ACCELERATOR PHYSICS CHALLENGES IN FRIB DRIVER LINAC*

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Abstract

FRIB (Facility for Rare Isotope Beams) is a heavy ion linac facility to accelerate all stable ions to the energy of 200 MeV/u with the beam power of 400 kW, which is under construction at Michigan State University in USA. FRIB driver linac is a beam power frontier accelerator aiming to realize two orders of magnitude higher beam power than existing facilities. It consists of more than 300 low-beta superconducting cavities with unique folded layout to fit into the existing campus with innovative features including multi charge state acceleration. In this talk, we overview accelerator physics challenges in FRIB driver linac with highlight on recent progresses and activities preparing for the coming beam commissioning.

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 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 of QWRs ($\beta = 0.041$ and 0.085) and HWRs ($\beta = 0.29$ and 0.53) with different geometrical beta. 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 $\beta = 0.041$ cryomodules housing four cavities and 11 $\beta = 0.085$ cryomodules housing eight cavities in LS1 (Linac Segment 1). We have 12 $\beta = 0.29$ cryomodules housing six cavities and 12 $\beta = 0.53$ cryomodules housing eight cavities in LS2 (Linac Segment 2). There are 6 $\beta = 0.53$ cryomodules followed by a space to add cryomodules for future upgrade in LS3 (Linac Segment 3). The total number of superconducting RF cavities is 332 including those for longitudinal matching in the Folding Segments. Each superconducting RF cavity is driven by an independent solid state amplifier. 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 charge state acceleration at high CW power. This poses accelerator physics challenges specific to the FRIB driver linac.

We reported beam physics challenges in FRIB at the previous series of this worksop [2]. Here, we don't repeat the challenges we identified at the previous workshop while we have been continuously pursuing those areas. As general accelerator challenges for high power linacs were summarized at the previous workshop [3], we try to focus in this paper on challenges specific to FRIB and/or those for

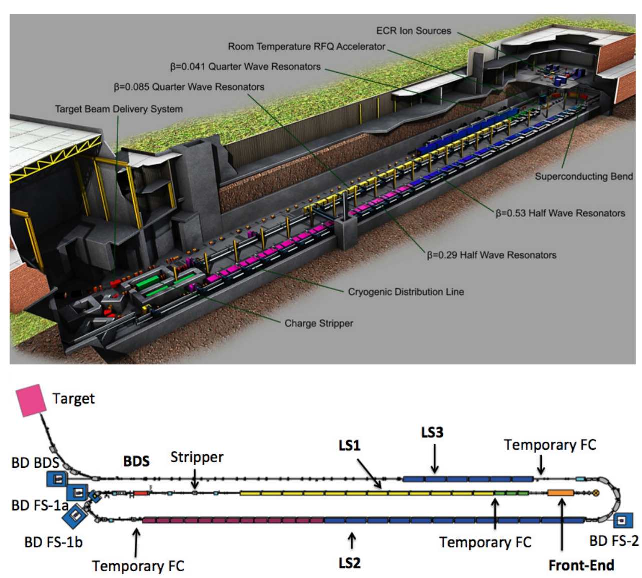

Figure 1: Layout of FRIB driver linac. Top: Cut view of FRIB driver linac building. Bottom: Schematic layout for the FRIB driver linac (top view).

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which active studies are on-going in FRIB.

In the next section, we review accelerator physics challenges for FRIB with emphasis on beam dynamics related issues. Before summarizing the paper, we also show present construction status of FRIB and its commissioning schedule briefly.

ACCELERATOR PHYSICS CHALLENGES

As a high power frontier accelerator, mitigation of uncontrolled beam loss is one of its major challenges for FRIB. This is especially true for FRIB as it is more difficult to detect heavy ion beam loss than lighter ions with sufficient sensitivity. In addition, as a user facility to support nuclear physics experiments, high beam availability of larger than 90 % is required with yearly beam on target of 5,500 hours. One of major challenges regarding the beam availability is to achieve swift enough switch over of ion species. It is typically requested to change ion species once in a week or two, and regarding retuning should be completed in one day or shorter.

Development of Online Model

To achieve the availability goal and to mitigate the uncontrolled beam loss during tuning, it is indispensable to develop efficient tuning schemes based on online model. To this end, it is required to develop a robust online model and flexible environment to develop application software for tuning. To support online tuning, we need to have a simple and quick model with minimum accuracy to serve for the tuning. As FRIB driver linac involves specific features which are not covered by usual fast models, we decided to develop a dedicated envelope model in house. Those features include multi-charge state acceleration, non-axial symmetric field for quarter wave resonators, and charge stripping.

In addition, we decided to develop an online model based on IMPACT [4] as a back up to serve for advanced tuning which may not be covered by a simple model. IMPACT is a three-dimensional particle-in-cell code originally developed to study space charge effects. Space charge effect is negligible in most part of FRIB linac thanks to its low peak intensity. None the less, IMPACT has been adopted as the reference code to develop FRIB lattice after extending it to cover multi charge state acceleration to take advantage of its robust framework. As advanced tuning, we anticipate halo mitigation (or matching beyond rms matching) and second order acrhomat tuning at arc sections. We also utilize IMPACT as a modeling engine for virtual accelerator, which enable us to benchmark tuning algorithms. Although execution speed is a main concern for IMPACT as an online model, we have confirmed that it can be run with around 1 second with a standard server for the first linac segment by turning off the space charge calculation and optimizing simulation conditions.

As for a simple model, we have developed a envelope model named FLAME [5]. This model was originally prototyped with Java and extensively benchmarked against

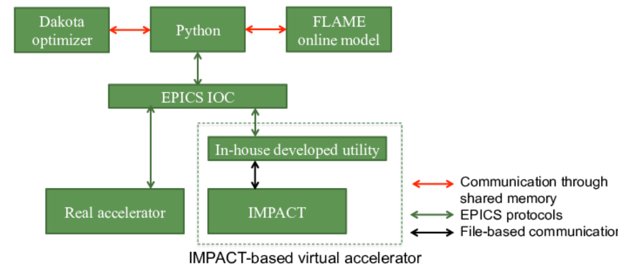

Figure 2: Schematic for commissioning application development environment.

IMPACT. After verifying its physics model, we converted it to a C++ code to further optimize the performance and to improve its interfaces. We expect that this model serves sufficiently for most of basic tunings such as orbit correction, rms matching, and phase/amplitude tuning.

We have developed an environment to develop commissioning applications with Python as a scripting language, FLAME as an online model, and Dakota as optimization tools as shown in Fig. 2. Both FLAME and Dakota have Python interfaces. We use IMPACT-based virtual accelerator to verify tuning algorithms. We have prototyped basic tuning applications with this environment. So far, Java prototype for FLAME is used for the prototyping and we are converting it to be FLAME-based.

Extended Error Studies and Model Enhancement

To achieve efficient tuning, we need deep understanding of the machine and a good model to represent it. To deepen our understanding of the accelerator, we are continuing error studies or case studies assuming realistic conditions, which will be our knowledge-base on possible responses of the machine to realistic errors [6]. Figure 3 shows an example of those extended error studies where longitudinal acceptance for LS1 assuming RF amplitudes ± 20 % off the nominal randomly. This study gives us a guidance to optimize operation parameters for RF cavities.

Accuracy of modeling for a linac is often determined by the modeling capability of its front-end. Space-charge effects are negligible for most part of FRIB due to relatively small peak current. However, an obvious exception is low energy beam transport immediately after ECR ion sources. In particular, existence of contaminant ion species and charge states make it complicated to model the dynamics in the charge selection process where unintended ion species and charge states are separated with a dipole magnet and eliminated with a slit. We are continuing efforts to improve the modeling of front-end using Warp code [7] with three dimensional field map [8].

Contaminant Ion Species Loss Study

We have identified a few mechanisms which could result in uncontrolled beam loss in FRIB linac, one of which is caused by contaminant ion species. In generating a heavy ion beam with an ECR ion source, other ion species but

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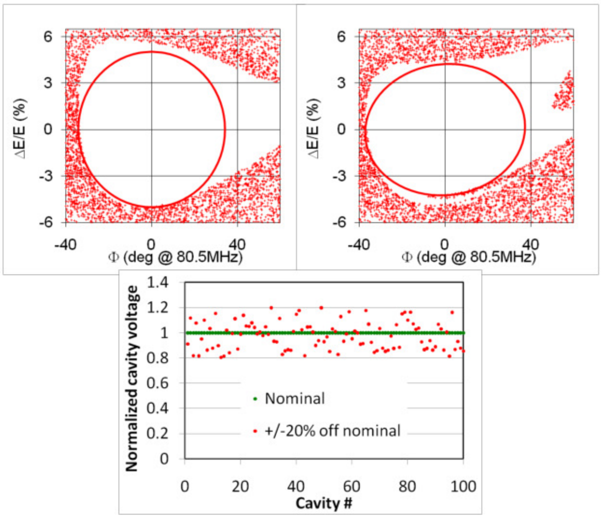

Figure 3: An example of extended error study with IMPACT. Longitudinal acceptance for LS1 with nominal RF amplitudes (top left) and that with RF amplitude ±20 % randomly off the nominal (top right). Bottom figure shows the RF amplitude distribution assumed in the case in top right.

with similar Q/A (or the charge to mass ratio) can contaminate the beam. In some cases contaminants come from supporting gasses, and in other cases from gasses introduced in previous experiments. Contaminants with similar Q/A can be accelerated with intended ions in the first linac segment. However, they could have very different Q/A after charge stripper as lighter ions are more easily stripped. Then, contaminant with very different Q/A has a mismatch to the optics, which can result in a beam loss after charge stripper. Those particles with different Q/A from intended are supposed to be eliminated at charge selector situated after the first dipole magnet in the arc section. However, Q/A of a contaminant could be too different to be delivered to the charge selector resulting uncontrolled beam losses between charge stripper and charge selector (See Fig. 4). One of examples for the contaminant is $^{14}N^{2+}$ for $^{238}U^{34+}$. They have exactly the same Q/A of 0.146 and hence they are both accelerated by LS1 being captured in an RF bucket. After the stripper, however, $^{14}N^{2+}$ may become $^{14}N^{7+}$ (Q/A=0.5) while typical charge state for uranium will be $^{238}U^{78+}$ (Q/A=0.328). Then, $^{14}N^{7+}$ will not reach the charge selector with optics tuned for $^{238}U^{78+}$ resulting a beam loss.

We are conducting a simulation study to find an optimum design of collimators to localize the losses from contaminants [9]. As we need to deliver various ion species for the experiment, the collimator system should accommodate a wide range of Q/A ratio between contaminant and intended ions. Figure 5 shows an example for the simulation where Q/A of contaminant is assumed to be 20 % larger than the intended beam.

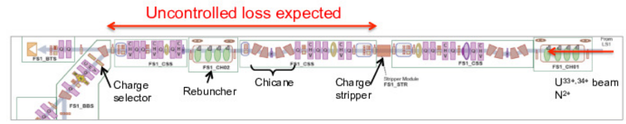

Figure 4: Schematic for lattice around charge stripper. Area with beam loss from contaminant anticipate is also shown.

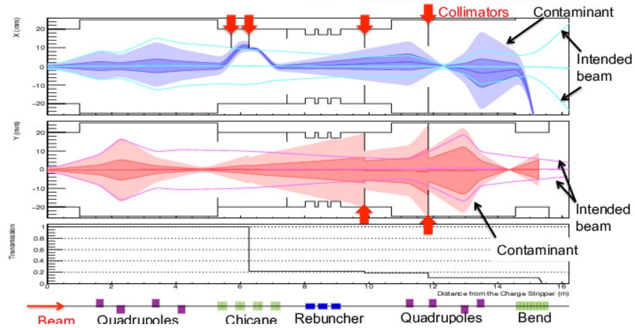

Figure 5: An example of IMPACT simulation for collimation of contaminant ion species. Assumed Q/A for contaminant is 20 % larger than the intended beam. Beam envelopes are simulated from charge stripper to charge selector. Top: horizontal envelope, middle: vertical envelope, and bottom: transmission efficiency of contaminant. Light blue and magenta solid lines show the envelopes of intended beam. Shaded areas in blue and red show the envelopes of contaminant. Locations of collimators under consideration are also shown with red arrows.

Residual Gas Stripping Loss Study

Another beam loss mechanism is residual gas stripping. Accelerated ions can lose electrons by scattering with residual gas molecules, and generated ions with irregular charge state can cause beam losses. The rate of residual gas stripping is determined by the vacuum pressure level and gas component, and single electron stripping is dominant where an ion lose an electron.

As the vacuum level is generally higher in room temperature sections than in superconducting sections, this loss mechanism is a concern in room temperature sections primarily. Residual gas stripping in dispersion section is a particular concern. If the single stripping occurs in non-dispersive segments, there is a large likelihood that the scattered particle stays in the acceptance. Meanwhile, if the stripping occurs in a dispersive area, generated ions with irregular charge state can have significantly different beam trajectory and result in a beam loss. It will be especially the case for vicinity of charge selector in the first 180 degree arc section, where we anticipate that beam absorber for charge selection can be a notable gas source. It led us to focus on residual gas stripping loss study for the first folding segment primarily.

We are conducting a simulation study to find an optimum design of collimators to localize the losses from residual

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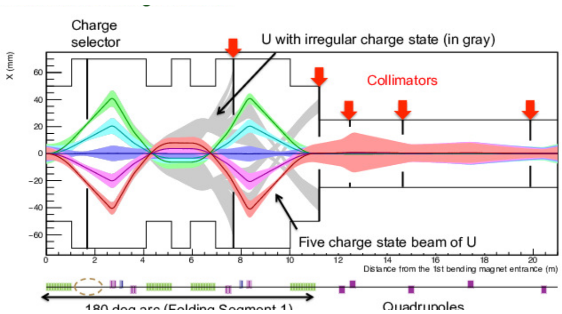

Figure 6: An example of IMPACT simulation for residual gas stripping. Shaded areas in green, light blue, violet, magenta, and red show the envelopes of five charge states of uranium which will be delivered to the second linac segment. Shaded areas in gray show the envelope of ions with irregular charges state generated at charge selector. Locations of collimators under consideration are also shown with red arrows.

gas stripping assuming the primary source of gas stripping is around charge selector [9]. Figure 6 shows an example for the simulation where ions with irregular charge state are generated at charge selector. The study will be extended to deal with residual gas stripping in other locations.

Other Technical Challenges

Although we emphasizes challenges in FRIB regarding beam dynamics in this section, we also have other challenges if we extend the scope to hardwares. We don't elaborate on this in this paper as it was summarized in a review paper in the previous workshop [3]. Representative examples of technical challenges for FRIB linac include charge stripper and MPS (Machine Protection System). As for charge stripper, we plan to adopt liquid lithium stripper to sustain the energy deposition [10]. In MPS, a particular challenge is to detect loss of heavy ions in low energy section with sufficient sensitivity where conventional ionization chamber is not sensitive enough. We are planning to adopt multiple detection methods with different sensitivity and response time to overcome this difficulty [11].

CONSTRUCTION STATUS AND SCHEDULE

As of July 2016, construction of FRIB building is progressing ahead of schedule especially for its front-end area. It allowed us to start to install technical equipment for front-end and transfer lines. We plan to start beam commissioning of ion source in September 2016 and beam commissioning of RFQ and MEBT (Medium Energy Beam Transport) in February 2017. It will be followed by start of beam commissioning of the first three cryomodules in LS1 in early 2018. The commissioning effort will be continued in a staged way until completion of the project in fiscal year 2021.

SUMMARY

FRIB is a high-power heavy ion accelerator facility presently under construction at Michigan State University to support nuclear physics experiments. FRIB consists of a driver linac and experimental facility, and its 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 accelerator physics challenges. In this paper, challenges for FRIB have been discussed with emphasis on beam dynamics issues avoiding the overlap with previous papers in this workshop series [2, 3]. We have reported recent activities on online model development, extended error simulations, and collimator design study to mitigate beam losses from contaminant ion species and residual gas stripping. The former two topics are preparations for beam commissioning and operation. The latter two are to finalize the design of collimators to localize the beam losses from anticipated beam loss mechanisms, which may eventually limit the reachable beam power.

We have also reported construction status of FRIB and updated schedule for its beam commissioning. The construction is progressing on track and we plan to start beam commissioning of one of two ion sources in September 2016.

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