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TRANSVERSE BEAM DYNAMICS STUDIES IN THE FRIB ACCELERATING CRYOMODULES

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Abstract

The accelerating segments in the Facility for Rare Isotope Beams (FRIB) linac contain superconducting RF (SRF) cavities accelerating the beam and superconducting solenoids providing transverse focusing. We have studied the transverse emittance growth in the post-stripper linear accelerating segment of the FRIB linac. To understand the cause of the emittance growth we employ a macroparticle tracking code to simulate 3D beam dynamics in this segment of the linac. The model is being developed and validated by beam measurements. The measurements are focused on the response of the transverse beam position along the segment after the beam is kicked by dipole steering magnets at the entrance to this segment. The results of the studies with various beam species and energies will be presented.

INTRODUCTION

The FRIB linac contains three linear accelerating segments, shown in Fig. 1. The studies presented focus on the second linear accelerating segment, LS2. LS2 contains 168 SRF cavities distributed across 24 cryomodules. The initial beam energy is between 16 and 20 MeV/nucleon, and the final beam energy is typically greater than 150 MeV/nucleon. A superconducting solenoid is located at the center of each cryomodule to provide transverse focusing. As shown in Fig. 2, each of the solenoids has both horizontal and vertical steering coils to provide trajectory correction to compensate for misalignments.

Emittance Growth Control

Significant transverse emittance growth has been observed in LS2 [1]. This emittance growth is sensitive to slight changes in beam rigidity. For a $^{48}Ca^{19+,20+}$ beam, emittance growth was measured for 20+, but not 19+. The magnetic fields in the LS2 solenoids are set to have alternating sign, which has been previously shown to reduce emittance growth. The transverse phase advance per period provided by the solenoid was high (120 degrees) in the first cryomodule and descended irregularly along LS2. New solenoid field settings were calculated so that the phase advance began at 90 degrees and descended smoothly to 35 degrees in the last cryomodule of LS2. After applying the new solenoid settings, the emittance growth was mitigated. We could not reproduce the emittance growth in our simulations, which motivated the studies presented in this paper, as we seek to increase our understanding of the transverse dynamics in LS2.

Trajectory Response Studies

We performed measurements to calculate misalignments and observe the behavior of the beam through LS2. As displayed in Fig. 3, the four quadrupoles upstream of the LS2 entrance were included in this study. These quadrupoles are used to match the Courant-Snyder (CS) parameters of the beam to LS2.

The measurements were performed by doing “corrector scans”, incrementally changing the current in a dipole steering magnet located upstream of the LS2 entrance. At each current setting, we used the downstream BPMs to measure the transverse beam position response. Multiple correctors were scanned in both the horizontal and vertical directions. The scans were performed using a 19.82 MeV/u $^{82}Se^{32+}$ beam and a 16.52 MeV/u $^{238}U^{75+}$ beam. For the uranium beam, LS2 was set up as normal, with all 168 SRF cavities providing acceleration. For the selenium beam, the LS2 cavities were deactivated and the solenoids were set to transport the 19.82 MeV/u beam with no acceleration.

MISALIGNMENTS

If the entrance of an element is misaligned horizontally by a distance Δ_i and the exit of the element is misaligned by Δ_e, then the phase space coordinates of the beam transform at the entrance of the misaligned element change as:

$$\begin{pmatrix} \tilde{x}_i \\ \tilde{x}'_i \end{pmatrix} = \begin{pmatrix} x_i \\ x'_i \end{pmatrix} - \begin{pmatrix} \Delta_i \\ 2\Delta_t/L \end{pmatrix} \quad (1)$$

where L is the length of the element and Δ_t is defined as $(\Delta_e - \Delta_i)/2$ [2]. Likewise, at the exit of the element, the coordinates transform as:

$$\begin{pmatrix} \tilde{x}_e \\ \tilde{x}'_e \end{pmatrix} = \begin{pmatrix} x_e \\ x'_e \end{pmatrix} - \begin{pmatrix} \Delta_e \\ 2\Delta_t/L \end{pmatrix} \quad (2)$$

We apply these transformations in our simulation codes to calculate misalignments of elements in the FRIB accelerator in both the horizontal and vertical direction.

Quadrupoles

Four quadrupoles directly upstream of the LS2 entrance were used in this study. As seen in Fig. 3, there are three BPMs in this area. The first is immediately downstream of the corrector being scanned, allowing us to use its measurements to determine proper initial conditions for our simulations. There are two quadrupoles in between each BPM, meaning the measurements from the second BPM were used to calculate misalignments of the first two quadrupoles, and

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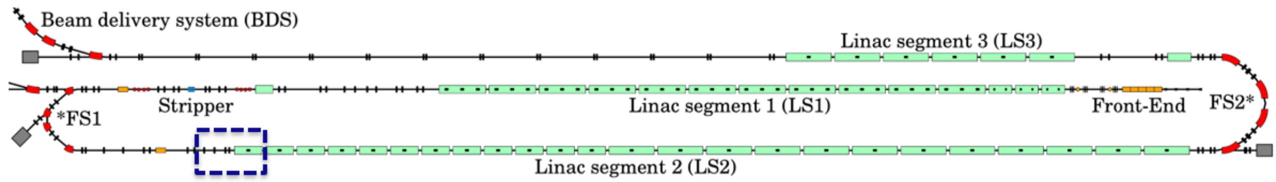

Figure 1: Layout of the FRIB linear accelerator. The misalignment studies focused on the boxed area, which is shown in greater detail in Fig. 3.

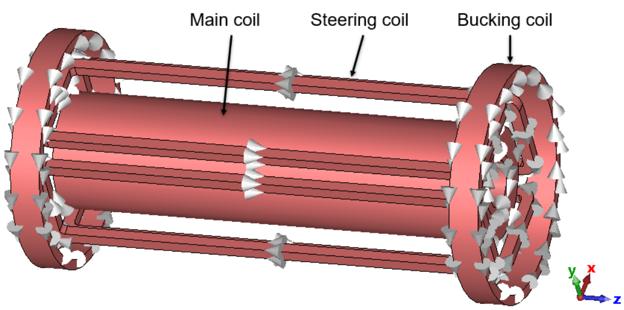

Figure 2: CST Studio model of LS2 solenoid.

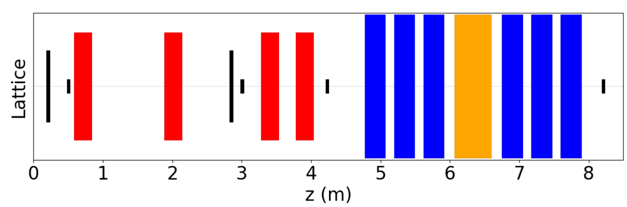

Figure 3: Lattice diagram of LS2 entrance and first cryomodule. Tall black bars are dipole correctors, short black bars are BPMs, red bars are quadrupoles, blue bars are RF cavities, orange bars are solenoids.

Table 1: Misalignments (mm)

Element	Δ_{ix}	Δ_{ex}	Δ_{iy}	Δ_{ey}
Quad 1	0.810	0.656	0.143	0.000
Quad 2	0.008	0.124	0.156	0.317
Quad 3	0.047	0.100	0.215	-0.111
Quad 4	-0.005	0.023	0.038	-0.078
Sol 1	0.317	-0.090	-0.271	0.506

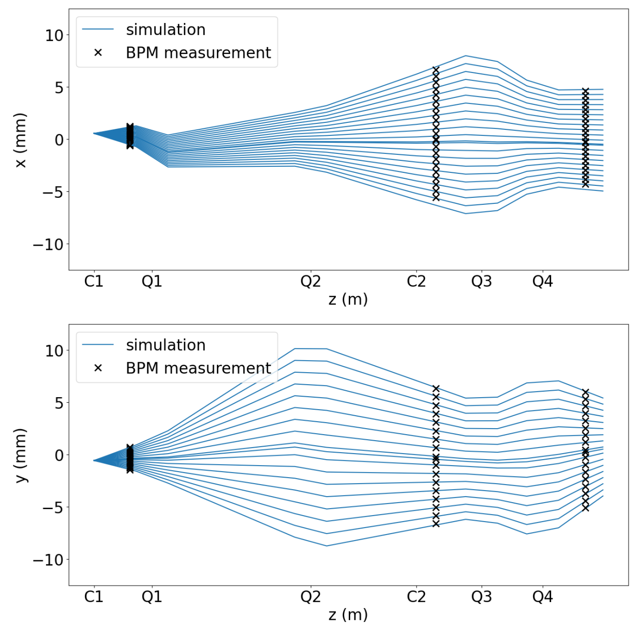

Figure 4: Comparison of BPM measurements and simulated trajectories of uranium beam with quadrupole misalignments. Corrector and quadrupole positions are marked on the x-axis.

the third BPM was used to calculate the misalignments of the third and fourth quadrupole.

We used JuTrack [3], a Julia-based accelerator modeling code, to simulate the trajectories of the beam and fit the quadrupole misalignments to the BPM measurements. These calculated misalignments were then verified by simulations in FLAME [4], a linear optics code developed at FRIB, and TRACK [5], a 3D macroparticle tracking that accepts 3D fieldmaps. Table 1 displays the misalignment values. These values were calculated assuming all BPMs work ideally. The simulated trajectories and BPM measurements for the uranium beam are shown in Fig. 4, and the results for the selenium beam are shown in Fig. 5.

Solenoids

To remove any effect of the SRF cavities, only the selenium beam measurements were used to calculate solenoid misalignments. Typically, the steering coils in LS2 solenoids are activated. However, during one set of corrector scan measurements with the selenium beam, we were able to turn off the steering coils in the first solenoid in LS2 without losing beam. The measurements used to calculate the solenoid misalignment come from this set of data. Similar to the quadrupoles, we first used JuTrack to optimize the misalignment values to best match the measurements in the BPM after the first cryomodule in LS2. Then we verified the results, shown in the bottom row of Table 1, with FLAME and TRACK simulations. Figure 5 includes the simulated trajectories and BPM measurements of the un-accelerated selenium beam through the first cryomodule. Due to hysteresis, there may be some residual magnetic field in the steering coils, affecting the BPM measurements.

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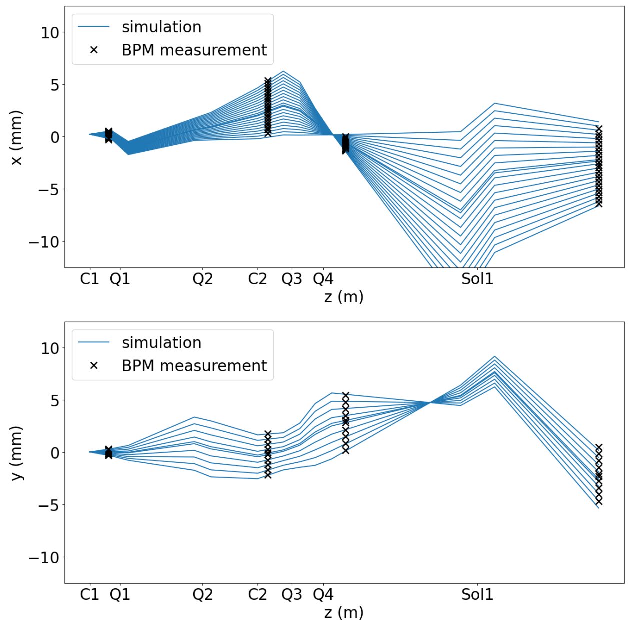

Figure 5: Comparison of BPM measurements and simulated trajectories of selenium beam with quadrupole and solenoid misalignments. Corrector, quadrupole, and solenoid positions are marked on the x-axis.

FUTURE STUDIES

We plan to use machine learning to increase the accuracy of our calculations. One possibility is to use a neural network trained on measured data to predict misalignments along the entire linac. A significant portion of beam development time at the FRIB linac is spent on trajectory correction due to both hysteresis and misalignments. This time can be greatly reduced if misalignments are known. Determining misalignments in the three achromatic bending sections of the linac will improve our models and reduce time spent on tuning quadrupoles to recombine trajectories of multi-charge-state beams [6]. Further work is also necessary to determine errors in the BPMs that affect our measurements, such as misalignments or improper calibration.

SUMMARY

Observed emittance growth motivated the measurements of transverse beam trajectories in LS2. These measurements were used to calculate misalignments of four quadrupoles and one solenoid. Future measurements are planned to extend and improve this misalignment calculation method. Our simulation models of LS2 require further improvement to more accurately simulate transverse beam dynamics and reproduce the measured emittance growth.

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