ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THYGBF4

ACCELERATOR PHYSICS ADVANCES AT FRIB*

P. N. Ostroumov†, N. Bultman, M. Ikegami, S. Lidia, S. Lund, G. Machicoane, T. Maruta, A. S. Plastun, E. Pozdeyev, X. Rao, J. Wei, J. Wong, T. Xu, T. Yoshimoto, Q. Zhao, Facility for Rare Isotope Beams, Michigan State University, 48824, East Lansing, MI, USA

Abstract

This paper presents recent developments of accelerator physics related topics for the Facility for Rare Isotope Beams (FRIB) being built at Michigan State University [1]. While extensive beam dynamics simulations including all known errors do not show uncontrolled beam losses in the linac, ion beam contaminants extracted from the Electron Cyclotron Resonance (ECR) ion source (ECRIS) together with main ion beam can produce significant losses after the charge stripper. These studies resulted in development of beam collimation system at relatively low energy of 16 MeV/u and room temperature bunchers instead of originally planned superconducting ones. Commissioning of the Front End enabled detailed beam physics studies accompanied with the simulations using several beam dynamics codes. Settings of beam optics devices from the ECRIS to Medium Energy Beam Transport (MEBT) have been developed and applied to meet important project milestones. Similar work is planned for the beam commissioning of the first 3 cryomodules in the superconducting linac.

INTRODUCTION

Our studies show that contaminant ion beams extracted from ECRIS and accelerated together with main beam thanks to similar charge-to-mass ratio can produce substantial losses after the stripping due to modified charge-to-mass ratio. A set of collimators is being installed in the Folding Segment 1 (FS1) to intercept contaminant ions produced by the ECRIS. In addition, these collimators will also intercept ions created in the FS1 due to stripping reactions with the residual gas.

The development and construction of new RT resonators to be used as re-bunchers in FS1 is briefly discussed. Progress with the commissioning of the FRIB front end and plans for the first 3 cryomodules is also reported in this paper. A brief description of the FRIB energy upgrade to 400 MeV/u is given.

ECRIS BEAMS

The high intensity beams extracted from an ECRIS may contain contaminant ions. The latter can be either residual gas components (oxygen, nitrogen and carbon) or remnant ion species from previous production runs. Table 1 shows some beams of interest for FRIB produced by an ECRIS with the highest available intensities and possible contaminants with very close mass-to-charge ratio, A/q, which cannot be effectively separated in the LEBT.

Table 1: Examples of Main and Contaminant Beams

Beam of interest	Contaminant	Δ(A/q)
$^{238}U^{34+}$	$^{14}N^{2+}$	0
$^{238}U^{35+}$	$^{204}Hg^{30+}$	0
$^{78}Kr^{18+}$	$^{82}Se^{19+}$	0.02
$^{78}Kr^{19+}$	$^{82}Se^{20+}$	0.01
$^{86}Kr^{19+}$	$^{48}Ca^{10+}$	0.02
$^{82}Se^{17+}$	$^{58}Ni^{12+}$	0.01
$^{48}Ca^{10+}$	$^{82}Se^{17+}$	0.02

FOLDING SEGMENT 1

One of the functions of the Folding Segment 1 (FS1) (see Fig. 1) is to separate and collimate unwanted charge states of the main ion beam. There are several sources that would induce beam losses in the FS1. The contaminant ions that propagate from the ECRIS to the stripper will have different trajectories from the main beam after the stripper due to modification of their charge-to-mass ratio in the stripper. Gas stripping reactions due to elevated pressure around the charge selector are another source of the beam losses. The rate of these reactions is enhanced by outgassing from the charge selector slits and lattice dispersion in the arc.

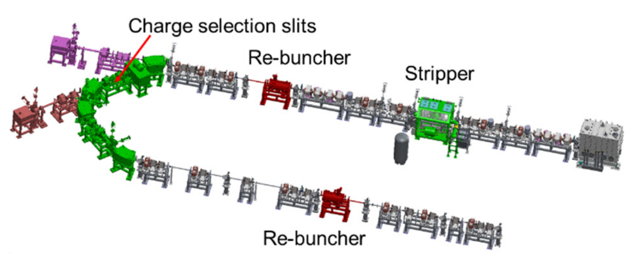

Figure 1: Layout of the Folding Segment 1 of the FRIB linac.

Charge Selection Slits

Recently we have revised the design of the charge selector in FS1 to reduce power deposition of unwanted charge states on the selection jaw slits. The criterion is to select, transport and accelerate multi-charge ion beams with the relative spread of charge states $-0.03\leq \Delta q/q \leq 0.035$. All ion beams within this charge state spread can be focused into the fragmentation target within 1 mm diameter. The power deposited on the FS1 collimation slits does not exceed 7 kW for any ion beam in FRIB. This results in a moderate size of the radiation shielding around the charge selector.

*Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661 and the National Science Foundation under Cooperative Agreement PHY-1102511, the State of Michigan and Michigan State University.
† Ostroumov@frib.msu.edu.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THYGBF4

Beam Losses and Collimation in FS1

The average charge state of the ion beam after stripper strongly depends on the ions' atomic numbers. Therefore, after the stripper, contaminant ions will have different $(q/A)_{CONT}$ than the main beam. For example, for uranium, q/A=78/238=0.328 while for fully-stripped nitrogen $(q/A)_{CONT}$ =0.5. The intensity of the contaminants can be as high as several percent of the main beam power at the stripper which is ~40 kW for the FRIB design 400 kW power. The contaminant beam power impinging onto the charge stripper can be up to a kilowatt and the loss of these contaminants must be controlled.

To avoid uncontrolled losses, we have designed a set of collimators installed along the FS1 that can intercept contaminant ions at relatively low energy of ~16 to 20 MeV/u depending on the ion species and localize losses in the designated areas with appropriate shielding. The optimal locations, dimensions and power rating of 10 collimators were determined from extensive beam dynamics studies. The first 5 collimators along the FS1 intercept contaminant ions. The remaining collimators intercept beam halo formed due to charge-exchange reactions in the FS1 or other sources. There is a 5º chicane following the stripper, which includes the collimator to intercept highest power, up to 1.7 kW, of nitrogen ion beam contaminant which can be accelerated with $^{238}U^{34+}$ beam. Due to the dispersion inside the chicane, this collimator is also responsible for intercepting contaminant light ion beams accelerated with other ion species of interest. The power ratings of the rest of collimators is low and ranging from 10 W to 320 W. Expected power losses in the collimators were calculated assuming 400 kW main beam on the target.

The set of 10 collimators and charge selection slits slightly reduce the acceptance of the FS1 to avoid any beam losses in the Linac Segment 2 (LS2) and Linac Segment 3 (LS3). Figure 2 shows horizontal and vertical phase planes at the entrance of the LS2. As can be seen, the design beam emittance without any errors and other imperfections is well inside the FS1 acceptance (dark grey area). The latter is smaller than LS2 acceptance (pale grey area). The calculations were done for $^{238}U^{78+}$. Each uranium charge state has slightly different orientation of the beam phase space portraits and acceptances.

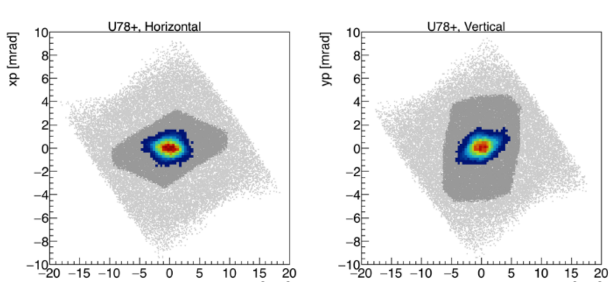

Figure 2: Acceptance of the LS2 (pale grey), acceptance of the FS1 formed with all collimators (dark grey) and the design beam emittance at the entrance of the LS2.

Normal Conducting Re-buncher

In the original FRIB design, both re-bunchers shown in Fig. 1 were based on 80.5 MHz SC cavities. The presence of the collimators on both sides of the re-buncher increases the risk of particulate contamination of SC cavities. In addition, for some contaminant ion species, the beam losses can take place inside the re-buncher. To avoid these complications we have decided to replace the SC re-bunchers with RT resonators. Detailed electrodynamics and beam dynamics studies have shown that an interdigital (IH) structure operating at room temperature is very efficient in this velocity range of ions and can be operated at 161 MHz to reduce the required re-bunching voltage. The model of the IH resonator is shown in Fig. 3. To provide adequate re-bunching of all FRIB beams from oxygen to uranium only 10 kW RF power is required. The design peak electric fields are below one Kilpatrick unit. The RT re-buncher is not sensitive to losses of contaminant beams inside the cavity. The fabrication of both re-bunchers is nearly complete and installation and commissioning is planned by the end of this year.

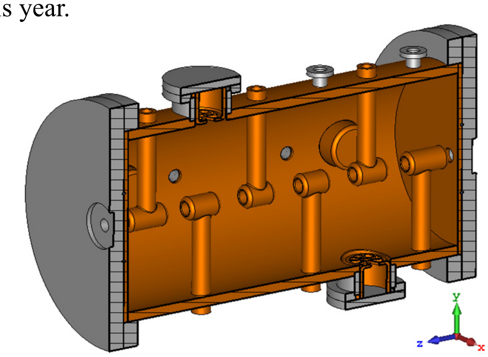

Figure 3: 3D model of the IH resonator.

LINAC COMMISSIONING STATUS

Front End

The performance of the FRIB Front End (FE) per project specification has been successfully demonstrated. The results are reported elsewhere [2]. After the project goals have been met, we had an opportunity for extensive beam physics studies in the FRIB FE. The beam optics devices such as solenoids, quadrupoles and dipoles were aligned with high accuracy. A beam-based alignment has been applied to charge selection slits, image viewers, Allison emittance scanner and profile monitors. This technique includes a steering of the beam center into the center of the focusing devices and alignment of the diagnostics devices with respect to the focusing devices. We worked mostly with $^{40}Ar^{9+}$ beam with the intensity from 10 μA to 110 μA. The beam emittance and σ–matrix elements were determined with 3 methods: (1) using Allison emittance scanner; (2) profile measurements along the Low Energy Beam Transport (LEBT) and (3) a quadrupole or solenoid scan and measurements of beam profiles. The Allison scanner provides information on the phase space distribution but does not provide coupling terms in the σ–matrix for the

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THYGBF4

magnetized beam extracted from the ECRIS. Typical emittance measurements with the Allison scanner located right after the charge selection slits are shown in Fig. 4. RMS normalized emittance in the wide range of argon beam intensity is below 0.1 π·mm·mrad which is the design specification for FRIB beams extracted from the ECRIS.

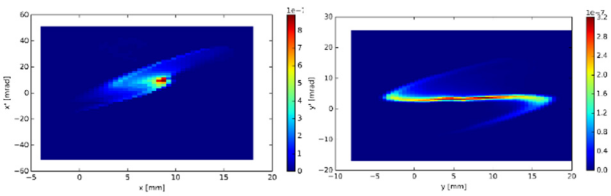

Figure 4: Typical beam emittances measured with the Allison scanner.

Figure 5 shows the RMS envelopes for 100 μA argon beam along the LEBT with the initial beam σ–matrix fitted to match the measured beam rms sizes along the LEBT. The argon beam energy of 0.5 MeV/u after the acceleration in the RFQ was verified using both 45º bending magnet and time-of-flight measurements with 4-button Beam Position Monitors (BPM). Similar measurements were performed for krypton beam. In addition, we have transported two charge states 17+ and 18+ of krypton beam in the LEBT and accelerated them in the RFQ simultaneously. The measured transmission is consistent with that from the simulations. Particularly, the LEBT is capable to transport 100% of dual charge state krypton beam.

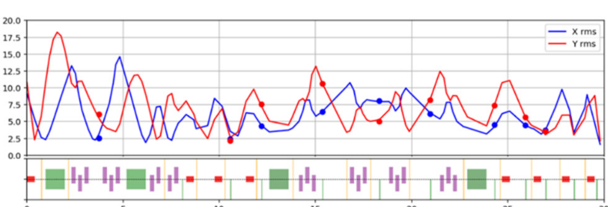

Figure 5: Argon beam RMS envelopes (solid lines) in the LEBT with the beam initial parameters fitted to match the measured (dots) beam RMS sizes along the LEBT.

Three Cryomodules With β=0.041 Cavities

The next stage of the FRIB linac commissioning is the acceleration of argon beam in the first 3 cryomodules with 12 β_{OPT}=0.041 SC cavities. The layout of the hardware for this stage commissioning is shown in Fig. 6. The temporary diagnostics station includes Beam Current Monitors, Faraday Cup, BPMs, Halo Monitor Rings, a profile monitor and a silicon detector (SiD). The initial phase and amplitude setting of SC cavities will be performed using SiD with very low intensity argon beam which does not require operation of Machine Protection System (MPS) and Run Permit System (RPS). After commissioning and activation of MPS and RPS, the transmission through the cryomodules and cavities' settings will be verified with higher intensity, ~25 μA pulsed beam.

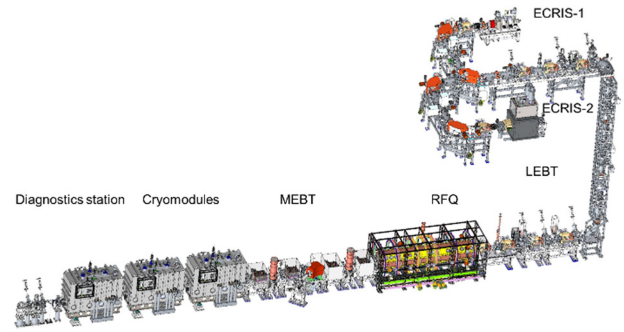

Figure 6: FRIB layout including Front End, the first 3 cryomodules and commissioning diagnostics station.

FRIB ENERGY UPGRADE

The optimal beam energy for fragmentation based production of rare isotopes is 400 MeV/u as was detailed in the early stages of a rare isotope accelerator design [3]. The current design energy of 200 MeV/u for the FRIB linac was selected due to cost limitations. Therefore, during the civil construction of the FRIB linac building, an 80-meter space in the tunnel was reserved for the future energy upgrade of the linac. The energy upgrade will be based on a five-cell, β_{OPT}=0.65, 644 MHz superconducting elliptical cavity shown in Fig. 7. The FRIB upgrade will include 11 cryomodules containing 5 cavities each [4]. The cavity design included extensive multi-physics optimization, mechanical and engineering analysis. Two cavities are being fabricated in industry. The detailed design studies of the cavity subsystems such as power coupler and dynamic tuner are currently being pursued. The testing of the first SC elliptical cavity is planned this year.

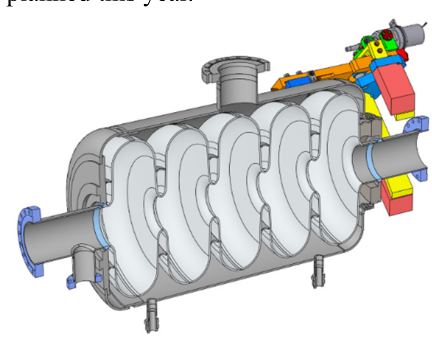

Figure 7: Proposed β_{OPT}=0.65, 644 MHz SC cavity in helium vessel with slow and fast tuners attached.

REFERENCES

[1] J. Wei *et al.*, "The FRIB Superconducting Linac - Status and Plans", in *Proc. LINAC'16, East Lansing, MI, USA, Sep. 2016*, pp.1-6.

[2] E. Pozdeyev, "FRIB Front End Construction and Commissioning", presented at IPAC'18, Vancouver, Canada, Apr.-May 2018, paper MOZGBF1, this conference.

[3] Nuclear Science Advisory Committee ISOL Task Force, "ISOL Task Force Report to NSAC", Nov. 1999.

[4] P.N. Ostroumov *et al.*, "Elliptical superconducting RF cavities for FRIB energy upgrade", *Nucl. Inst. Meth. Phys. Res. A*, vol. 888, 2018, pp. 53–63.