LOW-BETA CRYOMODULE DESIGN OPTIMIZED FOR LARGE-SCALE LINAC INSTALLATIONS*

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Abstract

This paper will present most recent design developments at FRIB to optimize low-beta cryomodules for large-scale linac installations. FRIB, which requires the fabrication of 53 cryomodules, has to emphasize ease of assembly and alignment plus low cost. This paper will present experimental results of a novel kinematic rail support system which significantly eases cryomodule assembly. Design choices for mass-production are presented. Results of vibration calculations and measurements on a FRIB prototype cryomodule will be reported.

INTRODUCTION

FRIB is a US $730 million nuclear physics project to be built at Michigan State University under a cooperative agreement with the US Department of Energy (DOE) with a 7-year timetable [1]. According to the current FRIB baseline schedule fabrication and procurement of linac components will start mid-2014. Actual linac installation will begin at the end of 2016 after completion of conventional facilities and cryoplant construction [2].

Due to the heavy mass and correspondingly low velocity of the accelerated ions, the FRIB driver linac [1] utilizes four different low-beta SRF resonator designs in cryomodules as shown in Fig. 1 and described in Table 1. The status of SRF system designs and overall acquisition strategies have been summarized in [2]. For high-beta applications superconducting RF has become an established technology with a history of industrial optimization efforts; however, for low-beta structures, FRIB will most likely be the first facility requiring industrially produced components on a larger scale [2].

*This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.
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Table 1: Required Cryomodule Configurations for FRIB. Quantities are shown in ( ) brackets.

Configuration (Qty/FRIB)	Resonator Type	Solenoid L_{eff} [m]	BPM
(3)	QWR $\beta = 0.041$ (4)	0.2 (2)	(2)
(11)	QWR $\beta = 0.085$ (8)	0.5 (3)	(3)
(12)	HWR $\beta = 0.29$ (6)	0.5 (1)	n/a
(18)	HWR $\beta = 0.53$ (8)	0.5 (1)	n/a
(2)	HWR $\beta = 0.29$ (2)	n/a	n/a
(2)	QWR $\beta = 0.085$ (3)	n/a	n/a
(1)	QWR $\beta = 0.53$ (4)	n/a	n/a

CRYOMODULE DESIGN

The FRIB cryomodules are based on a modular bottom-supported design which is optimized for mass-production and efficient precision-assembly as shown in Fig. 2. Four types of superconducting resonators and two solenoid lengths are used in multiple configurations for the FRIB linac driver as described in Table 1. In order to achieve alignment tolerance a precision machined and bolted cold mass rail system is utilized. A novel kinematic cold mass mounting system allows for thermal contraction while maintaining the alignment of the system. In order to achieve thermal isolation, the cold mass is supported by

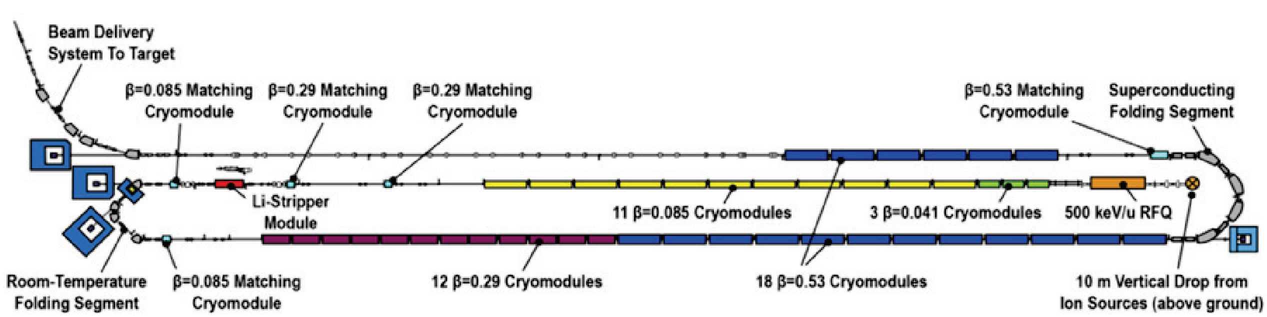

Figure 1: A schematic layout of the FRIB driver linac.

ISBN 978-3-95450-143-4

composite posts. The cold mass also contains a wire position monitor (WPM) to verify alignment. Alignment verification will take place on pre-production cryomodules for FRIB [3].

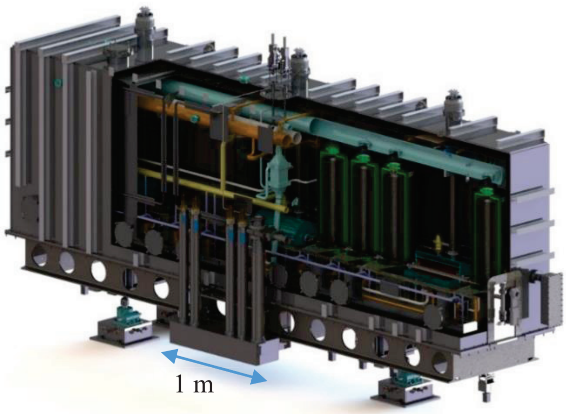

Figure 2: FRIB modular bottom-up cryomodule design. This cryomodule incorporates 8 β=0.085 QWRs, 3 solenoids, and 3 cold beam position monitors.

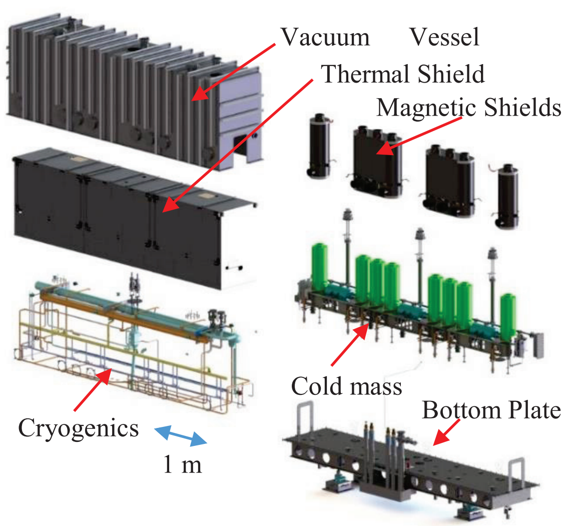

Figure 3: Sub-System of FRIB cryomodule design. Supported off the bottom plate is the cold mass system, where the resonators are protected by local magnetic shielding (right). The cryogenic system attaches to the cold mass. All assemblies are encapsulated by the thermal shield and vacuum vessel (left).

Figure 3 displays the subsystem break down of the cryomodule. To attenuate the magnetic field of earth and the surrounding environment a localized A4K metal shield is used around the resonators. The cryogenic systems allows for individual 2 K and 4.5 K liquid helium lines to the resonators and solenoids respectively. The thermal radiation shield is constructed of 6063-T5 Aluminium (UNS A96063). The cold mass is supported by the vacuum vessel bottom plate which is machined flat from low carbon steel (UNS G10200). Also attaching to the bottom plate is the vacuum vessel lid which is constructed of the same material.

An overall attempt was made to incorporate design for assembly and manufacture methods to reduce the number of parts, optimizing assembly time and material usage. Where practically possible the design has been optimized for minimal parts and designed for multiple functions [3].

Cold Mass

The cold mass contains the superconducting resonators and solenoids as shown Fig. 4. The solenoids are integrated with vertical and horizontal beam corrective steering dipoles magnets. The cold mass system also contains the commercially procured leads for the solenoid. For the quarter wave resonator cryomodules, cold beam position monitors are utilized.

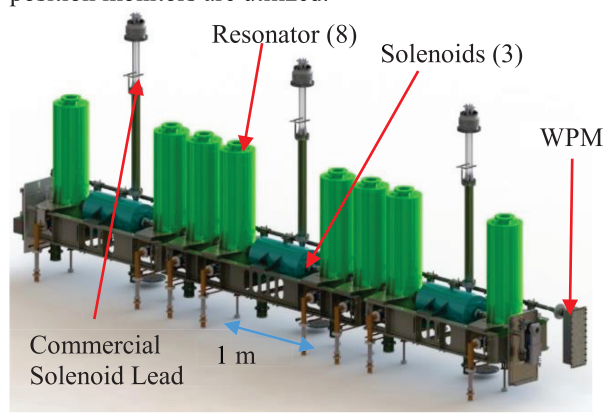

Figure 4: Cryomodule cold mass. Alignment rails support superconducting resonators and solenoid(s). Wire position monitor is used to verify alignment.

The resonators are housed in a commercially pure grade 2 titanium helium vessel. The quarter wave resonators are maintained on operating frequency via a linear actuating tuner with an external stepper motor and piezoelectric actuator. The half wave resonator makes use of a pneumatic tuner similar to that used by Argonne [4]. RF power is delivered to all resonators by fundamental power couplers via coaxial RF lines. Seen below in Fig. 5, are the fundamental power coupler and tuner drive system for the β=0.085 quarter wave cryomodule.

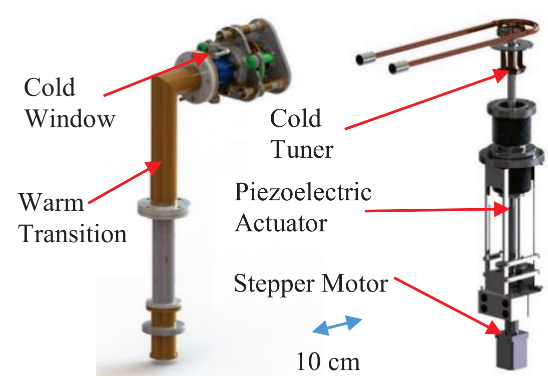

Figure 5: Quarter wave power coupler and warm transition by ANL (left). Tuner drive by FRIB (right).

The resonators and solenoids are assembled to a support structure, shown in Fig. 6, made from 316L stainless steel (UNS S31603) that is divided longitudinally into 3 pieces to minimize static deflections. This support structure holds the resonator and solenoid components during room temperature assembly and cryogenic operation [3].

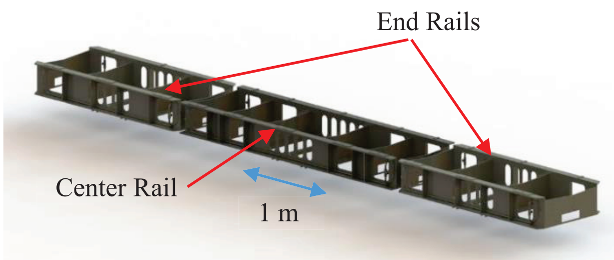

Figure 6: Alignment rail system for cold mass. Rails are fabricated of 316L stainless steel, and are annealed to relieve residual stress and restore magnetic permeability properties.

The interface between the cryogenic support structure and the room temperature bottom plate structure is composed of g-10 posts as shown in Fig. 7. The room temperature end of the composite posts rests on precision linear bearings which are pointed to a fixed location of thermal contraction. This design allows a low friction, high precision assembly using interchangeable parts that are machined to standard geometric tolerances. The reinforced bottom plate functions as a support platform for the resonator string, cryogenic sub-system, and is also an integral vacuum vessel component [3].

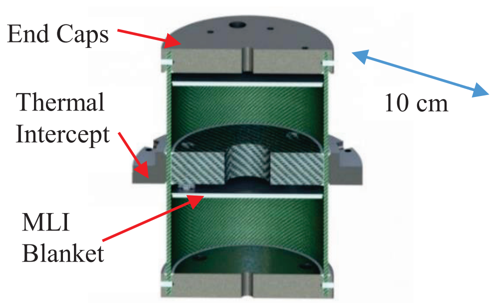

Figure 7: G-10 alignment post for cold mass. The alignment post provides thermal isolation from the bottom plate of the cryomodule vacuum vessel.

The transverse alignment specification for the solenoids and resonators is $\pm 2\sigma = \pm 1$ mm. This specification is achieved by utilizing a machine tolerance approach similar to that of Cornell [5]. Component drawings use standard geometric dimensions and tolerancing that results in tolerance stack up that is within the alignment specification. The WPM, shown on the cold mass in Fig. 4, will be used to track the alignment of the cold mass during cool down. The WPM can accurately measure displacements to ± 0.05 mm, and will be able to provide transient data during cryomodule cool down. Each resonator contains one WPM sensor while each solenoid contains two.

On each end of the cold mass are the cold mass hoods as shown in Fig. 8. The hoods temporarily attach to the end alignment rail and has a beam line vacuum connection to the resonators on the end to the cold mass string. This connection is intercepted both at 4.5 K and 38 K. The hood allows for easy installation of gate valves, cold cathodes, and burst discs all by conflat flange connections. When the cold mass is assembled with the vacuum vessel bottom plate, the hood is simply bolted and pinned into position and released from the of the end rail. When the vacuum vessel top is installed, it makes an O-ring seal to the cold mass hoods to complete the seal for insulating vacuum.

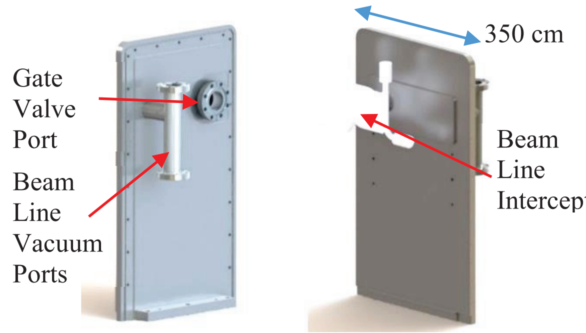

Figure 8: Cold mass hoods allow beam line vacuum to be maintained during cleanroom assembly and interface to the vacuum vessel for the insulating seal. The hoods also allow mounting for thermal intercepts, gate valves, burst discs, and cold cathodes.

The cold mass sub-system is assembled in a class 100 clean room similar to the SNS cold mass assembly process to minimize particulate contamination [6]. The required assembly and transport from the class 100 clean room utilizes the alignment rail system minimizing components that are needed.

Magnetic Shield

The magnetic field of earth and the surrounding environment is attenuated to meet the required 15 mG at the resonator surface by using a 1 mm thick A4K local shield as seen in Fig. 9. By using localized shielding, cost improvements were realized while improving attenuation. The A4K shields requires active cooling at 4.5 K to achieve their maximum effectiveness, prior to cooling the resonator below its superconducting temperature. The shields at the ends of the cold mass encompass a single resonator, while the shields for the center resonators encompass three resonators which provides improved magnetic shielding. The vacuum vessel sub-system is primarily composed of steel and further attenuates the surrounding magnetic field. Figure 10 displays the simulations results of magnetic shielding the presence of earth magnetic field. To prevent the potential of a magnetic component producing a remnant field after the solenoid is off, stringent degaussing procedures have been developed.

ISBN 978-3-95450-143-4

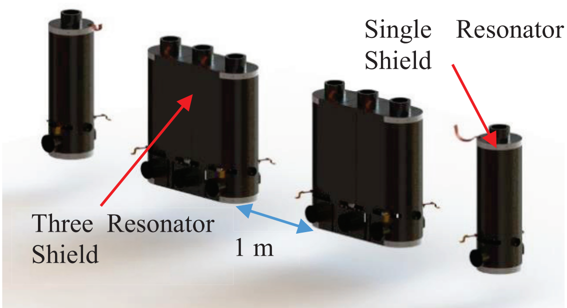

Figure 9: Localized magnetic shields for quarter wave resonators. The shields are constructed out of A4K and attenuate the magnetic field seen by the resonator to 15 mG.

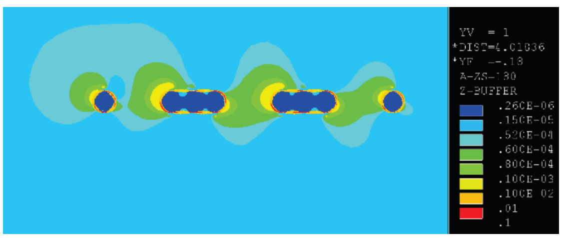

Figure 10: Magnetic shield simulation for the β=0.085 cryomodule. In the presence of 0.5 G earth magnetic field the resonator experience 12.5 mG, which is within specification.

Cryogenic System

The cryogenic system will have an independent helium circuit for the superconducting resonator (2 K) and solenoids (4.5 K). This allows for magnetic degaussing cycles to take place using the superconducting solenoid to remove any residual magnetic fields while the resonators are raised above niobium's superconducting temperature by heaters.

An additional helium circuit is utilized for efficient cryogenic operation by intercepting the heat conduction and radiation paths. This circuit supplies gaseous helium at 38 K to the minimize cryoplant plug in heat load [3].

Cryogenic design choices for the cryomodule were made at a project wide level and approaching it as an all-encompassing system composed of the cryogenic plant, distribution system, and cryomodules. Collaboration with JLAB on 2 K process improvements have yielded efficiency gains in the FRIB cryomodule. For safety, the helium vessels and cryogenic system are designed according to the ASME BPV and ASME 31.1 piping code.

To allow for efficient and repeatable cryomodule installation, a cryogenic bayonet box is employed as seen in Fig. 11. The bayonet box is welded directly to the bottom plate of the vacuum vessel and connects to the internal cryogenic plumbing of the cryomodule. This allows for the bayonet box to fabricated separate from the vacuum vessel, by vendors who deal with cryogenic construction. The interface between the cryogenic distribution line and the cryomodule is a set of five U-tube bayonet connections.

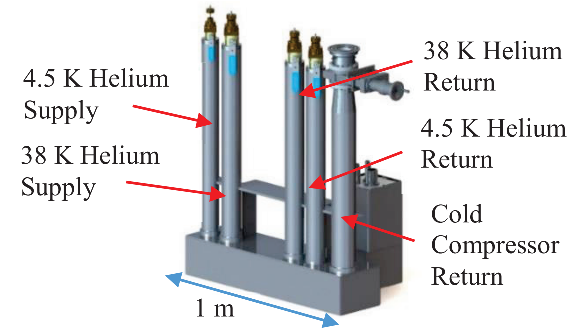

Figure 11: Cryomodule cryogenic bayonet box. The bayonet box connects to the distribution line by U-tube bayonets.

Thermal Radiation Shield

The thermal radiation shield is a segmented construction which simplifies assembly and allows for differential contraction between the three alignments rails as shown in Fig. 12. The thermal shield is constructed from 6063-T5 Aluminium (UNS A96063) and cooled via a custom extrusion to distribute 38 K helium. A parallel helium line is also included which is dedicated for intercepting heat conduction from tuners, FPC, warm beam line transitions, pressure reliefs, and composite support posts. The thermal shield is supported from the g-10 posts which attach to the vacuum vessel bottom plate. Cost analysis appraising material and assembly showed a benefit using aluminium vs. OFE copper (UNS C10100) for the production quantities [3].

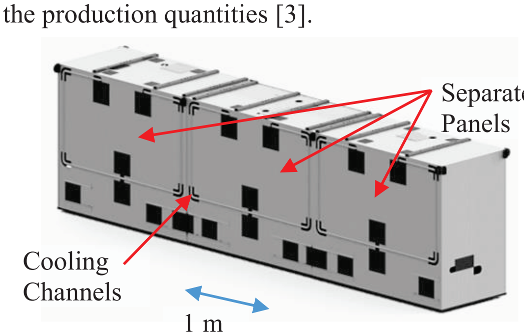

Figure 12: Thermal shield for β=0.085 cryomodule. Segmented construction allows for simplified assembly and allows for thermal contraction of the alignment rails.

Vacuum Vessel

The vacuum vessel is constructed primarily from low carbon steel (UNS G10200), seen in Fig. 13. The primary components are the bottom plate, the vacuum vessel lid, and the interfaces to the hermetically sealed beam line. This requires an ethylene propylene rubber, also known EPDM (ASTM D1418) O-ring that has been developed with industry to allow a 3-way seal. The vacuum load deflections were limited to 0.75 mm at the interfaces to limit force transmitting to the internal cryogenic sub-system. Side wall gusseting has been added after study to reduce and optimize material consumption [3]. For safety, the vacuum vessel reliefs were sized to limit the internal pressure to be less than 2 atm (1 atm gauge).

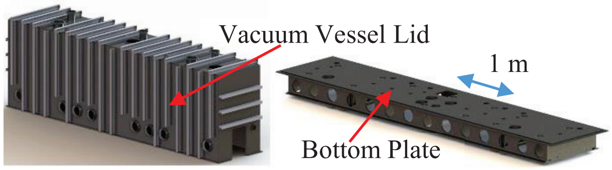

Figure 13: Vacuum vessel components. Vacuum vessel lid (left) is lowered onto bottom plate (right) and sealed by an EPDM O-ring. The three way seal is created around the cold mass hoods.

RESULTS

Engineer Test Cryomodule (ETCM)

The ETCM has been assembled at MSU. The ETCM is a 1/3 length model assembly of a β=0.53 cryomodule and it contains a vacuum vessel and an alignment rail segment. Two simulated resonators and a solenoid make up the simulated cold mass which were placed on the alignment rail system. The purpose of the ETCM was to verify the kinematic cold mass mounting system, evaluate the FRIB O-ring sealing concept, and gain experience with the wire position monitor system.

The ETCM was cooled several times to 80 K using liquid nitrogen to measure the alignment of the kinematic alignment system. Optical measurements were taken during the cool down and warming up process. The simulated cold mass components contained optical targets for tracking during thermal transients. Figure 14 displays the optical setup used during the ETCM testing. Similarly, the WPM was collecting data on the alignment during the processes as well.

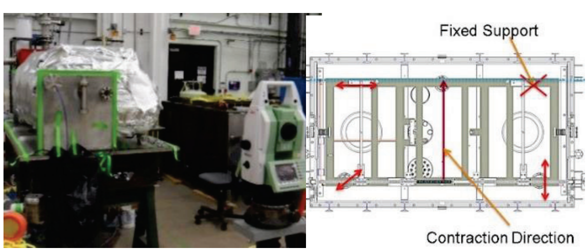

Figure 14: Optical target measuring setup of the ETCM (above). Each simulated cold mass components contains targets. Measurements were confirmed with the WPM system. Schematic of kinematic support system (below).

The results show the rail alignment behavior is repeatable during cool down and warm up. Alignment of the resonators and solenoid remained within the alignment specifications. The optical results demonstrated that the resonators stay within ± .08 mm horizontally, and the within ± .05 mm vertically, the WPM displayed within ± .08 mm horizontally, and within ± .03 mm vertically. The optical results demonstrated that the solenoid stays within ± .15 mm horizontally, and the within ± .03 mm vertically, the WPM displayed within ± .18 mm horizontally, and within ± .03 mm vertically. The solenoid tolerance was slightly higher than that of the resonator; therefore, a plan to analyze the solenoid contraction further to optimize the design to equalize with the resonator contraction will be executed.

The ETCM was pumped down during the cooling cycles to evaluate the effectiveness of the O-ring seal. The O-ring has been able to keep to pressure inside the ETCM at 6.0 x 10 -7 torr. A helium leak check was completed to verify the seal, with no leaks found.

Vibration Studies

Mechanical vibration simulations have been performed on the modular bottom up cryomodule configuration. The primary purpose of the simulations was to quantify that the amplification to the resonator. Focusing on the β=0.085 cryomodule, several simulations have been conducted to characterize the resonator response. The resonator's first modal response occurs between 40 and 50 Hz; from Fig. 15, it is shown that the modular bottom up design and kinematic cold mass support system adds little amplification and lower ordered modes.

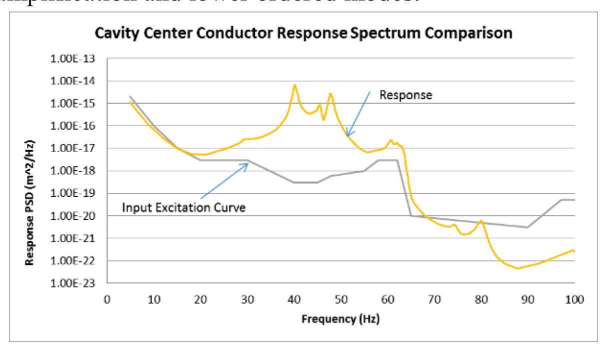

Figure 15: Response of the resonator on a center alignment rail segment of a β=0.085 cryomodule.

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ISBN 978-3-95450-143-4