

DESIGN OF THE FRIB CRYOMODULE*

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Abstract

A modular bottom-supported cryomodule design is described which is optimized for mass-production and efficient precision-assembly. The FRIB driver linac uses 4 types of superconducting resonators and 2 solenoid lengths which in turn requires 7 individual cryomodule configurations. To meet alignment tolerances a precision-machined, bolted cryomodule rail system is described. A novel, kinematic mounting system of the cold mass is introduced which allows for thermal contractions while preserving alignment. A first prototype will incorporate a wire position monitor for alignment verification. The cold alignment structure is supported by composite posts which also function as thermal isolators. The cryogenic system provides separate 2 K and 4.5 K liquid helium lines to resonators and solenoids. Details of the JT valves, heat exchanger, cool-down circuit and junction to cryogenic line are provided. Transient cool-down was simulated. An 1100-O Aluminium (UNS A91100) shield is used as a thermal radiation shield. The paper also describes cryomodule interfaces with the linac tunnel, the RF input cables, and the cryogenic distribution system.

REQUIREMENTS OVERVIEW

The cryomodule cold mass is composed of resonators, superconducting solenoids with integrated vertical and horizontal beam corrective steering dipole magnets and cold beam position monitors (BPM). The required configurations are described in Table 1.

Table 1: Required Cryomodule Configurations for FRIB
 Quantities are shown in () brackets.

Cryomodule 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

Alignment Requirements

The alignment requirements of the FRIB linac are summarized in Table 2.

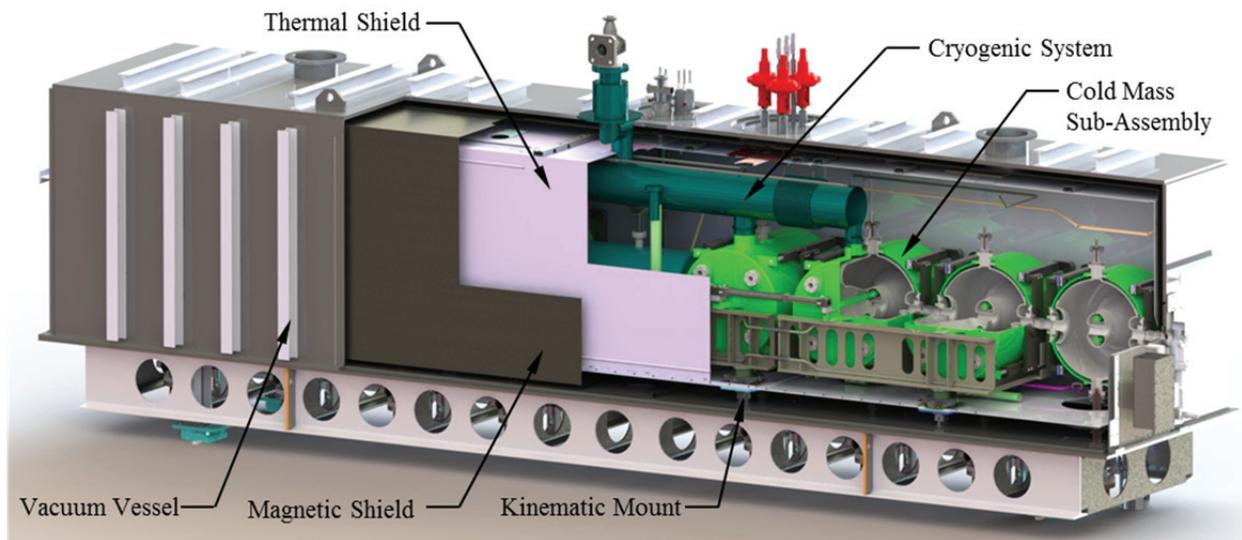


Figure 1: 322 MHz $\beta = 0.53$ Cryomodule Section.

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Table 2: Alignment Requirements for Cryomodule *Cold Mass* Components

Component	Transverse to Beam [mm]	Longitudinal [mm]
Resonator	$\pm 2\sigma = \pm 1$ mm	$\pm 2\sigma = \pm 2$ mm
SC Solenoid	$\pm 2\sigma = \pm 1$ mm	$\pm 3\sigma = \pm 3$ mm
BPM	$\pm 2\sigma = \pm 1$ mm	$\pm 2\sigma = \pm 1$ mm

Cryogenic Requirements

The cryogenics sub-system requires independent helium circuits for the resonators at 2 K and SC solenoids at 4.5 K. The two circuits allow magnetic degaussing cycles to be performed on the solenoid to remove magnetic fields while the resonators are raised above niobium's superconducting transition temperature via heaters. A third helium circuit is required for efficient cryogenic operation by intercepting heat conduction and radiation pathways. This third circuit supplies helium at 38 K to minimize cryoplant plug in power load [1].

Functional Requirements

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.

Accelerator robustness requires a spare cryomodule to be substituted by use of a modular interface to the cryogenics distribution without requiring warm up of a linac segment.

To reach maximum resonator Q_0 a magnetic environment for the resonators of 15 mG has been chosen as the cryomodule requirement.

RF power requirements are delivered to the resonators via a co-axial fundamental power coupler (FPC). Delivery is made below the vacuum vessel that interfaces to the internal resonator string.

Safety Requirements

Safety requirements for the cryomodule cover assembly, operation and maintenance. Failure scenarios of beam line or insulation vacuum require adequate pressure reliefs. The helium vessels and cryogenic system are designed according to the ASME BPV and ASME 31.1 piping code.

Ability to transport the cryomodule at an offsite location beyond the FRIB facility allows potential cost savings. A transport acceleration requirement of 6 g vertical, 2 g lateral and 5 g longitudinal was used [2,3].

DESIGN SPECIFICATIONS

To meet requirements, the FRIB cryomodule consists of five sub-systems: cold mass, cryogenic, thermal radiation shield, magnetic shield, and vacuum vessel.

The resonators and solenoids are assembled to a support structure made from #316 stainless steel (UNS S31600) 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. The interface between the cryogenic support structure and the room temperature bottom plate structure is composed of g-10 posts. The room temperature end of the composite posts rests on precision linear rails which are pointed to the center 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.

The transverse alignment requirement is $\pm 2\sigma = \pm 1$ mm. Alignment requirements are met using a machined to tolerance approach as done at Cornell [4]. Component drawing specifications using geometric dimensioning and tolerancing results in a worst case tolerance stack-up scenario of ± 0.87 mm.

The resonators are housed in a commercially pure grade 2 titanium helium vessel. The half wave resonators are maintained on operating frequency via a scissor jack tuner made of #316 stainless steel (UNS S31600) with an external stepper motor and gearbox. The HWR vessel is compliant to accommodate the tuning displacement where the QWR has a stainless steel formed bellows tuner interface on the resonator bottom. RF power is delivered to all resonators via coaxial RF lines.

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 [5]. The required assembly and transport from the class 100 clean room utilizes the same support structure made from #316L stainless steel (UNS S31603) used for alignment minimizing total required components.

Cryogenic Sub-System

The approach to satisfy cryogenic requirements started by consideration at a project wide level and approaching it as an all-encompassing system composed of the cryogenic plant, distribution system and cryomodules. Present work at JLAB for FRIB in 2 K process improvements is expected to yield efficiency gains that will be incorporated into the FRIB cryomodule. The independent 2 K and 4.5 K helium flow schematic is shown in figure 2. Joule-Thompson valves incorporated into the cryomodule produce liquid from the 3 ATM 5 K supercritical helium supply. To minimize the heat conduction a 4.5 K heat station is incorporated via a thermo-syphon loop from the 4.5 K circuit. A second heat station uses helium gas supply at 38 K and returned to the plant. The interface between the cryogenic distribution line and the cryomodule is a set of 5 U-tube bayonet connections shown in figure 3.

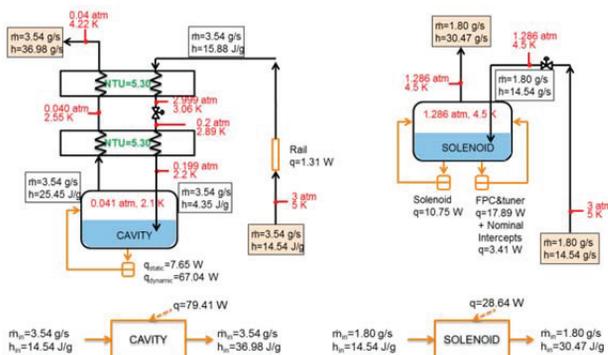


Figure 2: Independent cryogenic helium circuits operating at 2K and 4.5 K.

Thermal Radiation Shield

The heat load budget specifications and transient cooldown analysis is explained by Xu et al [1]. The thermal radiation shield is constructed from 1100-O aluminium (UNS A91100) 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 beamline transitions, pressure reliefs, and composite support posts. Cost analysis appraising material and assembly showed a benefit using aluminium vs. OFE copper (UNS C10100) for the production quantities.

Magnetic Shield

To attenuate the magnetic field of earth and the surrounding environment to meet the required 15 mG a 1.5 mm thick μ -metal shield is used. The vacuum vessel sub-system is primarily composed of steel and inclines to further lower the surrounding magnetic field. To prevent the potential of a magnetic component producing a remnant field after the solenoid is off degaussing stringent procedures are being developed to measure remnant fields of components assembled to the cold mass.

Vacuum Vessel

The vacuum vessel is constructed primarily from low carbon steel (UNS G10200). The primary components

are the bottom plate, the upper bell jar, and the interfaces to the hermetically sealed beamline. This requires an ethylene propylene rubber (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.

For safety, the vacuum vessel reliefs were sized to limit the internal pressure to be less than 2 atm (1 atm gauge).

INTEGRATION WITH FRIB CONVENTIONAL FACILITIES DIVISION

Specifications of the cryomodule support hardware such as electronics racks, cable tray, RF distribution piping, and cryogenic distribution system have been delivered to the Conventional Facilities Division and incorporated into the design of FRIB construction. The differential settlement of the tunnel floor is expected between 9.5 mm and 12 mm. Design specifications of the cryomodule stands incorporate a ± 38 mm adjustment.

ACKNOWLEDGMENT

Thanks to Brad Bull for FRIB conventional facilities division integration support. Matthias Liepe and Georg Hoffstaetter at Cornell for taking time to explain their machined part stack-up alignment plan. Tom Nichol for magnet lead flow and structural support system advice. And Tom Peterson for cryomodule design feedback.

REFERENCES

- [1] Y. Xu et al., "Integrated Thermal Analysis of the FRIB Cryomodule Design," WEPPD007.
- [2] T. Whitlatch et al., "Shipping ...Cryomodule," PAC 2001, Chicago, IL, 2001.
- [3] U.S. Department of Defense, "MIL-STD-810F Method 516.5 Shock," p.3-5 (January 2000).
- [4] E. Chojnacki et al., "Design of an ERL Linac Cryomodule," PAC 2009, Vancouver, BC, Canada.
- [5] W. J Schneider et. al, "Design of the SNS Cryomodule," PAC2001, Chicago, IL, June 2001.

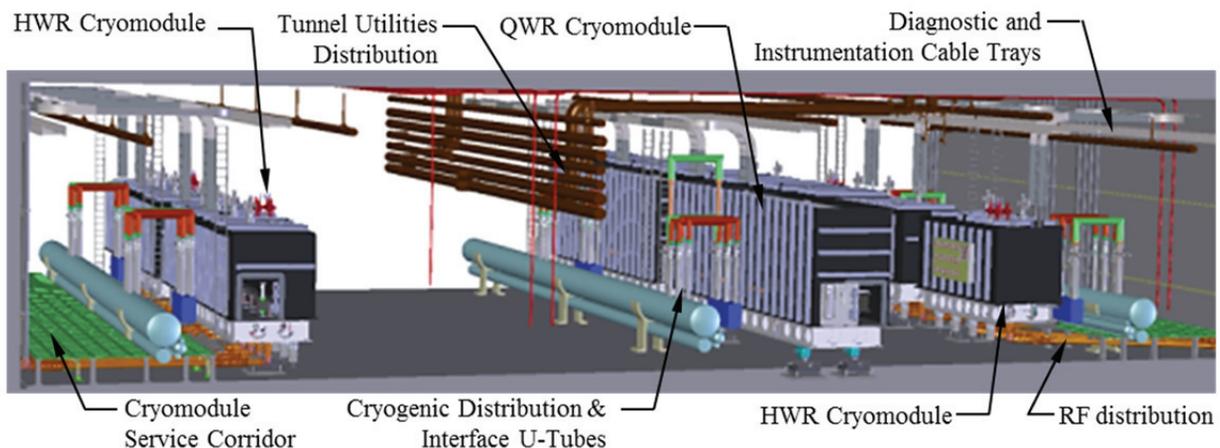


Figure 3: The FRIB tunnel integration between the three linac segments and the RF, utility, cryogenic systems.