BEAM COMISSIONING PLAN OF THE FRIB SUPERCONDUCTING LINAC*

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Abstract

The FRIB superconducting linac will deliver heavy ion beams with energy above 200 MeV/u, and beam power on target up to 400 kW for generation of short lived isotopes. Beam commissioning is the first step to prepare and tune the accelerator for high power operation. A staged beam commissioning plan of the FRIB linac has been developed, and beam tuning practices segment by segment through the FRIB linac are conducted, which include phase scan tuning of all the linac superconducting cavities, longitudinal beam matching, transverse beam matching with an horizontal and vertical beam coupling exists, and corrections of beam optics of achromatic and isochronous folding segments up to the second order for acceleration and transport of multi charge state beams simultaneously in the linac.

INTRODUCTION

The FRIB, Facility for Rare Isotope Beams, is currently under construction on the campus of MSU, Michigan State University. The project is funded by the US Department of Energy Office of Science, MSU, and the State of Michigan. The total budget of the project is about 730 million dollars, and it will be completed in 2022 [1].

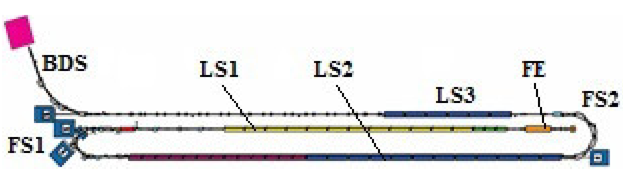

Figure 1: Schematic layout of the FRIB driver linac.

The FRIB driver linac consists of a front end (FE), three linac segments (LS), two 180° folding segments (FS), and a beam delivery system (BDS) which transport beams onto a fragmentation target for productions of rare isotopes. Details of the accelerator system designs and the associated technical challenges can be found in references [2]. Before operation, beam commissioning of the linac is necessary to prepare and tune the accelerator systems. As complexity of the linac itself and with schedule and resource limits, an 8-stage beam commissioning plan is developed [3, 4]. Beam commissioning tasks and beam exercises of the FRIB linac are discussed in more details in this paper.

BEAM TUNING OF SC CAVITY

The primary tasks for the linac beam commissioning are setting all the SC cavities to accelerate a beam to its design energy, and phase scan signature matching techniques [5] will be applied. It uses beam phase monitor (BPM) pairs to measure time-of-flight (TOF) of a beam while scan a cavity phase, then applies signature matching of the measurement against the RF cavity model to precisely measure the beam energy, the cavity amplitude and synchronous phase. To prevent from beam damaging of accelerator components or degradation of delicate SC cavities, a low duty, low current 20 ~ 50μA, and short pulse 20 ~ 50μs beam will be used in the cavity phase scan measurement.

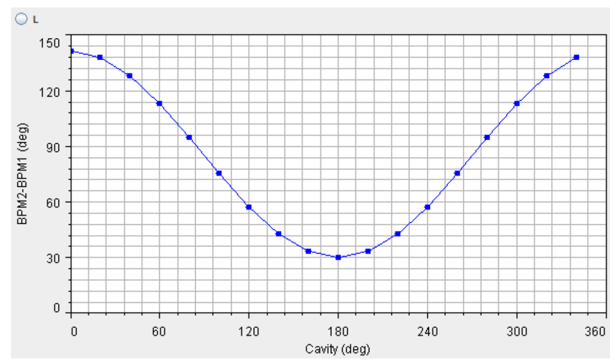

Figure 2: A cavity phase scan and the signature matching.

Figure 2 shows a cavity 2π phase scan and TOF signature matching in simulation with an online model, beam energy is approximately 55 MeV/u. The difficulty of phase scan is mainly at low energy as significant particle velocity change during the scan and 2π phase aliasing in the measurements. The problems can be solved with a proper cavity model [6] plus with multiple BPM pairs of different drift distances.

Table 1: Errors of Cavity Phase and Amplitude Tuning

	Energy (MeV/u)	Phase (º)	Amplitude (%)	Eerr (%)
LS1-A	1.5	0.18	0.12	0.34
LS1-B	17	0.48	0.84	0.41
LS2-A	55	0.56	0.92	0.43
LS2-B	150	0.54	0.90	0.42
LS3	200	0.59	1.00	0.43

Rms errors of the cavity phase scan tuning for different beam energies are listed in Table 1, which are mainly came from random BPM errors - measurements and calibrations, as well as alignment errors at low energy. Measurement error of the linac beam energy can be within 0.5%. At high energy, the error is reduced with a longer drift distance.

As the beam power is low in a cavity phase scan, beam loading induced RF fields in the downstream unpowered cavities are very small, and they do not significantly affect the beam, nor the phase measurements, therefore it is not needed to detune those unpowered cavities. Nonetheless, for high power operation, beam loading effects in the FRIB driver linac cannot be neglected anymore, and detuning of all the unpowered SC cavities becomes important.

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LONGITUDINAL BEAM MATCHING

In the FRIB driver linac, a liquid lithium charge stripper is installed to boost the charge state of heavy ion beam for more efficient acceleration at high energy [7], and a beam longitudinal matching is important to minimize the bunch length on the stripper to reduce dilutions of the longitudinal emittance caused by beam energy straggling. Bunch shape monitor (BSM) is utilized to measure bunch length of the beam and perform longitudinal beam matching.

Even though space charge effects in the SC linac can be ignored, the effects cannot be neglected in the front end, and beam current up to the operation should be used for the beam matching. To avoid any potential beam damaging to accelerator components or degradation of SC cavity, short pulse 2 ~ 5μs and a low duty beam will be used.

Procedures of the beam longitudinal matching are: scan rebuncher cavity amplitude and measure bunch length of the beam with the BSM, use an online model and numerical solvers to search for beam twiss parameters that reproduce the measured bunch length, then optimize amplitude of the rebuncher cavity and minimize bunch length on the charge stripper, finally, verify the result with BSM measurement; and iterate whenever it is needed.

Errors of the beam matching are mainly came from BSM measurement errors, and rebuncher cavity amplitude and phase errors. Currently in the FRIB linac design, a random BSM measurement error up to ±10% is acceptable.

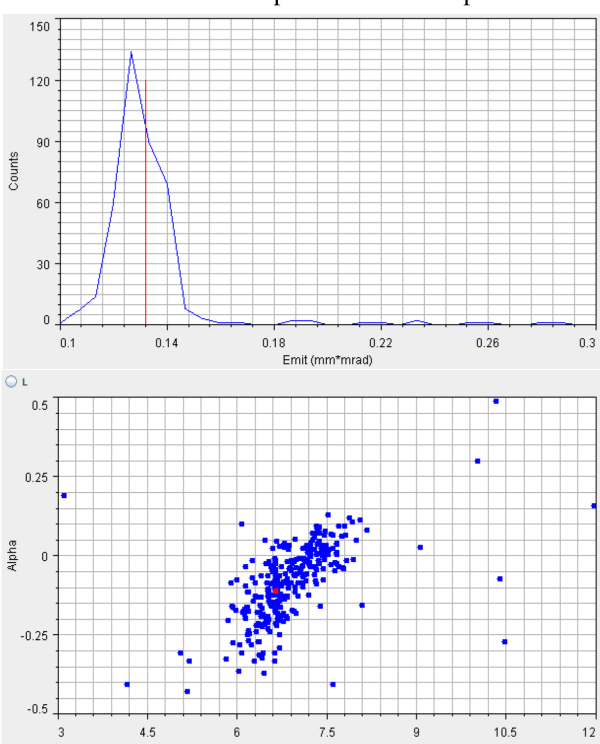

Figure 3: Longitudinal twiss parameters found with ±10% BSM measurement errors. Upper, emittance; lower, beta-alpha. Red, design parameters; Blue, solutions found.

Figure 3 shows results of longitudinal twiss parameters searching with ±10% random BSM errors in simulations. Solutions (blue) are scattered around the design parameters (red). The smaller a BSM measurement error, the closer the solution to the design beam parameters, which guarantees a better longitudinal beam matching.

Longitudinal beam matching at other locations of the FRIB linac, such as the entrance to each linac segment, is needed too, however, not as critical as the charge stripper. Normally, accurately tune rebuncher cavity amplitude and phase with the phase scan signature matching techniques should be sufficient. Therefore no more BSM is planned in the superconducting linac for beam commissioning.

TRANSVERSE BEAM MATCHING

Transverse beam matching is needed at several locations of the FRIB linac, include all of the solenoid-quadrupole lattice transition areas, entrances of each linac segment and each folding segment, the charge striper, and the fragment target. Two different transverse beam matching techniques are developed: array of multiple wire scanners and multiple quadrupole\solenoid scans. The first method uses a 4-WS or 5-WS array, while the second one applies for a matching with only one WS due to very compact lattice design [8].

Procedures of both of transverse matching methods are similar as the longitudinal matching: measure beam sizes with wire scanners, using online model search for beam twiss parameters that best reproduce the measured results, optimize all the matching magnets, and finally, verify the results with WS measurements. However, as a horizontal-vertical beam coupling exists in solenoid lattice, multiple solutions of the initial beam twiss parameter searching can be expected, which significantly increases the complexity and difficulty of transverse beam matching.

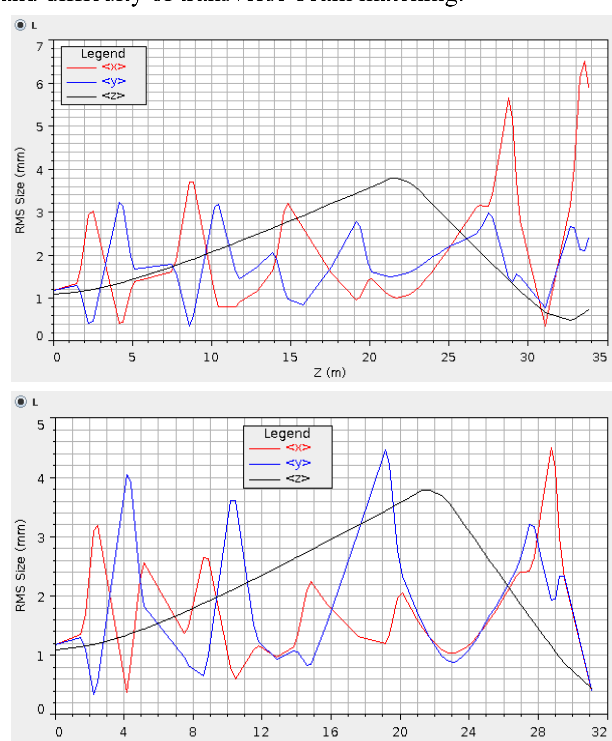

Figure 4: Beam sizes of the LS1-Stripper areas before and after simulated beam matching. Upper, before; lower, after.

Figure 4 shows beam rms sizes in simulations before and after matching at the LS1-Stripper areas. Before any beam longitudinal and transverse matching, neither bunch length nor transverse size on the charge stripper is satisfied to the requirements; while after a longitudinal beam matching with BSM measurement, and then a transverse one with 5-WS array, both beam longitudinal and transverse planes satisfy to the requirements.

Errors of transverse matching are mainly determined by WS measurement errors, and quadrupole\solenoid errors. In simulation studies, random WS measurement errors up to ±5% is required to the 5-WS array techniques to have a satisfactory beam matching, while multiple quadrupole (2-quad) scan techniques need to measure more beam profiles, therefore errors of the WS can be relaxed to about ±10%.

Similarly as a longitudinal matching, short pulse 2 ~ 5μs and a low duty beam will be used for transverse matching.

BEAM ORBIT CORRECTION

Beam orbit correction in the linac is important for beam commissioning as well as for high power operation. It will be performed multiple times: after cavity phase scan tuned, before and after a longitudinal matching, before and after a transverse matching. A low current 20 ~ 50μA, short pulse 20 ~ 50μs, and low duty beam, exactly as that of the cavity phase scan tuning, will be used.

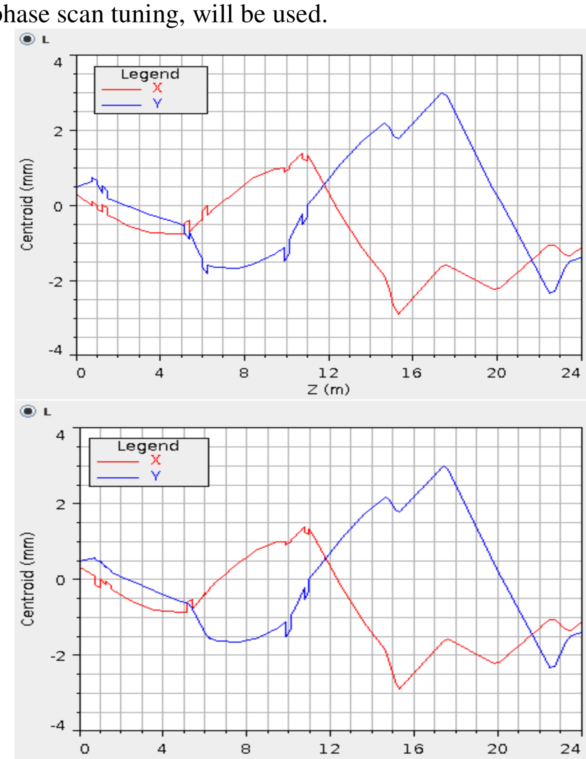

Figure 5: Online model based linac beam orbit differences. Upper: simulated beam offsets; lower: found with model.

Orbit response matrix based beam orbit correction using singular value decomposition algorithms is planned for the FRIB linac, and in simulation studies, it satisfies the beam commissioning requirements [9]. Online model based orbit corrections will also be performed, which uses beam orbit differences of the linac model against BPM measurements to search for the injection beam and the orbit offsets of the magnets as well as the BPMs. Especially, differences of the beam orbit offsets in a BPM with respect to the model can be directly used for marking misalignments of the BPM.

Figure 5 shows a model based beam orbit exercise, apply measurement of orbit differences against the online model, we may find orbit offsets in magnets and misalignments of BPMs. Apply a correction, beam orbit can be within 1 mm.

ACHROMATIC OPTICS TUNING

As acceleration and transport of multi charge state beams simultaneously, achromatic and isochronous beam optics up to the second order is required for all the bending areas of the FRIB linac for high power operations.

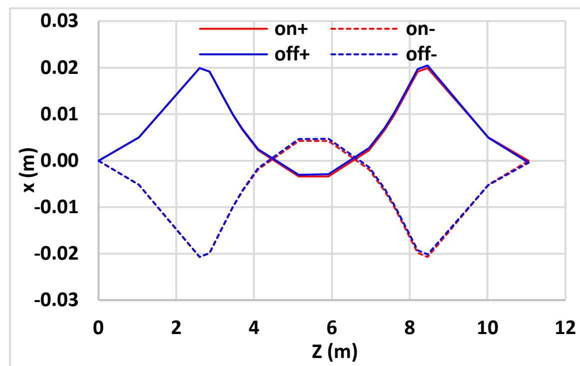

Figure 6: Beam horizontal centroids in the FS1 for different charge state beams (±), and with sextupoles on and off.

Optics corrections are based on BPM measurements in the arcs. Figure 6 shows beam centroids of U+80 and U+76 beams other than the reference U+78. Full correction with sextupoles only yields approximately 0.5 mm difference, so beam orbit within 0.1 mm is necessary prior to the optics correction. It needs precise alignments of the arc magnets, and beam based alignment orbit correction is mandatory.

CONCLUSIONS

Beam commissioning plan and beam tuning exercises of the FRIB driver linac are discussed. Major beam tasks and challenges for multi charge state beams tuning and high power operation are summarized briefly.

ACKNOWLEGEMENTS

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