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THE STATUS OF ARIEL e-LINAC RF SYSTEM*

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Abstract

Now the stage of the 30 MeV portion of ARIEL (The Advanced Rare Isotope Laboratory) e-Linac (1.3 GHz, SRF) is under commissioning which includes an injector cryomodule (ICM) with a single nine-cell cavity and the 1st accelerator cryomodule (ACM1) with two cavities configuration. This paper is focused on the recent advances towards high power operation which includes ICM MRO and e-gun tuner upgrade, PID loop test, continuous operation test.

INTRODUCTION

ARIEL e-Linac is a continuous-wave (CW) superconducting electron linear accelerator. The 'Demonstrator' phase of ARIEL was installed for initial technical and beam tests with successful beam acceleration to 22 MeV [1]. The ACM1 cryomodule, initially installed with one cavity, was then updated to 2 cavities [2] but still driven by a single klystron in vector sum as shows in Fig. 1. 30 MeV beam has been achieved after ACM1 which energy gain is about 20.6 MeV [3, 4].

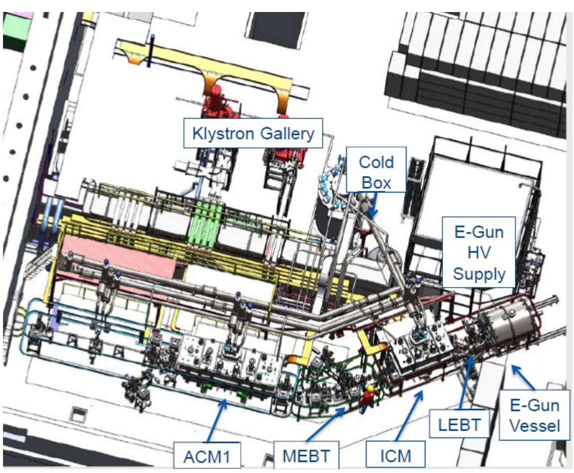

Figure 1: The present configuration of the e-Linac.

During the 2020-2021 shutdown, we made MRO for the ICM to recover performance. In 2021, 10 kW beam operation had been achieved with a 500 µA beam, using an Iterative Learning Controller (ILC) for beam loading compensation [5], and in 2023 upgraded the e-gun RF tuner. At the beginning of 2024, we successfully maintained three days of continuous operation. Recently, to improve beam current stability due to temperature fluctuations, we implemented a PID loop for current regulation using the ACCT signal as feedback.

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TEST PROGRESS

ICM MRO

The ICM cavity experienced a significant degradation in Q_0 due to pollution from venting and pumping. In 2016, the RF space of the ICM was vented too fast. Additionally, a 10 Torr pressure step occurred during pumping, increased the problem, particularly when the pressure dropped from 716 Torr to 708 Torr while the cavity was on the lower side.

Figure 2 illustrates the impact of these events. After the event, the cavity couldn't operate at 10 MV/m due to strong field emission. After pulse conditioning, it became possible to run at 10 MV/m, though this was accompanied by strong x-ray emissions and a reduced Q_0 factor, around 4×10^9. To prevent such operational errors, a slow pumping and venting system has been developed and implemented for each cryomodule. The ICM cavity was later refurbished in a clean room and pumped with slow venting/pumping system on beamline. The test results show successfully restoring its performance to a Q_0 factor of 1×10^{10} at a 10 MV/m gradient.

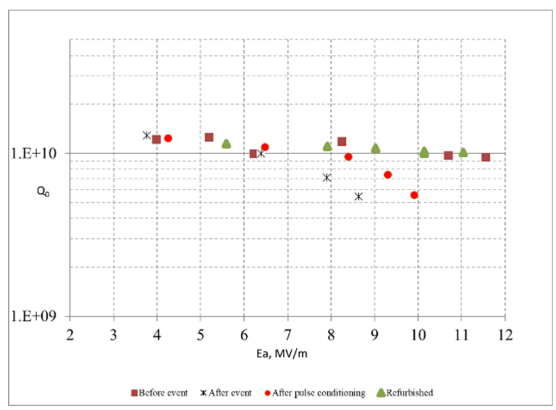

Figure 2: ICM Q_0.

Iterative Learning Controller

The e-Linac must operate at much lower power levels during commissioning and beam development. To achieve this, the e-Linac is pulsed with varying repetition rates and pulse lengths, which results in significant transient beam loading in the SRF cavities. Especially when the beam power ramp-up, which is accomplished by increasing the duty factor.

To improve beam loading compensation, Iterative Learning Control (ILC) is employed in parallel with the constant-gain feedforward controller [5] in each cryomodule LLRF. With the optimized ILC controller parameters, it can effectively compensate beam loading with varying repetition rates and pulse widths, as shown in Fig. 3. The average beam power successfully reached 10 kW with a current of 500 µA and an energy of 30.2 MeV.

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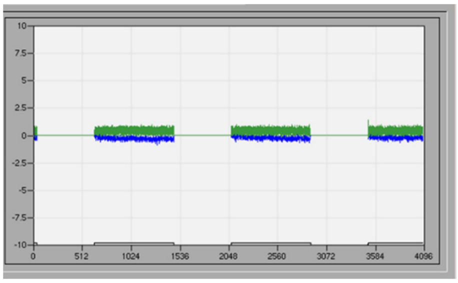
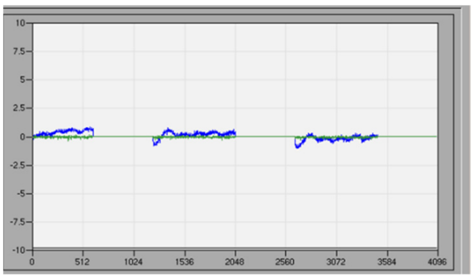


(a) Beam profile after ICM



(b) Beam profile after ACM

Figure 3: ILC performance.

E-gun Tuner Refurbish

During operation, the original e-gun RF tuner was highly unstable, making beam current adjustments difficult. The finger stock connections were fragile, and debris from them caused high-voltage failures several times. When this occurred, the entire e-gun had to be disassembled to clear the debris.

To improve beam current stability and operational reliability, the tuner as shown in Fig. 4 was refurbished with several key upgrades, including replacing all finger stock and the cathode connector with Bal Springs. The design was optimized for easier assembly and servicing by removing the longitudinal split feature and eliminating all plastic screws. Additionally, a new pickup port was added to support future feedback control updates.

Bench tests indicate that the matching frequency ranges from 465 MHz to 925 MHz with a 40 mm tuner adjustment range, and as shown in Fig. 5, the pickup (red curve) is functioning as expected.

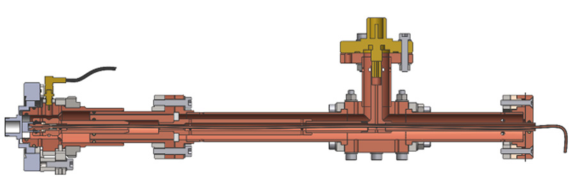


Figure 4: e-gun RF tuner.

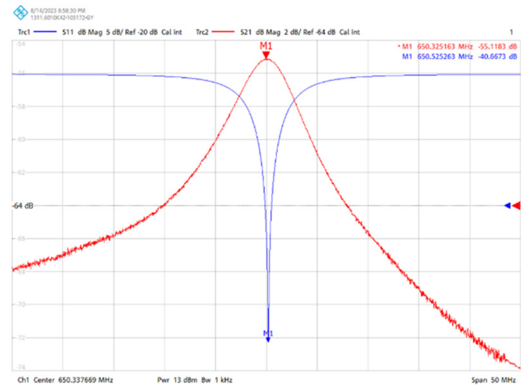


Figure 5: e-gun RF tuner bench test result.

Continually Beam Delivery Test

To further validate the system's operability and identify potential issues, a continuous beam delivery experiment was conducted. During this experiment, the RF system operated stably for five days as shown in Fig. 6. The primary cause of beam trips was ICM RF flickers which were later confirmed to be due to a bug in the LLRF system as shows in Fig. 7. This issue accounted for most of the total downtime, which amounted to 12 hours.

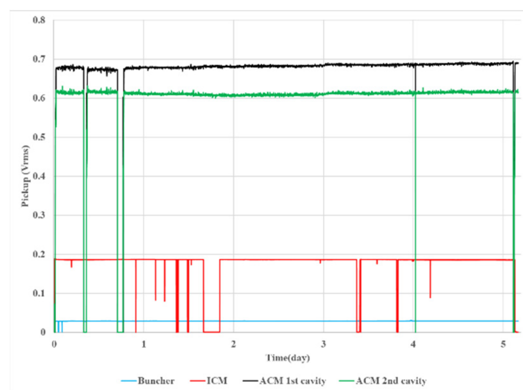


Figure 6: RF cavities pickup.

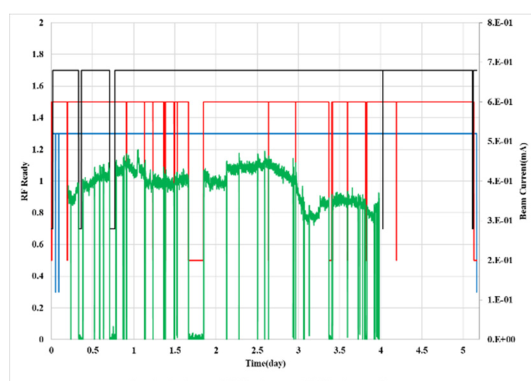


Figure 7: RF cavities status and beam current.

The experiment revealed several issues with the RF system. During the test, the beam current fluctuated between 290-480 µA, due to temperature changes in the e-gun RF rack. The e-gun RF system lacked feedback control, making it unable to regulate the output current effectively. This issue was eventually resolved by adding a PID loop, as

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described in the next section. The ICM RF flicker problem was addressed through modifications to the LLRF code. The LLRF racks don't have a proper temperature control, then environment temperature instabilities caused instability of the beam energy and result in beam trips.

E-gun Beam Current Feedback Loop

The performance of the E-gun is significantly affected by external temperatures, especially the temperature of the RF amplifier rack, which can impact the amplifier's performance and, consequently, the E-gun's output current strength. To address this, a PID feedback loop based on ACCT signals was designed and tested. The ACCT readings are used to regulate the e-gun's output beam current by adjusting the RF input to the amplifier.

The relationship between the beam current intensity of an e-gun and RACK temperature over time is shown in Fig. 8. The temperature ranges from 21°C to 30°C, and the beam current intensity fluctuates between 0.2 mA and 1.8 mA. This demonstrates that the current intensity is significantly affected by temperature changes.

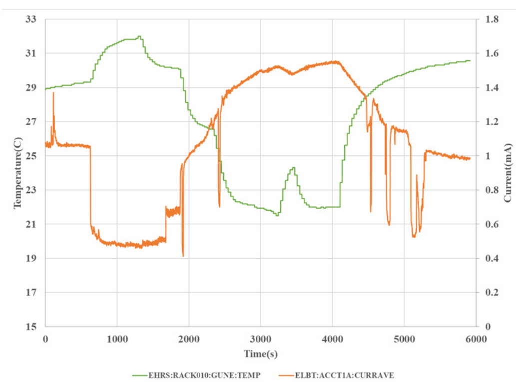

Figure 8: E-gun current fluctuates with temperature.

Figure 9 illustrates how the PID feedback loop adjusts the e-gun RF amplifier input to maintain a stable e-gun output current despite temperature changes. The e-gun output current, which remains relatively stable around 170 uA; the temperature, fluctuating between approximately 28°C and 31°C; the e-gun input attenuator, changing from 18.4 dB to 18.7 dB. This demonstrates that the feedback loop effectively compensates for temperature variations to keep the e-gun output current stable.

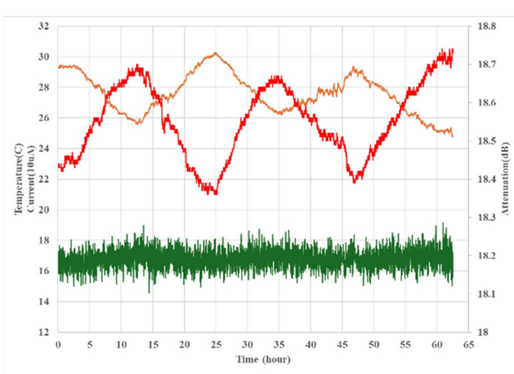

Figure 9: E-gun feedback loop performance.

CONCLUSION

The recent advances in the commissioning of the ARIEL e-Linac RF system resulted in significant improvements in system performance and stability of the RF system, and we run it continuously for five days. The MRO of the ICM, upgrade of e-gun tuner, and implementation of a PID feedback loop significantly enhanced the stability and reliability of beam operations. The ILC has effectively compensated for beam loading, providing stable operation. Some ongoing challenges remain, particularly the need for better environment temperature control in the LLRF racks to stabilize the beam energy. Overall, these developments represent important steps toward achieving consistent high-power operation and ensuring the long-term success of the ARIEL e-Linac.

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