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PLASMA PROCESSING OF SUPERCONDUCTING QUARTER-WAVE RESONATORS USING A HIGHER-ORDER MODE*

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Abstract

Plasma processing is being developed as a method to mitigate possible future degradation of superconducting resonator performance. Plasma processing tests were done on quarter-wave resonators using the fundamental power coupler to drive the plasma. A higher-order mode was used to reduce the mismatch. Before-and-after cold tests on 3 cavities showed a significant reduction in field emission X-rays after plasma processing.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a superconducting ion linac with acceleration provided by 104 quarter-wave resonators (QWRs) and 220 half-wave resonators (HWRs); user operations began in May 2022 [1].

Plasma processing is being developed to help reverse possible future degradation of QWR or HWR performance. In-situ plasma processing would be an alternative to removal and disassembly of cryomodules for refurbishment of each cavity via repeat chemical etching and rinsing, as the latter would be time-consuming and labour-intensive. In-situ plasma processing has been demonstrated at SNS [2]. Other plasma processing development efforts worldwide include work on HWRs [3] and spoke cavities [4].

Plasma processing is done at room temperature to avoid cryo-pumping of gases onto the cavity walls. The input coupling strength for FRIB cavities is such that there is a lot of mismatch at room temperature. Plasma processing tests on FRIB QWRs were done using a spare fundamental power coupler (FPC). As the FPC mismatch decreases with increasing frequency, a higher-order mode (HOM) at about 5 times the accelerating mode frequency was used for plasma processing with the FPC. Plasma processing with an HOM has been previously demonstrated for multicell $\beta = 1$ cavities using HOM couplers [5] and has been studied for spoke cavities using the FPC [4].

FRIB CAVITIES

Jacketed FRIB production cavities were procured from industrial suppliers. Bulk etching (buffered chemical polishing), hydrogen degassing, light etching, high-pressure water rinsing with ultra-pure water, cold testing [6], cryomodule assembly [7], and cryomodule testing [8] were done at FRIB. More information on FRIB cavity parameters and performance can be found elsewhere [6].

With FRIB production finished, present work is oriented toward producing spare cavities and cryomodules, along with improvements in preparation procedures to reduce the incidence of field emission. Plasma processing tests are being done on FRIB QWRs in conjunction with these efforts.

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PLASMA PROCESSING DEVELOPMENT

Development work was done on a FRIB $\beta = 0.54$ HWR (322 MHz) and a FRIB $\beta = 0.086$ QWR (80.5 MHz), driving the plasma with the fundamental mode. Input couplers with custom antenna lengths were used for an approximate match at room temperature. Some of the plasma parameters were inferred from the optical spectrum. More information can be found in a separate paper [9].

HWR with Matched Input Coupler

First plasma ignition and processing tests were done with an HWR. Plasma measurements were done with various gas mixtures and pressures; to determine the best gas parameters for efficient removal of surface hydrocarbons, reaction byproducts were monitored with a residual gas analyzer (RGA). After testing over a wide range of conditions, we inspected the inner surfaces and observed sputtered copper in the RF input port. We were able to remove the sputtered Cu with additional etching.

QWR with Matched Input Coupler

The first before-and-after cold tests of plasma processing were done using this configuration. The cavity (S85-986) had some field emission X-rays in the first cold test. Plasma cleaning was done with a mixture of neon and oxygen. A significant reduction in field emission X-rays was seen in the cold test after plasma processing [9]. Additional plasma processing and cold test iterations were done subsequently.

PLASMA PROCESSING: QWR WITH FPC

The FRIB QWR FPC includes a cold window [10]. Three FRIB $\beta = 0.086$ QWRs were plasma processed with the plasma driven through the FPC. A refurbished FRIB FPC was used, with the antenna position set near the maximum coupling strength ($Q_{ext,1} \approx 1 \cdot 10^{-6}$).

Higher-Order Modes

At room temperature, the FRIB FPCs are weakly coupled, with coupling factors ($\beta_1 = Q_0/Q_{ext,1}$) ranging from $2 \cdot 10^{-3}$ to 0.02 when set for maximum coupling strength. Accordingly, the RF electric field may be higher in the FPC than in the cavity. As seen in Fig. 1, HOM measurements show that the FPC mismatch decreases as the frequency increases. This indicates that, by driving the plasma with an HOM, we can reduce the coupler-field-to-cavity-field ratio. The TEM-$5\lambda/4$ HOM at about 404 MHz was selected

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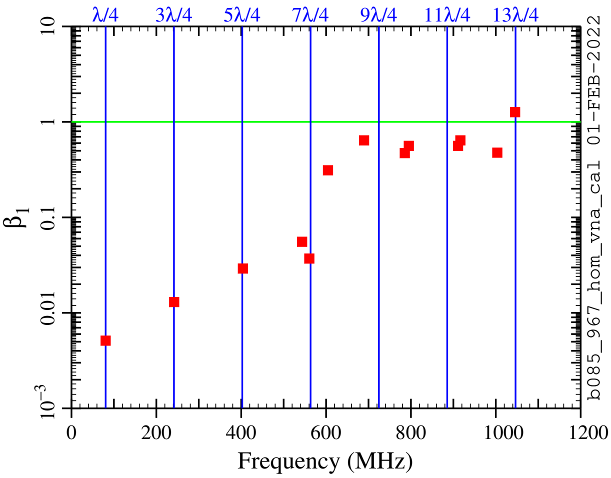

Figure 1: Network analyzer measurements of input coupling factors for some of the modes in a FRIB $\beta = 0.086$ QWR at room temperature (red squares). Blue lines: odd harmonics of the fundamental. Green line: unity coupling.

based on similarity of RF field distribution and availability of RF equipment. As seen in Fig. 2, both the fundamental and the $5\lambda/4$ modes have high fields in the vicinity of the beam's path. We note that, though there is less mismatch as the frequency increases, the RF power needed to ignite the plasma increases as the frequency increases.

Setup

The plasma processing setup is shown in Fig. 3. The gas supply and pumping system was the same as in the development tests [9]. The neon and oxygen gas mixture was flowed into the cavity via mass flow controllers (MFCs, 2.45 mg/min for Ne, 0.13 mg/min for O_2) through a gas filter. The cavity pressure was approximately 100 mtorr. A turbo-molecular pump (TMP) was used to reduce back-streaming of air.

Procedure

Plasma processing was done in about 10 sessions per cavity, each of 1 hour duration, with 1 or more days between sessions. After plasma ignition, the RF input power was reduced to 7 to 20 W for the first cavity and 7 W for the second and third cavities. Photographs of the cavity interior are shown in Fig. 4.

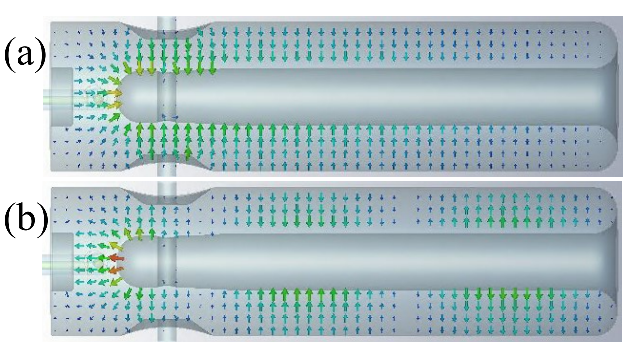

Figure 2: Electric field arrow plots from CST Microwave Studio for the (a) TEM-$\lambda/4$ and (b) TEM-$5\lambda/4$ modes.

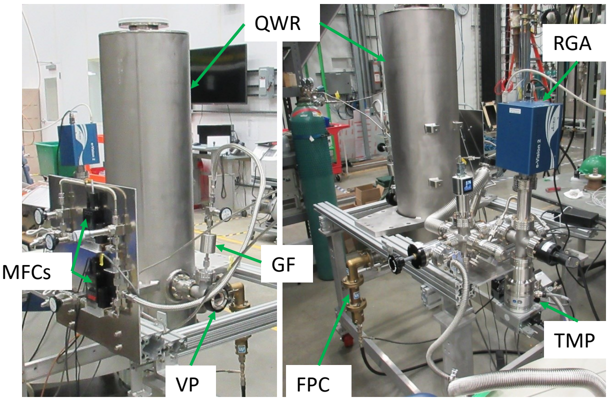

Figure 3: Plasma processing station: gas supply side (left) and pumping side (right). GF: gas filter; VP: viewport.

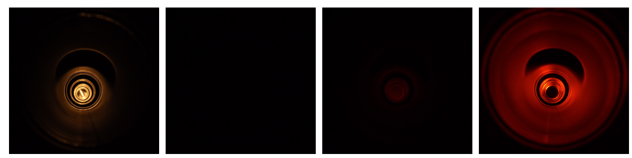

Figure 4: Cavity interior seen through the viewport. Left to right: ambient illumination; low RF field; medium RF field; high RF field.

RGA Measurements

We saw an increase in CO, CO_2, and H_2O and a decrease in O_2 after igniting the plasma. An example of RGA signals during a plasma processing session is shown in Fig. 5. The CO, CO_2, and O_2 typically returned to their base levels within 15 minutes or so, with the H_2O response lasting a bit longer. Though the RGA response went away by the

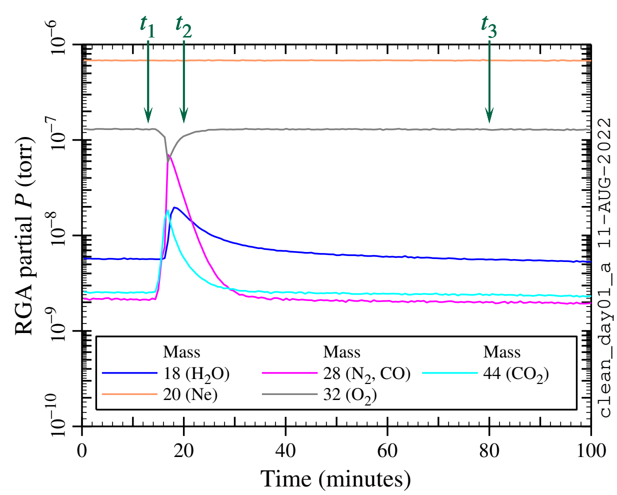

Figure 5: Partial pressures as a function of time for selected masses during the first plasma processing session for the third cavity (t_1: start of RF power ramp-up; t_2: RF power reduction to 7 W after plasma ignition; t_3: RF ramp-down and turn-off).

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end of one plasma session, gas production was seen again when we did another plasma session the next day. Larger RGA responses were seen in the first plasma sessions and when the plasma had been off for more than 1 day.

BEFORE-AND-AFTER COLD TESTS

All 3 QWRs were cold-tested before and after plasma processing with the FPC. Venting was needed to replace the FPC with an antenna suitable for matching in the cold test. Cold test results are shown in Fig. 6 and Fig. 7. There was little change in the quality factor, but all 3 cavities showed a decrease in field emission X-rays after plasma processing. Though the second and third cavities were plasma-processed with the same drive RF power, the second cavity improved more than the third cavity. Note that, in all cases, the field emission X-rays are below the level at which we expect to see a significant decrease in the quality factor [11].

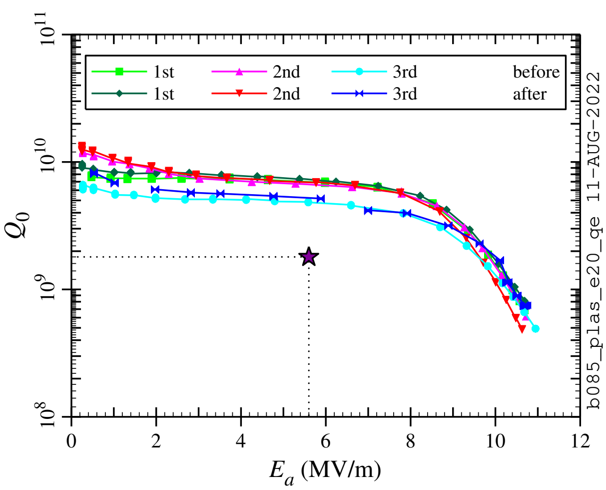

Figure 6: Measured quality factor at about 2 K as a function of accelerating gradient before (light colors) and after (dark colors) plasma processing. Green: first QWR (S85-967); magenta/red: second QWR (S85-979); cyan/blue: third QWR (S85-972).

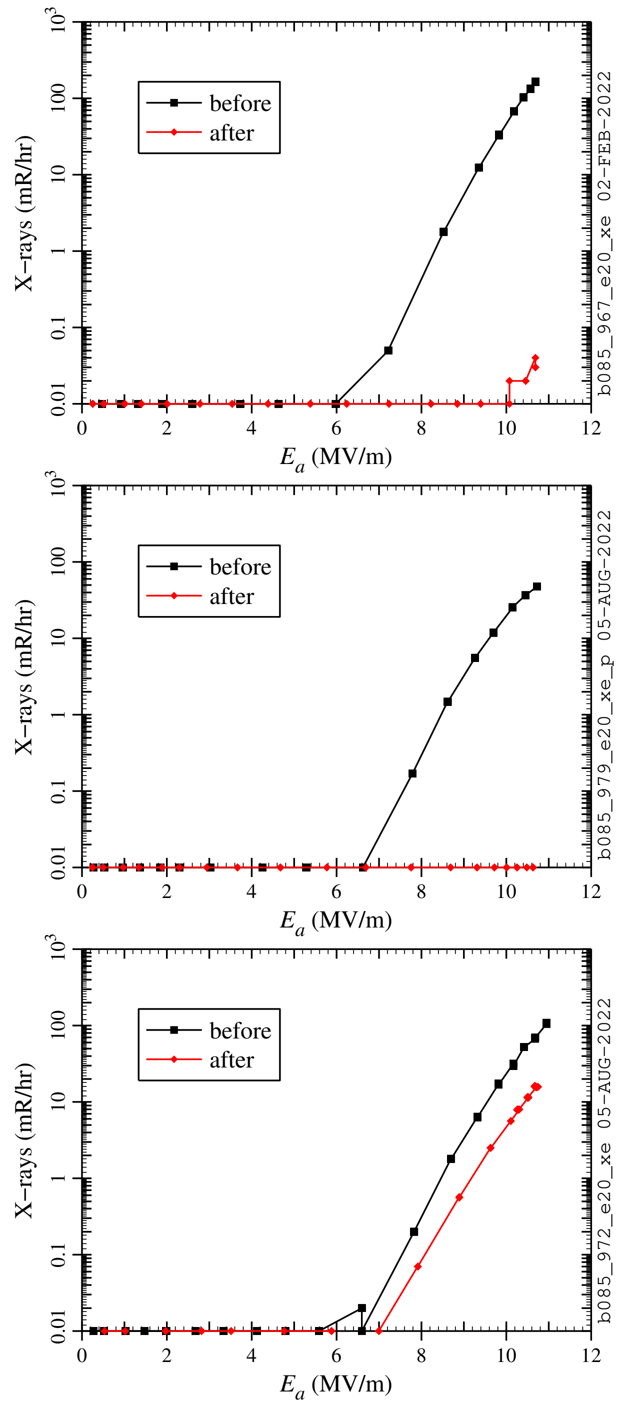

Figure 7: Measured X-rays at about 2 K as a function of accelerating gradient before and after plasma processing: first (top), second (middle), and third (bottom) QWR.

CONCLUSION

Plasma processing trials with before-and-after cold tests were done for 3 FRIB quarter-wave resonators, with the RF delivered via the fundamental power coupler using a higher-order mode. Results so far suggest that plasma processing can be a useful method to reduce field emission. In-situ plasma processing of FRIB cryomodules, if successful, could save significant time and expense if performance degradation occurs during long-term FRIB linac operation.

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REFERENCES

[1] J. Wei *et al.*, "Accelerator commissioning and rare isotope identification at the Facility for Rare Isotope Beams," *Mod. Phys. Lett. A,* vol. 37, p. 2230006, 2022. doi:10.1142/S0217732322300063

[2] S.-H. Kim *et al.*, "Overview of ten-year operation of the superconducting linear accelerator at the Spallation Neutron Source," *Nucl. Instrum. Methods. Phys. Res. A,* vol. 852, p. 20–32, Apr. 2017. doi:10.1016/j.nima.2017.02.009

[3] A. Wu *et al.*, "In-situ plasma cleaning to decrease the field emission effect of half-wave superconducting radio-frequency cavities," *Nucl. Instrum. Methods. Phys. Res. A,* vol. 905, pp. 61–70, Oct. 2018. doi:10.1016/j.nima.2018.07.039

[4] P. Berrutti, "Plasma Cleaning R&D at FNAL," presented at the June 2018 TeSLA Technology Collaboration Meeting, Saitama, Japan.

[5] B. Giaccone *et al.*, "Plasma Processing to Reduce Field Emission in LCLS-II 1.3 GHz SRF Cavities," in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 1231-1238. doi:10.18429/JACoW-SRF2019-FRCAB7

[6] C. Zhang *et al.*, "Certification testing of production superconducting quarter-wave and half-wave resonators for FRIB," *Nucl. Instrum. Methods. Phys. Res.* vol. 1014, p. 165675, Jul. 2021. doi:10.1016/j.nima.2021.165675

[7] C. Compton *et al.*, "Production status of superconducting cryomodules for the Facility for Rare Isotope Beams," in *Proc. SRF'17,* Lanzhou, China, Jul. 2017, p. 928–934. doi:10.18429/JACoW-SRF2017-FRXAA01

[8] W. Chang *et al.*, "Bunker testing of FRIB cryomodules," in *Proc. NAPAC'19,* Lansing, MI, USA, Sep. 2019, pp. 765-767. doi:10.18429/JACoW-NAPAC2019-WEPLM73

[9] C. Zhang *et al.*, "Development of In-Situ Plasma Cleaning for the FRIB SRF Linac," in *Proc. SRF'21: 20th Int. Conf. RF Superconductivity* (in press), Jun.-Jul. 2021, pp. 657-661. doi:10.18429/JACoW-SRF2021-WEPTEV011

[10] T. Xu *et al.*, "SRF Development and Cryomodule Production for the FRIB Linac," in *Proc. NAPAC'16,* Chicago, IL, USA, Oct. 2016, pp. 847-852. doi:10.18429/JACoW-NAPAC2016-WEB3IO01

[11] W. Hartung *et al.*, "Large-scale Dewar testing of FRIB production cavities: results," in *Proc. NAPAC19,* Lansing, MI, USA, Sep, 2019, p. 270–273. doi:10.18429/JACoW-NAPAC2019-MOPLO17