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LARGE-SCALE DEWAR TESTING OF FRIB PRODUCTION CAVITIES: STATISTICAL ANALYSIS*

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Abstract

The Facility for Rare Isotope Beams (FRIB) requires a driver linac with 324 superconducting cavities to deliver ion beams at 200 MeV per nucleon. About 1/3 of the cavities are quarter-wave resonators (QWRs, 80.5 MHz); the rest are half-wave resonators (HWRs, 322 MHz). FRIB cavity production is nearly complete, with more than 90% of the required cavities certified for installation into cryomodules. We have accumulated a large data set on performance of production QWRs and HWRs during Dewar certificating testing of jacketed cavities. In this paper, we will report on the data analysis, including statistics on the BCS resistance, residual resistance, and Q-slope. Additionally, we will discuss performance limitations and conditioning (multipacting, field emission).

INTRODUCTION

The Facility for Rare Isotope Beams' (FRIB) driver linac requires 4 types of superconducting radio-frequency (SRF) cavities: quarter wave resonators (QWRs) with β = 0.043 and 0.086 and half wave resonators (HWRs) with β = 0.29 and 0.54 [1, 2]. Drawings of the cavities are shown in Fig. 1; cavity parameters and operating goals are given in Table 1. The resonators are made of high-purity niobium sheet (RRR>250) by deep drawing and electron beam welding. Cavities with helium jackets are delivered to FRIB by industrial suppliers, and the final preparation steps are done at Michigan State University (MSU) [3, 4].

Cryogenic RF testing of the FRIB cavities is done in the SRF vertical test area (VTA) at MSU. Figure 2 shows a β = 0.086 QWR in the magnetically-shielded test cryostat. About one hour is needed for the cavity to cool down from the room temperature to 4.3 K. At 4.3 K, continuous wave (CW) and modulated RF measurements are done and multipacting is conditioned, if needed. During the cool-down from 4.3 K to 2 K, Q_0 is measured at approximately constant field. At 2 K, CW and modulated measurements are repeated and field emission is conditioned, if needed [3]. Statistical data on production resonator performance has been gathered for a large number of cavity tests. Data analysis results and performance limitations will be discussed in this paper.

Figure 1: Isometric sectional views of jacketed cavities.

Table 1: FRIB Production Resonators: RF Parameters, Operating Goals, and Cavity Counts (f_0 = resonant frequency; Q_0 = intrinsic quality factor; E_a = accelerating gradient; E_p = peak surface electric field; B_p = peak surface magnetic field)

Cavity Parameters				
Type	QWR	QWR	HWR	HWR
β	0.043	0.086	0.29	0.54
f_0 (MHz)	80.5	80.5	322	322
E_p/E_a	6.1	6.0	4.3	3.6
B_p/E_a [mT/(MV/m)]	10.8	12.4	7.7	8.6
Goals for linac operation (2 K)				
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	1.2E9	1.8E9	5.5E9	7.6E9
Cavity Certification Requirements (2 K)				
E_a (MV/m)	6.1	6.7	9.2	8.9
Q_0	1.4E9	2.0E9	6.7E9	9.2E9
Number of Cavities				
Needed	12	92	72	148
Tested	16	106	75	145
Certified	16	106	72	138
Completion	100%	100%	100%	93%

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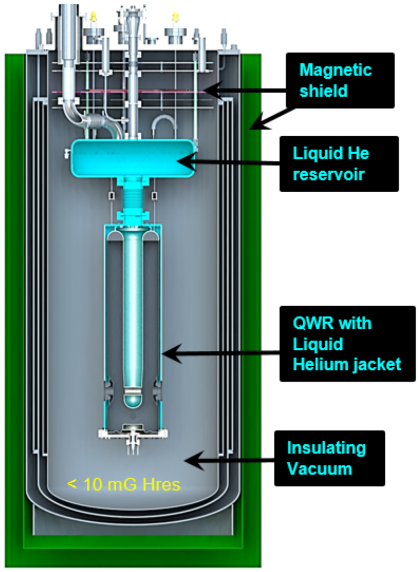

Figure 2: Jacketed β = 0.086 QWR in Dewar.

PERFORMANCE LIMITS

Table 2 provides an overview of FRIB SRF cavity performance limits. Most cavities do not show thermal breakdown at or below the FRIB gradient goal; only 5 out of 322 cavities had early TBD. Most cavities have multipacting barriers, but they can usually be conditioned in a relatively short time. Most cavities do not have serious field emission issues, though some were reworked to reduce the X-ray levels. The cavities show high field Q-slope, but this is above the FRIB gradient goals, so it is not an immediate concern.

Table 2: Cavity Performance Limits Overview

Limitation	FRIB Status
Thermal Breakdown (TBD)	Mostly good 5 out of 332: TBD below E_a goal (2%) 69 out of 332: TBD above E_a goal (21%)
Multipacting (MP)	Most cavities have MP, but can condition Conditioning times usually tolerable (<2 hr/test); varies from cavity to cavity
Field Emission (FE)	Mostly good Some reworks to reduce X-rays (~10%) Most cavities: X-rays <100 mR/hr at design E_a
High Field Q-slope (HFQS)	Good for present goals May need to do better for FRIB energy upgrade

Thermal Breakdown

No QWRs had early thermal breakdown (TBD field below the goal). Two β = 0.29 HWRs and three β = 0.54 HWRs quenched below the E_a goal. A number of cavities had TBD above the E_a goal: 6 out of 16 β = 0.043s at an average $E_a = \langle E_a \rangle$ of 11 MV/m; 9 out of 106 β = 0.086s ($\langle E_a \rangle$ = 10 MV/m); 22 out of 72 β = 0.29s ($\langle E_a \rangle$ = 13 MV/m); and 32 out of 138 β = 0.54s ($\langle E_a \rangle$ = 12 MV/m). Early TBD is likely due to imperfections on the inner surface or in the welds.

Multipacting

Multipacting is common for co-axial RF resonators, including the FRIB cavities. Low MP barriers are seen in the QWRs only; we are usually able to jump over them while filling the cavity. Middle barriers are seen for E_a below 0.5 MV/m; they can be conditioned with constant forward power of 1 to 6 W. High barriers are seen between 0.5 and 4 MV/m; they can be conditioned in CW with increasing forward power, up to about 25 W. The evidence suggests that the high barrier is first-order two-point MP on the short plate. In the HWRs, a "post-high-barrier" is often seen at higher field. Normally, the conditioning time is tolerable (less than 2 hours per test), and can be shorter if a variable input coupler is used (allowing us to better match to the lower Q_0 associated with MP).

Field Emission

Field emission is not a serious problem for the FRIB cavities; almost all cavities' X-rays are below 100 mR/hr at the FRIB operating gradient. Some cavities were reworked after the first test to reduce the X-ray level, as shown in Table 3. A few QWRs had heavy field emission in the first test, and showed scratches in the post-test inspection. These performed significantly better after mechanical polishing. Some of the early HWRs showed significant field emission X-rays in the first test. Improvements to the high-pressure water rinse (HPWR) system were made after these early tests (better coverage, nozzle redesign). The HWRs showed improved performance after re-rinsing.

Table 3: Field Emission Reworks for FRIB Cavities

β	Number of FE reworks	Reasons
0.043	2 out of 16 (~13%)	Contamination particles scratches on surface
0.086	9 out of 106 (~8%)	Contamination particles scratches on surface
0.29	7 out of 75 (~10%)	Contamination particles not optimized HPWR
0.54	22 of 141 (~16%)	Contamination particles not optimized HPWR

High Field Q-Slope

The FRIB cavities were prepared with chemical etching (buffered chemical polishing, BCP) [5]. BCP'ed cavities typically show high-field Q-slope, and a post-etch low-temperature bake does not improve it [6]. CW measurements on the FRIB cavities at 2 K are shown in Fig. 3: All of the cavities which we were able to measure above B_p ~ 85 mT (dashed blue lines) showed HFQS, including cases without X-rays. For the present FRIB goals (purple stars in Fig. 3), this is not a concern, since the HFQS onset is above the goal. However, for future projects with more ambitious gradient goals, electropolishing plus low temperature bake or BCP with a new recipe may be needed.

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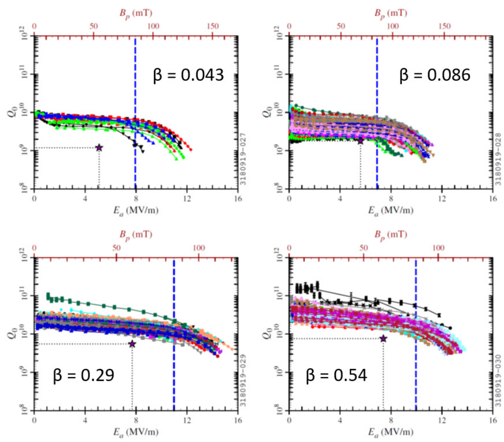

Figure 3: RF measurements on FRIB cavities at 2 K, showing high-field Q-slope above $B_p \sim 85$ mT.

MATERIAL PARAMETERS

We did CW measurements at low field ($E_a \sim 2$ MV/m typically) during the cool-down from 4.3 K to 2 K. We can infer the weighted-average surface resistance (R_s) from the measured Q_0. The BCS theory predicts the dependence of R_s on temperature. A simplified form is [7]:

$$R_S = C_{RRR} R_1 \frac{\Delta}{\kappa_B T} \left(\frac{f}{f_1}\right)^2 \exp\left(-\frac{\Delta}{\kappa_B T}\right) + R_{res} \quad (1)$$

In Eq. (1), the constants are $f_1 = 1.5$ GHz, $R_1 = 1 \cdot 10^{-5}\ \Omega$, and κ_B = the Boltzmann Constant; the variables are C_{RRR} (dependant on surface purity), Δ (energy gap of superconductor), and R_{res} (residual resistance); and the independent parameter is T (temperature).

We did 3-parameter fits to obtain C_{RRR}, Δ, and R_{res} using a non-linear least square method [8]. Figure 4 shows the relative error between the data and the fitted curve for a few cases. The disagreement is less than 6%.

The fitting results are summarized in Table 4. Some cavities were not included in the statistics (measured temperature did not agree well with the expected value from the bath pressure; bottom flange not retorqued; or E_a higher than 2.5 MV/m). The results for the QWRs are complicated by tuning plate contact issues [9]; the HWR results may be more indicative of the intrinsic properties of the niobium. In the HWRs, the fitted energy gap is relatively consistent with previously-reported values and C_{RRR} is consistent with high surface purity [8]; the measured residual resistance is about 3 to 4 nΩ.

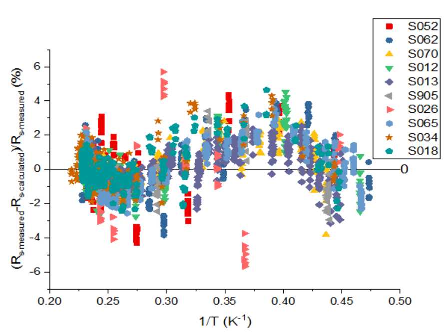

Figure 4: Relative difference between measured Rs and fitted Rs as a function of 1/T for ten β = 0.29 HWRs.

Table 4: Summary of fitting results for FRIB cavities (average and sample standard deviation)

β	Number counted	C_{RRR}	Δ (meV)	R_{res} (nΩ)
0.043	10	1.36 ± 0.21	1.28 ± 0.07	2.21 ±0.69
0.086	38	1.49 ± 0.36	1.23 ± 0.15	4.12 ±1.40
0.29	57	1.88 ± 0.22	1.59 ± 0.06	3.75 ±0.97
0.54	82	1.84 ± 0.17	1.57 ± 0.03	3.32 ±0.92

SUMMARY

The FRIB linac requires large-scale production of superconducting quarter-wave and half-wave resonators, for a total of 324 cavities. Dewar certification testing of the cavities is nearly complete. The production cavities are meeting the FRIB requirements, though some of them have required reworks. The Dewar tests provide statistical data on production resonator performance. High-field performance limits include thermal breakdown, field emission, and high-field Q-slope.

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