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EXPERIENCES OF SUPERCONDUCTING RADIO FREQUENCY COLD-MASS PRODUCTION FOR THE FRIB LINEAR ACCELERATOR*

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Abstract

The superconducting radio frequency (SRF) portion of the Facility for Rare Isotope Beams (FRIB) linear accelerator consists of 46 cryomodules of 6 different types. Each cryomodule contains a coldmass consisting of a string of SRF resonators. There are four different types of resonators; a Beta=0.041 quarter wavelength resonator (QWR), a Beta=0.085 QWR, a Beta=0.29 half wavelength resonator (HWR), and a Beta=0.53 HWR. In total there are 324 SRF resonators in the FRIB linear accelerator. This paper provides a summary of experiences from the assembly of all FRIB coldmass types in a clean room environment.

INTRODUCTION TO THE FRIB COLD-MASSES

All FRIB coldmasses consist of a set of similar major components. Though these components may vary in size or shape, their role on the finished coldmass will be the same. Below is a detailed introduction to each of the major coldmass components.

Coldmass Carts

Each coldmass is built upon a rolling cart (Fig. 1). The cart allows the coldmass components, and completed coldmass, to be moved as needed through the assembly process without the use of overhead lifting equipment.

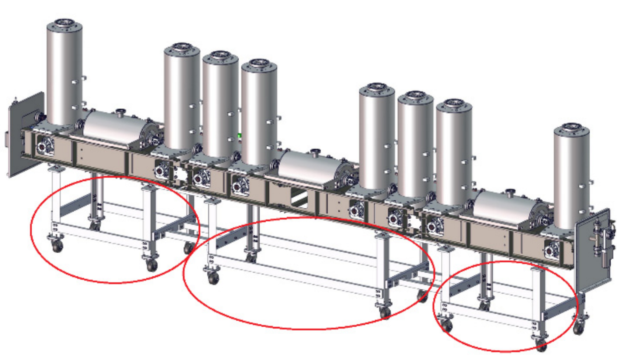

Figure 1: A Beta=0.085 coldmass with its three cart segments encircled.

The carts are a bolted aluminum structures with casters on which to roll, and levelling pads to support the coldmass rail. Typically a cart assembly will have four legs and support only one rail piece. A cart and rail together are referred to as a segment. Coldmasses of the Beta=0.085, and Beta=0.53 variety consist of entry, middle, and exit segments joined to together to form one complete coldmass. Beta=0.041, Beta=0.085 matching, and Beta=0.53 matching coldmasses consist of only one segment. The Beta=0.29 coldmasses consist of 2 joined segments.

Each cart is assembled outside of the cleanroom. After assembly the cart is checked for square and levelness, its fasteners are torqued to specification, and a rail piece is installed to it. The assembled cart and rail are then cleaned and rolled into the cleanroom.

Coldmass Rails

All of the coldmass beamline components are supported by a stainless steel rail. An example of this rail is shown in Fig. 2 below. Each rail piece is made from plate, bar, and tube welded together to form a rigid structure with built-in cooling channels.

Figure 2: Beta=0.085 matching coldmass with its single rail segment indicated.

The rail is a part of the bottom-up alignment scheme of the cryomodule [1]. After a completed coldmass is brought out of the cleanroom the entire coldmass will be lifted off of the cart and placed onto the vacuum vessel base. The rails have precisely located pads and hole features which are used to ensure alignment of the coldmass beamline components.

The rail fabrication sequence was carefully planned to produce a quality part. After welding, each rail segment is heat treated to remove stress from the welding, and reduce residual magnetic field. The precision pads and hole locations are machined only after heat treatment, so that they will not shift during the heat treatment. Each rail segment will undergo a visual inspection, leak check of the cooling

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channels, magnetic field inspection, and coordinate measurement machine (CMM) inspection before it is accepted for use.

Coldmass Hood Assembly

The coldmass hood assembly (Fig. 3) is the part which allows the beamline of the coldmass to pass through the vacuum vessel of the cryomodule. There is one hood assembly on each end of the coldmass beamline. The large stainless steel plate of the hood forms a seal with the cryomodule vacuum vessel, while vacuum components and a gate vale are connected to a vacuum chamber which is built into the hood.

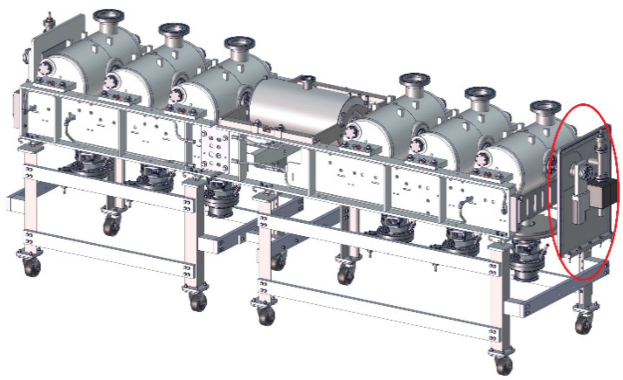

Figure 3: A Beta=0.29 coldmass with its exit side hood assembly circled.

The hoods are thoroughly cleaned before and after they enter the cleanroom because they form a part of the beamline vacuum envelope. A gate valve and cold cathode gauge are installed to every hood type. An ion pump or burst disc is also installed, depending on whether the hood is at the entry or exit side of the coldmass. After the vacuum components are installed to the hood it is leak checked and its vacuum components' function are verified before it is accepted for use on a coldmass.

Solenoids

Four of the six FRIB coldmass types contain superconducting solenoids for beam focus and steering. The Beta=0.041 coldmass (Fig. 4) has two solenoids. The Beta=0.085 coldmass has three solenoids. The Beta=0.29 and Beta=0.53 coldmasses each have one solenoid. Neither of the matching type of coldmasses contain a solenoid.

Solenoids for the FRIB coldmasses are provided by a supplier. The supplier performs all fabrication to FRIB specification, as well as performing leak checking, and cold test and field mapping. The solenoids undergo a thorough inspection and cleaning before they are brought into the cleanroom. Because they constitute a part of the beamline vacuum envelop they are cleaned again inside the cleanroom. Finally, the solenoid's alignment armature is installed and then the solenoid can be installed to the coldmass.

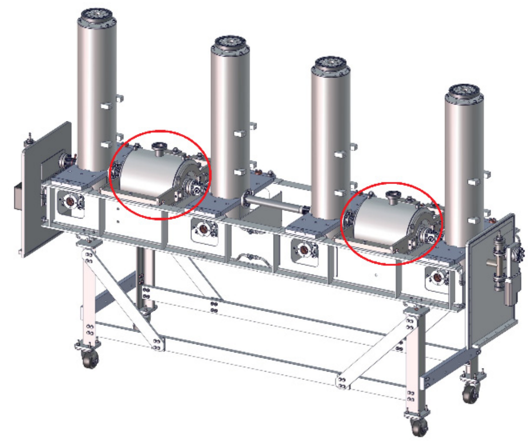

Figure 4: A Beta=0.041 coldmass with its two solenoids circled.

SRF Resonators (Cavities)

The SRF cavities (Fig. 5) of the coldmass are the primary driver of the FRIB linear accelerator. There are a total of 324 cavities in the FRIB linear accelerator. The cavities are fabricated primarily from sheet niobium, and have a titanium helium vessel.

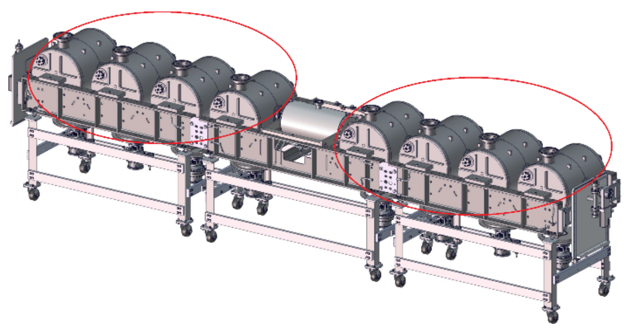

Figure 5: A Beta=0.53 coldmass with its 8 cavities circled.

Once received from the supplier, each cavity will undergo over 50 process steps before it can be certified for use on a coldmass [2]. These process steps include; visual inspection, leak checking, borescope inspection, ultrasonic cleaning, buffered chemical polish (BCP) etching to remove fabrication imperfections, CMM inspection, machining for alignment, hydrogen degassing at 600°C, BCP etching for fine tuning, high pressure rinsing (HPR) with ultrapure water (UPW). After drying overnight the cavity, and all of its components, would be inspected by a surface particle counter, assembled to a cryogenic test insert, and have its SRF performance measured at 4K and 2K [3]. Only when a cavity has successfully passed all of these processing steps will it be accepted for use on a coldmass.

Fundamental Power Couplers (FPCs)

Each cavity on an FRIB coldmass has a FPC to supply driving RF power to the cavity. FPCs for QWR cavities were assembled at FRIB, while HWR FPCs (Fig. 6) were assembled and conditioned by a supplier.

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Cavities certified for coldmass use proceed directly to coldmass assembly, without being high pressure rinsed after removal from the test insert. For QWR cavities, the FPC is installed in the cleanroom after testing and prior to installing the cavity to the coldmass rail. For HWR cavities, the cavity is installed to the rail and then the FPC is installed to the cavity. This difference in procedure was required due to FPC size and fit within the coldmass assembly.

FRIB cryomodule installation is planned to proceed in an order matching that which the beam will follow through the linear accelerator. This allows accelerator commissioning activities for lower Beta cryomodules to start sooner and proceed while higher Beta cryomodules are still being assembled and tested [4]. As seen in Figure 7, not all coldmasses were assembled in order of their Beta. This mixing was borne of a desire to prove out each module type as early as possible. This is why, for example, the first Beta=0.085 coldmass was finished more than a year before the last Beta=0.041 coldmass. Often there were multiple different coldmass types in various stages of assembly at the same time. This is evidenced around June 2017 when 3 different coldmass types were completed in just over 30 days.

Coldmass Inspection

Upon completion of each coldmass assembly, an inspection meeting was held to allow stakeholders to check over the assembly before it gets pumped to ultrahigh vacuum. This inspection meeting is held inside the cleanroom, hosted by the coldmass assemblers, and attended by cryomodule design and assembly personnel (Fig. 8). During the inspection, attendees review the coldmass using a checklist of ~25 characteristics which have the potential to cause problems if they were not completed properly during assembly. Some key items of the inspection checklist are; verification that sub-components have been leak checked prior to coldmass assembly, and that all required fasteners are present and properly tightened.

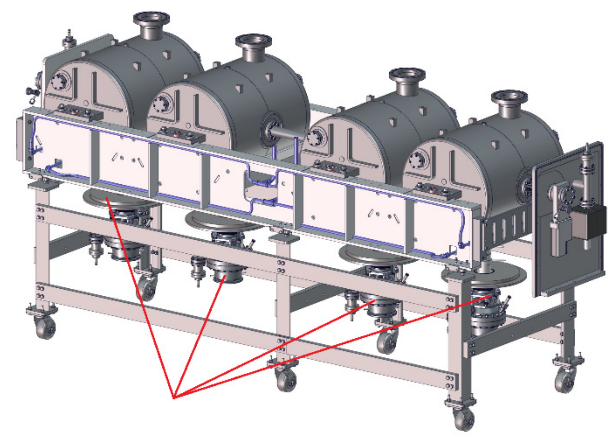

Figure 6: A Beta=0.53 matching coldmass with its 4 FPCs indicated.

FRIB COLDMASS PRODUCTION

The first FRIB coldmass to be completed was a Beta=0.085 coldmass completed September 30th, 2015. Since that date coldmass production has averaged one coldmass per month for the following four years.

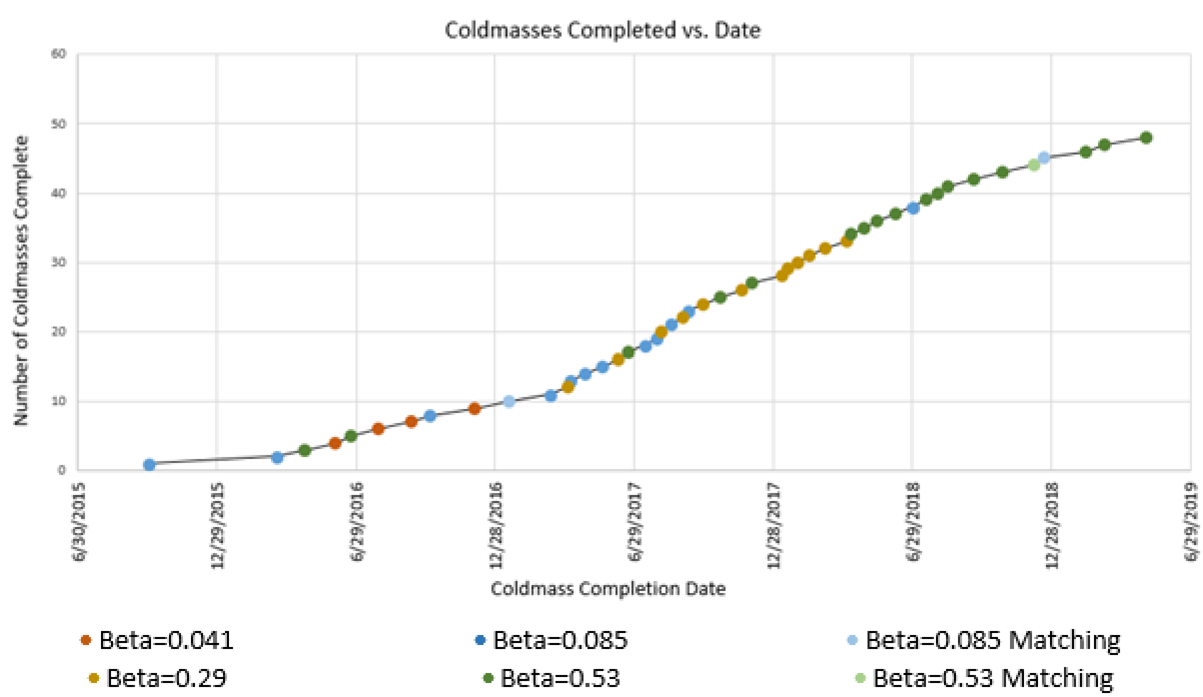

Figure 7: Plot showing the number of coldmasses completed at a given date. Markers on the plot are color coded based on which type of coldmass was completed on that date.

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Figure 8: Members of the FRIB team at the coldmass inspection for the last Beta=0.29 coldmass.

Despite a thorough inspection, seven of the forty-eight coldmasses completed so far have required repair work prior to being assembled into a cryomodule. All but one of those repairs were due to an unacceptable leak being found after the coldmass was evacuated.

PERFORMANCE DURING BUNKER TEST

After each coldmass is assembled into a cryomodule it undergoes a full system test before it is approved for installation into the FRIB linear accelerator [5]. These tests are done inside a radiation shielding test bunker. The systems verified during this test include; the cavities, the FPCs, the solenoids, cryogenic instrumentation and valves, alignment, and vacuum systems.

To date, 37 of the 46 cryomodules needed for FRIB have completed their bunker test. Contained within those 37 cryomodules are a total of 252 superconducting cavities. Of these 252 cavities only 12.3% (31 cavities) had any measured field emission at operating gradient during their bunker test. Figure 9 plots the field emission level, at operating gradient during bunker testing, for all cavities currently tested in FRIB coldmasses. Note that the operating gradient of each cavity type is different. The specified operating gradient for Beta=0.041, Beta=0.085, Beta=0.29, and Beta=0.53 cavities are 5.1, 5.6, 7.7, and 7.4 MV/m, respectively.

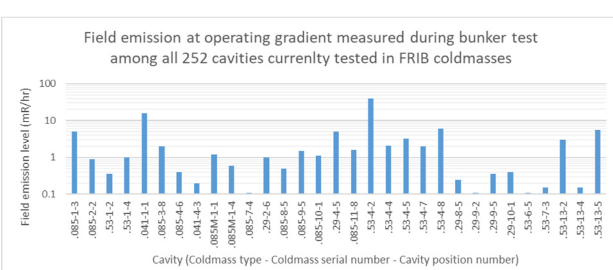

Figure 9: Chart showing field emission levels at operating gradient of cavities with measured field emission during bunker testing.

CHALLENGES AND LESSONS LEARNED

Leaks

Leaks were one of the most common causes of repair work during the assembly of FRIB coldmasses. Leaks happened on all sorts of parts, including; flanged connections made during the coldmass assembly, in custom fabricated components made by contracted suppliers (i.e. cavities, solenoids, FPCs, hoods), and even commercially available items.

A common method for helium mass spectrometry leak checking is to mask the area of the suspected leak with tape, then slowly pull the tape back while spraying helium to precisely find the leak location. This method can be very effective. However, occasionally residue from the tape will clog the leak path such that the leak no longer appears at all. This can trick operators into believing that the leak was never there in the first place. A thorough wiping with acetone will remove the residue and make the leak reappear.

Beamline Gate Valves

FRIB beamline gate valves were challenging for several reasons. The gate valves arrived from a supplier in several batch shipments. Only after several of the gate valves had been installed to coldmasses was it noticed that some of the valves had a tendency to slip, or drop, open. After much communication, and a visit to the supplier, it was determined that one of the linkages in the gate assembly was not appropriately tailored to the variation expected in each valve. Around the same time it was determined that the EPDM o-rings used in the gate valve should be replaced by a specific grade of o-ring which would be vacuum degassed at FRIB. To fix these problems many gate valves were sent back to the supplier for linkage and o-ring replacement. Additionally seven tested cryomodules needed to be purged from ultra-high vacuum so that their gate valves could be replaced.

As a result of these challenges, a thorough cleaning, adjustment, and characterization procedure was developed. Once received, each gate valve would be cleaned, have its open and closing speed adjusted, leak checked, and have particle counts taken during operation.

Information Availability

During coldmass production emphasis was placed on ensuring that assembly information was readily available to assemblers. The two most valuable pieces of assembly information were the coldmass mechanical assembly drawing and the coldmass assembly work instruction. The mechanical assembly drawing is a single sheet print depicting the coldmass and all of its subcomponents and their quantities. A laminated copy of this drawing was brought into the cleanroom and posted in the coldmass assembly bay. The work instruction defines the tools, process, and order required to properly build the coldmass. Tablets were used in the cleanroom so that assemblers could always have a copy of the work instructions at their fingertips.

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Having this information readily available was beneficial because it helped the assembler to correctly select the parts to be used, and orientation of installation, for whichever type of coldmass was being built at that time.

CONCLUSION

FRIB coldmass production began in mid-2015 with the completion of the first Beta=0.085 production coldmass. Since that time, coldmass production has proceeded steadily for four years towards completion of all FRIB coldmasses.

ACKNOWLEDGEMENTS

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