HIAT 25

EAST LANSING | MICHIGAN | USA

Proceedings of the
16th International Conference on

HEAVY ION ACCELERATOR TECHNOLOGY

JUNE 22-27, 2025

16th International Conference on Heavy Ion Accelerator Technology, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOX01

FRIB OPERATIONS: FIRST THREE YEARS*

J. Wei†, C. Alleman, H. Ao, B. Arend, D. Barofsky, S. Beher, J.S. Berryman, G. Bollen, J. Brandon, N. Bultman, F. Casagrande, W. Chang, H. Cheng, Y. Choi, S. Cogan, P. Cole, C. Compton, M. Cortesi, J. Curtin, K. Davidson, S. Di Carlo, A. Dombos, X. Du, K. Elliott, B. Ewert, A. Facco[1], F. Ferrell, A. Fila, K. Fukushima, A. Gade, V. Ganni, A. Ganshyn, T. Ginter, T. Glasmacher, A. Gonzalez, J. Guo, E. Gutierrez, Y. Hao, W. Hartung, N. Hasan, M. Hausmann, K. Holland, H. C. Hseuh, M. Ikegami, R. Iwai, D. Jager, S. Jones, N. Joseph, D. Kahl, T. Kanemura, J. Kim, S. H. Kim, C. Knowles, T. Konomi, B. Kortum, N. Kulkarni, E. Kwan, T. Lange, M. Larmann, T. Larter, K. Laturkar, M. LaVere, R. E. Laxdal[2], G. Lee, J. LeTourneau, Z.-Y. Li, S. Lidia, G. Machicoane, P. Manwiller, F. Marti, T. Maruta, D. McNanney, E. Metzgar, S. Miller, Y. Momozaki[3], A. C. Morton, M. Mugerian, D. Morris, P. Nariyoshi, I. Nesterenko, D. Newhart, C. Nguyen, S. Noji, P. Ostroumov, M. Patil, A. Plastun, L. Popielarski, M. Portillo, A. Powers, J. Priller, X. Rao, M. Reaume, S. Rodriguez, S. Rogers, K. Saito, B. M. Sherrill, M. K. Smith, J. Song, M. Steiner, A. Stolz, O. Tarasov, G. Timko, B. Tousignant, E. Wakai, R. Walker, J. Wan, L. Wang, X. Wang, J. Wenstrom, G. West, M. Wright, T. Xu, M. Yeck, R.G.T. Zegers, D. Zhang, T. Zhang, Q. Zhao, S. Zhao
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA
P. Hurh, Fermi National Accelerator Laboratory, Batavia, IL, USA
S. Prestemon, T. Shen, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[1]also at INFN - Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy
[2]also at TRIUMF, Vancouver, BC, Canada
[3]also at Argonne National Laboratory, Lemont, IL, USA

Abstract

The paper summarizes the operational experience and challenges during the first three years of FRIB user operations, covering accelerator improvement projects, expansions in user stations, and plans for facility upgrades.

INTRODUCTION

Upon completion of the Facility for Rare Isotope Beams (FRIB) construction project in April 2022, the scientific user program started in May 2022. During the first three years of user operations, the FRIB complex has safely accelerated more than a dozen different primary beams ranging from ^{16}O to ^{238}U to beam energies ~200 MeV/u (Fig. 1). The primary beam power has increased by a factor of 20, from the initial 1 kW to the present 20 kW, including the uranium beam (Fig. 2). More than 410 kinds of rare isotopes have been delivered to the user experiments. During the past year, the accelerator complex operated more than 6000 beam hours with ~95% availability serving both scientific and industrial users.

THE FRIB SCIENCE PROGRAM

At FRIB, the short-lived nuclei produced via fragmentation or fission can be used directly as fast beams for reactions; they can be stopped in a detection system that measures their decays, or they can be slowed down in a gas stopper and used in precision experiments or made into reaccelerated beams with energies ranging from hundreds of keV to well above the Coulomb barrier. Thanks to this unique scheme, FRIB provides isotopes of any element lighter than U for studies as fast, stopped, and reaccelerated beams. These complementary experimental opportunities allow users to directly address three of the four science challenges put forward in the 2023 Long Range Plan for Nuclear Science [1]. They also open up new avenues for the applications of rare isotopes for the benefit of the nation and society. The published experimental results from FRIB already address a wide variety of topics, including new-isotope discovery [2], the determination of a variety of nuclear observables obtained from nuclear decays [3–5] and reactions [6], and have reached the proton dripline for the precision mass measurements [7], for example.

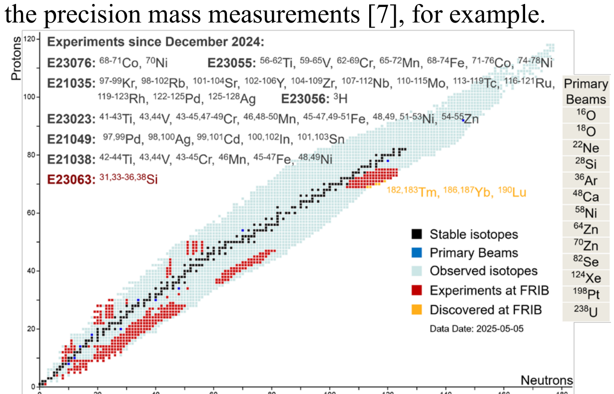

Figure 1: Rare isotopes delivered to scientific users of FRIB, and primary beams used in the driver linac [8].

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
† wei@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOY01

STATUS OF THE HIAF ACCELERATOR FACILITY IN CHINA*

J. C. Yang† and HIAF project team
Institute of Modern Physics of the Chinese Academy of Sciences, Lanzhou, China

Abstract

The High Intensity Heavy-Ion Accelerator Facility (HIAF) is one of the major scientific infrastructures in China. The project is managed by Institute of Modern Physics, Chinese Academy of Sciences, and the construction is started on December, 2018 in Huizhou City of Guangdong Province. The main feature of this facility is to provide high intensity heavy ion beam pulse for various experiments. At present, most of the accelerator equipment has been installed and tested. The beam commissioning is scheduled for the second half of 2025. In this paper, an overview of the status and perspective of the HIAF project is reported.

INTRODUCTION

The High Intensity heavy-ion Accelerator Facility is a new accelerator facility under construction at the Institute of Modern Physics (IMP) in China [1]. It is designed to provide intense primary heavy ion beams for nuclear and atomic physics, as well as other application fields. The accelerator consists mainly of a superconducting electron-cyclotron-resonance (SECR) ion source, a continuous wave (CW) superconducting ion linac (iLinac), a booster synchrotron (BRing) and a high precision spectrometer ring (SRing). A fragment separator (HFRS) is also applied as the beam line to connect BRing and SRing. Six experimental terminals will be built in phase-I at HIAF. The layout of the HIAF accelerator was shown in Fig. 1, and the main parameters are listed in Table 1.

The construction of the HIAF project was started officially in December 23rd, 2018. Up to now, all the construction of the accelerator tunnel and on-ground buildings has been completed. Auxiliary facilities such as cooling water, ventilation and air conditioning, high and low-voltage power distribution, power distribution, and cryogenic systems have been installed and debugged, and are now in operation. Almost all the accelerator components have been installed and online testing has been completed. An updated time schedule of HIAF construction is shown in Fig. 2. The first beam is expected to be launched at BRing in the middle of 2025. The Day-one experiment is proposed around the end of 2025.

Figure 1: Layout of the HIAF project and the on-site landscape.

Table 1: Main Parameters of the HIAF Accelerators

	SECR	iLinac	BRing	HFRS	SRing
Length / circumference (m)	---	114	569	192	277
Final energy of U (MeV/u)	0.014 (U^{35+})	17 (U^{35+})	835 (U^{35+})	800 (U^{92+})	800 (U^{92+})
Max. magnetic rigidity (Tm)	---	---	34	25	15
Max. beam intensity of U	50 pμA (U^{35+})	28 pμA (U^{35+})	10^{11}ppp (U^{35+})		10^{10}ppp (U^{92+})
Operation mode	DC or pulse	CW or pulse	fast ramping (12T/s, 3Hz)	Momentum-resolution 1100	DC or deceleration
Emittance or Acceptance (H/V, π·mm·mrad, dp/p)		5 / 5	200/100, 0.5%	±30mrad(H)/±15 mrad(V), ±2%	40/40, 1.5%, normal mode

* Work supported by the National Development and Reform Commission, China
† email address: yangjch@impcas.ac.cn.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOB01

FIRST RIB PRODUCTION WITH SPES EXOTIC BEAM FACILITY AT INFN-LNL

E. Fagotti*[1], T. Marchi[1], M. L. Allegrini[1], A. Andrighetto[1], L. Antoniazzi[1], P. Antonini[1], M. Ballan[1], C. Baltador[1], L. Bellan[1], D. Benini[1], G. Benzoni[4], G. Bisoffi[1], D. Bortolato[1], L. Centofante[1], D. Cittadino[5], S. Corradetti[1], L. De Dominicis[6], L. De Ruvo[1], J. Esposito[1], L. Ferrari[1], A. Galatà[1], C. S. Gallo[1], A. Goasduff[1], A. Gottardo[1], F. Gramegna[1], F. Grespan[1], M. Gulmini[1], G. Keppel[1], O. S. Khwairakpam[1,3], G. Lilli[1], A. Lombardi[1], M. Maggiore[1], M. Manzolaro[1], P. Mastinu[1], M. Miglioranza[1], P. Modanese[1], M. F. Moisio[1], A. Monetti[1], M. Montis[1], L. Mou[1], Y. K. Ong[1,2], A. Palmieri[1], A. Pisent[1], G. Prete[1], G. Pupillo[1], D. Rifuggiato[5], C. Roncolato[1], M. Rossignoli[1], L. Sarchiapone[1], D. Scarpa[1]

[1]INFN – Laboratori Nazionali di Legnaro, Legnaro, PD, Italy
[2]Università La Sapienza, Roma, Italy
[3]Universita di Siena, Siena, Italy
[4]INFN – Sezione di Milano, Milano, Italy
[5]INFN – Laboratori Nazionali del Sud, Catania, Italy
[6]Università degli Studi di Padova, Padova, Italy

Abstract

SPES (Selective Production of Exotic Species) is the INFN (Istituto Nazionale Fisica Nucleare) facility to produce and post-accelerate exotic nuclei for forefront research in nuclear physics and to produce radioisotopes for medical applications. The primary proton beam, extracted by a commercial cyclotron, irradiates targets like SiC, TiC or UCx where the ISOL (Isotope Separation On Line) technique is used to produce and extract exotic nuclei. Those are ionized, selected and either transported to low energy experiments or cooled with an RFQ (Radio-Frequency Quadrupole) cooler, purified from isobars contaminants through a HRMS (High-Resolution Mass Separator), sent to a CB (charge breeder), to increase charge state, injected into a RFQ accelerator and accelerated into ALPI (Acceleratore Lineare Per Ioni) superconducting Linac to finally reach experimental stations. The primary beamline has been fully commissioned, first radioactive beams have been produced and transported to low energy experiments, while the post-accelerator is under installation. A description of the entire facility as well as its commissioning status is given.

INTRODUCTION

SPES is the INFN project to develop an ISOL facility for reaccelerated exotic beams, mainly neutron rich [1]. The project is based on a high-power cyclotron [2] able to accelerate one or two proton beams with a final energy ranging from 35 to 70 MeV and a 750 μA maximum total current. In case of double extraction, the two proton beams have the same energy, but can have different current values. For example, it is possible to accelerate and extract a very low intensity beam, tens of nanoamps, on one arm of the cyclotron and hundreds of microamps on the other arm.

The cyclotron can supply up to eight users with corresponding beamlines: five on one arm and three on the other arm. Two beamlines are fully operational: one, the BL1 (Beam Line 1), to reach an ISOL target and the other, BL2 (Beam Line 2), to directly irradiate thin targets for nuclear and medical purposes. A third line is currently under installation to irradiate thick targets to be used for radiopharmaceuticals production.

The ISOL beamline is used to transport a 40 MeV 200 μA maximum current to an ISOL target. Although first beam commissioning are using SiC target, the final configuration will use mainly UCx target, designed to sustain up to 10 kW beam power to produce 10^{13} fissions per second inside target [3]. Reaction products are extracted by thermal process due to high temperature of the TIS (Target-Ion Source) system, in the order of 2000 °C and ionized by three types of ion sources according to requested beam: a SIS (Surface Ionization Source), a PIS (Plasma Ion Source) or a LIS (Laser Ion Source) [4, 5].

Inside the production bunker, a first mass selection is performed with a WF (Wien Filter) with a 1/100 maximum resolution. A LRMS (Low-Resolution Mass Separator), using two 45 deg dipole magnets and placed just outside the production bunker, performs a further mass selection improving resolution to 1/200. Except for WF and LRMS all transport lines are based on electrostatic components to guarantee the same transport to any beam with the same charge state and extracted at the same voltage. RIB (Radioactive Ion Beam) produced in the TIS and roughly selected by WF and LRMS, can follow three different paths:

- It can be transported to low energy experimental hall;
- It can be transported to BC (Beam Cooler) [6], for emittance reduction, that is coupled to HRMS [7] to guarantee a 1/20000 nominal resolution and then transported with electrostatic beam transport line to

* enrico.fagotti@lnl.infn.it

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOB03

DESIGN AND FABRICATION OF FRIB NORMAL CONDUCTING CAVITIES*

X. Rao†, N. Bultman, S. Miller, P. Ostroumov, A. Plastun
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

At FRIB, five unique designs of normal conducting cavities were developed for a 40.25-MHz Multi-Harmonic buncher (MHB), 80.5-MHz quarter-wave cavity MEBT bunchers, 161-MHz H-type cavity bunchers, 322-MHz H-type bunchers, and a quarter-wave 161-MHz buncher for a ReAccelerator (ReA). The paper will cover the main parameters for each type of bunchers, their design/fabrication, cooling design, RF contact design/effectiveness, tuning process, brazing design and fabrication challenges, coupler design, copper-to-stainless steel transitions, etc. The operation status of these bunchers will also be discussed.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) started user operation in May 2022 after ~10 years of project design and construction. FRIB since then has been used for scientific experiments for ~3 years successfully [1, 2], with recent achievement of 20 kW Uranium-238 beam on target, which is currently work record [3].

Eight normal conducting cavities with 5 unique designs are under operation along FRIB beamlines, primarily located within the Front End and Folding Segment 1 regions. Six cavities are under operations, and two more are planned summer of 2026.

Figure 1 shows the location of these normal conducting copper cavities: each type and locations.

Normal conducting cavities are made of high-purity copper using high-temperature furnace brazing. They are equipped with motorized tuners for real-time frequency control. An efficient water cooling is provided for CW operation. We have developed and applied a multi-step brazing technique to achieve high dimensional accuracy, reliable RF contacts, and accommodate large stainless steel-to-copper joints.

Superconducting cavities are the primary choice for acceleration because of their distinct advantages. Normal conducting cavities can still be beneficial due to their distinct characteristics and benefits depending on the application:

- Simpler Construction and Infrastructure
  - No cryogenics required
  - If far from other cryogenics devices
- Compact Size: Suitable for Front End

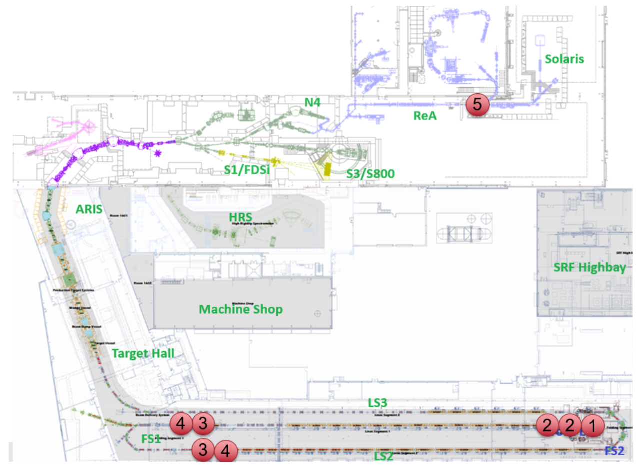

Figure 1: Layout of FRIB Normal Conducting Cavities. Mark 1: MHB at Front End; Mark 2: MEBT Buncher (X2) also at Front End; Mark 3: IH Buncher (X2) at Folding Segment 1 (FS1); Mark 4: 2H Buncher (X2) also at FS1; Mark 5: ReA Buncher.

- Better Protected against Intended or Un-intended Beam Loss
  - Less sensitive to mechanical vibrations
- Lower Cost
  - Drawing count is fewer for lower design cost
  - Fabrication generally quicker
  - Fabrication also generally less expensive
- Quicker Testing and Commissioning
  - Faster testing and conditioning cycles allow for quicker deployment and troubleshooting
- More Potential for RF Power Increase
  - Easy target to be requested for higher RF power
- Benefits for low beta, low duty cycle machine or at low frequency

DESIGN PARAMETERS

Table 1 shows major design parameters for four types of normal conducting cavities, including operating frequency, geometrical beta, aperture diameter, resonator diameter, calculated Q factor, vacuum level, and each cavity's max RF power.

For MHB, model frequencies are 40.25, 80.5 and 120.75 MHz, with total power for MHB is up to 100 Watts [4]. MHB has 3 couplers and 3 tuners. Differences to other cavities are that MHB cavity is on air side, with ceramic break as vacuum interface. Q values measured for MHB are 515, 325 and 244 for the three harmonic. The MHB buncher was manufactured, assembled, tested, installed and commissioned.

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.
† rao@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOZ03

HIGH POWER TARGETRY DEVICES AT FRIB: CHALLENGES, STATUS AND PLAN*

T. Kanemura†, B. Abdelmegied, N. Bultman, E. Fletcher, T. Ginter, R. Iwai, N. Jockheck, M. LaVere, G. Lee, F. Marti, T. Maruta, S. Miller, Y. Momozaki[1], P. Ostroumov, M. Patil, A. Plastun, R. Quispe-Abad, M. Reaume, D. Simon, J. Song, E. Wakai, X. Wang, J. Wei, Q. Zhao
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA
[1]also at Argonne National Laboratory, Lemont, IL, USA

Abstract

High-intensity heavy-ion accelerators have unique challenges in their beam intercepting devices that originate from the extremely high energy loss per distance traveled by heavy ions traversing their materials. These challenges often prohibit such accelerators from achieving higher beam power and thus determine the accelerator performance. In this paper, the challenges of operation of FRIB beam intercepting devices, as well as their statuses, and their future enhancements are discussed.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a U.S. Department of Energy Office of Science (DOE-SC) scientific user facility for rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC [1]. The ultimate goal is to deliver 400 kW beam power for all ions (especially uranium at an intensity of 8 pμA or 5×10^{13} ^{238}U/s) to the rare isotope production target at energies >200 MeV/u [2].

Compared to proton-based facilities, lower-energy, heavy-ion-based facilities face challenges, including high power density and high radiation damage in materials where beams are intercepted as discussed later. Heavy-ion facilities have been running at significantly lower beam powers compared to proton-based facilities [3]. FRIB is to push the power frontier of heavy-ion machines to 400 kW, closer to the power level similar to proton-based facilities.

Beam-intercepting devices (BIDs) are used throughout the FRIB facility. As is usually the case in high power accelerator facilities, the performance of the FRIB is currently limited by the capacity of its BIDs. In this paper, the BIDs statuses, their challenges, and their planned enhancements are discussed.

BEAM INTERCEPTING DEVICES AT FRIB

Figure 1 shows a layout of the facility, which consists of three major areas. The first one is the 400 kW superconducting radio-frequency linear accelerator (linac). The second is the rare isotope (RI) production and separation area, where rare isotopes are produced at the target and are transported to experimental areas. And the third is experimental areas.

In the FRIB linac, charge strippers (carbon and lithium strippers) are located in the Folding Segment 1 (FS1). After the first dipole magnet in the FS1, there is a charge selection collimator named the charge selector. The beam is further accelerated to its final energy, and delivered to the RI production target, which is located in the RI production and separation area. The unreacted primary beam is then delivered to the beam dump in the same area. Table 1 shows a list of major BIDs used at FRIB with the beam power and power deposition for full power operations at each BID.

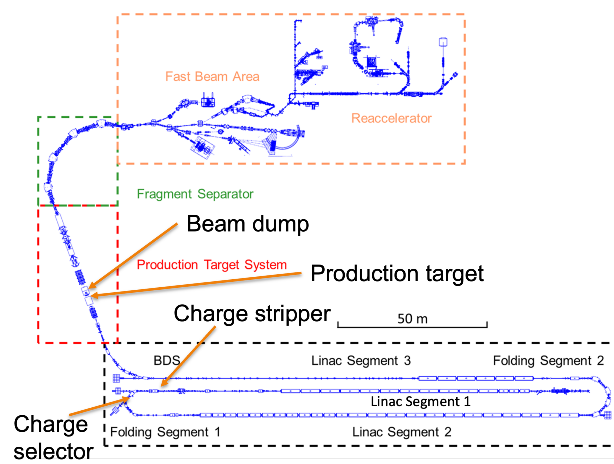

Figure 1: FRIB facility layout and locations of major beam-intercepting devices used in FRIB.

CHALLENGES

There are two major technical challenges in BIDs in heavy ion accelerators in general.

- Extreme thermal load (power density).
- Radiation damage (when a solid material is used).

Thermal Load

Figure 2 shows the energy deposition per unit length in carbon, a popular BID material, as a function of beam energy with selected ion species. Figure 2 illustrates that the heavier the ion is, the higher the energy deposition will be in the material. The energy deposition by ^{238}U is 3 orders of magnitude higher than proton at energies higher than 2 MeV/u. The energy deposition becomes lower with the beam energy. Therefore the interaction between heavy ion beams

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.
† kanemura@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOC01

COMMISSIONING OF THE S^3 SPECTROMETER: ADVANCES, CHALLENGES AND OUTLOOK

M-H. Stodel[1]*, M. Aburas[1], M. Authier[2], A. Drouart[2], F. Esnault[1], B. Jacquot[1], N. Lecesne[1], T. Lefrou[1], R. Levallois[1], F. Lutton[1], G. Olivier[3], J. Piot[1], H. Savajols[1], C. Stodel[1]
[1]GANIL, CEA/DRF-CNRS/IN2P3, Caen, France
[2]Département de Physique Nucléaire, IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[3] Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France

Abstract

The S^3 spectrometer is a new-generation spectrometer connected to the SPIRAL2 superconducting linear accelerator at GANIL. It aims to provide the nuclear physics community with opportunities to study the products of the fusion-evaporation reaction, producing proton-rich nuclei through to heavy and superheavy nuclei. The project began in 2010 and has now entered its final phase. This paper provides an update on the main equipment developed specifically for the spectrometer, details the challenges we have had to overcome, and looks ahead to the next phases of commissioning.

THE SPECTROMETER DESIGN

In order to take advantage of SPIRAL2's high-intensity beam and study the rare and very rare events produced in the target station, the spectrometer has been designed with 4 main features in mind (Fig. 1): it should accept a 10 kW beam, have a very good rejection rate of the primary beam (selectivity > 10^{13} in the first stage), have a fairly good transmission (> 50%), and also be capable of performing mass selection (> 450) in high-resolution mode.

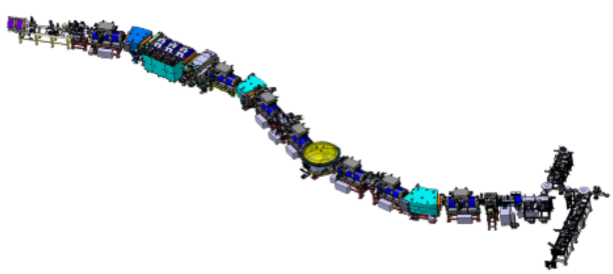

Figure 1: Super Separator Spectrometer overview.

The spectrometer is a symmetrical two-stage design [1]. The first stage, called the momentum achromat, comprises the target station and the main beam dump to get rid of the incoming beam that has not interacted with the target. The second stage, called the mass spectrometer, comprises an electrostatic dipole and a wide-angle magnetic dipole to achieve the appropriate resolution. In total, the spectrometer comprises 8 focusing triplets, 7 of which are superconducting and one of which is an open triplet at room temperature with a large aperture. At the final focal plane, two detection setups can be placed alternately.

There are two possible modes of operation, depending on whether the objective of the experiment requires good transmission or mass resolution of the reaction products. In the latter case, the aberrations of the 2nd and 3rd order modes will be cancelled by using dedicated sextupoles and octupoles in the superconducting magnets.

DEVICES AND THEIR STATUS

The rotating target station (Fig. 2) has been designed for heavy beams at 10 pμA (thermal heat calculation) at 5 MeV/u [2]. It has a large wheel of 670 mm diameter that supports 18 targets of 21.5 cm^2. It rotates at a speed up to 3000 rpm. The beam spot is very focused in the horizontal planes with standard deviation of 0.5 mm and 2.5 mm respectiveley. To ensure the integrity of the target, several sensors detect any damage in the target structure. These include an electron gun, an alpha source and a silicon detector, as well as two Rutherford backscattering detectors. The electronic control is able to synchronize the accelerator beam (using the slow chopper) with the rotation of the target. This prevents damage to the frames. The target station was commissioned off-line, then on-line using a cyclotron beam, and finally qualified with a real SPIRAL2 beam during stage A of the commissioning plan.

After the target the beam is conducted through the dispersive zone (Fig. 3), that comprises a magnetic dipole, a resistive triplet of quadripoles, and the beam dump. This beam dump is made to withstand a 10 kW power deposit. It comprises two chambers, the upstream chamber and the downstream chamber.

It is made of:

- 11 dump parts (5 fingers, 4 shutters, 2 stationary plates),
- 2 kW / finger (1 kW/cm^2). Tungsten/Copper, V shape,
- External and internal lead shielding so that the radiation will decay to 25 μS/h after 24 h cooling time for eventual maintenance in the zone.

The beam dump has been fully developped, produced and tested by CEA/Saclay, and its final installation will take place early 2026.

Another important development for this spectrometer is the Superconducting Multipole Triplet (SMT). There are

* marc-herve.Stodel@ganil.fr

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOP01

COMPUTATION MODEL FOR SPACE CHARGE EFFECT FOR BUNCHED BEAM IN COLLIDER RINGS*

H. Alamprese†, Y. Hao, Michigan State University, East Lansing, USA

Abstract

In the last two decades, numerical and experimental studies have extensively explored the impact of the space charge on bunched beams in both linear accelerators and storage rings. However, fully accounting for space charge effects over the entire accelerator is computationally intensive, especially in storage rings, where simulations must track beam dynamics over many turns and extended time periods. In many cases, space charge forces cannot be neglected, motivating the development of an alternative computational model. Here, we explore space charge-induced nonlinear dynamics using a model that approximates the Coulomb force by concentrating its effects at discrete locations along the accelerator. This approach enables efficient analyses of the full six-dimensional phase space evolution under space charge effects. Future work will apply this model to further investigate the interplay between space charge and beam-beam interactions in colliders, as well as to assess long-term stability criteria in ring accelerators.

INTRODUCTION

Over the past decades, collective effects have been studied for their role in causing instabilities in accelerators. Several simulation codes have been developed, playing a crucial role in machine design and optimization, as well as in the study of nonlinear beam dynamics, including instabilities and resonances. Currently, the most widely used model is Particle-in-Cell (PIC). However, this approach may be less efficient for circular accelerators due to the extensive demand of computation resources. Moreover, the difficulty in maintaining symplecticity makes it challenging to interpret the results of long-term tracking. A first possible attempt of implementing a symplectic model applicable to accelerators, such as rings and colliders, has been presented in [1]. However, its computational cost scales with the number of Poisson modes and macro particles ($N_{\text{modes}} \times N_{\text{particles}}$), and can become significantly high for simulations of over several thousand turns.

This work adopts a simplified Gaussian beam model to calculate space-charge forces in a proton beam propagating through a periodic FODO cell lattice, and compare two distinct approaches: one based on a two-dimensional (2D) beam phase space and the other on an approximate three-dimensional (2.5D) representation.

The first section presents the theoretical foundations of the implemented model and describes its assumptions in both the two-dimensional and three-dimensional case. The second section describes the simulation study of a coasting beam, where the two-dimensional method is employed, and a bunched beam in the presence of a radio-frequency (RF) cavity, where the three-dimensional method is applied.

DEVELOPMENT OF A TRANSFER MAP FOR SPACE CHARGE

The space charge force plays a crucial role in collective beam dynamics, as each particle in the bunch experiences the electromagnetic field generated by all other particles in the rest frame. This interaction directly affects the particle's momentum and leads to modifications of their trajectories, resulting in betatron tune and amplitude modulation.

The transverse electric field generated by the beam can be modeled using the 2-D Poisson equation. For a Gaussian beam, the field can be accurately expressed as the Bassetti-Erskine equation, which is derived from the potential of a two-dimensional Gaussian charge distribution. This formulation directly depends on the position of the particle inducing the electric field [2].

Assuming a 2D Gaussian beam distribution, the longitudinal profile is treated as *infinitely uniform*, implying that the electric field is independent of the longitudinal coordinate z. As a result, the transverse momenta is influenced by the electric field as shown in Eq. 1, where $K = 2r_0N/\beta^3/\gamma^3$ defines the perveance in terms of classical radius r_0 and number of particles N in the bunch.

$$dp_{x,y} = \sum_i^n K \cdot E_{x_i,y_i}(x_i, y_i, \sigma_x, \sigma_y) \cdot ds \tag{1}$$

For a bunched beam, the RF cavity compresses the longitudinal beam size, which can also be modeled as a Gaussian distribution (2.5D model). Consequently, the Bassetti-Erskine equation acquires the z-dependence, since the total charge distribution is no longer uniform. The corresponding linear charge density is given by the following.

$$Q\lambda(z) = Q\,\frac{e^{-\frac{z^2}{2\sigma_z^2}}}{\sqrt{2\pi}\sigma_z} \tag{2}$$

Due to the z-dependence, the transverse momentum kick is proportional to the longitudinal charge distribution, resulting in the following expression for the transverse momentum kick:

$$dp_{x,y} = \sum_i^n \lambda_{z_i} \cdot K \cdot E_{x_i,y_i}(x_i, y_i, \sigma_x, \sigma_y) \cdot ds \tag{3}$$

The circulating beam is subject to its own self-field throughout the entire ring, resulting in a continuous

* Work supported by the U.S. Department of Energy Office of Science under award number DE-SC0024170.
† alampres@msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOP04

MONTE CARLO SIMULATION ANALYSIS FOR RADIATION DAMAGE ON GLIDCOP Al-15 CAUSED BY 17-20 MeV/u HEAVY IONS*

E. Fletcher[1†], T. Ginter[1], P. Hurh[2], T. Kanemura[1], S. Lidia[1], A.S. Plastun[1], E. Wakai[1]
[1]Facility for Rare Isotope Beams, East Lansing, MI, USA
[2]Fermi National Accelerator Laboratory, Batavia, IL, USA

Abstract

The Facility for Rare Isotope Beams heavy-ion SRF linear accelerator is designed to accelerate all ions up to Uranium to a maximum beam power of 400 kW. Several beam intercepting devices are essential to the successful operation and maintenance of the accelerator, including a low power charge selector (LPCS) made of copper CONTAINING 0.15% precipitated Aluminum Oxide by weight called Glidcop Al-15. As FRIB ramps up the primary beam power beyond the current 20 kW level, the charge selector must withstand ever increasing heat loads and higher radiation damage rates. Significant beam induced radiation damage-including deformation, (e.g., swelling and blistering with cracking) has already been observed on a recently removed LPCS. We also observed physical features up to about 5.5 mm wide which appear to be deeper than the projected range of any ions.

This paper presents the results of Monte Carlo simulations carried out using the Particle and Heavy Ion Transport code System (PHITS), quantifying the total damage dose caused by ^{238}U from 2023-2024. Simulating an accurate irradiation history is essential to determining the scope of post irradiation examination (PIE) work. This paper will also present a PIE plan in detail.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) linear accelerator (linac) uses a charge stripper to increase the mean charge state of an ion beam, therefore increasing the energy gain of the beam from post-stripper linac cavities. This also creates multiple charge states of the beam. While the FRIB linac can simultaneously accelerate multiple charge states within a ΔQ/Q of about ± 3%, it cannot accelerate them all. The low power charge selector [1] (LPCS), as shown in Fig. 1, is a set of moving jaws that act as slits to intercept the lowest intensity charge states that cannot be accelerated and ensure that high-intensity charge states are allowed to pass through a gap between the jaws to be accelerated. This beam interception causes radiation damage due to the displacement of lattice atoms, ion implantation and other irradiation effects such as transmutation. While the effects of radiation damage are observable on the LPCS, there is little data available to show how the combined effects of different ion species and transmutation products affect damage mechanisms.

The best place to begin understanding the complex interplay between various radiation damage effects is by looking at the contributions of individual ion species, specifically the displacement damage measured in dpa that each species causes. This information can be used to localize regions of interest to perform PIE.

This paper intends to elucidate the process by which individual ion species are evaluated for their contributions to the displacement damage using ^{238}U as an example and explain how this information will be used to inform future PIE work.

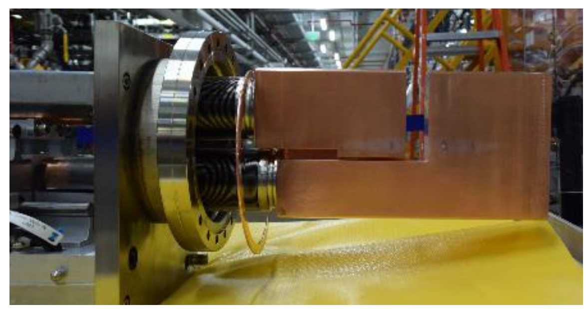

Figure 1: FRIB LPCS with visible radiation damage.

METHODOLOGY

Particle Current Calculations

To calculate the total displacement damage caused by ^{238}U, we must first calculate the total number of particles that were intercepted by the LPCS. This must be converted from electrical current given by FRIB beam current monitors (BCMs). The conversion is given by:

$$I_p = \frac{I_{euA}}{Q * e} \tag{1}$$

where I_p is the particle current (particles per second or pps), I_{euA} is the charge current in electrical micro amperes, Q is the ionic charge state and e is the elementary charge. Since multiple charge states are intercepted, and each charge state only composes a fraction of the total intercepted beam, Eq. (1) becomes:

$$I_{p_i} = \frac{I_{euA_i}}{Q_i * e} = \frac{I_{euA} * f_i}{Q_i * e} \tag{2}$$

where f_i denotes the fraction of the contribution of a particular charge state Q_i to the intercepted beam current. Summing over the contribution of all intercepted charge states, we get:

*This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633 and Office of High Energy Physics, under Award Number DE-SC0018362.
†fletcher@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOP05

THERMAL-HYDRAULIC ANALYSIS OF A 20 kW BEAM POWER WATER-COOLED MINI-CHANNEL BEAM DUMP AT FACILITY FOR RARE ISOTOPE BEAM*

R. Quispe-Abad†, N. Bultman, T. Kanemura, S. Miller, M. Patil, M. Reaume, J. Song,
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The Facility for Rare Isotope Beams (FRIB) is a high-power heavy-ion accelerator, completed in April 2022 [1], designed to accelerate heavy ions to energies exceeding 200 MeV per nucleon (MeV/u). These ions collide with a rotating graphite target, while the residual beam is absorbed by a water-cooled static beam dump positioned at a 6-degree angle to the beam path. The current beam dump consists of a machined C18150 copper alloy block, explosion-bonded to AL2219 alloy with precision-machined cooling grooves. Cooling water is supplied through 3D-printed Aluminum 6061 inlet and outlet components, facilitating heat dissipation from the beam stopper. This paper examines the thermal-hydraulic performance of the Mini-Channel Beam Dump (MCBD) under both nominal and off-nominal conditions. The MCBD is designed to handle operational beam power up to 20 kW, with planned optimizations to support a power ramp-up to 30 kW.

INTRODUCTION

This work presents the thermal-hydraulic analysis of a 20 kW beam power, water-cooled mini-channel beam dump. The analysis evaluates its performance under normal and off-normal operating conditions, establishing operational limits and guiding further optimizations. FRIB is primarily a nuclear physics research facility that produces rare isotope beams by striking a rotating target. Typically, the beam dump absorbs 75% of the power after the target, and its location is shown in Fig. 1. As FRIB follows a strategy of gradually increasing its beam power, the ultimate design power is 400 kW [2]. The first version of the beam dump had a 20-degree orientation with respect to the incoming beam, designed for a 1 kW primary beam power on target [3]. With the ramp-up plan, the subsequent version of the beam dump had a 6-degree orientation for a 10 kW beam power [4]. Both early versions of the beam dump absorber were made of Aluminum 2219. The current version of the 20 kW beam dump in operation (Fig. 2) consists of a machined C18150 copper alloy block, explosion-bonded to an AL2219 alloy, with precision-machined cooling grooves measuring 2 mm × 7 mm (Fig. 3), and is analyzed in this work.

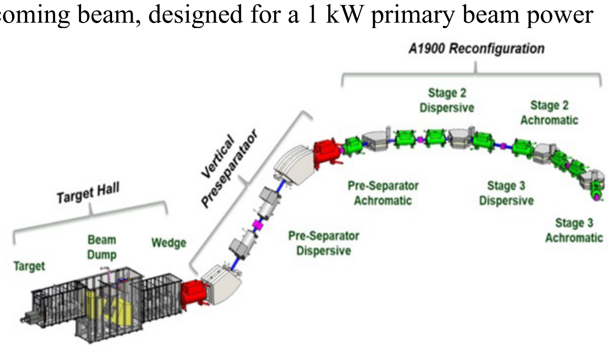

Figure 1: Beam dump location in the target hall [1].

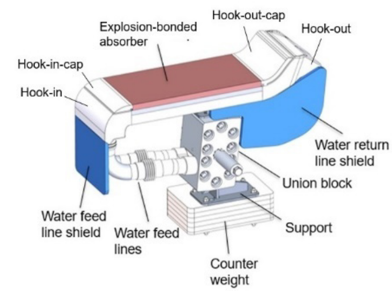

Figure 2: Mini-channel beam dump model (MCBD).

The bi-metal absorber enables higher power operation due to the improved thermal conductivity and strength of the absorber, while also preventing oxidation [4, 5].

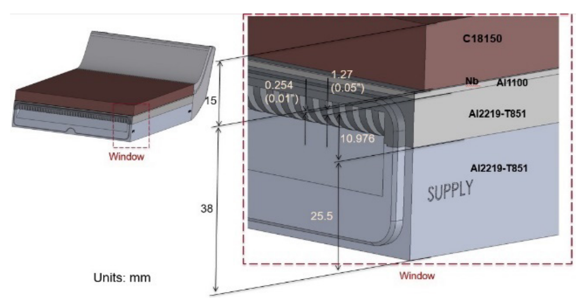

Figure 3: Mini-channel and some interstitial details.

THERMAL-HYDRAULIC ANALYSIS

Computational Fluid Dynamics (CFD) Model

A 3D SolidWorks® model is exported to Ansys Fluent® – Release 22.0, a commercial code based on the finite volume method [6]. The solid region of the absorber uses a structured (hexahedral) mesh, while areas with complex beam dump geometry are meshed using an unstructured grid. The structured mesh has a grid size of 0.75 mm, selected to appropriately capture thermal effects based on the size of a ^{238}U beam (Table 1). The fluid region within the channels is also meshed using a structured grid. The first layer adjacent to the wall is 0.1 mm thick, with four additional layers included to accurately capture thermal and

* Work supported by the Department of Energy Contract DE-SC0023633
† quispeab@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOP07

CONTROL OF MICROPHONICS FOR A SUPERCONDUCTING RADIO-FREQUENCY PHOTO-INJECTOR CRYOMODULE*

K. M. Villafania[1,†], J. Brown[1], W. Chang, S. Kim, T. Xu[1]
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA
[1]also at Michigan State University Physics and Astronomy Department, East Lansing, MI, USA

Abstract

A superconducting radio-frequency photo-injector cryomodule is being developed for the high-energy upgrade of the Linac Coherent Light Source (LCLS-II-HE). This effort is a collaboration between the Facility for Rare Isotope Beams at Michigan State University (MSU), Argonne National Laboratory, Helmholtz-Zentrum Dresden-Rossendorf, and SLAC National Accelerator Laboratory. The cryomodule features a 185.7 MHz superconducting quarter-wave resonator (QWR) designed to operate with an RF electric field of 30 MV/m at the photo-cathode. Mechanical vibrations must be controlled for operation with stable amplitude and phase. The first prototype cryomodule was cold-tested at MSU with a QWR, fundamental power coupler, tuner, and cathode stalk. In the first high-power RF cold test, we observed microphonics that made it difficult to control the RF phase at high gradient. The cryogenic circuit was identified as a likely culprit. This paper presents our studies of microphonics during the cryomodule cold test and follow-up investigations at room temperature. Our findings provided valuable feedback for modifications to the cryogenic circuit and a successful second cold test of the cryomodule.

INTRODUCTION

The LCLS-II high energy (HE) upgrade for SLAC adds 23 superconducting cryomodules which will increase the beam energy from 4 GeV to 8 GeV [1]. In addition to these 23 cryomodules, there is consideration of a Low Emittance Injector (LEI) that is parallel to the existing electron source [2]. The addition of this SRF electron source can improve the photon energy from 12.8 keV to 20 keV, which would enable studying dynamics on the atomic scale [3]. This LEI features a 185.7 MHz superconducting quarter-wave resonator (QWR). The cold mass of the cryomodule consisting of the cavity and its ancillary components is shown in Fig. 1. Table 1 has operational parameters of the cryomodule [4].

Constant cavity amplitude and phase is critical to providing uniform acceleration and maintaining accelerator synchronicity. In the case of light sources, this synchronicity is essential to producing high quality, coherent x-rays. Ambient vibrations from cryomodule systems and/or external sources can result in a change in cavity resonant frequency (microphonics), leading to amplitude and phase mismatch without feedback systems.

* This material is based upon work supported by the Department of Energy Contract DE-AC02-76SF00515 and DE-SC0018362.
† villafan@frib.msu.edu

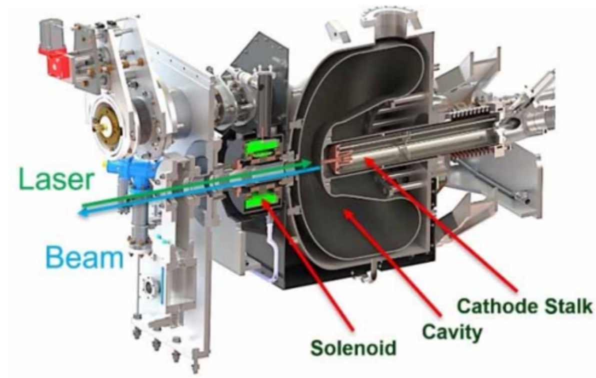

Figure 1: Model of cold mass in cryomodule [4].

Table 1: SRF-PI Cryomodule Performance Parameters [4]

Parameter	Units	Value
Operating Temperature	K	4.2
Cavity Frequency at 4.2 K, 1 bar	MHz	185.7
Cathode Gradient (Nominal/Maximum Operating)	MV/m	>30/35
Integrated E_z Field at 30 MV/m Gradient	MV	>1.6
Captured Dark Current at 30 MV/m Gradient	nA	<10
Cavity Q_0		$>1 \times 10^9$
RF Coupler Q_{ext} [1]		10^7
Static Heat Load at 4.5 K	W	<25

[1]SLAC Design Values

Mechanical tuners can provide countermeasures to slow detuning effects from variations in bath pressure and temperature or the Lorentz force detuning effect [5]. However, these tuners cannot account for fast changes in cavity resonant frequency. To make up for this, feedback systems for cavity amplitude and phase are implemented into the low-level RF controllers. These control loops do not tune the cavity; they merely provide more power to keep constant cavity amplitude and phase.

FIRST CRYOMODULE TEST

The first cryomodule test was with the QWR without cathode port, fundamental power coupler (FPC), and cathode stalk. During the test, 30 MV/m gradient was successfully reached but relatively strong microphonics were observed; see Fig. 2. The microphonics during testing made it difficult to close the RF phase loop at high accelerating gradient.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOP14

MECHANICAL VIBRATION STUDY OF LOW-ENERGY SUPERCONDUCTING LINEAR ACCELERATOR (SCL3) IN RAON*

M.O. Hyun†, O.R. Choi, H. Jang, Y. Kim, J. Shin
Institute for Basic Science (IBS), Daejeon, South Korea

Abstract

Recently, the Institute for Rare Isotope Science (IRIS, previously RISP) in the Institute for Basic Science (IBS), Daejeon, South Korea, finished the first beam commissioning for operating of low-energy superconducting linear accelerator (SCL3). SCL3 is composed of two types of cavity, quarter wave resonator (QWR) which has 81.25 MHz RF frequency and half wave resonator (HWR) which has 162.5 MHz RF frequency. During operation, RF control was very complicated due to many issues including mechanical vibrations coming from vacuum pump, cryogenic valve, or undefined source. In this paper, we will discuss the SCL3 mechanical vibration data measured by laser doppler vibrometer (LDV). In addition, the mechanical vibration of SCL3 cryogenic components such as transfer line and supports will be also described.

INTRODUCTION

IRIS has constructed a low-energy superconducting linac (SCL3) since 2012. Through enormous efforts by many researchers and engineers, SCL3 construction was finished by 2022, and the first beam commissioning was finished by August 2024. During operation, IRIS experienced many issues such as RF or cryogenic control problem, SSPA malfunction, and general utility error. Among them, we are trying to figure out the effect of mechanical vibration to the RF control problem. There are so many sources of mechanical vibration in the SCL3 tunnel, such as vacuum pumps, cryogenic valves, or utility pipes [1–4]. When vibration is excited, it can be transmitted to the connected structure, like rigid support, floor, wall, or cryomodule, and also excite other structures themselves. When this vibration reaches the cavity, then microphonics happen, and RF control can be failed. Therefore, to measure the mechanical vibration of the cryomodule and related connection is undoubtedly crucial for the view of RF control.

VIBRATION MEASUREMENT

First, we planned to measure the whole SCL3 linac region roughly and shortly, because we expected that we could find a tendency of mechanical vibration after two to three measurement. Figure 1 shows the measuring points of SCL3 Linac (Red dots). Three QWR cryomodules (02, 09, 20), two HWRA cryomodules (04, 09), and five HWRB cryomodules (02, 05, 09, 14, 19) were chosen for measuring points. To see the effect of connecting the structure, we measured both the cryomodule wall and support at each point. We started the measurement of mechanical vibration in December 2023, however, the first measurement became a rehearsal for next measurement, device troubleshooting and solving other technical issues. After troubleshooting, the vibration measurement data was gathered by February, March and September 2024. Table 1 shows the condition of every utility in the SCL3 linac.

Table 1: SCL3 Operating Conditions on Measuring

2024	February	March	September
CM Vacuum	On	On	On
CavityVacuum	On	On	On
SSPA	Off	Standby	Standby
Cryogenic	Off	Cooldown	4K Cooling
Water Utility	Running	Running	Running
Air Condition	Running	Running	Running

Figures 2 and 3 show the measurement of the cryomodule wall and stand. We used the Polytec© Portable Digital Vibrometer (PDV) 100 model for the measuring device. Figures 4 and 5 show the measured vibration results for both the cryomodule wall and support by February 2024. In Fig. 5, the main vibration at the support was near 10 Hz (9–12 Hz), and this peak was also shown in Fig. 4. However, near 28 Hz abnormal peak of QWR CM #20 has not been explained yet. We guess this abnormal peak can be excited by unexpected cryogenic valve control. Figures 6 and 7 show the measured vibration results for both the cryomodule wall and support by March 2024.

In Figs. 6 and 7, the main vibration peaks of the cryomodule wall and support were near 10 Hz (9–12 Hz), the same as the results of Feb. 2024. And, both cryomodule wall and support vibration tendencies were also very similar to each other, except for a near 60 Hz peak in support results. However, the magnitude of vibration in the cryomodule wall was greater than the support. We guess that, with Table 1, when the cryogenic system was turned on then the vibration of the cryogenic facility was excited and transmitted through the cryogenic pipeline, and was measured at the cryomodule wall and support. Figures 8 and 9 show the measured vibration results for both the cryomodule wall and support by September 2024.

Compared with previous vibration results, the vibration magnitude was reduced, and the frequency tendency was changed. In Fig. 8, between 10 to 14 Hz vibration peak was

* Work supported by the Institute for Basic Science (IBS-I001-D1)
† atikus43@ibs.re.kr

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOP18

EXTENDING JuTrack'S CAPABILITIES TO THE FRIB ACCELERATOR TO ENHANCE ONLINE MODELING *

C. T. Ratcliff†, K. Fukushima, Y. Hao, J. Wan
Facility for Rare Isotope Beams, East Lansing, MI, USA

Abstract

JuTrack is a Julia-based accelerator modeling and tracking package that utilizes compiler-level automatic differentiation (AD) to enable fast and accurate derivative calculations. While JuTrack provides a solid foundation for beam dynamics simulations, its capabilities must be extended to support the Facility for Rare Isotopes (FRIB) linac. This includes modeling heavy-ion linac accelerator components such as the liquid-lithium charge stripper, which facilitates efficient acceleration by remove electrons from heavy isotopes, and incorporating multi-charge state acceleration tracking, which allows for charge-dependent beam dynamics. These extensions address challenges such as the beam matching and optimization of multi charge state through various accelerating structures and beam-material interaction modeling while maintaining the auto differentiation capability. This work focuses on adapting JuTrack to incorporate these elements, enhancing its online modeling abilities. We present modifications to JuTrack's framework and demonstrate their performance in FRIB simulations.

INTRODUCTION

JuTrack is a differentiable accelerator modeling package written in Julia that leverages automatic differentiation for beam dynamics calculations [1]. A comprehensive description of JuTrack's architecture and capabilities can be found in a paper also submitted to this conference [2, 3]. The Facility for Rare Isotope Beams (FRIB) presents unique challenges for beam dynamics modeling due to its multi-charge state acceleration scheme and the presence of charge strippers. This work extends JuTrack to address these specific requirements while maintaining its differentiable nature.

The FRIB accelerator employs charge strippers to increase the charge state of heavy ions, enabling more efficient acceleration. After stripping, multiple charge states are simultaneously transported and accelerated through the downstream beamline. This multi-charge beam dynamics requires specialized tracking capabilities that were not present in the original JuTrack implementation.

FLAME vs. JuTrack APPROACHES

FLAME (Fast Linear Accelerator Model Engine) is an envelope-based beam dynamics code that models beam evolution using second-moment matrices [4]. It solves the envelope equations directly, providing fast computation of beam sizes and Twiss parameters. However, envelope codes make assumptions about the beam distribution and cannot capture certain nonlinear effects or detailed particle distributions.

In contrast, JuTrack performs element-by-element particle tracking through the accelerator lattice. This approach provides full 6D phase space tracking that captures nonlinear dynamics, unlike envelope methods that rely on linear approximations. JuTrack makes no assumptions about beam distribution shape, allowing it to model arbitrary particle distributions including non-Gaussian beams that may arise.

Most importantly for optimization applications, JuTrack maintains automatic differentiation capability throughout all calculations, enabling efficient gradient-based optimization algorithms with Enzyme, that would be difficult implement with traditional envelope codes [5].

MULTI-CHARGE BEAM IMPLEMENTATION

To support FRIB's multi-charge acceleration scheme, a new MultiChargeBeam class was implemented that manages multiple beam objects with different charge states. Each charge state has its own magnetic rigidity, requiring charge-dependent element parameters. Magnetic elements now scale their fields based on the charge-to-mass ratio relative to the reference beam.

Data Structure

The MultiChargeBeam structure maintains a dictionary of Beam objects indexed by charge state, allowing efficient access to individual charge state properties during tracking calculations. Each charge state has associated magnetic rigidity values ($B\rho$) that determine the particle trajectories through magnetic elements. The structure also stores a reference charge state and its corresponding reference $B\rho$ value, which serve as the baseline for scaling magnetic field effects across all charge states in the beam.

ORBTRIM ELEMENT IMPLEMENTATION

Orbit correction elements (ORBTRIM) were added to support beamline steering. These elements apply angular kicks to the beam:

$$\Delta x_i' = \frac{q_i}{A}\theta_x, \quad \Delta y_i' = \frac{q_i}{A}\theta_y \tag{1}$$

The implementation provides support for both horizontal and vertical kicks, allowing beam steering in both transverse planes. This implementation maintains full integration with JuTrack's automatic differentiation framework, enabling gradient-based optimization of corrector settings for beam trajectory control and orbit correction applications.

* Work supported by the U.S. Department of Energy Office of Science under award number DE-SC0024170 and Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
† ratcliff@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOP19

BUDGET-FRIENDLY DEFENSE AGAINST RADIATION-INDUCED CAMERA DAMAGE*

E. Daykin†, N. Bultman, M. LaVere, S. Lidia, D. McNanney, S. Rodriguez
Facility for Rare Isotope Beams, East Lansing, MI, USA

Abstract

Cameras observing scintillating viewers provide a valuable tool for tuning heavy ion beams. The close placement of these cameras near intense stray neutron and ion radiation, particularly at elements intercepting the primary beam, presents a unique reliability challenge. Commercial solutions are sparse, expensive, and sometimes tightly regulated. We present common failure modes observed at FRIB and propose solutions to extend the lifespan of unspecialized industrial cameras using consumer-grade hardware and open-source software.

INTRODUCTION

Scintillating viewers are a straightforward way to qualitatively observe the alignment and shape of an ion beam. FRIB's primary uranium beam reaches up to 200 MeV/u uranium, and higher energies are achieved for lighter species. The current primary power on target is 20 kW, with the eventual goal of reaching 400 kW. The interaction of this beam with interceptive devices (*e.g.* the charge stripper [1], production target [2], and separator slits [3]) creates stray radiation fields that damage conventional electronics.

This work does not seek to advance any particular state of the art – rather, we present inexpensive, accessible strategies undertaken at FRIB to mitigate the detrimental effects of radiation on cameras, which might apply in equal measure to other sensitive electronic devices.

PROBLEM ANALYSIS

Reactions caused by beam interaction with solid materials induce stray radiation on the order of 1 – 10 Gy y^{-1} total ionizing dose (TID) [4, 5], neutrons and photons. High-energy photons (X-rays and γ-rays) can cause electrical effects by disrupting electron-hole pairs in silicon, and neutrons can physically displace atoms in semiconductor crystal lattices. Preliminary work [4] estimates the total soft error rate in silicon to be roughly $2 \cdot 10^7$ FIT $\cdot$ MBit $\cdot$ $cm^{-2} \cdot s^{-1}$ at current beam power. That is, for a hypothetical device with a density of 1 Mbit in 1 cm^2 of area, a soft error latch-up would be expected every 50 hours of operation. Empirically, soft errors are seen once per 6 hours of operation at the liquid lithium charge stripper (LLCS), with hard errors and replacement during maintenance necessary after 500-1000 hours of operation on average. Figure 1 depicts typical performance during 20 kW operation.

This presents something of a gray area. Specifically designed radiation-hardened cameras are expensive with few existing options on the market, especially with respect to neutrons. Failures are mitigated, to a certain extent, with radiation-tolerant design (*e.g.* CMOS sensors vs. CCD). Other elements are just duplicated for redundancy, which extends the usable lifetime, but does not ultimately prevent radiation-induced failure. However, since these cameras are used primarily for qualitative measurements, sporadic failures are generally acceptable, *provided* the image remains legible and the latch-ups can be cleared remotely without operator intervention.

CONVENTIONAL DESIGN

Hardware

For general-purpose qualitative measurement and some thermographic applications in the near infrared, FRIB uses off-the-shelf general-purpose industrial cameras. Typically, FRIB uses The Imaging Source's 33GX265, featuring a 3.1MP monochrome Sony IMX265 CMOS sensor. It retails for about $550 USD[1]. Lenses are chosen from the Fujinon HF-XA-5M line, with no noticeable darkening in 3 years of operation. The cameras are generally aligned on kinematic mounts between 50 and 100 cm from the object.

Software

Incoming images from the cameras are handled by section of the linac on physical camera servers, with each camera's feed aggregated over a 10-Gigabit Ethernet fiber link. Camera control is accomplished with the camera's firmware implementing the GenICam control standard [6], with network communication implemented by Aravis [7], an open-source emulation of the GigE Vision protocol [8] Aravis, in turn, interfaces with the EPICS supervisory control system [9] via the AreaDetector ADAravis driver [10]. With the detector driver producing images, users may adjust the camera's raw feed and take statistics using the other AreaDetector plugins[2].

MITIGATING RADIATION DAMAGE

Dead Pixels

Depending on the placement of cameras with respect to interceptive devices, cameras on the beamline will develop dead or "hot" pixels due to radiation damage on the sensor. Visually, this can be mitigated by applying a median filter,

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
† daykin@frib.msu.edu

[1] *cf.* similar radiation-hardened models well into the thousands.
[2] The state machine, along with a sample skeleton EPICS IOC, can be found at `https://github.com/daykin/HIAT25-MOP19`.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOP21

PHYSICS APPLICATIONS IN SUPPORT OF FRIB BEAM TUNING AND OPERATIONS *

T. Zhang†, K. Fukushima, K. Hwang, T. Maruta, A. Plastun, Q. Zhao, P. Ostroumov
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

Physics application software plays a crucial role in the tuning and operation of the FRIB linear accelerator (LINAC). The software development began long before the initial commissioning, establishing core capabilities to support early machine setup. Numerous new applications have been created and continuously refined during the past three years of operations through collaboration between engineers and physicists. These efforts have significantly enhanced the beam tuning efficiency and delivery for the user experiments. This paper provides an overview of the status of the development of physics application software, highlights the key applications deployed in operations, and outlines the roadmap for future advancements.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) at Michigan State University is a unique modern user facility, featuring a large-scale superconducting LINAC capable of accelerating heavy ion beams from oxygen to uranium. It supports the generation of a wide range of rare isotope beams for nuclear science research [1]. A sophisticated high-level physics control software system has been developed prior to early commissioning, continually refined during staged commissioning phases, and remains under active evolution during user beam operations.

Built on top of the EPICS distributed control system [2], and leveraging efficient physics modeling codes, a systematic software framework named PHANTASY has been designed to address both the immediate and long-term requirements of accelerator commissioning and operation [3]. A model-based virtual accelerator engine was developed to simulate the EPICS environment, enabling early application development independent of hardware availability. The information flow within the accelerator, particularly for essential physics configurations, is carefully abstracted into high-level programming interfaces, allowing applications to operate seamlessly against either virtual or real machines. The Python scripting framework is implemented with consistent unit management to ensure accurate interpretation between machine controls and physics modeling environment.

To better support commissioning, user-friendly graphical interface applications have been developed by encapsulating the validated scripts. Modularized Qt widgets have been created to handle general use cases ranging from data visualization to the integration of physics models, streamlining the development of Python-based GUI applications.

To manage various types of control system data, multiple libraries and tools have been developed to integrate live and archived data into the Python ecosystem, facilitating the unified interface for advanced data analysis application development.

The rapid advancement of modern computing technologies enables the adoption of powerful new methods into the development workflow. For example, data-driven modeling techniques using machine learning are being actively explored, along with best practices for software engineering to ensure long-term code quality and maintainability.

These combined efforts contribute to the continuously improving efficiency of beam development and delivery at FRIB.

EARLY DEVELOPMENT AND COMMISSIONING SUPPORT

The FRIB accelerator began commissioning in 2017, while development of high-level physics applications started earlier, around 2015. Two critical components emerged during this phase: the physics modeling code and the overall software architecture for physics applications.

Physics Modeling

A key requirement at the time was a simulated EPICS environment with configurable virtual devices to support engineers and physicists in developing and testing applications. To meet this need, and to provide simulation responses more realistic than random noise, FLAME, a fast accelerator simulation engine, was proposed and developed.

FLAME (Fast Linear Accelerator Modeling Engine) is a novel beam envelope tracking code capable of efficiently modeling non-axisymmetric superconducting RF cavities and multi-charge state acceleration [4]. It features matrix-based models for major lattice components such as solenoids, quadrupoles, dipoles (magnetic and electrostatic), charge strippers, and supports misalignment modeling to reflect real-world conditions. Written in C++ for high performance, FLAME also offers native Python bindings for seamless integration with the high-level physics application framework. Its ecosystem continues to grow, with supporting libraries and tools aiding lattice design, optics calculations, and more. Further details are available on the project's GitHub page [5].

* Work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, and used resources of the FRIB Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633 and DE-SC0024707.
† zhangt@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOP29

UPDATED MAGNETIC RIGIDITY CALIBRATION OF ARIS*

A. C. Dombos†, K. Fukushima, M. Hausmann, D. Kahl, E. Kwan, M. Portillo,
B. M. Sherrill[1], M. K. Smith, M. Steiner, O. B. Tarasov
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA
[1]also at Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA

Abstract

The Facility for Rare Isotope Beams (FRIB) enables groundbreaking research in nuclear physics, astrophysics, and fundamental interactions, as well as the societal applications of this work. Critical to the science program at FRIB is the Advanced Rare Isotope Separator (ARIS), which separates, identifies, and purifies fragments produced via projectile fragmentation and fission using a variety of beamline elements, including eight superconducting dipole magnets. An accurate magnetic rigidity calibration of these dipole magnets is crucial for obtaining peak fragment yields with optimal transport conditions in minimal time and comparing to simulations. This work reports on the use of the FRIB linear accelerator to provide charge states of a ^{238}U beam of known energies, with accuracy of 0.1%, to calibrate the ARIS dipole field versus effective bend radius over a range of magnetic rigidities. Due to saturation of the iron in the dipoles, the effective radius varies significantly, especially above about 1.2 T. Details of the procedure and results will be presented.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) on the campus of Michigan State University (MSU) is a United States Department of Energy Office of Science user facility that enables a robust science program in fundamental and applied nuclear physics research. The FRIB linear accelerator (linac) currently provides heavy-ion primary beams up to 20 kW with a goal of reaching 400 kW at energies of 200 MeV/u for uranium and higher for lighter ions [1]. After the primary beam interacts with a production target, the resulting fragments, formed through projectile fragmentation or fission, are directed to the Advanced Rare Isotope Separator (ARIS) [2, 3] for the crucial steps of separating, identifying, and purifying the fragments relevant to a particular experiment.

ARIS Layout

ARIS separates fragments in three stages, with the first stage in the so-called preseparator and the second and third stages in the so-called C-Bend. The preseparator consists of four superconducting dipoles (referred to here as SCD1, SCD2, SCD3, and SCD4) that bend the fragments vertically, while the C-Bend has four superconducting dipoles that bend the fragments horizontally. Fragments of interest for an experiment are selected by their magnetic rigidity, based on $\texttt{LISE}^{++}_{cute}$ [4] simulations, after emerging from the target and passing through various detectors and wedge-shaped energy degraders. Therefore, an accurate calibration of these dipoles is crucial for the science program at FRIB.

In addition to dipole magnets, the beamline of ARIS contains six diagnostic boxes (DBs), which house beam-viewer systems. A beam-viewer system is also located in the wedge position in the preseparator. Each beam-viewer system consists of a viewer plate and camera. Hole patterns on the surface of the viewer plate are used to make an absolute position calibration of each viewer in order to accurately measure the beam spot size and position. When the beam strikes the scintillating surface of the viewer plate, light is emitted and captured in a video stream by the camera, thus allowing real-time optimization of the beam spot size and position using the Viola application [5].

A schematic diagram of ARIS showing the eight dipoles, preseparator wedge, and six diagnostic boxes is shown in Fig. 1.

MAGNETIC RIGIDITY CALIBRATION

Modeling

The design of the dipole is such that the reference trajectory experiences an integrated field,

$$K_z(I) = \int dS \cdot B_z = \varphi_0 \chi, \tag{1}$$

for excitation current I, bend angle φ_0, and $\chi = p/q$ is the magnetic rigidity of a particle of momentum p and charge q. The units of K_z are Tm. An effective radius R_e can be defined such that,

$$\chi = B_{\text{NMR}} R_e(I), \tag{2}$$

where B_{NMR} is the field measured by the NMR, somewhere in the dipole region that gives a reasonably good proportionality to the field integral. The dependence can be measured with beams of known χ in order to establish a calibration.

When beam data is lacking, one can estimate R_e from dipole field data over the path of the trajectory such that,

$$R_e(I) = \frac{K(I)}{\varphi B_{\text{NMR}}}. \tag{3}$$

Field data from 3D models and measured fields along the ideal trajectory have been used to determine R_e over the full

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
† dombos@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOP30

OPERATIONAL EXPERIENCE AND IMPROVEMENTS OF THE ATLAS IN-FLIGHT SYSTEM*

B. R. Blomberg†, C. A. Dickerson, A. F. Grabenhofer, M. R. Hendricks, C. Hoffman, J. McLain
Argonne National Laboratory, Lemont, IL, USA

Abstract

In 2018, the Argonne Tandem Linac Accelerator System (ATLAS) expanded its ability to produce and select radioactive in-flight beams through transfer reactions with the addition of a magnetic chicane for beam momentum selection referred to as the Radioactive Ion Separator or RAISOR. The ATLAS in-flight system consists of a production target positioned immediately upstream of RAISOR, followed by an RF sweeper to further refine beam purity. In this contribution, we present our experience operating the ATLAS in-flight system, operational and facility improvements, current limitations, and upgrade plans.

OVERVIEW

ATLAS is a DOE national user facility located at Argonne National Laboratory. ATLAS can provide all stable ion beams ranging from hydrogen to uranium [1], up to 20 MeV/u for lighter mass beams and 10 MeV/u for mid-mass and higher mass beams. In addition to stable beams, ATLAS has been producing radioactive in-flight beams (RIB) for many years via its in-flight system [2].

To expand the capabilities and address limitations, a significant upgrade to the in-flight system was undertaken in 2018. This upgrade included the installation of RAISOR, previously referred to as the Argonne In-Flight Radioactive Ion Separator (AIRIS), and a reconfiguration of the beam transport system [3, 4].

After the upgrade, the in-flight system consists of a production target, which can be either a gas cell [5] or a foil, located immediately after the last bank of accelerating cavities. Following the production target is a two-stage ion separator to remove unreacted primary beam, unwanted charge states, and contaminate beams.

The first stage of the ion separator is RAISOR, four dipole magnets arranged to create a vertical chicane in the beamline. Slits located at the midplane provide momentum selection of the desired radioactive beam while separating out a significant portion of the unreacted primary beam and any other unwanted reaction products.

The second stage of ion separation is via a radiofrequency (RF) sweeper located downstream of RAISOR. The RF sweeper uses the time-of-flight differences between beams to separate unwanted ions from the reaction products of interest (Fig. 1).

†bblomberg@anl.gov

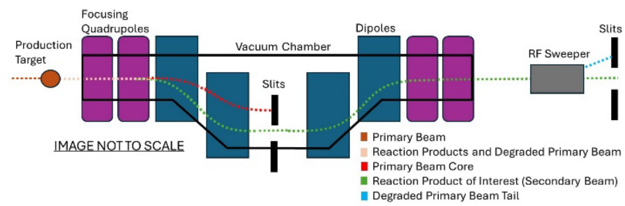

Figure 1: In-flight layout viewed from beam left.

Since the installation of RAISOR and the reconfiguration of the beam transport, the system has demonstrated a significant improvement in beam identification. With the enhanced resolution and selectivity provided by RAISOR, every scheduled RIB has been successfully identified and delivered to users, where previously some isotopes were challenging to identify. A representative particle identification plot is shown below (Fig. 2), illustrating the clear separation of isotopes and charge states now achievable with RAISOR and the current configuration.

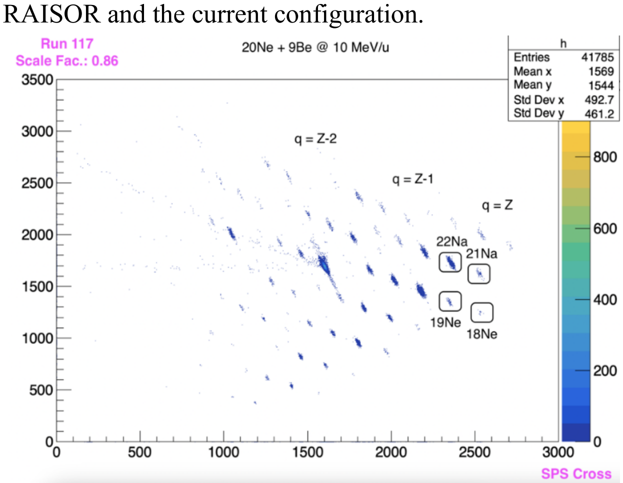

Figure 2: Particle identification plot of isotopes and charge states produced from a 20Ne beam at 10 MeV/u on a 9Be foil target.

Since the upgrade concluded, the new in-flight system has been used to study 24 radioactive beams produced from 18 stable beams. RIBs accounted for 17.8% of scheduled beam time (FY18-FY24).

IMPROVEMENTS TO THE CURRENT IN-FLIGHT SYSTEM

Since RAISOR was commissioned and the RIB transport was reconfigured, several modifications have been implemented that have significantly improved system performance and day-to-day operations of the RIB program, these improvements are as follows.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUX01

FUTURE CHALLENGES FOR CERN'S ION INJECTOR COMPLEX

M. Slupecki*, D. del Álamo, R. Alemany Fernández, H. Bartosik, G. Bellodi, T. Birtwistle, D. Bodart, R. Bruce, J.M. Cravero, H. Damerau, J.A. Ferreira Somoza, R. García Alía, E. Grenier Boley, A. Huschauer, V. Kain, D. Kuchler, J.B. Lallement, T.M. Lang, A. Lasheen, E. Mahner, A.I. Michet, B. Mikulec, G. Papotti, A. Rossi, F. Roncarolo, S. Ramberger, R. Scrivens, N. Thaus, E. Waagaard[1], A. Waets, B. Woolley, CERN, Geneva, Switzerland
[1]also at EPFL, Lausanne, Switzerland

Abstract

The ion injector complex at CERN supplies ions for collisions at the Large Hadron Collider (LHC) and for fixed-target physics programmes at the Super Proton Synchrotron (SPS) and Proton Synchrotron (PS). In recent years, there has been growing interest in experiments with ions lighter than lead within the ion-physics community. The NA61/SHINE collaboration has requested beams of oxygen, magnesium, and boron for Run 4 (2030-2033), while the HEARTS++ project proposal aims to enable switching between four ion species, with each transition occurring within 15 minutes. Additionally, LHC experiments are considering lighter-than-lead ion beams for Run 5 (2036-2041), pending an assessment of which particle species collisions offer higher nucleon-nucleon luminosity. Consolidating these future scenarios demands an evaluation of the light-ion performance of the present injector complex. This contribution discusses the challenges of the present injector complex in view of light-ion operation and a proposed upgrade of the ion complex to address future needs.

ION INJECTOR COMPLEX

The ion injector complex at CERN [1, 2] consists of the ion source, Linac3, Low-Energy Ion Ring (LEIR), Proton Synchrotron (PS) and Super Proton Synchrotron (SPS), which can deliver high-brightness ion beams for the LHC and experimental areas: East Area in PS, and North Area in SPS. The layout of the ion complex is shown in Fig. 1.

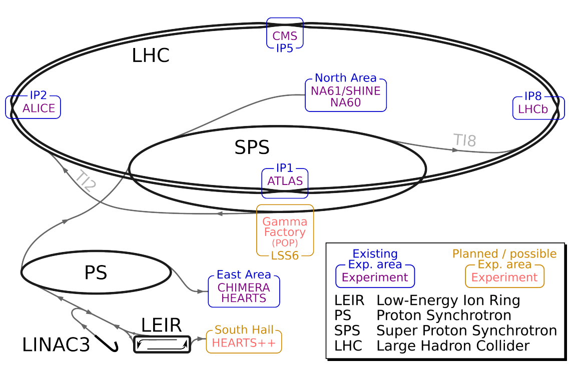

Figure 1: Layout of the ion injector chain, LHC, existing and future experimental areas that operate ion beams.

Ion beams are produced in the Electron Cyclotron Resonance (ECR) [3, 4] ion source of the Grenoble Test Source (GTS-LHC) type [5]. It uses a permanent hexapole, resistive solenoids, and 14.5 GHz microwaves to confine and breed highly-charged ions in a plasma, which are ejected from the plasma chamber at 10 Hz repetition rate with pulsed extraction voltage of up to 20 kV. The source design is optimized for lead production, simple maintenance, and quick, non-invasive replacement of material (lead) samples in both of its microovens to minimize the impact on operational availability. During lead operation, the downtime of the source due to oven refills is limited to half a day every month.

Downstream of the source, the beam passes through the Low Energy Beam Transport (LEBT) of Linac3, where a single charge state is selected (Pb^{29+}, O^{4+}, Ne^{5+}, Mg^{7+}, etc.) by a setup composed of spectrometer magnets and a slit. The kinetic energy acceptance of 2.5 keV/u of the subsequent Radio-Frequency Quadrupole (RFQ) defines the extraction voltage used at the source for each ion species. The RFQ bunches and accelerates the beam to 250 keV/u. A set of three interdigital-H cavities further increases the beam energy to 4.2 MeV/u. Here, the beam may be stripped to optimize the ion lifetime in the subsequent accelerators and facilitate transport through the transfer line to LEIR, in which the maximum dipole currents define the minimum transportable charge-to-mass ratio of 0.25. Before reaching LEIR, at the end of Linac3, there are two small RF systems capable of compensating for the evolving beam energy losses due to the ageing of a stripping foil, and ramping beam energy by ±2‰ along the 300 µs long beam pulse to improve the efficiency of multiturn injection in the LEIR.

In LEIR, up to eight Linac3 beam pulses can be accumulated and cooled with the electron cooler. This is achieved by reducing beam energy spread of each injected pulse, dragging the beam to lower energy, merging it with the circulating stack from the previous injections, and making full phase-space available for the next injection [6]. The coasting beam is then captured by the RF into one, two or three bunches, accelerated to around 70 – 100 MeV/u depending on the ion species and its charge state, and extracted towards the PS. The PS accelerates the beam to the proton-equivalent momentum of 26 GeV/c. Bunch splitting, or batch compression can be performed if the frequency range of PS cavities is suitable for a given ion species and bunch spacing required at SPS and LHC. These RF manipulations are generally useful to reduce the impact of space-charge and intrabeam scattering effects. Splitting the bunches in PS results in lower per-bunch intensity and reduction of associated collective

* maciej.slupecki@cern.ch

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUX02

AUTOMATED BEAM TUNING OF THE TRIUMF ISAC FACILITY*

O. Shelbaya†, P. Jung[1], O. Hassan[1], O. Kester[1]
TRIUMF, 4004 Wesbrook Mall, Vancouver, Canada
[1]also at the Department of Physics and Astronomy, University of Victoria, Victoria, Canada

Abstract

Modern heavy ion accelerators have increased in complexity in terms of energy variation and choice of isotope and A/q ratio. There TRIUMF did embark on a project program towards more automation of the beam tuning and beam delivery of the accelerator complex. This comprises high level applications, model based accelerator tuning and employing machine learning tools. Bayesian optimization is used for instance to correct the beam orbits in the TRIUMF accelerators. An overview and status of this program will be presented with some exciting new results that have been achieved in the past two years.

INTRODUCTION

TRIUMF is commissioning the ARIEL facility over the coming years, which will significantly expand the laboratory's capability to deliver rare isotope beams (RIBs) to experiments. This expansion, coupled with the growing demands of a diverse nuclear physics program, imposes increasingly stringent requirements on the precision and efficiency of RIB tuning through TRIUMF's ISAC RIB linac.

To address this challenge, we have developed an approach that integrates parallel modelling using the envelope code TRANSOPTR with a Bayesian optimizer for automated beam steering. This methodology underpins new in-house software that enables linac tuning through predictive models and optimization strategies, providing operators with unprecedented control over the optics of the linac during beam delivery.

In parallel, we have initiated a broad machine development (MDEV) program at ISAC. These campaigns bring together operators, students, and accelerator physicists to systematically improve our understanding of the linac and beamlines through hands-on experiments. This collaborative framework allows for both validation and advancement of beam optics models, tuning strategies, and control software, ensuring that our operational readiness keeps pace with the capabilities being unlocked by ARIEL.

A complete system model has been created using an XML-formatted database that stores the coordinates of each device within the system. This data is centralized in a Git-controlled repository, making configuration management more efficient and easier to handle. Additionally, a set of packages that allow us to automatically generate all necessary TRANSOPTR files for simulating the system has been developed. We've also implemented a web-based communication framework that enables reading and writing of system variables. To enable full machine tune modelling, the envelope code was suitably modified to enable the full simulation of the ISAC postaccelerator's various components, notably including a first order envelope model for the RFQ [1]. Field simulations of the ISAC-DTL's accelerating cavities DTL [2], a previously recorded time-dependent axially symmetric electric field linac simulation [3] has been used to implement the DTL's separated function lattice [4].

To achieve high-precision control of the beam optics in the ISAC linac, we employ parallel modelling to compute full machine tunes. Central to this approach is our use of the TRANSOPTR envelope code, which enables fast simulations of beam transport through the linac, with typically subsecond execution times.

ISAC Overview

The ISAC facility (Fig. 1) was added to the TRIUMF campus in the late 1990s as a user facility centered around production targets on one of the five 520 MeV cyclotron beamlines. Proton bombardment of the targets generates radioisotopes spanning the nuclear chart, which are then electromagnetically separated based on their mass-to-charge (A/q) ratio using a spectrometer with a mass resolution of up to $M/\Delta M = 2,000$. This beam can optionally undergo charge breeding via the CSB device before being delivered to a network of low-energy (E $\leq$ 60 keV) experiment stations, or injected into ISAC's RIB linac for delivery at low relativistic velocities ($0.2 \leq \beta \leq 0.6$). Experiments at the facility focus on studying exotic, often short-lived isotopes, performing spectroscopic investigations, precision mass measurements, cross-section measurements, parity investigations, and other related studies.

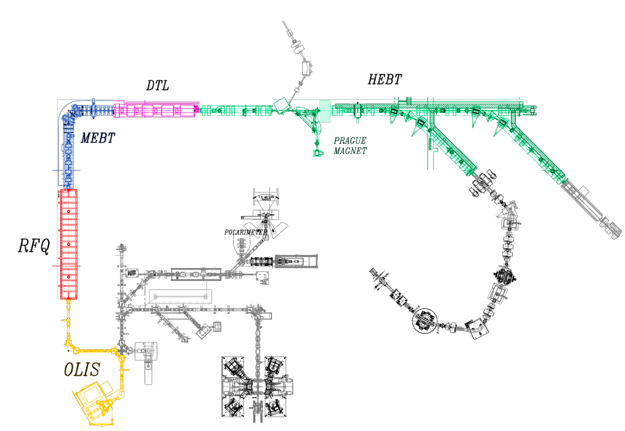

Figure 1: Overview of the ISAC-I RIB post-accelerator and beamline network.

* TRIUMF is funded under a contribution agreement with NRC (National Research Council Canada.
† oshelb@triumf.ca

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUX03

MAINTAINING OPTIMAL BEAM BRIGHTNESS AND LUMINOSITY USING MACHINE LEARNING*

W. Lin†, Brookhaven National Laboratory, Upton, NY, USA

Abstract

After many decades of successful operation, human operators have become very good at finding the optimal conditions that maximize the luminosity in the Relativistic Heavy Ion Collider (RHIC). However, since the entire accelerator chain for RHIC is a constantly varying complex system, maintaining such optimal condition is a demanding task. There is also no metric that can measurably determine if those optimal conditions are truly optimal, given the degrees of freedom are very high and there are multiple and competing objectives. In this work we will describe how we use machine learning and improved physics models to build systems for optimizing the beam brightness during injection at the BNL Booster and AGS synchrotrons and efforts to maintain maximum luminosity in RHIC.

INTRODUCTION

Large particle accelerators like the Relativistic Heavy Ion Collider (RHIC) are large systems that require analysis and optimization of thousands of parameters to operate at peak performance. With the more complex Electron-Ion Collider (EIC) planned for future construction, such analysis will quickly become impossible to be performed entirely by human operators. Machine learning (ML) has shown great promise in addressing long-standing challenges in accelerator physics, such as automated tuning and anomaly detection. In this work, we study two major ML techniques and their applications for finding and maintaining optimal beam quality in the RHIC complex: Bayesian optimization (BO) and reinforcement learning (RL).

MACHINE LEARNING METHODS

Bayesian Optimization

Bayesian optimization (BO) is a technique aiming to optimize an objective function f with as few samples as possible. It is particularly useful when the explicit expression of f is unknown and evaluation of f is expensive. Due to its sample efficiency and ability to learn without a preexisting model, BO has been widely implemented to solve complex particle accelerator control problems, as summarized in Algorithm 1 [1]. In general, BO consists of three steps. First, BO constructs a statistical surrogate model of the objective function and if necessary, constraining functions, based on measured data. The model is usually built with Gaussian process (GP) [2]. Second, BO defines an acquisition function based on the GP model, which quantifies the relative benefit of potential future measurements in input space in order to achieve optimization goals. And finally, BO solves for the point (or set of points) that maximizes the acquisition function, which means it is predicted to provide the most benefit towards the final optimization goals.

Algorithm 1 Bayesian Optimization

Require: Objective function f, observation dataset $\mathcal{D}_N$, GP prior $M = \mathcal{GP}(\mu(x), k(x, x'))$, acquisition function $\mathcal{A}(\cdot)$.
1: **for** $t = 1, 2, \ldots$ **do**
2: Decide a new sample point $x_{new} = argmax_x \mathcal{A}(x|\mathcal{D}_N)$.
3: Query the objective $y_{new} = f(x_{new}) + \epsilon$.
4: Update $\mathcal{D}_N$ and the GP model.
5: **end for**

Reinforcement Learning

Reinforcement learning (RL) is a machine learning framework where an agent interacts with an environment and learns to make decisions that maximize a reward [3]. Although less explored than BO, RL has also demonstrated success in accelerator control processes [4]. Despite its dependency on large amount of training data, RL algorithm is more suited for continuous control problems. In general, a RL system consists of several key components: an agent, an environment, a policy, and a reward, as summarized in Algorithm 2. An environment is the system that we want to optimize. A representation of the environment at a specific time is called a state. An agent interacts with the environment, receives observations, and make decisions based on its policy. The decisions made by the agent are called actions. A policy dictates how the agent choose actions, by establish a mapping between the states and the actions. A reward defines the goal of the algorithm. At each step, the environment generates a numerical reward that signals how close it is to the optimal state, and the agent aims to maximize the total reward it receives.

Algorithm 2 Reinforcement Learning

Require: Environment with initial state $\mathcal{S}_0$, policy $\mathcal{P}$, reward $\mathcal{R}$.
1: **for** $t = 1, 2, \ldots$ **do**
2: Agent observes system state $\mathcal{S}_t$.
3: Agent chooses an action based on policy $\mathcal{A}_t = \mathcal{P}_t(\mathcal{S}_t)$.
4: Agent receives a reward $\mathcal{R}_t$ based on action $\mathcal{A}_t$ taken on state $\mathcal{S}_t$.
5: Agent updates policy $\mathcal{P}$.
6: **end for**

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 and No. DE-SC0024287 with the U.S. Department of Energy.
† wlin1@bnl.gov

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUX05

BOOST OF ALPI SUPERCONDUCTING LINAC PERFORMANCES USING AI TECHNIQUES

L. Bellan*, I. R. Andriamaro, L. Antoniazzi, D. Bortolato, O. Carletto, L. Centofante, M. Comunian, E. Fagotti, A. Galatà, C. S. Gallo, F. Gelain, M. Giacchini, F. Grespan, D. Marcato, M. Montis, E. Munaron, Y. K. Ong[1], A. Pisent, M. Roetta, G. Savarese
INFN-LNL, Legnaro, Italy
[1]also at University of Sapienza, Rome, Italy

Abstract

The heavy ion superconductive linac ALPI has been operating at the Legnaro National Laboratories since its completion in the 1990s. As the first generation in Europe, it featured several innovative techniques and design weaknesses, such as very small transverse and longitudinal acceptances. This led to long setting times and low transmission rates of 35%, compared to 93% obtained using simulations. Additionally, the machine experienced instabilities, requiring frequent accelerator retuning. From 2011 to 2024, an extensive beam dynamics studies program was conducted, culminating in the introduction of Artificial Intelligence techniques in 2022-2024. These techniques made it possible to accelerate the accelerator setup, counteract instabilities and reach the nominal transmission of the linac, about 85%, in June 2024, 32 years after its construction. This paper presents the AI techniques involved, the studies performed, and how they impact routine operations.

INTRODUCTION

ALPI (Acceleratore Lineare Per Ioni) is the last stage of acceleration of the heavy ion facility of Legnaro National Laboratories. It is CW folded independent cavities linac, equipped with 77 superconductive quarter waves (QW) cooled down at 4 K, divided in three groups (low-β 0.055 at 80 MHz, medium-β 0.11, high-β 0.13 at 160 MHz both). ALPI has three injectors: an electrostatic accelerator of Tandem type, a superconductive 80 MHz RFQ (Radio Frequency quadrupole, with an output β = 0.0355) PIAVE, which delivers the stable heavy ions and the SPES RFQ, a normalconductive 80 MHz RFQ (output β = 0.0392), which will supply the radioactive ion beams (RIB) from the SPES facility [1]. The linac was designed in the '80s and built in the '90s, and, being one of the prototype in Europe, several improvements were achieved during its commissioning and construction, especially in terms of E_0 field (accelerating field) of the QWs, allowing to reach higher energy output ($^{238}U^{32+}$ at 7.4 MeV/u). However, a low transmission with respect to the simulations expectations (35% vs 93%) and a troublesome set up have since then affected the linac, moreover there are frequent instabilities which led to beam losses. After decades of improvement in the reliability of the accelerator, both from RF, controls, cryogenics, and beam dynamics model sides, in 2023-24 we began applying artificial intelligence techniques to speed up the setup of the accelerator (Fig. 1) and improve its performance.

BEAM DYNAMICS AND DIAGNOSTICS WEAK POINTS

Beam Dynamics

From the beam dynamics point of view, the main weak point is given by the ALPI lattice: as shown in Fig. 2, it is composed by 3 normal conductive quadrupoles (for transverse focusing) and by 8 QWs cavities. This very long period impacts the longitudinal phase advance, transverse RF defocusing, and the QWs magnetic steering coming from the residual magnetic field on axis. The three effects follow the Eq. (1):

$$\begin{aligned}\sigma_{0,l} &\propto E_0 \sin(-\Phi_s)/\beta^2 \\ K_{RF} &\propto E_0 \sin(-\Phi_s)/\beta^3 \\ y' &\propto B_x \sin(-\Phi_s)/\beta^2\end{aligned} \tag{1}$$

All effects are directly proportional to E_0 and to the $\sin(-\Phi_s)$. Therefore, once the accelerating fields improved of a factor of 4, we increased the effects described in Eq. (1) of the same amount. Moreover, as it is possible to see, the effects are indirectly proportional to the β^2, β^3 of the accelerating particle. This means that the initial acceleration stage (the low-β section and initial phases of medium-β) are the most subjected to losses, and it is mandatory to increase the energy of the beam as soon as possible. However, to avoid a longitudinal phase advance > 160 deg, we had to use the alternate phase focusing techniques (differently from the initial design), introducing some de-bunching phases into the longitudinal period, to reach $\sigma_{0,l}$ =65 deg.

However, the longitudinal acceptance resulted in being greatly reduced, as shown in Fig. 3, at ALPI input. The black areas are the acceptances, while the colored areas are the particle densities. As it is possible to see, the beam is not even fully covered by the acceptances, and in particular in the longitudinal plane, the instability area intrudes deeply in the centre. Moreover, the beam distributions change during time, due to the instabilities coming from the injectors. In PIAVE-ALPI, the instabilities can come as variation of transverse first order moments (steering at input of the linac) or as a variation of the reference phase between PIAVE and ALPI, which results in an off-centering of the beam phase with respect to the longitudinal acceptance. The reason for this

* luca.bellan@lnl.infn.it

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUY01

RECIRCULATING AND ENERGY RECOVERY ION LINEAR ACCELERATORS*

J. Qiang†, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

High-power superconducting ion linear accelerators play a vital role in both scientific research and industrial applications. However, their RF usage efficiency remains relatively low. In this paper, we review two innovative concepts: recirculating ion linear accelerators and energy recovery ion linear accelerators. These approaches significantly improve RF efficiency by enabling the ion beam to traverse the same superconducting cavity multiple times and by recovering the energy of the accelerated ion beam to return it to the RF cavities. We also propose a demonstrator for the recirculating ion linear accelerator using a scaled, low-energy electron accelerator, and discuss the potential application of the energy recovery ion accelerator in a full energy recovery electron-ion collider. These concepts offer promising avenues to substantially reduce both the construction and operational costs of superconducting linear accelerators.

INTRODUCTION

High-power superconducting ion linear accelerators (linacs) play a crucial role in both scientific research and industrial applications. They serve as drivers for spallation neutron sources, high-energy physics neutrino production, subcritical nuclear power plants, and nuclear waste transmutation. However, conventional single-pass superconducting ion linacs are less efficient in their use of RF cavities compared to circular accelerators, such as rapid cycling synchrotrons, where the beam passes through the same RF cavity multiple times. Despite their efficiency, circular accelerators suffer from slower acceleration rates and are susceptible to nonlinear resonances arising from machine imperfections.

Recirculating linacs combine the strengths of both linear and circular accelerators. They leverage the circular accelerator's ability to pass a beam through the same RF cavity repeatedly, achieving substantial energy gains, while retaining the fast acceleration characteristic of linacs. This approach significantly reduces the number of required RF cavities and cryomodules, leading to lower construction and operational costs compared to single-pass linacs.

In certain applications, such as electron-ion colliders or muon production, a portion of the ion beam retains substantial energy after interacting with a target. This high-energy portion can be redirected back into the superconducting linac and decelerated to low energy before being sent to a beam dump, thereby recovering energy and substantially reducing RF power consumption and operational costs.

* Work supported by the U.S. DOE under Contract No. DE-AC02-05CH11231.
† jqiang@lbl.gov

Recirculating and energy recovery electron linacs have been successfully built and operated for many years [1–4], offering an optimal balance of cost and performance between straight linear and circular accelerators. These accelerators have also been proposed for next-generation light sources [5–9], and a series of dedicated workshops has explored their development [10–14].

A key distinction between ion and electron beams is the significantly greater mass of ions (for example, a proton is about 1800 times heavier than an electron), resulting in much lower velocities for ions at the same kinetic energy. In an ion linac, as the ions accelerate from MeV to GeV energies, their velocity changes considerably. Efficient acceleration under these conditions requires different types of RF cavities with varying geometric lengths or frequencies. In contrast, electrons reach velocities close to the speed of light after only a few MeV of acceleration, so their velocity changes very little. As a result, only one type of RF cavity is needed in an electron linac, making recirculating and energy recovery schemes more straightforward for electrons, without sacrificing acceleration or deceleration efficiency across a range of beam energies.

RECIRCULATING ION LINEAR ACCELERATOR

In superconducting ion linear accelerators, good acceleration efficiency is important in order to reduce the number of RF cavities needed in the accelerator. The acceleration efficiency can be measured by the transit time factor. For a given RF cavity, the energy gain ΔE_c of a charged particle through the cavity can be written as:

$$\Delta E_c = qVT\cos(\phi) \quad (1)$$

where q is the charge of the particle, $V = \int_0^L |E_z(0,z)|dz$ is the voltage across the cavity, E_z is the longitudinal accelerating electric field on axis, T is the transit time factor, ϕ is the design phase with respect to the maximum energy gain. From the above equation, we can see that for a given design phase and voltage, in order to gain more energy, the transit time factor should be as large as possible. For a periodic RF cavity with harmonic distribution of electric field along the axis, i.e. $E_z = sin(\omega z/(\beta c))\exp(i\omega t)$, the normalized transit time factor T_0 can be given by [15, 16]:

$$T_0(\beta) = \frac{2\beta}{\pi n}\Big(\frac{\sin(\pi n(\beta-\beta_G)/(2\beta))}{\beta-\beta_G} - (-1)^n\frac{\sin(\pi n(\beta+\beta_G)/(2\beta))}{\beta+\beta_G}\Big) \quad (2)$$

where n is the number of cells in the cavity operating at π-mode, $\beta = v/c$ is the normalized particle velocity, β_G is the

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUY03

Nb_3Sn SUPERCONDUCTING CAVITY DEVELOPMENTS FOR HEAVY-ION BEAMS*

T. Petersen†[1], R. Agustsson[3], G. Eremeev[2], B. Guilfoyle[1], M. Kedzie[1], M.P. Kelly[1], S. Kutsaev[3], S. Posen[2], T. Reid[1], E. Spranza[3], B. Tennis[2], Y. Zhou[1]
[1]Argonne National Laboratory, Lemont, USA
[2]Fermi National Accelerator Laboratory, Batavia, USA
[3]RadiaBeam, Santa Monica, USA

Abstract

Nb_3Sn has been identified as the most promising next-generation superconducting material for accelerator cavities. This is due to the higher critical temperature (Tc = 18 K) of Nb_3Sn compared to niobium (Tc = 9.2 K), which leads to greatly reduced RF losses in the cavity during 4.5 K operation. This allows two important changes during cavity and cryomodule design. First, the higher Tc leads to negligible BCS losses when operated at 4.5 K, which allows for a higher frequency to be used, translating to significantly smaller cavities and cryomodules. Second, the reduced dissipated power lowers the required cryogenic cooling capacity, meaning that cavities can feasibly be operated on 5-10 W cryocoolers instead of a centralized helium refrigeration plant. These plants and distribution systems are costly and complex, requiring skilled technicians for operation and maintenance. These fundamental changes present an opportunity for a paradigm shift in how low-beta linacs are designed and operated. Fabrication and testing results of first prototypes are discussed.

INTRODUCTION

Heavy-ion linacs utilize niobium cavities designed to operate at a low frequency, minimizing the BCS resistance to keep dissipated RF power minimal. The BCS resistance is the largest contributor to surface resistance, and is a strong function of both operating frequency and temperature. Figure 1 plots calculated BCS resistances against temperature for niobium at two operating frequencies (72 MHz and 218 MHz), as well as Nb_3Sn at 218 MHz. When operating at 4.5 K there is almost an order of magnitude difference between 72 and 218 MHz, and another order of magnitude lower for Nb_3Sn even at this higher frequency. For the same geometry resonator, the physical size scales inversely with the fundamental frequency, meaning the physical size (and therefore cost) of a linac goes down drastically. This benefit, coupled with the reduced dynamic RF load (allowing operation on cryocoolers), allows for a shift in how cavities and cryostats are designed.

*This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract number DE-AC02-06CH11357, and the Office of High Energy Physics, under contract number DE-AC02-76CH03000. This research used resources of ANL's ATLAS facility, which is a DOE Office of Science User Facility

This manuscript has been authored by FermiForward Discovery Group, LLC under Contract No. 89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

With the substantially higher Tc, Nb_3Sn could allow low-beta cavity operation at frequencies up to near 1 GHz with a few nΩ of surface resistance. [1] Green field linacs could capitalize greatly on this design shift to smaller, higher frequency resonators.

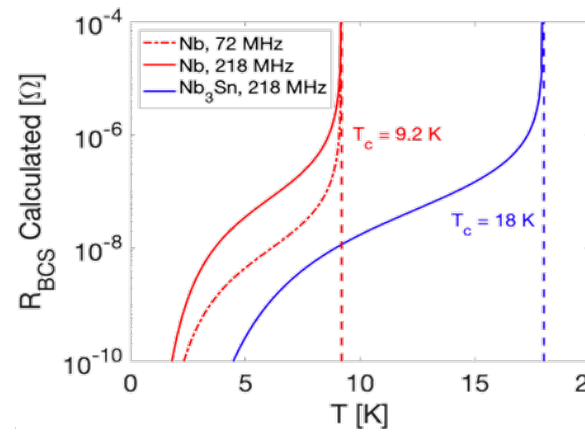

Figure 1: SRIMP calculated BCS surface resistance of Nb (at 72 MHz and 218 MHz) and Nb_3Sn (at 218 MHz) vs operating temperature.

FABRICATION OF 218 MHz PROTOTYPE

A first prototype quarter wave cavity was constructed with high purity (RRR>250) niobium (and reactor grade for all non-RF surfaces) to serve as a base for the thin Nb_3Sn coating. Figure 2 shows the completed cavity as well as a section view. The frequency chosen was 218 MHz, a harmonic of the ATLAS clock, and substantially higher than typical quarter wave cavities. Subassemblies were hydroformed at a local shop, Stuecklen Inc. The complex center conductor tip and gussets were machined by our collaborators at RadiaBeam. All welds were performed by electron beam welding at Sciaky Inc. The finished cavity was electropolished (125 µm) before cold testing without low temperature baking.

Following fabrication, the bare niobium cavity was cold tested to verify a good substrate for the thin film coating. The intent was to identify any possible defects that could cause early quench in the coated cavity testing.

The cavity had a low Q of 8×10^8, but this was expected as the cavity was not de-gassed and showed classic symptoms of Q-disease. However, the cavity met the design goal of 60 mT peak magnetic field, no defect-initiated quench. Coating and cold testing of the cavity followed, discussed below.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUB01

A SINGLE-SLICE ROTATING GRAPHITE TARGET AT FRIB*

J. Song†, N. Bultman, D. Cole, N. Jockheck, T. Kanemura, M. Larmann, D. Lee, G. Lee, S. Miller, M. Patil, M. Portillo, R. Quispe-Abad, M. Reaume, J. Simon, M. Steiner, J. Wei
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The FRIB accelerator, constructed and commissioned in 2022, serves as a leading facility for producing rare isotope beams and exploring elements beyond the limits of stability. These beams are produced by reactions between stable primary beams and a graphite production target. Meanwhile, approximately 20–40% of the primary beam power is deposited in the target, necessitating efficient heat dissipation. Currently, FRIB operates at a primary beam power of 20 kW. To enhance thermal dissipation efficiency, a single-slice rotating graphite target with a diameter of approximately 30 cm is employed. This paper presents an overview of the current status of the production target system and ongoing R&D efforts to enhance its performance and durability under high-power beam conditions.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB), a leading facility for rare isotope science, is undergoing a staged power ramp-up toward its ultimate goal of operating at 400 kW of primary beam power. FRIB currently delivers high-intensity stable ion beams ranging from oxygen to uranium and has been progressively increasing its operational beam power from 1 kW to 20 kW [1, 2] since commissioning in 2022 [3, 4]. This capability enables a wide range of nuclear science experiments, including studies of nuclear structure, reactions, and astrophysical processes. To address the intense thermal loads associated with rare isotope production, FRIB employs a single-slice rotating graphite target system [5]. This target is designed to withstand beam powers up to 50 kW, with thermal mitigation achieved by distributing the deposited energy over a larger surface area through disc rotation. This reduces surface power density and enhances thermal performance. The current system utilizes a disc approximately 30 cm in diameter, operating at moderate rotational speeds (500 rpm). The rotation speed is planned to increase to 2000 rpm in future operation to reduce both the peak temperature and the temperature gradient across the irradiated beam spot on the graphite disc. In addition to thermal and mechanical factors, radiation-induced degradation strongly influences the operational durability of the target. Radiation transport simulations indicate that radiation damage to the graphite remains relatively low on the order of 0.4 displacements per atom (DPA) even under worst-case uranium irradiation scenarios. This low damage level allows for multiple reuses of a single disc, with the operational plan calling for retirement after approximately ten irradiation cycles. The structural configuration of the target assembly is illustrated in Fig. 1. Since the initial operation in 2022, several key hardware improvements have been implemented, including the adoption of high-temperature bearings and the application of a high-emissivity internal coating ($\epsilon \approx 0.9$) to enhance radiative heat transfer.

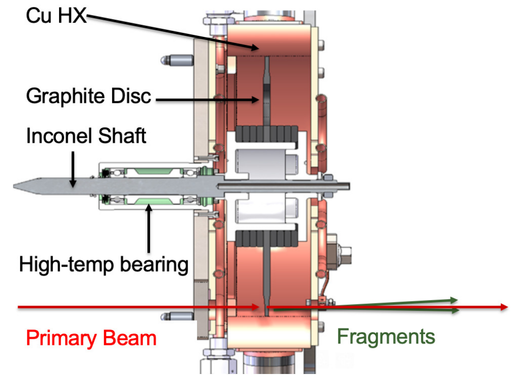

Figure 1: FRIB target assembly.

PRODUCTION TARGET

The production target system illustrated in Fig. 1 consists of a 30 cm diameter graphite disc (Mersen grade 2360), spacers made of the same graphite grade, a YSZ ceramic hub, high-temperature bearings (NSK), an Inconel shaft, and a copper heat exchanger. The interior surface of the heat exchanger was coated with a high-emissivity paint (Aremco 840-MS). Between 20–40 % of the primary beam power is deposited in production targets of varying thickness. The primary cooling mechanism is radiative heat transfer from the rotating graphite disc, with the emitted heat absorbed by side-mounted heat exchangers and water-cooled front and rear doors.

To accommodate various primary beams, eight production targets with different thicknesses are provided to optimize secondary beam yields. The configurations are summarized in Table 1. To achieve efficient secondary beam delivery, the most critical requirement is to maintain the target defect within ±2 %, which accounts for machining tolerances, material inhomogeneities, and mechanical deformations. Recent measurements using a wedge view with beam data from ARIS indicate that the total defect is approximately 1.6 % [6]. To support consistent quality in spare targets, a system [7] capable of directly measuring the physical thickness has been developed, it was confirmed that for targets with thicknesses ranging from 2.1 mm to 5 mm, the machining precision

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
† songj@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUZ01

INNOVATION FOR SUSTAINABLE ACCELERATING SYSTEMS: THE EUROPEAN iSAS PROJECT*

M. Baylac[1,†], J. D'Hondt[2], J. Knobloch[3,4], C. Pira[5], A. Stocchi[6]
[1]Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Univ. Grenoble Alpes, CNRS, Grenoble INP, LPSC - IN2P3, Grenoble, France
[2]NIKHEF, Amsterdam, Netherlands
[3]Helmholtz-Zentrum Berlin (HZB), Berlin, Germany
[4]Universität Siegen, Siegen, Germany
[5]Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Legnaro (LNL), Legnaro, Italy
[6]IJCLab Orsay, Université Paris-Saclay, CNRS/IN2P3, Orsay, France

Abstract

If particle accelerators have largely proven their value to society, they must now meet the challenge of energy sustainability. The European project to *Innovate for Sustainable Accelerating Systems* (iSAS) is dedicated to energy-saving of superconducting radiofrequency (SRF) accelerating systems. iSAS will develop, prototype and validate new impactful energy-saving technologies so that SRF accelerators can operate with the same or improved performance with significantly less energy.

INTRODUCTION

Particle accelerators are essential instruments for research infrastructures and for a variety of applications, accounting for 40,000 machines worldwide. In a context of sustainability, minimizing the energy consumption of accelerators is an unavoidable challenge. Funded by the EU (HORIZON-INFRA-2023-TECH-01-01), the project to *Innovate for Sustainable Accelerating Systems* (iSAS) was launched in 2024 to develop core technologies of SRF accelerating systems to minimize energy consumption [1]. It is complementary to other programs developing energy-efficient magnets or RF sources.

This project gathers 12 research laboratories or institutes (CEA, CERN, CNRS, DESY, EPFL, ESS, HZB, INFN, NIKHEF, UKRI, univ. Brussels, univ. Lancaster) as well as 6 industrial companies (ACS, Cryolectra, Euclid Tech labs, Research Instruments, Thin Film Equipment, Zanon) over a 4-year duration. The iSAS project addresses 3 key Technology Areas with substantial potential to reduce the energy consumption of accelerators:

- energy-saving from RF power, through coherent integration of the RF power source with smart digital control systems and with novel tuners that compensate rapidly cavity detuning from mechanical vibrations,
- energy-saving from cryogenics to develop superconducting cavities with high performance at 4.2 K instead of 2 K, thereby reducing the grid-power to operate the cryogenic system,
- energy-saving from the beam power, to enable efficient energy recovery of recirculating beams in superconducting cavities with couplers to damp the Higher-Order Modes (HOMs) excited by the passage of high-current beams in the cavities.

Enabled by its large consortium and the joint investment between research institutions and industry, iSAS envisages three Integration Activities to introduce these energy-saving Technology Areas into research facilities:

- integration into a sustainable cryomodule design, by addressing common engineering challenges to use the technologies on a parametric cryomodule design,
- integration into existing research infrastructures, by retrofitting existing accelerating systems. A cryomodule will be adapted, ready to demonstrate energy recovery of high-power recirculating beams in the PERLE research facility,
- integration into industrial solutions, with concrete co-developments with industry to expedite high Technological Readiness Level (TRL) for large-scale deployment of the new energy-saving solutions at current, future infrastructures and towards industrial applications.

The iSAS project concentrates on SRF accelerating systems with the largest leverage for energy savings. The developed technologies aim to optimize:

- ferro-electric fast reactive tuners,
- low-level radio frequency control system,
- coatings of Nb_3Sn on Cu cavities,
- couplers (fundamental, higher-order modes) and beam line absorbers.

iSAS aims to perform R&D on these technologies and to promote their implementation towards industry, by raising their TRL. Three main accelerator-driven ESFRI RIs are at the core of iSAS: ESS, EuXFEL and HL-LHC.

This paper presents the main technologies under development and the description of the work to be performed by the different laboratories within the work packages (WPs) of iSAS. The focus is set on the metric to evaluate the expected energy saving for each of these devices.

* Work supported by funding from the European Union's program Horizon-INFRA-2023-TECH-01 under GA No 101131435 – iSAS
† baylac@lpsc.in2p3.fr

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUZ02

PRIMARY BEAM DEVELOPMENT FOR FRIB EXPERIMENTS*

T. Maruta†, K. Fukushima, A. Gonzalez, K. Hwang, P.N. Ostroumov, A.S. Plastun, T. Zhang, Q. Zhao, Facility for Rare Isotope Beams, Michigan State University, East Lansing, USA

Abstract

Since starting the user operation of Facility for Rare Isotope Beams (FRIB) at Michigan State University in May 2022, the driver linac has provided more than a dozen ion beam species from Oxygen to Uranium to the production target. FRIB routinely provided 20 kW primary beams on target since March 2025, which is a factor of 20 higher than at the beginning of the scientific user operation. In this presentation, the recent progress of FRIB driver linac beam development, a discussion of efficient primary beam tuning procedures based on physics applications, and accelerator improvement projects for low-loss accelerator will be discussed.

INTRODUCTION

FRIB is a heavy ion accelerator facility constructed at Michigan State University under the corporate agreement with the U.S. Department of Energy Office of Science to support the Office of Nuclear Physics mission. The facility is comprised of the driver linac, fragment separator, and experimental area including 6 MeV/u reaccelerator. Construction was completed in January 2022, and user operation started in May 2022.

The driver linac is designed to provide a 400 kW continuous wave beam to the production target [1]. The required primary ions are generated in the Electron Cyclotron Resonance (ECR) source, selected after a 90° bend, and transported to the accelerator tunnel through 24-meter-long Low Energy Beam Transport (LEBT). The beam is accelerated by Radio Frequency Quadrupole (RFQ) and the following three linac segments (LS1, LS2 and LS3). The beam acceleration is provided by four types of Superconducting (SC) RF cavities with optimal β from 0.041 to 0.54. For the beam focusing in the cryomodules, we use SC solenoids equipped with horizontal and vertical steering coils. The layout of the linac is shown in Fig. 1. For a detailed description of the linac structure, we refer to earlier publications, for example, [2]. The beam accelerated by the LS1 interacts with the charge stripper, which is a highly beneficial technique for heavy ion accelerators. The electrons are stripped off the ions while passing through a thin material, which boosts the charge-to-mass ratio (q/A) of beams for efficient acceleration. FRIB has developed 20 – 30 µm thick liquid lithium film as the stripper (LLCS) [3] because of its high capability of thermal load and radiation resistance. Due to the stochastic nature of the stripping process, the output beam is distributed to several charge states. In most cases, the charge state distribution is a Gaussian function, and the fraction of beam intensity in a single charge state is low. Table 1 shows recently operated beams, including the stripping efficiencies measured in FRIB. The yield of the central charge state of the ^{238}U beam is only 21% of the initial intensity.

Table 1: Beam parameters during the recent beam operations. The stripping efficiencies were measured at 17 MeV/u for ^{124}Xe and ^{238}U, and 20 MeV/u for the rest of ions.

Ion	Charge states after stripper	Energy at the target [MeV/u]	Stripping efficiency 1q / Multi-q
^{48}Ca	19+, 20+	225	72% / 98%
^{58}Ni	26+, 27+	250	66% / 94%
^{64}Zn	28+, 29+	240	71% / 88%
^{82}Se	32+, 33+	200	74% / 88%
^{124}Xe	48+ ~ 50+	240	30% / 76%
^{238}U	73+ ~ 77+	177	21% / 83%

To provide higher stripping efficiency, the FRIB linac has been designed to accelerate multiple charge states simultaneously. To avoid the growth of the effective emittance due to trajectories' displacement, the bending systems in FS1, FS2 and BDS have been designed to satisfy achromat conditions and merge all charge states' central trajectories after the bends [4]. The aperture in the dispersive plane is sufficient to accept five charge states of the uranium beam with charge state spread $\Delta q/q_{cen}$, equal to 5.3%. The multi-charge acceleration substantially reduces the deposited power of unwanted charge states on the Charge Selection Slits (CSS) installed after the first bending dipole in the FS1 and reduces required radiation shielding. In the present CSS, absorbed beam power at the single spot is limited to 500 W. For example, after the stripping, the $^{48}Ca^{19+}$ fraction is 26% and the 500 W limit corresponds to approximately 13 kW of $^{48}Ca^{20+}$ only delivered to the target.

The beam time of most experiments is less than a week. Each experiment requires different primary ion species and energy on the target. Therefore, shortening the primary beam tuning time through efficient procedures is essential to provide more time for science.

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University. Also, part of this work is supported by the U.S. Department of Energy Office of Nuclear Physics under Award Number DE-SC0025531.
† maruta@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUC03

DEVELOPMENT OF PLASMA PROCESSING FOR SUPERCONDUCTING HALF-WAVE RESONATORS*

W. Hartung, W. Chang, K. Elliott, S.-H. Kim, T. Konomi, P. Tutt, T. Xu
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

INTRODUCTION

Degradation of accelerator performance during long-term operation may undermine the usefulness of accelerator facilities. For ion linear accelerators using superconducting radio-frequency (SRF) cavities, field emission may worsen over time. Field emission may be remedied by refurbishment of SRF cryomodules, but disassembly of the cryomodules for repeat etching and rinsing of the cavities is time-consuming, labor-intensive, and costly.

In-situ plasma processing of SRF cryomodules has been developed by several groups in recent years as an alternative to refurbishment. Results so far, mainly for multi-cell elliptical cavities, are promising: in-tunnel processing was first demonstrated at SNS and was applied to several cryomodules [1]; in-tunnel processing of CEBAF cryomodules is ongoing [2]. First studies of plasma processing for half-wave resonators (HWRs) and spoke cavities were done at IMP [3] and Fermilab [4]; more recent HWR plasma development studies were done at Argonne [5].

FRIB is an SRF linac which accelerates ions to ≥ 200 MeV per nucleon; user operations began in May 2022 [6, 7]. As the linac contains 324 SRF cavities [8], the risk of cavity performance degradation due to contamination is a concern for long-term operation. We are developing plasma processing for FRIB cavities as a method to mitigate possible future performance degradation [9, 10]. First results of plasma processing of a FRIB HWR using a fundamental power coupler (FPC) with before-and-after cold tests are reported herein.

OVERVIEW

Plasma processing is done with the cavities at room temperature. Major challenges for FRIB cavities are the FPC mismatch at room temperature, the absence of higher-order mode (HOM) couplers, and the limited view of the cavity interior through access ports. Ignition of plasma in the FPC rather than in the cavity is a concern, as this would risk damage to the FPC or cavity. Damage to the RF window ceramic after plasma generation was observed at IMP [11]; in two early trials with a FRIB HWR, sputtering of copper from the custom-length input antenna onto the niobium RF port was observed after coupler plasma ignition [9, 10].

APPARATUS AND METHODS

Most of the development work has been done using a neon-oxygen plasma at ∼ 100 mTorr. Mass flow controllers are used to set the gas flow rates. The gas is pumped through the cavity using a turbo-molecular pump. Some of the gas is sampled and analyzed with a residual gas analyzer (RGA). After plasma ignition, volatile reaction by-products are typically observed on the RGA [10].

We use up to about 100 W of of RF power to ignite and sustain the plasma. We use a bias T to monitor the dc current from the input coupler and apply a dc bias if desired. We monitor the resonant frequency with a network analyzer. We have recently implemented a software interlock to inhibit the RF drive power if coupler ignition is detected.

Initial HWR plasma studies were done with a custom antenna length for a better match at room temperature. We then transitioned to using the FPC, with the FPC position set to minimize the mismatch. At present, venting of the cavity is needed to swap couplers between plasma processing trials and cold tests.

Our basic plasma procedures are described in more detail in a previous paper [10]. We first ramp up the input RF power to ignite the plasma. At ignition, the transmitted power (P_t) jumps down, we observe light from the plasma, and we observe a dc current from the input coupler. After cavity ignition, the resonant frequency shifts up due to the change in effective permittivity from the plasma. We shift the generator frequency up to drive the cavity closer to the new resonant frequency, iterating due to further increases in the plasma density and resonant frequency as we raise the drive frequency. We choose the drive frequency to provide high plasma density while staying below the threshold for returning to neutral gas or coupler ignition.

EFFECT OF GAS PRESSURE

Early measurements of plasma ignition as a function of the gas pressure for a FRIB $\beta_m = 0.54$ HWR (β_m = optimum normalized beam speed v/c) with a custom antenna were reported previously [9]. These result were subsequently reinterpreted and additional measurements were done with an FPC, as shown in Fig. 1a. The plasma ignition threshold follows a "Paschen curve." The behavior for Ne/O_2 and Ar/O_2 mixtures is similar, though ignition of Ar/O_2 plasma is seen at a lower pressure than needed for Ne/O_2. The black circles indicate cases for which the maximum input power was reached without ignition.

Figure 1b shows the maximum frequency shift as a function of pressure. The circles indicate cases in which the frequency shift was limited by coupler ignition (red), a return to neutral gas (green), or prevented by not being able to ignite the plasma with the available input power (black). The highest frequency shifts, and hence highest plasma densities, are obtained with the lowest pressures. Plasma can

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUC04

DEVELOPMENT OF THE FIRST 1 GHz NIOBIUM-TIN QUARTER-WAVE CAVITY*

Y. Zhou[1,†], R. Agustsson[3], P. Davis[1], G. Eremeev[2], B. Guilfoyle[1], M. Kedzie[1], M.P. Kelly[1], T. Petersen[1], S. Posen[2], T. Reid[1], E. Spranza[3], B. Tennis[2]
[1]Argonne National Laboratory, Lemont, IL, USA
[2]Fermi National Accelerator Laboratory, Batavia, IL, USA
[3]Radiabeam Technologies LLC, Santa Monica, CA, USA

Abstract

This work aims to demonstrate the feasibility of coating a high-frequency 1 GHz, compact niobium-3 tin (Nb_3Sn) coated quarter-wave cavity for future ion accelerators. Nb_3Sn has a BCS surface resistance up to 2 orders of magnitude lower than pure niobium widely used for SRF, which implies Nb_3Sn cavities' better performance at much higher frequencies than for niobium. This presents an opportunity for transformative size reductions in accelerating cavities. Here, we have designed, built and tested a 1 GHz quarter-wave cavity sized similarly to a soda can. Cold tests have shown a critical temperatures of 14.5 K ± 0.1 K, which might be due to the coating layer damage or tin depletion. Notably, we observed an average quality factor ~8E8 at low accelerating electric fields, ~7 times higher than the theoretical limit for pure niobium at this frequency.

INTRODUCTION

Niobium-3 Tin (Nb_3Sn) is a promising alternative to pure niobium for low-beta ion accelerators due to its higher superconducting transition temperature of ~18 K and higher superheating field, and much lower RF losses even at high frequencies. At 4.5 K, the expected Bardeen-Cooper-Schrieffer resistance (BCS resistance) of Nb_3Sn is a few nano-Ohms at 1 GHz, with two orders of magnitude improvement compared to pure niobium (see Fig. 1). The low Nb_3Sn RF losses together with 18 K critical temperature allow the use of higher frequency, much smaller cavities while maintaining 4.5 K operation that is compatible with cryocoolers. This work aims to demonstrate the feasibility of coating a high-frequency 1 GHz, compact quarter-wave niobium cavity with Nb_3Sn. The development of this cavity has the potential to transform low-beta ion accelerators through size reductions and by enabling the replacement of large helium cryoplants with small plug-in cryocoolers.

We have designed, built, and tested a 1 GHz Nb_3Sn coated quarter-wave cavity. Nb_3Sn coating has been performed by vapor diffusion in a high vacuum furnace at Fermilab. Cryogenic cold tests show a quality factor of ~8E8 at low accelerating electric fields, or ~7 times higher than the theoretical limit for pure niobium at 1 GHz. This first coating does not yet meet our quality factor or gradient goals. We have stripped the coating layer and electropolished the cavity (~70 µm removal) and have the cavity re-coated at Fermilab. Cold tests for the second coating will take place shortly.

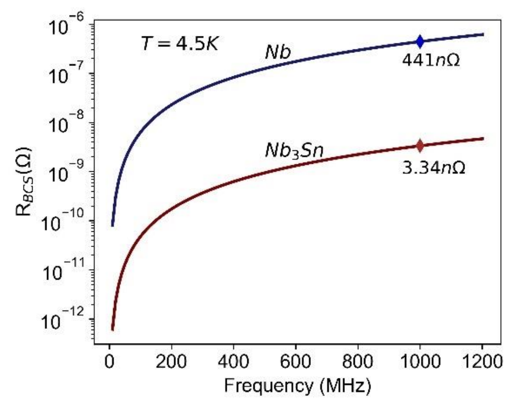

Figure 1: SRIMP calculated BCS resistance of Nb_3Sn and Niobium vs frequency at 4.5 K with material parameters from [1].

PROTOTYPE DESIGN AND FABRICATION

The cavity design was aimed to demonstrate the performance of Nb_3Sn coated low-beta quarter-wave cavity at ~1 GHz using the simplest possible design in this first study. The dimensions of the cavity are shown in Fig. 2(a). For simplicity, beam ports are neglected. A stainless-steel flange with RF drive and pick-up probes close the bottom of the cavity. RF losses in the stainless steel are minimized by extending the single port at the bottom of the cavity. EM simulation (Fig. 2(b)) gives a geometry factor of 49.8, peak electric field and peak magnetic field of 147 MV/m and 308 mT, respectively, for a stored energy of 1 J.

The 1 GHz prototype cavity was machined at RadiaBeam from two high purity (RRR~300) niobium cylindrical ingots (2.5'' OD, one 3'' long and the other 4.5'' long). The two parts (Fig. 2(c)) were electron beam welded (Fig. 2(d)) after buffered chemical processing. The finished cavity is roughly the size of a soda can.

* Work supported by Argonne LDRD seed funding award under the LDRD number 2024-0374 and the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357. This research used resources of ANL's ATLAS facility, which is a DOE Office of Science User Facility
† Email address: yang.zhou@anl.gov

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP01

OPTIMIZATION OF A MINI-CHANNEL BEAM DUMP FOR FRIB OPERATION*

S. Miller†, N. Bultman, T. Kanemura, M. Patil, R. Quispe-Abad, M. Reaume, J. Song
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA
D. Winder, Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract

The Facility for Rare Isotope Beams (FRIB) is a high-power heavy ion accelerator facility at Michigan State University began operations in 2022. Its driver linac is designed to accelerate all stable ions to energies greater than 200 MeV/u with primary beam power of up to 400 kW. Currently, FRIB is operating between 10 to 20 kW, delivering multiple primary beam species. The beam dump absorbs approximately 75% of the primary beam power. The existing beam dump head can accommodate up to 20 kW operation, with a planned upgrade to an optimized static mini-channel beam dump design with capability of 30 kW and beyond. Presented here is an overview of the mini-channel beam dump head design optimization and supporting analysis.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a major nuclear physics facility for research with fast, stopped, and reaccelerated rare isotope beams. FRIB will provide access to 80% of all isotopes predicted to exist in nature. FRIB construction started in 2013 and began operations in 2022. The FRIB facility is based on a heavy-ion continuous wave (CW) superconducting driver linac, capable of accelerating uranium ions to 200 MeV/u and higher energies for lighter ions with 400 kW power striking a target to produce rare isotope beams. FRIB has adopted an incremental approach toward the ultimate design beam power of 400 kW by prioritizing safe operation and to avoid any damage to the machine. In the delivery beam system, the beam dump is designed to absorb approximately 75% of the primary beam power. Currently, FRIB routinely delivers 20 kW primary beams on target, producing rare isotopes that are separated and analysed in the Advanced Rare Isotope Separator (ARIS). The beam dump location and ARIS are shown in Fig. 1 [1-4].

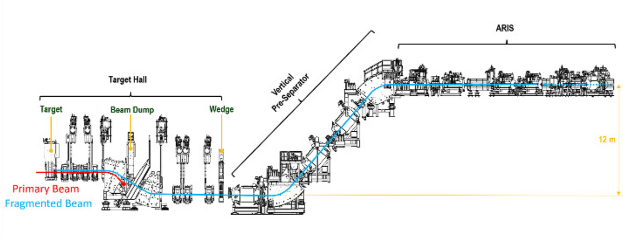

Figure 1: FRIB target hall and ARIS.

* Work supported by the Department of Energy Contract DE-SC0023633
#millers@frib.msu.edu

BEAM DUMP DESIGN

Figure 2 shows the development of the beam dump technology for FRIB. FRIB's power ramp up after initial operation is defined by specific Epochs: Epoch 1: 10 kW, Epoch 2: 20 kW, and Epoch 3: 50 kW.

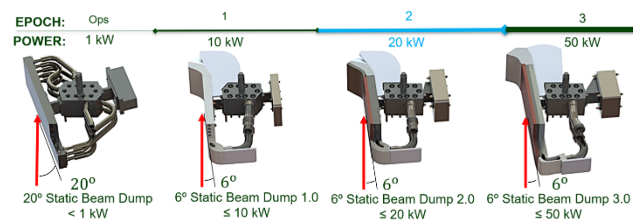

Figure 2: Beam dump design by Epoch.

20-degree Static Beam Dump: 1 kW

The 20-degree (with respect to the beamline) beam dump shown in Fig. 3, was used for FRIB initial operation, was constructed of aluminium alloys. This beam dump utilized a beam stopper (absorber) made of machined Aluminium 2219 with internal cooling passages with water flow. This beam dump design was limited to 1 kW of beam power. Copper alloys were excluded to avoid oxidation that is enhanced by chemical reactions with oxygen produced by secondary particles interactions with the cooling water [3].

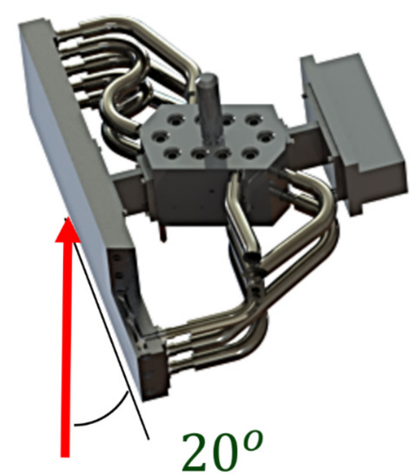

Figure 3: 20-degree beam dump design for 1 kW.

6-degree Static Beam Dump: 10 kW

The 6-degree (with respect to the beamline) beam dump, which was used for FRIB Epoch 1 of the power ramp up, as shown in Fig. 4, was also constructed of aluminium alloys. The beam dump consists of the beam stopper (absorber) made of machined Aluminium 2219 and 3D-

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP03

STUDY ON SYNERGISTIC IRRADIATION EFFECTS OF NUCLEAR MATERIALS BASED ON COCKTAIL ION BEAM TECHNOLOGY

Y. H. Zhai[1,2]†, L. Sun[1], Y. Yang[1], B. Zhang[1], H. Zhao[1]
[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China
[2] University of Chinese Academy of Sciences, Beijing, China

Abstract

Cocktail ion beams, composed of multiple ion species with independently adjustable energies and charge states, have emerged as a powerful tool for simulating the complex synergistic irradiation environments encountered by structural materials in advanced nuclear systems. In this study, we report the development and application of cocktail ion beams at the Low Energy high-intensity heavy ion Accelerator Facility (LEAF), where a superconducting Electron Cyclotron Resonance (ECR) ion source and a dedicated energy modulation system enable the generation of high-intensity beams with low energy spread. The integration of a drift tube linac (DTL) and rebunching cavities allows precise energy tuning of each ion species, facilitating control over their respective penetration depths to simulate localized and overlapping damage regions. To evaluate the irradiation-induced microstructural changes, single-crystal copper samples were subjected to various irradiation schemes. Post-irradiation analyses revealed that simultaneous multi-ion exposure leads to distinct damage patterns and defect evolution compared to sequential or single-ion irradiation, highlighting the critical role of dynamic ion-ion interactions and concurrent damage processes. Furthermore, recent advancements in LEAF have enabled the development of a three-ion cocktail beam configuration (e.g., $^{4}He^{+}$ + $^{16}O^{4+}$ + $^{131}Xe^{33+}$), which offers enhanced flexibility for simulating broader irradiation environments. This capability allows for more realistic reproduction of fusion and fission reactor conditions, providing a robust experimental foundation for exploring the coupled effects of hydrogen, helium, and heavy ions on nuclear materials.

INTRODUCTION

The LEAF [1] platform is an integrated experimental platform independently developed by the Institute of Modern Physics, Chinese Academy of Sciences (IMP-CAS). Its core objective is to deliver high-quality ion beams with variable energy ranging from 0.1 to 100 MeV, beam intensities reaching the milliampere level, and charge states spanning the full spectrum—from light ions (e.g., H_2^{+}, $^{4}He^{2+}$) to highly charged super-heavy ions (e.g., $^{238}U^{50+}$, $^{209}Bi^{55+}$).

As illustrated in Fig. 1, the LEAF facility consists of a 45 GHz fourth-generation superconducting ECR ion source (FECR) [2], a 100 kV high-voltage platform, a low-energy beam transport line (LEBT), an 81.25 MHz radio-frequency quadrupole accelerator (RFQ), a medium-energy beam transport line (MEBT), and several experimental terminals.

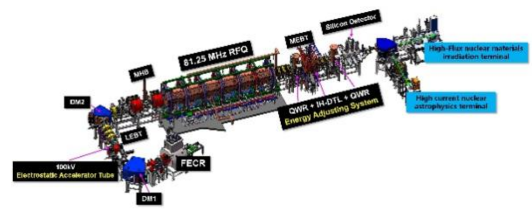

Figure 1: Layout of the LEAF platform.

Table 1: The Main Design Parameters of FECR

Spec.	Para.
ω_{rf}	28~45 GHz
RF power	≥20 kW
Conductor	Nb_3Sn
Mirror Fields	~6.4 T
Brad	~3.2 T
Chamber ID	~Ø140 mm
Lmirror	~500 mm

The design parameters of FECR are summarized in Table 1, and it is capable of efficiently generating high charge state beams such as $^{129}Xe^{40+}$ and $^{209}Bi^{55+}$. More importantly, it enables the production of multi-species cocktail beams, which provide unique irradiation conditions for studying synergistic damage effects in nuclear materials.

The LEAF-RFQ employs a four-vane structure, and in continuous wave (CW) mode, it stably accelerates particles with a charge-to-mass ratio (Q/A) between 1/2 and 1/7 from an injection energy of 14 keV/u to an output energy of 0.5 MeV/u. Given the fixed output energy of the RFQ, a dedicated energy modulation system has been integrated at the RFQ exit to broaden the range of beam conditions. This system includes an interdigital H-type drift tube linac which enables continuous modulation of the beam energy within 0.3–0.7 MeV/u [3]. To preserve beam quality during energy variation, a pair of quarter-wave resonator-based rebunchers are placed on either side of the DTL section to optimize longitudinal beam dynamics and compress energy spread [4].

COCKTAILED ION BEAM ACCELERATION

Cocktail ion beams, consisting of multiple ion species with precisely tailored mass-to-charge ratios (M/q), play a

†zhaiyuhan16@impcas.ac.cn.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP04

DESIGN AND EXPERIMENTAL THERMAL VALIDATION OF THE MINI-CHANNEL BEAM DUMP FOR FRIB *

J. Song†, N. Bultman, T. Kanemura, G. Lee,
S. Miller, M. Patil, R. Quispe-Abad, M. Reaume, J. Wei
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The FRIB, a leading experimental nuclear physics facility, produces high-intensity beams of proton- and neutron-rich nuclei. FRIB provides high-yield, high-purity rare isotope beams via primary beams interactions with a graphite target. After the target, the unreacted primary beam should be absorbed by a beam dump. To support operations at 20 kW, an intermediate beam dump system, called the mini-channel beam dump (MCBD), has been developed and implemented. This system features a static structure oriented at a 6^0 angle, reducing power density by 10 times. The MCBD is fabricated as a bimetal using an Al-Cu alloy, with a high-thermal-conductivity copper absorber for enhanced heat dissipation and 2 mm ×7 mm aluminum cooling channels that prevent copper oxidation and significantly improve cooling efficiency. The thermal performance of the MCBD was validated through experimental testing using a 17 keV e-beam at the Applied Research Laboratory, showing measured temperatures matching ANSYS simulation within 5 % uncertainty. These results indicate that the MCBD can reliably support FRIB operations at 20 kW or higher, ensuring effective heat dissipation under high-power conditions.

INTRODUCTION

FRIB is a major nuclear physics facility dedicated to rare isotope science and is progressing toward its ultimate goal of 400 kW primary beam operation. FRIB currently provides stable heavy ion beams ranging from oxygen to uranium and has been progressively increasing its operational beam power from 1 kW to 20 kW [1,2]. Following commissioning [3,4], a static aluminum beam dump was used for primary beam powers ranging from 1 to 10 kW [5]. Approximately 20–40 % of the primary beam power is absorbed by the graphite production target, while the remaining 60–80 % must be absorbed by the downstream beam dump system. Due to the limited thermal performance of the static dump beyond 10 W, the need for an intermediate beam dump, referred to as the mini-channel beam dump (MCBD) [6], was established. Key changes compared to the previous beam dump include the use of 2 mm-wide mini-channels on the water-cooling side, increasing the average convective heat transfer coefficient (CHTC) by more than a factor of 3 [7]. The design also adopts a CuCrZr/Al2219 bimetal structure, with a Cu alloy used as the beam absorber and Al2219 forming the cooling channels. The copper alloy offers ≈ 2.5 times higher thermal conductivity than Al2219, which was used in the previous design. Concepts for this system have been introduced in earlier studies [8, 9]. The prototype of the MCBD was fabricated in early 2024. To validate its thermal performance via comparison with simulations, a thermal test was conducted using a 17 keV electron beam at the Applied Research Laboratory of Penn State University. The test results are under analysis, and a portion of the preliminary results is presented in the following section.

MINI-CHANNEL BEAM DUMP

The main design considerations were to enhance thermal performance and minimize the operational impact of radiation damage on the beam dump. To improve thermal performance, a copper alloy was introduced, offering ≈ 2.5 times higher thermal conductivity than Al2219. This material change allowed an increase in the maximum allowable temperature from 200 ^{0}C to 250 ^{0}C, based on thermal stress analysis results. A 2 mm-wide mini-channel design was selected to achieve a CHTC approximately 3 times higher than the previous desgin, while maintaining a reasonable pressure drop (≈ 1 bar). Radiation damage is a critical concern, especially near the surface, as the FRIB primary beam stops whithin less than 1 mm from the surface. Since beam dump is not a beam window, and some surface damage may occur, the system is expected to remain fully functional under operational conditions. Additional structural analyses were performed to ensure safe operation under expected thermal loads [10].

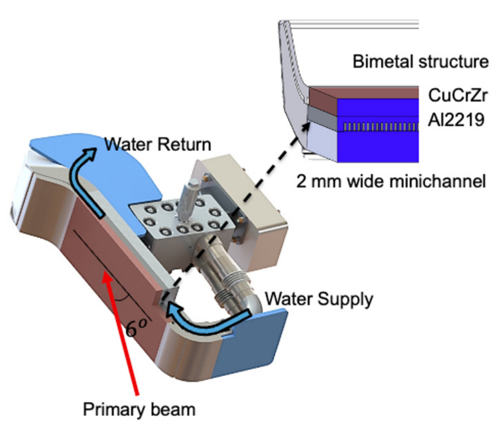

Figure 1: Schematic of the mini-channel beam dump (MCBD).

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
† songj@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP05

APPLICATION OF ASME BPVC SECTION VIII, DIVISION-2, DESIGN BY ANALYSIS REQUIREMENT TO FRIB STATIC BEAM DUMP*

M. Patil[†,1], N. Bultman[1], T. Kanemura[1], S. Miller[1], R. Quispe-Abad[1], M. Reaume[1], J. Song[1], D. Winder[2]
[1]Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA
[2]Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract

The Facility for Rare Isotope Beams (FRIB) at Michigan State University is a high-power heavy-ion accelerator, and began operation in 2022. Its driver linac is designed to accelerate all stable ions to energies exceeding 200 MeV/u, with a maximum beam power of 400 kW. Currently, FRIB operates at beam powers between 10 and 20 kW, delivering multiple primary beam species. Approximately 75% of the primary beam power is absorbed by the beam dump. The existing mini-channel beam dump (MCBD) absorber is designed to handle up to 20 kW, with plans for an optimized beam dump capable of supporting 30 kW and beyond. This paper presents the design-by-analysis procedures outlined in ASME Boiler and Pressure Vessel Code [1] that have been applied to the MCBD design.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB), a major nuclear physics facility for research with fast, stopped, and reaccelerated rare isotope beams, has adopted an incremental approach toward the ultimate design beam power of 400 kW prioritizing safe operation and avoiding any possible damage to the machine. Currently, FRIB routinely delivers 10-20 kW primary beams on target and beam dump, producing rare isotopes that are separated and analyzed in the Advanced Rare Isotope Separator (ARIS) [2].

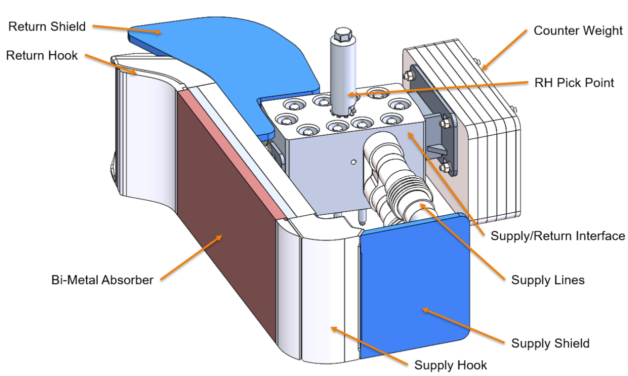

Figure 1: Details of the MCBD with key components as labelled.

The FRIB beam dump system (20kW operations) is shown in Fig 1. The primary components of the Mini-Channel Beam Dump (MCBD) consist of a C18150 copper alloy absorber plate explosion bonded to aluminum 2219 which has cooling channels. The higher thermal conductivity of the copper alloy will help to reduce the temperature increase due to beam heating. However, precautions are needed to ensure that the beam dump cooling water does not encounter the copper alloy, as copper is vulnerable to oxidation that is enhanced by chemical reactions with oxygen produced by secondary particles interacting with the water (oxidation may result in pitting of the material). Hence the cooling channels are made from aluminum alloy. The design is shown in Fig 2. This bi-metal absorber plate is welded to return and supply hooks (3D printed AlSi10Mg) that connect to the cooling water lines. An optimized version of this MCBD for 30 kW beam operation is currently being manufactured and will be installed in summer of 2025 [3]. This paper describes in brief the application of ASME BPVC Sec VIII, Div2 to the 20 kW beam dump. More detailed analysis with results can be found in the FRIB reports [4, 5]

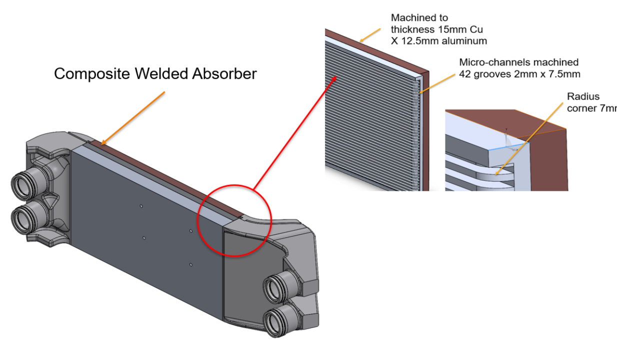

Figure 2: FRIB MCDB showing the mini channels used for cooling.

MATERIALS AND WELDS

Temperature dependent material properties are used as the input for the non-linear analysis. Material properties used for this analysis have been gathered from a mixture of in-house testing, material properties database (MPDB software) [6] and literature [7, 8]. Plasticity is modelled using a *Bilinear Isotropic Hardening* material model.

Welds are produced by the electron beam process (Al-2219 back plate to Al-2219 on the absorber plate with mini channels), and the TIG (GTAW) process for the Al-2219 to the 3D printed AlSi10Mg hooks. The welds are not modelled in the finite element model. All the weld joints are assumed bonded for the contact conditions. Our e-beam welding development and testing for AL-2219 T851 shows about 50% reduction in room temperature yield properties in the weld zone. So, the weld strength of Al 2219 has been derated by 50% in the analysis

*Work supported by the Department of Energy Contract DE-SC0023633
†patil@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP06

MONTE-CARLO SIMULATION OF VACUUM SYSTEM FOR ADVANCED CHARGE SELECTOR*

X. Wang †, S. Carter, S. Chrenka, T. Kanemura, A.S. Plastun, D. Simon
Facility of Rare Isotope Beams, Michgan State University, East Lansing, MI, USA

Abstract

To intercept unwanted charge states from stripped beams with high power densities, an advanced charge selector is currently under development at the Facility for Rare Isotope Beams (FRIB). This upgraded charge selector is designed to intercept beam spots that have a power of up to 5 kW and an rms size as small as 0.7 mm × 1.25 mm. To enhance heat dissipation and mitigate thermal stress, rotating graphite wheels are employed as the beam-intercepting medium.

An essential aspect of this design is the development of a robust vacuum system to ensure reliable and efficient operation while minimizing beam losses in downstream sections. The high graphite temperature, maintained over 1000 °C for radiation damage annealing during operation, raised concerns about gas load. To aid the vacuum system design, vacuum simulations were carried out using a Monte Carlo-based simulation code, MolFlow. The sublimation of graphite, outgassing from the vacuum chamber's inner wall and the effect of pumping speed on vacuum performance are considered. The results demonstrate that the proposed vacuum system can maintain a pressure under 3×10^{-7} mbar, ensuring adequate vacuum conditions for beam operations.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB), supported by the U.S. Department of Energy's Office of Science, is a cutting-edge user facility dedicated to advancing nuclear science. FRIB has progressively increased its primary beam power from 1 kW to 20 kW since commencing operations in 2022 [1]. The facility is currently being upgraded to 50 kW operation, with the charge selector as one of the key devices under development [2].

The charge selector is located in the first folding segment of the accelerator and is responsible for intercepting unwanted charge states produced after the beam stripper. Figure 1 shows the positions of the charge stripper and the charge selector.

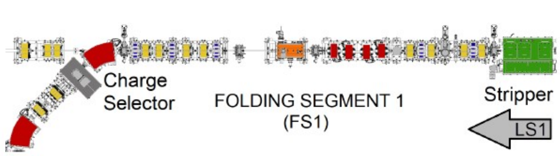

Figure 1: Layout of folding segment of the FRIB linac.

In general, the stripping of heavy-ion beams results in multiple charge states. As the stripped beam passes through a magnet, the charge states separate as a result of dispersion. The charge selector then intercepts those charge states that fall outside the acceptance of the downstream linear accelerator segment, while allowing the desired charge states to pass through for further acceleration.

Currently, an advanced charge selector using a rotating graphite wheel is being developed to replace the existing charge selector, a pair of copper-alloy-based water-cooled jaws. The upgraded charge selector is designed to intercept beam spots with powers up to 5 kW, beam energies ranging from 17 to 20 MeV/u, and rms sizes as small as 0.7 mm × 1.25 mm.

A critical aspect of the charge selector's design is the development of a robust vacuum system to ensure stable and efficient operation. During operation, the graphite is maintained at temperatures exceeding 1000 °C to facilitate radiation damage annealing, raising concerns about increased gas load from carbon sublimation. To support the vacuum system design, simulations were performed using the Monte Carlo–based code MolFlow [3]. These simulations accounted for carbon sublimation, thermal outgassing from the chamber's inner surfaces, and the impact of pumping speed on overall vacuum performance.

CHARGE SELECTOR

The advanced charge selector employs a pair of rotating graphite wheel that intercept unwanted charge states and radiate absorbed beam power to a water-cooled copper-alloy heat exchanger. Graphite is chosen mainly for its excellent thermal shock and radiation resistance, similar to its use in high-power target systems. Rotation spreads the heat load over a larger volume and surface area, reducing localized thermal stress and enabling high-power operation.

Figure 2 presents a model of the advanced charge selector. As shown in the figure, the graphite wheels are positioned within a heat exchanger to intercept the beams. The device employs ferrofluid rotary feedthroughs for torque transmission and linear actuators for positioning to intercept unwanted charge states across the beam profile. The device is shielded to reduce radiation exposure to the surrounding environment. The device incorporates complex features to ensure safe operation and maintenance [4].

VACUUM SYSTEM AND SIMULATION

Layout of the Vacuum System

Several challenges arose in developing the vacuum pumping system, including achieving sufficient pumping speed to

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.
† wangxiu@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP08

NUMERICAL MODELING TO PREDICT IGNITION THRESHOLDS FOR PLASMA PROCESSING OF SUPERCONDUCTING RADIO-FREQUENCY CAVITIES*

Z. Hosek[1,2], W. Hartung[1], P. Tutt[1,2], T. Xu[1,2]
[1]Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA
[2]Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA

ABSTRACT

Laboratories such as Oak Ridge, Fermilab, and Jefferson Laboratory have been developing plasma cleaning techniques for superconducting radio-frequency (SRF) cavities. These techniques show promise as an in-situ method of mitigating degradation in cavity performance via removal of surface contamination. Plasma cleaning studies for SRF cavities in the driver linac at the Facility for Rare Isotope Beams (FRIB) began in 2020. Both neon-oxygen and argon-oxygen plasmas have been found to be effective in improving FRIB accelerating cavities. Models have been developed to predict the threshold RF electric field for ignition of a diffusion-dominated plasma using the solution to the diffusion equation for a given cavity shape; a numerical solution is needed for realistic cavity shapes. Predictions for several cavity shapes using numerical techniques will be compared to analytic approximations and ignition and extinction threshold measurements.

INTRODUCTION

Careful surface preparation is needed for superconducting radio-frequency (SRF) cavities to ensure high performance in particle accelerators. Though SRF cavity assembly is done in a clean room, some particulate contamination may still be introduced. When a cavity is installed in a cryomodule and used for acceleration, there is a risk of further contamination.

Hydrocarbons on the cavity inner surface may lower the work function and worsen field emission [1]. Field emission can produce Bremsstrahlung X-rays, and, in severe cases, can reduce the cavity quality factor, such that the accelerating gradient of the accelerator must be reduced.

In-situ cavity cleaning techniques are highly desirable for reduction of contamination and improvement of performance without the need to remove and disassemble cryomodules, which is time- and labor-intensive.

Plasma processing has been developed as a method to remove contamination from SRF cavities via a weakly-ionized cold plasma. This is done by flowing a noble gas such as neon or argon through the cavity and ionizing the gas via a standing-wave RF electric field driven through an RF coupler. Oxygen is added to the noble gas to react with contaminants on the cavity surface. Byproducts from the chemical reaction of oxygen radicals with surface contaminants may be volatile (CO, CO_2, H_2O), such that they can be pumped out of the cavity. Though developed to target hydrocarbon contamination, plasma processing may be beneficial for other contaminants as well.

The Facility for Rare Isotope Beams (FRIB) uses 324 SRF cavities to accelerate ions [2]. Plasma processing is being developed for FRIB quarter-wave resonators (QWRs) and half-wave resonators (HWRs) in support of long-term operation of the FRIB superconducting linac [3].

Simplified models may be used to predict the RF electric field needed to ignite a given gas mixture. Inputs to the models may be obtained from analytic approximations or numerical calculations. In this paper, predictions based on analytic and numerical approaches will be compared to plasma measurements on FRIB SRF cavities.

DIFFUSION-DOMINATED MODEL

Plasmas within certain parameter ranges can be described approximately by a diffusion-dominated model [4]. The diffusion-dominated model is applicable for plasma ignition in FRIB cavities, and has been used to predict ignition thresholds for FRIB QWRs. However, the model's assumptions are not met for the case of plasma ignition in the FRIB fundamental power coupler (FPC), as the electron mean free path is not small compared to the relevant FPC dimensions [5].

The Diffusion Equation

In order to predict the plasma ignition threshold field E_t for a given cavity geometry, driving frequency, and gas mixture, it is necessary to properly describe the behavior of electrons as ionizing particles. The effective diffusion length Λ describes the average distance traveled by ionizing electrons before they are re-combined into neutral material [6]. A kinetics-based derivation of the effective diffusion length relies on the eigen-solution to a simplified Fick's Law diffusion equation [7]:

$$\nabla^2 n = -\frac{\nu}{D} n = -\frac{1}{\Lambda^2} n \,, \tag{1}$$

where n is free electron number density, D is the diffusion coefficient, and ν is the collision frequency, with the latter two determined by the gas mixture and state variables. The free electron number density n is assumed to be zero on the walls of the container due to electron re-combination at the conducting walls. Previous work used an analytic approach to find Λ for a simplified coaxial geometry which approximates the FRIB QWR shape. A numerical approach

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DESC0023633, the State of Michigan, and Michigan State University.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP09

DEVELOPMENT OF AUTOMATIC BEAM TUNING SYSTEM USING BAYESIAN OPTIMIZATION FOR HIGH INTENSITY HEAVY ION BEAMS AT RIBF

T. Nishi*, H. Fujii, N. Fukuda, Y. Morita, Y. Shimizu, T. Sumikama, A. Uchiyama
RIKEN Nishina Center, Wako, Saitama, Japan

Abstract

In general, accelerator facilities are controlled by a huge number of parameters. To optimize these parameters more efficiently and accurately, we are attempting to implement Bayesian optimization (BO). Given the importance of space charge effects and beam loading, it is desirable to adjust parameters at high beam intensity, making it crucial to develop an optimization system capable of handling high-intensity heavy ion beams. We have been working on developing indices suitable for high-intensity beams and exploring methods for optimization while maintaining operational safety. Currently, we are preparing for simulations and tests using beam line.

BAYESIAN OPTIMIZATION FOR HIGH-INTENSITY ACCELERATOR FACILITIES

The RIKEN RI Beam Factory (RIBF) [1, 2] , a heavy-ion accelerator complex consisting of several cyclotrons and Linacs, is controlled or influenced by more than 600 parameters, including environmental factors. So far we developed a technique that enables the simultaneous measurement of beam transmission and spot shape on the target by tracking charge-converted particles after passing through the target. Additionally, we are investigating the use of line BO with a safety function [3, 4] to ensure safe beam optimization. We employed an automatic beam tuning program based on Bayesian optimization using Gaussian Process Regression (GPR), originally developed at SACLA, SPring-8 [5]. This program estimates the objective function for unknown parameter sets from acquired data using GPR, including predictive uncertainties. Based on this estimation, the next set of beam parameters is determined by maximizing an acquisition function. By applying this new parameter set and re-evaluating the objective function, the program continues to learn and iteratively updates the beam parameters through sequential learning.

When adapting this program to RIBF, we identified the following two key development requirements.

1. Development of beam quality indicators applicable to high-intensity beams. At high-intensity beam facilities such as RIBF, space-charge effects and beam loading in RF cavities cause the optimal tuning parameters to vary with beam intensity. Therefore, it is essential to establish indicators that can appropriately represent both beam intensity and beam quality under such conditions.
2. Implementation of a safety system to prevent excessive beam loss during tuning. Even if the algorithm ultimately converges to optimal parameters, excessive beam losses during the optimization process could lead to equipment damage or operational risks. It is thus crucial to develop a safety scheme that monitors and limits beam loss during the tuning process to ensure safe operation.

In this paper, we first present the results of beam tuning in the low-energy section to investigate the basic characteristics of Bayesian optimization. We then explain the development of evaluation metrics suitable for high-intensity beams, followed by our ongoing efforts toward implementing a practical safety scheme.

APPLICATION FOR LOW ENERGY SECTION

We applied the developed optimization program to the low-energy section, where the ion beam from the 28 GHz ECR ion source is accelerated by RILAC-II and injected into the RIKEN Ring Cyclotron (RRC). The optimization targeted quadrupole, steerer, and dipole magnets located between the ion source and the RRC injection system, using Bayesian optimization to maximize the beam current at the cyclotron extraction point.

Prior to the optimization, the RRC tuning parameters were manually adjusted by experienced operators. The objective was to increase the beam current at the RRC exit by improving upstream beam transport and better matching the beam envelope to the cyclotron acceptance. Over 70 parameters were divided into 10 groups, with each group limited to no more than 10 parameters to maintain the efficiency of the Bayesian optimization process. For the steerer magnets, groupings were arranged to include at least two steerers in both the horizontal and vertical planes, in order to avoid convergence to local minima.

To reduce noise in the objective function, the value was averaged over five consecutive measurements taken at 0.2 second intervals, achieving precision at the few enA level for beam currents around 500 enA.

The optimization result is shown in Fig. 1. After tuning the parameter ranges through preliminary tests, the full optimization was performed over 40 minutes, with each iteration taking approximately 7 seconds, resulting in around 350 trials. As a result, the beam current at the RRC exit increased from 520–530 enA to 570–580 enA, representing an improvement of approximately 10%.

* takahiro.nishi@riken.jp

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP11

APPLICATION OF ML TOOLS FOR EXTRACTION OF BPM-Q AND TRANSVERSE BEAM MATCHING *

K. Hwang†, K. Fukushima, T. Maruta, P. Ostroumov, A. Plastun, T. Zhang, Q. Zhao
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

Training an accurate Beam Quadrupole Moment at BPM (BPMQ) model is challenging due to data inaccuracies. Similarly, reconstructing Courant-Snyder (CS) parameters from BPMQ predictions is difficult due to the limitations of the BPMQ model. Increasing the number of BPMQ predictions helps mitigate overfitting in CS inference caused by inaccurate BPMQ predictions. We present Bayesian Active Learning (BAL) to strategically acquire measurements, improving the inference of the CS parameters despite the limitations of the model.

QUADRUPOLAR MOMENTS OF THE BEAM AT BEAM POSITION MONITOR (BPMQ)

The beam quadrupole moment (BPMQ), defined by the difference in the transverse variances of the beam: $\sigma_x^2 - \sigma_y^2$, can be estimated using Beam Position Monitor (BPM) signals. For a circular cross section BPM with four pickups positioned at the top, left, right, and bottom, the BPMQ is given by [1]:

$$\text{BPMQ} = G\frac{U_R + U_L - (U_T + U_B)}{U_R + U_L + U_T + U_B} - (x^2 - y^2) \approx \sigma_x^2 - \sigma_y^2 \quad (1)$$

where G is a geometric factor that depends on the BPM cross-section geometry, U_T, U_L, U_R and U_B are the induced signal strength at the top, left, right, and bottom pickups, and x and y represent the horizontal and vertical beam centroids which are also a function of the 4 pickup signals. To minimize signal cross talk caused by prevalent sources of error throughout the linac, the induced signal strength U_i is defined as the amplitude of the 161 MHz component of the pickup signal.

VIRTUAL DIAGNOSTICS (VD) FOR BPMQ

As primary role of BPM is to measure the position of the beam, the BPMQ signal is significantly weaker compared to the centroid signal of the beam. Consequently, small errors, such as calibration inaccuracies, can lead to substantial errors in the BPMQ measurements.

We address the calibration of BPMQ using a Supervised Machine Learning (ML) approach. It is important to remark that the accuracy of the calibration model depends on the quality of the data.

* Work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award Number DE-SC0024707 and used resources of the FRIB Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633
† hwang@frib.msu.edu

Dataset

The dataset consists of four induced signals from four BPM pickups, which serve as input features. The target output (label) for the machine learning (ML) model is the BPMQ value. The collection of training data including the BPMQ labeling involves the following steps:

- Perform a quadrupole magnet scan (q-scan). At each q-scan step, measure the root-mean-square (RMS) beam size from the beam profile using a wire scanner, referred to as the Profile Monitor (PM).
- Reconstruct the Courant–Snyder (CS) parameters by fitting the measured beam sizes. This is achieved by minimizing the difference between the measured and simulated beam sizes using the beam envelope simulation code FLAME [2].
- With the reconstructed CS parameters, simulate the beam envelope at the BPM locations (for given quadrupole settings) using FLAME to compute the corresponding BPMQ values.

The reliability of the data depends on the accuracy of PM measurement, accuracy of the lattice model and quadrupole magnet strength calibration used in FLAME simulation, beam and machine stability during measurements, BPM signal noise. To reflect the quality of the data, the dataset is categorized into two fidelity levels:

High-fidelity data: This set includes samples collected through a structured q-scan procedure, where each step is paired with a PM measurement. These data points are the same ones used for CS parameter reconstruction. After the reconstruction, samples with high reconstruction loss are excluded to further improve quality. As a result, this dataset contains only well-matched measurements and simulations.

Low-fidelity data: This set includes two types of samples: (1) data collected during the q-scan procedure but rejected due to high reconstruction loss, and (2) data collected after the CS reconstruction process, using random quadrupole magnet settings without accompanying PM scans. In the second case, BPMQ values are labeled by simulating the beam envelope using the previously reconstructed CS parameters.

BPMQ Model

We explored two Artificial Neural Network (ANN) architectures for modeling BPMQ. This model will serve as virtual diagnostics (VD). First, we designed a model structure that incorporates physical constraints to improve interpretability and generalization. The model enforces the following form for BPMQ prediction:

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP13

FRIB MULTI-GAP BUNCHER CONDITIONING UP TO 30 KW*

H. Ao†, E. Gutierrez, D. Morris, X. Rao, S. Zhao
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI USA

Abstract

The Facility for Rare Isotope Beams commenced operations for scientific users in May 2022, and the driver linac currently operates at beam powers of up to 20 kW. To reduce beam loss in the linac, we plan to operate two multi-gap bunchers (MGBs) at higher accelerating voltages. This paper presents lessons learned from the initial stages of MGB operations and summarizes the phased high-power conditioning, which progressed from 18 kW to 26.5 kW, and then to 30 kW of continuous wave RF power. Both MGBs were successfully conditioned during maintenance periods. After approximately 100 hours of conditioning, MGB1 operated without tripping in the last 12 hours, and MGB2 experienced only three trips during the same period.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) is a scientific user facility for the U.S. Department of Energy Office of Science (DOE-SC), with financial support from and furthering the mission of the DOE-SC Office of Nuclear Physics. The FRIB driver linac was designed to accelerate stable ion beams exceeding 200 MeV/u with superconducting cavities and provide a beam power up to 400 kW. User operations commenced in May 2022, and the linac currently operates at beam powers of up to 20 kW [1].

Reducing beam losses is one of the biggest challenges as beam power increases. A recent beam study observed the beam loss in Linac Segment 2 (LS2, Fig. 1) due to an energy spread increase caused by the lithium stripper [2]. To increase the longitudinal acceptance, we plan to operate two 161-MHz normal conducting multigap bunchers (MGBs, Fig. 1) at higher voltages and introduce new second harmonic RF cavities [3].

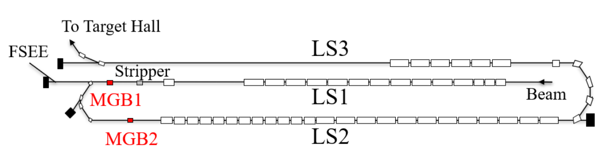

Figure 1: Layout of FRIB driver linac.

This paper provides lessons learned from the initial stages of MGB operations and summarizes the phased high-power conditioning of MGB1 and MGB2, conducted following the upgrade of the continuous wave RF amplifiers from 18 kW to 30 kW by adding two amplifier drawers in addition to the existing four drawers to each rack of the two-rack system, with each drawer operating at 2.5 kW.

COMMISSIONING GOALS

The primary goal was to verify that both MGBs operated stably. Secondary goals included evaluating interlock settings, assessing the accuracy of RF power readbacks, monitoring long-term stability, and investigating other factors relevant to user operation. Major criteria were as follows:

- Stable cavity operation for over one hour without trips at the highest operating voltages
- Vacuum pressure rise less than 1×10^{-6} Torr and as low as reasonably achievable during startup

The second one was defined to prevent the issue encountered during the initial stages of operation. Multiple startup failures occurred due to vacuum spikes in the MGB1 at 900 kV (Fig. 2, top). Although MGB1 had previously operated at voltages higher than 900 kV for approximately 100 hours, it had been turned off for about three months. After an additional 30 hours of conditioning, no vacuum spikes were observed (Fig. 2, bottom). However, the vacuum pressure still reached approximately 1×10^{-6} Torr during startup.

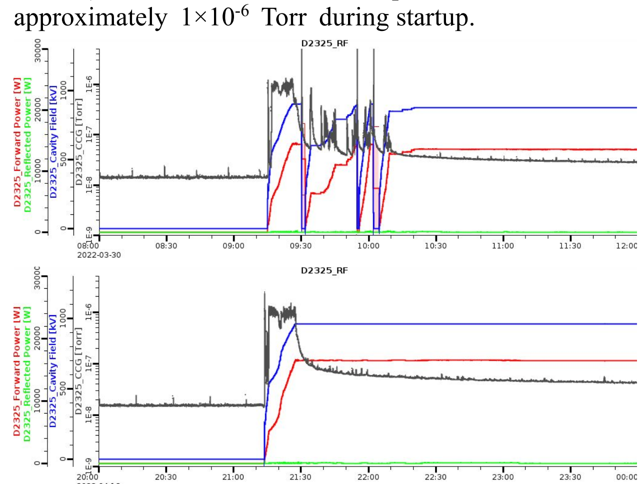

Figure 2: Pressure rise during cavity startup in the initial stages of MGB operations. Colors are consistent across all figures: red for forward power, blue for cavity voltage, and gray for vacuum pressure. (Top) Multiple trips occurred due to vacuum spikes following a three-month shutdown. (Bottom) After an additional 30 hours of conditioning, no further vacuum spikes were observed.

This result indicates that the MGBs need degassing before operating at higher voltages at which they have not been operated recently. This is primarily because higher power increases the temperature on the inner surface, which in turn generates more outgassing. The inner surface may capture residual gases during low-power operation, which are then released at higher power.

*This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633
†ao@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP14

AVOIDING BEAM INSTABILITIES AND RESONANCES WITH CIRCULAR MODES*

O. Gilanliogullari†, Illinois Institute of Technology, Chicago, IL, USA
B. Mustapha, Argonne National Laboratory, Lemont, IL, USA
P. Snopok, Illinois Institute of Technology, Chicago, IL, USA

Abstract

Beam instabilities and resonances affect the transverse dynamics in particle accelerators and, when encountered, can trigger emittance growth and beam loss. Resonance lines originate from non-linear elements and effects in the lattice, imposing strict constraints on the choice of working points and narrowing the available tune space. Circular modes are round coupled beams with non-zero angular momentum, provide an alternative beam motion and dynamics. In this study, we derive the third-order sextupole resonance conditions in the coupled (normal-mode) parametrization and show that, with circular-mode lattice design and beam operation, most of these resonance lines are naturally suppressed due to the inherent flatness of the mode.

INTRODUCTION

Accelerators aim to deliver high-quality beams depending on the objectives to be accomplished. The design of an accelerator depends on the beam species to be accelerated and the desired energy and intensity. An accelerator lattice design incorporates both linear and non-linear elements and collective effects. Linear elements are responsible for the total number of betatron oscillations, known as the tunes of the system in orthogonal planes. The inclusion of non-linear elements introduces systematic resonances within the lattice, as discussed in many textbooks [1]. The Courant-Snyder parameterization of the betatron motion [2] shed light on the periodic behavior of the beam and the resonance conditions. Uncontrolled resonances may lead to particle loss; therefore, resonance conditions constrain the selection of tune. Collective effects, such as space charge, also produce resonance conditions [3]. Non-linear static magnetic elements are used for corrections in accelerators. For example, sextupole magnets are used for correcting chromaticity. However, the addition of sextupole elements to the lattice introduces third-order resonances. The resonance diagram shows all possible resonances within a lattice, allowing us to visualize the tune space. In the case of chromatic or collective effects, the tune-shift value is constrained based on the resonance conditions.

Conventional accelerators are designed using the uncoupled Courant-Snyder parameterization [2]. Coupling is typically treated as an error or well-controlled by design. There exist three well-known coupling parameterizations: Edwards-Teng [4], Mais-Ripken [5], and Lebedev-Bogacz [6]. A circular mode beam is a unique type of beam that is inherently flat and has non-zero angular momentum. The dominance of angular momentum in circular modes results in strong coupling within the beam. The intrinsic flatness of the circular mode can be easily converted to real-space flatness, highly desirable for specific applications, by decoupling the beam. However, the early stages of acceleration in rings are affected by space-charge effects in the low-energy region, where flat beams are not preferred. The use of circular modes with round beams at low energy is an attractive solution, enabling flat beams at higher energies through decoupling.

In this paper, we introduce coupling and circular modes expressed using the coupled beam optics formalism. We use both Mais-Ripken and Lebedev-Bogacz parametrizations for coupled beams. We also discuss the resonances arising from the use of high order magnets, such as sextupoles in coupled dynamics and the circular modes case.

COUPLED BEAM PARAMETRIZATION AND CIRCULAR MODES

The description of a single particle in a coupled system can be expressed in terms of the Lebedev-Bogacz parameterization. This parameterization introduces the eigenvectors of the system and expresses the single-particle coordinates as a combination of projections of eigenmodes. The phase space vector $\vec{z} = [x, x', y, y']^T$ is given by:

$$\vec{z} = \frac{1}{2}\sqrt{2J_1}(\vec{v}_1 e^{-i\psi_1} + \vec{v}_1^* e^{i\psi_1}) + \frac{1}{2}\sqrt{2J_2}(\vec{v}_2 e^{-i\psi_2} + \vec{v}_2^* e^{i\psi_2}), \tag{1}$$

where $J_{1,2}$ are the modes' amplitudes, $\psi_{1,2}$ are the initial eigenmode betatron phases, and $\vec{v}_{1,2}$ are the eigenvectors given as:

$$\vec{v}_1 = \begin{pmatrix} \sqrt{\beta_{1x}} \\ -\frac{i(1-u)+\alpha_{1x}}{\sqrt{\beta_{1x}}} \\ \sqrt{\beta_{1y}} e^{i\nu_1} \\ -\frac{iu+\alpha_{1y}}{\sqrt{\beta_{1y}}} e^{i\nu_1} \end{pmatrix}, \quad \vec{v}_2 = \begin{pmatrix} \sqrt{\beta_{2x}} e^{i\nu_2} \\ -\frac{iu+\alpha_{2x}}{\sqrt{\beta_{2x}}} e^{i\nu_2} \\ \sqrt{\beta_{2y}} \\ -\frac{i(1-u)+\alpha_{2y}}{\sqrt{\beta_{2y}}} \end{pmatrix}, \tag{2}$$

where $\beta_{1x}, \beta_{2x}, \beta_{1y}, \beta_{2y}$ are the four betatron functions, $\alpha_{1x}, \alpha_{2x}, \alpha_{1y}, \alpha_{2y}$ are the alpha or slope functions, $\nu_{1,2}$ are the phases of coupling, and u is the strength of coupling. The phases of coupling determine how eigenmodes project onto the real phase planes, and the coupling strength measures how dominant the coupling is in the lattice. The search for matched solutions for coupled optics is described in detail in [7].

* This work was supported by the U.S. Department of Energy, under Contract No. DE-AC02-06CH11357.
† ogilanli@hawk.iit.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP16

DEVELOPMENT OF HIGH TEMPERATURE OVENS FOR SOLID ION BEAM PRODUCTION AT FACILITY FOR RARE ISOTOPE BEAMS (FRIB)*

H. Cheng†, J. Guo, G. Machicoane, X. Rao, M. Hu, A. Plastun, L. Tobos, R. Rencsok, J. Backlas
Facility for Rare Isotope Beams, East Lansing, MI, United States

Abstract

Inductive ovens are integral to Electron Cyclotron Resonance Ion Source (ECRIS), facilitating the generation of high-intensity solid ion beams. At the Facility for Rare Isotope Beams (FRIB), specialized inductive High Temperature Oven (HTO) has been developed to ensure the stable, consistent, and reliable production of solid ion beams for the High-Power ECR (HPECR) ion source. These HTOs have successfully supported the operation of various solid ion beams, including Silicon, Nickel, and Uranium. In alignment with the FRIB beam power ramp-up objectives, future requirements will include increased beam currents and prolonged operational durations for more species. To optimize HTO performance in response to these evolving demands, a series of design improvements have been implemented, drawing on insights from previous operational experience. These improvements, which address the susceptor's thickness, length, and positioning, are intended to enhance both operational stability and beam consistency. The detailed improved design, ANSYS® simulation results, and testing results will be presented and discussed.

INTRODUCTION

With the ongoing advancement of modern heavy-ion accelerator systems, there is an increasing demand for ion sources capable of delivering high-intensity, high-quality, and high-charge-state ion beams to ensure the production of accelerated ion beams with sufficiently high energy. These beams are increasingly pivotal in various scientific domains, including nuclear physics, atomic physics, and other interdisciplinary applications [1–4].

A primary method for producing such high-quality ion beams is through super conducting Electron Cyclotron Resonance Ion Sources (ECRIS). To achieve stable and intense beam production, ECRIS systems require a metal vapor pressure of approximately 10^{-3} torr. This vapor pressure is contingent upon the temperature of the evaporant material, with specific temperatures necessary to attain the desired vapor pressures for various metals, 586 °C for Bismuth, 616 °C for Lead, 1371 °C for Nickel, 1896 °C for Platinum, and 2258 °C for Molybdenum [5]. To meet these stringent temperature requirements, inductively heated ovens has been employed to ensure the stable and high-intensity production of ion beams.

While previous studies have demonstrated the efficacy of inductively heated HTOs in the production of ^{238}U beams with UO_2 at approximately 2000 °C [6–10], it is necessary to extend this technology to support the production of a diverse array of solid ion beams. In this paper, key considerations in this development include the selection of appropriate susceptor materials, the optimization of susceptor thickness, and the determination of susceptor length. These factors are critical in achieving a wide range of temperatures and ensuring a uniform temperature distribution within the susceptor, thereby enhancing stability and intensity of ion beam production and enabling the production of various solid ion beams using a single inductively heated HTO.

OVEN DEVELOPMENT

The HTO comprises several integral components, including induction coils, a susceptor (crucible), thermal insulation, a water-cooling system, a heating station, and an alternating current (AC) power supply. Prior research has demonstrated the successful production of approximately 52 eμA $^{238}U^{35+}$ ion beams with UO_2 at an oven temperature of 2000 °C [6].

To ensure the stable generation of vapor from the HTO, maintaining a uniform temperature distribution inside the susceptor is essential. During a one-week test at 2000 °C with uranium dioxide contained in the oven susceptor, partial blockage of the susceptor's front nozzle was observed. This was attributed to the condensation of uranium vapor, which originated from within the susceptor. In the initial oven design, the temperature peaked at the center of the susceptor, leading to preferential vaporization of the material in this region. The resulting vapor flux was directed toward both ends of the susceptor, where it ultimately condensed and accumulated, particularly at the front nozzle. This accumulation caused nozzle obstruction, adversely affecting the stability of the ion beam produced by the source. To address this issue, a more uniform temperature distribution within the susceptor was deemed necessary. Design modifications were implemented in a revised version of the HTO, including adjustments to the susceptor length and the addition of ceramic rings to better secure the susceptor's position.

In addition to achieving a uniform temperature distribution in the oven susceptor, to achieve the objective of utilizing the inductively heated HTO for the production of various solid ion beams, it is imperative to attain a broad temperature range and precise temperature control within the desired operating region. This necessitates the exploration of different susceptor materials, such as tungsten, in addition to the original tantalum susceptor. Due to the inherent variations in electrical resistivity and magnetic permeability among

* Work supported by the U.S. Department of Energy, Office of Science, under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
† cheng@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP18

COMPUTATIONAL ANALYSIS OF MULTIPACTING ACTIVATION AND SUPPRESSION IN 325 MHz FPC *

H. Do [1,†]
[1]Institute for Basic Science, Daejeon, Korea

Abstract

A 325 MHz RF Fundamental Power Coupler (FPC) designed to operate under 20 kW CW in the high energy Superconducting Linac (SCL) of the RAON. One of the most important consideration in the FPC EM design is to reduce and eliminate a multipacting (MP) activation in both TW mode and SW mode. Prior to the MP reduction design, the MP bands of the FPC was computed with CST Particle Studio. It was confirmed that third or higher order of MP bands were activated within the operating range on the surface condition of the coupler. Therefore, designs to suppress MP are needed. To eliminate MP, a DC voltage was applied to centre conductor of the FPC. Detailed the simulation modelling and computational analysis results where MP was effectively suppressed for both modes are presented.

INTRODUCTION

Rare isotope Accelerator complex for ON-line experiments (RAON) is a heavy ion accelerator for basic science is under development in Daejeon, Korea [1, 2]. Three SCLs of the RAON are composed of three kinds of Superconducting Radio-Frequency (SRF) cavities. One of them is the Single Spoke cavity is operating at frequency of 325 MHz in the high energy SCL. The high energy SCL is comprised of two cavity variants, SSR type I and SSR type II. SSR type I has an optimum beta=0.3 and 8.5 MV/m of high accelerating gradient (E_{acc}) in CW mode. SSR type II is an optimum beta=0.51 and 8.7 MV/m of E_{acc}. SSR type I and type II are required operating power the under 7 kW and 20 kW, respectively when the RF power is fully reflected.

Generally, the RF coupler is extremely over coupled (coupling beta > 1000) with the SC cavity for stable RF control. However, when the high-intensity beams are accelerated in the SC cavity, load impedance varies widely from the matched to the fully reflected as the beam is loaded and unloaded. The coupler for superconducting cavities has to be tested in both TW mode and SW mode.

One of the most important consideration in the RF coupler design is to reduce and eliminate MP [3] activation. MP is an RF resonant discharge that produces in vacuum RF structure due to the secondary electron emission. The electron multiplication, MP is mainly enhanced by the combination of the RF field and the surface of the high Secondary Emission Yield (SEY) metal. When MP is activated on the inner surface of the coupler, the residual gas on the surface of the coupler is desorbed. This desorbed gas can be attached to the surface of the cavity, the cavity performance may be degraded.

When the RF power was applied to prototype RF coupler, the MP was observed to become active in the SSR type I operating range. A setup and these results of the high-power experiment are presented. Computational research was conducted to apply a DC offset to the FPC to reduce or eliminate the MP. Detailed simulation results using various DC offsets are provided. And also, a summary and future work are described.

RF EXPERIMENT ON TEST BENCH

A high-power experimental setup for 325 MHz RF FPC is shown as Fig. 1. A test bench consists of two couplers and a test chamber as shown in Fig. 2. One of the ends of the test bench (the 1st coupler side) was connected with a Solid State Power Amplifier (SSPA). A water cooled dummy load was installed for TW mode testing or a short circuit was installed for SW mode testing on the other side of the test bench (the 2nd coupler side). In addition, the RF length of the short was changed so that the amplitude of electric field could be the maximum and the minimum at the RF window.

RF power was immediately cut off even during continuous operation when the RF power cut-off criterion was met. The vacuum level (> 1E-6 mbar), the signal level of electron pickup probes, the signal of arc detector and temperature level (>330 K) were used as interlock signals for RF trips. A vacuum gauge was mounted to between the two couplers. The electron pickup probe and the arc detector were installed in near the RF window. Figure 2 shows eight temperature sensors were installed on the test bench to measure the temperature increase with applied input RF power: RF windows, test chamber, 4K intercepts, 40K intercepts. During these experiments, the cavity tripped several times due to the rise of the pressure and temperature in the RF coupler. The MP activation was observed, which was figured out by the signal measured in the electron pickup probe, the rapid increase of the vacuum level and the temperature level. Additionally, additional RF loss at the high-power dual directional coupler was measured. However, the arc signal was not detected during the experiment.

Figure 3(a) shows the temperature change at each point on the test bench measured with increasing the applied RF power at SW mode. In the 1st RF window, constructive interference occurred and the field value was maximized. And the field null with destructive interference was positioned in the 2nd RF window. The change in temperature rise generally increased with increasing input RF power. However, when the MP was activated, the temperature increased more than expected.

* Work supported by the National Research Foundation of Korea(NRF) funded by Ministry of Science and ICT (RS-2022-00214790)
† email address: hdo@ibs.re.kr

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP19

THE 120 kW SOLID STATE AMPLIFIER SYSTEM FOR THE FRIB RFQ*

E. Gutierrez†, E. Bernal, D. Morris, S. Zhao
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The FRIB RFQ runs in continuous wave mode at 80.5 MHz with input power up to 110 kW. Although reliability of the current tetrode amplifier has been greatly improved during commissioning and early operations, some potential failures may cause long repair time and compromise overall system availability. FRIB is commissioning a 120 kW solid-state RF amplifier system that uses the same 2 kW modules as FRIB linear segment 1. The paper will detail the design and commissioning of this system

INTRODUCTION

Facility for Rare Isotope Beams (FRIB) is a heavy ion linear accelerator (linac) facility that came online following the completion of technical construction in April 2022. The FRIB driver linac includes 6 room temperature cavities and 324 superconducting (SC) cavities (housed in 46 cryomodules). During the first three years of user operations, the FRIB complex has safely accelerated more than a dozen different primary beams ranging from ^{16}O to ^{238}U to beam energies ~200 MeV/u [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 the linear particle accelerator to accelerate ions to the proper specifications that can best match space radiation conditions.

A tetrode amplifier was originally chosen for the RFQ cavity due to the high RF power requirements. The tetrode amplifier was designed and fabricated based on in-house expertise of RF coaxial resonator amplifier systems from NSCL and the ReA3 accelerator. While overall FRIB RF system availability is around 98%, the tetrode amplifier has been one of the leading causes of downtime (high voltage power supply issues, RF fingers, water leaks).

The transition to solid-state technology is possible due to improvements in reliability and power density of solid-state transistors, and is necessary due to concerns of long term availability of vacuum tubes and the associated design expertise. The cost of ownership is reduced by using the same 2 kW amplifier modules as the linac amplifiers, which allows sharing of spares and standardizes maintenance procedures. The modularity of SSA technology reduces troubleshooting and repair time compared to the complex tetrode amplifier system. The transistors are biased at 48 V which eliminates the high-voltage power supplies and related issues.

THE DESIGN

The 120 kW solid-state amplifier system includes eight amplifier racks that can output 15 kW each into a matched load (Fig. 1). The design required an upgrade from four to six amplifier modules per rack, which required modifications to the power distribution unit, driver-control unit (DCU), and N-way power combiner. This was all handled by the supplier.

With the successful commissioning of two multi-rack, solid-state amplifier systems for the Multi-Harmonic Group Bunchers, and subsequent power upgrade to 30 kW, the FRIB RF group has gained the experience necessary to design and commission a solid-state 120 kW amplifier system for the RFQ [2].

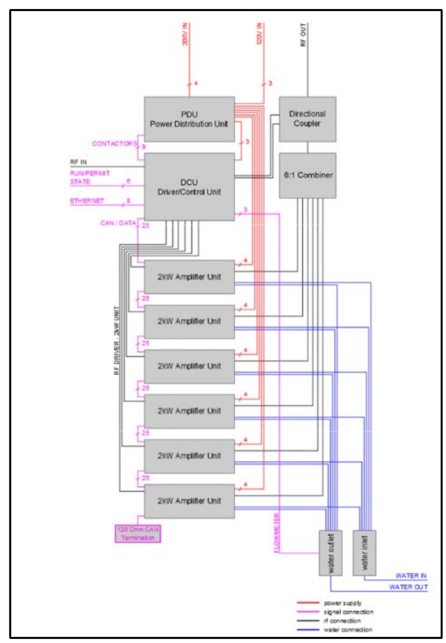

Figure 1: Amplifier rack system (TRUMPF Hüttinger GmbH + Co. KG).

The amplifier system uses 3 dB quadrature hybrid couplers in a 3-stage cascaded corporate power combiner scheme. The first stage combiners (4 in total) each sum the output of two racks. The second stage combines the two outputs from the first stage, essentially combining four racks into one output. The third stage combines two four rack systems into one output to reach the desired goal of 120 kW (Fig. 2).

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
† gutierel@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP21

STUDY ON PROPERTIES OF NEG DEPOSITED ON THE TITANIUM ALLOY LINED VACUUM CHAMBER

C.C. Li, J. Meng†, C. Luo
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China

Abstract

A ramping rate of 12 T/s is designed for the dipole magnet of BRing at HIAF. To reduce eddy current effects, a titanium alloy lined chamber with a titanium alloy inner liner by 3D printing and an 0.3 mm ultra-thin stainless steel outer wall has been adopted. To reduce the internal pressure and enhance the beam lifetime, a film of TiZrV is coated on the chamber.The ultimate vacuum of the titanium alloy-lined vacuum chamber is tested, which indicates that after coating with TiZrV, the pressure at the middle of the chamber reduced, effectively reducing the pressure in the central region. The life of the TiZrV film was studied by repeated venting and activation cycles under two conditions of N_2 or air filling. With N_2 filling, after 15 activation cycles, the pressure in the middle of the chamber showed no significant change. However, with air filling, after 7 activation cycles, the pressure in the middle degraded, indicating a decline in the pumping performance of the TiZrV film. Air exposure significantly impacts the life of the film, necessitating that TiZrV films should be protected with N_2 in applications and minimizing exposure time.

INTRODUCTION

In order to reduce gas desorption caused by particle bombardment to vacuum chamber, generate uniform pumping effect inside the slender and long vacuum chamber, and suppress dynamic vacuum effects, the method of coating the inner surface of the vacuum chamber with NEG film is widely used internationally. Among them, TiZrV film can be fully activated by vacuum baking at 180 ℃ for 24 hours, and the activation temperature meets the maximum baking temperature allowed by the vacuum chamber made of common accelerator materials [1, 2]. It is widely used in accelerator at home and abroad. The ramping rate of the dipole magnet of BRing in the new generation particle accelerator named HIAF is 12 T/s [3]. To reduce eddy current effects, IMP adopts a new structure of 0.3mm titanium alloy lined thin-walled ultra high vacuum chamber as the dipole vacuum chamber (see Fig. 1). The total length of the vacuum chamber is about 3.3 meters, consisting of some titanium alloy rings and a stainless steel thin-walled shell. The titanium alloy ring is made by 3D printing.

The conventional pumping scheme is installing sputtering ion pumps and titanium sublimation pumps on both sides of the dipole vacuum chamber. The pumps are far away from the middle of the dipole vacuum chamber, resulting in poor pressure in the middle and unable to meet the beam life requirements. By using magnetron sputtering coating technology with solenoid, TiZrV films are deposited onto the surface of a titanium alloy lined vacuum chamber to generate uniform pumping effect, reduce pressure gradient, and improve beam quality and life.

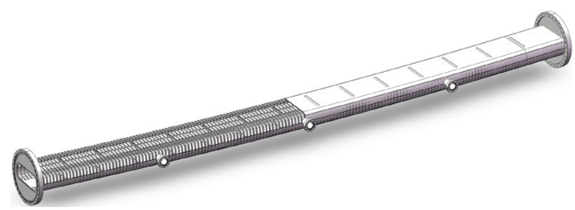

Figure 1: The model of titanium alloy lined vacuum chamber.

EXPERIMENTS AND RESULTS

Build a coating platform with solenoid to deposit TiZrV film on the surface inside the vacuum chamber [4]. The coating parameters are: discharge current of 0.2 A, discharge voltage of 500 V, working pressure of 1Pa, magnetic field intensity of 220 Gauss, and coating duration of 10 hours. Figure 2 is a image of glow discharge.

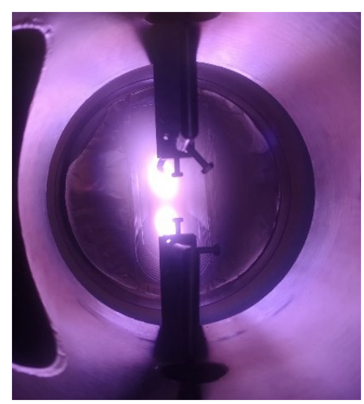

Figure 2: Glow discharge.

The surface morphology of TiZrV film was analyzed by SEM (see Fig. 3), and the results showed that the film morphology is located in the T zone (transition zone) [5], which is a dense and highly anisotropic columnar structure with good pumping performance. EDS was used to analyze the composition of TiZrV film (see Fig. 4), and the results showed that the prepared film had a Ti, Zr and V composition ratio (Ti:Zr:V=33.68%:21.24%:45.08%) located in the "low activation temperature zone" [6], with a low activation temperature and can be activated at 180 ºC.

†mengjun@impcas.ac.cn

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP23

DESIGN AND OPERATIONAL EXPERIENCE OF FRIB MAGNET AND ELECTROSTATIC POWER SUPPLIES *

K. Holland†, R. Bliton, A. Kohler, L. Nguyen
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

This paper will present design principles, procurement strategies, installation and testing plans, and availability data from commissioning and operation of over 1500 magnet and electrostatic power supplies at the Facility of Rare Isotope Beams (FRIB). This paper introduces the types of power supplies required for the FRIB which range in size from electrostatic high voltage power supplies less than 1 Watt to 150 kW magnet power supplies. The power supplies range in complexity from simple single quadrant units to four-quadrant pulsed electrostatic high voltage units to units requiring complex auxiliary equipment. Stability requirements of these power supplies range from 10 ppm for some sensitive experimental equipment to 3000 ppm for some multipole magnets.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a heavy ion linear accelerator (linac) nuclear physics research facility with fast, stopped, and reaccelerated rare isotope beams. The facility has been performing user experiments since May, 2022 [1], prior to this, staged beam commissioning started in 2017 and continued until January 2022 [2].

In total there are over 1500 power supplies (PS) in oprations at FRIB. Based on experience from commissioning and the first years of operations, this paper consists of five sections describing (i) design principles, (ii) procurement strategies, (iii) PS testing, (iv) availability, and (v) ongoing tasks.

DESIGN PRINCIPLES

The FRIB PS design is based on the flow down of functional requirements. To ensure high availability, while not arbitrarily driving up costs, the FRIB requirements include the flow down of field margin from Beam Physics, to Magnets, and finally to PS. This is important as adding margin to the current requirement for a magnet that is operating in saturation could result in much lower magnetic field margin. To further ensure high reliability, operational margin is added to the PS voltage and current for commercial off the shelf (COTS) PS (minimum 10 % each for 5 year warranty), or included in speciation for build to spec PS.

To ensure the best overall value for the magnet and PS systems, the PS requirements were optimized with stakeholders from Accelerator Physics, Magnet Engineering, and PS Engineering. The number of different types of magnets and power supplies was minimized, allowing for common spare parts, minimizing technical risk, labor risks, and life-cycle costs. PS types were further reduced by using modular topology, as shown in Fig. 1, with different numbers of modules in series or parallel, and different auxiliary equipment required to meet the requirements of each specific magnet. When compared to large standalone units that require repair in place, the modular PS reduces the mean-time-to-repair (MTTR) during failures as the faulted module can be swapped out fairly quickly, then repaired and tested off-line.

Figure 1: Modular type SCM PS.

The room temperature dipole magnet (RTDM) PS in Folding Segment 1 (FS1) and the Beam Delivery System (BDS) were optimized by serial magnet connection with higher voltage PS. This relaxed the ripple, stability, and machine protection system (MPS) threshold requirements by an order of magnitude. Trim coil magnets PS were installed, to provide some adjustment to compensate for alignment.

The four FS1 dipoles require a switch to allow 3 operating modes: (i) With the PS off, pass straight through to the first beam dump. (ii) With the first dipole energized to allow beam to bend and the second dipole off to allow beam to pass through to the second beam dump. (iii) With all four dipoles energized to pass beam to Linac segment 2 (LS2).

The FE electrostatic (e)-dipoles interface with both PPS (Personnel Protection System) and MPS, to prevent beam from entering the linac tunnel. PPS is done through

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
† holland@frib.msu.edu

16th International Conference on Heavy Ion Accelerator Technology, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP24

FEASIBILITY STUDY OF PLASMA PROCESSING FOR THE FRIB ENERGY UPGRADE 5-CELL SUPERCONDUCTING CAVITY*

Y.-L. Cheon†, W. Hartung, S. Kim, P. Tutt, T. Xu
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

A 5-cell medium-velocity elliptical superconducting radio-frequency (SRF) cavity (644 MHz, $\beta_{opt} = 0.65$) is being developed at Michigan State University for the proposed FRIB driver linac energy upgrade. The coupling strength of the fundamental power coupler (FPC) is relatively weak ($Q_{ext} = 2 \times 10^7$) and the cavity is not equipped with higher-order mode couplers, as the upgrade FRIB linac will be operated in the constant-wave (CW) mode with <1 mA beam current of heavy ions. A key challenge for future maintenance will be to perform effective plasma processing while avoiding plasma ignition in the FPC region, as FPC ignition could lead to copper sputtering onto the niobium cavity surfaces or damage to the FPC ceramic window. We examined the feasibility of plasma processing by driving higher-order modes through the FPC. With a combination of TE_{111} passband modes, we were able to generate plasma in every cell without FPC ignition. We measured the resonant frequency shift as a function of input RF power and drive frequency shift to find the maximum plasma density and FPC ignition thresholds. We applied hydrocarbon contamination to the inner surface of a 5-cell cavity and removed it with plasma cleaning, while monitoring the reaction by-products with a residual gas analyzer.

INTRODUCTION

Plasma processing of superconducting radio-frequency (SRF) cavities to remove hydrocarbon contaminants can be performed in-situ in accelerators to reduce field emission by lowering the work function of the niobium [1, 2]. Plasma processing methods for several types of multi-cell elliptical cavities have been developed. The first efforts were applied to 6-cell cavities at the Spallation Neutron Source (SNS), driving fundamental mode (FM, 805 MHz) RF power via the fundamental power coupler (FPC) [3, 4]. Fermilab partnered with SNA and SLAC to develop higher-order-mode (HOM) plasma processing for 9-cell cavities for LCLS-II [5, 6]. The use of HOM couplers was necessary in this case as the FPC coupling strength for LCLS-II was much weaker ($Q_{ext} = 4 \times 10^7$) due to continuous-wave (CW) operation at low beam current (< 0.3 mA), compared to the other pulsed machines. Jefferson Lab developed plasma processing for CEBAF cavities, driving the TE_{111} HOM through the FPC or HOM coupler [7].

* Work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the FRIB Operations, a DOE Office of Science User Facility under Award Number DE-SC0023633.
† cheon@frib.msu.edu

The FRIB energy upgrade (FRIB400) will require a 5-cell elliptical cavity (644 MHz, $\beta_{opt} = 0.65$) with an adjustable FPC ($Q_{ext} = 7.7 \times 10^6$ to 3.4×10^7) without HOM couplers. Even at the lowest Q_{ext}, the FM is not effective to generate plasma inside the cavity without ignition in the FPC due to large mismatch of the FM at room temperature. The TE_{111} HOM passband is suited better to drive the plasma, as it has the least FPC mismatch. A plasma processing method for the FRIB400 cavity has been developed using a full FPC assembly, including both cold and warm windows and the thermal transition between them.

PLASMA PROCESSING DEVELOPMENT

RF and Gas System

A schematic of the RF system for plasma process development is shown in Fig. 1. The low-level RF power from the signal generator is amplified by a broad-band amplifier (red). Two vector network analyzers (with output power ~20 dB lower than that of the signal generator) monitor the resonance frequency shifts for the TE_{111} passband (used to drive the plasma and infer the plasma density) and the TM_{020} passband (used to infer the plasma location). We anticipate that monitoring TM_{020} passband will be necessary to know which cell is ignited for future in-cryomodule processing, where we will be unable to see the plasma light though the viewports. The dc currents from the FPC and pickup antennas are monitored via bias T's. We observe a spike in the FPC current in the case of FPC ignition; this allows us to set up a software interlock which opens an RF switch to turn off the drive power if the FPC ignites from the plasma.

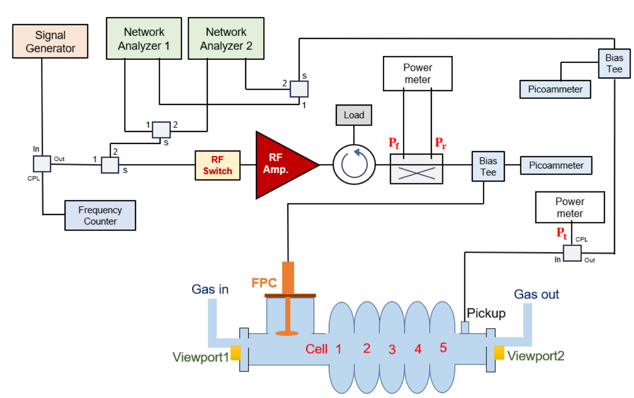

Figure 1: Schematic of the RF system for plasma processing of a FRIB400 5-cell cavity with FPC.

Figure 2 shows the plasma processing setup with the gas supply and vacuum systems. We used an 80% argon / 20%

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP25

HIGH RESOLUTION CURRENT CONTROL FROM SWITCHED MODE POWER SUPPLY*

D. Novak†, K. Bunnell, C. Dickerson, S. Klohe, S. Kumar, D. Santiago-Gonzalez, D. Stanton
Argonne National Laboratory, Lemont IL, USA

Abstract

The Argonne Tandem Linac Accelerator System (ATLAS) has been a National User Facility since 1985. Since the commissioning of the Californium Rare Isotope Breeder Unit (CARIBU) in 2012, it has used 2 bespoke water-cooled linear power supplies to allow for milliamp control of the isobar separator magnets, which allows for milligauss control of the magnets. During the upgrade to nuCARIBU, the aging linear power supplies were replaced with off-the-shelf (OTS) switched mode power supplies (SMPS). The benefit of the SMPS is higher efficiency, lower cost, and since they are air-cooled, no load on the water cooling infrastructure. The limitation of the SMPS is a decrease in resolution in current control. To overcome this limitation, a device was constructed that allows control of a sub-milliamp constant current sink, which is placed in parallel to the magnet. This arrangement allows the control system to “leak” a precise amount of current away from the magnet, effectively giving sub-milliamp control of the current going into the magnet.

INTRODUCTION

The CARIBU, Californium Rare Isotope Breeding Unit, facility at Argonne ATLAS was commissioned in 2012, and has been providing low intensity, high purity, and neutron-rich beams for re-acceleration through ATLAS. Due to issues with the procurement of Californium, it was decided to replace the Californium source and cask with a compact proton cyclotron. As a proton source, the cyclotron has the advantage of being a more reliable source of fission products, a higher overall fission rate, and easier to maintain and operate since it can be shut off [1].

BACKGROUND

CARIBU was designed with a compact high-resolution isobar separator [2, 3], which requires precise control of the magnetic field. This was previously achieved with a pair of bespoke linear power supplies, which operated with 6-digit current resolution, between 0 and 335 Amps in constant-current mode. As these power supplies aged, they began to require more and more maintenance, until they got to the point where they could no longer be controlled remotely. The original manufacture had been sold, and the new owner no longer supported the power supplies. When it came time for the nuCARIBU upgrade, it was decided to replace the power supplies for the isobar separator magnets [4].

Off-the-shelf SMPS were deemed an acceptable replacement for the bespoke supplies. SMPS power supplies have a number of benefits when compared to linear power supplies. SMPS power supplies operate at a much higher efficiency, requiring only air cooling, where as the linear supplies required water cooling. This reduces stress on the cooling systems in ATLAS, as well as reducing maintenance of the power supplies. The SMPS are off-the-shelf components from TDK-Lambda that are still in production and are well supported. The SMPS supplies operate at a much lower temperature, extending their useful lifespan. Due to the low cost from the economies-of-scale, it is economical to have spare supplies on-hand.

The downside of off-the-shelf SMPS is the finite output resolution across the product range. In basic SMPS designs, the output is controlled by the switching frequency and/or duty cycle of the switched element, but generally it is the duty cycle that controls the output. The duty cycle is digitally controlled by a Pulse Width Modulator, PWM, controller which is a peripheral of a micro-controller. Being digitally controlled, the PWM has a finite number of steps between minimum and maximum pulse-width. This finite number of steps defines the resolution of the power supply. To achieve economies of scale as well as the re-use of the control interface software, power supply makers will tend to re-use the digital part of the design across a broad range of power supplies. So power supplies capable of 50 Amps, will have the same number of output steps as supplies capable of 250 Amps. In other words, as voltage and current output increases, accuracy decreases due to the fixed number of steps in digital sub-system. Similar to the output, the read back channels also suffer from a fixed number of steps in the Analog to Digital Converter, ADC, used in the measurement side of the power supply. This means that the accuracy of voltage and current measurement goes down as output capability increases.

ISSUE

The magnetic field produced must be controlled to account for variations in the conditions of the CARIBU hall. The largest single influence on the magnets, and thus the field, is the water cooling system used by the magnets. The temperature of the cooling system water fluctuates, which affects the field. To account for these changes, a control loop is used within the control system to keep the field strength as constant as possible. As a result of the limitations of the SMPS supply, the algorithm to control the magnetic field had to be adjusted. This was mainly due to the current control resolution. The SMPS power supply is

* This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357. This research used resources of ANL’s ATLAS facility, which is a DOE Office of Science User Facility.
† dnovak@anl.gov

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP27

ASSESSMENT OF MAGNETIC QUADRUPOLE PICK-UP STRUCTURE AT FRIB*

C.A. Sarabia-Cardenas†, S.M. Lidia, P.N. Ostroumov,
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

A magnetic quadrupole pick-up structure is being assessed for creation and future use at The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU). The geometric design makes use of magnetic loops that couple with the radial magnetic field of a beam, allowing for rejection of the beam intensity signal of the beam, while leaving the dipole signal as the dominant signal and enhancing the quadrupole signal. Of interest is examining the response due to the multiple charge state heavy ion beams that FRIB produces and the ability to resolve the differing charge states. Presented here is the optimization of the device for the FRIB beamline.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) produces high intensity heavy ion beams of varied species and charge states [1]. Measurement of the beam's quadrupole moment is being investigated to characterize the transverse rms beam sizes and evaluate Courant Snyder parameters for proper matching in critical sections in the linac. There are a number of interceptive methods to capture the quadrupole moment, like wire scanners or viewers, but intercepting methods take a long time to evaluate the beam parameters in the phase space. In addition, non-destructive methods can be used during high-beam-power operations to assess beam envelopes in real time.

Non-destructive methods for estimating the quadrupole moment of the transverse beam distribution have existed since 1966 [2] using beam position monitors (BPMs), a standard diagnostic device of which there are many placed all throughout the LINAC sections in the FRIB beamline [3]. However, the usual design of an electrostatic position pick-up as a BPM generates very low signal corresponding to a quadrupole moment measurement. Electrostatic BPMs are largely optimized for linear response to beam displacement, while the quadrupole moment is measured from the quadratic term in beam displacement, leading to small signals. There have been efforts to make significant changes to BPM geometry and increase sensitivity to quadrupole components [4], but complicated electrode geometries pose their own challenges.

The method presented here instead is a magnetic quadrupole pick-up, which boasts a simpler geometry and the ability to supress the common mode of the beam, making the dipole and quadrupole signals of the beam much stronger and more easily measurable.

Preliminary work is being done to develop this device for FRIB based on the success that similar pick-ups have enjoyed at facilities like the CERN PS [5], though this device will be distinct and differently optimized, based on the needs of FRIB.

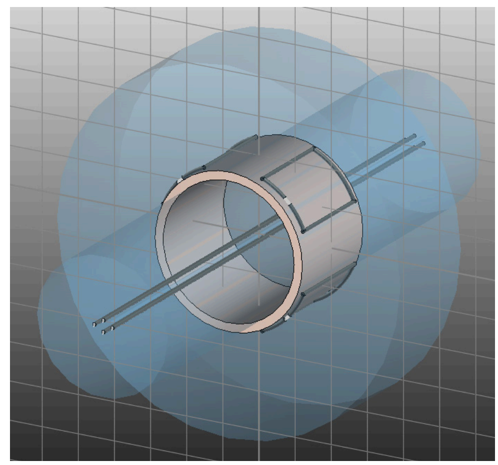

Figure 1: A 3D model of the magnetic quadrupole pick-up structure modelled in CST Studio Suite. The four wires at the center are a simple beam model.

PICK-UP DESIGN

The magnetic quadrupole pick-up structure, shown in Fig. 1, is designed with four wire loops at 45° angle to the horizontal plane. These loops are placed just outside a ceramic vacuum tube to interact with the beam's magnetic fields while avoiding issues of the loops being vacuum compatible or needing feedthroughs. The entire structure is placed inside a pillbox cavity to maintain the continuation of wall currents through the structure. Additionally, the radius of the pillbox should be at least twice that of the beam pipe so that the conducting walls of the pillbox do not interfere with the magnetic flux through the wire loops. The wire loops are oriented as shown in Fig. 1 to couple only with the radial component of the beam's magnetic field. To see this, the magnetic field of the beam is expressed in cylindrical coordinates as [5]:

$$\vec{B}(\rho,\theta) = -I\frac{\mu_0}{2\pi}\Big[\frac{1}{\rho}\,\hat{\theta} + \bar{x}\left(\frac{\cos\theta}{\rho^2}\hat{\theta} - \frac{\sin\theta}{\rho^2}\hat{\rho}\right) + \bar{y}\left(\frac{\sin\theta}{\rho^2}\hat{\theta} + \frac{\cos\theta}{\rho^2}\hat{\rho}\right) + \kappa\left(\frac{\cos 2\theta}{\rho^3}\hat{\theta} - \frac{\sin 2\theta}{\rho^3}\hat{\rho}\right) + \cdots\Big], \quad (1)$$

where κ is itself the quadrupole moment that is of interest to measure and is given by:

$$\kappa = \sigma_x^2 - \sigma_y^2 + \bar{x}^2 - \bar{y}^2, \quad (2)$$

*This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award Number DE-SC0025531 and Office of High Energy Physics, under Award Number DE-SC0018362
†sarabiac@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP29

CALIBRATING THE FRIB CHOPPER MONITOR*

J. Hartford†, E. Bernal Ruiz, M. Ikegami, Z. Li
Facility for Rare Isotope Beams, East Lansing, MI, USA

Abstract

At FRIB, a chopper in the low energy beamline is used for beam duty factor control as well as beam mitigation for machine protection. The chopper requires power to be applied to stop beam, which makes it non-failsafe. As such, monitoring the health of the entire chopper system is paramount, ensuring that: the chopper is functioning properly, undesired high-power beam will not be delivered downstream, and high-speed beam mitigation is available when requested. To ensure the functioning of the chopper system, a chopper monitor has been developed and has been in use to support operation in FRIB. In supporting its operation, it has been identified that particular attention must be paid to the calibration of the chopper monitor system. In this paper, we present the established calibration methodology for the chopper monitor system together with the associated analytical processes.

INTRODUCTION

The FRIB linac has a chopper in its low-energy beam transport [1] to generate a pulse structure in the heavy ion beam by deflecting a temporal portion of it with a transverse electric field. The deflected beam is intercepted with a downstream beam absorber. The chopper is used to 1) generate a regular notch (beam-off period) for beam diagnostics systems, 2) generate pulsed beams for beam tuning, and 3) mitigate the beam at an interlocked event for machine protection.

The chopper system has two deflecting plates to which the high voltage (HV) is applied by HV power supplies through HV switches. The FRIB Global Timing System (GTS) provides a beam pulse structure signal to the chopper monitor. The chopper monitor receives feedback signals from the HV switches representing the connected voltage level and the outgoing/incoming electric charge flow rate (current) (see Fig. 1).

The GTS signal, voltage levels, and outgoing/incoming charge flows are all compared to their expected values to ensure that the process is proceeding properly. Charge flow monitoring is seen as the primary indicator of system health due to it being a variable related to both voltage applied and load connected, informing the monitor that the chopper is connected and functioning. The chopper monitor, should it detect an issue with any of the monitored parameters or receive a beam mitigation request from the FRIB Machine Protection System (MPS) [2], quickly latches the chopper in the beam blocked state until operators intervene.

* Work supporting the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan and Michigan State University.
† hartforj@frib.msu.edu

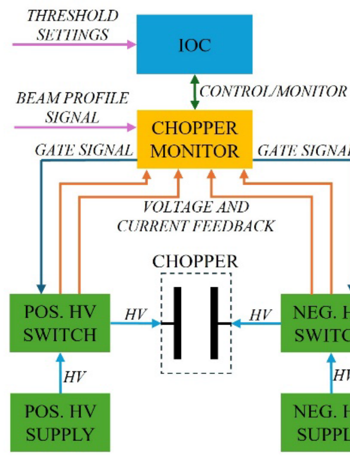

Figure 1: The basic chopper system.

The chopper monitor is a field programmable gate array (FPGA)-based system interfaced with the MPS, and utilizing an input/output controller (IOC) for the operator interface [3]. The IOC displays GTS signal parameters, HV level readings, and outgoing/incoming charge readings from the chopper monitor and sends to it trip thresholds. Due to the reality of integrating between the different components of the chopper system, data is represented in varying ways, requiring that a careful calibration be conducted to translate between these representations.

DATA TRANSLATION

The readback and threshold data are represented in three different ways as they move through the system (see Fig. 2).

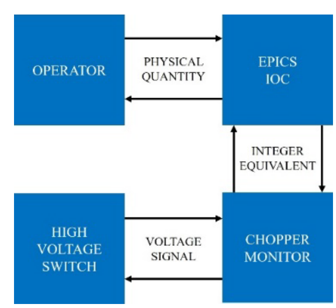

Figure 2: Varying data representations.

At the lowest level, between HV switch and chopper monitor, the data takes the form of a variable voltage. This voltage is received into the chopper monitor by way of analog-to-digital converters (ADCs). The low voltage signal representing HV level is received directly by an ADC while the low voltage signal representing current is first passed through an integrator circuit before being received by the ADC so that the ADC outputs a measurement of charge rather than current [3]. This conversion, from voltage level to its integer equivalent, is fixed and based on the ADCs.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-TUP30

SUPERCONDUCTING MULTIPOLE TRIPLETS MAGNETS COMMISSIONING FOR THE S^3 SPECTROMETER AT GANIL / SPIRAL2

M. Aburas[1,2], M. Authier[2], G. Brunet[1,3], F. Carville[1,2], G. Dilasser[2], F. Esnault[1,2], B. Haize[1,3], T. Lefrou[1,3], F. Lutton[1,3], H. Savajols[1,3], M-H. Stodel[1,3], G. Tocabens[3], A. Wagret-Quatromme[1,3]
[1]Grand Accélérateur National d'Ions Lourds (GANIL), Caen, France
[2]Commissariat à l'énergie atomique et aux énergies alternatives (CEA-IRFU), Gif-sur-Yvette, France
[3]Centre National de la Recherche Scientifique (CNRS-IN2P3), Orsay, France

Abstract

The “Super Separator Spectrometer” project S^3 is under technical commissioning at the GANIL facility (Caen-France). It is a new research installation designed for fundamental physics experiments with high intensity heavy ions beams produced from the SPIRAL2 linear accelerator. This spectrometer will open new horizons for nuclear physics. The S^3 spectrometer is made of seven Superconducting Multipole Triplets (SMT) to guide and focalize the beam and select the particles of interest.

This paper presents SMTs technology and their magnetic, electrical and cryogenic operating characteristics as well as their technical commissioning for the S^3 project.

S^3 SUPER SEPARATOR SPECTROMETER

S^3 Project aims to push the boundaries of nuclear physics by enabling the study of unstable nuclei and super heavy elements, particularly those beyond 104 in the periodic table [1]. The design of the primary target is optimized for fusion-evaporation production. **S^3** is a two-stage optical structure combining a large acceptance momentum achromat and a high-resolution mass separator (Fig. 1). Each stage includes 2 dipoles and 4 multipoles triplets. These multipoles are superimposed superconducting quadrupoles, sextupoles, octupoles and steerers mounted by 3 singlets in a SMT**.**

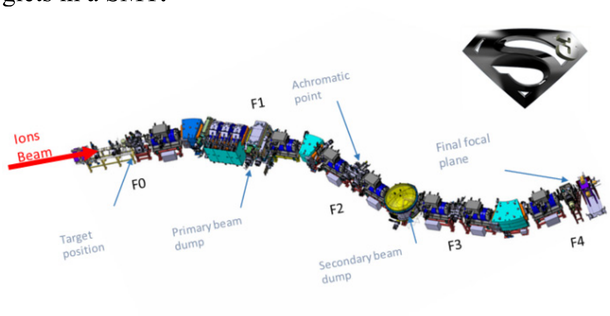

Figure 1: S3 Spectrometer.

Seven SMTs, 3 room temperature Dipoles, 3 open quadrupoles and 1 electric field dipole will allow **S^3** to achieve high transmission and high resolution in mass to charge ratio for scientists. **SMTs** (Fig. 2) are superconducting iron-free magnets designed to generate high-purity multipolar magnetic fields [2]. Each triplet is composed of three sets of independent singlets of multipoles assembly: quadrupoles, sextupoles, octupoles and steerers, allowing precise control of the magnetic field (Fig. 3).

SMT

Figure 2: SMT (CMI).

The multipole magnets were developed by AML [3] and their integration into the cryostat was perform by CMI [4].

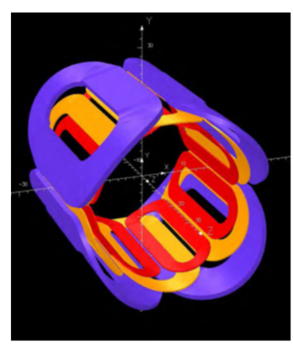

Figure 3: Coils of a singlet.

All the coils are made from NbTi superconducting wire with 5.6 K critical temperature at 2,65 T peak and a critical current of 597 A at 4.2 K The winding technic is based on Walstrom type coils and all high order harmonics are near zero. The maximum total energy stored in an **SMT** is 165 kJ (mainly in quads) and the system is designed to discharge quickly and safely in the event of a quench. The top current leads are high-temperature conduction-cooled superconductors with LN2 (top) and LHe (bottom). These HTS are made with BSCCO (Bi2223) and YBCO tapes for flexibility.

Each SMT is powered by a Power Supply System. A **PSS** consists of 8 power supplies (PS), a Magnet Safety System and a computer-based control system. There are 8 PS (one 100 A, three 600 A and four 400 A) for the 11 magnet

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEX01

STATUS OF HIGH PERFORMANCE ECR ION SOURCES: ACHIEVEMENTS AND PERSPECTIVES

L. Sun[1, 2†], H. W. Zhao[1,2]
[1]State Key Laboratory of Heavy Ion Science and Technology, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China
[2]School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing, China

Abstract

The demand for high-intensity (0.5–1.0 emA) highly charged heavy ion beams continues to grow among next-generation heavy ion accelerator facilities worldwide, yet their production remains a significant challenge in the field. Electron Cyclotron Resonance (ECR) ion sources, recognized as the most powerful technology for generating such beams, have been widely adopted by major heavy ion accelerator facilities globally, driving continuous advancements in this domain. Despite more than five decades of development since the first ECR ion source prototype was introduced, these sources remain at the forefront of high-charge-state and high-intensity ion beam production. This paper reviews the latest advancements in high-performance ECR ion sources, focusing on four key areas: (1) the development of new ion source designs, (2) high-performance operational achievements, (3) emerging technologies in the field, and (4) future prospects for delivering high-intensity beams for heavy ion accelerators.

INTRODUCTION

Heavy ion science plays an indispensable role in both fundamental research and societal applications. Heavy ion beams have served as essential tools for advancing our understanding of nuclear structure, synthesizing over a thousand new isotopes, and discovering dozens of new elements. Beyond fundamental science, heavy ion technology has significantly impacted industry and medicine. For instance, heavy-ion therapy systems worldwide have demonstrated remarkable efficacy in treating cancer, while nuclear track membrane [1] production—a rapidly growing industry—relies heavily on heavy ion accelerators. Additionally, single-event effect (SEE) studies enable critical advancements in space exploration [2]. To generate energetic heavy ion beams, heavy ion accelerators have undergone continuous development over the past 80 years. Among the key requirements for efficient acceleration is the production of highly charged ion beams. This demand has driven the invention of various ion sources, including Electron Cyclotron Resonance (ECR) ion sources, Electron Beam Ion Sources (EBIS), and Laser Ion Sources (LIS). Notably, ECR ion sources have proven unparalleled in delivering high-current, high-charge-state ion beams, solidifying their dominance in the field.

The ECR ion source was first proposed and prototyped by Richard Geller in the 1970s [3]. Over the past five decades, hundreds of such devices have been deployed worldwide, serving both scientific facilities and practical applications. The growing demand for high-performance heavy ion beams—particularly in power frontier projects like superconducting radiofrequency (SRF) linacs (e.g., FRIB) and intensity frontier programs such as synchrotrons (e.g., HIAF)—has driven the need for more advanced ECR ion sources. An ECR ion source operates by generating plasma through microwave heating within a min-B magnetic confinement structure. The interaction between microwave radiation and the magnetic field configuration critically determines the source's performance. Over the years, empirical scaling laws have been established to summarize the fundamental principles governing ECR ion sources, providing essential guidance for their continued development.

Guided by scaling laws, achieving high-performance ECR ion sources necessitates operation in high magnetic field (high-B) and high microwave frequency regimes. Superconducting ECR ion sources, which leverage the strong magnetic fields generated by highly excited superconducting coils, have emerged as the most promising solution for producing high-performance, highly charged ion beams. The first prototype of such a system, the SERSE ion source [4], was jointly developed by LNS-INFN and CEA-Grenoble in the late 1990s. Subsequently, modern high-performance superconducting ECR ion sources optimized for 24–28 GHz microwave frequencies were pioneered—most notably by the VENUS source (LBNL, 2002) [5], and the SECRAL source (IMP, 2005) that introduced a novel reserved magnetic configuration [6]. Further advancements were achieved with the SuSI source (MSU) [7] and the SCECRIS source (RIKEN) [8], diversifying the landscape of high-performance ECR ion sources. Despite these successes, challenges persist in extending ECR ion sources to high-power, high-current heavy-ion beam applications. This paper reports recent progress in addressing these challenges and discusses future perspectives for ECR ion source development.

NEW HIGH PERFORMANCE ECR ION SOURCES

In recent years, numerous high-performance ECR ion sources have been proposed, developed, or commissioned for routine operation. These ion sources—primarily designed for new heavy-ion accelerator facilities or upgrades of existing accelerator systems —are universally optimized to deliver high-charge-state heavy-ion beams with exceptional intensity. Their development has become critical to

†sunlt@impcas.ac.cn

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEX05

MEASUREMENT OF FORWARD-DIRECTED NEUTRONS GENERATED BY AN INVERSE KINEMATIC REACTION USING INCIDENT $^7Li^{3+}$ BEAM

T. Sakabe[1,†], A. Cannavo[1], G. Ceccio[5], M. H. Gamage[2], S. Ikeda[1], T. Kanesue[1], J. Kohl[6], M. Okamura[1,3], B. Schmitz[6], A. Smushkin[6], K. Takahashi[4], P. Zitzmann[6]
[1]Brookhaven National Laboratory, Upton, New York, USA
[2]Columbia University, New York City, New York, USA
[3]Institute of Science Tokyo, Tokyo, Japan
[4]Nagaoka University of Technology, Niigata, Japan
[5]Nuclear Physics Institute of the Czech Academy of Science, Husinec, Czech Republic
[6]Technische Universität Darmstadt, Darmstadt, Germany

Abstract

We are developing an accelerator-based neutron source using the inverse kinematic reaction between an energetic lithium-ion and a proton target. This reaction can achieve a naturally collimated neutron beam. Our group has proposed a compact neutron source with an intense lithium-ion beam, which can supply a converged neutron flux. The present study aims to investigate the angular distribution of neutrons produced by the inverse kinematic reaction. The neutron measurement experiment was conducted by making a collision between a lithium-ion and a polypropylene target at the Tandem Van de Graaf accelerator at BNL. Throughout the experiment, a large concentration of neutrons was observed in the forward direction, which agrees well with the feature of the inverse kinematic reaction.

INTRODUCTION

Neutron techniques are used in many fields due to their unique properties. They support non-destructive tests for the structure [1], composition [2], and imaging [3]. Neutrons also help produce isotopes by activating some elements [4, 5]. Various neutron sources are used depending on neutron beam requirements. Examples include radioactive isotopes, reactors, and accelerators. Each neutron method is designed to fit its specific application. Compact accelerator sources are gaining attention these days because they are easier to use and cheaper than large-scale facilities. Most traditional sources use proton beams with lithium or beryllium targets. However, such reactions emit neutrons in all directions. Many neutrons are wasted, and unwanted radiation occurs near the target. To resolve this issue, a neutron source using the inverse kinematic reactions was proposed [6, 7].

In the inverse kinematic scheme, a lithium beam is used instead of a proton beam. Neutrons can be focused in the forward direction thanks to the momentum of the heavier lithium beam compared to the proton target. This forward beam forms a narrow cone of neutrons. The cone becomes sharper near the reaction threshold energy (13.098 MeV [7]). It also increases neutron flux in the forward direction. As a result, radiation in other directions is reduced. This can lower the shielding needs of the facility. Hydrogen-rich targets like plastics or metal hydrides are suitable. One major limitation of the inverse kinematic scheme is the lithium ion beam current. Conventional accelerators typically reach peak currents of up to 100 μA, limiting neutron applications. Due to this limitation, prior studies on the inverse kinematic scheme are limited.

A compact accelerator-based neutron source utilizing an intense lithium-ion beam has been developed by our group at Brookhaven National Laboratory (BNL) to overcome conventional limitations. A peak pulsed current of 35 mA for the $^7Li^{3+}$ ion current was achieved using a laser ion source [8]. This advancement offers the potential for broadening the scope of neutron applications with a lithium-beam-driven neutron source. As the achieved beam energy is 1.43 MeV and remains below the reaction threshold, further post-acceleration is required. The system development is currently underway.

This study aims to experimentally characterize the angular distribution of neutrons from the inverse kinematic reaction over a range of 0 to 135 degrees for future applications. For this purpose, the Tandem Van de Graaf accelerator at BNL [9] was used to utilize an energetic lithium-ion beam. The accelerator system realized collisions between lithium ions and protons in a polypropylene target that was installed at the end of the beam line. The liquid scintillators were placed around the target chamber to investigate the angular distribution of neutrons. A shadow cone [10, 11], which was made of a low-carbon steel and borated polyethylene, was used to evaluate the contribution of scattering neutrons to the liquid scintillator measurement. The present paper reports the angular distribution of neutrons from the inverse kinematic reaction based on the measurement data by the liquid scintillators.

METHODOLOGY

Table 1 shows the experimental conditions. An incident $^7Li^{3+}$ ion beam was provided by the Tandem Van de Graaf accelerator at BNL. A polypropylene target was installed at the end of the beam line. A belt-conveyor-type of polypropylene target was adopted for the present experiment, as shown in Fig.1. The polypropylene roll was rotated during the beam operation to use the fresh surface of the target continuously for the collision.

The liquid scintillators (BC-501) were located around the target chamber as shown in Fig. 2. The angles of the scintillators were 0, 20, 40, 90, and 135 degrees, respectively. The top surface of the scintillator faced the target

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEY02

HIGH INTENSITY ^{50}Ti BEAM PRODUCTION FOR SUPERHEAVY ELEMENT RESEARCH*

D.S. Todd†, J.Y. Benitez, N. Brickner, P. Coleman, N. Intwala, S. Small, D. Thatcher
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

Elements 115-118 were discovered by bombarding transuranic targets with high-current ^{48}Ca beams, but a lack of heavier targets prevents extending the periodic table using these beams. The recent production of two atoms of element 116 by LBNL researchers using ^{50}Ti opens a new pathway for the discovery of elements beyond 118. The 88-Inch Cyclotron's acceleration and delivery of the puA ^{50}Ti beams used to create these two particles are discussed. In particular, we present the novel inductive oven used to provide a stable stream of ^{50}Ti vapor to LBNL's superconducting electron cyclotron resonance ion source Venus, extract >100 µA Ti^{12+}, and minimize consumption of this expensive, low-abundance isotope.

INTRODUCTION

Lawrence Berkeley National Laboratory (LBNL) has a long history of involvement in the discovery of radioactive elements, having been directly involved in or been the site of the discovery of 15 such elements (and one stable element). The last element discovered at LBNL, seaborgium (element 106), was produced by bombarding a californium target with oxygen beams [1]. Since that time, a further twelve elements have been discovered at other laboratories around the world. With its upcoming search for element 120, LBNL will once again try to expand the periodic table using a californium target, this time using ^{50}Ti projectile beams.

The six most recent element discoveries, elements 113-118, were the result of experiments with ^{48}Ca beams incident upon actinide targets of increasing atomic number from 94 to 98 (Pu to Cf). A lack of sufficient material for targets with atomic number greater than 98 prevents this successful projectile from extending the periodic table further. However, a potential way to continue in the same vein is to use projectile beams with higher atomic number.

The production of element 120 using ^{50}Ti projectile beams will require beam energies in the 5-6 MeV/u range to surpass the Coulomb barrier, and high currents (~pµA) for reasonable production rates of multiple-per-year of beam time. As a demonstration that ^{50}Ti beams can be used for superheavy (atomic number > 103) element production, high-current beams were developed by the Operations and Ion Source teams at LBNL's 88-Inch Cyclotron and used to bombard a ^{244}Pu target to produce element 116 (Lv) particles [2]. This result represents the first time that superheavy elements have been produced using titanium ion beams and paves the way for the upcoming element 120 search.

Based on predicted element 120 cross-sections, the 88-Inch Cyclotron staff has been charged with producing $^{50}Ti^{12+}$ beam currents in excess of 1 pµA to superheavy element experiments continually for multiple runs of ten-day-length. Additionally, as ^{50}Ti is a low-abundance, expensive isotope, we are tasked with producing these beams while maintaining a material consumption rate less than 5 mg/hour. In the following two sections we describe what this means for both the cyclotron and the source providing it beam. The difficulties titanium presents in the source are discussed and the novel inductive oven we have designed and used to demonstrate ^{50}Ti's viability in superheavy research is presented in the subsequent section. The two final sections give results using this oven and discuss further optimizations to be made to improve performance.

ACCELERATOR

LBNL's 88-Inch Cyclotron is a flexible, K140 cyclotron originally designed as a light ion accelerator. However, with the addition of increasingly advanced electron cyclotron resonance (ECR) ion sources, this cyclotron has accelerated over half of the naturally occurring elements. The acceleration frequencies of the cyclotron's single dee are between 5.6 and 16.5 MHz with a maximum dee voltage of approximately 70 kV. In recent years, the majority of this cyclotron's accelerated beams have been used for two purposes: single event space effects testing and superheavy element research. For the former, low-current beams (typically 10s of pA to 10s of nA) with energies between 5 and 20 MeV/u and masses across the periodic table are delivered to experimenters to test radiation effects on space-bound equipment. For the latter, high-current, moderate mass beams (up to a couple pµA with atomic mass in the 40-50 amu range) are delivered to heavy targets with energies in the 5-6 MeV/u range.

For the cyclotron, the production of high-current ^{50}Ti beams is an extension of well more than two decades' experience accelerating high-current beams for superheavy element production. After the completion of transmission improvements and the addition of a spiral inflector, the 88-Inch Cyclotron has demonstrated its ability to accelerate and deliver over 2 pµA $^{48}Ca^{11+}$ beams to superheavy element researchers [3]. The accelerated species for the titanium beams is $^{50}Ti^{12+}$, and since its mass-to-charge ratio is similar to the successful experiments with ^{48}Ca, transport through the injection line and spiral inflector is possible without any modifications. There is no reason to not expect similar cyclotron performance for titanium beams as was found for calcium, provided the ion source can produce the required beam currents.

ION SOURCE

The 88-Inch Cyclotron's primary injector source for high-current ion beams is the fully-superconducting ECR

* This work was supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract number DE-AC02-05CH11231 (LBNL).
† email address: dstodd@lbl.gov

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEB04

ALPI-PIAVE PERFORMANCE AT INFN-LNL WITH ADVANCED OPTIMIZATION ALGORITHMS

Y. K. F. Ong*[1], L. Bellan, D. Bortolato, M. Montis, M. Comunian, A. Pisent, E. Fagotti
INFN-LNL, Legnaro, Italy
[1]also at La Sapienza University of Rome, Rome, Italy

Abstract

The ALPI-PIAVE heavy-ion accelerator at INFN-LNL requires precise tuning due to its complex beam dynamics and high-dimensional parameter space. Although designed for a transmission efficiency of 60%, actual performance is typically limited to 15–20%, highlighting the need for more effective optimization strategies. In this work, we evaluate Bayesian Optimization (BO) and Trust Region Bayesian Optimization (TuRBO) to improve the tuning efficiency and robustness of the PIAVE injector line. To address the sensitivity of BO-based methods to parameter drifts, we incorporate Particle Swarm Optimization (PSO) and introduce controlled perturbations to assess algorithm performance under dynamic conditions. The results demonstrate the potential of these machine learning techniques for real-time accelerator optimization.

INTRODUCTION

Online accelerator optimization is a time-consuming but essential part of operating an accelerator facility, where users depend on the timely delivery of requested beams. This tuning process requires extensive manual adjustments and expert knowledge due to the large number and variety of accelerator components and parameters involved. At heavy-ion facilities like INFN-Legnaro, where a different ion beam is requested for each experiment, tuning efficiency becomes even more critical. Implementing automated optimization algorithms could streamline this process and help ensure that beam delivery remains on schedule.

Bayesian Optimization (BO) has emerged as a powerful tool for both offline and online accelerator tuning, valued for its flexibility, low initialization cost, rapid convergence, and robustness to noise [1]. BO constructs a probabilistic surrogate model, typically a Gaussian process [2] to approximate the objective function and its uncertainty. Then it uses an acquisition function to iteratively select evaluation points, effectively balancing exploration and exploitation. This strategy enables efficient identification of optimal parameters with relatively few evaluations.

This work aims to develop and evaluate advanced machine learning-based optimization techniques, including a novel Adaptive Region Bayesian Optimization (ARBO) algorithm and a hybrid BO–PSO strategy, for improving the efficiency, robustness, and scalability of online tuning in the ALPI-PIAVE accelerator complex at INFN-LNL.

* ysaong@lnl.infn.it

THE ALPI-PIAVE HEAVY-ION ACCELERATOR

The ALPI linear accelerator consists of 20 cryostats (CR), each housing four Quarter Wave Cavities that were initially designed to operate at 3 MV/m with a 10 mm bore aperture and require independent tuning based on the ion beam type. The linac period design incorporates a triplet and two cryostats (8 cavities) to maximize space. Currently, ALPI has two injectors for stable ions: the electrostatic accelerator TANDEM, which accelerates light ions, and the PIAVE superconducting RFQ, with an output energy of 587.5 keV/u [3]. A third injector, SPES-ADIGE, is currently being installed [4]. Both active injectors suffer from low transmission to ALPI due to its aggressive transverse focusing, which makes the system highly sensitive to beam misalignments. Although the ALPI-PIAVE accelerator complex was designed for a transmission efficiency of 60%, the actual transmission is approximately 15–20%.

The PIAVE injector line, shown in Fig. 1, includes an ECR ion source, LEGIS (LEGnaro ecrIS), which produces positive heavy ions. These ions are transported and injected into a superconducting RFQ, followed by three 80 MHz bunchers for proper longitudinal matching to the ALPI linac booster. The PIAVE line also features 11 sets of quadrupoles (1 singlet, 6 doublets, and 4 triplets) for transverse focusing and 10 horizontal and vertical steerers for beam trajectory correction. Before sending the beam to ALPI, its quality is evaluated using a Faraday cup (FC) located at PM9. For the following algorithm tests, a beam of $^{129}Xe^{25+}$ was transported and accelerated through the PIAVE line. The transmission was optimized by adjusting the beam trajectory and focusing using the steerers and quadrupoles while monitoring the beam current at the PM9 FC.

Adaptive Region Bayesian Optimization (ARBO) vs. Trust Region Bayesian Optimization (TuRBO)

For the first test, we compared the Python Bayesian Optimization (BO) module developed at MIT [5] with the Trust Region Bayesian Optimization (TuRBO) implementation from BoTorch [6]. We introduced an additional feature to the BO algorithm that allows the search region (R) to expand if the current best set point (S_{best}) lies near the boundary of the defined R. This expansion can be applied to one or multiple parameters, depending on their proximity to the boundary, and is evaluated after each iteration. From this point onward, we refer to this modified version of the algorithm as Adaptive Region Bayesian Optimization (ARBO). This algorithm was also used to optimize the longitudinal

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEZ01

SINGLE-BUNCH EXTRACTION AT THE 88-INCH CYCLOTRON*

M. Kireeff Covo†, J. Benitez, D. Todd, J. Cruz Duran, S. Blim, C. Anderson, M. Johnson, J. Garcia, B. Ninemire, D. Xie, L. Phair, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

The extraction system of the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory has been modified to enable single-bunch extraction. This is achieved by increasing the voltage of the first deflector to oversteer the beam, halting extraction, and then selectively switching it off using a high-voltage chopper to synchronize the deflector's operational voltage with the transit time of a single bunch, enabling its extraction. A pre-chopper positioned before the cyclotron limits the beam available for acceleration, minimizing activation and sputtering damage from discarded bunches. This cost-effective technique is crucial for time-sensitive experiments and provides precise control over dose delivery, broadening the cyclotron's range of applications. Future efforts will focus on increasing extraction frequency by optimizing the deflector electronics for faster recovery times, and exploring sequential switching of two deflectors to reduce the required oversteering voltage.

INTRODUCTION

Recent developments in pulsed power technology have led to significant enhancements in beam chopping systems for particle accelerators. High-voltage switching units composed of series and parallel arrays of modern semiconductors, such as MOSFETs, IGBTs, and SCRs, can now deliver fast switching performance with low jitter and high efficiency. These systems are capable of managing hundreds of kilovolts and tens of kiloamperes within sub-microsecond timescales, enabling precise temporal control of particle beams for high-resolution applications across various accelerator facilities [1, 2].

Tandem beam chopper systems are typically categorized as either fast and slow choppers or as pre-chopper and main chopper [3, 4]. In the first configuration, fast choppers are used in applications requiring nanosecond-scale resolution, such as precise bunch selection and timing control, while slow choppers serve broader intensity modulation purposes. In the latter configuration, the pre-chopper is generally positioned early in the acceleration stage to shape the beam before it gains significant energy, whereas the downstream main chopper further refines beam delivery by deflecting or transmitting bunches to either the target or the beam dump.

To enhance chopper system performance, researchers have explored advanced hardware and optimization techniques that improve synchronization between beam dynamics and switching events. High-speed electronics and real-time feedback loops enable precise control over bunch timing and beam intensity, capabilities crucial for time-of-flight experiments, neutron cross-section measurements, and laser-driven fusion diagnostics.

For the 88-Inch cyclotron, this precision is especially important for time-of-flight neutron spectroscopy, where accurate timing between pulses prevents overlap from sequential broad-spectrum bunch bursts, particularly in experiments using deuteron beams striking beryllium targets to generate fast neutrons.

PRE-CHOPPER AND MAIN CHOPPER TANDEM SCHEME

The 88-Inch Cyclotron at Lawrence Berkeley National Laboratory supports research in nuclear science and radiation effects using light and heavy ions produced by three electron cyclotron resonance ion sources: ECR, AECR, and VENUS [5], Fig. 1. These sources can deliver mixed ion species ("cocktails") through an injection line equipped with attenuators for beam intensity control and a pre-chopper that limits beam power into the machine.

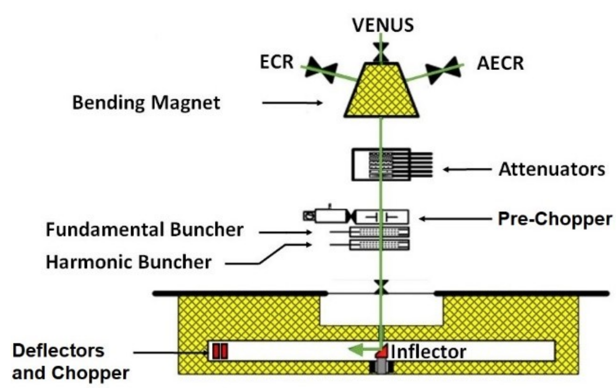

Figure 1: Layout of the extraction lines from the ion sources and the injection line into the cyclotron.

The beam is subsequently bunched by fundamental and harmonic bunchers for acceleration and extraction via three electrostatic deflectors. However, due to energy spread caused by particles arriving at different RF phases, bunches become radially dispersed, resulting in extraction across multiple RF cycles even if a single RF bucket is injected at the cyclotron [6].

Under normal conditions, injecting several consecutive RF bunches results in extraction on every RF cycle. Figure 2 shows how multiple-turn extraction arises when the chopper narrows the injection window to a single RF bunch. The remaining single bunch, after acquiring energy spread during acceleration, is extracted over multiple turns. Because

* Work supported by the Director, Office of Science, Office of Nuclear Physics, Division of Nuclear Physics, U.S. Department of Energy under Contract No. DE-AC02-05CH11231.
† mkireeffcovo@lbl.gov

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEZ02

ADVANCES IN TRANSVERSE BEAM HALO CHARACTERIZATION AND IMPLICATIONS FOR HL-LHC*

M. Rakic[1,†], P. Hermes, S. Redaelli
European Organization for Nuclear Research (CERN), Geneva, Switzerland
M. Seidel, Paul Scherrer Institute (PSI), Villigen, Switzerland
[1]also at École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Abstract

Measurements of the transverse beam halo in the LHC showed that it contains a non-negligible portion of the total stored beam energy, with potential implications for collimation system performance, machine availability and overall machine protection. In the HL-LHC era, when a significant increase in stored beam energy is planned, the understanding and modelling of the beam halo distribution becomes even more important. This applies particularly for the risk quantification in view of new failure scenarios not present in the LHC, like fast failures of the new crab-cavities or of the quench protection system of new triplet magnets. This contribution summarizes the recent progress in beam halo measurement, new findings from refined analysis methods, an overview of the employment of key measurement techniques, and advancements in experiments aiming to quantify the origin of beam halo. We describe the latest halo models and how they affect the performance of potential active halo control mechanisms in simulations. These developments form a critical input to HL-LHC machine protection strategies.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN is a synchrotron designed to accelerate and collide two beams of protons or heavy ions. Its original design specified a maximum stored energy of 362 MJ per beam at 7 TeV, with intensities of 1.15×10^{11} particles per bunch (ppb) [1]. This value was exceeded during the current operational Run 3, with stored energies reaching up to 430 MJ. Following the planned Long Shutdown 3 (LS3), the LHC will be upgraded to the High-Luminosity LHC (HL-LHC), where stored energies are expected to reach 680 MJ with 2.2×10^{11} ppb [2]. Even small particle losses from such high-intensity beams can trigger quenches in the superconducting magnets, reducing operational efficiency. In worst case scenarios, uncontrolled beam losses could even induce damage to accelerator hardware components. To mitigate these risks, the LHC employs a sophisticated multi-stage collimation system, which will undergo major upgrades to prepare for the HL-LHC era [3]. The collimation system is distributed around the ring, with key installations in Insertion Region (IR) 3 for off-momentum cleaning and IR 7 for betatron cleaning. The primary collimators (TCPs) are placed closest to the beam in normalized transverse space and intercept large-amplitude particles. Secondary (TCSG) collimators, shower absorbers (TCLA) and tertiary (TCT) collimators, are designed to absorb particles deflected from upstream collimators [4], and optimise the cleaning performance. The material and design of each collimator vary depending on its function [3, 5].

The term *transverse beam halo* refers to particles at large transverse amplitudes, arbitrarily defined beyond 3 σ, where σ is the RMS betatron beam size, computed using the nominal normalized emittance: $\epsilon^n_{\mathrm{LHC}} = 3.5$ µm rad for the LHC and $\epsilon^n_{\mathrm{HL}} = 2.5$ µm rad for HL-LHC [6]. In Run 3, the measured emittance ϵ^n_{M} is often lower, around 2 µm rad [7]. The most reliable method to characterize the transverse halo is collimator scraping, described in the following chapter. Measurements from LHC Run 1 and 2 indicated that up to 5 % of the beam could lie beyond 3 σ_{LHC} [8,9], close to the TCP collimators. Assuming linear scaling with beam intensity, this corresponds to a potential 35 MJ of stored halo energy in HL-LHC [9], though this extrapolation is subject to uncertainties due to changes in beam parameters and machine configuration. In scenarios involving sudden orbit changes—such as those triggered by a crab cavity failure, this halo energy could cause risk to collimators or operational efficiency due to frequent beam dumps [10]. Mitigation hardware (Hollow Electron Lenses [11, 12]) that was initially foreseen to be installed in HL-LHC, is not going to be available at the start of HL-LHC operation. A detailed understanding of the transverse distribution is therefore essential for realistic failure scenario modelling and effective mitigation [13]. This article provides a comprehensive overview of current methods for measuring and quantifying the beam halo, reviews existing analytical approaches, and introduces recent developments in halo distribution modelling. It concludes by discussing the implications of the updated models for halo depletion, supported by numerical simulations evaluating their impact on HL-LHC operation.

METHOD OF HALO MEASUREMENT

Collimator Scraping

The primary collimators in the LHC consist of two movable jaws positioned symmetrically around the circulating beam, at an amplitude of 5 σ_{LHC} at the top energy of 6.8 TeV in Run 3. These jaws can be independently moved toward the beam core in increments as small as 5 µm, thereby reducing the effective betatron cut. In IR 7, three primary collimators are installed per beam, enabling halo scraping in

* Research supported by the HL-LHC project.
† milica.rakic@cern.ch

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEC02

THE BEAM DYNAMICS CASE OF BEAM-BEAM WIRE COMPENSATORS FOR THE HL-LHC ERA

P. Bélanger[*,1], R. Baartman, D. Kaltchev, TRIUMF, Vancouver, Canada
G. Sterbini, CERN, Geneva, Switzerland
[1] also at University of British Columbia, Vancouver, Canada

Abstract

Beam-beam long-range interactions are known to be a strong source of non-linearities in hadron colliders, undermining the performance of the Large Hadron Collider (LHC) during proton-proton collisions. In order to enhance the luminosity production of the machine and increase the tolerance of the working point after the High Luminosity upgrade of the LHC (HL-LHC), dedicated correctors such as beam-beam wire compensators can be used. In this paper, the beam dynamics of this compensation problem is studied in details, ultimately showing that the linearity of the machine can be significantly improved throughout the beam core — and up to several sigmas — leading to an improvement of the dynamic aperture. This conclusion is shown to be supported by analytic calculations, simulation studies, as well as experimental results presented in earlier work. With the proposed approach, wire compensators can be positioned according to the collimation settings, simplifying their implementation in the machine for the HL-LHC era.

INTRODUCTION

The Large Hadron Collider (LHC) is soon to be upgraded into the High-Luminosity LHC (HL-LHC) which is planned to be operational by 2030. For this new era, the focus will be to increase the luminosity production of the machine by pushing the operational scenarios into increasingly challenging regimes. As such, controlling the non-linearities of the lattice and improving the beam lifetime is critical to reach the target of the HL-LHC project. Alongside electron clouds, the main source of non-linearities in the LHC is the beam-beam (BB) effect, arising from the electromagnetic interaction between the two counter-rotating beams. In the interaction regions (IRs), the two beams share a common beam pipe and perturb one another. Head-On (HO) collisions take place at the interaction points (IPs), whereas Long-Range (LR) interactions are distributed on both sides of the IPs. These interactions, akin to strong multipolar errors, occur several times (≈50) per IR for the nominal bunches and contribute to the excitation of high-order resonances, eventually leading to particle diffusion, particle losses and the reduction of dynamic aperture [1–3].

To mitigate this problem, current-carrying wires have been proposed as a correction device to compensate the BBLR kicks [4–6]. As shown in Fig. 1, these so-called beam-beam wire compensators (BBWCs) need to be installed after the separation dipoles in order to act separately on the two beams, which travel in opposite directions.

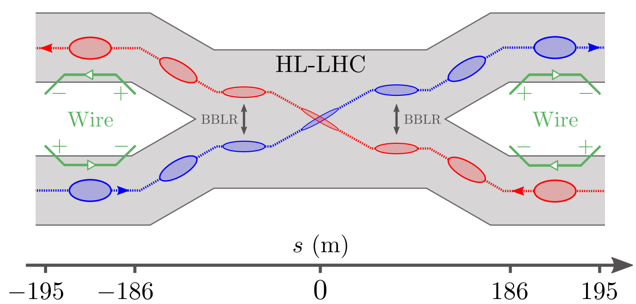

Figure 1: BBCW layout for HL-LHC around IP1 and IP5.

Table 1: HL-LHC Parameters (End of Lumi-Levelling)

Parameter		Value	Unit
Beam Energy	E	7.0	(TeV)
Bunch intensity	N_b	1.13×10^{11}	(p^+/b)
Norm. Emittance	$\varepsilon_x^N, \varepsilon_y^N$	2.5	(µm·rad)
Beta at the IP	β^*	15	(cm)
Half-crossing	$\theta_c/2$	250	(µrad)
Crabbing angle	θ_{cc}	−190	(µrad)
Octupoles	I_{oct}	−60	(A)
Chromaticity	$\Delta Q_x, \Delta Q_y$	15	

The Maxwellian equivalence between current-carrying wires and beams of charged particles has been well-established theoretically by several authors over the last few decades [4, 6, 7]. On the experimental front, successful beam-beam compensation was recently demonstrated in the LHC during dedicated machine development experiments [8, 9] as well as regular LHC operation [9]. However, the integration of a full-scale compensation system in the machine for the HL-LHC era — the first of its kind — requires additional considerations to optimize the effects on the beam dynamics, as discussed below.

In this paper, the linearity of the IRs is studied with and without BBWCs at various amplitudes using the non-linear residual, which will be introduced. This method complements the usual resonance driving terms (RDTs) approach, while reducing the complexity of the analysis by directly using generic tracking codes to reach its conclusions. To support the results, dynamic aperture scans are presented.

* philippe.belanger@cern.ch

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP03

MITIGATING THE THERMAL CHALLENGES IN CARBON STRIPPER: TEST BENCH SIMULATION TO ENHANCE DEVICE STABILITY*

B. Abdelmegied†, T. Kanemura, F. Marti
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The linear accelerator of the Facility for Rare Isotope Beams (FRIB) employs both liquid lithium and carbon strippers at a location where the beam energy reaches 17–20 MeV/u to increase the mean charge state of the beam being accelerated. Effective thermal management in carbon strippers is critical for ensuring reliability and component longevity. This study simulates beam heating using a 460 nm laser to investigate the thermal response of carbon foil, guiding future design improvements for heavy-ion beam applications. Key objectives include emissivity measurement under controlled conditions—vital for understanding heat transfer—and implementing mechanical upgrades such as replacing plastic components with metal gears and bearings, applying high-emissivity coatings inside the chamber, and integrating a proximity sensor for rotation monitoring. These enhancements aim to improve thermal efficiency, measurement accuracy, and overall system durability under high-temperature conditions

INTRODUCTION

Carbon stripper foils are subjected to intense thermal loads during operation, leading to thermal stress and potential degradation. Studies have shown that the thermal behavior of these foils is influenced by factors such as emissivity, thermal conductivity, and mechanical robustness. To address these challenges, research has focused on exposing foil to different beam species to evaluate the thermal response of carbon foils. Additionally, finite element simulations have been employed to model the temperature fields induced by irradiation, providing insights into minimizing the thermal stresses of the carbon stripper components should provide guidance for the design improvements [1-4].

The carbon stripper was the main charge stripper to support FRIB user program until October 2023 when the beam power was ramped up to 10 kW at the target from the previous 5 kW. The issue that temporarily made the carbon stripper suspended from operation was frequent rotation stalls that prevented continuous beam operation. It was assumed that plastic components surrounding the hot carbon foil expanded due to the heat conducting from the foil, and increased friction, which then seized the rotation. To investigate this behavior and test potential improvements, an identical experimental setup was made.

This study utilizes laser-induced heating, simulating beam heating, to examine thermal responses under dynamic conditions. It also explores hardware and structural modifications to improve the stripper's robustness and operational efficiency.

EXPERIMENTAL SETUP

The experimental arrangement features a vacuum chamber fitted with laser heating and thermal diagnostics. A blue laser beam, angled through an upper-right port, irradiates a carbon foil mounted inside. An infrared (IR) camera aligned with a ZnSe window on the bottom right port records real-time thermal images. A thermocouple inserted through a feedthrough port measures the wall temperature inside the vacuum chamber, whose inner surface is coated with a high-emissivity coating (Fig. 1).

Inside the chamber, the ANI carbon foil (from Applied Nanotech Inc.) is mounted on a custom-designed gear system, allowing both rotation and vertical motion. This dual-movement mechanism enables the laser beam to heat various foil segments, simulating dynamic beam-stripping conditions (Fig. 2). The diameter of the foil is 100 mm.

The current experiment utilizes adjustable rotation speeds between 100 and 500 RPM, spreading the thermal load along the foil's circumference. Vertical motion velocity was fixed at 7.5 mm/sec (this is the maximum speed in the middle of cyclic linear motion. The speed profile is sinusoidal repeating acceleration from and deceleration to zero speed at the turning points of the direction of motion), enabling the laser to sweep across a vertical span. The laser beam targeted a radial region between 20 mm and 40 mm, distributing heat more evenly and allowing analysis of radial thermal gradients.

The 460 nm laser delivers a maximum power of 55 W but is operated at 11.9 W for this test. Given the foil's 84% absorption efficiency at this wavelength, approximately 10 W is absorbed. The laser is focused on a 3 mm beam spot, producing localized, high-temperature regions on the foil. This condition represents the stripping of a ^{48}Ca beam being delivered to the rare isotope production target at a beam power of 10 kW.

The ZnSe viewport, with 98% IR transmission between 7–12 μm, allows thermal imaging without compromising vacuum integrity. This configuration supports non-contact, temperature diagnostics crucial for understanding the foil's response to transient heating.

* Work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633
†Abdelmegied@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP05

FREQUENCY DEPENDENCE OF BCS AND RESIDUAL RESISTANCE USING MULTI-MODE MEASUREMENT OF NITROGEN-DOPED SINGLE-CELL ELLIPTICAL CAVITIES*

S. M. Moskaitis, Y.-L. Cheon, S.-H. Kim, P. N. Ostroumov
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

Various cavity surface treatments have been found to significantly improve cavity quality factor, Q_0, with one such treatment being nitrogen-doping (N-doping). N-doped 1.3 GHz cavities were the first found to exhibit anti-Q slope, the increase of Q_0 with accelerating field, E_{acc}. However, even with the use of the same N-doping recipes, this anti-Q slope behavior has not been realized in sub-GHz frequency cavities. In this study, we measured the Q_0 and surface resistance, R_S, of our N-doped, single-cell, elliptical cavity for both the 644 MHz fundamental mode (FM) and 1.45 GHz higher-order mode (HOM). As a result of multi-mode measurements, the BCS and residual resistances, the temperature-dependent and temperature-independent RF surface resistances, could be determined without the influence of cavity-to-cavity surface treatment variations. We will discuss the frequency-dependent behaviors of the BCS and residual resistances.

INTRODUCTION

Maximizing Q_0 is critical for superconducting RF (SRF) accelerators as it reduces the cryogenic cost of operating the cavities. Past studies of GHz-range SRF N-doped niobium cavities have shown both improved Q_0 and the anti-Q slope, a positive Q slope in medium-field ranges (~10 to ~100 mT B_{peak}) [1].

Higher Q_0 and a possible anti-Q slope are of particular interest for the FRIB400 project, which aims for $Q_0 = 2*10^{10}$ at an accelerating gradient of 17.5 MV/m in 644 MHz 5-cell elliptical niobium cavities operating at 2 K [2]. Studying the frequency dependence of the BCS resistance (R_{BCS}) and residual resistance (R_0) using multi-mode measurement, thus removing the dependence of cavity-to-cavity surface treatment variations, could give directions towards reducing the Q-slope in 644 MHz 5-cell elliptical cavities for the FRIB400 upgrade.

EXPERIMENTAL SETUP AND METHODS

One elliptical single-cell niobium SRF cavity was the focus of this study. This cavity was nitrogen-doped at 800 °C for 2 minutes at 25 mTorr with no annealing under vacuum at 800 °C, a process known as 2N0 doping. This N-doping was preceded by an initial bulk electropolishing (EP) and followed by a post EP of 5µm.

To measure Q-curves at cryogenic temperatures in both 644 MHz TM_{010} FM and 1.45 GHz TM_{020} HOM, the cavity vertical test assembly was equipped with two variable couplers, one as an input coupler and the other as a pickup, as shown in Fig. 1. Since the 1.45 GHz HOM couples to the cavity much more strongly than the 644 MHz FM (Q_{ext} is ~20 dB lower), the variable coupler bellows were adjusted so that the input coupler Q_{ext} was close to 1e10 and the pickup Q_{ext} was close to 5e12. These adjustments could be made after the cavity had been clean-assembled and pumped out, outside the cleanroom, allowing both FM and HOM testing without disassembly.

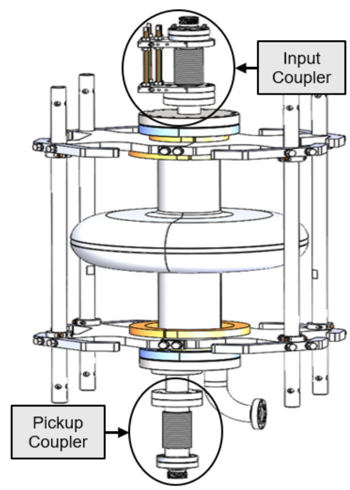

Figure 1: Model of vertical test assembly of the FRIB400 R&D cavity.

The vertical test dewar is equipped with magnetic shields and a field cancellation coil, which enables the reduction of the background magnetic field to nearly 1 mG. Additionally, a pair of Helmholtz coils was placed around the cavity to generate an artificial background magnetic field, B_{ext}, and study its effects on R_0.

In the cold tests, the cavity was slowly cooled down across the niobium critical temperature, T_c, to ensure all background magnetic fields were sufficiently trapped on the superconducting niobium surfaces without flux expulsion effects [3]. The cavity R_S was measured during pump-down from 4.3 K to 2 K at a constant cavity field (peak RF surface magnetic field B_{pk} at 9 mT) and fit to the following equation:

$$R_s = A\frac{f^2}{T}e^{\frac{-\Delta}{k_b T}} + R_0, \quad (1)$$

where A is a constant that depends on superconducting material properties, f is the cavity resonant frequency, T is the

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633. Work also supported by DE-SC0018362.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP06

IMAGE MAPPING FOR MULTIPLE CHARGE STATE BEAMS USING A BEAM INDUCED FLUORESCENCE PROFILE MONITORS*

A. Lokey†, Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

Work continues on a minimally invasive, nitrogen fluorescence gas sheet at the Facility for Rare Isotope Beams (FRIB). A low density gas sheet may be used to observe the 2D transverse beam profile of high intensity, multiple charge state beams with minimal interference. Spatially and temporally correlated profiles are of particular interest in locations where there is significant charge state spread, such as the FRIB linac folding segments. A low-density gas sheet measurement system offers advantages for gas handling in nitrogen sensitive areas, however signal intensity is significantly lower than techniques using higher density gas sheets and jets. This work discusses measurement considerations for photon distributions generated by several spatially separated interaction points and design considerations for a high-sensitivity optics system for handling the expected low signal intensity.

INTRODUCTION

Beam induced fluorescence (BIF) monitors are currently in use and under development at several facilities and offer a minimally interfering method to monitor the 2D transverse beam profile [1, 2]. In BIF devices, the beam excites a working gas which then emits photons during a de-excitation process. The gas can be shaped and positioned so that the resulting data collected correlates to the transverse beam profile.

Minimally interfering monitors are useful for high intensity beams, where component degradation with devices that intercept the beam become a concern. For example, the Facility for Rare Isotope Beams (FRIB) linac produces heavy ion beams of various species that can be selected to have multiple charge states. The linac consists of three folding sections with 60 degree bends. Achromatic optics are used to steer the beam through the turns, which causes spread in the charge states as it passes [3]. A 2D simultaneous profile in this area could give helpful insight to operators. Figure 1 shows a simulated example of this at four positions through the first folding section.

For this design, the profile will be measured by collecting photons generated by the interaction of the beam with low density nitrogen gas sheet. The beam interacts with the sheet at a 45-degree angle which encodes the x and y profile data in a coordinate transform [4]. Since relatively little gas is introduced into the system using a rarefied sheet, there are lesser requirements on gas handling and pumping systems. This is desirable for viewing profiles in areas that have somewhat tighter space constraints due to their small relative footprint. However, signal acquisition is a concern for low density gas sheets due to florescence cross sections generally being lower than other processes, as well as fewer interactions with the working gas.

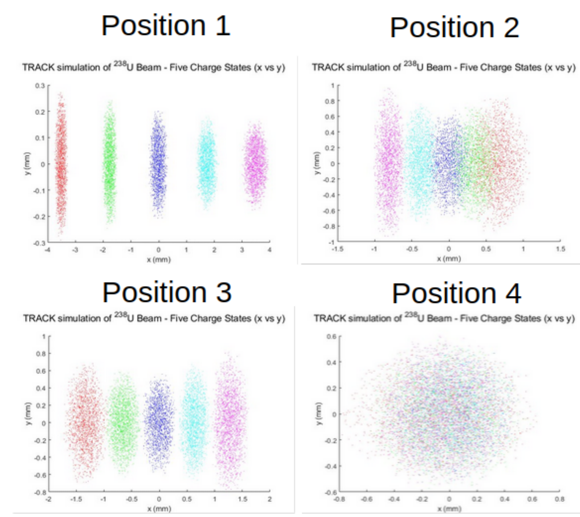

Figure 1: TRACK simulation of 5 charge state ^{238}U through the FS1 turn.

OPTICS AND ELECTRONICS CONSIDERATIONS

Fluorescence Process

The fluorescence cross section is proportional to the differential energy loss of the interaction and square of the charge state of the ion. This is advantageous for high charge state ions, as the photon production will be higher. During collision, the working gas undergoes both ionization and excitation, the former of which creates singly charged ions and secondary electrons. Neutral atoms are also excited by these secondary electrons, and both species de-excite releasing optical photons [5].

Photon Capture

Total photon yield is proportional to the gas pressure, the number of particles in a bunch, and the ion charge. Due to the low density of the gas molecules in the system, low fluorescence cross section even for favorable working gases, and a small solid angle of detection, the signal of the monitor is expected to be low.

* This material is based upon work supported by the U.S Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB), which is a DOE Office of Science User Facility, under Award Number DE-SC0000661
† lokey@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP07

BEAM LOSS DETECTION AND MITIGATION AT FRIB*

S. Cogan†, T. Kanemura, S. Lidia, T. Maruta, D. McNanney, P. Ostroumov, A. Plastun, Q. Zhao, S. Zhao, Facility for Rare Isotope Beams, East Lansing, MI, USA

Abstract

This work presents an overview of beam loss detection and mitigation at the Facility for Rare Isotope Beams (FRIB). A diverse array of loss monitoring systems—including ion chambers, neutron detectors, halo rings, fast thermometry, and differential beam current monitors (BCM)—are deployed to detect losses ranging from large events that risk machine damage to low-level losses that result in undesirable machine activation. To ensure protection, hundreds of detector thresholds with varying time responses are precisely configured for each beam mode, ion species, and energy. The Threshold Configuration Tool (TCT), a sophisticated software solution, optimizes these thresholds to safeguard the machine while minimizing false trips. Additionally, FRIB's high-power beam employs a novel self-healing liquid lithium film charge stripper, which introduces beam energy fluctuations and occasional gaps in the film, leading to downstream losses. Fast and slow feedback systems stabilize the post-stripper beam energy, effectively reducing these losses. This work will discuss how FRIB experiences running at 10kW beam power influenced the evolution of our systems and tools.*

LINAC OVERVIEW

The FRIB linac, utilizing superconducting RF cavities and consisting of over 500 meters of beamline, is designed to eventually deliver up to 400 kW of sustained heavy ion beam power to target. FRIB first delivered 1 kW of continuous beam power on target in May 2022 [1]. Since then, the maximum beam power on target has been steadily increasing, up to 2025 where we regularly deliver 20 kW of Uranium on target. Beam loss detection and mitigation has been a requirement from the start, and we have a robust Machine Protection System (MPS) [2] with an extensive network of sensors, detectors, controllers, and data acquisition systems which contribute not only diagnostic information, but fast-acting not-OK signals that can stop the beam delivery within 15 µs in order to protect the machine.

Machine Protection System

The Machine Protection System is one the most important and complex systems at FRIB. It directly connects to 400+ devices and controllers, with controllers interfacing with hundreds more detectors providing input. As FRIB increases the machine power, it is necessary and challenging to configure MPS appropriately to both protect the machine sufficiently and avoid frequent (unnecessary) faults which reduce beam time for experiments. There is an array of diagnostic devices which have responsibility for fast response to MPS, capable of detecting a problem condition in as fast as a few microseconds. As of 2025, we have integrated 13 non-intercepting beam current monitors (BCMs), 27 neutron detectors (NDs), and 44 ionization chambers (ICs) distributed throughout the linac to support the fastest MPS response. Each of these devices can respond to signals averaged over multiple timeframes, from 1 sec average down to 15 µs average. For these beam loss monitors alone, over 300 different MPS thresholds need to be managed in order to protect the machine in a wide variety of run conditions including beam development and tuning, pulsed modes with high peak power to various linac destinations, and continuous (CW) beam delivered to the production target.

Beam Stability in the Linac

As beam power is increased, not only must we protect the machine from large sudden losses, but we must limit low-level losses that arise from perturbations of our beam transport. The largest contributor of beam perturbations in our linac is our liquid lithium charge stripper (LLCS) [3] which is necessary to strip high power beam. It is comprised of a self-healing liquid lithium film, with laminar flow, in vacuum, to increase the ion charge state after the first linac segment. This film, while being remarkably stable, does experience occasional fluctuations or disruption in the flow. This can result in slow or sudden change of the post-stripper charge states, but more importantly, a different energy loss across the film, leading to different arrival times at RF accelerating cavities, and increasing beam instability and losses downstream. Several beam feedback mechanisms were introduced to mitigate these instabilities, as much as possible.

THRESHOLD CONFIGURATION TOOL FOR MPS

The FRIB linac undergoes a wide range of beam operations, each associated with varying levels of risk. At higher beam power, the tolerances for Beam Loss Monitor (BLM) Machine Protection thresholds need to be tight. At lower beam power, during beam tuning or beam development, these thresholds should be more relaxed to permit activities such as RF cavity tuning, which necessarily generate a noticeable but acceptable level of beam losses in certain locations.

With hundreds of individual thresholds to configure for a wide array of beam operating modes and a multi-dimensional problem space (ion species, beam energy, peak power, average power, pulsed modes, beam destination, etc) a highly automated tool is the only way to avoid over-

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633
† cogan@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP08

BEAM INTENSITY PREDICTION FOR ECR ION SOURCE USING MACHINE LEARNING

Y. Morita*, RIKEN Nishina Center, Saitama, Japan
K. Kamakura, Center for Nuclear Study (CNS), the University of Tokyo, Tokyo, Japan
A. Kasagi, Graduate School of Artificial Intelligence and Science, Rikkyo University, Tokyo, Japan
T. Nishi, RIKEN Nishina Center, Saitama, Japan
N. Oka, National Institute of Information and Communications Technology, Tokyo, Japan

Abstract

The Electron Cyclotron Resonance Ion Source (ECRIS) plays a vital role in generating highly charged ion beams for accelerator-based research. However, maintaining stable beam intensities remains challenging due to unmeasurable or slowly varying internal states. This study proposes a machine learning-based beam intensity prediction framework that incorporates both numerical operational data and plasma light images acquired through the extraction electrode. Experiments were conducted on two ion sources at RIKEN: the HyperECRIS and the RIKEN 28 GHz ECRIS. Predictive models with and without image data were developed and evaluated. The inclusion of plasma images led to improved prediction accuracy in both cases, indicating that such images effectively supplement hidden plasma conditions. These results demonstrate the potential of image-assisted modeling as a foundation for autonomous ECRIS control.

INTRODUCTION

The Electron Cyclotron Resonance Ion Source (ECRIS) is a powerful tool, particularly for the production of highly charged heavy ions. It is therefore widely used in accelerator facilities. However, especially in the generation of metallic ion beams, the conditions within the ion source such as plasma parameters can change rapidly, making it difficult to maintain a stable beam over extended periods. Currently, the operation relies on experienced operators performing manual optimization. Our aim is to automate this optimization process by incorporating machine learning techniques, thereby enhancing the sophistication of ECRIS operations. As a first step, we have developed a method for accurately monitoring changes in ECRIS conditions and continuously measuring beam intensity without interrupting beam delivery.

DATA COLLECTION

In machine learning, the input data is of critical importance. To effectively monitor changes in the ECRIS state, sufficient information must be supplied as model input. Operators typically monitor various parameters such as vacuum pressure and drain current, in addition to operational parameters, when tuning the ECRIS. However, changes in some parameters? such as vacuum level or vapor from high-temperature ovens? occur gradually and with delay, making immediate assessment difficult. Since not all internal states, like oven temperature, are directly measurable, beam intensity may change gradually even when observable parameters remain constant. To capture such dynamics, we focused on acquiring information about plasma conditions. However, it is currently difficult to obtain plasma characteristics like electron density and temperature without interfering with beam delivery. As an alternative, we opted to capture plasma light images using a camera [1]. These images can be easily obtained through the beam extraction aperture, and if proven useful for beam prediction, the method could be applied to various ECRIS. Experiments were conducted on two ion sources at RIKEN's RIBF facility: the HyperECRIS [2] and the RIKEN 28GHz ECRIS [3]. For the HyperECRIS, 17 parameters were used as machine learning inputs, including mirror coil current, 14 GHz RF power, gas valve settings, vacuum level, and beamline elements such as magnets and slits. Additionally, plasma light images were captured with a handheld camera through the extraction electrode (Fig. 1).

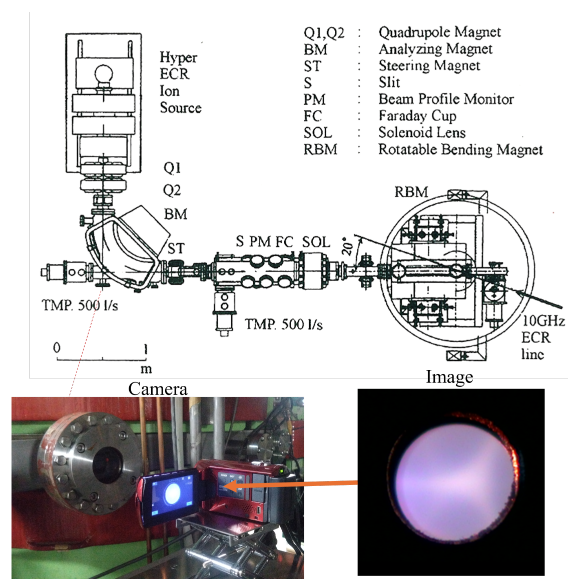

Figure 1: Plasma light imaging of HyperECRIS. Plasma light was captured with a handheld camera through a extraction electrode.

In the case of the RIKEN 28 GHz ECRIS, a similar approach was taken, but more parameters were included due

* yasuyuki.morita@riken.jp

16th International Conference on Heavy Ion Accelerator Technology, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP09

JuTrack, A Julia-BASED TOOL FOR ACCELERATOR MODELING AND TRACKING WITH AUTO-DIFFERENTIATION *

J. Wan†, H. Alamprese, Y. Hao, C. Ratcliff
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA
J. Qiang
Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA, USA

Abstract

JuTrack is a novel accelerator modeling and tracking package developed in the Julia programming language. Taking advantage of compiler-level automatic differentiation (AD), JuTrack allows rapid and accurate derivative calculations for arbitrary differentiable functions. This paper introduces the core capabilities of JuTrack, including lattice modeling and particle tracking, and demonstrates how AD-derived derivatives enhance the efficiency of beam physics studies through several practical examples.

INTRODUCTION

Derivatives are important in scientific computing tasks, such as accelerator modeling and particle tracking simulation. Traditional approaches to calculate derivatives primarily involve numerical and symbolic methods. While numerical methods can approximate derivatives for complex systems, they often suffer from precision limitations due to truncation errors and round-off errors, especially for ill-conditioned problems. On the other hand, symbolic methods, though accurate, struggle with deriving analytical expressions for complicated systems.

To address these challenges, automatic differentiation (AD) emerges as a robust alternative [1]. AD is a kind of computational technique used to evaluate the derivatives of functions in computer programs. Unlike numerical differentiation and symbolic differentiation, AD calculates derivatives of functions by decomposing functions into elementary operations and applying the chain rule to these operations sequentially. This method not only ensures computational precision but also enhances performance by avoiding the complexity and overhead associated with symbolic methods. So far, AD has been a fundamental tool in various fields such as machine learning, optimization, and numerical simulation [2].

To integrate AD capability in traditional particle tracking works, a novel accelerator modeling package, JuTrack [3], is developed in the Julia programming language. This package is specifically designed for numerical simulation of particle tracking using symplectic integration [4]. In addition to standard particle tracking, JuTrack also supports the computation of Truncated Power Series Algebra (TPSA) [5]. A powerful LLVM-level AD tool, Enzyme [6], is implemented in this code for swift and precise derivative computation at the compiler level.

* Work supported by DOE office of science, with award number DE-SC0024170.
† wan@frib.msu.edu

ACCELERATOR MODELING

Figure 1 shows the structure of the JuTrack code. It includes four main parts: lattice functions, TPSA functions, tracking functions, and utility functions. As a particle tracking tool, JuTrack supports 6-D tracking of the particle coordinates $[x, p_x, y, p_y, z, \delta]$, where x and y are the transverse coordinates, p_x and p_y are the transverse momentum normalized by the reference particle momentum p_0, z is the path lengthening with respect to the reference particle, and $\delta = \delta p/p_0$ is the momentum deviation with respect to the reference particle.

In addition to standard particle tracking, JuTrack also supports calculation of TPSA. The 6-D coordinates $[x, p_x, y, p_y, z, \delta]$ can be represented as coefficients of six polynomials and tracked as standard 6-D particle coordinates. The results of the TPSA tracking are also six polynomials representing the 6-D coordinates.

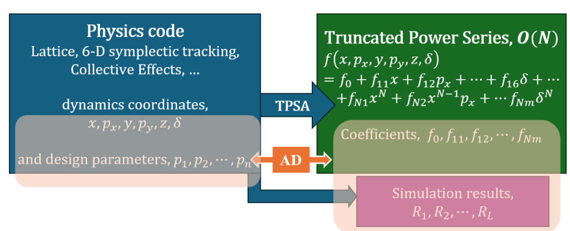

Figure 1: Overview of the JuTrack workflow. JuTrack applies AD to compute derivatives of both map coefficients and beam observables with respect to design parameters.

Taking the Hadron Storage Ring (HSR) of the Electron-Ion Collider (EIC) [7] as an example, in this section, we will demonstrate how to build such a complex accelerator lattice and how to calculate the Courant-Snyder parameters of the ring in JuTrack.

Figure 2 shows the optics of the storage ring. The periodic optics is solved based on the transfer matrix of the ring, which is calculated from the first-order TPSA tracking. Compared to the MAD-X [8], a well-known accelerator modeling tool used for the EIC design, the maximum difference of β_x and β_y is around 1% level. This error is due to the different treatment of dipole field errors in both codes. For a lattice without such dipole field error, identical optics and betatron tunes are obtained by both codes, e.g., the Electron Storage Ring (ESR) of the EIC shown in Ref. [3].

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP10

MACHINE-LEARNING-ASSISTED RAPID BEAM ENERGY CHANGE AT THE ATLAS HEAVY ION LINAC*

A. Ravichandran†, B. Mustapha
Argonne National Laboratory, Lemont, IL, USA

Abstract

Studying nuclear reactions to develop new medical isotopes requires the measurement of production cross sections at varying beam energies. To do this efficiently without wasting beam time available for experimentation, the energy needs to be changed rapidly over a very wide range. We present recent experimental results, employing machine learning methods for rapid tuning of ^{16}O &^{136}Xe beams following manual energy change. For the ^{16}O beam energy is changed from a base value of 106 MeV to 71 MeV and for the ^{136}Xe beam energy is changed from the base energy of 803 MeV to 671 MeV and 525 MeV. Retuning from the base energy took ~15 minutes compared to ~30 minutes for operator tuning. The collected data is then used to validate the same procedure in a virtual model of ATLAS running the TRACK simulation code with error ~6% across energies. Preliminary virtual model error is corrected by considering quadrupole misalignments and real values of input beam parameters obtained by Bayesian inference.

INTRODUCTION

Nuclear cross section data is critical to making informed decisions to produce isotopes. Renne et al. [1] discuss a rapid and cost-effective procedure relying on prompt gamma cascades, a short burst of high yield gamma emissions measured using the Gamma-sphere detector at the ATLAS linac in Argonne. This procedure, however, requires measurements made at a wide range of beam currents and energies that require manual operator energy change and magnet tuning that takes appreciable time. Figure 1 shows the beamline section of the Argonne linac considered here between the last accelerating cavity and the Gamma-sphere detector

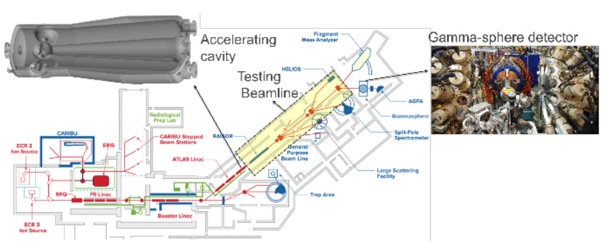

Figure 1: Testing beamline at ATLAS for ML model.

Scheinker et al. [2] discuss machine learning techniques using convolutional neural networks that do not require model retuning for complex time-varying systems.

Deep reinforcement learning based methods coupled with high-fidelity physics engines have been extensively studied at Los Alamos National Laboratory by Pang et al. [3], Argonne National Laboratory by Mustapha et al. [4] and the Stanford Linear Accelerator Centre by Edelen et al. [5]. This work explores a novel new approach of real-time tuning of a linear accelerator following energy change based on prior information available from a previous tune for a different beam energy. As discussed further, an instantaneous increase to ~50% beam transmission was achieved by applying the proposed technique presented here. Experimental data collected during the process is further used to refine a virtual accelerator model. The goal is to use model predictions to further improve the tuning procedure of the online ML model.

EXPERIMENTAL RAPID BEAM ENERGY CHANGE RESULTS

Experimental tune following a manual energy change procedure consists of performing a primary ML tune by Bayesian optimization with initial random data sets for a base energy (106 MeV for ^{16}O Beam). Figure 2 shows variation of magnet control settings during tuning procedure.

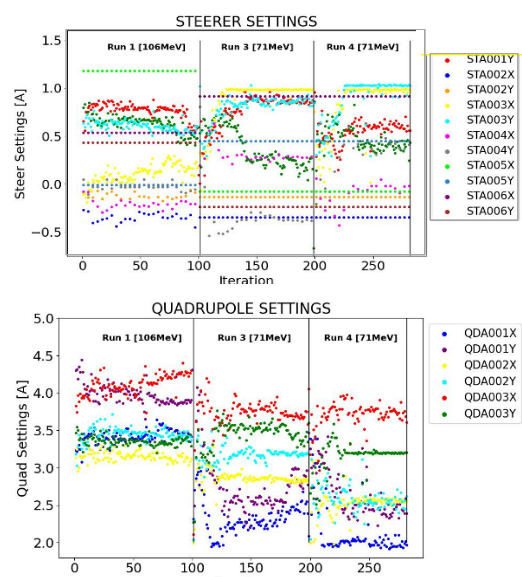

Figure 2: Element settings controlled by the ML model during the experimental tuning process for ^{16}O Beam.

Hard limits are set on magnet settings prior to performing the automatic ML tune to avoid damaging the devices. Figure 3 shows this initial ML tune (red dots) at 106 MeV clearly reaching 98% transmission. All magnet settings corresponding to this 98% transmission are stored. Next beam energy is manually changed by the operators to

* Work was supported by the U.S. Department of Energy, under Contract No. DE-AC02-06CH11357. This research used the ATLAS facility, which is a DOE Office of Nuclear Physics User Facility
† aravichandran@anl.gov

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP11

DESIGN IMPROVEMENT OF A MINICHANNEL BEAM DUMP WING THROUGH AI-DRIVEN GENETIC ALGORITHMS*

G. Lee†, N. Bultman, T. Kanemura, M. Patil, R. Quispe-Abad, J. Song
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The Facility for Rare Isotope Beams (FRIB) requires its beam dump to handle an increase in primary beam power from 20 kW to 50 kW. This paper presents a hybrid optimization framework that combines a Genetic Algorithm (GA) and Soft Actor-Critic (SAC) reinforcement learning to enhance the beam dump's thermal performance for 50 kW operation. The GA conducts a global search for key geometric design variables, while a SAC agent fine-tunes the local geometry to create a uniform heat distribution. The optimized design successfully lowered the maximum temperature across a range of beam sizes, achieving a nearly uniform temperature profile and enabling safe operation at 50 kW. A 3D simulation confirmed the design's even surface temperature and an 86% increase in power-handling capability compared to the original design.

INTRODUCTION

Beam dumps are the heat removal system directing unused beam power for heat removal. FRIB's current beam dump is a static, water-cooled structure where the beam strikes at a shallow angle (~6°) to spread out the energy deposition [1]. As FRIB upgrades its beam power from 20 kW to 50 kW, the existing dump design needs to be improved to handle the greater thermal load [2]. The primary goal is to prevent excessive localized heating by optimizing the geometry. This ensures that heat is distributed more evenly across the dump's surface for various beam sizes. Traditional engineering approaches struggle to optimize this problem, as they cannot easily account for the many interconnected geometric variables and multi-condition requirements. Therefore, advanced optimization techniques are needed.

Genetic Algorithms (GAs) are well-suited for such tasks and have been widely applied to complex engineering optimization problems due to their ability to perform global searches [3]. However, in high-dimensional design spaces, GAs may struggle to find the global optimum and can instead converge to a local minimum. Reinforcement learning (RL) has shown promise in optimizing control policies and continuous parameters in complex systems by learning through trial and error. For this reason, we selected RL to fine-tune the rough, low-dimensional design initially identified by the GA. In particular, the Soft Actor-Critic (SAC) algorithm utilizes a replay buffer to achieve high sample efficiency, making it well-suited for refining engineering designs in computationally expensive simulations [4].

Given these considerations, this work employs a hybrid GA+RL framework to redesign the FRIB beam dump for 50 kW operation. The approach first uses a GA to explore the global design space of the dump's geometry, and then an SAC agent locally refines the shape for optimal thermal performance. Our objective is to minimize the maximum temperature in the dump for several representative beam sizes, ensuring a robust design across the anticipated operating range.

METHOD

The beam dump consists of a bi-metal main plate and two 3D-printed side wings that are attached to cover multiple beam sizes. The bi-metal plate is a copper alloy (CuCrZr) bonded to an aluminium alloy (Al 2219) layer using explosion bonding on the beam-facing side [5-6]. This design combines high thermal conductivity with a protective aluminium layer to reduce water activation.

The optimization targeted a ^{238}U beam with a 2.1 mm thick graphite target. As shown in Fig. 1, four representative beam sizes (σ_x, σ_y) were selected to cover a wide operational range: (2.11, 7.68), (2.90, 14.20), (5.10, 19.25), and (6.97, 25.98), with units in mm.

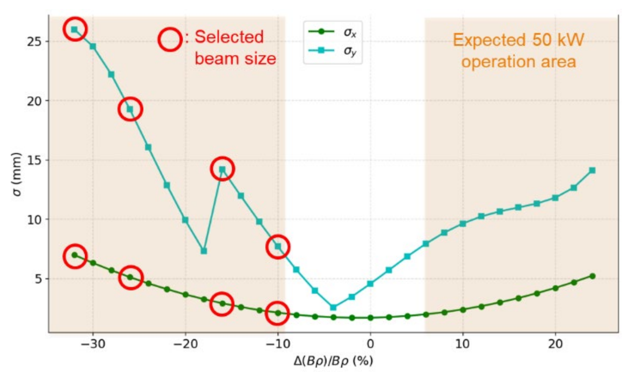

Figure 1: Variation of beam size with ^{238}U momentum deviation.

A custom 2D Finite Difference Method (FDM) thermal simulation code was developed in Python to reduce the extensive simulation time required by the GA and SAC algorithms. As shown in Fig. 2, this code divides the dump into four sections (S1–S4) corresponding to different material regions (the two wings as S1 and S4, and the bi-metal plate segments as S2 and S3). The overall design geometry was constrained to 600 mm × 140 mm by the facility's design boundary.

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
† leeg@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP14

BEAM DIAGNOSTICS IN ARIS TO INVESTIGATE WEDGE DEFECT AT FRIB*

D. Kahl†, E. Choi, M. Cortesi, S. Di Carlo, A. C. Dombos, K. Fukushima, M. Hausmann, D. Jacobson, E. Kwan, P. Manwiller, M. Portillo, L. Privatte, X. Rao, S. Rodriguez, B. M. Sherrill, M. K. Smith, M. Steiner, O. B. Tarasov, E. Wakai
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The Facility for Rare Isotope Beams (FRIB), operating at Michigan State University since 2022, produces a variety of nuclear species via projectile fragmentation or fission. Heavy ions are accelerated by the FRIB LINAC to energies of 110–290 MeV/u which impinge on mm-thick graphite targets to make the RIs inflight. The resulting cocktail of ions are separated and purified with the Advanced Rare Isotope Separator (ARIS). Magnetic separation of individual isotopes is accomplished with a wedge-shaped degrader that preserves achromaticity. As the first stage of ARIS involves a momentum compression of $k \approx 3$, the preseparator wedge geometric cross section is more complex than a simple isosceles triangle, having a parabolic shape to reduce aberrations. Here we report a comparison of different wedge materials using standard beam diagnostics from viewers and position-sensitive detectors. Particular attention is paid to the calibration procedure for parallel plate avalanche counters (PPACs).

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a DOE Office of Science User Facility that uses a variety of means to produce beams of rare isotopes (RIs) for experimental users. Using one of several ion sources coupled to a linear accelerator, we produce heavy-ion beams that impinge on a rotating carbon target, producing large cocktails of RIs inflight either by projectile fragmentation [1,2] or fission [3,4]. The cocktail beam is guided and purified by the Advanced Rare Isotope Separator (ARIS) [5] using momentum compression of $k \approx 3$ [6] to the users' specifications. Employing achromatic optics with a curved degrader at a dispersive focal plane, one can achieve significant purification of the fragment of interest (FOI) and nearby isotones [7, 8], which for higher-energy beams is a wedge-shaped degrader (now simply called a 'wedge'). Wedge inhomogeneities from imperfect machining or within the material itself (e.g., bubbles, density variations) can adversely affect the beam's phase space, resulting in a larger beam spot size and lower transmission.

The locations of the preseparator wedge (PSw) and the diagnostics box 2 wedge (DB2w) in ARIS, along with locations of beam diagnostics equipment, are shown elsewhere in these proceedings (Fig. 2 of Ref. [9]). Wedges are commonly made out of aluminum for their low proton number (Z), abundance, thermal conductivity, and machinability; we have considered other materials, but here we focus on wedges made from aluminum alloys. At FRIB, we make the wedges in house [10], where we have used the alloys AL6061 and AL7075 in the present study. We report on the findings with beam diagnostics that AL6061 is more consistent for minimizing inhomogeneities of the two materials.

METHODS

Beam Diagnostics

When the beam is reasonably intense ($\gtrapprox 10^4$ Hz) with a high purity, viewers (which stop the beam) and cameras are employed to directly look at the phosphorescence. The scintillator coating is made from rare earth (red) phosphor (Y_2O_2S:Eu). Because the cameras cannot be on the beam axis, a software transformation is performed to emulate the beam's view and to make quantitative measurements of the beam spot using the Viola package [11], developed at FRIB. Before each experiment, users confirm the fiducials used to make the transformation on each camera/viewer (*e.g.*, a camera's position might change by touching it during maintainence).

For cases with lower intensity or where the phase space may be significantly different for the FOI than the beam as a whole, ARIS has parallel plate avalanche counters (PPACs) installed at a number of focal points along the beam path. These delay-line PPACs [12,13] can be used for tuning and/or during experiments to track each ion event-by-event to assist in determining the particle identification (PID) by the ΔE-$B\rho$-ToF method (for details, see the Appendix of [14]). Here we layout a simple calibration scheme for each PPAC using a mask and an alpha source holder (ASH) mounted to the mask, which is easily able to provide the conversion from time to distance (including parallax), the central position (0,0), and orientation of each detector, shown in Fig. 1.

Beam Model

The quality of the wedges is evaluated using beam diagnostic equipment in conjunction with the LISE^{++}_{cute} code [15,16]. LISE^{++}_{cute} predicts the beam's phase space under ideal conditions and quantifies deviations caused by user-defined inhomogeneities, specified either as absolute values or percentages.

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
† kahl@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP19

STUDY OF PONDEROMOTIVE INSTABILITY IN THE FRIB $\beta = 0.53$ HALF-WAVE RESONATOR*

J. Brown[1,2†], W. Chang[1], S. Kim[1], T. Xu[1,2], S. Zhao[1],
[1]Facility for Rare Isotope Beams, East Lansing, MI, USA
[2]Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA

Abstract

Superconducting radio-frequency niobium cavities are susceptible to deformations caused by external or internal forces, leading to shifts in the cavity resonant frequency. One source of deformation comes from the radiation pressure of the cavity fields, producing the so-called Lorentz force detuning effect. This effect can couple to the cavity mechanical modes in a generator-driven mode, leading to the ponderomotive instability. In the FRIB 322 MHz, $\beta = 0.53$ Half-Wave Resonators (HWR), the instability appeared when the cavity was detuned, with thresholds depending on low-level RF control parameters, such as closed loop gain, as well as the accelerating gradient. Using a measured Lorentz transfer function, Simulink simulations were conducted to predict the instability thresholds, which were then compared with experimental results. We find good agreement for simulated and experimental thresholds on the negative side of the resonance curve and note inconsistencies with theory for proportional feedback systems and discuss paths forward for analytical studies.

INTRODUCTION

The $\beta = 0.53$ Half-Wave Resonator

The Facility for Rare Isotope Beams (FRIB) is a heavy ion, superconducting (SC), continuous wave (CW) linear accelerator capable of accelerating ^{238}U ions to 200 MeV/u [1]. The acceleration schemes employs $\beta = 0.53$, 322 MHz half-wave resonators (HWRs) as the highest beta cavity among four different types of SC cavities. The field profiles for the $\beta = 0.53$ HWR from CST Studio [2] are shown in Fig. 1.

The capacitance C is built up in the high electric field regions such as the accelerating gaps whereas the inductance L is formed in the high magnetic field regions of the cavity periphery. These two factors thus determine the resonance frequency of the cavity ω_0 via:

$$\omega_0 = \frac{1}{\sqrt{LC}}. \tag{1}$$

Since the capacitance and inductance are determined by the geometry, changes to the geometry result in a change in ω_0, which leads to a detuning from the generator frequency. CW linac operation allows for the choice of using relatively high Q_{ext} couplers, due to relatively weak beam loading effects compared to pulsed machines. This leads reduced RF power costs with narrow bandwidths. In this case, it is necessary to maintain frequency excursions due to detuning effects at the level of the loaded bandwidth or lower. Otherwise, the RF power required for amplitudes and phase stabilities could be even higher than the case of using a lower Q_{ext} couplers (a larger bandwidth) [3].

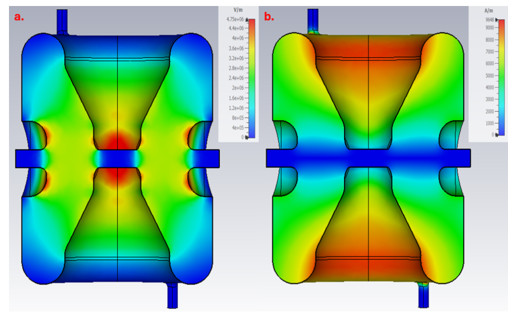

Figure 1: Fundamental electric field (left) and magnetic field(right). Internal energy normalized to 1 J .

In this work, we focus on a specific type of detuning effects: the Lorentz force detuning effect and the possible instabilities that can arise from its presence.

Lorentz Force Detuning

The RF fields in the cavity produce a radiative/Lorentz pressure on the walls of the cavity, leading to deformations. As such, this Lorentz pressure detunes the cavity. This effect can be divided into static and dynamic effects, depending on its coupling with the cavity's mechanical vibrational modes.

Static Lorentz Force Detuning In a steady-state case, as is most applicable to CW operation, the Lorentz pressure causes a static shift $\delta\omega$ in the resonance frequency. This shift is proportional to the square of the accelerating gradient E_{acc} [4]:

$$\delta\omega = -k_L E_{acc}^2, \tag{2}$$

where k_L is the so-called static Lorentz force detuning (LFD) coefficient. This coefficient is geometry dependent and relates the effect of deformation/detuning to the accelerating field.

This ponderomotive effect also creates a tilt in the resonance curve of the cavity as shown in Fig. 2, where a hysteresis region is created on the lower branch of the resonance curve. This now opens the door to the first kind of ponderomotive instability: the monotonic or jump instability.

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC0018362 and Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.
† brownjac@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP20

MULTI-Q BEAM STUDIES AT FRIB: SIMULATIONS AND MEASUREMENTS

A. Gonzalez*, K. Fukushima, T. Maruta, P. N. Ostroumov, A. S. Plastun
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The Facility for Rare Isotope Beams (FRIB) linear accelerator is capable of simultaneously transporting and accelerating multiple-charge-state heavy-ion beams. Accurate transverse and longitudinal matching of these beams is a challenging problem, particularly in achromatic bending segments of the linac. To solve it, we employ both macroparticle tracking and linear optics codes. The simulation models are being developed, cross-checked, and validated by beam measurements. The studies are focused on the beam size, envelope matching, charge state separation, and the response of the beam position. The results of the studies with the 16.5 MeV/u five-charge-state uranium beam will be presented.

INTRODUCTION

Charge stripping is essential for efficient acceleration of heavy-ion beams. When a heavy-ion beam is stripped, the resulting charge distribution is a Gaussian function centered on the mean charge state. The mean and standard deviation of this Gaussian depends on many factors like beam velocity, atomic mass of ions in the beam, stripper material and stripper thickness. For optimal placing of a 17 MeV/u uranium beam on the most uniform area of the FRIB liquid lithium stripper, a mean charge state of 75+ with 21% of initial beam intensity is produced [1]. Therefore, the post-stripper segments of the FRIB driver linac were designed to accept and simultaneously accelerate multiple charge states and deliver them to the target. In March 2025, we developed the linac tune to produce 20 kW of uranium beam on the target by accelerating five charge states after the stripper.

To support the beam dynamics optimization and simulations in the FRIB linac, two codes are used: TRACK [2] and FLAME [3]. TRACK is a 3-dimensional particle tracking code which simulates the dynamics of multi-charge-state heavy ion beams. FLAME, which stands for Fast Linear Accelerator Model Engine, is a linear optics code which uses matrices to simulate trajectories and beam envelopes. This makes it very useful for various optimization problems, such as the development of design magnet settings. After applying the FLAME-created settings to the machine, the Courant-Snyder (CS) parameters measured with profile monitors often do not match those in simulations.

In the FRIB linac, wire scanner profile monitors are used to measure the profile of a beam. To find the CS parameters, a technique known as a quadrupole scan is used. A set of 7-10 different currents in two quadrupoles close to the desired profile monitor are used and the horizontal, vertical, and diagonal beam sizes are measured at every step. Then, horizontal emittance, vertical emittance, and CS parameters are optimized in FLAME until the simulation best fits the measurements at each step. Each step of the scan takes about two to three minutes, meaning one complete scan can take around 15 to 30 minutes. For a five-charge-state uranium beam, measuring all charge states can take over two hours.

During primary beam development, we perform quadrupole scans at the entrance of all three linac segments, upstream of the stripper, and at the entrance of the Beam Delivery System (BDS). Better simulation accuracy will reduce the amount of measurements needed, greatly reducing beam tuning time, and improve the quality of beam matching, which in turn will mitigate the beam loss. These two reasons provided motivation to investigate the simulation models and try to improve their accuracy.

TRANSVERSE BEAM MATCHING IN FS1

These studies focus on the first 180° achromatic bend in the FRIB linac, Folding Segment 1 (FS1). In FS1, for a multi-charge-state beam, we do a quadrupole scan and reconstruct the beam envelopes with FLAME for each individual charge state. Based on the reconstructed envelopes, the quadrupole fields close to the entrance to Linac Segment 2 (LS2) are adjusted to match the beam to LS2. At the location of the stripper, the transverse beam size of each charge state should be equal. However, in the reconstructions, the rms beam size of each charge state at the stripper is different, as seen in the blue bars of Fig. 1, meaning the FLAME model is not accurate. Using a five-charge-state uranium beam with an energy of 16.5 MeV/u, measurements and simulation results were compared with the goal of improving the FLAME model.

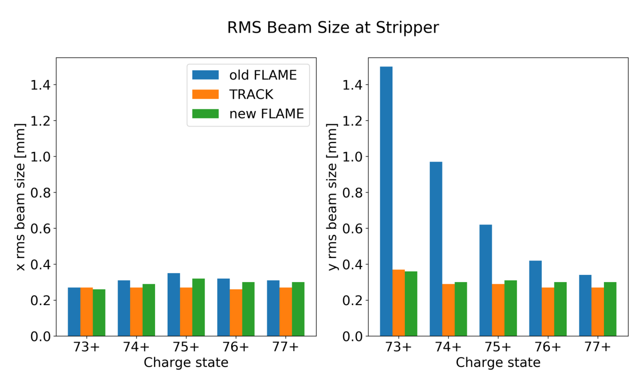

Figure 1: Comparison of rms beam sizes at lithium stripper for five-charge-state uranium beam.

* gonzalea@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP24

VARIABLE WEDGE FOR ARIS*

Z. Wu[1,2,†], M. Hausmann[1], X. Rao[1], B. Sherrill[1]
[1]Facility for Rare Isotope Beams, East Lansing, MI, USA
[2]Department of Mechanical Engineering, Michigan State University, East Lansing, MI, USA

Abstract

A variable wedge degrader system has been developed at the Facility for Rare Isotope Beams (FRIB) to purify in-flight rare isotope beams. The system incorporates three independently movable wedge pairs: two with quadratic profiles for angle tuning (covering 3–20 mrad) and one with a linear profile for fine thickness adjustment. To support experiments at FRIB's DB2 location, the system maintains an approximately linear relationship between beam angle and center thickness, typically following Angle ≈ 1.2 × Thickness, resulting in a thickness range of 2.5 – 16.67 mm. An automated MATLAB-based controller selects the appropriate operating mode—high-angle or low-angle—and calculates wedge positions and virtual stepper motor steps accordingly. Simulations confirm the system achieves target angle-thickness combinations across most of the range, with larger deviations observed near 4–5 mrad. This paper presents the design architecture, control logic, and simulation results validating system performance.

INTRODUCTION

Wedge-shaped degraders are widely used for in-flight purification of rare isotope beams, a technique first implemented at GANIL [1]. By placing a degrader at a dispersive focal plane, energy loss becomes position-dependent, creating an achromatic focus downstream and enabling ion separation based on magnetic rigidity [2–4]. This approach has been adopted in fragment separators at RIKEN [5, 6], GSI [7, 8], NSCL [9], and the Facility for Rare Isotope Beams (FRIB) [10, 11]. At FRIB, the Advanced Rare Isotope Separator (ARIS) system utilizes degraders at multiple focal points—including the Pre-Separator and DB2 diagnostic box—to achieve beam purification through the momentum-loss achromat method [10, 12, 13]. More than 60 fixed-profile wedges have been fabricated to support over 8,000 operational hours [14], with additional applications including momentum spread reduction by a factor of three [15]. Currently, each wedge is custom-manufactured based on pre-run LISE++ simulations [16], which limits flexibility during last-minute beamline adjustments and contributes to downtime between experiments. To address these challenges, we present a variable wedge degrader system inspired by the tunable design of Hwang *et al.* [17], which demonstrated real-time angle control via symmetric motion of quadratic-profile aluminum wedges. The proposed system integrates two pairs of angle-controlling wedges—one optimized for low-angle operation (≤ 7 mrad), the other for high-angle operation (> 7 mrad)—alongside a third linear-profile wedge pair for thickness compensation. This architecture enables simultaneous and decoupled tuning of beam angle (3–20 mrad) and center thickness (2.50–16.67 mm), covering the full operational envelope of the DB2 beamline. The following sections present the system design, operating principles, and simulation results validating its performance.

* Work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.
†wuz@frib.msu.edu

DESIGN

The 6-piece variable wedge system is designed to make each pair operate via symmetric displacement of its components to achieve the desired configuration. Based on the input angle and center thickness, the system automatically selects the appropriate mode and moves the unused pair(s) outside the effective region (beyond ±50 mm). This design allows for continuous and decoupled adjustment of both angle and thickness across the operational range.

The general form of the thickness-versus-position function for a wedge pair under symmetric displacement is defined as follows:

$$y = f(x) = f_a\left(x - \tfrac{1}{2}\Delta x\right) + f_b\left(x + \tfrac{1}{2}\Delta x\right) \quad (1)$$

For High Angle Wedges (≥7 mrad),

$$f_{1,2}(x) = 2(-a_1\Delta x + b_1)x + (c_1 + c_2) \quad (2)$$

Similarly, for Low Angle Wedges (<7 mrad),

$$f_{3,4}(x) = 2(-a_3\Delta x + b_3)x + (c_3 + c_4) \quad (3)$$

For Linear Shaped Wedges,

$$f_{5,6}(x) = -b_5\Delta x + (c_5 + c_6) \quad (4)$$

Where,

- $f_i(x)$ is the stacked thickness of the ith wedge as a function of transverse position, x. x is ranging from 0 to +200 mm.
- Δx is the distance between the center positions of two wedges within one pair, to represent the distance each wedge moves away from the center please use $\frac{1}{2}\Delta x$.
- $a_1 = 0.0001$ is the component of second order term for Wedge 1, a_1 and a_2 are only different in sign, so $a_2 = -0.0001$. Wedge 1 and Wedge 2 have the same component value on linear terms, so $b_1 = b_2 = 0.01$, then $c_1 = 0.5$ and $c_2 = 2.5$, representing different constant terms.
- Similarly, for Wedge 3 and Wedge 4, $a_3 = -a_4 = 0.00014$, $b_3 = b_4 = 0.0015$, $c_3 = c_4 = 1.1$.
- For Wedge 5 and Wedge 6, $b_5 = -b_6 = 0.03925$, $c_5 = 0.5$ while $c_6 = 8.35$.

The overall layout of the wedge system is shown below (Figs. 1 and 2). With desired angle and center thickness put in, the system will decide which pairs of wedges will be in the effective range and move away the unused pair(s).

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-THX03

HIGH ENERGY ION IMPLANTATION AT BNL*

D.B. Steski[1, †], C. Carlson[1], T. Kubley[1]
[1]Brookhaven National Laboratory, Upton, NY, USA

Abstract

Silicon carbide (SiC) has several properties such as wide band gap and high voltage breakdown, that give it a significant advantage over silicon for the next generation of medium and high frequency applications. To fully realize these advantages, requires deep ion implantation (~>6 µm). Unfortunately, the energy of conventional ion implanters limits the implantation depth in SiC to approximately 1µm. Brookhaven National Laboratory (BNL) has developed a system that uses the 15 MV MP-class Tandem Van de Graaffs to implant ions in SiC to a depth >15 µm. By changing the ion beam energy in discrete steps, the overlapping implantations can build a uniform implantation profile from the maximum implantation depth to the surface. To implant ions near the surface of the SiC wafer requires the use of an energy absorber to degrade the ion energy from 10's of MeV to a few keV. BNL has built a system to demonstrate the feasibility of this approach. The BNL system is described, and the results of high energy implantation for high voltage SiC devices are presented. Future improvements to the system are also discussed.

INTRODUCTION

The Tandem Van de Graaff Facility [1] at Brookhaven National Laboratory (BNL) (Fig. 1) consists of two MP-class tandems (MP6 and MP7) (Fig. 2). Each tandem can be operated independently at a terminal voltage of >14 MV. The tandems are connected to the BNL Booster synchrotron by a 900 m long transfer line and can provide a variety of ion species (from protons to gold) for use at the Relativistic Heavy ion Collider (RHIC) and the NASA Space Radiation Laboratory (NSRL). The tandems can also supply ion beams to two local target rooms (TR2 and TR4) for space and industrial applications.

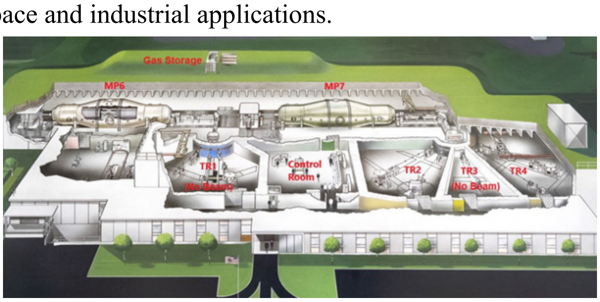

Figure 1: The BNL Tandem Van de Graaff Facility.

BNL was approached with the idea of using the Tandem Van de Graaffs to perform high energy implantations in silicon carbide (SiC).

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the US Department of Energy
† steski@bnl.gov

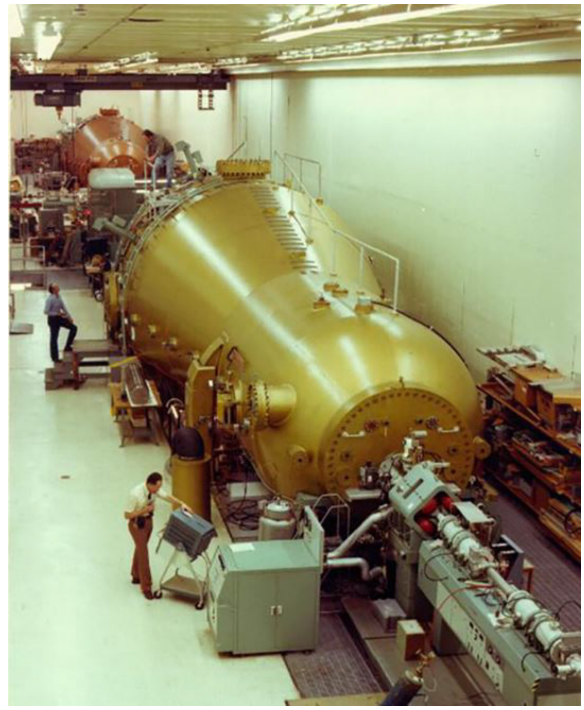

Figure 2: MP7 in foreground, MP6 in background.

The power electronics industry is very interested in the use of SiC in medium voltage and high frequency applications. Unfortunately, the low dopant diffusion constant for SiC limit the implantation depth of conventional implanters to <1µm. To fully take advantage of SiC's properties, deep implantations (>6 µm) are required. The BNL designed system, described below, has demonstrated implantation of aluminium and nitrogen in SiC to a depth of >12 µm.

HIGH ENERGY IMPLANTER

The high energy implanter [2] at BNL, uses an existing beam line in target room 2. The beam line has the unique feature that the diameter of the beam pipe increases from 100 mm to 710 mm just before the end vacuum chamber. This feature of the beam line allows the beam to be swept horizontally over a large area.

The implanter (Fig. 3) consists of a pair of horizontal deflector plates, an aluminium foil energy absorber, a series of Faraday cups for beam diagnostics and a vertical linear stage on to which the SiC wafers are mounted. The deflector plates sweep the beam horizontally at 400 Hz while the linear stage drives the wafers vertically through the swept ion beam at 10 mm/sec. This relatively slow speed ensures that the implantation is uniform over the entire wafer.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-THA03

SIX-DIMENSIONAL BEAM MATCHING WITH LINEAR ACCELERATOR STRUCTURES*

Y.K. Batygin†, Los Alamos National Laboratory, Los Alamos, NM, USA

Abstract

Beam matching is a common technique routinely employed in accelerator design to minimize beam losses and preserve beam quality. A matched beam occupies the smallest volume in 6D phase space, leading to improved beam brightness, a measure of the beam's quality. Six-dimensional beam matching involves adjusting beam parameters to match the accelerator's lattice. Here we present an analytical treatment of 6D beam matching of a high-intensity beam onto an RF structure. We discuss the application of the averaging method to attain an analytical solution for a set of matched 3D beam envelope equations. We then consider the more general self-consistent approach to beam equilibrium in 6D phase space based on Hamiltonian analysis. Finally, we discuss the role of the equipartitioning concept in beam matching.

AVERAGED BEAM ENVELOPES

Beam matching is often attributed to finding a periodic solution for beam envelopes in periodic accelerator structures using state-of-the-art codes as TRACE-3D [1]. The 3D equations for beam envelopes $R_x = \sqrt{5\langle x^2 \rangle}$, $R_y = \sqrt{5\langle y^2 \rangle}$, $R_z = \sqrt{5\langle \zeta^2 \rangle}$ can be written as

$$\frac{d^2 R_x}{dt^2} = -\frac{q\beta c}{m\gamma} G(z) R_x + f_x(R_x, R_y, R_z), \quad (1)$$

$$\frac{d^2 R_y}{dt^2} = \frac{q\beta c}{m\gamma} G(z) R_y + f_y(R_x, R_y, R_z), \quad (2)$$

$$\frac{d^2 R_z}{dt^2} = f_z(R_x, R_y, R_z), \quad (3)$$

where the functions f_x, f_y, f_z are

$$f_x(R_x, R_y, R_z) = \frac{\varepsilon_x^2 c^2}{\gamma^2 R_x^3} + \frac{\Omega^2 R_x}{2} + 3\frac{I}{I_c}\frac{c^2 M_x \lambda}{\gamma^3 R_y R_z}, \quad (4)$$

$$f_y(R_x, R_y, R_z) = \frac{\varepsilon_y^2 c^2}{\gamma^2 R_y^3} + \frac{\Omega^2 R_y}{2} + 3\frac{I}{I_c}\frac{c^2 M_y \lambda}{\gamma^3 R_x R_z}, \quad (5)$$

$$f_z(R_x, R_y, R_z) = -\Omega^2 R_z + \frac{\varepsilon_z^2 c^2}{\gamma^6 R_z^3} + 3\frac{I}{I_c}\frac{M_z c^2 \lambda}{\gamma^3 R_x R_y}, \quad (6)$$

m and q are the mass and charge of particles, β and γ are beam velocity and energy, $G(z)$ is the gradient of quadrupole lenses, $\varepsilon_{x,y,z} = 5\varepsilon_{x,y,z\_rms}$ are 5-rms normalized beam emittances, $\Omega = \sqrt{2\pi q E |\sin\varphi_s| / (m\beta\gamma^3\lambda)}$ is the longitudinal oscillation frequency, $E = E_o T$ is the amplitude of the accelerating wave, φ_s is the synchronous phase, λ is the RF wavelength, I is the beam current, $I_c = 4\pi\varepsilon_o mc^3 / q$ is the characteristic beam current, M_ϑ, $\vartheta = x, y, z$ are ellipsoid coefficients:

$$M_\vartheta = \frac{1}{2}\int_0^\infty \frac{R_x R_y \gamma R_z \, ds}{(R_\vartheta^2 + s)\sqrt{(R_x^2+s)(R_y^2+s)(\gamma^2 R_z^2 + s)}}, \quad (7)$$

and $R_\vartheta = R_x$, R_y, γR_z. Here we consider a typical case where the longitudinal oscillation frequency is changing slowly concerning the variation of the alternative-sign gradient of quadrupole lenses. Importantly, envelope equations contain rapidly oscillating parts determined by the function $G(z)$, and weakly oscillating functions f_x, f_y, f_z due to the variation of beam sizes $R_\vartheta = R_x$, R_y, R_z. The gradient of the focusing field with the focusing period S can be expanded into a Fourier series:

$$G(z) = \sum_{n=1}^{\infty} g_n \sin(\frac{2\pi nz}{S}). \quad (8)$$

According to the averaging method [2], solutions of differential equations of second order, containing fast oscillating and slow variable terms, can be represented as

$$R_x(z) = \bar{R}_x(z) + \xi_x(z), \qquad R_y(z) = \bar{R}_y(z) + \xi_y(z), \quad (9)$$

where $\bar{R}_x(z)$, $\bar{R}_y(z)$ are slow variable functions with respect to fast oscillation frequency determined by alternative-sign gradients, and $\xi_x(z)$, $\xi_y(z)$ are small-amplitude, rapidly oscillating functions. For the smooth part of the solution, application of the averaging method gives:

$$\frac{d^2 \bar{R}_x}{dt^2} = -\frac{1}{2}\sum_{n=1}^{\infty}\frac{F_n^2}{\omega_n^2}\bar{R}_x + f_x(\bar{R}_x, \bar{R}_y, R_z), \quad (10)$$

$$\frac{d^2 \bar{R}_y}{dt^2} = -\frac{1}{2}\sum_{n=1}^{\infty}\frac{F_n^2}{\omega_n^2}\bar{R}_y + f_y(\bar{R}_x, \bar{R}_y, R_z), \quad (11)$$

† batygin@lanl.gov

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-THY01

NEWGAIN PROJECT AT GANIL: CONSTRUCTION OF THE NEW HEAVY ION INJECTOR FOR SPIRAL2*

F. Chautard[1,†], D. Ackermann[1], J. Dumas[5], M. Di Giacomo[1], A. Fournier[2], F. Hanchin[1], C. Haquin[1], C. Jamet[1], J. Karam[1], C. Lesigne[1], M. Michel[1], G. Normand[1], Ph. Robillard[1], C. Peaucelle[3], O. Piquet[5], P. Sénécal[1], D. Simon[5], I. Stephan[4], T. Thuillier[3], Y. Trehudic[1]
[1]GANIL, Caen, France
[2]Université de Bordeaux, CNRS-LP2I, Bordeaux, France
[3]Université Grenoble Alpes, CNRS-LPSC, Grenoble, France
[4]Université Paris-Saclay, CNRS-IJCLAB, Orsay, France
[5]CEA/IRFU, Saclay, France

Abstract

The NEWGAIN (NEW GAnil INjector) project is now in the construction phase at GANIL. The goal is to accelerate heavier ions with the SPIRAL2 accelerator, ions with an A/q ratio of up to 7. With this upgrade, SPIRAL2 will provide high-intensity beams, from protons to uranium, strengthening GANIL international competitiveness, both in fundamental sciences and related applications. The paper will provide an update on the progress of the construction phase and the main milestones achieved and to come. The layout and the main technical components of the new injector, based on 2 ECR ion sources (one of them existing), two LEBT, one RFQ and a MEBT section to transport the beam into the present MEBT connected to the SPIRAL2 LINAC are presented.

INTRODUCTION

The NEWGAIN project aims to build a second injector designed for A/q = 3 to 7 ions, to produce very intense heavy ion beams up to uranium, far exceeding the performance of the existing injector. Thus, a new superconducting source will be developed to complement the existing sources and achieve high-intensity uranium beams.

Thanks to this improvement, the SPIRAL2 LINAC [1] will deliver, within the limits of its operating energy, the most intense beams in the world (Table 1) on a wide variety of ions ranging from protons to uranium, and will strengthen GANIL's international competitiveness, both in fundamental sciences and in associated applications.

The project is organized within a large technical collaboration framework, composed of the following French accelerator laboratories from CEA/DRF/IRFU and CNRS/IN2P3: GANIL, IRFU/DACM and DIS, LPSC, LPCCaen, IPHC, LP2iB, IJCLab. These different partners are already used to collaborate in different projects with GANIL, the latest example to date being the construction of the SPIRAL2 facility. The NEWGAIN project is coordinated by GANIL.

*This work benefited from state aid managed by the French National Research Agency under the Future Investment Program bearing the reference ANR-21-ESRE-0018
†chautard@ganil.fr

Table 1: Ion Beam Intensities in SPIRAL2 Actual Beamline and with the NEWGAIN Injector

Ions	Intensity [pμA]		
	SPIRAL2	NEWGAIN	
	Phoenix V3 A/Q≤3	Phoenix V3 A/Q≤6	SC Ion Source A/Q≤7
18O	80*	-	375
19F	>15	>40	>40
36Ar	16*	70	45
40Ar	3.6	70	45
36S	2.3	-	-
40Ca	2.9*	10	20
48Ca	1.2	10	20
58Ni	1.1*	4	8
84Kr	0.1	10	20
139Xe	0.001	7	>10
238U	<<0.001	0.1	10

*Measured, Foreseen

GENERAL LAYOUT

This second injector is designed to be fully compatible with the existing facility (Fig. 1) and to further enhance its 'multi-user' capabilities. It is composed of the following (Fig. 2):

- A high-performance superconducting ion source (Source 1/7) called ASTERICS [2],
- A low energy beam transport allowing the connection of both ion sources (superconducting ion source and existing room temperature ion source) to the RFQ (LBE3). The mass separation at the exit of the ion sources can be tuned up to 150, depending on the ion choices and the experiment needs,
- A RFQ that will accelerate heavy ions with minimal beam losses up to the injection energy for the superconducting LINAC (RFQ2),
- A medium energy beam transport to the LINAC (LME2), giving also the possibility to send the beam into an experimental area (to be built) in the future.

The injector will be installed in an existing cave built 15 years ago in the SPIRAL2 building. The view of the injector inside the existing facility is shown on Fig. 3.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-THY02

DEMONSTRATION OF CAVITY FIELD MAPPING BY FALLING DROPS OF LIQUID*

X. Du, L. Groening
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

Abstract

This paper presents a novel bead-falling method for precise mapping of electromagnetic fields in radio-frequency (RF) cavities, critical for accelerator design. Unlike the traditional bead-pull method, which relies on a wire-pulley system prone to mechanical errors, this technique uses free-falling beads to eliminate perturbations from wires. A compact, portable device integrates a bead release system, detection mechanism and a mini-computer for rapid and accurate field measurements. Tested on a three-gap buncher cavity and a scaled Alvarez-type cavity, the method demonstrates high precision even under low signal-to-noise ratios and environmental vibrations. This approach simplifies setup, enhances measurement speed, and offers potential as a new standard for RF cavity diagnostics.

INTRODUCTION

Radio-frequency (RF) cavities are fundamental components in particle accelerators, shaping electromagnetic fields to accelerate charged particles. Precise field measurements are essential for ensuring cavity performance aligns with design specifications, particularly for applications in high-energy physics and medical accelerators. The bead-pull method, rooted in Slater's perturbation theory [1], has been the standard for mapping field distributions by measuring frequency shifts induced by a bead moved through the cavity via a wire-pulley system. However, this method faces challenges, including mechanical complexities, wire-induced perturbations (especially for higher-order modes), and time-consuming setup processes.

To address these limitations, we developed a bead-falling measurement method, as detailed in [2], which eliminates the wire-pulley system by using free-falling beads or droplets to perturb the cavity field. This technique simplifies the experimental setup, reduces mechanical errors, and enables rapid measurements suitable for real-time monitoring. The method's versatility allows it to be applied to various cavity types, such as Radio-Frequency Quadrupoles (RFQs) and Drift Tube Linacs (DTLs), enhancing the efficiency of cavity tuning and diagnostics. This paper elaborates on the method's design, hardware, software, and experimental validation, demonstrating its potential to redefine RF cavity field measurements.

* Work supported by GSI Helmholtzzentrum für Schwerionenforschung GmbH

CONCEPTUAL DESIGN AND ADVANTAGES

The bead-falling method induces perturbations by releasing a bead or droplet to fall freely through the RF cavity along the beam axis, with a VNA capturing resulting phase or frequency shifts (Fig. 1). The bead's position is correlated with time using kinematic equations, accounting for gravitational acceleration, to map the field distribution accurately.

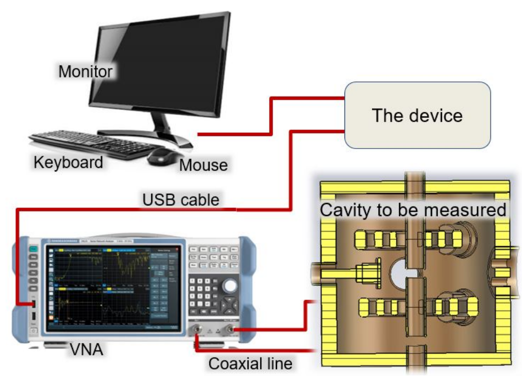

Figure 1: Scheme of bead-fall RF-measurements. The cavity is connected to two of the VNA ports. The device includes the bead/droplet release system and the bead detector. It is positioned such that the falling bead is aligned to the beam axis of the cavity. Beads are released from the top and fall freely through the bead-detector and subsequently through the cavity.

Compared to the bead-pull method, this approach offers several advantages:

- **enhanced precision**: small beads (0.5–1 mm) minimize field variations across their volume, and the absence of a wire eliminates perturbations, particularly for dipole modes.
- **rapid measurements**: free-fall durations of less than 0.5 s enable measurements at 2 Hz, supporting real-time field monitoring during tuning.
- **simplified setup**: eliminating the wire-pulley system reduces setup time and mechanical complexity, making the method adaptable to various cavity geometries.
- **material flexibility**: the use of liquid droplets (e.g., water) allows for rapid, iterative measurements, enhancing experimental efficiency.
- **robustness**: the method performs reliably under challenging conditions, such as low signal-to-noise ratios

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-THY03

OPERATION OF A PULSED GAS STRIPPER DURING REGULAR USER BEAM TIME AT GSI

P. Gerhard* and M. Maier
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

Abstract

The charge state spectrum of heavy ions like uranium stripped at 1.4 MeV/u using nitrogen as stripping target can be narrowed significantly by applying pulsed injection of hydrogen into a dedicated interaction chamber. Pulsing reduces the gas load of the pumping system to an acceptable amount. Such a setup is under construction at GSI. Time-resolved investigations of the build-up of the stripping target have been carried out. A prototype setup has been operated during six months of user beam time in 2024 and is currently again in operation for the user beam time 2025, mainly with nitrogen but also with hydrogen. A number of ion species has been stripped in the course of the beam times, and a considerable amount of data on stripping efficiencies have been measured using both gases. The contribution summarizes the challenges related to establishing such a setup, the results being obtained so far and lessons learned.

INTRODUCTION

The GSI accelerator facility, in particular the UNILAC (UNIversal Linear ACcelerator) and the heavy ion synchrotron SIS18, serve as injector for the upcoming Facility for Antiproton and Ion Research (FAIR), the commissioning of which will start in 2026. High intensity ion beams are provided by dedicated high current sources and pre-accelerated by the high current injector (HSI). The HSI is designed for handling ions with a mass-to-charge-ratio of up to $A/q = 65$, since the ions delivered by the high current sources have inherently low charge states [1]. A gas stripper is necessary to increase the charge state to enable efficient acceleration in the subsequent Alvarez drift tube linac. Stripping is applied at 1.4 MeV/u after acceleration in the HSI. Until recently, a continuous nitrogen gas jet was employed as stripping target [2]. Out of the charge state spectrum resulting from the stripping process, one charge state has to be separated for further acceleration. For heavy ions like uranium, this results in the loss of up to ≈87% of the beam.

In order to increase the yield into the desired charge state, introducing hydrogen and other gases as stripping targets was investigated [3]. With H_2, the width of the charge state distribution of heavy ions is significantly reduced and the stripping efficiency increased accordingly, e. g. by approximately 50% for $^{238}U^{28+}$. Additionally, an increase of the mean charge state can be achieved for all ions. The proof-of-principle was demonstrated successfully in 2016 [4–6].

The decision to introduce H_2 into regular operation induced several challenges. Since hydrogen is highly combustible, comprehensive safety measures have to be implemented. H_2 is also much more difficult to pump. It soon became clear that the gas load had to be reduced, which lead to the pulsed operation of the gas target. It exploits the low duty factor of the UNILAC by delivering only short pulses of high gas density synchronized with the beam pulse. This was realized via commercially available, fast injection valves. Together with the demand to have different gases (H_2 and N_2) and target densities available in parallel, the now pulsed gas stripper became a much more complex system than the jet stripper was. Therefore, a fully automated setup suitable for safe and regular operation has to be developed [7, 8].

In late 2023, it was decided to utilize the development setup for the user beam time 2024, putting the pulsed stripper into regular operation ahead of schedule. This was repeated for the beam time 2025. Several improvements were implemented to minimize the restrictions on operation given by the developmental status of the setup. The still incomplete implementation of the safety concept meant that only N_2 operation was possible for user operation.

DEVELOPMENT SETUP AND RECENT UPGRADES

A second generation stripper setup (Fig. 1) was designed after it was found during the proof-of-principle that the original valves would break down after only a few hours of operation [7]. It contains two fast injection valves of a new

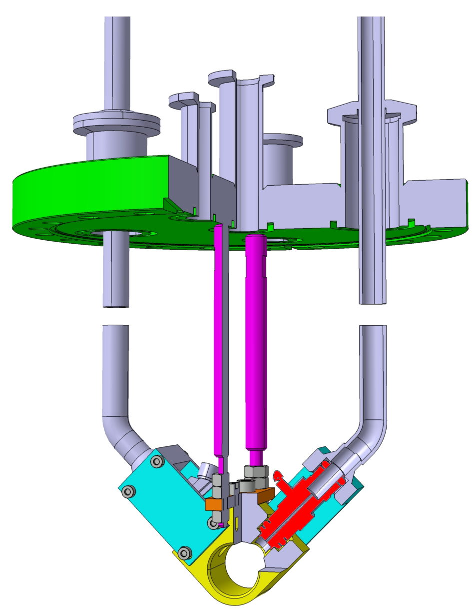

Figure 1: Sketch of the current pulsed stripper setup. The fast injection valve is indicated in red. More details in [7, 8].

* p.gerhard@gsi.de

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-THY04

RF POWER LIMITS OF 4-ROD RFQS*

H. Podlech†[1,2], P. Braun, H. Hähnel, K. Kümpel, U. Ratzinger[2], J. Storch, S. Wagner, C. Zhang[1,3]
Institute for Applied Physics, Goethe University, Frankfurt, Germany
[1]also at Helmholtz Research Academy Hesse for FAIR (HFHF),
GSI Helmholtzzentrum für Schwerionenforschung, Frankfurt, Germany
[2]also at Bevatech GmbH, Walldorf-Mörfelden, Germany
[3]also at GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

Abstract

Radio Frequency Quadrupoles (RFQ) are today the standard structures for focusing, bunching and accelerating a DC beam delivered by an ion source. Regardless of the used RF structure, 4 electrodes (rods, vanes) are periodically charged by RF fields and generate a time varying electric quadrupole field. The two most common RF structures are the 4-Vane RFQ and the 4-Rod RFQ. While the 4-Vane RFQ is a cavity operated in the TE_{211}-mode, the 4-Rod RFQ is a transmission line resonator consisting of a chain of strongly coupled RF cells. The 4-Rod RFQ is the most frequently used structure for frequencies below 250 MHz. In the past, the 4-Rod RFQ had problems with high power operation and high average thermal load. In the last years, a vigorous R&D program has been performed to make the 4-Rod RFQ suitable for such applications. The progress of the development of high power 4-Rod RFQs with associated projects are presented.

INTRODUCTION

RFQ accelerators operated with high power and high duty factor up to cw facing in general many challenges. The most common problems are local excessive heating due to high power densities and thermal instabilities resulting in significant frequency shifts. The most prominent example of a 4-Rod high power RFQ developed in the past is the SARAF RFQ. This 3.9 m long RFQ has been designed to accelerate a 4 mAdeuteron beam to 1.5 AMeV with 100% duty factor. The required total RF power of 250 kW resulted in a thermal load of more than 60 kW/m. Although the SARAF RFQ could successfully accelerate protons (cw) and deuterons (50%), it was not possible to reach the full power level. Finally, it was required to re-design the electrodes with lower beam energy (1.27 AMeV) to limit the RF power to 200 kW [1]. Based on this experience, an R&D program has been initiated to optimize the 4-Rod structure, especially with respect to high power operation.

176 MHZ RFQ PROTOTYPE

As part of the R&D program, the cooling of stems, electrodes, and tuning plates was optimized in particular. A new manufacturing method using thick-film copper plating was established. For this purpose, the cooling channels were milled into the individual blanks (electrodes, stems, tuning plates), filled with conductive wax, and then copper plated several millimeter thick. This was followed by final machining to the required dimensions and removal of the wax. Figure 1 shows the cooling channels of the 176 MHz proto-

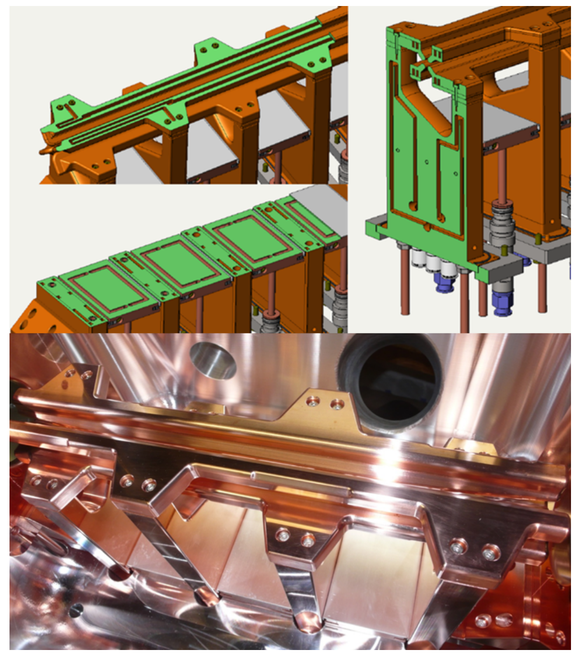

Figure 1: Cooling channels of the 176 MHz RFQ prototype (top), fabricated prototype (bottom).

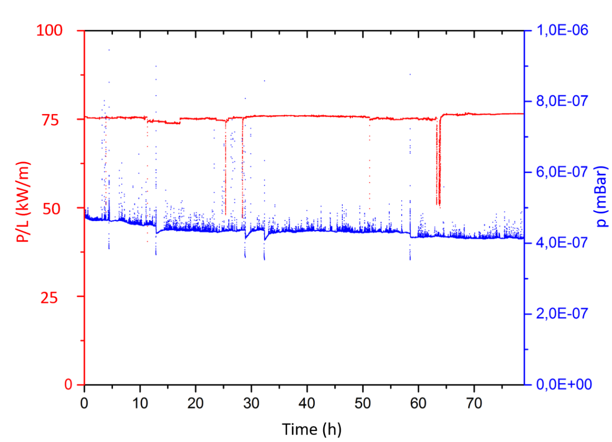

Figure 2: Prototype long run test with 30 kW (75 kW/m).

* BMBF Project No. 05P15RFRBA, HFHF, LOEWE No. HA1575/23-128
† h.podlech@iap.uni-frankfurt.de

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-FRX01

A CHARGE STRIPPER RING FOR RIKEN RI BEAM FACTORY

H. Imao*
RIKEN Nishina Center, Wako, Japan

Abstract

The Charge Stripper Ring (CSR), developed at RIKEN RI Beam Factory (RIBF), is designed to enhance the intensity of uranium heavy-ion beams. CSR features a structure in which multiple charge states of the beam are simultaneously circulated while undergoing repeated charge exchange with an internal target, enabling both high-efficiency charge conversion and continuous-wave operation. To address the complexity arising from stochastic charge-state transitions, a dedicated simulator based on linear beam dynamics was developed. Using this tool, tuning strategies and tolerance evaluations were performed, yielding favorable results. Furthermore, the CSR concept is extended to propose a new class of ring accelerator, termed "Chreostron," which recycles heavy-ion beams through internal targets with charge exchange. Its potential applications and associated theoretical challenges are discussed.

INTRODUCTION

The RIKEN Radioactive Isotope (RI) Beam Factory (RIBF) [1] is a major heavy-ion accelerator facility that has enabled extensive research on unstable nuclei. A key achievement of RIBF is the production of rare neutron-rich RI beams via in-flight fission of high-intensity uranium beams. These rare isotopes have been essential for experimental studies related to the astrophysical r-process, establishing RIBF as a central facility in the field. The scientific output from RIBF has significantly advanced low-energy nuclear physics and has promoted the development of next-generation RI beam facilities worldwide. The FRIB in the United States began operation in 2022, while RAON (Korea), HIAF (China), and FAIR (Germany) are under construction.

To further expand its scientific reach, an upgrade to RIBF is proposed to access proton-rich and heavy nuclei with atomic numbers greater than ~50. These nuclei are expected to exhibit complex and rich nuclear phenomena such as alpha clustering and fission. The production of rare RI beams in the region will be achieved via projectile fragmentation using more intense uranium beams.

A key technical limitation at RIBF is the low charge-state conversion efficiency at the charge strippers, which restricts further enhancement of uranium beam intensity. Addressing this issue is critical for realizing the full potential of the proposed upgrade and for accessing previously unexplored regions of the nuclear chart. Currently, two types of charge strippers are employed: a helium gas stripper [2–4] and a rotating graphite disk stripper [5, 6]. The combined conversion efficiency for uranium beams is approximately 5%, which imposes a significant constraint on the achievable beam intensity. This limitation directly impacts the overall performance of the RIBF accelerator complex. To overcome this limitation, a novel ring-based system known as the Charge Stripper Ring (CSR) [7, 8] has been proposed to significantly enhance charge conversion efficiency (Fig. 1).

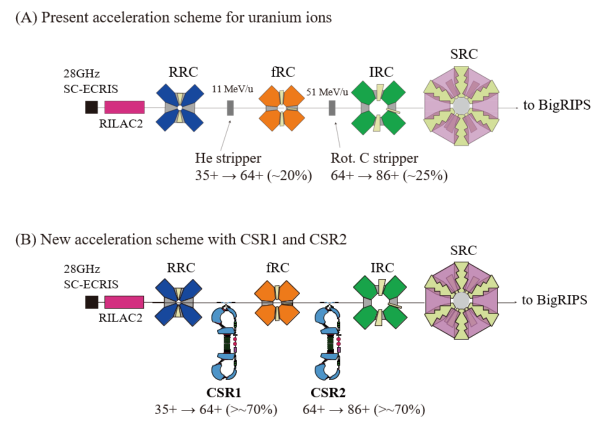

Figure 1: Comparison between the current acceleration scheme for uranium ions and the proposed new scheme utilizing CSR1 and CSR2. The new approach aims to enhance charge state conversion efficiency by a factor of ten, offering significant improvements in beam quality and overall acceleration performance.

CSR is a dedicated ring that incorporates an internal target (stripper), allowing the beam to repeatedly pass through the stripper and thereby increase the likelihood of charge-state conversion. The ring is designed to be isochronous, enabling ions of different charge states to circulate along paths of equal length, and supports continuous-wave (CW) operation similar to that of a cyclotron. It also includes energy-recovery cavities and charge-independent beam focusing elements to maintain stable and efficient beam transport.

Currently, RIBF is advancing the design works of CSR1, intended for use as the first stripper for uranium beams. The CSR1 operates at a circulation energy of 10.8 MeV/u, injecting uranium ions in the 35+ charge state and extracting ions in the 64+ state with an efficiency exceeding 60% (more than three times the current performance). This represents a promising technological advancement for increasing uranium beam intensity.

This report presents the principles, design, and beam tuning methodology of CSR, and introduces the conceptual framework of Chreostron, a generalized extension of CSR with broad potential applications.

BASICS OF CSR1

The CSR1 is employed as the first stripper for uranium beams at RIBF (Fig. 2). It operates with an initial injection

*imao@riken.jp

16th International Conference on Heavy Ion Accelerator Technology, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-FRA01

RARE ISOTOPE BEAM TUNING IN FRIB *

K. Fukushima†, A. C. Dombos, M. Hausmann, D. Kahl, E. Kwan,
P. N. Ostroumov, M. Portillo, B. M. Sherrill, M.K. Smith, M. Steiner
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The Facility for Rare Isotope Beams (FRIB) provides rare-isotope beams for user experiments in nuclear physics, nuclear astrophysics, fundamental symmetries, etc. A superconducting driver-linac accelerates heavy-ion beams onto the production target, and the Advanced Rare Isotope Separator (ARIS) collects and purifies the rare isotope fragments of interest. Subsequently, the transfer hall beamlines deliver isotopes to user setups at experiment stations. The isotope beam condition from ARIS strongly depends on the fragment of interest. Therefore, the beamline settings are optimized for each experiment based on various users' requirements on the fly. Two new beamlines in the transfer hall were commissioned in 2025, bringing the total number of available end stations to five. Since the first user experiments in 2022, ongoing beam tests and operations have continued to improve operational efficiency for users. Results and findings of beam tuning obtained from the commissioning and recent operations are reported in this paper.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) started the scientific user program in May 2022 [1, 2]. The driver linac accelerates all stable ions above 200 MeV/u onto the production target, and the Advanced Rare Isotope Separator (ARIS) [3, 4] provides in-flight separation of projectile fragments and fission fragments. Subsequently, the transfer hall beamlines deliver isotopes to user setups at experiment stations. The transfer hall setting is optimized for each experiment to satisfy various users' requirements. We commissioned the S1 and S2 beamlines in 2025 and started user experiments. Five experiment stations are currently in operation. To optimize the performance of the transfer hall beamline, we prepare and utilize a secondary beam from the production target dedicated to tuning, the so-called pilot beam.

In the following sections, we report on the beam tuning method to deliver the separated fragment beam to the user stations.

BEAMLINE LAYOUT

Figure 1 and Fig. 2 show the beam transmission and layout of the transfer hall beamlines, respectively. The transfer hall is located downstream of ARIS and connected at Diagnostics Box 5 (DB5). There are 5 destinations in the transfer hall: S1, S2, S3, N4S, N4N. The S1 to S3 lines are utilized for the in-flight experiments with different detectors at the end. The N4 lines are utilized for the gas-cell beam stopper and connected to the low-energy experimental area and the Re-accelerator beamline downstream. These beamlines consist of quadrupoles and switching dipoles, and both are superconducting. Typically, the transmission of the transfer hall beamlines shown in Fig. 1 is about 30 – 90%, which strongly depends on the emittance and the energy spread from ARIS. We installed a total of 18 viewer plates in the beamlines to measure the centroid and the spot size of the beam.

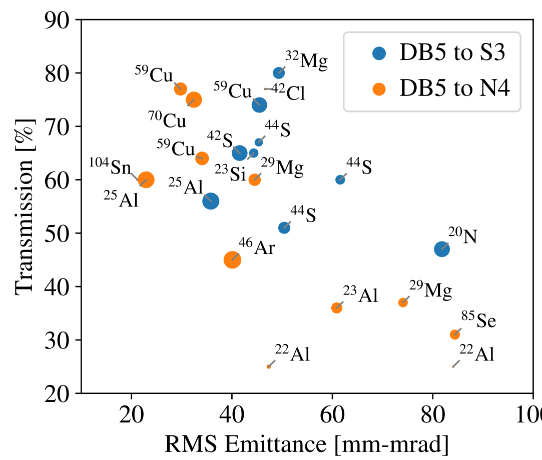

Figure 1: Transmission for user experiments from DB5 to S3 and N4 beamlines. The horizontal axis is the transverse RMS emittance at DB5, and the vertical axis is the transmission of the whole beam, including the fragment of interest (FOI), for each destination. Each dot shows the different experiments, and the dot sizes correspond to the purity of the label's FOI, which varies from 0.2% to 89.8%. Since we can measure the transmission of the whole beam only in most experiments on the fly, the transmission of the low-purity beams is less accurate.

BEAM TUNING

The beam tuning of the transfer hall is performed for each experiment, because the purity and the emittance of the beam from ARIS vary depending on the fragment of interest (FOI) required by the experiment.

As mentioned above, the purity of the fragment varies in experiments and could be lower than 1% in some cases. Also, the FOI is unevenly distributed with respect to the phase space of the entire beam. Therefore, the transmission

* Work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633 and DE-SC0024707.
† fukushim@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-FRA02

RARE-ISOTOPE PRODUCTION OPTICS OF ARIS PRESEPARATOR*

M. Portillo†, Y. Choi, S. Cogan, E. Daykin, A. Dombos, X. Du, K. Fukushima, M. Hausmann, D. Kahl, E. Kwan, S. Lidia, S. Miller, P. Nariyoshi, I. Nesterenko, F. Pereira, P. Ostroumov[1], X. Rao, B.M. Sherrill[1], M.K. Smith, J. Song, M. Steiner, O.B. Tarasov, T. Xu, T. Zhang,
Facility for Rare Isotope Beams, MSU, East Lansing, MI, USA
[1]also at the Department of Physics and Astronomy, MSU, East Lansing, MI, USA

Abstract

The Advance Rare Isotope Separator (ARIS) at FRIB provides in-flight purification of rare-isotope beams (RIB) generated by projectile fragmentation or fission on a target. Beams of stable ions from a driver linac impinge on a graphite target thin enough such that products maintain velocities close to that of the incident beam. The incident primary beam impinges on-target at about 200 MeV/u (for uranium and higher for lighter species). The energy may be lower than the maximum allowed, depending on the requirements of the experiment.

Using multi-charge state acceleration, the linac has most recently provided up to 20 kW on-target with a long-term goal of reaching 400 kW. Specialized magnets, collimators and other components have been integrated into the separator to withstand harsh conditions and facilitate maintenance. The optics properties at the beam dump are important since the power density must be kept low enough to avoid failure of the material. We describe the various optics modes that have been developed for safe operations and maximizing the beam power allowed for RIB production.

INTRODUCTION

The ARIS separator uses magnetic rigidity separation and momentum-loss achromat methods with wedged shaped degraders to purify beams of isotopes according to mass and atomic number Z [1].

The conceptual design was first introduced in a 2013 publication describing the optics and major components [2]. The layout addressed the major issues at the time, notably connecting the high-power driver linac (30 feet below ground level) to the existing experimental facility layout, while serving as a multi-stage in-flight separator. Figure 1 shows a schematic representation of the separator with labeled sections from target to diagnostic box DB5.

The description of each separation stage has already been described in detail by others [2, 3]. More details related to the separator role in operations at FRIB are also provided in these conference proceedings [4].

The focus here will be on the function of Stage 1 and the front-end optics solutions which have been developed for RIB operations. Details about beam transport after DB5 to experiments are described elsewhere [5].

Stage 1 Description

The first achromatic stage is often referred to as the vertical preseparator (PS). This stage is divided at wedge degrader position PSw, such that the front-end provides a momentum dispersion that is ~1/3 of that provided at the back-end, which ends at DB1. This is achieved by using 30º bend dipoles at the front-end and 50º at the back-end. A more detailed description of the magnets is provided in [6].

The latest optics solutions are very similar to the original design but have some slight differences due to slight changes during final construction. The first order matrix terms for the dispersion (x/d) and magnification (x/x) are listed in Table 1. The momentum compression factor can be determined to first order from the optics matrix terms using the following equation [7] :

$$\kappa = \frac{1}{(\mathrm{d/d})_{tot}} = -\frac{(x/\mathrm{d})_2}{(\mathrm{x/x})_2(\mathrm{x/d})_1} \quad (1)$$

Table 1: PS Optics Properties as Described in Text

Optics property	
$(x/d)_D$ Target to Dump [cm/%]	0.92
$(x/d)_1$ Target to PSw	-2.5
$(x/d)_2$ PSw to DB1	7.7
$(x/x)_2$	1.02
p-compression	3.0

The front-end components are exposed to the highest levels of beam loss and radiation from mainly target and beam dump. High power components of the beam are absorbed as much as possible in collimators and thermal shielding on magnets. Beam power after DB1 is typically well below a few watts.

Optics Modes

Three optics modes from target to PSw have been developed to maintain levels of power density to a minimum at beam dump while maximizing the power on-target. They are given names A, B, and C-optics and their first order properties are described by the plots in Fig. 2 and values listed in Table 2. The momentum resolving power is based on first order and a 1 mm beam spot at target.

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
† portillo@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-FRA03

PARTICLE IDENTIFICATION USING TRAJECTORY RECONSTRUCTION WITH THE ARIS SEPARATOR SYSTEM AT FRIB*

E. Kwan†, S. Watters[1], O. B. Tarasov, A. C. Dombos, M. Hausmann, D. Kahl,
D. Kaloyanov[1], M. Portillo, B. M. Sherrill[1], M. K. Smith, M. Steiner
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA
[1]also at Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA

Abstract

The production of radioactive beams is crucial for advancing our understanding of the structure of atomic nuclei away from stability. The operation of the Facility for Rare Isotope Beams (FRIB) enables access to previously unreachable unstable nuclei. Radioactive beams produced at FRIB can be selected and purified using the Advanced Rare Isotope Separator (ARIS) for experimental studies. Ions are identified on based on measurements of energy loss (ΔE), magnetic rigidity ($B\rho$), gamma rays, time of flight (ToF), and total kinetic energy (TKE) using a suite of detectors. The transport of these cocktail beams to the end of ARIS can alter the ion path length and, consequently, the measured ToF. Such variations introduce uncertainty in the particle identification and can degrade the timing resolution if not properly accounted for. Characterizing ion optics with position-sensitive detectors enables corrections to the ions' flight paths. When combined with transfer matrices, this information allows for the reconstruction of ion trajectories, providing event-by-event corrections to the measured ToF.

In addition to improving the ToF resolution, trajectory reconstruction improves the precision of $B\rho$ measurements by enabling a more accurate determination of the momentum deviation ($\delta p/p$) based on reconstructed position and angle information. These corrections are essential for accurate charge-state identification, particularly in high-resolution optics modes. The impact of implementing this trajectory reconstruction method in ARIS operations will be presented.

INTRODUCTION

The production of radioactive beams is important for advancing our understanding of the evolution of nuclear structure in atomic nuclei far from stability and for enabling the study of key nuclei involved in stellar nucleosynthesis processes. At FRIB, radioactive beams are typically produced via projectile fragmentation or in-flight abrasion-fission using various primary beams, from oxygen to uranium. These beams impinge on carbon targets [1] to produce a wide range of nuclear fragments, which are predominantly lighter than the original projectile. These reaction products, which are produced at velocities close to that of the projectile and with a narrow momentum distribution, are then selected and purified using the ARIS separator [2]. The $\texttt{LISE}^{++}_{cute}$ package [3, 4] incorporates various reaction mechanisms using empirically determined parameters to model fragment production yields and charge-state distributions, to optimize separator settings based on simulated ion optics transport.

At FRIB energies, high-Z fragments are often produced in multiple charge states and may undergo further charge exchange in downstream material. Thus, high precision in the mass-to-charge ratio (A/q) is necessary to resolve neighboring isotopes with similar A/q values. A dedicated reconstruction method has been developed from scratch and has recently been implemented in ARIS. The following sections will present results demonstrating its impact on the particle identification resolution.

THE ADVANCED RARE ISOTOPE SEPARATOR

ARIS is a third-generation fragment separator located on the campus of Michigan State University, following the A1200 and A1900 fragment separators. ARIS is designed for multistage separation to reduce the rate of contaminants in the cocktail beam and supports selectable optical modes [5]. Diagnostic boxes (DBs) in the second stage of ARIS are equipped with a suite of detectors (see Ref. [6, 7]). DBs are positioned at both achromatic image planes, where ions with different momenta converge spatially, and dispersive planes, where ion positions vary with momentum. This configuration enables nearly simultaneous measurement of the kinematic properties of the ions, allowing trajectory reconstruction and identification of the atomic number (Z) and A/q.

Parallel-plate avalanche counters (PPACs) [8] are used to characterize ion optics by measuring the position, angle, and ToF of the ions as they traverse the separator. Information from the PPACs, in conjunction with forward and inverse ion-optics mapping, enables the local reconstruction of the ion phase-space vector, as well as the global reconstruction of the momentum and emission angle at the target. This also allows for confirmation of the phase space during tuning [9].

PARTICLE IDENTIFICATION

High-precision measurements of ToF, $B\rho$, ΔE, and TKE are essential to improve the resolution and separability of neighboring fragments, particularly for heavier masses. The particle identification using this approach has been thoroughly described in the appendix of Ref. [10].

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University.
† kwan@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-FRA04

THE SPES-ISOLPHARM BEAMLINE FOR THE PRODUCTION OF MEDICAL RADIONUCLIDES AT INFN-LNL

A. Arzenton[1,*], D. Chen[1,†], M. Lunardon[1], S. Moretto[1],
G. S. Valli[1], INFN, Padova Division, Padova, Italy
A. Andrighetto, S. Corradetti, A. Leso[2], M. G. Martello, D. Serafini[3],
INFN, Legnaro National Laboratories, Legnaro, Italy
E. Mariotti[3], INFN, Pisa Division, Pisa, Italy
[1]also at University of Padova, Department of Physics and Astronomy "G. Galilei", Padova, Italy
[2]also at University of Ferrara, Department of Physics and Earth Sciences, Ferrara, Italy
[3]also at University of Siena, Department of Physical Sciences, Earth and Environment, Siena, Italy

Abstract

The ISOLPHARM project, headed by the Legnaro National Laboratories of the Italian National Institute for Nuclear Physics (INFN-LNL), has the aim of developing innovative radiopharmaceuticals based on the radionuclides produced at the SPES Isotope Separation On-Line (ISOL) facility. Regarding the infrastructure, in late 2024 a key milestone of SPES was achieved: the production of the first radioactive ion beam by irradiating a silicon carbide target with an intermediate-energy proton beam. Moreover, the ISOLPHARM implantation station for radionuclide delivery to users, IRIS, is currently being installed online. Since its beginning in 2014, ISOLPHARM has built a broad network of universities, hospitals and research centers. The β^- emitter silver-111, in particular, obtainable using uranium carbide targets, has aroused a great interest in the collaboration as a theranostic candidate for targeted radionuclide therapy; a dedicated experimental campaign performed the first in-vitro tests and in-vivo imaging in 2024. This contribution will provide an overview on the status of the beamline and on the main results achieved by the preclinical experiments involving silver-111.

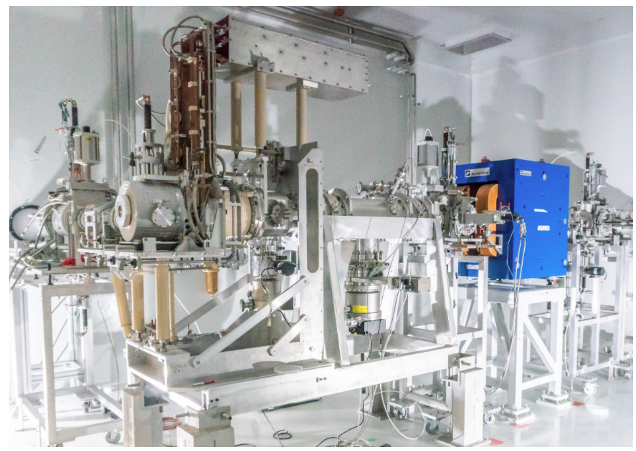

Figure 1: SPES ISOL bunker at INFN-LNL.

RADIOACTIVE ION BEAM PRODUCTION

SPES, standing for "Selective Production of Exotic Species", is an INFN project aimed at developing a second-generation ISOL facility at the LNL [1]. The facility hosts a B70 cyclotron (Fig. 1) produced by BEST Cyclotron Systems operating at proton beam energy of 30 to 70 MeV with intensity up to 750 µA. Such beams can be used for direct activation or, if proper targets are used, to generate Radioactive Ion Beams (RIBs) with the ISOL technique. In SPES, these targets are made of 7 disks of fissile materials, such as uranium carbide (UC_x), or non-fissile materials, such as silicon carbide (SiC) and titanium carbide (TiC) [2]. The disks are spaced in a convenient way to obtain a uniform temperature distribution inside the box. The exotic species originating from the proton-induced nuclear reactions can leave the target box through a transfer line with a characteristic escape time depending on their chemical properties (*e.g.*, their volatility). After that, they reach the ion source, where they can be ionized by three different mechanisms [3, 4]:

- surface ionization, occurring when atoms of the first group touch a hot surface;
- laser photo-ionization, based on stepwise excitation and subsequent ionization by interaction with laser beams tuned on a specific scheme of wavelengths for the element of interest;
- plasma ionization, consisting in an electron plasma hitting and ionizing all atoms with high efficiency and low selectivity.

Once ionized, the atoms can be accelerated by a high voltage and form the RIB. Finally, the beam passes through a Wien filter and becomes isobaric. This allows an extremely pure beam to be obtained, without isotopic contaminants of the desired radionuclides. The ISOLPHARM beamline, described in the next section, takes care of the collection of radionuclides of medical interest in dedicated substrates for subsequent radiochemical processing.

RADIONUCLIDE IMPLANTATION

The ISOLPHARM beamline, as shown in Fig. 2 (left), is installed in the low-energy experimental area of SPES. It is

* alberto.arzenton@pd.infn.it
† daiyuan.chen@phd.unipd.it

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-FRA05

REACCELERATING LONG-LIVED RADIOISOTOPES AT FRIB*

A. Henriques†, S. Nash, X. Chen, N. Gamage, C. Izzo, A. Lapierre, S. Schwarz, H.J. Son, C. Sumithrarachchi, A.C.C. Villari, Q. Zhao
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The ReAccelerator at Facility for Rare Isotope Beams (FRIB) started the stand-alone program in May 2021. Several technical upgrades were implemented to expand the scientific capabilities, including a new BMIS source, a room-temperature rebuncher, and the ReA6 accelerator with its corresponding experimental vault.

Following the commissioning of these upgrades, over 25 beams were delivered to experiments, including six long-lived RIBs: Be-7, Be-10, Al-26, Si-32, Ni-56 and As-73.

In this contribution, we outline the key steps that led to the success of the stand-alone program, including a description of the upgrades, results from the ReA6 commissioning, approaches to mitigating isobaric contamination, and future activities for the ReA stand-alone program.

INTRODUCTION

The ReAccelerator (ReA) [1] at FRIB [2] at Michigan State University has proven to be a unique facility, reaccelerating stopped beams produced by in-flight fragmentation.

In 2021, when the Coupled Cyclotron Facility at National Superconducting Cyclotron Laboratory [3] ceased operations to accommodate preparations for FRIB, ReA continued operations in a stand-alone mode. Ever since FRIB started its scientific program in May 2022, stand-alone beams have been also available to users.

At FRIB, rare isotopes produced by in-flight fragmentation are stopped using linear gas stoppers [4]. These beams can be used for stopped beam experiments or injected into the reaccelerator. Additional sources like the hot-cathode discharge source or surface ionization source, and the Batch Mode Ion Source (BMIS) [5] provide stable and long-lived rare isotope beams (RIB), respectively.

At the ReA front-end, an Electron Beam Ion Trap (EBIT) [6] defines the ion charge state for reacceleration. Ions at 12 keV/u pass through a Q/A separator (R~600) and into the Multi-Harmonic Buncher, before being injected into a 80.5 MHz four-rod RFQ. After, the beam enters the ReA3 superconducting linac with three cryomodules housing 80.5 MHz quarter-wave resonators (β= 0.041 and 0.085) and solenoids for transverse focusing.

Beams up to 1.4 Tm in rigidity can be transported to the ReA3 experimental area where three beam lines can be used for experiments. Beams can also be directed to the ReA6 linear accelerator. This third step of acceleration doubles the beam energy using eight 80.5 MHz quarter-wave resonators (β = 8.5%) .

The current configuration was ready at start of the stand-alone program: BMIS enabled delivery of both stable and long-lived RIBs, and the beam energy available was doubled with the ReA6 accelerator, a new vault, and two beamlines. A new room-temperature re-buncher was also developed and installed.

UPGRADES FOR THE REA STAND-ALONE OPERATION

Batch Mode Ion Source

The Batch Mode Ion Source (BMIS) was installed near the two gas cells, making use of existing beam lines to deliver beams to both the low-energy and ReA areas (Fig. 1).

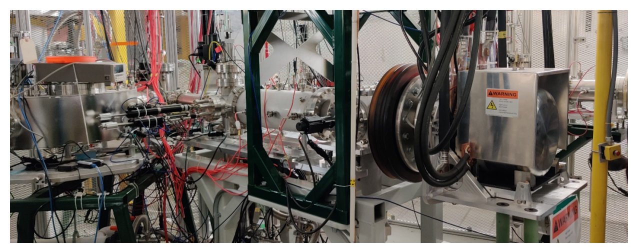

Figure 1: BMIS module and extraction beam line.

The sample material is placed in an oven capable of reaching temperatures up to 2000 °C. Heating the oven initiates the evaporation of the sample. It has a gas handling system for introducing a reactive and/or support gas on-line to enhance this process. The resulting atoms are diffused through a transfer tube, which is maintained at an even higher temperature to facilitate the transport of ions to the ionizer. Various types of ionizers can be employed, such as a Forced Electron Beam-Induced Arc Discharge (FEBIAD) ionizer or a surface ionizer. These devices supply electrons to ionize the neutral atoms. The resulting ions are then extracted using an extraction electrode. The efficiency of beam extraction depends on several factors, including ion source parameters, oven temperature, physical and chemical properties of sample compound, and the operating pressure of the support gas.

BMIS beam development starts with the study of the optimal chemical form to extract the RIB from the source. The desired chemical form is selected and synthesized to have a melting point within the operational range, optimized to reduce melting points and provide the desired yields, while simultaneously not enhance yields of other species that may be also present in the sample [7]. A stable isotope of the

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility of Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.
† henrique@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-FRB02

DEVELOPMENT OF COMPACT ACCELERATOR BASED NEUTRON SOURCES FOR CANADA, THE PC-CANS PROJECT

O. K. Kester[1,2†], D. Marquardt[3], R. Laxdal[1,2], M. Abbaslou[2], A. Gottberg[1]
[1]TRIUMF, Vancouver, Canada
[2]University of Victoria, Victoria, Canada
[3]University of Windsor, Windsor, Canada

Abstract

Neutron scattering has proven to be one of the most powerful methods for the investigation of structure and dynamics of condensed matter on atomic length and time scales. The neutron science community faces a decline of sources for neutrons with research reactors shutting down and even with new spallation neutron sources coming online. In an effort to address this challenge, the global neutron community is responding by taking advantage of recent advances in accelerator technology to develop compact accelerator-based neutron sources (CANS). The Canadian community embarks on a prototype Canadian CANS (PC-CANS) development to perform the first step towards a national Canadian facility of a next generation CANS. The technical development towards this new concept in context on activities in North America will be presented.

INTRODUCTION

Innovation in material developments underpins technology solutions that address many aspects of challenges Canada like other countries is facing. This is the driver for thousands of research teams across Canada to study materials, using probes like neutrons, synchrotron radiation, etc. Neutron beams are versatile probes of materials, complementing X-rays amongst other techniques, because many research problems in materials can only be solved using neutron beams, including in situ observation of small atoms such as lithium in battery cathodes or hydrogen in soft and biomaterials, and determination of magnetic structures and excitations in quantum materials.

Because neutron beams are versatile and irreplaceable tools for materials research, they have been in high demand globally since the 1960s. Their scientific value is why Canadian physicist Bertram Brockhouse won 1994 a Nobel Prize in Physics for pioneering neutron spectroscopy techniques, and why many billion dollars have been invested in neutron infrastructure projects globally since the year 2000. However, neutron beams are increasingly scarce due to closures of old facilities with high replacement costs (typically over $1B) creating a need for lower-cost neutron sources. Compact Accelerator-driven Neutron Sources (CANS) [1] are being explored in Canada to fill this need

A CANS takes advantage of recent advances in accelerator technology to generate neutrons via the bombardment of light metal targets, for example lithium (Li) or beryllium (Be) with intense pulsed proton beams with energies on the order of 5-20 MeV [2]. A Be target is best used to lower costs and reduce size and is efficient beyond ~3MeV beam energy. Be is preferable up to 20 MeV, then metal targets made from Nb (up to 35 MeV) and Ta become more efficient. CANS can provide a local neutron source at a fraction of the cost of a spallation source (or a reactor) given the 100-fold reduction in the required energy, the related cost of a linac as well as the target moderator system and reduced radiation safety requirements. The lower energy also reduces the required shielding and allows neutron instruments to be placed closer to the source (hence, 'compact'). The source can also be highly optimized to meet the end requirements of each instrument, resulting in the production of brilliant beams to rival that of medium sized reactor and spallation sources. Further, the low cost of the linac and target, but high proton beam intensities allow to run several targets moderator assemblies in parallel for independent targets producing cold, thermal, or hot neutrons, each optimized for different end uses, but served by the same driver accelerator via a multiplexer [3].

CANADIAN INTEREST IN A CANS

Following the age-related closure of the NRU Reactor and the Canadian Neutron Beam Centre in Chalk River in 2018, Canadian universities established the national neutron strategy to rebuild capacity for materials research with neutron beams. This strategy envisions an infrastructure laid out in a Neutron Long Range Plan (LRP) [4] program for infrastructure and for research and development with neutron beams. Thus, a Canadian R&D program in CANS technology, and as recommended by the Canadian Neutron Long Range Plan, the focus of the neutron community's activities toward new sources must be established.

The ultimate goal of the community would be a neutron users facility delivering neutron flux comparable to ISIS in the UK [5], based on a High-current compact accelerator-driven neutron sources (HiCANS) [6]. The European neutron strategy published by the League of Advanced European Neutron Sources (LENS) concludes the only route for entirely new facilities with significant capacity that could occupy the role played by national reactor-based sources in the past are HiCANS. A staged approach towards this national facility is planned with a first step of a Prototype Canadian Compact Accelerator-driven Neutron Source (PC-CANS), that can produce neutron beams that are (a) bright enough for neutron diffraction and imaging for some high-throughput experiments and thus meet some of the demand from neutron beam users from across Canada, and (b) low-cost enough (e.g. under $30M) to warrant development of

† okester@triumf.ca