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TRANSVERSE MATCHING OF HORIZONTAL-VERTICAL COUPLED BEAMS FOR THE FRIB LINAC *

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Abstract

FRIB driver linac will deliver all heavy ion beams up to uranium with energy above 200 MeV/u and maximum beam power on fragment target 400 kW. Strong horizontal-vertical coupling exists in the linac since superconducting solenoids are installed to focus multi charge state beams. Further, the low beta SRF cavities have raised quadrupole field components, and the combined effects make beam transverse matching challenging. In this paper, we study transverse matching of horizontal-vertical coupled beams based on beam profile measurements with multiple wire scanners. Issues such as the initial beam conditions fit with coupling not unique, and errors of beam diagnostics and magnets introduce further complications are addressed. Nonetheless, the simulation studies show that satisfactory transverse matching can be achieved with proper tuning.

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].

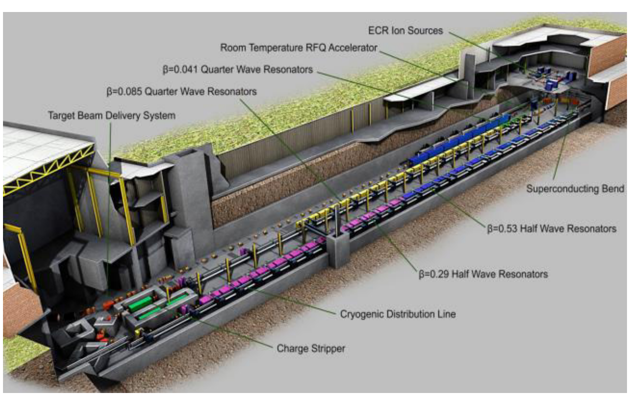

Figure 1: Layout of the FRIB driver linac.

The major accelerator system of the facility is a SRF continue-wave (CW) linac, the FRIB driver linac, which consists of a front end, three linac segments (LS), two 180° achromatic isochronous folding segments that connect the three LS, a liquid lithium charge stripper for more efficient accelerations of high power heavy ion beams, and a beam deliver system which transport the primary beams onto the fragment target for production of rare isotopes for nuclear physics research. The FRIB drive linac will be installed underground about 10 meters deep on the campus of MSU. Figure 1 shows the layout of the driver linac [2]. To reach the design beam power for the heaviest ions, multi charge beams are accelerated simultaneously in the linac: in the design, two charge states in LS1, and up to 5 charge states in LS2 and LS3. In the linac, superconducting solenoids are used for transverse beam focusing.

Because the injection beam is generated within a strong magnetic field from an ECR ion source [3], the beam distribution has strong correlation. Since generally beams emerging from ECR ion sources are not axisymmetric, the ion particles are born with x-y coupling. In addition, beam asymmetries further develop due to dispersions in bending magnets of the folded linac lattice. Even in the solenoid lattice of the straight linac segment, significant dipole and quadrupole components within the quarter wave resonators (QWRs) impact on the beam acceleration and transport, particularly at low energy, usually the beam is significantly deviated from axisymmetric [4]. Due to these effects, for transverse matching of the FRIB linac, we have to deal with a strongly coupled beam which is not axisymmetric.

PARAMTERS OF X-Y COUPLED BEAM

To describe a horizontal-vertical (x-y) coupled beam, second order moments of 4D beam matrix are applied:

$$\sigma = \begin{pmatrix} \langle \boldsymbol{xx} \rangle & \langle \boldsymbol{xx'} \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle \boldsymbol{xx'} \rangle & \langle \boldsymbol{x'x'} \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle xy \rangle & \langle x'y \rangle & \langle \boldsymbol{yy} \rangle & \langle \boldsymbol{yy'} \rangle \\ \langle xy' \rangle & \langle x'y' \rangle & \langle \boldsymbol{yy'} \rangle & \langle \boldsymbol{y'y'} \rangle \end{pmatrix} \qquad (1)$$

Because of symmetry, there are 10 independent variables in the matrix. Two parameterizations are often utilized to deal with linear coupling: Edwards-Teng [5] and Ripken [6]. Implements of these two parameterizations can be found in, e.g. MAD-X [7] and Elegant [8]. Relationships between the two methods are analysed by Lebedev and Bogacz [9]. We use Ripken's parameterization method.

The 10 parameters chosen are: 4 alpha functions, 4 beta functions, and 2 emittances (β_{1x}, β_{1y}, β_{2x}, β_{2y}, α_{1x}, α_{1y}, α_{2x}, α_{2y}, ε_1, ε_2). Additionally, for beam envelop solution 2 phase advances (ν_1, ν_2) are needed [9]. The phase advances can be derived from these alpha and beta functions. Measurable beam rms sizes along x, y, and at 45° diagonal (d) are [9]:

$$\sigma_x = \sqrt{\varepsilon_1\beta_{1x} + \varepsilon_2\beta_{2x}} \qquad (2)$$

$$\sigma_y = \sqrt{\varepsilon_1\beta_{1y} + \varepsilon_2\beta_{2y}}$$

$$\sigma_d = \frac{\sqrt{\sigma_x^2 + \sigma_y^2 + 2\delta\cdot\sigma_x\sigma_y}}{\sqrt{2}}$$

where, $\delta = \dfrac{\sqrt{\beta_{1x}\beta_{1y}}\,\varepsilon_1\cos\nu_1 + \sqrt{\beta_{2x}\beta_{2y}}\,\varepsilon_2\cos\nu_2}{\sigma_x\sigma_y}$

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SEARCHING FOR BEAM PARAMETERS

The first and the most difficult step of beam transverse matching is to determine parameters of the injection beam using the beam rms sizes measured with available wire scanners (WS). Due to the sensitivity of SRF systems and high beam power, in the design, no WS is installed adjacent to any cryomodules to avoid accidental contamination of the delicate SRF cavities. Also, in the warm sections, as a result of compact lattice design, we cannot install WS in the most sensitive configurations: evenly distribute the WS in a 90 degree phase advance. To synthesize experimental data, IMPACT [10] simulations are applied to generate the rms beam sizes at the locations of planned WS. Then we run Open XAL [11] to search of the initial beam parameters based on the simulated beam sizes. We study LS3 which consists of 6 SC solenoids and a downstream 60m transport lattice with quadrupole doublet focusing.

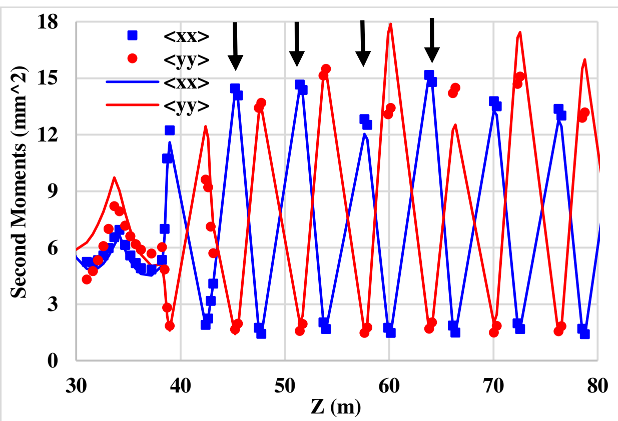

Figure 2: Simulation results with a 4-WS measurement. Dots - IMPACT simulations for WS measurements, lines – beams found with Open XAL, arrows – locations of 4-WS.

Figure 2 shows simulations of a 4-WS study. Each WS is equipped with x, y, and 45° wires. Because multiple solutions exist for the coupled beam, even if Open XAL Solver finds out a solution with beam sizes all agree with the IMPACT simulations at all the WS locations, beam parameters may still not the same. Beam parameters used in the WS simulations and those found by Open XAL are listed in Table 1. Matching fails when use the above results.

Table 1: Initial Beam Parameters for the 4-WS Study

Para.	α_{1x}	β_{1x}	α_{2y}	β_{2y}	α_{1y}	β_{1y}	α_{2x}	β_{2x}	ε_1	ε_2
WS	-0.06	3.1	0.06	4.7	0.0	0.0	0.0	0.0	1.2	1.2
Found	-0.05	2.1	0.18	2.8	-0.5	2.7	0.2	2.8	1.0	1.0

It is noted that beam size measurements are critical for matching of a coupled beam. A 5-WS study is summarized in Table 2, and Figure 3 shows a satisfactory result.

Table 2: Initial Beam Parameters for the 5-WS Study

Para.	α_{1x}	β_{1x}	α_{2y}	β_{2y}	α_{1y}	β_{1y}	α_{2x}	β_{2x}	ε_1	ε_2
WS	-0.06	3.1	0.06	4.7	0.0	0.0	0.0	0.0	1.2	1.2
Found	-0.05	1.6	0.04	2.5	0.0	1.5	0.0	2.4	1.2	1.2

Though the initial beam parameters are different for the 5-WS study too, the beam envelops agree closely with the IMPACT simulations over the entire LS3 lattice, as shown in Figure 3. Because the model found with Open XAL can be extended correctly from the 5-WS array to the upstream as well as the downstream lattices, a transverse matching based on the 5-WS measurements is expected to be correct.

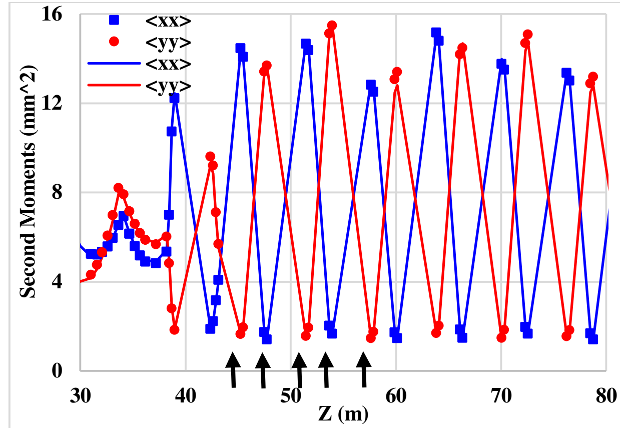

Figure 3: Simulation results with a 5-WS measurement.

In both cases, a wide searching range and an initial beam guess far away from the simulation is used. When a narrow searching range closer to the simulated beam without any errors is used, both the 4-WS and 5-WS cases converged to exactly the simulated beam used for generation of the WS data. Therefore in principle, a 4-WS array may also work.

BEAM TRANSVERSE MATCHING

Once the injection beam parameters are solved correctly from the WS measurements, the next step of transverse matching can be performed by optimizing the quadrupole and/or solenoid magnets. There are many accelerator codes that can be used for this purpose, and here we use Open XAL again.

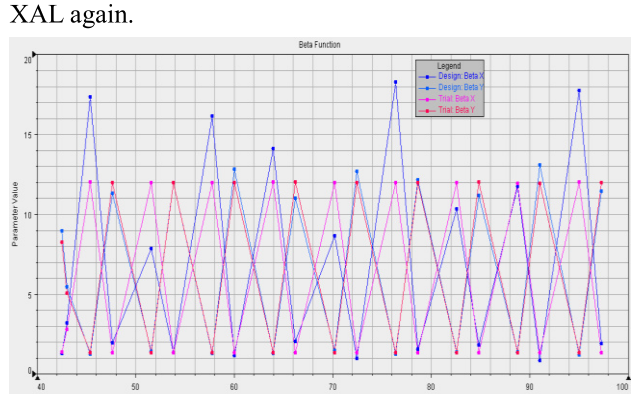

Figure 4: An Open XAL application, Energy Manager, is used in the beam transverse matching. Blue and Cyan – x and y, before matching; Pink and Red – after matching.

Beam matching to the LS3 quadrupole doublet lattice needs to smooth the beam transverse beta beating when an injection beam is different from the design, an Open XAL application - Energy Manager, is used for this transverse matching. Two solenoids and 4 matching quadrupoles are adjusted to match the beam. Figure 4 shows the transverse beta functions of the LS3 doublet lattice before and after the matching. In principle, 4 variables are sufficient to perform the matching as only 4 target parameters: <xx>,

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<xx'>, <yy>, and <yy'> are required. However, we use 6 variables for two reasons: 1. To minimize change in magnet settings, especially for the SC solenoids as they must be varied slowly; 2. To maintain a small beam size within the matching region too as the the aperture is limited. No skew quadrupole is installed in the FRIB lattice, and there is no plan to correct the beam tilt angle from the coupling. As long as beam sizes satisfy the requirements on the charge stripper and on the final target, the tilt angle is not an issue.

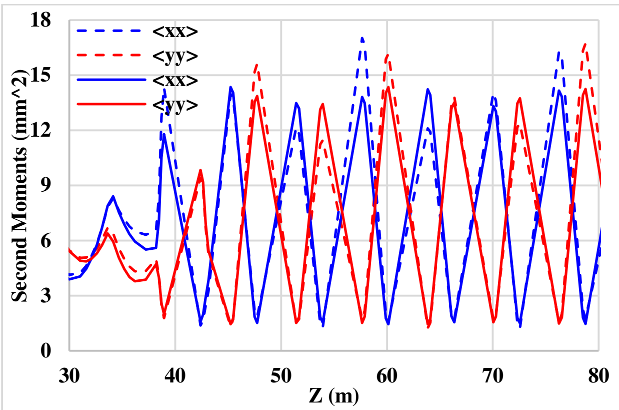

Figure 5: Before and after matching with the IMPACT simulated beam. Dashed lines – before; Solid lines – after.

Since the beam parameters found with the model are not exactly the same as those used for the WS data as well as the matching, one more step of our study uses the simulated beam parameters to verify it, as shown in Figure 5. It is noted that even after the matching, the lattice is not perfect. However, the result is good enough for normal operations.

MULTIPLE QUADRUPOLE SCAN

Error analysis shows that the matching procedure with ±10% WS measurement errors becomes unreliable. The parameter found can be far away from that of the real one. For satisfactory matching, a WS measurement error should be within ±5%. There are different ways to increase the accuracy of WS measurements, such as taking multi WS measurements and averaging etc. We developed a multiple quadrupole scan technique that is time consuming but can handle ±10% WS errors. More importantly, there is no space to install a 5-WS array at a few locations in the FRIB linac where a beam matching is necessary.

In a single quadrupole scan which is associated with WS measurements, usually one plane is solved correctly while the other plane is not. Switching polarities of the quadruple in the scan to correctly solve both planes sequentially is doable, but not as practical as a multiple quadrupole scan where two or more quadrupoles are varied and downstream beam sizes are measured with a WS.

Table 3: Initial Beam Parameters for a 2-Quad Scan

Parameter	α_{1x}	β_{1x}	α_{2y}	β_{2y}	ε_1	ε_2
Scan	-0.12	3.8	-0.49	4.9	1.2	1.3
Found	-0.19	3.8	-0.51	4.9	1.1	1.3

Table 3 lists the results of a 2-quad scan where 3 steps are taken for each quadrupole - a total of 9 measurements. WS errors of ±10% and quadrupole strength errors of ±1% are assumed. Beam parameters found with Open XAL are close enough to those of the injection beam. Starting from these initial values, we may reasonably expect a successful transverse matching, as shown in Figure 6.

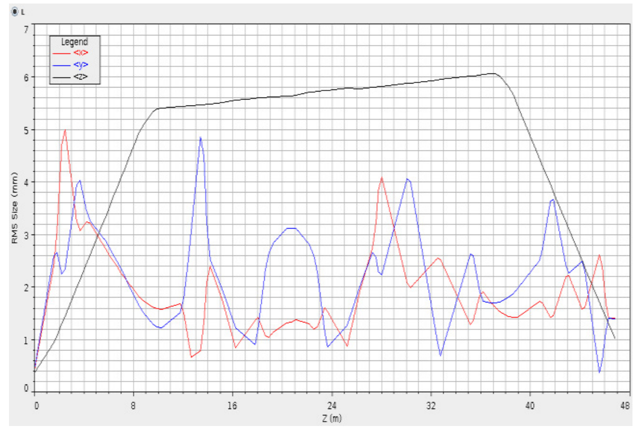

Figure 6: After a beam matching at the entrance into LS2. Beam rms sizes are shown as <x>, <y>, and <z>. With 10% WS and 1% quad errors, the matching is satisfactory.

CONCLUSIONS

Transverse matching techniques of a horizontal-vertical coupled beam for the FRIB driver linac are developed consistent with the planned beam diagnostics systems including 4-WS and 5-WS arrays, and multiple quadrupole scan measurements. Strong beam coupling, errors in the measurements, and errors of the accelerator components make the transverse matching a challenging task. However, we show that with adequate linac models and application software, such as Open XAL, satisfactory transverse beam matching can be achieved. This verification is important in the high power operation of the FRIB accelerator system since beam loss exacerbated by poor transverse matching could severely damage the accelerator components.

ACKNOWLEGEMENTS

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