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EXPERIENCE AND LESSONS IN FRIB SUPERCONDUCTING QUARTER-WAVE RESONATOR COMMISSIONING*

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Abstract

The superconducting (SC) linear accelerator (linac) for the Facility for Rare Isotope Beams (FRIB) has one quarter-wave resonator (QWR) segment and two half-wave resonator (HWR) segments. The first linac segment (LS1) contains twelve $\beta = 0.041$ and ninety-two $\beta = 0.085$ QWRs operating at 80.5 MHz, and thirty-nine SC solenoids. Superconducting radiofrequency (SRF) commissioning and beam commissioning of LS1 was completed in April 2019. The design accelerating gradients (5.1 MV/m for $\beta = 0.041$ and 5.6 MV/m for $\beta = 0.085$) were achieved in all cavities with no multipacting or field emission issues. The cavity field met the design goals: peak-to-peak stability of ±1% in amplitude and ±1° in phase. We achieved 20.3 MeV/u ion beams of Ar, Kr, Ne, and Xe with LS1. In this paper, we will discuss lessons learned from the SRF commissioning of the cryomodules and methods developed for efficient testing, conditioning, and commissioning of more than 100 SC cavities, each with its own independent RF system.

INTRODUCTION

The FRIB SC driver linac is designed to accelerate stable ion beams, from hydrogen to uranium, to 200 MeV/u. The linac is divided into three segments with two 180º bending sections. The first segment, LS1, contains twelve $\beta = 0.041$ QWRs and ninety-two $\beta = 0.085$ QWRs operating at 80.5 MHz, house in 15 cryomodules along with 39 SC solenoids. Table 1 shows details of the LS1 cryomodules. The next two segments, LS2 and LS3, contain seventy-two $\beta = 0.29$ HWRs and one hundred forty-eight $\beta = 0.53$ HWRs operating at 322 MHz, housed in 31 cryomodules along with 30 SC solenoids [1]. In the phased commissioning of the FRIB driver linac, we completed commissioning of all LS1 cryomodules with beam and achieved 20.3 MeV/u ion beams with four different ion species (Ne, Ar, Kr, and Xe) [2, 3]. The design operating temperature of the LS1 cavities is 2 K but they were operated at 4.5 K at this stage of the phased commissioning.

Commissioning of QWR cryomodules in LS1 will be discussed in this paper. The status of HWR cryomodule production for LS2 and LS3, offline bunker testing, and tunnel installation is presented elsewhere [2,4-6].

Table 1: Configuration of LS1 Cryomodules. All Cavities are QWRs Operated at 80.5 MHz

Cryomodule type	CA	CB	CH
Number of cryomodules	3	11	1
β	0.041	0.085	0.085
Cavities per cryomodule	4	8	4
Design accelerating gradient E_a (MV/m)	5.1	5.6	5.6
SC solenoids per cryomodule	2	3	0
Design solenoid magnetic field (T)	8	8	N/A

CAVITY PERFORMANCE

Accelerating Gradients

Figure 1 shows the average accelerating gradient (E_a) reached in each cryomodule. The measured gradients exceeded the design goals in all 104 cavities. For this stage of linac commissioning, the highest operating E_a was limited to 5-10% higher than the design E_a by an administrative decision; in offline cryomodule bunker tests, many cavities were tested to approximately 20% higher than the design E_a [4].

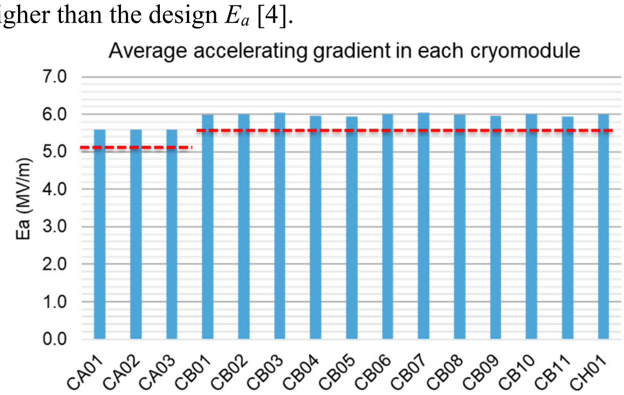

Figure 1: Accelerating gradients achieved in LS1. Solid blue bars: average accelerating gradient in each cryomodule. Dashed red lines: design gradients.

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Field Emission

The measured field emission (FE) X-rays were reasonably low in all 104 cavities, as can been seen in Fig. 2. In the worst cavity, FE X-rays are 3 mR/hr measured at ~1 m away from the cavity, hence there are no concerns about degradation of the cavity quality factor or radiation damage to ancillary components. There are no major changes in X-ray production between the cryomodule bunker test and the performance during linac commissioning, which means that no major particulate contamination has been introduced into the cavities during (i) transportation of the cryomodules from the bunker to the linac tunnel or (ii) opening the gate valves to connect the cryomodule beam line space to the warm beam diagnostic stations.

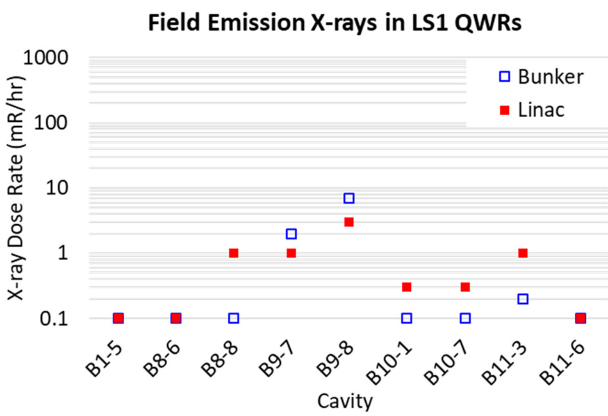

Figure 2: Field emission X-rays at design E_a for cavities with X-ray dose rates >0.1 mR/hr. The red dots (linac) were measured after opening the beam line gate valves at each end of each cryomodule.

Multipacting

Up to three different multipacting (MP) bands are seen in the QWRs [6], as shown in Table 2. MP conditioning is done in the cavity certification test and the cryomodule bunker test, but there is no conditioning memory after thermal cycling to room temperature, so reconditioning is needed in the linac.

The highest MP bands in all 104 cavities were conditioned in continuous-wave (CW) mode; it took approximately 20 minutes per cavity to completely condition the high barrier. The RF power dissipation during high barrier conditioning is 10 to 20 W, so multiple cavities could be conditioned simultaneously at 4.5 K without excessively loading the cryogenic system.

The lowest MP barrier, on the other hand, usually cannot be conditioned even with ~1 hour of CW conditioning. However, if we turn on with an initial RF power of ~20 W, the cavity fills faster than the time needed for the multipacting to turn on, so we are able to “jump over” the barrier.

The same jump method can be applied to the middle barrier. The middle barrier, like the high barrier, is also amenable to CW conditioning.

After application of the MP mitigations described above, none of the cavities were stuck in MP during SRF commissioning or beam commissioning.

Table 2: Accelerating Gradients at which Multipacting Bands are Observed in the FRIB QWRs

Band	**β = 0.041**	**β = 0.085**
Low	2 – 5 kV/m	4 – 7 kV/m
Middle	not seen	0.05 – 0.08 MV/m
High	0.6 – 1.0 MV/m	0.5 – 0.9 MV/m

Amplitude and Phase Control

The measured amplitude and phase errors of the cavity voltage were well below the design requirements. As shown in Fig. 3, the measured peak-to-peak errors were below ±0.05% in amplitude and below ±0.2° in phase. The corresponding requirements are < ±1% in amplitude and < ±1° in phase. All cavities were measured at the design E_a.

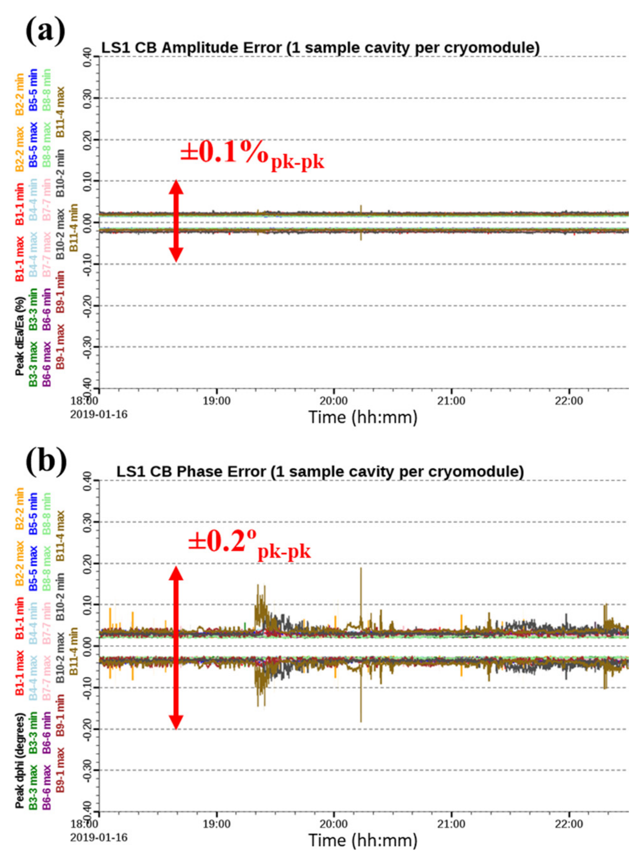

Figure 3: Measured amplitude and phase errors without beam: (a) fractional amplitude, (b) phase. The plots show the minimum or maximum value measured for every one second bin with the 100 kHz bandwidth. The horizontal time span is 5 hours. Eleven cavities in CB cryomodules are shown, i.e. one cavity per cryomodule. The other LS1 cavities show similar performance.

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Additional amplitude and phase stability measurements were performed with the beam. The main purpose of these tests were to observe the amplitude and phase change due to transient beam loading with high-peak-current pulsed beams. The peak current was 130 µA, equivalent to one third of the maximum design beam current. The pulse length was 6 ms, comparable to the cavity RF filling time of 8 ms. With the pulsed beam, the peak-to-peak fluctuations were up to ±0.1% in amplitude and ±0.2° in phase, as shown in Fig. 4. During these measurements, the RF feedback control adjusted the forward RF power and forward RF phase to compensate for the beam loading effect on the cavity voltage; for example, in one of β = 0.085 QWRs, the forward RF power increased by 16% and the forward RF phase changed by 3° when the bunch passed through the cavity [3]. Note that this compensation was made by only the RF feedback control and no feed-forward control.

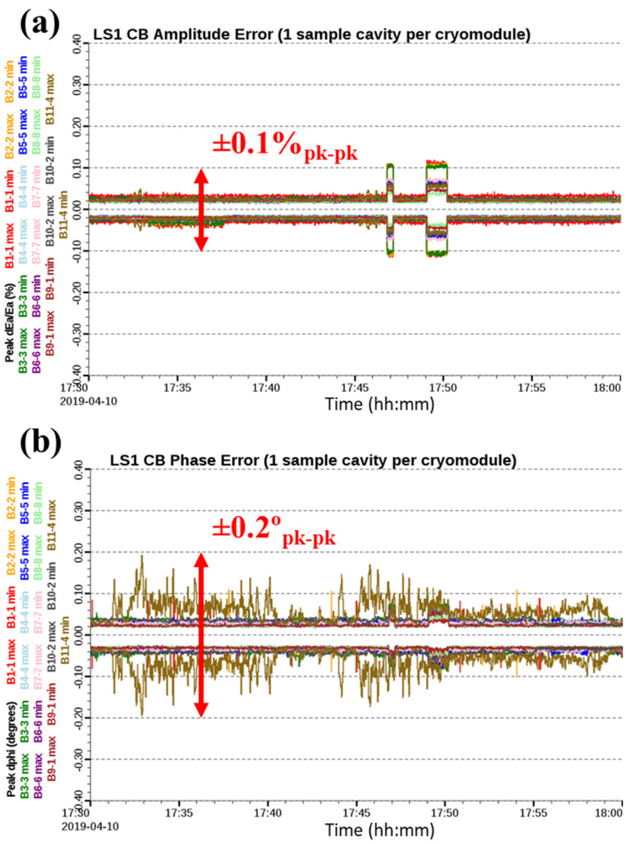

Figure 4: Measured amplitude and phase errors with beam: (a) fractional amplitude , (b) phase. The measurements are the same as shown in Fig. 3, but with a time span of 30 minutes and two intervals with the high-peak-current pulsed beam on. The beam was accelerated at 17:47 (for ~20 seconds) and 17:49 (for ~90 seconds).

LESSON LEARNED

In this stage of linac commissioning, the cavities were stable with the resonance control so that we could perform all LS1 beam commissioning at 4.5 K. This is favored by the fact that the shift in the resonant frequency due to helium bath pressure fluctuations are smaller than the cavity bandwidth. The frequency sensitivity to bath pressure (df/dP) is −2.0 to −2.9 Hz/torr for β = 0.041 QWRs and −2.1 to −5.1 Hz/torr for β = 0.085 QWRs. The cavity bandwidth (set by the RF coupler combined with the matched load in the circulator) is in the range of 27 to 40 Hz for β = 0.041 QWRs and 25 to 61 Hz for β = 0.085 QWRs. Figure 5 shows a typical resonance control performance at 4.5 K. In this example, the bandwidth is 41 Hz (RF input coupler with $Q_{ext} = 2.0\times10^6$) and $df/dP = -2.8$ Hz/torr. The slow detuning due to ~1 Hz or slower bath pressure changes is compensated by the slow frequency tuner. Since the tuner control is "on/off" with a hysteresis band of ±5°, the slow detuning is kept within ±5° (note that the stepping motor moved only 20 times over 6 hours). The fast detuning is small enough such that the forward RF power required to keep the amplitude and phase lock < 10% beyond nominal except for one spike, which is 25% higher than nominal.

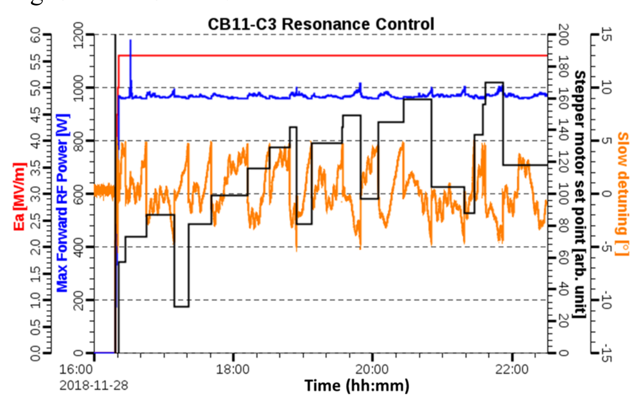

Figure 5: Resonance control of a β = 0.085 QWR at 4.5 K. The slow detuning (orange) is the phase difference between the input and pickup RF signals, filtered by a 3 Hz low-pass filter. The peak forward RF power (blue) is measured every second with a 100 kHz bandwidth. Red: accelerating gradient. Black: stepping motor position set point.

Commissioning provided an opportunity to see the long-term reliability of SRF hardware. One issue we found for the first time during linac commissioning was with the stepping motor for the slow frequency tuner [7]. Several cavities had large frequency jumps (larger than the bandwidth) when the tuner changed direction, resulting in cavity trips. The trip rate was low, a few to several trips for all LS1 in a ~15 hour run. Hence it was not easy to see the problem during cryomodule bunker tests, where cavity operation was in the order of 1 hour. We found that the frequency jumps could be mitigated by using higher-torque stepping motors for the affected cavities [7]. The larger motor can produce a linear force of 500 lbs on the tuning plate (in contrast to the 150 lbs delivered by the baseline motor). The problematic cavities did not show any trips after stepping motor replacement.

Since installation tasks for LS2 and LS3 were being performed in parallel, the time available for LS1 SRF commissioning was limited. Efficient commissioning was

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initially a challenge. One useful technique we developed is a low-level RF integration test at low power: we excited the cavity with the RF clock signal and measured the phase error of the cavity voltage with the amplitude and phase loops open and with the tuner control loop active. Being at low power, this test can be carried out while the tunnel is open for installation work. The test uses the LLRF controller and the RF signal cables connected to the patch panels in the amplifier gallery, which allowed us to identify and fix several connection problems and controller issues before high-power RF testing. More importantly, tuner control parameters could be optimized in advance and we verified that there were no harmful microphonics before high-power RF testing. With preambulatory low-level RF integration tests as well as organization for efficient commissioning, one cavity operator was ultimately able to complete SRF commissioning of one LS1 cryomodule per day (eight cavities per eight hour shift).

CONCLUSION AND OUTLOOK

All FRIB cryomodules for the first linac segment (LS1), containing a total of 104 superconducting quarter-wave resonators, have been commissioned in the linac tunnel. The design accelerating gradient, amplitude stability, and phase stability was achieved in all of the cavities. During beam commissioning with the LS1 cavities, we achieved 20.3 MeV per nucleon ion beams with four different ion species.

During SRF commissioning, we verified there was no major degradation in cavity performance after the cryomodule bunker test and no major particulate contamination after gate valve cycling. We were able to achieve stable resonance control of the LS1 cavities even at 4.5 K (where the helium bath pressure is less stable than at the design temperature of 2 K). Further measurements of the cryogenic load are planned to see which operating temperature is more efficient for LS1, as the FRIB cryogenic system allows us to operate LS1, LS2, and LS3 at different temperatures, if required. Compensation of the beam loading effect by the RF feedback control was measured, and we found that the amplitude and phase are still well controlled with peak beam power up to 1/3 of the design goal. Beam loading compensation will be useful for future beam power ramp up: the beam duty factor can be increased after fine tuning of the beam optics with high peak current [3].

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