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AUTOMATION OF FRIB SRF CAVITIES AND SC SOLENOIDS TURN-ON/OFF*

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Abstract

The superconducting driver Linac for the Facility for Rare Isotope Beams (FRIB) is a heavy ion accelerator that accelerates ions to 200 MeV per nucleon. The Linac has 46 cryomodules that contain 324 superconducting radio frequency (SRF) cavities and 69 superconducting (SC) solenoid packages. For operation of all cryomodules with high efficiency and reliability, automation for SRF cavity and SC solenoid fast turn-on/off is essential. Based on cryomodule commissioning results and expert experience, all manual cavity and solenoid turn-on/off procedures and steps have been replaced by automatic programs for FRIB linac operation. This allows the operators to turn the systems on and off without expert-level training. Automation reduces the risk of human error, speeds up beam recovery after user access to experimental areas, and increases beam availability. The cavity turn-on procedure makes sure that the cavity can operate at low field with expected read backs, ramps up the field, and makes sure that the RF amplitude and phase are stable. The design, implementation, and operating experience with automation will be presented.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) driver linac is designed to accelerate heavy ion beams from hydrogen to uranium. After commissioning of the FRIB linac, completed with acceleration of heavy ions to energies above 200 MeV/u, the first scientific user experiment was conducted in May 2022 [1].

The FRIB driver linac has a folded layout, as shown in Fig. 1, which consists of three linac segments (LS1, LS2 and LS3) connected with two folding segments (FS1 and FS2). A beamline at the end of LS3 delivers the accelerated beam from LS3 to target hall. Another beam delivery system was built at the end of LS1, dedicated to the FRIB Single Event Effects (FSEE) experimental station to serve industrial users.

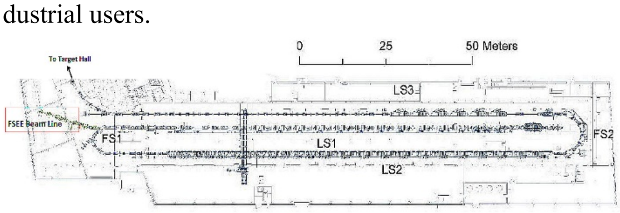

Figure 1: Layout of the FRIB driver linac.

Linac segments and folding segments have 46 cryomodules with a total 324 superconducting radio frequency (SRF) cavities and 69 superconducting (SC) solenoid packages [2]. Turn-on and shut-down of this large scale SC device complex with high availability presents a challenge.

EXPERIENCE CONVERTED TO AUTOMATION

The FRIB cryomodules have 104 quarter-wave resonators (QWRs, beta = 0.041 and 0.085), 220 half-wave resonators (HWRs, beta = 0.29 and 0.53) and 69 SC solenoid packages [3]. After commissioning of all cryomodules in the tunnel, all information about optimum control parameters, and each device start-up or shut-down procedures, were well defined and documented. With this information, based on operational experience, all devices can be operated simply by following the correct procedure. However, manual turn-on/off of such large scale and complex system takes a huge cost in terms of time. Moreover, the complexity of these procedures requires expert-level training. To perform this system start-up and shut-down with high efficiency and reliability, the conversion of expert-level experience to automation programs is essential.

In FRIB, all the optimum control parameters for SRF cavities and SC solenoids are saved in files. Automation tools for parameters checks can be used for parameter consistency check before any device is turned on. Once this pre-check is done, the automation procedures for SRF cavities and SC solenoids turn-on can be executed. Automation programs for shut-down of all devices is also important. Once any emergency event happens, a shut-down of all devices through "one button click" allow people to leave the area as fast as possible.

SRF CAVITIES AUTO TURN-ON

Single Cavity Auto Turn-on Logic

All 104 QWRs and 220 HWRs have been manually commissioned one by one. With this commissioning experience, turn-on procedures have been developed, tested and confirmed through specific commissioning tasks and then converted to automatic programs.

For QWR auto turn-on, the logic is:

1. Set field-low interlock to 0 MV/m;
2. Set amplitude as open mode and phase as self-excited mode;
3. RF turn on with initial field set-point 1.5 MV/m to jump through the multipacting low barrier;
4. Tuner lock turn on, tuning the cavity frequency to the centre;

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5. Switch phase to open loop mode;
6. Check cavity initial forward power and field level ratio (S21 ratio) to make sure the field calibration is consistent with stored values;
7. Adjust feed forward (FF) gain for amplifier to get consistent cavity field read back;
8. Set field-low interlock to 1 MV/m;
9. Amplitude and phase loop lock;
10. Ramp-up field to final set-point;
11. Set field low interlock 66% of field set-point.

The single HWR auto turn-on logic is similar to the QWR one, just a few steps are different:

1. Turn on pneumatic tuner valves and adjust tuner pressure to the set-point position;
2. Set field-low interlock to 0 MV/m;
3. Amplitude and phase set both to open loop mode;
4. RF turn-on with initial field set-point 1.5 MV/m;
5. Tuner lock turn-on;
6. S21 ratio check;
7. Adjust FF gain;
8. Set field-low interlock to 1 MV/m;
9. Amplitude and phase loop lock;
10. Ramp-up field to final set-point;
11. Set field-low interlock 66% of field set-point.

Group Auto Turn-on

After single cavity auto turn-on programs have been successfully tested, duplicated programs have been implemented for all QWRs and HWRs. To meet the fast start-up purpose, all single cavity auto turn-on programs are integrated into three groups for LS1, LS2 and LS3 in higher system level. All cavities in each linac segment can undergo fast turn-on through "one button click". Figure 2 shows the user interface panel for a group of cavities auto turn-on. Once all amplifiers are on, and all interlock latches are reset, each group of cavities can be turned on with one command only.

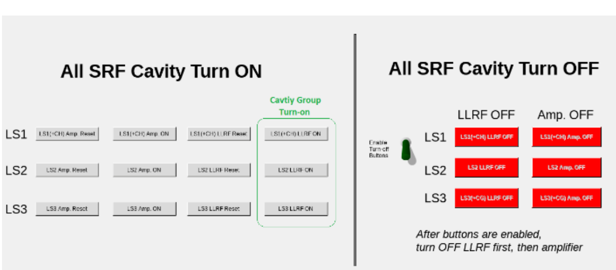

Figure 2: All SRF cavity group turn-on/off graphic user interface.

Figure 3 shows the case for a group of SRF cavity auto turn-on. Every cavity has the automatic turn-on procedure executed. The time required from start to ramp-done is about 2 minutes.

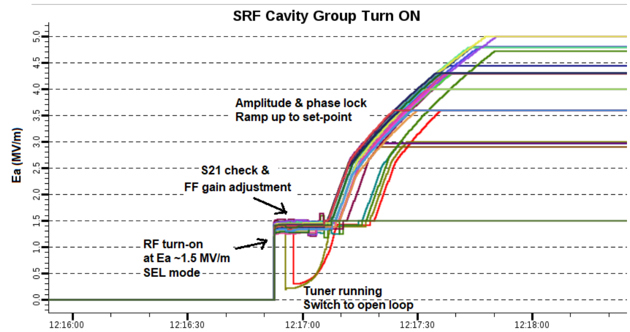

Figure 3: SRF cavity group auto turn-on.

Cavity Field Reduce & Recover

The cavity field reduce & recover tool is made to avoid that the FRIB QWR cavities become stuck to the low field multipacting barrier. This barrier can be jumped through by a special setting of the initial RF switch-on parameters [3]. This requires also that adjacent cavities run without generating field emission (FE) electrons. When a QWR needs to be turned on, but adjacent cavities have high FE, the "reduce & recover" tool first reduces the adjacent cavity field to below the FE level, and then, after the required QWR is ramped above multipacting, it brings the cavity back to its previous settings ("recover" part). This automation program includes these steps:

1. Open the phase lock loop for the high FE cavity;
2. Reduce the field low interlock of the high FE cavity;
3. Ramp down the high FE cavity field to 1.5 MV/m (no FE at this field level);
4. Turn the tripped cavity back on;
5. Once the required cavity is turned on and the field level is above the multipacting low barrier, ramp up the high FE cavity field to previous set-point;
6. Set the high FE cavity phase loop close lock again and also set the field low interlock back to the previous value.

Figure 4 shows an example of a QWR cavity turn-on with adjacent high FE cavity "reduce and recover".

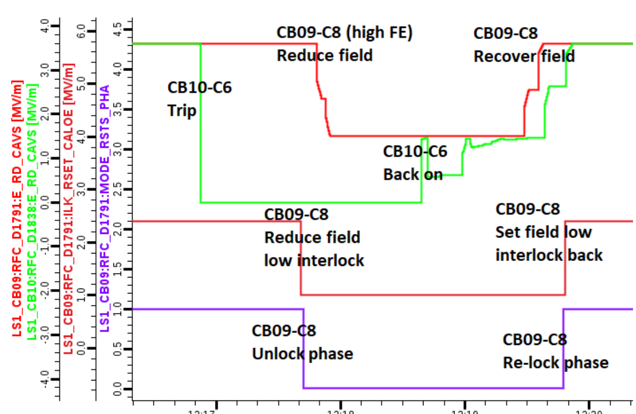

Figure 4: LS1 QWR cavity turn back on from trip with adjacent high FE cavity run "reduce & recover" tool.

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HWR Pneumatic Tuner Valve Auto-calibration

Turning on all 220 HWRs requires to control 440 solenoid valves. Each FRIB HWR is equipped with a pneumatic tuner, with two solenoid valves to charge or discharge helium gas pressure in order to tune the cavity frequency [4]. The valve's calibration, which is part of the regular check in maintenance period, is needed to check the "valve opening" control voltage versus the gas flow rate. Errors in the valve calibration cause instabilities of the tuner control and possible cavity trips. Manually checking the calibration of 440 valves takes 3 person-days, and repetitive work also increases risk of human errors. The automation tool for this calibration was developed to achieve both high efficiency and reliability. The auto-calibration program can run valves either in 1 cryomodule sequentially, or in all cryomodules in parallel. Figure 5 shows the pneumatic tuner pressure changes during automatic calibration of valves. This automatic procedure cuts the time cost significantly, from 3 person-days to 2 hours.

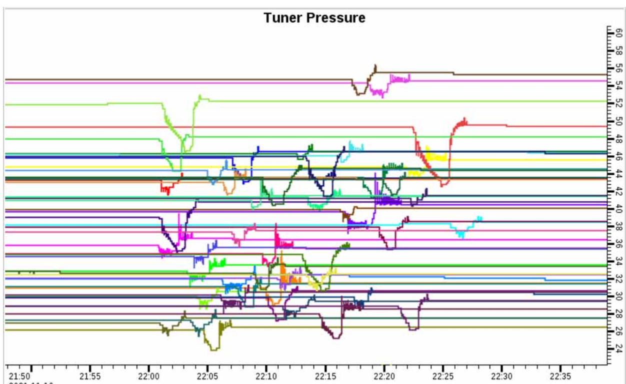

Figure 5: Automatic calibrating HWR pneumatic tuner valves in Parallel.

Cavity Dynamic Heat Load Auto Compensation

Start-up of all SRF cavities, due to the large dynamic heat load from cavities which must be compensated by the cryogenic control, requires a long time to reach a stable configuration. The dynamic heat load is significant especially for the LS1 cavities operated at 4 K. A sudden change in cryomodule RF power causes a fast drop of the cryomodule liquid helium level, and the liquid He low-level interlock threshold, which stops all cavities may be reached. This sudden change also impacts cryogenic thermal equilibrium. Cryogenic control system is relatively slow and it needs a relatively long time to reach a new thermal equilibrium. Thus, all cavities need to be turned on gradually, in a long enough time to mitigate the impact on the cryogenic system. Additionally, the FRIB linac run with different beam types (different mass-to-charge ratio: q/A) that requires different cavity field levels, which also have different dynamic heat load powers and make the thermal equilibrium configuration even more complex. The commissioning experience shows that this kind of thermal equilibrium changes usually take about 1 hour to be stabilized. To mitigate this time cost issue, automatic compensation of cryomodule internal heaters was implemented. The internal heater will keep power on all the time before the cavity turn-on. Once the ramp-up to the set-point is completed, the heater power is adjusted to compensate the cavity dynamic heat load at that field level. The reduced heater power values, saved in files for automation, are based on commissioning results. With this auto-compensation, the whole cryomodule is able to keep thermal equilibrium all the time, no matter if cavities are on or off and all SRF cavities can be fast turned-on/off within 2 minutes (Fig. 6). Especially for FSEE experiments, which require frequent SRF cavities turn-on/off to allow users to replace samples in the tunnel, this automatic compensation is critical.

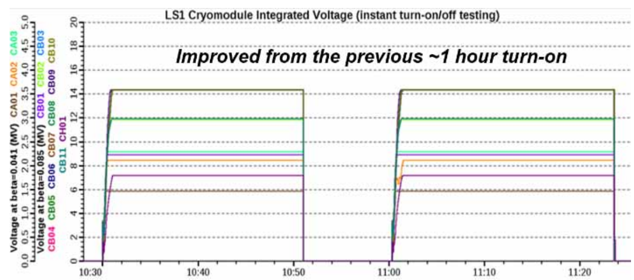

Figure 6: LS1 QWRs fast turn-on/off with heater automatic compensation.

SOLENOID PACKAGES AUTO TURN-ON AND DEGAUSSING

The energization procedure for SC magnets is based on commissioning experience. To mitigate the potential risks of long term operation, necessary checking steps have been added to the start-up procedure. The automatic program includes the steps listed below:

1. Turn 'lead flow' valve on, wait 3 minutes to make sure that the valve is not leaking;
2. Turn on the power supply for the solenoid package;
3. First step ramp-up, current up to 30 A for the solenoid;
4. Check current stability for 4 minutes, check lead voltage stability for 1 minute;
5. Second step ramp-up, current up to 50 A;
6. Current and lead voltage stability check again;
7. Final step ramp-up, current up to final set-point.

Single solenoid auto turn-on is also duplicated to all devices. Then five group turn-on functions are implemented for LS1-CA (QWR be-ta=0.041 cryomodule), LS1-CB (QWR be-ta=0.085 cryomodule), LS2-CC (HWR be-ta=0.29 cryomodule), LS2-CD (HWR beta=0.53 cryomodule), LS3-CD (HWR beta=0.53 cryomodule) cryomodules. With automatic program implemented, operators are able to ramp up all solenoids in each group through "one button clicking" (Fig. 7).

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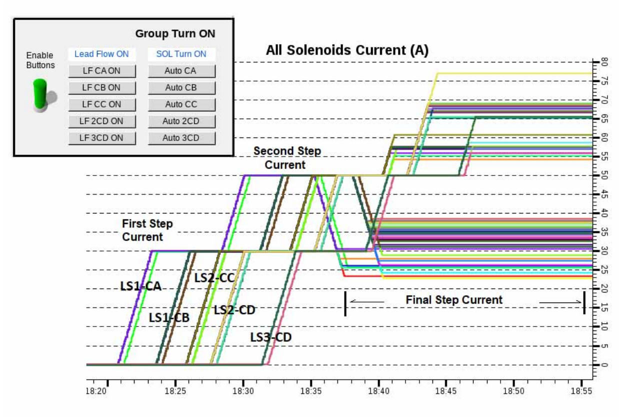

Figure 7: LS1 QWRs fast turn-on/off with heater automatic compensation.

The automatic logic of degaussing is similar to the solenoids normal turn-on. Except for the ramping part, all other parts are the same. The degaussing ramping has 20 steps for ramp-up or ramp-down. Both solenoid and two steering dipoles are ramped at the same time on each step. Once all magnets current have reached sub-step set-points, the next ramping will start with no current or lead voltage stability checks (Fig 8).

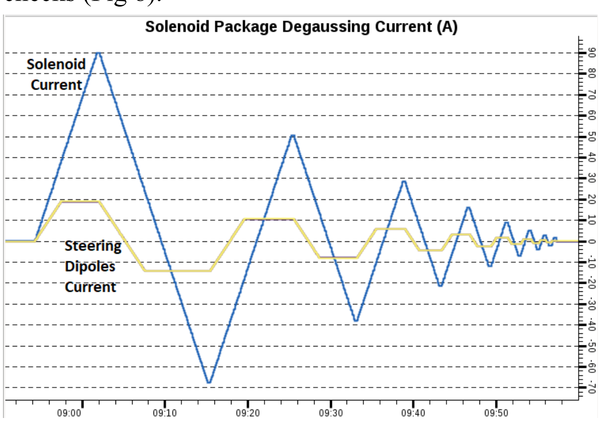

Figure 8: Solenoid package auto degaussing.

AUTOMATION TOOLS UPGRADE

The first version of automation programs are based on Control System Studio (CS-Studio) Operator Interface (OPI) with embedded Python and JavaScript scripts. As for the initial version, it is good for cryomodule commissioning purpose, and function changes which are feedbacks from commissioning results are easy to implement. But the execution of the program is through a standalone workstation. Since the cryomodule start-up and shut-down gradually transit to operation level, with reliable operation as a fundamental requirement, upgraded programs are further developed and implemented. All Python and JavaScript automation programs are upgraded to sequencer modules running on EPICS IOC (Experimental Physics and Industrial Control System Input/Output Controller) level [5].

The IOC level automation tools support multi-workstation operating and also have operation permission security control. Once the automation program is running, all other workstations are able to notice the procedure executing status. The IOC security control is able limit executing permission only for cryomodule experts or for trained operators.

EMERGENCY SHUT-DOWN

To protect machine from damage due to emergency events, an emergency shut-down procedure, able to shutdown all devices of the FRIB linac through "one click" button, is required. For this purpose, fast shut-down procedures for all SRF cavities and SC solenoids have been developed and linked to the linac main emergency shut-down on EPICS IOC level.

Thanks to the heater power auto compensation, all SRF cavity can be shut-down instantly by turn-off RF drive signal and amplifier without causing cryogenic system instability. Solenoid packages shut-down first step is the rampdown of all magnets' current to zero. Then, after10 seconds, the power supply is turned off and the lead flow valve is closed.

SUMMARY

For linac operation, automation is essential for fast device turn-on/off, fast turn-back-on from trips, and emergency shut-down. In this paper, we provide experiences of automating the large scale cryomodule operation at FRIB. The implementation of automation tools is critical in order to achieve high reliability and availability of the overall machine.

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