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STATUS OF 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, is approaching the commencement of user operation in 2022 as planned. The readiness of the linear accelerator for the production of rare isotopes was verified by the acceleration of Xenon-124 and Krypton-86 heavy ion beams to 212 MeV/u using all 46 cryomodules with 324 superconducting cavities. 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 heavy ions with a thin liquid lithium film flowing in an ultrahigh vacuum environment, and simultaneous acceleration of multiple-charge-state heavy-ion beams. These technologies are required to achieve ultimate FRIB beam energies beyond 200 MeV/u and beam power up to 400 kW. High intensity pulsed beams capable in delivering 200-kW beams to the target in CW mode were studied in the first segment of the linac.

INTRODUCTION

The FRIB includes a high-power superconducting driver accelerator, an isotope production target, and a fragment separator. The layout of the FRIB is shown in Fig. 1. The FRIB driver 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 previous HB workshops, see for example, [2-5]. 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 FS will be capable to capture large-emittance rare isotope beams resulting from production reactions, i.e., angular acceptance is ± 40 mrad in both transverse directions and momentum acceptance is ± 5%. The maximum magnetic rigidity of the fragment separator can reach 8 T·m. While many isotopes will be studied in the in-flight experiments, FRIB will use upgraded National Superconducting Cyclotron Laboratory (NSCL) facilities to prepare and re-accelerate stopped isotopes up to 12 MeV/u.

In a continuous wave (CW) superconducting (SC) linac, the 400-kW beams can be achieved with a low beam current, below 1 emA. Therefore, the space charge effects are mostly negligible in the linac except the ion source and the Low Energy Beam Transport (LEBT). Although the performance of Electron Cyclotron Resonance Ion Sources (ECRIS) has been significantly improved in the past decades, they cannot produce sufficient intensities of the heaviest ions, in order 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. Also, multiple-charge-state acceleration after the stripper dramatically reduces the total power of unwanted charge states dumped in the first folding segment. Therefore, the multiple-charge-state acceleration will be used for all ion species with a mass above ~60.

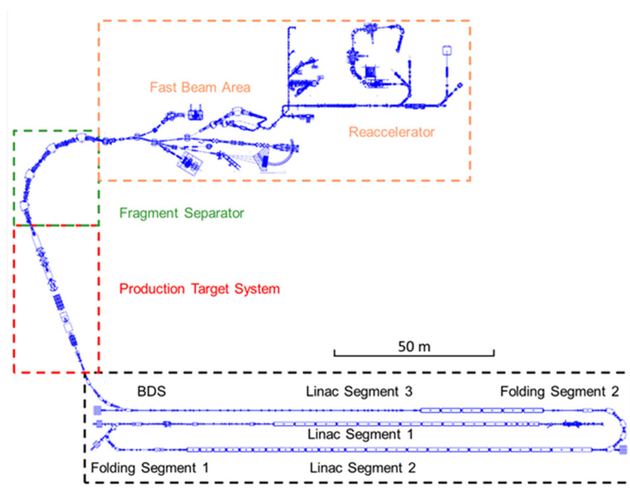

Figure 1: Layout of the FRIB driver accelerator, target, fragment separator, re-accelerator and existing infrastructure. The driver linac consists of three straight segments, Linac Segment 1 (LS1), Linac Segment 2 (LS2), Linac Segment 3 (LS3) and two folding segments, Folding Segment 1 (FS1) and Folding Segment 2 (FS2).

The staged beam commissioning was adopted for the FRIB. The beam commissioning started in 2017 with the Front End (FE) and continued until April 2021. All this time, the installation of the accelerator equipment has been taking place. The current state of the tunnel is shown in Fig. 2. Each stage of the beam commissioning took less than two weeks. The results of each stage were reported in multiple journal papers [6-9]. In this paper, we report the results of the recent commissioning progress. The Kr and Xe beams were accelerated to 212 MeV/u and delivered to

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the beam dump at the linac's end using all 46 cryomodules with 324 superconducting cavities [10].

Figure 2: FRIB tunnel after the completion of installation.

FRONT END STATUS

A significant experience has been gained with the 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. It should be noted that the FRIB LEBT, unlike many other LEBTs elsewhere, is designed and built to extract and accelerate all ion beam components produced in the ECRIS to their final energies. 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 as well as the whole FRIB LEBT can provide the no-loss achromatic transport of dual-charge-state heavy ion beams.

We noticed, however, 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. The most sensitive parameter is a 6D vector of the beam position in the phase space downstream of the RFQ. The ECRIS itself has many parameters that are hidden or fluctuating during the operation. Therefore, the parameters of multi-component ion beams extracted from the ECRIS are also changing. To better understand the beam dynamics of the multi-component ion beams, we have developed a 3D computer model of the ECRIS and beam transport line. The extraction of the ion beams from the ion source is simulated using particle tracking in the CST Particle Studio [11] and TRACK code [12], taking into account the 3D fields of the ECRIS and assuming that the plasma is neutral. After the extraction, the multi-component ion beam is simulated in TRACK, including 2D space charge particle-in-cell (PIC) calculations and charge neutralization. The neutralization factor and the plasma temperature were adjusted in the computer model to fit the Allison scanner emittance measurements of the beam after the charge selector. Figure 3 shows the simulated and measured beam images after selecting a particular charge state of the xenon beam. The tuned model reproduces beam images well. The model can reproduce the phase space plots from the Allison scanner as well.

The focusing distance in the transport channel downstream of the ECR is a function of the charge-to-mass ratio. 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.

Currently, we are developing Machine Learning (ML) algorithms for the quick tuning of LEBT to maintain the beam vector in the MEBT close to the reference tune. The ECRIS-LEBT simulations and measurements will be used for the training of the ML algorithm.

AUTO-START OF RESONATORS

FRIB consists of 324 SC 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) [13]. The operational experience shows that the peak-to-peak errors of the amplitudes and phases of RF fields are within ±0.2% and ±0.1° which are an order of magnitude less than the original specification. From the early stage of installation and RF conditioning of resonators, it was realized that the resonators could be taken to the nominal accelerating gradients by computer programs. The auto-start procedure programmed at the Input-Output Control (IOC) level reduces the resonator turn-on time to about 40 seconds and excludes possible human error. A typical sequence of events during the auto-start for a half-wave resonator (HWR) is shown in Fig. 4. Most HWRs experience multipacting after a warm up event and require conditioning. Now, this multipacting conditioning is also automated.

The auto-start procedure is especially beneficial for the high availability of the RFQ operating in CW mode since occasional sparking can occur, and fast recovery is required. The RFQ recovery from occasional sparks takes 3 seconds for the amplitude and 30 seconds for the phase. 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.

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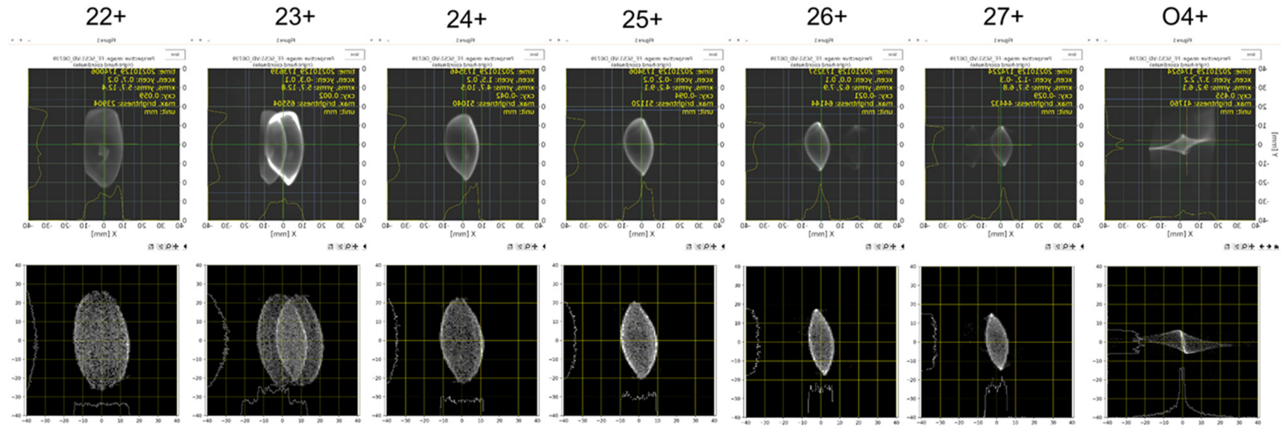

Figure 3: The measured (top) and simulated (bottom) xenon beam images and profiles on the viewer after the selection of particular charge state shown above the images.

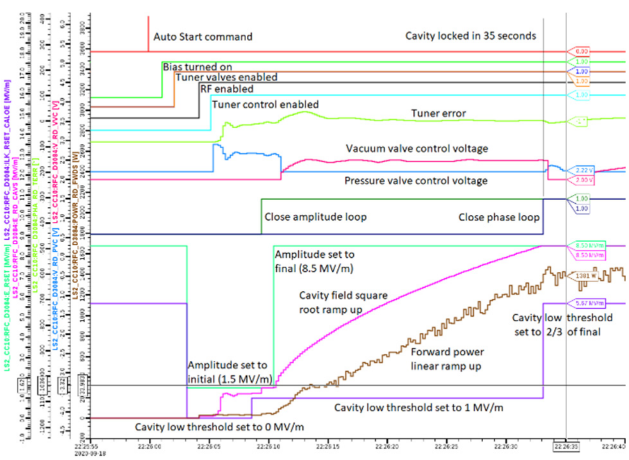

Figure 4: Time sequence of the RF, resonator and tuner events during the auto-start procedure.

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 [7]. 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 much faster. The model-based ORM method works best if it is applied to short sections of the linac containing 6-8 correctors and a slightly larger number of BPMs. In most cases, the second iteration is not required if the beam alignment goal is ±0.5 mm. The second iteration may be necessary for longer linac sections due to misalignment of the beam optics devices and minor hysteresis in the superconducting (SC) dipole coils. Figure 5 shows the beam offset in horizontal and vertical directions in each BPM along the entire linac after completing of the $^{86}Kr^{34+}$ beam acceleration to 212 MeV/u.

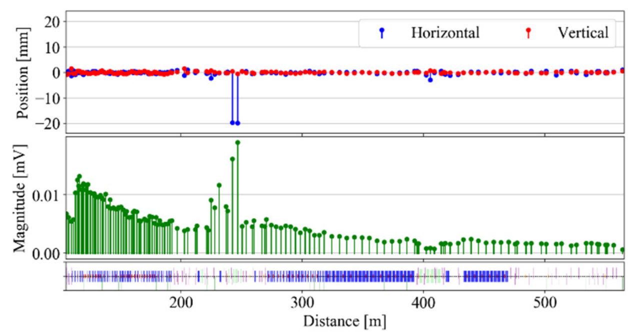

Figure 5: BPM readings along the linac after the completion of the $^{86}Kr^{34+}$ beam steering correction. The large signals from the FS1 BPMs is related to the fact that the 180°-bend was intentionally tuned for charge state 33.5+.

PHASE SCAN PROCEDURES

The phase scan procedure was applied to determine 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 ref. [7,8]. Since the auto-start of resonators became 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 is alternated with the model-based beam steering correction to align beam with the accelerator axis.

The experiments with rare isotope beams are limited in time, just about a week or less. The FRIB linac should provide various primary beams at different energies, and shortening the accelerator setup time is critical to meet the requirements of the FRIB Users community. Using 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 of 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 the CST models. The accelerator model can calculate the optimal phase setting of all resonators for the required energy of the given ion species if the calibration data

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is provided. The field level in the resonator is calibrated with the beam. The phase calibration data is generated using the standard phase scan procedure with the beam of known energy for each resonator and BPM. 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 was applied to 88 $\beta_{opt} = 0.085$ quarter wave resonators (QWRs) in the Linac Segment 1. The calibration data was collected during the phase scan to set up 17 MeV/u $^{86}Kr^{17+}$ beam. Then, the instant setting was applied in the same section to accelerate $^{86}Kr^{17+}$ beam to 20 MeV/u. The instant phase setting procedure resulted in the same beam energy as in the case of the standard phase scan procedure. The synchronous phase difference in the cavities obtained by two phase setting methods is plotted in Fig. 6.

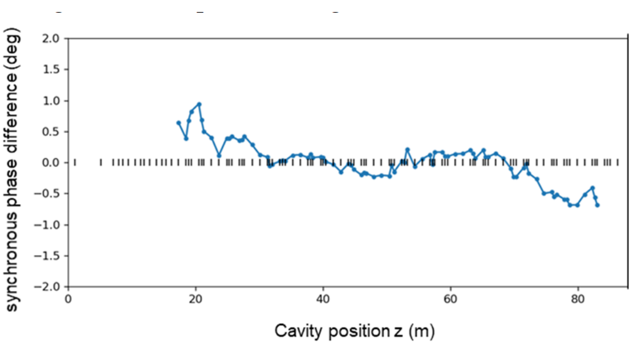

Figure 6: Synchronous phase difference between the standard phase scan procedure and instant phase setting in the LS1.

LIQUID LITHIUM STRIPPER TESTING WITH BEAM

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 MeV/u. The solid metal 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 [14]. The charge stripper is based on molten liquid lithium film with a 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 $^{124}Xe^{26+}$, $^{36}Ar^{10+}$, and $^{238}U^{36+}$ beams through the charge stripper. Figure 7 shows the charge state distributions of xenon and uranium beams after the liquid lithium stripper. The average charge state after the stripper was compared with the ETACHA4 [15] simulations. We found that the average charge state of xenon beam is ~2.6% higher than ETACHA prediction, while the uranium average charge state is lower by 0.7% for incident beam energies of 17 MeV/u and 20 MeV/u.

COMMISSIONING OF THE ENTIRE LINAC

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 in less than three hours on the first attempt. Later, the ^{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 operation of all accelerator systems per design specifications, including:

- FRIB's helium refrigeration system and cryogenic distribution system,
- All linac superconducting radiofrequency cryomodules and superconducting magnets operating at cryogenic temperatures below 4.5K,
- All linac normal conducting electromagnetic devices,
- Lithium and carbon charge strippers co-existing for enhanced availability.

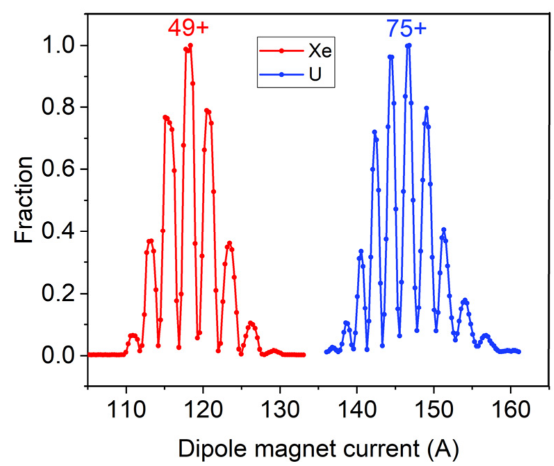

Figure 7: Xenon (red) and uranium (blue) charge state distributions after the liquid lithium stripper. The thickness is 1.05 mg/cm^2 for the xenon and 1.40 mg/cm^2 for uranium beams.

CONCLUSION

The FRIB linac beam commissioning is complete, and various primary beams are available for rare isotope production for nuclear physics experiments. The beam commissioning of the fragment separator is scheduled for January 2022. The first Program Advisory Committee approved 34 experiments with nine different primary ion beams to be started in early 2022.

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