

## DESIGN STATUS OF THE SRF LINAC SYSTEMS FOR THE FACILITY FOR RARE ISOTOPE BEAMS\*

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### Abstract

The Facility for Rare Isotope Beams (FRIB) will utilize a powerful, superconducting heavy-ion driver linac to provide stable ion beams from protons to uranium, at energies of  $>200$  MeV/u at a beam power of up to 400 kW. ECR ion sources installed above ground will be used to provide highly charged ions that will be transported into the linac tunnel approx. 10 m below ground. For the heaviest ions, two charge states will be accelerated to about 0.5 MeV/u using a room-temperature 80.5 MHz RFQ and injected into a superconducting cw linac, consisting of 112 quarter-wave (80.5 MHz) and 229 half-wavelength (322 MHz) cavities, installed inside 51 cryomodules operating at 2K. A single stripper section will be located at about 17 MeV/u (for uranium). Transverse focusing along the linac will be achieved by 9 T superconducting solenoids within the same cryostat as the superconducting rf accelerating structures. This paper describes the matured linac design, as the project is progressing towards a Department of Energy performance baseline definition in 2012. Development status of the linac subcomponents are presented with emphasis on the superconducting RF components.

### INTRODUCTION

Michigan State University is currently designing a U.S. Department of Energy (DOE) Office of Science national user facility for research with rare isotope beams. This accelerator facility for basic nuclear science research, the "Facility for Rare Ion Beams (FRIB)", will provide intense beams of rare isotopes produced by fast fragment separation. The rare isotope beams will be created from high-current beams of stable isotopes (from He to U) accelerated in a superconducting radio-frequency linear accelerator to kinetic energies above 200 MeV/u for all ions with beam powers of up to 400 kW. As a comparison, MSU's current state-of-the-art rare isotope user facility, the National Superconducting Cyclotron Laboratory (NSCL) supported by the National Science Foundation, can provide 1 kW of beam power on target.

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On the scientific side, FRIB will incorporate the significant experimental infrastructure available at NSCL. A full set of already developed scientific instruments for fast, stopped, and re-accelerated radioactive beams will make FRIB immediately available for rich scientific output. A facility layout, an architectural rendering, and a functional system diagram of the FRIB facility are shown in figure 1, figure 2, and figure 3 respectively.

In December 2008 DOE has selected MSU to establish FRIB. A corresponding cooperative agreement has been signed between DOE and MSU in June 2009 with an expected project cost of \$614.5M (\$520M DOE-funded, and \$94.5M MSU-funded). CD-1 approval (Conceptual Design Complete) has been granted by DOE in September 2010. The project is currently pursuing CD-2 (Accelerator and Experimental Systems Preliminary Design Complete) and CD-3a (Conventional Facility Detail Design Complete) approvals for May 2012. Pending DOE approval, the project will start tunnel construction in 2012.

### SUPERCONDUCTING DRIVER LINAC

The FRIB accelerator systems are based on a heavy-ion, superconducting driver linac capable of achieving a minimum energy of 200 MeV/u for uranium (higher for lighter ions) at beam power of up to 400 kW. Charge stripping at about 17 MeV/u energy (for uranium) is needed to reach the final energy for the heaviest ions. In

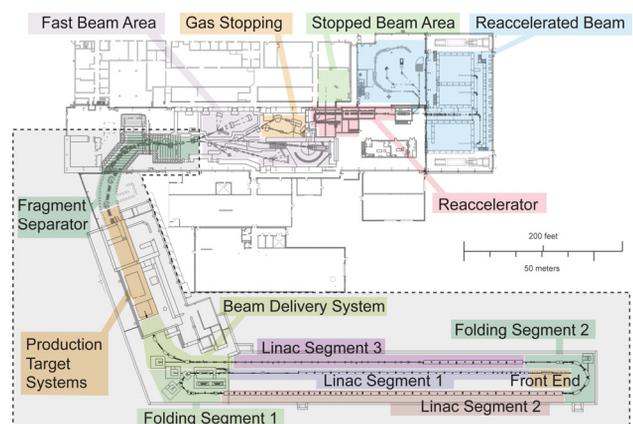


Figure 1: The FRIB facility layout includes the driver linac, a 400 kW nuclear production target, a radioactive in-flight fragment separator, and scientific instruments for fast, stopped, and re-accelerated radioactive beams [1].



Figure 2: Michigan State University is currently designing a U.S. Department of Energy (DOE) Office of Science national user facility for research with rare isotope beams. This accelerator facility for basic nuclear science research, the “Facility for Rare Ion Beams (FRIB)”, will provide intense beams of rare isotopes produced by fast fragment separation. Site preparation and relocation of utility lines in the tunnel vicinity has started in 2011. Pending DOE approval tunnel excavation is planned for 2012.

order to reach the beam power for the heaviest ions and due to ion source limitations the driver linac is designed to accept two charge states between source and stripper and five charge states after the stripper for simultaneous acceleration. The overall linac architecture is described in more detail in references 2 and 3.

The FRIB driver linac is installed in a tunnel 10 m below ground. A three-story service building and a 15 kW cryoplant are located above the tunnel on ground level. To minimize tunnel construction cost the linac has been folded into three sections to minimize the tunnel concrete wall perimeter length (which drives the cost). However,

that cost reduction comes at the expense of a more complex linac ion optics design and more complex interfaces between conventional facilities and the linac folding sections. A CAD rendering and schematic layout of the FRIB linac is shown in figure 4.

### Linac Architecture Overview

As explained schematically in figure 2, the FRIB driver linac accepts beam from a state-of-the-art, superconducting Electron Cyclotron Resonance (ECR) high-charge-state ion source [4]. To meet intensity requirements for the heaviest ions (heavier than krypton)

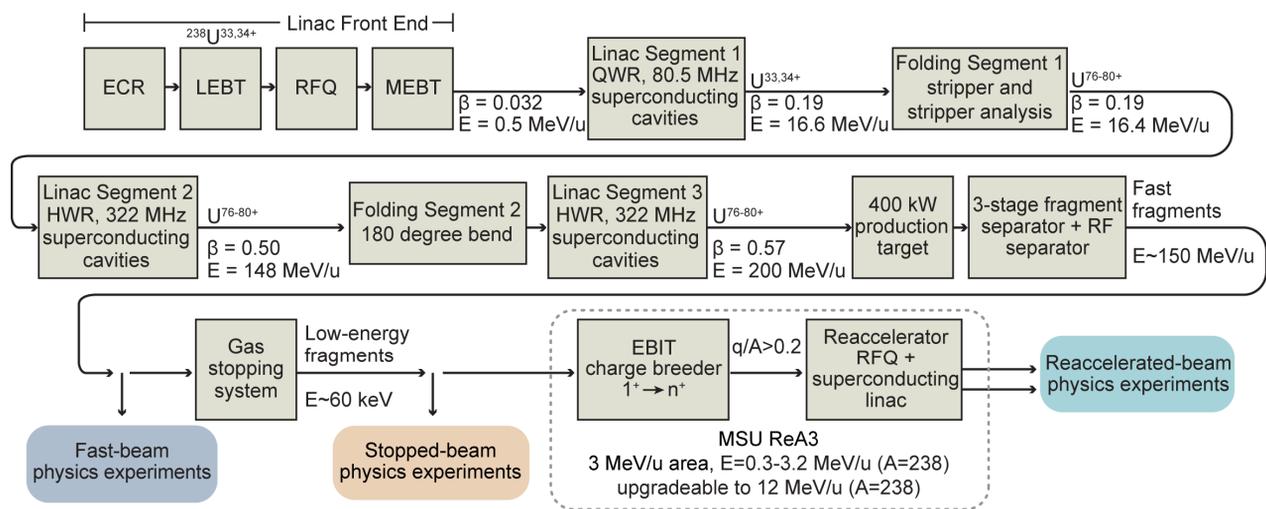


Figure 3: Detailed system diagram [1] of the 200 MeV/u (for uranium), 400 kW FRIB driver linac, the target and fragment separator. Experimental systems include facilities for fast, stopped, and re-accelerated radioactive ion beams.

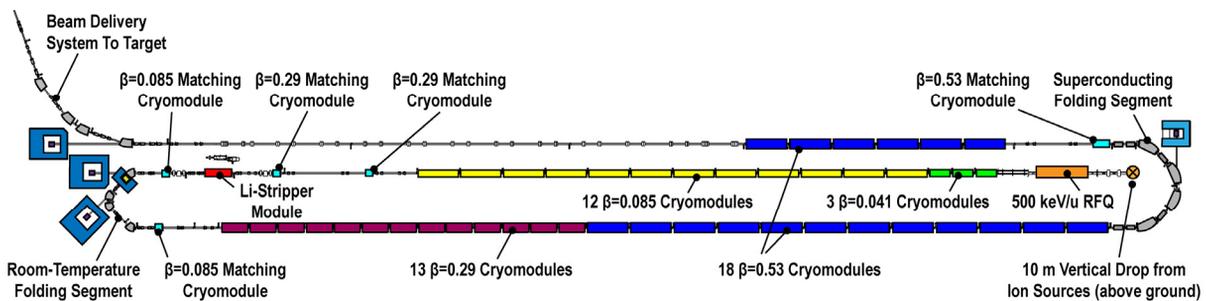
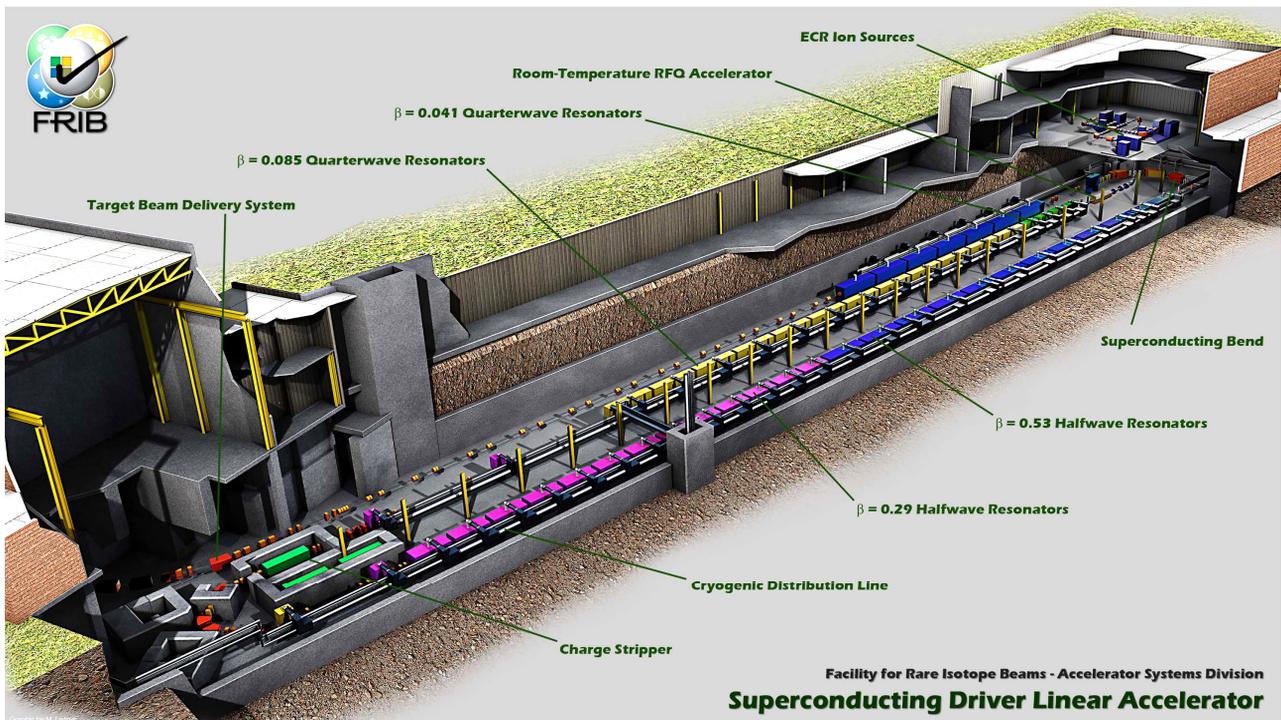


Figure 4: A CAD rendering and schematic layout of the FRIB linac. By combining the technical features of a heavy-ion and a high-power accelerator the FRIB linac becomes uniquely challenging in several aspects as outlined in the text.

the low energy beamline connecting the above-ground ion sources with the linac 10 m below ground has to be able to identify and achromatically transport two adjacent charge states.

The two charge states are subsequently velocity-matched by a unique buncher arrangement for injection into a 500 keV/u four-vane 80.5 MHz RFQ capable to operate continuously. A medium energy beamline that includes space for a fast chopper (for beam modulation capabilities desired by the nuclear science experiments) connects the front end with the superconducting linac.

Superconducting technology has been chosen since it most efficiently allows 100% duty factor operation required to reach the beam power on target. All FRIB cavities will be operated at 2 K superfluid helium temperature. Linac cost optimization balancing efficient acceleration at optimum  $\beta$  with the minimum amount of different cavity types led to a design utilizing only four low-beta cavity structures described in more detail further below. A fundamental decision has been made to only use two-gap accelerating cavities in order to increase operational reliability. That way lower-performing

cavities can be compensated for by remaining cavities. To reach 200 MeV/u (for uranium) the linac requires 341 cavities in total.

As mentioned above the linac consists of three approximately 150 m long segments connected by  $\sim 7$  m and  $\sim 12$  m radius bend sections (see figure 1 and figure 4):

- Linac segment 1 will utilize two types of quarter-wave resonators (QWR) operated at 80.5 MHz and  $\beta_{\text{opt}} = 0.041$  and  $\beta_{\text{opt}} = 0.085$ . It accelerates the heaviest ion (uranium) up to 17 MeV/u. This is the optimum energy for the single, liquid-lithium stripper section utilized in the FRIB accelerator.
- Folding segment 1 will provide charge-state analysis after the stripper, collimation (at 40 kW continuous beam power leading to stringent shielding requirements), and phase match of up to 5 charge states into the subsequent linac section.
- Linac section 2 introduces the only linac frequency jump and the introduction of a new half-wave resonator type. Two half-wave resonator (HWR)

types operated at 322 MHz and  $\beta_{opt} = 0.29$  and  $\beta_{opt} = 0.53$  accelerate the heaviest ion up to 110 MeV/u.

- Folding segment 2 employs saturated, 2 T superconducting bend magnets, and rematches the beam into linac segment 3 which continues to accelerate up to 200 MeV/u (for uranium) utilizing  $\beta_{opt} = 0.53$  HWRs. Linac section 3 reserves space for 14 more cryomodules for future upgrades.
- An achromatic beam delivery system and final focus magnet arrangement can transport and focus five charge states of uranium into a 1 mm diameter spot size on target with stringent stability requirements to achieve the resolution necessary for the downstream radioactive fragment separator.
- Transverse beam confinement along the linac is achieved by quadrupole focusing in the folding segments and solenoid focusing along the linac utilizing up to 0.5 m long, 9 T superconducting coils that also incorporate sets of steering dipoles. The use of solenoids in the linac is primarily driven by the need for multi-charge-state acceleration.

### Linac Challenges

By combining the technical features of a heavy-ion and a high-power accelerator the FRIB linac becomes uniquely challenging in several aspects:

- Multiple charge states of heavy ions need to be accelerated simultaneously to the target leading to complex ion optics constraints in the linac and folding segments. For optimum isotope production the linac must be designed to be able to accelerate a wide range of ions [5].
- The slow moving heavy ions require distinctive low-beta, superconducting accelerator structures with complex shapes. The challenge for FRIB is to develop these structures towards lowest cost at

enough technical confidence to go forward with timely linac construction.

- Solid charge strippers cannot survive the high-power heavy ion beam. A liquid-ribbon lithium charge stripper, initially developed at Argonne National Laboratory, has to be used for FRIB. A helium gas-stripper is developed in parallel as backup.
- A civil-engineering limit on the overall tunnel width (for cost reasons) leads to difficult accelerator physics/engineering issues related to the tight spacing of optical elements.
- Characteristic for high-power accelerators the linac is designed to limit uncontrolled beam loss along the beamline to less than 1 W/m. That requirement demands an appropriate low-loss lattice design, beam collimation, shielding, and machine protection systems.
- Fragment separator optics desire 90% of the 400 kW primary beam inside a 1 mm diameter spot on target. The resulting CW power density combined with stringent beam-on-target stability requirements make FRIB unique and require strategic planning for operational power ramp-up.

## SRF LINAC SYSTEMS

### Introduction

FRIB requires 51 cryomodules and 341 low-beta cavities to accelerate uranium up to 200 MeV/u. However, the total SRF acquisition scope is 55 cryomodules and 435 cavities once spare cryomodules and cavities, 10% excess (damaged) cavities, plus development and pre-production runs are included. Tables 1 and 2 summarize a more detailed cryomodule/cavity breakdown by production phase and cavity type.

The FRIB cryomodules are one of the major cost

Table 1: FRIB cryomodule and cavity production count (includes linac components plus spares)

Quarter Wave Cryomodules			
		Number of Cryomodules	Number of Cavities
$\beta = 0.041$	Accelerating Cryomodules:	3 + 1 spare	12 + 4 spare
	Matching Cryomodules:	-	-
$\beta = 0.085$	Accelerating Cryomodules:	12 + 1 spare	96 + 8 spare
	Matching Cryomodules:	2	4
Half Wave Cryomodules:			
		Number of Cryomodules	Number of Cavities
$\beta = 0.29$	Accelerating Cryomodules:	13 + 1 spare	78 + 6 spare
	Matching Cryomodules:	2	4
$\beta = 0.53$	Accelerating Cryomodules:	18 + 1 spare	144 + 8 spare
	Matching Cryomodules:	1	3
<b>TOTAL:</b>		<b>51 + 4 spare</b>	<b>341 + 26 spare</b>

Table 2: FRIB cavity acquisition scope including pre-production runs (fabrication timeframes are indicated)

Quarter Wave Resonators (QWR):						
Type	<i>Development Run</i> (no helium vessel)	<i>Pre-Production Run</i> (with helium vessel)	<i>FRIB LINAC</i>	<i>10% excess</i>	<i>spare</i>	<i>TOTAL</i>
	<i>FY 2011 – FY 2012</i>	<i>FY 2012 – FY 2013</i>	<i>FY 2014-FY 2017</i>			
$\beta = 0.041$	-	-	<b>12</b>	1	3	<b>16</b>
$\beta = 0.085$	2	10	<b>100</b>	10	8	<b>130</b>
Half Wave Resonators (HWR):						
Type	<i>Development Run</i> (no helium vessel)	<i>Pre-Production Run</i> (with helium vessel)	<i>FRIB LINAC</i>	<i>10% excess</i>	<i>spare</i>	<i>TOTAL</i>
	<i>FY 2011 – FY 2012</i>	<i>FY 2012 – FY 2013</i>	<i>FY 2014-FY 2017</i>			
$\beta = 0.29$	2	10	<b>82</b>	8	6	<b>108</b>
$\beta = 0.53$	2	10	<b>147</b>	14	8	<b>181</b>
<b>TOTAL:</b>			<b>341</b>			<b>435</b>

drivers of the project. At the same time, they constitute one of the leading technical risks to the success of the project. To reduce that risk, FRIB had initiated a  $\beta = 0.53$  cryomodule R&D program which includes the construction of a “Two-Seater” test cryomodule (see figure 5) with two  $\beta = 0.53$  half-wave resonators (including two FRIB power couplers) and one 9 T solenoid. This cryomodule will also serve as R&D platform to prove operation of the cryogenic systems required for 2 K operation (all four cavity types will be operated at 2 K superfluid helium temperature).

The “Two-Seater” R&D program addresses the development needs for the half-wavelength cryomodules. On the other hand, the quarter-wave cryomodules have

been developed during the construction of the FRIB re-accelerator ReA [6, 7]. Two  $\beta = 0.041$  cryomodules are already operational, and the first  $\beta = 0.085$  cryomodule will be completed mid 2012.

### Cavity Development Status

Due to the large quantity of cavities required for FRIB the cavity development efforts focus strongly on fabrication cost minimization. Cavity design details and experimental results can be found in [8 to 16]. Figure 6 displays the design evolution of the FRIB cavity types from the conceptual design to the current design level. The cavity development status is briefly summarized below:

#### $\beta = 0.041$ (12 cavities in FRIB linac) [9,10]

- 7 cavities are fully tested and operational 24/7 in ReA [6] cryomodules (at 4 K). Figure 7 shows the ReA  $\beta = 0.041$  coldmass.
- We have allocated FRIB schedule time to optionally implement design improvements developed during the FRIB  $\beta = 0.085$  cavity re-design.

#### $\beta = 0.085$ (100 cavities in FRIB linac) [8, 11]

- Development has been delayed due to additional R&D required to improve the performance of the cavity’s bottom flange design which had complex RF contact design issues.
- Over the last year the design has been systematically optimized and the cavity reliability improved by:
  - elongation of the cavity (to reduce bottom flange RF currents),
  - a new flange joint design (to improve RF contact), and

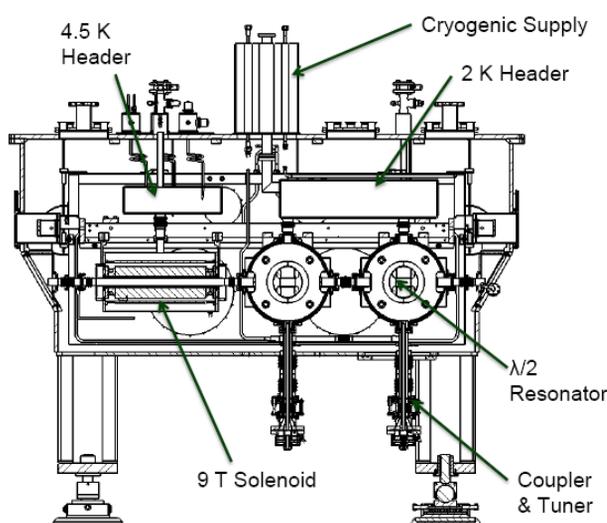
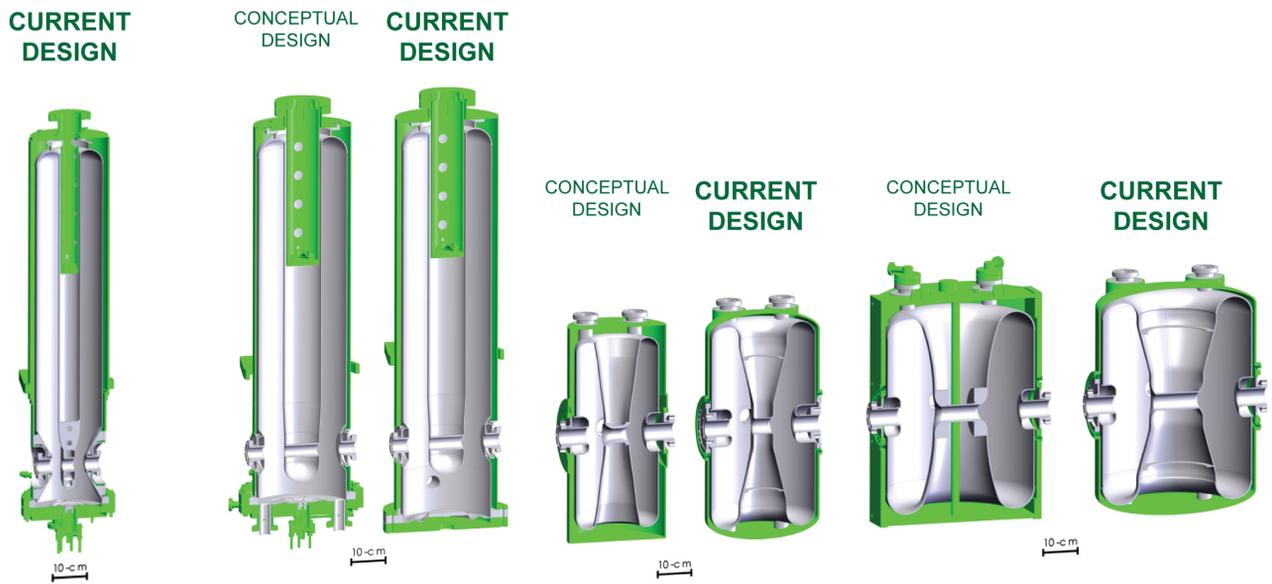


Figure 5: FRIB is currently assembling a “Two-Seater” test cryomodule with two  $\beta = 0.53$  half wave resonators and one 9 T solenoid. It serves as half-wave cryomodule R&D platform as well as 2K systems test.



**$\beta = 0.041$  cavity (12 cavities in FRIB linac)**       **$\beta = 0.085$  cavity (12 cavities in FRIB linac)**       **$\beta = 0.29$  cavity (12 cavities in FRIB linac)**       **$\beta = 0.53$  cavity (12 cavities in FRIB linac)**

Figure 6: Linac cost optimization balancing efficient acceleration at optimum  $\beta$  with the minimum amount of different cavity types led to a design utilizing only four low-beta cavity structures. The first linac section will utilize  $\beta = 0.041$  and  $\beta = 0.085$  quarter-wave resonators. Linac sections 2 and 3 will consist out of  $\beta = 0.29$  and  $\beta = 0.53$  half-wave resonators. All FRIB cavities will be operated at 2 K superfluid helium temperature. This figure displays the design evolution of the FRIB cavity types from the conceptual to the current design level. Due to the large quantity of cavities required for FRIB the cavity development effort focuses strongly on fabrication cost minimization.

- implementation of a side power coupler (to reduce bottom flange heating).
- 11 ReA cavities are currently being refurbished and will be used in ReA cryomodules.
- FRIB cavities at 2K can operate at higher gradients than originally planned allowing a reduction of the amount of cryomodules.
- FRIB cavity procurement plans: 2-cavities development run in 2011/2012, 10-cavities pre-production run in 2013, and production in 2014.

$\beta = 0.53$  (147 cavities in FRIB linac) [14 - 16]

- The  $\beta = 0.53$  cavity serves as prototypical half-

wavelength cavity design for FRIB. It is highly optimized for cost and ease of production.

- 5 cavity prototypes have been successfully built, so far three have been outfitted with a He-vessel.
- The cavity design/fabrication has been shaken out and is matured. However further work is still required on outside stiffening ribs and tuner optimizations.
- The FRIB cavities will incorporate a stainless steel He-vessel.
- FRIB cavity procurement plans: 2-cavities development run in 2011, 10-cavities pre-production run in 2013, and production in 2016.

$\beta = 0.29$  (82 cavities in FRIB linac) [12, 13]

- The  $\beta = 0.29$  cavity is similar to the  $\beta = 0.53$  design (except for the outer diameter size) incorporating the same fabrication details.
- Since this cavity type has been developed only recently, we've continued to push the design to further minimize  $B_{peak}$ .
- Argonne National Laboratory has developed an alternative [12] to the MSU design with the proposal to operate at higher gradients. This cavity is also optimized for EP processing.
- FRIB cavity procurement plans: 2-cavities development run in 2011, 10-cavities pre-production run in 2013, and production in 2015.



Figure 7: The ReA  $\beta = 0.041$  coldmass assembled in the MSU cleanroom [5]. The ReA  $\beta = 0.041$  cryomodule serves as prototype cryomodule for FRIB.



Figure 8: Vacuum baking and RF conditioning teststand for the FRIB HWR power couplers.

### *Power Coupler Development Status*

Two FRIB HWR power coupler units to be assembled inside the  $\beta = 0.53$  R&D cryomodule have been successfully RF-conditioned after several days of vacuum bake-out [17]. Figure 8 shows the power coupler conditioning setup which can condition two couplers at the same time. We plan to ultimately operate three such conditioning setups in parallel to support the FRIB cryomodule assembly rate.

Due to the lower power requirements in the QWR cryomodules, more simplified QWR power couplers [18] have been installed on ReA and serve as prototype for FRIB. However, the recent redesign of the  $\beta=0.085$  cavities moved the coupler location from the bottom to the side of the cavity. This requires a redesign of the coupler and cryomodule to incorporate a side-coupler. We are currently exploring a dual-window coupler for that cavity type.

### *Cavity Procurement Strategy*

FRIB has begun the process to qualify, compete, and subsequently engage in a long-term, contractual relationship with a single supplier to deliver all FRIB cavities of a certain type at a guaranteed hourly fabrication rate. The goal is to have FRIB cavity suppliers in place before DOE CD-2 approval (Preliminary Design Approval) in spring 2012. The  $\beta = 0.53$  request for quotation (RFP) has been released in July 2011, we plan to release the  $\beta = 0.29$  RFP in the August/September 2011 and the  $\beta = 0.085$  RFP in the September/October 2011 timeframe.

The cavity procurement strategy tries to aggressively reduce vendor risks in order to achieve best price and is guided by following principles:

- FRIB will work directly with the vendors to understand their risk concerns. Vendor risks will differ from vendor to vendor. For instance, not all vendors have etching and frequency measurement experiences. Machining, e-beam welding capabilities, and cavity fabrication approaches differ

from vendor to vendor. To achieve best price, FRIB has several options to remove risks from the vendors:

- Perform tasks where vendor has no capability (e.g. chemical etching),
- Adjust cavity designs to allow vendor to implement familiar fabrication approaches,
- Identify key-personnel bottlenecks at the vendor, and support building up staff,
- Work closely with vendor in mass-production planning,
- Accept cavities on mechanical properties instead of electromagnetic performance,
- FRIB purchases niobium material instead of the vendor.
- Reduce/Mitigate risk of vendor default:
  - FRIB will review the appropriate financial ratings of the supplier and evaluate how this project fits into their total capabilities.
  - All cavity vendors currently envisioned for FRIB production are capable of building any FRIB cavity type. In case a vendor defaults or fails to deliver the FRIB cavity production goal, FRIB could decide to switch vendors as backup. Schedule contingency will be held for such possibilities.
- The long-term supplier relationship for FRIB mass production of each cavity type will grow in task orders:
  - Task Order 1: We will build two cavities to prove the fabrication process and successful cavity performance. During that task order we will work with the supplier to assure a thorough understanding of key areas such as surface quality demands, fabrication tolerances, e-beam welding parameters, and frequency shifts during fabrication.
  - Task Order 2: We will build a minimum of ten cavities, including a stainless steel helium vessel, to test mass-production techniques, assure repeatability and evaluate work flow optimizations.
  - Task Order 3: We will begin with a six month ramp up to attain full production rate (3 cavities per week at peak).

### *Cryomodule Procurement Strategy*

The FRIB cryomodule design is currently finalized for the half-wave resonators and will be completed in 2012 for the quarter wave resonators. The FRIB cryomodule design has evolved significantly over the last year. Key features, including rail system, support system, heat and magnetic shields have been simplified. The assembly and alignment approach is improved compared to previous cryomodules.

Figure 9 shows the new cold-mass design which incorporates a torque-resistant structural frame made of stainless steel. As a novel feature for a low-beta cryomodule we've incorporated machined fiberglass compression posts, which support the coldmass in the

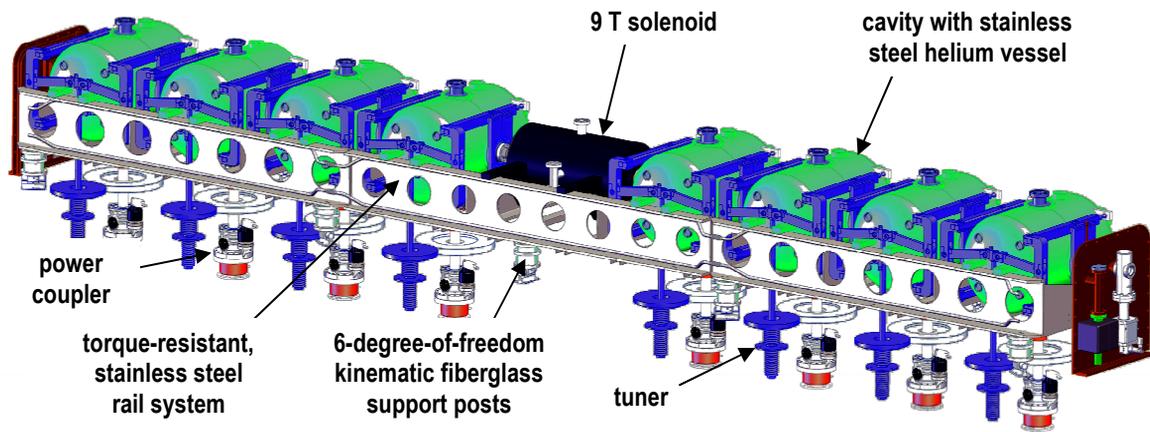


Figure 9: The FRIB coldmass design, which incorporates a torque-resistant structural frame made of stainless steel, has advanced through several prototype stages, and is now highly optimized for mass-production. Cavity and solenoid attachment points to the rails are all machined after welding in order to guarantee a consistent assembly of all cryomodules.

cryomodule vacuum vessel. Three posts with spheres and V-grooves oriented towards the center of thermal contraction serve as true 6-degree-of-freedom kinematic supports. Cavity and solenoid attachment points to the rails are all machined after welding in order to guarantee a consistent assembly of all cryomodules.

We are currently optimizing FRIB plans for a cryomodule production rate of 2 per month. Cavity processing, vertical testing, and coldmass assembly will all be performed at MSU. As indicated in figure 10, the cryomodule thermal shield, magnetic shield, cryogenic plumbing, and vacuum vessel will be procured from industry as complete “plug-in” units ready for assembly in the cryomodules. Final cryomodule assembly and cold-testing will be done at MSU.

### Cavity Processing and Coldmass Assembly

FRIB is currently finalizing its cavity processing and certification steps for cavity mass-production. For instance, we have recently decided to implement hydrogen degassing into the regular cavity processing steps. This decision has been made after successful  $\beta = 0.53$  cavity experiments using the hydrogen de-gassing furnace at the JLAB Institute for SRF Science and Technology.

During FRIB construction, cavity processing (except bulk etching which we plan to perform at the cavity vendors) and coldmass assembly will be performed at MSU. The FRIB schedule requires a peak cavity production rate of 3 cavities per week. Since we have to

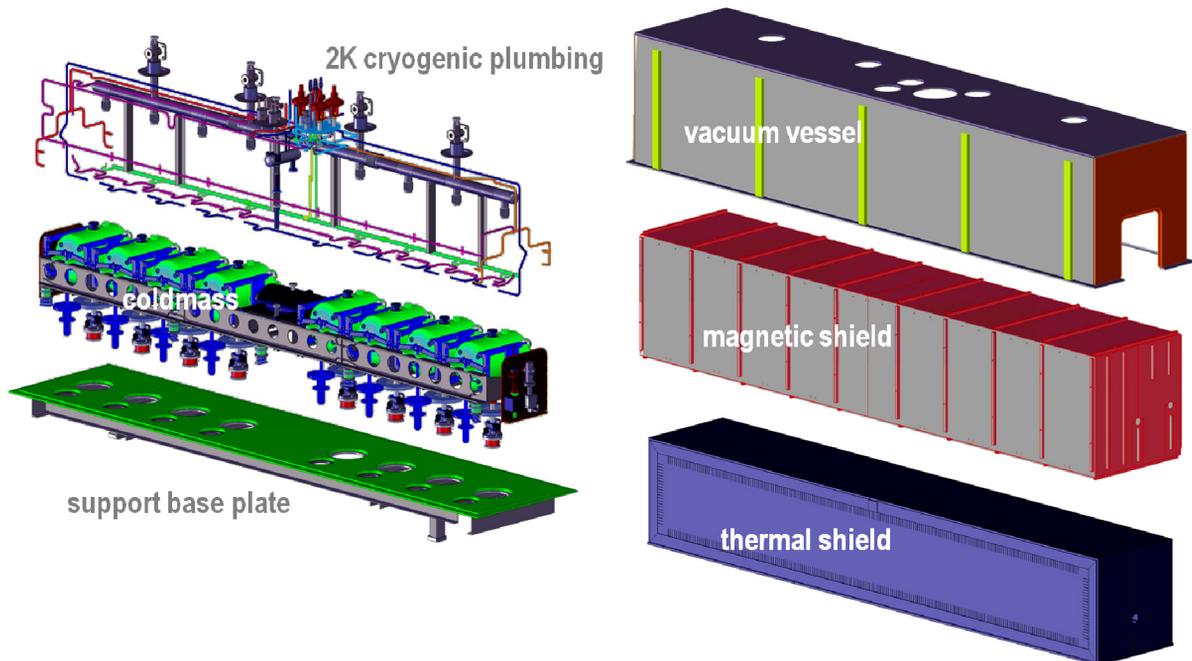


Figure 9: The FRIB cryomodule thermal shield, magnetic shield, cryogenic plumbing, and vacuum vessel will be procured from industry as complete “plug-in” units ready for assembly in the cryomodules. Final cryomodule assembly and cold-testing will be done at MSU.

account for re-processing and test-failures the actually required cavity processing and testing rate will be higher. FRIB is currently developing plans for 5 cavity processes per week and 2 cryomodule assemblies per month to guarantee minimum production rate.

To achieve the required consistency in cavity preparation we have invested in several additional measurement tools (particle counters, water monitoring devices, and a high-resolution inspection camera) to quantify cleanroom parameters during cavity cleaning and assembly [19, 21].

In addition, we are currently upgrading or planning to expand the available SRF infrastructure, including two new vertical test facilities, cryomodule bunkers, and a helium recovery system. Next year we will undertake a major re-build of our cleanroom and etching facilities [19, 20]. Process flow analysis with the help of a manufacturing engineer allowed us to develop cost and time-saving factory layouts for FRIB mass production.

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