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CRYOMODULE OPERATION EXPERIENCE FOR THE FRIB CONTINUOUS-WAVE SUPERCONDUCTING LINAC*

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Abstract

The superconducting (SC) driver linac for the Facility for Rare Isotope Beams (FRIB) includes 46 cryomodules for acceleration of heavy ions to 200 MeV/u. FRIB cryomodules have been supporting sustainable and reliable delivery of high-power heavy ion beams, including 10 kW uranium beams, to the target for production of rare isotopes for user experiments in nuclear physics. The linac operates in continuous-wave mode for maximum utilization of beam from the ion source. A total of 104 quarter-wave resonators (QWRs; β=0.041 and 0.085; 80.5 MHz) equipped with stepper-motor frequency tuners and frictional mechanical dampers are operated at 4 K. A total of 220 half-wave resonators (HWRs; β=0.29 and 0.53; 322 MHz) equipped with pneumatic frequency tuners are operated at 2 K. We will present resonance control and phase stability performance as well as experience with tuner systems in linac operation. FRIB cavities are designed to be operated at a peak surface electric field of approximately 30 MV/m. We will present cavity field emission performance over the years of linac operation and discuss field emission reduction measures such as pulsed RF conditioning (presently in use) and plasma processing (in development). Automation is a key aspect of efficient delivery of beams to users. We will present our experience with automation of SC devices such as start-up, shut-down, and fast recovery from an RF trip as well as performance tracking of linac SC devices.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a 400 kW superconducting linac which accelerates stable ions up to uranium to energies of ≥ 200 MeV/u [1]. The linac has a folded layout with 3 accelerating segments and 2 folding segments, as shown in Fig. 1. The linac has a total 324 superconducting radio frequency (SRF) cavities and 69 superconducting (SC) solenoids. The quarter-wave resonators (QWRs) in Linac segment 1 (LS1) operate at 4.5 K; the half-wave resonators (HWRs) in Linac Segment 2 and 3 operate at 2 K; all SC solenoids operate at 4.5 K [2].

Beam is delivered to the target at full energy or to the FRIB Single Event Effects (FSEE) experimental station downstream of Segment 1. On 22 December 2023, the FRIB linac reached a record high beam power of 10.4 kW Uranium with energy up to 177 MeV/u. The facility is currently delivered 10 kW primary beam power for users. An increase in beam power to 20 kW is planned in 2024 [3].

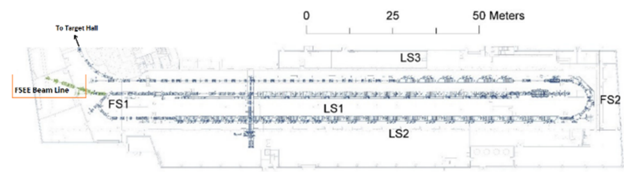

Figure 1: Layout of the FRIB driver linac.

CRYOMODULE PERFORMANCE AND IMPROVEMENTS

Cavity Field Level and Field Emission

Figure 2 shows the achievable average accelerating gradient (E_{acc}) for each cryomodule. Though some cavities are operated at lower field, neighbouring cavities can operate at higher E_{acc}, such that the average gradients are above the design goals.

Figure 3 shows the measured field emission (FE) X-rays from the cavities. Compared with 3 years ago (FRIB cryomodule commissioning), a few cavities have stronger FE X-rays. Conservative administrative limits are used to keep the X-rays below ~10 mR/hr for most cavities to reduce the risk of further performance degradation. As a result, a few of the cavities are operated below their design field, as mentioned above.

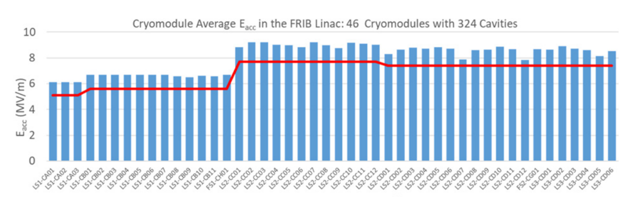

Figure 2: Average gradients in the FRIB cryomodules.

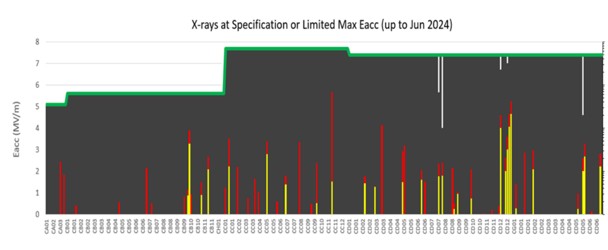

Figure 3: Field emission X-rays in the FRIB Linac.

High power pulsed RF conditioning and in-situ plasma processing can reduce field emission. Several cavities improved after pulse conditioning [4]. Plasma processing has

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been tested successfully on a spare QWR cryomodule (SCM813, β = 0.085), as shown in Fig. 4. Four cavities had FE X-rays before processing; after plasma processing, 2 cavities showed no X-rays and 1 cavity showed a higher FE onset field. Plasma processing in the FRIB tunnel during a future maintenance period is planned.

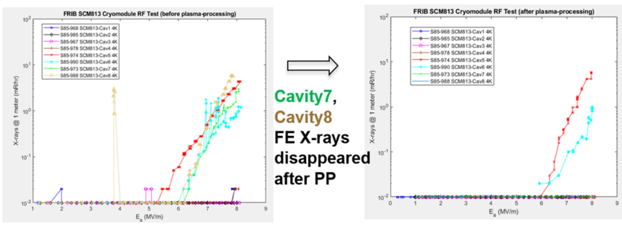

Figure 4: Field emission before and after in-bunker plasma processing of a spare QWR cryomodule (SCM813).

Frequency, Amplitude and Phase Control

All QWRs in LS1 are operated at 4.5 K with stepper-motor-actuated tuners [5]. The tuners keep the resonant frequency within ±10 degrees of the clock frequency. A few cavities were observed to have sudden jumps in the resonant frequency during operation. A first solution was to replace the original stepper motor with a bigger motor with higher torque (Fig. 5, middle). This was a good short-term solution, but the jumps recurred during long-term operation. For a more durable solution, a different type of stepper motor was tested and installed (Fig. 5, right). The new stepper motor has a gear, which allows the tuner to be parked without a holding current. Figure 6 shows 18 tuners' long-term performance, which is improved with the new stepper motor type.

All HWRs in LS2 and LS3 are operated at 2 K with pneumatically-actuated tuners. Two solenoid-actuated valves are used to raise or lower the helium gas pressure in the tuner bellows [5]. For stable operation, the control voltage must be calibrated for each valve. An automation tool for this procedure was developed to reduce the calibration time from 3 days per operator to 2 hours total [6]. A non-linear proportional-integral method was developed for improved tuner control [7]. All HWRs' detuning phase can be been controlled within ±10 degrees.

Amplitude and phase control for all cavities is well within the FRIB requirements (amplitude ±1%, phase ±1°) with slow tuner control. Figure 7 shows the amplitude and phase peak-to-peak error during a recent operational period (uranium, 177MeV/u, 10 kW, 28 June 2024).

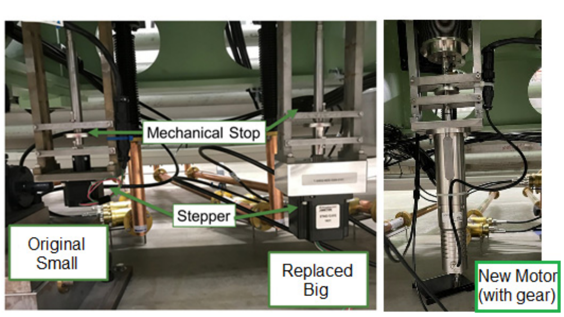

Figure 5: Stepper motors for FRIB QWR tuners.

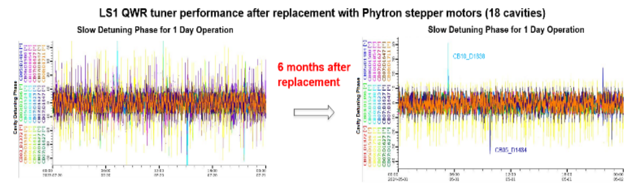

Figure 6: Improvement in QWR tuner performance with the installation of geared stepper motors.

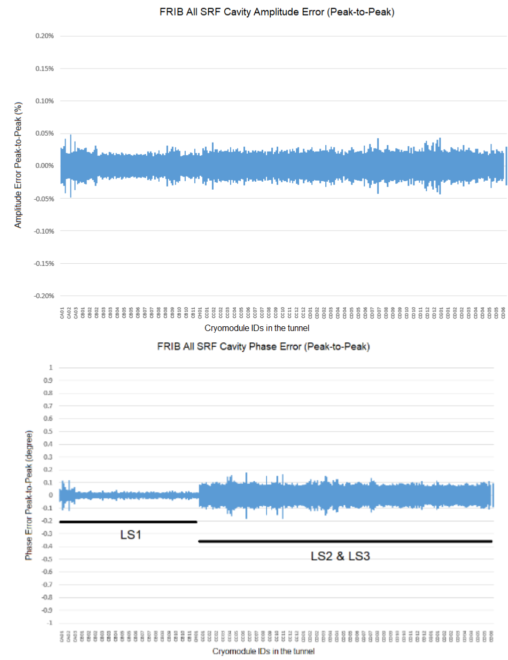

Figure 7: SRF cavity amplitude and phase peak-to-peak error (requirements: amplitude ≤ ±1%, phase ≤ ±1°).

AUTOMATION

Group Controls

Group auto turn-on programs have been developed and optimized for all of the SRF cavities and SC solenoids. Fast turn-on is done with 1 button for each linac segment. All SRF cavities and solenoids can be turned off safely with 1 button; one linac segment can also be turned off individually. The shut-down screen is shown in Fig. 8. The solenoids must be degaussed before maintenance periods; this procedure is now automated as well.

Figure 8: FRIB fast shut-down screen.

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Dynamic Heat Load Compensation

A change in a cryomodule's heat load requires the cryogenic control system to come to a new equilibrium state. The response time of the system, and hence that of the control loop, is relatively slow. Thus a large change in the heat load may result in a drop in the liquid helium level and cavity trips. However, the FRIB linac must accelerate ions with different charge-to-mass ratios for different experiments, which requires changes in the cavity field levels, producing sudden changes in the dynamic heat load. Moreover, for FSEE experiments, the LS1 cryomodules must be turned on and off several times per shift to allow users to access experimental areas. Heaters in the liquid helium are used for fast compensation of these dynamic heat load changes. Heater compensation based on the field level set points allows for stable operation when cavities are switched on, switched off, or ramped to a different field. Figure 9 shows an example of turning on and off LS1 cryomodules repeatedly.

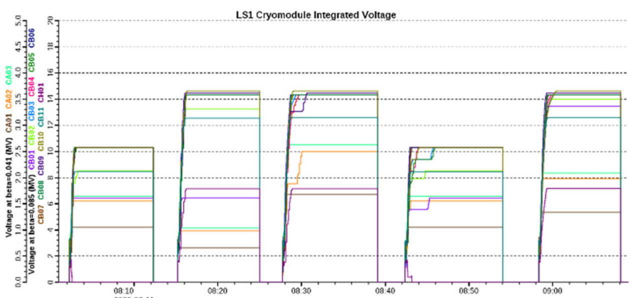

Figure 9: Rapid turn-on and turn-off of LS1 cavities for FSEE user operations.

Fast Recovery from Cavity Trips

Fast recovery tools for cavity trips can allow for increased machine availability. The QWRs have a low-field multipacting barrier which may prevent cavity turn-on after a trip if adjacent cavities are running at full field with some field emission [8]. Reduction of the field in nearby cavities allows for the tripped cavity to jump over the low barrier. To facilitate this, a cavity field ramp-down and ramp-up tool was developed in CS-Studio Phoebus, as shown in Fig. 10. Operators are able recover from cavity trips more rapidly using the tool.

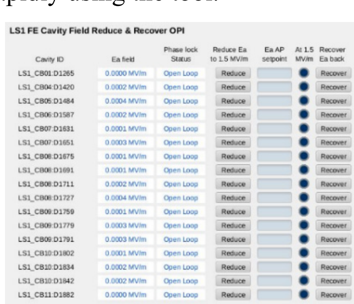

Figure 10: "Reduce and Recover" tool for QWR trips.

Software Tools for High-Availability Operation

Monitoring of the cryomodules is important for linac performance tracking. Tracking, issue/trip recording, and issue resolutions not only help the operators and on-call staff to recover from trips more quickly, but also help to identify recurring issues earlier.

Automated scanning tools are being developed for efficient cryomodule performance tracking. These scanning tools can track SRF cavity operational stability, FE X-rays changes, and jumps in fast thermometer signals. The tools can notify personnel when abnormal events are identified, including increases in FE X-rays or temperature increases due to beam loss. In case of a cavity trip, fast signals (cavity forward/reverse/transmitted power) can be recorded by the low level RF controller. Slow changes, including cryogenic read backs, tuner position, coupler temperature, and pressure are recorded as well (Fig. 11). The trip data can be used for root cause analysis, future trip prediction, and guidance for maintenance work.

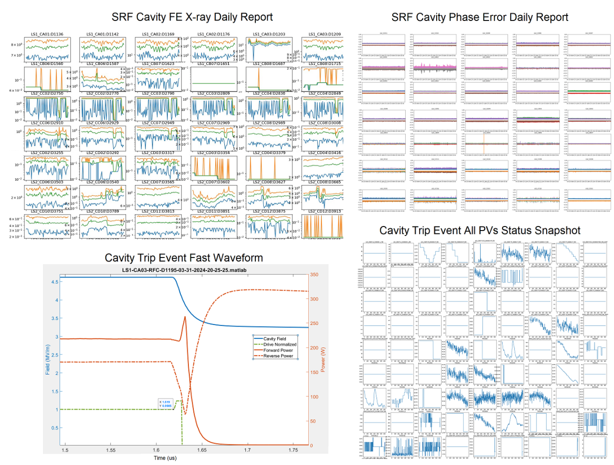

Figure 11: Auto-scanning tools for cryomodule performance tracking and cavity trip analysis.

SUMMARY

The FRIB superconducting linac has provided stable and reliable beams for user operations for the first 2 years of user operations. Performance tracking and improvement are in the development and implementation stages. Future cryomodule operations will focus on high availability, high reliability, and ramp-up of the beam power.

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