ACCELERATOR AND BEAM PHYSICS CHALLENGES IN SUPPORT OF FRIB EXPERIMENTS

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Abstract
The Facility for Rare Isotope Beams (FRIB), a major nuclear physics facility for research with fast, stopped and re-accelerated rare isotope beams, started operation in May 2022. Since then, a dozen nuclear physics experiments have been successfully accomplished. Typically, the experiments with rare isotope beams last a week or two. Each experiment requires a different primary beam species and energies. Shortening the accelerator and fragment separator setup time is critical to meet the demands of the FRIB Users community. Currently, the primary focus in the linac is reducing the accelerator setup time and beam power ramp-up. Many physics applications have been developed and used to set up the accelerator and beamlines. The simultaneous acceleration of multiple charge states of heavy ion beams is routinely used to minimize the beam power deposition on the charge selector slits after the stripper. This paper discusses the challenges of linac tune development for the acceleration of various ion species.

INTRODUCTION
The FRIB includes a high-power heavy-ion superconducting driver accelerator, an isotope production target, a fragment separator, and multiple experimental instruments. The layout of the FRIB superconducting driver linac is shown in Fig. 1. The beam path from the RFQ to the target is 600 meters, as shown in all the following figures. The FRIB driver linac is capable of accelerating uranium ions to 200 MeV/u and higher energies for lighter ions with 400 kW power on the target [1]. The progress with the FRIB linac construction, development, and commissioning was reported in multiple publications; 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). While many isotopes can be studied in the in-flight experiments, some can be stopped and re-accelerated up to 12 MeV/u.

The linac is designed to accelerate multiple-charge-state beams to achieve 400 kW beam power on the target. 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 FS1 (see Fig. 1). To date, the primary ion beams of 36Ar, 48Ca, 86Kr, 70Zn, 82Se, 124Xe, and 198Pt up to 227 MeV/u have been delivered to the target and used to produce nearly 200 unstable isotopes. The acceleration of the three charge-state platinum beam was especially beneficial due to the limited intensity to deliver a 2 kW beam with the currently available setup of the ion source.

LINAC TUNING
The development of the linac tune for a new ion beam starts with the pre-calculated setting of all beam optics devices and RF cavities for the entire linac. A pre-calculated linac setting is not sufficient to achieve no-loss tuning so far. To fine-tune the linac from the ECRIS to the target and to expedite the linac tuning process, we have developed many physics applications. The RF cavities’ phases and amplitudes for any given ion species and its energy are calculated using a model-based instant phase setting (IPS) procedure as described in ref. [6]. The IPS relies on an alignment survey, the phase offset calibration of each resonator and BPM relative to the master clock. Such a calibration is performed by the phase scan procedure of each cavity and takes a long time, about 24 hours, for 324 SC resonators. Our experience shows that this calibration remains unchanged for many months.

The 3D beam envelope code FLAME [7] imports the IPS setting of the RF cavities and generates the optimal setting of all linac devices as a file. The “Setting Manager” application [8] in the accelerator controls network imports the FLAME-generated file and applies it to the linac devices. As an example, the envelopes for the 210 MeV/u 36Ar beam in the post-stripper section of the linac are shown in Fig. 2.

To complete the linac tuning, we need to apply beam steering correction and provide matching in the transverse phase space, typically in 7 sections of the linac. In these sections, the quadrupoles’ settings are modified with respect to the FLAME calculations and based on beam profile measurements. The beam Twiss parameters are evaluated using (a) the quadrupole scan and profile measurements or (b) profile measurements in multiple locations. We use the Orbit Response Matrix (ORM) method for the beam steering correction based on the FLAME model.

The evaluation of the beam Twiss parameters in the transverse phase space is required upstream of the following linac segments:
- LS1, to match beam into the quasi-periodic solenoidal focusing channel;
- Stripper, to obtain the required beam rms size on the stripper;
- FS1, to match into the 180-deg achromatic bend;
- LS2, to match beam into the quasi-periodic solenoidal focusing channel;
- FS2, to match into the 180-deg achromatic bend;

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Figure 1: Layout (top view) 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 $\beta=0.041$ QWR cryomodules; 4 – eleven $\beta=0.085$ QWR cryomodules; 5 – $\beta=0.085$ bunching cryomodule; 6 – Lithium and carbon stripper modules; 7 – multi-gap buncher; 8 – room temperature folding segment; 9 – twelve $\beta=0.29$ HWR cryomodules; 10 – twelve $\beta=0.54$ HWR cryomodules; 11 – superconducting folding segment; 12 – $\beta=0.53$ bunching cryomodule; 13 – six $\beta=0.53$ HWR cryomodules; 14 – beam transport to the target; 15 – beam delivery system (BDS); 16 – fragmentation target. Linac Segment 1 (LS1): 3-5; Folding Segment 1 (FS1): 7-8; Linac Segment 2 (LS2): 9-10; Folding Segment 2 (FS2): 11; Linac Segment 3 (LS2): 12-14; Beam Delivery System (BDS): 15.

Figure 2: $^{36}$Ar beam rms envelopes in the linac section from the stripper to the target.

- LS3, to match to the focusing channel;
- BDS, to form the required beam size on the target.

After completion of beam tuning in the linac, we perform a mapping of the longitudinal and transverse beam envelopes to verify the quality of the final tuning. The concept of the beam phase envelope mapping was presented in ref. [6]. Using two medium energy beam transport (MEBT) bunchers, the bunch center in the longitudinal phase space is placed on a matched ellipse and moved along the ellipse contour. We collect the BPM phase signals for bunch positions from all 140 downstream BPMs along the linac. The results of such measurements are plotted in Fig. 3 for the case when the ellipse area is equal to $4.0 \times 10^4 \text{keV/u\cdot nsec}$, which exceeds the rms emittance of the beam in the MEBT by a factor of 20. The phase trajectories remain stable despite the large ellipse area and are consistent with the IPS simulations. The latter has been performed for the same area in the phase space. We perform similar measurements for the mapping of transverse envelopes. In this case, the beam center is moved along the Twiss ellipse using corrector magnets. Figure 4 shows the transverse mapping in the BDS. The area of the ellipse was equal to the rms emittance. After verification of the longitudinal and transverse envelopes in the linac, we send the beam to the target and ramp up beam power up to the desired value. So far, up to the power level of 5 kW, these procedures have worked very successfully, and there are no unexpected beam losses in the linac.

Figure 3: $^{48}$Ca bunch phase envelope mapping results in the entire linac. The IPS simulation of the phase envelope is shown in blue.

Figure 4: Transverse envelopes mapping of $^{36}$Ar beam in the BDS.
Multiple Charge State Beams

Tuning of multiple charge state beams in the linac brings additional challenges. Even at low beam power levels on the target, below 5 kW, we utilize the three-charge state acceleration of heavy ions starting from $^{124}$Xe. The main reason is to reduce the beam power deposition on the charge selection slits after the stripper and minimize the cooling water and air activation. Since the stripping efficiency of the heaviest ions into a single charge state is low, about 20-30%, the power deposition of unwanted charge states is high if we accelerate only a single charge state. On another occasion, the three-charge-state acceleration of $^{198}$Pt was utilized to maximize beam power on the target since the ion source limits the intensity of the heaviest ion species. The linac tuning for multiple charge states [9] includes additional procedures to set up achromatic bends in FS1, FS2, and BDS:

- Alignment of the transverse position of the central charge state $q_0$ in each quadrupole of the FS1, FS2, and BDS by varying fields in the bending magnets.
- Tuning of charge states $q_0-1$ and $q_0+1$ to the same transverse position after the bend by varying quadrupoles’ settings in the achromatic region while the sextupoles are off. Neighbouring charge states have a transverse offset from the central charge state $q_0$ after the 180° bend due to the second-order effects, which are proportional to the squared charge spread.
- Tuning of sextupoles to minimize the position offsets between all charge states in the 6D phase space.

To match multiple charge state beams to the target, we measure Twiss parameters for each charge state and adjust the quadrupoles’ field to obtain the beam waist on the target position with the rms radius of 0.25 mm. An example of beam envelopes of three-charge-state $^{124}$Xe is shown in Fig. 5. The thermal image of the 227 MeV/u 5 kW three-charge-state $^{124}$Xe beam on the target is shown in Fig. 6. The target is rotated with an angular speed of 500 rpm. The temperature of the target under the beam trace is ~770°C.

There are no losses in the LS2 for light ions such as argon and calcium beams. However, we observe minor beam losses below ~0.02 W in the linac segment 2 (LS2) for xenon and platinum beams when we use a carbon stripper [5]. Most likely, there is a small fraction of ions outside the longitudinal acceptance of the linac after the stripper. Possibly this is related to the radiation damage of the carbon foil, which is severe when the energy deposition on the foil is higher than ~7 keV/nm [10]. A detailed study of high-power (~5 kW on the target) heavy ion stripping with liquid lithium film is planned for May 2023.

Power Ramp Up

The machine setting is developed using a pulsed beam with the highest available peak intensity. The ramp-up to the 5 kW CW beam on the target is performed using attenuators and slits in the LEBT. At higher power, we plan to increase the beam power on the target within several minutes by continuously raising the beam duty factor and varying the beam repetition rate with a chopper. The chopper can support up to 25 kHz repetition rate.

Currently, we are using a rotating single-slice carbon disk as a fragmentation target. Depending on the primary ion species, this target can receive up to 70 kW beam power. We plan to deliver up to 10 kW primary beams to the target starting next fiscal year. The demonstration of the 10 kW capability will take place before August 2023.

CONCLUSION

The FRIB driver linac has accelerated seven primary ion beams up to 227 MeV/u and provided up to 5 kW beam power on the target for a dozen nuclear physics experiments. The simultaneous acceleration of multiple charge states of heavy ion beams is routinely used to minimize the beam power deposition on the charge selector slits after the stripper. We plan to demonstrate a 10 kW ion beam on the target in early summer and make it available for nuclear physics experiments.

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REFERENCES


