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LARGE-SCALE DEWAR TESTING OF FRIB PRODUCTION CAVITIES: RESULTS*

W. Hartung, W. Chang, S.H. Kim, D. Norton, J.T. Popielarski, K. Saito, J.F. Schwartz, T. Xu, C. Zhang, Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The superconducting driver linac for the Facility for Rare Isotope Beams requires 104 quarter-wave resonators (QWRs, 80.5 MHz) and 220 half-wave resonators (HWRs, 322 MHz). The resonators are Dewar tested before installation into cryomodules. All of the required QWRs have been fabricated and certified via Dewar tests; 95% of the HWRs have been certified (as of August 2019). The certification tests have provided valuable information on the performance of production QWRs and HWRs.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) [1, 2], under construction at Michigan State University (MSU), requires a superconducting linac to accelerate ion beams to ≥ 200 MeV per nucleon. Quarter-wave resonators (QWRs) and half-wave resonators (HWRs) for the linac are produced by industrial suppliers; they are etched, rinsed, and tested at MSU before installation into cryomodules.

All of the required $\beta_m = 0.043$ QWRs, $\beta_m = 0.086$ QWRs, and $\beta_m = 0.29$ HWRs resonators have been certified (β_m = optimum normalized beam speed v/c); as of August 2019, 138 out of 148 of the $\beta_m = 0.54$ HWRs have been certified. After Dewar testing, certified cavities are assembled into a cryomodule [3]; the cryomodules are bunker tested [4] prior to tunnel installation. In-tunnel RF commissioning [5] and beam commissioning [6] of the QWR cryomodules is finished, and the cool-down of the first HWR cryomodules is in progress. QWR beam commissioning was done at 4.5 K, but 2 K operation is planned for both QWR and HWR cryomodules.

Methods and results of Dewar certification testing of FRIB production resonators have been presented previously [7, 8]. This paper will provide updated information about Dewar testing. Results for the $\beta_m = 0.54$ HWRs (the cavity type needed in largest quantity for the linac) will be presented as an example. Conditioning of multipacting and mitigation of field emission will be discussed. A statistical analysis of the FRIB Dewar test results can be found in a separate paper [9].

RESONATOR FABRICATION AND PREPARATION

Drawings of the FRIB resonators and RF parameters can be found in previous papers [7–9]. Resonators are made from high-purity sheet Nb via deep drawing and electron beam welding. Parts for a production $\beta_m = 0.54$ HWR are shown in Fig. 1. Jacketed resonators are delivered to FRIB. Dimensional checks, surface inspections, bulk etching (Buffered Chemical Polishing, BCP), hydrogen degassing, light etching (BCP), high-pressure water rinsing (HPWR), and clean-room assembly are done at MSU [10].

CERTIFICATION TESTING

Resonators are tested in the FRIB SRF facility at MSU [11]. Testing is done with liquid helium in the jacket surrounded by insulating vacuum, which approximates the cryomodule environment. Continuous wave (CW) measurements are done at 4.3 K and about 2 K with a solid state RF amplifier (50 to 100 W). Conditioning of multipacting barriers is usually done in CW at 4.3 K. Results of 4.3 K measurements, 2 K measurements, and pump-down measurements for all 4 cavity types were presented previously [8]. Updated results for the $\beta_m = 0.54$ case (including 16 additional cavities) will be presented in this section.

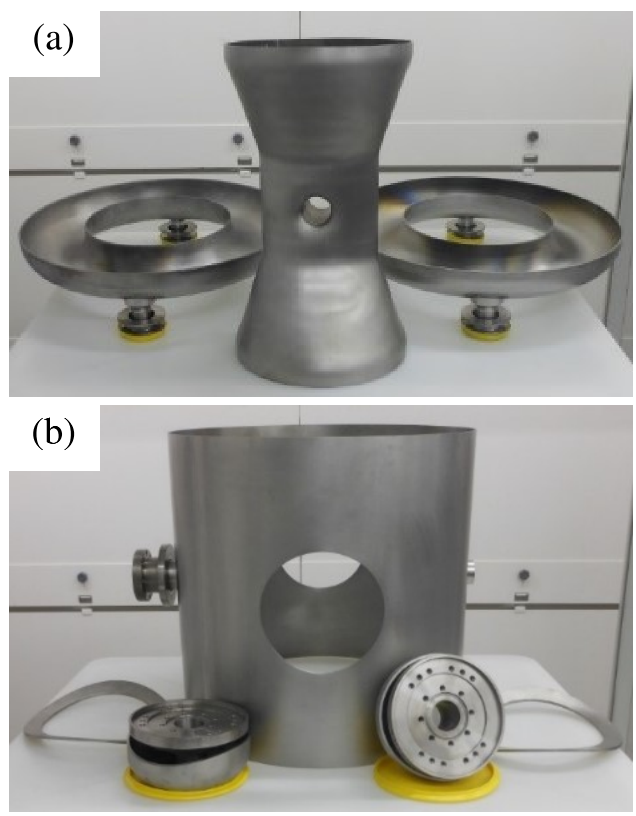

Figure 1: Partially-assembled $\beta_m = 0.54$ HWR: (a) inner conductor and short plates; (b) outer conductor and beam port cups.

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Measurements at 2 K

Dewar test results for certified $\beta_m = 0.54$ HWRs are shown in Fig. 2. The intrinsic quality factor (Q_0) is based on RF measurements. The X-ray signal (Fig. 2b) is measured with a sensor outside the Dewar, inside the radiation shield. Most resonators meet the Q_0 and E_a goals with a comfortable margin. The cavities generally show some "high field Q-slope," but the onset is above the FRIB gradient goal.

Pump-Down Measurements

We do CW measurements during the pump-down from 4.3 K to 2 K, typically with $E_a \approx 2$ MV/m. We can calculate the RF surface resistance (R_s) from Q_0. Results for the $\beta_m = 0.54$ case are shown in Fig. 2c. According to theory and measurements, R_s should have an approximately exponential dependence on the reciprocal of the temperature ($1/T$) plus a residual term [12, 13]. Figure 2c includes some theoretical curves for different residual resistances (R_0) and coefficients (C_{RRR}, dependent on the surface purity) which bracket the measured values approximately. A more advanced analysis is done in a separate paper [9].

Field Emission

As can be seen in Fig. 2b, a significant fraction of the cavities show field emission (FE) X-rays at high field. In some cases, X-rays were not seen initially, but the FE "turned on" partway through the measurements. For some cavities, CW or pulsed conditioning helped to reduce the X-rays.

For most cavities, the X-ray level is < 1 mR/hr at the FRIB gradient goal ($E_a = 7.4$ MV/m). In the Dewar certification test, we require $E_a = 8.9$ MV/m (20% margin on the operating goal). Some cavities had more X-rays in the initial Dewar test and were reworked. FE reworks consisted of (i) repeat water rinsing (HPWR), (ii) repeat etching (BCP) and HPWR, or (iii) mechanical polishing [14], BCP, and HPWR. Figure 3 shows the Q_0 and X-ray level at high field for $\beta_m = 0.54$ HWRs before (red) and after (green) FE reworks. The Q_0 and X-rays values are either at $E_a = 8.9$ MV/m (solid markers) or, if the maximum E_a was < 8.9 MV/m, at the maximum E_a (hollow markers; $E_a = 7.5$ to 8.8 MV/m). Some FE reworks required multiple iterations; intermediate tests with high-field X-rays > 100 mR/hr are included in Fig. 3 (magenta). Cavities certified without FE rework are shown in gray. As can be seen, there is a systematic decrease in Q_0 when the X-rays are $\gtrsim 1000$ mR/hr. After rework, high-field Q_0 values are $\gtrsim 10^{10}$ and high-field X-rays are < 100 mR/hr.

Multipacting Barriers

Multipacting (MP) barriers are observed in most cavity tests. Typically, we are able to condition the barriers in $\lesssim 2$ hours, though the time varies significantly from one test to another. The barrier field levels are shown in Fig. 4. The QWRs have a "low barrier" below $E_a = 0.01$ MV/m (black), but usually we are able to jump over it when turning on. The "middle barrier" (blue) and the "high barrier" (red)

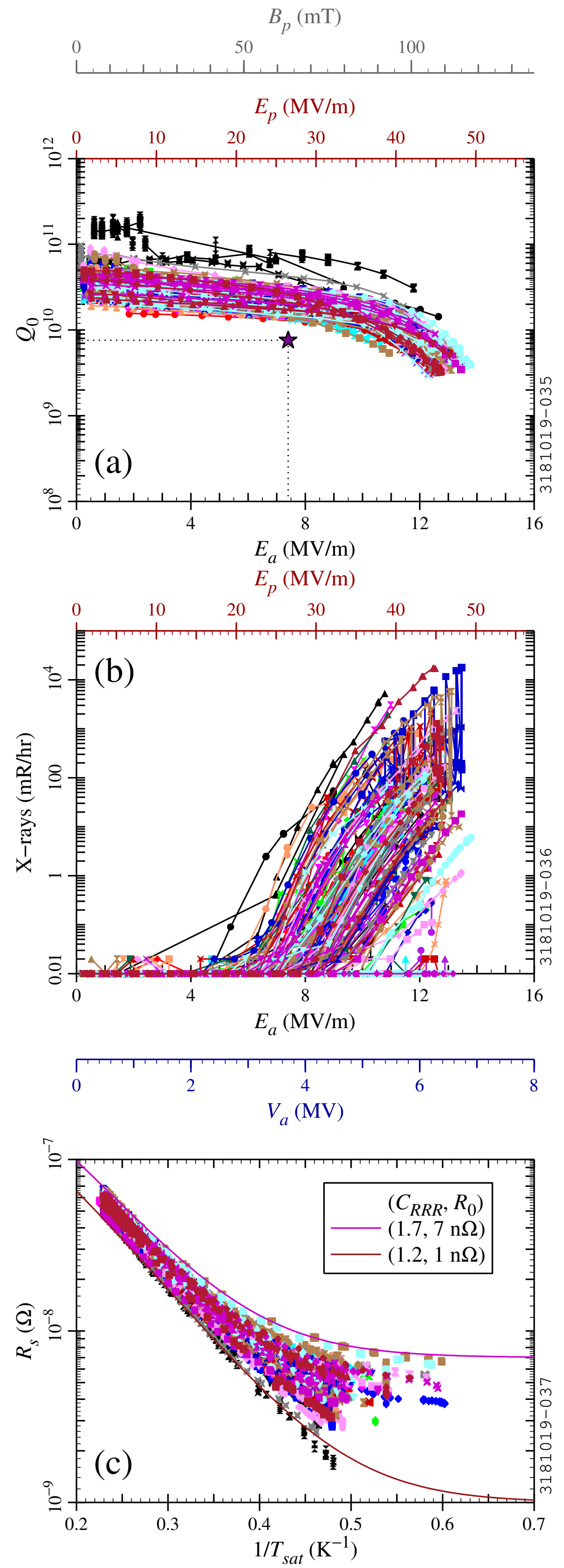

Figure 2: Dewar test results for $\beta_m = 0.54$ HWRs: (a) Q_0 at 2 K; (b) X-rays at 2 K; (c) R_s during pump-down. Purple star: FRIB operating goal.

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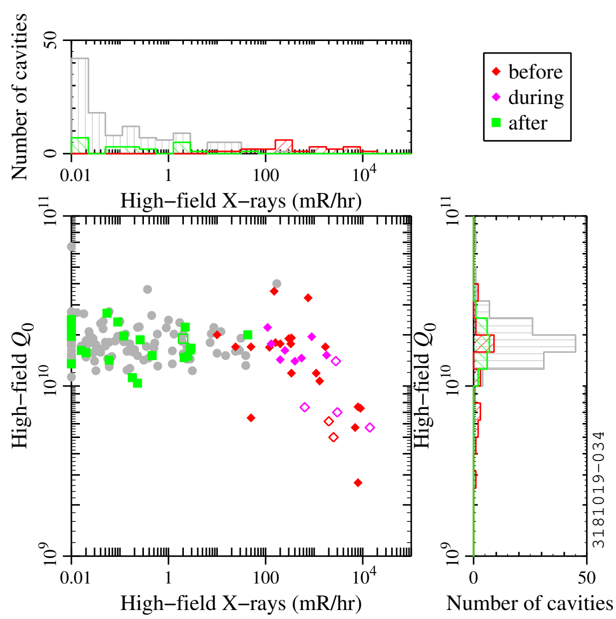

Figure 3: X-ray level and quality factor at high field before and after FE rework for β_m = 0.54 HWRs. Histograms of the X-ray level (right) and quality factor (top) are included.

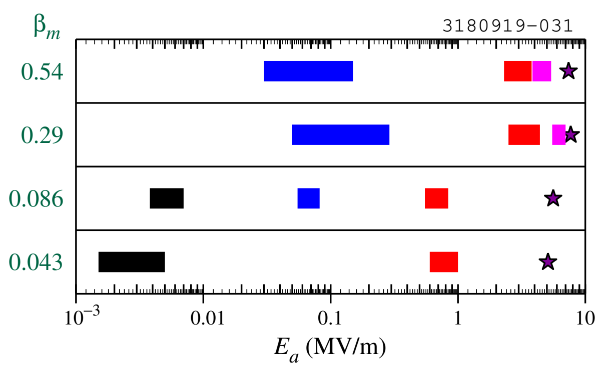

Figure 4: Map of field levels where multipacting barriers are observed in FRIB resonator Dewar tests.

can usually be conditioned in CW. We see steady X-rays when conditioning HWR high barriers, but see no X-rays for QWRs. The field levels for the high barrier are consistent with 2-point MP in the short plate region. In HWRs, we often observe X-ray spikes ("post-high barrier," magenta) at 4.3 K, after conditioning the high barrier. The X-ray spikes usually do not return during 2 K measurements. The post-high barrier may be due to the field pattern set up by the mismatched input coupler and the cavity.

Figure 5 shows an example of MP in a β_m = 0.54 HWR test. The middle barrier (blue) is seen at low field; Q_0 decreases to < 10^8 during conditioning. The high barrier (red) starts at $E_a \approx$ 2.5 MV/m and produces X-rays. An X-ray sawtooth can be seen as we step up the power slowly to condition. We see additional X-ray spikes (magenta) above the high barrier. After conditioning, the X-rays return to the background level and the Q_0 does not drop (green). In this

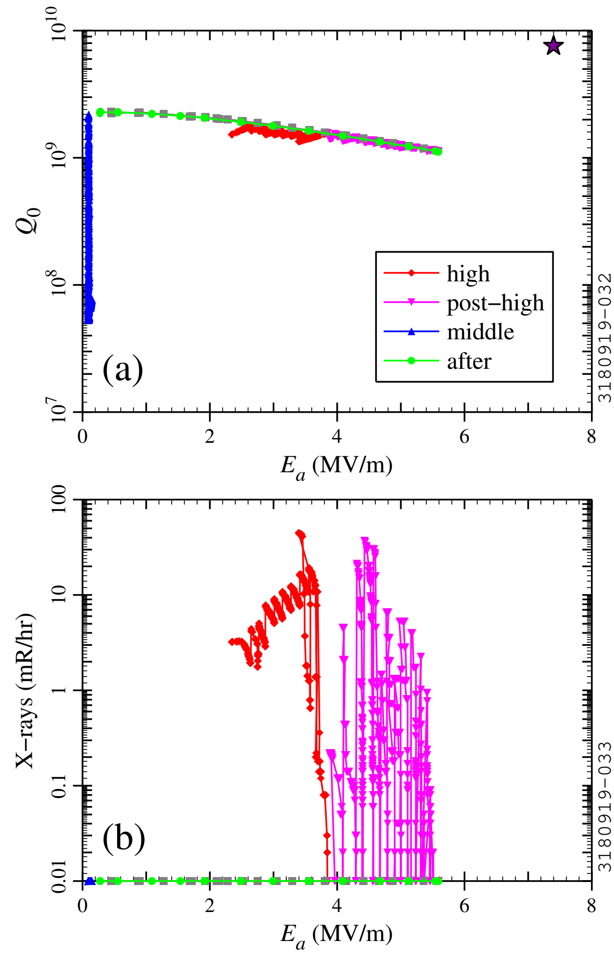

Figure 5: CW measurements at 4.3 K for a β_m = 0.54 HWR (S53-091) with MP barriers included: (a) Q_0; (b) X-rays.

example, the conditioning times were 93 minutes (high barrier), 37 minutes (post-high barrier), and 65 minutes (middle barrier); the total conditioning time was above average.

CONCLUSION

Nearly all of the required superconducting resonators for FRIB have been Dewar tested. Almost all of the resonators are meeting the performance goals, most of them with a comfortable margin, though some required reworks. FRIB cryomodule assembly is nearly complete, with 42 out of 46 cryomodules finished. Quarter-wave cryomodule beam commissioning is finished, and half-wave cryomodule beam commissioning is planned to begin in March 2020 [15].

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