DESIGN INTEGRATION OF THE FRIB DRIVER LINAC*

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Abstract

The Facility for Rare Isotope Beams (FRIB) driver linac will deliver all stable heavy ion beams with energy more than 200 MeV/u and beam power on target up to 400 kW. Since FRIB is the first SRF linac for high power heavy ion beams, design and integration of the accelerator components are important and there are many challenges. Several issues on design and integration of the linacare introduced and studies which include developments of the accelerator online model, minimize uncontrolled beam loss, beam diagnostic systems for linac beam tuning and for machine protection system (MPS), appropriate degauss process with SC solenoids in cryomodules, RF system, vacuum system and cryogenic system are briefly discussed in this paper.

INTRODUCTION

FRIB is a seven-year, US $700 million nuclear physics project to be built at the Michigan State University under a corporate agreement with the US Department of Energy (DOE) [1]. As shown in Figure 1, the driver linac consists of Electron Cyclotron Resonance (ECR) ion sources, an electrostatic low energy beam transport (LEBT) line, a Radiofrequency Quadrupole (RFQ), a medium energy beam transport (MEBT) line, three straight linac segments with SC quarter wave resonators (QWR) and half wave resonators (HWR), two 180° folding segments, a charge stripper, and a beam delivery system (BDS) to transport 400 kW beam onto target for rare isotope production [1].

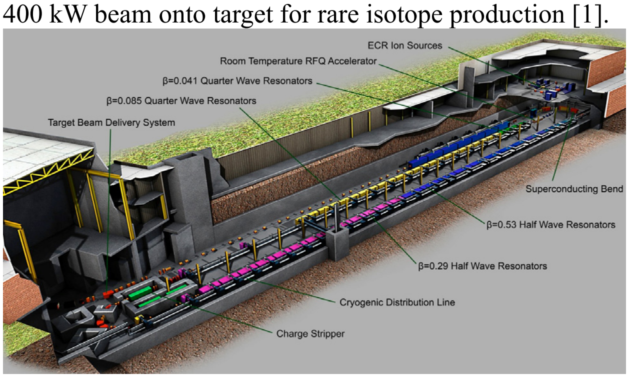

Figure 1: Layout the FRIB driver linac.

The first linac segment consists of cryomodules with β=0.041 and β=0.085 QWRs which accelerate ion beams from 0.5 MeV/u to 20 MeV/u, and at end of the segment higher charge states beams are generated when passing through a liquid lithium charge stripper [2]. Then these beams are further accelerated by β=0.29 and β=0.53 HWRs at the second and the third linac segments to more than 200 MeV/u up to uranium. Resonate frequency of the QWR is 80.5 MHz and that of the HWR is 322 MHz. To achieve a maximum power for the heaviest ions, multi charge states beams are accelerated simultaneously: up to two charge states in the first linac segment and then up to 5 charge states after the lithium charge stripper. In the baseline design, there are 44 acceleration cryomodules, 5 rebuncher cryomodules plus necessary spares, totally over 50 cryomodules and about 400 SC cavities to be built. As multi charge states beam acceleration is involved and the cavity aperture is limited: QWR 36-mm and HWR 40-mm in diameter, 9-T superconducting (SC) solenoids are installed in all the acceleration cryomodules for transverse focusing. Total beam path of the FRIB driver linac is about 520 m.

CRYOMODULES

In the design, beam vacuum and insulation vacuum of the FRIB cryomodules are separated, and to improve SRF performance, operation temperature of the SC cavities is 2 K. However, operation temperature of the SC solenoids is 4.5 K. To make the FRIB cryomodules more complicated, beam phase/position monitors (BPMs) are installed in all the acceleration cryomdoules at the first linac segment, as beam transverse phase advance in each QWR cryomodule is nearly 180° and the BPM installed at room temperature area between each cryomodule alone is not sufficient to perform beam trajectory correction reliably. The BPMs installed inside cryomodules are called cold BPMs just to distinguish them from the warm BPMs – those installed at room temperature areas.

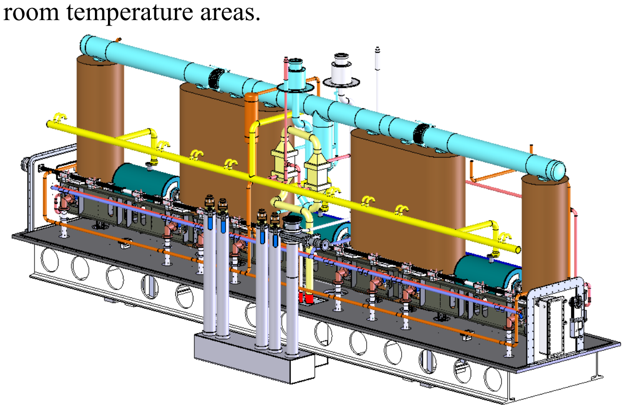

Figure 2: β = 0.085 cryomodule, vessel and shielding omitted.

A β=0.085 cryomodule is shown in Fig. 2 with vacuum vessel and thermal shielding omitted. Total length of the cryomodule is approximately 6 m and major components include 8 QWRs, 3 solenoids (50-cm long), 3 cold BPMs mounted on each solenoid respectively, 2K and 4K liquid helium headers, and bayonets to connect it with helium distribution lines; also shown in Fig. 2 is a wire position

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monitor (WPM) system for monitoring the alignments of cold elements [3, 4].

In cryomodules, a key parameter is SRF performance of the cavity which is determined by many factors, such as multipacting. We studied multipacting in cavities and RF couplers with both EM simulations and experiment. Several multipacting barriers are found. RF conditioning could pass through multipacting barriers in the cavity, but multipacting in the HWR coupler is rather strong, and it is time consuming to mitigate multipacting by conditioning, and more importantly, after each cool-down and warm-up cycle, multipacting barriers reappear and we have to go through the RF conditioning process again. It is less a problem to a linac with few cavities, but at FRIB as with a total of 230 HWR couplers, conditioning might become a painful process. To be on the safe side, we redesign the coaxial RF coupler from conventional 50 ohm impedance to a 75 ohm transition structure which in simulation eliminates the coupler multipacting completely [5]. Figure 3 shows the new RF coupler design.

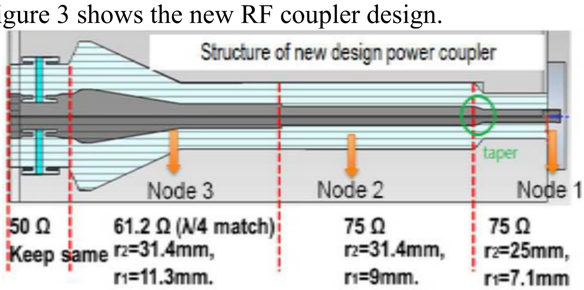

Figure 3: Multipacting free RF coupler for the HWR cavity.

Because alignment of cold elements is an issue, beam trajectory correction will be necessary even with a WPM. In the driver linac, each SC solenoid is equipped with two correctors for both horizontal and vertical corrections. As solenoids are installed in an SRF environment, bucking coils which is winded in the opposite direction are utilized to reduce the stray fields of the solenoids to prevent the adjacent cavities from quenching and Q_0 decreasing [6]. Practically, stray fields near cavity surfaces are limited to less than a few hundred Gs of a 9-T solenoid, roughly the same as those of the SC correctors even though the dipole fields are only about 1 kGs at the magnet center, since no bucking coils are designed for the correctors.

In cryomodules, ferrimagnetic materials are prohibited near the surfaces of SC cavities, however it is discovered that an adequate degaussing process using solenoid itself is essential to reduce the remnant magnetic fields after operation of the solenoid [7]. For FRIB, the required residual magnetic fields near cavity is no more than 15 mGs, and it will be more efficient to perform degaussing with solenoid and both dipole correctors coherently as the stray fields of the correctors and the solenoid near cavity surfaces are similar.

Gate valves at both ends of a cryomodule are important for installation, operation and maintenance purposes, each individual cryomodule could be processed independently. There are several areas in the driver linac which are not so SRF friendly, include ion sources, RFQ, charge stripper, charge selector and the fragment target. In the design, in addition to gate valves on each cryomodule, fast acting valves are installed at the entrance and the exit of each linac segment to prevent all the cryomodules from contaminations in the event of a vacuum excursion at the above mentioned locations.

CRYOGENIC SYSTEM

The FRIB cryogenic system consists of a cryoplant and helium distribution lines. It has the capabilities needed to support the operations of all the SC cavities at sub atmospheric pressure and SC magnets at 4.5 K. The system also provides liquefaction loads at 4.5K for the magnets current leads and shielding loads in between 38 K and 55 K. The distribution system consists of 3 separate linac segment lines and 1 separator distribution line and cryogenic U-tubes. To simple maintenance, each segment could be cooled down and warmed up independently. Cryomodules and magnets are also allowed to be warmed up or cooled down independently. JLAB cryogenic team is working with the FRIB team on the design.

Table 1: Heat Loads of the Driver Linac Cryogenic System

Source	Heat Load (W)		
	2 K	**4.5 K**	**38/55 K**
Cryomodules	2423	1414	6234
Magnets	0	670	1000
Cryodistribution	0	950	5000
Beam Loss	0	25	0
Total Load	2423	3059	12234

Table 1 summarizes heat loads of the cryogenic system. Figure 4 shows connection to a cryomodule through U-tubes with the helium distribution line in the linac tunnel.

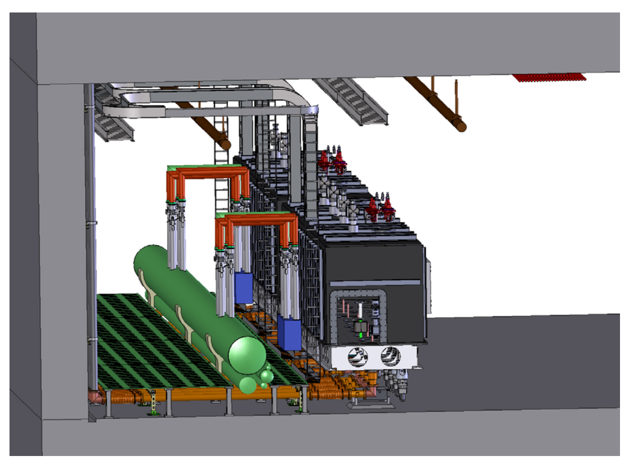

Figure 4: Schematic drawing of connections to a cryomodule through U-tubes with the helium distribution lines in the FRIB linac tunnel.

RF SYSTEM

Major components of the RF system include amplifiers, RF power transmission lines, reference clock distributions and low level RF control systems (LLRF). Solid-state RF

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amplifier modules of 2 kW are integrated to provide RF powers for all the SC cavities: β=0.041, 2 kW; β=0.085, 4 kW; β=0.29, 4 kW; β=0.53, 8 kW. Frequency of reference clock is designed at 10.0625 MHz as which is compatible with frequencies from 20.125 to 322 MHz as required by different cavities and BPMs. LLRF controller uses active disturbance rejection control (ADRC), and performances are superior to the general proportional-integral derivative controllers (PID) [8]. Beam loading effects to the RFs are also taken into account but they are not so severe. Figure 5 shows a block diagram of the FRIB LLRF controller.

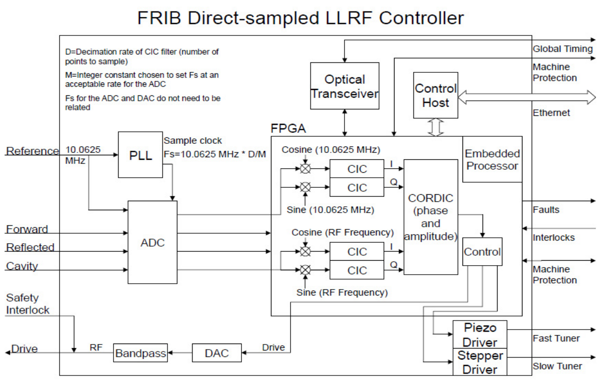

Figure 5: Block diagram of the FRIB LLRF controller.

BEAM DIAGNOSTICS AND MPS

Beam diagnostics systems include several Faraday cups (FC) and beam emittance scanners at the Front End, wire scanners for beam transverse profile measurement, bunch shape monitors (BSM), beam current monitors (BCM), BPMs, halo scrapper rings (HSR) [9], BLMs and neutron detectors (ND). In our plan, no interceptive device is allowed to be installed in the cryomodule areas to avoid contamination by incidental beam heating or damages. Non-interceptive beam profile monitors and BSMs are under investigations; they will become more and more important for high power operation of the driver linac. All the interceptive devices, such as beam stops, beam profile monitors and BSMs are to be installed at warm areas.

The activation signature from the losses of low energy heavy ion beams is small making detection of beam loss using traditional ion-chamber BLMs to be very difficult especially in the presences of a strong X-rays background from the SRF cavities and losses cross-talks among linac segments. The HSR that measures the loss current directly will be the primary beam loss monitor at FRIB.

Because of the high beam powers and sensitive SRF components, it is important to have a machine protection system (MPS) to protect the FRIB driver linac from beam damages. The total execution time of the MPS is less than 35 μs, and its triggers include all RFs, BCMs, HSRs, BLMs and several critical bending magnets [10].

ONLINE MODEL

A thin lens model for multi charge states acceleration is under development for FRIB, and the preliminary results are very encouraging [11]. As the scale and complexities of the driver linac are outstanding, multi-particle tracking codes, such as IMPACT [12] - even can be more accurate, are not suitable for online applications. IMPACT is used in the FRIB linac lattice design [13]. But for online beam tuning, it is necessary to develop a much faster online model. Figure 6 shows a benchmark of the thin lens model against IMPACT at the first 180° folding for 17 MeV/u uranium beam with 5 charge states: from +76 to +80.

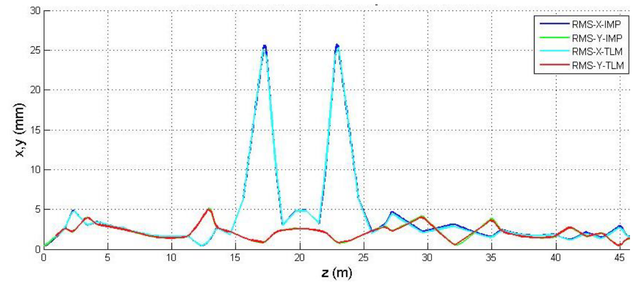

Figure 6: Beam envelop tracking with thin lens model (TLM) closely agrees with multi-particle tracking simulations using IMPACT (IMP) for multi charge state beams.

For commissioning and operation which is a few years ahead, now we decide to adopt OpenXAL [14], an open source software under development with collaborations among several national laboratories and institutes, include SNS, CSNS, ESS, FRIB, GANIL, and TRIUMF. Even though there are still a lot of works needed to make this accelerator software system properly functional for FRIB and for any other accelerators, it is a very promising solution us because resources can be shared and efforts be aligned among different institutes.

SUMMARY

There are many technical challenges for the FRIB project, including many not covered in this short paper. However, because with the strong team that has been built and the successful R&D efforts of recent years, all these challenges – including more important issues such as the lithium stripper and the fragment target not discussed here – are being properly addressed. We are on track to deliver this powerful new facility.

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