Automation of FRIB SRF Cavities and SC Solenoids Turn-on/off

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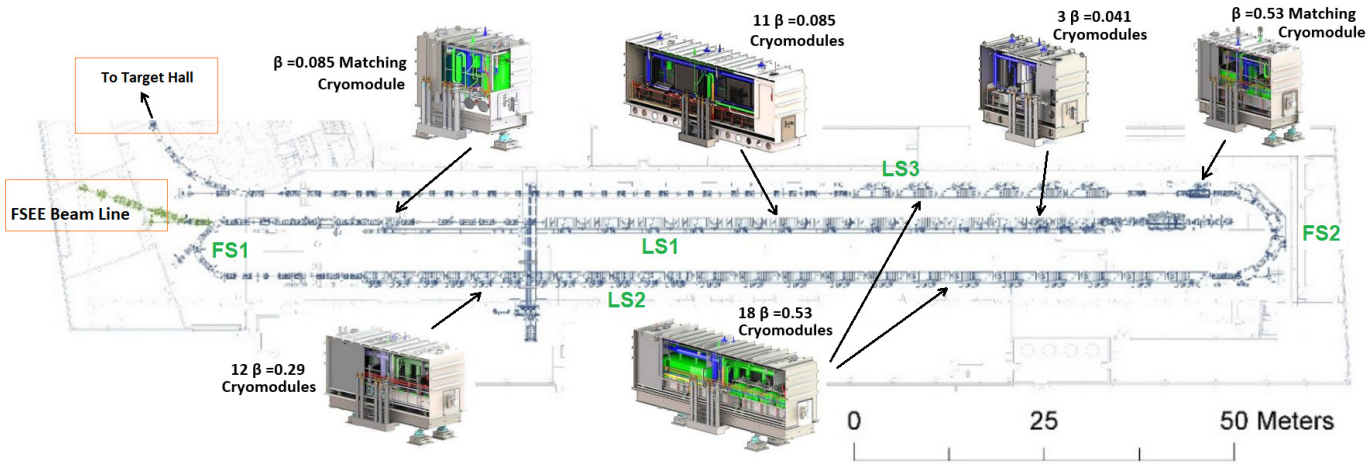
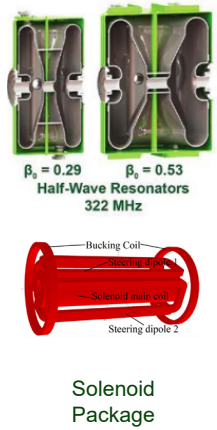
Outline

- Introduction
- Cryomodule commissioning experiences convert to automation
- Automation implementation
  - For SRF cavities
  - For superconducting (SC) solenoid packages
  - Emergency shut-down
- Summary

Introduction

- FRIB Linac contains 324 SRF cavities and 69 SC solenoid packages in 46 cryomodules accelerating different heavy ions to 200 MeV/u
  - LS1 & FS1: 104 QWRs with stepper motor tuner operated at 4 K
  - LS2, FS2 & LS3: 220 HWRs with pneumatic tuner operated at 2 K
  - Two beam delivery system send beam to target hall or FRIB Single Event Effects (FSEE) experimental station
- Challenge of this large scale complex system operation
  - Different start-up configurations for different beam types
  - High availability requires fast start-up, recovery from trip and shut-down

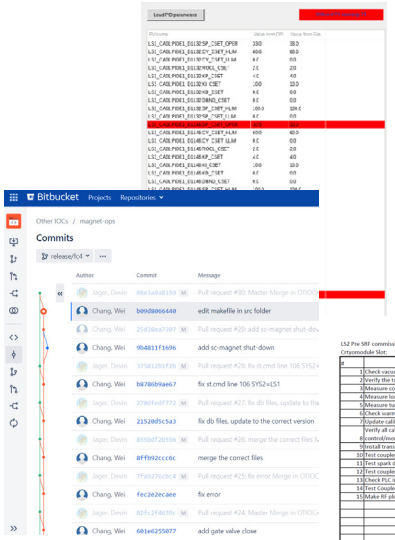


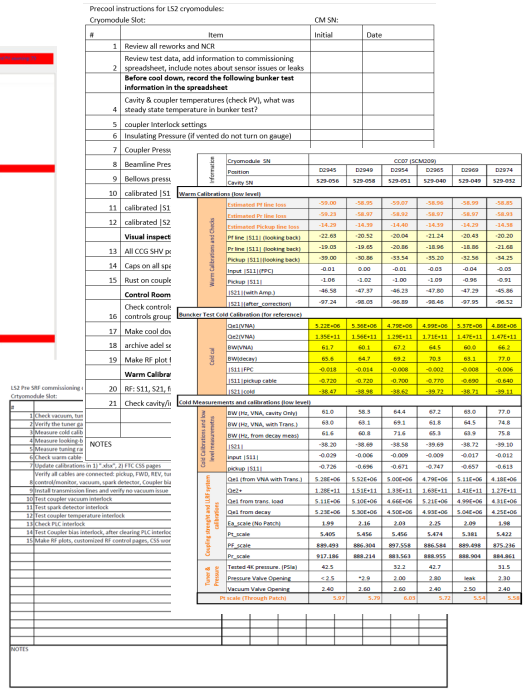


Solenoid Package

Cryomodule Commissioning Experience Convert to Automation

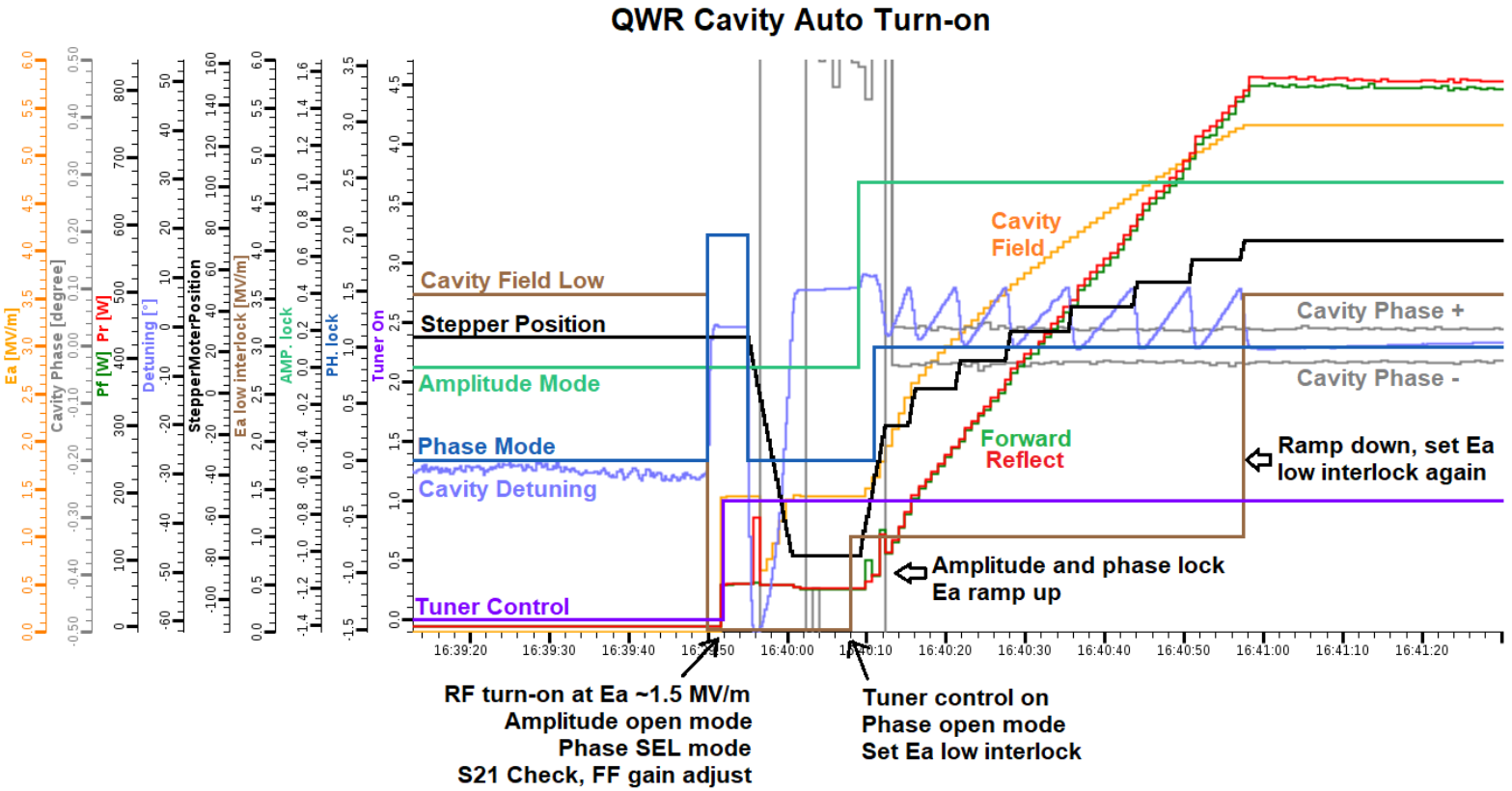
- Details manual procedures for commissioning
  - Sequences checklist for SRF cavity and Solenoid start-up and shut-down
  - Device stability status check methods for start-up
  - Recovery from trip operating steps
- Tracking parameters changes on commissioning tasks
  - Calibration parameters
  - Control parameters
- Automation procedure iteration based on test feed back
  - Find out the optimized method from different procedures
  - Failure turn-on cases tracking, troubleshooting, improving and test





QWR Auto Turn-on

- Start with SEL mode then run stepper tuner to tune cavity frequency
- Check S21 and adjust FF gain, close amplitude and phase loop, ramp-up cavity field to set-point

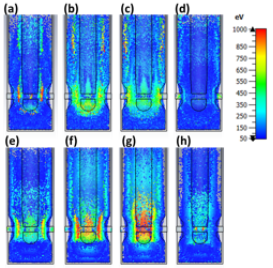


LS1 QWR Fast Recover From Trip

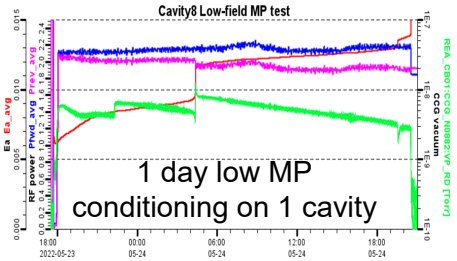
Auto Procedure Help Low Multipacting Barrier Jump Through

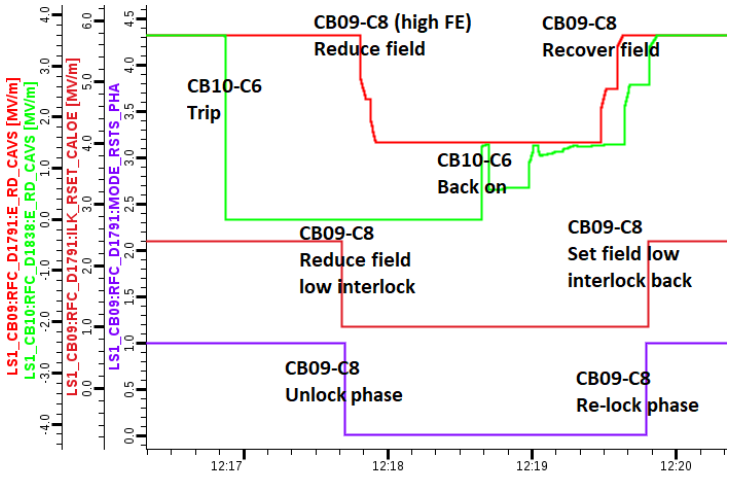
- QWR low multipacting (MP) at low field
  - Requires a long conditioning time (> 1 day)
  - MP enhancement due to field emission (FE) from neighboring cavities (cavity recover from trip will stuck into low MP)
  - Reduce neighboring high FE cavity field to help tripped cavity jump through the low MP

MP particle tracking @ E_{acc} = 12 kV/m for one RF period starting from 300 ns: 1st order, 2 point coaxial MP



S. Kim, NAPAC'22

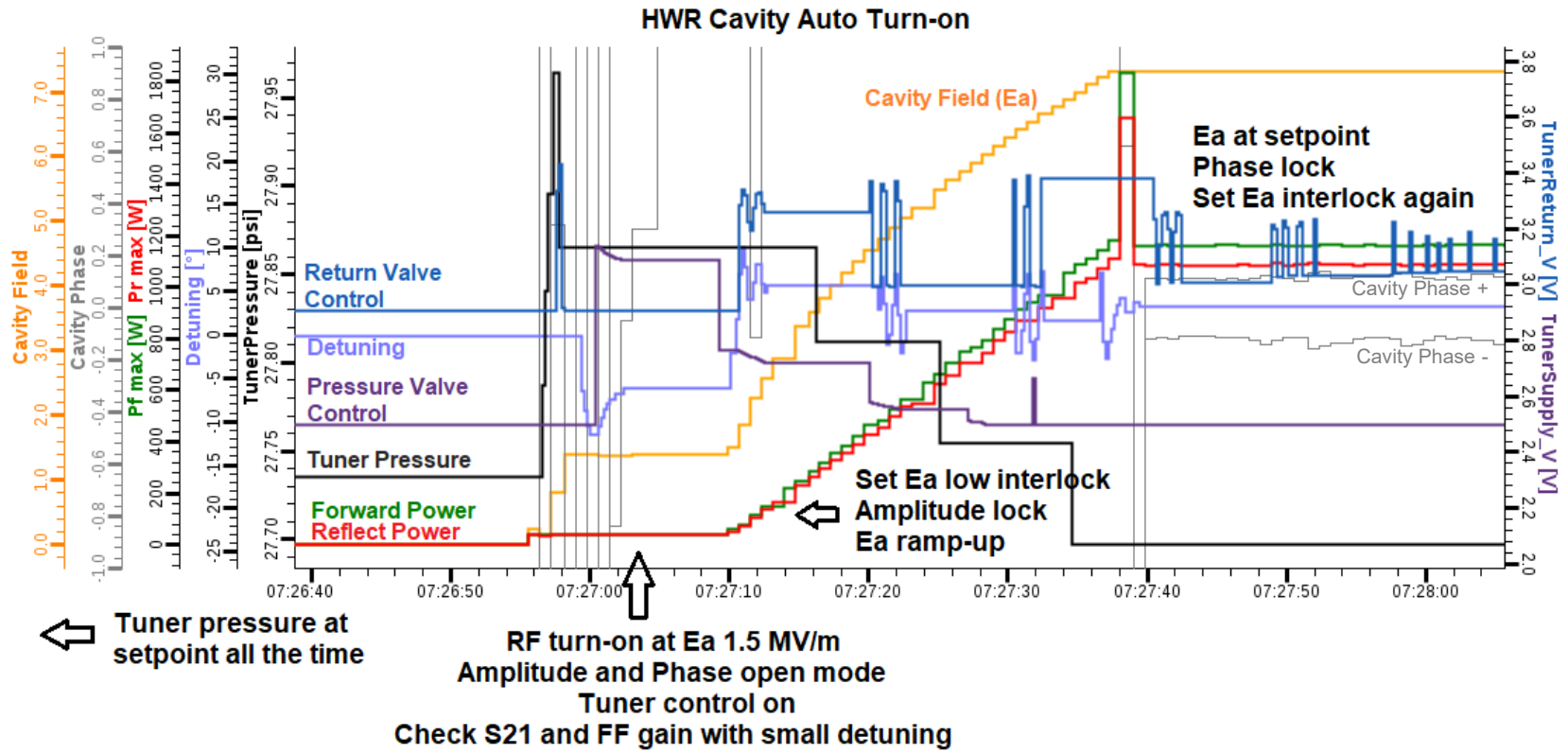




- Low MP jump through method confirmed in commissioning
  - Manual procedure requires multi-setting changes on neighboring FE cavities
- Implemented auto-run for high FE cavity field reducing then recovery
  - Fast recover cavity from trip by ~2 minutes
  - Reduce the required training level for operators

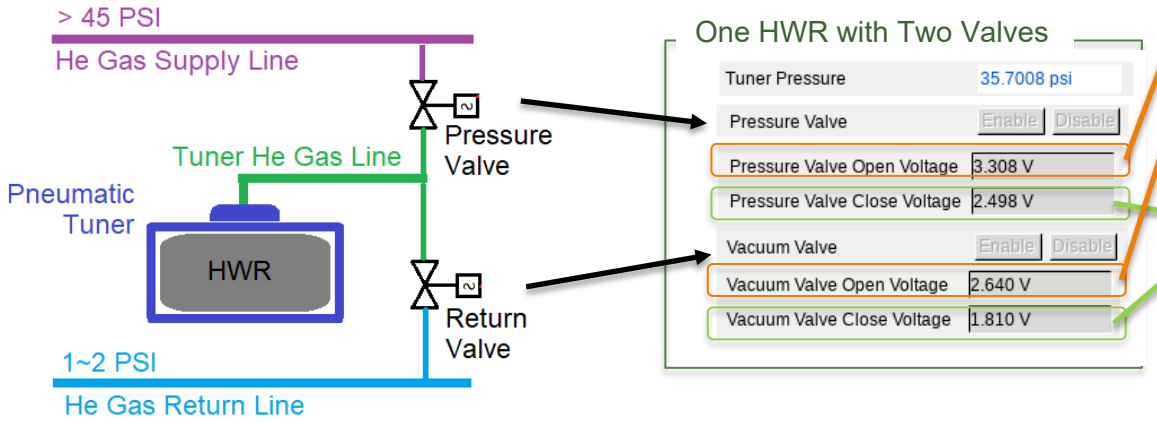
HWR Auto Turn-on

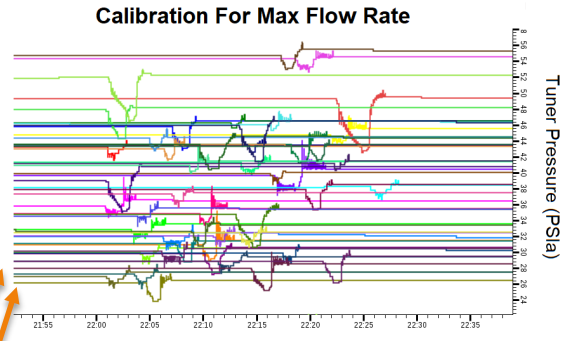
- Tuner valves control the tuner pressure at set-point before RF on
- Open loop mode for initial start then tuner run cavity to the center to do S21 check, FF gain adjust, amplitude lock and ramp-up

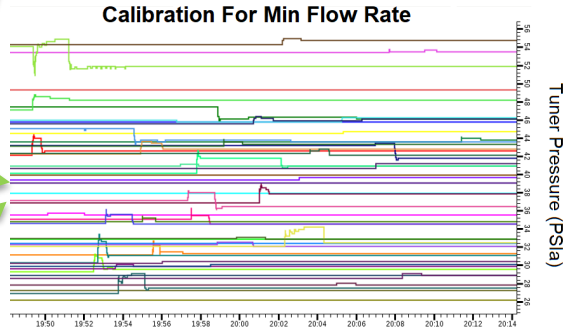


HWR Automation Improvement
Pneumatic Tuner Valve Calibration

- Necessity of pneumatic tuner valve automatic calibration
  - Critical to HWR cavity automatic turn-on and tuner performance
  - Manual calibration by expert takes 3 min per valve, 440 valves must be calibrated to run the 220 HWRs
- Automation significantly reduces the time cost
  - Calibrate valves in parallel
  - Manual calibration of 440 valves takes **3 person-days** of SRF expert effort; reduced to **2 hours** of machine effort



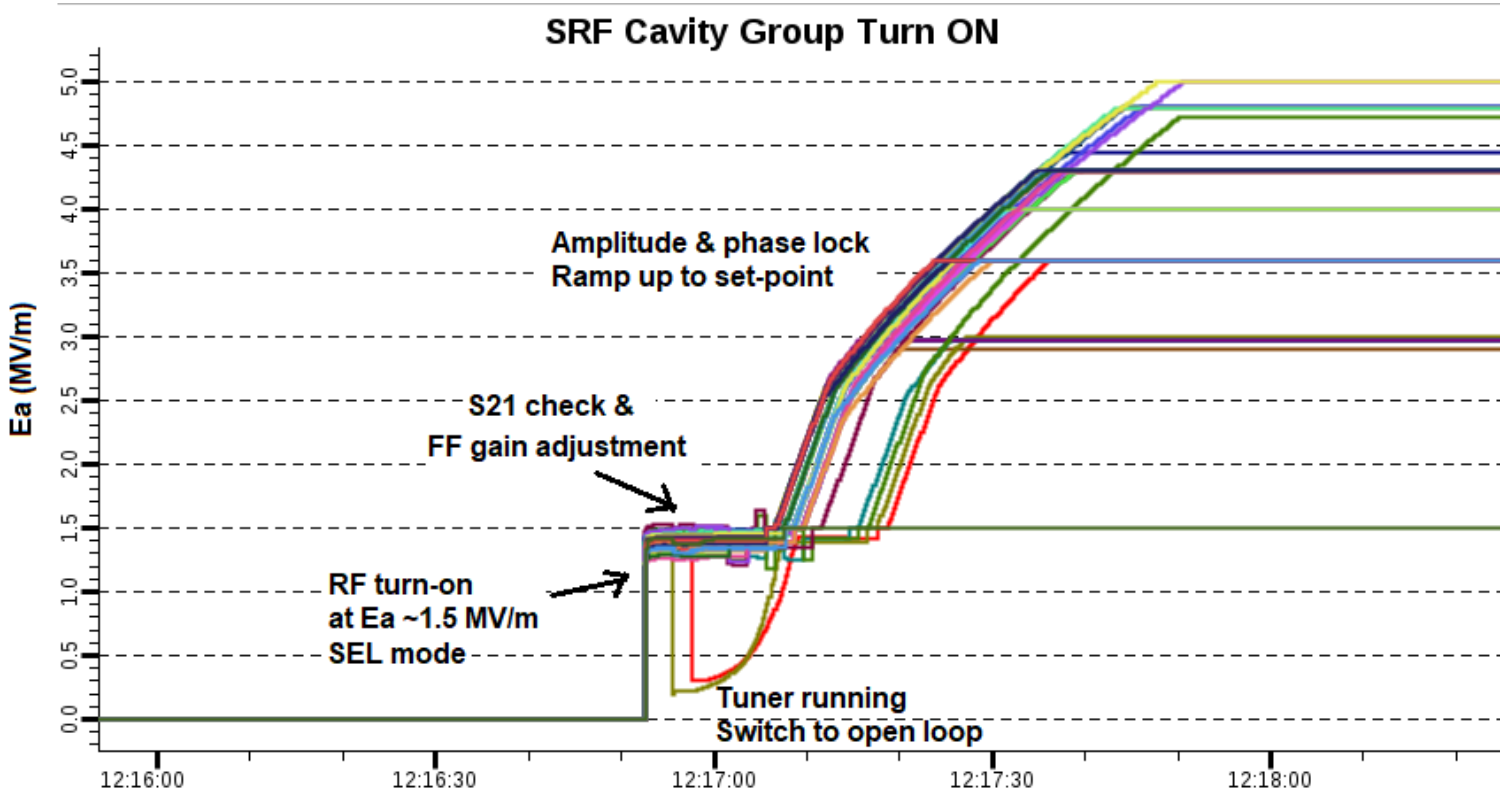




Calibration for all valves:
1 hour for 'Open Voltage', 1 hour for 'Close Voltage'

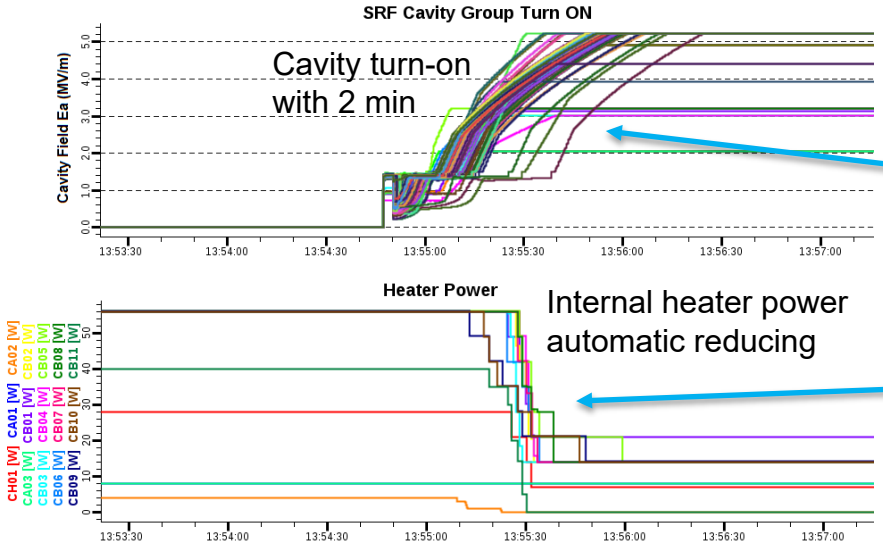
SRF Cavity Group Auto Turn-on

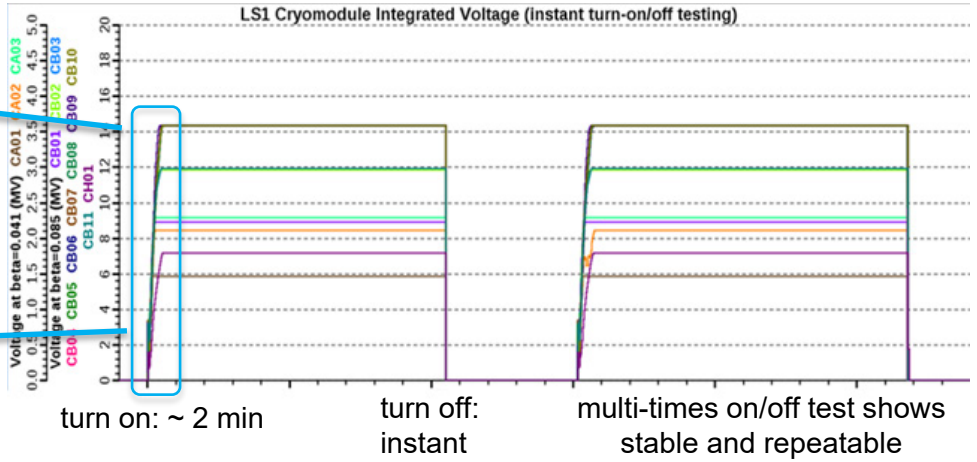
- SRF cavities be turned on by three group (LS1, LS2 & LS3)
  - Cavities in each group is able to be turned on within ~2 minutes



Cavity Dynamic Heat Load Auto Compensation

- Cavity fast turn-on/off with cavity auto-start and heater power auto compensation
  - Heater power configuration determined by AP, SRF and Cryo. and tested in commissioning
  - Available for FSEE (FRIB Single Event Effects) quick tunnel access (access tunnel four or five times a day)
    - »All 104 QWRs can be turned on in **2 minutes** and turned off in **2 seconds**

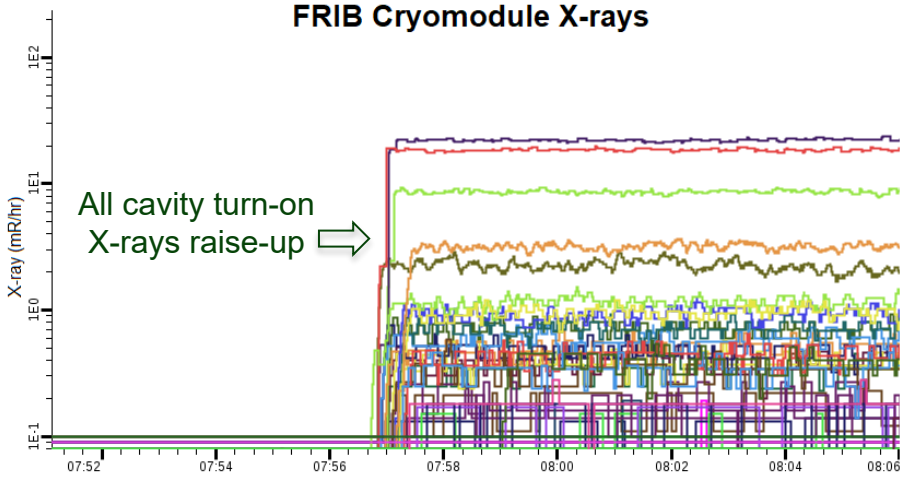


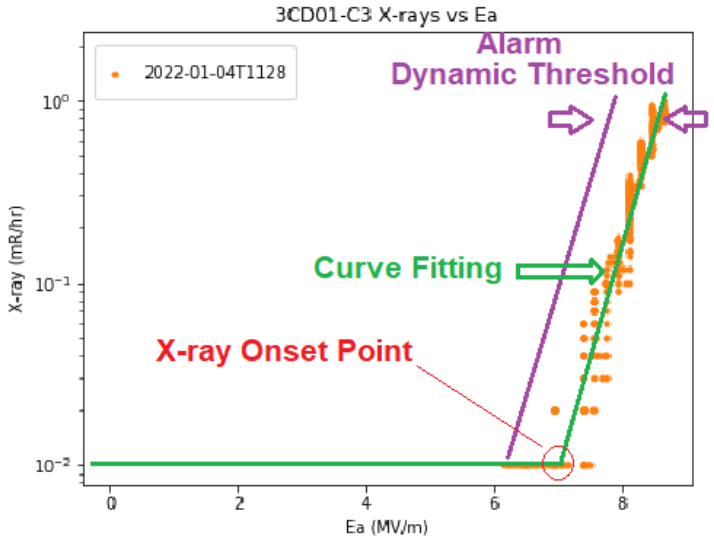


Improved from the previous ~1 hour turn-on

FE X-rays On-line Monitor/Alarm

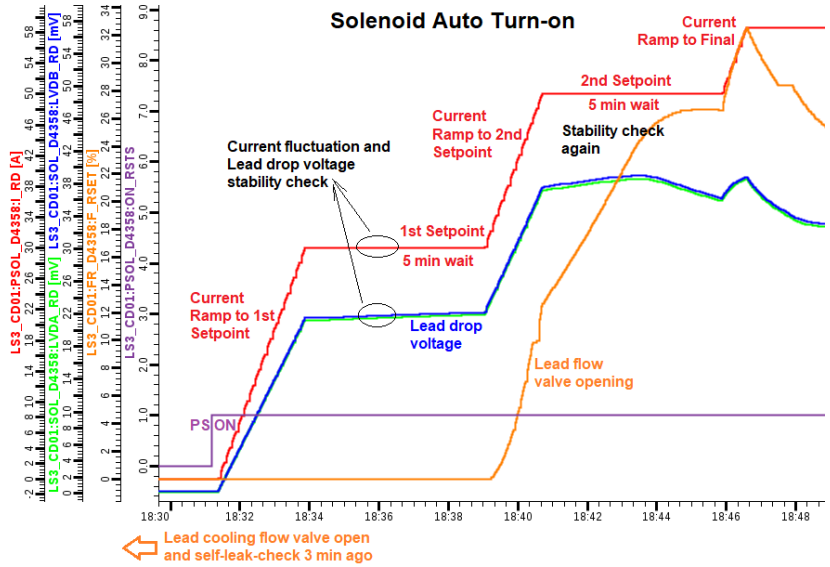
- X-ray sensors installed on all 46 cryomodules
  - 2 sensors for each cryomodule (upstream & downstream) to track FE cavity performance
  - Monitor X-ray jump event and send out alarm
  - Fixed threshold for current alarm setting
  - Dynamic threshold settings for future
    - »Curve fitting based on FE cavity X-ray vs field scan data
    - »New alarms will match with different cavity at different fields

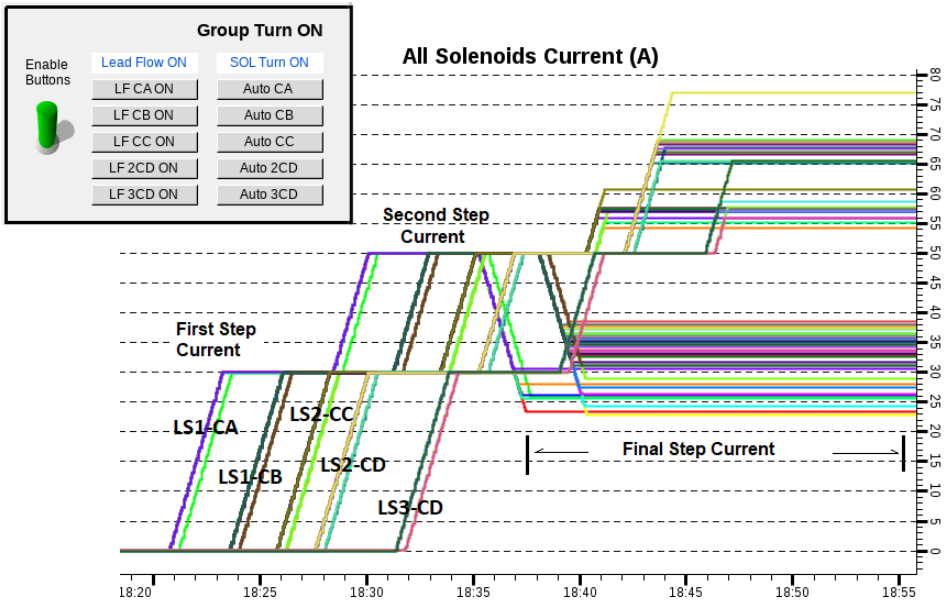




Solenoid Auto Turn-on

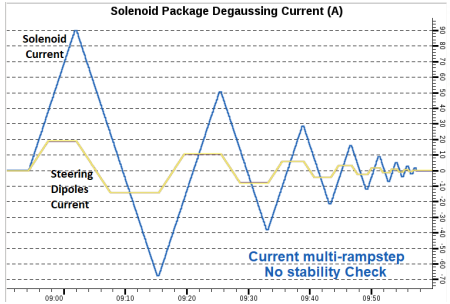
- Single solenoid auto start
  - Three steps current ramp-up with stability check for turn on procedure
- Five group turn-on implemented for 69 solenoid packages
  - All solenoid packages done with ramp-up and stability check within 30 minutes before the beam operation.

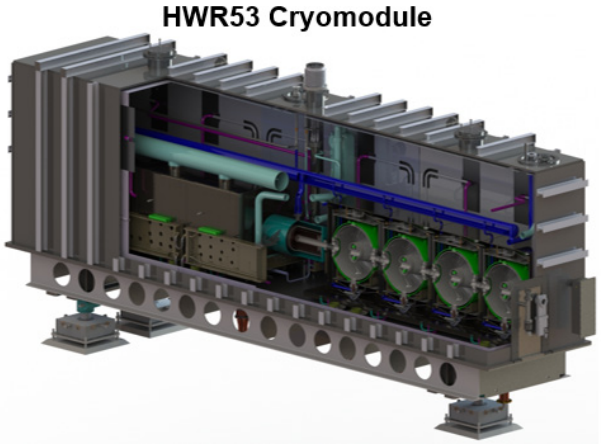


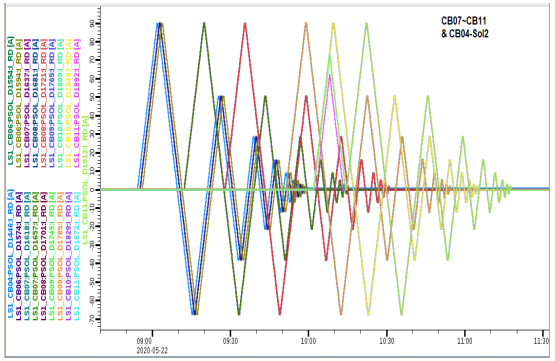


Solenoid Auto Degaussing

- Routine operation: degauss the solenoid prior to warm-up
  - Warm-up without degaussing observed 60% increase of the dynamic load.
  - Will establish an operation plan concerning about the unscheduled warm-up
- Fast run degaussing
  - One button automatic run multi-steps ramp on multi-solenoids

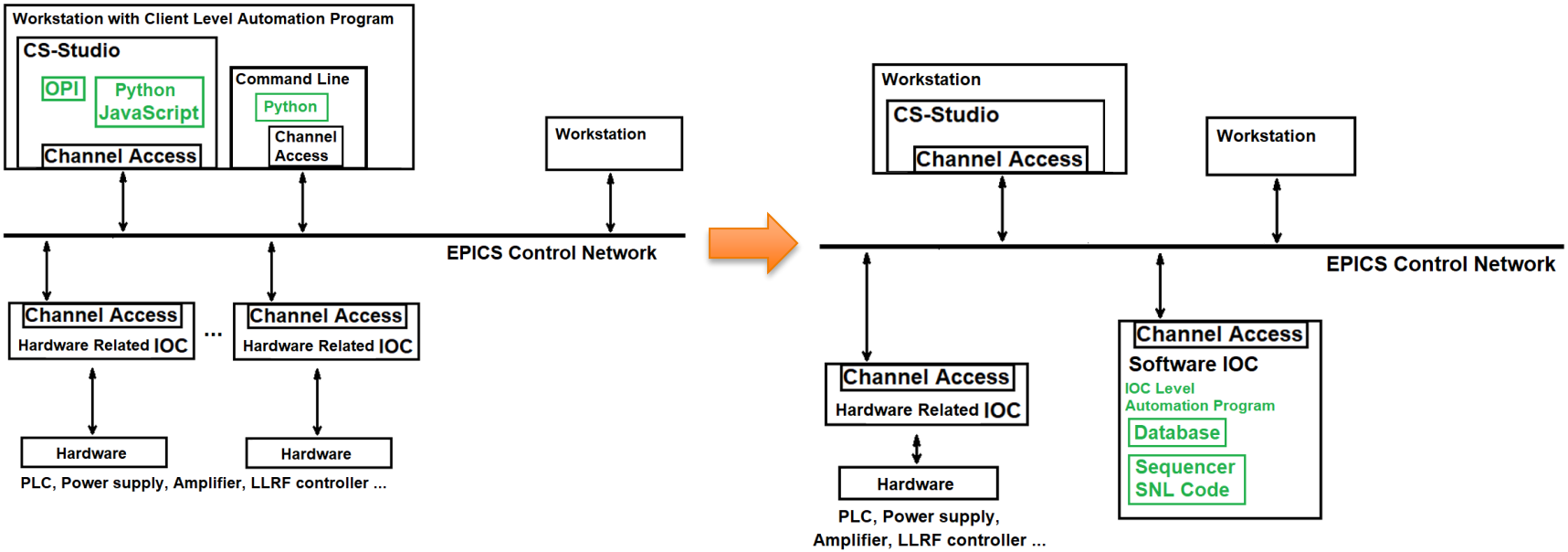






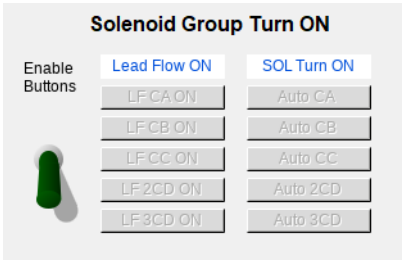
Automation Tools Implementation

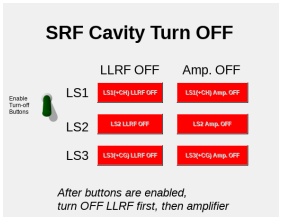
- Initial version “Client Level” scripts developed at the beginning
  - Easy to apply new changes (feedback from commissioning results)
- Final version automation programs are all transferred to “EPICS IOC Level”
  - More stable and reliable than client level machine
  - Access security control set limited permission for experts and operators

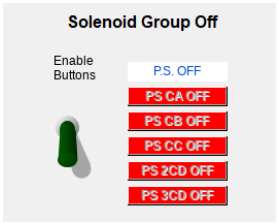


User Interface (UI) For Automation Tools

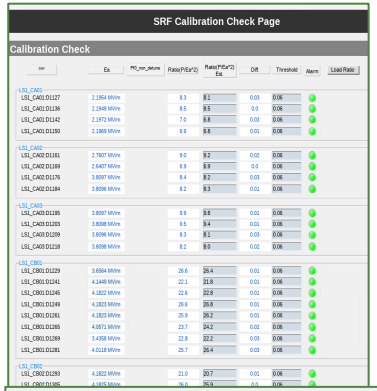
- Transition smoothly to operations
  - For operators: very simple UI, using friendly, minimized training effort
  - For experts: all details contained, available for single/multi/group device operation, easy for troubleshooting

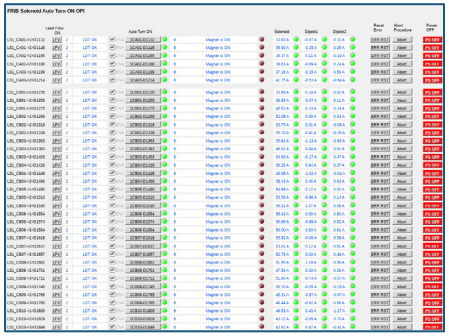


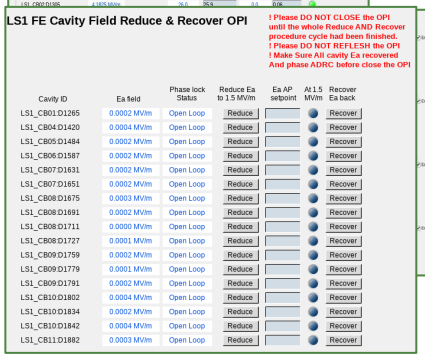




UI pages for operators





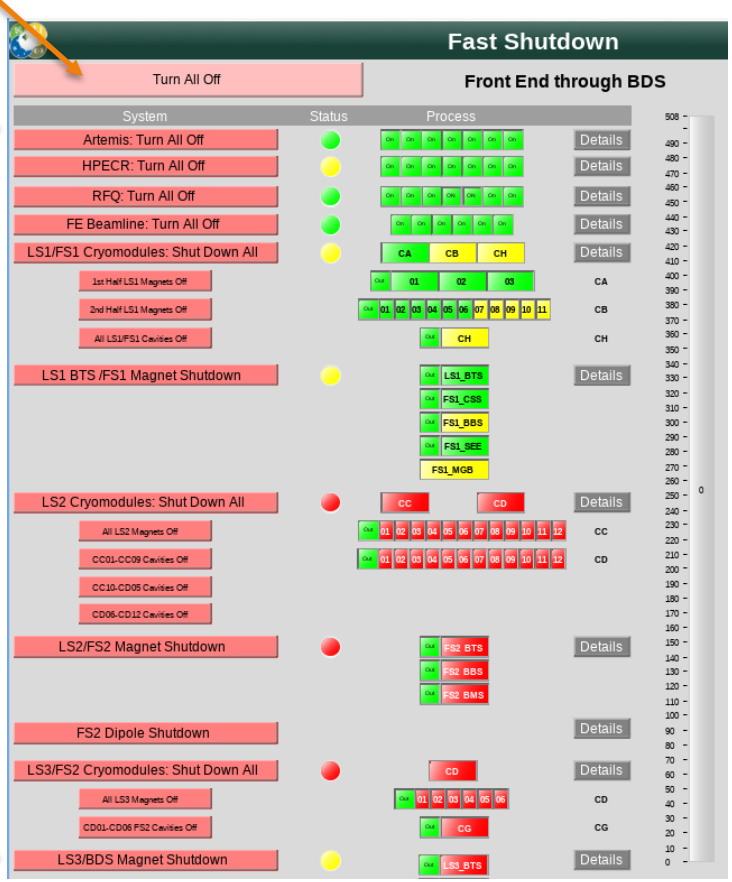


UI pages for experts

Emergency Shut-down

One button shut-down all devices

All devices status



- Protect machine when emergency event happen
  - Top level one button shut-down everything
  - SRF cavity and SC solenoid shut-down linked to top one button
    - »SRF cavity: turn off LLRF drive first, then amplifier
    - »SC solenoid: ramp down coil current to zero, waiting 10 s, turn off power supply, close lead cooling flow valve
  - All devices shut down through one click on Feb 13, 2023 MSU campus mass shooting

Summary

- Automation is essential for large scale superconducting devices operation. Automatic turn-on/off tools for FRIB SRF cavities and SC solenoid packages are implemented.
  - SRF cavity auto turn-on
    - »Internal heater power auto compensation
    - »Cavity field reduce and recover
    - »Pneumatic tuner auto calibration
  - Solenoid package auto turn-on, auto degaussing
  - Group fast turn-on 324 SRF cavities and 69 Solenoid packages (include solenoid degaussing execution)
  - Emergency one button fast shut-down
- Future automation tools will focus on machine high availability and reliability operation goal

Thanks for your attention!