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FRIB COMMISSIONING*

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Abstract

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

INTRODUCTION

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

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

LINAC COMMISSIONING

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

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

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

Front End (FE)

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

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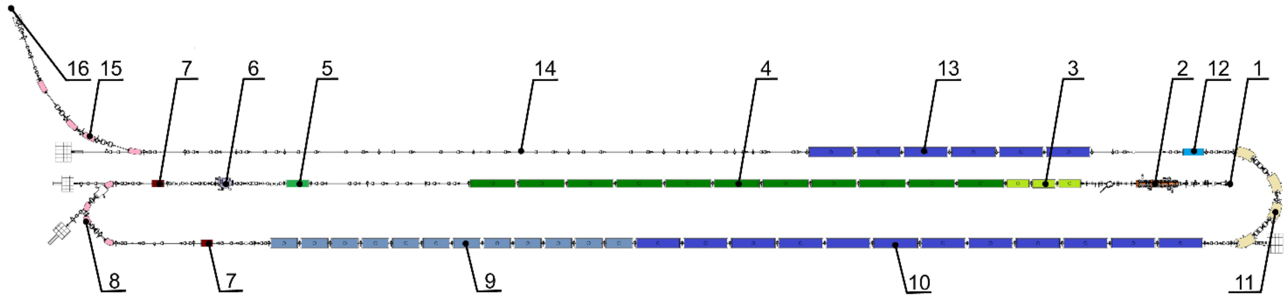

Figure 1: Layout of the FRIB accelerator in the tunnel (the above-grade portion of the Front End is not shown). 1 – ten-meter vertical drop from ion sources (above ground); 2 – 0.5 MeV/u RFQ; 3 – three β=0.041 QWR cryomodules; 4 – eleven β=0.085 QWR cryomodules; 5 – β=0.085 bunching cryomodule; 6 – Lithium and carbon stripper modules; 7 – multi-gap buncher; 8 – room temperature folding segment; 9 – twelve β=0.29 HWR cryomodules; 10 – twelve β=0.54 HWR cryomodules; 11 – superconducting folding segment; 12 – β=0.53 bunching cryomodule; 13 – six β=0.54 HWR cryomodules; 14 – beam transport to the target; 15 – beam delivery system; 16 – fragmentation target.

Figure 2: FRIB tunnel after the completion of installation.

The FRIB LEBT, unlike many other LEBTs elsewhere, has been designed and built to extract and accelerate all ion beam components produced in the ECRIS. The energy of the ions of interest is 12 keV/u. The accelerated beam components are separated and selected after the first 90° bending magnet. The charge selection segment and the whole FRIB LEBT can provide the no-loss achromatic transport of dual-charge-state heavy ion beams.

ECR ion sources have many parameters that cannot be measured directly, are cross-coupled, and fluctuate during the ion source operation. Therefore, the parameters of multi-component ion beams extracted from the ECRIS are also changing. We found the 6D vector of the beam position in the phase space downstream of the RFQ is one of the most sensitive beam properties. We also noticed that if the ECRIS is cold started to produce the same ion species that were used previously, there is a slight deviation of the beam phase space parameters after the charge state selection.

If the transport system is slightly misaligned, the 4D beam position of the ions of interest in the multi-component ion beam depends on the space-charge forces. It results in a change of the 6D beam position vector downstream of the RFQ. The beam energy and phase after the RFQ are sensitive to the beam transverse misalignment in the multi-harmonic buncher and the first accelerating cells of the RFQ. There is a correlation of the 6D beam vector downstream of the RFQ with the total ECRIS platform drain current even if the current of the ion of interest remains unchanged. We have developed a beam dynamics model to adjust the parameters of the LEBT and re-tune the beam 6D vector in the MEBT to the reference value if the beam extracted from the ECR behaves differently. This model will be improved by using machine learning shortly.

Auto-start of Resonators

FRIB consists of 324 SC [8] and 8 Room Temperature (RT) resonators operating at five different frequencies. The stable operation of resonators is provided by the FRIB-developed digital Low-Level RF (LLRF) control system [9]. The operational experience shows that the peak-to-peak errors of the amplitudes and phases of RF fields are mostly within ±0.2% and ±0.1°, which are an order of magnitude less than the original specification. Since the early stage of RF conditioning of resonators, an automated turn-on procedure has been developed. The auto-start code implemented at the Input-Output Control (IOC) level reduces the resonator turn-on time to about 40 seconds and excludes possible human operator errors. Most HWRs experience multipacting after a warm-up event and, therefore, require reconditioning. Now, this procedure is also automated.

The auto-start and fast-recovery capabilities are especially beneficial to meet the high availability requirement of the RFQ operating in CW mode. The cold start of the RFQ requires up to 45 minutes to the highest power level due to using of the cooling water flow for the frequency tuning. Whereas the fast-recovery in a warm state takes no more than 30 seconds.

Model-Based Beam Steering Correction

There are 144 Beam Position and Phase Monitors (BPM) and 127 correctors distributed along the linac. The orbit response matrix (ORM) method was applied previously for the beam steering correction in the first segment of the linac [10]. This method was based on the measured response matrix elements. This method works well but takes too much time for the measurements. Therefore, we have decided to use a response matrix calculated with the computer model of the linac. This approach also works well, and it is

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much faster. The model-based ORM method works best if it is applied to short sections of the linac containing 10 correctors and a slightly larger number of BPMs. In most cases, the one iteration is sufficient for the beam trajectory alignment within ±0.5 mm. The second iteration sometimes is necessary for longer linac sections due to misalignment of the beam optics devices and minor hysteresis in the superconducting (SC) dipole coils.

Phase Scan Procedures

The phase scan procedure was applied to set the synchronous phases for SC resonators and bunchers. This procedure constitutes the measurement of the beam-induced signal in downstream BPMs as a function of the resonator RF field phase, as described in [11]. Since the auto-start of resonators has become available, the phase scan procedure is also automated and can be applied to many cavities without human intervention. The phasing of short sections of the linac (6–8 cavities) is usually alternated with the model-based beam steering correction to align the beam with the accelerator axis.

The experiments with rare isotope beams last just about a week or less. For different experiments the FRIB linac should provide various primary beams at different energies, and shortening the accelerator setup time is, therefore, critical to meet the requirements of the FRIB Users community. An automated phase scan procedure reduces the tuning time, but setting up a new velocity profile in the entire linac requires at least 15 hours.

Recently we developed and tested a model-based instant phase setting in the linac segments 1, 2, and 3. The coordinates of the resonators along the linac are well known from the alignment survey, and RF field distributions are available from simulation models. The accelerator model can calculate the phase settings of all resonators for the required energy of the given ion species if the cavity calibration data is provided. The field levels in resonators are calibrated with the beam time-of-flight measurements. The phase calibration of each resonator and BPM is generated using the standard phase scan procedure with the beam of known energy. As a result of such calibration, a static phase shift in each RF line and BPM cable can be determined with respect to the RF reference clock. The model-based Instant Phase Setting (IPS) was verified with standard phase scan procedure in all linac segments. Currently, we use IPS routinely for the machine setting to run 1 kW beams and quickly recover from fault-cavity cases. The IPS dramatically reduced the machine setting time. In April 2022, the beam tune from the ion source to the target was established in just 6 hours. With minor adjustments near the charge stripper this tune was used during the first FRIB user experiment.

Liquid Lithium Stripper Testing

To achieve the design heavy ion beam energies above 200 MeV/u and beam power up to 400 kW, the FRIB linac requires a stripper at an intermediate energy of 17-20 MeV/u. The solid foils used previously for stripping heavy ions are easily damaged at the beam intensities required for the FRIB primary beams on the fragmentation target. To overcome the existing technical limitations associated with the stripping of high intensity heavy ion beams, FRIB developed and commissioned a liquid lithium stripper [12]. The charge stripper is based on a molten liquid lithium film with thickness of ~10–20 µm, flowing at ~60 m/s in the ultra-high vacuum environment. We experimentally confirmed that the windowless liquid lithium thin film could be used as a charge stripper by successfully running ^{124}Xe, ^{36}Ar, and ^{238}U beams through the charge stripper. Figure 3 shows the charge state distributions of xenon and uranium beams after the liquid lithium stripper. The long-term operation with the liquid lithium stripper was tested during the user experiment with the primary ^{48}Ca beam.

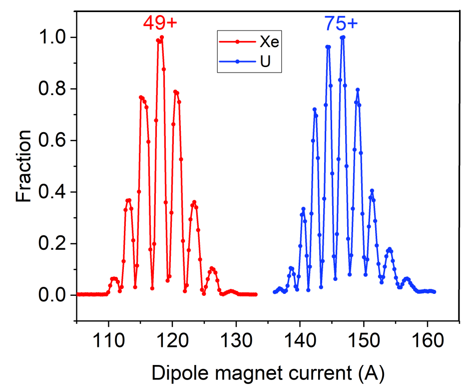

Figure 3: Xenon (red) and uranium (blue) charge state distributions after the liquid lithium stripper. The thickness is 1.05 mg/cm^2 for the xenon and 1.40 mg/cm^2 for uranium beams.

EARLY OPERATION

The Linac has been tuned for the ^{48}Ca primary beam in April 2022 to enable the first FRIB experiment for the production of rare isotopes. In June, we ran ^{82}Se for the second FRIB experiment. Currently, 1 kW beam power on the target is limited by the operational safety envelope. In October, the linac will provide up to 3 kW beam power on the target with the following increase to 10 kW in a year.

Carbon Stripper

While the liquid lithium stripper was used for extended operation during the first experiment, we have decided to use a rotating carbon stripper for the beam power on a target below 10 kW. The carbon stripper is attractive due to the simplicity of operation. The carbon foils with a diameter of 100 mm and thickness of 1.0 mg/cm^2 and 1.5 mg/cm^2 are being used for stripping FRIB ion beams. The foil's rotation speed can be as high as 150 rpm. Also, the foil is moved vertically to cover the entire area. The calculations show that for the heaviest ions at 10 kW on the target, the stripper lifetime is limited by radiation damage and equals

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to about a week. The damaged stripper foil can be replaced in several hours. Figure 4 shows the viewer image of the stripper foil, rotating at 101 rpm with a 440 W, 20 MeV/u krypton beam on it. In this particular case, the temperature of the interaction spot can reach ~600 °C, and a long tail of the heated area is seen in the image.

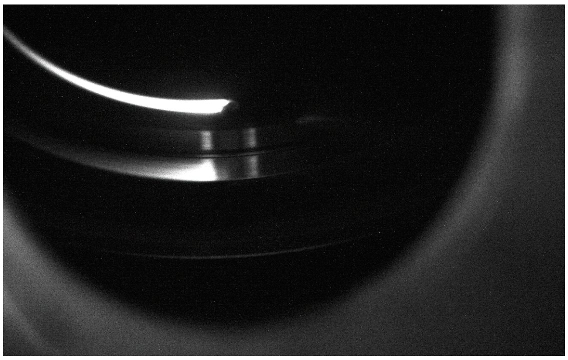

Figure 4: Krypton beam on the rotating carbon stripper.

Beam energy after the stripper fluctuates due to the slight difference in the foil thickness at different radii, as shown in Fig. 5.

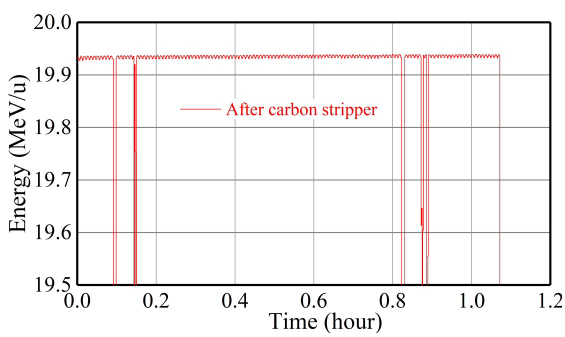

Figure 5: ^{82}Se beam energy after the stripper.

Linac Operation

Since the preparation for the first experiment, the linac started to operate around the clock, and the training of operators to support the machine operation was a high priority for the accelerator physicists. The linac "reference tune" is developed and set up for the operation by accelerator physicists. Several user-friendly high-level applications have been developed and handed over to operators to verify the beam quality and restore the reference tune. The "Settings Manager" application has been developed to manage the accelerator physics settings, which features convenient device settings loading and saving and value scaling to work with various ion species. The "Settings Manager" was recently upgraded to save beam signals from non-interceptive diagnostics devices.

During the linac operation for the rare isotope production, the operators watch the beam parameters from 144 BPMs. Typical BPM readings plotted as differences between live and reference linac signals are shown in Fig. 6. The gradual increase of the phase difference in ~100 m drift space after the LS3 corresponds to a slight change of the beam energy by ~20 keV/u with respect to the reference energy of 165 MeV/u. The higher magnitude of the BPM live readout corresponds to a slightly higher beam current and power than for the reference tune. The operators can identify possible issues with the accelerator subsystems by watching the live differential data from the BPMs.

Run permit and machine protection systems (MPS) are fully functional at the FRIB facility. The MPS system watches the status of nearly all devices, namely the RF resonators, bending magnets, charge stripper rotation, vacuum levels, target state, etc.. For the operation with 1 kW beam power, the Beam Loss Monitors (BLM) were incorporated into the MPS system.

Beam Power

The FRIB was designed and built to deliver a 400 kW beam to the target and produce rare isotopes for science. We have developed a plan to increase the beam power on the target within six years. There are two main reasons for such an approach:

- many experiments do not require high power and it is reasonable to conduct these experiments in early stages of the FRIB operation;
- we need to gain experience with maintaining the linac with low uncontrolled beam losses and handling high power beams in the target hall.

The machine setting is developed using a low average power pulsed beam. The power ramp-up of the CW beam is performed using attenuators and slits in the LEBT. While working with a 1-kW beam, we do not see notable uncontrolled beam losses. Figure 7 shows the ^{82}Se beam current along the linac. The beam current increases after the stripping (D2353) and drops after selecting the charge state 33^+. The signals from the Halo Monitor Rings (HMR), Neutron Detectors (ND), and Ionization Chambers (IC) [13] in the post- stripper linac are plotted in Fig. 8. We see elevated neutron flux coming from the stripper and target. The beam losses were not observed on the HMRs installed between the cryomodules.

The primary beam has been tuned to the target with the 0.3 mm·rms radius. The 1 kW beam image on the beryllium target is shown in Fig. 9. A four-segment collimator with temperature sensors upstream of the target helps to control the beam position.

CONCLUSION

The FRIB linac beam commissioning is complete, and various primary beams are available for rare isotope production for user experiments. Two nuclear physics experiments have been conducted with 1 kW primary beams.

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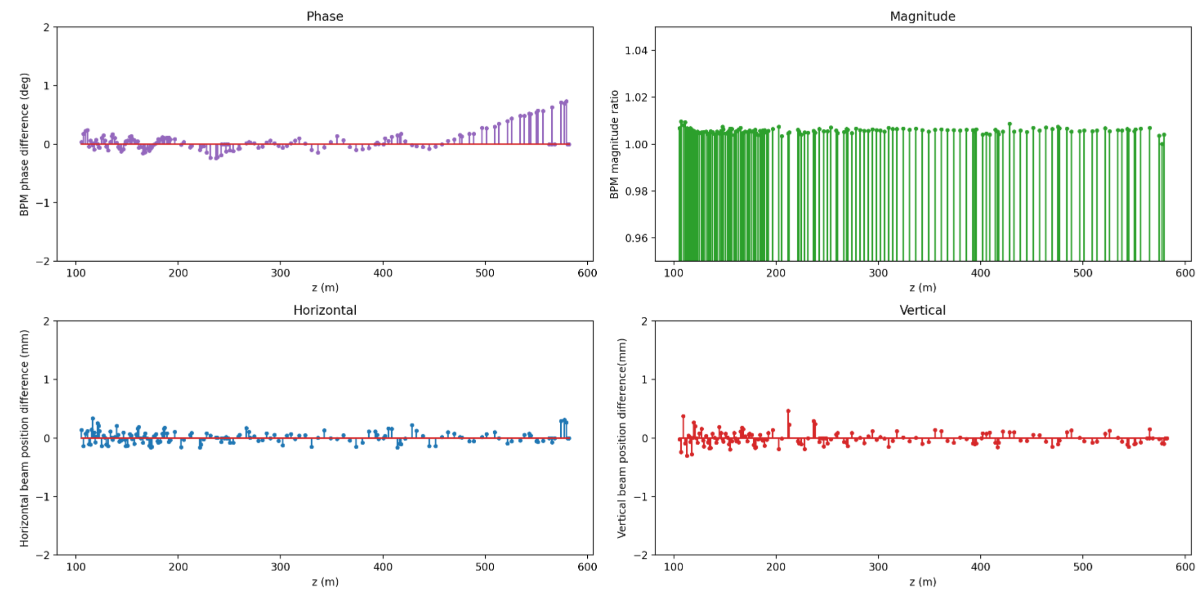

Figure 6: BPM readings during the operation. Plots show the difference between the readout and reference setting of the linac for the bunch phase (top-left), horizontal and vertical (bottom) beam positions. Plot (top-right) shows the BPM signal magnitude normalized to the reference signal strengths.

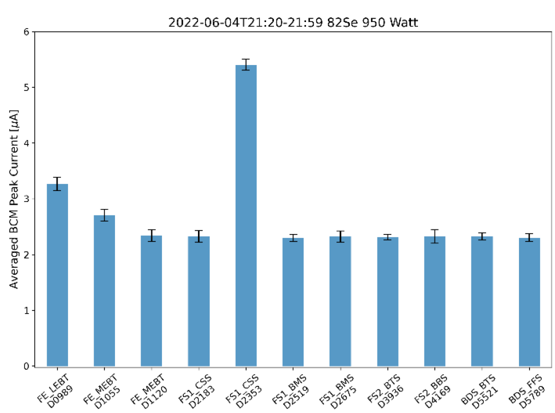

Figure 7: The ^{82}Se beam current averaged over the 60 sec along the linac. The error bar shows the standard deviation due to the noise in the signal. The D-numbers near the horizontal axis show the location of the BCMs along the linac in decimeters. The first BCM is located upstream of the RFQ. The last BCM is located upstream of the target.

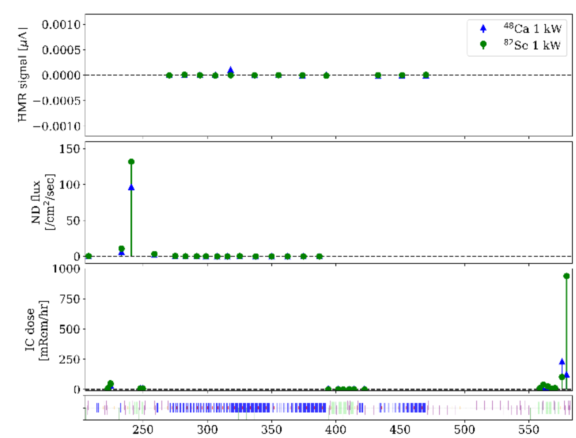

Figure 8: The signals from the beam loss monitors in the post-stripper section of the linac.

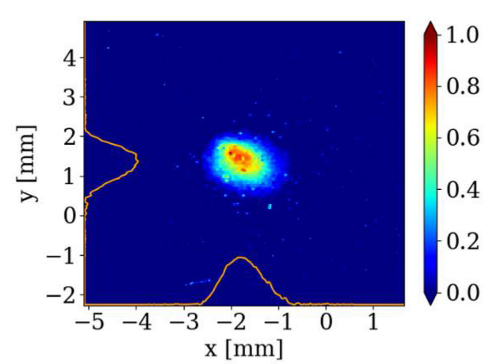

Figure 9: The 1 kW ^{82}Se beam image on the beryllium target.

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