Automation of RF and Cryomodule Operation at FRIB

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Team(s) Effort

- SRF and SC-magnet team
  - Ting Xu, John Popielarski, Walter Hartung, Sang-hoon Kim, Wei Chang
- Room temperature device owner
  - Haitao Ren
- RF team
  - Dan Morris, Tom Larter, Eleazar Gutierrez, myself and Shriraj Kunjir
- Control team
  - Evan Daykin, Enrique Bernal-Ruiz
- Previous team members
  - Nathan Usher, Harsh Maniar, Martin Konrad

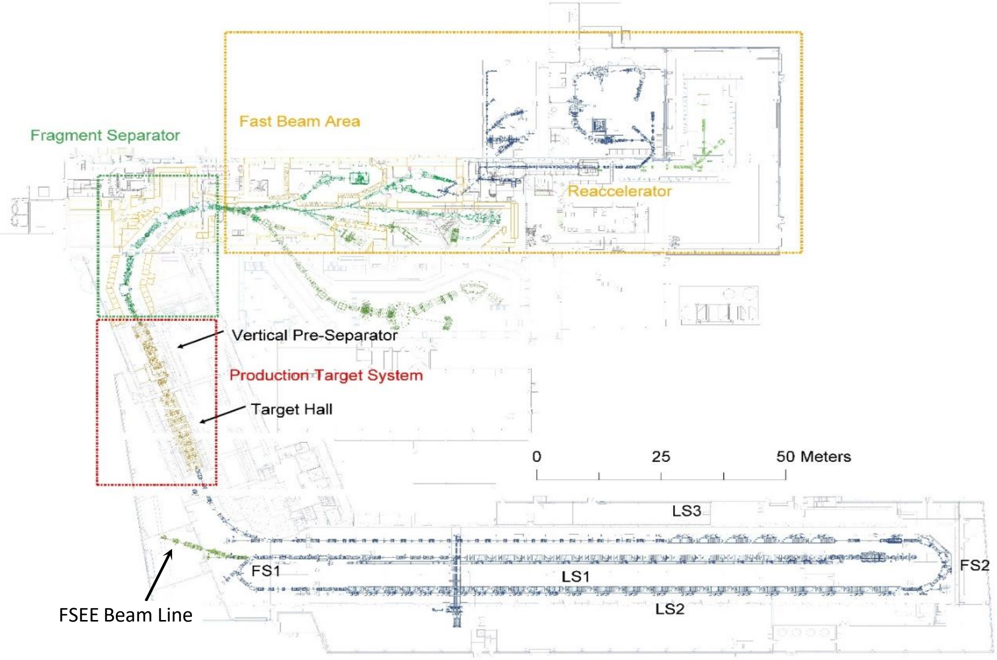
Outline

- FRIB introduction
- Why automation
- The evolution of automation at FRIB
- Automation examples
  - Device level
  - Facility level
- Implementation consideration
- Reflection and outlook
- Summary

Introduction

- Overview of FRIB project (A new heavy ion machine come online)
- Ribbon cutting (5/2)
- First user experiment (5/11-5/16)
- Second user experiment (6/15-6/21)

Beam energy: 200 MeV/u
Beam power: 400 kW



Why Automation

- Efficiency, productivity
  - Particularly import for large scale facilities
  - FRIB has more than 300 superconducting cavities and magnets
- Consistency, less human error
  - Human always makes mistake
- Faster response (compare to human)
  - Room temperature cavity fast recovery
- Experience of system experts is formalized into routines
- Free expert from routine work and more time for more creative work
- Reduce the level of training required for operators

Road Map of Automation

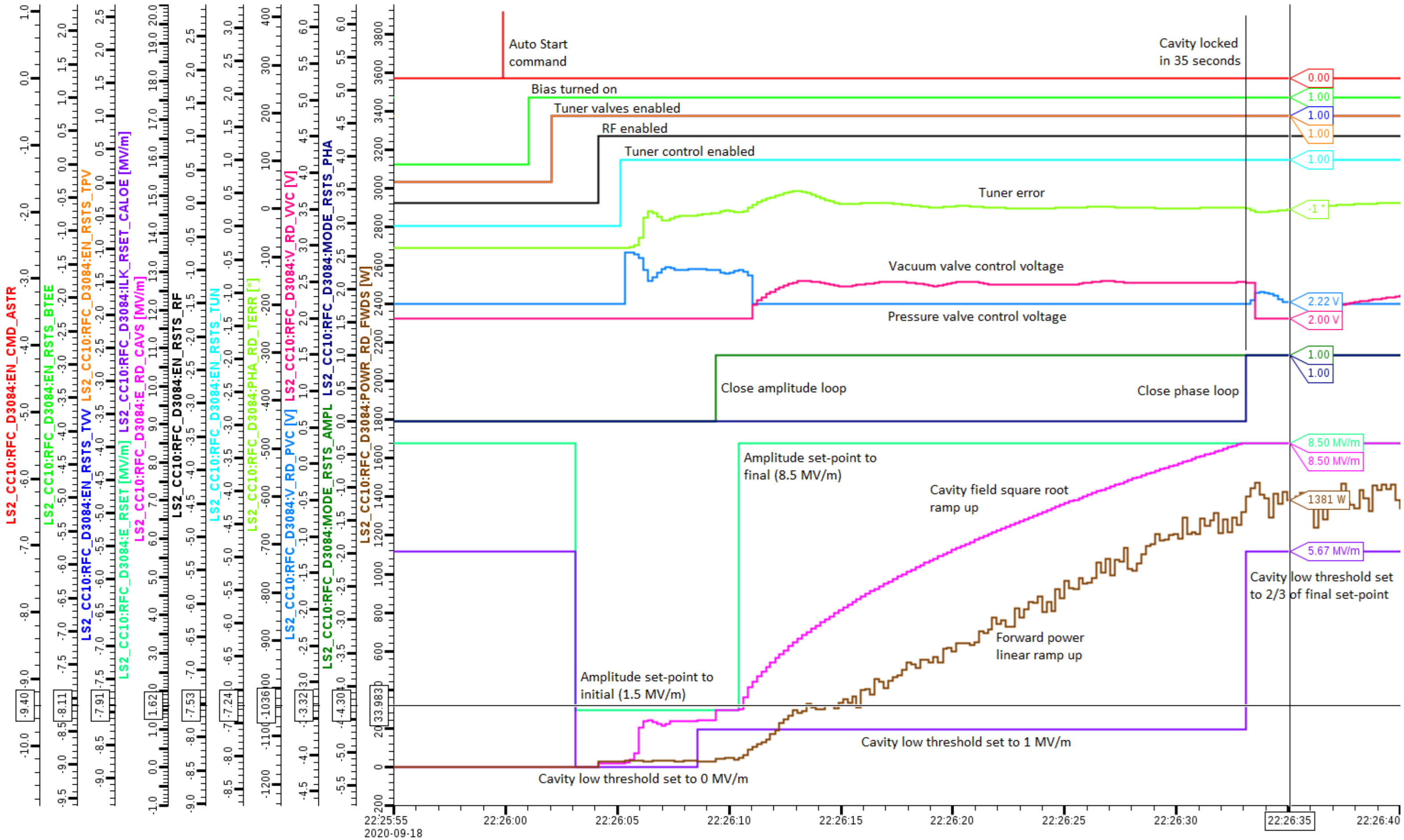
- Cavity auto-start
  - QWR -> RFQ -> MEBT -> MGB -> HWR (reduces turn on effort)
  - Fast recover for room temperature cavities (reduces downtime)

Cavity	Type	Tuner	Start-up Time	Complexity	Fast Recover
MHB	RT	N/A	< 30 s	low	< 30 s
MEBT	RT	2-phase	~ 3 min	medium	< 20 s
MGB	RT	5-phase	~ 10 min	medium	< 20 s
RFQ	RT	water	~ 45 min	high	< 20 s
QWR	SC	2-phase	< 60 s	medium	N/A
HWR	SC	pneumatic	< 60 s	medium	N/A

- Auto-off for cavities and magnets for emergency shut down
- Auto-start for magnets developed and deployed

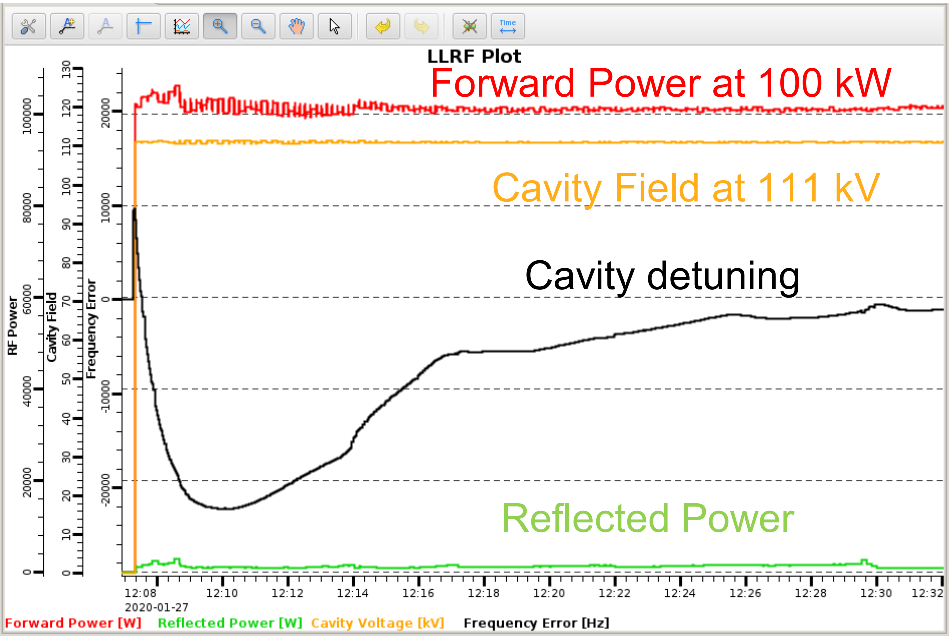
HWR Auto-start (Device Level)

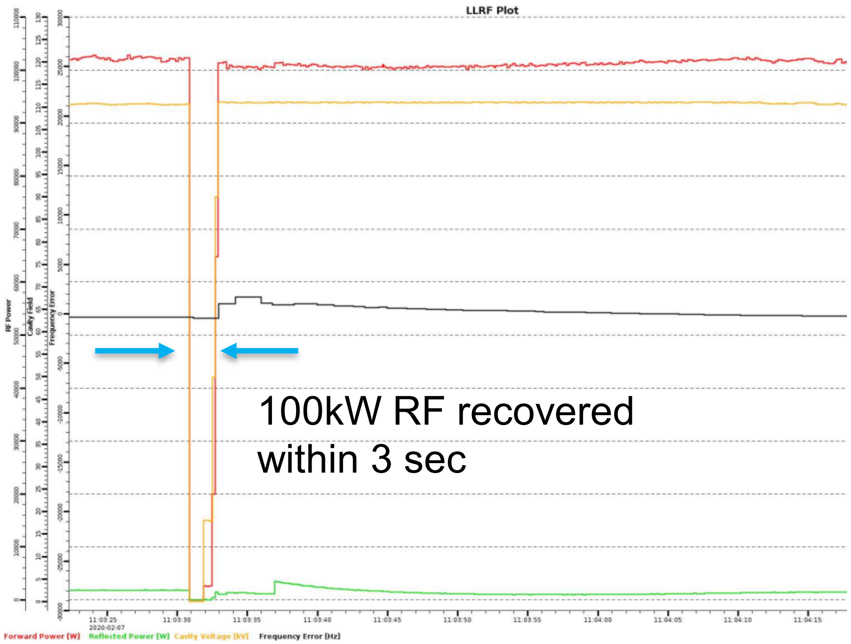
- One button turn on



RFQ (RT) Auto-start and Fast Recovery

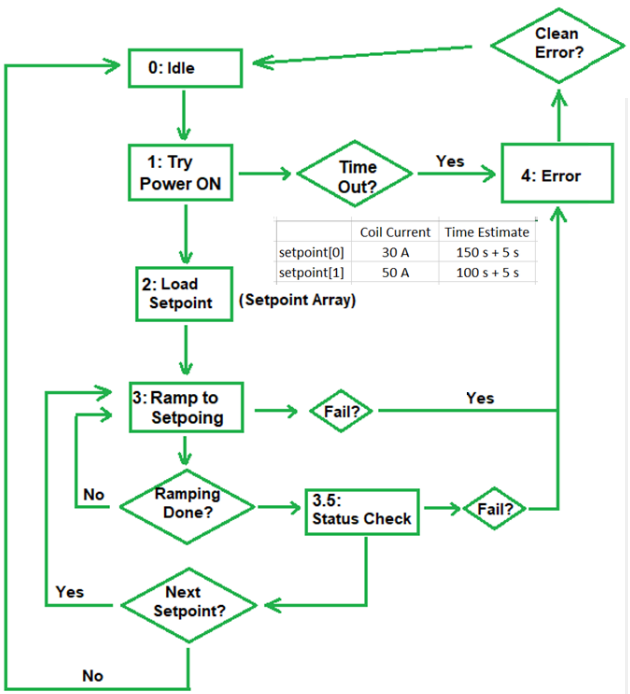
- Auto-start from cold condition to 100 kW CW
  - Ready for beam: 40 ~ 50 min
  - Maximum detuning: less than 30 kHz
  - Reflected power: 2 ~ 3 kW
- Fast recovery at 100 kW for S11 high or reflected power high trips
  - Power recover: within 3 sec (less than 3 kHz detune)
  - Ready for beam: ~ 10 sec

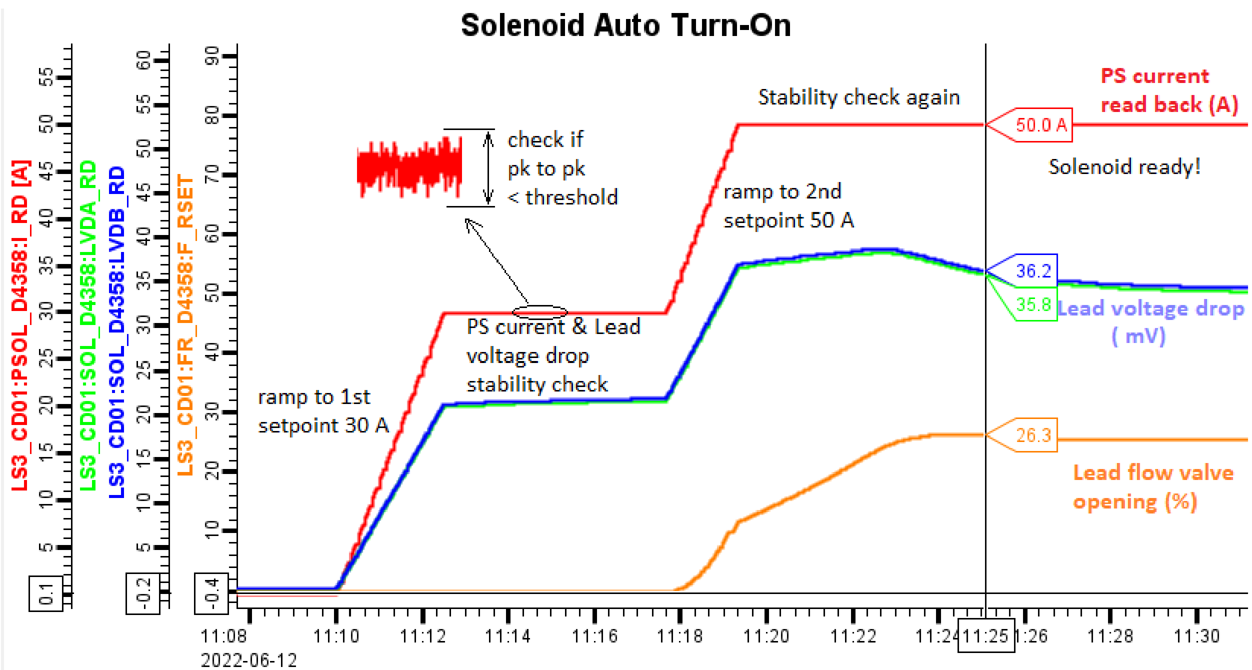




Solenoid Auto Start (Device Level)

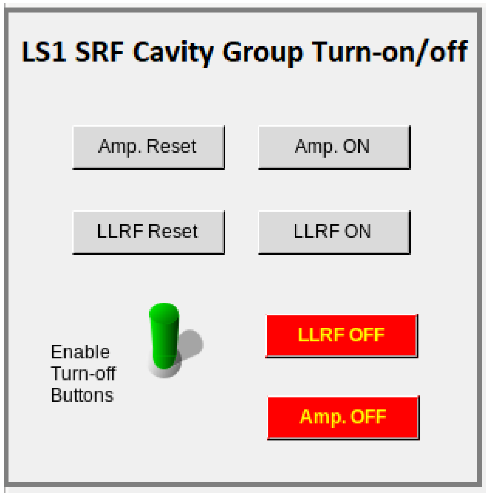
- One button turn on and stability auto check

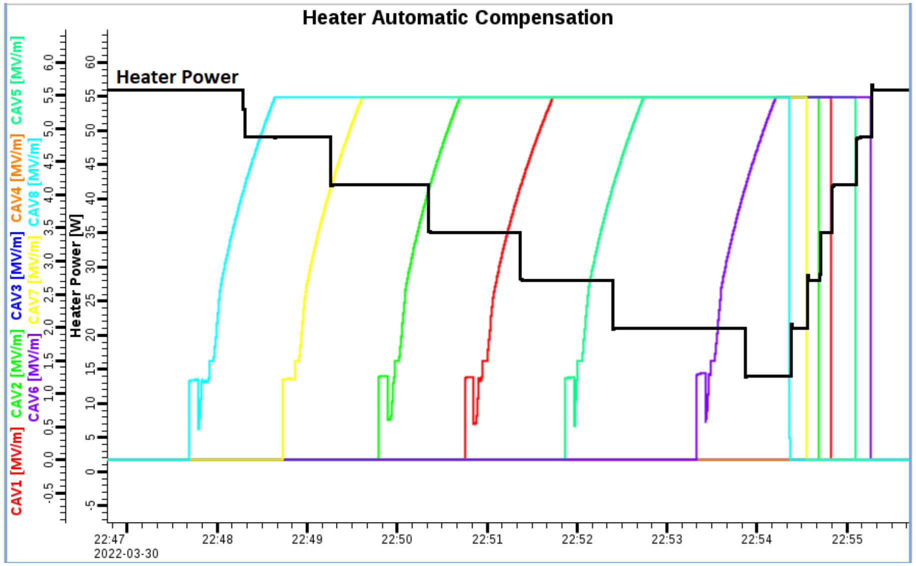


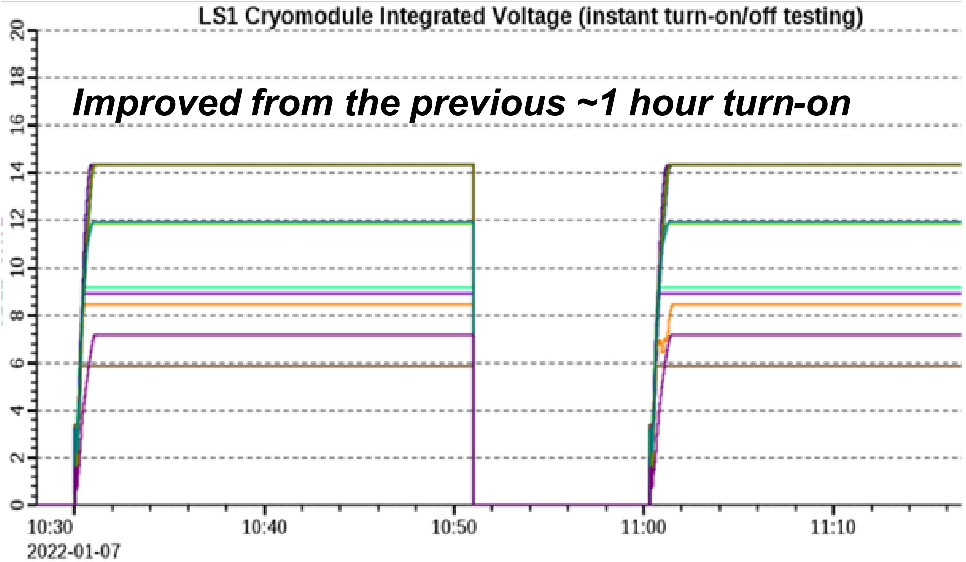


FRIB Single Event Effects (Facility Level)

- LS1 SRF cavities fast turn-on/off with cavity auto-start and heater power auto compensation
  - 104 QWRs
- Access tunnel four or five times a day (quick tunnel access)
  - Turn on: ~2 minutes; Turn off: ~2 seconds;

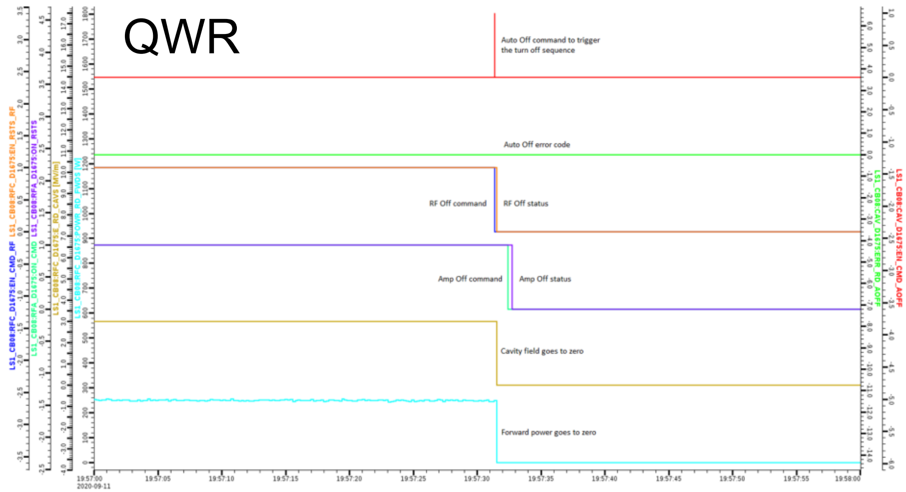


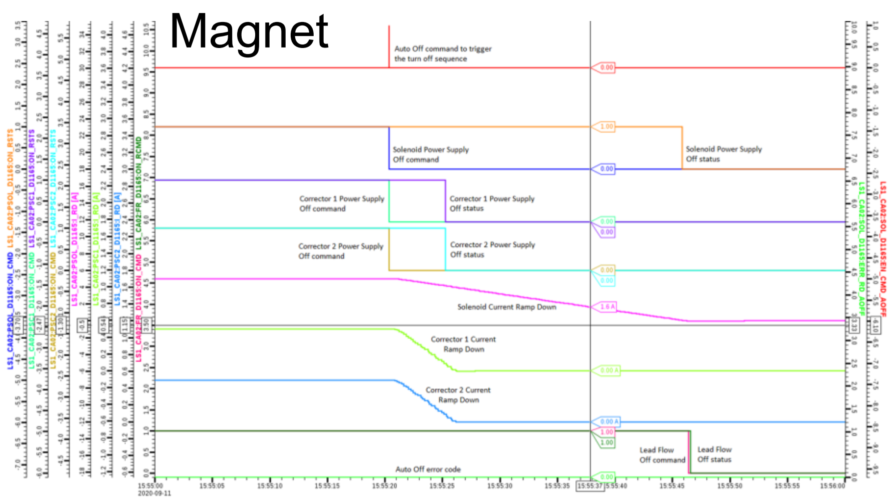


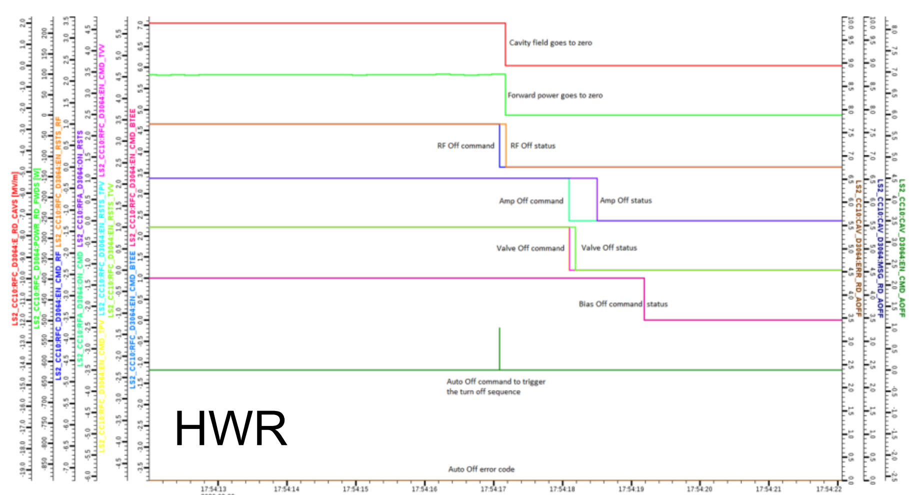


Auto-off for Emergency Shutdown

- For cryomodule
  - QWR
  - HWR
  - Magnet
- Turn off logic required
  - Lead flow has to be turned off only after all three power supply currents ramp to zero

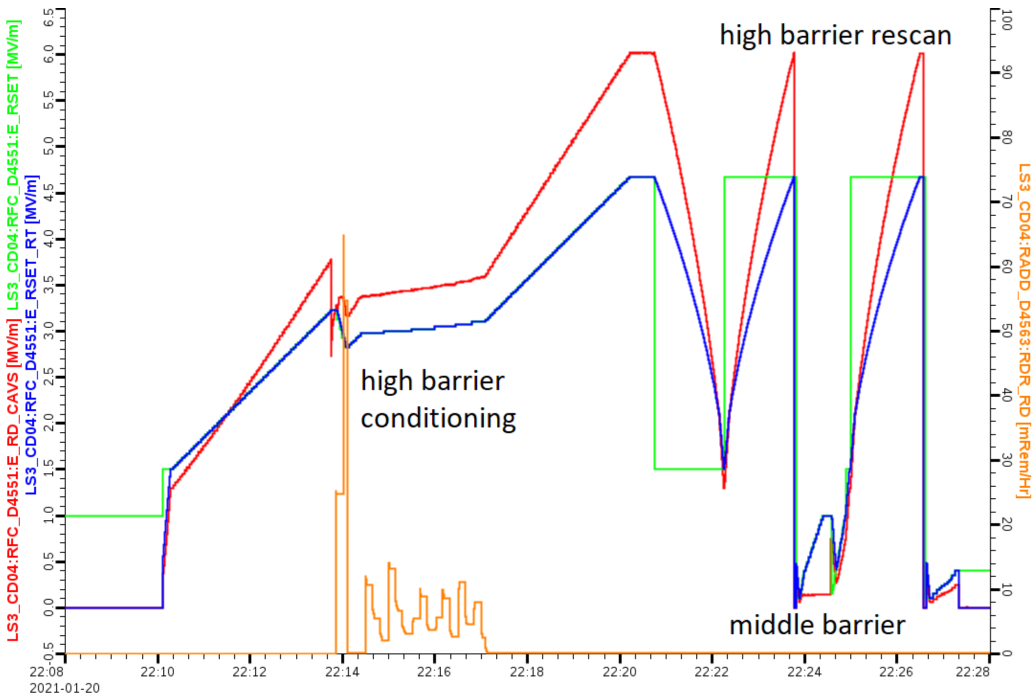






Other Examples (1)

- Automatic Multipacting Conditioning
  - Tested during LS3 SRF commissioning
  - Check for X-ray level while increasing power
  - Condition both high barrier and middle barrier
  - Rescan to confirm
  - Take 20 ~ 50 minutes depending on cavities



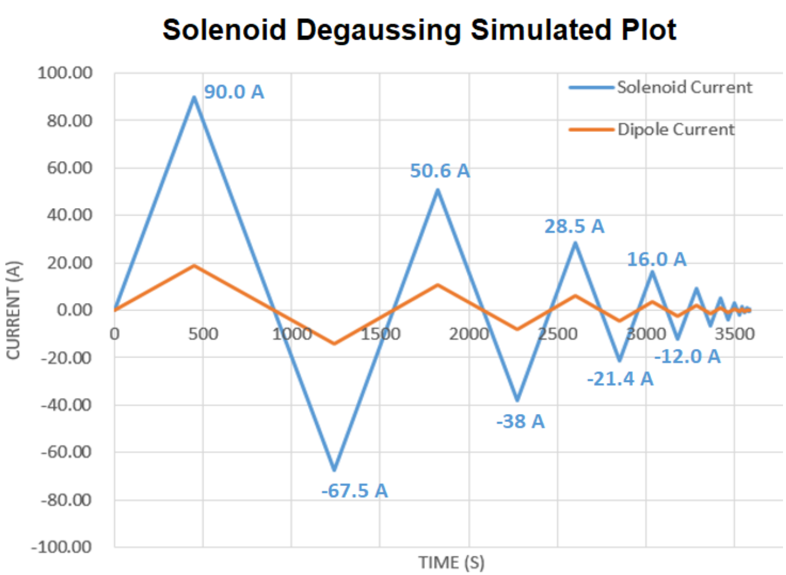
LS3CD04D4551 MP log.txt - Notepad

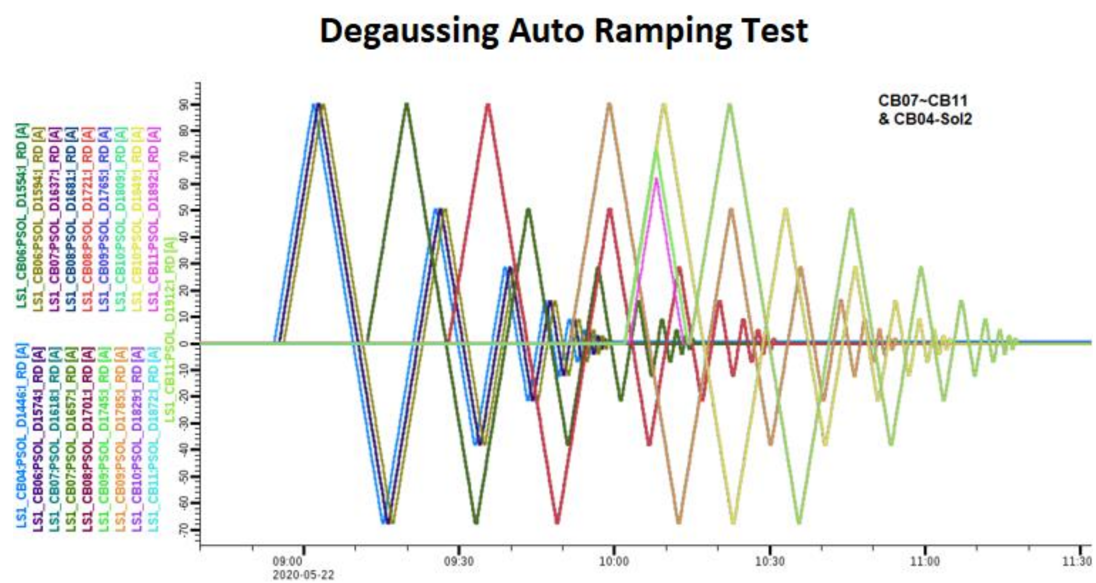
File Edit Format View Help

```
LS3_CD04:RFC_D4551

zhaos@work-ftc-r1632-02:~/Public/PythonScripts$ python3 MPCondition.py
Program starts at 1611198606.3604567:
Calibration is done! RevFwdRatio = 0.9210855333655896    CavFwdRatio = 0.018014993876237288
Current setpoint: 1.525 MV/m
Current setpoint: 1.5499999999999998 MV/m
Current setpoint: 1.5749999999999997 MV/m
Current setpoint: 1.5999999999999996 MV/m
Current setpoint: 1.6249999999999996 MV/m
Current setpoint: 1.6499999999999995 MV/m

Current setpoint: 3.174999999999994 MV/m
Current setpoint: 3.199999999999994 MV/m
Current setpoint: 3.224999999999994 MV/m
X-ray high, wait ...
X-ray high, wait ...
X-ray too high! Decrease amplitude setpoint, current setpoint: 3.124999999999994 MV/m
X-ray too high! Decrease amplitude setpoint, current setpoint: 3.0249999999999937 MV/m
X-ray too high! Decrease amplitude setpoint, current setpoint: 2.9249999999999936 MV/m
X-ray too high! Decrease amplitude setpoint, current setpoint: 2.8249999999999935 MV/m
X-ray high, wait ...
Current setpoint: 2.8499999999999934 MV/m
Current setpoint: 2.8749999999999933 MV/m
Current setpoint: 2.8999999999999932 MV/m
Current setpoint: 2.924999999999993 MV/m
Current setpoint: 2.949999999999993 MV/m
Current setpoint: 2.974999999999993 MV/m
X-ray high, wait ...
X-ray high, wait ...
X-ray high, wait ...
X-ray high, wait ...
X-ray high, wait ...
X-ray high, wait ...
X-ray high, wait ...
X-ray high, wait ...
X-ray high, wait ...
Current setpoint: 2.999999999999993 MV/m
X-ray high, wait ...
X-ray high, wait ...

Current setpoint: 4.5749999999999975 MV/m
Current setpoint: 4.599999999999998 MV/m
Current setpoint: 4.624999999999998 MV/m
Current setpoint: 4.649999999999999 MV/m
Current setpoint: 4.674999999999999 MV/m
High barrier conditioned
High barrier rescaned
Middle barrier found
Middle barrier conditioned
Middle barrier not found
```

Other Examples (2)

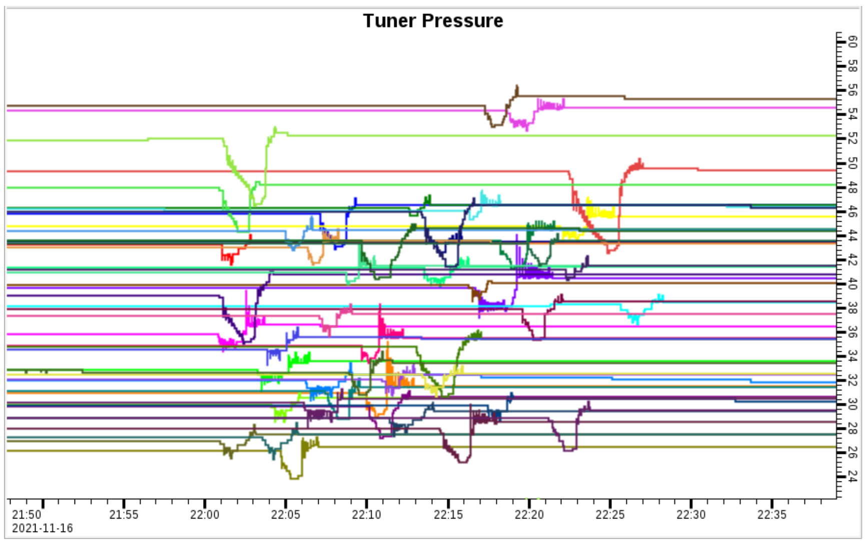
- Solenoid Auto Degaussing
  - Can run in parallel for multiple solenoids
  - Ramp up to maximum current, then each step ramp the set-point to reversed current as 75% amplitude as the last set-point until the current set-point below 1 A.
  - Auto ramping and check status for 16 set-points
  - Run 69 solenoids at the same time by group start button



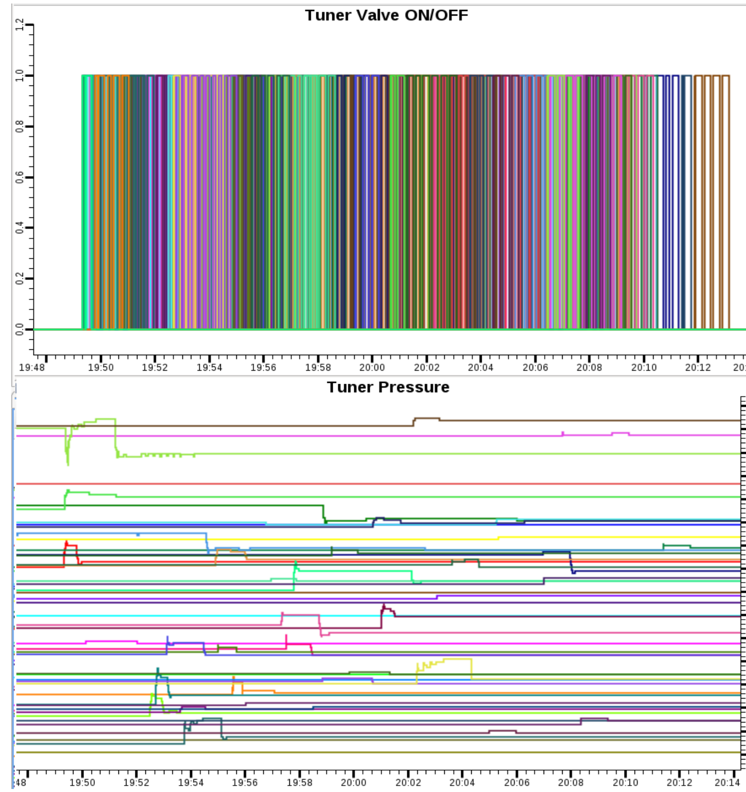


Other Examples (3)

- Pneumatic Tuner Valve Calibration
  - Automation significantly reduces the time cost
  - Calibrate valves within a cryomodule sequentially, but do all cryomodules in parallel
  - Manual calibration of 440 valves takes **3 person-days** of SRF expert effort; reduced to **2 hours** of machine effort



‘Open’ voltage calibration for all valves: 1 hour



‘Close’ voltage calibration for all valves: 1 hour

Implementation Consideration

- Python
  - Advantage: flexible, quick iteration
  - Disadvantage: prone to mistake, subject to access control
  - Use case: prototype or read-only operation
- IOC
  - Advantage: resolve access control issue, rigorous procedure for deployment
  - Disadvantage: prone to mistake, subject to access control
  - Use case: final implementation or constant monitoring in the background
- LLRF software
  - Feedforward phase auto adjustment for room temperature devices
    - » Was done in IOC, better in
    - » Removed complexity to deal with network delay
    - » 30 lines of code in software, 60 lines in IOC
    - » 20 Hz vs 0.2 to 0.5 Hz

Reflection and Outlook

- Looking back
  - Should start automation as early as possible
    - » HWR auto-start
    - » MP conditioning
- Looking forward
  - System debugging process needs to be automated to minimize down time
  - Trip report button (Python)
    - » Give a snapshot of the event and provide recommended actions
    - » Reset and restart,
    - » Potential hardware failure
  - Cryo-module health monitoring (IOC)
    - » Couple temperature, He level, X-ray level, etc.
  - Maintenance tasks
    - » Firmware/software update
    - » Pre-run checking
  - Data analysis: trends, predict failure, statistics

Summary

- Motivation for automation
  - Naturally strong for large scale facilities
- Examples of automation at FRIB
  - Device level
    - » Cavity auto start
    - » RT cavity fast recovery
    - » Solenoid auto start
  - Facility level
    - » FSEE operation
- Implementation consideration
  - Pros and cons of different implementation approaches
- Future tasks
  - Troubleshooting
  - Health monitoring

Questions and Comments

Thanks for your attention!