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AUTOMATION OF RF AND CRYOMODULE OPERATION AT FRIB*

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Abstract

The Facility for Rare Isotope Beams (FRIB) has been commissioned, with rare isotopes first produced in December 2021 and the first user experiment conducted in May 2022. The FRIB driver linear accelerator (linac) uses 6 room temperature cavities, 324 superconducting cavities, and 69 superconducting solenoids to accelerate ions to more than 200 MeV/nucleon. Because of the large scale, automation is essential for reliable linac operation with high availability. Automation measures implemented during linac commissioning include turn-on of the cavities and solenoids, turn-on and fast recovery for room temperature devices, and emergency shut down of linac devices. Additional automated tasks include conditioning of multipacting barriers in the cavities and calibration of the control valves for the pneumatic tuners. To ensure a smooth transition to operations, we are currently working on real-time health monitoring of the linac cryo-modules, including critical signals such as X-ray levels, RF coupler temperatures, and cryogenic parameters. In this paper, we will describe our automation procedures, the implementation details, and the experience we gained.

INTRODUCTION

Facility for Rare Isotope Beams (FRIB) is a new heavy ion linear accelerator (linac) facility just came online recently, following the completion of technical construction in January 2022 [1]. The ribbon cutting event on May 2, 2022 marks the commencement of the FRIB user program and the first scientific user experiment was conducted in the weeks that followed in May 2022.

The FRIB driver linac includes 6 room temperature cavities and 324 superconducting (SC) cavities along with 69 SC solenoids housed in 46 cryomodules [2]. It is capable of accelerating heavy ions (up to uranium) to an energy of more than 200 MeV/nucleon. There are also 19 SC magnets spread in the folding segment 2 (FS2), target hall, vertical pre-separator and fragment separator areas (see Fig. 1).

FRIB single event effects (FSEE) facility is a purpose-built beamline at the end of the linac segment 1 (LS1), with experimental station, and user control room with complete diagnostic equipment and controls. The dedicated FSEE experimental area allows users to test the effects of radiation on their devices to make sure they are safe for commercial and scientific use. FSEE facility uses its linear particle accelerator to accelerate ions to the proper specifications that can best match space radiation conditions.

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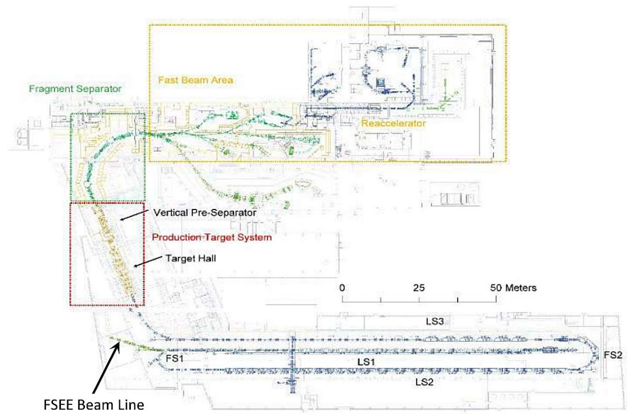

Figure 1: FRIB driver linac layout.

THE IMPORTANCE OF AUTOMATION

For a facility with hundreds of devices like FRIB, operation with high availability can only be achieved by automation.

First, automation reduces time for turning on/off devices, therefore increases time available for scientific experiments.

Automation not only improves efficiency and productivity, it also provides consistency to task execution and eliminates potential human errors. Also for certain tasks that require immediate response, for example fast recovery for room temperature cavities from a trip, automation is the only choice.

The essence of automation is to formalize the operation experience of system experts into routines, and perfect them through iterations. Eventually the devices become "smart" and require minimal human intervention. This allows operators to run complex devices without expert-level training for each type of device.

As a result, the system experts are freed from routine work and can devote more time for creative work. This also reduces the level of training required for operators.

DEVICE LEVEL AUTOMATION

During the construction phase of the FRIB project, the re-accelerator (ReA) program [3] at the National Superconducting Cyclotron Laboratory (NSCL) was already in operation. From the ReA operation experience we learned that it is important to have the auto turn on feature. We started with the quarter wave resonators (QWRs) and then expanded it to the room temperature (RT) cavities. Lastly we applied it to the half wave resonators (HWRs). During the FRIB front end (FE) commissioning, due to the long turn on time (30 to 40 minutes) of the radio frequency quadruple (RFQ) we realized fast recovery is also very important for RT cavities. Later we applied the similar idea

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to the magnet turn on process. Below are the details about each case.

Cavity Auto Turn On

To efficiently and reliably operate a large scale facility with over 300 cavities of various types could be very challenging. Automatic turn on procedures have been developed and implemented on the input/output controller (IOC) level for all FRIB cavity types to address this challenge. After resolving the difficulty in pneumatic tuner control, the auto on feature was implemented and tested for the HWRs [4].

Figure 2 shows a typical HWR auto turn on process. After the auto start command is issued by the operator, the high voltage for the bias tee is turned on and the tuner valves are enabled. The RF drive is enabled at the initial level (1.5 MV/m) afterward, followed by enabling the tuner control. Once the cavity is on resonance, the amplitude control switches to closed-loop and starts ramping to the final amplitude set-point. The phase control will switch to closed-loop once the final amplitude set-point is reached and the automatic turn on process completes. The whole process takes about 35 seconds. During the first beam run of the 4th accelerator readiness review (ARR4) in March 2020, without the auto turn on, each HWR was turned on manually and took about 2 minutes for each cavity.

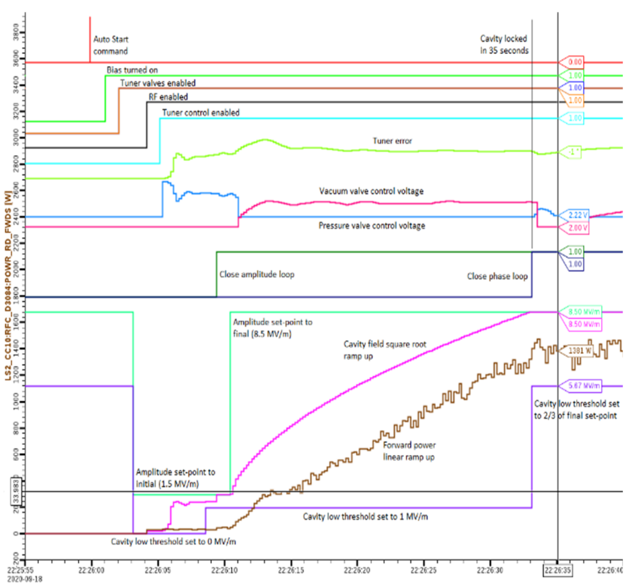

Figure 2: HWR auto turn on process.

Room Temperature Cavity Fast Recovery

For room temperature cavities, in certain cases (typically reflected power high or s11 high events due to sparking), it's important to recover the power of the device in a few seconds to keep the temperature of the cavity which is essentially the tuning of the cavity. So that the cavity can be resumed for beam operation with minimal delay. It was demonstrated that the RFQ operating at 100 kW continuous wave (CW) can resume beam operation in less than 20 seconds [5] (Figure 3).

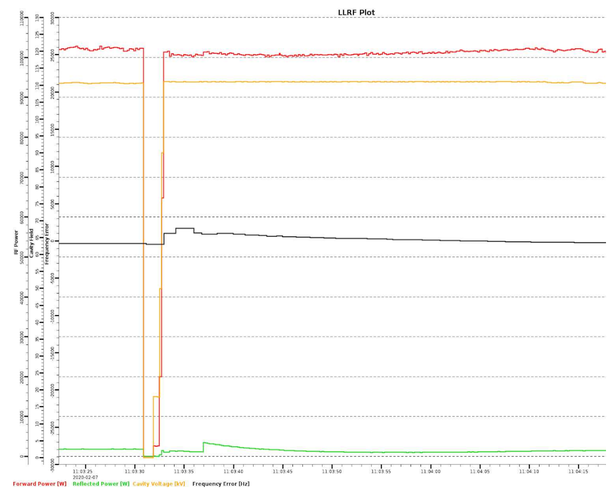

Figure 3: RFQ fast recovery after an s11 trip.

Solenoid Auto Turn On

Solenoid auto turn on is relatively simple. It is a two step ramp up process. At each step the stability of the power supply current is checked (see Figure 4).

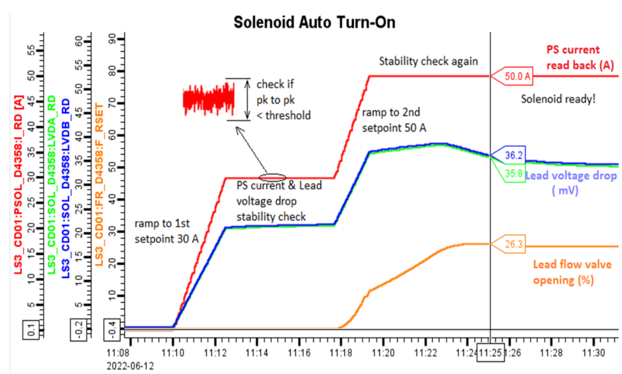

Figure 4: Solenoid auto turn on sequence.

FSEE OPERATION

Unlike typical scientific experiments, for which the beam is sent to the experimental area on the ground level, the FSEE experiments happen in the tunnel. The users usually need to frequently access the experimental area and each time tunnel access is requested, all superconducting radio frequency (SRF) cavities need to be turned off. This can happen 4 to 5 times a day.

This presents a challenge to the accelerator operation. First turning on and off the SRF cavities frequently perturbs the cryogenic system. Second, even with automatic turn on implemented, turning on cavities one at a time (104 SRF cavities are used for FSEE operation) still takes a lot of time.

To address the challenges mentioned above, heater compensation is first applied to stabilize the cryogenic operation. The accelerator physicist group provides cavity amplitude set-points for the experiment; SRF group calculates expected heat load for each cavity; cryo control group sets the heater compensation values based on the calculation. A hard-wired signal is sent from the low level radio fre-

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quency (LLRF) controller to the programmable logic controller (PLC) to indicate the RF on/off status, which triggers the heater. Figure 5 shows the heater being turned off and on as the SRF cavities are being turned on and off.

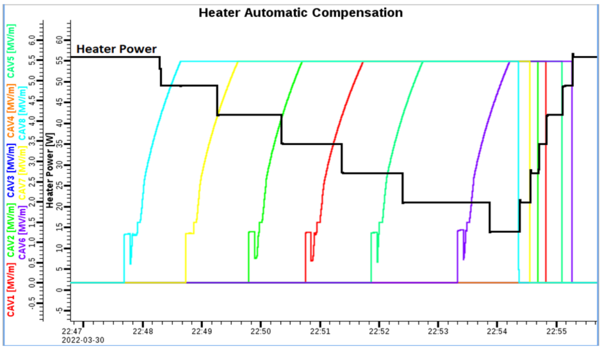

Figure 5: Cryo heater compensation based on cavity status.

Secondly, a much more simplified operator interface (OPI) is also developed with only six buttons (Figure 6) to operate all of the QWRs.

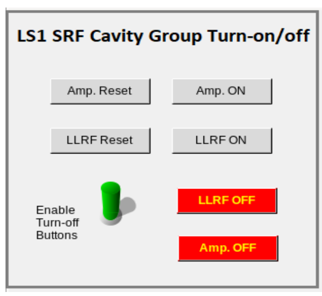

Figure 6: OPI for turning on/off LS1 SRF cavities.

With the proper heater compensation for stable cryo system operation and the simplified OPI, the LS1 SRF cavities can be turned on in 2 minutes and turned off in 2 seconds as shown in Fig. 7.

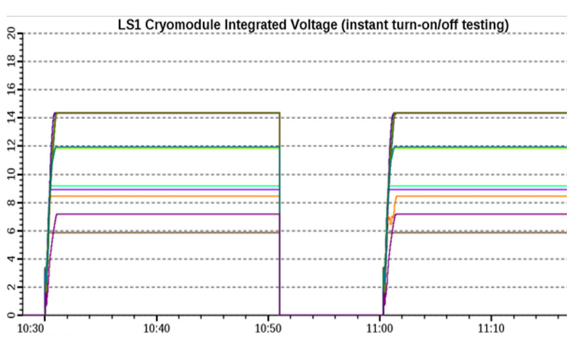

Figure 7: Efficient turning on and off of LS1 SRF cavities.

IMPLEMENTATION CONSIDERATION

There are different ways to implement the automation tasks. Below we will discuss several options being used at FRIB and their use cases.

Python script is a very powerful tool with versatile libraries and provides maximum flexibility. Since no compilation is needed, the development can be iterated very quickly. It has been used to prototype the auto turn on and fast recovery of the cavities. For the same reason, it's also prone to mistakes. That is why FRIB has a script use policy that prohibits the use of scripts for safety features and when beam power is greater than 2 W. However Python scripts can be safely used to handle read only tasks, e.g. parameter checking, health monitoring, etc.

The sequencer module in the IOC can be utilized to automate tasks as well. The development follows a more rigorous process. The source code is version controlled and peer reviewed. Testing of IOC scripts requires a work control plan and deployment of IOC scripts requires a configuration change request. After prototyping, the auto turn on and fast recovery Python scripts for cavities are all converted to IOC scripts to enforce formality. The emergency shutdown for the cavities and solenoids is also implemented in the IOC scripts.

Lastly, some tasks can be automated at the device level, provided the device has its own processor to run software routines. The power ramp up of RT cavities is done in the self-excited loop mode. During the process the feed-forward phase setting needs to be adjusted. Previously this was done in the IOC scripts. Later we migrated the implementation to the LLRF controller software to remove the complexity of dealing with network delay. This results in a significant code size reduction from 60 lines in IOC to 30 lines in LLRF controller. Meanwhile the code runs at a much faster rate of 20 Hz in LLRF instead of 0.5 Hz in IOC.

ONGOING TASKS

Now as FRIB transits from construction and commission to operations, efficient automation tools for performance tracking and real-time health monitoring will be needed.

Currently we are working on automatic health monitoring for critical signals of the cavities and cryomodules, such as He level, X-ray levels, coupler temperatures, etc. which were monitored by experts previously. Abnormal patterns will be identified and warnings or alarms will be set depending on the severity of the situation.

Another important task is cavity trip troubleshooting and action recommendation. For some trips it is easy to identify the cause, but for others it may be time consuming. We envision a single button solution. When a cavity trip event happens, the operators only need to click the button and the script will generate a trip report and provide recommendations of actions, such as reset and restart, or contact system experts in case of potential hardware failures.

Other maintenance tasks such as pre-run check and LLRF controller firmware/software update can also benefit from automation.

SUMMARY

In this paper, we shared our experience of automating the RF and cryomodule operation at FRIB. The motivation is naturally strong for large scale facilities. We gave examples of the automated tasks at the device level as well as the facility level. The pros and cons of the different implementation approaches were compared. We hope this provides some useful information for future accelerator projects.

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