BEAM TUNING OF ACHROMATIC BENDING AREAS OF THE FRIB SUPERCONDUCTING LINAC *

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Abstract

To achieve the design power for the heaviest ion species, it is required to accelerate and transport multi charge state beams simultaneously in the FRIB SC driver linac, which imposes a great technical challenge especially to the folded linac lattice design. An achromatic and isochronous beam optics up to the second order must be established precisely in the bending segments. Because system errors and beam element imperfections always exist in the real machine, beam tuning and optics corrections of the bending areas are critical to high power operation. In this paper, beam tuning algorithms of achromatic arcs of the FRIB driver linac are introduced and the simulation studies discussed.

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].

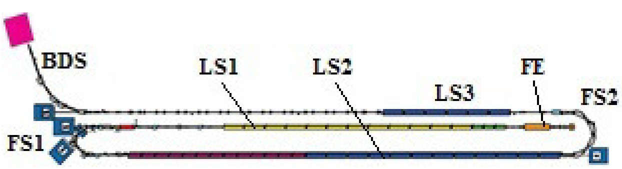

Figure 1: Schematic layout of the FRIB driver linac.

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 the production of rare isotopes. Shown in Figure 1 is a schematic layout of the FRIB linac. For the heaviest ion species, accelerate and transport multi charge state beams simultaneously in the linac are required to achieve the design power of 400 kW, thus the second order achromat is needed to all the folding areas including the BDS, and meanwhile isochronous beam optics should be tuned accurately for the two 180° folding segments.

ACHROMATIC LATTICE

In the design of an achromatic bend, beam particle at the final location shall be independent to the momentum, and the bend will produce the same output beam regardless of the momentum spread. In an isochronous bend, the arrival time of beam particle is independent to the momentum and the transverse location, essentially, injection particles with different momentum and transverse positions arrive at the same time. Using the notations of TRANSPORT [2], first order elements $R_{16} = 0$ and $R_{26} = 0$ in an ideal achromatic system. In an isochronous system, $R_{51} = 0$, $R_{52} = 0$, and $R_{56} = 0$. It is noted that in an isochronous system, $R_{56} = (1-\beta^2)\cdot L$ is generally required for a low energy particle beam as the velocity changes substantially with the momentum. In the FRIB linac however, as the energy and velocity of various charge state beams are similar, so that in the bend different rigidities of those multi charge state beams are analogous to momentum differences, thus $R_{56} = 0$ is required instead, though which is generally for a high energy electron beam.

As charge states of uranium beams from +76 to +80 are equivalent to about ±3% momentum variations, the second order achromat is needed, therefore sextupoles are installed in all the bends. Figure 2 shows transfer matrix elements of the LS1 arc in simulation with MAD-X [3], the symmetric bend totally consists of four 45° dipoles, four quadrupoles, and two sextupoles. In the lattice design, locations of the quadrupoles are selected to have $R_{16} = R_{52,}$ and $R_{26} = R_{51}$, therefore once an achromat is established, the bend is also isochronous. Because of compact lattice design, available knobs and spaces are limited, it is not a perfect achromatic system. Sextupole magnets are installed for manipulating second order dispersions, both longitudinal and transverse.

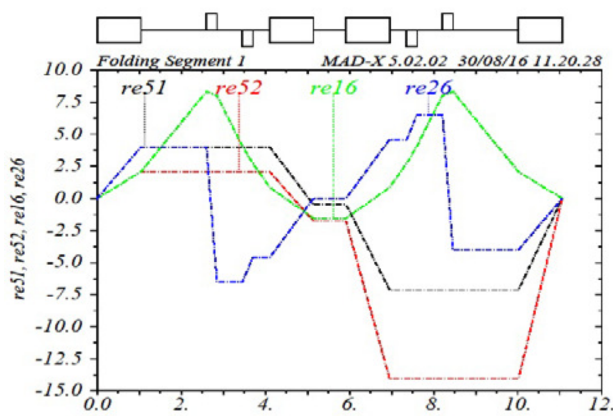

Figure 2: Beam transfer matrix elements R_{16}, R_{26}, R_{51}, and R_{52} of the LS1 lattice in calculation with MAD-X.

BEAM TUNING BASED ON MODEL

Since in the real world beam element imperfections and system errors cannot be completely avoidable, beam tuning of the bending segments becomes important for high power operation of the driver linac. Algorithms of beam tuning and optics corrections have been introduced briefly in the FRIB linac beam commissioning plan [4], while detailed analysis is described in this paper. Figure 3 shows ideal horizontal orbits of difference charge state beams in the

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FS1 arc with respect to that of the reference charge state U^{+78} beam. At the maximum dispersion spot, a beam orbit offset is up to 2 cm, and at exit of the bend however, the beams are merged together again. Based on this lattice design model, an achromatic and isochronous beam optics correction could be processed for the bending area.

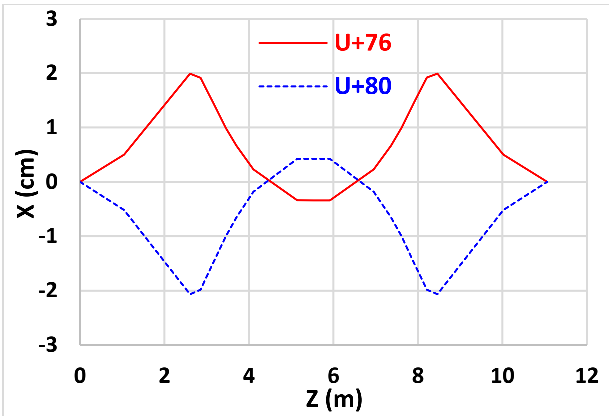

Figure 3: Ideal horizontal beam orbits of different charge state beams in the FS1 bending area.

After the reference charge state U^{+78} beam been tuned and orbit finely corrected, a charge selector is adjusted to transport a beam of another charge state (e.g. U^{+76} or U^{+80}) through the bend, the horizontal beam orbit is measured with beam position monitors (BPMs) in the arc and at exit of the arc. Because misalignments and errors of the beam elements it is expected that the measured orbit not perfectly agrees with model prediction. To tune the arc correctly for an achromatic and isochronous transport system, scans of the arc quadrupole magnets will be conducted. Figure 4 shows a simulated arc quadrupole scan exercise.

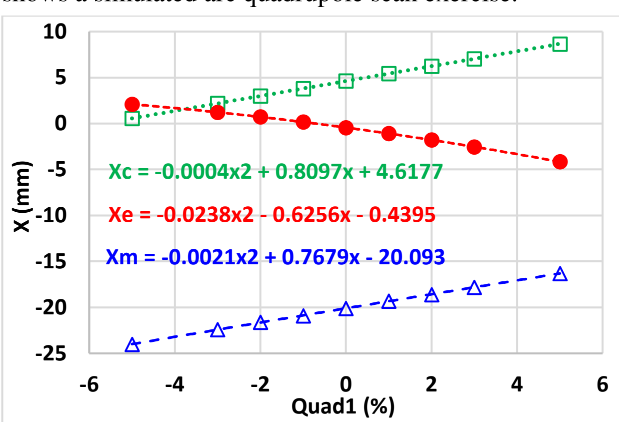

Figure 4: Simulated horizontal beam offsets of U^{+80} at the maximum dispersion spot Xm, the arc center Xc, and the exit Xe, while scan the first quadrupole in the FS1 arc and with the sextupole magnets turned off.

In the above quadrupole magnet scan exercise, BPMs in the arc and at exit of the arc are used for the beam orbit difference measurements against the reference beam, and tune all the quadrupole magnets to generate an horizontal orbit which closely agrees with the model predictions, and complete the beam tuning of achromatic bend. In principle, tuning of an isochronous lattice can also be conducted with the design model. Figure 5 shows changes of the absolute beam phase and the horizontal beam position at exit of the FS1 arc versus scan of the first quadrupole in the arc. If phase resolution of the BPM is sufficient, precise tuning of an achromatic and isochronous arc could be achieved at the same time with this model based method.

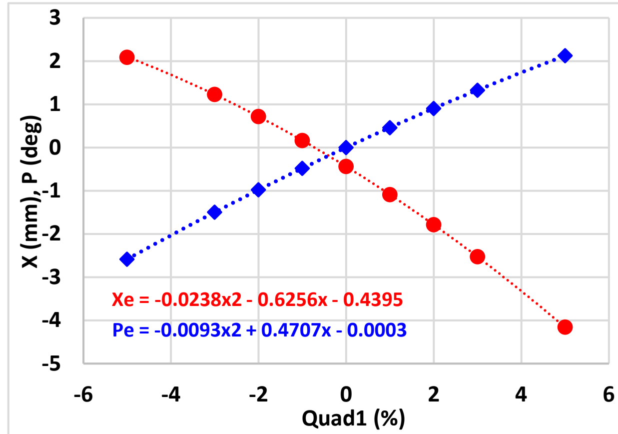

Figure 5: Simulated changes of the absolute beam phase Pe and horizontal beam orbit Xe of U^{+80} at exit of the FS1 arc.

Misalignments of beam elements significantly affect the beam tuning with the model however, because resolution of the BPM is only about 0.1 mm. Even after a beam based alignment (BBA), a beam offset of approximately 0.1 mm will be expected in the FS1 arc [5]. Model based correction of the first order achromat could be less a problem, but it might be very difficult to tune the second order.

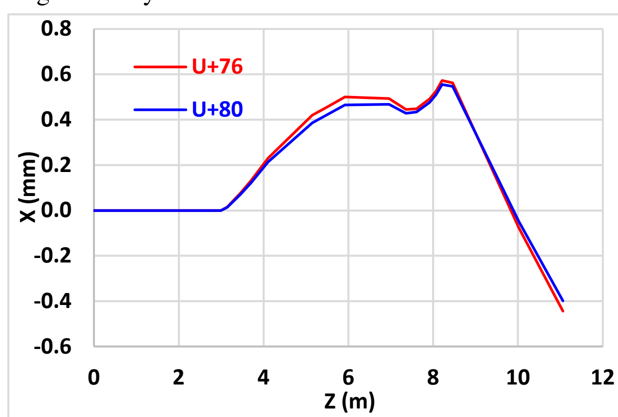

Figure 6: Beam orbit differences for U^{+76} and U^{+80} beams with sextupole magnets of the FS1 arc turned on and off.

Figure 6 shows simulation studies of orbit differences of U^{+76} and U^{+80} beams with the sextupoles turned on and off for the beam tuning of the second order achromat, which is merely 0.4 to 0.5 mm in the FS1 arc and at the exit. To reduce the tuning errors, a beam orbit of 0.1 mm is needed. Though it is demonstrated that a 0.1 mm orbit is achievable with BBA for a single charge state beam, correction of the orbits of all different charge state beams to within 0.1 mm cannot be guaranteed for large misalignments.

BEAM TUNING WITHOUT MODEL

Tuning of the second order achromat of all the bending segments is important for high power operation with multi charge state beams, while a model based method is difficult

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to satisfy the requirements due to the limitations of element misalignments and beam orbit corrections, we developed a new method which does not depend on any model.

Beam horizontal position, horizontal divergence, and the longitudinal position at the exit of an arc depend on those of the injection beam and dispersions of the arc. Ignore all higher order terms, output parameters are approximately:

$$\begin{aligned} x &= x_0 + \delta \cdot R_{16} + \delta^2 \cdot T_{166} \\ x' &= {x_0}' + \delta \cdot R_{26} + \delta^2 \cdot T_{266} \\ z &= z_0 + \delta \cdot R_{56} + \delta^2 \cdot T_{566} \end{aligned} \quad (1)$$

where, δ is the beam momentum error,

Using BPMs at exit of the arc and further downstream to measure the beam position and the absolute phase, and meanwhile conducting a rigidity scan of all the magnets in the arc simultaneously – including dipole and quadrupole magnets, the dispersion terms R_{16}, R_{26}, R_{56}, T_{166}, T_{266}, and T_{566} – up to the second order – can be directly measured. The rigidity scan does not change the reference charge state, instead it changes the reference beam orbit in the arc. During a scan, variation of the reference orbit is equivalent to the changes between U^{+76} and U^{+80}, and the same beam U^{+78} is used for measuring the dispersion terms accurately. Therefore, an achromat tuning is simplified to minimizing all the above dispersion terms based on the measurements, which may not necessarily agree with the design model perfectly, due to element imperfections, misalignments, and system errors.

As the new method only uses the same reference beam for achromat tuning, uncertainty of beam orbits associated with different injection beams is eliminated completely, and an initial beam orbit within 0.1 mm in the arc can be established with BBA, which is needed for the beam tuning of the second order achromat.

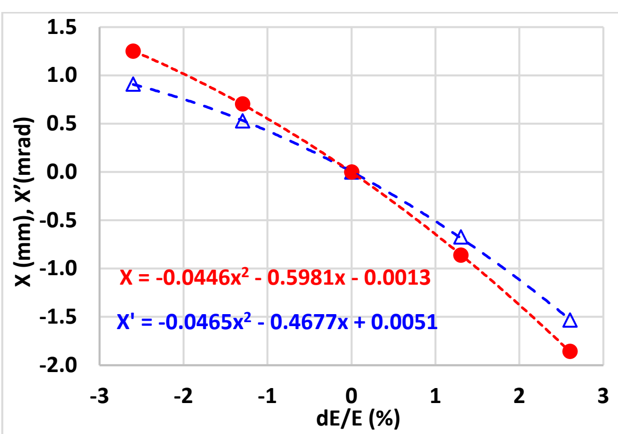

Figure 7: Simulations of the FS1 rigidity scan with the first arc quadrupole 3% less than the design, and all sextupole magnets turned off.

Figure 7 shows a scan exercise of the FS1 arc, with the first arc quadrupole 3% less than design and all sextupole magnets turned off. In the measurements, $R_{16} \approx 0.06$, $R_{26} \approx 0.05$, $T_{166} \approx 0.4$, and $T_{266} \approx 0.5$. Series of such rigidity scans will be conducted with different quadrupole strengths, and after errors of all the quadrupole magnets been corrected finely, the tuning of the first order achromat is completed. Then a beam tuning of the second order achromat with all the sextupole magnets can be processed similarly.

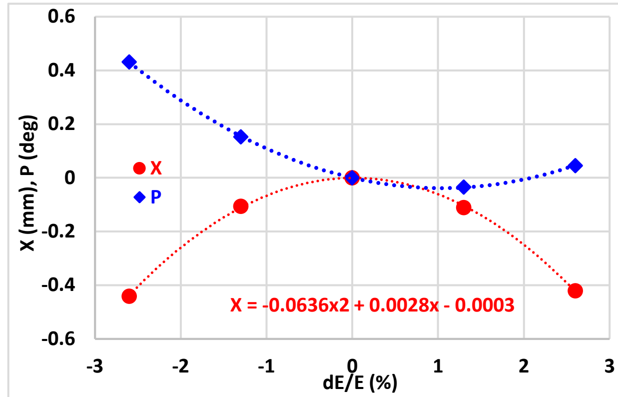

Figure 8: Simulation of a rigidity scan of the FS1 arc after the first order achromat corrected and with all the sextupole magnets turned off: X – beam horizontal position at exit of the FS1 arc, P – the absolute beam phase.

Figure 8 shows an exercise after the first order achromat corrected for the FS1 arc, before sextupole magnets turned on. In this measurement $R_{16} \approx 0.0003$, which is sufficiently small and can be ignored. However, $T_{166} \approx 0.6$, which is not negligible, therefore a tuning of the second order achomat with the sextupole magnets is necessary. In this exercise, as horizontal beam positions vary approximately 0.4 mm in the rigidity scan, an initial reference orbit in the bend no worse than 0.1 mm is required to accurately tune all the sextupole magnets. Also shown in the figure is the changes of the absolute beam phase at exit of the arc; in principle, measurement and beam tuning of an isochronous arc up to the second order can be applied at the same time with this rigidity scan method.

CONCLUSIONS

It is a challenge to achieve the design beam power of 400 kW for the FRIB driver linac, particularly for acceleration and transport of multi charge state beams simultaneously in the folded linac lattice, as beam tuning and corrections of achromatic and isochronous bending segments up to the second order are necessary. Two different tuning methods for the beam achromat corrections are investigated, and the simulation studies show that precise achromat beam tuning up to the second order could be achieved with the proposed arc magnets rigidity scan method and BPM measurements.

ACKNOWLEGEMENTS

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