# CONSTRUCTION AND PERFORMANCE OF FRIB QUARTER WAVE PROTOTYPE CRYOMODULE*

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*Abstract*

The driver linac for the Facility for Rare Isotope Beams (FRIB) will require the production of 48 cryomodules. FRIB has completed the fabrication and testing of a β=0.085 quarter-wave cryomodule as a pre-production prototype. This cryomodule qualified the performance of the resonators, fundamental power couplers, tuners, and cryogenic systems of the β=0.085 quarter-wave design. In addition to the successful systems qualification; the ReA6 cryomodule build also verified the FRIB bottom up assembly and alignment method. The lessons learned from the ReA6 cryomodule build, as well as valuable fabrication, sourcing, and assembly experience are applied to the design and fabrication of FRIB production cryomodules. This paper will report the results of the β=0.085 quarter-wave cryomodule testing, fabrication, and assembly; production implications to future cryomodules will also be presented.

## INTRODUCTION

FRIB is a high-power heavy ion accelerator facility now under construction at Michigan State University under a cooperative agreement with the US DOE [1]. Its driver linac operates in continuous wave mode and accelerates stable ions to energies above 200 MeV/u with the beam power on target up to 400 kW. The linac has a folded layout as shown in Figure 1, which consists of a front-end, three linac segments connected with two folding segments, and a beam delivery system to deliver the accelerated beam to target [2].

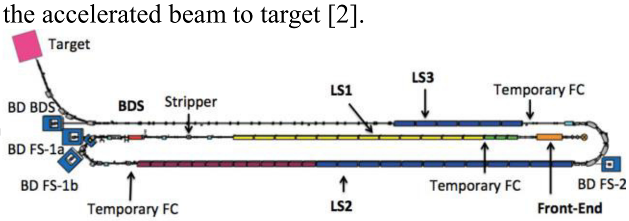


Figure 1: Schematic layout for FRIB driver linac.

Due to the heavy mass and correspondingly low velocity of the accelerated ions, the FRIB driver linac utilizes four different low-beta SRF resonator designs in cryomodules as described in Table 1. 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 be the first facility utilizing industrially produced resonators on a larger scale [3].

Table 1: Required cryomodule configurations for FRIB. Resonator and solenoid quantities per cryomodule are shown in parenthesis. The β=0.041 will cryomodule utilize a $L_{eff}$ =0.25 m solenoid and all other cryomodules will utilize a $L_{eff}$ =0.50 m solenoid.

| Type | Cryomodule Qty. | Resonator Qty. | Solenoid Qty. |
|---|---|---|---|
| β=0.041 | 3 | 12 (4) | 6 (2) |
| β=0.085 | 11 | 88 (8) | 33 (3) |
| β=0.29 | 12 | 72 (6) | 12 (1) |
| β=0.53 | 18 | 144 (8) | 18 (1) |
| Matching Modules | 3 (β=0.085)<br>1 (β=0.53) | 12 (4)<br>4 (4) | N/A |
| **Total** | **48** | **332** | **69** |

Each cryomodule will be equipped with niobium resonators operating at 2 K with focusing solenoids, which include x-y steering, operating at 4.5 K. Due to the large number of cryomodules the FRIB project lends itself to a manufacturing mind-set that incorporates large scale production into the design of individual module types. As a part of this manufacturing mind-set FRIB has manufactured a prototype cryomodule that utilizes two superconducting quarter-wave resonators (QWR) and one superconducting solenoid, and is referred to as the ReA6 cryomodule as seen in Figure 2. The completion of the ReA6 cryomodule not only tested the general cryomodule design, but also the manufacturing methods and assembly [4].

## CRYOMODULE DESIGN

The FRIB cryomodules are based on a modular bottom-supported design which is optimized for mass-production and efficient precision-assembly. Figure 3 displays the subsystem break down of the cryomodule. Four types of superconducting resonators (β=0.041, β=0.085, β=0.29, β=0.53) and two solenoid lengths ($L_{eff}$ = 0.25 m and 0.50

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m) are used in multiple configurations for the FRIB linac driver as described Table 1. FRIB cryomodules have been designed with a focus on optimizing commonality between the cryomodule types while incorporating robust manufacturing methods and minimizing material usage and assembly time. The following sections describe in detail the ReA6 cryomodule construction.

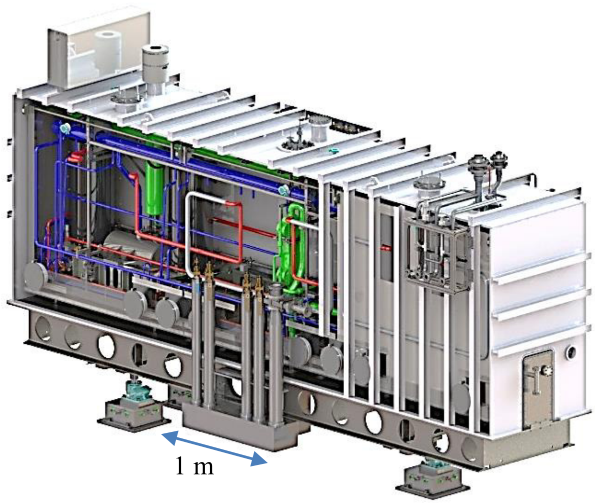


Figure 2: ReA6 modular bottom-up cryomodule design. This cryomodule incorporates 2 β=0.085 QWRs and 1 solenoid.

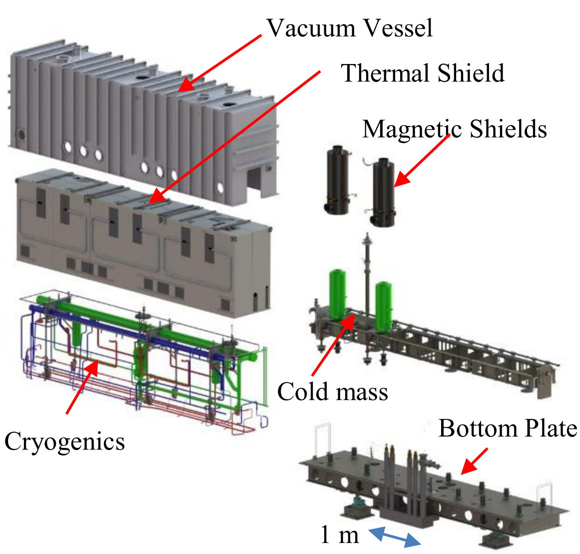


Figure 3: Sub-System of FRIB cryomodule design. Supported off the bottom plate is the cold mass system, where the resonators are protected by local magnetic shielding (right). The cryogenic system attaches to the cold mass. All assemblies are encapsulated by the thermal shield and vacuum vessel (left).

## *Cold Mass*

The base of ReA6 cold mass was made up of three 316L stainless steel (UNS S31603) welded alignment rail segments which are annealed to relieve residual stress and restore magnetic permeability prior to precision machining. The structure is divided longitudinally into 3 pieces to minimize static deflections. For the ReA6 build, the beam exit rail was populated with two SRF resonators each housed in a commercially pure grade 2 titanium helium vessel and one solenoid consisting of vertical and horizontal beam corrective dipole magnets as seen in Figure 4.

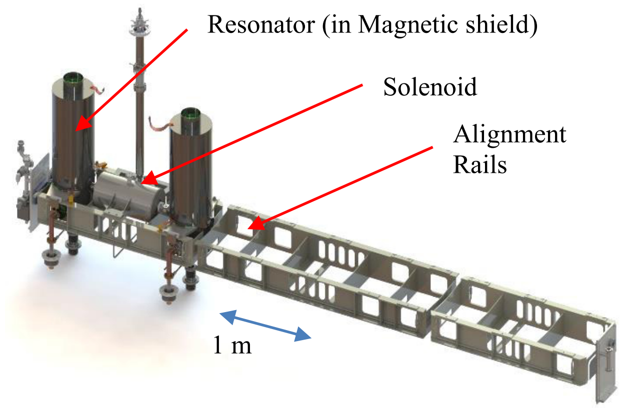


Figure 4: Cryomodule cold mass. Alignment rails support superconducting resonators and solenoid.

These cold string elements are fixed to the near side of alignment rail as seen in Figure 4. A custom set of hardened copper bearings support the floating side of the cold string elements and allow for their differential thermal contraction. Installation of a beam position monitor, beamline bellows, fundamental power couplers (FPC), RF pickups, and a beamline end assembly rounded out the cleanroom portion of the ReA6 build.

After removal from the cleanroom, the resonator tuners, which allow for the adjustment of the resonator operating frequency via a stepper motor driven linear actuator and a piezoelectric actuator are installed. RF power is delivered to all resonators by FPCs via coaxial RF lines. Shown in Figure 5 are the fundamental power coupler and resonator tuner assemblies for the ReA6 cryomodule.

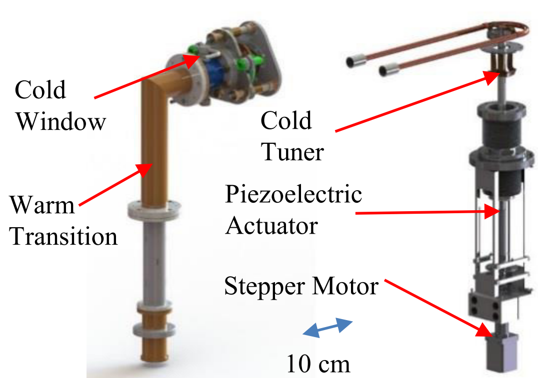


Figure 5: Quarter-wave power coupler assembly and warm transition by ANL (left). Tuner drive by FRIB (right).

The wire position monitor (WPM) tracked the alignment of the cold mass during cool down. The WPM can accurately measure displacements to ±0.05 mm, and is able to provide transient data during cryomodule cool




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down. Each resonator of the ReA6 cryomodule contained one WPM sensor while the solenoid contained two.

On each end of the cold mass are the cold mass hoods. The hoods temporarily attach to the end alignment rail and have a beam line vacuum connection to the resonators on the end to the cold mass string. This connection is intercepted at 88 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. Installation of the vacuum vessel cover makes an O-ring seal to the cold mass hoods to completing the seal for insulating vacuum.

### *Magnetic Shield*

The magnetic field of earth and the surrounding environment is attenuated to meet the FRIB required permeability of μ=10,000 (at 500 mG) by using a 1 mm thick A4K local shield for the two resonators as seen in Figure 4. By using localized shielding, cost improvements were realized while improving attenuation. To achieve maximum attenuation, the A4K magnetic shields were passively cooled to 4.5 K prior to cooling the resonators to their superconducting temperature. The vacuum vessel sub-system is primarily composed of steel and further attenuates the surrounding magnetic field.

### *Cryogenic System*

To allow for efficient and repeatable cryomodule installation, a FRIB standard cryogenic bayonet box is employed as seen in Figure 6. This design will benefit the FRIB production linac as it will allow for a single cryomodule to be warmed and disconnected from the linac segment. 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 specialize with cryogenic system construction. The interface between the cryogenic distribution line and the cryomodule is a set of 5 U-tube bayonet connections.

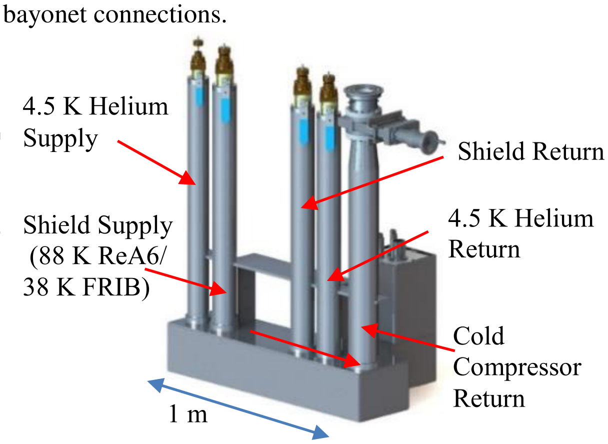


Figure 6: Cryomodule cryogenic bayonet box. The bayonet box connects to the distribution line by u-tube bayonets. The box is shown as it would supply for FRIB.

The cryogenic system has an independent helium circuit for the superconducting resonator (2 K) and solenoids (4.5 K). These independent circuits allow for magnetic degaussing cycles to take place using the superconducting solenoid to remove any residual magnetic fields while the resonators are warmed above the superconducting temperature of niobium. A liquid nitrogen thermal shield circuit, operating at 88 K, adds to the cryogenic efficiency by intercepting the heat conduction and radiation paths while minimizing the cryoplant plug in heat load. For FRIB, this circuit will be run with helium at 38 K [4].

Cryogenic design choices for the cryomodule were made at a project wide level, approaching it as an all-encompassing system composed of the cryogenic plant, distribution system, and cryomodules. Collaboration with Thomas Jefferson National Accelerator Facility (J-Lab) 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 31.3 Process Piping Guide.

### *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 Figure 3. The thermal shield is constructed from 1100-H14 Aluminium (UNS A911000) and cooled via a custom extrusion to distribute 88 K nitrogen. A parallel nitrogen 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.

### *Vacuum Vessel & Baseplate Assembly*

Following the installation of the lower cryogenic supply system, the cold mass support and alignment posts were mounted. These consist of a universal, precision machined G-10 post assembly that is mounted in fixed and floating configurations to allow for pre-determined individual differential contraction of cold mass segments. The floating element in this mounting system consists of either a single stainless steel linear rail and bearing or a cross stacked set of rails and bearings for bi-directional compliance.

The vacuum vessel is constructed primarily form A36 (UNS K02600) seen in Figure 7. The main components are the bottom plate and vacuum vessel cover which interfaces with the hermetically sealed beamline cold mass hoods. Insulating vacuum space is sealed by an O-ring gasket which allows for simultaneous horizontal and vertical sealing. This O-ring gasket was developed by FRIB engineers with the support of industry partners and is constructed from ethylene propylene rubber more commonly known as EPDM (ASTM D1418) [5].

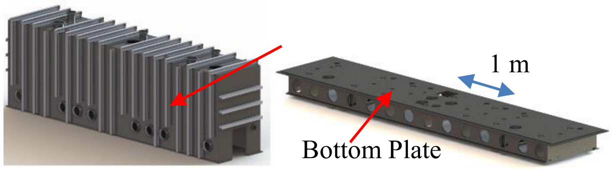


Figure 7: Vacuum vessel components. Vacuum vessel lid (left) is lowered onto bottom plate (right) and sealed by an EPDM O-ring.

## TEST RESULTS

The ReA6 cryomodule served as a validation program for many of the critical FRIB items. A specific focus was placed on testing the completed QWR subsystems, the innovative cryomodule design solutions that were described in the REA6 cryomodule design, and the integrated cryomodule performance in operation. A validation milestone was achieved with the ReA6 cryomodule by completing a 24 hour operation in steady state conditions matched to those of FRIB.

### *QWR Performance*

The aforementioned goal of the ReA6 testing, was to validate the cryomodule system. Both QWRs in the module were phase and amplitude-locked continuously for 24 hours to a reference signal at $E_a$=6.2 MV/m (110% FRIB operation). Continuous monitoring and recording of the resonator field, phase error, amplitude error, resonator detuning (Forward phase error, locked), helium pressure, ground noise, tuner operation, RF power (Forward, Reflected, and Transmitted), and temperature (RF couplers and cryomodule critical positions) were performed during the 24 hour run.

Table 2: Measured parameters of the QWRs in the ReA6 cryomodule compared to the FRIB 2 K goal.

| 4.3K Test | QWR 1 | QWR 2 | 2 K Goal |
|---|---|---|---|
| Gradient $E_a$ (MV/m) | 6.2 | 6.2 | 5.6 |
| Detuning σ (Hz) | 0.4 | 0.4 | <2.25 |
| Detuning pk-pk (Hz) | 6.9 | 9.1 | <20 |
| Phase σ (deg) | 0.11 | 0.06 | <0.25 |
| Phase pk-pk (deg) | 0.66 | 0.58 | <2 |
| Amplitude σ (%) | 0.03 | 0.04 | <0.25 |
| Amplitude pk-pk (%) | 0.47 | 0.99 | <2 |

The results of the test were excellent; operation was reliable and within specifications. The QWR performance was very good with no field emission and a large margin in $E_a$. The resonator and cryomodule mechanical stability were well controlled. The resonator maximum detuning was less than fifty percent of the RF bandwidth (40 Hz), as specified. The resonators phase and amplitude locked by FRIB low level radio frequency (LLRF) controllers were reliable and with small errors. The 4.5 K helium pressure was very stable and expected to be even more stable in FRIB at 2 K. The summary of results of the QWR testing in the cryomodule are seen in Table 2.

### *Mechanical Stability*

Another area of validation during the ReA6 testing was the QWR and cryomodule mechanical stability. During operation, frequency-changing mechanical vibrations were monitored in real time with high sensitivity (down to ~1 Hz detuning) through the residual phase error analog signal. The QWR fundamental mechanical mode of ~45 Hz was often excited but only to a very low level, as expected (<10 $Hz_{p\text{-}p}$). The QWR mechanical damper assisted this reduction and turned off this mode quickly when the forcing signal disappeared. Higher frequency (~300-500 Hz) vibrations could be periodically observed in the signal, with no significant effect in the residual phase error. Mechanical coupling between the QWRs was not observed during the 24 hour operation. Overall, the ReA6 bottom-up cryomodule fulfilled the FRIB requirements for mechanical stability.

### *Tuner and FPC Performance*

The QWR tuner and FPC (Figure 5) performed reliably and within the FRIB specifications. In the preparatory phase of the ReA6 test it was found that the initial setting for the tuner control current was too low, causing critical reduction of tuner force, reduced tuning range and sporadic resonator unlock. Once restored to the proper settings, the tuner performed at specification; however, the dedicated chip in the LLRF controller required extra air cooling. A major tuner validation achievement was realized as the stepper motors driving the tuners were able to track the cavity frequency without the aid of the piezoelectric actuators. This may eliminate the need for the costly piezoelectric actuators as a fine tuning element as the speed, force and resolution of the present tuner fulfill the FRIB specifications.

The FPC during operation maintained a stable temperature with no multipacting. The power coupler operated up to 800 W. Precise bandwidth of the FPC was also achieved.

### *Cryomodule Heat Load*

The ReA6 cryomodule heat load was also confirmed during testing. The total helium heat load at 2 K was 4.1 W/QWR at 6.2 MV/m where the FRIB budget is 4.5 W/QWR at 5.6 MV/m. The heat load was calculated with the thermal shield operating at liquid nitrogen temperature, whereas the FRIB thermal shield will operate with gaseous helium at 38-55 K.

The heat load results can be seen in Table 3. From this table, it is seen that the static heat load was larger than the goal for both 2 K and 4.2 K; however, at the FRIB operational temperature of 2 K the dynamic and total heat load is less than the FRIB goal. It should also be noted that during the ReA6 test the gradient was at 6.2 MV/m which is higher than nominal FRIB operation at 5.6 MV/m. The total heat load budget for a FRIB 8-QWR




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cryomodule is 36 W. Using the data taken from ReA6 (2-QWR cryomodule) the heat load is projected to be 32.8 W which is less than the budget.

Table 3: Measured heat load of the QWRs in ReA6 cryomodule compared to the FRIB 2 K goal.

| Test Temperature | Static (W/CM) | Dynamic (W/QWR) | Total (W/QWR) |
|---|---|---|---|
| **4.2 K** 2 QWR @ 6.2 MV/m | 5.2 | 4 | 6.6 |
| **2 K** 2 QWR @ 6.2 MV/m | 5.2 | 1.5 | 4.1 |
| **2 K FRIB** 8 QWs @ 5.6 MV/m | ≤ 4 | ≤ 4 | ≤ 4.5 |

### *ReA6 Alignment*

FRIB cryomodule alignment control can be broken into three main areas. The first step is to have the manufacturing and assembly steps to produce an accurate cold mass assembly with meaningful and reliable external fiducials for installation. Measurements taken on the cold mass during the ReA6 construction validated this step. The second step, is to control and verify the warm-to-cold offset movements during cryomodule cool-down. Cold movements were monitored during the ReA6 cool-down by the WPM and the direct measurement of the tuner position. The last step is to install and accurately place the cryomodule assembly in the FRIB tunnel. Installation and placement was checked during the installation of the ReA6 cryomodule into a test bunker simulating the FRIB tunnel condition.

To support the alignment measurements required for ReA6, a local floor monument network was established around the build as seen in Figure 8. Spacer shims were built to allow structural coupling of the baseplate and the vacuum vessel while allowing access to the common interface flanges. Multiple support jacks were obtained to provide multi-point support of the baseplate required to level it during assembly and measurement. The resonators and solenoid components have fiducial locators machined into the flanges and are fiducialized prior to cold mass assembly. Alignment fiducials were spot welded to the baseplate and vacuum vessel surfaces for external reference and were used for beamline installation.

Several key conclusions were identified during the assembly of the ReA6. Measurements needed to assist the assembly process have been identified for the future. Desired structural behavior of the key components (baseplate, rails and vacuum vessel assembled to the lower subassembly) have been verified. The baseplate machined accuracy goals were reached and the baseplate can be reliably and repeatedly supported for cold mass assembly. The fixed-side hole alignment goal on the rails was reached on transverse component placement. The baseplate and vacuum vessel bolted assembly does perform as a rigid assembly when the adjuster mounts are manipulated and can be treated as a rigid assembly during installation. Transverse and vertical alignment of the resonators and solenoids was demonstrated to be within FRIB specification. Table 4 shows the results of the cryomodule alignment. The more stringent requirement for solenoid pitch and yaw error (< 0.3 mm common axis within the cryomodule) will require a new adjustment feature to be incorporated into the mount for cryomodule production.


Figure 8: ReA6 cryomodule build with local network established to support alignment measurements.

Table 4: Summary of the overall measured cryomodule component alignment. Alignment budget is 1 mm for the transverse and vertical alignment of both the resonators and solenoids.

| Component | Assembly (mm) | Cool-down (mm) | Overall (mm) |
|---|---|---|---|
| Resonator Transverse | 0.237 | 0.254 | 0.491 |
| Resonator Vertical | 0.505 | 0.327 | 0.832 |
| Solenoid Transverse | 0.362 | 0.181 | 0.543 |
| Solenoid Vertical | 0.580 | 0.102 | 0.682 |

To support the warm-to-cold measurement of the cryomodule the resonators and solenoid components have WPM sensors to indicate motion during vacuum pumpdown and cryogenic cooling. The resonators also used dial indicators on the tuner as a secondary method of measurement. A monument network was placed in the test bunker to support the measurements during cryomodule alignment and testing. Transverse alignment measurements of the resonators and solenoid, shown in Table 4, are in close agreement with the predicted thermal contraction as measured by the WPM (and confirmed by dial indicator data on tuner) and was repeatable during two measured cool-downs.

## ASSEMBLY AND PRODUCTION IMPLICATIONS

Throughout the assembly of ReA6 there were several items that were identified that require improvement for production for FRIB. Items were recorded in non-conformance reports (NCRs) and tracked during assembly and appropriately communicated to FRIB engineering. The major areas for improvements were identified as areas in process piping simplification, value engineering for major components, and design for assembly for the modular cryomodule design. The next steps for FRIB is to complete the design for a FRIB Beta=0.085 cryomodule based from the lessons learned for ReA6. This involves product improvement reviews, manufacturing reviews with the fabricator and assembly teams, and major procurement reviews with the FRIB procurement department.

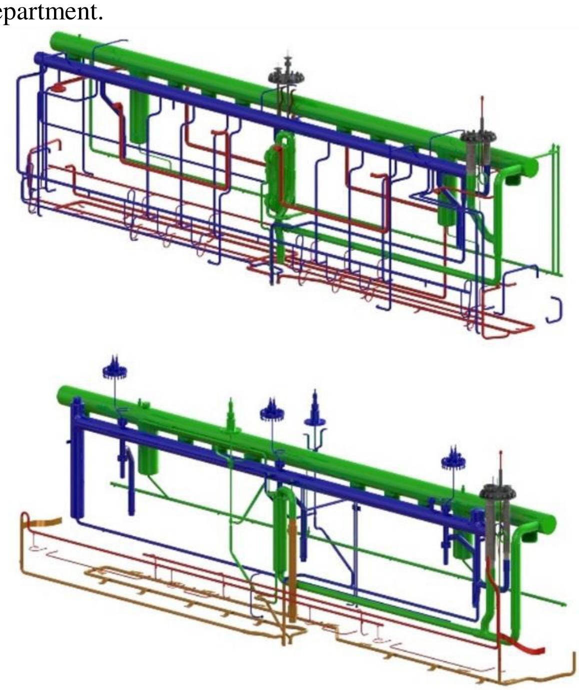

Figure 9: FRIB Beta=0.085 cryogenic systems (below) is greatly simplified when compared to the ReA6 cryogenic systems (above).

The process piping for ReA6 was a complex design and a demanding fabrication. This was one of the major areas that the FRIB design team looked to update for production readiness. The design intent for the ReA6 cryogenics was a manufacturing approach which relied on vendors to deliver completed sub-assemblies. These would then be directly mounted to the cryomodule with minimal field welding. The design also relied heavily on bent piping to minimize the number weld joints. As the ReA6 fabrication and assembly got underway, it was difficult to find a qualified supplier for pipe bending. Although pipe bending technology does exist, finding the correct vendor for the build proved to be challenging. For the FRIB Beta=0.085 cryomodule, the cryogenic system has been designed such that fittings shall be used throughout the welded assemblies and the sub-assemblies are broken down so that individual vendors may fabricate them. The final welds will be handled at FRIB to bring the systems together. The ReA6 cryogenic system is shown in Figure 9. Another design intent of ReA6 was to actively thermally intercept the tuner drives and beamlines. Fabrication of these actively cooled lines proved to be problematic due welding requirements and spatial constraints. It was determined for ReA6 that the benefits of active cooling were not great enough to outweigh the fabrication simplicity of passive cooling. For FRIB cryomodule design, most of the thermal intercepts have been updated to a passive design. This simplified design can be seen in Figure 9.

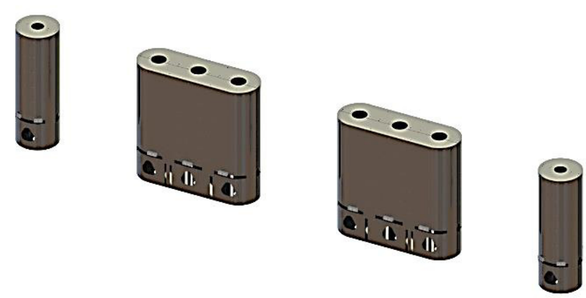

Figure 10: Value engineering was applied to the magnetic shield for the FRIB Beta=0.085 cryomodule design to eliminate complex sheet metal forming.

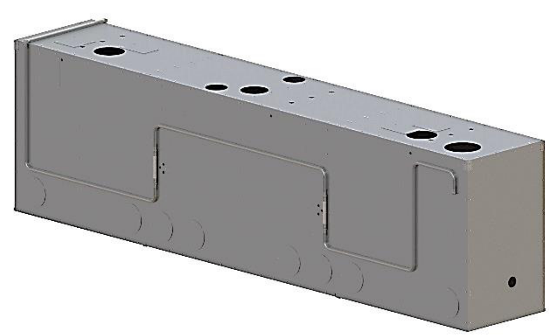

Figure 11; Value engineering was applied to the thermal shield for the FRIB Beta=0.085 cryomodule design to utilize a panelized configuration.

Value engineering is another area in which ReA6 provided many lessons learned. The magnetic shield on ReA6 required complex sheet metal forming and many of the panels were difficult to manufacture as designed. The


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thin material extensions made the assembly difficult. Panel sizes on the magnetic shield were not optimized for material sheet sizes on ReA6 and required extensive continuous welding to join the material. The ReA6 magnetic shield also utilized pop rivets which impart a significant vibratory shock during installation and would require the rivets to be drilled out during disassembly. The thermal shield on ReA6 was similar to the magnetic shield in terms of the need for value engineering. For the FRIB cryomodule both the thermal and magnetic shield will be a panelized design which utilizes simplified geometry and eases installation. The panels are now matched to commercially available material sheet sizes which eliminates excess welding and wasted material. Additionally, the fastening has been updated from rivets to self-broaching nuts that are welded to the panels which will ease assembly and disassembly. Figure 10 displays the value engineered designs for the FRIB Beta=0.085 cryomodule.

Design for assembly is being considered throughout the product improvement of the FRIB cryomodule. Several areas have been identified where common components may be used. As aforementioned, the cryogenic systems, magnetic and thermal shield have already had these considerations implemented.

Figure 12: Lowering the vacuum vessel cover into place on the ReA6 cryomodule.

Other areas such as the vacuum vessel cover being lowered on the baseplate are being optimized for assembly. Shown in Figure 12, is the lowering of the vacuum vessel cover into place over the MLI covered thermal shield on ReA6. This operation required the aligning of the component penetrations on the top of cryomodule, while ensuring the cover did not contact with components underneath. This effort was time consuming and the vacuum vessel cover is now designed to install without this critical alignment of the penetrations. This was accomplished by enlarging and reconfiguring the penetrations on the top of the vacuum vessel cover.

### *Future Cryomodule Design*

Design is now underway for the Beta=0.085 cryomodule for FRIB (which utilizes eight superconducting quarter-wave resonators (QWR) and three superconducting solenoid), with the design projected to complete in August of 2015. Procurement of components for this cryomodule has already started and all major components will have procurement in process by August 2015. Continuous vendor interaction will be essential to ensure critical features for alignment, performance, and functionality are maintained. FRIB plans to deliver the pre-production Beta=0.085 cryomodule by the end of 2015. Additionally, effort is now underway on design for the Beta=0.041 and Beta=0.53 cryomodules. The Beta=0.041 cryomodule design is being developed in collaboration with JLAB and is expected to complete at the end of 2015. Design is expected complete on Beta=0.53 in early 2016.

## CONCLUSION

The ReA6 cryomodule was successfully tested under FRIB conditions and achieved its design goals. The testing validated the QWR subsystems and system level performance in the cryomodule. Alignment requirements during assembly and cool-down were also verified. The completion of the ReA6 build also validated the FRIB bottom-up design method.

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