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LLRF COMMISSIONING OF THE CEBAF C75 UPGRADES SAM 2024/25 *

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Abstract

During Jefferson Lab's Scheduled Accelerator Maintenance (SAM) in 2024, two C75 cryomodules were installed in CEBAF with JLab's Low Level RF (LLRF) 3.0 digital control system. Three key processes of JLab's LLRF commissioning include completing Interlock verification, klystron characterization, and cavity characterization. This paper summarizes the preparation, automation and commissioning efforts for the new cryomodule installation and controls checkout.

INTRODUCTION

C75 Cryomodules, SRF Commissioning/ Installation

During the SAM 2024, two cryomodules with C20 type cavities in CEBAF, which were installed in the early 1990s, were replaced by new C75 style refurbished cryomodules. The C75 cavities are 5-cell cavities manufactured by Research Instruments (RI), GmbH in Germany with an operational accelerating gradient (Eacc) of 19.1 MV/m and a quality factor (Qo) of at least 8×10^9 at a temperature of 2.07 K (helium pressure of 29 ±0.1 Torr) [1].

Each of the cavities was combined and tested as pairs in the Vertical Test Area (VTA) prior to the cryomodule assembly. These cryomodules were then tested in the Cryomodule Test Facility (CMTF) for operational conditions (maximum gradient, Field emission) before being installed in the LINAC [1]. One of the cryomodules was plasma processed for high field emission detected during these tests [1]. These cryomodules were installed in the North LINAC (1L09) and South LINAC (2L05).

High Power Installation - CPS and HPA

The existing instrumentation and connections were removed from the selected zones so that new components could be installed. The Cathode Power Supply (CPS) and Main Distribution Panel (MDP) breakers were replaced with higher rated current breakers. The transformer, diode stack, HV wiring, and HV capacitor were also replaced. A Silicon Controlled Rectifier (SCR) was installed to allow the high voltage in the zone to be adjusted electronically.

LLRF COMMISSIONING

The C75 cavities are controlled by JLab's LLRF 3.0 systems, which were developed to replace the legacy LLRF systems in CEBAF [2,3]. These systems utilize the Self-Excited Loop Amplitude and Phase (SELAP) algorithm for cavity control. This algorithm is a fully functional phase and amplitude locked Self Excited Loop [2, 3].

LLRF Installation

As a part of the controls upgrade, the Field Control Chassis (FCC) were installed along with the heater/High Power Amplifier (HPA)/interlock/resonance chassis, and their associated power supplies. The heater, IR, probe, and stepper motor cables are connected to the cryomodule. The external calibrations (ECAL) and internal calibrations of the FCC receivers were measured in-situ. These calibrations are critical for determining cavity quality factor and gradient.

ECAL values primarily address cable losses, waveguide coupling factors, and additional attenuation in the FCCs, while also including the cavity's external quality factor and beam-based calibration factor [4]. This additional attenuation is added to the FCC inputs to adjust the input signal, ensuring that the maximum input power to the chassis remains slightly below the ADC saturation point. This approach maximizes the ADC counts for the applied input power. Single-point calibrations are performed to determine and verify these values. The mean waveguide coupling factor is approximately 40 dB, while the mean cable loss between the service buildings (which house the FCCs) and the LINAC tunnel is approximately 3 dB [4].

Pre-Commissioning - Part 1: Testing into Shorts

As a standard test practice to verify the functionality of CPS and HPA, shorting plates were installed on the waveguide. With the shorting plates installed, HPA can be tested without applying any power into the cavities. As a part of the testing RF was applied to generate less than 100 watts of power. During the test, the Klystron Reflected Power (KRRP) readback was monitored to verify the corresponding KRRP interlock, which removes the RF drive to the Klystron to prevent damage. All of the klystrons/FCCs were checked to ensure the forward power (CRFP) and reflected power (CRRP) measurements were similar and were also verified by measuring with an independent power meter.

Klystron characterization was performed next to measure the performance of the klystron. It involves ramping the drive power from minimum to maximum for a very short time interval with a single fixed frequency (tone) while the cavity forward power magnitude and phase are measured. The klystron characterization is a critical step of commissioning because it enables a mapping between the FCC drive signal (GASK) and the power measured by the coupler downstream of the isolator. It also establishes the

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phase delay at various power levels. This simple characterization confirms that the klystron is behaving correctly and is not being driven into saturation. This test may be completed while shorting plates are installed or when connected to the cavity. Short pulses are important because the klystron has sufficient bandwidth to drive the signals while preventing the cavity from filling when connected. The klystron characterization is also used to calculate the Klystron power and SELAP power limits. The maximum klystron powers from the klystron characterization are in the Table 1 with an example of the klystron characterization screen in Fig. 1.

Table 1: Maximum Klystron Power From the Klystron Characterization

Cavity	1L09 (kW)	2L05 (kW)
1	5.15	5.65
2	4.75	5.90
3	5.22	5.78
4	Bypassed	5.51
5	5.00	4.76
6	5.18	5.42
7	4.90	4.95
8	5.18	5.26

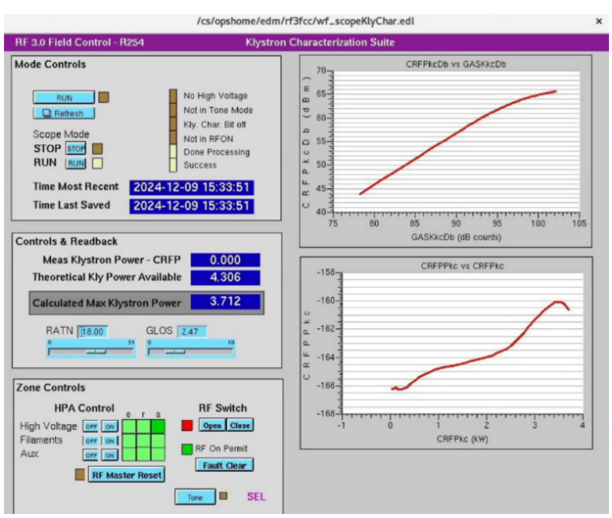

Figure 1: The klystron characterization screen.

Once the initial test results were within the expected range based on tap settings and calibrations, the waveguides were connected to the cavities (which are cooled to 2K).

Pre-Commissioning - Part 2: Testing Cavities

Cavity Interlocks, calibrations As with most of the systems, cryomodules rely on certain interlocks for protection. The LLRF system monitors five such interlocks. These interlocks monitor cavity waveguide window temperature, waveguide vacuum, beamline vacuum, arcing in the cavity, and helium levels. Therefore, the initial testing step involved verifying the functionality of these cavity interlocks. fault limits were adjusted to verify the functionality of these interlocks. This is verified by making sure the RF drive was shut off to the cavity when values exceeded the established thresholds.

The waveguide window sits between the cold cavity (held under vacuum) and the pressurized waveguide, with temperature sensors monitoring both sides. The corresponding interlocks were tested by adjusting the limit values [4]. Similarly, the cavity waveguide vacuum and beamline vacuum interlocks were tested in coordination with the Instrumentation and Control group.

Each cavity contains arc detector, which primarily protects ceramic windows in the input waveguides from damage caused by electrical arcs. The signal from this detector is monitored by LLRF, and RF power is shut off when an arc forms to protect the window. This interlock functionality is periodically verified by activating an LED installed inside the arc detector.

The helium level interlock is tested by adjusting the upper and lower limits to more conservative values at different times. This interlock is critical because fluctuations in liquid helium level can cause localized temperature increases on the cavity surface, potentially leading to a quench.

Finally, the fiber connections are checked to ensure the Fast Shut Down (FSD) from LLRF to the Machine Protection System (MPS) is functional and the signals are propagating to the FSD multi-tree.

Stepper motor settings and low power commissioning Prior to tuning the cavities to machine frequency, the tuner settings are configured (stepper limits, stepper current, etc.). At this point, the RF power of less than 100 watts is applied to each cavity. With applied RF power cavity detune frequency is measured, and cavity is tuned to the machine frequency.

Pre-Commissioning - Part 3: Cavity Setup for Operations

After verifying the interlock functionality and tuning the cavity to the machine frequency, SRF team commences the next phase of commissioning. This part of the commissioning includes determining the operational conditions of the cavities and cryomodule in their installed configuration. During this commissioning phase, the SRF team measures external quality factors (Qext), intrinsic quality factors (Q_0), and the stored energy (accelerating gradient) of the cavity. These measured values are then stored in JLab's CEBAF Element Database (CED) to support the final cavity configuration for operations.

Once the operational gradients were determined by the SRF, the cavity characterizations are followed to confirm the Q_{ext} values, the optimal loop gains are entered and finally the cavities are operated in SELAP mode for beam operations.

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The values from the cavity characterization is as follows in Table 2. The waveforms from a cavity characterization are shown in Fig. 2. The cavity characterization and external calibration are available on their own screens (Fig. 3). Figure 4 shows the CRFP and the Detune angle graphs for the cavities.

Table 2: External Quality Factor Values From the Cavity Characterizations Followed

Cavity	1L09 (x10^7)	2L05 (x10^7)
1	2.7	1.2
2	2.9	1.5
3	1.7	1.8
4	-	1.4
5	1.3	1.6
6	1.2	1.7
7	1.7	2.6
8	1.8	2.1

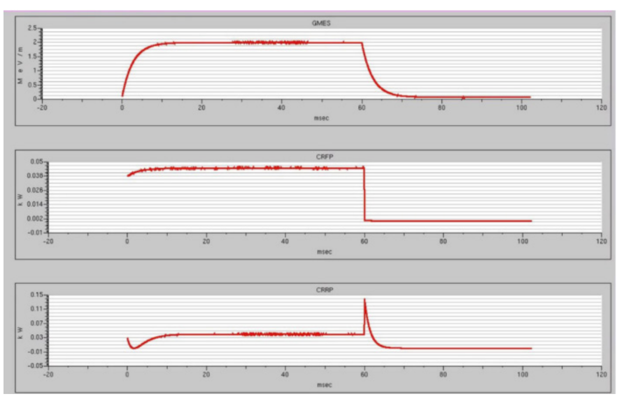

Figure 2: Characteristic waveforms of a cavity, GMES, CRFP and CRRP from top to bottom.

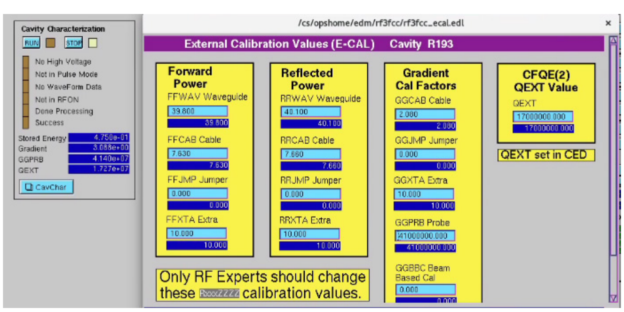

Figure 3: Cavity characterization screens and the external calibration screens.

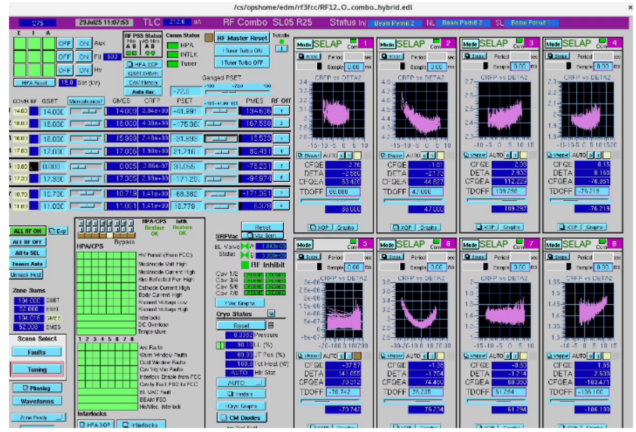

Figure 4: CRFP and the detune angle graphs when the zone is operational with the gradient and phase values.

CONCLUSION AND FUTURE PLANS

Two of the zones in CEBAF were upgraded with new C75 cryomodules and related LLRF 3.0 digital control systems. The upgrades included LLRF commissioning both before and after connecting the cavities to the waveguides. Both cryomodules are now operational, and we are currently procuring and building additional LLRF 3.0 systems to upgrade six more zones over the next several years.

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