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PRODUCTION STATUS OF SUPERCONDUCTING CRYOMODULES FOR THE FACILITY FOR RARE ISOTOPE BEAMS (FRIB) PROJECT*

C. Compton†, H. Ao, J. Asciutto, B. Bird, S. Drake, S. Enness, K. Curtain, W. Hartung, J. Holbert, S. Miller, J. Popielarski, L. Popielarski, M. Reaume, K. Saito, M. Shuptar, S. Stark, T. Stine, B. Tousignant, J. VanAken, E. Wellman, K. Witgen, T. Xu, W. Zheng
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, 48824, U.S.A.

Abstract

The Facility for Rare Isotope Beams (FRIB) is an SRF accelerator project in full production at Michigan State University (MSU). With the civil construction nearly complete, the installation of accelerator equipment into the tunnel has taken center stage. A total of 46 superconducting cryomodules are needed for the FRIB linac to reach 200 MeV per nucleon. The linac consist of four cavity types (beta = 0.041, 0.085, 0.29, and 0.53) and 6 different cryomodule designs. Cryomodule assembly is done in 5 parallel bays, each one compatible with every cryomodule type. Completed cryomodules undergo full system testing in bunkers before being accepted and delivered to the tunnel. The current status of the cryomodule assembly effort will be presented, including lessons learned and overall experience to date.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) is an approved project funded by a cooperative agreement between MSU and The US Department of Energy (DOE) for advancement in the study of rare isotopes. The driver linac for the FRIB project is a 200 MeV/u superconducting linac with final beam power reaching 400 kW [1].

The FRIB linac will require the fabrication of 46 cryomodules housing both superconducting cavities and superconducting solenoids. There are 4 main cryomodule types; utilizing 6 cryomodule designs. There are 4 accelerating cavity designs; beta=0.041 quarter-wave (80.5MHz), beta=0.085 quarter-wave (80.5 MHz), beta=0.29 half-wave (322MHz), and 0.53 half-wave (322MHz). There are also two matching cryomodule designs, one housing beta=0.085 cavities and one housing beta=0.53 cavities, which do not install solenoids. These FRIB all cryomodules are shown in Figure 1.

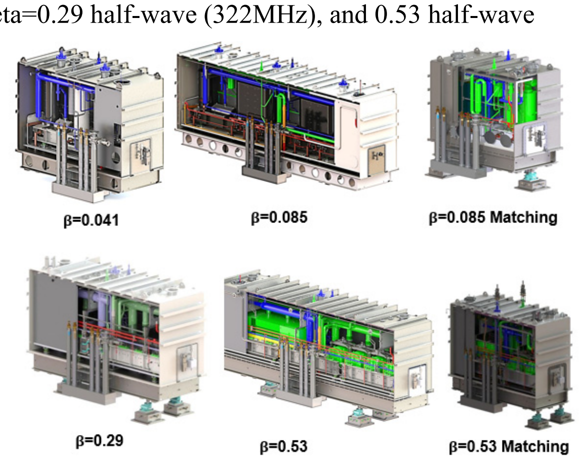

Figure 1: FRIB cryomodule designs.

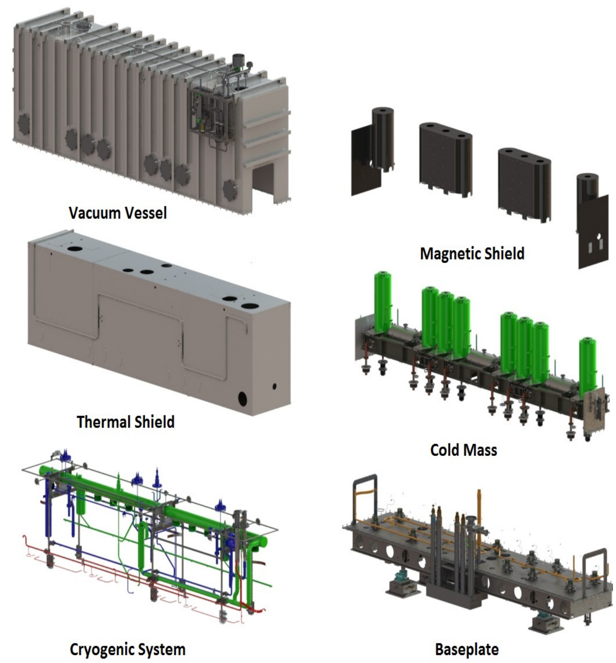

Figure 2: Bottom-up cryomodule design approach.

CRYOMODULE DESIGN AND CRYOMODULE ASSEMBLY

All cryomodule designs use the bottoms-up assembly concept [2]. The major cryomodule components are illustrated in Figure 2. The designs have two cooling lines: cavities at 2 K and solenoid package at 4.5 K. In this building approach, a coldmass which cavities dressed helium jacket and solenoid packages with helium jacket are mounted on multi alignment rails tightly connected into one, is put on a cryomodule base plate. The coldmass is thermally insulated using mounting posts constructed from a glass composite (G-10). G-10 supports of 4 to 6 pieces are used depending on the rail length. One is fixed and

* Work supported by *the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661*
† compton@frib.mes.edu

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Figure 3: Coldmass mounting on the cryomodule baseplate.

Figure 4: Pipe welding of the cryomodule inside.

others can move according to the thermal contract directions of the rail [3].

Once mounted to the base plate, the remaining systems are built around the coldmass. The local magnetic shields are dressed on the cavities. Figure 3 shows a working view of mounting a 0.085QWR coldmass on the baseplate. A cryogenic support structure is mounted from the coldmass rails and used to support the cryogenic piping and headers during the construction. Welders make final connections from subassemblies to coldmass elements (Figure 4). In parallel, a set of alignment frames are mounted from the base plate and sets critical interface positions for where the vacuum cover interfaces (making vacuum seals) with penetrating elements.

Once completed, the cryomodule internal assembly is wrapped with multiple layers of insulation and the thermal shield/vacuum cover being installed from above and making a vacuum seal with the base plate. A pictorial view of the assembly sequence is provided in Figures 5, which is for 0.53HWR cryomodule and shows the steps from the coldmass completion to the installation the module into the bunker for cryomodule certification test.

WORKFLOW

FRIB cryomodule assembly is ongoing and currently being built in 5 assembly bays in parallel, as shown in Figure 6. All 5 assembly bays are sized to build any of the six cryomodule designs. Completed coldmasses are sequenced to the cryomodule floor from the FRIB cavity processing group in the SRF Highbay. Cryomodules do not move during assembly and remain in assigned bay through completion. Once construction is completed, a full, cold systems test is done on all cryomodules. Completed cryomodules are sequenced to one of two commissioned test bunkers: one is located nearby this cryomodule assembly area, and other in the SRF Highbay.

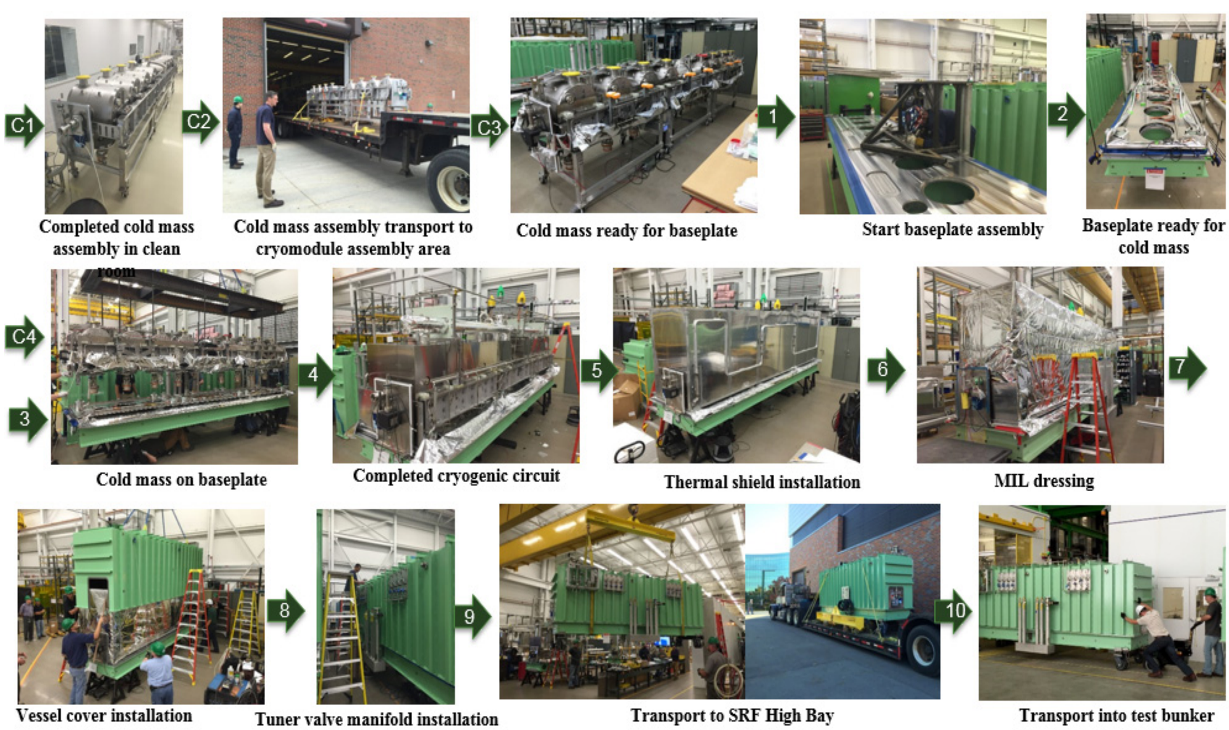

Figure 5: Sequence of the FRIB cryomodule assemble.

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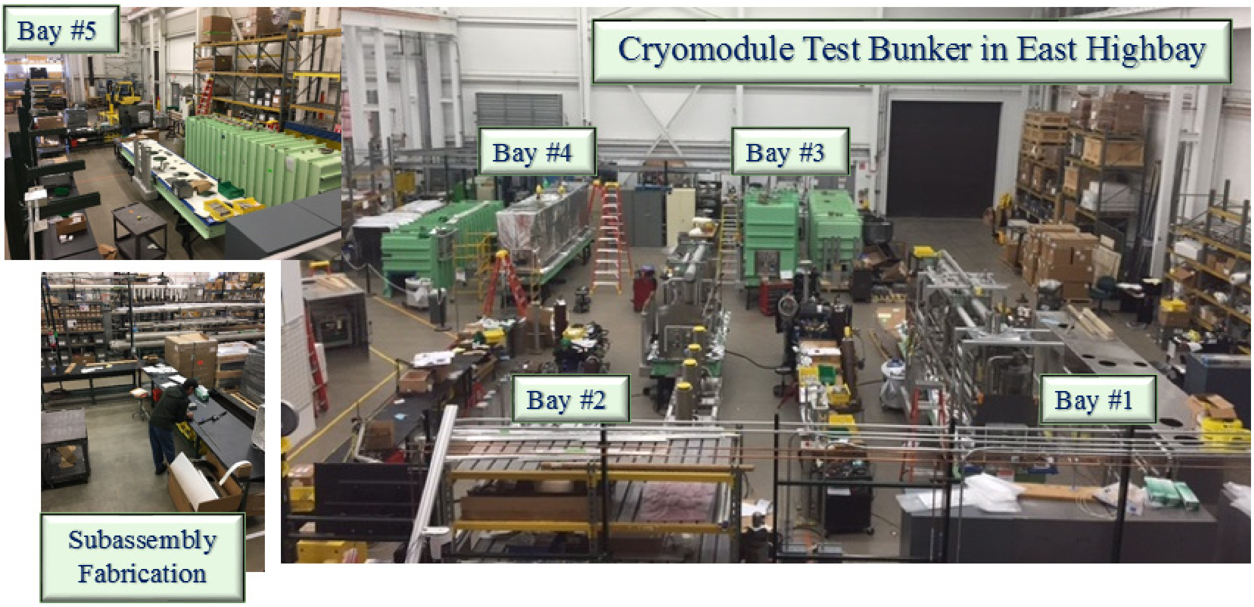

Figure 6: FRIB production cryomodule assembly bays secured in the East Highbay building in MSU campus.

A single team is used on the cryomodule assemble floor.The assembly team is made of multiple skill sets; assemblers, welders, diagnostics, leak checking, inventory, and management oversight. Resources are balanced throughout the assembly floor and are assigned to a particular bay as there skilled work in required.

Inventory and Kitting

The assembly workflow is summarized in Figure 7. All incoming components and subassemblies are inspected to an Acceptance Criteria List (ACL) before acceptance into the FRIB inventory system. Once accepted, the item is inventoried into general cryomodule supplies. Once a Bay has been assigned to a cryomodule type (i.e. beta=0.085 cryomodule serial number SCM8XX), all required components, subassemblies, and hardware are kitted to the individual bay's assembly shelf. From here, technicians are provided everything required to complete the work in that bay.

Each cryomodule build is completed in a single bay. The assembly is not transported from station to station in an assembly line format as mention earlier.

Work Instructions/Weld Maps/Reworks/

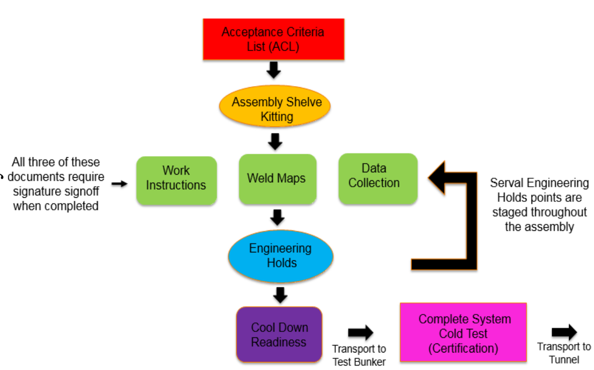

Figure 7: FRIB cryomodule assembly workflow.

Engineering Hold Points

All work is controlled by a set of documents that follow each cryomodule throughout its construction as shown in Figure 8. The work instruction provides the step by step instructions of the assembly and provides information on needed components/hardware or dimensional requirements. As assembly steps are completed, technicians completing the task sign and date the document. A similar document is used for welding, providing weld maps that welders must sign and date as steps are completed. A third document bidder follows the build collecting all required measurements during assembly. Examples of this include vacuum leak check reports, RF bandwidth measurements, alignment measurements, and diagnostic/wiring checks.

Within the work instructions are defined holds points where assembly progress must stop until approval to move on has been signed off by appropriate stake holders. These are referred to as Engineering Hold Points and general require a review of the build to date including cross checking all prior measurements documentation to ensure all systems have been checked and meet design parameters.

Trello

In parallel, assembly tasks and inventory is tracked electronically using Trello software as shown in Figures 8 and 9. The Trello software is a smart phone accessible application that allows technicians and engineers to sign off (automatically time stamped) completion of tasks or what was removed from inventory. Information files can also be linked to the Trello data cards to provide quick links to incoming inspection information or prior design measurements.

CRYOMODULE ASSEMBLY STATUS

Cryomodule assembly is in full production. A status of the six required cryomodule designs is provided below.

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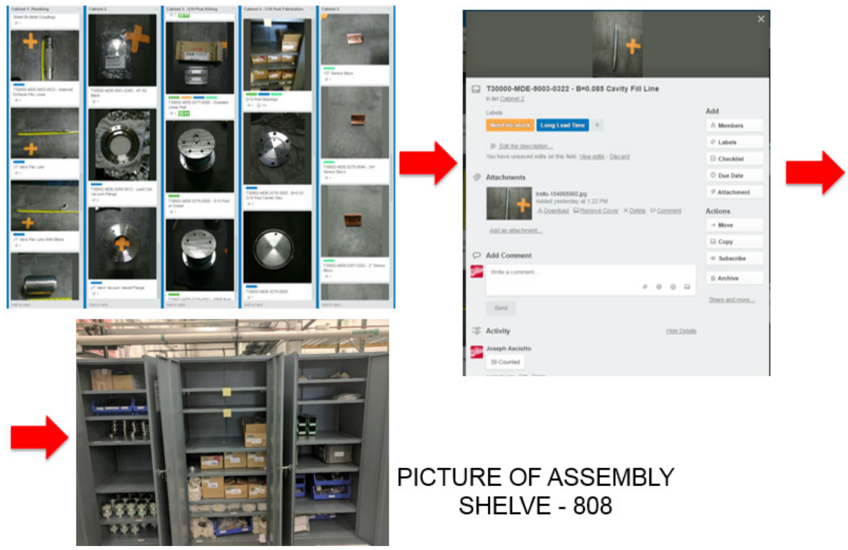

Figure 8: Inventory and assembly status tracked using Trello (electronically).

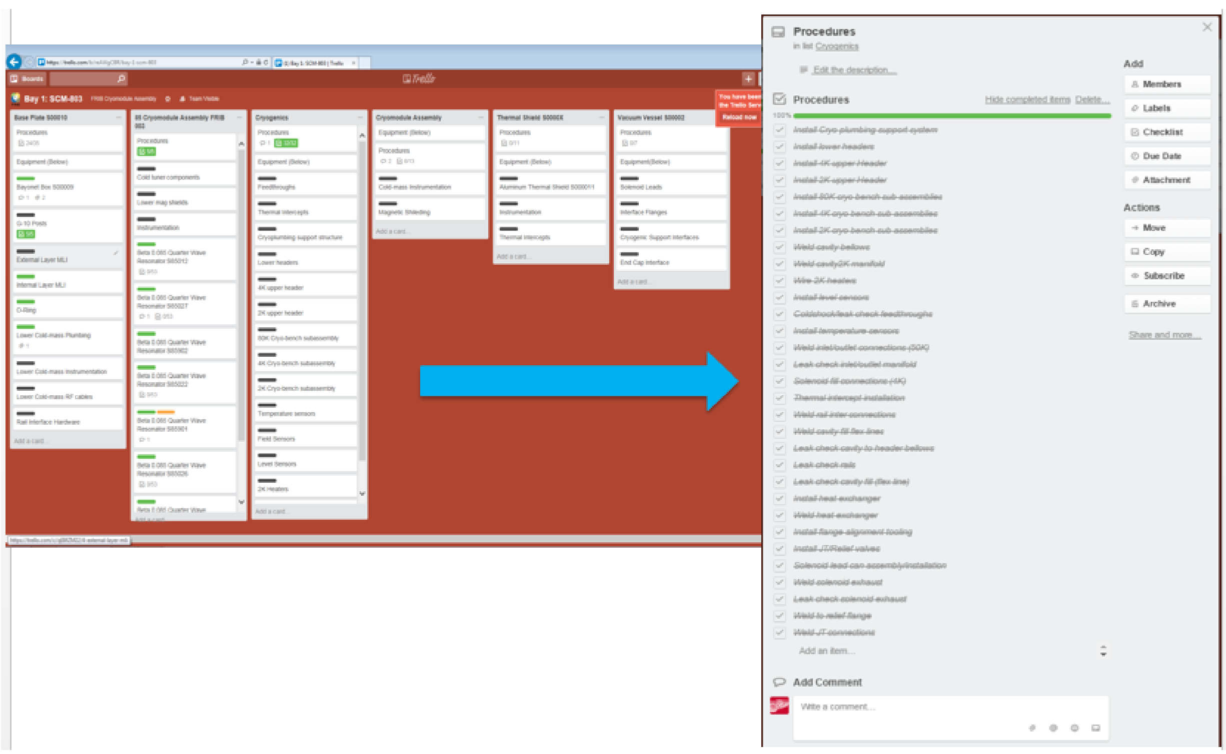

Figure 9: Assembly Status and Trask Completion Tracked using Trello (electronically).

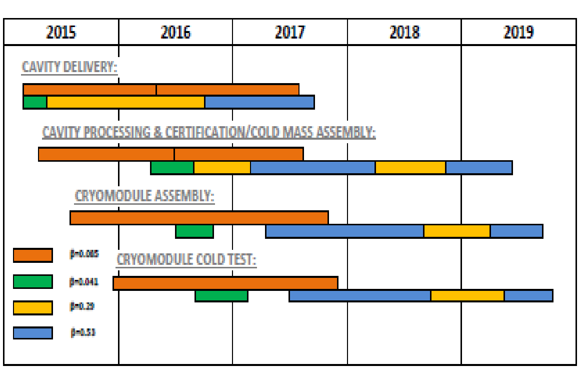

Figure 10: FRIB cryomodule production goal.

FRIB cryomodule production goal is presented in Figure 10. The beta=0.041 cryomodules are to be assembled and bunker tested by early 2017, 0.085 cryomodules by the end of 2017, 0.029 cryomodules are scheduled for mid-2019, and 0.053 cryomodules at the end of 2019.

0.041 Accelerating Cryomodules

Three beta=0.041 cryomodules are required for the FRIB linac. Each cryomodule houses four quarter-wave cavities and two 25 cm superconducting solenoids. All three cryomodules have been assembled, tested, and installed into their slot position in the FRIB linac tunnel as

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Figure 11: Installed 0.041 three cryomodules in the FRIB tunnel.

shown Figure 11. In addition to the three required accelerating units, one spare cryomodule was also built.

0.085 Accelerating Cryomodules

Eleven beta=0.085 cryomodules are required for the FRIB linac. Each cryomodule houses eight quarter-wave cavities and three 50 cm superconducting solenoids. Of the eleven units, four have been built, tested, and installed in tunnel. Three more cryomodules are completed and being sequenced through testing. The goal is to have all eleven cryomodule completed by the end of 2017.

0.085 Matching Cryomodules

One beta=0.085 matching cryomodules is required for the FRIB linac. The cryomodule houses four quarter-wave cavities and no superconducting solenoids. This cryomodule has been built, tested, and is being sequenced for installation in the tunnel.

0.29 Accelerating Cryomodules

Twelve beta=0.29 cryomodules are required for the FRIB linac. Each cryomodule houses six half-wave cavities and one 50 cm superconducting solenoids. Of the twelve units, the first article has been assembled and is currently under testing.

0.53 Accelerating Cryomodules

Eighteen beta=0.53 cryomodules are required for the FRIB linac. Each cryomodule houses eight half-wave cavities and one 50 cm superconducting solenoids. Of the eighteen units, the first article has been assembled, tested, and installed in the FRIB tunnel. The second unit is currently under assembly.

0.53 Matching Cryomodules

One beta=0.53 matching cryomodules is required for the FRIB linac. The cryomodule houses four half-wave cavities and no superconducting solenoids. The cryomodule design is completed, but assembly is not schedule until 2019.

To date, all tested cryomodules have been certified for use in the FRIB accelerator [REF - JPOP]. In some cases, minor repairs were required before transportation to the FRIB tunnel. This repairs have been minor and are mostly related to diagnostics (temperature sensor) and cavity bandwidth. Repairs were completed using designed cryomodule accesses ports, with no major disassembly required.

LESSONS LEARNED

Cryomodule assembly is progressing nicely and currently on schedule. With the completion of ~ 20% of the required cryomodules, the assembly team continues to evaluate overall progress and investigate issues that have influenced production rate.

Incoming Inspection

All received components or subassemblies are sequenced through FRIB incoming inspection to ensure the quality of the final product. Prior to shipment to FRIB, supplying vendors are also contracted to preform and document final inspections. Verification of vendor requirements is critical to success. Vendors must understanding the requirements they are inspecting to and have appropriate training on the methods to ensure these requirements.

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, shown in Figure 12. 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.

Figure 12: The bi-metal transition on helium vessel (Top) and the location cut from the leaked bi-metal transition (Bottom).

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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, shown in Figure 13. The vacuum vessel cover was leak checked at the vendor 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 vendor and sending FRIB technical representative to the vendor for training.

Figure 13: Vacuum leak location of the SCM501 cryomodule vacuum cover. Leak location was vessel welding defect.

Human Error

Human assembly is the major element in cryomodule production. Like all human activities, the concern and occurrence of human error is a factor that must be managed. Identifying, reviewing, and implementing corrective actions are key to sustaining high quality and reducing human error, as well as, increasing safety of workers and assembly support equipment.

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, mindful of purge locations, and grounding. Some different or unexpected issues that have been reported so far during cryomodule production. Care must be used when using vacuum equipment in parallel with welding activities. 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.

An additional welding related issue discovered early is removing purge gas (Argonne) from cryogenic systems prior to leak checking. Leak checkers do not operate well in a (mostly) pure Argonne environment. Pumping on these systems in close proximity to welding activities will result in errors from leak detectors. Cryogenic circuits must be flushed with low pressure gas (nitrogen or air) before leak checking circuit.

Grounding is an important part of welding and is required to produce the required potential. Care must be taken to ensure stable grounding and avoid paths that will run current through diagnostics. FRIB requires cryomodule assembly welders to double ground to further ensure quality and safety of welds. Other personnel doing work near welding must be aware of grounding and purged gas areas so that the welding operation will not be compromised during assembly.

Diagnostic are an important part in the assembly of cryomodule. Diagnostics installation must be handled with care to ensure all systems work properly during testing and operation of the cryomodules. These diagnostics, in most cases, are the only "eyes" available to monitor performance in an operating state. To maintain a high level of quality, workflow must be controlled.

To best ensure quality of diagnostic wiring, installation work should be pushed as far along the build as possible. Most diagnostic wiring is very thin and can be easily broken if snagged by work going on around. Welding has been reported to damage internal cryogenic wiring because of close location to pipe walls and getting hot enough to burn during welding. FRIB has adopted internal spacers to ensure wires are centred in cryogenic pipes and not exposed to direct welding heat.

Ease of Assembly/Fabrication

After completion of first article cryomodules, several design changes were reported to engineering to ease future cryomodule assembly and ease fabrication efforts from vendors. Some examples of requested design changes are shown below.

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 vendors 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.

As mentioned above, FRIB uses a bottoms-up cryomodule design which requires the need to lift and place several large components over top of the build. During these lifts and positioning activities, many penetrations must fit through ports as objects are being lower over top. To prevent bumping and damage to these penetrating components, guide covers were fabricated and installed prior to lifts. The covers were also fabricated in bright colours to help technician visibly see them as the lift/lower activity is happening, as shown in Figure 14.

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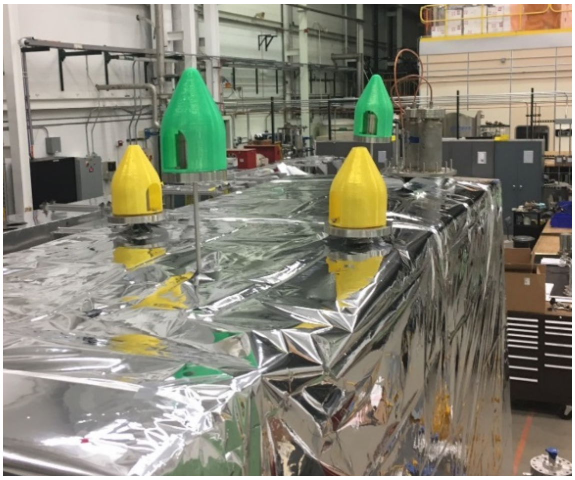

Figure 14: Protective covers for vacuum cover penetrations during installation.

INCREASING EFFICIENCE

Though FRIB cryomodule assembly is on the critical path to complete the project, assembly rates are meeting project demands. As more is learned from assembly experience, efforts are continuously being made to further increase efficiency and build possible schedule margin. With the cryomodule required for linac segment one scheduled for completion by years end, focus has started on the half-wave cryomodule production. Two areas are being investigated as possible ways to improve assembly time; the use of orbital welding and pushing further off-build welding of subassemblies.

Orbital Welding

In the half-wave cryomodule design, the power couplers require cryogenic cooling. These cooling lines are fabricated from stainless tubing that daisy chains from coupler to coupler. To ease the assembly and decrease welding time, FRIB is exploring the use of orbital welding as a means to make the final welded connections between couplers.

Subassembly Welding

Also as part of the half-wave cryomodule production, the assembly team is exploring changing the assembly sequence to include more parallel subassembly fabrication. FRIB will begin fabricating the header cryogenics as a subassembly that can be interfaced with the coldmass rails once positioned to the base plate, shown in Figure 15. Welding the header cryogenics as a subassembly will ease welding and reduce risk of welding over the coldmass.

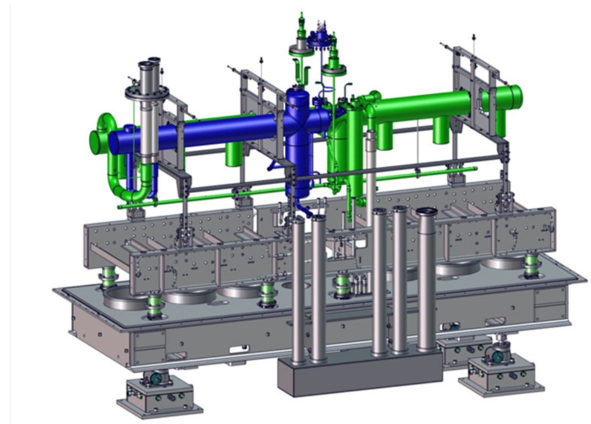

Figure 15: Header cryogenic system welded together as a subassembly and lowered onto base plate after coldmass installation.

CONCLUSION

FRIB cryomodule assembly is in full production and on pace with project schedule. FRIB has implemented the required acceptance inspections to ensure quality of incoming components. Cryomodule assembly is controlled by a check and balance system between work instructions, task sign-offs, standard operational procedures, and engineering hold points. Assembly work flow is optimized by upfront inventorying and kitting to several assembly bays working in parallel. FRIB is continuing to learn and implement changes to increase quality/reduce risk and seeking opportunities to further increase efficiency.

ACKNOWLEDGEMENTS

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