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COMPLETION OF THE FRIB SUPERCONDUCTING LINAC AND PHASED BEAM COMMISSIONING*

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Abstract

The Facility for Rare Isotope Beams (FRIB) is an accelerator-based facility funded by the US Department of Energy for nuclear physics research. FRIB is nearing the end of technical construction, with first user beams expected in Summer 2022. Key features are the delivery of a variety of rare isotopes with a beam energy of ≥ 200 MeV/u and a beam power of up to 400 kW. The facility is upgradable to 400 MeV/u and multi-user capability. The FRIB driver linac consists of 324 superconducting resonators and 69 superconducting solenoids in 46 cryomodules. FRIB is the first linac to deploy a large number of HWRs (220) and the first heavy ion linac to operate at 2 K. We report on the completion of production and installation of the FRIB cryomodules and phased beam commissioning results.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) has been a US Department of Energy Office of Science (DOE-SC) User Facility since September 2020. The FRIB superconducting driver linac (Fig. 1, bottom) can accelerate ion species up to ^{238}U to energies of ≥ 200 MeV per nucleon for rare isotope production; a beam power of up to 400 kW is planned [1]. FRIB will use existing beam lines and experimental areas for fast, stopped, and reaccelerated beams of the Coupled Cyclotron Facility (CCF), outlined in blue in Fig. 1.

Figure 2 shows the time line of the project. In August 2013, DOE-SC approved the project baseline and start of civil construction (CD2-3a) with a total project cost of $730M, funded by DOE, MSU and the State of Michigan. FRIB obtained CD-3b approval from DOE in August 2014, and technical construction began in October 2014. The project is on track to be completed by January 2022, with the first user experiments expected in Summer 2022.

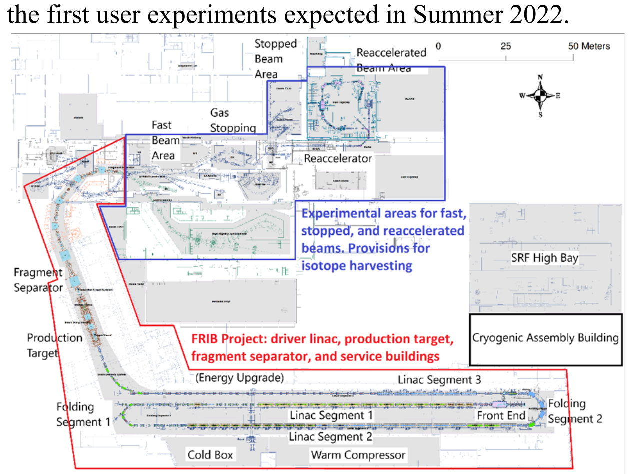

Figure 1: Layout of the FRIB linac, target, fragment separator, and experimental areas.

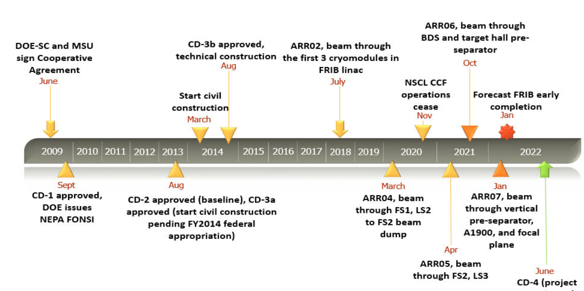

Figure 2: Time line of the FRIB project.

The driver linac technical construction has been completed. The system utilities were ready in June 2017 and the Li Stripper was installed in March 2021, marking the

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beginning and ending of linac technical installation. A total of 46 cryomodules, 4 superconducting dipoles, 242 warm magnets, 7 warm bunchers, 2 charge strippers, and 1 radio-frequency quadrupole (RFQ) were installed. Figure 3 shows the linac layout. All cryogenic devices are connected to the cryo-distribution system via U-tube connections, which provide flexibility for installation and commissioning as well as future repair and maintenance.

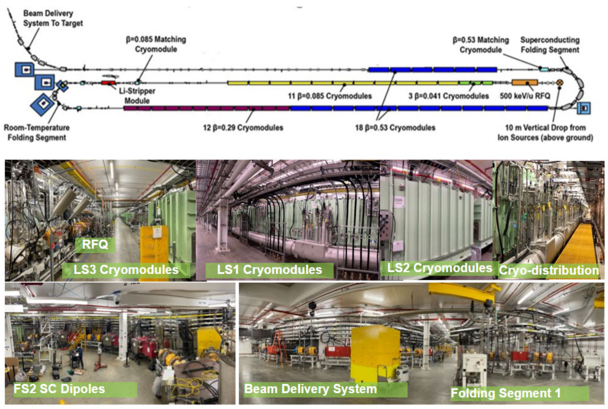

Figure 3: Layout of the driver linac, with photographs of equipment in each linac segment (LS1, 2, 3) and folding segment (FS1, 2).

SRF PRODUCTION SUMMARY AND STATISTICS

Superconducting Radio-Frequency (SRF) cryomodule production was completed in May 2020; 4 cavity types [2] and 6 cryomodule types [3] were designed, fabricated, and tested by MSU with industrial suppliers. A dedicated SRF processing and cryogenic testing facility [4] was built in 2014 to support in-house SRF production. Delivery of all 46 cryomodules for the linac was completed in 6 years, with the first production cavity (β = 0.53 HWR) received by MSU in January 2015; the last cryomodule was installed in the tunnel in June 2020, after the COVID-19 Pandemic shut down. The last linac segment (LS3) was cooled down in November 2020 and energized in February 2021.

A total of 49 cryomodules were produced, including one for the ReAccelerator [5, 6]. Cavity processing statistics are summarized in Table 1. As shown in Fig. 4, field emission and Q_0 below the FRIB requirement were major reasons for cavity reprocessing.

The peak production rate was 3 cold masses and 1.5 cryomodules per month. Clean room assembly and cryomodule assembly are in different buildings, as seen in Fig. 5. Figure 6 shows the assembly time for each cryomodule. There are four assembly stages delimited by engineering inspections. The unique FRIB "bottom-up" cryomodule design allows the cryomodule to remain in the same assembly bay throughout the assembly process, in contrast to other projects such as XFEL and LCLS-II in which the cryomodules move to different work stations or along a rail system [7, 8]. A total of 5 assembly bays were established during peak cryomodule production; the average time on the assembly floor was about 110 days per cryomodule.

There were two major reworks during FRIB cryomodule production. (1) The beam line vacuum of a β = 0.085 QWR module (SCM805) was vented after a tuner bellows failure during cryomodule assembly due to operator error. All cavities were reprocessed and retested. (2) A β = 0.53 HWR (in SCM511) developed a beam line vacuum leak (~10^{-6} torr) during cool-down in the cryomodule bunker test due to a cavity weld failure. The failed cavity was replaced in the clean room without reprocessing of the other cavities on the cold mass. Both cryomodules were certified after completion of the reworks.

Table 1: FRIB Production Cavity Processing Summary

Cavities processed	343
Cavity tests	410
Reprocess rate	22%
Cavities certified	337

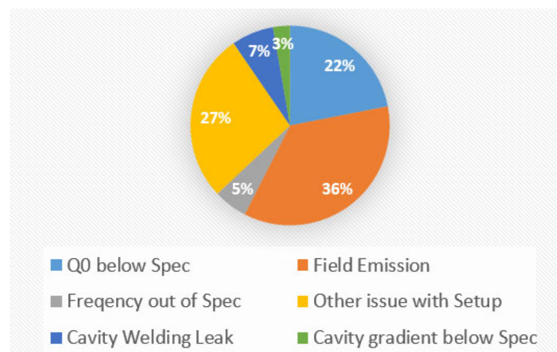

Figure 4: Distribution of cavity certification issues.

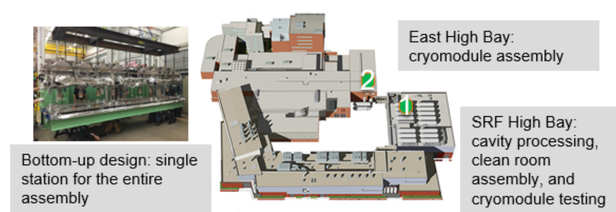

Figure 5: FRIB cryomodule production facility layout.

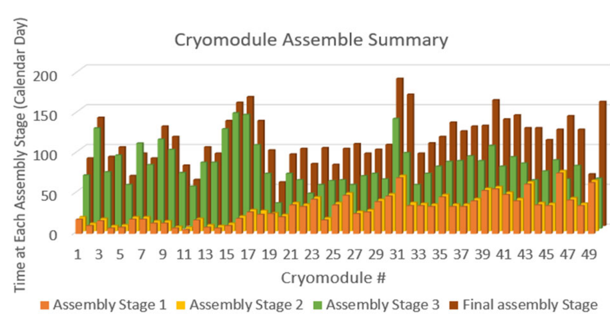

Figure 6: Times at each assembly stage for FRIB cryomodules. 1: baseplate pre-assembly ready; 2: cold mass ready to install to baseplate; 3: cryogenic system installed; 4: final assembly ready.

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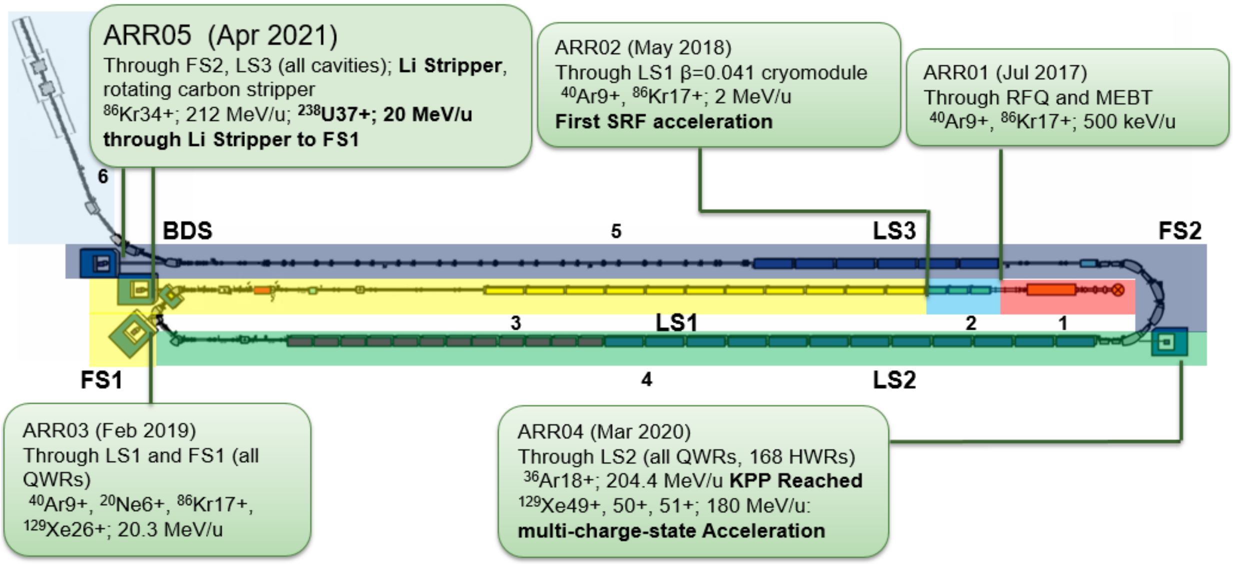

Figure 7: FRIB linac phased beam commissioning: configuration, timeline, and results.

FRIB LINAC BEAM COMMISSIONING RESULTS

Phased beam commissioning was done in parallel with technical installation in the tunnel. Seven beam commissioning stages were planned, with an Accelerator Readiness Review (ARR01-07) preceding each stage [9].

Linac commissioning was done in ARR01-05; target and secondary beam line commissioning are planned for ARR06-07. Figure 7 shows the configuration and timeline for each linac commissioning stage, including ARR dates and beam species.

First acceleration through the cold linac was done in July 2018 (ARR02), when we commissioned argon and krypton beams through the RFQ and the first three β = 0.041 cryomodules, with a temporary downstream diagnostic box [10]. The FRIB energy goal was demonstrated in March 2020 (ARR04), when an Ar beam was accelerated through LS1 and LS2 (37 cryomodules), reaching 204.4 MeV/u. Subsequently, the first multi-charge-state Xe beam (^{129}Xe49+,50+,51+) was accelerated to 180 MeV with the same linac configuration [11]. In May 2021, after ARR05, ^{86}Kr34+ was accelerated through all 324 superconducting resonators to 212 MeV/u and delivered to the Beam Delivery System dump.

Operation of the liquid lithium charge stripper and uranium beam acceleration were two highlights of ARR05 beam commissioning. The Li stripper is a key technology for future high-power beam operation, while U has the highest mass-to-charge ratio of all the beam species. As shown in Fig. 8, the linac layout allows for both the liquid Li stripper and a carbon foil stripper for high operational availability. ^{124}Xe26+ at 17 MeV/u and ^{38}U37+at 20 MeV/u have been accelerated through LS1 and stripped to higher charge states by the Li stripper. High power beam also has been tested successfully using ^{36}Ar10+ at 400 W with a duty cycle of 5.4%. A rotating C foil stripper was installed and tested at 20 rpm with beam.

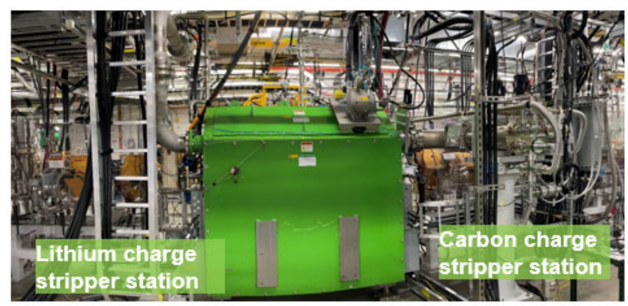

Figure 8: Liquid lithium and rotating carbon foil charge strippers installed downstream of LS1.

CRYOMODULE PERFORMANCE

Cavity performance has been tracked through cavity certification testing (VTA), cryomodule bunker testing, and linac commissioning; no Q_0 degradation has been observed. We will discuss the LS2 HWRs (168 cavities) as an example.

Dynamic Load

The design goal was for a dynamic load ≤ 1 kW at 2 K for LS2 [2]. The Q_0 was measured in the cavity test [12] and remeasured in the cryomodule bunker test. In the cryomodule test, Q_0 was measured by the rate of bath pressure change for He-II (dP/dt), cross-checked with electrical heaters, as shown in Fig. 9. One interesting finding is that the dynamic heat load measured in the cryomodule bunker test is consistently lower than in VTA by an average of 22%. The total LS2 dynamic load at the FRIB gradient based on VTA and bunker test results are 385 W and 302 W, respectively. In the linac, the dynamic load was measured using a heater to compensate for turning RF off with constant 2 K mass flow, as shown in Fig. 10. The LS2 total dynamic heat load based on the compensation heater measurement is ~280W, which matches the bunker results reasonably well. Possible causes of the lower measured Q_0 in

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VTA include additional magnetic flux trapping due to thermo-electric current generated in the fast VTA cool-down or residual magnetic flux due to the differences in magnetic shielding between VTA and cryomodule. Further investigation is ongoing to identify the root cause.

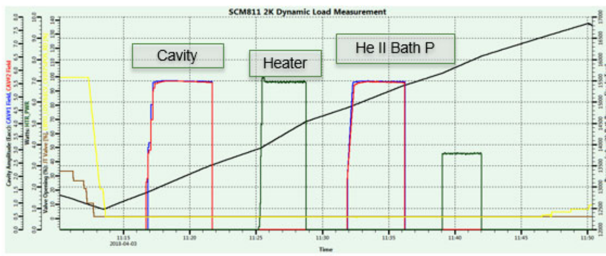

Figure 9: Dynamic load measurement for a FRIB cryomodule using *dP*/*dt* with an electrical heater.

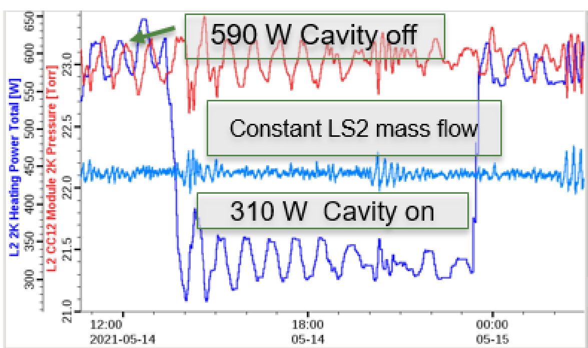

Figure 10: ARR05 run with LS2 at 2 K. Red: 2 K header pressure. Blue: total electrical heater power. Cyan: mass flow of 2 K system.

Cavity Field Level

The cavity field measured via RF power and via beam are generally in good agreement. Figure 11 compares the cavity gradient measurement by RF power and beam position monitor (BPM) measurements. The beam-based measurement has higher noise-to-signal ratio toward the end of LS2 due to the shorter drift length between the BPMs.

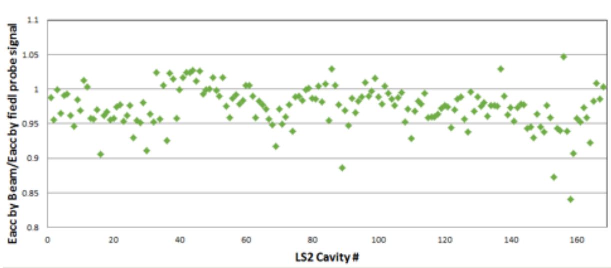

Figure 11: Comparison of E_{acc} measurements by beam and pick up antennas for LS2 cavities.

Control of Frequency, Amplitude, and Phase

All cavities' initial turn-on, conditioning, and resonance control development were done at 4 K. In the linac, the cryomodule bath pressure fluctuations are dominantly slow oscillations (period ~ 1 hour), which are easily compensated by the tuners. High frequency oscillations are small for both 2 K and 4 K operation, as shown in Fig. 12. Cavity amplitude and phase peak-to-peak errors are shown in Fig. 13. The amplitude and phase are well within the requirements without fast tuning. Amplitude and phase control is comparable at 2 K and 4 K due to the stable bath pressure, as discussed above.

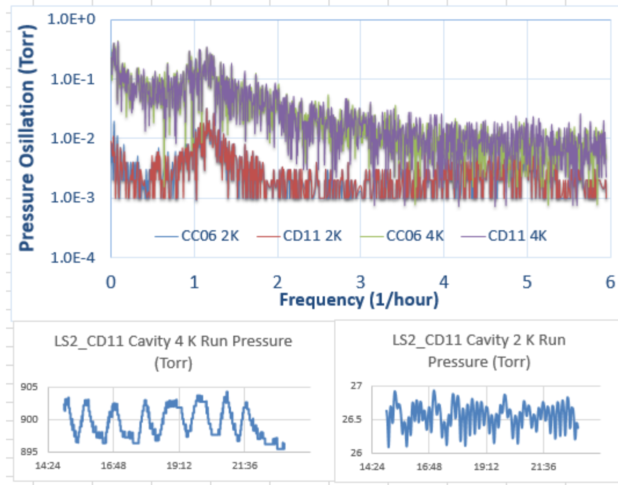

Figure 12: Bath pressure stability at 2 K and 4 K for a β = 0.29 cryomodule (CC06) and a β = 0.53 cryomodule (CD11) in LS2 during ARR05.

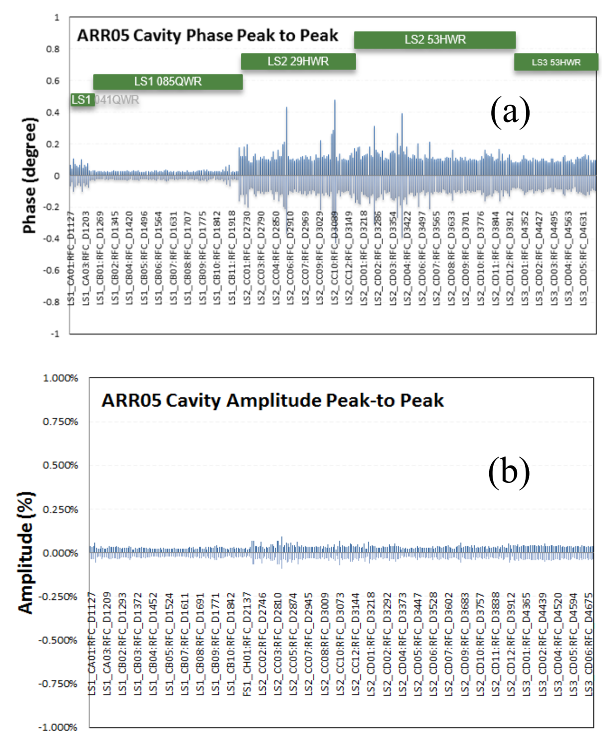

Figure 13: ARR05 cavity resonance control performance: peak-to-peak (a) phase and (b) amplitude.

Field Emission

Field emission from the cavities has been tracked and monitored. Figure 14 compares X-ray levels at the FRIB design field measured in the cavity Dewar test (VTA), cry-

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omodule bunker test, and linac. Two X-ray sensors are permanently installed under each cryomodule (with a total of 92 sensors) in the linac. Conservative administrative limits for X-rays (~10 mR/hr) are used in the linac for most cavities to reduce the risk of deconditioning. As a result, a few cavities are kept below the design field, as shown in Fig. 15. Pulsed RF conditioning has improved a few cavities. In-situ plasma processing development has been initiated and is in the early stages [13].

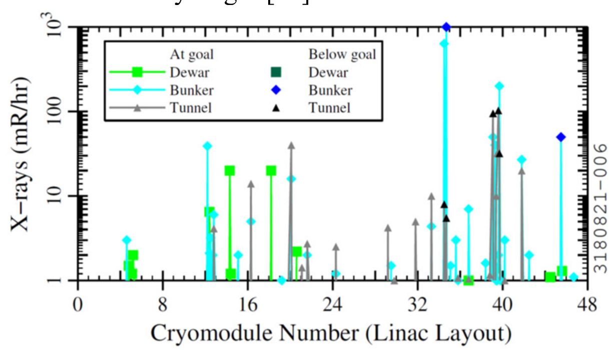

Figure 14: Cavity field emission in VTA, bunker test, and linac commissioning.

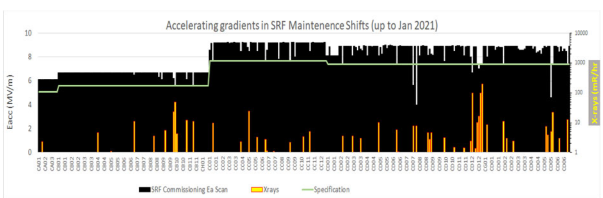

Figure 15: X-ray scan of linac cavities before ARR05.

Operating Gradients

FRIB is the first linac to deploy a large number of HWRs (220) and the first heavy ion linac to operate at 2 K. Linac commissioning confirmed that FRIB design goals for Q_0, E_{acc}, and bandwidth were reasonable. Operation at significantly higher gradients than the FRIB baseline will be challenging; it will require more resonance control development and mitigation of high-field Q-slope. Operation at gradients 10-15% above the FRIB goal has been demonstrated in some of the HWRs in the linac. This allows us to compensate for non-conforming cavities or cavities limited by the X-ray administrative limit.

Multipacting

There are two Multipacting (MP) barriers for FRIB HWRs: the middle barrier at E_{acc} ~0.5 MV/m and the high barrier around 3-5 MV/m. MP in the HWRs is relatively easy to condition (1-2 hours), but requires careful handling to avoid deconditioning, especially the high barrier.

A DC bias (−1 kV) is used to suppress MP in the RF input couplers (FPCs). The FPCs were high-power conditioned by the vendor or/and FRIB before installation.

Pneumatic Tuners

The HWR pneumatic tuners operate smoothly. Each tuner has manual isolation valves and pressure sensors in addition to the remotely-operated valves for active control, as shown in Fig. 16. Stringent control of cavity frequency allows the tuners to operate between 18 and 70 psia. The tuner gas distribution system is integrated with the cryogenic gas distribution system. Running above atmospheric pressure allows the tuner gas to be returned through the magnet leads' gas return in a closed loop (total flow ~1 g/min) and minimize contamination of the cryogenic system.


Figure 16: Pneumatic tuner manifold for the β = 0.53 HWR cryomodule.

Interlocks

A 3-level interlock scheme is used to protect the cavity, FPC, and amplifier, which provides good protection and flexibility for commissioning. The interlock levels are (1) external fast protection via the analog signals from the FPC cold cathode gauge (CCG), spark detector, and bias voltage read-back; these are routed directly to the low-level RF (LLRF) controller; (2) external slow protection via the signals from the beam line CCG, FPC CCG, helium level sensors, pressure gauges, and FPC cold window temperature; this are routed through programmable logic controllers (PLCs) to the LLRF controller; (3) LLRF-level configurable protection based on read-backs for signals such as the cavity field, forward power, reverse power, and tuner pressure.

SUMMARY

The FRIB superconducting driver linac is complete, with 46 cryomodules and 324 cavities now installed in the tunnel. FRIB is now the largest heavy-ion superconducting linac in the world. After 5 stages of commissioning, we successfully commissioned beam through the entire linac and demonstrated the energy goal of 200 MeV/u (a key performance parameter for the project). Other key features have been demonstrated, including multi-charge acceleration and lithium stripping. We are currently installing equipment in the target area and fragment separator area for the final commissioning stages. The project is on track for early completion in January 2022.

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