

SRF CAVITY PROCESSING AND CHEMICAL ETCHING DEVELOPMENT FOR THE FRIB LINAC*

I. Malloch[#], M. LaVere, E. Metzgar, L. Popielarski, Facility for Rare Isotope Beams (FRIB), Michigan State University, East Lansing, MI 48824, USA

Abstract

In preparation of a rigorous superconducting RF (SRF) cavity processing and test plan for the production of the Facility for Rare Isotope Beams (FRIB) driver linac, a state-of-the-art chemical etching tool has been installed in the FRIB coldmass production facility. This paper seeks to summarize the etching equipment design, installation, and validation program and subsequent etching results for a variety of SRF cavity types and etching configurations. Bulk etching, light etching, and custom (frequency tuning) etching results for different FRIB cavities are discussed. Special emphasis is placed on the etching removal uniformity and frequency tuning reliability of these processes.

INTRODUCTION

The chemical etching of SRF cavities with buffered chemical polish (BCP) has been performed at NSCL/FRIB for fifteen years, and recently, the next step in the evolution of this process was realized with the installation of an automated, recipe-based etching tool. This tool has been used in a preproduction capacity for approximately one year to validate not only the equipment design and functionality, but also to finalize the etching fixtures and procedures that will be used in the processing of all SRF cavities for the FRIB linac.

All four of the FRIB cavity types (beta=0.041 and beta=0.085 quarter-wave resonators (QWR), and beta=0.29 and beta=0.53 half-wave resonators (HWR)) have been etched during this development phase, and these etching procedures have provided valuable data on niobium removal rates, etching uniformity, and cavity frequency shift. These data have been, and will continue to be, applied to the etching of cavities for FRIB coldmasses to improve process throughput and cavity performance.

ETCHING INFRASTRUCTURE

Design and Installation

The NSCL/FRIB chemical etching facility constructed in the year 2001 was designed for the etching of small, elliptical style SRF cavities for research and development purposes. During the processing of large quarter-wave and half-wave SRF cavities for the ReA3, ReA6, and FRIB test cryomodules, the design constraints of the equipment became more apparent, and it was clear that the facility had outlived its useful life expectancy. This

*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.
#malloch@frib.msu.edu

facility was demolished in July 2015 to make way for other project needs. In the SRF Highbay building erected to house technical infrastructure necessary for the FRIB project, a new and more technically advanced chemical etching facility was constructed to accommodate the cavities and processing throughputs necessary for the timely and high-quality production of FRIB SRF cavities [1, 2] (Fig. 1).



Figure 1: FRIB production chemical etching facility.

This etching facility includes a chemical storage fume hood with a maximum capacity of 200 L of BCP, a cavity etching cabinet equipped with custom mechanized fixturing for manipulating cavities during etching procedures, and a parts etching fume hood used for processing cavity subassemblies. All aspects of this system are controlled by means of a programmable logic controller (PLC) with an integrated touch-screen operator interface. To neutralize chemical vapors and gaseous etching by-products, and to maintain negative pressure in the etching facility, a gas scrubber with a maximum flowrate of 57 m³/min is installed and ducted directly into the etching equipment (Fig. 2). Automated louvers are installed in each of the ducting branches to maximize the ventilation in any workstation actively being used by an operator.



Figure 2: Toxic gas scrubber unit.

The safety and process alarm tags in the cavity etch tool control logic are programmed into a visual alarm board posted outside of the etching facility to allow any potential hazards or system faults to be identified prior to entering the work area (Fig. 3). This alarm board is available remotely to aid in the identification and risk-analysis of any potential after-hours alarms. Several alarms are also programmed into an auto-dialer system that transmits email, text, and phone call alarm messages to designated operators if faults remain active without immediate intervention. In addition to the display of alarm statuses, the etch tool's PID/process control screen is also mirrored in this system to permit process status and operational parameters to be monitored by off-site engineering, managerial, or safety staff.

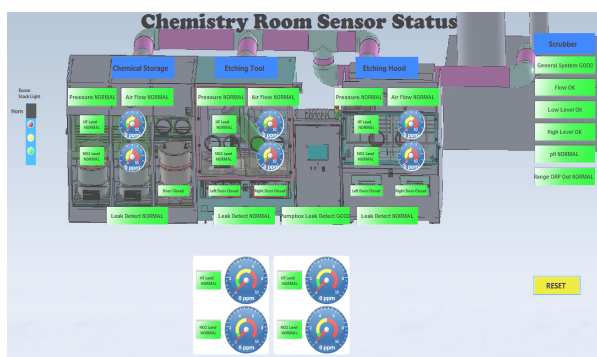


Figure 3: Alarm status board screen.

Equipment Installation and Validation

Prior to the shipment and installation of the etching equipment in June 2014, a week-long factory acceptance test was performed at the vendor's production facility to validate the functionality of the equipment. The chemical etching equipment was subsequently installed in the FRIB etching facility over a span of two weeks. During this installation period, extensive refinement and testing of the mechanical, controls, and safety systems was performed jointly by engineers from FRIB and the vendor. Once installed, the equipment was run through an endurance testing program spanning more than two weeks. Each of the pneumatically-operated control valves was actuated 150 times, and the system was run in an operational state for 24 hours to validate the functionality of the chemical pumping system. The automated acid transfer system was also tested extensively, and the integrity of all of the plumbing joints in the BCP-handling utility compartment were verified three times throughout the endurance testing period. Similarly exhaustive testing was performed on the fixtures used to support and manipulate the cavities during etching.

Fixture Design

There are two categories of etching fixtures used in the FRIB chemical etching tool: cavity and component support fixtures, and BCP handling flanges. While concepts from past etching configurations were carefully considered during the design process, the fixtures

designed for use with the etching tool are entirely new and unique to this system.

The cavity handling fixture is novel, because previously, only stationary tables and support frames could be used to hold cavities during etching. The new cavity handling fixture interfaces with threaded titanium bosses located on the helium vessels of all four FRIB cavity types, can support a maximum load of 400 kg, and has a servo motor and transmission capable of rotating 360° in either direction (Fig. 4) and providing 850 N-m of torque to the shaft of the cavity mounting plate. This stability and rotational functionality allows for a high degree of flexibility with respect to accommodating many different cavities and etching configurations, and ensures sufficient stability while cavities are full of BCP and weigh in excess of 225 kilograms. Additionally, the cavity handling fixture is equipped with heavy-duty locking drawer slides to aid in the loading and unloading of cavities into the etching tool.

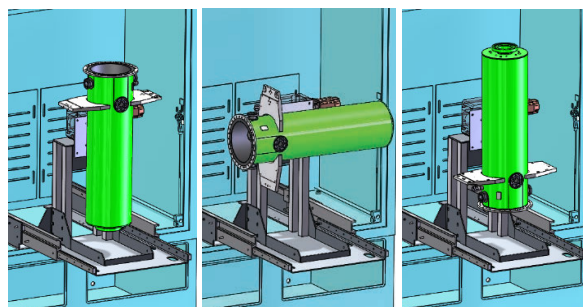


Figure 4: SRF cavity etching rotational fixture.

While there has been a steady progression of improvements to the performance of FRIB cavity etching flanges over the past several years [3, 4], this new system provided the opportunity to address some of the lingering issues with the flanges that were symptoms of the inherent design constraints of the old etching facility. Inconsistent etching uniformity was a lingering problem with cavities etched in this facility. Many of these issues arose from a combination of a lack of space in the cavity mounting area, and a pumping system incapable of supplying adequate acid flowrates to prevent stagnant, low etch-rate pockets of acid inside cavities being etched. The pump installed in the new cavity etch tool is an air-driven Teflon bellows pump with the ability to supply a maximum of 7 bar of pressure and 130 liters per minute of acid flow. While these operational extremes are never reached during cavity etching, the flexibility provided by this powerful system allows for precise tuning of process parameters to ensure consistent, repeatable etching.

Detailed flow analyses were performed during the design process of the BCP-handling flanges to simulate the dispersion patterns and flow paths of BCP during etching (Fig. 5). Each cavity has several unique sets of flanges for controlling the flow direction and BCP liquid level, providing an unprecedented level of process control during cavity etching.

In addition to cavity etching flanges, part etching fixtures have been designed to allow as many as six

tuning plates to be etched simultaneously (Fig. 6), which maximizes production throughput and process efficiency. This fixture allows tuning plates at different stages in the processing workflow (before and after tuning puck welding, final assembly etch, etc...) to be etched together in the same bath of BCP without any time-consuming fixture change-overs.

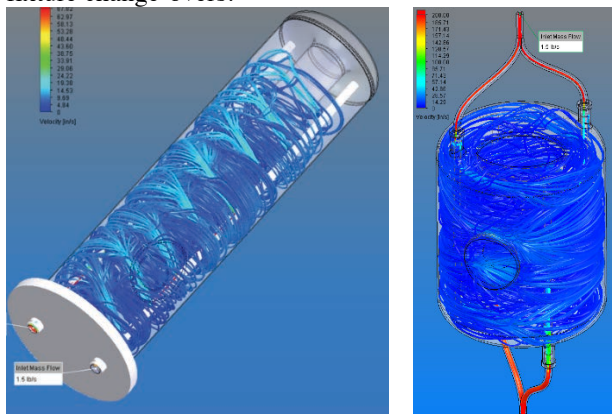


Figure 5: Flow simulation for beta=0.085 quarter-wave (left) and beta=0.53 half-wave (right) cavity etching.

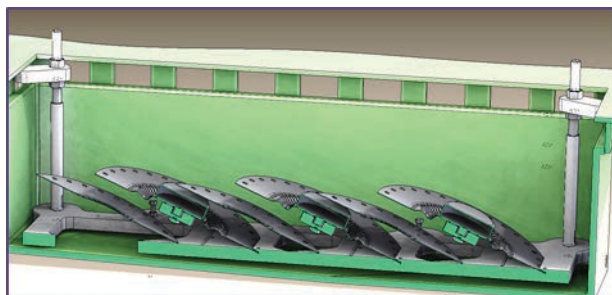


Figure 6: Cross-section of tuning plate etching fixture.

CHEMICAL ETCHING PROGRESS

Process Improvements

Perhaps the most notable improvement to the SRF cavity etching process has been a significant increase in both cavity etch rate and BCP longevity. These two factors have allowed significant cost and time savings to be realized by decreasing the amount of time (and labor) required to etch cavities, and increasing the amount of time that each batch of BCP can be used prior to being discarded due to high niobium concentrations impacting the etch rate. Cavity etch rates are as much as twice as high as they were with the previous cavity etching system, and the usable lifetime of each batch of BCP has increased by more than 60% (Figs. 7, 8).

The increased etch rate in particular has advantageous schedule implications for a project like FRIB that has a large cavity processing workload. This development has allowed multiple cavity and subassembly etch cycles to be performed in a day, whereas only one cavity process was previously possible in a standard workday. By increasing the cavity throughput in the etching facility, it can be ensured that down-stream processes like cavity degassing, high-pressure rinsing, cavity and coldmass

assembly, and RF testing are provided an ample and ready supply of cavities.

An additional time savings has also been realized in the ability of a lone operator to perform all etching operations without a second operator to accompany them. The etching tools are equipped with nitrogen dioxide and hydrogen fluoride gas detectors both inside and outside of the etching zones, airflow and air pressure monitors, fail-safe door latches, short-term emergency backup power, and an emergency shutdown feature that safes the system in the event of process disruption. These safety features, along with durable and easy to use cavity lift-assist equipment, ensure safe and convenient operation of the etching equipment by a single operator, and allows secondary chemistry operators previously committed to chemical work to be provide support in other processing workcenters.

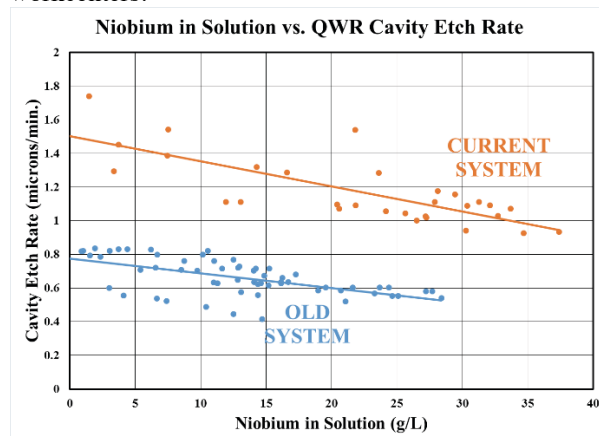


Figure 7: QWR cavity etch rate comparison.

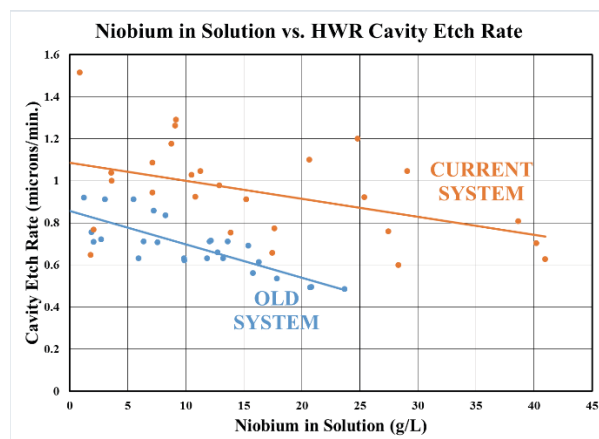


Figure 8: HWR cavity etch rate comparison.

Quarter-Wave Cavities

As all of the FRIB beta=0.041 QWR cavities have been received, as well as several beta=0.085 QWR cavities, these cavities have occupied the majority of the time in the chemical etching facility. More than 40 etch cycles have been run on quarter-wave cavities since the facility became fully operational in November 2014 (Fig. 9). While the cavity dimensions vary, functionally, the

etching procedures used on each of the quarter-wave cavity variants are the same due to similar geometries. To verify the etching uniformity on these cavities, ultrasonic thickness measurements (USTM) have been used extensively to map the material removal amounts resulting from etching. This data-gathering effort has allowed for refinement of etching process variables, and has resulted in etch removal amounts for both quarter-wave cavity types that now consistently fall within 5% of the desired surface removal.

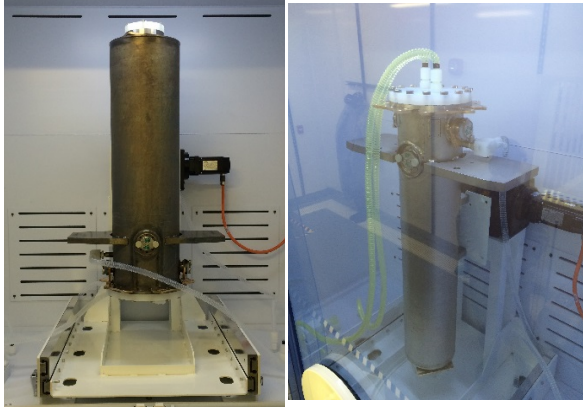


Figure 9: beta=0.085 (left) and beta=0.041 (right) QWR cavity etching.

Half-Wave Cavities

Fewer half-wave cavities have been etched than quarter-wave cavities, but to increase the amount of data available for analysis, these cavity processes have been split into multiple etching cycles (28 total cycles since November 2014) (Fig. 10). For example, the bulk etch of a cavity may be split into two or three cycles with a frequency measurement and USTM between each. While this results in slower processing throughput in the short term, this data will be applied to the etching of FRIB cavities in the future to improve understanding of the etching behavior for further process improvement.

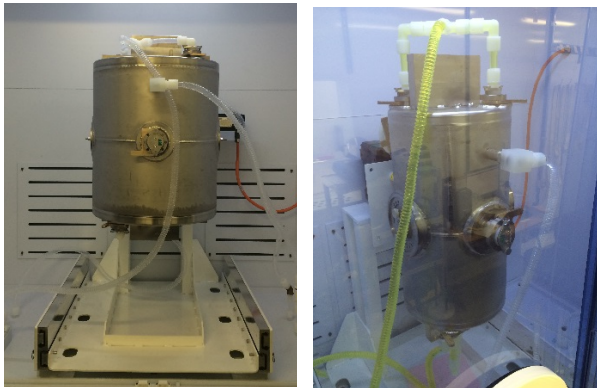


Figure 10: beta=0.29 (left) and beta=0.53 (right) HWR cavity etching.

Unlike the QWR cavities, access is severely limited to the internal surfaces of the HWR cavities. The analysis of the frequency shift in these cavities from etching is more reliable than USTM at determining etching removal amounts. Since frequency measurement has started being

ISBN 978-3-95450-178-6

used as the benchmark for removal estimation, etch process times have gotten significantly more accurate, and surface removals are within 7% of the goal removal amount.

Frequency Adjustment

Due to the relatively narrow mechanical tuning range of the FRIB SRF cavities, the frequency adjustment of cavities through chemical etching (also known as differential or custom etching) has been the focus of intense interest. There are several other methods that are used to control cavity frequency; the use of reference components during the cavity subassembly stack-up process, “virtual” welding, and tuning puck length adjustment to name a few. These processes tend to take place earlier in the cavity fabrication and processing cycle, however, so if any unexpected frequency deviations arise, custom etching may be required.

In the case of the beta=0.041 and beta=0.085 quarter-wave resonator cavities, the frequency shift resulting from bulk etching is quite small, on the order of 0.1-0.3 kHz per micron of removal. However, selectively etching either the high electric field or high magnetic field regions of these cavities will cause a significantly larger shift in frequency for an equivalent etch time (Fig. 11). For beta=0.085 cavities, the cavity for which the most differential etching data is currently available, average frequency shifts of 0.65 kHz/ μm have been observed while etching the high electric field region. Etching performed on the high magnetic field region has resulted in a frequency shift of -1.05 kHz/ μm . Up to the point that mechanical stability of the cavity under vacuum becomes a concern due to decreased wall thickness, removals of up to 200 microns can be used to provide a tuning range of +130 to -210 kHz through custom etching.

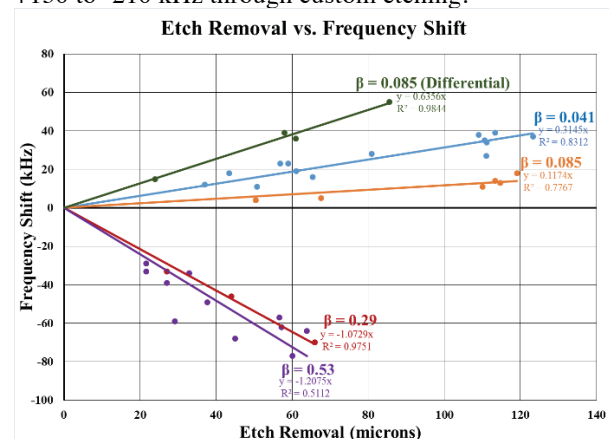


Figure 11: Cavity etching frequency shift analysis.

As it is difficult, if not impossible, to etch the high-electric field regions of the beta=0.29 and beta=0.53 HWR cavities exclusively (that is, to etch only around the beam ports of the cavity without etching the short plate regions), the frequency of these cavities can only be shifted negatively through custom etching. The frequency shift observed during bulk etching, which ranges between -1.0 and -1.2 kHz/ μm , is so large that the bulk etching

procedure doubles as the differential etch, providing a maximum possible frequency shift of approximately -350 kHz. It is critically important during the etching of the half-wave cavities that the cavity frequency does not sink below the goal frequency. Since differential etching cannot be used to increase the frequency on these cavities, the only method available to salvage a jacketed cavity with too low of a frequency is to perform virtual welding on the helium vessel. This can result in significant delays to progression of the cavity to subsequent workcenters, and, by extension, coldmass production. With the large amount of etching data that has been gathered thus far, there is a high degree of confidence in the ability to use differential etching as a consistent and reliable method to tune the cavities required for the FRIB linac.

FUTURE OF ETCHING AT FRIB

More than 330 cavities are required for the FRIB linac, and each of these cavities will require a minimum of two to three etch cycles before they are ready for installation to a coldmass string. This workload will keep the FRIB etching facility operating at full-capacity until the completion of FRIB cavity processing. The design of FRIB's chemical etching equipment was done with FRIB cavities as the primary consideration, however, the cavity etch tool, with its 1.6 m x 1.6 m x 1.1 m cavity mounting area, is large enough to accommodate ILC-style elliptical and other research and development cavities both large and small. This flexibility is beneficial, and will allow cavity etching to continue at FRIB for many years into the future, either in a research or in a production capacity.

SUMMARY

Over the span of more than a decade, significant progress has been made in the development of the SRF cavity etching program at Michigan State University and FRIB. With the design and installation of the new etching equipment, and fabrication of all-new etching fixtures, the foundation for a successful cavity processing run of SRF cavities for the FRIB linac and future research activities is securely in place.

ACKNOWLEDGMENT

The authors would like to thank all members of the NSCL & FRIB staff whose dedicated efforts have made a significant contribution to this work. In particular, Ryan Brunk, Alex Clark, Alyssa Dobrzynski, Daniel Ignatowski, Samuel Miller, John Popielarski, Andy Rauch, Greg Velianoff, Daniel Victory, Evan Wellman, Joseph Whaley, Caleb Whetstone, and Ken Witgen.

REFERENCES

- [1] L. Popielarski, et al., "SRF Highbay Technical Infrastructure for FRIB Production at Michigan State University," in *Proceedings of LINAC2014*, Geneva, Switzerland, 2014, pp. 954-956.
- [2] L. Popielarski, et al., "Low-Beta SRF Cavity Processing and Testing Facility for the Facility for Rare Isotope Beams at Michigan State University," TUPB022, *These proceedings: SRF2015*, Whistler, Canada, 2015.
- [3] L. Popielarski, et al., "Buffered Chemical Polishing Development for the Beta=0.53 Half-Wave Resonator at Michigan State University," in *Proceedings of SRF2011*, Chicago, IL USA, 2011, pp. 526-529.
- [4] K. Elliott, et al., "SRF Cavity Etching Developments for FRIB Cavity Processing," in *Proceedings of PAC2013*, Pasadena, CA USA, 2013, pp. 826-828.