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BUNKER TESTING OF FRIB CRYOMODULES*

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Abstract

The Facility for Rare Isotope Beams' (FRIB) superconducting driver linac requires 104 quarter-wave resonators (QWRs, β = 0.041 and 0.085), 220 half-wave resonators (HWRs, β = 0.29 and 0.53), and 74 superconducting solenoid packages (8 packages of length 25 cm, and 66 packages of length 50 cm). The resonators and solenoids are installed onto a cold mass and assembled into a cryomodule. Four accelerating cryomodule types (β = 0.041, 0.085, 0.29, 0.53) and 2 matching cryomodule types (β = 0.085, 0.53) are required. Each cryomodule undergoes cryogenic and RF testing in a bunker prior to installation in the tunnel. The cryomodule test verifies operation of the cavities, couplers, tuners, solenoid packages, magnetic shield, and thermal shield at 4.3 K and 2 K. All of the required cryomodules for β = 0.041, 0.085, and 0.29 have been bunker tested and certified. As of August 2019, eight of the β = 0.53 cryomodules are certified; the remaining cryomodules are being assembled or are in the queue for testing. This paper will present test results for certified cryomodules, including cavity statistics (accelerating gradient, field emission X-rays at operating gradient), solenoid package statistics (operating current, lead flow), and cryomodule 2 K dynamic heat load.

INTRODUCTION

The driver linac for the Facility for Rare Isotope Beams (FRIB) is designed to accelerate ion beams to 200 MeV/u using 46 superconducting cryomodules (SCMs) [1]. The four accelerating SCM types are SCM041 (β = 0.041), SCM085 (β = 0.085), SCM29 (β = 0.29), and SCM53 (β = 0.53). The two matching SCM types are SCM085-matching (β = 0.085) and SCM53-matching (β = 0.53).

Two bunkers in the FRIB complex are used for FRIB cryomodule tests, one in the SRF High Bay (SRF Bunker), the other in the East High Bay (ReA6 Bunker) [2]. They allow us to test and certify up to 2 SCMs per month.

As of August 2019, all SCM041, SCM085, SCM085-matching and SCM29 cryomodules are certified and installed in the FRIB tunnel [3], and ten SCM53 cryomodules are certified. Updated bunker test statistics are shown in the Table 1. Five cryomodules have been certified since the last bunker testing report [4].

CERTIFICATION TESTING

The SCM bunker certification test includes testing of cavities, RF input couplers, tuners [5], and solenoid packages [6]. All of the components must meet the FRIB requirements. Tables 2 and 3 list the main requirements for the cavities and solenoid packages.

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Table 1: FRIB Cryomodule Bunker-Test Certification Status

FRIB Cryomodule Type	Certified | Operation Need	Completed
SCM041	3 | 3	100%
SCM085	11 | 11	100%
SCM085-matching	1 | 1	100%
SCM29	12 | 12	100%
SCM53	8 | 18	44.4%
SCM53-matching	0 | 1	0%
Totals	35 | 46	76.1%

Table 2: Main Cavity Requirements (f = resonant frequency, E_a = accelerating gradient; BW = bandwidth)

Parameter	QWR041	QWR085	HWR29	HWR53
f (MHz)	80.5	80.5	322	322
E_a (MV/m)	≥5.1	≥5.6	≥7.7	≥7.4
BW (Hz)	43	41.5	57	33.3
2 K Heat Load (W)	≤1.32	≤3.85	≤3.55	≤7.9

Table 3: Main Solenoid Package Requirements

Package	Maximum field on axis	Ramp rate	Current
25 cm solenoid	≥8 T	≥ 0.3 A/s	≤ 91 A
25 cm dipoles	≥0.06 T·m	≥ 0.5 A/s	≤ 20 A
50 cm solenoid	≥8 T	≥ 0.3 A/s	≤ 91 A
50 cm dipoles	≥0.03 T·m	≥ 0.5 A/s	≤ 20 A

Bandwidth Measurements

Figure 1 shows BW measurements and requirements for 37 FRIB SCMs. Although the results show cavity BWs have some offset relative to the specifications, all of values are acceptable for the beam operation. A few cavities' coupler positions were adjusted to increase the BW to mitigate microphonics issues.

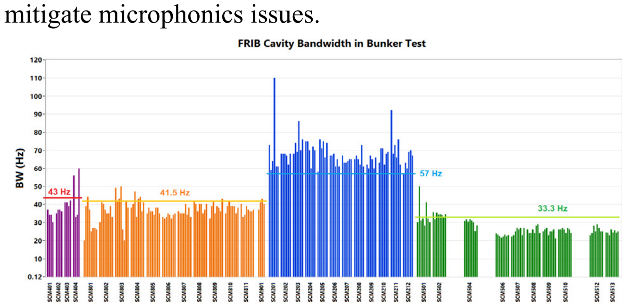

Figure 1: Measured cavity bandwidths.

High-Power Testing

All SCM cavities are tested at high RF power. Initial RF turn-on, calibration verification, and conditioning are done in the self-excited loop mode of the FRIB low-level RF controller (LLRF) [7]. Typically, the high multipacting (MP) barrier is conditioned first, then the middle MP

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barrier is checked and conditioned. After the high MP barrier is conditioned, field emission (FE) conditioning is done if needed. A typical MP conditioning process is shown in Fig. 2.

To verify the cavity performance in the SCM, the cavity gradient is increased to at least the FRIB E_a requirement. If there is no strong FE and no thermal breakdown, the cavity is excited to 10 ~ 20 % higher than the required gradient. The maximum gradients for bunker-tested are shown in Fig. 3 (as of August 2019). All of the cavities meet the gradient requirements.

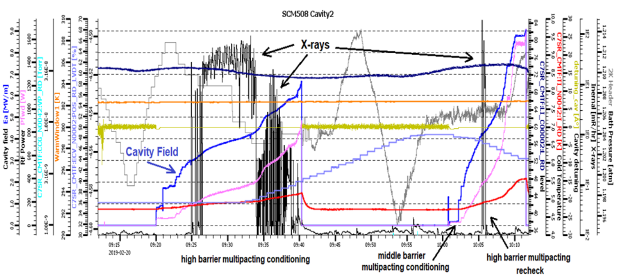

Figure 2: Conditioning of multipacting for a β = 0.53 HWR (SCM508, Cavity 2): cavity field (blue), X-rays (black), forward power (pink), and coupler temperature (red).

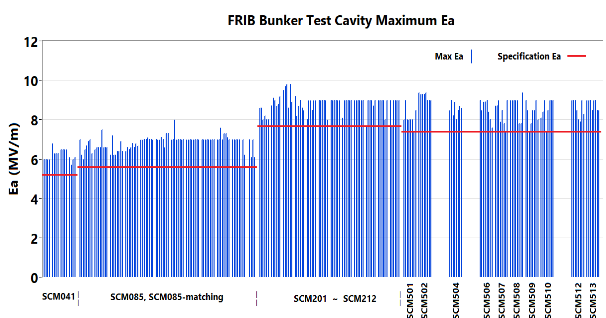

Figure 3: Gradients reached in bunker tests. Blue bar: measured gradient; red line: FRIB requirement.

Some cavities had FE X-rays at high gradient in the bunker test. Pulsed conditioning of the emitters was done for these cases. Typically, after one or several "electrical breakdown" events, the cavity FE onset was improved and the FE X-rays at high gradient decreased to a modest level. For the SCM29 and SCM53 cryomodules tested so far, the performance of 24 out of 152 cavities was improved by pulsed conditioning. However, one β = 0.53 HWR did not improve with pulsed conditioning (in SCM505); additional conditioning in the tunnel is planned. Figure 4 shows FE X-rays measured in the bunker tests so far. The background level for the X-ray sensor in the ReA6 Bunker is 0.1 mR/hr (where SCM207, SCM504, SCM 507, all SCM041, and all SCM085 cryomodules were tested). For the SRF Bunker, the background level is 0.01 mR/hr (where the rest of the cryomodules were tested). The X-ray signal is below 10 mR/hr for most cavities.

Locking

The cavities' RF amplitude and phase stability is measured in the bunker test. For certification, the

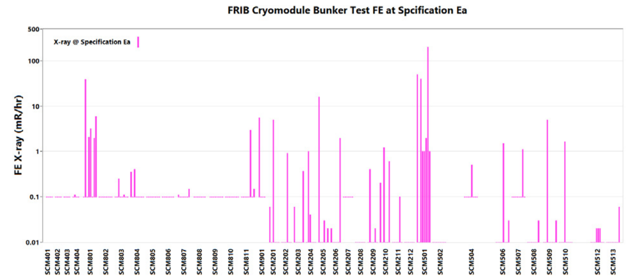

Figure 4: Field emission X-rays measured at the operational gradient in bunker tests.

amplitude and phase must be locked with the LLRF controller for at least 1 hour at the FRIB gradient. Typically, the cavity is locked at higher E_a (up to 10% higher) if there is low risk for deconditioning. The FRIB requirement is amplitude stability of < ±1% and phase stability of < ±1°.

All SCM041, SCM085 and SCM085-matching cryomodules passed the locking test at 4.3 K in the ReA6 Bunker. Almost all SCM29 cavities were locked at least one hour at 4.3 K, though a few SCM29 cavities, and most SCM53 cavities, were locked at 2 K instead of 4.3 K. The ReA6 Bunker cannot support long-term 2 K testing, and the SCM53 cavity has a large heat load at 4.3 K (at E_a = 5.6 MV/m, the estimated heat load is 70 W). Hence, for the two SCM53 cryomodules tested in the ReA6 Bunker, the cavities were locked for 1 hour at 4.3 K, but at lower field (E_a = 5.6 MV/m).

A typical β = 0.53 locking test is shown in Fig. 5. The cavity was locked for 1 hour at 2 K with E_a = 8.1 MV/m (about 10% higher than the FRIB requirement), with amplitude and phase stability meeting the specification.

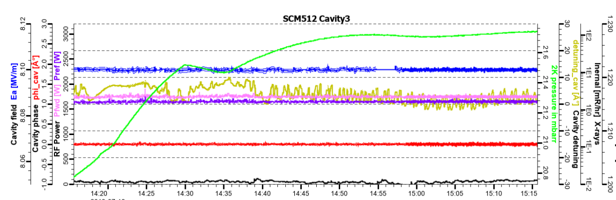

Figure 5: Locking test for 1 hour at 2 K (CM512, Cavity 3): cavity field (blue), cavity phase (red), cavity detuning (gold), bath pressure (green), X-rays (black), forward power (pink), reflected power (purple).

Dynamic Heat Load

At ~2 K, the cavity dynamic heat load is checked against the requirement (Table 2). The load measurement method compares different rates of pressure rise for the helium bath (dP/dt). The helium supply valve and return valve are closed after the bath is pumped to 20 mbar. The heat from the cavity or a resistive heater will affect dP/dt. Three modes are used: (1) cavity RF and heater off; (2) two cavities on at the FRIB gradient; (3) cavity RF off and heater on.

Figure 6 shows a typical 2 K dynamic heat load measurement. When comparing the dP/dt values of the different modes, we can see whether the cavity load is less

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than the FRIB specification. Two measurements are done with the heater (Mode 3), one with the heater power set to the FRIB goal and another with the heater power closer to what is expected based on the cavities' Dewar tests. For example in Fig. 6, with the cavities on, dP/dt is less than the 6 W case but more than the 3 W case. The estimated heat load is 5 W for the cavities-on case. In the corresponding RF measurements in Dewar tests, the heat load for these two cavities was about 6 W. With the methods described above, an estimate of the 2 K dynamic heat load is made for each cryomodule, as shown in Fig. 7. The horizontal lines indicate the FRIB requirements.

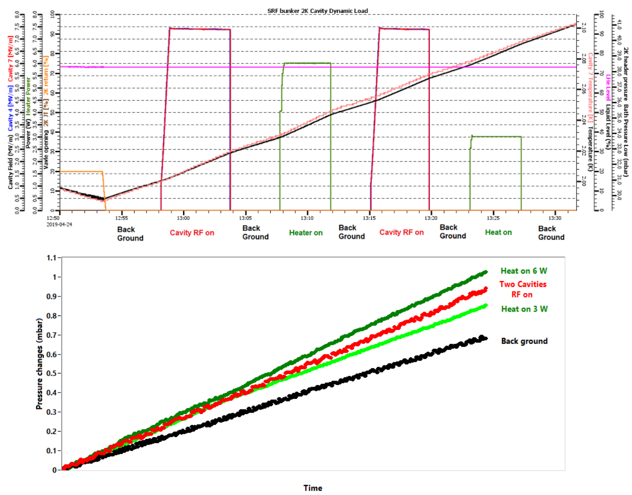

Figure 6: Dynamic heat load measurement at 2 K. Top: bath pressure (black), cavity fields (blue, red), and heater power (green) as a function of time. Bottom: zoomed-in P as a function of t (red: both cavities on; dark and light green: heater on; black: cavities and heater off).

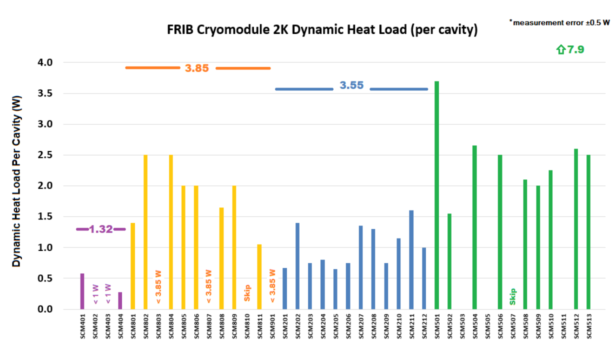

Figure 7: Estimated dynamic heat load per cavity at 2 K.

Solenoid Package Testing

The procedure for solenoid package testing includes four parts: (1) individual test: solenoid, dipole x and dipole y are energized individually; (2) combination test: all magnets are energized together; (3) integration test: all magnets are energized with the 2 adjacent cavities operated at the FRIB gradient. As shown in Fig. 8, the solenoid current is +91 to −91 A, and the dipole currents are +19 to −19 A. The solenoid package is certified if the magnets have no quenches, the cavity RF has no trips, and there are no temperature or vacuum trips. As of August 2019, 37 SCM solenoid packages have been tested, and all are certified. The statistics are given in Table 4.

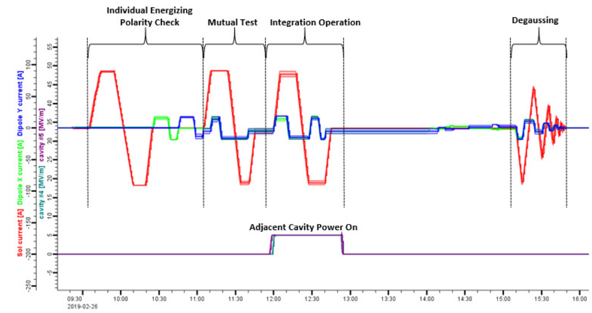

Figure 8: A typical solenoid package bunker test. Red: solenoid current; green: dipole x current; blue: dipole y current (from Ref. [4]).

Table 4: Solenoid Package Bunker Certification Statistics

SCM Type	Number of SCM certified	Solenoid package length (cm)	Number of solenoid packages per SCM
0.041	4	25	2
0.085	11	50	3
0.29	12	50	1
0.53	10	50	1

SUMMARY

Bunker testing of FRIB cryomodules is well underway. As of August 2019, all β = 0.041, β = 0.085, β = 0.085 matching, and β = 0.29 cryomodules are certified; 44.4% of the β = 0.53 cryomodules are certified. About 75% of the cryomodules required for the FRIB linac are certified.

REFERENCES

[1] T. Xu *et al.*, "Progress of FRIB SRF Production," in *Proc. 18th Int. Conf. RF Superconductivity (SRF'17)*, Lanzhou, China, Jul. 2017, pp. 345-352. doi: 10.18429/JACoW-SRF2017-TUXAA03

[2] J. T. Popielarski *et al.*, "Performance Testing of FRIB Early Series Cryomodules," in *Proc. 18th Int. Conf. RF Superconductivity (SRF'17)*, Lanzhou, China, Jul. 2017, pp. 715-721. doi: 10.18429/JACoW-SRF2017-THYA01

[3] J. Wei *et al.*, "The FRIB SC-linac: installation and phased commissioning," presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper MOFAA3.

[4] W. Chang *et al.*, "Progress in FRIB Cryomodule bunker tests," presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper THP062.

[5] J. T. Popielarski *et al.*, "FRIB Tuner Performance and Improvement," presented at the North American Particle Accelerator Conf. (NAPAC'19), Lansing, MI, USA, Sep. 2019, paper WEPLM70, this conference.

[6] K. Saito *et al.*, "FRIB Solenoid Package in Cryomodule and Local Magnetic Shield," presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper MOP072.

[7] S. Zhao *et al.*, "The LLRF Control Design and Validation at FRIB," presented at the North American Particle Accelerator Conf. (NAPAC'19), Lansing, MI, USA, Sep. 2019, paper WEPLM03, this conference.