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PERFORMANCE OF FRIB PRODUCTION QUARTER-WAVE AND HALF-WAVE RESONATORS IN DEWAR CERTIFICATION TESTS*

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Abstract

The superconducting driver linac for the Facility for Rare Isotope Beams will accelerate ions to 200 MeV per nucleon. The linac requires 104 quarter-wave resonators (QWRs) and 220 half-wave resonators (HWRs). The resonators are optimized for 4 different beam velocities. Dewar certification testing of the resonators is nearly complete. The certification tests have provided valuable statistics on the performance of production QWRs and HWRs at 4.3 K and 2 K.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is under construction at Michigan State University (MSU) [1, 2]. FRIB requires a superconducting driver linac to accelerate heavy ion beams to 200 MeV per nucleon; light ions will be accelerated to higher energies. The linac requires quarter-wave resonators (QWRs) and half-wave resonators (HWRs). Jacketed resonators are tested at MSU before installation into cryomodules.

The required cryomodules for $\beta_m = 0.043$, 0.086, and 0.29 have been completed and certified (β_m = optimum normalized beam speed v/c); as of June 2019, 92% of the $\beta_m = 0.54$ HWRs have been certified [3]. Beam commissioning of the QWR cryomodules is completed [4], and the cool-down of the first HWR cryomodules is in progress. QWR beam commissioning was done at 4.3 K, but 2 K operation is planned for both QWR and HWR cryomodules.

Results of Dewar certification testing of production FRIB QWRs and HWRs have been presented previously [5]. This paper provides updated and more detailed information about FRIB resonator performance.

BACKGROUND

Cavity Design

The design of the FRIB production resonators incorporates experience with early prototypes, experience with small-scale production for the MSU re-accelerator [6], optimization efforts, and advanced prototypes. The final resonator design includes stiffening features and Legnaro-style frictional dampers for the QWRs to mitigate microphonic excitation. The helium jacket, made from Ti sheet, is an integral part of the structural design. The HWRs include 4 rinse ports for better access during the final rinse.

The QWR design includes a Nb tuning plate with indium joints for RF and vacuum sealing. The $\beta_m = 0.086$ QWR design was modified significantly to address issues that were encountered during production for the re-accelerator. Modifications included moving the tuning plate farther away from the center conductor nose and relocating the RF ports to the outer conductor [7].

Drawings of the final cavity designs are shown in Fig. 1. Table 1 summarizes the RF parameters and linac operation goals for the final designs.

Cavity Fabrication and Preparation

Resonators are made from high-purity sheet Nb (RRR > 250) via deep drawing and electron beam welding. Jacketed resonators are delivered to FRIB by industrial vendors. Final preparation steps are done at MSU, including borescope inspection; bulk etching (Buffered Chemical Polishing, BCP, to remove 120 to 140 μm); hydrogen degassing (600 °C for 10 hours); light etching (BCP, 20 μm typically); and high-pressure water rinsing (HPWR) with ultra-pure water using a robotic system. HPWR and assembly onto the insert for Dewar testing are done in a clean room (ISO 5). Additional information on cavity preparation and guided repair can be found elsewhere [8, 9].

Cavity Deployment

After Dewar testing, certified cavities are returned to the clean room, where the cavities, high-power couplers, and focussing solenoids are assembled into a cold mass [10]. The cold mass is removed from the clean room and assembled into a cryomodule [11]. The cryomodules are bunker

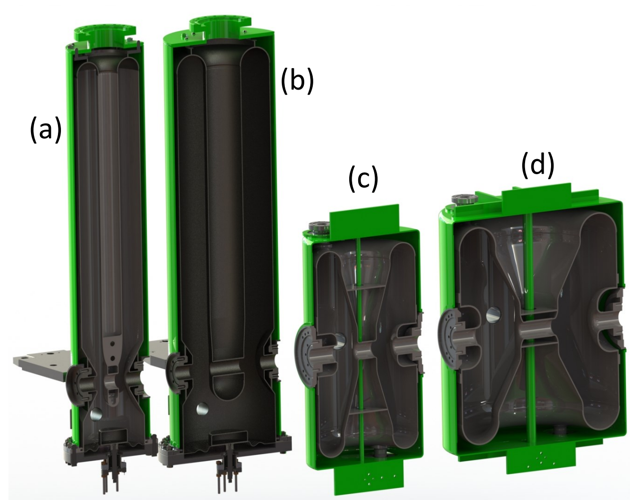

Figure 1: Isometric sectional views of the FRIB production resonators: (a) $\beta_m = 0.043$ QWR, (b) $\beta_m = 0.086$ QWR, (c) $\beta_m = 0.29$ HWR, (d) $\beta_m = 0.54$ HWR. Green: helium jacket.

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Table 1: FRIB production resonators: RF parameters, operating goals, and cavity counts; f_0 = resonant frequency; R_a = shunt impedance (linac definition); Q_0 = intrinsic quality factor; G = geometry factor; V_a = accelerating voltage; E_a = accelerating gradient; E_p = peak surface electric field; B_p = peak surface magnetic field.

Cavity Parameters				
β_m	0.043	0.086	0.29	0.54
Type	QWR	QWR	HWR	HWR
f_0 (MHz)	80.5	80.5	322	322
R_a/Q_0 (Ω)	401.6	455.4	224.4	229.5
G (Ω)	15.3	22.3	77.9	107.4
Goals for 2 K Operation				
V_a (MV)	0.81	1.78	2.09	3.70
E_a (MV/m)	5.1	5.6	7.7	7.4
E_p (MV/m)	30.8	33.4	33.3	26.5
B_p (mT)	54.6	68.9	59.6	63.2
Q_0	$1.2 \cdot 10^9$	$1.8 \cdot 10^9$	$5.5 \cdot 10^9$	$7.6 \cdot 10^9$
Number of Cavities				
Needed	12	92	72	148
Tested	16	106	75	141
Certified	16	105	72	136

tested to verify the performance of the cryogenic system, cavities, couplers, tuners, and solenoids [3]. Certified cryomodules are then installed into the linac. The final steps are cryomodule testing in the tunnel [4] and beam commissioning [1]. Though the cavities are tested after cryomodule assembly, the quality factor cannot be easily measured in the cryomodule, since the high-power input coupler is overcoupled and has a large mismatch. Hence the Dewar test provides the best cavity-by-cavity information about Q_0.

DEWAR CERTIFICATION TESTING

Resonators are tested in the FRIB SRF facility at MSU [12]. Using 2 Dewars and 5 inserts, up to 5 cavities per week can be tested. The number of cavities tested so far is included in Table 1. To approximate the cryomodule environment, resonators are tested with liquid helium in the jacket surrounded by insulating vacuum (Fig. 2). The cool-down from room temperature to 4.3 K takes about 1 hour. Continuous wave (CW) measurements are done at 4.3 K and about 2 K with a solid state RF amplifier (50 to 100 W) and a phase-lock loop. The cavities are tested with a fixed input coupler or a variable input coupler designed and fabricated by TRIUMF. Conditioning of multipacting barriers is usually done in CW at 4.3 K. To be certified for installation into a cryomodule, a cavity must meet the requirements for accelerating gradient, quality factor, resonant frequency, pick-up coupling strength, and vacuum integrity [5]. The requirements for E_a and Q_0 are more stringent than the linac operating goals, in order to provide some performance margin.

Dewar test results are shown in Fig. 3 through Fig. 6. The calculated intrinsic quality factor (Q_0) is based on RF measurements. The X-ray signal is measured with a radiation monitor located outside the Dewar, inside the radiation

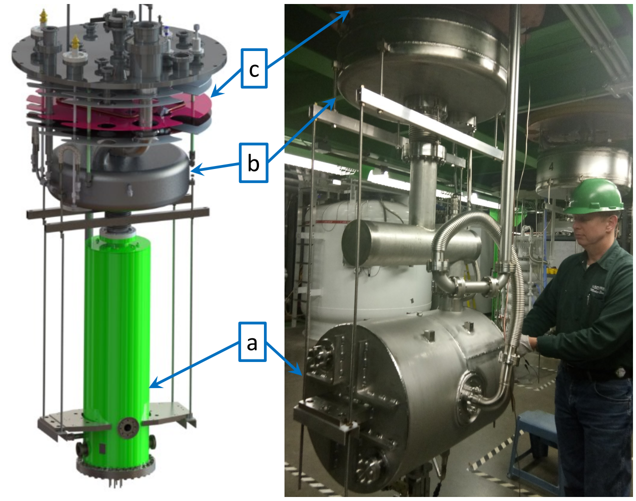

Figure 2: Drawing of a $\beta_m = 0.086$ QWR on an insert (left) and photograph of a $\beta_m = 0.54$ HWR being prepared for testing (right): (a) jacketed cavity; (b) liquid helium reservoir; (c) baffles for thermal and magnetic shielding.

enclosure. The linac (2 K) operating goals are indicated by a purple star.

Measurements at 4.3 K

In the CW measurements at 4.3 K (Fig. 3–6, top), the field is usually limited by the available RF power. A significant decrease in the quality factor ("Q-slope") with field is observed for all cavity types. The measured Q_0 is relatively consistent for different cavities of the same type.

Measurements at 2 K

In the CW measurements at 2 K (Fig. 3–6, middle), there is less decrease in Q_0 at lower field, but the "high field Q-slope" is generally observed, as expected for cavities prepared with BCP. The high-field Q-slope starts at $B_p \sim 50$ mT.

In the 2 K CW measurements, a significant fraction of the cavities show field emission X-rays (Fig. 3–6, bottom; note that the background level is 0.01 mR/hour for most tests, but some early QWR tests were done with a different sensor with background of about 0.5 mR/hour). In a significant fraction of the field emission cases, X-rays were not seen initially, but the emission "turned on" partway through the measurements. For some cases, we were able to reduce the field emission in CW. Pulsed conditioning was attempted in some cases, and occasionally helped.

Pump-Down Measurements

We do CW measurements during the pump-down from 4.3 K to 2 K, adjusting the drive power to keep the cavity field approximately constant ($E_a \approx 2$ MV/m typically). This allows us to obtain the shift in frequency with bath pressure and low-field Q_0 as a function of temperature. We can calculate the RF surface resistance (R_s) from Q_0 and the geometry factor (G). This R_s value is an average over the inner surface of the cavity, weighted according to the surface magnetic field.

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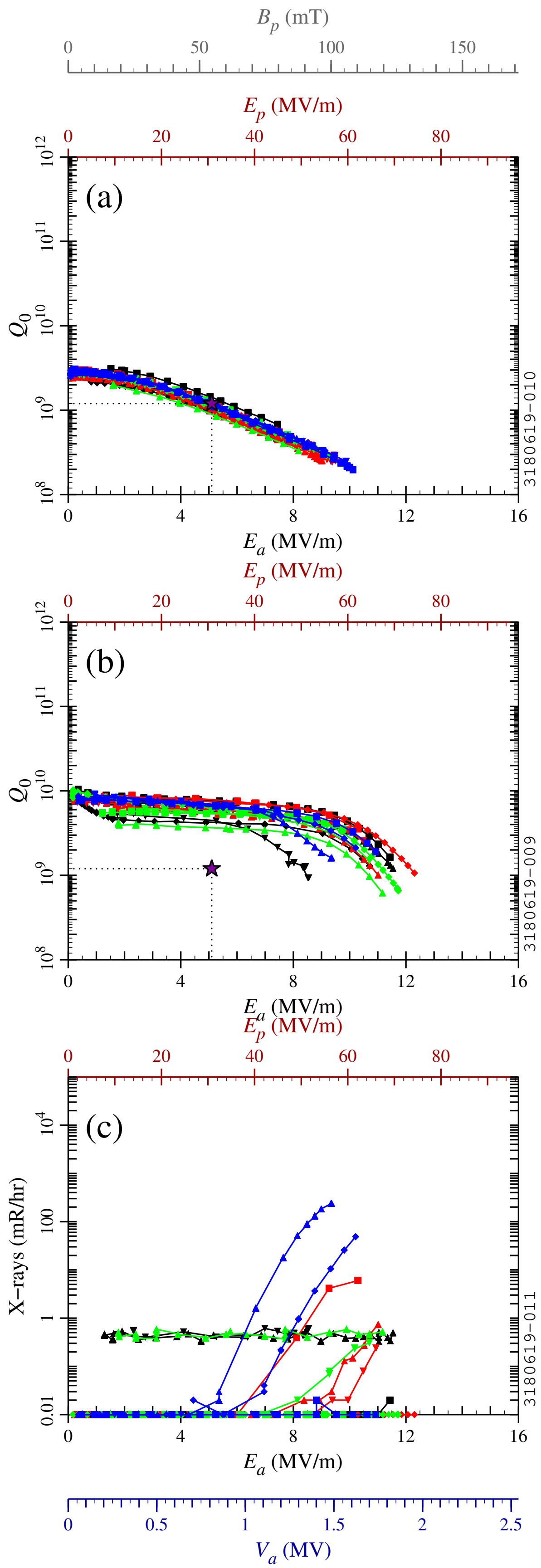

Figure 3: Dewar test results for $\beta_m = 0.043$ QWRs: (a) Q_0 at 4.3 K; (b) Q_0 at 2 K; (c) X-rays at 2 K.

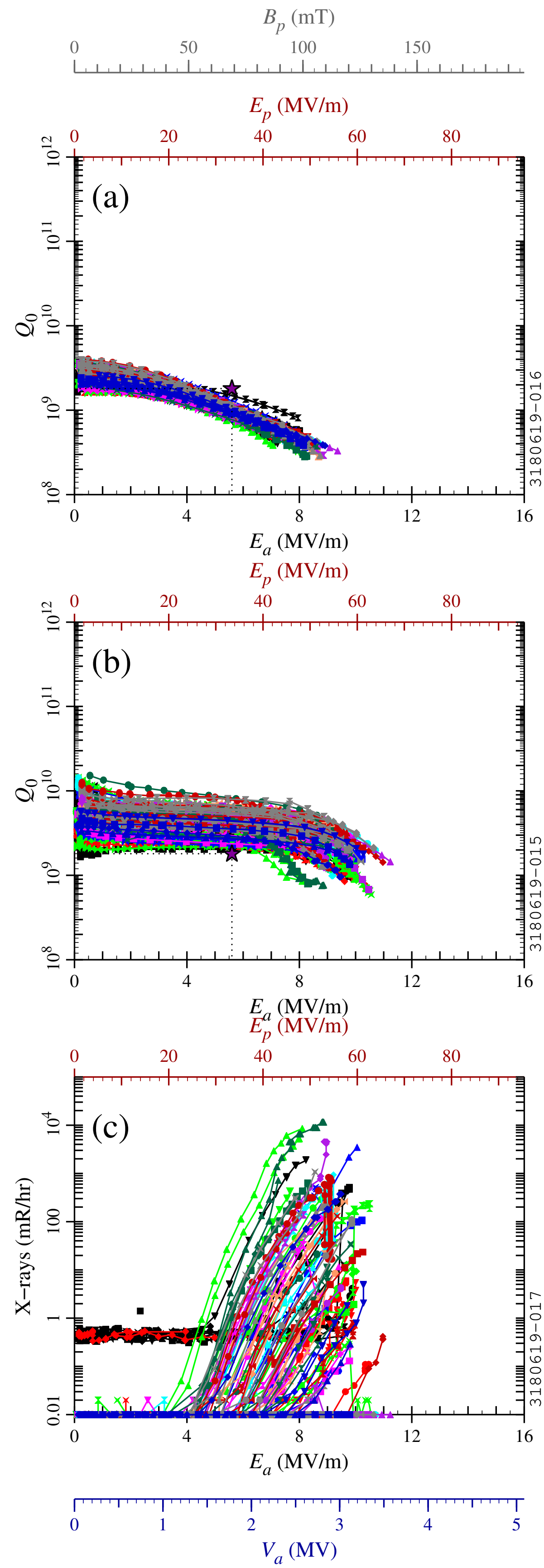

Figure 4: Dewar test results for $\beta_m = 0.086$ QWRs: (a) Q_0 at 4.3 K; (b) Q_0 at 2 K; (c) X-rays at 2 K.

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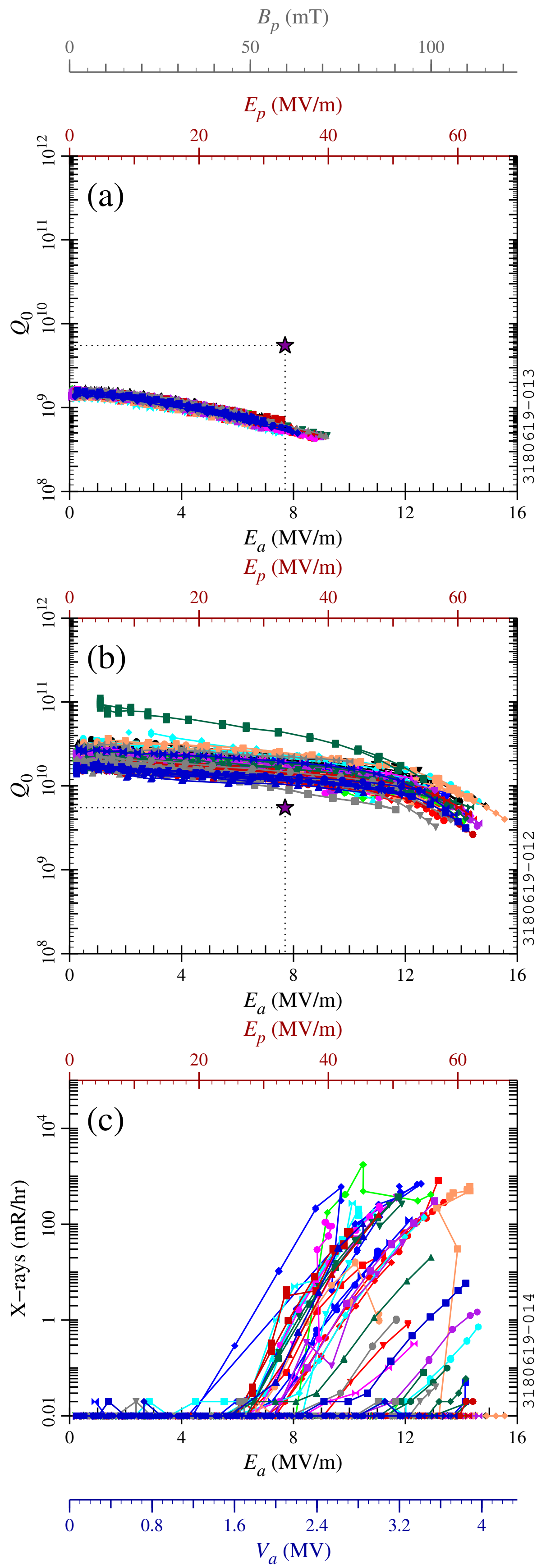

Figure 5: Dewar test results for $\beta_m = 0.29$ HWRs: (a) Q_0 at 4.3 K; (b) Q_0 at 2 K; (c) X-rays at 2 K.

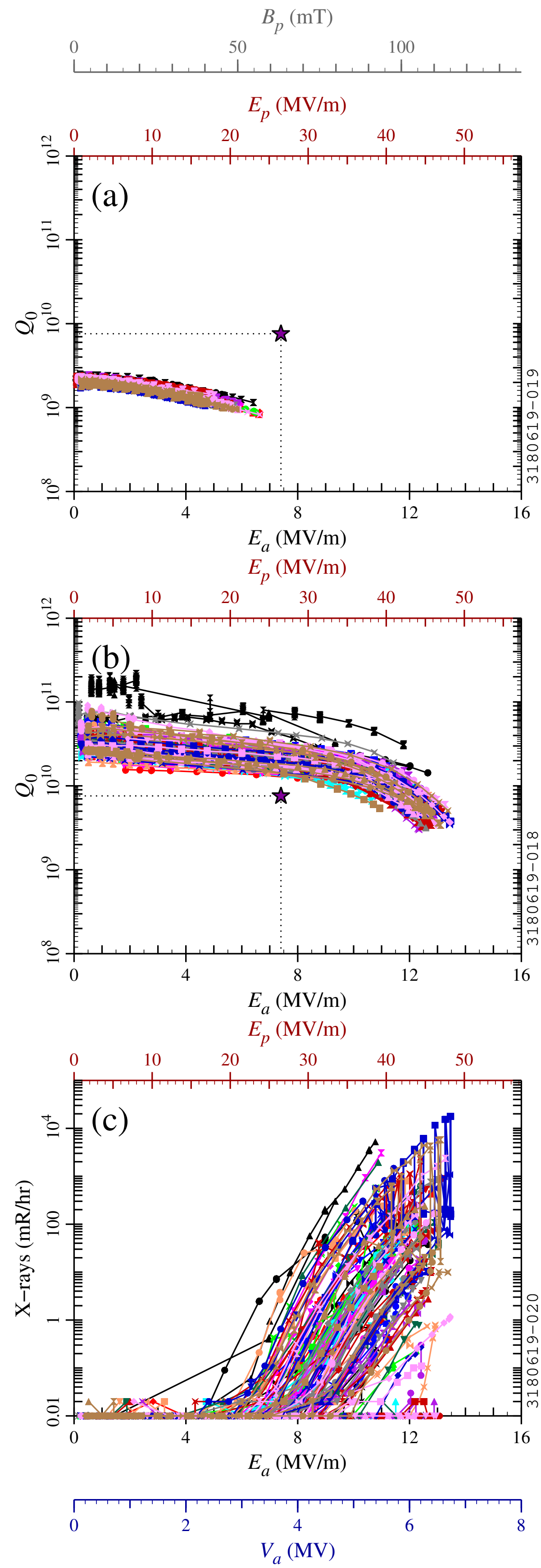

Figure 6: Dewar test results for $\beta_m = 0.54$ HWRs: (a) Q_0 at 4.3 K; (b) Q_0 at 2 K; (c) X-rays at 2 K.

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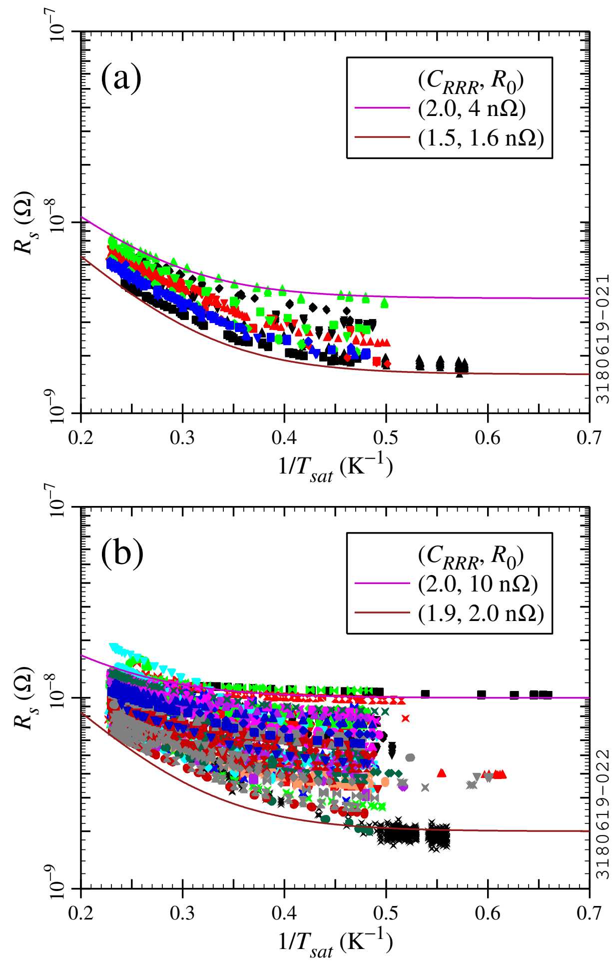

Figure 7: Measured dependence of surface resistance on temperature for QWRs: (a) $\beta_m = 0.043$, (b) $\beta_m = 0.086$.

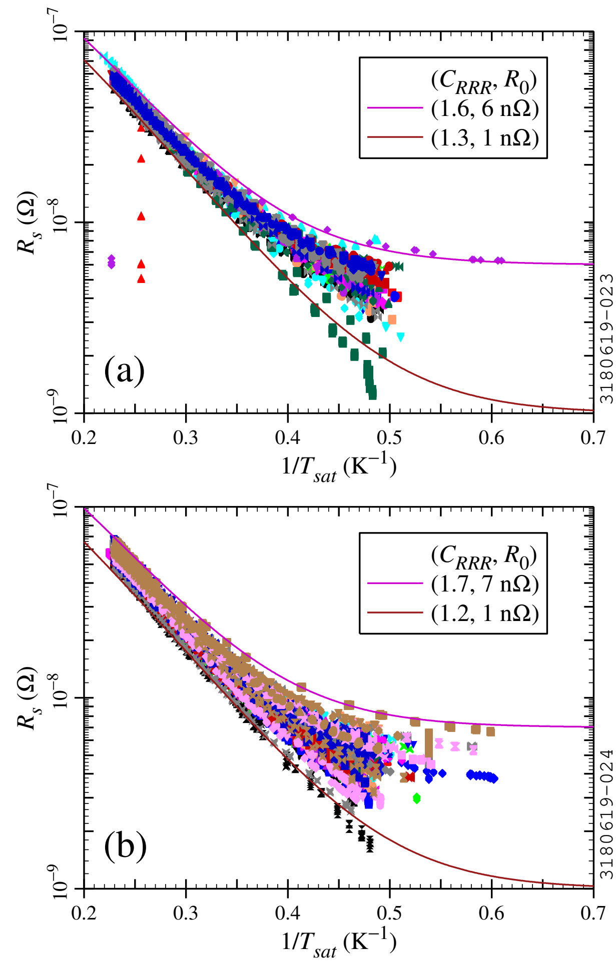

Figure 8: Measured dependence of surface resistance on temperature for HWRs: (a) $\beta_m = 0.29$, (b) $\beta_m = 0.54$.

Measured results are shown in Fig. 7 and Fig. 8. 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 [13, 14]. For reference, Figs. 7 and 8 include some theoretical curves for different residual resistances (R_0) and coefficients (C_{RRR}, dependent on the surface purity) which bracket the measured values approximately. The values of R_0 range from 1 nΩ to 10 nΩ and the values of C_{RRR} range from 1.2 to 2, which is in reasonable agreement with past experience (we expect $C_{RRR} \sim 1.5$ for high-purity Nb).

Performance of $\beta_m = 0.086$ QWRs

For $\beta_m = 0.086$ QWRs, as seen in Fig. 4, there is more spread in the Q_0 values at both 4.3 K and 2 K; correspondingly, there is more spread in the R_s values during pumpdown (Fig. 7b). This performance spread was prominent during early FRIB production, with a significant fraction of the tests having Q_0 below the goal. Eventually we found that the performance was improved and the performance spread was reduced when we added a re-torquing step for the indium-sealed tuning plate flange, which suggested that the problems were mainly due to creep flow of the indium joints. Fortunately, even in early production, we re-torqued the bottom flange during cold mass assembly, so we believe that the performance problems seen in the Dewar tests are not adversely affecting the cryomodule performance. Additional information on the investigation of this issue can be found in another paper [5].

CONCLUSION

Nearly all of the required superconducting resonators for FRIB have been Dewar tested, and $> 96\%$ of the cavities are certified. FRIB cryomodule assembly is nearly complete, with 42 out of 46 cryomodules finished. QWR cryomodule beam commissioning is finished, and HWR beam commissioning is planned to begin in March 2020.

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