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FRIB CAVITY AND CRYOMODULE PERFORMANCE, COMPARISON WITH THE DESIGN AND LESSONS LEARNED*

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Abstract

The superconducting driver linac for the Facility for Rare Isotope Beams (FRIB) requires the production of 46 cryomodules. Design is complete on all six cryomodule types which utilize four superconducting radio frequency (SRF) cavity designs and superconducting solenoids. The FRIB cryomodules utilize an innovative bottom up approach to achieve alignment tolerance and simplify production assembly. The cryomodule testing includes qualification of the resonator performance, fundamental power couplers, tuners, and cryogenic systems. FRIB beam commissioning has been performed on 15 cryomodules in the FRIB and validates the FRIB cryomodule bottom up assembly and alignment method. This paper will report the FRIB cryomodule design, performance, and the alignment results and their impact on beam commissioning.

INTRODUCTION

The Facility for Rare Isotope Beams (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]. FRIB's 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].

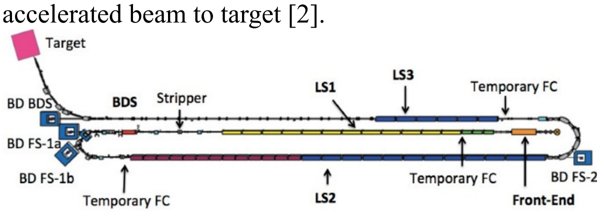

Figure 1: Schematic layout for FRIB driver linac.

FRIB conventional construction started in March 2014, and the accelerator systems construction began in late 2014. The FRIB accelerator building was complete in 2016. Installation of the liquid helium distribution lines in the tunnel is nearly complete; cryomodule production started in 2017 [3]. Linac commissioning has completed on the first 15 cryomodules in the FRIB Linac. The FRIB driver linac utilizes four different low-beta superconducting radio frequency (SRF) resonators in six cryomodule designs as described in Table 1. The β=0.041 and β=0.085 accelerating structures are utilizing quarter wave resonators (QWRs), while the β=0.29 and β=0.053 are utilizing half wave resonators (HWRs).

Table 1: Required cryomodule configurations for FRIB. The β=0.041 cryomodules utilize a L_{eff}=0.25 m solenoid and all other cryomodules utilize a L_{eff}=0.50 m solenoid.

	β	Type	Component Counts (Baseline + Spare)		
			Cryomodules	Cavities	Solenoids
Quarter Wave Resonator	0.041	Accelerating	3+1	12+4	6+2
	0.085	Accelerating	11+1	88+8	33+3
		Matching	1+1	4+4	-
Half Wave Resonator	0.29	Accelerating	12	72	12
	0.53	Accelerating	18	144	18
		Matching	1	4	-
		Totals	46+3	324+16	69+5

Each cryomodule is 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 modules such as the β=0.53 cryomodule shown in Fig. 2 [4].

CRYOMODULE DESIGN

FRIB cryomodule design was complete in 2017 as shown in the timeline in Figure 3. The FRIB cryomodules are based on a bottom-supported design which is optimized for mass-production and efficient precision-assembly. Figure 4 displays the subsystem break down of a typical 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 m) are used in multiple configurations for the FRIB linac driver as described in Table 1. FRIB cryomodules have been designed with a focus on optimizing commonality between the cryomodule types while incorporating robust manufacturing methods

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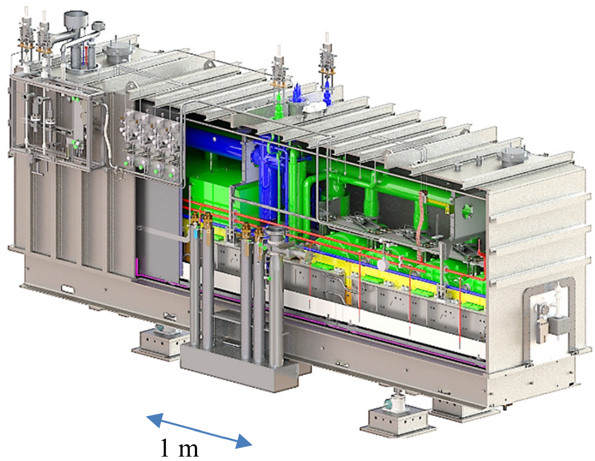

Figure 2: β=0.53 production cryomodule bottom-up design. This cryomodule incorporates 8 β=0.53 HWRs and 1 solenoid.

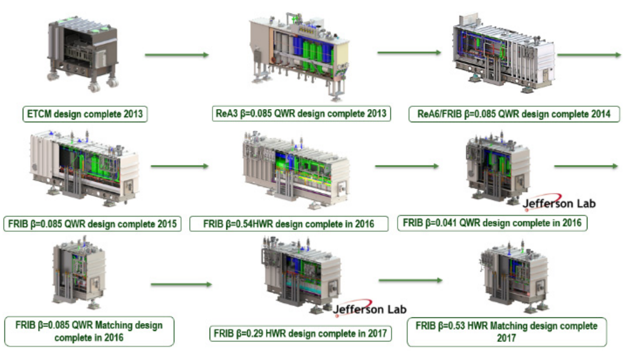

Figure 3: Cryomodule design timeline. Cryomodule design was complete in 2017.

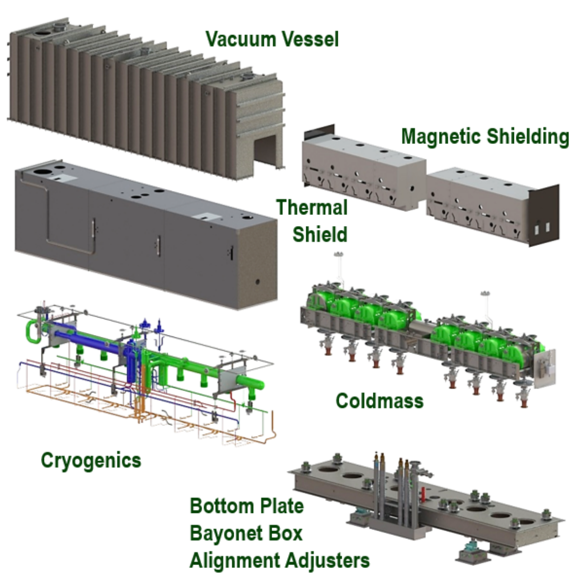

Figure 4: Sub-Systems of FRIB cryomodule design. Supported off the bottom plate is the coldmass system, where the resonators are protected by local magnetic shielding (right). The cryogenic system attaches to the coldmass. All assemblies are encapsulated by the thermal shield and vacuum vessel (left).

and minimizing material usage and assembly time. The figures used in this paper will be primarily of the β=0.53 cryomodule.

Coldmass

The support of the coldmass was designed 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 for the β=0.085 and the β=0.53 cryomodules and into 2 pieces for the β=0.29 cryomodules to minimize static deflections and as shown on a β=0.53 cryomodule in Fig. 5. The remaining cryomodules, being shorter in length, use a single rail. The cold string elements are fixed to the near side of alignment rail. 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 beamline bellows, fundamental power couplers (FPC), RF pickups, and a beamline end assembly rounded out the cleanroom portion of the design [5].

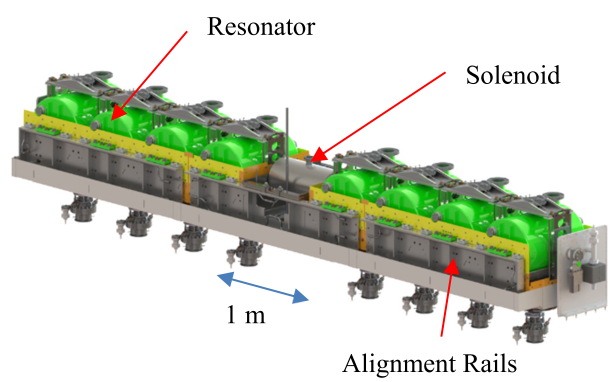

Figure 5: β=0.53 cryomodule coldmass. Alignment rails support superconducting resonators and solenoid.

After removal from the cleanroom, the resonator tuners, which allow for the adjustment of the resonator operating frequency via a helium gas piston, are installed. RF power is delivered to all resonators by FPCs via coaxial RF lines. Shown in Figure 6, are the fundamental power coupler and resonator tuner assemblies for the design [6].

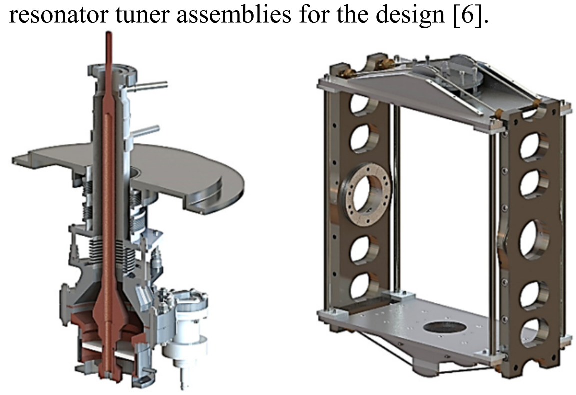

Figure 6: Half-wave power coupler assembly (left). Tuner mechanism by ANL (right).

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On each end of the coldmass are the coldmass hoods. The hoods temporarily attach to the end alignment rail and have a beam line vacuum connection to the resonators on the ends of the coldmass string. This connection is intercepted at 38 K. The hood allows for easy installation of gate valves, cold cathodes, and burst discs, all by conflat flange connections. When the coldmass is assembled with the vacuum vessel bottom plate, the hood is simply bolted and pinned into position and released from the end rail. Installation of the vacuum vessel cover makes an O-ring seal to the cold mass hoods which completes 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). This is accomplished by using a mu-metal shield for the resonators as seen in Figure 5. The vacuum vessel sub-system is primarily composed of steel and further attenuates the surrounding magnetic field [6].

Cryogenic System

To allow for an efficient and repeatable cryomodule installation, a FRIB standard cryogenic bayonet box is employed as seen in Figure 7. This design will benefit the FRIB production linac as it allows 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 be fabricated separate from the vacuum vessel by suppliers who specialize in cryogenic system construction. The interface between the cryogenic distribution line and the cryomodule is a set of 5 U-tube bayonet connections.

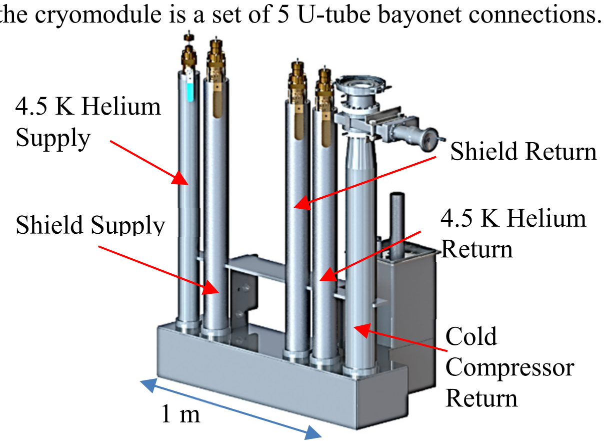

Figure 7: Cryomodule cryogenic bayonet box. The bayonet box connects to the distribution line by u-tube bayonets.

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 gaseous helium thermal shield circuit, operating at 38 K, adds to the cryogenic efficiency by intercepting the heat conduction and radiation paths while minimizing the cryoplant plug in heat load [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 has yielded stable and efficient operation of the FRIB cryomodules.

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 4. The thermal shield is constructed from 1100-H14 Aluminium (UNS A911000) and cooled via a custom aluminium extrusion to distribute 38 K helium. To connect to the cryomodules's cryogenic systems, explosion bonded joints are utilized to weld the stainless steel to the aluminium. A parallel 38 K helium line is also included which is dedicated for intercepting heat conduction from the 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

The vacuum vessel is constructed primarily from A36 (UNS K02600). 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 a novel O-ring gasket which allows for simultaneous horizontal and vertical sealing. This O-ring gasket is constructed from ethylene propylene rubber more commonly known as EPDM (ASTM D1418) [7].

FRIB CRYOMODULE PRODUCTION

Dewar Testing

Resonators are delivered with their helium jacket. The Dewar test is done in such a way to approximate the cryomodule environment, with liquid helium in the jacket and the Dewar under vacuum. An insert, which contains a helium reservoir with the jacketed cavity, is prepared and installed into the Dewar. After cool-down to 4.3 K, initial testing begins along with thorough conditioning of multipacting barriers. After 4.3 K testing, the insert is pumped down and testing at approximately 2 K begins. After successful 2 K testing the insert is warmed up and removed from the Dewar [8].

Figure 8 shows the performance of the resonators which passed the certification Dewar test. The production resonators have performance margin for both gradient and Q_0. The "high-field Q-slope" is observed at gradients above the FRIB design goals and is seen with and without X-rays. Reworks due to field emission have been

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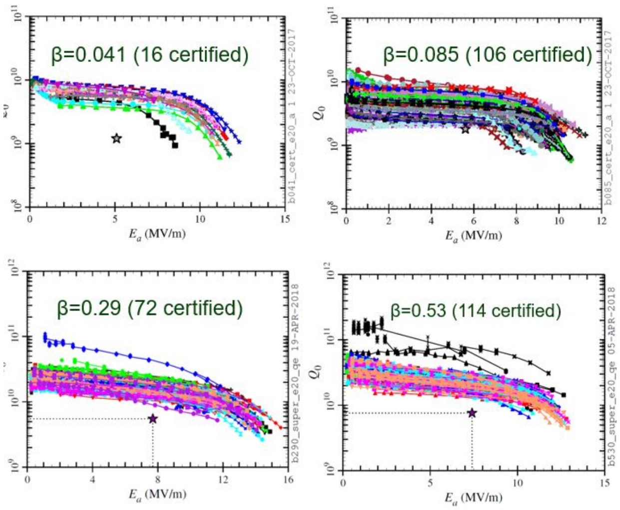

Figure 8: Dewar certification results of FRIB resonators at 2 K. Following testing the resonators are installed onto the coldmass.

infrequent and high X-rays are not typically observed at the FRIB design gradient [8].

Coldmass Assembly

The coldmasses are assembled in a cleanroom. The resonators are vented with particulate-free pure nitrogen gas after dewar testing. Particulate contamination is monitored by taking particulate count measurements on the flanges prior to connections being made on the cold string. Resonator degradation is not observed between Dewar testing and cryomodule bunker testing [3]. The coldmasses are removed from the cleanroom after assembly, as seen in Figure 9, and sequenced the cryomodule production floor for final assembly.

Figure 9: β=0.53 coldmass. The coldmass is the undergoing final inspection checks prior to removal.

Cryomodule Assembly

The cryomodule completes final assembly at FRIB. Five cryomodule assembly bays are utilized to produce the cryomodule at a rate of one cryomodule per month. A total of 33 cryomodules have been produced of the required 46 cryomodules. The assembly bays are sized to build any of the six cryomodules designs as described in Table 1. Cryomodules remain assigned to a bay throughout the duration of their build. Upon completion of the cryomodule a full system cold test is performed. FRIB utilizes two cryomodule test bunkers to perform the cold testing.

The coldmass is installed on the cryomodule baseplate, and the subsystems are assembled to and around the coldmass. The local magnetic shield are assembled around the cavities. The cryogenic piping is installed to the coldmass via a cryogenic support structure which supports the headers and is attached to the coldmass alignment rails as shown in Figure 10. The cryogenic piping is then welded to the coldmass elements. Upon verification that the cryogenic piping is leak tight, the coldmass is wrapped in multilayer insulation and then the thermal shield is installed. The thermal shield is then also wrapped with multilayer insulation. The vacuum vessel is then installed making the insulating seal of the cryomodule [9].

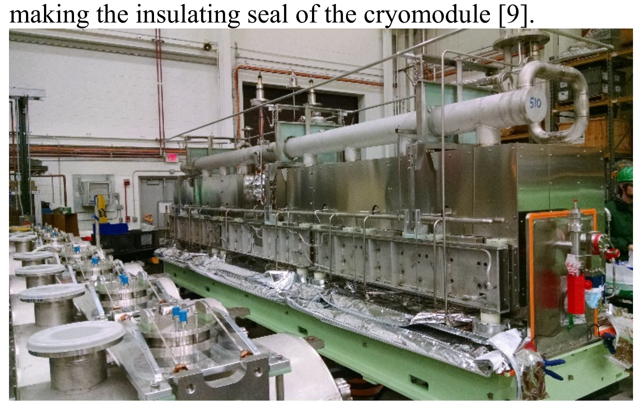

Figure 10: β=0.53 cryomodule on assembly build floor. Cryogenic piping and magnetic shields are installed.

Cryomodule Assembly Alignment

FRIB cryomodule alignment control can be broken into three main areas. The first step is to have the manufacturing and assembly steps produce an accurate coldmass assembly with meaningful and reliable external fiducials for installation. The second step is to control and verify the warm-to-cold offset movements during cool-down (Figure 11). Cold movements are monitored during the cryomodule by direct measurement of the tuner (QWR) or FPC (HWR) position. The last step is to install and accurately place the cryomodule assembly in the FRIB tunnel.

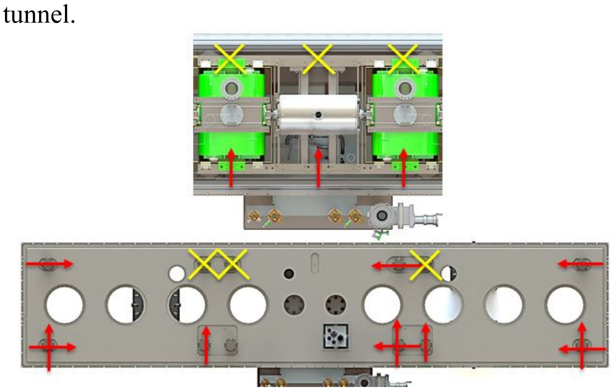

Figure 11: Cryomodule thermal contraction motion. Thermal contraction offsets are built into the cryomodule alignment.

To support the alignment measurements required for cryomodules, local floor monument networks are established around the build. Shims are installed to provide multi-point support of the baseplate to level it during assembly and measurement. The resonators and solenoid components have fiducial locators machined into the

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flanges and are fiducialized prior to coldmass assembly. Alignment fiducials are spot welded to the baseplate and vacuum vessel surfaces for external reference and are used for are used for alignment to the beamline.

Several key conclusions were identified during the assembly and alignment of the cryomodules. 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 coldmass 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 2 shows the results of the cryomodule alignment. The more stringent requirement for solenoid pitch and yaw error (< 0.2 mm common axis within the cryomodule) makes use of an adjustment feature that is incorporated into the solenoid mount.

Table 2: Summary of the overall measured cryomodule component alignment. Alignment budget is 1 mm for the transverse and vertical alignment of the resonators and solenoids. The * indicates one outlier that was removed from the data set which was a pre-production module.

Cryomodule	Resonator		Solenoid	
	Horizontal RMS/Max Error (mm)	Vertical RMS/Max Error (mm)	Horizontal RMS/Max Error (mm)	Vertical RMS/Max Error (mm)
β=0.041 (4)	0.12/0.26	0.19/0.52	0.12/0.26	0.05/0.13
β=0.085 (11)	0.26/0.79	0.24/0.72	0.13/0.37	0.11/0.43
β=0.085M (1)	0.07/0.15	0.07/0.13	-	-
β=0.29 (12)	0.32/0.89	0.26/0.	0/0	0/0
β=0.53 (12*)	0.28/0.71	0.56/0.89	0/0	0/0
β=0.053M (1)	0.11/0.157	0.11/0.26	-	-

Cryomodule Testing

FRIB cryomodules are tested before installation into the FRIB tunnel; 33 cryomodules have been tested to date. There are two testing bunkers utilized at FRIB. Several assessments are performed in the course of testing a cryomodule. During resonator testing, the frequency and bandwidth are checked, the field level is calibrated, X-ray production is measured as a function of field, and degradation in resonator performance is checked against performance in the Dewar test. The superconducting solenoid package (solenoid and two pairs of steering dipoles) is tested as well. Both the static and dynamic heat loads are measured. Alignment contraction is also monitored during cool-down and warm-up [8].

FRIB cryomodules have tested well. On the production cryomodules, all cavities were locked in amplitude, phase, and frequency within the FRIB requirements. For the β = 0.29 and β = 0.53 cryomodules, testing revealed the need to bias the input coupler inner conductor to suppress multipacting barriers. In general, the 2 K dynamics loads were less than the design goals and no appreciable degradation was observed relative Dewar certification tests [8].

CRYOMODULE DESIGN AND ASSEMBLY LESSONS LEARNED

Cryomodule assembly is currently on track to finish as scheduled. With the completion (cryomodules installed in tunnel) near 70% of the required cryomodules, the design and assembly groups continue to evaluate overall progress, efficiency, and issues that influence production rate.

Cryomodule Assembly Incoming Inspection

All fabrications and subassemblies are sequenced through FRIB incoming inspection to complete their quality checks. Contracted suppliers are required to provide their quality data and material certifications to FRIB prior to shipment which allows FRIB to evaluate whether the requirements are achieved and minimizes product return. Additionally, on critical products, FRIB engineering visits to suppliers to review timeline, quality, and shipment were performed.

Several bimetal transitions are used in the cryomodule construction, with some leaks reported during leak checking. The bimetals used are produced using an explosion bonding processes. Components are cut from large sheets of exploded bonded materials. Care must be taken in harvesting these parts to ensure a good bonding in the parts. Ultra sound mapping is used to locate good and bad areas of the sheet. Every part is serialized and matched to a record of where the part was removed from the sheet. Using these records, FRIB is able to work with the vendor to investigate areas of reported failed parts and improve the mapping of sheets and improve the inspection criteria of parts prior to shipping [9].

A vacuum leak was reported during the final assembly step of the first 0.53 cryomodule (SCM501). The leaking location was found in a weld completed at an outside vendor. The vacuum vessel cover was leak checked at the supplier before FRIB delivery, but the leak checking method was unreliable. Leak checking of large vessels can be a technical challenge. FRIB mitigated the issue by educating the supplier and sending a FRIB technical representative to the supplier for training.

Welding is a major piece in the assembly of FRIB cryomodules. There are many concerns relating to welding on the assembly floor that must be managed. Most concerns are of the obvious natural, such as hot surfaces, fire watch, mindfulness of purge locations, and grounding. Extreme care must be used when using vacuum equipment in parallel with welding activities which was an unexpected issue that was realized during cryomodule production. FRIB has seen a high failure rate of vacuum gauge controllers when in the presence of welding. All vacuum gauges and controllers must be switched off and unplugged before welding can be performed on a given cryomodule.

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Cryomodule Assembly Efficiency

After completion of first article cryomodules, several design changes were reported to engineering to ease future cryomodule assembly and ease fabrication efforts from suppliers.

As mentioned before, welding is a major step in cryomodule assembly. To ease the welding and reduce in-field-welding on the build, many subassemblies are welded on the "bench" and then installed - requiring only final connections welds in the field. To help increase tolerance, flexline connections have been implemented to ease final fit-ups in the field.

FRIB cryomodules use local magnetic shields around the cavities. FRIB worked with magnetic shield suppliers to develop the easiest designs to fabricate. The designs use available material sheet sizes and broke subassemblies down in a way that allowed maximum use of annealing furnaces. In addition, the FRIB design uses Pem nut fasteners to provide easy assembly and disassembly [9].

CRYOMODULE TRANSPORATION

Upon successful completion of testing, the cryomodules are prepared for transportation to the tunnel. The cryomodules are transported with the beam line/cavity space under vacuum and they are actively pumped with a battery-powered ion pump while the cryomodule is being moved. The insulating space is vented with nitrogen gas prior to transportation.

The cryomodule is rigged with a beam and straps and then lifted and placed on a low deck truck which is necessary for lift clearance in the FRIB building. Wood cribbing is placed underneath the cryomodule to provide clearance of the transportation wheels attached to the baseplate of the cryomodule. Ratchet tie-downs secure the cryomodule to the truck bed seen in Figure 12. The overhead rigging is not removed until the ratchet straps are installed to assure that the load does not move. Prior to transportation, accelerometers are attached to the cryomodule baseplate to monitor loading during transit to the FRIB building and subsequent lowering of the cryomodule in the FRIB tunnel.

Figure 12: β=0.53 cryomodule being loaded onto low deck truck. The cryomodule is secured to the deck of low boy truck by ratchet straps prior to rigging removal.

When the cryomodule arrives in the FRIB loading bay the overhead lifting beam and straps are attached. Once the cryomodule is securely rigged without tension; the ratchet straps are removed. The cryomodule is lifted off the truck and translated to clear the truck deck. Using the overhead crane the cryomodule is maneuvered over the FRIB tunnel shaft and lowered as depicted in Figure 13.

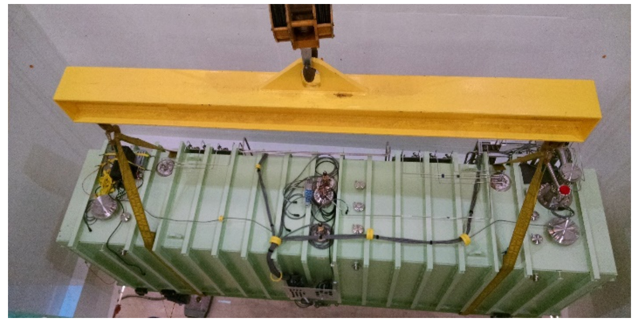

Figure 13: β=0.53 cryomodule being lowered in FRIB shaft. After removal from the truck in FRIB loading bay, the cryomodule is lowered to the FRIB tunnel floor.

Once the cryomodule is landed in the tunnel the rigging is unhooked and removed. At this point, the cryomodule is on four transport casters. Jacks are used in the tunnel to lift one end of the module approximately one inch while the self-propelled crawler drive unit is moved into place. The cryomodule is then lowered to rest on the drive unit. The cryomodule is moved around the accelerator tunnel to its designated location. Once at location, the cryomodule is placed onto adjusters which allow for precision alignment to the FRIB beamline. All transport components are removed from the cryomodule once it is placed on the beamline.

FRIB LINAC SEGMENT 1 BEAM COMMISSIONING

SRF commissioning of the linac segment 1 (LS1) cryomodules was performed prior to the beam commissioning. All 104 QWRs in 15 LS1 cryomodules met the design goals of the accelerating gradient, 5.1 MV/m for β=0.041 QWR and 5.6 MV/m for β=0.085 QWR, with no field emission or multipacting issues. Also, the phase and amplitude stabilities less than peak-to-peak ±0.2 degrees and ±0.1% were achieved, 5 and 10 times better than the design goals, respectively. The SRF commissioning of 92 β=0.085 QWRs in 12 cryomodules was started at the end of November 2018; almost 1 cryomodule was completed per day with an 8-hour shift. The high-power RF operation of the LS1 SRF cavities was performed at 4.5 K, a more conservative condition (in regards to microphonics) than the baseline design, 2 K. This could be done as the 2 K bath pressure was stabilized and the cryogenic supply pressure was optimized to eliminate potential microphonics sources at the cavity mechanical resonance frequencies [10].

The beam commissioning of linac segment 1 met all goals ahead of baseline schedule. Three one-week beam shifts were scheduled from February to April 2019 alternating with the ongoing equipment installation in the tunnel. Starting with low beam power of < 2 W, a phase

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scan procedure was applied to all 104 SC cavities to accelerate $^{40}Ar^{9+}$ beam to 20.3 MeV/u. The transverse beam dynamics was verified by beam profile measurements. $^{20}Ne^{6+}$, $^{86}Kr^{17+}$ and $^{129}Xe^{26+}$ were also accelerated to a beam energy of 20.3 MeV/u by simply scaling of all electromagnetic fields with respect to $^{40}Ar^{9+}$ tune with appropriate charge-to-mass ratios. The beam transmission through the LS1 was 100% for all beams with measurement uncertainty < 1%. The beam-charge state distributions after the stripper were measured by using a 45° bending magnet and charge-state selection slits [11].

CRYOMODULE ALIGNMENT IN FRIB

The survey and alignment group has aligned all of LS1 which includes β=0.041 and β=0.085 cryomodules. The success of LS1 alignment was tested and quantified during beam commissioning, which only required 25% of available corrective dipole current to steer the beam on-axis within ± 1mm. Alignment of LS1 cryomodules required two things: internal alignment of cavities and solenoids within each cryomodule, and also alignment between cryomodules relative to the theoretical LS1 beamline. These two alignment steps—internal alignment and relative alignment between cryomodules—are the two sources of alignment error contributing to the final as-aligned positioning of cavities and solenoids shown in Figure 14 and 15.

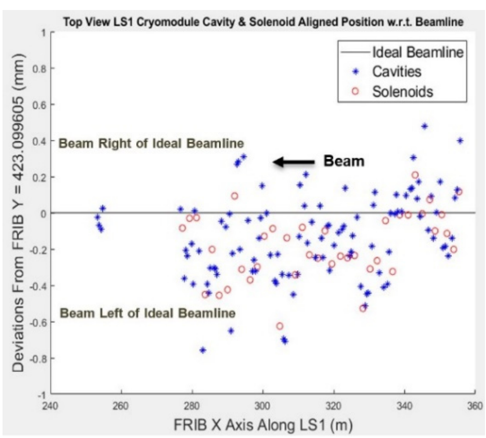

Figure 14: Top view of calculated LS1 cryomodule cavity and solenoid as-aligned positions to the beamline.

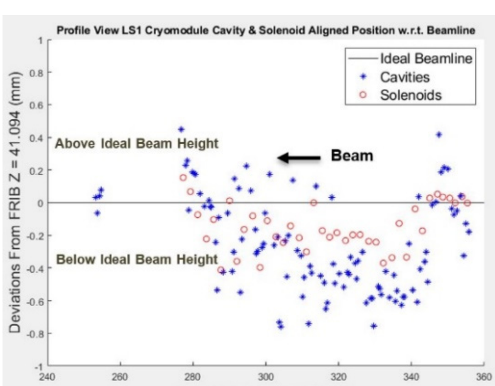

Figure 15: Profile view of calculated LS1 cryomodule cavity and solenoid as-aligned positions to the beamline.

These as-aligned positions are calculated because direct measurement is not possible once visibility is lost to vacuum jacket installation. The final calculation of cavity and solenoid as-aligned positions takes into account the following factors and measurements: 1. solenoid mapping magnetic offset data, 2. cavity and solenoid fiducialization data, 3. assembly measurements relating cavity and solenoid fiducials to cryomodule baseplate fiducials, 4. offset corrections for thermal effects of cool down, 5. measured baseplate distortion between assembly and vacuum jacket installation and transport, 6. as-aligned baseplate fiducial measurements. Table 3 below shows the statistics for cryomodule cavity and solenoid alignment. The solenoid alignment statistics are better than cavities because solenoids were prioritized in the alignment process. A least-squares best fit line through the magnetic centers of a cryomodule's solenoids was used to characterize the primary axis to align each cryomodule

Table 3: LS1 cavity and solenoid as-aligned 2D transverse offset positions from theoretical beamline statistics

Statistic (mm)	Resonator	Solenoid
Maximum Offset	0.878	0.671
Average Offset	0.423	0.287
Sample Std from Average Offset	0.199	0.163

CONCLUSION

FRIB is progressing on schedule and cost, with beam commissioning completed through the first 15 of 46 superconducting cryomodules, and with heavy ions accelerated above 20 MeV/u. The cryomodule bottom up assembly method produces an accurate and repeatable beamline alignment. FRIB cryomodule assembly is in full production and on pace with project schedule. FRIB is continuing to learn and implement changes to increase quality/reduce risk and seeking opportunities to further increase efficiency.

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