



FRIB

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

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MICHIGAN STATE
UNIVERSITY



U.S. DEPARTMENT OF
ENERGY

Office of
Science

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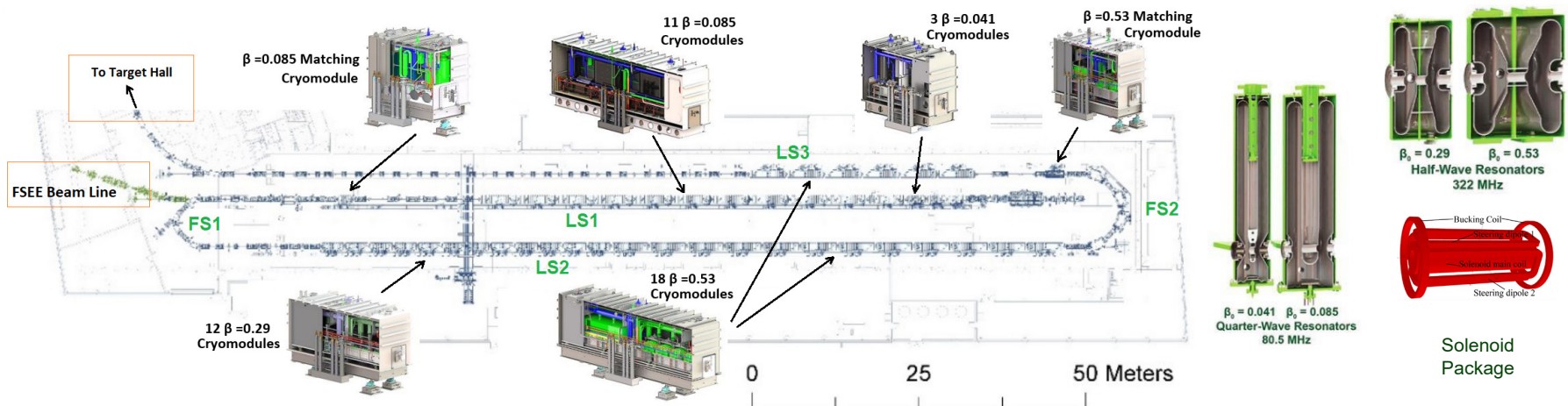
Outline

- 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



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

Bitbucket Projects Repository

Commits

Author	Commit	Message
laser/Dev	4843481230	Full request #32 Master Merge in CRDC
Chang, Wei	3003066440	edit makefile in src folder
Chang, Wei	2518842197	Full request #20 add to-magnet shut-down
Chang, Wei	0448111596	add to-magnet shut-down
laser/Dev	37841281749	Full request #28 fix to-magnet line 106-51024
Chang, Wei	382808467	fix to-magnet line 106-51024+51
laser/Dev	2768168772	Full request #27 fix to-do files, update to the
Chang, Wei	2152807543	fix do files, update to the correct version
laser/Dev	8950128199	Full request #26 merge the correct files &
Chang, Wei	8FF921616C	merge the correct files
laser/Dev	7F42925534	Full request #25 fix error message in CRDC
Chang, Wei	7F42925534	fix error
laser/Dev	8012926199	Full request #24 Master Merge in CRDC
Chang, Wei	6818425877	add gate valve close

Precool instructions for LS2 cryomodules:

Cryomodule Slot: _____ CM SN: _____

#	Item	Initial	Date
1	Review all requests and NCR		
2	Review test data, add information to commissioning spreadsheet, include notes about sensor issues or leaks		
3	Before cool-down, record the following bunker test information in the spreadsheet		
4	Cavity & coupler temperatures (check PVI), what was already static temperature in bunker test?		
5	Coupler interlock settings		
6	Insulating Pressure (if vented do not turn on gauge)		
7	Coupler Press		
8	Beamline Press		
9	Bellevue press		
10	calibrated 1S1		
11	calibrated 1S2		
12	Visual inspect		
13	All CCG SHV ps		
14	Caps on all sps		
15	Rust on coupler		
16	Control Room		
17	Make cool-down		
18	archive add st		
19	Make RF plot		
20	Warm Calibra		
21	Check cavity		

Parameter	02945	02949	02954	02955	02969	02974
Pressure	529-056	529-058	529-051	529-048	529-049	529-052
Count Rate						

Parameter	02945	02949	02954	02955	02969	02974
Temperature (K)	-93.00	-93.00	-93.07	-93.00	-93.00	-93.00
Pressure (Pa)	59.23	-93.07	-93.02	-93.07	-93.07	-93.03
Count Rate (cps)	14.20	14.20	14.40	14.70	14.20	14.20
Pressure (Pa) (looking back)	-92.89	-93.92	-93.04	-93.24	-93.41	-93.20
Pressure (Pa) (looking back)	-93.05	-93.05	-93.86	-93.86	-93.86	-93.86
Pressure (Pa) (looking back)	39.00	30.86	-93.54	-93.20	32.56	34.25
Count Rate (cps)	-0.41	0.00	0.00	-0.01	-0.01	-0.01
Pressure (Pa)	-1.06	-1.02	-1.00	-1.09	-0.96	-0.91
Pressure (Pa) (with jump)	-46.58	-47.87	-46.23	-47.80	-47.29	-45.86
Count Rate (cps)	97.24	98.00	95.89	96.40	97.00	96.32

Parameter	02945	02949	02954	02955	02969	02974
Temperature (K)	3.710109	3.381008	4.170101	4.099101	3.737106	4.069101
Pressure (Pa)	1.195111	1.344111	1.294111	1.711111	1.474111	1.474111
Count Rate	61.7	60.1	62.1	64.1	60.1	64.1
Pressure (Pa)	65.6	64.7	62.2	70.3	65.1	77.0
Temperature (K)	-0.018	-0.014	-0.008	-0.002	-0.008	-0.006
Pressure (Pa)	-0.120	-0.120	-0.200	-0.200	-0.000	-0.000
Pressure (Pa)	-38.47	-38.48	-38.41	-39.21	-38.11	-39.11

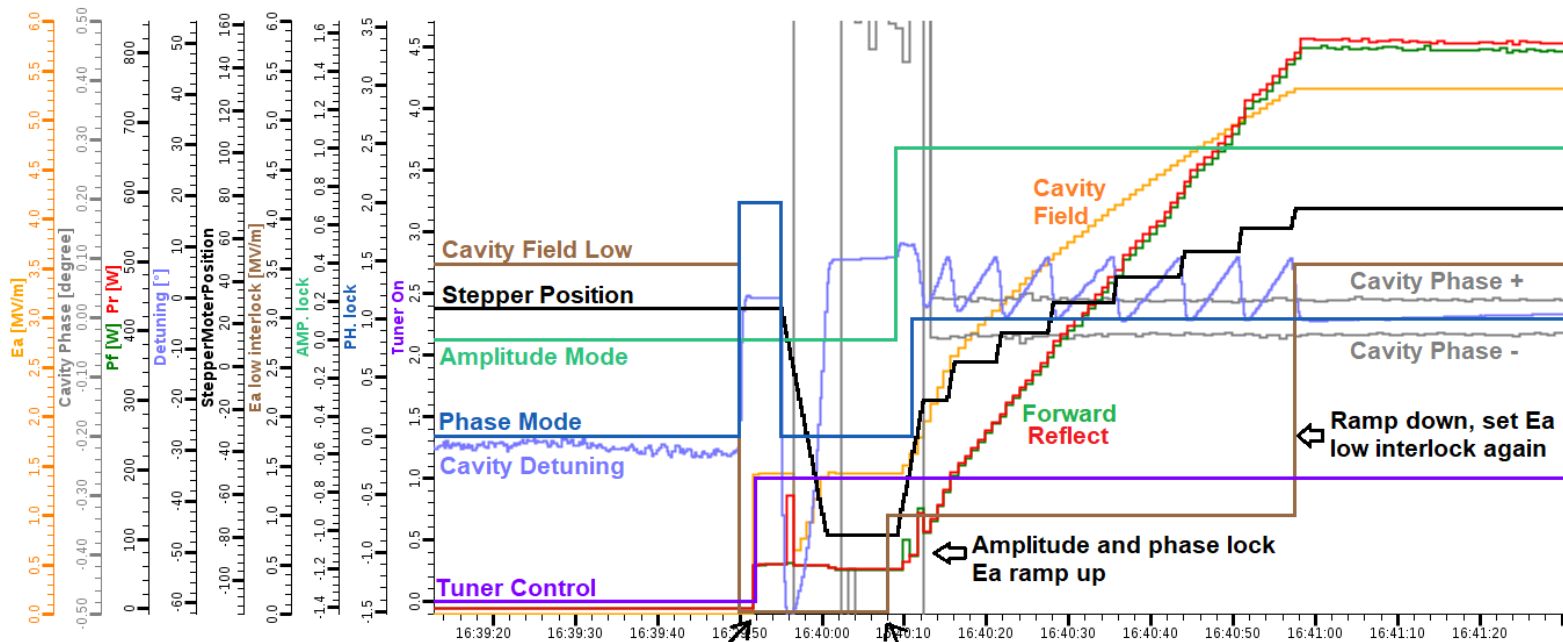
Parameter	61.0	60.9	64.4	67.2	69.0	77.0
Temperature (K)	63.0	63.1	64.4	67.2	69.0	77.0
Pressure (Pa)	63.0	63.1	64.4	67.2	69.0	77.0
Count Rate	63.0	60.8	71.6	65.3	69.0	75.0
Pressure (Pa)	-98.00	-98.99	-98.98	-99.00	-98.92	-99.00
Pressure (Pa)	-0.029	-0.006	-0.000	-0.009	-0.017	-0.012
Count Rate	-0.728	-0.698	-0.871	-0.747	-0.657	-0.613
Temperature (K)	3.288106	3.516106	3.600106	4.706106	3.116106	3.086106
Pressure (Pa)	1.295111	1.511111	1.511111	1.511111	1.416111	1.272111
Count Rate	5.111106	5.202106	4.938106	5.211106	4.996106	4.916106
Pressure (Pa)	1.499	1.416	1.499	1.206	1.499	1.499
Count Rate	5.495	5.456	5.456	5.456	5.381	5.422
Pressure (Pa)	889.893	886.204	892.524	886.584	889.498	875.216
Count Rate	832.146	869.214	863.561	868.913	888.003	884.861
Pressure (Pa)	42.5	42.5	32.2	42.7	31.5	31.5
Temperature (K)	-1.5	+1.8	1.00	1.80	0.88	2.30
Pressure (Pa)	3.40	3.40	3.40	3.40	3.50	3.40
Pressure (Pa)	5.07	5.70	6.80	2.41	5.40	5.00



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

QWR Cavity Auto Turn-on



RF turn-on at Ea ~1.5 MV/m
 Amplitude open mode
 Phase SEL mode
 S21 Check, FF gain adjust

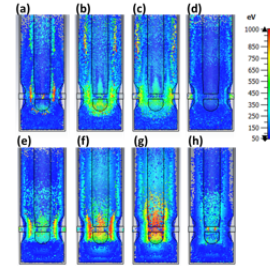
Tuner control on
 Phase open mode
 Set Ea low interlock

LS1 QWR Fast Recover From Trip

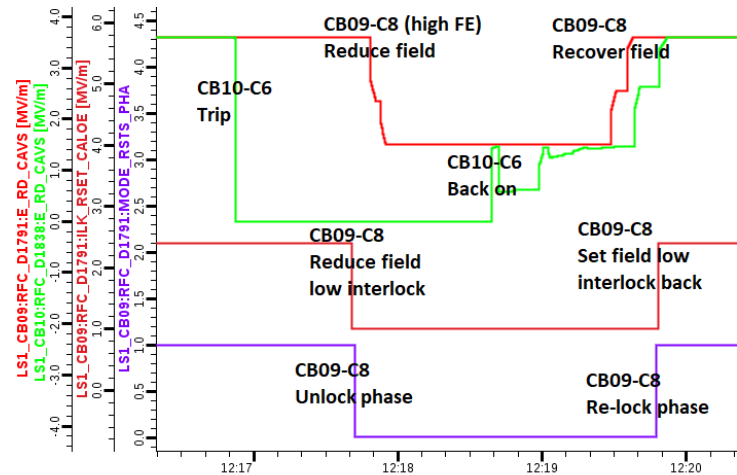
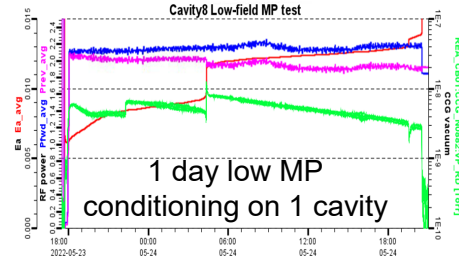
Auto Procedure Help Low Multipacting Barrier Jump Through

- 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



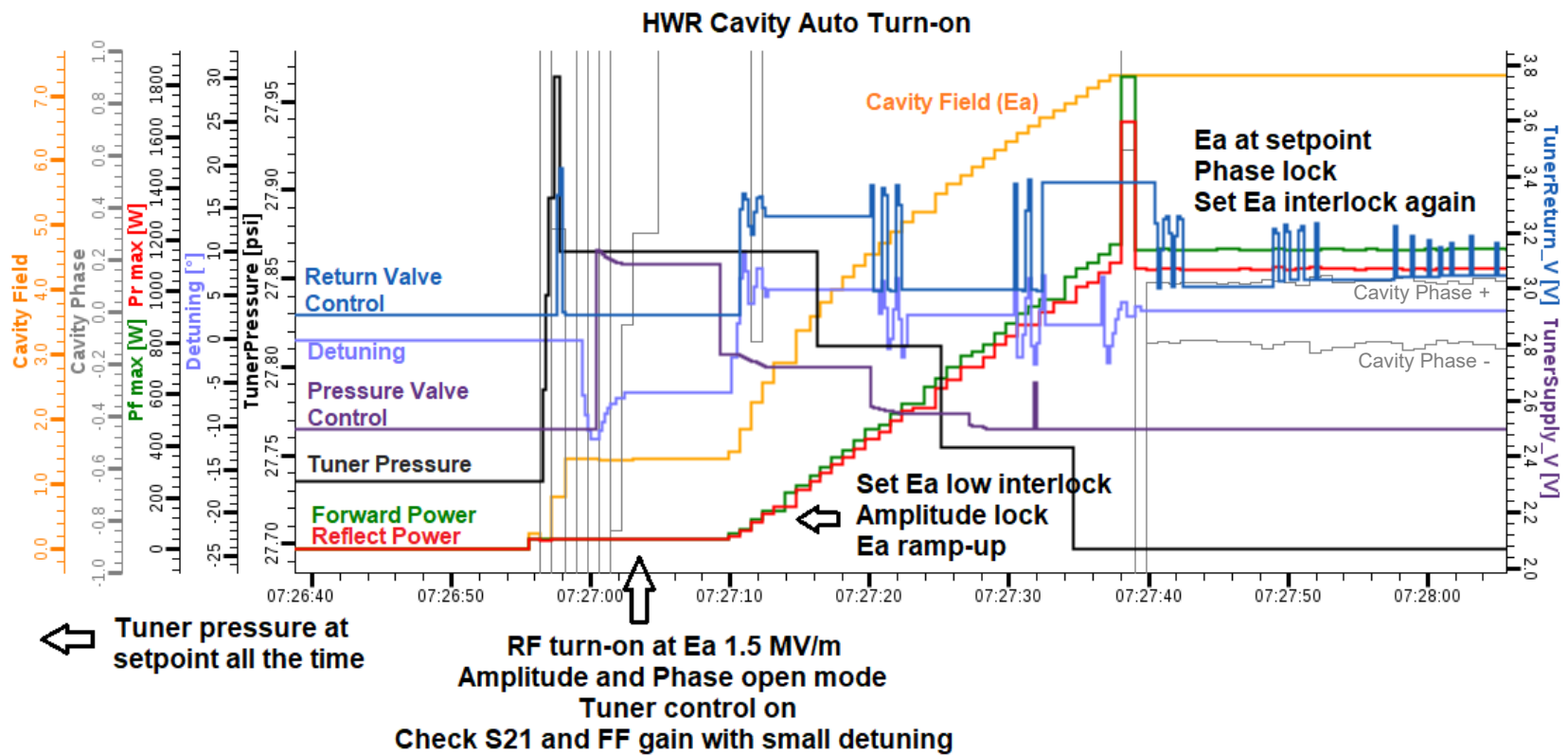
S. Kim, NAPAC'22



- 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

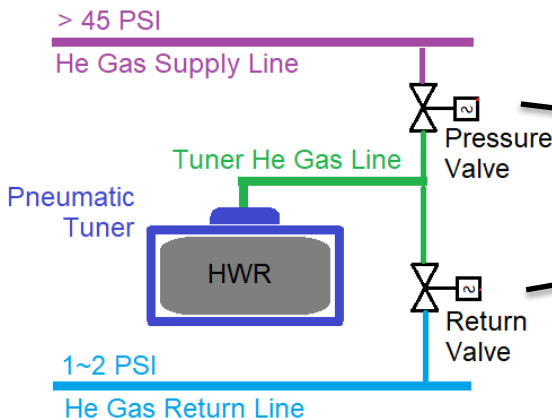
- Tuner valves control the tuner pressure at set-point before RF on
- Open loop mode for initial start then tuner run cavity to the center to do S21 check, FF gain adjust, amplitude lock and ramp-up



HWR Automation Improvement

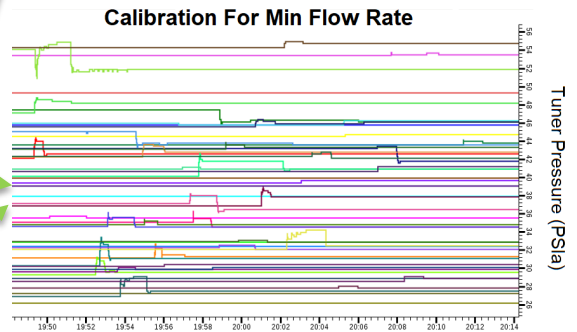
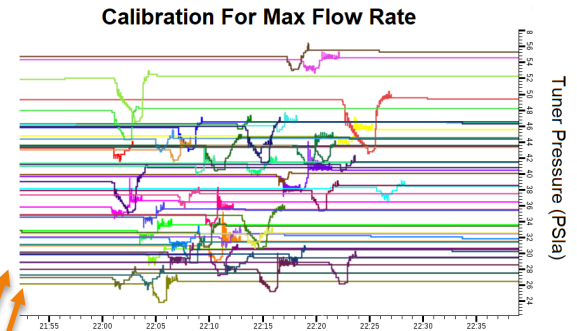
Pneumatic Tuner Valve Calibration

- 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



One HWR with Two Valves

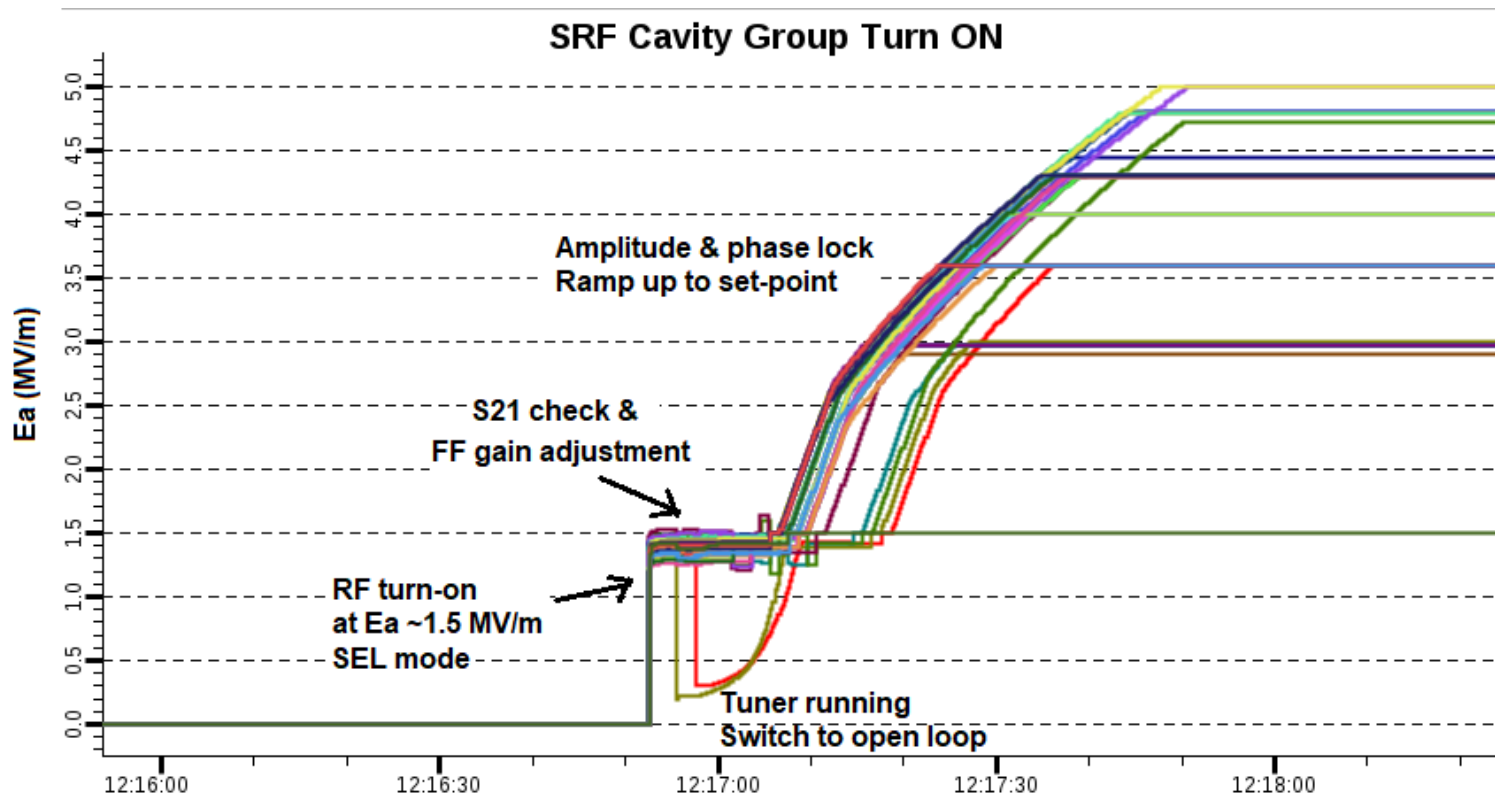
Tuner Pressure	35.7008 psi
Pressure Valve	<input type="button" value="Enable"/> <input type="button" value="Disable"/>
Pressure Valve Open Voltage	3.308 V
Pressure Valve Close Voltage	2.498 V
Vacuum Valve	<input type="button" value="Enable"/> <input type="button" value="Disable"/>
Vacuum Valve Open Voltage	2.640 V
Vacuum Valve Close Voltage	1.810 V



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

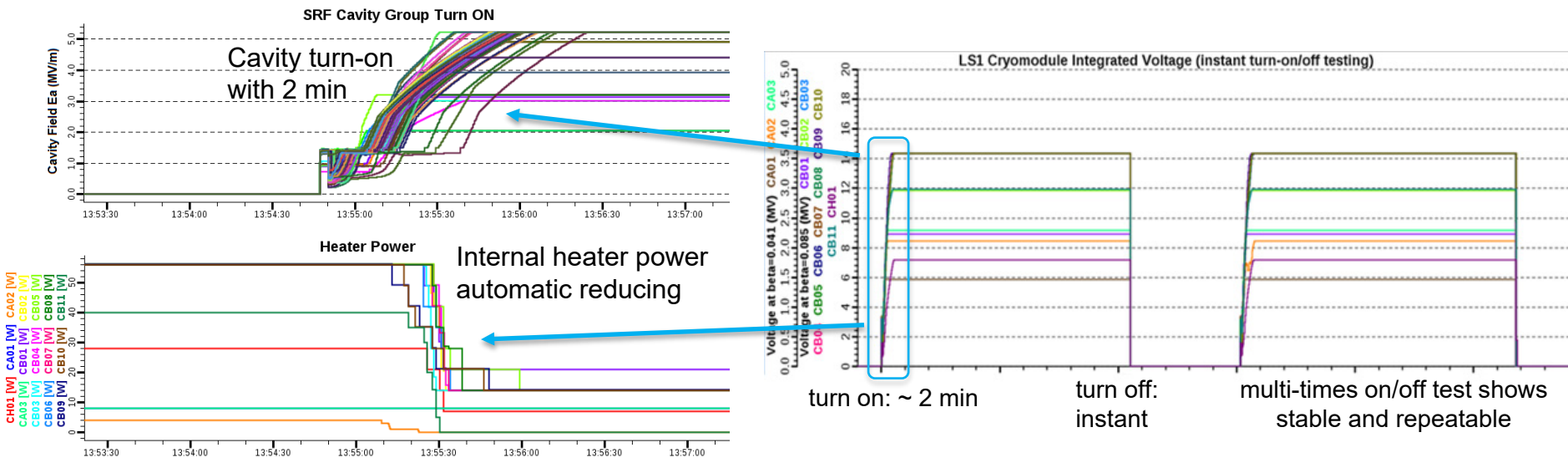
SRF Cavity Group Auto Turn-on

- 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

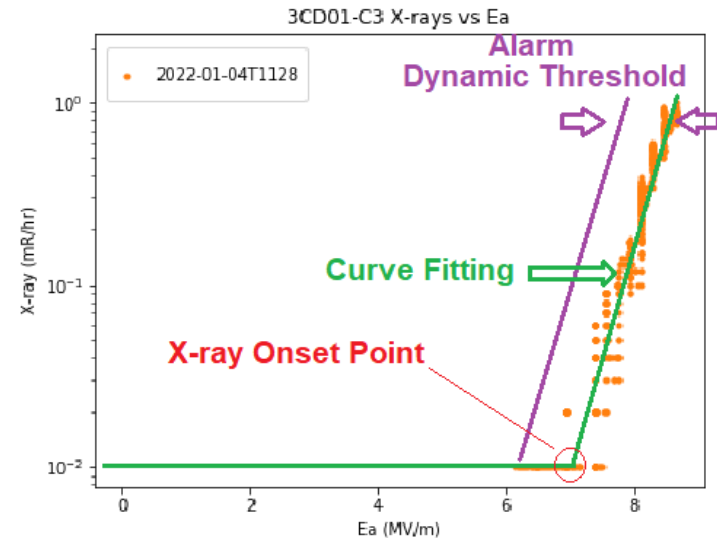
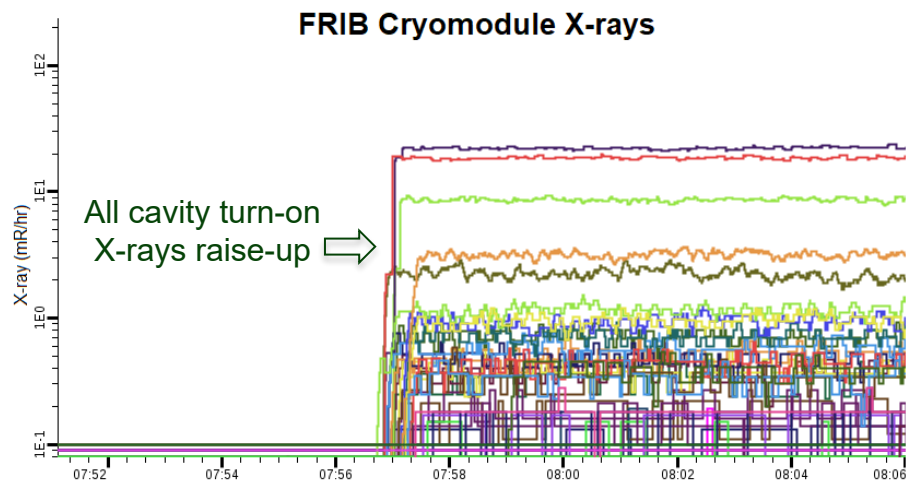
- Cavity fast turn-on/off with cavity auto-start and heater power auto compensation
 - Heater power configuration determined by AP, SRF and Cryo. and tested in commissioning
 - Available for FSEE (FRIB Single Event Effects) quick tunnel access (access tunnel four or five times a day)
 - » All 104 QWRs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



Improved from the previous ~1 hour turn-on

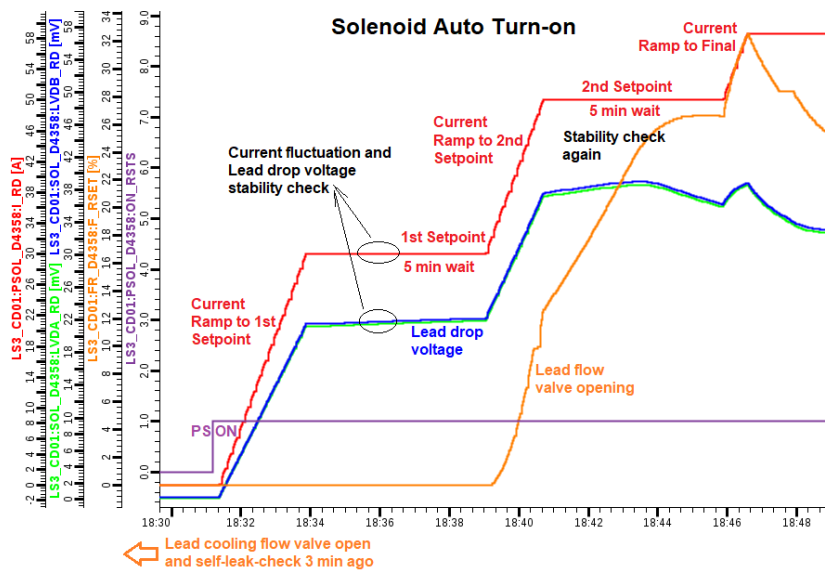
FE X-rays On-line Monitor/Alarm

- 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

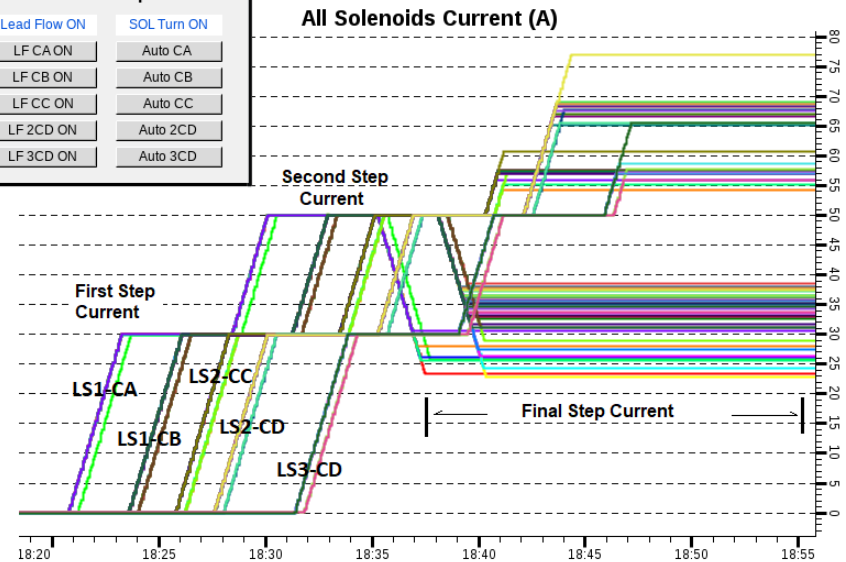
- Single solenoid auto start
 - Three steps current ramp-up with stability check for turn on procedure
- Five group turn-on implemented for 69 solenoid packages
 - All solenoid packages done with ramp-up and stability check within 30 minutes before the beam operation.



Group Turn ON

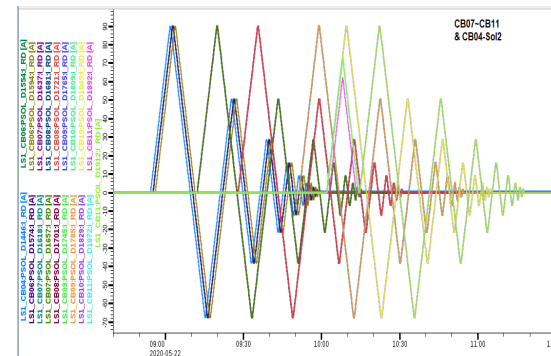
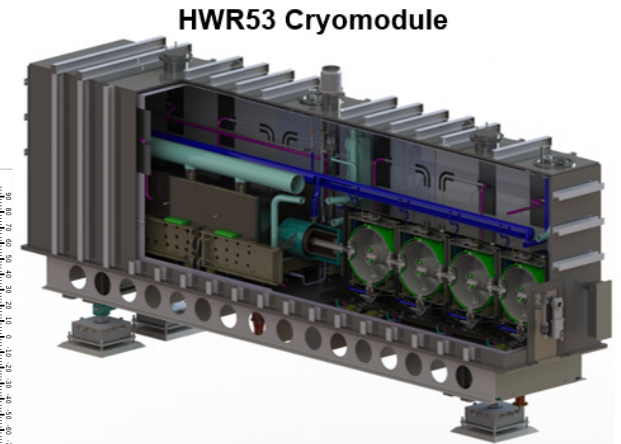
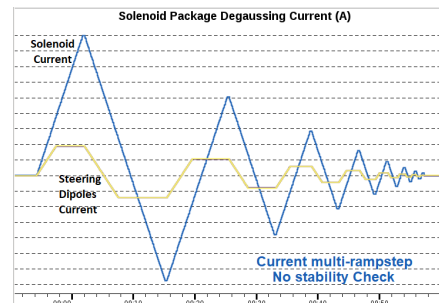
Enable Buttons:

Lead Flow ON	SOL Turn ON
LF CA ON	Auto CA
LF CB ON	Auto CB
LF CC ON	Auto CC
LF 2CD ON	Auto 2CD
LF 3CD ON	Auto 3CD



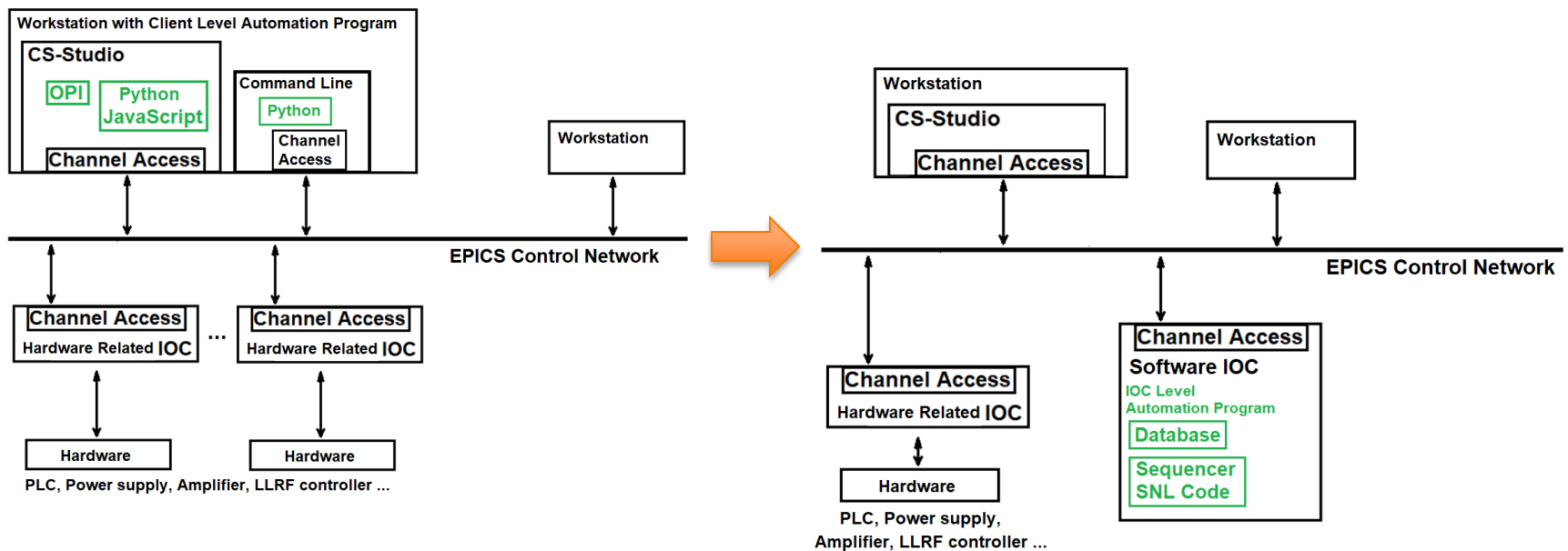
Solenoid Auto Degaussing

- 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

SRF Cavity Turn ON

Solenoid Group Turn ON

SRF Cavity Turn OFF

Solenoid Group Off

SRF Calibration Check Page

id	Ea	PLCn_Mvms	RampRate	Phase(Deg)	DR	Threshold	Alarm	LoadRate
LS1_CA01	2.054 Mvms	8.3	8.1	0.0	50K			
LS1_CA01D127	2.054 Mvms	8.5	8.5	0.0	50K			
LS1_CA01D142	2.054 Mvms	7.9	8.8	0.0	50K			
LS1_CA01D150	2.054 Mvms	8.9	8.8	0.0	50K			

FRIB Selected Auto Turn On OPI

Lead Type	Auto Turn On	Beam	Check	Cancel	Power	Phase	Drift	Alarm
LS1_CA01D127	ON	LS1_CA01D127	OK	OK	0.000	0.000	0.000	OK
LS1_CA01D142	ON	LS1_CA01D142	OK	OK	0.000	0.000	0.000	OK

LSI FE Cavity Field Reduce & Recover OPI

Cavity ID	Ea field	Phase lock Status	Reduce Ea	Ea AP	At 1.5	Recover
LS1_CB01D1265	0.0002 Mvms	Open Loop	Reduce	Reboot		Recover
LS1_CB04D1420	0.0004 Mvms	Open Loop	Reduce			Recover
LS1_CB05D1484	0.0002 Mvms	Open Loop	Reduce			Recover
LS1_CB06D1587	0.0002 Mvms	Open Loop	Reduce			Recover
LS1_CB07D1631	0.0002 Mvms	Open Loop	Reduce			Recover
LS1_CB07D1651	0.0002 Mvms	Open Loop	Reduce			Recover
LS1_CB08D1675	0.0003 Mvms	Open Loop	Reduce			Recover
LS1_CB08D1661	0.0002 Mvms	Open Loop	Reduce			Recover
LS1_CB08D1711	0.0000 Mvms	Open Loop	Reduce			Recover
LS1_CB08D1727	0.0001 Mvms	Open Loop	Reduce			Recover
LS1_CB09D1727	0.0002 Mvms	Open Loop	Reduce			Recover
LS1_CB09D1719	0.0001 Mvms	Open Loop	Reduce			Recover
LS1_CB09D1791	0.0002 Mvms	Open Loop	Reduce			Recover
LS1_CB10D1802	0.0004 Mvms	Open Loop	Reduce			Recover
LS1_CB10D1834	0.0002 Mvms	Open Loop	Reduce			Recover
LS1_CB10D1842	0.0004 Mvms	Open Loop	Reduce			Recover
LS1_CB11D1862	0.0003 Mvms	Open Loop	Reduce			Recover

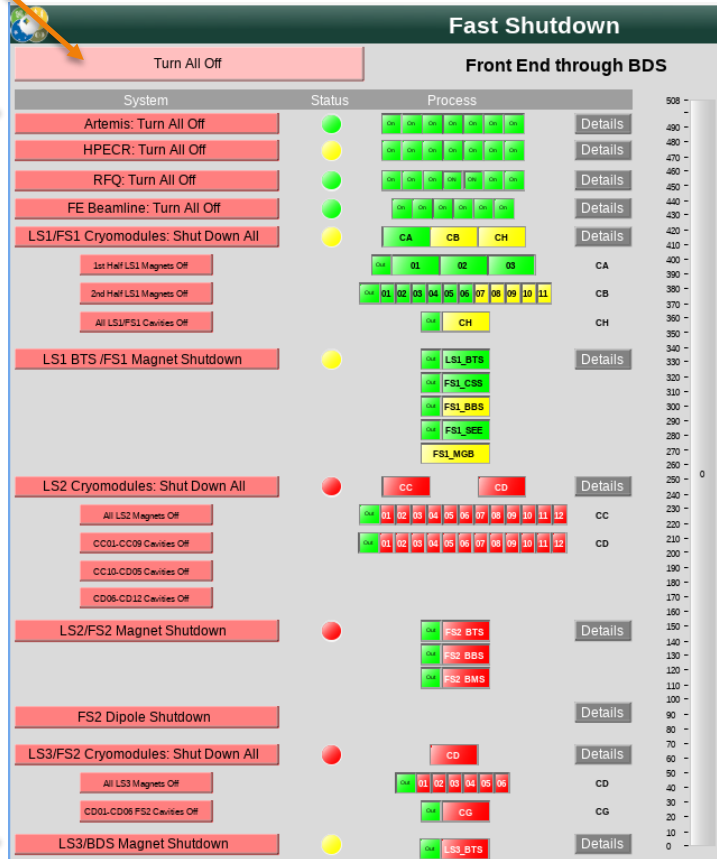
UI pages for operators

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!



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University