BEAM TUNING STRATEGY OF THE FRIB LINAC DRIVER *

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Abstract

The FRIB linac driver will deliver heavy ion beams up to uranium, with beam energy of 200 MeV/u and total power on target 400 kW. In the design, multi-charge-state beams are accelerated simultaneously in the SRF linac to reach the power requirements for all stable ions. Beam tuning of the linac driver is among the most challenging tasks. In this paper, we discuss beam tuning strategy including cavity synchronous phase and acceleration gradient setups, beam trajectory correction, and transverse matching for heavily coupled beams as superconducting solenoids are used for transverse focusing in the linac segments that cause horizontal-vertical coupling.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is funded by the U.S. government and operated by Michigan State University (MSU). On September 2010, Critical Decision 1 for FRIB was approved. The FRIB accelerator systems include a front end that consists of a superconducting ECR ion source and a normal conducting RFQ, an SRF linac, and a beam delivery system. The linac accelerates high-power heavy-ion beams onto a fragmentation target to produce rare isotopes. The facility also includes several beam lines and an SRF re-accelerator for fast, stopped and re-accelerated radioactive ion beams [1].

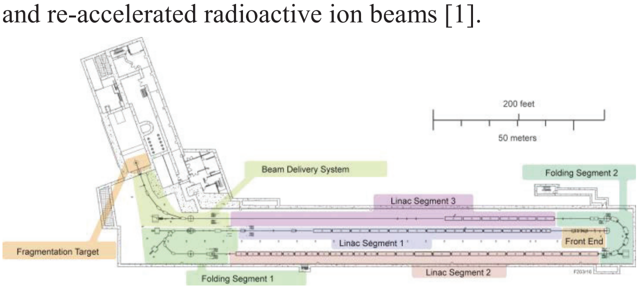

Figure 1: Layout of the FRIB linac driver.

The FRIB linac driver consists of 3 linac segments each over 100 m long, 2 folding segments each bending the beams by 180°, and a beam delivery system (Figure 1). There are 44 acceleration cryomodules and 5 matching cryomodules with a total of 330 quarter-wave (QWR) and half-wave resonator (HWR) cavities in the linac. The beams are focused by 9-Tesla superconducting solenoids in all the acceleration cryomodules, and by normal-conducting quadrupoles elsewhere. Up to two different charge-state beams, such as U^{+33} and U^{+34}, are accelerated in linac segment 1; and after a charge stripper, up to 5 charge-state beams, from U^{+76} to U^{+80}, are accelerated in the downstream segments simultaneously. Efficiently tuning over 300 cavities and precisely matching beams in both transverse and longitudinal phase spaces are among the most challenging tasks.

CAVITY PHASE AND AMPLITUDE

Phase scan signature matching is planned to tune both cavity phase and acceleration gradient [2]. To maintain beam availability, it is necessary to setup both phase and amplitude accurately in order to perform fast cavity phase scaling technique [3] when needs to vary beam energy or ion specie, or when an RF fault persists in the operation. Although a SC cavity could be modulated as a beam phase detector to tune the synchronous phase [4], it is not sufficient to the cavity gradient. On the other hand, phase detector requires a continue-wave (CW) beam – in a situation that the beam power is not appreciated for time consuming phase scan, since it is important to minimize the power during beam tuning of the SRF linac. Figure 2 shows a simulated beam loading signal in a FRIB cavity for a long pulse (CW beam), and compares with that of a short pulse for a drifting beam measurement [5], as shown in Figure 3. It is noted that beam induced signal is the same, about 1.4 kV in both cases, but the beam power is 100 times larger with a CW beam.

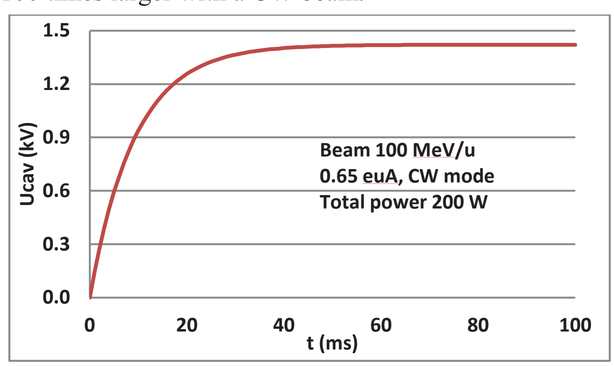

Figure 2. Simulated beam loading for a long pulse.

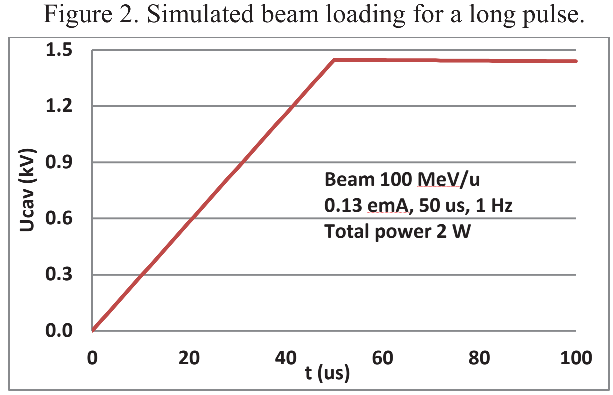

Figure 3. Simulated beam loading for a short pulse.

Although in normal operations the linac accelerates a CW beam, a short-pulse beam is preferred for linac beam tuning at a low duty factor. During the pulsed mode of beam tuning, stability of the cavity low-level RF (LLRF)

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system is a concern under the transient beam loading conditions.

We investigate LLRF system of the re-accelerator at MSU, where an active disturbance rejection control is applied successfully [6] in the absence of beam loading. To simplify the problem, a more general proportional-integral-derivative (PID) control is studied, as the LLRF system is also equipped with a PID controller.

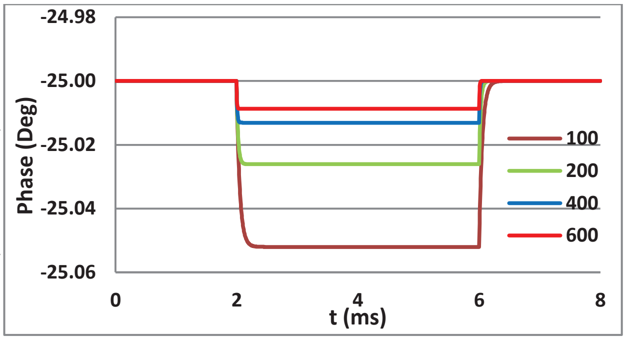

Figure 4. Phase fluctuations from transient beam loading, loop delay about 8 µs and gain varies from 100 to 600.

Figure 4 shows simulated cavity phase fluctuations for a 0.655 mA, 4 ms pulsed beam, with a loop delay about 8 µs and gain varies from 100 to 600. The fluctuation is less than 0.01° with the loop gain of 600, similarly, amplitude fluctuation is less than 0.05% – both can be ignored. In theory, the loop gain could be as high as 1000, as bandwidth of the cavity is only 30 Hz.

Beam position\phase monitor (BPM) pairs are needed to perform time-of-flight (TOF) measurement. Low-duty factor beam with a current close to that of the full power CW beam will be used for cavity phase and amplitude setup, and most other beam tuning tasks, such as beam trajectory correction and transverse matching, can be performed in the same pulsed-beam mode.

We plan to transport a single beam through the linac for most tuning tasks, and if necessary, switching to another charge state and verify the tuning before sending multi-charge-state beams into the linac. Figure 5 shows a simple case of beam phase differences between U^{+33} and U^{+34}, which can be easily measured with all the linac BPMs and benchmarked against the linac longitudinal model. This type of measurement could help us tune cavity phase and gradient correctly for all the different charge states.

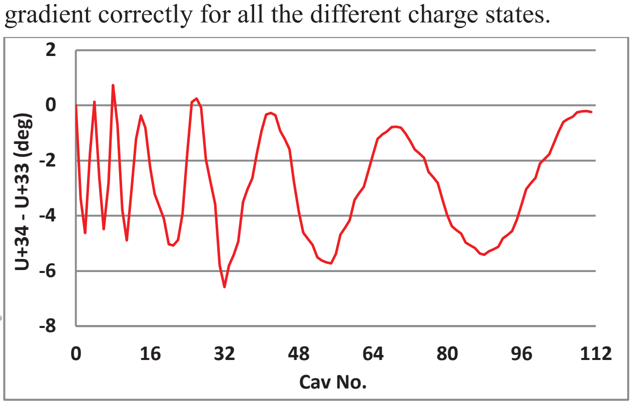

Figure 5. Phase differences between U^{+33} and U^{+34} in all the cavities of linac segment 1.

BEAM TRAJECTORY CORRECTION

There are several issues influence the beam trajectory, such as misalignment of elements, cool down uncertainty of superconducting solenoids and beam steering from QWRs [7]. As beam trajectory correction is necessary, each SC solenoid is equipped with both horizontal and vertical correctors. Usually, beam trajectory correction for a single beam is straight forward: orbit response matrix (ORM) based beam trajectory correction method is fast and sufficient to the linac. But as long as time permits, a more precise beam based trajectory correction technique could be applied too.

At FRIB however, a major difficulty is the correction of multi-charge-state beams. Because beams with different charge states will receive different corrections from a corrector even if beam energy is exactly the same. It is possible to measure and correct beam trajectory with all the different charge states present at the same time. But in which case, actually charge center instead of beam center is corrected from BPMs' measurements, as beam currents may vary significantly for different charge states. To solve the problem, an accurate multi-reference-beam model is needed to study element misalignments and the trajectory corrections under realistic conditions. In the linac beam tuning, correct the beam trajectory for a reference charge state first, and then verify other charge state beams. Fine correction could be necessary by a global optimization for all the different charge states with trajectories measured separately, which requires a robust optimizer in addition to the multi-reference-beam linac model.

TRANSVERSE MATCHING

Transverse matching is difficult for x-y coupled beam. Because SC solenoids are used for transverse focusing, and in such a case, it could be much easier if a round beam transport through the linac. But unfortunately, this is not always true even in solenoid lattice.

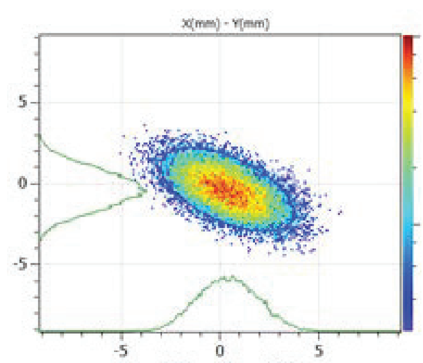

Figure 6. Beam profile in the linac which consists of SC solenoids and QWRs with injection of a round beam.

Figure 6 shows simulation result of a beam profile in the linac which consists of SC solenoids and QWRs with injection of a round beam. Beam is tilted and not round anymore because of asymmetry RF fields of the cavities. A constant polarity of all solenoids may smear the effects of RF fields, but when the injection beam is not round – which is highly likely from an ion source, we may have to face the transvers matching for x-y coupled beam. Also in the linac driver, quadrupole focusing is applied at the folding segments where isochronous and achromatic transport should be established. Consequently, transverse matching is always necessary for a coupled beam.

A full 4D beam matrix σ can be represented by Eq. (1) which includes 4 coupling terms and 6 normal terms. For an uncoupled beam, all the coupling terms vanish. In other words, 10 beam parameters instead of 6 needs to be determined for the coupled beam. Because the presence of errors in all measurements, it is challenging to reconstruct the 4D beam matrix reliably and correctly.

$$\sigma = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle xy \rangle & \langle xy' \rangle & \langle y^2 \rangle & \langle yy' \rangle \\ \langle x'y \rangle & \langle x'y' \rangle & \langle yy' \rangle & \langle y'^2 \rangle \end{pmatrix}, \quad (1)$$

Generally, profile measurements including horizontal, vertical and diagonal profiles are required to reconstruct the full 4D beam matrix, and to determine the 10 beam parameters which need at least 10 profile measurements, either taken during scans of focusing magnets or through parallel beam profile measurement at 4 or more locations. However, a simulation result shows that when realistic measurement errors are considered, beam matching with this general technique could be suspicious. A different matching technique for coupled beam is developed which gets rid of measurement of the diagonal profiles, though it still needs both horizontal and vertical profiles: In serial scans of 4 upstream skew quadrupoles, measure 2D beam emittances from horizontal and vertical profiles. Finally, minimize transverse emittances in both planes [8]. It not only provides a solution to match x-y coupled beam in the presence of measurement errors, but also introduces a method to decouple the beam. This is equally important, since x-y coupling could cause emittance dilutions in both planes. Stanford Linear Accelerator Center also develops a matching technique based on solenoid scans, which is very effective to manipulate a coupled beam [9].

Transverse coupling could be measured even without a profile. Using the singular value decomposition (SVD) modes in model independent analysis (MIA), it could solve the coupling matrix by using BPMs only [10]. This technique is very promising, because usually beam profile measurement is time consuming. However, application of this method in a linac has not been studied.

Many beam techniques are developed and successfully applied in rings, but may not work as well in a single-pass linac. Fortunately, horizontal-vertical coupling is not so crucial as in a ring – as far as it is within the tolerance of the linac. In particle tracking simulations [11], we did not observe any issues caused by the x-y coupling. Therefore, we are not planning to install skew quadrupoles for the purpose of decoupling the beam.

Transverse matching is necessary at several locations such as entrance of the linac, charge stripper, two folding areas and the beam delivery system. Beam intercepting diagnostics can be installed at these areas. Additionally, there are two transition areas: cryomodules from beta 0.041 to 0.085, and from 0.29 to 0.53 – we call them cold transition. Although in simulations, it is not necessary to install non-intercepting beam profile monitors at the cold transition areas for transverse matching, because errors are tolerable with the linac design. It is well known that abnormal beam loss usually happens at lattice transition areas in a high power linac. Consequently, if beam loss in the linac becomes an issue in the future, we may need to install non-intercepting beam profile monitors at the cold transition areas for high power operation.

BEAM POWER RAMP UP

After the linac is tuned with a short-pulse beam, a power ramp up campaign will be followed by increasing both the pulse length and the repetition rate. Beam loss may appear during the beam power ramp up. We plan to use beam loss monitors (BLMs) at high energy, while at low energy, as a consequence of the three-folding design, ion chambers and neutron detectors are not so helpful because the beam loss signal is bland completely by those from the high energy sections. Beam halo scraper rings will be installed as beam loss monitors at low energy [12]. Temperature sensors on beam pipes in the cold areas may also help beam loss measurement for low-energy beams.

CONCLUSION

Beam tuning strategy of the linac driver is developed. It is very challenging to accelerate multi-charge state beams simultaneously in the linac, particularly for high power. More beam dynamics studies are necessary for realistic error analysis and for beam tuning applications.

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