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SUPERCONDUCTING CAVITY COMMISSIONING FOR THE FRIB LINAC*

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Abstract

The superconducting driver Linac for the Facility for Rare Isotope Beams (FRIB) is a heavy ion accelerator which has 46 cryomodules with 324 superconducting (SC) cavities that accelerate ions to 200 MeV per nucleon. Linac commissioning was done in multiple phases, in parallel with technical installation. Ion beams have now been accelerated to the design energy through the full linac; rare isotopes were first produced in December 2021; and the first user experiment was completed in May 2022. All cryomodules were successfully commissioned. Cryomodule commissioning included establishing the desired cavity fields, measuring field emission X-rays, optimizing the tuner control loops, measuring the cavity dynamic heat load, and confirming the low-level RF control (amplitude and phase stability). Results on cryomodule commissioning and cryomodule performance will be presented.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) driver linac is designed to accelerate ion beams, from hydrogen to uranium, to 200 MeV/u with 46 superconducting cryomodules (SCMs). Four accelerating SCM types SCM041 (beta = 0.041), SCM085 (beta = 0.085), SCM29 (beta = 0.29), SCM53 (beta = 0.53) and two matching SCM types SCM085-matching (beta = 0.085), SCM53-matching (beta = 0.53) has been built in three straight segments, Linac Segment 1 through 3 (LS1, LS2, LS3), and two folding segments (FS1 and FS2). LS1 contains 3 SCM041 and 11 SCM085, LS2 contains 12 SCM29 and 12 SCM53, LS3 contains 6 SCM53, 1 SCM085-matching and 1 SCM53-matching are located in FS1 and FS2, as shown in Fig. 1.

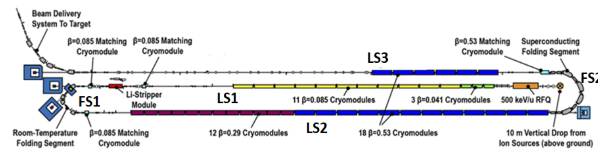

Figure 1: Layout of the FRIB driver linac.

Four types of cavity (Fig. 2): beta = 0.041 quarter-wave resonator (QWR), beta = 0.085 QWR, beta = 0.29 half-wave resonator (HWR) and beta = 0.53 HWR make up FRIB six different types of SCM [1]. Table 1 shows the configuration of FRIB SCMs. A total of 324 cavities has been installed in FRIB SCMs.

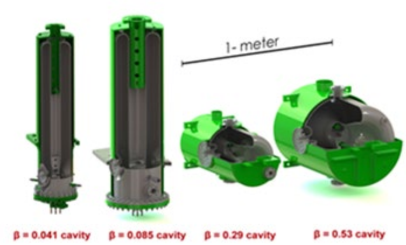

Figure 2: FRIB beta = 0.041 QWR, beta = 0.085 QWR and beta = 0.29, beta = 0.53 HWR cavities.

All cavities had been successfully commissioned in 3 phases. In the first phase all QWR cavities in LS1 and FS1 were commissioned [2]; in the second phase 168 HWRs in LS2 were commissioned; in the last phase the rest 52 HWRs in LS3 and FS2 were commissioned.

Table 1: Configuration of FRIB Cryomodules

Cryomodule type	CA	CB	CH	CC	CD	CG
Number of cryomodules	3	11	1	12	18	1
β	0.041	0.085	0.085	0.29	0.53	0.53
Operation frequency (MHz)	80.5	80.5	80.5	322.0	322.0	322.0
Cavity type	QWR	QWR	QWR	HWR	HWR	HWR
Cavities per cryomodule	4	8	4	6	8	4
Design accelerating gradient E_a (MV/m)	5.1	5.6	5.6	7.7	7.4	7.4

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CAVITY COMMISSIONING PREPARATION

Detailed preparation steps lead to efficient cavity commissioning. We keep parallel preparation steps with phased linac cool-down. Figure 3 shows the regular preparation steps and documents for HWR cavity commission. Before the commission start, all steps are performed during SCM warm and cool-down period within 3 days. Fully documented checking and testing procedures are performed. With the help of these preparation procedures, all potential issues were found and fixed earlier.

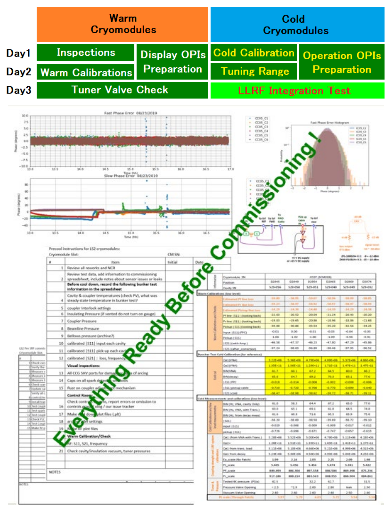

Figure 3: Cavity commissioning preparation: inspections, calibrations, display tools preparations, tuner check and LLRF controller integration test with fully documented procedures.

CAVITY PERFORMANCE

Accelerating Gradients

The cavity accelerating gradient (E_a) had been scanned in the commissioning. The average measured gradients for each SCM exceeded the design goals. Figure 4 shows the E_a achieved in each cryomodule.

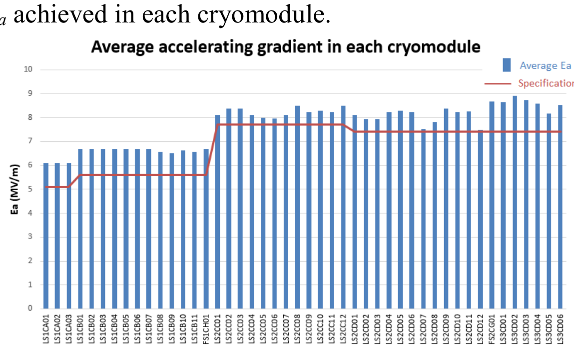

Figure 4: Average accelerating gradients achieved. Blue bars: average accelerating gradient in each cryomodule. Red lines: design gradients.

Field Emission

All 324 cavity field emission (FE) X-rays had been measured at the design specification E_a level, as can been seen in Fig. 5. There are five cavities X-ray measurement were under administration limited E_a field level (Purple bar measurement X-rays value was under limited E_a: two cavities in LS2 CD07, E_a was limited at 76.2% and 54.1% specification level; two cavities in LS2 CD12, E_a was limited at 92%; one cavity in LS3 CD05, E_a was limited at 62.2%), these cavities had relatively high FE during the bunker test, so we limited E_a maximum level during the cavity commissioning in FRIB tunnel. In future maintenance period, the FE X-rays scan will be planned to track the cavity FE performance.

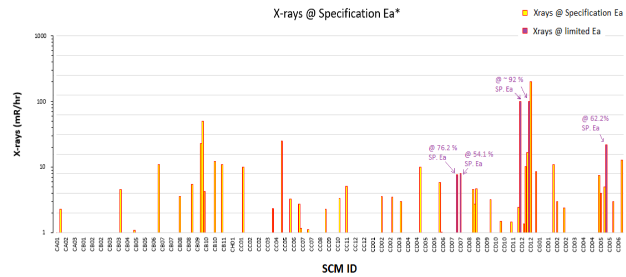

Figure 5: FE X-rays measurement at specification E_a.

Tuner Operation

The stepper motor tuner has been used for FRIB QWRs [3]. With LLRF resonance control, the cavity detuning from the reference clock can be tuned back by stepper motor. At the first phase of cavity commissioning, frequency jumps were found with original small stepper motor. After the small stepper motors being replaced by big stepper motors (with more force on the tuning plate), the frequency jump issue was fixed and no large jumps happened in the next few months [2]. But after long term operation, the frequency jumps came back again. So the stepper motor life time tracking and replacement need to be planned. In the future during each maintenance period replacement will be performed based on the stepper tuner performance tracker. New method to mitigate this frequency jump is also required and is under development. The frequency jumps do not trip cavity immediately. It start to show up with a relatively small spike, and then it will get worse gradually with operation time increasing. So far, about 10 early installed big stepper motors had been replaced. The average life time for them is about 1 to 2 years. The frequency jumps and the regular tuner operation comparison is shown in Fig. 6. The tuning dead zone setting for the QWR is ± 8 degrees, if no frequency jump happens, the cavity detuning will be limited within the dead zone range with no large jump.

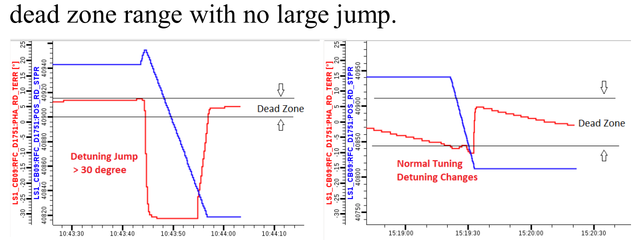

Figure 6: Red curve is QWR cavity detuning, blue curve is stepper motor moving. Left: detuning jump more than 30 degree. Right: regular tuner operation reached dead zone limit, stepper motor moving and detuning changes without jump.

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The FRIB HWR use a pneumatic tuner [3]. The helium gas charges or de-pressurizes the tuner bellow, which can tune the frequency of the HWR. To change the pressure of the pneumatic tuner bellow, two solenoid valves have been installed. The helium gas flow into the pneumatic tuner bellows through "pressure" valve, gas flow out and back to the helium gas return line through the "return" valve. The valve opening is controlled by LLRF controller. With good control and stable cryogenic status, the cavity detuning phase can be limited within a reasonable range during long time operation. Figure 7 shows the LS3 and FS2 all HWRs commissioning at 2 K, tuner performance test, most of cavities were run at specification field level (7.4 MV/m) for this testing. Test result shows the detuning phase can be controlled within ±10 degrees.

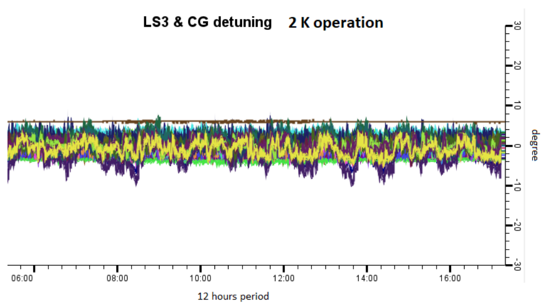

Figure 7: LS3 and FS2 all HWRs commissioning at 2 K, detuning phase within ±10 degrees in 12 hours.

Cavity Amplitude and Phase Stability

Commissioning result shows all 324 cavity amplitude and phase error meet the FRIB cavity stability requirement < ±1% in amplitude and < ±1° in phase. Long time running test shows all QWR cavity amplitude error (peak to peak) is less than ±0.06%, all HWR cavity amplitude error (peak to peak) is less than ±0.08%. Almost all cavity phase error (peak to peak) within ±0.2°, one QWR in LS1 (LS1-CB11-Cav3) and one HWR in LS2 (LS2-CD04-Cav5) show a little bit large phase error ±0.5°. Figures 8 and 9 show all FRIB cavity amplitude and phase stability measurement result in one hour time period.

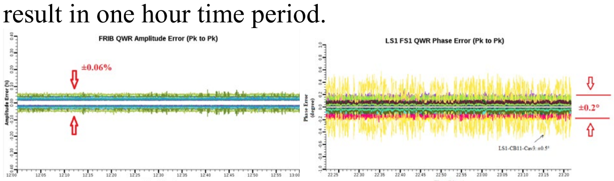

Figure 8: All QWRs amplitude and phase error test result in 1 hour.

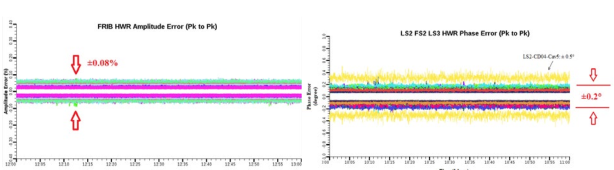

Figure 9: All HWRs amplitude and phase error test result in 1 hour.

Dynamic Heat load

The cavity dynamic heat load was measured in bunker test [4] Based on the measurement result, the cryogenic heater compensation has been implemented. In each SCM, the compensated heater power is the total heat load contribution from all cavities in this SCM run at the specification. When cavities are off, the heater in this SCM will turn on. Once all cavities are on at the specification E_a, the heater power will turn off. Testing cryogenic system changes between these two states, will show whether the compensated heat power matches the previous bunker test result or not. The test result shows at the same liquid helium level, the cryogenic JT valve position changes between these two states is small, so the dynamic heat load in FRIB tunnel is similar to that in the bunker test. Figure 10 shows LS2 CD01 heater compensation at 2 K test result, the JT valve position (green curve) had small changes after the 20 W heater power (heat load 2.5 W per cavity, 8 cavities) off and all cavity RF turned on at specification, which shows no heat load increase in the tunnel. Cavity performance has no degradation during the SCM transfer from bunker to the tunnel.

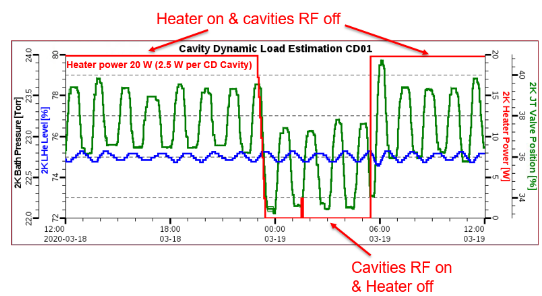

Figure 10: SCM LS2-CD01 2 K dynamic heat load heater compensation test result. Red line: compensated heater power 20 W in total, 2.5 W per cavity (beta = 0.53 HWR at 2 K at specification E_a); green line: 2 K JT valve position; blue line: 2 K header liquid helium level.

CONCLUSION

All 324 cavities for FRIB drive linac have been successfully commissioned in the FRIB tunnel. The SCM average accelerating gradient, cavity performance, tuner control, cavity dynamic heat load, amplitude and phase stability all meet the design goal.

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