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HIGH VOLTAGE UPGRADE OF THE 14UD TANDEM ACCELERATOR

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Abstract

The 14UD at the Australian National University's Heavy Ion Accelerator Facility (HIAF) operated at a maximum voltage of 15.5 MV after the installation of tubes with a compressed geometry in the 1990s. In recent years, the performance of the accelerator has shown a gradual decline to a maximum operation voltage of ~14.5 MV. There are some fundamental factors that limit the high voltage performance, such as SF6 gas pressure, field enhancement due to triple junctions and total voltage effect. In addition, there are non-fundamental factors causing high voltage degradation. These are: operation with faulty ceramic gaps; operation at inappropriate voltage and SF6 pressure combinations; SF6 leaks into the vacuum space; use of SF6 and O2 as a stripper gases; poor electron suppression in the high energy stripper and frequent use of highly reactive ions such as sulphur and fluorine. In 2019 ANU initiated a feasibility study of available options to upgrade the entire population of supporting posts, acceleration tubes and grading resistors. In this paper we will discuss the preferred technologies and strategies for successful implementation of this development. The chosen design is based on NEC tubes with magnetic electron suppression and minimized steering of ion beams.

INTRODUCTION

Accelerator users are most familiar with tubes that are the products of three commercial suppliers: NEC, HVEC and Dowlish. Each manufacturer features a particular type of electron suppression technology.

The original NEC 333 kV tubes were assembled with "dead" sections of the lowest longitudinal field containing a substantial radial component to suppress the multiplication of particles that originated on electrodes. In the later compressed geometry, "dead" sections were removed and in order to restore strong axial field modulation, the electrodes were of variable diameter and dished [1, 2]. In Munich, the 25 mm thick, 25 mm diameter heater plate was replaced by a "zero" length 25 mm diameter electrode resulting in inferior trapping efficiency for ions and electrons originating from the aperture and from ionization of residual gas. To improve the trapping, V-shaped electrodes with angles ranging from 30 up to 50 degrees were successfully introduced to replace the flat electrode.

Still, no suppression existed for gas ionizations near the axis. In the 1990s, the overall length of a single tube increased to allow for operation up to 500 kV. Each section contained 21 live gaps with V-electrodes every 10 or 11 gaps. The trapping efficiency of Vs installed in the middle of tubes was weaker. In later tube designs, the V-electrodes were removed completely and weak magnets added to provide suppression of particles that originated on apertures and in gas [3]. The transverse magnetic field rotates by 90 degrees after every ~7 gaps of the tube.

However, this scheme was not optimum. After the New Delhi machine, NEC changed the tubes to use two pieces per MV, with either 20 or 21 ceramic gaps depending on the accelerator modules. NEC has used 20 and 21 gap tubes with 50 degree cones without external magnets in at least 7 accelerators, including the 20UR at JAEA-Tokai. This solution works even though the lack of suppression may limit heavy-ion beam currents.

At the same time, NEC has used similar tubes with 22 gaps but without cones in tandems up to 6 MV, and they conditioned very well. Again, the lack of suppression may limit heavy-ion beam currents. Based on these results, NEC has made a short-term decision to add weak magnets to the 22 gap tubes for 6 MV systems. In this module, there are 4 apertures per 1 MV, without cones, with 1 aperture in the middle on each 22 gap tube, that is, 11/11. The magnetic field reaches 47 gauss on axis between apertures and falls off near each aperture because the field is rotated 90 degrees from one set of 11 gaps to the next. In the 6 MV case, the modelling shows an average electron energy of only 222 keV and, with just 6 MV of length, an easily correctable net deflection for protons. These new tubes all have one internal 1 inch aperture, so for the modules of the 14UD there would be four 10-gap intervals between apertures per MV. NEC does not use cones in any apertures. These tubes have been used in all "U-series" accelerators since New Delhi and, at least up to 6MV and 8MV, NEC finds them to be well behaved. The U-series use the ceramic posts as in the 14UD, as opposed to smaller S-series, which uses an acrylic column. Magnets are external, hidden in the spark gaps.

The focus of this study is to evaluate suppression efficiency for charged particles originating on axis and on the surfaces of Ti electrodes. Suppression devices should not compromise the transmission of the ion beam, both CW, pulsed, chopped and bounced (AMS) in the full ranges of accelerating voltages from a few MV up to 14.5 MV and mass range from M=1 (protons) up to M=244 (Pu).

The goal of this study to select an appropriate tube technology which will deliver at least the same performance of the 14UD accelerator or exceed it in terms of transmission, e-suppression and improved beam loading. This will be strongly dependent on simulations as the practical confirmation is mainly demonstrated in 6 MV machines, which are much smaller than the 14UD.

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STATUS AND PERSPECTIVE OF ELECTRON CYCLOTRON RESONANCE BASED CHARGE BREEDERS

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Abstract

Since their invention in the late 1990s, Electron Cyclotron Resonance (ECR) based Charge Breeders (CB) have been used in several Isotope Separation On Line (ISOL) facilities to study radioactive ions. Many developments were carried out on these devices to enhance their performances and improve the knowledge on the ECR charge breeding process in laboratories worldwide. At LPSC, recent experiments in pulse mode were carried out to estimate plasma parameters such as the ionisation, charge exchange and confinement times, providing indications on the high charge state ions confinement. A new model of the 1+ beam capture was also proposed and experimentally verified by studying the stopping of injected ions of different masses. Present ECR charge breeder optimum efficiencies vary from 10 to 20% depending on the ion species and the facilities specifications. The total efficiency ranges from 35 to 90% and the charge breeding time from 10 to 25 ms/q. Electron Beam Ion Source (EBIS) is an alternate CB technology with lower contamination yield, yet limited injection flux capability. ECR CB sustains a higher 1+ beam intensity acceptance and its prospects to improve the efficiency, charge breeding time and beam purity are identified.

INTRODUCTION

In flight and Isotope Separation On Line are complementary methods used to produce radioactive ions. For nuclear astrophysics and nucleus structure studies far from the valley of stability, the energy of the particles have to be raised in the MeV/u range. Elements are produced at rest in the ISOL case and a post accelerator is used to obtain the final energy. Several criteria must be fulfilled to allow successful investigation of these particles which are often produced at low yield or with a short half-life (<1 s) : in particular the beam purity, the possibility to tune the final energy, a low radiation background and the beam optics quality. Since the acceleration of the particles scales with the charge state, a Charge state Breeder is typically installed before the LINear ACcelerator (LINAC) or the cyclotron. Presently 8 ISOL facilities using a CB are in operation worldwide, or in final construction phase. Table 1 summarizes the characteristics of these facilities.

In these facilities, the Radioactive Ion Beam (RIB) production yield ranges between 10^2 up to 10^{10} ions/s and different types of 1+ sources are used. The CB has to be adapted to the configuration and experiment (ion mass, 1+ beam optics, requested charge state . . .) and reach optimal performances. Two different technologies are presently in use : EBIS and ECRIS (ECR Ion Source). Recently 2 facilities were converted to EBIS CB mainly to increase the purity of the re-accelerated beams. This paper presents the ECRIS CB technology and possible ways to improve its performances.

ECR CHARGE BREEDING

ECR CB Origin

Charge breeders based on the use of Electron Cyclotron Resonance ion sources emerged in the frame of the PIAFE project [1]. Neutron rich radioactive ions with a mass ranging between 75 to 150 amu were to be produced from the bombardment of ^{235}U target by the high neutron flux (5×10^{13} n/(cm^{2}s)) of the ILL reactor. The species were to be ionised, accelerated at 10-30 keV, mass separated and transported to LPSC (formerly named ISN) over a 400 m distance. The ion charge state had to be increased in order to allow the post acceleration of the particles with the LPSC double cyclotron system «SARA». The idea came up to use the ECR ion source plasma as a «plasma catcher» where the RIBs would be stopped before interacting with the metallic walls, thus suppressing the sticking time of the solid-state catcher which was used until then. In the same time, the ECR plasma had to increase the charge state of the incoming RIBs up to high charge states. The first charge breeding experiments with an ECR ion source were carried out in 1995 with the 10 GHz ISOL MAFIOS ion source using the «backward» injection method, i.e. through the extraction electrode. Soon the injection through the upstream side of the source was tested and adopted : comparable efficiencies were reached in a simpler way and injection in continuous mode was possible, which was of high interest for post acceleration with cyclotrons or LINACs operating in continuous mode [2]. This injection scheme is presently used by all the ECR charge breeders.

ECR CB Principle

ECR CB are based on minimum-B type ECR ion sources. Modern configurations consist of a set of 2 or 3 coils and a yoke to generate an axial magnetic field profile with a maximum B_{inj} at injection, a local maximum B_{ext} at extraction and a minimum B_{min} in between, as illustrated in Fig. 1. An

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DEVELOPMENTS TOWARDS A COMPACT CARBON ION LINAC FOR CANCER THERAPY*

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Abstract

Hadron therapy offers improved localization of the dose to the tumor and much improved sparing of healthy tissues, compared to traditional X-ray therapy. Combined proton/carbon therapy can achieve the most precise dose confinement to the tumor. Moreover, recent studies indicated that adding FLASH capability to such system may provide significant breakthrough in cancer treatment. The Advanced Compact Carbon Ion Linac (ACCIL) is a conceptual design for a compact ion linac based on high-gradient accelerating structures operating in the S-band frequency range. Thanks to this innovation, the footprint of this accelerator is only 45 m, while its capabilities are well beyond the current state of the art for hadron therapy machines and include: operation up to 1000 pulses per second, pulse to pulse energy variation to treat moving tumors in layer-by-layer regime. ACCIL is capable of accelerating all ions with mass-to-charge ratio A/q ~2 to a full energy of 450 MeV/u, and that includes protons, helium, carbon, oxygen and neon. With very short beam pulses of ~1 μs and high instantaneous dose delivery, ACCIL is capable of delivering FLASH-like doses (>100 Gy/sec) for most ion species. In close collaboration between Argonne and Radiabeam, we have developed different design options and prototypes of the high-gradient structures needed for ACCIL. Following an overview of the ACCIL design and its capabilities, the most recent results from the high-gradient structure R&D and future plans will be presented and discussed.

ACCELERATORS IN HADRON BEAM THERAPY – WHY NOT A LINAC?

Cyclotrons are currently dominating the field of proton therapy while synchrotrons are being used for ion beam therapy, especially carbon ions. A cyclotron is a continuous-wave (cw) fixed-energy machine; it does not offer the flexibility of adjusting the time structure or the energy of the beam by simple tuning. Energy degraders are used to adjust the beam energy, these are material blocks that also degrade the primary beam quality and generate secondary radiation requiring significant shielding.

Synchrotrons are pulsed accelerators which offer more flexibility in pulse structure and pulse-to-pulse change in energy without significant radiation or deterioration in beam quality. However, due to the multi-turn acceleration in a synchrotron and typical beam extraction, these changes could take a few seconds.

Being a single-pass machine, a pulsed linear accelerator (linac) is in principle capable of adjusting the pulse repetition rate and the beam energy hundreds of times per second (~200 Hz). So, why ion linacs are not deployed in cancer therapy? Linacs have already been proposed for protons [1], but using the same technology used for high-intensity research machines [2], such a linac would be hundreds of meters long. This have limited their deployment in a hospital or university setting, and it is the main reason why synchrotrons are currently dominating the field of ion beam therapy.

However, the intensity requirements for ion beam therapy are rather modest, 10^{10} p/s for proton and 10^9 p/s for carbon, which could in principle be delivered in very short pulses (~μs) at a relatively low duty cycle (~10^{-4}). Combined with the possibility of using small-aperture accelerating sections, these features enable the use of high-frequency high-voltage copper cavities. Due the wide-spread use and commercial availability of S-band RF sources, the frequency range of ~3 GHz was a natural choice. And, taking advantage of high-gradient accelerating structure developments for CLIC [3], an accelerating gradient of 50 MV/m seems quite achievable in this frequency range, and was taken as a goal for current and future therapy linac proposals [4].

Finally, a fast-pulsed linac will enable the much-desired flexibility in beam tuning and the fast and efficient beam scanning to allow 3D dose painting, as well as real-time image-guided therapy and targeting of moving targets. By changing the pulse repetition rate, the beam intensity could be adjusted up to 10^9 ions per second (10^{10} for protons), typically needed for therapy. The carbon beam energy could be changed continuously up to the full energy of 430 MeV/u required to penetrate the depth of a human body, which is equivalent to a 30 cm of water. The beam delivery from a linac will be similar to synchrotron beam delivery through fixed beam lines or gantry systems. However, the beam quality of the linac could enable much smaller magnets and therefore more compact gantries.

ACCIL – THE ADVANCED COMPACT CARBON ION LINAC

The Advanced Compact Carbon Ion Linac (ACCIL) is the most compact full-energy carbon ion linac proposed for therapy [5]. In Europe, there are proposals for a combined cyclotron and linac (cyclinac) and an all-linac for carbon beams [6], in addition to the ongoing LIGHT project for a

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ESTABLISHMENT OF THE NEW PARTICLE THERAPY RESEARCH CENTER (PARTREC) AT UMCG GRONINGEN

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Abstract

After 25 years of successful research in the nuclear and radiation physics domain, the KVI-CART research center in Groningen has been re-established as the PARticle Therapy REsearch Center (PARTREC). Using the superconducting cyclotron AGOR and being embedded within the University Medical Center Groningen, it operates in close collaboration with the Groningen Proton Therapy Center.

PARTREC uniquely combines radiation physics, medical physics, biology and radiotherapy research with an R&D program to improve hadron therapy technology and advanced radiation therapy for cancer. A number of further upgrades, scheduled for completion in 2023, will establish a wide range of irradiation modalities, such as pencil beam scanning, shoot-through with high energy protons and Spread Out Bragg Peak (SOBP) for protons, helium and carbon ions. Delivery of spatial fractionation (GRID) and dose rates over 300 Gy/s (FLASH) are envisioned. In addition, PARTREC delivers a variety of ion beams and infrastructure for radiation hardness experiments conducted by scientific and commercial communities, and nuclear science research in collaboration with the Faculty of Science and Engineering of the University of Groningen.

PARTREC FACILITY

The PARticle Therapy REsearch Center (PARTREC) is a newly established research facility at the University Medical Center Groningen (UMCG). It builds on the success of the former KVI-CART research center and utilizes the superconducting cyclotron AGOR (see Fig. 1) for experimental research, mainly in radiation physics and biology.

Built by a French-Dutch collaboration in Orsay in the period 1987 – 1994 and commissioned in Groningen in 1996, AGOR operated within the KVI-CART research center [1]. It was used for 25 years to perform research in nuclear physics and on fundamental symmetries [2] as well as for detector development, radiation hardness testing [3,4] and radiobiological experiments. Recently besides nuclear physics, radiation and accelerator physics and radiobiology,the research focus has been shifting towards medical applications and therefore the facility and its personnel was integrated into the University Medical Center Groningen (UMCG). Hence,

Figure 1: Photograph of the AGOR accelerator.

the new structure, additional goals and the new infrastructure (described in the chapters below) have been formalized via a creation of the new research center named PARTREC (logo in Fig. 2) was created.

Working in close collaboration with the UMCG Groningen Proton Therapy Center (GPTC), PARTREC research activities encompass medical physics, radiation biology experiments, tests of different radiation therapy treatment modalities and development of detector technology. In addition, it provides opportunities for experiments in the domain of radiation hardness, for both the scientific and commercial communities, and nuclear science, in collaboration with the Faculty of Science and Engineering of the University of Groningen.

Figure 2: Logo of new PARticle Therapy REsearch Center (PARTREC).

BEAM DELIVERY CAPABILITIES

The magnetic field of AGOR has a varying value between 1.7 to 4.1 T. It is produced by two superconducting main coils and fifteen trim coils for the precise field shaping, with three iron hill sectors for focussing and defocussing of the circulating beam (see Fig. 3).

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HEAVY ION STRIPPING

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Abstract

Ion stripping is primarily an essential technique for heavy ion accelerators in order to reach higher beam energies within reasonable size and budget limits. Due to the stochastic nature of the stripping process, the resulting ion beam contains ions of different charge states. Therefore, high beam loss is typically associated, making the net stripping efficiency one of the decisive elements of the overall performance of an accelerator facility. Several technical implementations of strippers have been developed and are still being investigated in order to obtain optimal stripping for different ion beams by employing different kinds of stripping targets, namely gaseous, solid and more recently fluid materials. Strippers of the first two types are in operation at GSI. High beam intensities resulting in prohibitive energy deposition and target destruction are increasingly challenging. The foil stripper situated in the transfer line from the UNILAC to SIS18 employs a magnetic sweeper as a possible remedy. At the same time, it offers four stripping options to be used in parallel. Optimizing a stripper may potentially increase the overall performance by a large factor with less effort than other actions. This gave rise to the pulsed gas stripper project at the GSI UNILAC, which aims at the introduction of hydrogen as regular stripping target.

INTRODUCTION

The GSI accelerator facility consists of the UNIversal Linear ACcelerator UNILAC, the SchwerIonenSynchrotron (heavy ion synchrotron) SIS18, two storage rings (ESR and CRYRING@ESR) and the decelerator HITRAP. Several stripping devices are operated in the area of UNILAC and SIS18 in order to facilitate acceleration and deliver ions with the charge states required by the various experiments. Regarding the wide range of ion energies and beam intensities, different stripping technologies are applied. Figure 1 shows a schematic overview of the UNILAC and the locations of the stripping devices. Stripping at the lowest energy of 1.4 MeV/u between the high current injector and the Alvarez DTL is achieved by a gas stripper, while all subsequent strippers use foils or sheet metal. The SIS18 area and its strippers are not shown. UNILAC and SIS18 possess the unique feature to deliver individual beams made from up to three different ion species in a rapid time multiplex scheme. This has to be supported by the strippers as well.

UNILAC together with SIS18 will serve as the heavy ion injector chain for the Facility for Antiproton and Ion Research (FAIR) [1], currently under construction. The reference projectile for FAIR is the heavy ion ^{238}U. To meet the beam requirements for FAIR, upgrade programs for both accelerators have been and are being conducted to increase the delivered beam intensities especially for heavy ions. The task for the UNILAC is to deliver $\approx 3 \cdot 10^{11}$ U^{28+} ions within 100 µs pulse length and adequate emittance at repetition rates of up to 2.7 Hz to the subsequent synchrotron. A major step in this pursuit will be the use of hydrogen in the gas stripper in addition to the traditional nitrogen operation. The hydrogen stripping target will improve the mean charge state of all stripped ions. For heavy ions, the width of the charge state distribution will be decreased, which results in an enhanced beam intensity of up to 60% [2]. This makes use of the electron capture suppression associated with low Z targets.

STRIPPING FUNDAMENTALS

A stripper consists of a gaseous or solid, infrequently liquid or plasma stripping target, which is placed in the beam line. While the ions cross it, they experience collisions with the target atoms. Many devices will therefore lead to stripping as a side effect. Stripping is the result of charge transfer processes caused by the collisions between the fast moving ions of the particle beam and the stationary target atoms.

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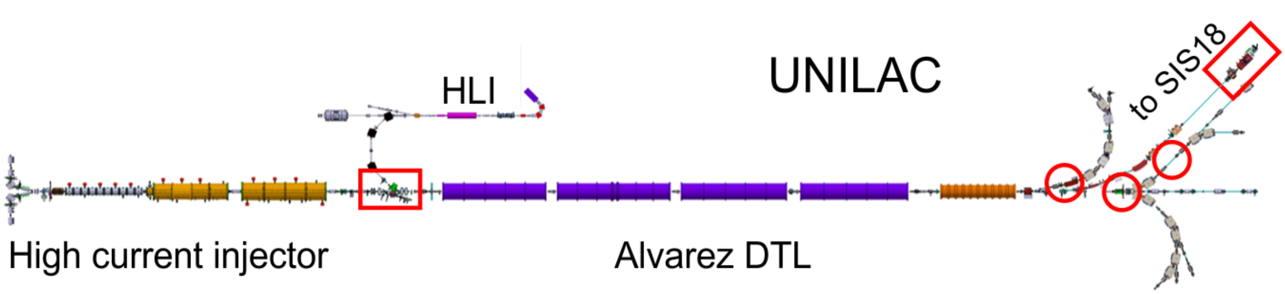

Figure 1: The UNILAC and its main constituents: The high current injector with two source terminals and an RFQ/IH-DT linac (left), the high charge state injector HLI (top centre), and the main Alvarez-DT linac (centre). To the right are several user branches and the transfer channel to the synchrotron. Stripper sections for general accelerator operation are framed with red boxes, strippers for special user requirements with red circles.

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LIQUID LITHIUM CHARGE STRIPPER COMMISSIONING WITH HEAVY ION BEAMS AND EARLY OPERATIONS OF FRIB STRIPPERS*

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Abstract

The Facility for Rare Isotope Beams (FRIB) at Michigan State University is a 400 kW heavy ion linear accelerator. Heavy ion accelerators normally include a charge stripper to remove electrons from the beams to increase the charge state of the beams thus to increase the energy gain. Thin carbon foils have been the traditional charge stripper but are limited in power density by the damage they suffer (sublimation and radiation damage) and consequently short lifetimes. Because of the high beam power, FRIB had decided to use a liquid lithium charge stripper (LLCS), a self-replenishing medium that is free from radiation damage. FRIB recently commissioned a LLCS with heavy ion beams (^{36}Ar, ^{48}Ca, ^{124}Xe and ^{238}U beams at energies of 17-20 MeV/u). Since there had been no experimental data available of charge stripping characteristics of liquid lithium, this was the first demonstration of charge stripping by a LLCS. The beams were successfully stripped by the LLCS with slightly lower charge states than the carbon foils of the same mass thickness. The LLCS started serving the charge stripper for FRIB user operations with a backup rotating carbon foil charge stripper. FRIB has become the world's first accelerator that utilizes a LLCS.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) at Michigan State University produces rare isotopes through nuclear reactions between a production target and heavy ions that are accelerated to energies above 200 MeV/u by a driver linac [1]. Figure 1 shows the configuration of the FRIB driver linac, which consists of three linac segments and two folding segments. At FRIB, the charge stripping occurs in the 1st folding segment (FS1), where beams are accelerated to 17-20 MeV/u after the 1st linac segment (LS1). When the facility is operated at the full power, the beam power at the stripper would reach 40 kW.

It is known that heavier ion beams deposit higher energy in matters as the beams traverse them [2]. Full power uranium beams at FRIB would deposit a thermal power of 1600 W within a 1.5 mg/cm^2 thick carbon foil, or a thermal density of about 70 MW/cm^3 assuming the beam diameter is 2 mm. This ultra-high thermal load would cause serious damages to the carbon foil. The solid carbon foil would also suffer radiation damages. Even the best performance carbon foil that has been successfully used in RIKEN's Radioactive Isotope Beam Factory (RIBF) [3] would not allow continuous full power operations at FRIB.

To overcome this, a self-replenishing medium was sought because it is free from radiation damage and could be a good heat remover. A helium gas stripper has been successfully operated at RIKEN's RIBF [4], and a new charge stripping device based on the helium gas stripper (charge stripper ring, CSR) has been proposed [5]. A drawback of using a gas as the stripping medium is that the equilibrium charge state is significantly lower than solids or liquids. Therefore FRIB has decided to use liquid lithium as the stripper medium as proposed by Nolen [6]. FRIB also considered the helium gas stripper as a backup option of the liquid lithium charge stripper. The key technology to develop was an efficient isolation between the high-pressure helium cell and the ultra-high-vacuum beamline. Because of the limited space available in the driver linac, FRIB cannot use a differential pumping system like the one used in RIKEN, thus sought to develop a "plasma window" [7]. The recent results are published elsewhere [8].

Recently FRIB commissioned a liquid lithium charge stripper (LLCS) with heavy ion beams [9], which was the world's first demonstration of a LLCS. FRIB has also started user operations after the successful completion of its construction. The LLCS as well as a rotating carbon foil charge stripper were used in user operations. This paper describes the results obtained in those tests and operations.

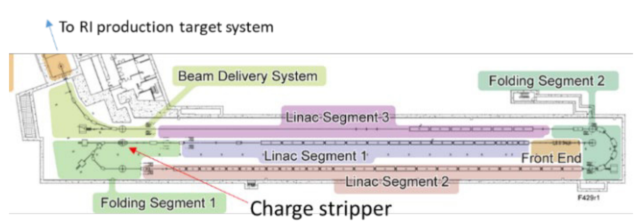

Figure 1: FRIB driver linac configuration. There are three linac segments (LS1, LS2 and LS3) and two folding segments (FS1 and FS2). The charge stripper is located at FS1 before the beam makes a 180 degree turn where the desired charge state(s) is selected for the acceleration at LS2 and LS3.

LIQUID LITHIUM CHARGE STRIPPER SYSTEM AT FRIB

Figure 2 shows a sketch of the FRIB LLCS system. Since liquid lithium is reactive with air, water, and many other materials, safety in use of liquid lithium is the key to

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DEVELOPMENT, FABRICATION AND TESTING OF THE RF-KICKER FOR THE ACCULINNA-2 FRAGMENT SEPARATOR

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Abstract

The Acculinna-2 radioactive beam separator was designed and built between 2012 and 2014, installed and tested by Sigmaphi in 2015 and in full operation since 2016 at the Flerov laboratory of JINR in Dubna. In order to achieve efficient separation of neutron-deficient species, an RF kicker was foreseen since the beginning of the project but was put on hold for many years.

In 2016 Sigmaphi got a contract to study, build, install and test an RF kicker with a variable frequency ranging between 15 and 21 MHz and producing 15kV/cm transverse electric fields in a 10 cm gap over a 1m distance.

The paper briefly recalls the rationale of an RF-kicker to separate neutron-deficient species. It then goes through the different steps of the study, initial choice of the cavity structure, first dimensioning from analytical formulas, finite elements computations and tuning methods envisioned, down to a final preliminary design.

The fabrication and tests of a 1/10 mock-up and final study, design, construction and factory testing of the real cavity are presented but, because of U400M cyclotron closure, no beam tests have been performed so far.

INTRODUCTION

A detailed description of the Acculina-2 RI beam separator and a comparison with other separators can be found in [1–3] and references therein. The purpose of the RF kicker in the Acculinna-2 separator is outlined in [2] and with more details in [3], which, as a review paper, provides a very complete panorama of intended experiments with Acculinna-2.

In the present paper, we describe the design, fabrication, installation and testing of the RF kicker. The choice of Sigmaphi by JINR is the continuation of the long-time collaboration during which Sigmaphi studied, built, installed and helped starting a large part of the Acculinna-2 facility.

The reader will find information on the rationale for RF kickers for RIB beamlines in references [4–6] and we only briefly summarize them here for consistency. Proton-rich (aka neutron-deficient) isotopes, are difficult to separate because

- being close to the dripline, they are usually produced with very low yields.
- their magnetic rigidity BΔ is similar to the rigidity of the low energy tail of species close to the stability zone, which are produced in much larger quantities.Hence, they are shadowed by a more intense background and magnetic separation is inefficient.

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However, these “magnetically entangled” species differ in their velocities v, hence in the time TOF it takes for them to travel the distance D between their point of production and a further away location in the beamline.

$$B\rho = \left(\frac{p}{Qq}\right) = \left(\frac{mv}{q}\right)\left(\frac{A}{Q}\right) = \frac{1}{TOF}\left(\frac{Dm}{q}\right)\left(\frac{A}{Q}\right) ,$$

$$TOF = \left(\frac{Dm}{B\rho q}\right)\left(\frac{A}{Q}\right) = C^{ste}\left(\frac{A}{Q}\right) .$$

In the case of fully stripped ions, we have

$$TOF = C^{ste}\left(\frac{Z+N}{Z}\right) = a + \frac{b}{Z} ,$$

a and b being 2 constants, which we can summarize as: For the same number of neutrons and identical rigidities, the time-of-flight increases as atomic number decrease.

Every such “TOF-different” component of the beam enters the kicker at a different time and experiences inside it a different vertical electric field, kicking some components up, some down -and any in-between- according to the time structure of the beam and that of the electric field. After some drifting distance, the vertical kick is transformed into a vertical distance to the optical axis and a suitable set of slits and vertical steering magnets allow selecting the part of the beam one is interested in. An RF-kicker/deflector/sweeper is a TOF to vertical deflection transformer.

SCOPE OF WORK

- Cavity design: variable frequency and high mechanical and thermal stability, cooling, vacuum pumps and gauges.
- Motorized coupling, tuning and fine-tuning loops, measuring pick-up loops
- Cavity fabrication and factory tests
- RF generator and amplifier
- Command and control system
- On-site start-up and tests

CAVITY DESIGN

Most requirements are given in Table 1 (identical required and achieved values), to which we must add maximum height of 2300 mm and weight of 3000 kg. See also graphical summary of these parameters in Fig. 1.

The dimensional constraints advocate for a quarter-wave coaxial resonator, a cavity of a similar type as the one built for RIBF [7]. Analytical formulas for such a simple geometry e.g. [8] permit fast preliminary estimates.

In order to address the frequency change in the rather large requested range, modifying the inductance, the capacitance or a mix of both were envisioned.

Changing the inductance requires a sliding short-circuited plate around the central pillar that reduces the cavity length

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A 3D PRINTED IH-TYPE LINAC STRUCTURE – PROOF-OF-CONCEPT FOR ADDITIVE MANUFACTURING OF LINAC RF CAVITIES*

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Abstract

Additive manufacturing (AM or "3D printing") has become a powerful tool for rapid prototyping and manufacturing of complex geometries. A 433 MHz IH-DTL cavity has been constructed to act as a proof of concept for additive manufacturing of linac components. In this case, the internal drift tube structure has been produced from 1.4404 stainless steel using 3D printing. We present the concept of the cavity as well as first results of vacuum testing and materials testing. Vacuum levels sufficient for linac operation have recently been reached with the AM linac structure.

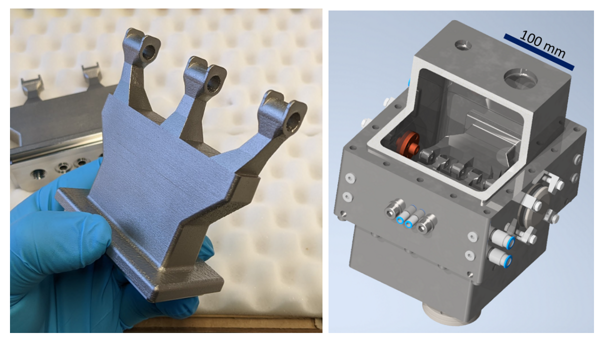
INTRODUCTION

Additive manufacturing (AM) of metal parts may provide an interesting new way to manufacture accelerator components. As technology is evolving, the quality and accuracy of parts manufactured this way is improving. Recently, a number of studies on the topic of AM for linear accelerator components have been published [1–5]. Based on these promising results, we aim to evaluate the suitability of AM parts for direct manufacturing of normal conducting linac structures. To that end, a reproduction of the beam pipe vacuum tests in [2, 3] was performed and upon success, a prototype cavity with a fully printed drift tube structure was constructed. The cavity is designed to be UHV capable and includes cooling channels reaching into the stems of the drift tube structure for power testing with a pulsed 30 kW rf amplifier.

Prototype Design and Concept

The prototype cavity was designed for a resonance frequency of 433.632 MHz, which is a harmonic of the GSI UNILAC operation frequency [6]. In combination with a targeted proton beam energy of 1.4 MeV this scenario allows for a compact accelerator at the limits of feasibility and is therefore a good benchmark for the new approach. The internal drift tube structure is fully 3D printed from stainless steel (1.4404), see Fig. 1a. Due to the lower complexity of the cavity frame and lids, they are manufactured by CNC milling of bulk stainless steel. Printing those parts would not be cost efficient.

The cavity is just 22 cm wide and 26 cm high (outer walls), with a length of 20 cm on the beamline (flange to flange). A center frame acts as the foundation for the cavity. This 7 cm high center frame provides the precision mount points for the girder-drift tube structures and end-drift tubes. While the end-drift tubes are mounted in vacuum, the girders have a vacuum sealing surface at the bottom. Two half shells are mounted on the top and bottom of the center frame. The cavity is equipped with four CF40-Flanges for vacuum, rf-coupler and tuner, as well as metal sealed KF40 flanges for the beamline and smaller ports for diagnostics. Rf simulations show that the bulk of the rf losses during the operation of this cavity is concentrated on the drift tube structure and the cavity frame. Therefore, water channels are included in the girders up to the drift tubes and also in the center frame. A 3D CAD view of the full construction is shown in Fig. 1b.



(a) (b)

Figure 1: Overview of the cavity geometry and printed parts. (**a**) 3D printed girder drift tube structure. (**b**) Cross section of the assembled cavity model.

RF Simulations

The cavity design was optimized for a frequency of 433.632 MHz. To minimize the need for support structures during the manufacturing process, the shape of the girder-drift tube structure was optimized to reduce overhang. Simulations of electromagnetic fields in the cavity were performed with the CST Microwave Studio eigenmode solver. Figure 2 shows the resulting electric field distribution in the cavity, with the typical characteristics of a $\beta\lambda/2$ IH-type structure. From the idealized design model, the simulated dissipated power for the effective acceleration voltage of $U_{eff} = 1$ MV is $P_{loss} = 24.82$ kW. With an inner wall length of 146 mm, this corresponds to an effective shunt impedance of $Z_{eff} = 287.13$ MΩ/m[1], showing the high efficiency of such an IH-type structure.

EXPERIMENTS

Since the first construction of the cavity in late 2020/early 2021, several experiments have been conducted to evaluate certain aspects of the cavity suitability for linac operation. The following sections will explore the different experiments.

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[1] The stated value in [7] was much too low, due to a typo.

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DEVELOPMENT AND COMMISSIONING OF THE K500 SUPERCONDUCTING HEAVY ION CYCLOTRON*

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Abstract

The K500 Superconducting Cyclotron (SCC) has been developed indigenously and commissioned at VECC. The three-phase Radio-Frequency (RF) system of SCC, consists of three half-wave cavities placed vertically 120 deg. apart. Each half-wave cavity has two quarter-wave cylindrical cavities tied together at the centre and symmetrically placed about median plane of the cyclotron. Each quarter-wave cavity is made up of a short circuited non-uniform coaxial transmission line (called "dee-stem") terminated by accelerating electrode (called "Dee"). The SCC, operating in the range 9 to 27 MHz, has amplitude and phase stability within 100 ppm and 0.1 deg. respectively. The overview of all the subsystems of the cyclotron along with low-level RF (LLRF), high and low power RF amplifiers, cavity analysis, absolute Dee voltage measurement using X-ray method, amplitude and phase control loops will be presented in the talk. The commissioning of the cyclotron with first harmonic Nitrogen4+ beam extracted at 252 MeV, while operating at 14 MHz RF frequency, along with the correction of first harmonic magnetic field error by repositioning the cryostat within 120 micron accuracy, will be discussed briefly.

INTRODUCTION

The Variable Energy Cyclotron Centre (VECC) at Kolkata, India, has been focused on building cyclotrons as a tool for nuclear physics experiments and medical applications. The center has developed a $K130$ cyclotron with normal conducting coils and a $K500$ cyclotron with superconducting coils. Also, VECC has been operating IBA-make 30MeV Medical Cyclotron from production of radioisotopes.

Recently, the first harmonic $Nitrogen^{4+}$ beam of 18 MeV/A was extracted from the $K500$ SCC (as shown in Fig. 1). A 14 GHz Electron Cyclotron Resonance (ECR) ion source (Fig. 2) is integrated with the cyclotron using 28 meters long low energy beam transport line. Initially, the internal beam could be accelerated up to the extraction radius, but could not be extracted due to imperfection of ~ 50 Gauss of 1^{st} harmonic magnetic field (B_1) at the extraction region prohibiting the beam's extraction. The root cause of the imperfection was a damaged dowel resulting in erroneous position of the coil and cryostat. The machine was dismantled and corrected. Subsequently, the coil and cryostat were repositioned with an accuracy within 120 µm, by devising a new positioning mechanism for precise radial movement of the cryostat. Three radial screws were used to move the 12 Tonnes cryostat. Dial gauges at the outer radius of the cryostat were used to estimate the movement of the cryostat. The final measurement of the cryostat position was taken with a portable CMM machine. Extensive mapping of magnetic field at different excitations of primary coils was carried out. The gross reduction of the imperfection of B_1 achieved to ~7 Gauss at extraction radius resulted in successful extraction of the beam.

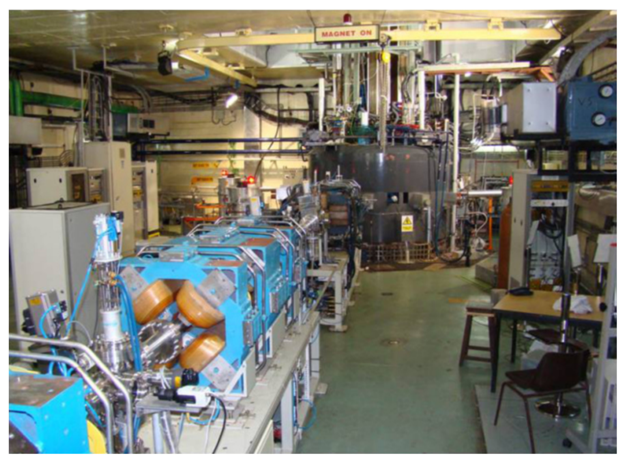

Figure 1: The K500 superconducting cyclotron at VECC.

Figure 2: 14GHz ECR ion source and injection beam line.

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BEAM TUNING AUTOMATION ACTIVITIES AT TRIUMF*

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Abstract

The particle accelerator complex at TRIUMF provides beams for secondary particle production including rare isotopes. The post acceleration of rare isotope ions demands frequent changes of beam properties like energy and changes of the ion species in terms of isotope and charge state. To facilitate these changes to beam properties and species, a High Level Applications (HLA) framework has been developed that provides the essential elements necessary for app development: access to sophisticated envelope simulations and any necessary beamline data, integration with the control system, version control, deployment and issue tracking, and training materials. With this framework, one can automate collection of beam data and subsequently pull that data into a model which then outputs the necessary adjustments to beam optics. Tuning based on this method is model coupled accelerator tuning (MCAT) and includes pursuits like the training of machine learning (ML) agents to optimize corrections benders. A summary of the framework will be provided followed by a description of the different applications of the MCAT method — both those currently being pursued, and those envisioned for the future.

MOTIVATION

Programs that aid accelerator operation are often developed in an ad-hoc manner by physicists — *particularly for themselves as end-users* — as the facility expands.

In the case of TRIUMF, a lab more than 50 years old, there are various tools and programs that have been developed by experts for different operating systems using different programming languages for a variety of different accelerators across the campus. However, this approach does not scale well as the size and complexity of the lab increase — too many tools can end up being duplicated and not all are well maintained.

The newly installed e-linac and upcoming new proton beamline from the main cyclotron will drive rare istope beam (RIB) production via new target stations and associated beamlines in ARIEL. This is expected to triple the number of deliverable RIB hours to experiments.

To allow for reliable operation in this new era, a High Level Applications (HLA) task force was established at TRIUMF in 2017 [1] with the mission to reduce facility overhead and improve beam reliability [2]. To accomplish this, the taskforce was to create a standard software framework for creating applications that can be easily used at any of our many accelerator facilities, as depicted below in Fig. 1.

Figure 1: Layout of TRIUMF beamlines based on data from acc xml files. E-linac devices are shown in orange, primary proton beamlines in red, the new ARIEL RIB transport beamlines in green, and ISAC RIB transport beamlines in blue.

HLA FRAMEWORK

The software development framework itself is critical to the development of robust apps as well as enticing staff members to contribute to existing code repositories rather than working alone.

Jaya – Integration with the Control System

Jaya is a web application acting as the middle layer that allows communication with the underlying low-level control system. It currently maintains channel access (CA) monitors on over 5000 process variables (PVs) distributed over five independent EPICS subnets at TRIUMF.

PV values are stored in an in-memory database (Redis). This way, any HLAs that request to read PV values only poll the HLA server database and don't produce any additional load on the EPICS networks.

A second noteworthy component of jaya is the additional backend processes that allow for long running measurements. Jaya uses a Python task queue package called Celery, which allows passing of jobs between the jaya web application and the Celery backend process via Redis. Using this tool, jaya allows users to create custom scans or measurements that allow for setting, waiting, and saving of data as required by the users. An example of this functionality is shown in Fig. 2. In the measurement shown [3], the current of a magnetic quadrupole was changed in various step sizes and directions, while saving magnetic field data to an HLA database used for storing beam measurements (beamDB).

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BEAM INSTRUMENTATION, CHALLENGING TOOLS FOR DEMANDING PROJECTS – A SNAPSHOT FROM THE FRENCH ASSIGNED NETWORK

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Abstract

Particle accelerators are thrusting the exploration of beam production towards several demanding territories that is beam high intensity, high energy, short time and geometry precision or small size. Accelerators have thus more and more stringent characteristics that need to be measured. Beam diagnostics accompany these trends with a diversity of capacities and technologies that can encompass compactness, radiation hardness, low beam perturbation, or fast response and have a crucial role in the validation of the various operation phases. Their developments also call for specialized knowledge, expertise and technical resources. A snapshot from the French CNRS/IN2P3 beam instrumentation network is proposed. It aims to promote exchanges between the experts and facilitate the realization of project within the field. The network and several beam diagnostic technologies will be exposed. It includes developments of system with low beam interaction characteristics such as PEPITES, fast response detector such as the diamond-based by DIAMMONI, highly dedicated BPM for GANIL-SPIRAL2, emittance-meters that deals with high intensity beams and development for MYRRHA, SPIRAL2-DESIR and NEWGAIN.

NETWORKS AT THE IN2P3

The scientific programs carried out at the French National Institute of Nuclear and Particle Physics (IN2P3) require specific instruments that can only be developed within the laboratories themselves. Indeed, the expected performance of the instruments are more and more constrained in terms of granularity, sensitivity, dynamics, resolution, speed, tolerance to radiations, integration and transparency.

Instrumentation therefore mobilises a large number of professions and skills and becomes, in itself, a strategic axis of Research & Technology (R&T). The hyper-specialisation of professions and the current context of resources have led to rationalising this R&T upstream, by promoting the emergence of networks of experts across laboratories around the main families of detectors and associated transverse techniques for examples mechanics, gas detectors, cryotechnics, semi-conductors, photo-detection, beam instrumentation.

These networks are intended to be privileged exchange tools allowing experts to best share the know-how acquired between projects and between laboratories. They are an important factor of cohesion and efficiency, just as they generate specific training.

This network organisation makes it possible to identify emerging technologies, local skills, and to support them. Exchanges between experts promote the sharing of best practices, the identification and management of common engineering tools, and the rationalisation of resources.

THE BEAM INSTRUMENTATION NETWORK (RIF)

The Beam Instrumentation Network (in French, RIF i.e. Réseau Instrumentation Faisceau) is one of the identified transverse structures in the IN2P3. The RIF was born at the end of 2018 with the aim of bringing together experts in the field of diagnostics and associated instrumentation for particle beams in accelerators.

Missions

The Network animates, coordinates, encourages, and promotes interdisciplinary initiatives carried out in the various fields of beam instrumentation. As part of these missions, the network undertakes structuring actions that aim to:

- Take an active part in scientific and technological monitoring and, in particular, on the subject of the evolution of research support.
- Identify and promote the skills and expertise of the Network by updating pools of experts, and by ensuring a prospective analysis of skills in conjunction with the IN2P3.
- Ease communication and skills and/or information exchange between its members (sharing of good business practices, know-how) in the form of seminars or feedback.
- Pool experiences, with a view to solve particular technical problems, and capitalise to eventually make available, and manage a set of common tools, operating methods or best practices.
- Develop proposals relating to its missions for CNRS bodies, institutes and, more broadly, higher education and research bodies.
- Identify and help promote one or more research themes relating to technological locks in the field in order to boost R&D.

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PREPARATION OF LOW-ENERGY HEAVY ION BEAMS IN A COMPACT LINEAR ACCELERATOR/DECELERATOR

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Abstract

High precision tests of fundamental theories can often unfold their full potential only by using highly charged ions (HCI) at very low energies. Although in light of the envisaged energies at FAIR, experiments in the keV to MeV range may sound like backpedaling, these two techniques are in fact complementary, since the production of heavy HCI is virtually impossible without prior acceleration and electron stripping. However, subsequent preparation, transport, storage and detection of low-energy HCI bring new, surprising sets of problems and limitations. Here we will give an overview of the CRYRING@ESR local injector [1] and the HITRAP linear decelerator [2]. These two facilities consist out of one or two accelerator or decelerator stages, with a total length of around 10 meters, making them "compact" in comparison to other GSI accelerators. The following sections describe their main design parameters, the achieved ion numbers, challenges of beam detection, as well as some special features such as multi-turn injection and single-shot energy analyzers. The conclusion will present the current status and will also give an outlook of the planned applications of low-energy ions at the FAIR facility.

WHAT ARE LOW ENERGIES?

Although the term "low-energy" is often used with ease to describe stored ion beams, there is no strict definition of the term and the actual energy can range over several orders of magnitude. In a storage ring, beams of highly charged ions are labeled as slow already below 10 MeV/u, although their velocity still amounts to about 10% the speed of light c. A small-scale linear accelerator brings charged particles to a few hundred keV/u, while in a linear decelerator and a subsequent ion trap, ions can be slowed down almost to rest, pulling the energy over eight orders of magnitude to the sub-eV range. Therefore a more practical description of "low energies" would relate to a diffuse lower limit of a system, behind which a different way of handling ions is necessary, if compared to a "high energy" range of the same system, e.g. an accelerator. It should be noted that the reason for this discrepancy can be both physical, such as scaling of cross sections [3] or beam emittance, and technical, such as device stability or detector noise.

For precision experiments, low energy storage rings like CRYRING@ESR, or Penning traps like HITRAP are the devices of choice. They can provide excellent experimental conditions since effects like Doppler corrections and corresponding uncertainties at low energies are either smaller and/or they can be controlled with higher accuracy, while providing high luminosity or density at the same time. At CRYRING@ESR, electron cooling at comparably low beam energies is enhanced by transversal expansion of the electron beam upon leaving the high magnetic field produced by a superconducting magnet [4]. This process effectively reduces the temperature of the electron beam and consequently of the ion beam, enabling unprecedented experimental accuracy.

Even lower energies can be reached by extracting the ion beam from a storage ring and then employing a linear decelerator, such as HITRAP. Given the energy after multi-stage deceleration is sufficiently low for electrostatic manipulation, ions can be injected into a Penning trap [5], such as the cooling trap of HITRAP, giving the possibility to store ions basically at rest. Trapped ions are then either readily available for experiments, or they can be prepared according to the needs of an experiment and extracted at a desired energy. At this point, for convenience, the energy unit of eV/mass unit (u) commonly used for magnetic beam steering is replaced by eV/charge (q) which is more suitable for electrostatic, low-energy beam manipulation. The HITRAP transport beamline [6] typically operates at 4 keV/q, which requires a separation of doublets around a meter over the full transport length, with diagnostic elements after each pair, before the beam either hits a target or is retrapped by an experiment.

CRYRING@ESR LINEAR ACCELERATOR

The magnetic rigidity ranging from 1.4 Tm down to 0.08 Tm offers the CRYRING@ESR storage ring the possibility to work with very low ion energies. Next to heavy, highly charged ion beams from the GSI accelerator, CRYRING@ESR can also store lighter ions from a local compact injector without the use of the full accelerator chain. The properties of this compact ion source and linear accelerator are given in Table 1.

Typically, a compact electron-cyclotron resonance ion source (ECRIS) is used to deliver up to 50 µA of mass-separated D^+ ions in chopped ion bunches 7 – 50 µs in length. Also multiple charge states like Ne^{3+} are possible, though with considerably lower intensity. A Nielson type ion source (MINIS) is used as a backup, delivering slightly lower ion currents. Both ion sources are constructed in a high voltage cage, allowing extraction energies of up to 40 kV/q.

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BUNCH MERGING AND COMPRESSION: RECENT PROGRESS WITH RF AND LLRF SYSTEMS FOR FAIR

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Abstract

Besides the realization of several new RF systems for the new heavy-ion synchrotron SIS100 and the storage rings CR and HESR, the FAIR project also includes an upgrade of the RF systems of the existing accelerator rings such as SIS18. The SIS18 RF systems currently comprise two ferrite cavities, three broadband magnetic-alloy cavities and one bunch-compressor cavity. In addition, the low-level radio frequency (LLRF) system has been continuously upgraded over the past years towards the planned topology that will be implemented for all FAIR ring accelerators. One of the challenges for the SIS18 RF systems is the large RF frequency span between 400 kHz and 5.4 MHz. Although the SIS18 upgrade is still under progress, a major part of the functionality has already been successfully tested with beam in machine development experiments (MDE). This includes multi-harmonic operation such as dual-harmonic acceleration and further beam gymnastics manipulations such as bunch merging and bunch compression. Many of these features are already used in standard operation. In this contribution, the current status is illustrated and recent MDE results are presented that demonstrate the capabilities of the RF systems for FAIR.

INTRODUCTION

During the past years, the low-level radio frequency (LLRF) system at the heavy-ion synchrotron (Schwer-Ionen Synchrotron) SIS18 has been gradually upgraded towards the planned LLRF topology [1] for the Facility for Antiproton and Ion Research (FAIR).

The currently available radio frequency (RF) cavity systems with selected technical parameters that are currently used during standard machine operation are summarized in Table 1, where N denotes the number of cavities of the given type in the ring. Besides cavities loaded with ferrite ring cores, magnetic alloy (MA) cavities have been installed that enable, among other scenarios, a dual-harmonic acceleration. In addition, a bunch compressor cavity (BC) has been commissioned for a fast bunch rotation in longitudinal phase space before extraction [2].

The revolution frequency in SIS18 varies between 215 kHz and 1.36 MHz and typical harmonic numbers are $h = 2$ for the MA cavities and $h = 4$ for the ferrite cavities. Nevertheless, a variety of other harmonic numbers (e. g. $h = 1, \ldots, 8$) has been used for different scenarios and beam manipulations. The LLRF system has been designed to cope with this flexibility, including changes of harmonic numbers at dedicated White Rabbit (WR) timing events. Particular challenges are the large frequency span, fast ramping rates of the RF frequency of at least 10 MHz/s, and a required phase and amplitude accuracy under dynamic conditions of ±3° and ±6%, respectively.

Table 1: SIS18 RF Cavity Systems

Type	N	RF frequency	Typical voltage per cavity
Ferrite	2	800 kHz - 5.4 MHz	up to 14 kV_p
MA	3	400 kHz - 2.7 MHz	up to 13 kV_p
BC	1	800 kHz - 1.2 MHz	30 kV_p

At SIS18, the cavity systems produce single-harmonic RF voltages and multi-harmonic operation is realized by operating different systems at different harmonic numbers. In contrast to multi-harmonic cavity systems (e. g. [3]), the local signal generation for one cavity is therefore simpler, but the complexity of the higher-level LLRF is higher. In the following, we demonstrate the status and performance of the SIS18 LLRF systems.

SIS18 LLRF TOPOLOGY

A simplified diagram of the LLRF topology of SIS18 is shown in Fig. 1 with an emphasis on the cavity synchronization that ensures a synchronization of the gap voltages of all involved RF cavity systems (which may be configured to different harmonic numbers) in frequency and phase. The main signal sequence is as follows: The measured gap voltages are transmitted from the accelerator tunnel to the RF supply area.[1] In the supply area, the gap signals are distributed to a Switch Matrix. This matrix also receives reference signals from Group DDS (direct digital synthesis) modules that are based on clock signals of the bunch phase timing system (BuTiS, cf. [4]). At SIS18, four such modules exist ($i \in \{A, B, C, D\}$) that are configured independently with a harmonic number h_i, such that each module generates a reference signal with frequency $f_{RF,i} = h_i \cdot f_R$ as a multiple of the revolution frequency f_R. A phase calibration eliminates remaining phase errors between the analog output signals of the Group DDS [5].

Via equally structured signal paths using lines of the same type that have been assembled to a specified electrical delay, it is ensured that all input signals of the Switch Matrix have

[1] For FAIR, a signal transmission via optical and via coaxial lines is planned. At SIS18, the coaxial lines are currently the main transmission path.

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NEW METHOD FOR OVERCOMING DIPOLE EFFECTS OF 4-ROD RFQs

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Abstract

A new-type stem has been developed and simulated for 4-rod RFQs. Different than the conventional stem, its two electrode holders have different longitudinal positions (in the beam direction) in order to balance the difference in length of the current paths from the ground plate to the upper and lower electrodes. The dipole effect at different settings for the longitudinal positions of the electrode holders were examined and will be discussed.

INTRODUCTION

The asymmetrical structure of 4-rod RFQs will cause dipole modes. Which can have a negative impact on the design beam performance.

As shown in Fig. 1 a 4-rod RFQ can be described by a chain of capacitively shortened $\lambda/4$ resonators. Like for any quarter wave structure, there is a voltage gradient along the height of the stem structure, which leads to higher potential on the upper electrodes (see also Fig. 1) [1]. This is the origin of the dipole effect for 4-rod RFQs.

To compensate this effect the current path lengths of the two stems must be balanced. The classical way to compensate the dipole field is to make an inner cutting on the stem (see Fig. 2). Various new methods to compensate dipole field components have been proposed, which use path deviations or alternating stem displacements perpendicular to the beam axis [2]. Inner cuttings can be used to provide more space for magnetic field that can evolve to increase charge transport to the undersupplied lower electrodes [3].

In this paper, a new idea to modify the electrode holder of the arm to the lower electrodes based on the classic method is being proposed. It prolongs the current path to the lower electrodes by shifting the electrode holder in longitudinal direction by Δz.

Figures 2 to 3 are showing the basic concepts of a model with newly developed stems. Intensive simulations with CST Studio Suite [4] have been performed on the new model with different settings for Δz as well as the rotating angle α of the top part of the arm (see Fig. 3).

MODEL DEVELOPMENT

An existing 4-rod RFQ model with inner cutting was used as a starting point to create the new model. The main parameters of the existing model are shown in Table 1, with a design frequency of 197.5 MHz. Added was the possibility to shift the electrode holder of the arm to the lower electrodes by an arbitrary value. Additionally α—connecting the fixed part of the arm to the lower electrodes to the electrode holder—can be freely chosen (see Fig. 3).

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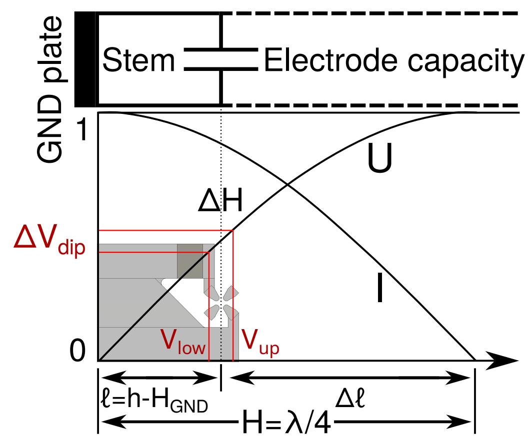

Figure 1: Potential distribution along the height of the stem. Showing the voltage difference between the upper and lower electrode pair [1].

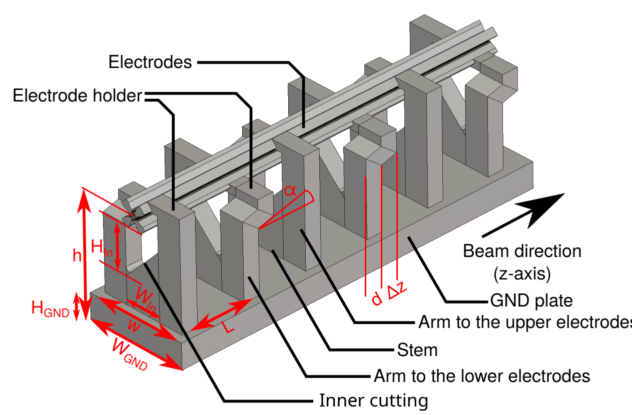

Figure 2: New type 4-rod RFQ model. This particular model uses a $\Delta z = 20$ mm with $\alpha = 15°$.

Table 1: Main Geometric Parameters

Name	Value	Description
Average aperture	3.6980 mm	a (radius)
Electrode radius	2.7735 mm	e
Stem width	106 mm	w
Inner cutting ang.	45°	β
Inner width	44.107 mm	W_{In}
Inner height	44.666 mm	H_{In}
Stem thickness	20 mm	d
Stem z-spacing	80 mm	L (center to center)
GND plate height	30 mm	H_{GND}
GND plate width	126 mm	W_{GND}
Beam axis height	142 mm	h (incl. GND plate)
Cavity radius	140 mm	incl. GND plate
Rotating angle	0°, 15°, 30°	α
Electrode holder shift	0 to 40 mm	Δz (in 10 mm steps)

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PROTOTYPE ROOM TEMPERATURE QUADRUPOLE CHAMBER WITH CRYOGENIC INSTALLATIONS

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Abstract

The synchrotron SIS100 at FAIR accelerator complex at the GSI Helmholtzzentrum will generate heavy ion beams of ultimate intensities. As medium charge states have to be used, the probability for charge exchange in collisions with residual gas particles of such ions is much lager than for higher charge states.

In the last years, several measures have lowered the residual gas density to extreme high vacuum conditions. For example 55% of the circumference of SIS18 have already been coated with NEG, which provides high and distributed pumping speed. Nevertheless, this coating does not pump nobel and nobel-like components, which have very high ionization cross sections. A cryogenic environment at e.g. 50-80 K provides a high pumping speed for all heavy residual gas particles. The only typical residual gas particle that cannot be pumped at this temperature is hydrogen. With the pumping speed of an additional NEG coating in these areas, the pumping will be optimized for all residual gas particles.

The installation of cryogenic installations in the existing room temperature synchrotron SIS18 at GSI has been investigated. Measurements on a prototype chamber and simulations of SIS18 with cryogenic installations based on these measurements are presented.

INTRODUCTION AND MOTIVATION

The SIS100 synchrotron at the FAIR accelerator complex will provide high intensity heavy ion beams, with a goal of $5{\cdot}10^{11}$ [1] particles per pulse. To achieve this goal, medium charge states have to be used as this will shift the space charge to higher numbers of particles and avoids stripping losses. However the probability for charge exchanges of medium charge ions with the residual gas particles is much higher than for higher charge states. Ions with a different charge state than the reference ion will be deflected differently and hit the vacuum chamber wall at some point, see Fig. 1. At the impact location they will release gas particles into the vacuum chamber via ion impact induced desorption processes. This leads to a localized higher density of residual gas particles, resulting increase in charge exchanges in this area. As a result even more ions hit the vacuum chamber walls downstream. This self-amplification process is called dynamic vacuum and can evolve up to complete beam loss [2].

To avoid this process, several upgrade measures have been realized in the existing heavy ion synchrotron SIS18, at

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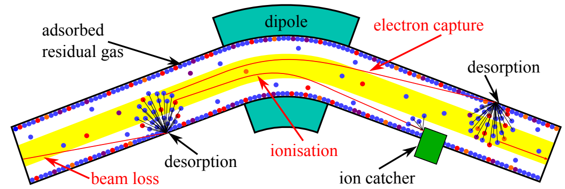

Figure 1: Principle of ionization loss and dynamic vacuum [2].

GSI [3]. Ion-catchers with low desorption surfaces have been installed to reduce the gas production by ionization beam losses. Furthermore to lower the residual gas density 65% of SIS18 vacuum chamber walls have been coated with NEG. This provides a high pumping speed for light residual gas particles like hydrogen. With these upgrades an improvement of the beam intensity was achieved [4]. However this current setup cannot reach the intensity goal for FAIR, as shown by different simulations of SIS18 [2]. Since the NEG coating only provides a high pumping speed for light particles and not for nobel and nobel-like gases, like argon and methane [5], which unfortunately have a high cross section for charge exchanges with U^{28+} [6], see Fig. 2, these particles have to be pumped differently to reduce the density of this residual gas particle species even further. However these can be pumped by cryogenic installations around 77 K. These pumps in combination with the already existing NEG coating can pump every residual gas component in SIS18 efficiently.

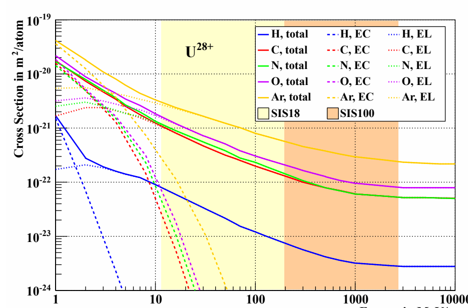

Figure 2: Cross sections for charge exchange of U^{28+} for different targets, distinguished for electron capture (EC), electron loss (EL) and total cross section. The energy regimes of SIS18 and SIS100 are marked [7].

PROTOTYPE TEST SETUP

To test the performance of cryogenic installations in a room temperature environment, a prototype quadrupole

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CRYOGENIC SURFACES IN A ROOM TEMPERATURE SIS18 IONCATCHER

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Abstract

For FAIR operation, the existing heavy ion synchrotron SIS18 at GSI will be used as booster for the future SIS100. In order to reach the intensity goals, medium charge state heavy ions will be used. Unfortunately, such ions have very high ionization cross sections in collisions with residual gas particles, yielding in beam loss and a subsequent pressure rise via ion impact stimulated gas desorption. To reduce the desorption yield, room temperature ioncatcher have been installed, which provide low desorption surfaces. Simulations including cryogenic surfaces show, that their high sticking probability prevents the vacuum system from pressure built-ups during operation. Such, the operation with heavy ion beams can be stabilized at higher heavy ion intensities, than solely with room temperature surfaces. A prototype ioncatcher containing cryogenic surfaces has been developed and built. The surfaces are cooled by a commercial coldhead, which easily allows this system being integrated into the room temperature synchrotron. The development and first laboratory tests including fast pressure measurements of this system will be presented.

MOTIVATION

The FAIR accelerator complex will provide heavy ion beams of highest intensities. The goal is to reach $5 \cdot 10^{11}$ particles per pulse [1]. In order to reach this intensity goal, medium charge state heavy ions have to be used to avoid stripping losses and to shift the space charge limit to higher number of particles. Unfortunately the probability for further charge exchange of medium charge state heavy ions in collisions with residual gas particles is much higher than for higher charge states. Ions which underwent a charge exchange process will be separated from the circulating beam in ion optical elements, as their magnetic rigidity differs from the reference ion. These ions will get lost at the vacuum chamber wall and release a huge amount of gas via ion impact induced gas desorption. This increases the rest gas density locally, which in turn increases the probability for further charge exchange. Such, a self-amplification up to complete beam loss can evolve. The rest gas density is no more constant during operation, wherefore this process is also called "dynamic vacuum". It limits the maximum achievable heavy ion beam intensity. The process is also illustrated in Fig. 1.

To shift this limit to higher intensities, several measures are possible. One is to reduce the residual gas density, another is the installation of low desorbing surfaces, which are called "ioncatcher". Both measures, besides others, have been carried out in SIS18. 65% of its vacuum chamber wall, including the ioncatcher chamber are coated with Non-Evaporable-Getter (NEG) [2]. This did lead to an increase of the maximum achievable intensity [2]. But the intensity goal could still not yet be reached. Even prediction from simulations do not reach the goal [3]. The same sort of simulation however hints, that the installation of cryogenic surfaces would increase the maximum intensity, as the sticking probability of such surfaces is much higher than on NEG surfaces.

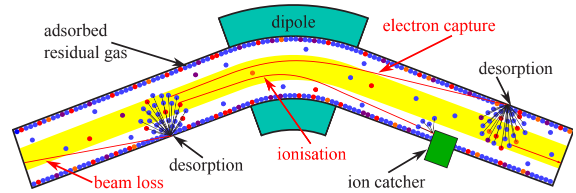

Figure 1: The principle of ionization loss and dynamic vacuum.

In [3] cryogenic magnet chamber were assumed. Different approaches are currently investigated. One approach is the installation of cryogenic pipes cooled by liquids inside the quadrupole magnet chambers [4]. Another approach, which is subject of this proceeding, is the installation of coldhead cooled surfaces around the ioncatcher. This is the location, where most of the gas gets produces during operation by ion impact stimulated desorption and an increased sticking probability shows maximum effect.

MECHANICAL DESIGN

In cryogenic systems, temperatures well below 18 K are desirable. Even Hydrogen, the main part of the desorption gases, will get pumped by such temperatures. Commercially available coldheads can reach 4.2 K while still providing a reasonable cooling power of 1.0 W[1]. The biggest issue of coldheads in combination with UHV-system is, that coldheads can not be baked out because of their delicate mechanics. Even if one removes the sensitive parts, which is already outside of the usual application, only temperatures up to 60°C - 100°C can be used without the risk of damage at the coldhead housing. This is far below the activation temperature of the NEG coatings of 250°C - 300°C, rendering coldheads useless for a baked room temperature vacuum system. On the other hand, a coldhead is more simple in application, than cooling with cryogenic liquids.

A way had to be found for being able to remove a coldhead from the system without breaking the vacuum. To find

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[1] Coldhead RDK-408D2 with compressor F50 by Sumitomo

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EFFICIENT HEAVY ION ACCELERATION WITH HIGH BRILLIANCE

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Abstract

It is challenging to realize an efficient and brilliant RFQ for accelerating high current heavy ion beams, as space charge effects are most pronounced at the low energy end. Here “efficient” means an as short as possible accelerating structure with minimum RF power consumption, while “brilliant” means high beam transmission and low emittance growth. Using the > 9 m long HSI RFQ accelerator, one of the longest RFQs in the world, as an example, a promising solution has been presented.

INTRODUCTION

As the starting accelerating structure of the UNILAC that is the main injector to the GSI accelerator complex, the 36.136 MHz HSI RFQ can accelerate a wide variety of particle species from protons to uranium ions in the energy range of 2.2 keV/u – 120 keV/u. Some major milestones in the development of the HSI RFQ are as follows:

- In 1996: the design of the first HSI RFQ (design ion: U^{4+}, design beam current I_{in}: 16.5 emA) was started [1].
- In 1998: the first HSI RFQ (hereafter referred to as Version-1998) was constructed [2].
- In 1999: the Version-1998 RFQ was put into operation.
- In 2004: the electrodes were renewed with an improved radial matching section for a larger acceptance.
- In 2008: the second HSI RFQ (hereafter referred to as Version-2008) was designed (still for U^{4+} but I_{in} was increased to 20 emA) and produced [3]. For this upgrade, the inter-vane voltage U was increased from 125 kV to 155 kV.
- In 2009: the Version-2008 RFQ was put into operation.
- From 2009 until now: the Version-2008 RFQ is in routine operation (in 2019, the electrodes were renewed but still based on the same design).
- Since 2015: in order to meet the beam intensity requirement for FAIR, the R&D for a third version of the HSI RFQ has been started.

The main design parameters of the two constructed HSI RFQs can be found in Table 1. The design goals for the new version are as follows:

- I_{in} = 20 emA with $T \geq 90\%$ (for real operation, 18 emA and 16.2 emA will be expected at the entrance and the exit of the RFQ, respectively).
- The maximum surface electric field $E_{s,\,max}$ should be lower than that of the Version-2008 RFQ.
- L should be kept same so that the same tank can be used.

Table 1: Design Parameters of the Constructed HSI RFQs

Parameters	Version-1998	Version-2008
W [keV/u]	2.2 – 120	2.2 – 120
U [kV]	125	155
I_{in} [emA]	16.5	20
$\varepsilon_{t,\,in,\,un,\,total}$ [π mm-mrad]	138	210
$\varepsilon_{t,\,in,\,n,\,rms}$ [π mm-mrad]	0.050	0.076
$\alpha_{Twiss,\,t,\,in}$	0.43	0.6
$\beta_{Twiss,\,t,\,in}$ [cm/rad]	4.6	13.6
$E_{s,\,max}$ [MV/m]	31.8	31.2
L [cm]	921.749	921.7
T [%]	89.5	88.5

DESIGN STRATEGY

For the third HSI RFQ, several solutions have been already proposed:

- In 2016: using one single cavity with U = 125 kV [4] and $E_{s,\,max}$ = 30.2 MV/m.
- In 2020: using multiple short and independent cavities with $E_{s,\,max}$ = 30.9 MV/m (U varies from 120 kV to 147 kV, but it is constant in each cavity) [5].

All these solutions have not only lowered maximum surface electric field of the electrodes but also improved beam performance.

The motivation for this new study is to develop another single-cavity design at U = 120 kV to further lower $E_{s,\,max}$, save more RF power, and improve beam quality.

The brilliance is an important index to measure the beam quality. There are different definitions for the brilliance B and the one used by this study is given as follows:

$$B \equiv \frac{I}{\varepsilon_x \varepsilon_y}. \quad (1)$$

where I is the beam current in mA and ε_x and ε_y are the transverse emittances in π mm mrad (for B, the factor $1/\pi^2$ can be left out). No matter which definition is used, for a given input beam, a design with a high B means high beam transmission and low emittance growth.

For the new HSI RFQ design with U = 120 kV (hereafter referred to as Design-2022), the high efficiency has been achieved by using the New Four Section Procedure that

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RF CHOPPER FOR PREBUNCHED RADIOACTIVE ION BEAMS

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Abstract

An RF chopper system is being designed for the Re-Accelerator (ReA) linac at the Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU). The chopper system is designed to clean out satellite bunches and produce a 16.1 MHz bunch structure, which allows for time-of-flight separation of the isotopes. The chopper system's location in the beamline is between the ReA3 and ReA6 cryomodules. In ReA, the beam can be prebunched at the frequency of 16.1 MHz and accelerated in a 80.5 MHz RFQ, producing four satellite bunches for every one high-intensity bunch. The chopper system includes an RF deflector operating at 64.4 MHz, which is the beat frequency of 80.5 MHz and 16.1 MHz. The deflector deflects every bunch to spatially separate high-intensity and satellite bunches. The beam trajectory is biased by a constant magnetic field to ensure the high-intensity bunches do not experience any total deflection. The kicked bunches are low in intensity and will be sent to a beam dump, resulting in a clean 16.1 MHz beam structure injected into the ReA6 cryomodule.

INTRODUCTION

The Re-Accelerator [1] is a superconducting linear accelerator that "re-accelerates" rare isotopes produced in experiments done with the FRIB linear accelerator. ReA was commissioned in 2015 and includes three general purpose beamlines and a beamline dedicated to astrophysics experiments. The ReA6 cryomodule was added in 2021 to provide higher beam energies. ReA can accelerate ions with an A/Q ratio between 2 and 5. The chopper system will produce a beam with a clean 16.1 MHz bunch structure, which will allow ReA users to perform time-of-flight measurements. The ReA beamline includes a radio-frequency quadrupole

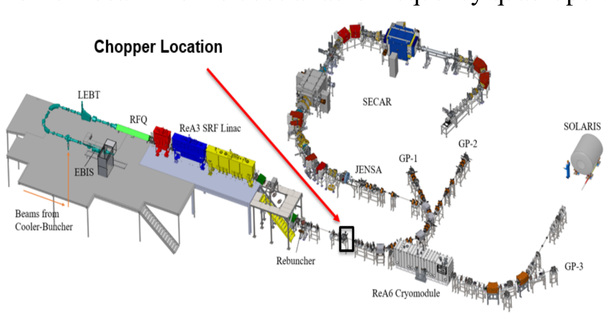

Figure 1: ReA layout.

(RFQ), which generates an 80.5 MHz bunch repetition rate. Upstream from the RFQ is a multi-harmonic buncher (MHB) which produces high-intensity bunches at a frequency of 16.1 MHz. This means that, after the RFQ, there are four low-intensity ("satellite") bunches for every one intense ("main") bunch. This chopper system uses a combination of an RF electric field with a frequency of 64.4 MHz and a static magnetic field to deflect the satellite bunches while keeping the main bunches on axis. Two potential locations were considered for the chopper system. The first location, between the RFQ and the first ReA3 cryomodule, has a lower beam energy (0.5 MeV/u), but was not chosen because there is limited space (only about 70 cm) for the chopper system. The second location, shown in Fig. 1, is between the ReA3 cryomodules and the ReA6 cryomodule. The beam energy at this location is around 3 MeV/u. This location was chosen because there is plenty of space for both the chopper and a beam dump for the deflected satellite bunches. The beam dump will be located about 1.4 meters downstream of the chopper.

DESIGN

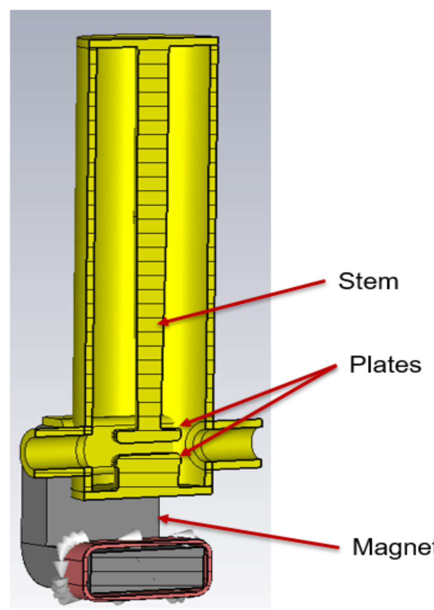

Figure 2: Cross-section view of the final RF chopper cavity model designed in CST Studio (dimensions shown in Table 1).

RF Deflection

The RF chopper design is based on a quarter-wave resonant cavity (QWR) with deflecting plates that kick the beam bunches in a vertical direction. The cavity cross-section is shown in Fig. 2 The resonant frequency of the cavity is 64.4 MHz, which in combination with the bunch frequency of 80.5 MHz (driven by the RFQ frequency) produces a 16.1 MHz deflection waveform. Indeed, the cavity resonates at the beat frequency of the actual bunch frequency and the desired 16.1 MHz bunch repetition rate. At this frequency, the QWR is a 1.1 meter-high cavity, whereas the 16.1 MHz

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TUNING AND RF MEASUREMENTS OF THE LILAC RFQ*

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Abstract

A new linac for the NICA ion collider is under construction for JINR at BEVATECH GmbH. As first cavity the 2.5 m long RFQ was manufactured. Within this length it accelerates particles with a mass to charge ratio up to three to an energy of 600 keV/u. The operation frequency is 162.5 MHz and the 4-Rod structure consists of 23 RF cells that need to be adjusted using tuning blocks in order to provide the required field distribution along the electrodes. The status of the manufacturing and the upcoming tuning process including the overall RF setup of the RFQ are summarized in this paper.

INTRODUCTION

The NICA collider will be fed with various ion beams accelerated in the Nuclotron [1]. Heavy particles with A/Q=6.25 will use the HILAC (Heavy Ion Linac) [2] as injector and will be injected into the booster synchrotron before they will be finally accelerated by Nuclotron. Light ions with A/Q=3 will use the Light Ion Linac (LILAC) [3] and directly injected into the Nuclotron. LILAC will be fed with ions from two different ion sources, the SPI (Special Polarized Ion Source) for protons and deuterons, and LIS – a Laser Ion Source for ions such as C^{3+} for example [1]. Between the ion sources and the LILAC RFQ a LEBT will transport and focus proton beams with 50 keV from the ion source. In addition deuterons with only 25 keV/u beam energy from the ion source will be post-accelerated and matched to the RFQ acceptance. A solution to match the carbon beams is under investigation.

The emittance of the beam from the ion source is limited to 0.3 mm mrad which was measured as worst case for the SPI. Larger emittances can be transported by the LEBT, but will not be accepted by the RFQ.

RFQ DESIGN

Based on the measured output from the SPI and LIS, the LEBT beam dynamics design and the required matching to the following IH Drift Tube Linac, the LILAC RFQ beam dynamics design parameters are listed in Table 1. The design plots in Figure 1 show a stable output emittance against changes of the input emittance for an injected C^{3+} beam with maximum 15mA of beam current. For the worst case input emittance of 0.3 mm mrad (rms), the LILAC RFQ design provide transmissions of around 89%. The LILAC RFQ is chosen to be of the 4-Rod type RFQs.

The RF design parameters of the RFQ resonant structure have been simulated in CST. The RF design was performed taking the longitudinal end fields [4] as well as dipole correction [5] into consideration. The RF design parameters are listed in Table 2.

Table 1: LILAC RFQ Beam Dynamics Design Parameters

Parameter	Value	Unit
Input energy	25	keV/u.
Output energy	600	keV/u.
Input emittance $\epsilon_{n,rms,xy}$	0.3	mm mrad
Output emittance $\epsilon_{n,rms,xy}$	0.31	mm mrad
Energy spread (@15 mA, A/Q=3)	1.8	%
Transmission[1]	89	%

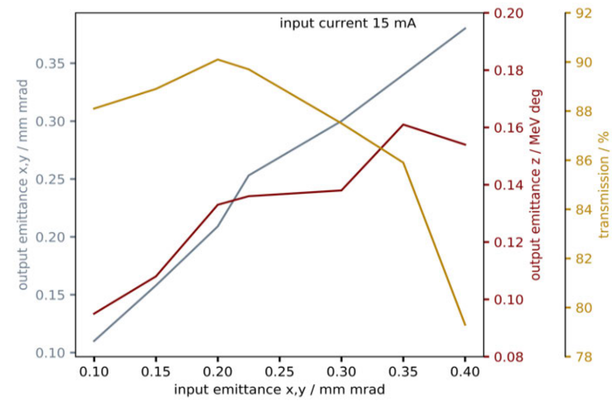

Figure 1: Output emittance and transmission as a function of the input emittance for a beam current of 15mA.

Table 2: LILAC RFQ Design Parameters

Parameter	Value	Unit
Operating frequency	162.5	MHz
Shunt impedance Z_{eff} (CST)	116	kΩ*m
Recommended RF power (Amplifier)	300	kW
Quality factor (CST)	5800	
Flatness	±3.5	%
Kilpatrick	1.60	

TECHNICAL DESIGN

The base of the technical design of this RFQ is derived from a well established and successful design of rectangular RFQ tanks [6,7] which have water cooling feedthroughs realised in the ground plate. In the case of the LILAC RFQ only the stems will be cooled. In addition, the rectangular tank has a cover plate allowing for easy access to the 4-rod structure and tuning plates. The tuning plates are mounted

[1] For input emittances 0.3 mm mrad

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HIGH POWER TESTS OF A NEW 4-ROD RFQ WITH FOCUS ON THERMAL STABILITY

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Abstract

Due to strong limitations regarding operational stability of the existing HLI-RFQ a new design and prototype were commissioned. Three main problems were observed at the existing RFQ: A strong thermal sensitivity, modulated reflected power, and insufficient stability of the contact springs connecting the stems with the tuning plates. Although the last problem was easily solved, the first two remained and greatly hindered operations. To resolve this issue and ensure stable injection into the HLI, a new RFQ-prototype, optimized in terms of vibration suppression and cooling efficiency, was designed at the Institute of Applied Physics (IAP) of Goethe University Frankfurt. To test the performance of this prototype, high power tests with more than 25 kW/m were performed at GSI. During those, it was possible to demonstrate operational stability in terms of thermal load and mechanical vibrations, calculating the thermal detuning, and proof the reliability of the proposed design.

INTRODUCTION

In 2010, a new 4-rod RFQ had been commissioned and integrated into the existing High Charge State Injector (HLI) at GSI [1].

Shortly after the implementation, several problems occurred. Those included the contact springs between the tuning plates and stems, periodically reflected power due to mechanical oscillations of the electrodes, and a high thermal sensitivity. Even though the first one could be resolved rather quickly, the mechanical oscillations and thermal sensitivity posed big challenges for the operator, since only several pulse lengths were accepted by the RFQ, and thermal detuning limited the possible power increase. [3]

To overcome those problems and ensure stable operation conditions, the development of a new RFQ was commissioned. This RFQ was optimized in terms of mechanical vibration suppression as well as efficient cooling while still reaching the set goals for power efficient acceleration. [2, 4]

To test the success of the proposed design, a prototype had been constructed. This shorter RFQ with an electrode length of roughly one fourth of the final design had been conditioned up to high power levels. During this process, mechanical observations had been performed as described in [5], to verify the success in terms of reduced mechanical vibrations. Additionally, the heating had been carefully observed as well as compared to simulations.

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EXPERIMENTAL SETUP

A schematic depiction of the experimental setup is shown in Figure 1. Overall, the setup was divided into two parts: The bunker with the RFQ, tuner, and sensors; and the RF-gallery with the RF-sender (see Figure 2), power meter, and observation station. Especially to mention is the fact that the tuner was manually controlled through a voltage source.

Even though the RFQ was designed for CW-capable usage, due to restrictions by the sender the maximum pulse length was 6.5 ms in a 20 ms interval.

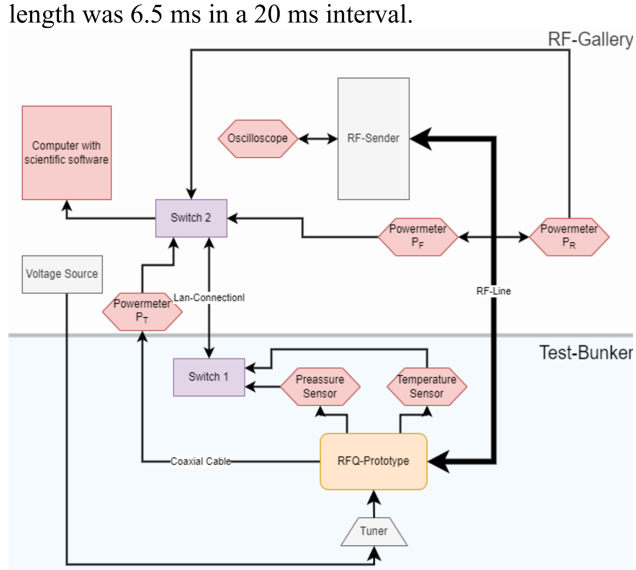

Figure 1: Schematic depiction of the experimental setup at GSI Darmstadt.

CONDITIONING PROCESS

Usually during RF conditioning, the power inside the cavity is slowly increased. Several conditioning effects, as multipathing, degassing, and flashovers, pose great threads to the conditioned cavity as well as the used equipment. This makes conditioning in most cases a time intensive and complicated endeavor.

Figure 2: RF-Sender used.

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UPGRADE AND OPERATION OF THE ATLAS RADIATION INTERLOCK SYSTEM (ARIS)*

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Abstract

ATLAS (the Argonne Tandem Linac Accelerator System) is a superconducting heavy ion accelerator which can accelerate nearly all stable, and some unstable, isotopes between hydrogen and uranium. Prompt radiation fields from gamma and or neutron are typically below 1 rem/hr at 30 cm, but are permitted up to 300 rem/hr at 30 cm. The original ATLAS Radiation Interlock System (ARIS), hereafter referred to as ARIS 1.0, was installed 30 years ago. While it has been a functional critical safety system, its age has exposed the facility to high risk of temporary shutdown due to failure of obsolete components. Topics discussed will be architecture, hardware improvements, functional improvements, and operation permitting personnel access to areas with low levels of radiation.

THE ATLAS FACILITY AND ARIS

ATLAS

ATLAS is a DOE user facility [1] located at Argonne National Laboratory outside Chicago, Illinois in the United States. ATLAS has three ion sources: two ECR sources, and an EBIS source used as a charge breeder coupled to the CARIBU radioactive ion source [2]. ATLAS can deliver beams consisting of stable and unstable isotopes from protons through uranium. Superconducting Radio Frequency (RF) cavities accelerate ions from 10 to 20 MeV/A for light mass ions. During a typical year, ATLAS hosts several hundred users from as many as a dozen countries. Experiments at ATLAS range from 2 days to a month, with the average length being a week. At the end of which the ATLAS operations staff will reconfigure the facility and tune a new beam of differing mass, energy, and current, all in under 24 hours. Despite the constant reconfiguring for new experiments and regular maintenance, ATLAS delivers ~6000 operational hours per year.

The ATLAS operations group and Argonne Physics Division Radiation Safety Committee have developed controls to allow users and staff access to accelerator and experimental areas with low-level radiation (< 5mrem/hr @ 1m from source), including areas which may have beam present. Given the wide range of ion species, energies, and various experimental end stations, this level of facility access is vital for setup and debugging new experiments in 24 hours or less.

The main safeguard against unnecessary radiation exposure includes a combination of training, administrative controls, and shielding. ARIS is an engineered control (safety system), designed to protect personnel from radiation exposure should the other safeguards fail. ARIS serves as active monitoring of radiation in 16 experimental and accelerator areas as well as adjacent areas, these areas are referred to as ARIS-controlled areas. ARIS-controlled areas are equipped with radiation monitors, interlocked gates, and area status displays that are connected to ARIS. Access to these areas is allowed, provided certain conditions are satisfied and the area is in the correct access state (access states will be discussed in greater detail later).

ARIS 2.0

ARIS 1.0 has been in operation since August 1st, 1992 [3], during which time there has been no accidental personnel radiation exposure. However, the system's age has presented various limitations concerning system improvements and expansion. Additionally, an upgrade was needed to avoid accelerator operation interruptions caused by possible malfunctions of outdated components of the ARIS 1.0 system and to add functionality to the system that augments administrative controls with engineered controls. ARIS 2.0 was developed as an extension and upgrade of ARIS 1.0 system and began service on June 22nd, 2021. Below is an overview of ARIS 2.0 architecture, operating principles, and improvements over ARIS 1.0.

Architecture

The ARIS system uses a computer-PLC network composed of the following nodes (Fig. 1) [4]:

- A Programmable Logic Control computer system, the ARIS PLC, which has sensing, control, and some informational functions.
- A Linux-based PC, the ARIS Linux PC, which performs only sensing, informational, and logging/recording functions.
- Ancillary Linux PC, which performs informational and logging/recording functions.

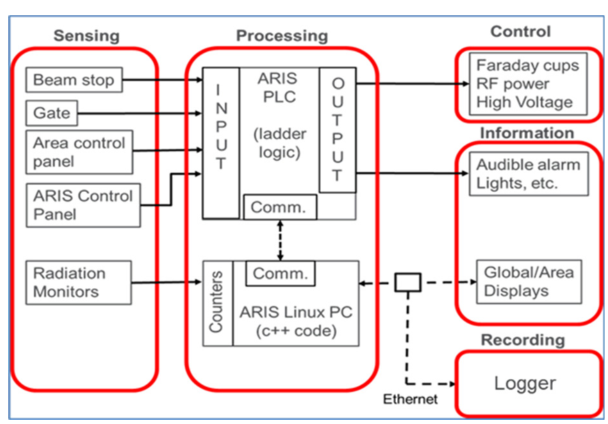

Figure 1: Schematic overview of the ARIS computer-PLC network.

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STUDY OF INJECTION LINE OF THE CYCLOTRON C70XP OF ARRONAX

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Abstract

The cyclotron C70XP is an accelerator built for the production of non-conventional radionuclides for nuclear medicine, research in physics, radio-chemistry and biology. Its injection section has been designed for 4 types of ions (HH+, D-, He2+ & H-), 3 types of ions reach the end of the beamline (H+, He2+ & D+) at the maximum energy of 70 MeV (H- & He2+). It is important that regular and standard runs provide similar beam features with a good emittance quality. An investigation, focused on the beam in the injection, cover beam measurements and potential beam geometry constraints. The beam transverse characteristics in the injection line has been studied with an Allison-type emittance meter and a simple instrumented collimator installed inside the injection line. With these 2 devices, it is scrutinized how the beam emittance evolves as a function of settings of the injection magnets and the source parameters. Dependencies found between the emittance, beam hotspots and tunings are discussed, as well as the protection performed by the collimator. Future of this work with a potential collimator design is introduced.

INTRODUCTION

The Arronax Public Interest Group (GIP Arronax) aims at providing well-defined transverse ion-beam dimensions. This, to secure reliable production of radio-isotopes at high intensity and deliver an adequate beam as-homogeneous-as-possible at low intensity for research and detector studies. A study program of the beam in the various sections of the accelerator, mainly transport beamlines and injection section, has been put in place. The study includes first emittance measurements performed in the injection section [1]. The installation of the emittance-meter and the outcomes of the measurements are described in the paper, including the code devised to analyze the data. The observations have pointed out that several high-density spots could be obtained, depending on the machine parameter settings. To check the rejection capacity of these spots, a slit was mounted in the injection section. Measurements of the beam dimensions at the end of two beamlines were performed. The results trigger the need to explore the design of a new collimator system adapted to low energy and high intensity beams.

MEASUREMENTS WITH THE EMITTANCE-METER

Installation

A 2D (x,x') Alison type emittance meter built in the frame of the EmitM collaboration [2] was installed in the injection line of the C70XP for a measurement campaign [3].

The injection line is composed of two ion-sources (a multicusp for H-/D- ions and an ECR for He2+ ions), a first solenoid, a first steerer, a 90° selection dipole, a quadrupoles triplet, a second steerer, a second solenoid, and a buncher.

A flange on the injection line was modified to allow the insertion device, i.e. a lengthened dedicated flange was built, the penning IKR050 gauge was deported as well as the PV AL25PK pipeline vacuum valve, and the Faraday-cup of the injection line was removed.

Due to the limited space available for the installation 30 cm downstream the buncher, the emittance-meter was positioned in a single plane measurement mode only.

The emittance-meter was aligned by a vertical laser at the geometrical center of the line to define the reference point of the displacements of the head of the emittance-meter.

Experimental Preparation

To ensure the comparability of the measurements, each morning at the start of the day, series of measurements are carried out with the low energy beam (~40keV). For this, systematic emittance measurements are achieved while increasing the arc current of the multicusp source.

Also every morning, the source and magnetic elements were set for low and high beam intensity, and emittance measurements were performed for later comparison.

For the measurement, we start with the optimization for high beam current, each parameter of the injection line was studied systematically and in defined step before returning to the starting value.

During the whole manipulation, no parameter that could affect the acquisition of the signal was changed. All these precautions have been taken in order to make the measurements as comparable as possible.

Prior to the emittance measurements, the reference beam intensity is measured on a radial probe inside the cyclotron at 150 mm of the center of the cyclotron, downstream the spiral inflector.

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SEVEN DECADES OF SCIENCE WITH ACCELERATORS AT IPHC

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Abstract

The Institut Pluridisciplinaire Hubert Curien (IPHC) is a laboratory with solid foundations and perspectives to overcome future challenges. It is a component of the Centre National de Recherche Scientifique (CNRS) and the University of Strasbourg. It has been founded in 2006 after fusion of three local laboratories leading research in the field of analytical chemistry, ecology/environment and subatomic physics. The activities related with subatomic physics present a rich history which goes back to the 40's and is now evolving towards new challenges at the frontier of the knowledge with the contribution of other sciences as biology, chemistry, medicine and radiobiology. The paper will cover a number of past and current activities with emphasis on the link between research and technology.

INTRODUCTION

Before being a well-established laboratory in the French and European landscape IPHC went through several periods marked by continuous evolution, contrasting activities and remarkable results. Among the various fields of research explored today such as chemistry, ecology, ethology, physiology, radiobiology and subatomic physics, this article focuses on the activities developed with accelerators. The history of the Institute will be covered through six periods: origin, growth, confirmation, maturation, change in trend and metamorphosis.

THE ORIGIN

Activities related with nuclear physics applied to medicine have started in 1941 during second war, German occupation and evacuation of Strasbourg's university in Clermont-Ferrand and Dordogne. The "Medizinisches Forschungs Institut" is built inside the hospital and near the faculty of medicine with four departments in biology, chemistry, medicine and physics, see Fig. 1.

Figure 1: First accelerator building with Cockcroft Walton neutron generator at the civil hospices in Strasbourg DC, 1944.

First beam was produced after the liberation of the city in 1944 and the ensuing turbulences in 1948 with a neutron generator based on a 1.5 MV Cockcroft Walton accelerator, see Fig. 2. The goal was to produce isotopes for radiotracers (^{32}P) with ^{2}H beam induced neutrons on Be target and to perform radiobiology on cells, one of the first facility in Europe at the time. Research is driven by recent discoveries: neutron as a new particle, induced radioactivity, fission, etc. Activities are stimulated by competition with Heidelberg and two French laboratories, that of F. Joliot located in Ivry and the Collège de France.

Figure 2: Cockcroft Walton 1.5 MV electrostatic accelerator stands on the putting green nowadays of IPHC on the Strasbourg campus.

These investments were supplemented by a new X-rays generator, an electron microscope and a cyclotron purchased in 1942. It should be noted that the first lecture in the field of nuclear physics was given in 1947 by Pr S. Gorodetsky, a friend of F. Joliot-Curie. From the beginning, the research has been characterized by the support of leading scientists, a strong interaction between theory and experiment, and the sustainability of the program in the field of nuclear physics (structure of the nucleus, spectroscopy, EM transition, interactions and life time measurements), and nuclear chemistry (chemical effects of nuclear reactions and ionizing radiations). These developments appear after the first works started in the 1930s on X-rays at 100 keV, the sources of natural radioactivity (gamma at 2 MeV with ^{226}Ra source) and the need to study deeper effects with more energetic light ions [1-6].

Figure 3: New nuclear physics research center built in the western part of Strasbourg in 1959.

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BEAM DYNAMICS AND SPACE CHARGE STUDIES FOR THE INNOVATRON CYCLOTRON*

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Abstract

At IBA a high-intensity compact self-extracting cyclotron is being studied. There is no dedicated extraction device but instead, a special shaping of the magnetic iron and the use of harmonic coils to create large turn-separation. Proton currents up to 5 mA are aimed for. This would open new ways for large-scale production of medical radioisotopes. The main features of the cyclotron are presented. A major variable of the beam simulations is the space charge effect in the cyclotron centre. Using the SCALA-solver of Opera3D, we attempt to find the ion source plasma meniscus and the beam phase space and current extracted from it. With these properties known, we study the bunch formation and acceleration under high space charge condition with our in-house tracking code AOC. We also discuss a new tool that automatizes optimization of cyclotron settings for maximizing beam properties such as extraction efficiency.

INTRODUCTION

Radioisotopes for nuclear medicine can be produced either by reactors or accelerators. Commercial cyclotrons (E = 15–70 MeV) achieve currents up to or just above 1 mA. Large-scale production of radioisotopes needs a high-intensity cyclotron technology. The self-extracting cyclotron is a promising tool for producing high quantities of SPECT radioisotopes such as Tc-99m or new emerging PET radioisotopes [1]. The InnovaTron 14 MeV H^+ machine features a magnetic field with a very steep fall-off near the outer pole radius, allowing the beam to extract spontaneously. First harmonic coils increase the turn-separation at the entrance of the extraction path. The prototype, installed in Fleurus (Belgium) in 2000, achieved a current close to 2 mA [2]. More details on the concept can be found in [3]. Main goals set for the project are: i) improvement and optimization of the magnet, extraction elements and central region, ii) space charge simulations, iii) improvement of turn-separation at extraction. We discuss results obtained for i) and ii).

MAGNET OPTIMIZATION

The following improvements have been implemented as compared to the prototype: i) the magnet (and also the accelerating structure) has perfect 2-fold symmetry. This allows irradiation of two targets stations at opposite exit ports and to place two internal ion sources. The latter will increase cyclotron reliability and uptime, ii) the groove in the extraction path used in the prototype (Fig. 1a) is replaced by a "plateau" (Fig. 1b). This reduces the strong sextupole component in the extraction path and improves the extracted beam quality, iii) the pole gaps still have a quasi-elliptical shape, decreasing towards larger radii, but the iso-gap contours follow equilibrium orbits. This enables a steeper transition from the internal stable orbit towards the non-stable extracted orbit.

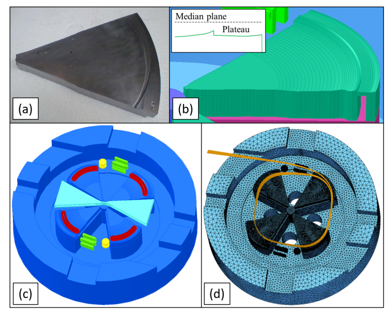

Figure 1: InnovaTron improved magnet design.

Figure 1c shows a view on the lower half of the magnet developed in Opera3D. The harmonic coils (in red) and the dees (in light blue) are also shown. The gradient correctors (in green) provide radial focusing to the extracted beam. The beam separators (in yellow) are used to intercept parts of the beam that are not properly extracted. A beam simulation of the last 5 turns superimposed on the FEM model is shown in Fig. 1d. Automatic and parametrized FEM models have been developed, for the magnet but also for the central region and dees. More details are given in [4].

CENTRAL REGION STUDIES

We do an effort for a self-consistent simulation of the space charge dominated beam in the central region. This method consists of three steps. In the first step the SCALA space charge solver of Opera3D [5] is used to find the plasma meniscus of the ion source. In the second step the same central region model is solved again, but now with the TOSCA electrostatic solver of Opera3D. Here the meniscus surface is put at ground potential. This provides the 3D electric field map everywhere in the central region, including the source-puller gap. In a third step the beam extracted from the meniscus is simulated in the 3D field map using the self-consistent in-house space-charge code AOC [6]. This code has been extended to also simulate the bunch formation process in the first gap.

SCALA Simulations

The plasma-free boundary module of SCALA calculates the plasma meniscus and the extracted beam phase space and current density on the meniscus, in a DC electric field.

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FIRST TESTS OF MODEL-BASED LINAC PHASING IN ISAC-II

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Abstract

As the e-linac and ARIEL facilities at TRIUMF progress, the impending complexity of operating three simultaneous rare ion beams (RIBs) approaches. To help prepare for this, a framework for the development of High Level Applications has been constucted, upon which multiple avenues for improvement towards model-based and automated tuning are being pursued. Along one of these avenues, the 40-cavity superconducting ISAC-II heavy ion linac has been studied and modelled in the envelope code transoptr. This has allowed for real-time integration through the on-axis fields, fitting focal strengths of solenoids to achieve desired beam waists, and calculation of necessary cavity phases to achieve a desired output energy for given input beam parameters. Initial tests have been completed, successfully phasing up to 37 cavities using the transoptr model and achieving a final output energy within 1% of the expected while maintaining nominal (>90%) transmission. A summary of the calibration of the model to the machine is given, followed by results of the phasing tests and an outlook towards future improvements.

INTRODUCTION

The Isotope Separator and ACcelerator (ISAC) facility at TRIUMF serves a wide assortment of experiments that study nuclear structure, materials science, nuclear astrophysical reaction rates, and more. Stable beams from the Off-line Ion Source (OLIS) or radioactive ion beams from the target stations can be delieved to low, medium, or high energy sections depending on the amount of post-acceleration required. The ISAC-I medium energy section, completed in 2001 [1], provides ion beams from 0.15 to 1.8 MeV/u while the ISAC-II high energy section, completed in two phases in 2006 and 2010 [2], can deliver beams from 1.5 up to as high as 16.5 MeV/u.[1]

Acceleration in the ISAC-II linac is provided by forty superconducting two-gap quarter wave niobium cavities, operating at 4.2 K. Cavities are distributed over eight cryomodules, each containing one superconducting solenoid.

MOTIVATION

Typical experiments served by the ISAC-II linac run for approximately 7 days. Overhead for these experiments to adjust the accelerators for new beam properties is typically scheduled for 24 hours. The portion of this overhead required for the optimization of the ISAC-II linac is regularly over 8 hours and requires expert assistance or senior operators.

The optimization itself is a complex process, as it involves the user turning on one cavity at a time and scanning the phase to identify the desired setpoint. This is further complicated by the large energy gain relative to the incoming energy for the first few cryomodules, which impacts the transverse tune and requires re-optimization of solenoids and quadrupoles.

Basically, it is a problem of a large configuration space with interdependent tuning parameters:

- 40 cavities x 2 adjustable parameters (phase, amplitude)
- 8 solenoids x 1 adjustable parameter (current)
- 8 cryomodules x 2 adjustable parameters (x, y steerers)

This has motivated a more model-based approach to the operation of the ISAC-II superconducting linac.

HIGH LEVEL APPLICATIONS AT TRIUMF

The high-level applications (HLA) taskforce [3, 4] is tasked with using model-based tuning integrated with the control system to improve beam quality and reduce tuning overhead. This project is one of multiple such areas of study at TRIUMF and utilizes various components of the HLA framework, including python to EPICS communication, xml beamline information, and TRANSOPTR for beam envelope simulations.

MODEL CALIBRATION

Diagnostics

The time structure of the beam at three locations of known distance along the beamline are measured using flight time monitors (FTMs). Shown below in Fig.1, FTMs are an assembly consisting of a $50\mu m$ diameter biased tungsten wire that intersects the beam and emits secondary electrons.

These electrons are detected by a micro-channel plate (MCP) detector with a time resolution of < 100 ps, giving a resulting energy/nucleon resolution of under 0.1% [5]. The velocity or the ion beam is calculated as a weighted average using the arrival time at each of the possible 3 pairs of monitors [6].

With no time diagnostics within the linac itself, these three monitors located approximately 3, 5, and 14 metres downstream of the last accelerating cavity are the primary diagnostics used for both measuring the beam velocity and calibrating cavity phases in the model.

Phase Shifters

The fourty cavities in the ISAC-II linac are each driven independently, so each cavity has its own designated phase

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[1] 16.5 MeV/u is achievable here for A/q of 2.

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FRIB COMMISSIONING*

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Abstract

The Facility for Rare Isotope Beams (FRIB), a major nuclear physics facility for research with fast, stopped and reaccelerated rare isotope beams, was successfully commissioned and is in operation. The acceleration of Xe, Kr, and Ar ion beams above 210 MeV/u using all 46 cryomodules with 324 superconducting cavities was demonstrated. Several key technologies were successfully developed and implemented for the world's highest energy continuous wave heavy ion beams, such as full-scale cryogenics and superconducting radiofrequency resonator system, stripping of heavy ions with a thin liquid lithium film, and simultaneous acceleration of multiple-charge-state heavy ion beams. In December 2021, we demonstrated the production and identification of ^{84}Se isotopes and, in January 2022, commissioned the FRIB fragment separator by delivering a 210 MeV/u argon beam to the separator's focal plane. The first two user experiments with primary ^{48}Ca and ^{82}Se beams have been successfully conducted in May-June 2022.

INTRODUCTION

The FRIB includes a high-power superconducting driver accelerator, an isotope production target, and a fragment separator.The layout of the FRIB superconducting driver linac is shown in Fig. 1. The linac will provide stable nuclei accelerated to 200 MeV/u for the heaviest uranium ions and higher energies for lighter ions with 400 kW power on the target [1]. The progress with the FRIB linac construction, development, and testing was reported in multiple publications; see, for example, [2–4]. The 400 kW ion beams will be delivered to a thin fragmentation target which is followed by a large-acceptance high-resolution fragment separator (FS). The FRIB rare isotope FS has an angular acceptance of ±40 mrad in both transverse directions, and momentum acceptance of ±5%. The maximum magnetic rigidity of the FS can reach 8 T·m. While many isotopes will be studied in the in-flight experiments, some isotopes will be stopped and re-accelerated up to 12 MeV/u.

In a continuous wave (CW) superconducting (SC) linac, the beam power of 400 kW can be achieved with a low beam current, below 1 emA. Therefore, the space charge effects are mostly negligible in the linac except for the ion source and the Low Energy Beam Transport (LEBT). Although the performance of Electron Cyclotron Resonance Ion Sources (ECRIS) has significantly improved in the past decades, they still cannot produce sufficient intensities of the heaviest ions to reach 400 kW on target in a single charge state. To achieve 400 kW power on the target for the heaviest ion beams, multiple charge states of the same ion species are accelerated simultaneously. Particularly, in the case of uranium, two charge states (U^{33+} and U^{34+}) will be accelerated before the stripping and five charge states after the stripping at 17 MeV/u. Additionally, multiple-charge-state acceleration after the stripper dramatically reduces the power of unwanted charge states dumped in a charge selector in the first folding segment. The multiple-charge-state acceleration will be used for all ion species with mass numbers above ~60.

LINAC COMMISSIONING

The staged beam commissioning was adopted for the FRIB and started in 2017 and continued until January 2022. The current view of the linac tunnel is shown in Fig. 2. Each of the seven beam commissioning stages took less than two weeks. The results of each stage were reported in multiple journal publications and summarized in the HB'21 paper [5]. In the current paper, we report the completion of the beam commissioning at FRIB and initial experience working with 1 kW ion beams for the first two nuclear physics user experiments.

On April 25, 2021, the FRIB accelerator became the highest energy continuous wave linear accelerator in the world after acceleration of ^{86}Kr ion beam to 212 MeV per nucleon (MeV/u), achieving 100-percent beam transmission. Later, ^{124}Xe ion beam was accelerated to the same energy of 212 MeV/u. All 46 cryomodules with a total of 324 superconducting cavities were powered for the acceleration of ion beams. Successful beam commissioning of the FRIB linac validates the operation of all accelerator systems per design specifications.

Later, in December 2021, we demonstrated the production of 84Se isotopes from ^{86}Kr ions of the primary beam. The FRIB project was completed in January 2022, and the preparation for user experiments has started [6].

Front End (FE)

Since the early commissioning stages in 2017, significant experience has been gained in operation and tuning of the FE for various ion beam species. The tuning procedure of the FE for any ion beam species from scratch has been developed. Currently, there is a library of settings for about ten different ion beam species.

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THE NEW GANIL BEAMS: COMMISSIONING OF SPIRAL 2 ACCELERATOR AND RESENT DEVELOPMENTS

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Abstract

The GANIL installation at Caen in France has been operating with warm temperatures cyclotrons for heavy ion beam physics since 1983. The accelerated stables beams widely ranges from Carbon to Uranium beams. Low energy and post accelerated radioactive ion beams are also being provided.

The GANIL laboratory has newly increased their different ion beams and energies available with the installation and commissioning of a superconducting linear accelerator – SPIRAL2 and its experimental areas. The construction of SPIRAL2 started in 2011, the first beam was extracted at low energy in late 2014 with pre-acceleration in 2017 and since 2021 the new installation delivers beam for nuclear physics experiments.

This paper will cover the commissioning and power ramp up of the SPIRAL2 installation at GANIL with its superconducting LINAC – but also the latest development of stable and radioactive ion beams at the cyclotron facility of GANIL.

GANIL COMPLEX

GANIL will in November 2022 celebrate the 40 years from the first extracted beam from the two separated sector cyclotrons (SSC). The first accelerated and extracted beam was a $^{40}Ar^{16+}$ beam, accelerated to 44 MeV/A. The same beam was used for an experiment 2 months later in January 1983.

Figure 1: The Running GANIL facilities in 2022. On the right is the cyclotron facility and on the left is the SC-LINAC facility.

In the 2015 version of HIAT conference O. Kamalou presented an article of the GANIL Operation Status and New Range of Post-Accelerated Exotic Beams [1]. In the same conference J. M. Lagniel presented the Advances of the SPIRAL2 PROJECT [2] which had just commissioned the ion sources and the low energy beam transfer lines (LEBT), the SC-LINAC was still under installation.

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Today GANIL is running two separated facilities, not yet connected as can be seen in Fig. 1. On the right hand side of the Fig. 1 is the cyclotron complex. The ion beams are produced on the far right hand side before accelerated in one or two steps in the two SS cyclotrons up to 95 MeV/A. On the left in the cyclotron buildings are the RIB factory SPIRAL1. The experimental halls, were the users from different fields explore the stable and radioactive beams, are on the upper part of the figure. On the left hand side in Fig. 1 is the SPIRAL2 installation with a more detailed description in Fig. 2. The four injectors used at GANIL are opposite to

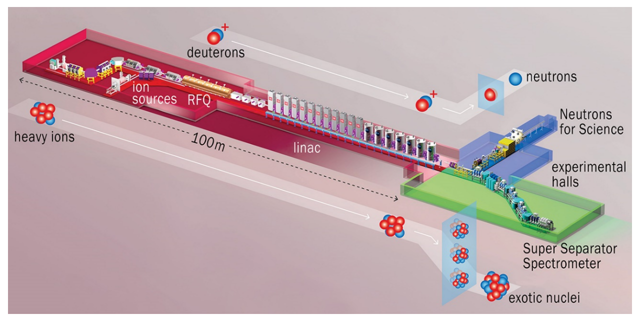

Figure 2: A schematic view over the SPIRAL2 installation, the two injectors on the right hand side.

each other in the two facilities. In the near future the two facilities will be connected and beam from either of the two facilities will be used in a new experimental area as seen in the section “Next steps for GANIL”.

From here we will refer to the cyclotron facility and the SC-LINAC facility (Fig. 3). In total GANIL is running seven ECR ion sources, one FEBIAD ion source, one ECR charge breeder, four injectors, five cyclotrons, one RFQ and one superconducting LINAC, delivering stable ion beams (SIB) and radioactive Ion beams (RIB) to nine experimental areas. The facility is operated 24h 7 days a week for 8 to 9 months per year. Since 2019 the cyclotrons and the SC-LINAC facilities are sharing the operation time, meaning that at GANIL there is a cyclotron season and a super conducting LINAC season. This arrangement divide individually the two facilities into separate 4-6 months uptime periods with 6-8 months maintenance and upgrading periods each year. This gives an opportunity to work on upgrades and regular improvements of ion beam transport and new beams while providing beams 8-9 months a year.

While the Cyclotron facility celebrate 40 years of operation the SC-LINAC is still in the first years of regular operation. In here we will present the resent upgrades at the cyclotron facility presented in details in several articles [3] and a short resume of the SC-LINAC commissioning as requested [4].

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REINFORCEMENT LEARNING AND BAYESIAN OPTIMIZATION FOR ION LINAC OPERATIONS*

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Abstract

The use of artificial intelligence can significantly reduce the time needed to tune an accelerator system such as the Argonne Tandem Linear Accelerator System (ATLAS) where a new beam is tuned once or twice a week. After establishing automatic data collection procedures and having analysed the data, machine learning models were developed and tested to tune subsections of the linac. Models based on Reinforcement Learning (RL) and Bayesian Optimization (BO) were developed, their respective results are discussed and compared. RL and BO are well known AI techniques, often used for control systems. The results were obtained for a subsection of ATLAS that contains complex elements such as the radio-frequency quadrupole (RFQ). The models will be later generalized to the whole ATLAS linac, and similar models can be developed for any accelerator with a modern control system.

INTRODUCTION

The Argonne Tandem Linear Accelerator System (ATLAS) [1] is a DOE/NP User Facility for studying low-energy nuclear physics with heavy ions. It operates ~6000 h per year. The facility (see Fig. 1), uses three ion sources and services six target areas at energies from ~1–15 MeV/u. To accommodate the total number of approved experiments and their wide range of beam-related requirements, ATLAS reconfigures once or twice per week over 40 weeks of operation per year. The start-up time varies from ~12 to 48 hours depending on the complexity of the tuning, which will increase with the upcoming Multi-User Upgrade designed to deliver beams to two experimental stations simultaneously [2].

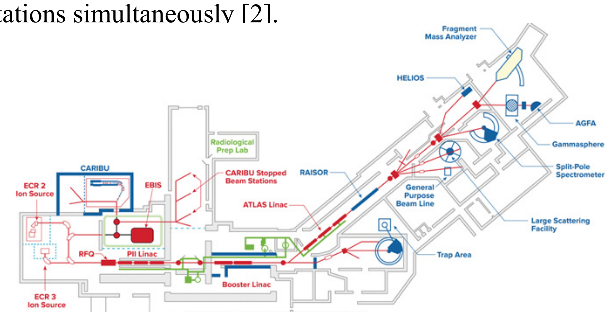

Figure 1: ATLAS Layout.

The procedure of tuning such an accelerator system is time-consuming and relies heavily on the intuition and experience of the operators. The uncertainties involved in tuning are in part due to unknown misalignments of the beamline components and the limited number of diagnostic devices to properly characterize the beam. The use of machine learning (ML) and artificial intelligence (AI) has the potential of filling the information gap and significantly reduce the time needed to tune the accelerator.

By reducing the time for beam tuning, more beam time will be available to help relieve the over-booked experimental nuclear physics program at ATLAS. In addition to beam tuning, AI/ML models can be used to improve beam quality with the installation of new diagnostics and real-time data acquisition. These improvements will increase the facility's scientific throughput and the quality of the data collected.

To support these developments, DOE/NP has approved a project to use AI/ML to support ATLAS operations. Following a description of the project objectives and future plans, the results from the most recent developments will be presented and discussed.

PROJECT OBJECTIVES & PLANS

The main project goal is to use AI/ML techniques to streamline beam tuning and help improve machine performance. The idea is to leverage artificial intelligence for linac operations, as shown in Fig. 2., with the ultimate goal of developing an AI model to tune the machine while also acquiring all kind of information from the AI model that could help improve operations.

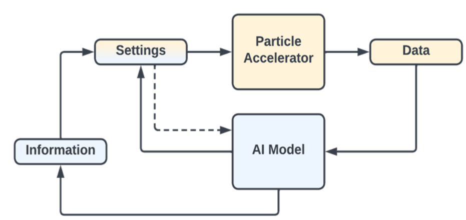

Figure 2: Basic representation of how an AI model could help particle accelerator operations.

The project objectives are threefold:

- Establish data collection, organization, and classification, towards a fully automatic and electronic data collection for both machine and beam data.
- Develop an online tuning model to optimize operations, shorten beam tuning time and make more beam time available for the experimental program.
- Develop a virtual machine model to enhance our understanding of the machine behavior, improve machine performance, optimize particular aspects and help develop new operating modes.

DATA COLLECTION

In any AI project, data collection is the first and most important step. Along with the data collection, cleaning and organizing the data are also the most time-consuming tasks. Therefore, the primary focus at the beginning of this project was on collecting the data on the state of the machine and the beam to be used for AI/ML modeling to support beam tuning and daily machine operations. Due to the

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AUTOMATION OF RF AND CRYOMODULE OPERATION AT FRIB*

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Abstract

The Facility for Rare Isotope Beams (FRIB) has been commissioned, with rare isotopes first produced in December 2021 and the first user experiment conducted in May 2022. The FRIB driver linear accelerator (linac) uses 6 room temperature cavities, 324 superconducting cavities, and 69 superconducting solenoids to accelerate ions to more than 200 MeV/nucleon. Because of the large scale, automation is essential for reliable linac operation with high availability. Automation measures implemented during linac commissioning include turn-on of the cavities and solenoids, turn-on and fast recovery for room temperature devices, and emergency shut down of linac devices. Additional automated tasks include conditioning of multipacting barriers in the cavities and calibration of the control valves for the pneumatic tuners. To ensure a smooth transition to operations, we are currently working on real-time health monitoring of the linac cryo-modules, including critical signals such as X-ray levels, RF coupler temperatures, and cryogenic parameters. In this paper, we will describe our automation procedures, the implementation details, and the experience we gained.

INTRODUCTION

Facility for Rare Isotope Beams (FRIB) is a new heavy ion linear accelerator (linac) facility just came online recently, following the completion of technical construction in January 2022 [1]. The ribbon cutting event on May 2, 2022 marks the commencement of the FRIB user program and the first scientific user experiment was conducted in the weeks that followed in May 2022.

The FRIB driver linac includes 6 room temperature cavities and 324 superconducting (SC) cavities along with 69 SC solenoids housed in 46 cryomodules [2]. It is capable of accelerating heavy ions (up to uranium) to an energy of more than 200 MeV/nucleon. There are also 19 SC magnets spread in the folding segment 2 (FS2), target hall, vertical pre-separator and fragment separator areas (see Fig. 1).

FRIB single event effects (FSEE) facility is a purpose-built beamline at the end of the linac segment 1 (LS1), with experimental station, and user control room with complete diagnostic equipment and controls. The dedicated FSEE experimental area allows users to test the effects of radiation on their devices to make sure they are safe for commercial and scientific use. FSEE facility uses its linear particle accelerator to accelerate ions to the proper specifications that can best match space radiation conditions.

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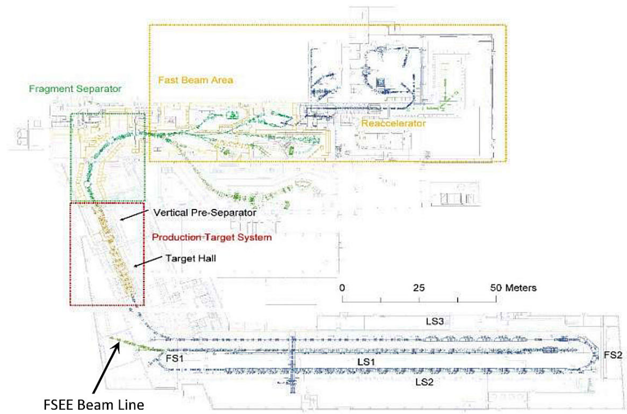

Figure 1: FRIB driver linac layout.

THE IMPORTANCE OF AUTOMATION

For a facility with hundreds of devices like FRIB, operation with high availability can only be achieved by automation.

First, automation reduces time for turning on/off devices, therefore increases time available for scientific experiments.

Automation not only improves efficiency and productivity, it also provides consistency to task execution and eliminates potential human errors. Also for certain tasks that require immediate response, for example fast recovery for room temperature cavities from a trip, automation is the only choice.

The essence of automation is to formalize the operation experience of system experts into routines, and perfect them through iterations. Eventually the devices become "smart" and require minimal human intervention. This allows operators to run complex devices without expert-level training for each type of device.

As a result, the system experts are freed from routine work and can devote more time for creative work. This also reduces the level of training required for operators.

DEVICE LEVEL AUTOMATION

During the construction phase of the FRIB project, the re-accelerator (ReA) program [3] at the National Superconducting Cyclotron Laboratory (NSCL) was already in operation. From the ReA operation experience we learned that it is important to have the auto turn on feature. We started with the quarter wave resonators (QWRs) and then expanded it to the room temperature (RT) cavities. Lastly we applied it to the half wave resonators (HWRs). During the FRIB front end (FE) commissioning, due to the long turn on time (30 to 40 minutes) of the radio frequency quadruple (RFQ) we realized fast recovery is also very important for RT cavities. Later we applied the similar idea

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CAVITY DESIGNS FOR THE CH3 TO CH11 AND BELLOW TUNER INVESTIGATION OF THE SUPERCONDUCTING HEAVY ION ACCELERATOR HELIAC*

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Abstract

New CH-DTL cavities designs of the planned Helmholtz Linear Accelerator (HELIAC) are developed in collaboration of HIM, GSI and IAP Frankfurt. The in cw-mode operating linac with a final energy of 7.3 MeV/u, is intended for various experiments, in particular with heavy ions at energies close to the Coulomb barrier for research on SHE. Twelve sc CH cavities are foreseen, divided into four different cryostat each equipped with two dynamic bellow tuner. After successful beam tests with CH0, CH3 to CH11 were designed. Based on the experience gained so far, optimizations were made, which will lead to both an increase in performance in terms of reducing the peak fields limiting superconductivity and a reduction in manufacturing costs and time. In order to optimize manufacturing, attention was paid to design many parts of the cavity, such as lids, spokes, tuner and helium shell, with the same geometrical dimensions. In addition, a tuner test rig was developed, which will be used to investigate the mechanical properties of the bellow tuner. For this purpose, different simulations were made in order to realize conditions as close as possible to reality in the test rig.

INTRODUCTION

The HELIAC at GSI in collaboration between IAP, HIM and GSI is a superconducting Linac operating in cw to be built. Since UNILAC, which is currently as part of the FAIR project being upgraded, will no longer be suitable for superheavy element (SHE) synthesis experiments, HELIAC will replace it for these kind of experiments [1]. For this purpose, a demonstrator cavity CH0 was already designed, built and successfully tested [2]. After this the two identical cavities CH1 and CH2 were designed, built and also successfully characterized in cold state [3]. Through various experiments at GSI, HIM [2, 4–7] and IAP [8–17] as well as different adaptations and investigations of the CH cavity design, different experiences could be gained. The HELIAC will consist of four cryomodules, each containing three superconducting CH cavities, two superconducting bunchers and one solenoid. In summer 2018 the design of the remaining nine 216.816 MHz sc CH-cavities (CH3 to CH11) for the HELIAC has started [18]. The design of these cavities is based on the design of the CH1 and CH2 cavities [3]. During this design process, various adjustments were made to the design. A modular cavity design for superconducting CH cavities was developed at IAP, which simplifies manufacturing and thus reduces both production time and costs. In addition to the design cavities, a bellow tuner test bench was designed, which is palned to be used to test the mechanical properties of the bellow tuners made of pure niobium.

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CAVITY DESIGN

The basic design of the 216.816 MHz sc CH cavities is the same for all cavities (see Fig. 1). They differ only in some parameters like the number of gaps, the gap lengths, the radius and the total length. All cavities are designed to incorporate two static tuners for frequency adjustment during manufacture and two dynamic bellow tuners for frequency adjustment during operation.

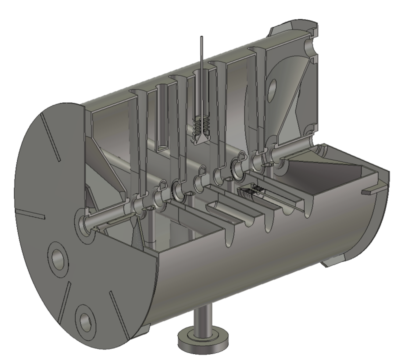

Figure 1: Layout of CH-cavity CH4 without helium vessel. The basic design of all cavities is the same except for the number of gaps, the gap lengths, the radius and the length.

The radius of the individual cavities increases steadily from CH3 to CH11, since the increasing beta causes the gap mean distances to increase from cavity to cavity and thus the capacity on the beam axis decreases. The total length of the cavities, on the other hand, varies strongly, since the gap

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LONGITUDINAL BEAM DIAGNOSTICS R&D AT GSI-UNILAC

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Abstract

GSI UNILAC provides a wide variety of ion types from energies ranging from 1.4 MeV/u to 11.5 MeV/u with a large dynamic range in the beam intensities to the experimental users or to the downstream accelerators. This flexibility in beam parameters requires a frequent tuning of the machine parameters for optimal operation of the UNILAC. Therefore, there has been a constant and pressing need for operationally convenient, accurate, fast and potentially non-destructive beam diagnostics for longitudinal charge profile and energy distribution. This contribution discusses the recent progress on longitudinal charge profile distribution measurements at GSI UNILAC. The outcome of recent devices like Fast Faraday cups (FFCs), transition radiation in GHz regime (GTR) is shown in comparison with phase probes or pick-ups. Other past developments aimed at longitudinal diagnostics at UNILAC like single particle detectors and RF deflector type methods are also briefly discussed.

INTRODUCTION

GSI Universal linear accelerator (UNILAC) is a complex set of resonators where detailed knowledge of longitudinal phase space is desired for optimizing the beam brilliance under flexible beam settings [1]. Past experiences suggest that the crucial locations for longitudinal phase determination is at the exit of High current injector (HSI), charge stripper sections and transfer channel to SIS-18. Figure 1 shows a schematic of the UNILAC where the various components of the UNILAC are shown along with the longitudinal diagnostics installations. Also marked is the measurement station X2 where most of the measurements discussed in this contribution were performed.

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Longitudinal diagnostics are primarily concerned with the measurement of beam kinetic energy W_k, energy spread ($\delta = \Delta W_k/W_k$) and particle time/phase ($\Delta t/\Delta\phi$) of arrival spread with respect to the RF. Kinetic energy measurements are performed with Time of Flight (ToF) measurement between two or more phase probes (also referred as pick-ups/BPMs) and is routinely done at several locations along the UNILAC. The correlated distributions of beam energy spread and phase spread with respect to synchronous particle form an ellipse in longitudinal phase space. The area of the phase space ellipse is referred to as longitudinal emittance. The orientation of the ellipse at various accelerator locations can be controlled via bunchers and drifts. Typical strategy of determining full longitudinal phase space ellipse is by measuring one of the projection of longitudinal phase space) under various buncher settings and then performing tomographical reconstruction [2]. The measurement of phase/time of arrival spread also referred to as "longitudinal charge distribution" or loosely just "bunch length or bunch shape" is considered more accessible. The problem of longitudinal emittance determination is thus reduced to accurate measurement the longitudinal charge distribution. The devices used for longitudinal charge distribution is the main topic of this paper.

Longitudinal charge distribution measurements for relativistic charges ($\beta \approx 1$) or “long” charge distributions ($\Delta t \gg 1$ ns) is satisfactorily and non destructively performed using phase probes or wall current monitors until the electromagnetic design limitations. However, for UNILAC energies, i.e. $\beta < 0.15$ and the particle arrival time spread of about 0.4–2 ns (σ of a Gaussian distribution), the beam transverse field distribution is elongated significantly in comparison to charge distribution. This effect is here onward referred to as “field dilution”. Equation 1 shows the expression of the transverse field of a moving charge q with

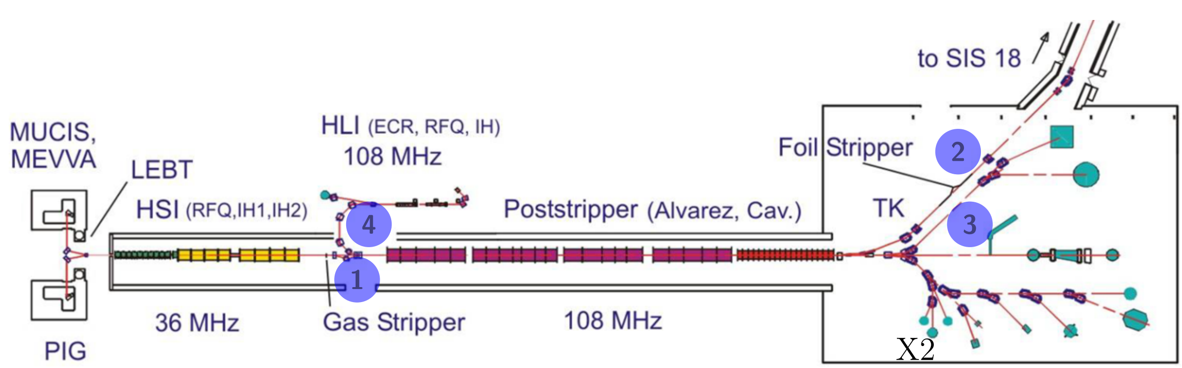

Figure 1: Schematic showing the UNILAC facility marking the location of various diagnostics. 1) Particle detectors 2) Dispersive section with RF deflector and screens 3) Gas Ionization BSM and 4) Feschenko BSM. R&D on FFC and GTR is ongoing in the area marked as “X2”.

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SIGNAL ESTIMATION AND ANALYSING OF COLD BUTTON BPMs FOR A LOW-BETA HELIUM / PROTON SUPERCONDUCTING LINAC*

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Abstract

We develop a formula including the low-beta effect and the influence of long cable issues for estimating the original signal of cold BPMs. A good agreement between the numerical and the measured signal with regard to two kinds of beam commissioning, helium and proton beams, in a low-beta helium and proton superconducting linac, proves that the developed numerical model could accurately estimate the output signal of cold button BPMs. Analysing the original signal between the first and the last cold BPM in the cryomodule, it is found that the signal voltage in the time domain is increased with the accelerated beam energy. However, the amplitude spectra in the frequency domain has more high frequency Fourier components and the amplitude at the first harmonic frequency reduces a lot. It results in a decline of the summed value from the BPM electronics. The decline is not proportional to a variety of the beam intensity. This is the reason why BPMs give only relative intensity and not absolute value for low-beta beams with a Gaussian distribution.

INTRODUCTION

Cold button BPM, as a normal diagnostic element in the Cryomodules (CMs), play an important function for monitoring the beam position, phase, and energy. Using the summed values from cold button BPMs to measure the beam intensity is our desirable thing. Thus, for a low-beta ion beam, estimating the original signal of cold button BPMs is important since the induced imaging bunch shape is expanded. Furthermore, the signal will be transmitted through a long cable to the electronics. An influence of cable's attenuation and dispersion on the transmission should be confirmed. If an accurate signal estimation in the time domain (TD) could be proven, we could perform the Fast Fourier Transform (FFT) to obtain the amplitude spectra in the frequency domain (FD) and analyse what signal is processed in the digital electronics. At last, we find the summed values of cold button BPMs processed by the digital electronics are decreasing along the superconducting (SC) linac. We will discuss these unexpected summed values and prove that they could not be used for monitoring the absolute beam intensity in a low-beta SC Linac

CAFe AND ITS COLD BUTTON BPMs

CAFe is a low-beta helium / proton superconducting LINAC. It is as a demo LINAC for China initiative Accelerator-Driven System and constructed at the Institute of Modern Physics, Chinese Academy of Science, as shown in Fig. 1. This facility includes two ion sources with an output energy of 20 keV/u before a 4-vane type copper structure radio frequency quadrupole (RFQ) with an accelerated energy of 1.5 MeV/u. The first is an electron cyclotron resonance (ECR) proton source of 10 mA with an energy of 20 keV, and the second includes an ECR helium source of 2 mA. After the RFQ section, they have the same layout, including a medium energy beam transport (MEBT), four cryomodules (CMs) and a high energy beam transport (HEBT) line. In four CMs, there are 23 half-wave resonance (HWR) SC cavities, 23 SC solenoids, and 19 cold button BPMs [1-3].

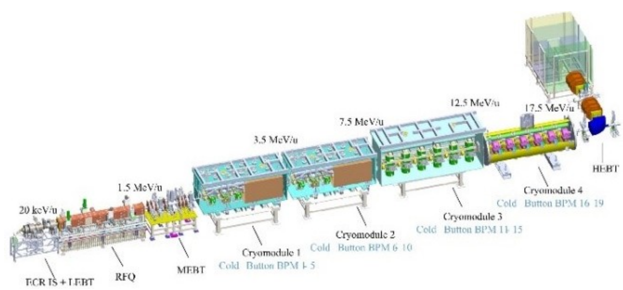

Figure 1: Schematic layout of Chinese ADS Front-end superconducting demo LINAC (CAFe).

Cold Button BPMs are both nonlinear and dependent on the position in the orthogonal plane. A general rule of thumb is that the button width should be approximately 60° wide, leaving a 30° gap between buttons. An initial design and test of the system was published in Ref. [4]. Our button parameter is optimized to an angular coverage ϕ of 62.2° to obtain high sensitivity. The surface is shaped as a section of a cylinder to be flush with the vacuum chamber surface, as shown in Fig. 2.

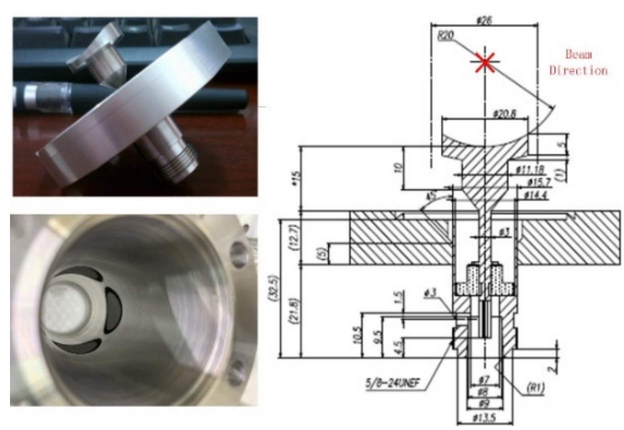

Figure 2: Button electrode, assembling picture and its drawing [4].

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A NOVEL CW RFQ FOR EXOTIC AND STABLE BEAMS

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Abstract

Meaning of ^{a} and $_b$

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 (Medium Energy Beam Transport). The RFQ is composed of 6 modules about 1.2 m long each. Each module is basically composed of a Stainless Steel Tank and four OFE CopperElectrodes. A copper layer is plated on the tank inner surface and a spring joint between tank and electrode is used in order to seal the RF. In this contribution, the main design steps of the RFQ, the construction concepts and the results obtained for the first assembled modules are shown.

INTRODUCTION

SPES, acronym of Selective Production of Exotic Species, is a CW radioactive ion beam facility under construction at LNL INFN in Italy, aimed at the production and acceleration of neutron-rich radioactive ions, in order to perform nuclear physics experiments, which will require beams above Coulomb barrier [1]. The main functional steps of the facility are shown in Figure 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 breed-er 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 configurations maximizes the RNB efficiency but needs 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 from 20 to 40 keV 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 [1].

RFQ MAIN PARAMETERS AND BEAM DYNAMICS CHOICES

The RFQ (see Table 1) operates in a CW mode (100% duty factor) at a frequency of 80 MHz. This frequency is the same of the lowest energy ALPI superconducting structures. The SPES RFQ is provided with internal bunching, in order to improve beam transmission. The injection energy of ions is set to 5.7 keV/u. This choice is aimed at getting more cells at low energy i.e. low output longitudinal emittance. The extraction energy was set to 727 keV/u (respect to the 588 keV/u of the present super-conducting RFQ, named “PIAVE”), in order to optimize the beam dynamics of the SRF ALPI linac (see Table 1).

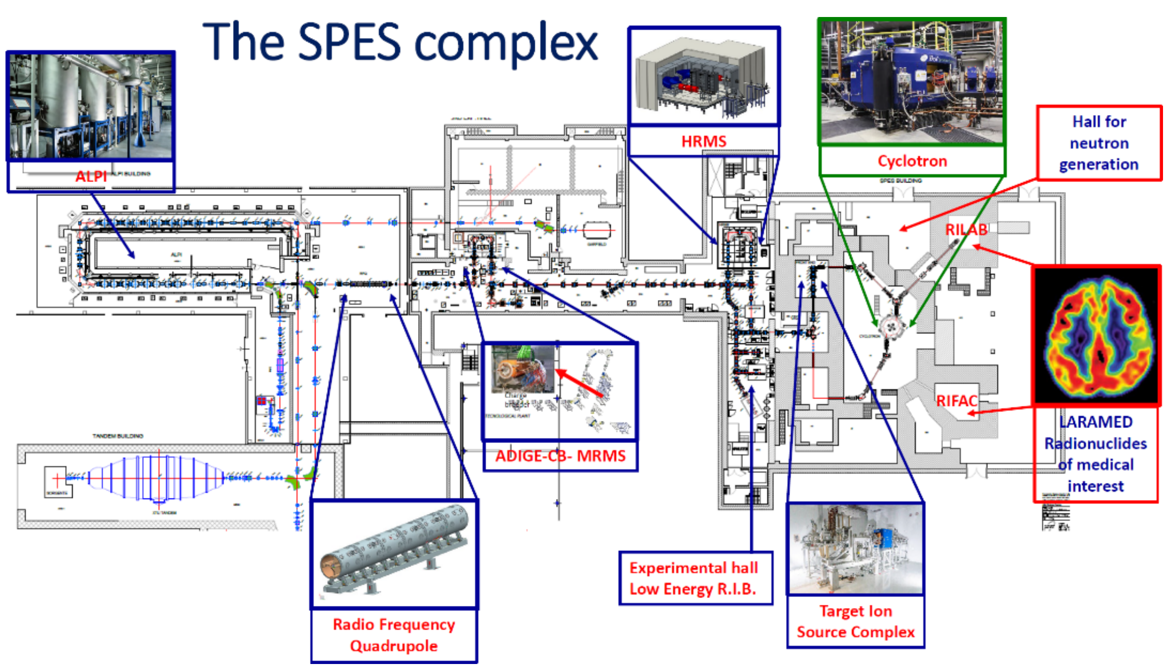

Figure 1: General SPES layout with main areas.

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ALTERNATING PHASE FOCUSING BASED IH DTL FOR HEAVY ION APPLICATION

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Abstract

The continuous wave (CW) operated HElmholtz LInear ACcelerator (HELIAC) is going to reach the next milestone with the commissioning of the superconducting (SC) Advanced Demonstrator cryomodule, comprising four SC Crossbar H-mode (CH) cavities and SC steerer magnets. In parallel with the commissioning of the SC main accelerator, the normal conducting injector consisting of an ECR ion source, a RFQ and two Interdigital H-mode (IH) cavities will be built based on an Alternating Phase Focusing (APF) beam dynamics scheme. Both IH cavities will provide a beam energy gain from 300 keV/u to 1400 keV/u with a maximum mass to charge ratio of 6, requiring only one external quadrupole triplet and beam steerer elements between them. The APF concept allows stable and effective beam transport with transverse and longitudinal focusing, enabling an efficient and compact design. Due to the stringent requirements of the APF concept on the voltage distribution and the CW operation, optimization of each cavity in terms of RF, mechanical and thermal properties is crucial for successful operation of the HELIAC injector. The current layout of the APF based and CW operated injector will be presented.

INTRODUCTION

At GSI Helmholtzzentrum für Schwerionenforschung (GSI, Germany), the UNIversal Linear ACcelerator (UNILAC) [1–3] is being upgraded to deliver high intensity, low repetition rate beam to the main synchrotron SIS100 [4] of the Facility for Antiproton and Ion Research (FAIR), which is currently under construction. The new scope of operation of UNILAC will have an impact on beam supply for the GSI material and superheavy element research program, which requires ideally a low peak current, continuous wave beam. To allow for further discoveries of new superheavy elements [5], a dedicated linear accelerator is under construction, namely the HElmholtz LInear ACcelerator (HELIAC, see Fig. 1). The operational parameters of the new machine are listed in Table 1; the machine has been specially designed to allow for a variable output beam energy [6, 7].

Whilst the variable output energy is attained by employing the EQUidistant mUltigap Structure (EQUUS [8]) beam dynamics concept in the superconducting accelerator [9, 10], the normal conducting injector has to deliver a fixed output energy and high beam quality. Thus, the normal conducting cavities in the warm injector are designed using a different beam dynamics approach, namely Alternating Phase Focusing (APF [11–15]).

Table 1: General Characteristics of the HELIAC Accelerator

Property	Value
Frequency	108.408 MHz (216.816 MHz[1])
Mass-to-charge ratio	≤ 6
Repetition rate	Continuous wave
Beam current I	≤ 1 mA
Output energy	3.5 MeV/u to 7.3 MeV/u
Injector output energy	1.4 MeV/u
Normal conducting cavities	3
Superconducting cavities	12

[1] The SC CH cavities operate on the second harmonic.

This beam dynamics approach is very attractive, as it allows removing (costly) internal magnetic quadrupole multiplets from the cavities, and thus offers for a high beam quality, compact, and modular layout of the injector, supporting stable long-term operation of the machine. In order to omit internal magnetic lenses in the cavities, the beam is focused also transversally using the electric fields in between the drift tubes. Commonly, negative synchronous phases (i.e., the RF phase when the accelerated particle beam passes the RF gap) are employed to provide for longitudinal focusing (and transverse defocusing). Positive synchronous phases have the opposite effect on beam focusing, so that the beam is transversely focused and longitudinally defocused.

In order to alter the synchronous phases (and thus the focusing properties) in between individual gaps, the lengths of the neighboring tubes are adjusted

$$L_{\text{cell}} = \frac{\beta\lambda}{2} + \beta\lambda\frac{\Delta\phi}{360^\circ} \quad , \tag{1}$$

with the relative velocity $\beta = v/c_0$, RF wavelength λ, and change of synchronous phase in between two neighboring gaps $\Delta\phi = \phi_{i+1} - \phi_i$.

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RECENT UNILAC UPGRADE ACTIVITIES

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Abstract

The GSI UNILAC is the section of the GSI accelerator facility that has been in operation the longest. UNILAC (Fig. 1) is able to accelerate ions from hydrogen to uranium up to 20 MeV (p+) and 13 MeV/u (uranium). The main focus of the recent upgrade measures is to meet the FAIR requirements and to provide reliable and long term beam operation conditions. Besides post stripper upgrade and upgrade of the UNILAC controls, a particular attention is paid to improve the performance of the High Current Injector (HSI) [1-7] and to intensify spare part management for the ageing accelerator. In order to ensure operational reliability, the main focus lies on extensive spare part management and replacement of outdated equipment. Modified beam dynamics design for the frontend system and the use of advanced technologies are needed to improve the UNILAC performance. Among other things, a modified Low and Medium Energy Beam Transport section design for the HSI and installation of reliable (non-destructive) high intensity beam diagnostics devices are in progress. This paper addresses the status of current development efforts and specific plans for the UNILAC upgrade.

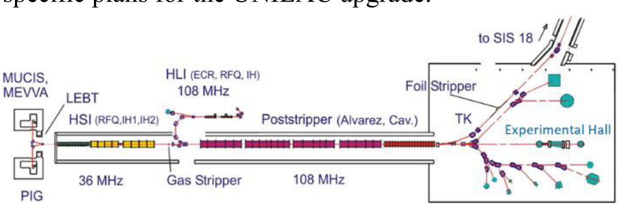

Figure 1: Overview of the UNILAC accelerator sections.

INTRODUCTION

In its more than 50 years of operation, the UNILAC (Fig. 1) has experienced extensions and optimizations in almost all sections. This has resulted in a diverse mix of components of different ages. The current strategy for maintaining and improving operational reliability can be classified into several categories. Complex components of the accelerator structures are being repaired or even replaced. Moreover, measures are being taken towards a complete system renewal. These include the installation of a new vacuum control system, the implementation of the current FAIR accelerator control system and the successive upgrade of the RF amplifier systems. Furthermore, two major linac projects have been started, which aim for the replacement or connection of a complete accelerator section such as the reconstruction of the Alvarez section (poststripper upgrade) [8] and the link of the HELIAC (HElmholtz LInear ACcelerator) to supply the experimental hall with cw-heavy ion beams. Finally, a comprehensive UNILAC upgrade program was defined that aims to achieve FAIR operating parameters, including the installation of the hydrogen gas stripper [9-12], increasing the intensity of the HSI and the development of non-destructive beam diagnostics to permanently monitor high current operation [13-17]. In particular, this proceeding reports on the individual measures of spare parts procurement and the upgrade activities to increase the beam intensity at the HSI.

SPARE PARTS MANAGEMENT

At the UNILAC Alvarez DTL accelerator section, about one drift tube per year has had to be replaced in the recent past due to water leakages. Operation is still possible, depending on which cooling circuit is affected. As a result, the focusing strength and/or the duty cycle is limited. In addition, two manufacturing types - solid copper body or stainless steel hollow body - are available for installation (Fig. 2). These are then brought to the specific length of each drift tube. In the last three years one type each has been newly manufactured. Especially for the copper version, drawings were required to be corrected and manufacturing processes had to be re-established, so that a relatively long manufacturing time of 12 months was required.

Figure 2: Drift tube of Alvarez section, as installed (left); opened drift tube with defective quadrupole lens (right).

In front of the three beam branches of the UNILAC experimental hall, a complex magnet septum has been in operation for decades, which deflects the beam into the three beam branches accordingly. So far, the water leaks that occurred at the coils of this septum magnet (see Fig. 3) could be repaired selectively, which is no longer successful due to the age-related poor condition of the coils. A complete rebuild of the beam section with the aim of separating the coils and the vacuum section is considered to be unaffordable at present. Thus, the 40-year-old manufacturing technology had to be reactivated. With regards to this it is crit-

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HIGH INTENSITY PROTON BEAMS AT GSI (HEAVY ION) UNILAC

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Abstract

A significant part of the experimental program at FAIR is dedicated to pbar physics requiring a high number of cooled pbars per hour. The primary proton beam has to be provided by a 70 MeV proton linac followed by two synchrotrons. The new FAIR proton linac will deliver a pulsed high intensity proton beam of up to 35 mA of 36 µs duration at a repetition rate of 4 Hz. The GSI heavy ion linac (UNILAC) is able to deliver intense heavy ion beams for injection into SIS18, but it is not suitable for FAIR relevant proton beam operation. In an advanced machine investigation program it has been shown, that the UNILAC provides for sufficient high intensities of CH_3-beam, cracked (and stripped) in a supersonic nitrogen gas jet into protons and carbon ions. This new operational approach results in up to 3 mA of proton intensity at a maximum beam energy of 20 MeV, 100 µs pulse duration and a rep. rate of 4 Hz. For some time now, UNILAC proton beam operation with higher intensities has been offered as standard for users. Recent linac beam measurements will be presented, showing that the UNILAC is able to bridge the time until the FAIR-proton linac delivers high-intensity proton beams.

INTRODUCTION

Besides two ion source terminals and a low energy beam transport system (LEBT) the High Current Injector (HSI) [1] of the UNILAC (Fig. 1) comprises a 36 MHz IH-RFQ (2.2 keV/u up to 120 keV/u) and an IH-DTL with two separate tanks, accelerating the beam up to the final HSI-energy of 1.4 MeV/u. After stripping and charge state separation the Alvarez DTL provides for beam acceleration up to $\beta = 0.155$. In the transfer line (TK) to the synchrotron SIS18 a foil stripper and another charge state separator system can be used. In order to provide the highest heavy ion beam currents (15 emA, U^{28+}), as required for FAIR, the HSI must deliver up to $2.8 \cdot 10^{12}$ U^{4+} ions per pulse [2].

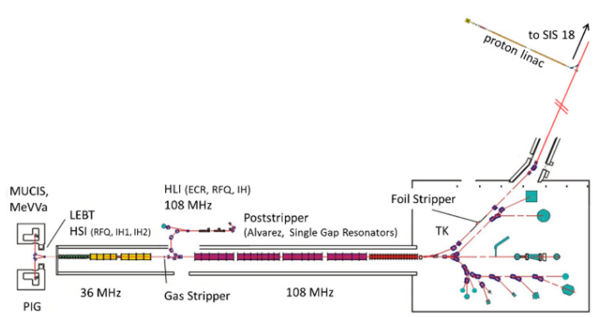

Figure 1: Schematic overview of the GSI UNILAC, experimental area and new FAIR proton linac.

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Highly charged heavy ion beams as well as protons, both with high average intensities (but low pulse intensities), from an ECR ion source of CAPRICE-type are accelerated in the High Charge State Injector (HLI) to 1.4 MeV/u. The HLI as well as the HSI serve in a time sharing mode for the Alvarez DTL. The FAIR proton linac [3] has to provide the high intensity primary proton beam for the production of antiprotons. It will deliver a 70 MeV beam to the SIS18 with a repetition rate of 4 Hz. The proton linac will be located north of the existing UNILAC complex. The main beam parameters are listed in Table 1.

Table 1: Main Parameters of the FAIR Proton Linac

Final energy	70 MeV
Pulse current	up to 70 mA
Protons per pulse	$7 \cdot 10^{12}$
Repetition rate	4 Hz
Transversal beam emittance	4.2 µm (tot. norm.)
rf-frequency	325.224 MHz

PROTON BEAMS AT HEAVY ION LINACS

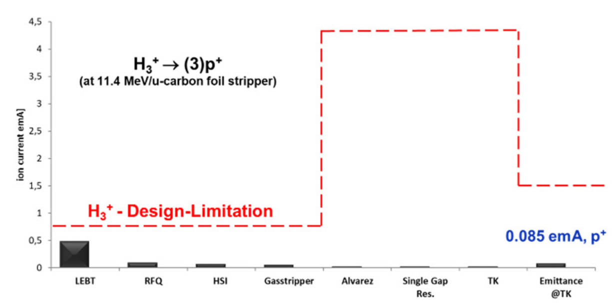

Figure 2: Standard proton beam operation at GSI-UNILAC.

The GSI heavy ion linac (UNILAC) is able to deliver intense heavy ion beam for injection into SIS18, but it is not suitable for FAIR relevant proton beam operation. A strong limitation for light ion beam operation is the low extraction voltage, applied at the ion source due to the fixed specific ion energy of 2.2 keV/u at the RFQ entrance. This limits strongly the extracted beam current from the ion source. Due to the huge emittance in the LEBT only ≤20% of the H_3^+-beam could be accepted by the HSI-RFQ, minor additional particle losses in the matching section to the HSI-IH-DTL limits the overall HSI-transmission to 17%.

Anyway, the significantly higher design limit at Alvarez DTL for H_3^+-beam and for high energy proton beam behind carbon foil stripping can by far not be utilized in standard operation (see Fig. 2).

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MODE ANALYSIS OF SINGLE SPOKE RESONATOR TYPE-2 (SSR2) FOR RISP *

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ABTRACT

Rare Isotope Science Project (RISP) in the Institute of Basic Science (IBS), Daejeon, South Korea, is developing the high-energy superconducting (SC) linac composed of two types of superconducting cavities, single spoke resonator type-1 (SSR1) and type-2 (SSR2) [1]. Both cavities have same RF frequency of 325MHz, but different beta, 0.3 for SSR1 and 0.51 for SSR2. For operating SC cavity within the target frequency, all external disturbances must be removed or avoided. From a view of mechanical vibration, comparably low frequency up to 20kHz always happens as a consequence of combination between outer disturbance and resonant frequency of SC cavity. In this paper, we will show the design layout and the specifications. Also, the mechanical resonance analysis for both bare and dressed cavity will be conducted with a numerical analysis program.

SSR2 SC CAVITY

SSR2 SC cavity prototyping was started from 2018, and its design concept was balloon-variant which came from the research collaboration with TRIUMF, the national laboratory of Canada [2]. For suppressing multipacting, the balloon-variant design is applied to both SSR1 and SSR2 of RISP. Table 1. shows the comparison result of SSR1 and SSR2 specifications [3].

Table 1: Specifications of SSR1 and SSR2

Spec.	SSR1	SSR2
Operating Frequency	325MHz	
Beta	0.3	0.51
Epeak	35MV/m	
Vacc	> 2.4MV	> 4.1MV
Q0	>3.2E9	>5E9
df/dP	<10Hz/mbar	
Aperture	50mm	
Pressure Envelope @ 300K	2 bars	
Pressure Envelope @ 2K	5 bars	

Figure 1 shows the layout of SSR2 SC cavity. RISP is now making six SSR2 SC cavities for prototyping [4]. Until now, 4 cavities are fabricated as a bare cavity and ready for cryogenic test, and 2 cavities are now on the electron beam welding (EBW) stage. Figure 2 shows the EBW finished SSR2 bare cavity.

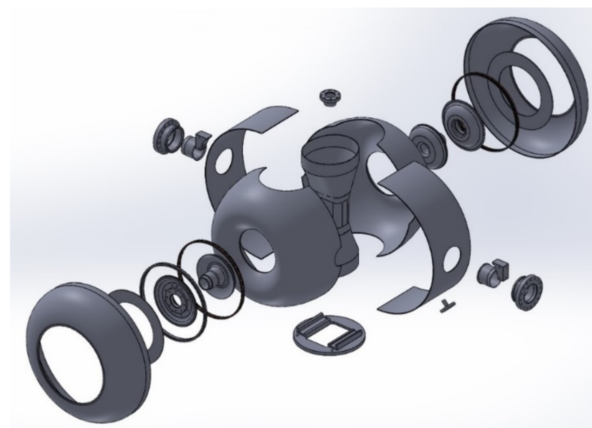

Figure 1: Layout of SSR2 Dressed Cavity.

Figure 2: Fabricated SSR2 Bare Cavity.

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