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# BEAM ENVELOPE RECONSTRUCTION FOR FRIB-FS1 TRANSPORT LINE USING BEAM POSITION MONITORS*

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*Abstract*

The Facility for Rare Isotope Beam (FRIB) includes a heavy ion superconducting (SC) linac. Recently, we completed beam commissioning of the Linac Segment 1 (LS1) and 45° bend section of the Folding Segment 1 (FS1). Four ion species, $^{40}Ar^{9+}$, $^{20}Ne^{6+}$, $^{86}Kr^{17+}$, and $^{129}Xe^{26+}$ were successfully accelerated to an energy of 20.3 MeV/u. We also explored the possibility of non-invasive beam diagnostics for online beam envelope monitoring based on beam quadrupole terms derived from Beam Positon Monitors (BPMs). In future operations, various ion beam species will be accelerated and minimization of beam tuning time is critical. To address this requirement, it is beneficial to use BPMs to obtain beam Twiss parameters instead of wire scanners. We report the first results of BPM-based beam Twiss parameters measurement [1] in the FS1.

## INTRODUCTION

The beam commissioning of the first superconducting (SC) segment of the FRIB linac took place in two stages: the first three cryomodules were commissioned during the summer of 2018 and the whole LS1 including the fraction of the FS1 was commissioned in the spring of 2019 [2-4]. This significant milestone was achieved after acceleration of four ion species, $^{40}Ar^{9+}$, $^{86}Kr^{17+}$, $^{10}Ne^{6+}$ and $^{129}Xe^{26+}$ to 20.3 MeV/u in 14 cryomodules with 99 of two types of SC cavities: $\beta_{opt}$ = 0.041 and $\beta_{opt}$ = 0.085 [5, 6]. The layout of the FRIB superconductive linac is shown in Fig. 1.

As was noted during the commissioning of LS1 with 20 MeV/u ion beams, the conventional quadrupole scans with wire profile monitors can result to two undesirable effects: increased neutron production due to the beam interaction with the wire scanner and vacuum degradation due to the outgassing. Therefore, a non-invasive beam diagnostic technique for the measurements of the transverse beam parameters would be an attractive approach. We propose an evaluation scheme of quadrupole terms of the BPM signals to reconstruct the beam phase space information. Non-destructive monitoring and control of the beam parameters can maximize beam availability during the routine operation of the facility.

This paper reports initial experimental studies of BPMs' response studies on extraction of the information on beam Twiss parameters and emittances.

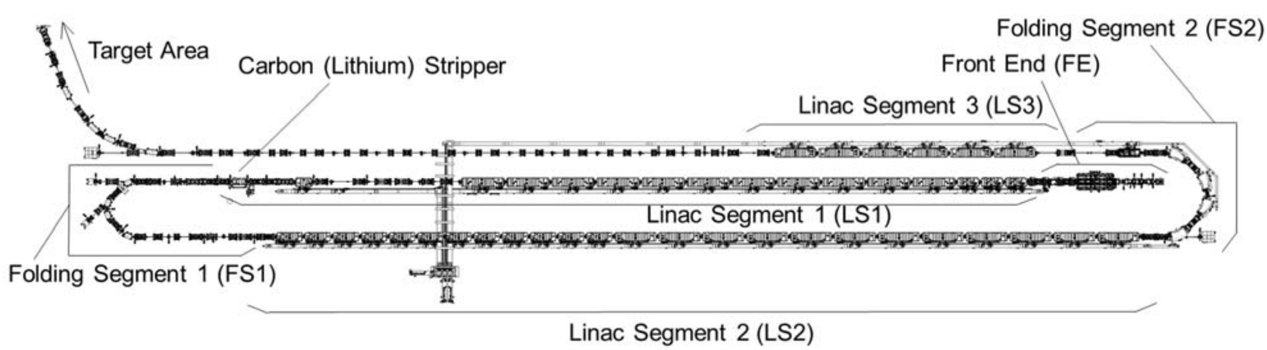


Figure 1: Schematic layout of the FRIB linac which comprises the Front End (FE) (the ion sources and vertical beam transport are not shown in the figure), and three superconductive Linac Segments (LS1, LS2, and LS3).

## DIAGNOSTIC SYSTEM OF BEAM POSITION MONITOR

BPMs used in the FRIB linac have four button electrodes (diameter is 20 mm), and are installed in a vacuum pipe (radius $R$ is 20.65 mm) as shown in Fig. 2. The typical beam rms sizes are a few millimetres in longitudinal and transverse directions. The longitudinal beam size is comparable to the button electrode size. Therefore, a conventional approximation that the bunch length is much longer than the size of the electrodes does not apply to FRIB beams. To emulate realistic BPM response, three dimensional electromagnetic calculations based on actual BPM geometries were extensively performed using CST Studio Suite [7] as shown in Fig. 3. The beam energy in the FS1 is 20 MeV/u, corresponding to a relativistic beta $\beta$ of 0.2.

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The time response of the BPM was simulated in CST for the typical beam parameters: $\beta = 0.2$ and the bunch length of several millimetres. Then, the transverse beam position of a pencil beam was varied with 2 mm step in both the horizontal and vertical directions. The time response of the electrode is shown in Fig. 4. Their response in frequency domain is shown in Fig. 5.

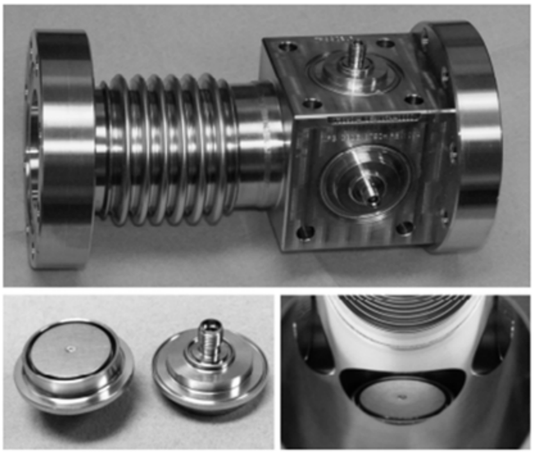

Figure 2: A type of BPM with the inner diameter of 41.3 mm, installed along the FRIB linac [9].

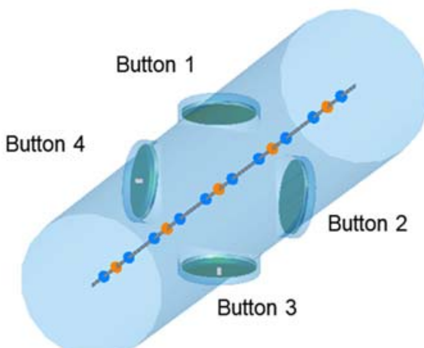


Figure 3: BPM model with four button electrodes in CST simulation.

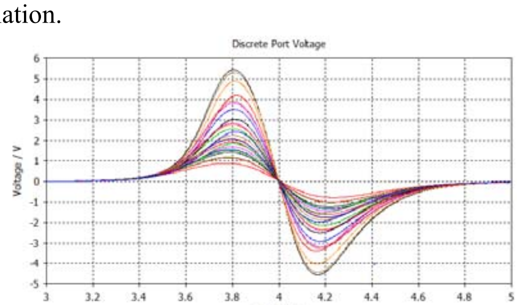


Figure 4: Induced voltage responses of the button 2 in time domain.

FRIB BPM diagnostic system is designed to report magnitudes and phases of 161 MHz harmonic of a signal. Using the voltage amplitude of each electrode at 161 MHz from the CST simulations, we can make a realistic beam response map for a pencil beam, which expresses the excited voltage of an electrode at different transverse beam positions, as shown in Fig. 6. In the next step, we assumed a Gaussian beam distribution transversely, and emulated a total voltage of each electrode for the Gaussian beam by accumulating contributions from multiple pencil beams. Then, the electrode voltages were utilized to calculate the quadrupole term $J_{\mathrm{quad}}$ which is defined as $(V_2+V_4-V_1-V_3)/(V_1+V_2+V_3+V_4)$. Here, the induced electrode voltage is $V$, its numbering code follows the electrodes as shown in Fig. 3. It is noted that we assume the beam is on the axis of a BPM.

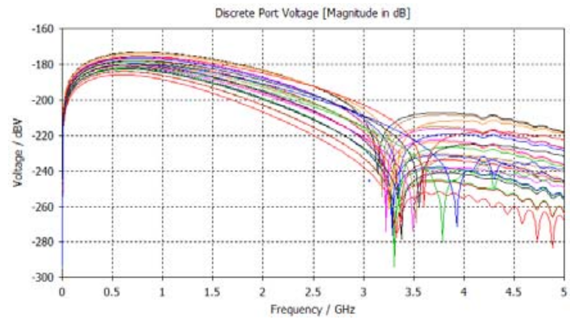


Figure 5: Induced voltages on the button 2 in frequency domain for different beam positions.

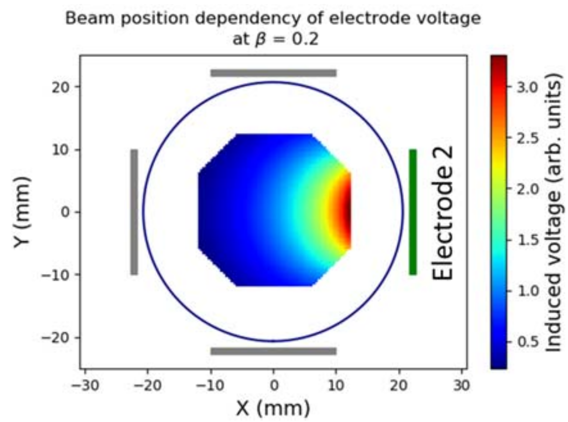


Figure 6: Induced voltage map of the button electrode 2. Horizontal and vertical axes depict a transverse position of the pencil beam. The colour represents the magnitude of the induced voltage at 161 MHz.

## MEASUREMENTS

Responses to the beam were recorded from all BPMs along the FS1.The voltage response map of the BPM was interpolated with the polynomial function as shown in Fig. 6. This map was also used for accurate beam position calculations ($X_{cen}$, $Y_{cen}$) of a pencil beam [8]. The detail explanation of this conversion calculation was given in Ref. [9].

In real measurements, the beam is not always on the axis of BPMs, typically submillimeter off-axis. Therefore, we need to remove a beam centroid effect from the uncorrected beam quadrupole term calculated from the BPM responses, $(V_2+V_4-V_1-V_3)/(V_1+V_2+V_3+V_4)$, as shown in Fig. 7. With the empirically determined geometric factor $g = 1.57$ to remove the beam centroid effect (see in Fig.7), the beam quadrupole term was calculated with the correction of the beam position, $J_{\mathrm{quad}} = (V_2+V_4-V_1-V_3)/(V_1+V_2+V_3+V_4) - g\times(X_{cen}^2 - Y_{cen}^2)/R^2$. With obtained data of the beam quad-

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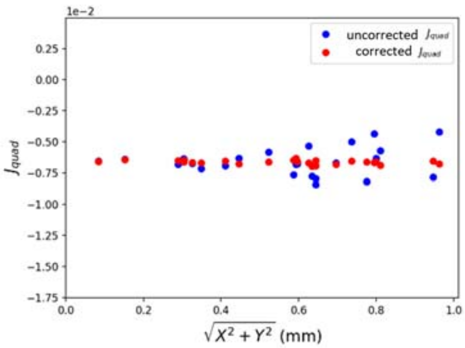


Figure 7: Measured data of the beam quadrupole term with and without correction of the beam position.

rupole terms along the FS1 and the above response map obtained for the realistic geometry of the BPM electrodes, we estimated the initial six Twiss parameters ($\alpha_x$, $\beta_x$, $\varepsilon_x$, $\alpha_y$, $\beta_y$, $\varepsilon_y$) at the end of the LS1 (the start point in Fig. 8), that reproduced the experimental quadrupole term results as shown in Fig. 8.

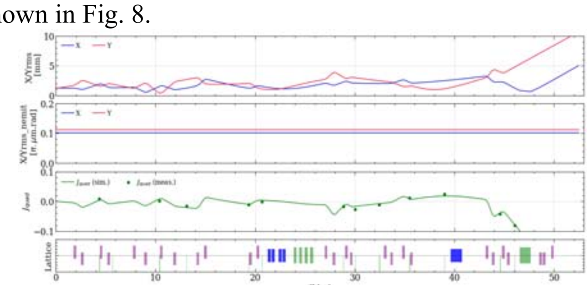


Figure 8: Reconstructed beam envelopes along the FS1, based on beam quadrupole terms derived from BPMs. The purple, blue, and green objects in the lattice (the bottom plot), denote quadrupole magnets, cavities, and bending magnets, respectively.

This optimization was performed with a matrix-based envelope code called FLAME [10]. The results are summarized in Table 1 and compared to the profile monitor measurements performed with a conventional quadrupole scan. The beam Twiss parameters obtained with two different methods were reasonably consistent, although the vertical beta function $\beta_y$ and emittance $\varepsilon_y$ discrepancies were 80% and 36%, respectively. Further studies are required to improve the accuracy of the beam quadrupole term calculation using the BPM data.

Table 1: Comparison of beam Twiss parameters. The emittances are normalized rms values.

| Parameters | BPM | Wire monitor |
|---|---|---|
| $\alpha_x$, | 0.34 | -0.08 |
| $\beta_x$, m/rad | 3.3 | 4.3 |
| $\varepsilon_x$, πμm.rad | 0.10 | 0.12 |
| $\alpha_y$, | -0.36 | -0.56 |
| $\beta_y$, m/rad | 2.6 | 4.7 |
| $\varepsilon_y$, πμm.rad | 0.11 | 0.15 |

## SUMMARY

We explored the possibility of non-invasive beam diagnostics for online beam envelope monitoring based on the beam quadrupole terms derived from BPMs. In this studies, we used the beam response map of a full 3D BPM model obtained with the CST calculations to optimize beam Twiss parameters. The BPM signals were correlated to the beam position and quadrupole term using the 3D response map. The latter was obtained with the modelling in CST particle studio. These initial studies show applicable deviation of the beam Twiss parameters from those obtained from the quadrupole scan with profile monitors. Further experiments will be performed to improve the accuracy of quadrupole term evaluation from the BPM data.

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