ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP005

THE FACILITY FOR RARE ISOTOPE BEAMS SUPERCONDUCTING CAVITY PRODUCTION STATUS AND FINDINGS CONCERNING SURFACE DEFECTS*

C. Compton†, H. Ao, J. Asciutto, J. Craft, K. Elliott, W. Hartung, S. Kim, E. Metzgar, S. Miller, E. Oswald, J. Popielarski, L. Popielarski, K. Saito, T. Xu
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, 48824, U.S.A.

Abstract

The Facility for Rare Isotope Beams (FRIB) will require 324 Superconducting Radio Frequency (SRF) cavities for the driver linac. Four types of cavities of two classes, quarter-wave ($\beta = 0.041$ and 0.085) and half-wave ($\beta = 0.29$ and 0.53), will be housed in 46 cryomodules. To date, FRIB has Dewar tested over 300 cavities as part of the certification procedures. Incoming cavities, fabricated by industry, are sequenced through acceptance inspection and checked for non-conformances. If accepted, the cavities are processed, assembled onto an insert, and cold tested. A large database of cavity surface images has been collected with the aid of a borescope camera. Borescope inspection is performed for each cavity at incoming inspection, after bulk etching, and after failed tests (if necessary), in order to locate non-conformances. Findings of surface defects relating to degraded cavity performance will be presented. Examples of guided repair via mechanical polishing will be provided.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) on the campus of Michigan State University (MSU) is an approved project funded by a cooperative agreement between MSU and the US Department of Energy to advance the study of rare isotopes. The main accelerator for FRIB is a 200 MeV per nucleon superconducting linac for ions with a final beam power of 400 kW.

The FRIB linac requires 324 superconducting radio frequency (SRF) cavities of 2 classes, operating at 2 different frequencies (Figure 1): 80.5 MHz quarter-wave resonators (QWR) and 322 MHz half-wave resonators (HWR). QWRs with $\beta = 0.041$ and 0.085 are used in Linac Segment 1; HWRs with $\beta = 0.29$ and 0.53 are used in Linac Segment 2 and Linac Segment 3. The final cavity designs incorporate experience from prototyping, design optimization, and iterative improvements for both QWRs [1–3] and HWRs [4–6].

CAVITY PRODUCTION

FRIB contracted the fabrication of the 4 cavity types to industrial suppliers for mass production [7]. The required cavity counts for the driver linac are listed in Table 1.

Cavities are fabricated from polycrystalline niobium sheet. The cavities' helium vessels are made of titanium. FRIB manages the procurement, quality assurance, and delivery of niobium to the cavity vendors, including replacement materials. All materials are tracked by the cavity vendors; they manage quantities and map material serial numbers to cavity components as they are fabricated.

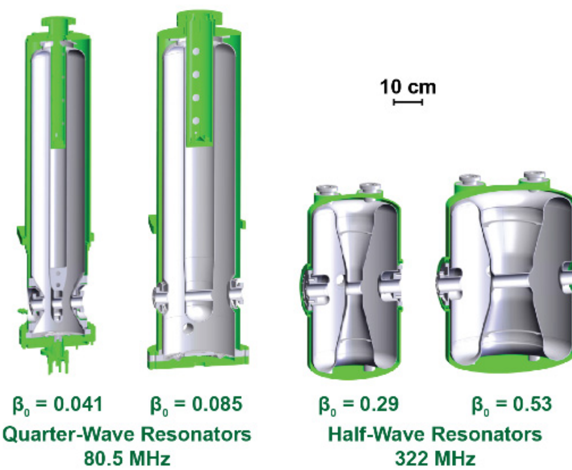

Figure 1: FRIB production SRF cavity designs.

Table 1: Cavity Counts for FRIB Production

β	0.041	0.085	0.29	0.53	Total
Required	12	92	72	148	324
Received	16	123	83	141	363
Accepted	16	123	80	141	360
Tested	16	106	75	141	338
Certified	16	105	72	136	329
Certified on 1st test	84%	89%	87%	73%	

All cavities undergo incoming acceptance inspection at FRIB upon receipt from the vendor. Cavities are checked against an Acceptance Criteria List (ACL). The ACL includes a visual inspection of all internal surfaces and welds using a borescope.

CAVITY STATUS

The first production cavities were delivered by the vendors in January 2014. Delivery of $\beta = 0.041$ QWRs was completed in June 2015; $\beta = 0.085$ delivery was completed in December 2017; $\beta = 0.29$ delivery was completed in May 2017; and $\beta = 0.53$ delivery is scheduled for completion by the end of 2019. Table 1 includes the quantities of

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

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP005

cavities received, accepted, and certified for FRIB as of June 2019.

Accepted cavities undergo FRIB standard cavity surface preparation, including etching of the inside surface and high-pressure water rinsing with a robotic system [8, 9]. The cavities are then Dewar tested. Cavities not meeting the certification requirements in the Dewar test are reworked and retested. If an uncertified cavity had heavy field emission, a thermal quench, or a "Q-switch," it is first re-inspected with the borescope to check for any significant features on the inner surface. Features can be the result of problems during manufacturing or processing, or can be due to mishandling of the cavities. All findings are documented in an inspection report which is then reviewed to decide whether to attempt mechanical polishing.

About 96% of the cavities required for the FRIB driver linac have been certified. More information on cavity Dewar tests results can be found elsewhere [10, 11]. Table 1 also includes the percent of cavities that were certified in the first Dewar test without rework.

CAVITY SURFACE POLISHING

If a cavity is not certified in the Dewar test due to poor performance at high field, it is re-inspected to search for internal features that could be contributing to the performance degradation. A borescope is used to inspect the RF surfaces, including electron-beam welds, with particular attention to the areas that are most critical for cavity performance. Prior to inspection, the inspector reviews the cavity test report, as the report may suggest where to place extra scrutiny during the inspection: in the high electric field regions (in case of heavy field emission) or the high magnetic field regions (in case of a quench or Q-switch).

Once the borescope inspection is completed, the inspection report is reviewed and subsequent steps are planned. In most cases, mechanical polishing is done, followed by repeat etching, repeat rinsing, and another Dewar test of the cavity. Surface polishing follows the same methodology for most features and mostly varies based on location and size.

Surface Polishing Methods

FRIB uses a GE Everest XLG3 VideoProbe System for internal borescope inspections. In the borescope inspections, we look for interior surface defects, some of which may be visible only after etching. Defects may be due to manufacturing errors (dents, weld repair features, and foreign inclusions, etc.) or may be introduced during cavity surface preparation.

Mechanical polishing is done by hand or with hand-held rotary power tools. The mechanical polishing can produce an acceptably smooth surface in preparation for final chemical etching. We use aluminum oxide abrasive media in successively finer stages to achieve the desired surface finish. For large features, we start with coarse abrasive grit paper (P80-P120) or rotary flapper wheels to quickly plane the surface topography or remove foreign inclusions. We then use less aggressive grits (P240-P320) remove residual scratches and, lastly, flexible ScotchBrite abrasive pads (P320-400) which conform to the interior contours to lightly polish the surface uniformly.

Access to the inside surface is difficult for HWRs, which have no large openings. HWRs have 4 rinse ports (one of which is used for the RF pickup coupler), 2 beam ports, and one RF input port. When polishing an HWR, the borescope camera is inserted through a bushing fixture secured to a nearby port and focused on the target area. The operator then inserts the polishing tool through a different port that allows adequate movement to abrade the surface, as shown in Figure 2. The real-time borescope view of the polishing region improves the final results by helping to localizing the polishing to only the desired area; additionally, the condition of the defect can be monitored while polishing it.

Polishing tools are made by bending ¼ inch (6.4 mm) stainless tubing, which is wrapped in protective tape, into a shape that avoids inadvertent contact with the soft niobium interior, as shown in Figure 3. If the target feature is within line-of-sight through a cavity port, a power tool is used in lieu of manual polishing: a rotary flapper wheel or abrasive pad is fixed to a composite rod, which is driven by a cordless drill/driver.

Figure 2: HWR polishing using the borescope (right) and a manual polishing tool (left).

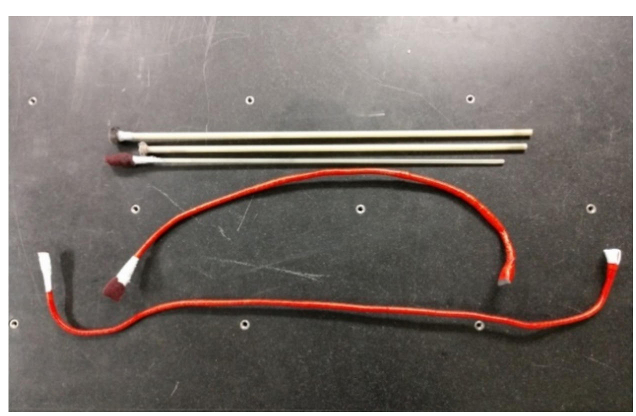

Figure 3: Examples of cavity polishing tools. The tools are bent as needed to reach features via the available access ports.

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP005

Successful Polishing Reworks: Field Emission

Cavities not passing certification due to heavy field emission are re-inspected with extra attention to high electric field regions. These areas are at or near the mid-plane of the cavity where the beam travels; the vicinity of the beam ports and drift tube are the most critical. The inspection focuses on possible fabrication or processing errors that may have produced scratches, dents, or protrusions. Most of these surface features are a result of mishandling during manufacturing. Surface features from cavity processing have also been seen, such as acid vapour, acid ledges/erosion, or high-pressure rinsing oxide. Figure 4 through Figure 7 show examples of surface features believe to have caused field emission in Dewar tests.

Figure 4: Scratch along the inner conductor observed after the first Dewar test (β = 0.085 QWR, S85-952).

Figure 5: Electron-beam weld repair of inner conductor to short plate blow-through with plug not fully melted, observed during incoming inspection (β = 0.53 HWR, S53-125).

Figure 6: Surface scratches/ledges on the drift tube, possibly due to acid erosion, observed after the first Dewar test (β = 0.53 HWR, S53-113).

Figure 7: Acid vapour marks on outer conductor observed after first Dewar test (β = 0.085 QWR, S85-951).

Figure 8 (cyan and magenta) shows an example: two cavities which had heavy field emission in the first Dewar test, as seen by X-ray levels increasing rapidly with field and corresponding decreases in the quality factor. In the borescope inspections after Dewar testing, features were observed on the inner conductor (see Figure 4) and drift tube. These features were mechanically polished, and the cavities were reprocessed and retested. The post-polishing tests show a significant improvement in the quality factor at high field and a corresponding reduction in field emission X-rays (Figure 8, blue and red).

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP005

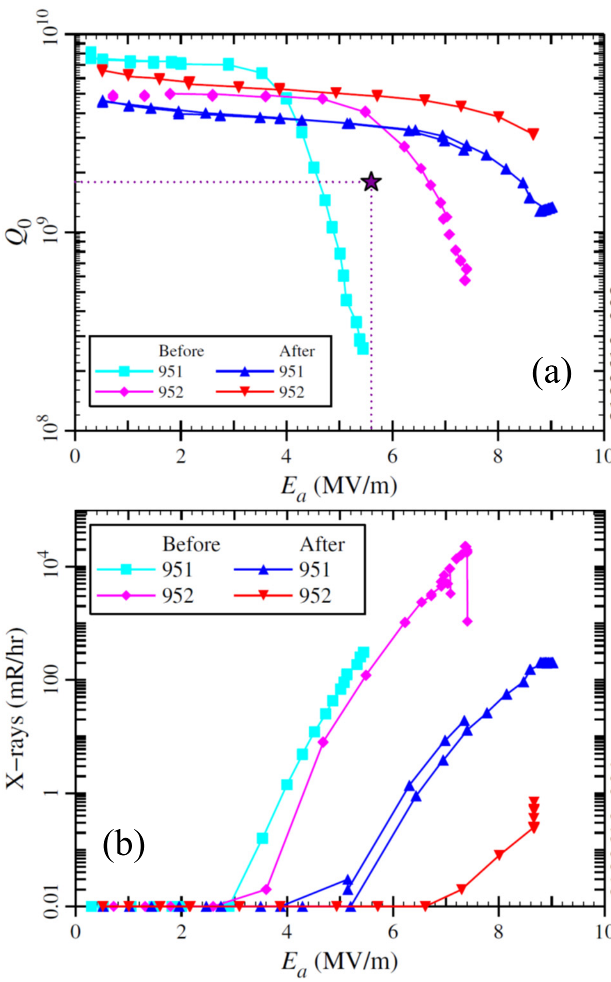

Figure 8: Dewar test results at 2 K for two β = 0.085 QWRs before and after mechanical polishing: (a) quality factor and (b) X-rays as a function of accelerating gradient (E_a). Purple star: FRIB operating goal.

Successful Polishing Reworks: Q-Switches

Cavities not certified in Dewar tests due to thermal quench or "*Q*-switch" behaviour are re-inspected with extra attention to areas of high magnetic field. As foreign inclusions could cause quenching or *Q*-switching, the cavities are salt-water soaked prior to borescope re-inspection, in the hope that the salt-water will produce oxidation at the inclusion site. Two examples of successful mechanical polishing of *Q*-switch cavities will be discussed in this section.

Cavity S53-128 (β = 0.53 HWR) showed marginal performance in the first certification test and had a *Q*-switch behaviour, as shown in Figure 9 (cyan): Q_0 and the field jumped downward at E_a = 5 MV/m and dropped further at about 8 MV/m. The incoming borescope inspection had shown a surface feature on the beam cup to outer conductor weld (Figure 10a). The initial thought was that the feature was residual oxide from acid etching or a weld inclusion; hence a polishing rework was implemented.

During the initial stages of polishing, the feature "opened up" revealing additional voids in the weld and along its edges (Figure 10c). Further material removal showed the area was a weld overlap with a void underneath, producing a small pocket (Figure 10d). The material over the pocket was polished away and the remaining pocket was blended into the adjacent sides (Figure 10e). Partway through polishing, a piece broke away (Figure 10f).

After polishing, the cavity was reprocessed and Dewar tested again. In the second test, it met the FRIB certification requirements with good margin for field and quality factor (Figure 9, blue).

Cavity S53-132 (another β = 0.53 HWR) did not meet the certification requirements in the first Dewar test, and also had a *Q*-switch near 5 MV/m (Figure 9, magenta). The borescope inspection revealed a feature on the outer conductor to short plate weld, as indicated by oxide coming from the weld, shown in Figure 11. The vendor's report indicated that a weld blow-through occurred in the suspected area, and that a repair was done using a niobium plug.

Initial polishing caused the feature to "open up" revealing more dark, oxide-like material (most likely foreign material). Polishing was continued until no traces of foreign material were visible. Salt-water soak and inspection were repeated after mechanical polishing, with no foreign material observed.

After polishing, the cavity was reprocessed and retested. The post-polishing test showed considerable improvement in performance (Figure 9, red), such that the cavity met the requirements for Q_0 and field.

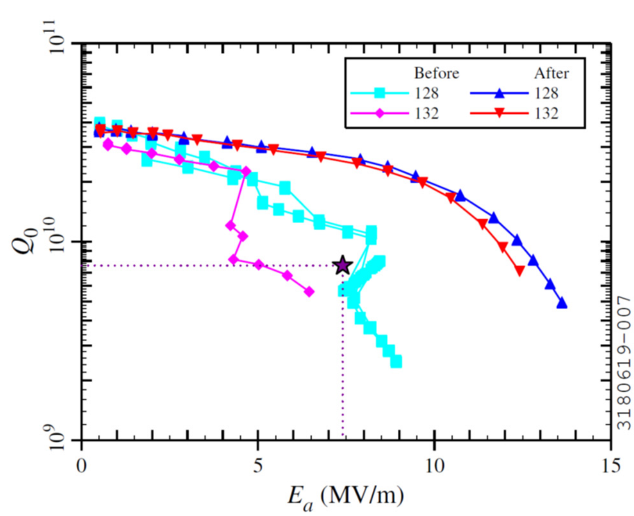

Figure 9: Dewar test results at 2 K for two β = 0.53 HWRs before and after mechanical polishing.

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-MOP005

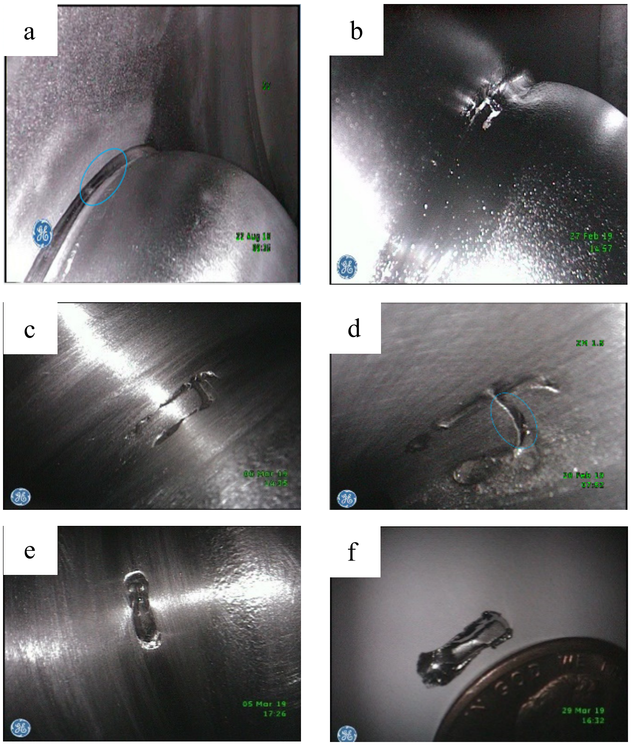

Figure 10: Polishing of S53-128 feature: (a) as received, before etching; (b) after etching and test; (c) after initial polishing, "opening up"; (d) shelving with void underneath; (e) top material removed, blending void area to adjacent surface; (f) fragment broken off during polishing.

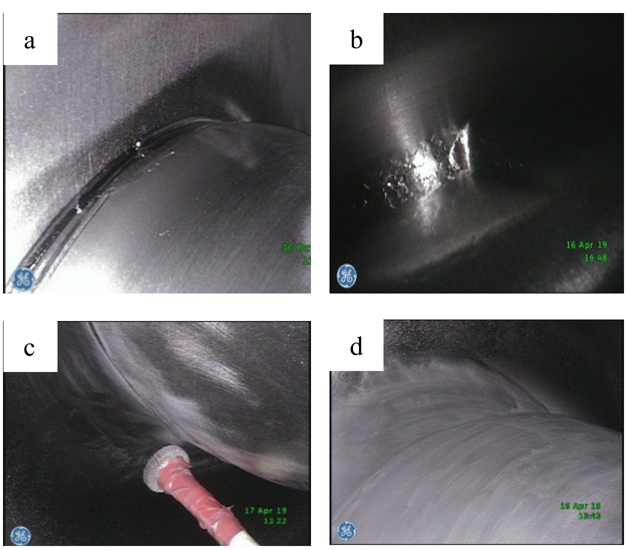

Figure 11: Polishing of S53-132 feature: (a) as received, before etching; (b) after etching and test; (c) during polishing; (d) after polishing.

CONCLUSION

FRIB cavity production is nearly complete, with about 96% of production cavities certified, and only the $\beta = 0.53$ cavity delivery unfinished. Though cavity certification rates remain high, some cavities cannot be certified on the first test and require rework. In some cases, cavities with degraded performance at high field due to field emission or *Q*-switching have been improved with mechanical polishing. Examples have been presented in this paper. A more detailed analysis of FRIB production cavity reworks is planned.

REFERENCES

[1] W. Hartung *et al.*, "Superconducting Coaxial Resonator Development for Ion Linacs at Michigan State University," in *Proc. 25th Linear Accelerator Conf. (LINAC'10)*, Tsukuba, Japan, Sep. 2010, Paper THP039, pp. 845-847.

[2] A. Facco *et al.*, "Superconducting Resonators Development for the FRIB and ReA Linacs at MSU: Recent Achievements and Future Goals," in *Proc. 3rd Int. Particle Accelerator Conf. (IPAC'12)*, New Orleans, LA, USA, May 2012, Paper MOOAC03, pp. 61-63.

[3] A. Facco *et al.*, "Faced Issues in ReA3 Quarter-Wave Resonators and Their Successful Resolution," in *Proc. 16th Int. Conf. RF Superconductivity (SRF'13)*, Paris, France, Sep. 2013, Paper THIOD02, pp. 873-877.

[4] J. Popielarski *et al.*, "Development of a Superconducting Half Wave Resonator for Beta 0.53," in *Proc. 23rd Particle Accelerator Conf. (PAC'09)*, Vancouver, Canada, May 2009, Paper WE5PFP039, pp. 2080-2082.

[5] J. P. Holzbauer, W. Hartung, and J. Popielarski, "Design of a $\beta = 0.29$ Half-wave Resonator for the FRIB Driver Linac," in *Proc. 24th Particle Accelerator Conf. (PAC'11)*, New York, NY, USA, Mar.-Apr. 2011, Paper TUP090, pp. 997-999.

[6] S. J. Miller, J. Binkowski, M. J. Johnson, Y. Xu, and A. Facco, "Design for Manufacture of Superconducting Half Wave Cavities," in *Proc. 15th Int. Conf. RF Superconductivity (SRF'11)*, Chicago, IL, USA, Jul. 2011, Paper MOPO051, pp. 213-215.

[7] C. Compton *et al.*, "Production Status of SRF Cavities for the Facility for Rare Isotope Beams (FRIB) Project," in *Proc. 17th Int. Conf. RF Superconductivity (SRF'15)*, Whistler, Canada, Sep. 2015, Paper WEBA03, pp. 961-966.

[8] L. Popielarski *et al.*, "Low-Beta SRF Cavity Processing and Testing Facility for the Facility for Rare Isotope Beams at Michigan State University," in *Proc. 17th Int. Conf. RF Superconductivity (SRF'15)*, Whistler, Canada, Sep. 2015, Paper TUPB022, pp. 597-601.

[9] I. M. Malloch, E. S. Metzgar, L. Popielarski, and S. Stanley, "Design and Implementation of an Automated High-Pressure Water Rinse System for FRIB SRF Cavity Processing," in *Proc. 28th Linear Accelerator Conf. (LINAC'16)*, East Lansing, MI, USA, Sep. 2016, pp. 468-471.

[10] J. T. Popielarski *et al.*, "Performance Testing of FRIB Early Series Cryomodules," in *Proc. 18th Int. Conf. RF Superconductivity (SRF'17)*, Lanzhou, China, Jul. 2017, pp. 715-721.

[11] W. Hartung *et al.*, "Performance of FRIB Production Quarter-Wave and Half-Wave Resonators in Dewar Certification Tests," presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, Paper THP061, this conference.