THE MSU-PROPOSED SUPERCONDUCTING DRIVER LINAC FOR THE FRIB PROJECT*

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Abstract

The superconducting (SC) driver linac developed for the proposed Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) will be able to accelerate stable beams of heavy ions to > 200 MeV/u with beam power up to 400 kW. The driver linac front end will include superconducting Electron Cyclotron Resonance (SCECR) ion sources, a beam bunching system for multi-charge-state beams and a Radio Frequency Quadrupole (RFQ). The SC linac will have a base frequency of 80.5 MHz, primarily using SC cavities and cryomodules developed for the Rare Isotope Accelerator (RIA) project, the predecessor of the FRIB. A charge-stripping chicane and multi-charge-state beam acceleration will be used for the heavier ions in the driver linac. A beam switchyard will transport beam to the in-flight fragmentation target station. Recent progress in the accelerator system for the MSU-proposed FRIB SC driver linac will be presented in this paper.

INTRODUCTION

FRIB [1], as a Department of Energy (DOE) national user facility, will be a critical component to understand the fundamental forces and particles of nature in nuclear matter. It will provide intense beams of rare isotopes for nuclear science researchers to address the forefront scientific questions in nuclear structure and nuclear astrophysics. In 2008, the DOE undertook a merit review and evaluation process resulting in the selection of MSU for the proposed FRIB site. The FRIB facility described here will be evaluated on numerous occasions by its many stakeholders including the DOE, the FRIB technical team, and the nuclear science community. As a consequence, the detailed design of the FRIB facility is expected to mature from the presently proposed concept.

FRIB 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 (see Figure 1). The facility will have production target facilities, a three-stage in-flight fragment separator, gas-stopping stations, and a reaccelerator to reach 12 MeV/u, providing research opportunities of fast, stopped and reaccelerated beams.

To meet the FRIB beam requirements, the SC driver linac 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 SC driver linac consists of a room temperature front end to accelerate beams to 0.3 MeV/u, two segments of SC linac to achieve a beam energy of 200 MeV/u for uranium (400 MeV/u can be reached by adding a third linac segment), and a beam switchyard to deliver the multi-charge-state beam to the fragment production target. Table 1 lists the representative beams accelerated in the MSU-proposed FRIB SC driver linac.

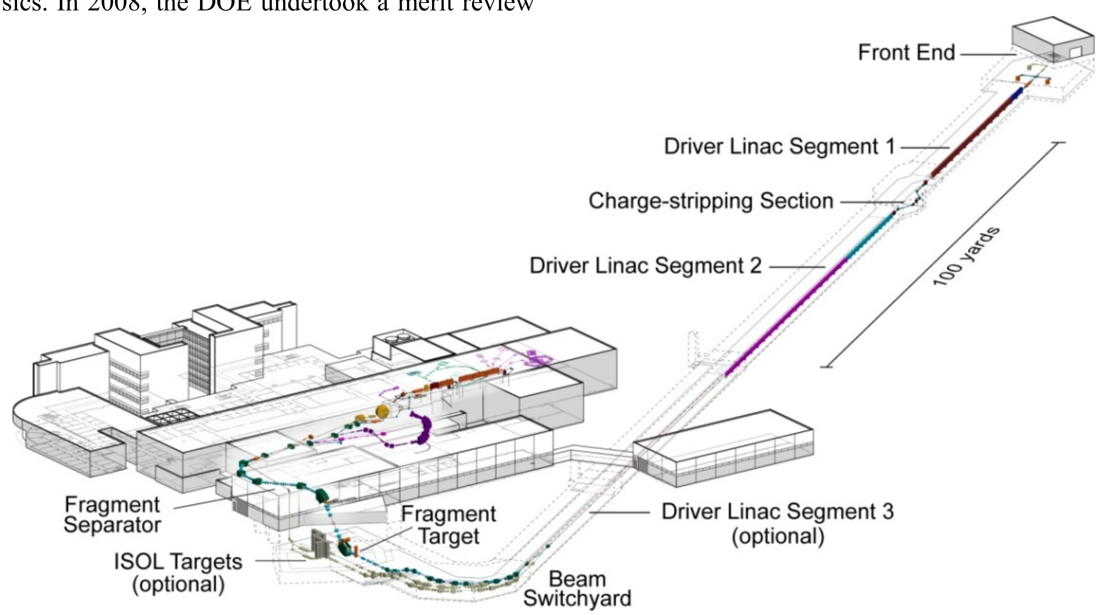

Figure 1: Layout of the FRIB Driver linac.

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Table 1: Representative beams from the FRIB SC driver linac. Q is the average final charge state

Ion	Q	Energy (MeV/u)	Current (pμA)	Power (kW)
Proton	1	610	656	400
^{48}Ca	20	270	31	400
^{86}Kr	35	265	18	400
^{208}Pb	70	210	9.2	400
^{238}U	79	210	8.0	400

FRONT END

The FRIB driver linac front end is comprised of SCECR ion sources, a Low Energy Beam Transport (LEBT) system, a room-temperature RFQ and a Medium Energy Beam Transport (MEBT) system, as shown in Figure 2. To meet the intensity for the heaviest ion beams required for FRIB, two-charge-state beams can be produced and accelerated in the front end.

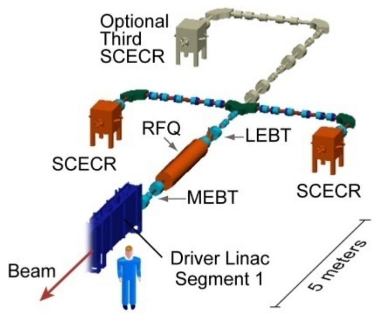

Figure 2: Layout of the FRIB driver linac front end.

Two SCECR ion sources will be used to ensure reliability and to allow offline beam development, with the option of adding a third ion source in the future. The VENUS SCECR developed by LBNL has already demonstrated capability to achieve beam intensities and charge states suitable for the FRIB needs. Also, the Superconducting Source for Ions (SuSI) recently commissioned at NSCL has shown promising potentials to meet the FRIB beam requirements [2]. 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 LEBT transports and matches the beam from the SCECR ion sources into the RFQ. It consists of two achromatic beam selection systems to minimize multi-charge-state beam emittance growth, 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 RFQ will accelerate all ion beams from 12 keV/u to 0.3 MeV/u. Its design was optimized for minimum emittance degradation for multi-charge state beams, while maintaining reasonable RF power requirements and structure size. The nominal inter-vane voltage is 70 kV, resulting in a moderate peak surface field of 1.6 $E_{kilpatrick}$. Together with the external MHB, the 4 meter long RFQ achieves a longitudinal emittance (99.5%) of ~1.1 keV/u-ns for two-charge-state uranium beam with an effective transmission of ~82%.

Finally, the MEBT transports and matches the beam into the SC linac for further acceleration. The option to add a microbunch based beam differential loading system [3] to independently vary beam intensities on multiple targets simultaneously has also been studied.

SC LINAC

The FRIB 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 drove the SC linac design. The proposed SC linac has an 80.5 MHz base frequency and utilizes four cavity types with only one frequency transition and one charge-stripping station.

Linac Segment 1 will accelerate two-charge-states (+33, +34) of uranium from 0.3 MeV/u to 17.5 MeV/u, using two types of Quarter Wave Resonators (QWRs) at 80.5 MHz with β_{opt} of 0.041 and 0.085. Following stripping in the Charge-Stripping Section (CSS), up to five charge states (+77 to +81) of uranium will be accelerated to 200MeV/u in Linac Segment 2, using two types of Half Wave Resonators (HWRs) at 322 MHz with β_{opt} of 0.285 and 0.53. The frequency transition occurs in the charge-stripping section where space is available to accommodate longitudinal beam diagnostics. Transverse focusing in the SC linac is provided by SC solenoid magnets inside the cryomodules. Figure 3 shows the SC accelerating structures used in Linac Segments 1 and 2. Table 2 lists the main cavity and cryomodule parameters.

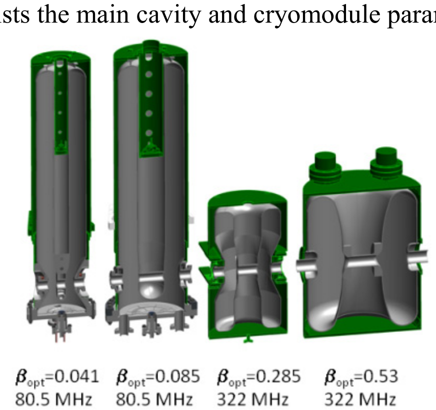

Figure 3: SC Quarter-Wave Resonators and Half-Wave Resonators used in FRIB SC linac Segments 1 and 2.

Linac Segment 3 is the space reserved for a possible future upgrade to 400 MeV/u for uranium by adding cryomodules with SC elliptical structures wth β_{opt} = 0.63 and 0.83. Initially, only transverse focusing quadrupoles and beam diagnostics will be used in Linac Segment 3 to transport beams from Linac Segment 2 to the beam switchyard.

Table 2: Main parameters of SC accelerating structures and cryomodules used in Linac Segments 1 and 2

SC linac	Segment 1		Segment 2	
Cavity Type	QWR	QWR	HWR	HWR
Frequency (MHz)	80.5	80.5	322	322
β_{opt}	0.041	0.085	0.285	0.53
Aperture (mm)	30	30	30	40
E_p (MV/m)	30	30	30	32
B_p (mT)	53	67	82	77
N_{cavity} per module	8	8	6	8
N_{cryo}	2	12	12	19
Operating Temp. (K)	4.5	4.5	2	2
Solenoid field (T)	9	9	9	9
$N_{solenoid}$ per module	7	3	1	1

The prototypes for the two QWR types with β_{opt} = 0.041 and 0.085 have been fabricated and tested at MSU, reaching the gradients and quality factors required by FRIB. They are also being used for the ReA3 project [4], a 3 MeV/u reaccelerator currently being constructed at MSU. A prototype for the 322 MHz HWR with β_{opt} of 0.285 has also been fabricated and tested at MSU, meeting the FRIB design requirements. The 322 MHz HWR with β_{opt} of 0.53 has been designed and a copper model fabricated [5]. A niobium cavity will be prototyped as part of R&D for FRIB in the near future.

Extensive end-to-end beam simulations for the FRIB SC driver linac [6] were performed using IMPACT, with realistic 3D fields for accelerating structures and focusing solenoids with alignment and rf errors included. The results demonstrate that the SC linac design has adequate transverse and longitudinal acceptance, with uncontrolled beam loss below the required 1 W/m limit.

BEAMLINE SYSTEM

The FRIB driver linac beamline system will consist of two parts: the Charge-stripping Section (CSS, see Figure 4) between Linac Segments 1 and 2, and the Beam Switchyard (BSY) after the Linac Segment 3.

The first part of the CSS, is a matching section to control the beam size and bunch length at the stripper, in order to minimize the beam emittance growth caused by multiple scattering, energy straggling and stripper thickness variation. The stripper increases uranium beam mean charge state from 33.5 to 79. A second-order achromatic magnetic chicane with reverse bending dipoles and correction sextupole magnets is then used for charge state selection while limiting the multi-charge beam emittance growth. For uranium, five charge states (+77 to +81) are selected. Two QWRs with β_{opt} = 0.085 are used in the middle of the chicane to control the bunch length.

At the end of the CSS, a cryomodule with two HWRs with β_{opt} = 0.285 and two solenoids is used to match the multi-charge-state beam transversely and longitudinally, prior to further acceleration in the Linac Segment 2.

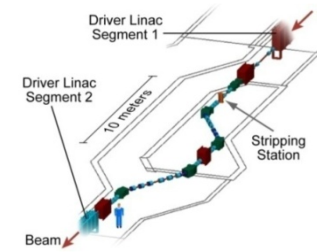

Figure 4: Layout of the Charge-Stripping Section.

The BSY, shown in Figure 5, will initially deliver 200 MeV/u, 400kW multi-charge-state uranium beam on a single fragmentation target with a beam spot diameter of ~ 1mm. The magnets of the BSY can accommodate a beam energy up to 400 MeV/u for uranium (higher energy for lighter ions) for the future energy upgrade. The bending sections in the BSY are achromatic with correction sextupole magnets for multi-charge-states beam transport. The BSY and target gallery areas are designed to allow up to three target stations and corresponding beamlines. The BSY can also accommodate a future beam distribution system to feed multiple target stations simultaneously.

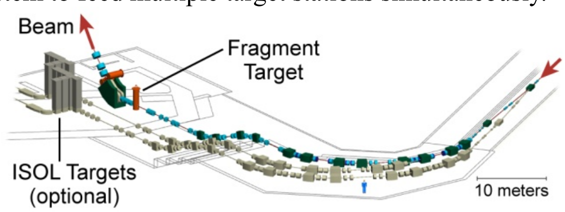

Figure 5: Layout of the BSY.

SUMMARY

A SC linac capable to accelerate stable beams of heavy ions to > 200 MeV/u with beam power up to 400 kW has been designed at MSU for the proposed FRIB driver linac. The proposed design has provisions for a future energy upgrade to 400 MeV/u and additional target stations. The detailed design of the FRIB driver linac is expected to mature from the presently proposed design with further alternative analysis.

REFERENCES

[1] R.C. York, "FRIB: A New Accelerator Facility for the Production of Rare Isotope Beams", these proceedings.
[2] G.Machicoane et al., "Performance Investigation of the NSCL 18 GHz Superconducting ECR Ion Source SUSI", these proceedings.
[3] M. Doleans et al., "Beam Distribution System for the MSU-RIA Driver Linac", proceedings of LINAC2006, Knoxville, TN, USA, August 2006.
[4] X. Wu et al., "The Status of MSU Re-Accelerator", proceedings of Linear Accelerator Conf. (2008).
[5] J. Popierlarski et al., "Development of a Superconducting Half Wave Resonator for Beta = 0.53", these proceedings.
[6] Q. Zhao et al., "Beam Dynamics Studies for the FRIB Driver Linac", these proceedings.