PRODUCTION STATUS OF SRF CAVITIES FOR THE FACILITY FOR RARE ISOTOPE BEAMS (FRIB) PROJECT

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Abstract

As the Facility for Rare Isotope Beams (FRIB) project ramps into production, vendor relations, cavity quality, and schedule become critical to success. The driver linac will be constructed of 332 cavities housed in 48 cryomodules and designed with two cavity classes (quarter-wave and half-wave) and four different betas (0.041, 0.085, 0.29, and 0.53). The cavities will be supplied to FRIB from awarded industrial vendors. FRIB's experience with SRF cavity fabrication will be presented including acceptance inspections, test results, technical issues, and mitigation strategies.

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.

The FRIB linac will require the fabrication of 332 superconducting radio frequency (SRF) cavities housed in 48 cryomodules. Two classes of cavities at two different operating frequencies will be used; 80.5 MHz quarter-wave cavities and 322 MHZ half-wave cavities, shown in Figure 1. Both cavity classes will have two different operating betas; 0.041 and 0.085 quarter-wave cavities [1,2] will be used in segment one of the linac and 0.29 and 0.53 half-wave cavities[3] will make up the accelerator in both segments 2 and 3.

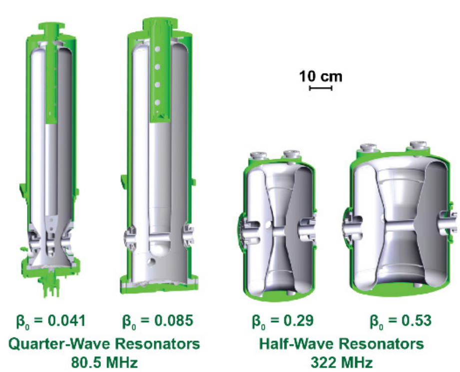

Figure 1: FRIB production SRF cavity designs.

CAVITY PRODUCITON

FRIB has contracted the fabrication of the four cavity types to industrial vendors for production fabrication. Total required cavity counts for the FRIB main driver are provided in Table 1.

Cavities are fabricated from bulk polycrystalline niobium with titanium helium vessels. FRIB manages the procurement, quality, and sequencing of niobium materials to the vendors, including replacement materials. All materials shall be tracked by cavity vendors; managing quantities as well as mapping material serial numbers to cavity components fabricated.

All cavities are sequence through incoming acceptance inspection upon receipt from vendor to FRIB. Cavities are checked against the Acceptance Criteria List or ACL. The ACL criteria for cavity acceptance is:

- Inspection of Vendor required documentation
- Check the cavity is properly labelled with correct serial number
- Dimensional inspection (measuring critical dimenisons)
- Surface inspection (RF surfaces, seal interfaces and welds)
- Frequency check
- Vacuum leak check (both cavity and helium space)

Table 1: Cavity Production Quantity Requirements and Received Cavities to Date (Shown in Red)

Beta	Development	Preproduction	Production	TOTAL
0.041	2(2)		17(17)	19(19)
0.085	2(2)	10(10)	103	115(12)
0.29	2(2)	10(3)	68	80(5)
0.53	2(2)	10(8)	150	162(10)

CAVITY STATUS

FRIB has begun to receive vendor cavities of all four types starting in January 2014. The beta=0.041 contract was completed in April of 2015. Table 1 provides the numerical status of cavities received to FRIB as of September 1, 2015.

All accepted cavities are certified in vertical testing before being accepted for cold-mass assembly. Cavities

ISBN 978-3-95450-178-6

are heat treated, processed, and tested in vertical Dewar as part of standard FRIB procedures [4]. Cavities are sequenced through processing and vertical test as defined in the FRIB vertical test priorities document that defines critical paths for FRIB construction and cavity vendor quality control specifications.

FRIB has successfully processed and tested vendor cavities of each type meeting FRIB performance specifications. A sampling of vertical tests results are provided in Figures 2-5.

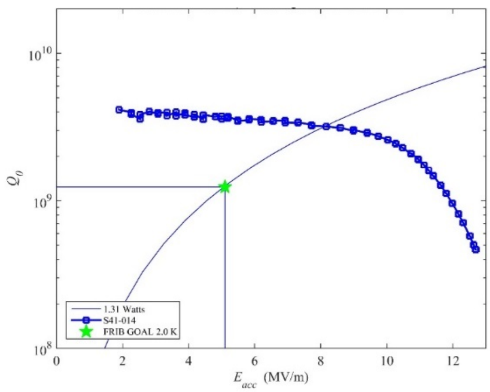

Figure 2: 80.5 MHz, beta=0.041 vertical test result.

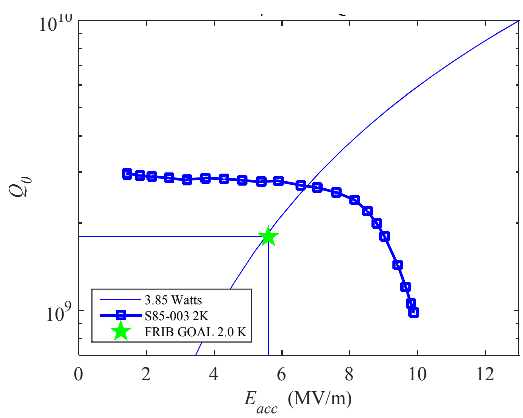

Figure 3: 80.5 MHz, beta=0.085 vertical test result.

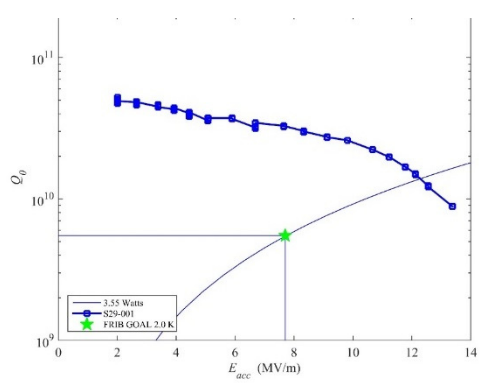

Figure 4: 322 MHz, beta=0.29 vertical test result.

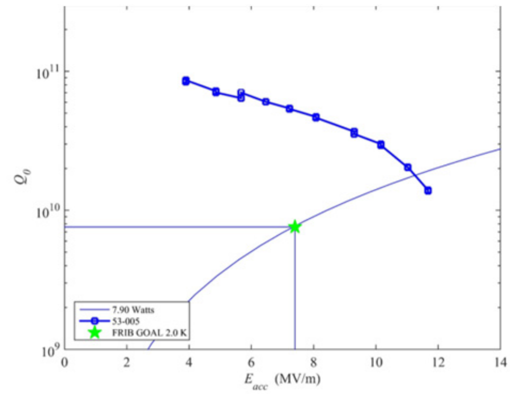

Figure 5: 322 MHz, beta=0.53 vertical test result.

CAVITY PRODUCTION

By establishing strong working relationships with contracted vendors, FRIB has been successful in working through technical challenges in cavity fabrication while increasing/maintaining product quality and optimizing production schedule.

CAVITY FREQUENCY CONTROL

The final frequency of the cavity is critical to the operation of the accelerator. FRIB has developed frequency-tuning strategies for both quarter-wave and half-wave cavities including several “knobs” for fine frequency adjustment during the fabrication process.

Quarter-wave Cavities

FRIB uses a traditional stack-up and trim method to meet frequency goals of the unjacketed quarter-wave cavities. The cavity is first fabricated as three subassemblies; outer conductor, inner conductor, and short plate. The outer and inner conductors are fabricated with extra material on the ends that interface with the short plate. The short plate is fabricated to print dimension. The subassemblies are assembled or “stacked-up”, using tooling to ensure good electrical contact across unwelded interfaces. The frequency is measured of the stacked structure and compared to frequency goals set for warm temperature cavities without helium vessel. The outer and inner conductors are then trimmed to length by using the difference of the measured frequency to goal frequency and using a predetermined delta frequency/delta length ratio. Compensation must be made for excepted weld shrinkage in weld interfaces. Once the unjacketed frequency goal is met, the cavity subassemblies can be electron-beam welded together; completing the unjacketed cavity. Care must be taken when integrating the helium vessel to the cavity. Controlling the heat during vessel welding is critical, as well as following a repeatable welding procedure to avoid unplanned distortion that can result in unpredicted cavity frequency shift.

After the completion of the helium vessel assembly, if the final frequency of the cavity is outside the tolerance, there are two options to allow for fine frequency tuning. Following similar concepts developed at TRIUMF [5], FRIB has defined procedures to shift the cavity's frequency by controlled differential etching and/or adjustment of the tuning plate penetration height into the cavity space. Frequency tuning ranges have been defined for both procedures. Differential etching can tune the frequency ~ 0-60 kHz positive in quarter-wave cavities. Tuning plate puck adjustment has a tuning range of ~ 100 kHz. To date, all received quarter-wave cavities have met FRIB frequency goals using the tuning procedures detailed above, as shown in Figure 6.

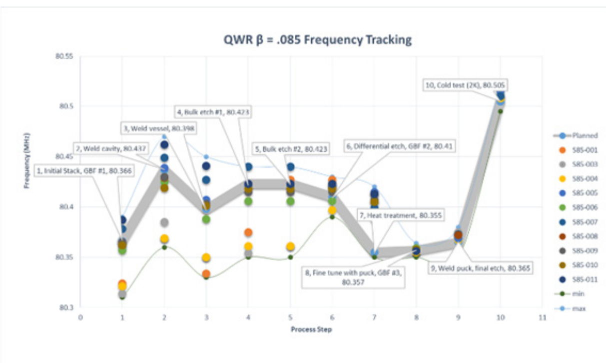

Figure 6: Beta=0.085 frequency tracking through cavity fabrication and processing.

Half-wave Cavities

FRIB also uses a traditional stack-up and trim method for the frequency assembly of half-wave cavities. For the development cavities, the tuning processes of adjusting the beam cup position was used to control frequency. The cavity was fabricated to completion with all welds fused except the beam port subassembly to the outer conductor. The beam cup subassembly was designed with a cup interface to the outer conductor that produces a sliding fit, shown in Figure 7. The sliding joint allowed for fine adjustment to the beam port subassembly depth into the cavity. Using adjustment tooling, the depth of the beam port subassembly is adjusted in and out of the outer conductor; tuning the frequency of the cavity. When the goal frequency is reached, the beam port depth is set and the beam port subassembly position is welded into location. The method was changed after the first two cavities to a stack-up method similar to the quarter-wave cavities because of complications with the welding of the beam port subassembly. Using the new method, the outer and inner conductors were fabricated long, with extra material on both ends for frequency trimming. The outer conductor is fabricated with the beam port subassembly welded in at a designed depth. The four remaining subassemblies (outer conductor, inner conductor, and (2) short plates) are stacked-up and trimmed in reference to frequency measurements, shown in Figure 8.

Figure 7: Early method for setting frequency of half-wave cavities using the beam cup subassembly prior to welding.

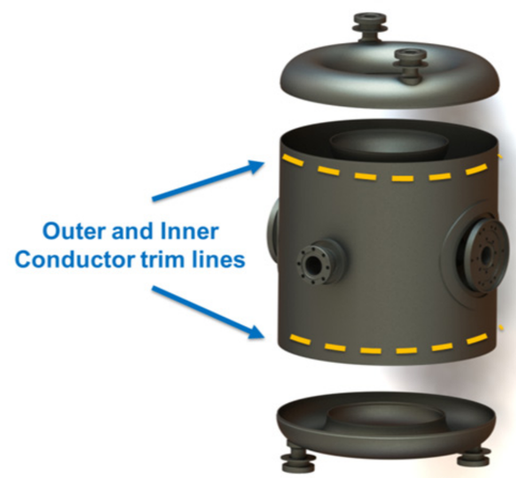

Figure 8: Current method for set frequency of half-wave cavities prior to welding.

To improve the reliability of the stack-up frequency measurements, a set of calibrated, copper reference fixtures were fabricated and used in the stack-up of subassemblies, as shown in Figure 9. In set-up one, the niobium short plates, fabricated to print, are stacked-up (one at a time) with a copper cavity of calibrated frequency. The copper cavity with the niobium short plate measurement qualifies the short plate for use. The sequence is repeated with the second short plate. In step-up two, the niobium outer and inner conductors are stacked and trimmed using a set of copper short plates (fabricated to match the final frequency of the cavity). At the completion of the reference measurements, the niobium subassemblies are processed and electro-beam welded completing the unjacketed cavity.

Prior to the helium vessel integration, FRIB has developed two methods for fine tuning the frequency of unjacketed cavities; mechanical deformation and virtual welding. Mechanical deformation is a method used to shift the cavity frequency in negative direction by pushing the beam port subassembly into the cavity space.

ISBN 978-3-95450-178-6

Figure 9: Copper reference fixture developed to increase reproducibility in frequency stack-up of cavity subassemblies prior to welding.

To allow for frequency tuning in the positive direction, FRIB has developed a virtual welding technique. Virtual welding is a process of applying a set of non-structural welds to strategic locations on the cavity. The virtual welds produce weld shrinkage in the cavity that results in a frequency shift to the structure. Electro-beam weld calibration studies have yielded power verse frequency curves that have proven repeatable across multiple cavities, shown in Figure 10.

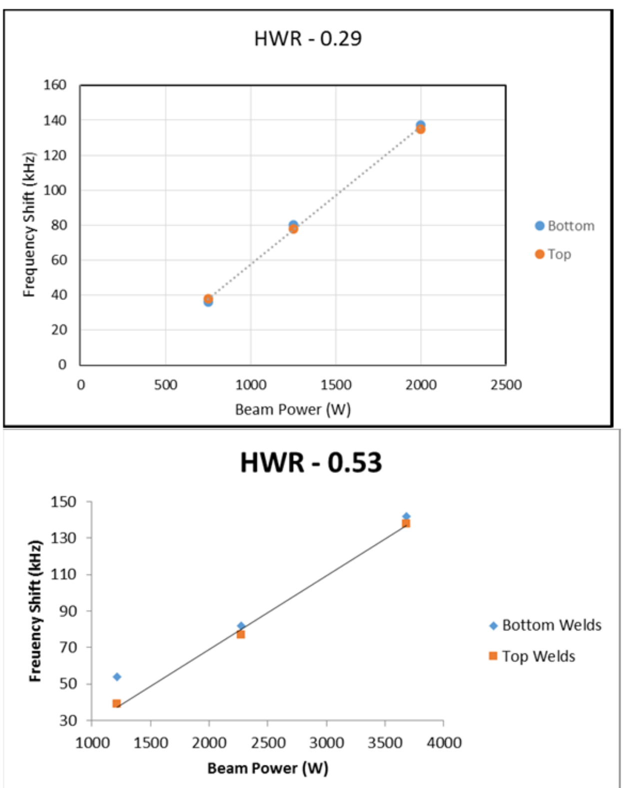

Figure 10: Electron-beam power calibration plots for adjusting cavity frequency using virtual welding.

After the completion of the niobium cavity, the helium vessel is assembled to the cavity using a set procedure to control frequency shifting. Care must be taken to produce repeatable welds during final integration to the cavity structure. Two methods for final frequency tuning have been developed for fine tuning cavity after the helium vessel integration; differential etching and virtual TIG welding. Differential etching, as used in quarter-wave cavity frequency adjustment, is a proven technique used in past accelerator projects. Experience at FIRB have set the tuning range by differential etching to be ~ 0-80 kHz down in half-wave cavities.

Virtual TIG welding follows the same idea as the virtual electro-beam welding described above. Non-structural TIG welds are places in locations on the helium vessel to shift frequency in need directions. The mapping of frequency shifts during helium vessel integration provides strategic locations to apply the virtual welds.

CAVITY FABRICATION – APERTURE ALIGNMENT

All received cavities are sequenced through a set of incoming dimensional inspections. Using a CMM, critical dimensions of the cavity are measured to ensure interface points are within tolerance relating to fit and function in cavity processing and cryomodule assembly. Of the critical dimensions measured, the aperture alignment is key to the successful delivery of beam through the accelerator. Using an extension arm to the CMM probe, the drift tube aperture can be swept and measured in reference to the position of the beam port apertures. The FRIB tolerance specification is +/-0.38mm (+/-0.015 inch).

FRIB worked with contracted vendors to develop procedures to ensure the alignment of the cavity apertures. Corrective actions were implemented in both quarter-wave and half-wave fabrication to improve final positioning of the apertures. Corrective efforts were largely focused on improvements to electro-beam welding fixtures. Care must be taken when setting the final trim heights of the inner and outer conductors to meet both frequency goals and aperture tolerances. Weld shrinkage seen in interfaces between inner and outer conductor to short plates will influence the cavity's final frequency and aperture position. Optimizing fixtures resulted in an improvement in aperture position; an example in shown in Figure 11.

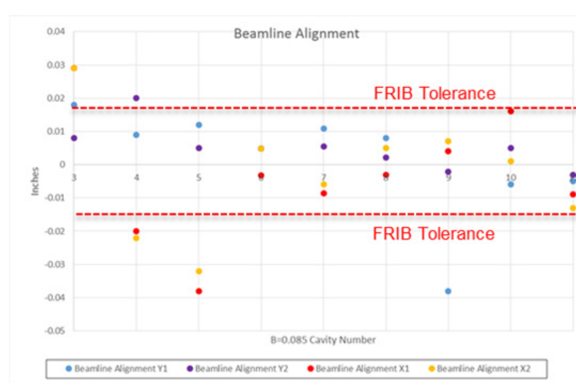

Figure 11: Aperture alignment tracking of production 0.085 cavities; reduce in spread over increasing cavities.

CAVITY VACUUM RELIABILITY

Vacuum reliability is a concern in cryomodule assembly as FRIB will use a separated vacuum system, isolating beamline and cryostat vacuum spaces. The fact the cryogenic system will operate at 2K also increases vacuum sensitivity in both dimensional tolerances and use of differential materials (difference in thermal expansion coefficients). Beginning quality efforts focused on fabrication dimensionality and work to control the tight tolerance requirements in niobium-titanium material. Early observation in reliability studies reported a visual degrading of the knife-edge profile over multiple uses, as seen in Figure 12. A study was used to investigate the breakdown of the knife-edge; looking at assembly practices, material proprieties, and tolerance spread. FRIB also began exploring possible redesign to the sealing geometry by changing the knife-edge profile. There are two general standards used in the fabrication of Conflat flange and differ in the knife-edge profiles. The American standard uses a small radius at the knife tip (0.05mm radius) and a shallow counter slope angle (0-5 degrees). The European standard uses an increased radius at the tip (0.105mm radius) and a larger counter slope angle (20-40 degree) to reduce point loading. FRIB performed a study in which several flanges were fabricated using both American and European Conflat profiles. After fabrication, the flange profiles were measured very accurately using a Zeiss coordinate measuring probe. The probe takes a measurement of the depth of the knife-edge tip from the top of the Conflat flange face. After measurements, the flanges were assembled to a mating American standard, stainless steel, Conflat flange using a copper gasket and standard FRIB Conflat assembly procedures. Once together, the assembly was vacuum leak checked, cold shocked, and re-leak checked. The flanges were then disassembled and the sealing profiles re-measured. The pre- and post-measurements are used to track the breakdown or deformation to the knife-edge from sealing. The cycle was repeated several times with the degrading tracked, shown in Figure 13.

At the conclusion of the test, all Conflats maintained vacuum in all assemblies and cold shocks. Effects of the multiple assemblies showed differently in the two knife-edge profiles. In the American standard flanges, the knife-edges began to show the breakdown signs observed in earlier flanges. American knife-edge profiles began showing rough surface and probe measurements recorded an increase in depth after each cycle (increase distance between knife-edge tip and flange surface). The European flanges exhibited little breakdown in both optical inspection and probe measurements and was adapted to all FRIB cavity designs.

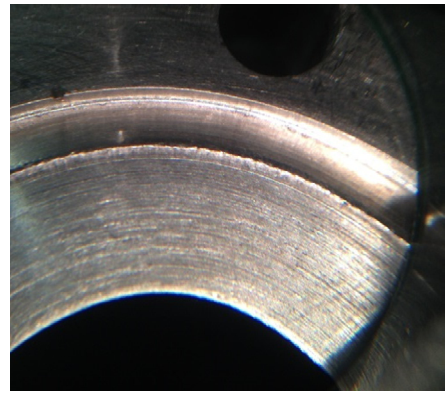

Figure 12: Observed deformation of knife-edge after multiple assemblies.

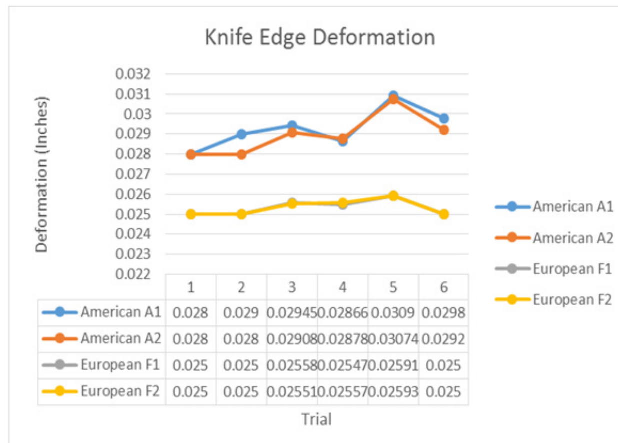

Figure 13: Tracking of deformation of American and European Conflat knife-edge tips as a distance from the flange face.

THREADS

In efforts to optimize cavity spacing within the cryomodule, tapped holes are used with fasteners to assemble beam line vacuum connections. The tapped holes are fabricated into the beam port flanges made of niobium-titanium material. Because of the high spring back behaviour of titanium based materials, threads produced using standard thread forming dies resulted in tapped holes of poor quantity. In efforts to monitor and ensure quality, the use of GO/NOGO gauges are a required quality control step implemented at both the vendor and FRIB incoming inspection. Inspection of formed threads reported nonconfomance in meeting standard GO/NOGO gauge measurements. The resulting threads lead to fasteners becoming stuck during disassembly.

Thread milling can be an effective approach to improving thread quality in titanium materials. The choice of tool speed and feed rate is highly critical to the quality of the milled threads. Surface finish of the threads is a property highly effected by these variables and is critical when assembling systems with high cleanliness

ISBN 978-3-95450-178-6

specifications. All hardware and components are prepared in standard cleanroom environments (typically Class 100 or better). The cleanliness specification also requires assemblies to be completed using hardware having no lubrication to ease fiction in the threads. This combined with poor surface finish during fabrication can lead to galling and stuck fasteners. FRIB completed a study looking at friction, galling, and particle generation of different materials and finishes of assembly hardware in thread milled tapped holes. Tested assemblies were cleaned and assembled using standard FRIB procedures. Assemblies were subjected to a cold shock/leak test before disassembly. A judgement of fiction is documented during assembly and disassembly. In addition, particle generation was measured with each fastener assembly combination using a surface particle counter. At the conclusion of the study, a stainless steel, electro-polished fastener was chosen for FRIB coldmass assembly requiring thread milled tapped holes. The EP fastener recorded the lowest particle generation and showed very little fiction when engaging threads.

CONCLUSION

FRIB cavity production is quickly ramping up with awarded contacts and the development of multiple SRF cavity vendors with the required infrastructure and expertise to execute large scale accelerator projects. A project focus on vendor management is required to ensure high quality products and maintain delivery schedules. FRIB has implemented a strong acceptance inspection philosophy with corrective action tracking of reported nonconformances. Critical design features such as frequency, aperture alignment, and vacuum reliability have been defined, with a raised focus from contracted vendors to control tolerance specifications. Early nonconformances have been successfully mitigated by strong working partnerships with awarded vendors and continuous communication in tracking workflow activities. FRIB will continue to monitor and work with vendors to meet all project deliverables.

ACKNOWLEDGEMENTS

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University.

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