

First plasma processing trial of a quarter-wave resonator cryomodule at the Facility for Rare Isotope Beams

Walter Hartung[✉], Wei Chang, Yoo-Lim Cheon, Kyle Elliott, Sang-Hoon Kim, Taro Konomi, Patrick Tutt[✉], Yuting Wu[✉], and Ting Xu[✉]

Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan, USA



(Received 30 July 2025; accepted 3 December 2025; published 29 January 2026)

Studies of plasma processing for reduction of field emission in quarter-wave resonator (QWR) cryomodules are underway at the Facility for Rare Isotope Beams (FRIB), where a total of 104 QWRs are presently in operation. Driving the plasma with a higher-order mode allows for less mismatch at the fundamental power coupler and higher plasma density. The first plasma processing trial for FRIB QWRs in a cryomodule was conducted in January 2024. In-bunker cold tests of the cryomodule showed a significant reduction in field emission x-rays after plasma processing.

DOI: [10.1103/psx7-jp78](https://doi.org/10.1103/psx7-jp78)

I. INTRODUCTION

Superconducting radio-frequency (SRF) cavities provide high accelerating gradients with low power dissipation for modern particle accelerators, but they cannot always operate in the best possible environment and do not always reach the best possible performance. Plasma processing, developed and widely adopted by the electronics industry for modification of surfaces [1], has been applied to SRF cavities in recent years, with the goal of improving SRF cavity performance or reversing performance degradation. *In-situ* plasma processing provides an alternative to time-intensive and labor-intensive removal and disassembly of cryomodules for refurbishment of each cavity via repeat chemical etching and rinsing.

Pioneering work at the Spallation Neutron Source (SNS) showed that plasma processing can be beneficial for an SRF accelerator [2,3]. Plasma processing studies are now underway at several other facilities [4–17]. Notable recent results include in-cryomodule plasma processing for LCLS-II [11] and in-tunnel plasma processing work at CEBAF [15], both further demonstrating performance improvement with plasma processing. In addition to the work on multicell elliptical SRF cavities for SNS, CEBAF, LCLS-II [9–11], and on ILC-type cavities [5,16,17], plasma processing is being studied for quarter-wave resonators (QWRs) at IJCLab [14], half-wave resonators (HWRs) at IMP [6–8] and Argonne [12], and spoke resonators at Fermilab [4,13].

The Facility for Rare Isotope Beams (FRIB) is an SRF linac which accelerates ions to ≥ 200 MeV per nucleon; user operations began in May 2022 [18]; a beam power ramp-up is ongoing [19]. As the linac contains 104 QWRs (80.5 MHz) and 220 HWRs (322 MHz) [20], the risk of cavity performance degradation due to contamination is a concern for long-term operation. This concern led us to initiate a plasma processing development effort for FRIB cavities in 2020. This paper presents the first results of off-line plasma processing of a spare FRIB QWR cryomodule, with before-and-after cold tests to assess the impact of plasma processing on cryomodule performance. Additional details can be found in a separate report [21].

II. FRIB CAVITIES AND CRYOMODULES

FRIB production cavities were fabricated from sheet niobium; jacketed cavities were delivered by industrial suppliers [22] and then cold tested at FRIB [20] after buffered chemical polishing (BCP) and high-pressure water rinsing (HPWR). Certified cavities were assembled into cryomodules [23] and cold tested at FRIB [24] before installation into the linac tunnel. Radio frequency pulse conditioning has been used to mitigate field emission during cryomodule bunker testing and in the linac [25].

Additional spare cryomodules are presently being fabricated. The first spare $\beta_m = 0.086$ QWR cryomodule was used for the first FRIB cryomodule plasma processing trial ($\beta_m =$ optimum normalized beam speed v/c). The cryomodule contains 8 cavities interleaved with 3 superconducting solenoids, all operating at 4.5 K [26]. Several of the cavities for the spare cryomodule were tested more than once, with iteration on BCP and HPWR in an effort to reduce field emission. All of the cavities had a low-temperature bakeout prior to their final Dewar test.

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

III. PLASMA DEVELOPMENT STAGES

Plasma processing is done with the cavities at room temperature. Major challenges for FRIB cavities are (i) the fundamental power coupler (FPC) mismatch at room temperature, (ii) the absence of higher-order mode (HOM) couplers, and (iii) the limited view of the cavity interior through access ports. These raise concerns about ignition of plasma in the FPC rather than in the cavity, which would risk damage to the FPC or cavity.

The use of a higher-order mode is helpful in reducing mismatch and mitigating the risk of coupler ignition. HOMs have been found useful for the LCLS-II [11] and CEBAF [15] cavities, both of which have more FPC mismatch at room temperature than the SNS cavities. The plasma ignition threshold rf field increases in an approximately linear manner with rf frequency [27], so the rf power required for plasma ignition using HOMs may be larger than that needed for the fundamental mode. The uniformity of the plasma distribution is a concern when using HOMs.

Plasma process development steps for FRIB cavities were described in previous papers [28–30], including first trials with custom antennas, measures to detect and avoid coupler plasma, and first trials of cavity plasma driven via the FPC with a drive frequency ramp-up to increase the plasma density. Most of this development work was done using a neon-oxygen plasma at ~ 100 mTorr.

IV. PLASMA PROCESSING SYSTEM AND METHODS

A. Coupler position

The FPCs for the FRIB QWRs allow for manual coupling adjustment [31], which is straightforward for “on-the-bench” plasma processing. Hence, the FPC was set for stronger coupling in the plasma development stage. However, adjustment of the FPCs in a QWR cryomodule requires venting of the insulating space, removal of access ports, and partial disassembly of the thermal shield and multilayer insulation. Consequently, we kept the FPC in its nominal position for QWR cryomodule plasma processing; this worsens the coupling factor by about a factor of 2 [21] and reduces the maximum plasma density by about a factor of 3.

B. Drive modes

Two HOMs were selected to drive the plasma for the cryomodule trial, the TEM $5\lambda/4$ mode (~ 404 MHz) used in previous bench trials, and the second dipole mode (~ 605 MHz). Fields from CST Microwave Studio [32] are shown in Fig. 1. One would expect high plasma density where the electric field is high, though we observe that the plasma tends to ignite in only one high-field region, which is a disadvantage for HOMs. Previous studies showed analogous behavior in multicell elliptical cavities: if the

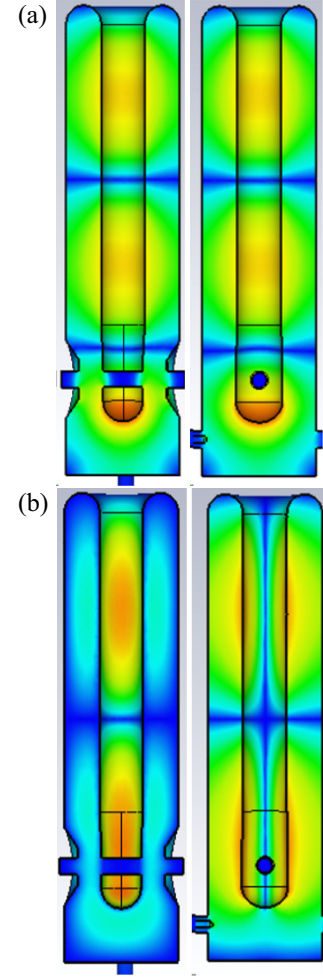


FIG. 1. Sectional views of the FRIB $\beta_m = 0.086$ QWR with intensity maps (blue = low, red = high) of the electric field magnitude for (a) the 404 MHz TEM mode and (b) the 605 MHz dipole mode. The side views (left) show the beam ports and drift tube. The front (“beam’s eye”) views (right) show the rf ports for the input/FPC and pickup probe couplers below the beam line.

TM₀₁₀ π mode is used with the hope of producing a uniform plasma throughout the cavity, the plasma tends to ignite in only one cell [33].

The 404 MHz TEM mode has a favorable plasma distribution, as the plasma consistently ignites in the bottom of the three high-electric field lobes, which provides good coverage of the surfaces likely to produce field emission in operation; however, the coupler mismatch does not allow for very high plasma density (limited by the onset of coupler ignition). This mode still allows for a plasma density more than 300 times higher than that of the fundamental mode. The preferential formation of plasma in the bottom lobe is likely due to the higher electric field at the lower tip of the inner conductor [Fig. 1(a)].

The 605 MHz dipole mode has a less favorable plasma distribution, with plasma likely present in only 1/4 of the cavity, based on bench studies. On the other hand, higher

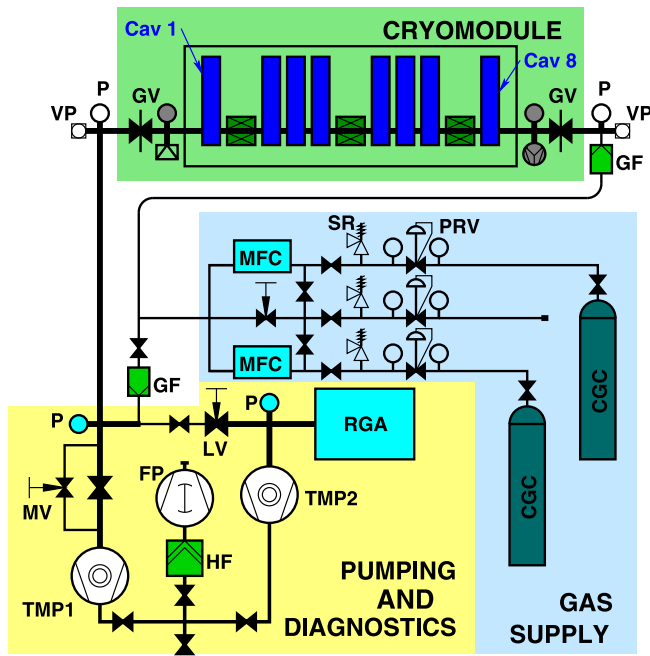


FIG. 2. Schematic of the gas supply and pumping system for cryomodule plasma processing. CGC: compressed gas cylinder; FP: fore pump; GF: gas filter; GV: gate valve; HF: HEPA filter; MFC: mass flow controller; LV: leak valve; MV: metering valve; P: pressure sensor; PRV: pressure regulation valve; RGA: residual gas analyzer; SR: safety relief valve; TMP: turbomolecular pump; VP: viewport. Cyan: signals recorded by the data acquisition system. Gray: components turned off for plasma processing.

plasma density can be reached (limited by the available rf power). We chose this mode because it provided the highest plasma density we could achieve using the same rf components as for the 404 MHz mode.

C. System and interlocks

The circuit for gas supply and pumping is shown in Fig. 2; the rf system is shown in Fig. 3; photos of the setup are shown in Fig. 4. The gas supply and pumping system is similar to the system used in bench trials. Temporary clean-room hoods were used when connecting the gas supply and pumping lines to the upstream and downstream ends of the cryomodule [Fig. 4(d)]. Pressure gauges and viewports were added with the gas supply and pumping connections [Figs. 4(b) and 4(c)]. The cryomodule insulating space was vented to be sure to avoid cavity overheating during plasma processing. As seen in Fig. 2, inlet gas flow rates were set by mass flow controllers. A turbomolecular pump (TMP1) was used to pump process gases and byproducts out of the cavity. The outgoing gas was sampled by a residual gas analyzer, with a leak valve and second turbo pump (TMP2) to provide lower pressure for the RGA.

The rf system is similar to the version used for on-the-bench plasma processing. It includes a 100 W solid state amplifier to drive the plasma and bias T's to ground the

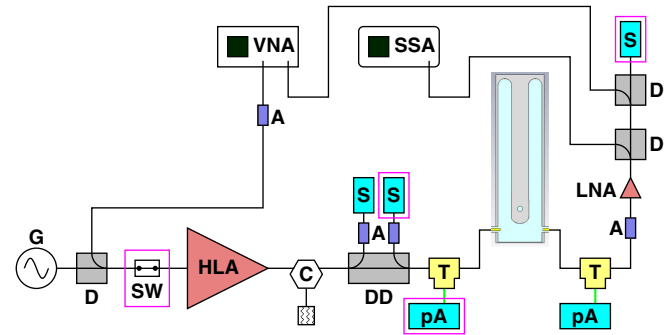


FIG. 3. Schematic of the rf system for cryomodule plasma processing. A: attenuator(s); C: circulator with load; D: directional coupler; DD: dual-directional coupler; G: rf signal generator; HLA: high-level amplifier; LNA: low-noise signal amplifier; pA: picoammeter; S: power sensor; SSA: spectrum analyzer; SW: rf switch; T: bias T; VNA: network analyzer. Signal paths are shown in black (rf) and green (dc). Cyan: signals recorded by the data acquisition system.

couplers' inner conductors and monitor the dc current. We monitored the resonant frequency using a network analyzer (VNA), following the approach developed by the Fermilab team [34].

Coupler ignition produces a sharp increase in the FPC current (I_{FPC}), a drop in the reverse power (P_r), and a drop in the transmitted power (P_t). We added interlocks to inhibit the rf drive in case of coupler ignition: (1) a high $|I_{FPC}|$ interlock, (2) a low P_r interlock, and (3) a low P_t interlock. The interlocks were implemented in software with inhibition of the drive power via an rf switch. Components used for the interlocks are highlighted in magenta in Fig. 3.

D. Procedure and validation

Table I shows the gas parameters we used for cryomodule plasma processing. One gas cylinder contained pure Ar and the other contained an 80%/20% Ar/O₂ mixture (Fig. 2). The resulting 90% Ar/10% O₂ gas mixture at ~ 60 mTorr differs from the 95% Ne/5% O₂ mixture at ~ 100 mTorr used for most of the QWR plasma development. Relative to Ne plasma, an Ar plasma allows plasma ignition at a similar threshold field with lower Ar pressure; this is observed for our QWRs and HWRs at IMP [6] and FRIB [35], as well as for elliptical cavities [34]. Lower gas pressure allows for higher plasma density [35]. Our pressure is lower than used for Ar processing of CEBAF cavities [36], but is within the range studied for PIP-II spoke cavities [13]. The 90% Ar/10% O₂ mixture is within the range previously used for CEBAF cavities [37]. Our mass flow rate corresponds to a molar flow rate of about 1.9 sccm, which is lower than the flow ranges of 5 to 30 sccm used at SNS [2] and Jefferson Lab [36]. A lower flow rate may have the advantage of providing a better signal-to-background ratio for the RGA. We must

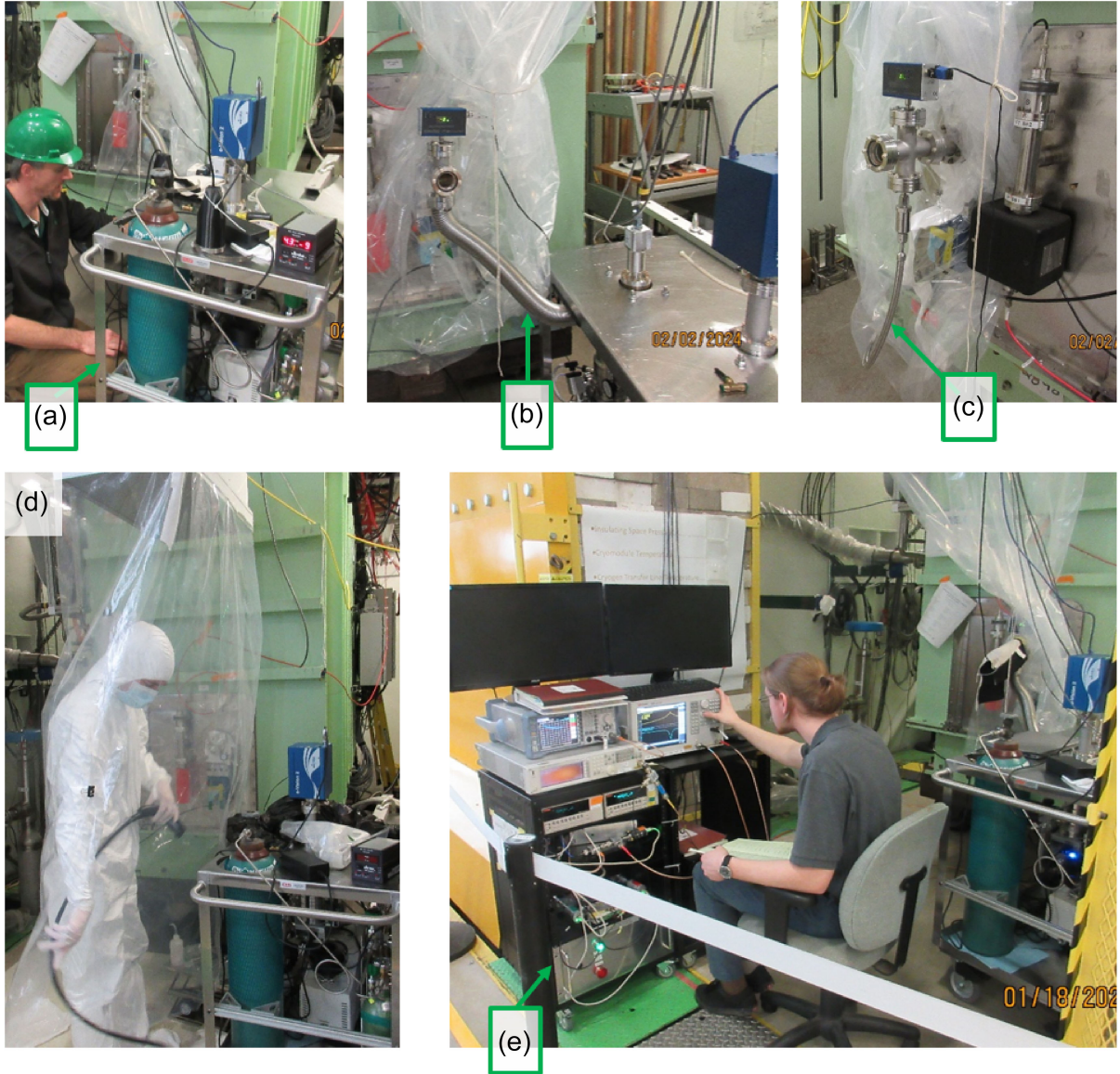


FIG. 4. Cryomodule plasma processing: (a) gas supply/pumping cart; (b) pumping line connection; (c) gas supply line connection; (d) clean-room hood for beam line connections; and (e) rf cart for plasma generation and monitoring.

emphasize that we have not yet carried out systematic studies to identify an optimum gas mixture and flow rate for plasma cleaning of FRIB cavities.

Plasma processing steps were (i) ramp-up the rf power and ignite cavity plasma, (ii) set the rf power to the desired level, (iii) shift the drive frequency up to increase plasma

density, and (iv) process with continuous wave (cw) rf power for 1 h.

Commissioning and validation of the new plasma processing system, procedures, and interlocks were done via bench plasma processing of a FRIB QWR (S85-982) prior to starting work on the cryomodule. Before-and-after cold tests showed no field emission x-rays before plasma processing, and none after plasma processing.

In the cryomodule (SCM813), 5 iterations per cavity were done, using one or both modes (consecutively), for a total of 5 or 10 h of plasma processing per cavity. Processing was done on 4 cavities (5–8) which showed field emission x-rays. The remaining cavities (1–4) were not treated with plasma, but all cavities were checked in the before-and-after cold tests (Sec. VI).

TABLE I. Process gas parameters.

Inert gas	Argon (Ar)
Reactive gas	Oxygen (O ₂)
Inert gas flow rate	2.934 mg/min
Reactive gas flow rate	0.326 mg/min
Cavity pressure	~ 58 mTorr ($\sim 7.7 \times 10^{-5}$ bar)

TABLE II. Measured forward power (P_f), drive frequency shift (Δf_d), and calculated power dissipation (P_d) during cryomodule plasma processing; N_{CIT} = number of trips due to coupler ignition (not including trips during frequency limit measurements).

Cavity	404 MHz				605 MHz			
	P_f	Δf_d	P_d	N_{CIT}	P_f	Δf_d	P_d	N_{CIT}
	(W)	(MHz)	(W)		(W)	(MHz)	(W)	
8	12.0 ± 1.2	$1.0 \rightarrow 0.8$	0.15 ± 0.012	6	10.8 ± 0.5	$4.2 \rightarrow 3.5$	0.53 ± 0.05	0
7	11.9 ± 1.2	0.8	0.14 ± 0.011	2	...	...	...	...
6	...	...	...	...	10.9 ± 0.5	$3.9 \rightarrow 3.8$	0.55 ± 0.06	0
5 initial	12.7 ± 1.3	$0.9 \rightarrow 0.8$	0.16 ± 0.013	4	15.4 ± 0.7	3.6	0.65 ± 0.07	0
5 final	12.2 ± 1.2	0.8	0.17 ± 0.013	1	22.5 ± 1.0	$4.9 \rightarrow 5.1$	0.83 ± 0.08	1

V. PLASMA PROCESS MEASUREMENTS AND MONITORING

A. Radio frequency power and frequency shift

Summary information about the forward power, drive frequency shift, and power dissipation during plasma processing is provided in Table II. We processed near the maximum frequency shift (~ 0.9 MHz for the 404 MHz mode and ~ 3.5 MHz for the 605 MHz mode) to maximize the plasma density. Near the frequency limit, the drive frequency is approximately equal to the shifted resonant frequency. The plasma density can be inferred from the resonant frequency shift, which is a result of the decrease in the effective permittivity due to the plasma [1,38]. For a uniform plasma density, the electron number density n_e is related to the unperturbed resonant frequency f_0 and perturbed resonant frequency f via

$$n_0 = 4\pi^2 \frac{\epsilon_0 m_e}{q_e^2} (f^2 - f_0^2), \quad (1)$$

where ϵ_0 is the permittivity of free space, m_e is the electron mass, and q_e is the electron charge. We calculate $n_e \approx 0.9 \times 10^{13} \text{ m}^{-3}$ for the 404 MHz mode and $n_e \approx 5 \times 10^{13} \text{ m}^{-3}$ for the 605 MHz mode. As the plasma distribution is not uniform, these densities are approximate, weighted by the drive mode's field distribution.

The error estimates for P_f and P_d in Table II are based on the estimated systematic errors in the rf power measurements (Appendix A); P_d was calculated indirectly (Appendix B 1). The P_f and P_d values are averaged over a total of 5 h of processing. An exception is cavity 5, which we processed with lower P_f and Δf_d in the initial rounds (1–2) and higher P_f and Δf_d in the final rounds (3–5); two rows are accordingly provided for cavity 5 in Table II. Plots of P_f and P_d as a function of time are included in Appendix C. We observe some increase in P_d over time, correlated with a more pronounced increase in the rf stored energy U . The increase in U is more noticeable for the 404 MHz mode, being of order 2 dB.

The values of P_d in Table II include both the power dissipation in the walls of the cavity and the power

dissipation by the plasma (P_x). We estimate $P_x = 0.75P_d$ for the 404 MHz mode and $P_x = 0.9P_d$ for the 605 MHz mode; the basis for these estimates is discussed in Appendix B 2. Plots of P_x as a function of time are included in Appendix C. Generally P_x tracks P_d closely, though this may be a result of the underlying assumptions.

We measured the “frequency limits” for each cavity before the first and after the third round of processing. Some examples are shown in Fig. 5. In these measurements, we ramped up the rf power while driving the mode on resonance, ignited cavity plasma, adjusted the forward power, ramped up the drive frequency to measure the maximum frequency shift before loss of cavity plasma, and repeated the steps for different P_f values. As seen in Fig. 5, we are able to achieve a higher frequency shift (and hence a higher plasma density) with higher rf power up to the coupler ignition threshold.

For the 404 MHz mode, we transitioned to coupler plasma at high forward power [Fig. 5(a), red circles]; otherwise, we transitioned to neutral gas at the frequency limit. Thus, coupler ignition limits the plasma density, with the highest plasma density obtained for $P_f \sim 11$ to 12 W. For the 605 MHz mode, the highest plasma density is obtained with the highest forward power.

Initially, we were able to reach higher frequency shift (Fig. 5, magenta triangles), but we found that the plasma was not stable enough for 1-h processing sessions. After 3 iterations of plasma processing, we measured lower frequency limits (Fig. 5, cyan circles). The ranges for Δf_d in Table II reflect these trends.

The red squares and blue diamonds in Fig. 5 indicate the drive frequency and power used for plasma processing. The horizontal spread is due to a downward drift in P_f over 1 h. We tried to find a balance between processing at the highest possible Δf_d versus processing with lower Δf_d for reduced risk of plasma extinction or coupler ignition. We often had to back off on Δf_d during plasma iterations, as seen in Fig. 5(a). The dipole mode in cavity 5 [Fig. 5(b)] was an exception in which we were able to process with higher P_f and higher Δf_d in later iterations, while maintaining a comfortable margin away from plasma extinction.

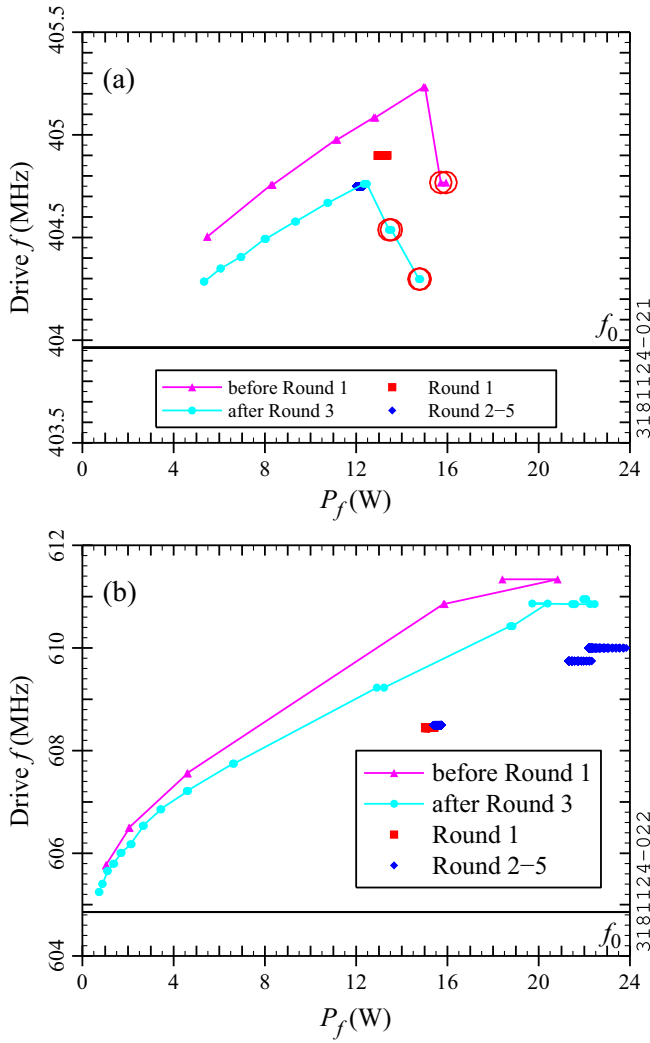


FIG. 5. Forward power and drive frequency for cavity 5 using (a) the 404 MHz TEM mode and (b) the 605 MHz dipole mode. Light markers: maximum frequency shift with cavity plasma. Red circles: coupler ignition. Dark markers: drive frequency and forward power during plasma processing. Black lines: unshifted resonant frequency (f_0). Note the different vertical scales for the two modes.

B. Monitoring of reaction by-products

As shown in Fig. 6, peaks in the RGA signals for mass 44 (CO_2) were seen with plasma on; the signals decreased with time and with iterations. Mass 28 (CO or N_2) showed similar behavior [21]. The peaks tended to drop to lower values when we used both the 404 MHz and the 605 MHz modes. Signals were produced not only with steady plasma, but also when we adjusted the rf power and frequency shift for frequency limit measurements prior to the first iteration and after the third iteration. The RGA response tended to be larger for the 605 MHz mode, even though processing was done with the 404 MHz mode first.

Figure 7 compares several RGA signals for the first round of plasma processing on cavity 5. Mass 28 and mass

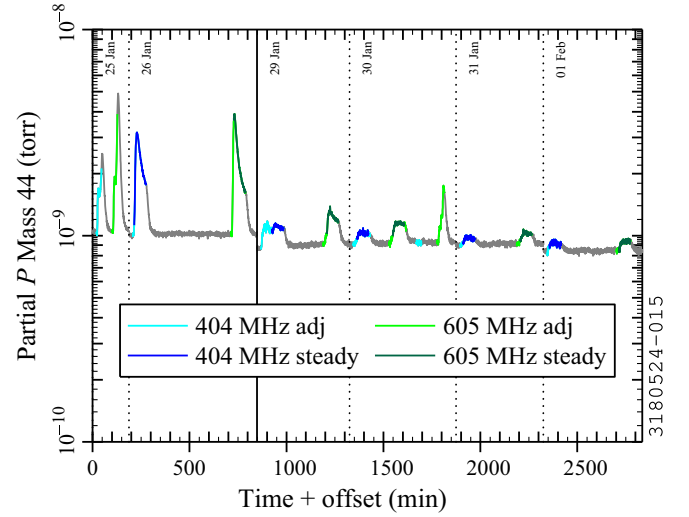


FIG. 6. RGA signals for mass 44 during plasma processing of cavity 5. Dark blue, dark green: steady plasma; light blue, light green: adjusting drive power and drive frequency; gray: plasma off. The time axis is adjusted to focus on intervals with plasma on (vertical lines indicate temporal “cuts”).

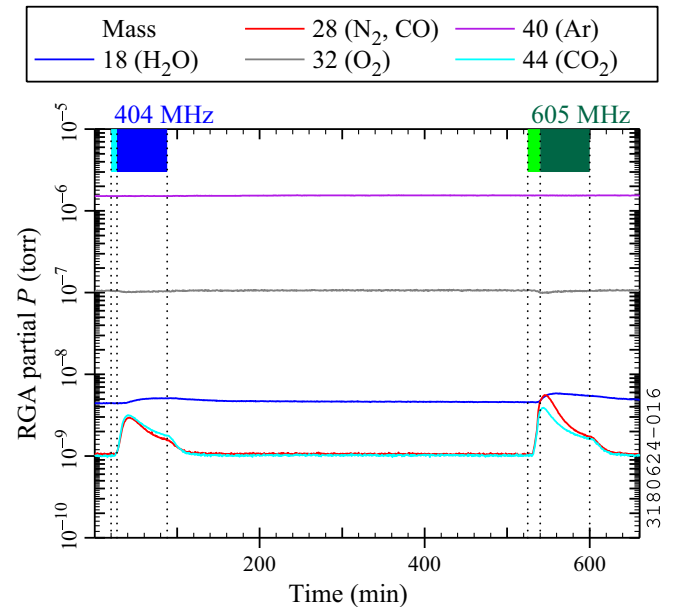


FIG. 7. Enlarged view of RGA signals for selected masses in the first round of plasma processing for cavity 5. The shaded areas and dotted lines indicate rf power and frequency ramp-ups (lighter shades) and steady plasma (darker shades).

44 show the largest response. A small increase in mass 18 (H_2O) can be seen, with a slower response time, which may indicate that heating of the cavity walls by the plasma produces water. A small decrease in mass 32 (O_2) can be seen, evidently due to O_2 consumption as CO_2 and CO are produced. The signal for mass 40 (Ar) remains steady. Though changes are clearly visible in the first round,

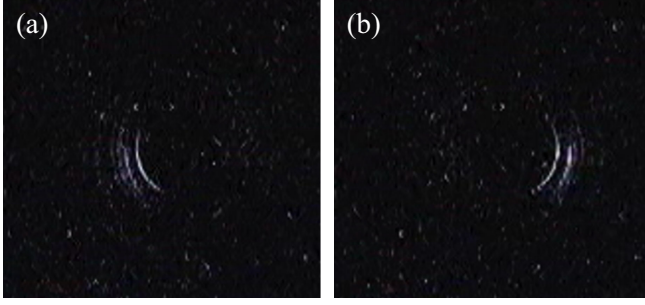


FIG. 8. Images of the plasma in cavity 8 driven by the 605 MHz mode in (a) round 3 and (b) round 4.

mass 18 and mass 32 showed little or no response to the plasma in subsequent rounds.

C. Plasma monitoring: Light and current

We monitored the light from the plasma using viewports on the ends of the cryomodule (as seen in Fig. 2). Figure 8 shows light from the 605 MHz mode. There is a clear left-right asymmetry, indicating that the plasma is present in the left or right lobe of the dipole mode [per Fig. 1(b), front view], but not both. Similar behavior was seen in the bench trials. In the 404 MHz case, the light was rather dim, but was more left-right symmetric [21], consistent with the field distribution [Fig. 1(a)].

The measured current from the FPC with steady plasma is shown in Fig. 9. Time cuts, indicated by vertical lines, are used to focus on the steady-plasma intervals. For the 404 MHz mode [Fig. 9(a)], I_{FPC} started out positive and slowly drifted down to a steady-state value of order -200 nA, though sometimes showing a jump between plasma iterations. We can speculate that the downward drift in I_{FPC} could be due to reduction in the secondary electron yield of the copper FPC antenna.

In the 605 MHz case [Fig. 9(b)], $|I_{\text{FPC}}|$ tended to be of order $1 \mu\text{A}$, 100 nA, or 1 nA, correlated with the light distribution. For example, $|I_{\text{FPC}}|$ was high when reflected light was seen on the left [Fig. 8(a)] and lower when reflected light was seen on the right [Fig. 8(b)]; the yellow highlights in Fig. 9(b) indicate the intervals during which the still images of Fig. 8 were recorded. As the FPC is on the right side relative to the photos, this makes sense—reflected light opposite the FPC due to plasma on the FPC side of the cavity is correlated with a larger $|I_{\text{FPC}}|$. The drift in I_{FPC} over time for the 605 MHz mode is less pronounced than for the 404 MHz mode.

Our diagnostics support the inferences that, for the 404 MHz TEM mode, we always ignite the bottom portion of the cavity, where the surface electric field is highest. For the 605 MHz dipole mode, there is some randomness as to which portion of the cavity ignites. The cases with very low $|I_{\text{FPC}}|$ likely correspond to plasma distributions in the upper half of the cavity, far from

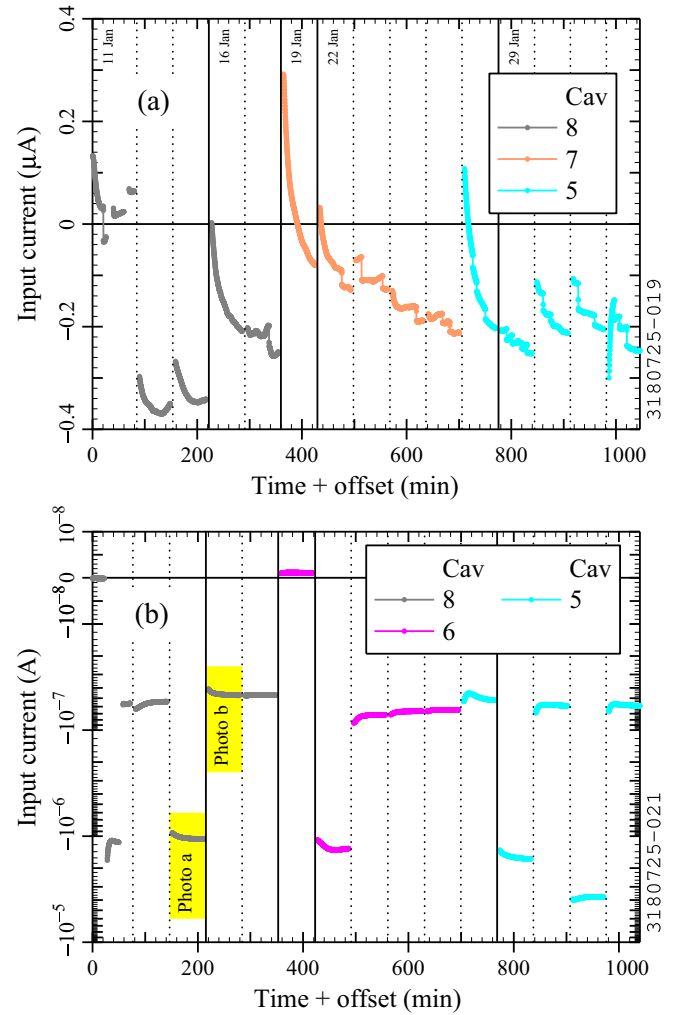


FIG. 9. Measured dc current collection by the FPC as a function of time with steady plasma for (a) the 404 MHz mode and (b) the 605 MHz mode.

the FPC. When measuring the dipole mode frequency limits (Sec. VA), we did not see any change in the maximum drive frequency shift for different plasma locations (though likely we would if the frequency shift was limited by coupler ignition).

D. Plasma ignition thresholds

Plasma processing iterations and frequency limit measurements allowed us to measure the cavity plasma ignition threshold repeatedly. The measured forward power at ignition (P_f^*) was ~ 23.5 W for the 404 MHz mode and ~ 4.8 W for the 605 MHz mode. The calculated values of stored energy at ignition (U^*) were $\sim 2.9 \mu\text{J}$ for 404 MHz and $\sim 5.4 \mu\text{J}$ for 605 MHz. Based on the CST model, we estimate peak surface electric fields at ignition of 14 kV/m for 404 MHz and 18.5 kV/m for 605 MHz. A statistical analysis of these results and uncertainty estimates can be found in Ref. [21].

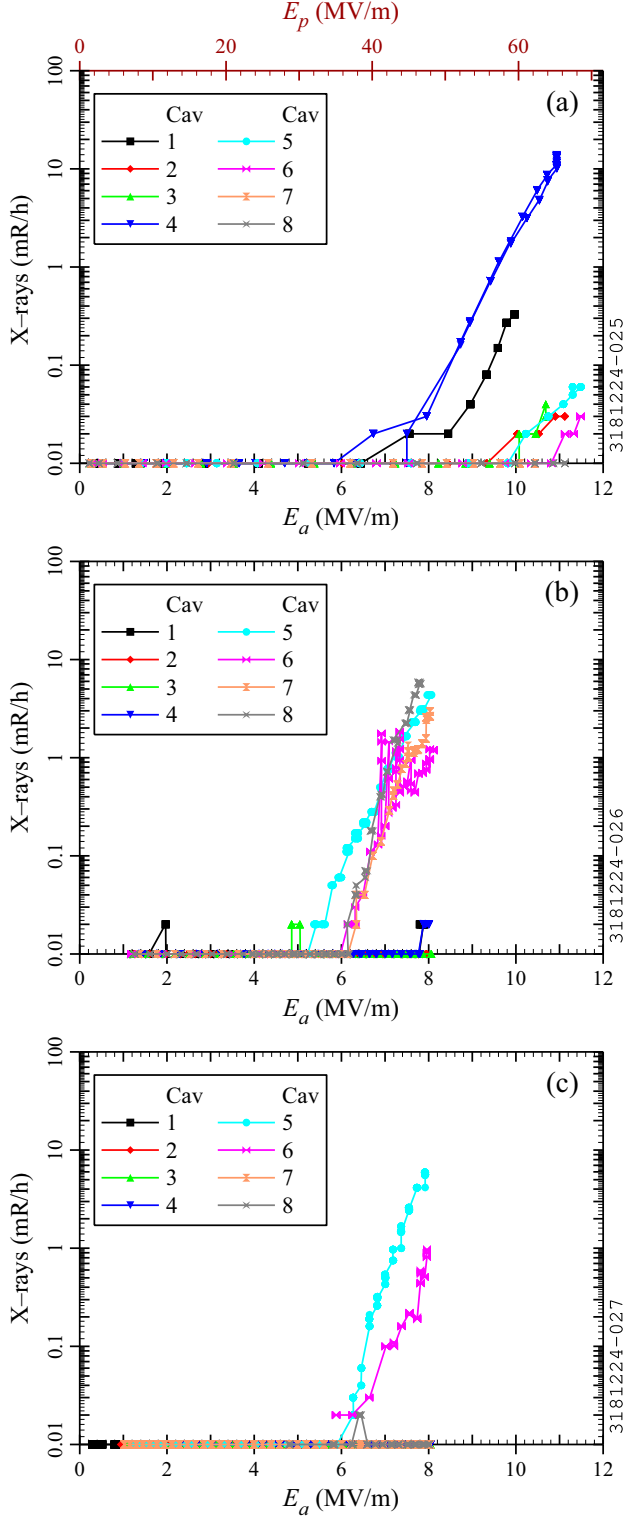


FIG. 10. Measured x-rays as a function of rf field in cold tests: (a) cavity certification tests; bunker tests (b) before and (c) after plasma processing. The background x-ray level is 0.01 mR/h, with signals above ~ 0.02 mR/h being significant. E_a = accelerating gradient; E_p = peak surface electric field.

VI. BEFORE-AND-AFTER COLD TESTS

Cold testing of the cryomodule was done in the test bunker before and after plasma processing. The cryomodule was installed in the FRIB driver linac in the Summer 2024 maintenance period in order to refurbish one of the original QWR cryomodules. In-tunnel cold testing of the cryomodule was done in September 2024.

A. Field emission

Figure 10(a) shows x-ray measurements from the cavity certification tests before installation in the cryomodule. The cavities showed no field emission x-rays below $E_a = 7$ to 8 MV/m. Figure 10(b) shows measurements in the cryomodule before plasma processing. Cavities 5 through 8 show x-ray onset fields of 5 to 6 MV/m, likely due to some contamination introduced between the cavity tests and the bunker test. (High-risk in-clean-room steps between cavity testing and bunker testing include venting of the cavity, installation of the FPC, and assembly of the cavity onto the cold mass.)

Figure 10(c) shows the cold test results after plasma processing of cavities 5 through 8. Table III provides summary information about processing and FE onsets. The unprocessed cavities (1–4) showed background x-rays before and after. Cavity 7 (orange hourglasses) and cavity 8 (gray crosses) improved significantly after processing; cavity 5 (cyan circles) showed a small improvement; and cavity 6 (magenta bow-ties) showed similar performance before and after processing. Thus, the FE was reduced after plasma processing for 3 out of 4 cavities.

X-ray measurements showed no performance degradation between the final bunker test and the tunnel test (administratively-limited to $E_a = 6.7$ MV/m). Cavity 5 may have improved a bit, as it showed no x-rays in the tunnel test. The field emission onset for cavity 6 was similar.

We infer that processing with only the 605 MHz mode (as was done for cavity 6) may be less effective for FE mitigation. However, it is difficult to draw strong

TABLE III. Cryomodule plasma processing modes, durations, and field emission onsets in cryomodule cold tests.

Cavity	Mode(s) (MHz)	Total process time (h)	FE onset E_a (MV/m)	
			Before	After
8	Both	~ 10	~ 6.0	≥ 8.0
7	404	~ 5	~ 6.2	≥ 8.0
6	605	~ 5	~ 6.0	~ 6.0
5	Both	~ 10	~ 5.3	~ 6.0

conclusions based on four cavities; we note that cavity 5 and cavity 8 had the same treatment with different results.

B. Multipacting

The $\beta_m = 0.086$ QWR has a multipacting (MP) barrier at $E_a \sim 0.75$ MV/m [20]. Figure 11(a) shows the time to condition the high barrier in the bunker test before plasma processing (dark green squares) and in the tunnel test after plasma processing. After plasma processing, cavities 5 through 8 conditioned more rapidly (purple triangles), in contrast to cavities 1 through 4, which were not plasma processed (gray diamonds).

As the high barrier may condition more rapidly with higher rf power, the conditioning time alone is not the best indicator of barrier strength. Hence Fig. 11(b) shows the integral over time of the estimated power dissipated in the

high barrier during conditioning. The trends are consistent: less conditioning energy is needed after plasma processing (purple triangles), in contrast to the unprocessed cavities (gray diamonds).

Thus, there is a clear weakening of the high barrier due to plasma processing. Interestingly, the easiest conditioning case is cavity 6, which was plasma processed with the 605 MHz dipole mode only, with no significant reduction in FE x-rays.

Figure 11 shows longer in-tunnel conditioning times for the cavities which did not receive plasma processing. This could be due to migration of H_2O from the processed cavities to the unprocessed cavities. As seen in Fig. 2, the gas flow was oriented such that the reaction by-products were pumped through the unprocessed cavities.

VII. CONCLUSION

Efforts are underway to develop *in-situ* plasma processing capability for the FRIB superconducting linac. A first plasma processing trial was done on a spare FRIB quarter-wave resonator cryomodule using two higher-order modes to drive the plasma. Before-and-after cold tests showed a significant reduction in field emission and a significant reduction in the time needed to condition the high multipacting barrier after plasma processing.

The TEM $5\lambda/4$ (~ 404 MHz) mode appears well suited for reduction of field emission via plasma processing; a dipole mode at ~ 605 MHz appears helpful for multipacting but less useful to reduce field emission. We are able to reach higher plasma density and higher power transfer into the plasma with the dipole mode, but the plasma distribution appears less favorable for cleaning surfaces that are likely to produce field emission.

We are investigating other HOMs and “dual-tone” plasma generation [39] for their potential to provide more effective processing. We plan to do a first plasma processing trial in the FRIB tunnel in the next long maintenance period. Plasma processing shows good potential to save significant downtime and refurbishment labor if performance degradation occurs during long-term FRIB linac operation.

ACKNOWLEDGMENTS

Early FRIB plasma development work was led by Cong Zhang. John Popielarski provided valuable guidance and support for the FRIB plasma efforts until his untimely passing in 2022. Sara Zeidan assisted with plasma measurements and development. We thank Pete Donald, James Erdelean, Dave Norton, John Schwartz, and Dean Thelan for their support and assistance. Igor Nesterenko provided valuable help and guidance with digital cameras and optics for plasma imaging and monitoring. Our work is a collaborative effort with the FRIB cryogenics team, the FRIB cavity preparation team, and the rest of the FRIB laboratory. We thank the plasma teams at Oak Ridge National Laboratory,

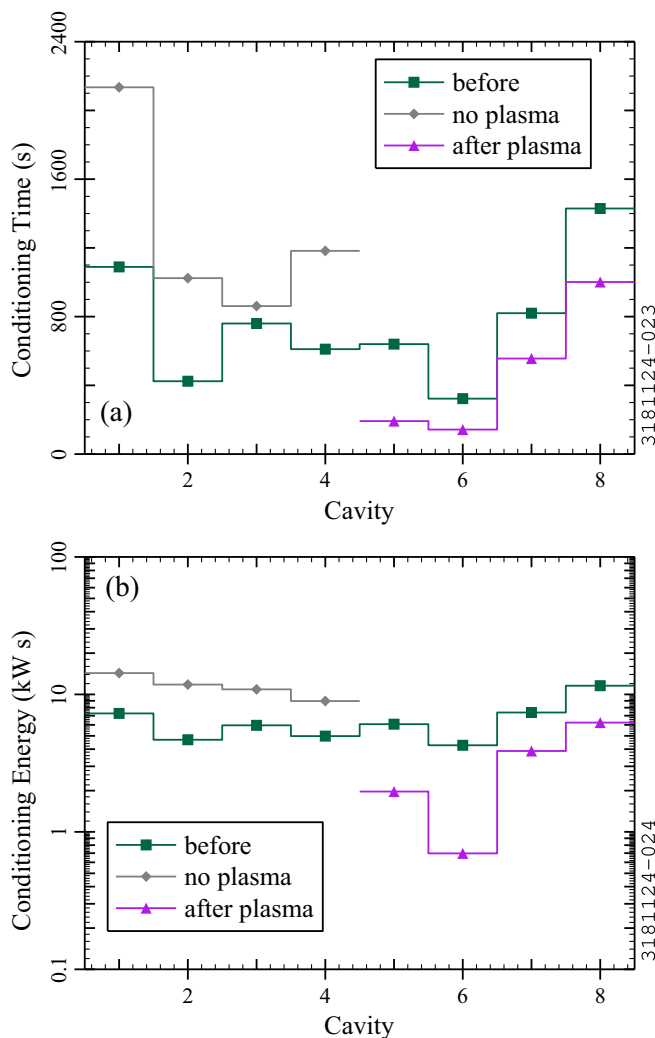


FIG. 11. High multipacting barrier conditioning statistics from cryomodule cold tests: (a) time to condition and (b) time integral of power dissipation into MP. Green squares: before plasma processing. Purple triangles, gray diamonds: after plasma processing of cavities 5 through 8.

Jefferson Laboratory, Fermilab, IJCLab, Argonne National Laboratory, and Brookhaven National Laboratory for useful discussions, information sharing, and suggestions. We are especially thankful to colleagues at Oak Ridge and Fermilab who shared their plasma processing expertise. The encouragement from Fermilab/BNL colleagues to implement VNA monitoring of the resonant frequency, explore additional higher-order modes, and consider lower gas pressures was particularly valuable for our development work. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Cooperative Agreement DE-SC0023633. Additional support was provided by the State of Michigan and Michigan State University.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: ERROR ANALYSIS: RF POWER MEASUREMENTS

An analysis was done to estimate the systematic errors in the measured rf power values (P_f , P_r , P_t). The results were used to propagate the errors to the calculated values of stored energy (U) and power dissipation (P_d). The uncertainties in P_f and P_d in Table II and the systematic error estimates for the ignition thresholds (P_f^* , U^*) are based on this analysis.

1. Uncertainty evaluation: P_f and P_r

Directivity errors and mismatch are the major sources of systematic error for our measurements of P_f and P_r . These sources were considered in recent analyses for measurements on SRF cavities by Holzbauer and colleagues [40,41]. In our case, we do not consider the mismatch from imperfect rf components to have a major impact on the measured values of $Q_{\text{ext},1}$, $Q_{\text{ext},2}$, and the low-field Q_0 , as we are able to obtain them from network analyzer measurements without additional components such as circulators and bias T's in the circuit. Hence we are concerned primarily with the dual-directional coupler directivity and mismatches between the dual-directional coupler and the cavity due to their adverse impact on the overall directivity.

A vector method can, in principle, be used to correct for directivity [41]; however, we are not able to apply such a method, as we are not equipped to measure rf phases.

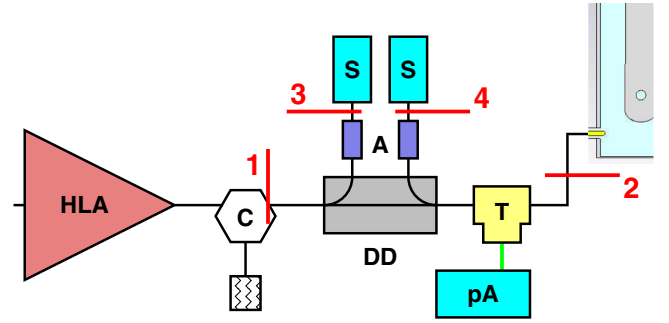


FIG. 12. Detail of the plasma processing rf system schematic. Red lines: planes for measurements to characterize the directivity and mismatch between the dual-directional coupler and the FPC. A: attenuators; DD: dual-directional coupler; pA: picoammeter; S: power sensor; and T: bias T.

Likewise, we do not consider the correlations between the forward and reverse systematic errors.

Figure 12 shows an enlarged view of the rf system where P_f and P_r are measured. For the error analysis, we did additional measurements on the portion of the circuit delimited by the red lines. The circulator is not included, as it is upstream of the dual-directional coupler, so that its mismatch does not adversely affect P_f and P_r measurements (though the circulator mismatch can produce “ripple” in the forward power reaching the cavity as the drive frequency varies). The bias T is included, as it is downstream of the dual-directional coupler and hence its mismatch affects the measured values.

Referring to Fig. 12, we measure the forward scattering parameters (S_{21} , S_{31} , S_{41}) with an incident forward wave at port 1 and the reverse scattering parameters (S_{12} , S_{32} , S_{42}) with an incident reverse wave at port 2, with a matched load to terminate unused ports. We consider the relationship between the forward and reverse amplitudes at plane 2 ($V_{f,2}$, $V_{r,2}$), representing the signals to and from the cavity, and the signal amplitudes ($V_{fs} = V_3$, $V_{rs} = V_4$) reaching the power sensors. In terms of scattering parameters, we can write

$$V_{fs} = V_3 = \frac{S_{31}}{S_{21}}(V_{f,2} + \epsilon_f V_{r,2}), \quad (\text{A1})$$

$$V_{rs} = V_4 = S_{42}(\epsilon_r V_{f,2} + V_{r,2}), \quad (\text{A2})$$

where

$$\epsilon_f \equiv \frac{S_{32}S_{21}}{S_{31}}, \quad (\text{A3})$$

$$\epsilon_r \equiv \frac{S_{41}}{S_{21}S_{42}}. \quad (\text{A4})$$

In the expressions for ϵ_f and ϵ_r , the coupling parameter is in the denominator and the “leakage” or “cross-talk” parameter is in the numerator. The transmission parameter (S_{21}) is present because we are expressing the coupling port signals in terms of the forward and reverse amplitudes at port 2.

When the cavity is connected, the cavity’s reflection coefficient $\Gamma_{\text{cav}} = V_{r,2}/V_{f,2}$ can be used to express the forward and reverse signals in terms of the corresponding forward and reverse amplitudes only, without cross terms:

$$V_{fs} = \frac{S_{31}}{S_{21}} (1 + \Gamma_{\text{cav}} \epsilon_f) V_{f,2}, \quad (\text{A5})$$

$$V_{rs} = S_{42} \left(\frac{\epsilon_r}{\Gamma_{\text{cav}}} + 1 \right) V_{r,2}. \quad (\text{A6})$$

Our scalar correction corresponds to an assumption of no cross-talk, so that $\epsilon_f = \epsilon_r = 0$. Upper bounds on the relative error due to this approximation are hence $|\Gamma_{\text{cav}} \epsilon_f|$ for P_f and $|\epsilon_r/\Gamma_{\text{cav}}|$ for P_r .

In general, the S -parameters are frequency-dependent, so the scalar or vector correction should be frequency-dependent as well. However, for narrow-band measurements, frequency-independent scalar corrections are generally used. In our case, because we are shifting the drive frequency by up to several MHz and often observe some ripple in the signals as a function of frequency, we used a frequency-dependent scalar correction in the final analysis of the measured values (P_f , P_r , P_t). However, this did not make much difference relative to the other effects we have described.

In Ref. [40], a trombone phase shifter is used to vary the phase difference between the dual-directional coupler and the cavity and gauge the impact of the phase on the measured signals. For our measurements, we swept the frequency to produce a similar effect. Figure 13(a) shows polar plots of ϵ_f and ϵ_r obtained from measurements of the complex S -parameters with a 20 MHz span; the phase change is about 4π radians over this frequency range. In Fig. 13(b), the mean delay for each of the measured S -parameters is subtracted. With this adjustment, the ϵ_r values appear as approximate circles, as would be expected for the sum of two signals with a varying relative phase. We interpret this to be the sum of a smaller direct cross-talk signal from the forward wave to the reverse port of the dual-directional coupler and a larger signal reflected by downstream mismatches (primarily from the bias T) and coupled to the reverse port. The ϵ_f values are significantly smaller in magnitude than the ϵ_r values, but still show some frequency dependence, likely due to reflections upstream of the dual-directional coupler.

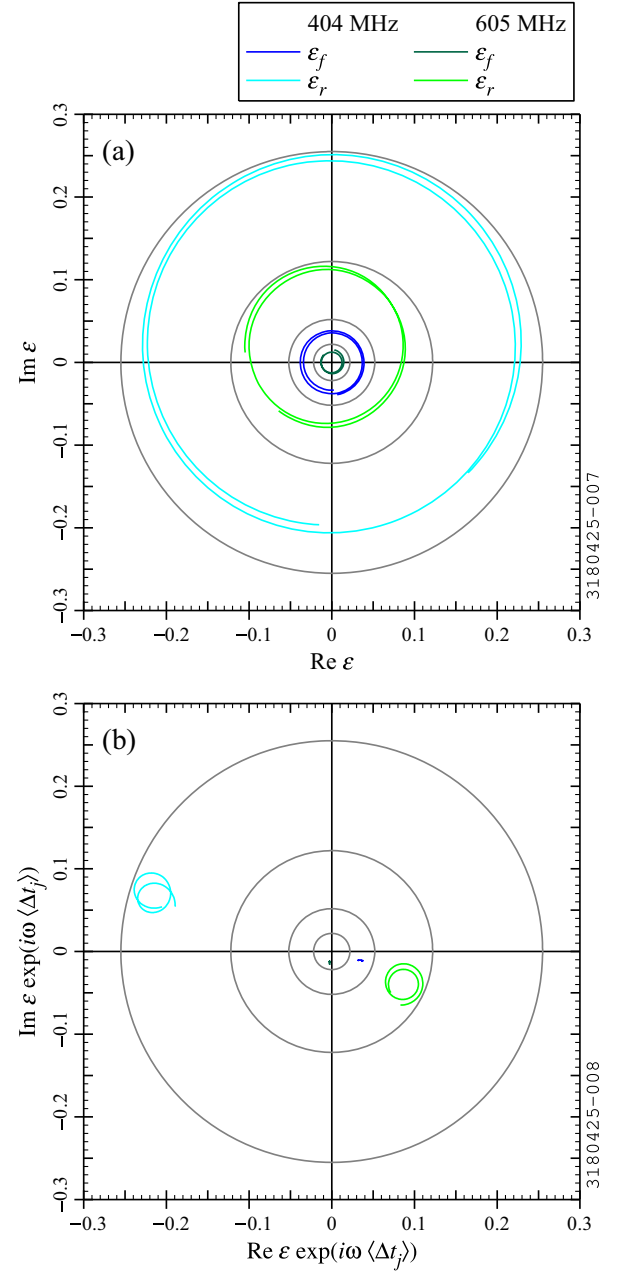


FIG. 13. Relative error coefficients calculated from VNA measurements of the dual-directional coupler, bias T, and associated cables. (a) Without delay adjustment; (b) with adjustment of the phase according to the mean delay ($\langle \Delta t_j \rangle$). Gray circles: magnitudes used in the systematic error analysis.

The gray circles in Fig. 13 represent the “worst-case” values of $|\epsilon_f|$ and $|\epsilon_r|$ used for the error analysis. These values are listed in Table IV, along with $|\Gamma_{\text{cav}}|$ values used for the various cases. We note that $|\Gamma_{\text{cav}}|$ includes the FPC cold window, rigid transmission line, warm window, and rf adapters (though their contribution to the return loss is small). The systematic error estimates for P_f and P_r given in the text are based on the values shown in Table IV after conversion from amplitude to power.

TABLE IV. Systematic error analysis parameters.

Frequency	404 MHz	605 MHz
$ \epsilon_f $	5.2×10^{-2}	2.2×10^{-2}
$ \epsilon_r $	2.55×10^{-1}	1.22×10^{-1}
$ \Gamma_{\text{cav}} $ (plasma off)	0.97	0.80
$ \Gamma_{\text{cav}} $ (plasma on)	0.97	0.98
$ \epsilon_t $	6.0×10^{-2}	1.0×10^{-1}

2. Uncertainty cross-checks: P_f and P_r

For the measurements described above, we terminated unused ports with a matched load. An alternative approach is to measure S_{31} and S_{42} with different terminations (load, open, short) on the unused port 2 or port 1 and subtract the results. We did such measurements to obtain alternative values of ϵ_f and ϵ_r as a cross-check. The gray circles in Fig. 13 correspond to the worst-case scenario for both approaches. This resulted in larger circles for the ϵ_f cases.

The values of ϵ_f and ϵ_r correspond to an overall directivity that is significantly worse than the directivity specification for our dual-directional coupler: the worst case of $\epsilon_r = 2.55 \times 10^{-1}$ corresponds to a directivity of about 12 dB, in contrast to the specified directivity of 35 dB or higher. This can be explained by the mismatch in the system, as seen by reflection measurements (S_{11} and S_{22}). A simple analysis indicates that $|\epsilon_r|$ should be between $|S_{11}|$ and $|S_{11}/(S_{21}S_{12})|$; our measured values are consistent with this prediction. Our reflection measurements are roughly consistent with what we expect based on the bias T mismatch specified by the manufacturer (SWR = 1.3). Thus, the accuracy of the measurements could be improved by reducing the mismatch between the dual-directional coupler and the cryomodule.

3. Uncertainty evaluation: P_t

Because the probe pickup antenna is weakly coupled, we expect signals reflected from the rf measurement circuit back toward the cavity to be reflected again toward the power sensor, adding to or subtracting from the direct signal to produce a systematic error in the measured value of P_t . Hence we used mismatch measurements to infer a worst-case relative error in V_t , with error propagation for P_t and U . In this model, the first-order worst-case relative error in V_t is ϵ_t , which is the product of the measured reflection S -parameters looking “upstream” toward the cavity pickup antenna and looking “downstream” to the rf measurement circuit for P_t . The corresponding $|\epsilon_t|$ values, included in Table IV, were used for the estimated systematic error in U^* . The bias T on the pickup line again provides additional mismatch and worsens the systematic errors.

APPENDIX B: POWER DISSIPATION CALCULATIONS

The method for estimating the total power dissipation in the cavity (P_d) and the power dissipation in the plasma (P_x) will be described in this appendix, providing the basis for the corresponding results in Sec. VA.

1. Total power dissipation

The total power dissipation P_d in the cavity can be obtained from the measured values via a direct calculation:

$$P_d = P_f - P_r - P_t. \quad (\text{B1})$$

When the input coupler is poorly matched, the direct calculation is problematic, because $P_r \approx P_f$ and hence $P_d \approx 0$. This can be seen in Fig. 14(a): the solid triangles indicate the calculated P_d during steady plasma processing

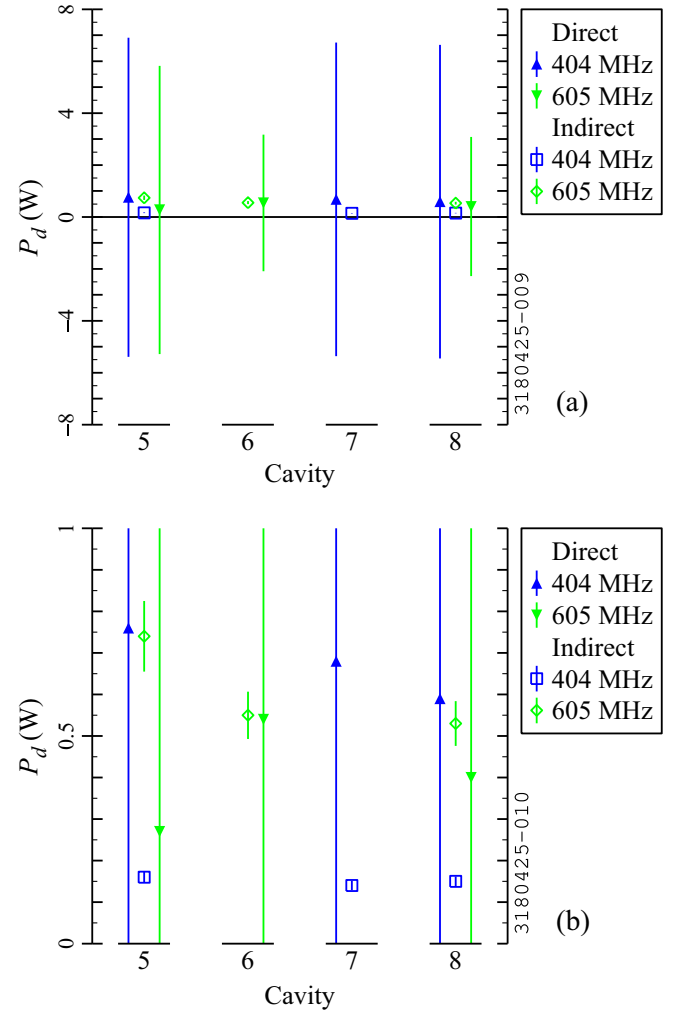


FIG. 14. Calculated power dissipation during steady plasma processing with estimated errors: (a) overview and (b) close-up view.

for each cavity and mode combination. Propagation of the estimated errors in P_f and P_r (per Appendix A) leads to a large uncertainty in P_d and does not rule out negative P_d values.

If $Q_{\text{ext},1}$ and $Q_{\text{ext},2}$ are known, we can calculate P_d from P_f and P_t without making use of P_r . In the case of a weakly coupled pickup ($Q_{\text{ext},2} \gg Q_0$), we can write

$$P_d \approx P_t \frac{Q_{\text{ext},2}}{Q_{\text{ext},1}} \left(2 \sqrt{\frac{Q_{\text{ext},1} P_f}{Q_{\text{ext},2} P_t}} - 1 \right). \quad (\text{B2})$$

A derivation of the above equation can be found in a separate report [42]. The hollow squares and diamonds in Fig. 14(a) show P_d values calculated using Eq. (B2). The error bars can be seen more clearly in the enlarged view shown in Fig. 14(b). The values are significantly different and the uncertainties are significantly smaller when calculating P_d indirectly. The values listed in Table II are calculated using the indirect method.

2. Power transfer to the plasma

In Sec. VA, we provided estimates of the fraction of the power dissipated in the plasma relative to the total power dissipation. These estimates are based on the assumption that the input and pickup coupler strengths ($Q_{\text{ext},1}$, $Q_{\text{ext},2}$) and the cavity's "unperturbed intrinsic quality factor" (Q_0) do not change with plasma on. (The assumption of constant $Q_{\text{ext},1}$ and $Q_{\text{ext},2}$ is used in the previous section as well.) We define Q_0 to be the quality factor associated with the power dissipation in the cavity walls due to Ohmic losses, not including the power dissipation in the plasma. As the plasma may perturb the field distribution of the resonant mode being used to drive the plasma, the assumptions

about constant Q_0 and coupling strengths may not be exactly correct. (In principle, a measurement of the bandwidth with frequency sweep or decay time with amplitude modulation after plasma ignition would provide a way to infer $Q_{\text{ext},1}$ and $Q_{\text{ext},2}$ with the plasma on, but such a measurement is not altogether straightforward.) Though the answer may not be exact, estimation of the power dissipated in the plasma is nevertheless useful to get an idea of the process efficiency.

Assuming that $Q_{\text{ext},1}$, $Q_{\text{ext},2}$, and Q_0 are the same as measured at low power without plasma, we use the measured value of P_t to infer U . We infer the power dissipation in the cavity walls from U and Q_0 . Subtraction of this quantity from the calculated (total) power dissipation P_d gives the power P_x dissipated in the plasma:

$$P_x = P_d - \frac{\omega U}{Q_0} = P_d - \frac{Q_{\text{ext},2}}{Q_0} P_t, \quad (\text{B3})$$

where ω is the resonant (angular) frequency. Again, $Q_{\text{ext},2}$ and Q_0 are the values measured at low field without plasma.

APPENDIX C: PLASMA MONITORING: RF POWER

Figure 15 shows several quantities as a function of time with steady plasma. The forward power P_f is measured; the stored energy U is inferred from the measured P_t . The total power dissipation in the cavity (P_d) is calculated from P_f and P_t via the indirect method, per Eq. (B2). The estimated power dissipation in the plasma (P_x) is calculated via Eq. (B3). See Sec. VA for further discussion of these results.

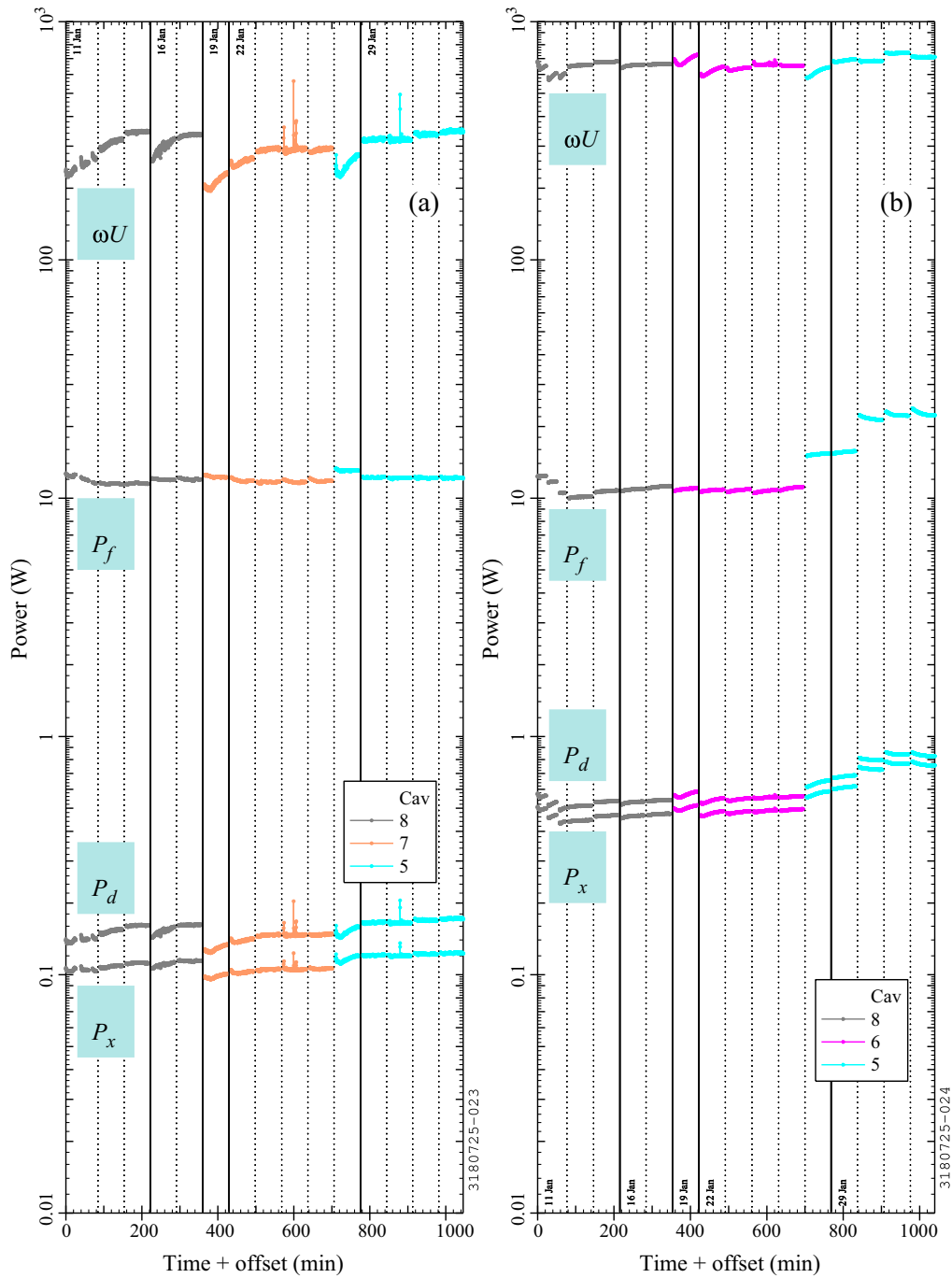


FIG. 15. Measured and calculated rf values as a function of time with steady plasma for (a) the 404 MHz mode and (b) the 605 MHz mode.

- [1] M.A. Lieberman and A.J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*, 2nd ed. (Wiley, Hoboken, NJ, 2005).
- [2] M. Doleans *et al.*, Plasma processing to improve the performance of the SNS superconducting linac, in *Proceedings of the 28th International Linear Accelerator Conference, Linac 2016, East Lansing, MI, USA* (JACoW, Geneva, Switzerland, 2016), pp. 679–682, [10.18429/JACoW-LINAC2016-WE2A03](https://doi.org/10.18429/JACoW-LINAC2016-WE2A03).
- [3] S.-H. Kim, R. Afanador, D. L. Barnhart, M. Crofford, B. D. Degraff, M. Doleans, J. Galambos, S. W. Gold, M. P. Howell, J. Mammoser, C. J. McMahan, T. S. Neustadt, C. Peters, J. W. Saunders, W. H. Strong, D. J. Vandygriff, and D. M. Vandygriff, Overview of ten-year operation of

- the superconducting linear accelerator at the Spallation Neutron Source, *Nucl. Instrum. Methods Phys. Res., Sect. A* **852**, 20 (2017).
- [4] P. Berrutti, Plasma cleaning R&D at FNAL, in *Proceedings of the 2018 TeSLA Technology Collaboration Meeting, Saitama, Japan* (RIKEN, Saitama, Japan, 2018), <https://indico.desy.de/event/20010/contributions/37577/>.
 - [5] P. V. Tyagi, A. Moss, P. Goudket, S. Pattalwar, J. Herbert, R. Valizadeh, and P. McIntosh, Plasma ignition and tuning in different cells of a 1.3 GHz nine-cell superconducting radio frequency cavity: Proof of principle, *Nucl. Instrum. Methods Phys. Res., Sect. A* **893**, 95 (2018).
 - [6] A. D. Wu *et al.*, Experiment of plasma discharge on HWR cavity for *in-situ* surface cleaning study, in *Proceedings of the 28th International Linear Accelerator Conference, Linac 2016, East Lansing, MI, USA* (JACoW, Geneva, Switzerland, 2016), pp. 133–135, [10.18429/JACoW-LINAC2016-MOPRC029](https://doi.org/10.18429/JACoW-LINAC2016-MOPRC029).
 - [7] A. Wu, L. Yang, C. Hu, C. Li, S. Huang, Y. Li, Q. Chu, P. Xiong, H. Guo, W. Yue, Y. Hu, F. Pan, L. Chen, S. Zhang, Y. He, and H. Zhao, *In-situ* plasma cleaning to decrease the field emission effect of half-wave superconducting radio-frequency cavities, *Nucl. Instrum. Methods Phys. Res., Sect. A* **905**, 61 (2018).
 - [8] S. C. Huang *et al.*, The effect of helium processing and plasma cleaning for low beta HWR cavity, in *Proceedings of the 19th International Conference on RF Superconductivity, SRF 2019, Dresden, Germany* (JACoW, Geneva, Switzerland, 2019), pp. 1228–1230, [10.18429/JACoW-SRF2019-FRCAB6](https://doi.org/10.18429/JACoW-SRF2019-FRCAB6).
 - [9] B. Giaccone *et al.*, Plasma processing to reduce field emission in LCLS-II 1.3 GHz SRF cavities, in *Proceedings of the 19th International Conference on RF Superconductivity, SRF 2019, Dresden, Germany* (JACoW, Geneva, Switzerland, 2019), pp. 1231–1238, [10.18429/JACoW-SRF2019-FRCAB7](https://doi.org/10.18429/JACoW-SRF2019-FRCAB7).
 - [10] B. Giaccone, M. Martinello, P. Berrutti, O. Melnychuk, D. A. Sergatskov, A. Grassellino, D. Gonnella, M. Ross, M. Doleans, and J. F. Zasadzinski, Field emission mitigation studies in the SLAC Linac Coherent Light Source II superconducting rf cavities via *in situ* plasma processing, *Phys. Rev. Accel. Beams* **24**, 022002 (2021).
 - [11] B. Giaccone, P. Berrutti, M. Martinello, S. Posen, A. Cravatta, A. Netepenko, T. Arkan, A. Grassellino, B. Hartsell, J. Kaluzny, A. Penhollow, D. Gonnella, M. Ross, J. Fuerst, G. Hays, J. T. Maniscalco, and M. Doleans, Plasma cleaning of the SLAC Linac Coherent Light Source II high energy verification cryomodule cavities, *Phys. Rev. Accel. Beams* **25**, 102001 (2022).
 - [12] M. McIntyre *et al.*, *In-situ* plasma processing on a 172 MHz HWR cavity at the Argonne Tandem Linac Accelerator System, in *Proceedings of the 21st International Conference on RF Superconductivity, SRF 2023, Grand Rapids, MI, USA* (JACoW, Geneva, Switzerland, 2023), pp. 219–223, [10.18429/JACoW-SRF2023-MOPMB049](https://doi.org/10.18429/JACoW-SRF2023-MOPMB049).
 - [13] P. Berrutti, Plasma cleaning at FNAL: LCLS-II HE vCM results and ongoing studies on spoke resonators, in *Proceedings of the International Conference on RF Superconductivity, SRF 2023, Grand Rapids, MI, USA* (JACoW, Geneva, Switzerland, 2023), pp. 219–223, [10.18429/JACoW-SRF2023-MOPMB049](https://doi.org/10.18429/JACoW-SRF2023-MOPMB049).
 - [14] C. Cheney, Overview of plasma processing activities at IJCLab, in *Proceedings of the TeSLA Technology Collaboration Meeting, Batavia, IL, USA* (Fermilab, Batavia, IL, 2023), <https://indico.fnal.gov/event/60446/contributions/277987/>.
 - [15] T. Powers *et al.*, An overview of plasma processing of SRF cavities at JLAB, in *Proceedings of the 32nd Linear Accelerator Conference, Linac 2024, Chicago, IL, USA* (JACoW, Geneva, Switzerland, 2024), pp. 577–582, [10.18429/JACoW-LINAC2024-THXA005](https://doi.org/10.18429/JACoW-LINAC2024-THXA005).
 - [16] D. Hedji *et al.*, Development of plasma processing of 1.3 GHz superconducting radiofrequency cavities at TRIUMF, in *Proceedings of the 32nd Linear Accelerator Conference, Linac 2024, Chicago, IL, USA* (JACoW, Geneva, Switzerland, 2024), pp. 801–804, [10.18429/JACoW-LINAC2024-THPB089](https://doi.org/10.18429/JACoW-LINAC2024-THPB089).
 - [17] T. Zhu, X. Bao, Y. He, Z. Xue, Y. Qiu, C. Li, W. Xue, T. Jiang, Q. Chu, H. Guo, S. Huang, Z. Yang, W. Yue, J. Chen, M. Xu, S. Zhang, K. Zhang, H. Zhao, T. Tan, and A. Wu, Plasma characterization and modulation techniques for 1.3 GHz, 9-cell superconducting rf cavity cleaning, *Phys. Rev. Accel. Beams* **27**, 123101 (2024).
 - [18] J. Wei *et al.*, Accelerator commissioning and rare isotope identification at the Facility for Rare Isotope Beams, *Mod. Phys. Lett. A* **37**, 2230006 (2022).
 - [19] J. Wei *et al.*, Technological developments and accelerator improvements for the FRIB beam power ramp-up, *J. Instrum.* **19**, T05011 (2024).
 - [20] C. Zhang *et al.*, Certification testing of production superconducting quarter-wave and half-wave resonators for FRIB, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1014**, 165675 (2021).
 - [21] W. Hartung *et al.*, Report on first plasma processing trial for a FRIB quarter-wave resonator cryomodule, [arXiv: 2511.06732](https://arxiv.org/abs/2511.06732).
 - [22] T. Xu *et al.*, Progress of FRIB SRF production, in *Proceedings of the 18th International Conference on RF Superconductivity, SRF 2017, Lanzhou, China* (JACoW, Geneva, Switzerland, 2017), pp. 345–352, [10.18429/JACoW-SRF2017-TUXAA03](https://doi.org/10.18429/JACoW-SRF2017-TUXAA03).
 - [23] C. Compton *et al.*, Production status of superconducting cryomodules for the Facility for Rare Isotope Beams, in *Proceedings of the 18th International Conference on RF Superconductivity, SRF 2017, Lanzhou, China* (JACoW, Geneva, Switzerland, 2017), pp. 928–934, [10.18429/JACoW-SRF2017-FRXAA01](https://doi.org/10.18429/JACoW-SRF2017-FRXAA01).
 - [24] W. Chang *et al.*, Bunker testing of FRIB cryomodules, in *Proceedings of the 4th North American Particle Accelerator Conference, NAPAC 2019, Lansing, MI, USA* (JACoW, Geneva, Switzerland, 2019), pp. 765–767, [10.18429/JACoW-NAPAC2019-WEPLM73](https://doi.org/10.18429/JACoW-NAPAC2019-WEPLM73).
 - [25] Y.-L. Cheon *et al.*, RF pulse conditioning to reduce field emission in FRIB SRF cryomodules, in *Proceedings of the 32nd Linear Accelerator Conference, Linac 2024, Chicago, IL, USA* (JACoW, Geneva, Switzerland, 2024), pp. 355–358, [10.18429/JACoW-LINAC2024-TUPB013](https://doi.org/10.18429/JACoW-LINAC2024-TUPB013).

- [26] S. Miller *et al.*, FRIB cavity and cryomodule performance, comparison with the design and lessons learned, in *Proceedings of the 19th International Conference on RF Superconductivity, SRF 2019, Dresden, Germany* (JACoW, Geneva, Switzerland, 2019), pp. 742–749, [10.18429/JACoW-SRF2019-WETEA5](#).
- [27] P. R. Tutt *et al.*, Investigation of coupler breakdown thresholds for plasma processing of FRIB quarter-wave resonators with fundamental and higher-order modes, in *Proceedings of the 21st International Conference on RF Superconductivity, SRF 2023, Grand Rapids, MI, USA* (JACoW, Geneva, Switzerland, 2023), pp. 893–897, [10.18429/JACoW-SRF2023-WEPWB127](#).
- [28] C. Zhang *et al.*, Development of *in-situ* plasma cleaning for the FRIB SRF linac, in *Proceedings of the 20th International Conference on RF Superconductivity, SRF 2021, East Lansing, MI, USA* (JACoW, Geneva, Switzerland, 2022), pp. 657–661, [10.18429/JACoW-SRF2021-WEPTEV011](#).
- [29] W. Hartung *et al.*, Plasma processing of superconducting quarter-wave resonators using a higher-order mode, in *Proceedings of the North American Particle Accelerator Conference, NAPAC 2022, Albuquerque, NM, USA* (JACoW, Geneva, Switzerland, 2022), pp. 267–270, [10.18429/JACoW-NAPAC2022-MOPA91](#).
- [30] W. Hartung *et al.*, Investigation of plasma processing for coaxial resonators, in *Proceedings of the 21st International Conference on RF Superconductivity, SRF 2023, Grand Rapids, MI, USA* (JACoW, Geneva, Switzerland, 2023), pp. 960–967, [10.18429/JACoW-SRF2023-THIXA01](#).
- [31] T. Xu *et al.*, SRF development and cryomodule production for the FRIB linac, in *Proceedings of the 3rd North American Particle Accelerator Conference, NAPAC 2016, Chicago, IL, USA* (JACoW, Geneva, Switzerland, 2016), pp. 847–852, [10.18429/JACoW-NAPAC2016-WE-B3IO01](#).
- [32] U. Becker, CST’s commercial beam-physics codes, in *Proceedings of the 9th International Computational Accelerator Physics Conference, ICAP 2006, Chamonix Mont-Blanc, France* (JACoW, Geneva, Switzerland, 2006), THM2IS03, https://jacow.org/icap06/TALKS/THM2IS03_TALK.PDF.
- [33] M. Doleans, Ignition and monitoring technique for plasma processing of multicell superconducting radio-frequency cavities, *J. Appl. Phys.* **120**, 243301 (2016).
- [34] P. Berrutti, B. Giaccone, M. Martinello, A. Grassellino, T. Khabiboulline, M. Doleans, S. Kim, D. Gonnella, G. Lanza, and M. Ross, Plasma ignition and detection for *in-situ* cleaning of 1.3 GHz 9-cell cavities, *J. Appl. Phys.* **126**, 023302 (2019).
- [35] W. Hartung *et al.*, Development of plasma processing for superconducting half-wave resonators, in *Proceedings of the 16th International Conference Heavy Ion Accelerator Technology, HIAT 2025, East Lansing, MI, USA* (JACoW, Geneva, Switzerland, 2025), pp. 118–121, [10.18429/JACoW-HIAT2025-TUC03](#).
- [36] T. Powers, N. C. Brock, and T. D. Ganey, In situ plasma processing of superconducting cavities at Jefferson Lab, in *Proceedings of the 20th International Conference on RF Superconductivity, SRF 2021, East Lansing, MI, USA* (JACoW, Geneva, Switzerland, 2022), pp. 485–489, [10.18429/JACoW-SRF2021-TUPTEV004](#).
- [37] T. Powers, N. C. Brock, and T. D. Ganey, In situ plasma processing of superconducting cavities at JLab, 2023 update, in *Proceedings of the 21st International Conference on RF Superconductivity, SRF 2023, Grand Rapids, MI, USA* (JACoW, Geneva, Switzerland, 2023), pp. 701–705, [10.18429/JACoW-SRF2023-WEPWB054](#).
- [38] M. Doleans *et al.*, Plasma processing R&D for the SNS superconducting linac rf cavities, in *Proceedings of the 16th International Conference RF Superconductivity, SRF 2013, Paris, France* (JACoW, Geneva, Switzerland, 2013), pp. 551–557, <https://proceedings.jacow.org/SRF2013/papers/tup057.pdf>.
- [39] P. Tutt *et al.*, Feasibility study for dual higher-order-modes for plasma processing of FRIB superconducting coaxial resonators, in *Proceedings of the 32nd Linear Accelerator Conference, Linac 2024, Chicago, IL, USA* (JACoW, Geneva, Switzerland, 2024), pp. 348–351, [10.18429/JACoW-LINAC2024-TUPB011](#).
- [40] J. P. Holzbauer, Y. Pischalnikov, D. A. Sergatskov, W. Schappert, and S. Smith, Systematic uncertainties in rf-based measurement of superconducting cavity quality factors, *Nucl. Instrum. Methods Phys. Res., Sect. A* **830**, 22 (2016).
- [41] J. P. Holzbauer, C. Contreras, Y. Pischalnikov, D. Sergatskov, and W. Schappert, Improved rf measurements of SRF cavity quality factors, *Nucl. Instrum. Methods Phys. Res., Sect. A* **913**, 7 (2019).
- [42] W. H. Hartung, W. Chang, S.-H. Kim, T. Konomi, and T. Xu, Two-port CW measurements on RF cavities: Notes on self-consistency assessment and indirect methods, [arXiv:2601.14583](#).