THE OVERVIEW OF THE ACCELERATOR SYSTEM FOR THE FACILITY FOR RARE ISOTOPE BEAMS AT MICHIGAN STATE UNIVERSITY*

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Abstract

The Facility for Rare Isotope Beams (FRIB) will accelerate stable beams of heavy ions to > 200 MeV/u with beam powers of up to 400 kW onto an in-flight fragmentation target to produce rare isotopes. The accelerator system will include a room-temperature front end, a double-folded superconducting driver linac, and a beam delivery system. The front end will include superconducting ECR ion sources, a beam bunching system and a radio frequency quadrupole. The driver linac will include three acceleration segments using superconducting λ/4 and λ/2 cavities with frequencies of 80.5 and 322 MHz, and two 180 degree folding systems to minimize the cost of conventional construction. Charge-stripping and multi-charge state beam acceleration will be used for the heavier ions to increase acceleration efficiency. The beam delivery system will transport accelerated stable beams to the in-flight fragmentation target. End-to-end beam simulations have been performed to evaluate the performance of the driver linac. We will discuss recent progress in the accelerator design and the beam dynamics studies for the baseline accelerator system.

INTRODUCTION

FRIB [1], currently being designed at Michigan State University, will be a Department of Energy (DOE) national user facility capable to provide intense fast, stopped and re-accelerated beams of rare isotopes for nuclear science researchers to address the forefront scientific questions in nuclear structure and nuclear astrophysics. Since the selection of MSU for the proposed FRIB site in 2008, possible FRIB driver linac configurations have been evaluated by its many stakeholders including the DOE, the FRIB technical team, and the nuclear science community, and the double-folded driver linac configuration, as shown in Fig. 1, was chosen as the preferred Alternative for FRIB in 2010. The change of the driver linac is largely driven by goal to reduce overall project construction cost while maintain the driver linac performance and upgrade potential.

FRIB accelerator system is based on a heavy ion SC driver linac capable of achieving a minimum energy of 200 MeV/u for uranium (higher for lighter ions) at a beam power of 400 kW. The required uncontrolled beam loss in the driver linac is < 1 W/m. FRIB experimental system will have a projectile-fragmentation target and a three-stage in-flight fragment separator to produce intense fast rare isotope beams. With gas-stopping stations, EBIT charge-breeder and a re-accelerator [2] capable to reach 3 MeV/u currently being constructed at the NSCL (possible to 12 MeV/u in future upgrade), FRIB will be able to provide fast, stopped and re-accelerated rare isotope beams for nuclear science researchers for years to come.

To meet the performance requirements, the FRIB accelerator system is designed to minimize beam loss, and achieve high reliability at low cost. Multi-charge state beam acceleration from the ECR ion sources and charge-stripping are used for heavier ions. The double-folded SC driver linac consists of a room temperature front end to accelerate beams from 12 keV/u to 0.3 MeV/u, three segments of SC linac separated by two folding segments (changing beam directions by 180°) to achieve a beam energy of ~200 MeV/u for uranium (higher for lighter ions), and a beam delivery system to deliver the multi-charge state beams to the fragment production target.

FRONT END

The double-folded driver linac front end consists of SCECR ion sources, achromatic charge-selection system, a Low Energy Beam Transport (LEBT) system, a room-temperature RFQ and a Medium Energy Beam Transport

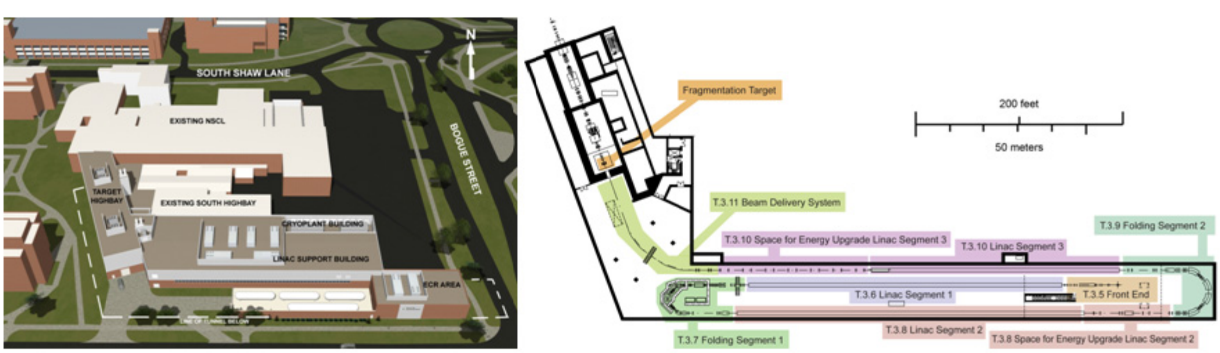

Figure 1: The planned FRIB surface building (left) and the layout of the double-folded SC driver linac (right).

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(MEBT) system, as shown in Fig. 2. To meet the intensity for the heaviest ion beams required for FRIB, two-charge state beams of heavy ions (Xe or heavier) can be produced and accelerated in the front end.

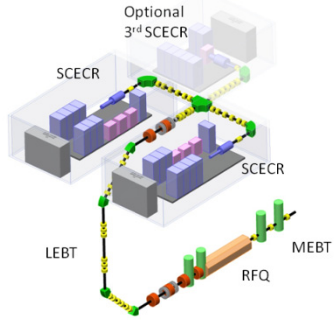

Figure 2: Layout of the double-folded driver linac front end.

Two SCECR ion sources, positioned on the ground level, are used to ensure reliability and allow offline beam development, with the option of adding a third ion source in the future. VENUS developed by LBNL has demonstrated capability to achieve beam intensities and charge states suitable for the FRIB needs. Also, the Superconducting Source for Ions (SuSI) at NSCL has also shown promising potentials to meet the FRIB beam requirements. The nominal ion source extraction voltage will be ~30 kV, and the SCECR systems will be placed on adjustable high-voltage platforms to ensure the same velocity for all ions for injection into the RFQ.

The achromatic charge selection system will be used to select the desired charge states and minimize beam emittance growth. The LEBT then transports and matches the beam into the RFQ. It consists of a vertical achromatic beam transport system to bring beam down to the linac tunnel, a transverse beam collimation system, a beam chopper, and a beam pre-bunching section with an external Multi-Harmonic Buncher (MHB) to achieve minimum longitudinal emittance, an adjustable high-voltage platform and a Velocity Equalizer (VE) for two-charge-state beam matching into the RFQ.

The 80.5 MHz room temperature cw RFQ will accelerate all ion beams from 12 keV/u to 0.3 MeV/u with transmission efficiency of ~82%. Finally, the MEBT will transport and match the beam into the SC linac for further acceleration.

SC LINAC

The double-folded SC linac will consist of three SC linac segments, accelerating beam to at least 200 MeV/u for uranium (higher energy for lighter ions) at a beam power of 400 kW. The most challenging multi-charge state uranium beam acceleration droves the SC linac design. The double-folded SC linac has an 80.5 MHz base frequency and utilizes four cavity types with only one frequency transition at charge-stripping.

SC Linac Segment 1 will be ~86 m long and will accelerate two-charge states (+33, +34) of uranium from 0.3 MeV/u to ~16.6 MeV/u, using two types of Quarter Wave Resonators (QWRs) at 80.5 MHz with β_{opt} of 0.041 and 0.085. As shown in Fig. 3, the two types of cryomodules (β_{opt} of 0.041 and 0.085), used in this segment, contain four (eight) QWRs and two (three) SC solenoid magnets with dipole correctors. Planned beam diagnostics stations are located in the warm region between cryomodules.

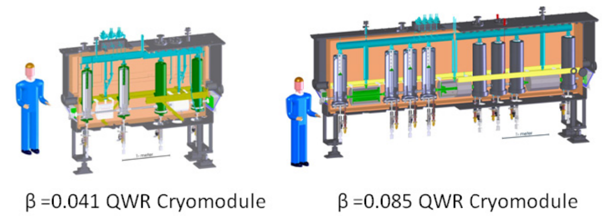

Figure 3: QWR cryomodules used in double-folded SC Linac Segment 1.

Following charge-stripping in the Folding Segment 1, up to five charge states (+76 to +80) of uranium beams will be accelerated to ~105MeV/u with solid stripping in Linac Segment 2, using two types of Half Wave Resonators (HWRs) at 322 MHz with β_{opt} of 0.285 and 0.53. With Gas stripping the output energy will be lower due to the lower charge states of the beams. Also, the frequency transition occurs in the Folding Segment 1, where space is available to accommodate longitudinal beam matching and required beam diagnostics, minimizing beam emittance growth and possible beam loss due to frequency transition. Transverse focusing is also provided by SC solenoid magnets inside the cryomodules. In addition, Linac Segment 2 has space for four additional HWR cryomodules of β_{opt} = 0.53 for possible future energy upgrade. Similarly, beam diagnostics stations are located in the warm region between cryomodules. Figure 4 shows the two types of cryomodules used in Linac Segments 2.

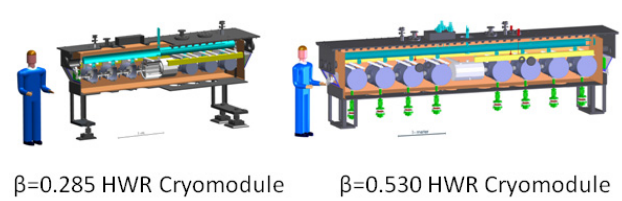

Figure 4: Two types of HWR cryomodules used in double-folded SC Linac Segment 2.

Linac Segment 3 will be ~110 m long, using the same cryomodules of β_{opt} of 0.53 HWR as in Linac Segment 2, to accelerate uranium beams to ~200 MeV/u with solid stripping. Linac Segment 3 has space for seven additional cryomodules to ensure the double-folded SC driver linac output energy reach 200 MeV/u even with gas stripping.

BEAMLINE SYSTEM

The double-folded FRIB driver linac beamline system will consist of three segments: Folding Segments 1 and 2, which connect the SC linac segments, and the Beam

Delivery system delivers accelerated beams to the fragmentation target.

As shown in Fig. 5, Folding Segment 1 begins with a matching section to control the beam size and bunch length at the charge-stripping station, to minimize the beam emittance growth caused by multiple scattering, energy straggling and stripper thickness variation. The solid charge-stripper then increases uranium beam mean charge state from 33.5 to 78 (lower with gas stripper) [3] at beam energy of 16.6 MeV/u. Five charge states (+76 to +80) of uranium beam are then selected and transported through a 180°, second-order achromatic magnetic bending section with correction sextupole magnets while limiting the multi-charge beam emittance growth. Longitudinal beam matching through Folding Segment 1 is accomplished by a cryomodule with two QWRs of β_{opt} = 0.085, and two cryomodules, each with two HWRs of β_{opt} = 0.285. The separation between Linac Segments 1 and 2 is 7.75 m. About ~20% of beam power in undesired charge states will be lost in the beam collimation system after the 1st dipole magnet in the bending section.

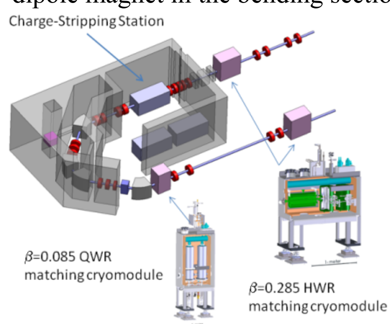

Figure 5: The layout of Folding Segment 1 and required matching cryomodules.

Folding Segment 2 is similar to Folding Segment 1 except there is no charge-stripping station. Five-charge-state uranium beam from Linac Segment 2 is bended by 180° and transported by an achromatic bending section consisting of four dipoles, fourteen quadrupoles and four sextupoles while maintains beam quality. Then a matching section with a cryomodule with two HWRs of β_{opt} = 0.53 is used to match beam transversely and longitudinal into Linac Segment 3. The separation between Linac Segments 2 and 3 is 11.85 m, resulting in a 4.1 m separation between Linac Segments 1 and 3.

The Beam Delivery System delivers ~200 MeV/u, 400 kW multi-charge state uranium beam onto a single fragmentation target with a beam spot diameter of ~ 1mm. It begins with a short matching section followed by a 70° achromatic bending section with correction sextupole magnets in order to minimize multi-charge state beam emittance growth during transport. The final focusing system delivers multi-charge state beam to the fragmentation target with required beam conditions.

BEAM DYNAMICS

Extensive end-to-end beam simulations for the double-folded SC driver linac were performed using IMPACT. The results show that the double-folded SC driver linac design has adequate transverse and longitudinal acceptances, and traverse and longitudinal emittance growths through the driver linac are acceptable. Figure 6 shows the beam envelope of accelerating uranium beam to ~ 200 MeV/u through the SC linac and beamline system of the driver linac without errors. The initial beam phase spaces were obtained from front-end beam simulations started from the LEBT entrance with beam energy of 12 keV/u. The uranium beam transverse and longitudinal emittances (rms-normalized) from the same simulation are shown in Fig. 7. High statistics beam simulations with errors are underway. Beam dynamics studies has shown that the double-folded SC driver linac meets the performance requirement of accelerating stable beams of heavy ions to > 200 MeV/u with beam power up to 400 kW, while minimize overall FRIB project cost and maintain future upgrade potentials.

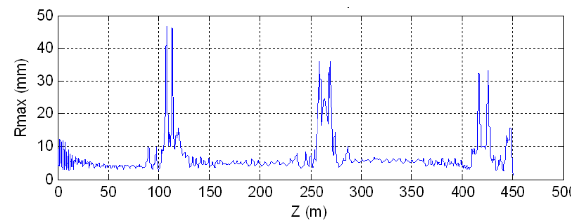

Figure 6: Uranium beam envelope along the SC driver linac.

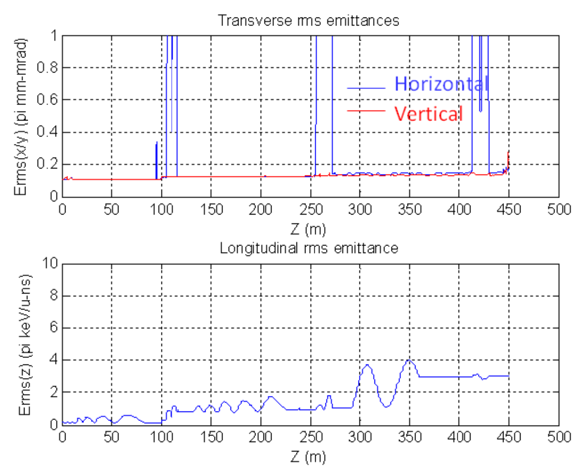

Figure 7: Uranium beam transverse (top) and longitudinal (bottom) emittances along the SC driver linac.

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