jefferson Lab, a green field ion injector complex is composed of several ion sources, one linac with charge stripper, and one booster ring. The original linac design contains a short warm front end and a long SRF section with QWR/HWR cavities, capable of accelerating H^- to 285 MeV or Pb^{67+} to 100 MeV/u. Such a linac is a major cost driver of the project, despite that the required duty factor of this linac is very low. In this paper, we will compare alternative options for this ion linac, including the possibilities to lower the linac energy and choose a warm linac.

ION BEAM FORMATION AND THE CHOICE OF LINAC ENERGY

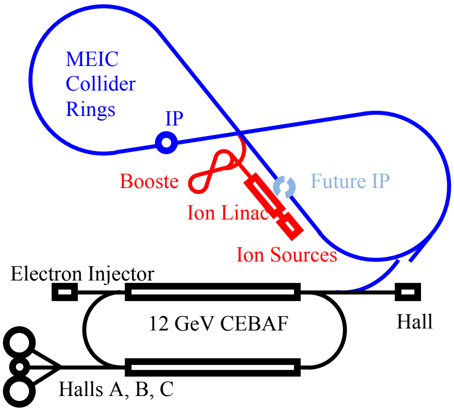


Figure 1: Layout of MEIC.

The MEIC proposed by JLab is a high luminosity electron-ion collider with 3-10 GeV electrons and 20-100 GeV protons (or ions with the same range of magnetic rigidity, i.e. lead ion with 12-40 GeV per nucleon) [1, 2]. The ion collider ring's beam current design goal is 0.5A, with the possibility for further upgrade. Figure 1 shows the layout of the collider with electron and ion injectors. The baseline ion injector complex contains the following components: 1) ion sources providing polarized H^- and other light ions, as well as un-polarized heavy ions up to lead; 2) a pulsed SRF linac; 3) a booster ring with 1/9 of the circumference of the collider ring (239.4m), kinetic energy E_k up to 7.9 GeV for proton (momentum 8.79 GeV/c/q for different ions) with DC cooling. The process to accumulate and accelerate ion beam toward collision is illustrated in Fig. 2 and outlined below [3]:

1. Eject the used beam from the collider ring, cycle the magnets
2. Accumulate strip-injected beam from the linac into the booster, perform DC electron cooling if needed
3. Capture the beam into a bucket of 0.7 circumference
4. (proton only) Ramp the booster to 2 GeV and perform DC electron cooling
5. Ramp to 7.9 GeV for proton, or to the same momentum per elementary charge for the other ion species
6. Compress the bunch length to 0.7/N of the booster circumference (N determined by booster charge)
7. Transfer the beam into the collider ring bucket to bucket, cycle the booster magnets
8. Repeat steps 2-7 by 9×N times, perform bunched beam (BB) electron cooling while stacking
9. Ramp the collider ring to the collision energy 12-100 GeV; perform bunch splitting; ready for collision.

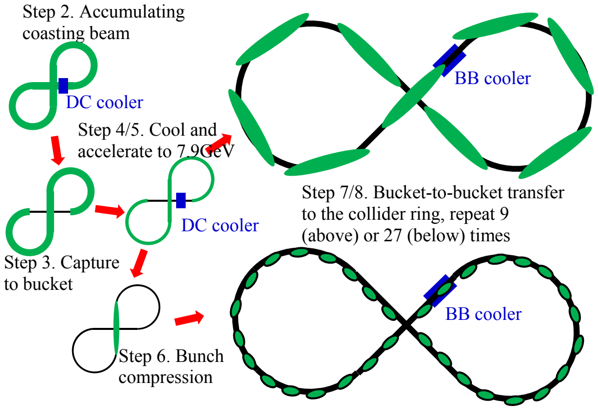


Figure 2: Illustration of the ion beam formation process, step 2-8 as listed above.

The major bottleneck for the ion injection is the space charge (SC) tune shift in the booster ring and the collider ring, especially during step 3 and 8. With given aperture (or emittance) and space charge tune shift in the collider ring at step 8, the booster's extracted beam energy determines the maximum beam current of the collider ring; the linac's extracted beam energy determines how much charge the booster ring can accumulate in each booster cycle.

Table 1 lists the space charge tune shift and the beam aperture for different linac and booster extraction energies and beam charges, with the maximum tune shift set at 0.15. With the original 285 MeV proton linac energy, it takes 9 booster cycles to form 0.5 A proton beam current in the collider ring; for 100 MeV/u lead ions from the linac, 9 booster cycles are not enough for 0.5 A colliding beam current, we need to double the number of booster cycles to 18. If we drop the linac energy to 120 MeV for proton and 40 MeV for lead, we need to increase the

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#jguo@jlab.org

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CHARGE STATE SELECTIVE ION BEAM ACCELERATION WITH RFQ LINAC

J. Tamura*, Japan Atomic Energy Agency, Ibaraki, Japan
Y. Fuwa, Kyoto University, Kyoto, Japan
T. Kanesue and M. Okamura, Brookhaven National Laboratory, New York, USA

Abstract

DPIS (Direct Plasma Injection Scheme) is one of the effective methods for high-intensity heavy ion beam acceleration. In the DPIS, multiple charge state ions are simultaneously injected into an RFQ. And then, ions whose charge states are comparable with that of ions desired for an RFQ acceleration are captured by the RF bucket. To prevent the unneeded ions from being accelerated, we investigated the motion of multiple charge state ions in an RFQ. We found that the discontinuous transition of a synchronous phase inhibits the unneeded ion's acceleration without a significant loss of desired ions. The particle tracking simulation for C^{5+} acceleration shows that 89% of C^{5+} and 9% of C^{6+} are accelerated with the discontinuous transition of the synchronous phase, whereas 96% of C^{5+} and 73% of C^{6+} are accelerated with the smooth transition. To validate the designed cell parameters, we manufactured new 4-rod RFQ electrodes and planed to perform beam acceleration test using the new RFQ electrodes.

BACKGROUND

We have been investigating high-intensity carbon beam acceleration using DPIS (Direct Plasma Injection Scheme). In this scheme, high-intensity carbon plasma generated by irradiating a graphite target with a pulsed laser is directly injected into an RFQ [1, 2]. And then, ions are extracted at the entrance of the RFQ. Because the DPIS doesn't have an LEBT (Low Energy Beam Transport), multiple charge state ions are simultaneously injected into the RFQ. The simultaneous injection of multiple charge state ions is unavoidable. And also, the beam is not matched for the RFQ injection [3].

Ions whose charge states are comparable with that of ions desired for the RFQ acceleration are captured by RF bucket and accelerated with the desired ions [4]. Therefore, we have investigated an RFQ which doesn't accelerate unneeded ions (different charge state ions) [5]. And then, we manufactured new RFQ electrodes based on the result of particle tracking simulation. In this paper, the designed RFQ cell parameters and the tracking simulation result are shown.

MANUFACTURED RFQ ELECTRODES

The new RFQ was designed to accelerate C^{5+} and not to accelerate different charge state carbon ions such as C^{6+} and C^{4+}. The differences of A/Q gives the smallest value for carbon ion under this condition. Ions which charge state is higher than that of ions desired for an RFQ acceleration are captured by the longitudinal RF bucket more than lower charge state ions. Therefore, the requirement for the new RFQ is to prevent C^{6+} from being accelerated and not to decrease the rate of the accelerated C^{5+}.

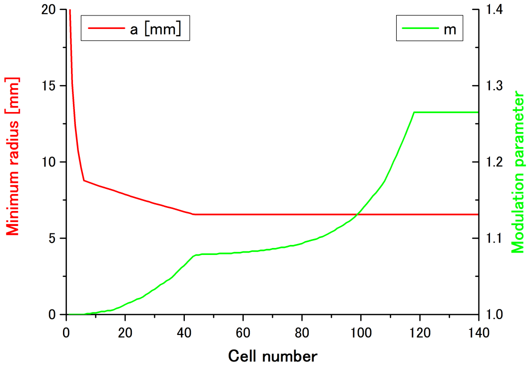

Figure 1: The minimum aperture and modulation factor.

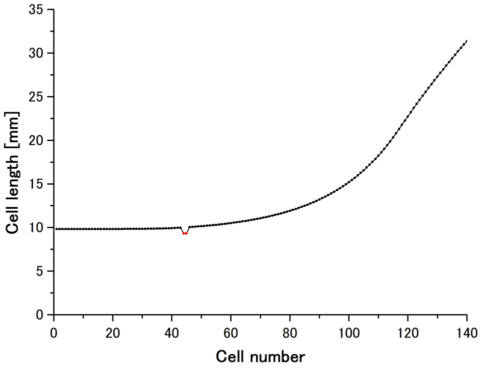

Figure 2: The cell length.

The designed RFQ have a discontinuous transition of the synchronous phase in the bunching section. The cell parameters for the RFQ are shown in Fig. 1 and Fig. 2. The cell length is shorten at the 43th and 44th cell as shown in Fig. 2, whereas the cell length is smoothly increased in an usual RFQ acceleration. This shortening of the cell length shifts the synchronous phase smaller (to negative direction) and leads to the discontinuous transition of the synchronous phase. In the smooth transition of the synchronous phase, the synchronous phase is gradually increased from -90 degree to positive direction.

The new 4-rod RFQ electrodes were manufactured in Hiroshima and delivered to J-PARC in Tokai site of Japan

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[*] jtamura@post.j-parc.jp

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THERMO-MECHANICAL CALCULATIONS FOR THE SPES RFQ

L. Ferrari, A. Palmieri, A. Pisent, INFN-LNL, Legnaro (PD), Italy

Abstract

Within the SPES project at INFN-LNL[1] a new injection line will be built at INFN LNL [2]in order to transport and match the RIBs to the existing ALPI superconducting linac. This line includes a new RFQ that will operate in a CW mode (100% duty factor) at the operating frequency of 80 MHz. The RFQ is composed of 6 modules about 1.2 m long each. Each module is basically composed of a Stainless Steel Tank (AISI LN 304) and four OFE Copper Electrodes. A copper layer will be electrodeposited on the tank inner surface and a spring joint between tank and electrode is used in order to seal the RF. Moreover, the electrodes are equipped with two brazed SS inserts in order to allow coupling with the tank. In order to remove the RF power (about 100 kW) as well as to allow frequency control during high power operation for a given cooling channel layout, a set of thermo-structural simulations was performed, whose input data were the RF Power densities calculated with 2D and 3D codes. In this paper the analytical and numerical methods used, as well as the main outcomes of these studies are presented.

THE SPES RFQ

The SPES RFQ is designed in order to accelerate beams in CW with A/q ratios from 3 to 7 from the Charge Breeder through the MRMS and the selection and injection lines up to the MEBT. The main parameters of the RFQ are listed in Table 1:

Table 1: Main RFQ Parameters

Paramater [units]	**Design value**
Frequency [MHz]	80
In/out. Energy [keV/u]	5.7-727 (β=0.0035-0.0359)
Accelerated beam current [μA]	100
Inter-vane voltage V [kV, A/q=7]	63.8 – 85.84
Vane length L [m]	6.95
Average radius R_0 [mm]	5.27÷ 7.89
Synchronous phase (deg.)	-90 ÷ -20
Focusing Strength B	4.7 ÷ 4
Pole tip radius ρ	4.01÷5.97 (0.76 R_0)
Stored Energy [J]	2.87
RF Power [kW] (30% margin)	98
Q value (30% margin)	14000
Max power density [W/cm^2]	0.31 (2D), 11 (3D)

The voltage law is a linear function along z $V(z)=V(0)+a\cdot z$ with a=3.177 kV/m and V(0) depending on the A/q of the ion to be accelerated. Such law is implemented by designing the RFQ in order to obtain a constant TE_{21} cut-off frequency fc=79.5 MHz along the structure and by properly shaping the vane undercuts at the Low and High Energy Ends of the RFQ. This choice sets the tuner tuning range of the RFQ in the interval [79.5 MHz, 80.5 MHz]. In order to compensate the R_0 variations, the capacitive region is varied along the RFQ (Fig.1). Therefore the electrode thickness is constant and equal to 48 mm and the tank inner radius R is equal to 377 mm.

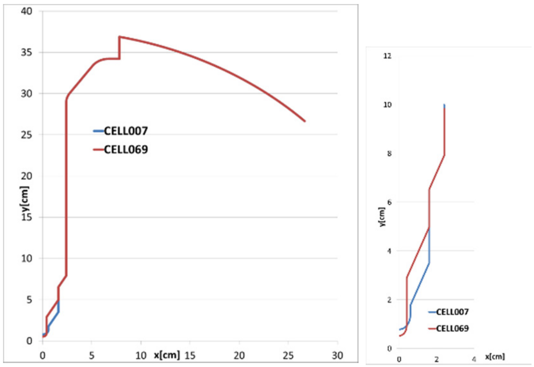

Figure 1: Capacitive tuning of the RFQ sections corresponding to the highest (Cell007) and lowest (Cell069) R_0 values.

The RFQ Cooling system is designed to remove power and to finely tune the cavity resonant frequency during operation by temperature regulation. For such a purpose, it is necessary to have two independent water loops with two temperature set points: a “cold” circuit for the tank, and a “warm” one for the vanes. By mixing with a 3-way valve the cold inlet water with part of the warm water coming from the cavity, it is possible to vary the resonant frequency of the RFQ and to tune the cavity accordingly. Therefore a thorough thermo-structural analysis of the RFQ is needed in order to determine, for s given cooling channel layout and inlet temperature, the associated temperature and displacement fields in the RFQ as well as the mechanical stresses. The outcomes of this analysis are the frequency sensitivities vs water temperatures and/or RF input powers in order to determine the actual tuning range with water temperature during RFQ operation. This analysis was carried out both in 2D (SUPERFISH) for the input parameters (power densities) and in 3D (ANSYS Electromagnetic Suite and ANSYS 16).

Preliminary simulations permitted to determine the position of the cooling channel and the cooling water path arrangements (Figs. 2 and 3) and the water input temperatures for vane and tank. It is important to notice

HEAVY-ION BEAM ACCELERATION AT RIKEN FOR SUPER-HEAVY ELEMENT SEARCH

E. Ikezawa, M. Fujimaki, Y. Higurashi, O. Kamigaito, M. Kase, M. Komiyama,
T. Nakagawa, K. Ozeki, N. Sakamoto, K. Suda, A. Uchiyama, K. Yamada
RIKEN Nishina Center, Wako, Saitama, Japan
K. Kaneko, T. Ohki, K. Oyamada, M. Tamura, H. Yamauchi, A. Yusa
SHI Accelerator Service Ltd., Tokyo, Japan

Abstract

The RIKEN heavy-ion linear accelerator (RILAC) comprises a variable-frequency Wideröe linac as the main linac, an 18 GHz electron cyclotron resonance ion source, a variable-frequency folded-coaxial radiofrequency quadrupole linac as a pre-injector, and a charge-state multiplier system as a booster. An experiment to search for a super-heavy element (Z=113) was carried out using the RILAC at the RIKEN Nishina Center for Accelerator-Based Science, from September 2003 to August 2012. As a result, three events for Z=113 were successfully observed. This paper presents heavy-ion beam acceleration at RIKEN for the super-heavy element search.

INTRODUCTION

The project to construct a heavy-ion accelerator complex (linac-cyclotron) at RIKEN was initiated in 1974. The construction of six RIKEN heavy-ion linear accelerator (RILAC) resonators (RILAC No.1 - No.6) was completed in 1980 [1]. These are variable-frequency Wideröe linac-type resonators. The frequency tunable range of the resonators is from 17 to 45 MHz. The stand-alone mode operation of the RILAC to supply ion beams for experiments was started in 1981. The injection-mode operation of the RILAC to inject ion beams into the K540MeV RIKEN Ring Cyclotron (RRC) [2] was initiated in 1986.

In 1996, the pre-injector of the RILAC, a direct-current (DC) high-voltage terminal, was converted into a combination of a powerful 18 GHz electron cyclotron resonance ion source (18GHz-ECRIS) [3] and a very efficient low-β accelerator, which is a variable-frequency folded-coaxial radiofrequency quadrupole linac (FC-RFQ) [4]. The frequency tunable range of the FC-RFQ is from 17.7 to 39.2 MHz.

A new project for the RIKEN Radioactive Isotope Beam Factory (RIBF) [5] was proposed to extend radioactive isotope beams to heavy mass range. Since the project aimed principally at producing an intense heaviest-ion (uranium) beam, a charge-state multiplier system (CSM) [6] was proposed to minimize the inevitable beam-loss during the charge stripping process after the RILAC. In 2000, as an energy upgrade program of the RILAC in collaboration with the Center for Nuclear Study, University of Tokyo, six CSM resonators (CSM A1-A6) were installed after the existing accelerator of the RILAC. CSM A1 and CSM A2 are variable-frequency type resonators that have a frequency tunable range from 36.0 to 76.4 MHz. The other four resonators (CSM A3-A6) are

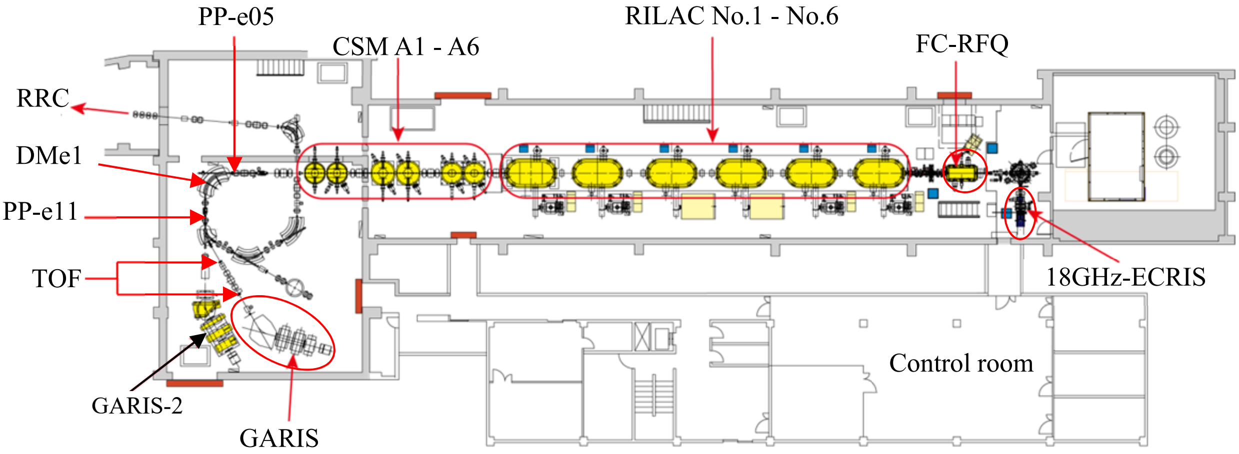

Figure 1: Layout of RILAC and GARIS.

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ikezawa@riken.jp

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THE COST OPTIMIZATION STUDIES OF THE SUPERCONDUCTING LINAC*

Y. Tao[a,b], Z.J. Wang[a], Y. He[a,*], S.H. Liu[a], W.S. Wang[a], C. Feng[a], P.Y. Jiang[a], H. Jia[a], W.L. Chen[a,b]
[a]Institute of Modern Physics, the Chinese Academy of Sciences, Lanzhou 73000, China
[b]University of the Chinese Academy of Sciences, Beijing 100049, China

Abstract

The research superconducting linac is growing in energy and power which induces an increase of the project cost. The RF cavities and RF power supplies mainly contributes the cost of the superconducting linac, which is a competitive technology for high power machine. A code internally with optimization algorithm is developed to optimize the geometric beta value of superconducting cavity family and transition energy to increase the acceleration efficiency of the whole linac. In this paper, the CADS Linac is taken as example to demonstrate the design procedure and the preliminary results of the CADS linac is also presented. The new method can be also used in other high power superconducting facilities.

INTRODUCTION

The applications of the research accelerator are becoming more and more diverse, from the very low power medical accelerators to the high power driven sub-critical accelerators. One of the main advantages of the linear accelerator is its capability for producing high-energy and high-intensity charged-particle beams with high beam quality, where high beam quality can be related to a capacity for producing a small beam diameter and small energy spread, which make it widely used sufficient to resolve problems. With the development of superconducting RF technology, the high energy high intensity superconducting linac is becoming more and more popular. The main superconducting linac projects all over the world are shown in the Fig.1. From the Fig.1, the beam power of the existed projects is round 1 MW, while for the further planned projects, the beam power will be ten times higher. The huge cost of the superconducting linac has been a factor, which is limit to the development of the linac. However, for the time being the accelerator optimization is concentrated on optimizing the lattice; the linac is merely matching the beam to transport line. It is necessary to find a new method to optimize the cost of superconducting linac.

The China Accelerator Driven Sub-critical System (CADS) [1] which aim to solve the nuclear waste problem is a 1.5 GeV and 10 mA continue wave superconducting linac project consists of two injectors and a main superconducting linac. The CADS roadmap is shown in the Fig. 2. The beam power will reach 10-15 MW. There will be more than two hundred of superconducting cavities and 20-25 MW RF power need for the whole project. Increasing the acceleration efficiency and utility of RF power is necessary and essential for the project cost optimization.

In this paper, the optimization concept as well as optimization procedures are presented in detail.

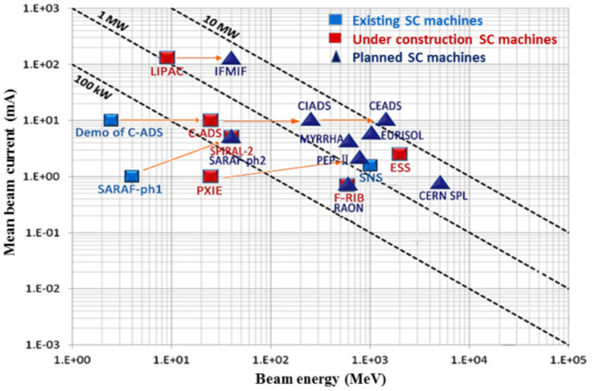

Figure 1: The superconducting linac in the world.

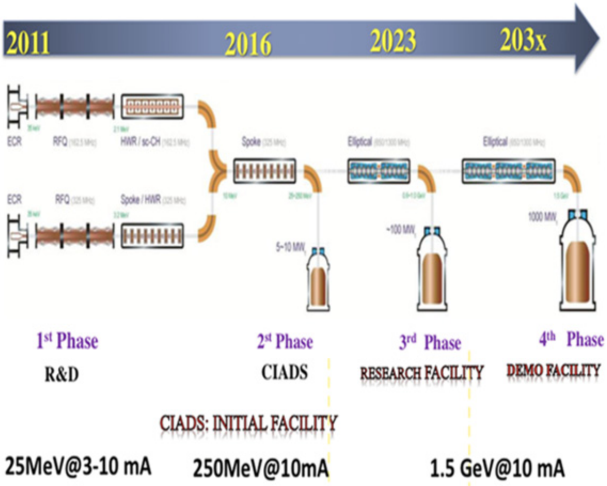

Figure 2: The roadmap of CADS project.

THE FOUNDATION OF PHYSICS

To select a reasonable geometric beta and transition energy is of great importance for the superconducting linac since an over specified value which will not be reached will result to a linac reduce the cost. How to choose the geometric beta and transition energy is an optimized problem, and the optimization result cannot be easily found by using the traditional method. As few papers studying the cost optimization of the superconducting linac [2], the new method which using a

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*hey@impcas.ac.cn

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CONCEPTUAL DESIGN OF LEBT FOR C-ADS LINAC ACCELERATOR*

W.L.Chen, Z.J.Wang, Y. He, H.Jia, Q.Wu, Y.Tao, IMPCAS, Lanzhou, China.

Abstract

In order to avoid the hybrid ions like H_2^+, H_3^+ injecting into the RFQ and the residual gas H_2 tracing through the RFQ which may lead the RFQ cavity performance degradation, we present the conceptual design of the Low Energy Beam Transport (LEBT) for the China Accelerator Driven Sub-Critical reactor system (C-ADS) accelerator. The LEBT, consisting of one bending magnet and three solenoids and four short-drift sections, match the CW proton beam with 35KeV and 10mA to the entrance of a radio frequency quadrupole (RFQ). This bending LEBT can easily separate the unwanted ions. With the edge angles and one quadrupole to correct the beam asymmetry causing by the bending magnet, the simulation results meet the RFQ entrance requirements.

INTRODUCTION

A project named China Initiative Accelerator Driven Sub-Critical System (C-IADS) has been proposed to treat the spent nuclear fuel and began construction since 2011[1]. Under three years commissioning, the demo facility had accelerated 10mA CW proton beam to 2.56MeV, and recently 2.7mA CW proton beam had accelerated up to 5.17MeV. The layout of the demo facility is shown in the Fig 1.Some beam experiments in the CW mode had taken on the LEBT recently, and find that the component of H_2^+ and H_3^+ is about 32% and 5% at 1.6E-3Pa vacuum degree. And in our accelerator we find the transmission efficient from the LEBT to the RFQ is almost 62.5% (FC1=16mA, ACCT1=10mA). Another question is the H_2 removal from the ion source to the RFQ and even to the downstream superconducting cavity. Long-time operation with residual gas RFQ performance may decline has reported in paper, and residual gas removal to the SC may lead the cavity quench. This paper presents the detailed description about a new LEBT for C-ADS accelerator.

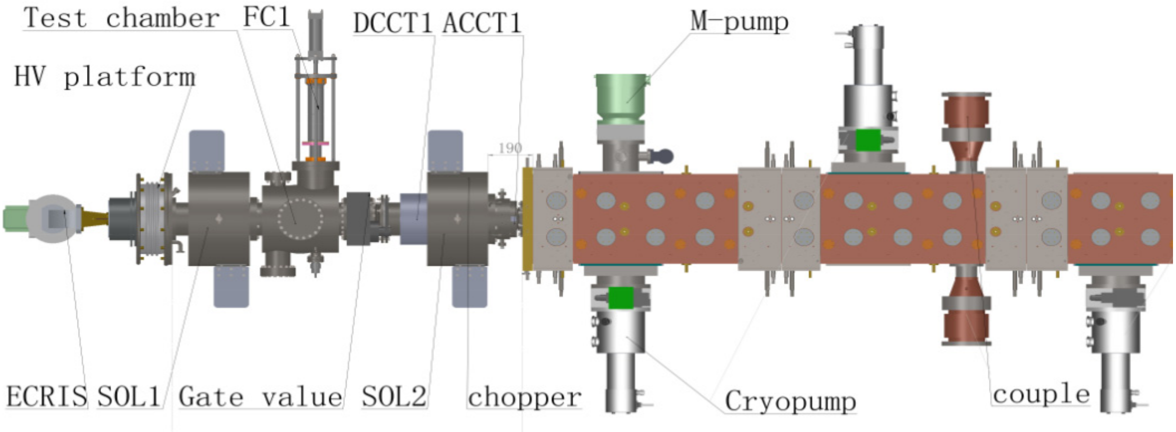

Figure 1: The layout of the ADS LEBT and parts of RFQ.

LEBT SYSTEM

The 10mA proton DC beam with the energy of 35KeV is extracted from a 2.45 GHz ECR ion source, after the LEBT transmission, focusing to the RFQ accelerator with the normalized RMS emittance at the entrance of RFQ less than 0.2 π.mm.mrad. The LEBT is used to transport and match the proton beam to the RFQ. Table 1 shows the key parameters of the front end to the RFQ which had met well with the downstream in the demo facility commissioning.

To meet the proton fraction requirement, a bending magnet and collimator have been considered to substantially reduce the contaminants, such as H2+ and H_3^+[3]. In order to decrease the beam divergence, we shorten the distance from the ion source to the first solenoid. And in order to reduce the space charge effect, the bending magnet is installed as close as possible to the first solenoid. Bending magnet will contribute the asymmetric ingredient to transverse axis, so we chose a little rotation angle into the magnet. After the separator, another two solenoids is used to match the Twiss parameters to the requirements. The next section will show the simulation results by TraceWin [2].

Table 1: required parameters before the RFQ

Parameters	Numbers	Units
Energy	35	KeV
Current	20	mA
Repetition frequency	50	Hz
Pulse width	CW	-
Twiss parameter α	1.21	-
Twiss parameter β	0.0479	mm/π.mrad

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STATUS OF SUPERCONDUCTING QUARTER WAVE RESONATOR DEVELOPMENT AT MHI

T. Yanagisawa #, K. Sennyu, H. Hara, A. Miyamoto, R. Matsuda, Mitsubishi Heavy Industries, Ltd (MHI), Tokyo, Japan
O. Kamigaito, H. Okuno,N. Sakamoto, K. Yamada, K. Suda
K. Ozeki, Y. Watanabe, RIKEN Nishina Center, Wako, Saitama, Japan
E. Kako, H. Nakai, K. Umemori, KEK, Tsukuba, Ibaraki, Japan

Abstract

MHI's activities for development of Superconducting Quarter Wave Resonator (QWR) are reported. MHI has experiences of developments and fabrications of several superconducting ellipse cavities. And now MHI is developing the superconducting QWR for heavy ion accelerators.

INTRODUCTION

Mitsubishi Heavy Industries (MHI) has supplied the superconducting RF cavities and the cryomodules for various electron accelerator projects, such as a STF and c-ERL project at KEK [1][2]. Moreover, MHI is developing the superconducting low beta cavities for proton or heavy ion accelerator using cultivated technique by electron accelerator development. Now MHI develops the superconducting Quarter Wave resonator and cryomodule for RIKEN RI beam Factory(RIBF) upgrade project[3][4] in collaboration with RIKEN and High Energy Accelerator Research Organization (KEK).

This report describes Frequency analysis of QWR cavity, forming test for cavity parts and status of preparation of manufacturing equipment for QWR cavity.

QWR CAVITY AND CRYO MODULE

In collaboration with RIKEN and KEK, MHI designs the prototyping of the superconducting QWR cavity and cryomodule. The cross section and the structure of QWR cavity are shown in Figure 1. The superconducting QWR cavity is made by pure niobium, and the formed or machined parts of QWR cavity are assembled by electron beam welding (EBW). The resonance frequency of the prototype superconducting QWR cavity for RIKEN RIBF upgrade is 75.5MHz, Height is 1055mm and inner diameter is 300mm.In order to correct a machining error and a welding error in process of manufacture, after the subassembly of cavity, it is necessary to perform adjustment processing.

Scheme drawing of the prototype cryostat for QWR cavity is shown in Figure 2. It is the design which can store two superconducting QWR cavities. An operating temperature is 4.2K and 40K Thermal shield cooled by a small refrigerator is installed. [5]

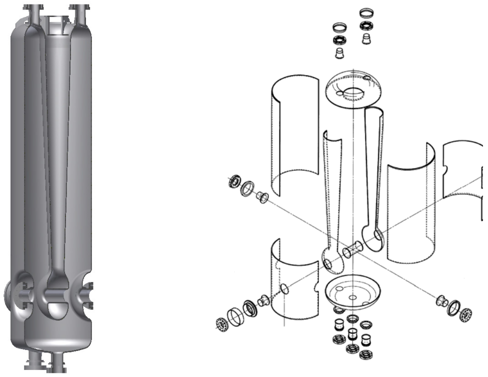

Figure 1: QWR cavity.

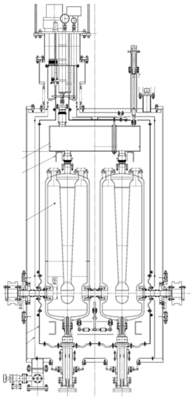

Figure 2: Cryomodule for QWR cavities.

FREQUENCY ANALYSIS OF QWR CAVITY

In order to determine the manufacturing procedure and the adjustment value of parts for frequency tuning, MHI did the frequency analysis using electromagnetic field analysis software MWS in collaboration with KEK. The model of analysis is shown in Figure 3. The following cases were assumed as a dimensional change in a process of manufacture.

A: The length change of the body lower part
B: The length change of the body upper part
(A stem is also included)
C: A gap of a drift tube and the body

#takeshi_yanagisawa@mhi.co.jp

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LASER ABLATION ION SOURCE FOR HIGHLY CHARGE-STATE ION BEAMS

Naoya Munemoto[#, A ,B], Naoto Takakura[C], Susumu Takano[B], Isao Yamane[B], Ken Takayama[A,B,D,E]
[A)] Tokyo institute of Technology, Nagatsuta, Kanagawa, Japan
[B)] High Energy Accelerator Research Organization, Tsukuba, Ibaraki, Japan
[C)] Nagaoka University of Technology, Nagaoka, Niigata, Japan
[D)]The Graduate University for Advanced Studies, Hayama, Kanagawa, Japan
[E)] Tokyo City University, Tamadsutsumi, Tokyo, Japan

Abstract

KEK Laser ablation ion source (KEK-LAIS) has been developed to generate highly ionized metal ions and fully ionized carbon ions since 2012. Laser ablation experiment has been carried out by using Nd-YAG laser (838 mJ/pulse, 20 ns) at the KEK test bench. Basic parameters such as momentum spectrum and plasma current have been obtained. Experimental results are compared with the existing results, which had been obtained by Munemoto at BNL. In addition, the newly designed electrostatic analyzer and a plan of the future experiment are discussed.

INTRODUCTION

The High Energy Accelerator Research Organization Digital Accelerator (KEK-DA) is a 10 Hz fast-cycling induction synchrotron without a large-scale injector [1] The KEK-DA is capable of accelerating any species of ion, regardless of its possible charge state. At this moment, low-charge-state gaseous ions are provided from the X-band ECRIS [2], which is installed in the high-voltage platform.

Induction synchrotron was proposed as an alternative to a RF synchrotron. Recently an ideal induction synchrotron has been designed as a hadron driver for cancer therapies [3]. It does not use a conventional injector system consisting of RFQ, DTL, and carbon stripper foil. It is indispensable to produce full-stripped carbon ions in the ion source. Demonstration of such an ion source is strongly demanded.

The laser abrasion ion source (LAIS) has been developed at KEK since 2012, as a method to easily produce highly charged ions at low cost. R&D works on the LAIS to produce high intensity ion beam is going on based on preceding studies [4]. Plasma in the LAIS is produced as a result of interaction between the laser and a target substance, and drifts downstream to the extraction region, where an ion beam is extracted from the plasma by applying a few tens kV across the acceleration gap.

Laser irradiation on the graphite target was tried at BNL by using two laser systems of Quantel Brilliant b (1064 nm, τ=6 ns, E=750 mJ) and Ekspla (1064 nm, τ=150 ~ 550 ps, E=500 mJ) in 2013. Then a similar ion source test bench employing the Spectron SL800 was constructed at KEK in 2014 and the laser irradiation experiment has been conducted. Its first priority is to reproduce the experiment results obtained at BNL and to acquire further information.

Comparison between the existing experimental results and recent results newly obtained at the test bench of the KEK-LAIS is discussed here.

EXPERIMENTAL SETUP

Layout of the KEK-DA LAIS Chamber is depicted in Fig. 1. The chamber consists of the optical components and target unit. Graphite (IG-110) is used as a target material, which has the density of 1.77 g/cm^3, the homogeneous fine grain structure, and 5 mm in thickness. The maximum laser irradiation area on the target is 169 cm^2. All of optical components are located inside the chamber. The laser beam is guided into the chamber through the anti-reflection coated BK7 window (ϕ40 mm), reflected by the coated mirror (ϕ30 mm), and delivered to the focusing lens (ϕ25 mm, f=200 mm). Spot size on the target is controlled by adjusting the focusing lens position so as to minimize the TOF of plasma from the target to the Faraday cup (FC) (see Fig. 1). In the other ward, the laser focusing parameter is determined so that the observed velocities of particle become maximum. The laser has an incident angle of 30° against the target surface. These optical components are securely protected from vapor contamination from the target by the thin aluminum shielding. Schematic of the KEK-LAIS test bench is depicted in Fig. 2, where LAIS chamber, solenoid guide system, FC measuring system, and static electric analyzer are shown.

Vacuum of plasma chamber and FC chamber are 2×10^{-4} Pa and 2.5×10^{-5} Pa, respectively. Spectron Laser system SL800 Nd-YAG laser (λ=1064 nm, τ=20 ns, E=838 mJ) is used. If its laser profile is assumed to be Gaussian, the spot size and energy density can be calculated using following formula [5]:

[#] munemoto.n.ad@m.titech.ac.jp

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DEVELOPMENT OF THE NEW DECRIS-PM ION SOURCE.

V. Bekhterev, S. Bogomolov, A. Efremov,FLNR, JINR, Dubna, Moscow Reg., Russia
N. Konev, ITT-Group, Moscow, Russia

Abstract

Super-heavy-element factory is under development at the Flerov Laboratory for Nuclear Reactions, JINR, Dubna. The factory will include DC-280 cyclotron, which will be equipped with two 100 kV high voltage platforms. All-permanent magnet ECRIS will be installed on one of the platforms. The request for the source is a production of medium mass ions with A/q=4÷7.5 such as $^{48}Ca^{8+}$. Results of the detailed design of the DECRIS-PM ion source will be presented.

INTRODUCTION

One of the basic scientific programs which are carried out at the FLNR is a synthesis of new elements requiring intensive beams of heavy ions. To enhance the efficiency of experiments for next few years it is necessary to obtain accelerated ion beams with the following parameters:

Ion energy	4÷8 MeV/n
Ion masses	10÷238
Beam intensity (up to A=50)	10 pμA
Beam emittance	≤ 30 π mm×mrad
Efficiency of beam transfer	> 50%

These parameters have formed the base for the new cyclotron DC-280 [1]. Some expected beam intensities are collected in Table 1.

Table 1: DC-280 Cyclotron - Basic Technical Parameters

Ion	Intensity from ion source μA	Intensity on physical target pps
$^{20}Ne^{3+}$	150	1×10^{14}
$^{40}Ar^{7+}$	300	1×10^{14}
$^{48}Ca^{8+}$	150	5×10^{13}
$^{58}Fe^{10+}$	125	4×10^{13}
$^{136}Xe^{23+}$	150	2×10^{13}
$^{238}U^{40+}$	1	1×10^{11}

The axial injection system of the DC-280 cyclotron will include two high voltage platforms which will allow for efficient injection of ions from helium to uranium with an atomic mass to charge ratio in the range of 4÷7. Each HV-platform will be equipped with the low power consuming ECR ion source. For production of ions with the medium masses (from He to Kr) the all permanent magnet (PM) ECR ion source will be used. In this paper we report the design of the magnetic system of the new DECRIS-PM ion source.

SOURCE DESIGN

Many good performance all-permanent magnet ECRISs have been built around the world: NANOGAN series [2], BIE series [3], LAPECR2 [4] and others. The main advantages of all permanent magnet ECRISs are low power consumption, low pressure in the cooling water system, simplified operation, etc. However there are few significant drawbacks of all permanent magnet ECRISs. First of them is the fixed distribution of the magnetic field and comparatively low field strength. Thus, the designed magnetic configuration should be optimized for the desired operation mode from the very beginning. Another drawback is strong mechanical force acting on the individual parts of the system. As a result the correction of the magnetic field after the assembly of the magnetic system is practically impossible without the degaussing of it.

Some deviations from the required field distribution can occur for many reasons. The magnetic material itself has scatter in parameters of up to 5%. Furthermore, the magnetic rings that form the axial magnetic field consist of several blocks. In calculations of the magnetic field it is almost impossible to take into account the influence of gaps between individual blocks. Figure 1 illustrates this problem. The figure shows the distribution of the magnetic field in front of one of the hexapole poles which is made of five blocks of identical magnetic material. With the gaps of about 0.1 mm the oscillations in the magnetic field measured at a distance of 3 mm from the pole are around 10%.

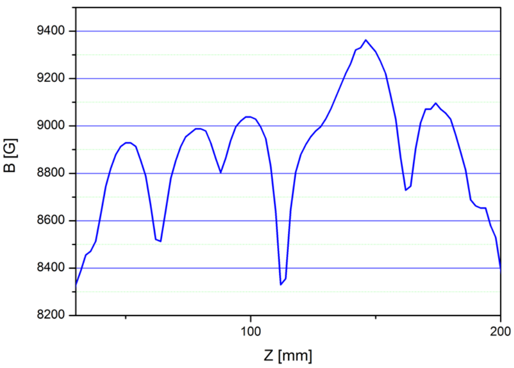

Figure 1: Measured magnetic field distribution along the hexapole pole.

For this reason it is desirable to provide a possibility for correction of the field distribution in the case of finding an

NEW DUAL-TYPE ELECTRON CYCLOTRON RESONANCE ION SOURCE FOR A UNIVERSAL SOURCE OF SYNTHESIZED ION BEAMS*

Y. Kato,[#] F. Sato and T. Iida, Osaka Univ., 2-1, Yamada-oka, Suita-shi, Osaka, Japan

Abstract

A new dual-type source has been constructing on the basis of electron cyclotron resonance (ECR) plasma for producing synthesized ion beams in Osaka Univ. Magnetic field in the 1st stage consists of all permanent magnets, *i.e.*, cylindrically comb shaped one, and that of the 2nd stage consists of a pair of mirror coil, a supplemental coil and the octupole magnets. Both stage plasmas can be individually operated, and produced ions which energy controlled by large bore extractor also can be transported from the 1st to the 2nd stage. Fundamental operations and effects of this source, and analysis of ion beams and investigation of plasma parameters are conducted on produced plasmas in dual plasmas operation as well as each single operation.

INTRODUCTION

A new concept on magnetic field of plasma production and confinement has been proposed to enhance efficiency of an electron cyclotron resonance (ECR) plasma for broad and dense ion beam source under the low pressure [1]. We make this source a part of new dual-type ion source for the 1st stage. We are also constructing the large bore 2nd stage for synthesizing ions, extraction and beam analysis [2]. We investigate feasibility and hope to realize the device which has wide range operation window in a single device to produce many kinds of ion beams, *e.g.*, from multiply charged, to molecular, cluster ions, nanotube, fullerenes, including impurities trapped as iron-endohedral fullerene, *etc.*, as like to universal source based on ECR ion source (ECRIS). We consider to being necessary to device that is available to individual operations with different plasma parameters, and then obtain concept of dual ECRIS from relevant previous works.

EXPERIMENTAL APPARATUS

The top view of the dual-type ECRIS and the beam line for the ion extraction and the analysis are shown in Fig.1. The 1st stage of the device is large-bore one using cylindrically comb-shaped permanent magnets, *i.e.* octupole magnets with a pair of ring magnets whose polarity is opposite each other [3-5]. Two frequencies microwaves are supplied to the plasma chamber (200mm in diameter and 320mm in length) [6]. Incident and reflected microwaves are tuned by the stainless steel/aluminum plate tuner. We are investigating positional dependence of this tuner to ion beam currents and plasma parameters in detail [7].

Ion produced in the 1st stage is extracted and transferred to the 2nd stage by the large bore extractor consisted of three electrode plates CE1-3 (V_{CE1-3}) with multi-holes (200 holes of 8mm in diameter) and the effective diameter 154mm, and the ion beam current $I_{FCx,y}$ is measured by two faraday cups. The typical extraction voltages range within about 1.0kV.

The magnetic configuration of the 2nd stage is mirror field formed by the coil A, B, and C, and superimposed the octupole magnetic field by permanent magnets [8]. The ECRIS performance is very sensitive to shape, intensity, and gradient nearby the ECR zone around bottom of mirror field, and we are available to control them precisely by the coil C [8]. The plasma chamber of the 2nd stage is about 160mm in diameter and 1000mm in length. 2.45 GHz microwaves are launched by the Ti rod antenna from the side wall. The single aperture extractor assembly is set at the mirror end plate with the aluminium plate for the microwave mode. The extractor consists of three electrodes, *i.e.*, the plasma electrode PE, the mid-electrode E1, and the extractor electrode E2. The typical extraction voltage (V_{PE}) and the extractor voltage (V_{E2}) are usually 10kV and the ground, respectively. The mid-electrode voltage (V_{E1}) is used on optimizing extraction of each ion species. We also install the ion-beam irradiation system (IBIS) in the downstream beam line for beam profiles, emittance measurements, and various beam-material applications.

In the both stages, plasma parameters and pressures are measured by Langmuir probe and Bayard-Alpert (B-A) gauges. The electron density n_e and the temperature T_e are measured from the probe current I_p and voltage V_p characteristics. We have also estimated electron energy distribution function (EEDF) from these probe data [9].

We confirmed that the ion beam is flowed from the 1st to the 2nd stage. From the result, we can become possible to conduct experiment at least on the dual-type ECRIS.

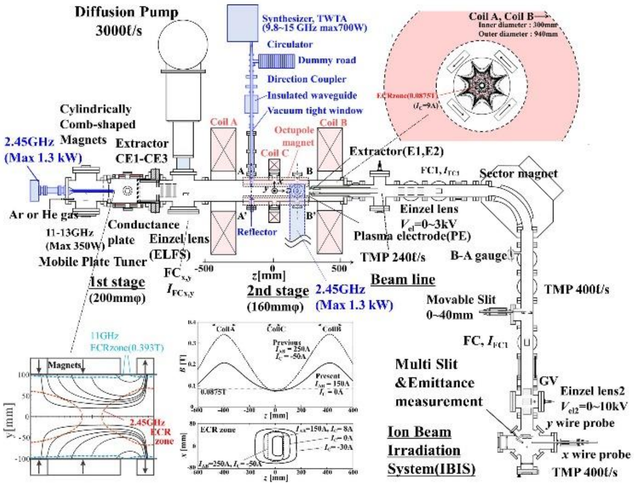

Figure 1: Schematic drawing of the top view of the new dual-type ECRIS (Osaka Univ.).

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#kato@eei.eng.osaka-u.ac.jp

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SUPPLY OF METALLIC BEAMS FROM RIKEN 18-GHz ECRIS USING LOW-TEMPERATURE OVEN

K. Ozeki#, M. Kidera, Y. Higurashi, T. Nakagawa, RIKEN Nishina Center, Saitama, Japan

Abstract

At the RIKEN 18-GHz ECR ion source, in order to enhance the intensity and stability of medium-heavy metallic beams, a low-temperature oven has been put into practical use. The supply methods, operational test results, and operational statuses for several metallic beams are reported herein.

INTRODUCTION

At the RIKEN Radioactive Isotope Beam Factory (RIBF) [1], beams of medium-heavy metals, such as ^{23}Na, ^{24}Mg, ^{27}Al, ^{48}Ca, ^{58}Ni, and ^{70}Zn, are supplied from the RIKEN 18-GHz electron cyclotron resonance ion source (ECRIS) [2]. Until recently, these metallic beams were produced using the rod-insertion method (except for Ni beams, which were produced using the Metal Ions from VOlatile Compounds (MIVOC) method [3]). In this method, a sintered rod of metallic oxide (fluoride for a Na beam) is inserted directly into the plasma generated in the ECRIS. The rod is heated by the plasma, and the metallic atoms are evaporated and fed into the plasma. The typical intensities of the ^{48}Ca^{10+} and ^{70}Zn^{15+} beams produced using this method were slightly below 20 eμA. However, the ECRIS required frequent tuning to maintain constant beam intensity. Therefore, we had tried to produce beams of medium-heavy metals using a low-temperature oven, which was already in use at several facilities [4-7], with the goal of enhancing the beam intensity and stability.

In this contribution, the supply methods and conditions, operational test results, and operational statuses of beam supplies to the experiments for ^{48}Ca, ^{70}Zn, and ^{27}Al beams are reported. The temperature dependences of the vapor pressures of Ca, CaO, Zn, ZnO, and Al, which are obtained obtained from Ref. [8], are shown in Fig. 1.

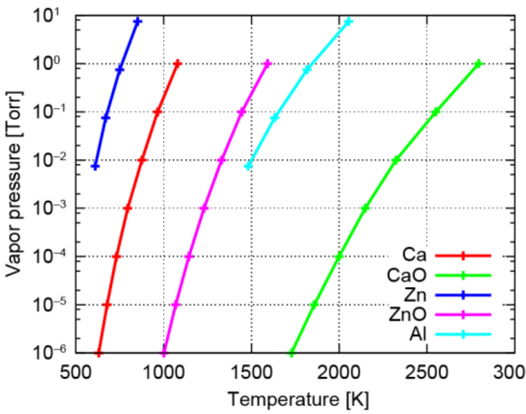

Figure 1: Temperature dependences of vapor pressures of Ca, CaO, Zn, ZnO, and Al (obtained from Ref. [8]).

STRUCTURE OF LOW-TEMPERATURE OVEN

The details of the structure of the low-temperature oven is described in Ref. [9]. It has been found that the oven temperature can be increased up to about 1000°C without damaging the oven. The crucible and Pt wire are replaced after each operation.

CALCIUM BEAM

For the supply of a ^{48}Ca beam, $CaCO_3$ which is highly enriched with ^{48}Ca (from a natural abundance of 0.2% to 70%-80%) is prepared. $CaCO_3$ is reduced to CaO by heating $CaCO_3$ to above 900°C. A mixture of CaO and Al powders is placed in the crucible. Then, the low-temperature oven is installed in the ECRIS. By heating the material to about 850°C, metallic Ca is produced through the following reductive reaction:

$$3CaO + 2Al \rightarrow 3Ca + Al_2O_3.$$

Ionized helium gas is used to generate the plasma.

Because the material is so expensive, it is quite important to reduce its consumption rate. Therefore, we adopted the so-called “hot liner” method [5,10,11]. In this technique, the inner surface of the plasma chamber in the ECRIS is thermally decoupled from the cooling water jacket to be kept at a high temperature heated by the plasma. Using this method causes the metallic atoms attached to the inner surface to re-evaporate. The details of operational tests that confirm the effectivity of using a hot liner, as well as the effectivity of applying a negative bias to the low-temperature oven itself, are reported in Refs. [9, 12].

The ^{48}Ca^{11+} beams produced using a low-temperature oven were first supplied twice to the experiments in the old RIBF facility [12]. After that, the ^{48}Ca^{10+} beams produced using a low-temperature oven were supplied to the new RIBF accelerator complex, from November 2014 until December 2014. Figure 3 shows the obtained charge distribution of ^{48}Ca ions. The RF power fed to the ECRIS was 370 W. The beam intensity at the exit of the ECRIS and the oven current are shown in Fig. 4. The beam intensity was adjusted to meet the experimental requirements by changing the slit aperture at the exit of the ECRIS. A beam intensity of about 35 eμA with the maximum slit aperture was maintained throughout the experiments. The status of beam supply is summarized in Table 1.

We succeeded in supplying ^{48}Ca beams twice as intense as those using the rod-insertion method, with nearly one-tenth of the material consumption rate.

#k_ozeki@riken.jp

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DEVELOPMENT OF ELECTRON CYCLOTRON RESONANCE ION SOURCES FOR CARBON-ION RADIOTHERAPY

M. Muramatsu, A. G. Drentje, and A. Kitagawa,
National Institute of Radiological Sciences, Chiba, Japan

Abstract

Compact Electron Cyclotron Resonance (ECR) ion sources have been developed for high energy carbon-ion radiotherapy (C-ion RT). Three compact ECR ion sources have been developed as the prototype at National Institute of Radiological Sciences (NIRS). The first ion source was used the microwave of 2.45 GHz to reduce the construction cost of the source as much as possible. It was required to produce 150 μA for C^{2+}. This ion source could not obtain enough intensity of C^{2+} because there were problems in microwave injection and beam extraction system. The second and third ion sources, named Kei and Kei2, solved these problems and set a target of 200 μA for C^{4+}. The structure of Kei and Kei2 were similar, however Kei2 improved on the magnetic field configuration and the beam extraction system. The beam intensity of 260 μA and 780 μA for C^{4+} were obtained by Kei and by Kei2, respectively. Kei2 was modified to connect with an injector linac for C-ion RT facility.

All of later C-ion RT facilities in Japan, the Gunma University Heavy Ion Medical Center, the Saga Heavy Ion Medical Accelerator in Tosu, and the Ion-beam Radiation Oncology Center in Kanagawa, installed copies of Kei2 and named them KeiGM, KeiSA, and KeiGM3. On the other hand, the original Kei2 have been installed in the Heavy Ion Medical Accelerator in Chiba (HIMAC) at NIRS and produces carbon beams for experimental use. Kei2 is still improving and is utilized for the development of ion sources at present.

KEI SERIES

The NIRS-ECR ion source [1] with normal conducting coil has been supplied the carbon ion for medical use with good stability. However, NIRS-ECR has large electric power supply (maximum current and voltage are 600 A and 60 V) for mirror magnet in same high voltage platform. Therefore, the size of high voltage platform include ion source, electric power supplies, vacuum system and controllers is large with 5.3 m length and 6.9 m width. Case of the NIRS-ECR, there is a fault that the running cost increases by occasion of three of the following. 1) A large amount of water is needed to cooling the electromagnet and power supply. 2) From the operating experience with about ten years, the klystron power amplifier (KPA) for microwave source had many troubles. 3) The breakdowns in the control system for power supply etc. by the aged deterioration has increased from there are a lot of numbers of parts that compose the ion source, too.

In order to solve these problems, a compact ECR ion source for the carbon ion production with all permanent magnet has been developed. The electric power and cooling water can be decreased by using a permanent magnet. Therefore, size of ion source with utility such as water cooling can be reduced. Moreover, a permanent magnet is given maintain easy because the number of parts is less than that of the electromagnet. However, it is difficult to obtain an optimal magnetic field for production of target ion under the uncontrollable magnet.

Three compact ECR ion sources have been developed as the prototype. The first prototype ion source is used the microwave frequency of 2.45 GHz aiming to reduce the cost of the source as much as possible. It was required to produce the C^{2+} by 150 μA in this ion source [2]. Figure 1 shows schematic view and magnetic field of the first prototype ion source. An enough performance was not obtained in this ion source because there were problems in microwave injection and beam extraction system [3]. In the microwave injection, the introduced microwave reflected almost from the plasma chamber, and was not absorbed to plasma. The production of the highly charged ion was difficult as the result. In the beam extraction, the puller was made by iron because increasing the mirror field at extraction side. However, distance between puller and plasma electrode could not be optimize for beam extraction. From this problem, the beam defocuses immediately extraction, and was not able to transport the beam to the downstream side. And the cost and size of the accelerator is increased because target ion was C^{2+}.

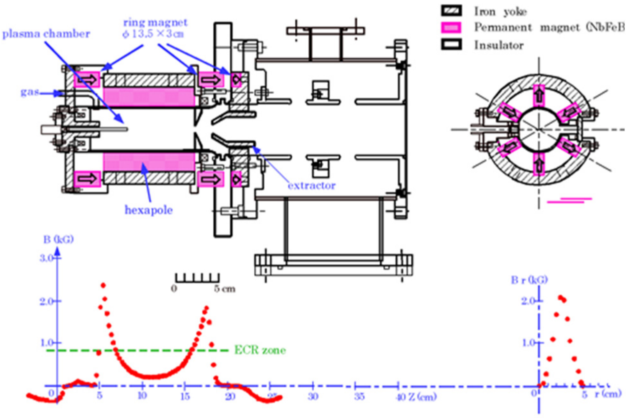

Figure 1: Schematic drawing of 2.45 GHz compact ECR ion source.

The second and third prototype ECR sources (Kei and Kei2), these were developed for solution of problem of the 2.45 GHz compact ECR ion source. The target is change to 200 μA for C^{4+}. Figure 2 shows schematic drawing of Kei source. The fixed magnetic field of the Kei and the Kei2 are copied from that of the 10 GHz NIRS-ECR source at HIMAC, which has already been proven to be reliable

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DEVELOPMENT OF AN ONLINE EMITTANCE MONITOR FOR LOW ENERGY HEAVY ION BEAMS*

V. Tzoganis#, RIKEN, Saitama, Japan , Liverpool University, Liverpool, UK, The Cockcroft Institute, Warrington, UK
T. Nagatomo, M. Kase, O. Kamigaito, T. Nakagawa, RIKEN, Saitama, Japan
C.P. Welsch, Liverpool University, Liverpool, UK, The Cockcroft Institute, Warrington, UK

Abstract

RIKEN's 18 GHz ECR [1] (electron cyclotron resonance) ion source supplies the AVF cyclotron with beams ranging from protons to heavy ions as xenon. From comparison with the use of the RILAC (RIKEN Linear Accelerator) and beam transport simulations it was found that the transport efficiency is much lower. To this extend and with the aim to understand the ECR beam production, beam dynamics and optimize the beam transfer we have developed an emittance monitor based on the pepperpot method. The device is composed of a perforated copper plate, transparent scintillator and a CMOS camera for image capturing. Parameters of interest for scintillator's performance are the light yield and radiation hardness. Quartz was found to be resilient to damage and having linear light emission. A real time algorithm written in LabVIEW manages the data acquisition and the 4D phase space distribution calculation. Provided this information, we can investigate parameters such as inter-plane correlation and emittance dependence on extraction specifications, beam current and the magnetic field in the ion source. In this contribution we are presenting the emittance meter design, algorithm description and a set of typical measurements.

INTRODUCTION

For efficient beam transport in LEBT (low energy beam transfer) lines, the understanding of the beam production and beam dynamics is of very high importance. Beam transverse emittances are key parameters to quantify the beam quality and for an improved beam transfer, emittance matching between the ion source and the LEBT's acceptance is required.

For the case of RIKEN's 18 GHz superconducting ECR ion source, user experience has shown that the transport efficiency is much lower compared to the use of RIKEN's linear accelerator as injector. It has been confirmed experimentally with use of a scintillating screen at the entrance of the LEBT, that the beam size is larger than the LEBT aperture while the beam diameter at the extraction is around 1 cm. Moreover, preliminary beam dynamics studies suggested that the transport efficiency is about 16% and the beam emittance blows up in the area between the ion source and LEBT (~ 1m).

Studies by L. Groening et al and C. Xiao et al [2–4] on the concept of emittance reduction and emittance exchange have shown that it is possible to improve ion beam quality transport efficiency by exchange between the 2 transverse emittances.

With those considerations in mind and the goal to better understand beam transfer and improve beam quality we have developed an emittance monitor that allows for real time beam emittance measurements. The device is based on the pepperpot method which has been well studied and applied in multiple beam sources of electrons and ions..

EMITTANCE MONITOR

ECR Ion Source

The 18 GHz ECR ion source is used to provide various ion beams to the RIKEN AVF cyclotron. From there they are either further accelerated for RIBF or used for RI production and nuclear physics experiments. The ion source design is based on 4 superconducting solenoid magnets and a permanent hexapole magnet that generate a mirror magnetic field for plasma confinement. Different gases depending on the desired ions are injected in the ion source and heated up by microwaves produced by an 18 GHz reference source and amplified by a TWTA (traveling wave tube amplifier).

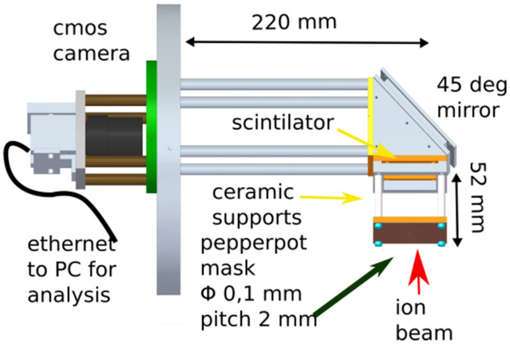

Figure 1: Emittance monitor schematic.

Pepperpot Device

The pepperpot device used here, Figure 1, is mounted on an ICF203 flange about 3m from the beginning of the LEBT. A 70x70 mm perforated copper plate with hole diameter of 0,1mm and pitch 2 mm intercepts the ion beam and splits it in small beamlets. The plate is electrically isolated so it can be used for direct beam current measurements for a measure of beam stability. Absolute current measurements are not possible as there is no secondary electrons suppression. The ion beamlets

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*Work supported by STFC, Cockcroft Institute grant and Liverpool - Riken collaboration.

#Vasileios.tzoganis@riken.jp

DEVELOPMENT OF A BUFFER GAS-FREE BUNCHER FOR LOW ENERGY RI ION BEAM

M. Togasaki, K. Kurita, K. Yamada, Rikkyo University, Tokyo, Japan
R. Toba, Nagaoka University of Technology, Nagaoka, Niigata, Japan
M. Hara, T. Ohnishi, and M. Wakasugi, RIKEN Nishina Center, Wako, Japan

Abstract

A new-type buncher which is buffer gas-free and workable under the ultra-high vacuum for low energy RI ion beams based on a linear RFQ ion trap was developed. Our idea is to make active use of the fringing fields in a region close to the entrance or the exit of the RFQ to decelerate and stack ions continuously injected into the buncher. As a result of performance experiments, ion beams extracted from the buncher with pulse width of about 500 µs and a stacking efficiency of ^{133}Cs^{+} of 10 % were obtained for the operating frequency of 10Hz. It is usable for bunching ion beams provided from the ERIS (Electron-beam-driven RI separator for SCRIT) in the SCRIT (Self-Confining RI Ion Target) electron scattering facility at RIKEN RI Beam Factory.

INTRODUCTION

The SCRIT (Self-Confining RI Ion Target) is an internal target formation technique for electron scattering off short lived unstable nuclei [1–3]. In the SCRIT electron scattering facility at RIKEN RI Beam Factory [4], we constructed an ISOL-type RI beam generator named ERIS (Electron-beam-driven RI separator for SCRIT) [5]. the ERIS supplys continuous RI ion beam with the energy of 50 keV at maximum. In order to efficiently inject the RI beam from the ERIS into the SCRIT device equipped in an electron storage ring and to produce a sufficiently high luminosity for SCRIT experiment, it is absolutely necessary to bunch the beam with a pulse width of about 500 µs without deteriorating of a vacuum level of less than 10^{-7} Pa.

Therefore, we developed a new-type buncher system for the RI ion beam based on a technique of a linear radiofrequency quadrupole (RFQ) ion trap such as in reference [6] but without using buffer gas and working under the ultra-high vacuum. Our idea is to make active use of the fringing fields in a region close to the entrance or the exit of the RFQ. In this paper, we report results of a verification of the new technique using numerical simulations, and of performance experiments of the buncher system.

PRINCIPLE OF THE BUFFER GAS-FREE BUNCHER

Fringing fields of a linear RFQ

an ideal electrostatic potential generated by rods of a linear RFQ [7] lying along the z-axis with a bore radius r_0, $\phi(x, y, t)$, is given by

$$\phi(x, y, t) = V_{\mathrm{DC}} + \frac{x^2 - y^2}{r_0^2} V_{\mathrm{RF}} \cos \omega t \qquad (1)$$

where V_{RF} and ω are amplitude and angular frequency of an RF voltage respectively, and V_{DC} is an adittional DC voltage applied to the rods. In a region close to end-cap electrodes (hereafter called “barrier” electrodes), however, fringing fields [8–10] are not negligible. The potential $F(x, y, z, t)$ in this region is expressed approximately by

$$F(x, y, z, t) = f(z)\phi(x, y, t) \qquad (2)$$

$$f(z) = 1 - \exp[-az - bz^2] \qquad (3)$$

where a and b are coefficients dependent on the ratio of a distance from the rods to the barrier electrode to r_0, and $z = 0$ corresponds to the position of the barrier electrode [9, 10].

According to the above equations, ions in this region are longitudinally accelerated or decelerated by the RF fringing fields. If energys of the decelerated ions come to be lower than the DC voltage applied to the barrier electrode, the ions should be stacked in the longitudinal barrier-potential well and a bunch beam can be produced by extracting the stacked ions within a short time.

Ion stacking by the fringing fields

We verified the ion stacking phenomenon by the fringing fields using Monte Carlo particle simulations. Numerical solutions of the three-dimensional Laplace equation were employed as models of the fringing fields. Where DC voltage applied to the barrier electrodes is $V_{\mathrm{Barr}} = V_{\mathrm{Acc}} - 0.70$ V, as an example, Figure 1 shows the time evolution of averaged survival rate $\langle S \rangle_{\mathrm{RF}}(t)$ of ^{133}Cs^{+} ions injected into the RFQ within one RF cycle T_{RF} from $t = 0$ for some different values of V_{DC}. $V_{\mathrm{Acc}} = 6.0$ kV is accelerating voltage of ions, and amplitude and frequency of the RF voltage are $V_{\mathrm{RF}} = 300$ V and $\omega / 2\pi = 1.6$ MHz respectively.

Total number of stacked ions $N(t)$ in RFQ with continuous beam-injection time t is expressed by

$$N(t) = \frac{I_{\mathrm{inj}} T_{\mathrm{RF}}}{e} \sum_{i=0}^{n} \langle S \rangle_{\mathrm{RF}}(t - iT_{\mathrm{RF}}) \qquad (4)$$

where I_{inj} is the injected beam current, time t is multiple of the RF cycle T_{RF} and

$$n = \frac{t}{T_{\mathrm{RF}}} \qquad (5)$$

Therefore, ion stacking efficiency $\epsilon(t)$ defined as the ratio of the $N(t)$ and total number of injected ions $I_{\mathrm{inj}} t / e$ can be written as

$$\epsilon(t) = \frac{T_{\mathrm{RF}}}{t} \sum_{i=0}^{n} \langle S \rangle_{\mathrm{RF}}(t - iT_{\mathrm{RF}}) \qquad (6)$$

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DEVELOPMENTS OF LEBT AND INJECTION SYSTEMS FOR CYCLOTRONS AT RCNP

T. Yorita#, K. Hatanaka, M. Fukuda, H. Ueda, K. Shimada,
Y. Yasuda, T. Saito, H. Tamura, S. Morinobu, K. Kamakura
RCNP, Osaka University, Osaka, Japan

Abstract

Developments of injection systems for cyclotrons at Research Center for Nuclear Physics (RCNP) Osaka University have been carried recently in order to improve the highly intense heavy ions in MeV region for the secondary RI beam, et al. The cyclotron cascade consists with injector AVF cyclotron of K=140 and Ring cyclotron of K=400. The additional glazer lens on axial injection of AVF cyclotron is one of those and it has been installed for the purpose of increasing beam transmission to the inflector in center region of cyclotron. Another development is additional buncher for the heavy ion injection like Xe which requires high voltage in comparison with proton case. Extension of baffle slits on injection line of Ring Cyclotron also has been done to extend the flexibility of injection orbit. Modification of low energy beam transport (LEBT) from 18 GHz Superconducting (SC)-ECR ion source [1] to AVF injection axis also has been carried.

LEBT FOR 18 GHz SC-ECR

Modification of LEBT from 18GHz SC-ECR to injection of AVF cyclotron has been done. Schematic views of previous LEBT and modified LEBT are shown in Fig 1. Previous LEBT has 110 degree bending magnet and 20 degree electrostatic deflector. With this geometry, beam transmission from FC1 to FC3 shown in Fig. 1 was reaching an upper limit of 80 %. According to the calculation of beam envelope using MadX code [2], it is proved that the beam with emittance of more than 200 pi*mm*mrad is limited by baffle of 80 mm in diameter [3]. (See upper figure in Fig. 2.) In the case that these bending magnet and electrostatic deflector are changed by simple 90 degree bending magnet, it is expected that beam transmission would be improve due to the looser limitation as shown in lower figure in Fig. 2. After this modification of LEBT, beam transmission more than 90 % has been achieved except the case that large magnetic field leakage from AVF cyclotron which median plane locates 6m below the LEBT, even additional steering magnets shown in Figure 1 have been used to cancel the leakage field. It is also confirmed that beam with more than 200*pi*mm*mrad emittance measured by emittance monitor shown as EM in Fig. 1 has been transported.

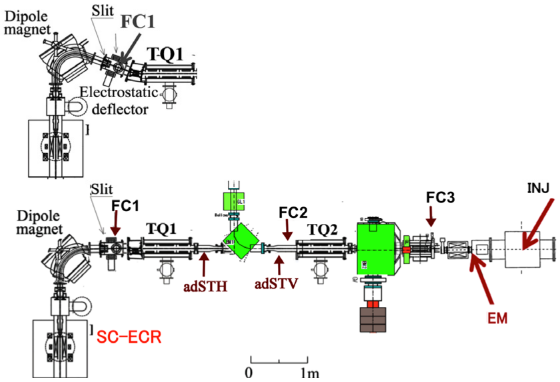

Figure 1: Schematic views of 18 GHz SC-ECR and LEBT components: upper figure shows previous LEBT and lower shows new LEBT. adSTH and adSTV are steering magnets, TQ1 and TQ2 are electrostatic Triplet Q lenses and FC1~3 are Faraday cup.

INJECTION AXIS OF AVF CYCLOTRON

To improve the beam current accelerated by AVF cyclotron, some components have been added to injection axis. Those are additional buncher and glaser lens.

Buncher

To improve the beam current of heavy ion, especially of Xe, additional buncher has been installed on injection axis. In Fig. 3, existing buncher is shown by "b" and located 2550mm above median plane (MP) of AVF. This existing one makes saw wave by RF combining with 1x, 2x and 3x harmonics and maximum saw voltage is

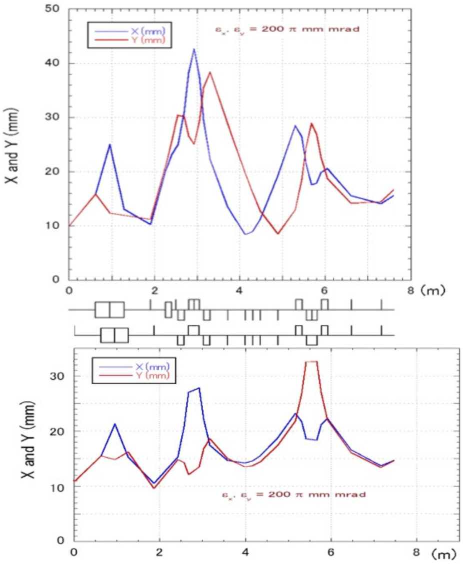

Figure 2: The beam envelopes for previous LEBT and new LEBT calculated by MadX[1]. Both envelopes are assumed the beam emittance of 200 pi*mm*mrad.

#yorita@rcnp.osaka-u.ac.jp

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CONTROL OF LASER ABLATION PLASMA BY PULSED MAGNETIC FIELD FOR HEAVY ION BEAM PRODUCTION*

S. Ikeda#, Tokyo Institute of Technology, Yokohama, Kanagawa 226-8502, Japan, and
RIKEN, Wako, Saitama 351-0198, Japan
M. Costanzo, T. Kaneuse, R. Lambiase, C-J. Liaw, and M. Okamura
BNL, Upton, NY 11973, USA

Abstract

To improve the total charge and quality of a beam pulse from the laser ion source (LIS) operated at Brookhaven National Laboratory (BNL), we attempt to modify the beam current profile to be flatter by applying a pulsed magnetic field to the plasma. For this purpose, we investigated the suitable magnetic field experimentally with a quasi-steady field. We found that a magnetic field decreasing from 90 G to 60 G within 10 µs is expected to create a flat current profile. To drive such a current, we designed a coil and a modified LC discharge circuit. The coil will be installed into LIS at BNL and the effect will be tested.

INTRODUCTION

In the laser ion source (LIS), a pulsed ion beam is extracted from plasma generated by laser irradiation on a solid. The source provides many ion species such as Li, C, Al, Si, Fe, and Au ions to the Relativistic Heavy Ion Collider and the NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory (BNL) [1]. Typically, the plasma drifts and spreads three-dimensionally with a constant velocity distribution in the absence of an external force [2]. The current of the ion beam extracted from the freely spreading plasma varies drastically in time within a single beam pulse. The shape of the current waveform is determined by the velocity distribution and cannot be controlled without applying an external force. In this case, the total charge in a pulse is maximized when the peak current is equal to the space charge limit current while current in most part of beam pulse is less than the limit current by several tens of percent. This means that we can increase the total charge if we can control the current waveform. In addition, the extraction from the varying plasma flux causes larger emittance than estimated by the thermal energy spread. Therefore, as an upgrade of LIS for NSRL operation, we attempt to generate a flat-topped, long beam pulse by controlling the plasma plume with a pulsed magnetic field. A magnetic field can modify the plasma shape. Therefore, we expect to generate a flat-topped beam current by changing the magnetic field in accordance with the plasma density distribution.

To predict a suitable pulsed magnetic field, we investigated the dependence of the plasma flux waveform on the strength of a quasi-steady magnetic field. We designed a coil and a pulse circuit for Fe plasma on the basis of the experimental results.

EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The laser target was a Fe plate. Laser energy, spot size, and power density on the target were 380 mJ, 0.1 cm^2, and 6x10^8 W/cm^2, respectively. The power density was almost the same as that of LIS at BNL and mainly produces singly charged ions. A six-turn coil with a 50 mm diameter and 5 mm length was placed at a distance of 260 mm from the target. The distance was determined with the configuration of the present LIS at BNL. The coil current was generated by a pulse circuit composed of 50 µF storage capacitor. The time scale of the current change was much larger than the duration of plasma passing through the coil. The decrease in magnetic field during the plasma traversal was 10%, small enough to consider the field generated by the coil as steady. A negatively biased ion probe with a 2 mm diameter aperture was used to measure the plasma flux as an ion-saturated current density. The bias voltage was -180 V. The probe was placed at a distance of 690 mm from the target.

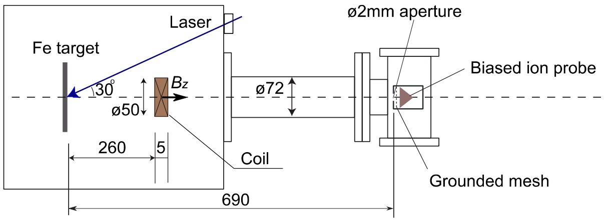

Figure 1: Experimental setup.

RESULTS AND DISCUSSIONS

Figure 2 is the graph of the measured plasma flux. The horizontal axis is time from laser shot. The red curve is the flux without the magnetic field and the other curves are with the field. As shown in the figure, the fast and slow parts of the plasma were enhanced by several tens of gauss magnetic field. In addition, as the field increased, the peaks of both parts increased more while the peak times of the fast part were almost constant and those of the slow part shifted forward.

Based on these results, we can design a suitable pulsed magnetic field. Because the two parts of the plasma were

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#ikeda.s.ae@m.titech.ac.jp

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OBSERVATION OF SUBLIMATION EFFECT OF MG AND TI IONS AT THE HYPER-ELECTRON CYCLOTRON RESONANCE ION SOURCE

H. Muto[#], Center of General Education, Tokyo University of Science, Suwa, 5000-1,
Toyohira, Chino Nagano 391-0292, Japan
Y. Ohshiro, Y. Kotaka, S. Yamaka, S. Watanabe, H. Yamaguchi, S. Shimoura, Center
for Nuclear Study, University of Tokyo, 2-1 Hirosawa, Wako Saitama 351-0198, Japan
M. Kase, S. Kubono, K. Kobayashi, M. Nishimura, Nishina Center for
Accelerator-Based Science, RIKEN, 2-1 Hirosawa, Wako Saitama 351-0198, Japan
M.Oyaizu, Institute of Particle and Nuclear Studies, High Energy Accelerator Research
Organization, 1-1 Oho, Tsukuba Ibaraki 305-0801, Japan
T. Hattori, Heavy Ion Cancer Therapy Center, National Institute of Radiological
Sciences, 49-1 Anagawa, Inage Chiba 263-8555, Japan

Abstract

Light intensities of a grating monochromator during plasma chamber baking, $^{24}Mg^{8+}$ and $^{48}Ti^{13+}$ beam operation were observed at the Hyper -Electron Cyclotron Resonance (ECR) ion source. During chamber baking almost all light intensities were Fe I and Fe II. However, when MgO or TiO_2 rod was inserted into the plasma, and the beam operation was started, the light intensity spectrum significantly changed. In particular, most of the Fe I and Fe II lights disappeared, and Mg or Ti light intensities appeared. In this paper we describe the sublimation pump effect of Mg and Ti ions of ECR ion source during chamber baking and beam tuning.

INTRODUCTION

A grating monochromator with a photomultiplier has been used for beam tuning at the Center for Nuclear Study Hyper-ECR ion source [1,2]. Hyper-ECR ion source has been successfully used as an injector of the multi-charged ion beams of high intensity for RIKEN Azimuthal Varying Field (AVF) cyclotron [3]. Light intensity observation is an especially useful technique for an identification of the ions of the same charge to mass ratio in the plasma [4]. These ions are difficult to separate by an analyzer magnet. Before the operation of multi-charged metal ion beams chamber baking (degassing from the plasma wall) must be done to obtain a required vacuum condition. At the beginning low RF power (~100W) is fed to the residual gas in the plasma chamber, and a degassing process is conducted with increasing RF power gradually until the vacuum gauge reading is settled (1~5 x 10^{-5} Pa order) to start a metal rod insertion into the plasma chamber. In this paper we describe the light intensities during baking, $^{24}Mg^{8+}$ and $^{48}Ti^{13+}$ beam operation.

EXPERIMENTAL

$^{24}Mg^{8+}$ and $^{48}Ti^{13+}$ ions have been produced in the 14.2 GHz Hyper-ECR ion source. The structure and present operation condition of the ion source are described in Ref. 3. At the beginning of the chamber baking RF power of ~100 W was fed to the residual gas of the plasma chamber. Extraction voltage was set to 10 kV. Then a vacuum gauge reading rapidly dropped down to less than 10^{-4} Pa from 10-5 Pa order, and a brake-down of the high voltage power supply happened because of a huge extraction current. Several hours later the extraction voltage was recovered, and vacuum gauge reading also reached 10-5 Pa order. RF power gradually increased to ~ 600 W until obtaining a required vacuum condition (1~5 x 10^{-5} Pa), and a row extraction current of less than 2 mA. After baking of the plasma chamber, a pure metal or an oxidized metal rod was gradually inserted into the chamber without an excessive heat. An excessive heat causes a brake-down of the power supply because of a huge extraction current. The RF power was ranging between 500 and 600W for a highly multi-charged ion production. Argon, Neon, Oxygen and Helium gases were used as supporting gases to keep the plasma condition stable. A grating monochromator (JASCO CT-25C) and a photomultiplier (Photosensor module H11462-031, Hamamatsu Photonics) were used for a light intensity observation during chamber baking and beam operation. Beam resolution of the grating is 0.1 nm (FWHM). L-37 and R-64 filters are used for preventing both second and third order light signals. Wavelengths of the observed lines were determined in accordance with the NIST Atomic Spectra Database [5].

RESULTS AND DISCUSSIONS

Figure 1 shows the optical line spectrum of the Hyper-ECR ion source under plasma chamber baking after three hours from the start. A vacuum gauge reading was 5.7 x 10^{-5} Pa. A drain current (an extraction current) was 12 mA. RF power was 100 W. In this figure most of all peaks were Fe I and Fe II. There were some C, N and O optical lines in the spectrum. However, those lines were all disturbed by Fe I and Fe II strong lights, and therefore it was difficult to separate those. Relative intensities of those Fe I and Fe II are quite strong. Figure 2 shows the optical line spectrum of the ECR plasma during $^{24}Mg^{8+}$ ion beam tuning. A vacuum gauge reading was 1.7 x 10^{-5} Pa. A drain current was 1. 8 mA. RF power was 611 W.

[#] guatemalacocoa@gmail.com

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OPTICAL DESIGN OF THE EBIS CHARGE BREEDER SYSTEM FOR RAON IN KOREA

Hyock-Jun Son, Handong Global University, Pohang 791-708, Rep. of Korea
Jongwon Kim ,RISP, Institute for Basic Science, Daejeon 305-811, Rep. of Korea
Young-Ho Park RISP, Institute for Basic Science, Daejeon 305-811, Rep. of Korea
Moses Chung ,Ulsan National Institute of Science and Technology, Ulsan 689-798, Rep. of Korea

Abstract

Electron beam ion source (EBIS) will be used for charge breeding of rare isotope beams in Rare Isotope Science Project (RISP) the ISOL system. Simulations of EBIS charge breeder system are reported here. The electron beam simulation has been performed by using TRAK code. The electron beam collector deign was optimized based on these electron beam simulation. Ion beam simulation, including acceptance calculation, has also been performed by using TRAK and SIMION codes. In this work, we will also report simulation results on the charge breeding processes in addition to the electron and ion beam dynamics.

INTRODUCTION

In Korea, a heavy ion accelerator facility called RAON is being designed to produce various rare isotopes under the Rare Isotope Science Project (RISP). The RAON has a unique feature of having both Isotope Separation On-Line (ISOL) and In-Flight fragmentation (IF) systems for the various rare isotope productions. Electron beam ion source (EBIS) will be used for main charge breeder in the ISOL system. The EBIS charge breeder has significant advantages over the ECR option for high ion beam intensities, providing higher efficiency, shorter breeding times and significantly better purity of highly charged radioactive ion beams for further acceleration [1]. To reduce emittance of a beam injected into the EBIS, an RFQ cooler is planned to be used as in other facilities. Beam emittance is expected to be reduced by an order of magnitude to around 3 π mm·mrad at 50 keV [2]. The main design and simulation parameters were chosen based on those of the EBIS for the CARIBU project at Argonne National Laboratory [1].

SIMULATION AND OPTICAL DESIGN

The simulation of EBIS system is mainly classified into three parts such as the electron beam dynamics, the ion beam dynamics and electron-ion beam interaction. The TRAK, SIMION and CBSIM codes have been used to design the EBIS charge breeder system for the RISP.

Electron Beam Simulation

The electron gun with IrCe cathode is designed by BINP. The electron beam current is set to be 3 A at the beam energy of 20 keV. The electron beam simulation has been performed from an E-gun cathode to a collector by using TRAK code [3]. The electron beam trajectories are shown in Figure 1. The electron beam current density can reach up to 500 A/cm^2 by maximum magnetic field of about 6 T. This region, which has a maximum electron beam current density, is called ion trap region. The electron beam radius is around 0.45 mm in this region. The radial ion trapping is achieved through the space charge of the electron beam in the ion trap region. The axial trapping is achieved by biasing drift tubes.

The electron beam trajectories in the collector are shown in Figure 2. The electron beam is rapidly spread out from the entrance of the collector because magnetic fields are decreased by a magnetic shield. Furthermore, the electron beam trajecories depend on the potential applied to the repeller and collector body electrode. For the case of Figure 2, the applied voltages of the collector body and the repeller are 1 kV and -10 kV, respectively. The trajectories of electron beam are directly related to the corresponding power density distributions along the inner cylindrical collector surface. Figure 3 presents the corresponding power density distributions under different electrode voltage conditions.

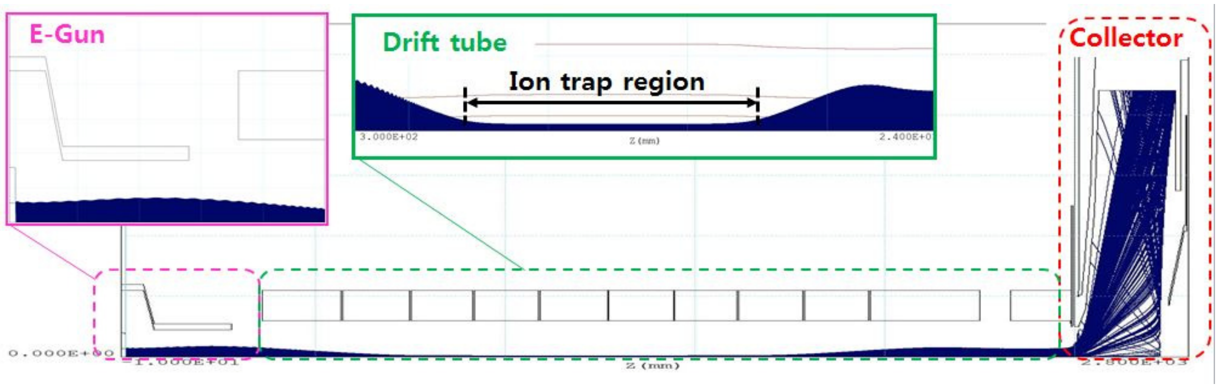

Figure 1: The electron beam trajectories from an E-gun cathode to a collector.

CHALLENGES FOR THE NEXT GENERATION ECRIS

L. Sun[#], H. W. Zhao, J. W. Guo, Y. Yang, W. Lu, W. Wu, L. Z. Ma
Institute of Modern Physics, CAS, 509 Nanchang Rd., Lanzhou 730000, China

Abstract

As an indispensible device to produce intense highly charged ion beams, ECR ion source has evolved into the 4th generation or the next generation. Knowledge from the development of the 3rd generation ECR ion sources could provide valuable reference for the next generation machine design and fabrication, however there are still many challenges with regards to several key technical issues and physics approaches. This paper will review what we have learned from the state of the art ECR ion sources, and then critical aspects concerning the higher performance next generation ECR ion sources development will be discussed.

INTRODUCTION

For existing facilities, or projects to be done, such as FRIB project, SPIRAL2 project, HIRFL facility, RIBF project, RHIC, LHC, FAIR and etc., the preinjectors are essentially important. Higher Q/M or charge state Q from an ion source makes the downstream accelerators more compact and less costly. High Charge state Ion (or HCI) beam at the preinjector is delivered from a HCI source. But because of the capacity and characteristics of an ion source is inherent, the choice of ion beam charge state is a tradeoff between ion beam intensity and charge state. Therefore, the choice of the ion source is also strongly depending on the accelerator needs, for instance, EBIS is the ion source solution to RHIC preinjector [1], and ECRIS is the must-have choice for FRIB project [2]. For high charge state intense CW or long pulse (~ms) ion beams solution, ECR in source is still the dispensable one. HIAF or High Intensity heavy ion Accelerator Facility project to be launched in China, 50 pμA of U^{34+} beam production performance should be demonstrated by the injector ion source so as to ensure the possibility to operate the ion source routinely with an intensity of 40 pμA. The state of the art high performance ECR ion source such as VENUS can produce a beam intensity of ~11.7 pμA U^{34+} [3]which is barely 1/4 of the desired beam intensity. Thanks to the recent intense development with SECRAL, 22 pμA Bi^{31+} has been obtained, which is an indication that with a proper oven that gives sufficient uranium vapour, ECR ion source of 3rd G. can also produce an equivalent beam intensity of U^{34+}. However, this value still needs to be multiplied by a factor of 2.3 to get the HIAF goal.

ECRIS development stepped into the era of the 3rd G. when the LBNL colleagues got the 1st beam with VENUS at 18 GHz in 2002[4]. Together with the following-up development of superconducting ECR ion sources in IMP, MSU and RIKEN, it have been evidenced that the 3rd G. ECR ion source is virtually a very powerful machine in terms of intense highly charged ion beam production. The empirical frequency scaling laws still works well with a 3rd G. ECRIS. According to the scaling laws, one must build a min-B device with high enough magnetic field to confine the much denser plasma that are induced by higher frequency microwave heating, so as to produce intense HCI beams since $\Sigma n_q = n_e$ and $n_e \propto \omega^2$, where n_q is the ion density of charge state q and ω is the microwave frequency. Therefore, to produce highly charged ion beam intensities beyond the 3rd G. ECRIS capacity, a 4th G. ECRIS is very likely the only economical solution. Learned from experience during the development of a 3rd G. ECRIS, there are many technical and physics challenges that need long-term R&D and probably some big break-through. In this paper, we will review and discuss the challenges and difficulties that we could envision during the development of a 4th G. ECRIS.

DEVELOPMENT OF 3RD G. ECRIS

3rd G. ECRISs have shown obvious performance enhancement over the 2nd G. ones, however there are many technical and physics challenges during the ion source development that makes the device more complicated and expensive. In this section, a general review of the typical issues that the ECRIS community have learned during a high performance superconducting ECR ion source development. Figure 1 gives the layout of a typical ECR ion source and the analysing beam line system which.

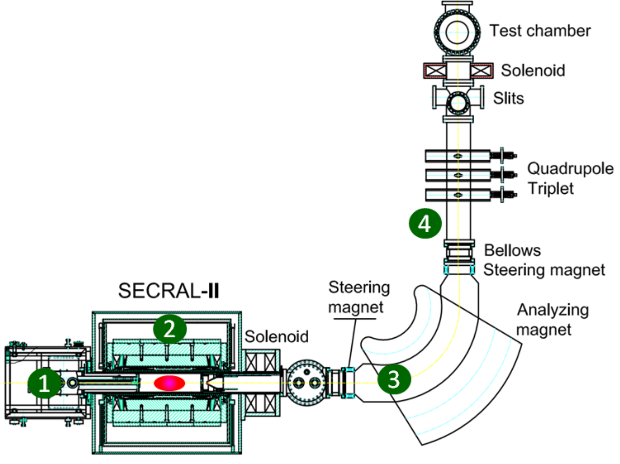

Figure 1: Layout of a typical ECRIS test bench, 1-Ion source injection part; 2-Ion source magnet; 3-ECR beam line; 4-Ananlysing beam line and beam diagnostics.

Superconducting Magnet

One typical feature of the 3rd G. ECRIS is that they are all incorporated with NbTi superconducting magnet technique so as to provide sufficient magnetic field confinement for the optimum operation at 24~28 GHz. Superconducting magnet design and construction is of the

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[#] sunlt@impcas.ac.cn

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PERFORMANCE OF THE LOW CHARGE STATE LASER ION SOURCE IN BNL*

M. Okamura#, J. Alessi, E. Beebe, M. Costanzo, L. DeSanto, J. Jamilkowski, T. Kanesue, R. Lambiase, D. Lehn, CJ. Liaw. D. McCafferty, J. Morris, R. Olsen. A. Pikin, D. Raparia, A. Steszyn
BNL, Upton, NY 11973, USA
S. Ikeda, TITech, Yokohama, Japan/RIKEN, Saitama, Japan

Abstract

On March 2014, a Laser Ion Source (LIS) was commissioned which delivers high brightness low charge state heavy ions for the hadron accelerator complex in Brookhaven National Laboratory (BNL). Since then, the LIS has provided many heavy ion species successfully. The low charge state (mostly singly charged) beams are injected to the Electron Beam Ion Source (EBIS) where ions are then highly ionized to fit to the following accelerator's Q/M acceptance, like Au^{32+}. Recently we upgraded the LIS to be able to provide two different beams into EBIS on a pulse-to-pulse basis. Now the LIS is simultaneously providing beams for both the Relativistic Heavy Ion Collider (RHIC) and NASA Space Radiation Laboratory (NSRL).

INTRODUCTION

In 2007, we started to study low charge state heavy ion beam creation using a laser ion has been originally studied for high current highly charged beam production. It was confirmed that by adjusting the laser power density between a few 10^8 W/cm^2 and about 10^9 W/cm^2, the induced ablation plasma contains mostly singly charged ions from various materials [1]. Although highly charged beam has high intensity with short pulse length, the observed low charge state beams had a much longer pulse of more than a few tens μs at a position of 1 m away from the laser target, with moderate beam currents. Also it was found that the damage of the target surface was quite small since the low charge state production mode needs gently focused spot on the target. This enabled us to apply multiple shots on the same target spot. In 2010, the low charge state laser ion source project was funded by NASA. The project was to enhance the versatility of the EBIS pre-injector [2], which provides various heavy ions to NSRL, by establishing fast species switching in a few second. Unlike other ion sources, the plasma created in a LIS is formed independently from surrounding environments including vacuum chamber wall, residual gases, magnetic confinement field or resonant modes of microwave. Thus, in a LIS, by only mechanically changing target material, we can change the ion species provided without any hysteresis effects.

In March 2014, the first beam was delivered to the EBIS and then ten days later, the beam was supplied to NSRL. Since then most of the solid based ions used in NSRL have been supplied by the LIS [3].

UPGRADE FOR RUN15

Upon the successful beam commissioning of the LIS, we decided to install another laser and target in the system to provide beams to the Relativistic Heavy Ion Collider (RHIC) without any interferences in providing beams to NSRL. The over view of the LIS is shown in the Fig.1.

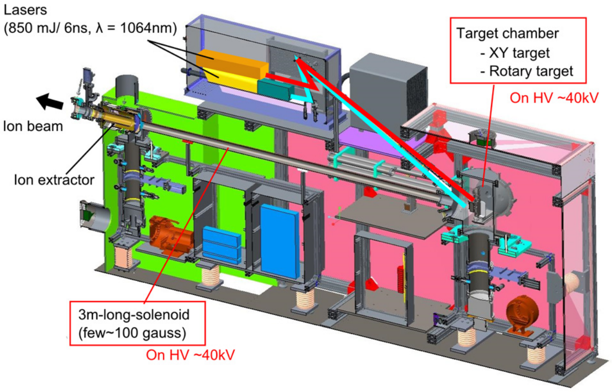

Figure 1: Cut view of the LIS.

In the enclosure made of aluminium on the top of the frame, we have a Quantel Brilliant B Twin laser (6 ns, 1064 nm) which has two independent oscillators [4]. One of the oscillators is used as a backup in case of a failure. In the same enclosure, we added another Quantel Brilliant B laser (single oscillator model). The beam paths of lasers in the enclosure are shown in Fig. 2.

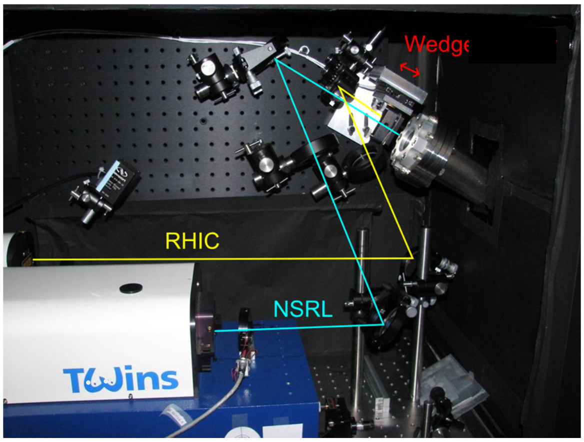

Figure 2: Laser paths in enclosure.

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okamura@bnl.gov

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60 GHz ECR ION SOURCES*

T. Lamy, J. Jacob, J. Angot, P. Sole, T. Thuillier
LPSC, Université Grenoble - Alpes, CNRS/IN2P3, Grenoble, France
M. Bakulin, GYCOM Ltd, Nizhny Novgorod, Russia
A.G. Eremeev, I. Izotov, B. Movshevich, V. Skalyga, IAP/RAS, Nizhny Novgorod, Russia
F. Debray, J. Dumas, C. Grandclement, P. Sala, C. Trophime, LNCMI, Grenoble, France

Abstract

Electron Cyclotron Resonance Ion Sources (ECRIS) deliver high intensities of multicharged heavy ions to accelerators; nowadays the evolution of science requires extremely intense ion beams. Since 1987, semi empirical scaling laws state that the ECR plasma density, in a minimum-B magnetic field configuration, varies like the square of the electromagnetic waves (EM) frequency or of the resonant magnetic induction. The present most performing ECRIS are operated at 28 GHz. In order to significantly increase the ion beam intensities, the use of EM with frequencies of the order of 60 GHz is evaluated worldwide. Conceptual studies based on superconductors are performed and different magnetic configurations accepting such a high ECR frequency are proposed by several groups. Since 2009, LPSC collaborates with IAP-RAS (Russia) and LNCMI (CNRS) and has built the first ECRIS with a topologically closed 60 GHz ECR resonance zone, using radially cooled polyhelices. Unique ion beam intensities have been extracted from this prototype, like 1.1 mA of O^{3+} through a 1mm hole representing a current density of 140 mA/cm^2. The worldwide high frequency ECRIS research status is presented along with a focus on the present LPSC-IAP-LNCMI strategy.

ECRIS STATE OF THE ART

The production of intense multi charged heavy ion beams is performed worldwide with Electron Cyclotron Resonance Ion Sources (ECRIS) using a minimum-B magnetic field to confine the ECR plasma. It is generated by the superimposition of an axial field, produced by at least two solenoids, with a hexapolar radial field produced by permanent magnets or superconducting coils. Until now, the ECRIS development and optimization has been driven by scaling laws [1] specifying semi-empirical values for the optimal magnetic induction on the peak fields of the axial mirror and the radial field at wall. This magnetic field insuring the plasma confinement has to be much higher than the ECR magnetic field value B_{ECR}:

$$B_{ECR} = \frac{\omega_{\mu w} \times m_e}{e}, \quad (1)$$

where $\omega_{\mu w}$ is the frequency of the microwaves (μw), m_e and e, the mass and the charge of the electron. Following the scaling laws, the axial magnetic induction on the axis of an ECRIS, at the injection side, has to be of the order of three to four times B_{ECR}, and the radial magnetic field has to be at least twice this value inside the plasma chamber. Presently, the highest μW frequency injected into a minimum-B ECRIS is 28 GHz [2–6] ($B_{ECR} = 1$ T), that means 3 to 4T for the axial field on the axis and more than 2T for the hexapolar radial field. In such an ECRIS, it is considered that the plasma density is close to the critical one, this assumption allows to say that the plasma density varies like the square of $\omega_{\mu w}$ or B_{ECR}.

These ECRIS, using NbTi superconductors to provide the appropriate magnetic induction, are called 3rd generation ones. Their performances are excellent and more or less in the same range, they produce about 800 to 1400 μA of Ar^{12+} (see previous references for various ion beam data). However their cost is high (a few M€), the development time is long (~5 years) and their construction process presents non negligible risks of failure. The new generation accelerator facilities requiring higher intensities of highly charged heavy ions, a strong research and development activity is necessary to define the so-called 4th generation ECRIS (higher ECR frequencies in the range 40-60 GHz). Such ECRIS are expected to operate with a plasma density up to four times higher than the present 3rd generation. However it necessitates the doubling of the magnetic field induction. A 60 GHz ECRIS magnet, featuring a 3 to 4 T hexapole with a 7T injection peak field requires the use of Nb3Sn superconductor technology [7]. The construction of Nb3Sn magnet is very difficult and risky, because once reacted, the Nb3Sn cable is very brittle. So far, no one has built such a prototype. Experimental research and development activities on ECRIS have reached a bottle neck. We will describe in the next paragraphs the different options evaluated worldwide for ~ 60 GHz ECRIS.

MAGNETIC FIELD CONFIGURATIONS FOR ~60 GHz ECRIS

A few groups in the world began to evaluate and design the next generation ECRIS. The Lawrence Berkeley National Laboratory in USA and Institute of Modern Physics at Lanzhou in China worked on the optimization of the present magnetic structures associating superconducting solenoids and hexapole using either NbTi or Nb_3Sn or both material [7, 8], and they show the difficulty to build such systems. Some other original minimum-B magnetic structures issued from fusion devices are proposed too, like the ARC-ECRIS source [9, 10], consisting in a 'yin-yang' coil creating magnetic field inductions and mirror

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ULTRA HIGH IMPEDANCE DIAGNOSTICS OF ELECTROSTATIC ACCELERATORS WITH IMPROVED RESOLUTION

N.R. Lobanov[#], P. Linardakis, D. Tsifakis and T. Tunningley
The Department of Nuclear Physics, Research School of Physics and Engineering,
The Australian National University, Canberra, Australia

Abstract

This contribution describes a new technique to diagnose faults with high-voltage components in electrostatic accelerators. The main applications of this technique are non-invasive testing of high-voltage grading systems; measuring insulation resistance or determining the volume and surface resistivity of insulation materials used in column posts and acceleration tubes. A simple and practical fault finding data interpretation procedure has been established based on simple concepts. As a result of efficient in-situ troubleshooting and fault elimination techniques, the relative resistance deviation ΔR/R is kept below ±2.5% at the conclusion of maintenance procedures. In 2015 the technique was enhanced by increasing the test voltage from 40 V to 100 V. Experimental verification of the improved resolution was conducted during recent scheduled accelerator maintenance in May-June 2015.

INTRODUCTION

In electrostatic accelerators, a voltage gradient between electrodes in acceleration tubes is established by resistors conducting current from the high voltage terminal to ground at the entry (low energy) and exit (high energy) of the insulating gas containment tank. The configuration of the 14UD accelerator produced by National Electrostatic Corporation is described in [1]. Typical resistors and ceramic failure modes have been classified by severity in [1–3].

A novel technique to diagnose issues with high-voltage components of electrostatic accelerators is described in [1, 4]. Recently, the resolution of the technique was improved by increasing the test voltage from 40 V to 100 V. The verification of the resolution improvement at higher test voltage is the main purpose of the investigation of this paper. The first section outlines the general concept of high impedance measurement and describes the experimental design, together with the protocols for collecting data and the data analysis procedures. The second section presents key experimental results collected from maintenance performed on the 14UD in May-June 2015 during tank opening (TO) #124. The third section presents the interpretation of the main test results.

METHODS

A good voltage measuring technique for electrostatic accelerators can be accomplished in the most efficient way by using an electrometer [5]. The basic configuration of the method is shown in Fig. 1.

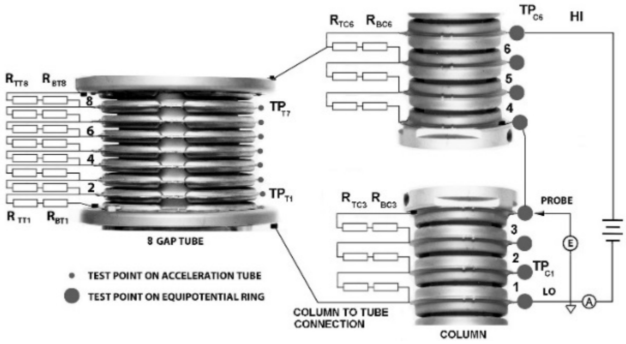

Figure 1: The constant voltage method for diagnostics of the high voltage grading system. The eight gap acceleration tube and the three gaps of the bottom and top section of the column posts are shown. There is a pair of resistors for each column post gap, R_{TCi} and R_{BCi}, and a pair for each acceleration tube gap, R_{TTi} and R_{BTi} where i is the gap number. E and A are the electrometers.

The measured voltage distribution across an eight gap acceleration tube and the corresponding six column post gaps is recorded and shown in Table 1. The measurement set up shown in Fig. 1 illustrates the configuration for an eight gap acceleration tube. A voltage of 100 V is applied to six gaps on the column post by connecting cable leads to equipotential rings marked as LO and HI. Through the column to tube connection, this same voltage is consequently applied to the top and bottom gaps of the eight gap tube. The voltages U_{meas} at each test point is recorded. The voltage drop per tube or column gap U_{gap} is then calculated leading to a mean value of voltage drop per gap $<U_{gap}>$. The error value is calculated by $\Delta[\%]=100(U_{gap}/<U_{gap}>-1)$.

For a chain of N identical resistors of value R in series with applied voltage U_{meas}, if the value of single resistor is changed by ΔR, the relative resistance change is $\Delta R/R = \Delta U \times N/(U_{meas} - \Delta U)$. The resolution of this method is limited by the electrometer accuracy of the voltage measurement, $\Delta U/U = 0.1\%$. For an eight and eleven gap tube structure and $U_{meas} = 100$ V, the $\Delta R/R_{8GT} = 0.8\%$ and $\Delta R/R_{11GT} = 1.1\%$ correspondingly. For six and five gap post structure and the same test voltage, the calculated $\Delta R/R_{6GP} = 0.6\%$ and $\Delta R/R_{5GP} = 0.5\%$. Evaluation of the data presented in a table provides a feel of what is going on in the high impedance circuit under examination. Components with a measured error above ± 2.5% are considered faulty. In the example results presented in Table 1, two faults are highlighted. It suggests that there

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*Work supported by Heavy Ion Accelerators Education Investment Fund
#Nikolai.Lobanov@anu.edu.au

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CONSTRUCTION OF THE 6 MV TANDEM ACCELERATOR SYSTEM FOR VARIOUS ION BEAM APPLICATIONS AT THE UNIVERSITY OF TSUKUBA*

K. Sasa#, S. Ishii, H. Oshima, Y. Tajima, T. Takahashi, Y. Yamato, D. Sekiba, T. Moriguchi, E.Kita
UTTAC, University of Tsukuba, Tsukuba, Ibaraki, Japan

Abstract

The 12UD Pelletron tandem accelerator at the University of Tsukuba was completely destroyed by the Great East Japan Earthquake on 11 March 2011. A replacement has been designed and constructed at the university as part of the post-quake reconstruction project. We planned to install a new horizontal-type 6 MV tandem accelerator. A three-year plan for the new accelerator's construction was started in 2012. The new accelerator system consists of the 6 MV tandem accelerator, four new ion sources, the Lamb-shift polarized ion source, and twelve beam courses. The 6 MV tandem accelerator will be used for various ion beam applications. Routine beam delivery and experiments will start in 2015.

INTRODUCTION

The University of Tsukuba's Tandem Accelerator Complex (UTTAC) is a major center of ion beam research in Japan. We had the 12UD Pelletron tandem accelerator, a 1 MV Tandetron accelerator, a 1 MV high-resolution Rutherford back scattering (RBS) system, and a positron annihilation spectrometry system. The 12UD Pelletron accelerator was a vertical-type large tandem accelerator made by National Electrostatic Corp. (NEC), USA; and was installed at UTTAC as a first Pelletron tandem accelerator in Asia in 1975 [1]. Its main accelerator tank was 17.9 m long and 4.8 m in diameter; its total weight was 120 metric tons. The maximum terminal voltage of 12 MV was available for various ion beam applications.

The Great East Japan Earthquake (9.0 magnitude) of 11 March 2011 severely damaged the 12UD Pelletron tandem accelerator [2]. A seismograph at the University of Tsukuba (part of the National Research Institute for Earth Science and Disaster Prevention, Kyoshin-Net infrastructure [3]) measured the earthquake's maximum acceleration as 371.7 cm/s^2 (gal) and its duration as about 300 s. The vertical-type tandem accelerator was damaged by the sustained shock of the earthquake, and all the high-voltage accelerating columns collapsed in the accelerator tank. Repairing the 12UD Pelletron tandem accelerator was not feasible, and it was shut down in 2011.

We planned to install a new horizontal-type 6 MV tandem accelerator in the experimental room on the first floor to replace the damaged accelerator. The 6 MV tandem accelerator will be used for various ion-beam research projects, such as accelerator mass spectrometry (AMS), microbeam applications, particle-induced X-ray emission (PIXE) analysis for geoscience and materials research, heavy ion RBS and elastic recoil detection analysis, nuclear reaction analysis for hydrogen in materials, and high-energy ion irradiation for semiconductor and nuclear physics.

In this paper, we report the construction status of the 6 MV tandem accelerator and the research programs at the University of Tsukuba.

DESIGN OF THE 6 MV TANDEM ACCELERATOR FACILITY

All experimental equipment is installed on the first floor at UTTAC. Figure 1 gives an overview of the equipment on the first floor. The new accelerator system consists of a horizontal-type 6 MV tandem accelerator, four new ion sources, the Lamb-shift polarized ion source (S1 in Figure 1), and five new beam courses. After the 105° analyzer magnet, the beam line is separated in two directions by the 40° switching magnet in the accelerator room. A high-energy beam transport line equipped with a vertical ion-irradiation system is connected from the accelerator room to the existing experimental room, which houses seven beam courses. A total of 12 beam courses will be available for nuclear physics, ion beam applications, and AMS.

The Lamb-shift polarized ion source was used as the injector of polarized proton and deuteron beams to the old tandem accelerator on the 9th floor at UTTAC [4]. After the earthquake, this ion source was moved to a new experimental building outside the accelerator building. In the accelerator room, there are four negative-ion sources. In Figure 1, S2 is a high-current Cs-sputtering negative-ion source (SNICS II), and S3 is a radio frequency charge exchange ion source (Alphatross) to produce He$^-$ beams for injection into the 6 MV Pelletron tandem accelerator. S4 and S5 are the multi-cathode Cs-sputtering negative-ion sources (MC-SNICSs) for AMS.

In the accelerator room, the ion beam analysis (IBA) system equipped with a high-precision four-axis goniometer is located on the L1 beam course. The L2 beam course has a large environmental testing chamber (1 m diameter) that will be mainly used for the radiation-resistant testing of semiconductor devices for space satellites. The L3 beam course is constructed as the microbeam system for high-sensitivity PIXE analysis of structural materials. The L4 beam course is the rare-particle detection system for AMS. The L5 beam course is a general-purpose line for ion beam applications. Figure 2 shows a photograph of the accelerator room.

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ksasa@tac.tsukuba.ac.jp

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PRESENT STATUS OF A SUPERCONDUCTING ROTATING-GANTRY FOR CARBON THERAPY

Y. Iwata#, K. Noda, T. Shirai, T. Fujita, T. Furukawa, K. Mizushima, Y. Hara, Y. Saraya,
R. Tansho, S. Matsuba, S. Mori, S. Sato, K. Shoda, NIRS, Chiba 263-8555, Japan
T. Fujimoto, H. Arai, AEC, Chiba 263-0043, Japan
T. Ogitsu, KEK, Ibaraki 305-0801, Japan
N. Amemiya, Kyoto University, Kyoto 615-8530, Japan
Y. Nagamoto, T. Orikasa, S. Takayama, Toshiba, Tokyo 105-8001, Japan

Abstract

A superconducting rotating-gantry for carbon therapy is being developed. This isocentric rotating gantry can transport carbon ions with the maximum energy of 430 MeV/u to an isocenter with irradiation angles of over ±180 degrees, and is further capable of performing three-dimensional raster-scanning irradiation. The combined-function superconducting magnets were employed for the rotating gantry. The superconducting magnets with optimized beam optics allowed a compact gantry design with a large scan size at the isocenter; the length and the radius of the gantry are approximately 13 and 5.5 m, respectively, which are comparable to those for the existing proton gantries. A construction and installation of the superconducting gantry is in progress, and beam commissioning will begin from this autumn. We will report an overview as well as a present status of the superconducting rotating-gantry.

INTRODUCTION

In recent years, an application of high-energy particle accelerators to cancer therapy has attracted many attentions, and a number of medical particle accelerators were constructed around the world. In the ion radiotherapy, the rotating gantry is a very attractive tool, because a treatment beam can be directed to a target from any of medically desirable directions, while a patient is kept in the best position. This flexibility of the beam delivery for this type of the gantry, *isocentric rotating gantry*, is advantageous to treat tumors having wide range of tumor sites and sizes.

For proton cancer therapy, rotating gantries were commonly constructed around the world. However, it would be very difficult to construct a rotating gantry for carbon therapy, because the required magnetic rigidity for carbon beams having energy of 430 MeV/u is roughly three times higher than that for proton beams having energy of 250 MeV/u, and hence the size and weight for the gantry structure, including magnets and its counterweight, would become considerably larger. To overcome this problem, a superconducting rotating gantry for carbon therapy is being developed [1]. The construction as well as installation of the superconducting gantry is in progress, and beam commissioning will begin from this autumn. In this paper, an overview as well as a present status of the gantry is presented.

OVERVIEW OF THE GANTRY

Figure 1 shows a three-dimensional image of the superconducting rotating gantry. This rotating gantry has a cylindrical structure with two large rings at both ends. The end rings support the total weight of the entire structure, and are placed on turning rollers so as to rotate the beam line on the rotating gantry along the central axis over ±180 degrees. Carbon beams, provided by the HIMAC, are transported with ten sector-bending superconducting magnets, mounted on the gantry structure through each of their supporting structures; they are directed on a target located at the isocenter

Figure 2 shows a schematic drawing of the beam line, installed in the rotating part of the gantry. The beam line consists of ten sector-bending superconducting magnets (BM01-10), a pair of scanning magnets (SCM-X and SCM-Y), and three pairs of steering magnets as well as a beam profile monitor (STR01-03 and PRN01-03). To design the compact gantry, combined-function superconducting magnets are employed except for BM07 and BM08. These superconducting magnets have a surface-winding coil structure, and can provide both dipole and quadrupole fields.

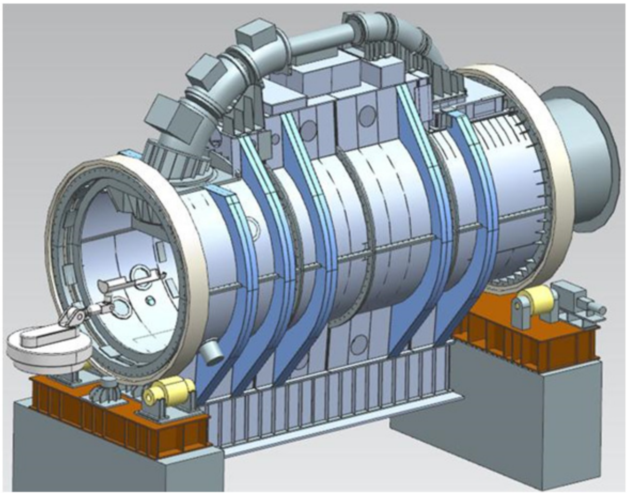

Figure 1: Schematic drawing of the superconducting rotating gantry.

#y_iwata@nirs.go.jp

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A COMPACT HADRON DRIVER FOR CANCER THERAPIES WITH CONTINUOS ENERGY SWEEP SCANNING

Leo Kwee Wah[1], Toshikazu Adachi[2,3], Tadamichi Kawakubo[2], Takumi Monma[2,4], Tanuja Dixit[5], and Ken Takayama[2,3,4,6]
[1]Malaysian Nuclear Agency, Bangi, Kajang, Malaysia
[2]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan
[3]The Graduate University for Advanced Studies (SOKENDAI), Hayama, Kanagawa, Japan
[4]Tokyo Institute of Technology, Nagatsuda, Kanagawa, Japan
[5]Society for Applied Microwave Electronics Engineering & Research (SAMEER), Mumbai, India
[6]Tokyo City University, Setagaya, Tokyo, Japan

Abstract

The compact hadron driver for future cancer therapies based on the induction synchrotron concept, which has been proposed recently, is discussed. This is a fast cycling synchrotron that allows the energy sweep beam scanning. Assuming a 1.5 T bending magnet, the ring can deliver heavy ions of 200 MeV/au at 10 Hz. A beam fraction is dropped from the barrier bucket at the desired timing and the increasing negative momentum deviation of this beam fraction becomes enough large for the fraction to fall in the electrostatic septum extraction gap, which is placed at the large *D(s)* region. The programmed energy sweeping extraction makes spot scanning beam irradiation on a cancer area in depth possible.

INTRODUCTION

3D spot scanning of hadron beams to cancer tissues of human organs is of most concern in this society [1]. We will focus on spot scanning by the energy sweeping extraction from a fast cycling induction synchrotron [2]. A hadron bunch captured in the barrier bucket is continuously accelerated by the induction flat voltage and a fraction of the beam bunch is spilled out from the stable barrier bucket by non-adiabatically changing timing of the acceleration voltage controlling trigger signal in the desired time period. Equilibrium orbits of spilled out particles move inward depending on the dispersion function *D(s)* and those particles enter into the electrostatic septum gap region to be further deflected inward, and then propagate through the extraction region downstream consisting of extraction device such as a Lamberson magnet to put on the extraction beam line. Start of the extraction and a number of spilled out particles are simply determined by controlling of the gate signal. Thus, we can obtain a driver beam for the cancer therapy with the function of 3D spot scanning, the energy of which changes continuously in the same acceleration cycle as shown in Fig. 1 by integrated with the ramping pattern of guiding magnet. Details of this scheme have been proposed in Reference [3]. Its essence will be described here.

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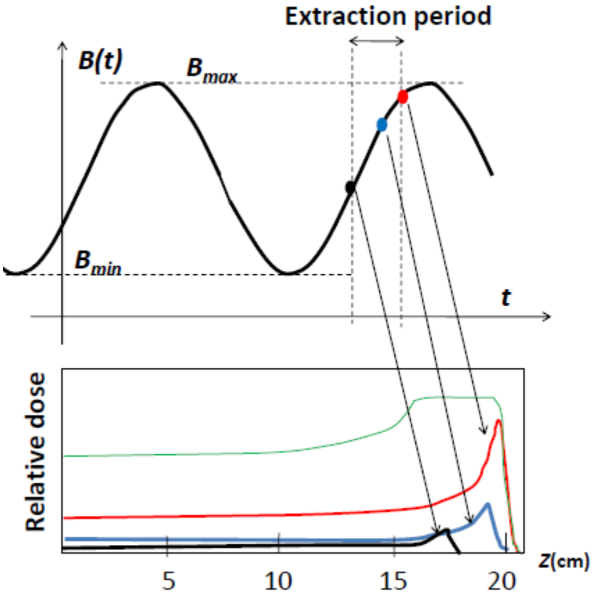

Figure 1: Energy sweep extraction in the same acceleration cycle and integrated dose along the path, where *B(t)* is the magnetic flux density of the guiding magnet.

In this paper, a practical method to realize the energy sweeping extraction from a fast cycling synchrotron is proposed.

Ring Lattice

Properties of the lattice design and machine parameters [3] as shown in Fig. 2 and Table 1must comprise of:

i) Dispersion-free region for induction acceleration devices and injection device.
ii) Localized large flat dispersion region for the extraction device with the length of 3 m.
iii) Local betatron phase advance of $\pi/2$ for the fast extraction.

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leo@nuclearmalaysia.gov.my

DESIGN, FABRICATION AND TESTING OF COMPACT DIAGNOSTIC SYSTEM AT IUAC

R.V.Hariwal, [1, 2, #] H.K.Malik, [2] R. Mehta, [1] S.Kedia, [1] and V. Verzilov [3]
[1]Inter-University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi 110067, INDIA
[2]Plasma Waves and Particle Acceleration Lab, Department of Physics, I.I.T Delhi 110016, INDIA
[3]Accelerator Division, TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T2A3, CANADA

Abstract

High Current Injector (HCI) [1] is an upcoming accelerator facility at Inter-University Accelerator Centre, New Delhi, India. This comprises of high temperature superconducting Electron Cyclotron Resonance (HTS-ECR) ion source [2], normal temperature Radio Frequency Quadrupole (RFQ), IH-type Drift Tube Linear (DTL) resonators [3] and low beta superconducting Quarter Wave Resonator (QWR) cavities to accelerate heavy ions having $A/q \leq 6$. The compact diagnostic system consists of Faraday cup, slit scanner and capacitive pick up to measure the current, profile, position and bunch length of incident ion beam respectively. It is especially designed and fabricated to measure the beam parameters at the entrance of each of six IH-DTL resonators. The compactness is preferred to minimize the transverse and longitudinal emittance growth at the entrance of DTL resonators. The beam current and profile measurements of various heavy ion beams at different energy have been carried out to validate the design and fabrication of the diagnostic system. Here we are presenting the detailed information about its design, fabrication and various test results.

DEVELOPMENT OF COMPACT DIAGNOSTIC SYSTEM

Compact Diagnostic Box (CDB)

A compact diagnostic chamber (Fig.1) is made of 12 mm thick stainless steel (SS-304) material. As the drift space between two DTL cavities is crucial, to accommodate the diagnostic chamber and quadrupole triplet, we need to minimize the drift. A highly compact diagnostic chamber has been designed and fabricated indigenously. The diagnostic chamber is of 70 mm longitudinal length. The radial dimension of the box is approximately 160 mm and the beam aperture is 20 mm. It has eight faces, in which two of them are orthogonal to each other and they have been designed specifically to mount the Faraday cup and slit scanner. The chamber was leak tested at the leak rate of 1×10^{-11} mbar.l/s. Without any separate pumping station, the vacuum of 1×10^{-7} mbar was achieved, but this can be further improved by adding a separate pumping station.

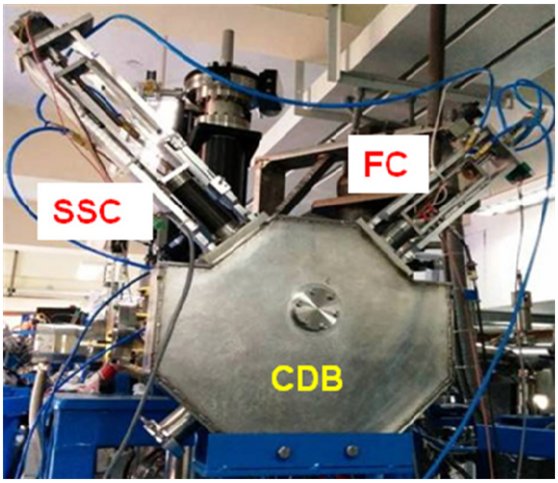

Figure 1: Compact Diagnostic Box.

Faraday Cup (FC)

A water cooled Faraday cup (FC) has been fabricated to measure the current. The cup has a beam aperture of 25 mm and its length is 20 mm along the beam direction (Fig. 2). It is made of Oxygen Free High Conductivity (OFHC) copper material. Based on the expected beam power from HCI the FC is designed for few hundred watts of beam power. The suppressor ring, which retains the secondary electrons on the cup, is made of SS 304 material. The FC is completely shielded by the 3 mm thick tantalum sheet. The linear movement of FC is controlled by a pneumatic cylinder, which provides the 60 mm strokes in the diagnostic box.

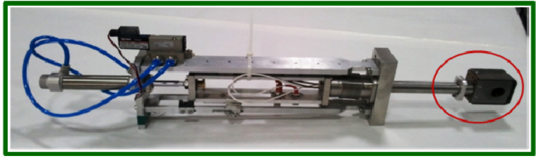

Figure 2: Faraday Cup.

It is a very compact design and can be used to measure the current of the order of few nanoamperes to hundreds of microampere current.

Slit Scanner (SSC)

The slit scanner (Fig. 3) is fabricated indigenously for the measurements of beam positions and beam profiles in HCI beam line. It scans the beam in both transverse directions with the help of two 500 micron slits. The slits are made orthogonal to each other and moves linearly in such a way that they cut the ion beam in x and y directions.

[#] hariwal@gmail.com

HEAVY ION LABORATORY, UNIVERSITY OF WARSAW – A UNIQUE RESEARCH CENTER IN POLAND

J. Choinski, P. Gmaj, Heavy Ion Laboratory University of Warsaw, Warsaw, Poland

Abstract

On behalf of the staff of the Heavy Ion Laboratory of the University of Warsaw (HIL) we present the current state of development of the laboratory. HIL is a user facility operating a K_{max}=160 isochronous heavy ion cyclotron, unique in central Europe. Two ECR ion sources, a homemade 10 GHz and a commercial (Supernanogan Pantechnik) 14.5 GHz, supply ions to the machine. In the center of the machine a "spiral" type inflector bends the ion beams into the median plane. The current system allows ions from He up to Xe to be accelerated with energies up to 10 A MeV. The research program of HIL includes nuclear physics, solid state physics, medical radioisotope production, biology and detector testing. In 2012 HIL launched a new facility - the Radiopharmaceuticals Production and Research Center (RPRC). This is a fully GMP compliant production facility of radiopharmaceuticals for PET. It operates a General Electric PETtrace 840 cyclotron and a complete production line of FDG. An external beam line with target station, designed and constructed by the Laboratory, allows metallic and powdered samples to be irradiated, extending medical isotope research by using proton and deuteron beams.

THE HEAVY ION LABORATORY OF THE UNIVERSITY OF WARSAW

The Heavy Ion Laboratory [1] is situated in the centre of the University of Warsaw and the Polish Academy of Sciences Scientific Campus Ochota, 500 m from the Public Central Teaching Hospital affiliated to the Medical University of Warsaw (MUW) - see Figure 1.

Figure 1: Scientific Campus Ochota.

HIL was founded in 1979 by an agreement between three state institutions: the Ministry of Science and Higher Education, the Polish Academy of Sciences and the National Atomic Energy Agency. The Laboratory plays the role of a user facility and is an inter–faculty unit of the University of Warsaw. Currently, HIL operates two cyclotrons: a U-200P heavy ion cyclotron and a compact cyclotron accelerating protons and deuterons. In order to host both accelerators the HIL building was divided into two parts. The main part is assigned to the heavy ion cyclotron with its research infrastructure. The second part is dedicated to the compact cyclotron and is located in the underground part of the HIL building, see Figure 2.

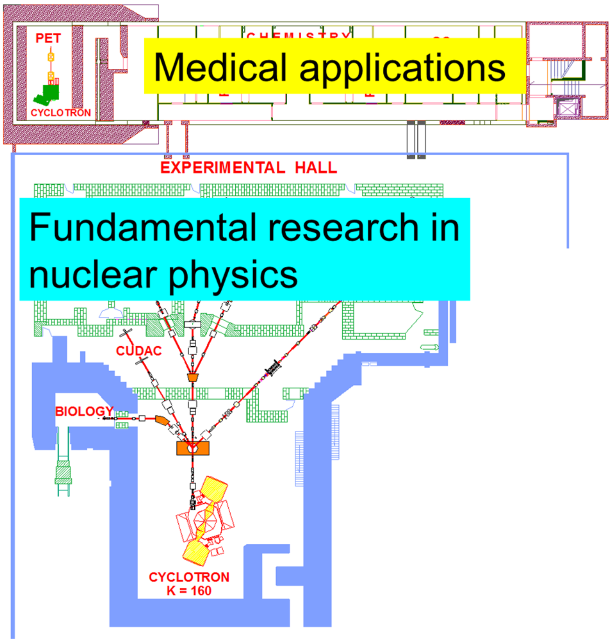

Figure 2: A scheme of the building.

With two cyclotrons HIL is the perfect place to carry out fundamental research in nuclear physics, solid state physics, medical radioisotope production, biology and detector testing. All the above mentioned activities are based on the heavy ion cyclotron with a K value varying from 120 to 160. This is an isochronous cyclotron with four straight sectors. The stripper foil system allows ions with energies from 2 to 10 MeV/A to be extracted.

Two ECR ion sources supply ions to the machine. The older ECRIS, homemade, operates at 10 GHz and delivers beams of light elements from He to Ar. The second ion source, a commercial Supernanogan from Pantechnik, bought a few years ago, operates at 14.5 GHz and delivers beams up to Xe. It is equipped with a high temperature oven and a “Sputtering” system. With this source not only gaseous but also metallic ions are available for acceleration. The sources are mounted in the basement of the cyclotron cave and connected to the machine via an

RADIOACTIVE ION BEAMS PROGRAMME AT VECC-KOLKATA, INDIAN EFFORTS

Alok Chakrabarti#, VECC, Kolkata, India

Abstract

An ISOL type Radioactive Ion Beam (RIB) facility has been built at VECC with *K*130 cyclotron that delivers proton and alpha particle beams as the driver accelerator. So far ion beams of $A/q \leq 14$ have been accelerated up to 414 keV/u using a Radio Frequency Quadrupole (RFQ) linac and three IH-Linacs. Two more IH Linac modules are being added to increase the energy to 1.0 MeV/u. A few RIBs have been accelerated with typical intensities of 10^3 to 10^4 pps at the separator focal plane.

In the next phase, the plan is to construct a new facility called ANURIB (Advanced National facility for Unstable and Rare Isotope Beams) at the upcoming new campus of VECC at New Town in Kolkata. ANURIB aims to attract a wider user community in nuclear physics, nuclear-astrophysics, and materials science and is being built as a national facility. There will be two primary accelerators in ANURIB aimed at producing both neutron-rich and proton-rich beams. One is a 50 MeV 100 kW superconducting electron linac photo-fission driver that is being developed in collaboration with TRIUMF Canada and the other a 50 MeV proton injector to be developed indigenously. To be built in phases starting from low energy of few keV/u in Phase-I to a final energy of 100 MeV/u in Phase-II, ANURIB will be a combined ISOL and PFS type facility.

INTRODUCTION

It was in the mid-nineties that the idea of developing a Radioactive Ion Beam facility took shape at VECC, prompted by exciting physics opportunities in study of exotic nuclei that led to activities world-wide for construction of RIB facilities. It was realized that this would need design and development of advanced accelerators, ion-sources and detector systems. It was decided: a) to proceed in small R&D steps to acquire the capability, and b) to collaborate with an international laboratory that has already started working in this field and has the experience of designing and building advanced accelerators.

To meet these objectives and to keep the budget small, it was decided to use the existing *K*130 room temperature cyclotron as the driver or the primary accelerator and construct an ISOL type RIB facility around the same [1-3]. A collaboration agreement with RIKEN, where RI Beam Factory project was just about to start, was signed in 1996. The VECC RIB project received some seed money in 1998 for design of the facility. Funding for construction of accelerators was made available in 2003 and again in 2007. These have led to development of a number of linear accelerators [4-10], the physics designs of which were mostly done in collaboration with RIKEN. Also, facilities for material science and laser spectroscopy of exotic nuclei have been built. Proton and alpha particle beams from the cyclotron have been used to produce rare isotopes using suitable targets. Using a gas-jet recoil transport coupled ECR technique [11, 12] radioactive atoms, ion beams of ^{14}O ($t_{1/2}$=71 sec), ^{42}K ($t_{1/2}$=12.4 hrs), ^{43}K ($t_{1/2}$=22.2 hrs), ^{41}Ar ($t_{1/2}$=109 min) have been produced at the facility. RIB of ^{111}In ($t_{1/2}$= 2.8 d) has been developed in the off-line mode.

ACCELERATOR DEVELOPMENT

A layout of the facility is shown in Fig. 1. The scheme is to produce rare isotopes using a suitable target in alpha/proton induced nuclear reactions, ionize the reaction products in two ion-sources in tandem [2, 6], mass separate the reaction products to choose the rare isotope of interest and finally accelerate the beam in a series of linear accelerators. The charge breeder is an ECR ion-source operating at 6.4 GHz. The post- accelerators are – a Radio Frequency Quadrupole (RFQ) linac that accelerates heavy-ions of $A/q \leq 14$ to 100 keV/u, followed by five IH linac tanks for further acceleration to 1 MeV/u. Two superconducting QWR modules to boost the energy to 2 MeV/u are also planned.

First, a 1.7 metre long RFQ [4, 5, 8] was constructed with the aim to study machining and fabrication aspects and conduct comprehensive beam tests. Commissioned in September 2005 this was the first RFQ to be built in India and was a major milestone in the RIB project. Operating in CW mode at 33.7 MHz, this RFQ accelerates ion beams from energy 1.38 to 29 keV/u. Typical measured beam transmission is 85%. This RFQ is now a part of the material science beam-line (Figure 1). A second RFQ (Fig. 2), operating at 37.8 MHz and 3.4 m long has been commissioned in year 2008 [9]. The high power RF sources for RFQ and linacs have been developed indigenously in collaboration with SAMEER, Mumbai. The critical components of the RFQ viz. the copper electrodes and supporting posts have been machined at Central Mechanical Engineering Research Institute, a CSIR laboratory at Durgapur, 200 km from Kolkata. Other components have been made in Indian industry.

#alok@vecc.gov.in

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