BEAM DYNAMICS STUDIES FOR THE FACILITY FOR RARE ISOTOPE BEAMS DRIVER LINAC*

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Abstract

The Facility for Rare Isotope Beams (FRIB) is a high-power heavy ion accelerator facility presently under construction at Michigan State University to support nuclear physics. FRIB consists of a driver linac and experimental facility, and the linac accelerates all stable ions including uranium to kinetic energies of more than 200 MeV/u and continuous wave beam power up to 400 kW. This beam power is more than two orders of magnitude higher than the existing heavy ion linac facilities, resulting in various beam dynamics challenges for the driver linac. In this paper, we review these challenges for the FRIB driver linac and undergoing studies to address them.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a high-power heavy ion accelerator facility now under construction at Michigan State University under a cooperative agreement with the US DOE [1]. Its driver linac operates in CW (Continuous Wave) mode and accelerates all stable ions to kinetic energies above 200 MeV/u with the beam power on target up to 400 kW. This novel facility is designed to accelerate and control multiple ion species simultaneously to enhance beam power. The linac has a folded layout as shown in Fig. 1, which consists of a front-end, three Linac Segments (LSs) connected with two Folding Segments (FSs), and a Beam Delivery System (BDS) to deliver the accelerated beam to the production target. The front-end consists of two ECR (Electron Cyclotron Resonance) ion sources, a normal conducting CW RFQ (Radio Frequency Quadrupole), and beam transport lines to separate, collimate, and bunch the multiple ion charge states emerging from the ECR sources. Ion sources are located on the ground level (not shown in Fig. 1) and an extracted beam from one of two ion sources is delivered to the linac tunnel through a vertical beam drop. In the FRIB driver linac, superconducting RF cavities are extensively employed. After acceleration up to 0.5 MeV/u with a normal conducting RFQ, ions are accelerated with superconducting QWRs (Quarter Wave Resonators) and HWRs (Half Wave Resonators) to above 200 MeV/u. There are two types each for QWRs ($\beta = 0.041$ and 0.085) and HWRs ($\beta = 0.29$ and 0.53). The frequency and aperture diameter for QWRs are 80.5 MHz and 36 mm respectively, and those for HWRs are 322 MHz and 40 mm respectively. We have three $\beta = 0041$ cryomodules with four cavities each and 11 $\beta = 0.085$ cryomodules with eight cavities each in LS1 (Linac Segment 1). We have 12 $\beta = 0.29$ cryomodules with four cavities each and 12 $\beta = 0.53$ cryomodules with six cavities each in LS2 (Linac Segment 2). There are 6 $\beta = 0.53$ cryomodules followed by a space to add cryomodules for future upgrade. The total number of superconducting RF cavities is 330 including those for longitudinal matching in the Folding Segments. Transverse focusing in the superconducting linac sections is provided by superconducting solenoids (8 Tesla, 20 mm bore radius). It is unique to have such large scale linac sections with low-β superconducting RF cavities together with multi-species transport at high CW power. This poses beam dynamics challenges specific to the FRIB driver linac.

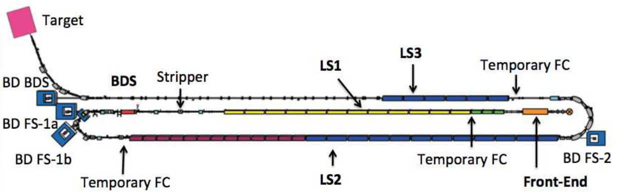

Figure 1: Schematic layout for the FRIB driver linac.

In addition to realizing high CW beam power, stringent beam-on-target requirements are imposed for the FRIB driver linac to support novel experimental program it nuclear physics. It is of essential importance at these high power levels to control and mitigate beam losses to avoid damage and excessive radio-activation of accelerator components. Detection of beam losses and halo collimation are major elements of beam loss mitigation, both of which requires careful beam dynamics considerations in their design.

In this paper, beam dynamics studies now under way in support of the FRIB driver linac are reviewed. We briefly outline five major areas and their particular challenges.

SPACE-CHARGE EFFECTS AT LOW ENERGY FRONT-END

While the FRIB driver linac is at the frontier of CW power, its space-charge intensity is modest as high average beam power is realized by CW operation. Due to this modest intensity, space-charge effects are negligible for most of the FRIB driver linac. The exception to this in the front-end where the beam kinetic energy is low. Space-charge effects are especially important for beam transport between the ECR ion source and the first bending magnet for charge selection. Species with unwanted charge states are transported together with the (typically) two desired species in this section. This increases space-charge intensity by a factor of 15 (typical).

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Transverse focusing is provided with two solenoid magnets in this section, and the field from the upstream one is significantly overlapped with the solenoid field of ECR ion source. The section includes a ~ 50 kV grated electro-static gap to accelerate ions to 12 keV/u. The gap field overlaps with the fringe field of the downstream solenoid magnet. These overlapped applied fields are modeled in detail with the Warp code [2] to evaluate space-charge effects and the influence of the structure of the beam emerging from the ECR sources. We are investigating the sensitivity of operating points on the initial distribution including space-charge [3]. Figure 2 shows a typical phase space distribution obtained with the Warp code. The simulations are deepening our understanding on underlying physics of transport in this section due to many species (~ 20) with space-charge, magnetized ions with large canonical angular momentum emerging from the ECR, coupled solenoid focusing with overlapping elements, and acceleration. Preliminary results are encouraging and simulations are being extended to the downstream part of the front-end to more throughly evaluate space-charge effects in the initial species separation and collimation.

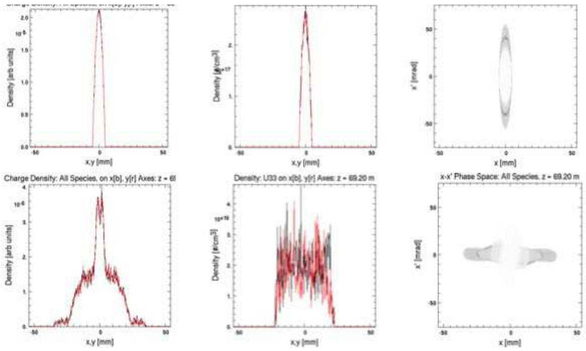

Figure 2: Typical phase-space distribution near ECR front-end obtained with the Warp code. Top: initial distribution, and bottom: distribution before entering the first bending magnet. Left: Real space beam density for all species combined, middle: that for U^{33+}, and right: phase space distribution for all species combined.

MULTI-CHARGE STATE ACCELERATION

It is difficult to have sufficiently high beam intensity from ECR ion sources for some of heavy ion species. We plan to accelerate several charge states simultaneously to overcome this limitation. In the FRIB driver linac, we plan to accelerate up to two charge states before the charge stripper located after LS1, and up to five charge states after the stripper. As beam components with different charge states gain energy in the RF cavities, they undergo synchrotron oscillations with significantly different amplitudes. They also have different transverse betatron oscillations due to differences in magnetic rigidity. This necessitates a second order achromat for the arc sections in FS1 and FS2 to suppress emittance growth due to dispersion. The components with different charge states must overlap each other both transversely and longitudinally to meet stringent on-target requirements. These requirements include the spot size containing more than 90 % of the beam of smaller than 1 mm in real space and ±5 mrad in divergence angle at the target. Also, the 95 % bunch length and energy spread should be smaller than 3 ns and ±0.5 %. This poses a significant challenge for machine tuning. There also are requirements at the stripper to minimize potential degradations in beam quality from stripping. We have confirmed by multi-particle simulation with the IMPACT code [4] that the requirements can be met as shown in Fig. 3. Studies are now underway to identify efficient tuning methodologies. More detailed discussion on this topic will be found in [5].

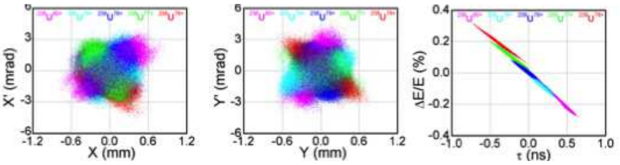

Figure 3: On-target phase space distribution for a five-charge-state uranium beam simulated with IMPACT. Left: horizontal, middle: vertical, and right: longitudinal phase-space plane. Different colors represent different charge states.

NON-AXISYMMETRIC FIELD COMPONENT OF QUARTER WAVE RESONATORS

We adopt QWRs (Quarter Wave Resonators) in LS1 (Linac Segment 1) with superconducting solenoid magnets for transverse focusing. LS1 includes 100 QWR cavities. Non-axisymmetric field components exist in QWRs due to geometrical asymmetries. Among these non-axisymmetric components, the effect of dipole field components have been extensively studied and mitigation schemes have been developed [6, 7]. We are presently studying the effect of quadrupole components of field assymetries [8, 9]. While the quadrupole component is typically small, its effect can accumulate over a number of QWRs. Because we employ solenoid focusing in LS1 and frequently steer to compensate for misalignments, the matched beam develops significant deviations from transverse rotational symmetry about the longitudinal axis only if non-axisymmetric field components (quadrupole and higher) of QWRs are not negligible. Asymmetries between the horizontal and vertical planes induced by the quadruple field component in LS1 is shown in Fig. 4. Tuning methodologies is being studied using IMPACT code and reduced models, and mitigation schemes shall be implemented on that basis.

BEAM LOSS DETECTION

In addition to minimizing prospects of beam losses by careful linac design, careful planning of potential fault situations is crucial. Detection of beam losses is a key to realize

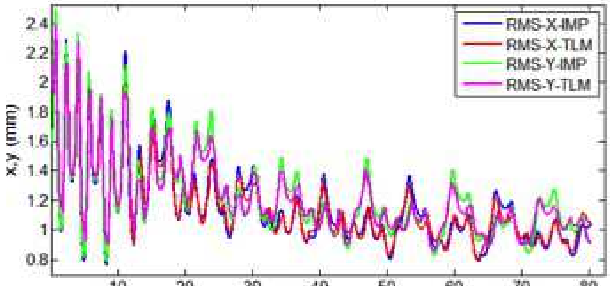

Figure 4: Horizontal and vertical plane beam envelopes in LS1 including quadrupole field components of QWRs. Blue: horizontal with the IMPACT code [4], red: horizontal with thin lens model [8], green: vertical with the IMPACT code, and magenta: vertical with a thin lens model.

high power transport while protecting the machine from damage or excessive radio-activation. Beam loss monitors detecting radiation, such as ion chambers, are widely used in various accelerators. However, it is difficult to employ these monitors to protect the low energy part of the FRIB driver linac because lost low energy heavy ions generate insufficient radiation but still can damage the machine. We plan to adopt HMRs (Halo Monitor Rings) to mitigate limitations of conventional beam loss monitors [10,11]. A HMR consists of a fixed aperture made of a thin niobium disk, and the beam current intercepted by the disk is monitored. The aperture of a HMR is supposed to be adjusted to intercept particles which will be lost downstream if there is no HMRs. A HMR will be placed in every warm section between cryomodules. A schematic for HMR is shown in Fig. 5. The design of HMRs requires careful beam-dynamics consideration of its aperture size and the phase advance between HMRs. We plan to adopt a similar approach to the design of the collimator system with multiple jaws although there is no intent to aggressively collimate halos with HMRs. We adjust the HMR apertures to limit the acceptance and adjust the phase advance to adequately to maximize its efficiency in capturing beam losses. An adjustable aperture HMR is not employed to avoid the risk of cavity degradation due to particulates from movable structures. Instead, we plan to secure adequate tuning margin for solenoid strength to adjust the relative aperture size to the beam size. IMPACT simulation studies to confirm feasibility of the design and to optimize the design parameters are now underway.

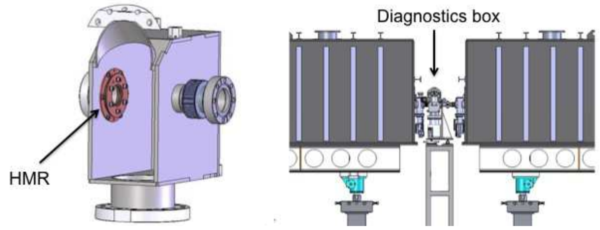

Figure 5: Halo Monitor Ring (HMR). Left: diagnostics box equipped with a HMR, and right: HMR location in diagnostics box between cryomodules.

COLLIMATOR DESIGN

In the multiple charge-state acceleration in the linac, up to five charge states are selected at a charge selector placed after the charge stripper. The charge selector is located in the FS1 arc section and has two movable jaws on opposite sides to scrape the beam in the horizontal direction. Different charge states are separated horizontally at the location of charge selector due to lattice dispersion. We can select specific charge states by adjusting the edge position of the movable jaws. Each charge state at charge selector intrinsically has a halo around the beam core due to large angle scattering events in the stripper. The halos fill in space between different charge states transmitted through the charge selector and form a horizontal halo after exiting the FS1 arc section. There will also be a vertical halo due to large angle scattering. These halos could cause beam losses in the downstream sections. It is desirable to mitigate the potential risk of cavity degradation due to the halo induced beam losses over long term operation of the machine. Space is reserved in the lattice between the exit of FS1 arc and the entrance of LS2 to place a collimator system to eliminate the halos. The base design calls for two collimators each for the horizontal and vertical directions, and each collimator has two movable jaws on both sides of the beam. The feasibility of this design has been confirmed by simulations with the IMPACT code (see Fig. 6) which shows that a halo expected from the stripper can be effectively scraped while preserving core intensity. More elaborate simulations are planned to further explore possible issues involved with collimation of the stripper induced halo.

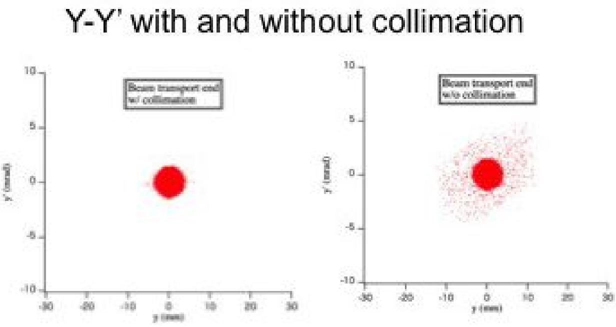

Figure 6: Simulated phase space distribution at the entrance of LS2 with (left) and without (right) halo collimation. An artificial halo is generated at the exit of FS2 arc section which covering the most part of transverse acceptance of the transport line to demonstrate the effectiveness of the collimation.

SUMMARY

Beam dynamics studies now under way for the FRIB driver linac has been reviewed with emphasis on five areas for particular beam dynamics challenges.

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Due to modest beam intensity, space charge effects are not important for most of the linac, which is a notable difference from other high power accelerators. The only exception to this is in the front-end where the beam kinetic energy is sufficiently low before the RFQ. We are developing a detailed model for the front-end utilizing the Warp code. This should aid in addressing any issues that may occur in machine commissioning and augment limited diagnostic capabilities near the sources.

To have the flux on-target, we plan to accelerate multi-charge-state beams (both from ECR sources and after a stripper) which poses tuning challenges to meet stringent beam-on-target requirements. We extensively adopt superconducting cavities from low β section with superconducting solenoids for transverse focusing. It also poses a specific challenge for tuning where it is required to deal with non-axisymmetric coupled beams. Careful design of tuning methodologies is one of important issues for beam dynamic studies for the FRIB driver linac.

Both detection of beam losses and halo collimation require careful consideration of beam dynamics for effective designs. For beam loss detection, the design of HMRs should be fully optimized consistent with considerations from beam dynamic simulations to mitigate the intrinsic difficulty in detecting losses of a low energy heavy ions while minimizing potential risks of adverse effects. We may need an more accurate stripper model to better evaluate the design of the halo collimator system following the stripper.

The topics which has not been covered in this paper yet having significant importance include fault studies to identify fault recovery scenarios and to optimize the MPS (Machine Protection System) design, and model-based tuning in switching ion species to realize good availability. Elaborated studies are actively conducted at FRIB on all the front.

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