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FABRICATION AND COLD TEST RESULT OF FRIB BETA=0.53 PRE-PRODUCTION CRYOMODULE*

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Abstract

The Facility for Rare Isotope Beams (FRIB) project fully utilizes superconducting cavities from a low energy: β=0.041 and 0.085 quarter-wave resonators (QWRs) and β=0.29 and 0.53 half-wave resonators (HWRs). Following the QWR, a β=0.53 pre-production cryomodule was assembled and cold tested as the first FRIB HWR cryomodule. The HWR cryomodule includes many different design features compared to the QWR. However, all cavities achieved and locked at the design field of 7.4 MV/m within phase and amplitude specifications. A total dynamic load of 33 W was sufficiently smaller than the specification of 63 W, and no Q_0 degradation was observed. An 8-T superconducting solenoid functioned as designed, and the degaussing procedure worked properly. This successful cold test allows for the start of production of HWR cryomodules for the next step.

INTRODUCTION

FRIB is a new joint project for a nuclear science facility funded by the DOE Office of Science, Michigan State University, and the State of Michigan [1, 2]. The FRIB driver linac accelerates stable ion beams (from protons to uranium) to energies more than 200 MeV/u, and at continuous wave beam power up to 400 kW, requiring full utilization of four types of superconducting cavities after an RFQ [3, 4].

The superconducting cavities consist of 80.5-MHz β=0.041 and 0.085 quarter-wave resonators (QWRs) and 322-MHz β=0.29 and 0.53 half-wave resonators (HWRs). Six different designed cryomodules contain four to eight of these resonators (see Fig. 1 and Table 1).

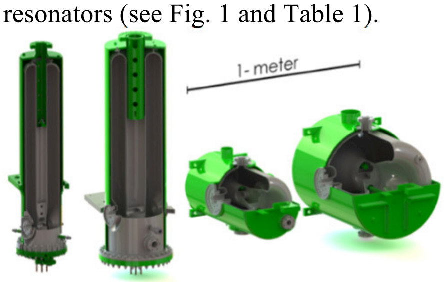

Figure 1: FRIB SRF cavities, from left, β=0.041, 0.085, 0.29, and 0.53.

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Assembly of the FRIB cryomodules began with a pre-production QWR (β=0.085) cryomodule in 2015. Completed at the end of 2015, the pre-production QWR cryomodule was cold tested and its performances were validated successfully. Production of QWR cryomodules is in progress [5].

Following the QWR, a β=0.53 pre-production cryomodule was assembled as the first FRIB HWR cryomodule. Since the HWRs make up two-thirds of the FRIB cryomodules, the production of the HWR cryomodules are critical for the project. Compared to the QWR, the HWR cryomodule incudes different design features (e.g. RF couplers, pneumatic frequency tuners, magnetic shields, etc.). Due to these different features, a cold test of the HWR cryomodule is a significant milestone to validate the FRIB HWR cryomodule design.

This paper will review and discuss the assembly of the β=0.53 pre-production cryomodule and mainly the cold test results.

Table 1: FRIB Cryomodules and Configuration

Type	Quantity		
	Cryomodule	Resonator	Solenoid
β=0.041	3	12	6
β=0.085	11	88	33
β=0.29	12	72	12
β=0.53	18	144	18
β=0.085M*	1	4	0
β=0.53M*	1	4	0
Total	46	324	69

*Matching module

CRYOMODULE ASSEMBLY

Figure 2 shows the assembly sequence of the β=0.53 pre-production cryomodule. In the beginning, a cold mass and a baseplate are prepared as subassemblies (see from C1 to C3 in Fig. 2), then the cold mass is lifted onto the baseplate in the mid-sequence.

All beam line elements, resonators, solenoids, RF couplers, and beam line bellows, are assembled as the cold mass in an ISO 5 (class 100) clean room. All resonators are vertical tested and certified in advance of the clean room assembly, in addition to RF coupler conditioning.

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Figure 2: Assembly sequence of β=0.53 pre-production cryomodule.

The cold mass is moved to the cryomodule assembly area for welding of cryogenic piping and installation of related components, such as heaters, temperature sensors, magnetic shields, and multi-layer insulation (MLI). These steps take a few weeks.

The baseplate assembly starts by welding a bayonet box, followed by the installation of G10 posts, MLI, lower thermal shields, thermal shield piping, and instrumentation wiring [6]. All resonators and the solenoid are surveyed and aligned immediately after the cold mass is lifted on to the baseplate. Cryogenic systems (e.g. 2K and 4K headers) are then welded on the cold mass. The cold mass and the cryogenic system are covered by MLI, thermal shields, a vacuum vessel cover, and then finally the external components are attached.

The pre-production cryomodule assembly began in April 2016 and was completed in September 2016 (about 5 months). This timeline included 2 months of rework and other mitigating issues, therefore we expect 3 months for production.

COLD TEST

Cavity Conditioning

The bunker is equipped with two sets of high-power amplifiers operating at 8 kW, 322 MHz. The amplifiers are mounted on the roof of the bunker, and eight RF lines penetrate the bunker below (see Fig. 3). The RF line from each amplifier can be manually switched between cavity RF feeds at the outside of the bunker.

Figure 4 shows a cut view of the cryomodule indicating the cavities and the solenoid. We energized the resonators, up to 2 resonators at one time, and observed E_{acc}, forward power, and X-ray. Figure 5 shows these results.

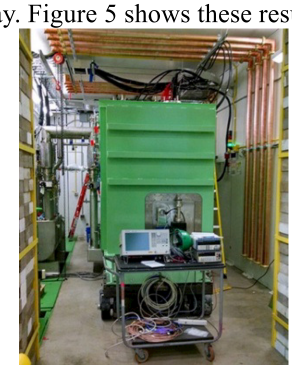

Figure 3: β=0.53 pre-production cryomodule in bunker.

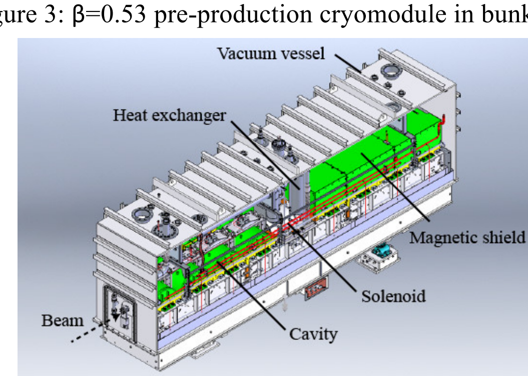

Figure 4: β=0.53 cryomodule includes eight 322-MHz HWRs and one 50-cm 8-T superconducting solenoid.

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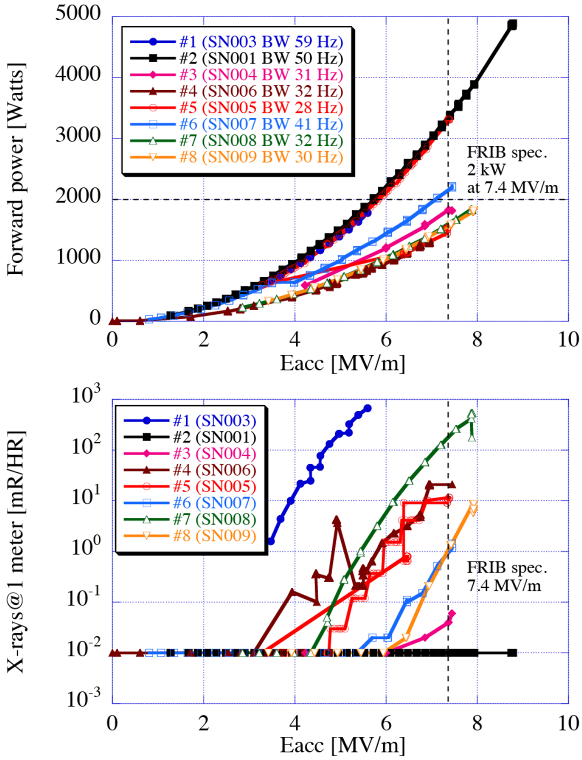

Figure 5: Cavity conditioning results. E_{acc} vs. forwarded power (top), E_{acc} vs. X-rays (bottom).

The results show that all cavities (except for #1) could achieve the FRIB specification of 7.4 MV/m. Coupler multipacting slowed initial conditioning progress for locking at 7.4 MV/m. To solve this problem, a DC bias voltage of ±1 kV on an inner conductor of a coaxial RF coupler was applied [7]. Even with the bias voltage applied, it took some time to condition cavity multipacting. Cavity #1 still needed more conditioning to reach the specified field at this point.

The input coupling on cavity #1 was decreased to 17 Hz to improve the conditioning progress, so that less power was needed to reach multipacting levels. Consequently, cavity #1 could successfully achieve up to 8.1 MV/m. Figure 6 shows the progress of the conditioning. The bandwidth was reduced from 60 to 21 Hz, and finally adjusted to the specified bandwidth of 30 Hz.

LLRF Control

All cavities were locked with a bandwidth of 30 Hz at 4 K within an amplitude and phase specification: 2° peak-to-peak, 0.25° RMS and 2% peak-to-peak, 0.25% RMS. Figure 7 shows the cavity phase of the cavity #8 operating at 4K and 7.4 MV/m. Phase controller gain was adjusted at the time≈2000. The plot clearly shows the impact of adjusted phase control gain on the cavity phase.

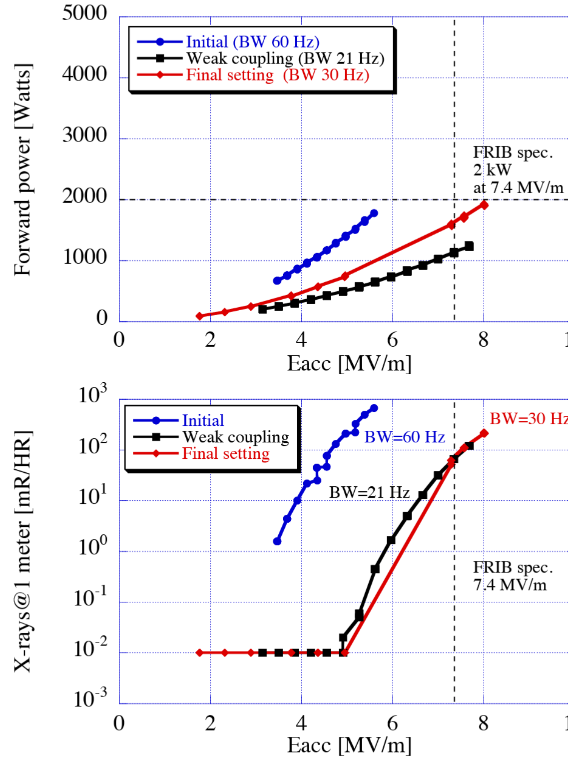

Figure 6: Progress of cavity #1 conditioning. Weak cavity coupling (i.e. bandwidth) reduced X-rays.

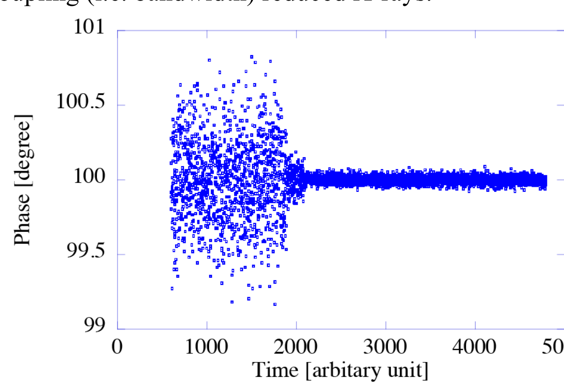

Figure 7: Phase stability before and after LLRF optimization of Cavity #8 (4 K, 7.4 MV/m).

Figure 8 shows statistics plots of the phase and amplitude for Cavity #8. The phase and amplitude were controlled within 0.17° peak-to-peak, σ= 0.0236, and 0.035% peak-to-peak, σ= 0.0034%, respectively after RF parameter optimization.

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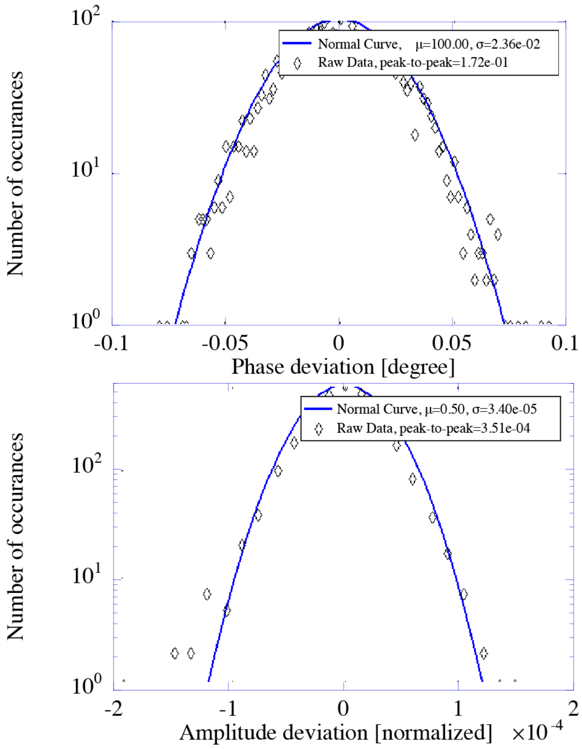

Figure 8: Phase and amplitude deviation of Cavity #8 (4 K, 7.4 MV/m).

Pneumatic Frequency Tuner

FRIB and ANL have collaborated to develop a pneumatic frequency tuner for the HWRs [8]. Figure 9 shows the pneumatic frequency tuner for the β=0.53 HWRs. As shown in Table 2, all cavities were tuned to an operating frequency of 322 MHz within a maximum helium pressure of 50 psig.

Figure 9: Pneumatic frequency tuner. Helium gas pressurizes the piston actuator, compressing the cavity in the beam line direction by the tuning arms.

Table 2: Cavity Frequency and Tuner Pressure

Cavity	VT* (2K) [MHz]	2K Pressure [psig]	Freq. [MHz]	Pressure at 322 MHz [psig]
#1	322.074	14.2	322.008	20.9
#2	322.075	13.9	322.015	25.7
#3	322.063	10.9	322.008	17.8
#4	322.071	11.9	322.016	24.0
#5	322.086	12.1	322.034	39.8
#6	322.091	19.5	322.009	27.5
#7	322.073	27.4	321.998	27.8
#8	322.082	23.9	322.012	34.3
			Average	27.2

*Vertical test

Heat Load Measurement

Table 3 shows the dynamic heat loads for individual cavities. The averaged dynamic heat load of 4.09±1.5 W corresponds to $Q_0=(1.58\pm0.37)\times10^{10}$ at 7.81 MV/m, which is sufficiently higher than the FRIB specification of 7.6×10^9 at 7.4MV/m. No Q_0 degradation was observed.

Table 3: Dynamic Heat Load

Cavity	Field [MV/m]	2K heat load [W]
#1	7.5	4.5
#2	8.0	3.5
#3	8.0	2.6
#4	8.1	3.5
#5	8.0	3.5
#6	8.0	2.6
#7	7.4	7.0
#8	7.5	5.5
Average	7.81	4.09
Total 2K dynamic load		32.7
(Specified 2K dynamic load		63.2)

Excitation of 8-T Superconducting Solenoid

The β=0.53 cryomodule includes one 8-T superconducting solenoid, which is identical to β=0.085. It has an inner diameter of 40 mm and a length of 50 cm, and corrector magnets (horizontal and vertical) are included in the solenoid package. This type of solenoid already has been tested and validated in some β=0.085 cryomodules [9].

We energized up to the design currents: solenoid ±87A, dipole ±19A, successfully under both adjacent cavities (#4 and 5) operating at 7.5 MV/m.

To evaluate the degaussing procedure, the dynamic heat loads of the adjacent cavities were compared before and after degaussing and warming up cavities to 20 K. Since no difference was observed, we confirmed the degaussing works properly.

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SUMMARY

All cavities achieved the design accelerating voltage of 7.4 MV/m, and the LLRF system locked all cavities with a RF bandwidth of 30 Hz at 4 K within the phase and amplitude specifications: 2° and 2%. The total dynamic load was 33 W, which has sufficiently smaller than the specification of 63W, and no Q_0 degradation was observed. The superconducting solenoid functioned as designed, and the degaussing procedure worked properly.

The successful cold test allows for the start of production of HWR cryomodules for the next step, which means the FRIB project reached another significant technical milestone.

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