FRIB LLRF Status Update and Early Operation Experience

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U.S. DEPARTMENT OF ENERGY | Office of Science

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Outline

- FRIB Project Overview
- Linac Commissioning
  - Cavity control performance
  - Pneumatic tuner control improvement
- Transition to Operation
  - Automation
  - Spare parts management
  - Availability
  - Issues
- New LLRF Development
- Summary

FRIB Team

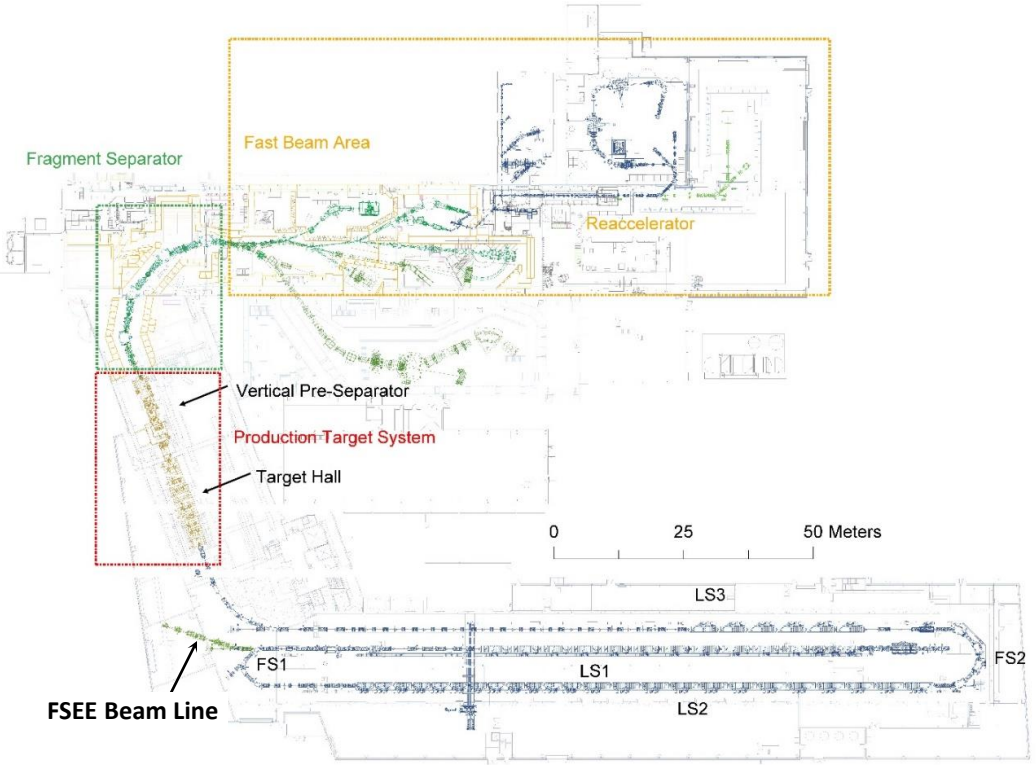
- RF team
  - Low Level RF
    - » Shen Zhao and Shriraj Kunjir
  - High Power RF
    - » Dan Morris, Cody Knowles, John Brandon, Eleazar Gutierrez
- Controls team
  - Enrique Bernal-Ruiz, Evan Daykin
- SRF team
  - Ting Xu, John Popielarski, Walter Hartung, Sang-hoon Kim, Wei Chang
- Room temperature device team
  - Hiroyuki Ao, Xing Rao, Alexander Plastun

FRIB Project Overview

- Heavy ion linac focused on rare isotope research (now a DOE facility)
- Ribbon cutting on May 2nd, 2022

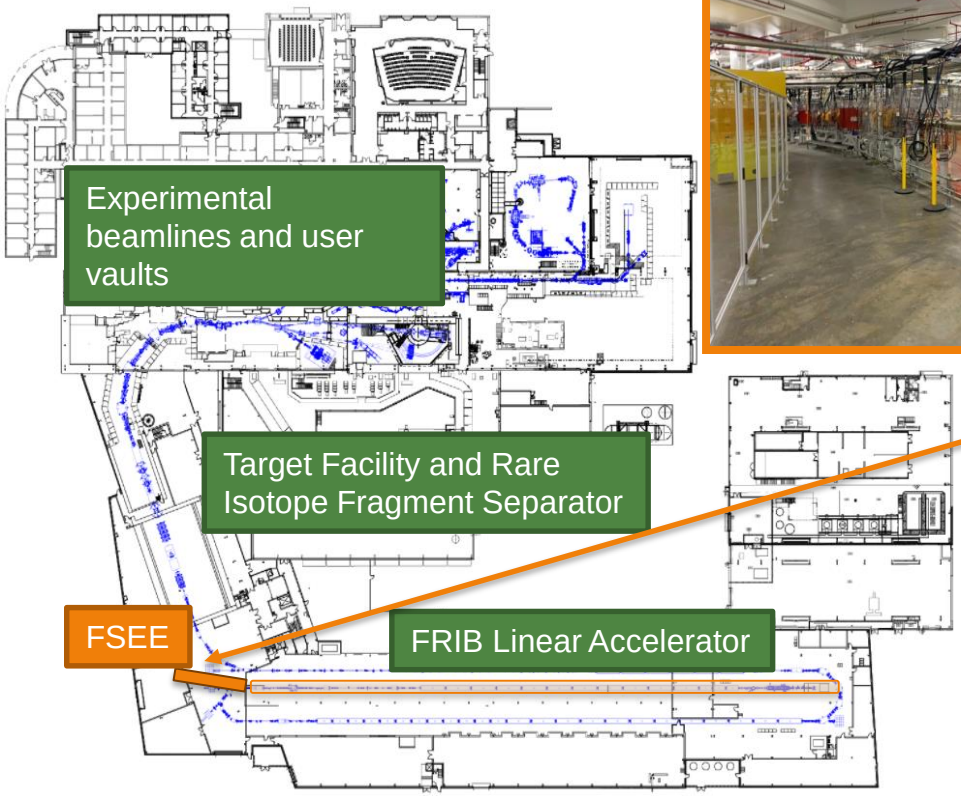
Experiment	Date	Beam Power
First	5/11 - 5/16	1 kW
Second	6/15 - 6/21	1 kW
Third	7/27 - 8/2	1 kW
Fourth	11/20 - 11/26	3 kW

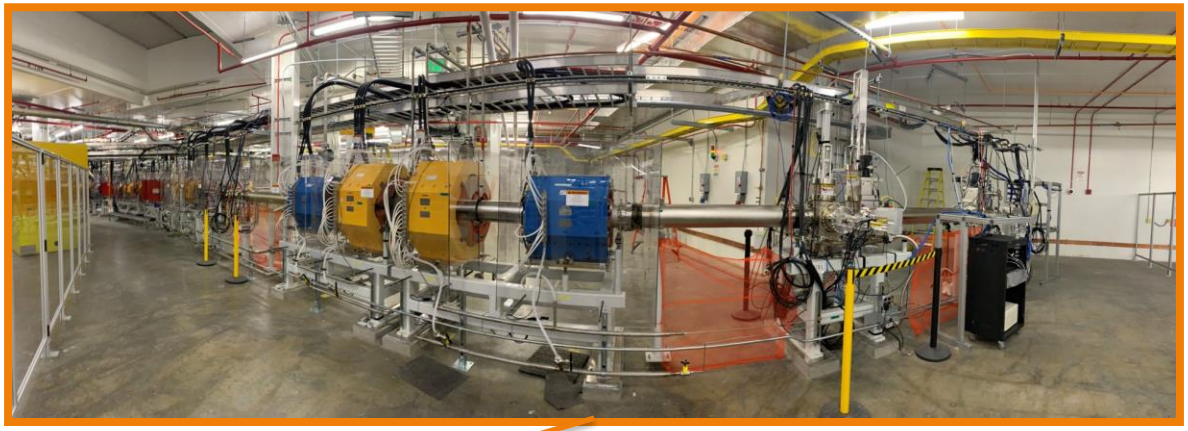
Key parameters:
Beam energy: 200 MeV/u
Beam power: 400 kW



FRIB Layout

FRIB Single Event Effects Beamline Operating
Industrial User Program Started in 2022



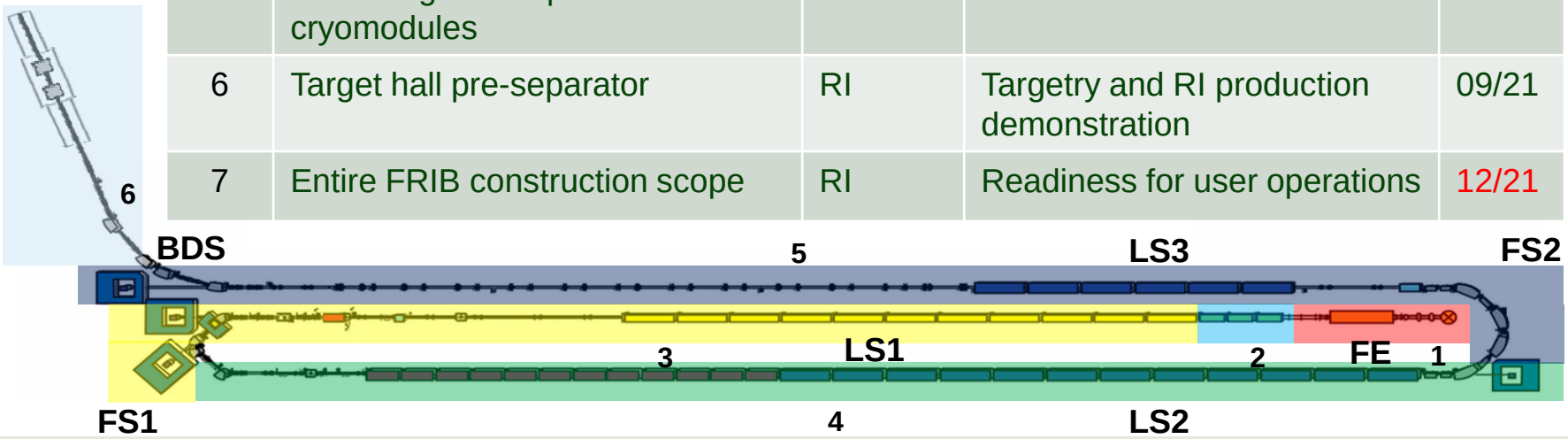


FSEE uses the ion source, Front End, and first segment of the FRIB linac.

Phased Beam Commissioning Efforts

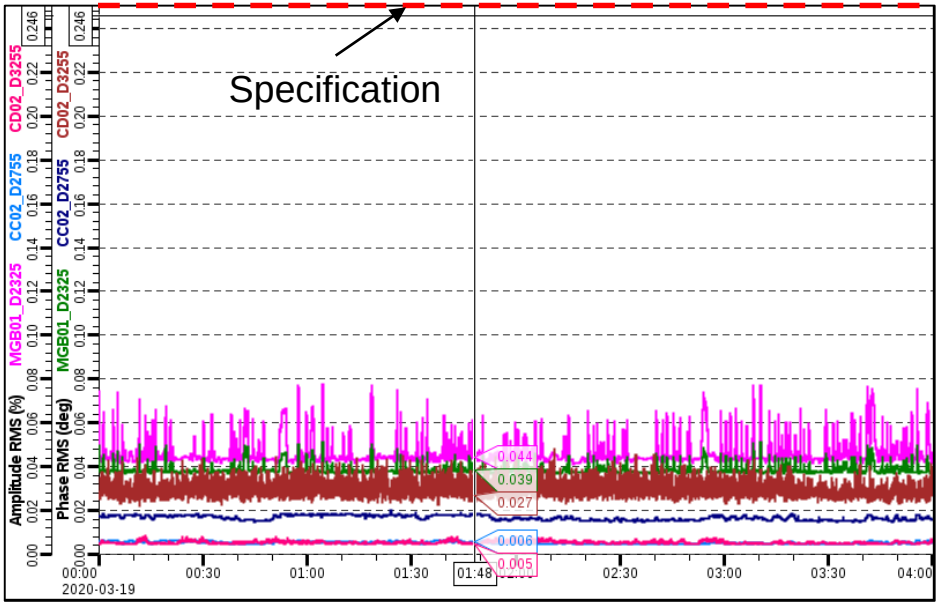
TUIYGD3, IPAC'22

Run	Area with beam	Energy [MeV/u]	Goal	Date
1	*Ion source, LEBT, RFQ, MEBT*	*0.5*	*Front end and civil integration*	*07/17*
2	*Linac Segment 1 with β=0.041 cryomodules*	*2*	*Cryogenic integration*	*05/18*
3	*LS1 with β=0.041 and 0.085 cryomodules*	*20*	*QWR and charge stripping validation*	*02/19*
4	**Linac Segment 2 β=0.29 and 0.53 cryomodules**	**200**	**2 K cryogenics and HWR validation**	**03/20**
5	Linac Segment 3 β=0.53 cryomodules	> 200	Driver linac validation	04/21
6	Target hall pre-separator	RI	Targetry and RI production demonstration	09/21
7	Entire FRIB construction scope	RI	Readiness for user operations	12/21

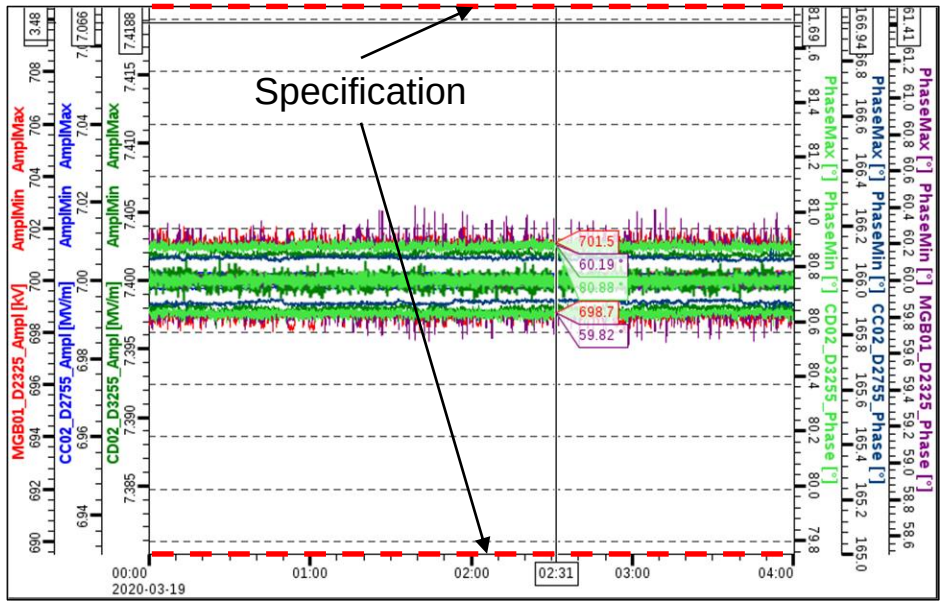


Cavity Control Performance Meets Specification

Selected Cavities	Amplitude (%)				Phase (degree)			
	Specification		Measurement		Specification		Measurement	
	peak	rms	peak	rms	peak	rms	peak	rms
MGB01_D2325 (161 MHz, RT)	1.5	0.5	0.3	0.08	1.5	0.5	0.5	0.06
CC02_D2755 (322 MHz, β=0.29, SRF)	1	0.25	0.04	0.007	1	0.25	0.15	0.02
CD02_D3255 (322 MHz, β=0.53, SRF)	1	0.25	0.05	0.008	1	0.25	0.2	0.05



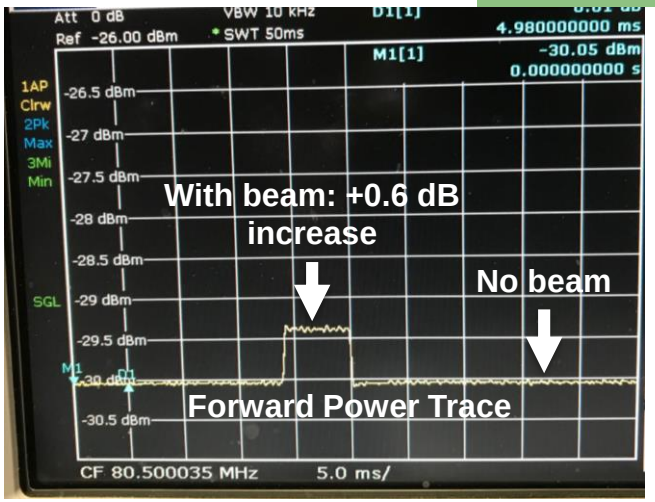
RMS Error

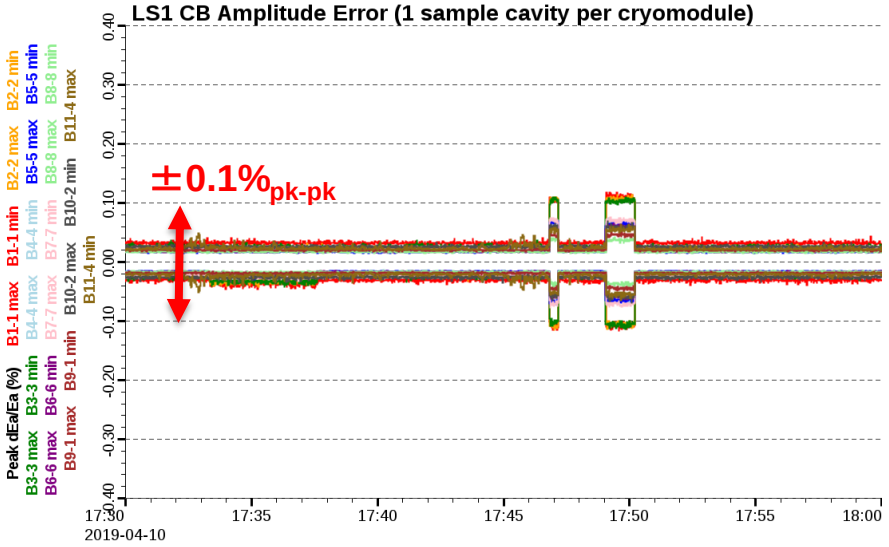


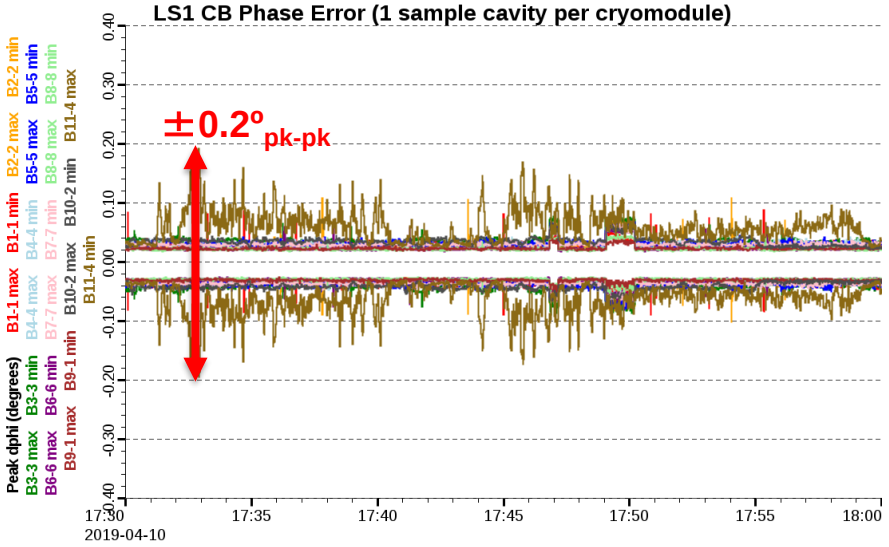
Peak Error

Control Performance with Beam

- Pulsed beam during LS1 commissioning
  - Peak current 130 μA
    - » 1/3 max design current
  - Pulse length 6 ms
    - » Cavity RF filling time 8 ms
  - Repetition rate: 5 Hz

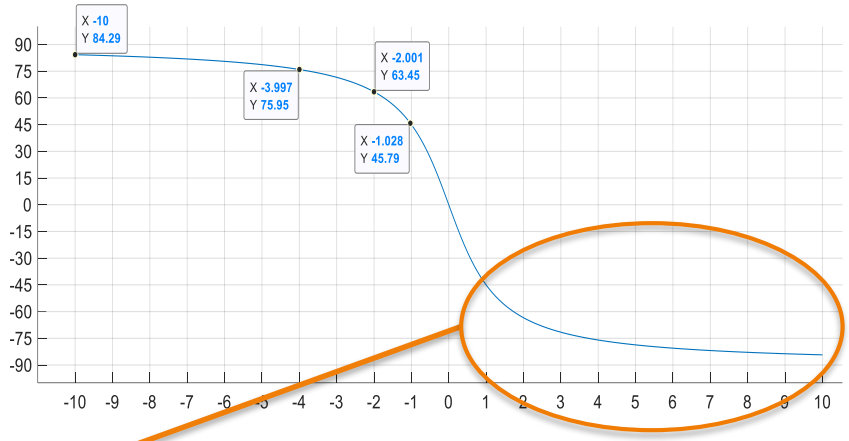


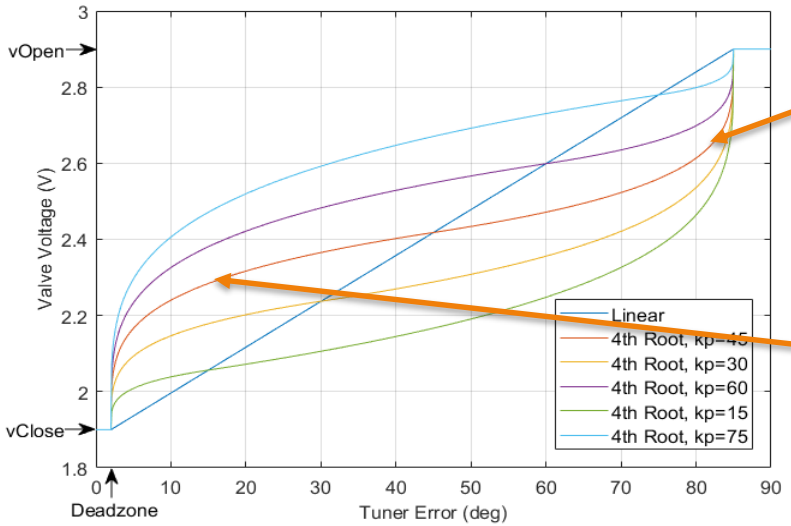


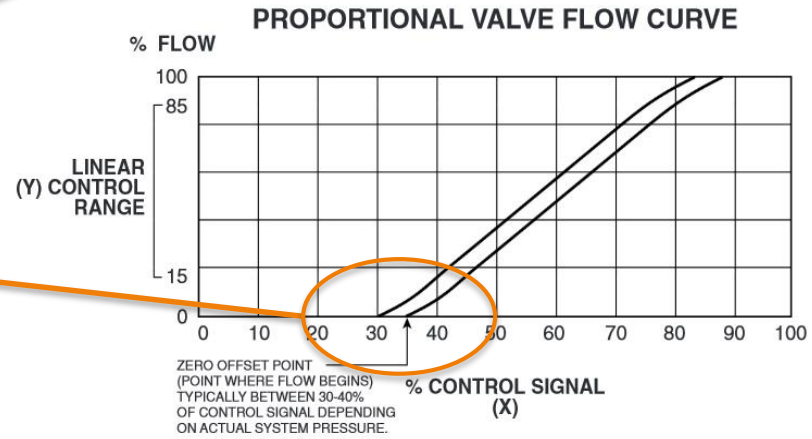


Pneumatic Tuner Control Improvement

- Two nonlinear sections to map tuner error to valve control voltage
  - Phase curve nonlinearity
  - Valve dead-zone
  - Flat in mid-range
- Proportional-integral control
  - Proportional gain moves curve up/down
  - Adjustable integration limit







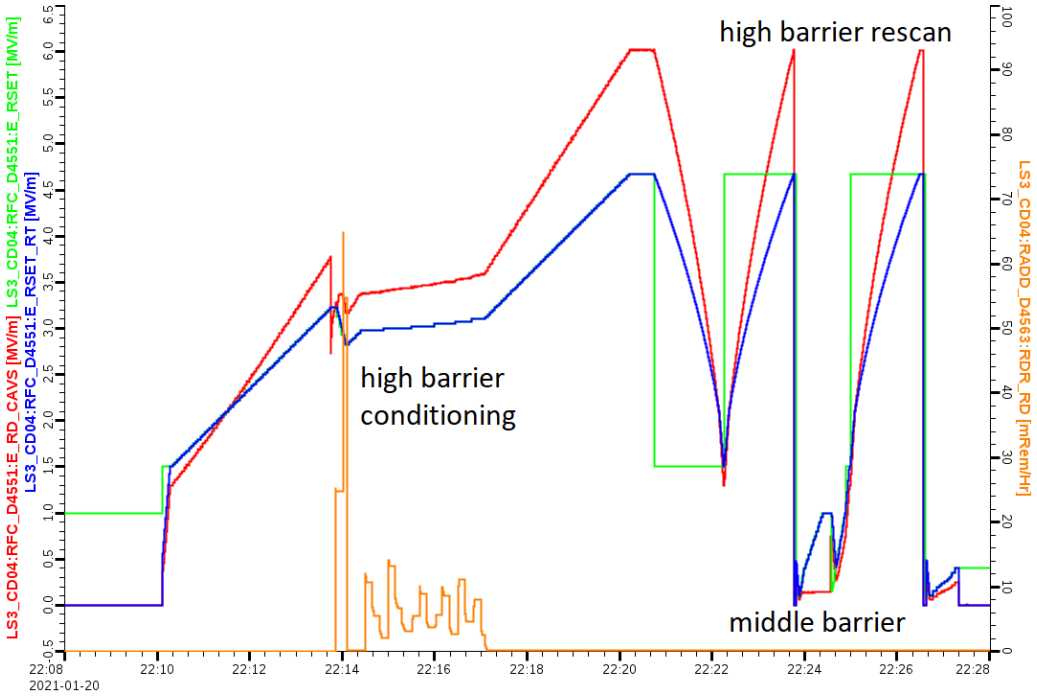
Automation Effort

TH1C3, HIAT'22

- Motivation
  - Efficiency, productivity
  - Consistency, less human error
  - Faster response (compared to human)
  - Reduce the level of training required for operators
  - Free experts from routine work and allow more time for creative work
  - Experience of system experts is formalized into routines
  - Make the devices smarter
- Tasks
  - Cavity level: multipacting conditioning, auto-start, fast recovery
  - Facility level: FSEE operation, emergency automatic shutdown
- Implementation
  - Python
  - Input / Output controller (IOC)
  - LLRF Software

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



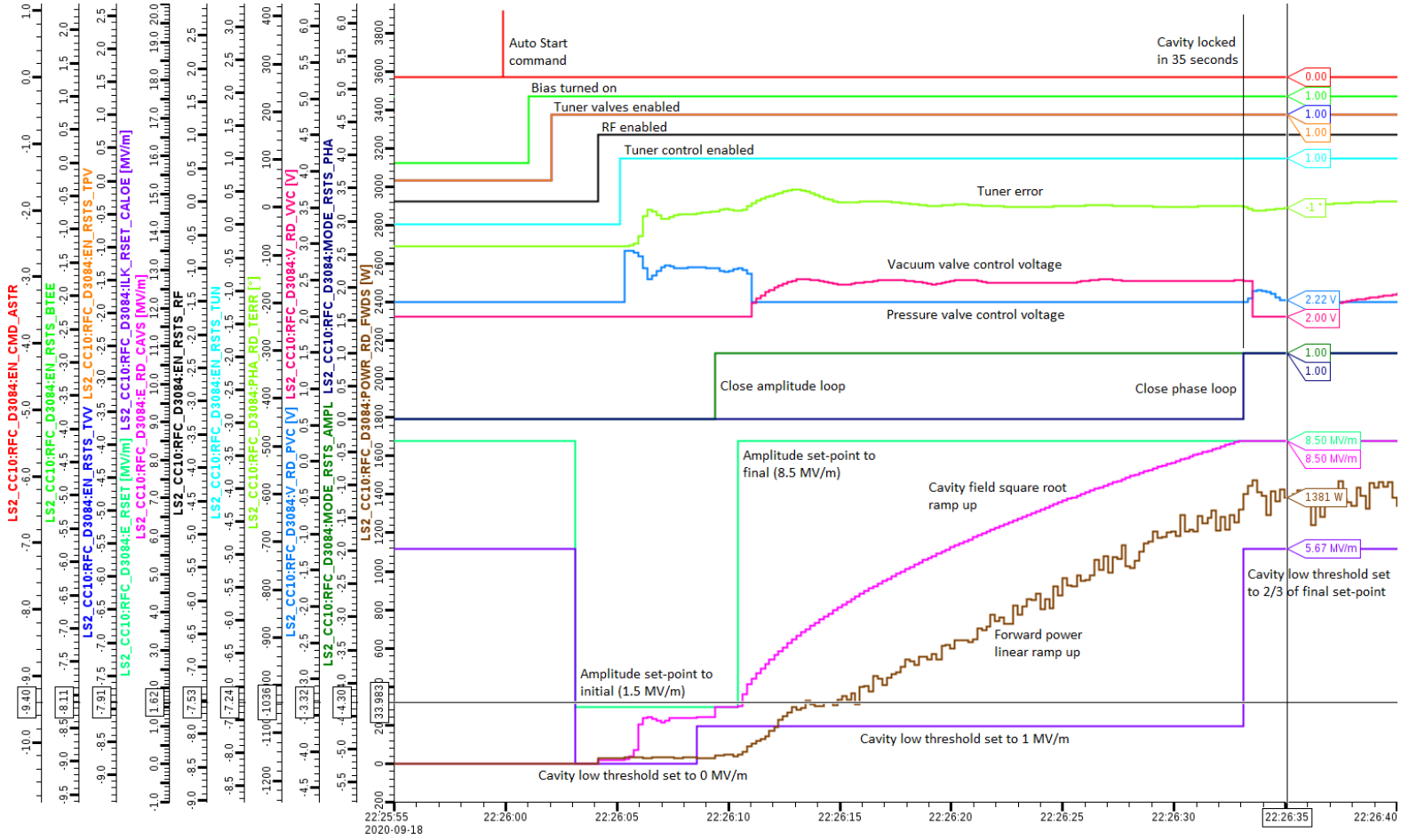
LS3CD04D4551 MP log.txt - Notepad

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
```

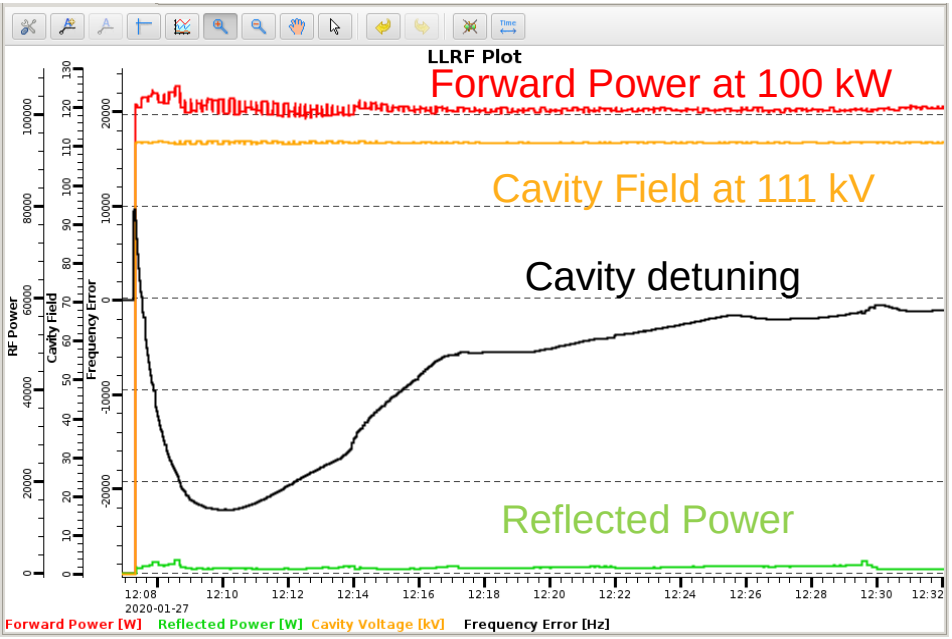
Cavity Auto-start

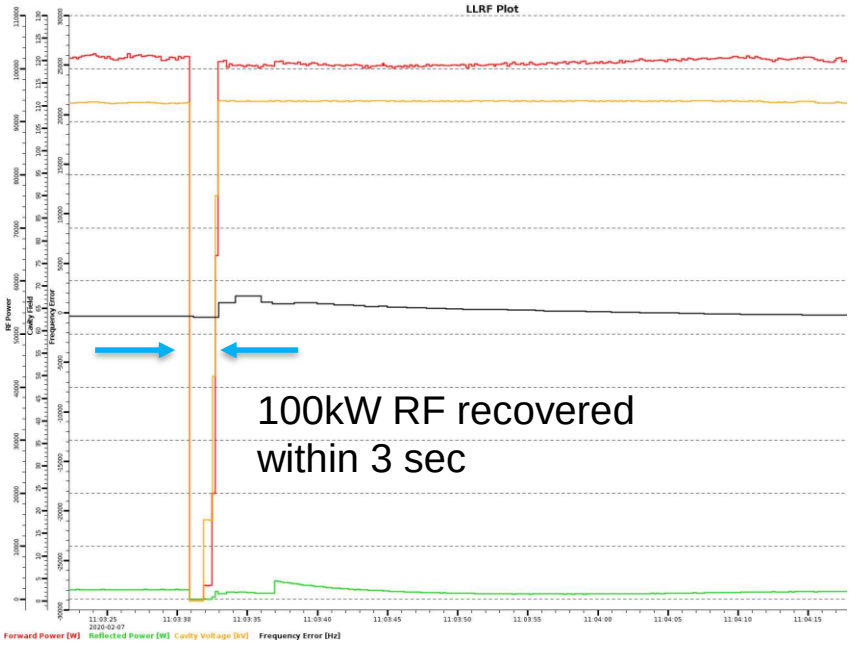
- Half wave resonator example



RFQ (RT) Auto-start and Fast Recovery

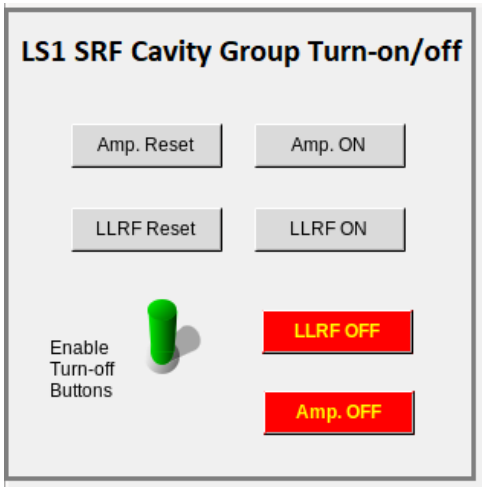
- Auto-start from cold condition to 100 kW CW
  - Ready for beam: 40 ~ 50 min
  - Maximum detuning: less than 30 kHz
  - Reflected power: 2 ~ 3 kW
- Fast recovery at 100 kW for S11 high or reflected power high trips
  - Power recover: within 3 sec (less than 3 kHz detune)
  - Ready for beam: ~ 10 sec

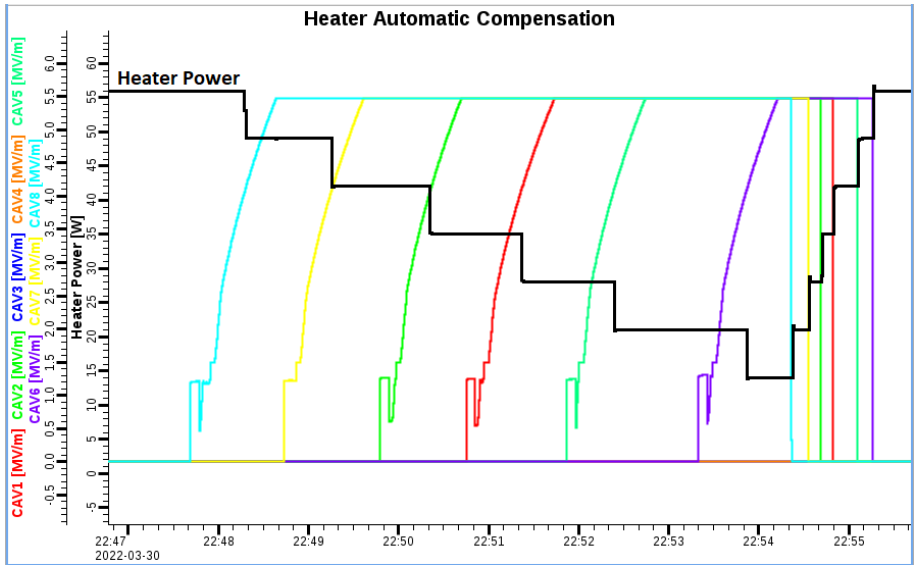


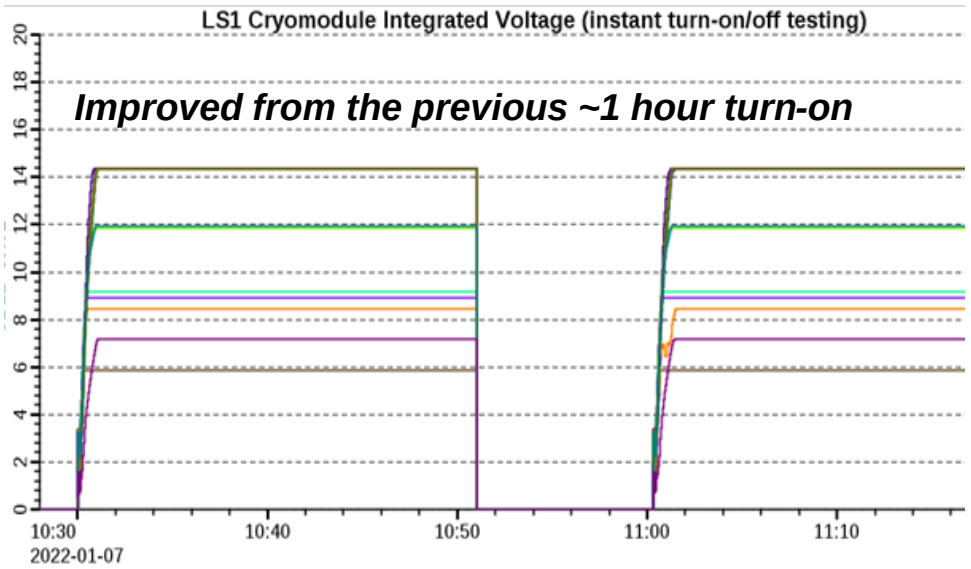


Fast Turn-On/Off of SRF Cavities

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

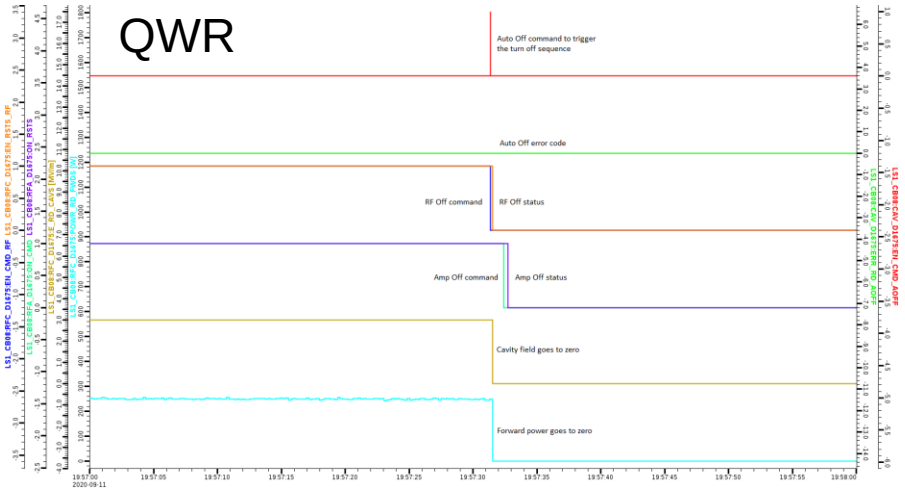


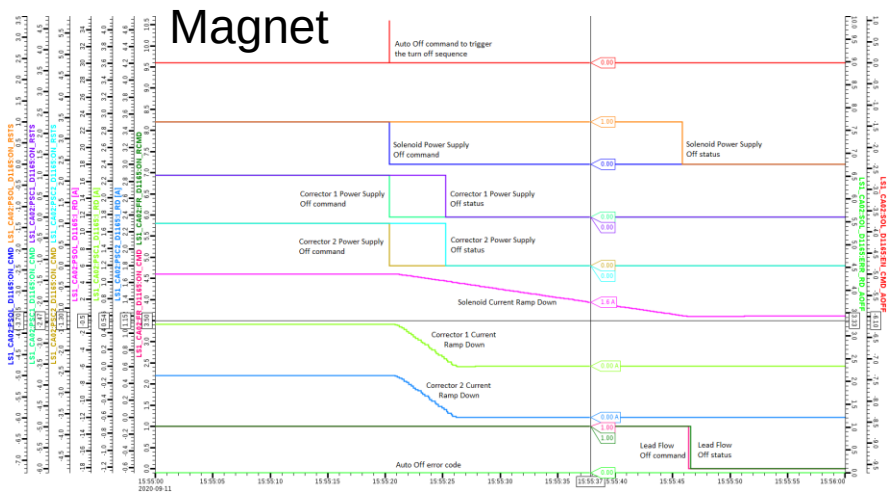


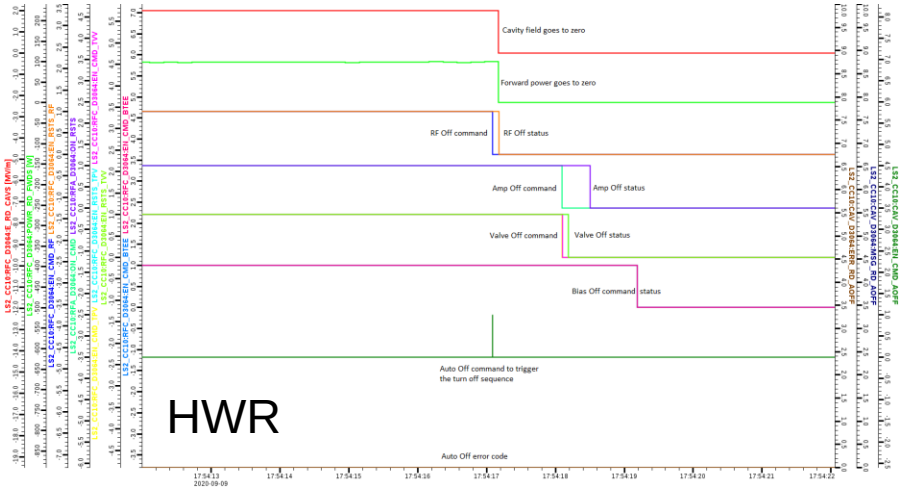


Auto-off for Emergency Shutdown

- Developed for all cryomodules
  - QWR
  - HWR
  - Magnet
- Turn off logic required
  - Lead flow has to be turned off only after all power supply currents ramp to zero







Spare Parts Management

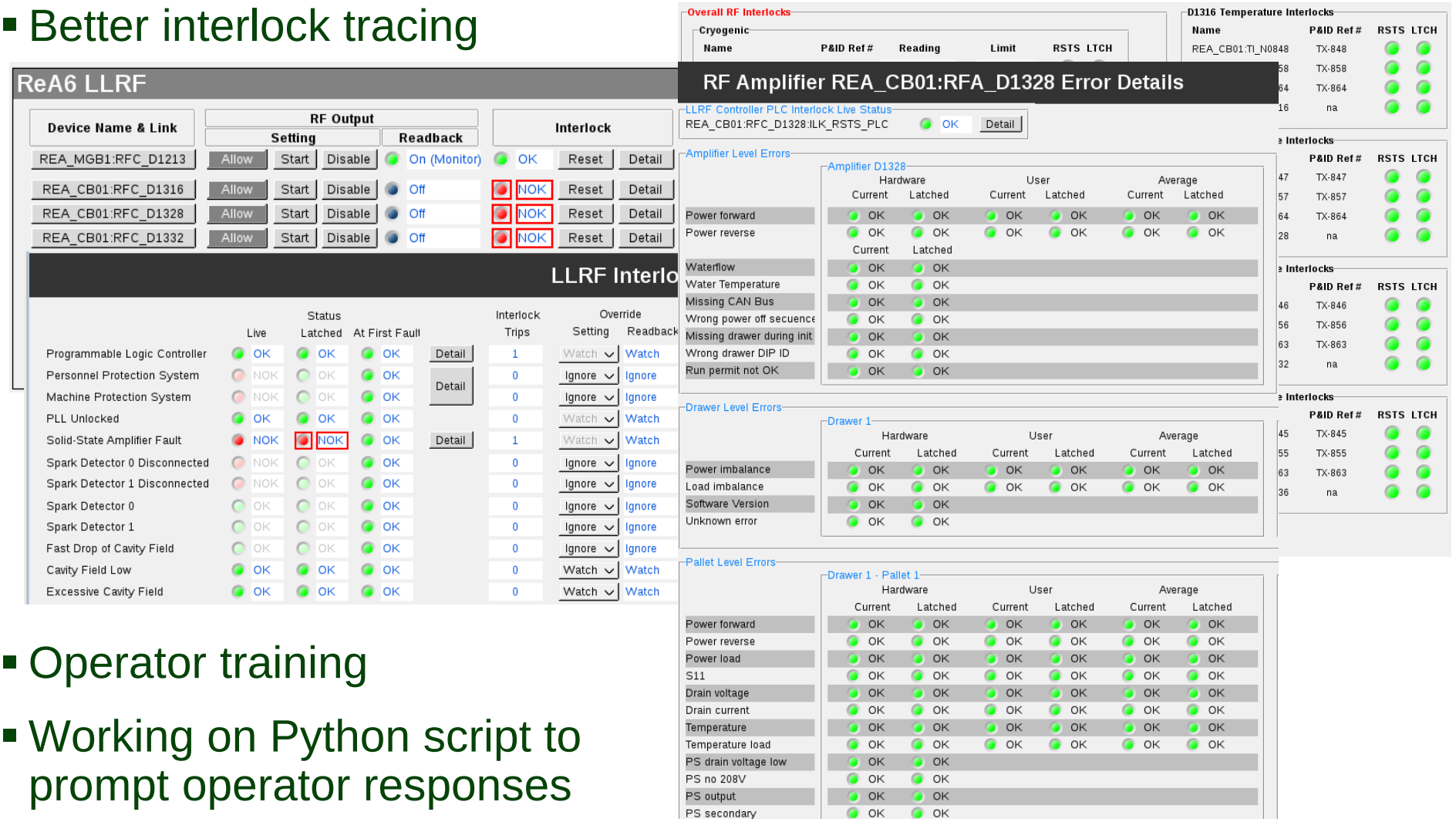
- Four LLRF controller variants
  - With mix and match of three RF board variants and two types of tuner board
  - Support all FRIB cavity types

LLRF	RF Board	Tuner Board	For Cavity Types	Qty	Need
S01xxx	S01xxx (80.5/322)	Stepper	MHB_F2, MEBT, QWR041, QWR085, ReA MHB_F1, ReA RFQ	144	134
S02xxx	S01xxx (80.5/322)	Analog	RFQ, HWR29, HWR53	234	223
S03xxx	S02xxx (40.25/120.75)	N/A	MHB_F1/F3, VE	4	2
S04xxx	S03xxx (161/241.5)	Stepper	MGB, ReA MHB_F2/F3	6	4

- A total of 388 controllers were built
  - Including at least 5% controller level spares for each type (25 in total)
  - Additional 3% board level spares
- Firmware/software always in sync with production LLRF controllers

Operator Interface Improvement

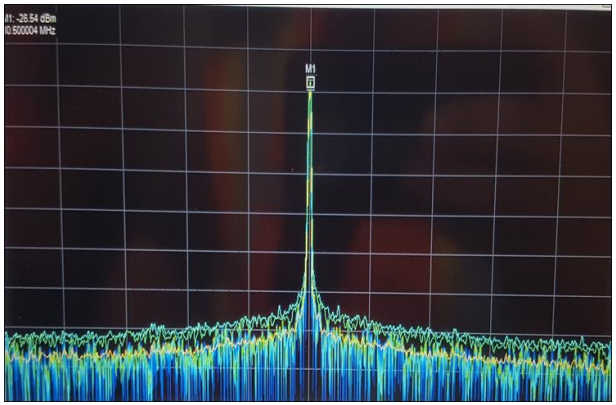
- Better interlock tracing



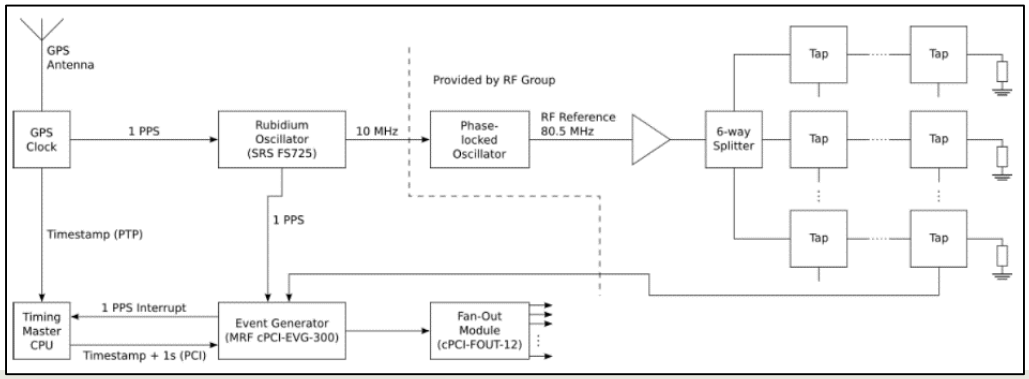
- Operator training
- Working on Python script to prompt operator responses

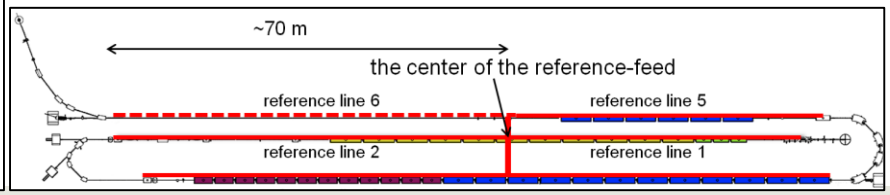
FRIB Reference Clock System

- Clock oscillator phase locked to Global Timing System (GTS) master
  - Low phase noise (1.5 ps RMS)
- 500W distribution amplifier
- 6-way power splitter in tunnel
- Taps and phase stabilized cable installed in home run tray
  - 62 tap groups with 450 taps
    - » LLRF, beam positioning monitor, GTS timing master, target wedge
  - Phase drift at 80.5 MHz
    - » Measured: ±0.21 degrees (Specification: ±0.35 degrees)



Global Timing System / Reference Clock Distribution





Achieving High Availability

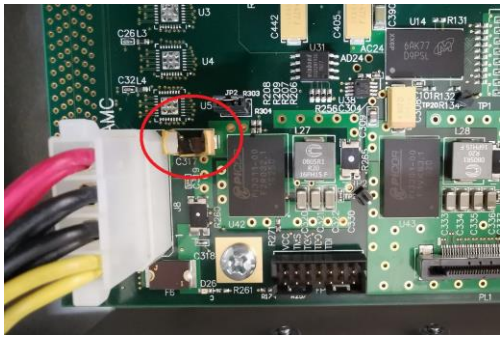
RF Systems Operational Availability

CY	Operational Time (hrs)	RF Downtime (hrs)	RF Availability (%)
2019	895	17.5	98.0
2020	1030	4.9	99.5
2021	1621	11.3	99.3
2022*	1200	4.2	99.6

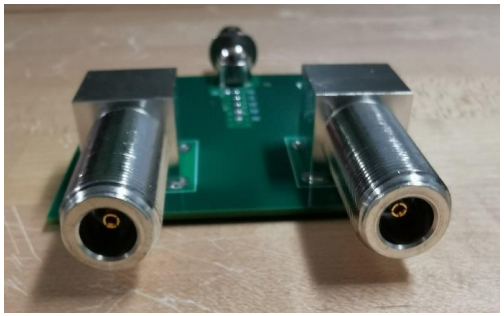
* Through April 2022

Issues and Resolutions

- Component failures
  - Capacitor failure on the digital board for 12 V power supply
  - Op-Amp failure on the RF board for spark detection circuit
  - Resolution
    - » Replace LLRF controller with spare
    - » Pre-run checklist
    - » Fixed by replacing the parts (no failure on the new parts, suspect bad batch of parts)
    - » Failures being tracked, procedures established to address similar issue quickly



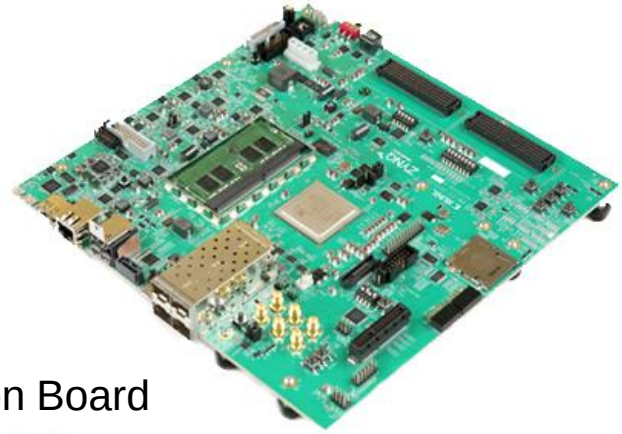
- System issues
  - Interface panel connection
    - » Effect: Cause cavity calibration change
    - » Resolution: quick response procedure developed
  - Stepper tuners
    - » Effect: Cause cavity trips
    - » Resolution: replace NEMA small (150 lbs.) with bigger (500 lbs.) or new type (Phytron, 2 kN)
  - Reference clock
    - » Effect: Cause phase jumps in LS2 CC cryomodules during commissioning
    - » Resolution: Fix connection; added monitoring; spare clock system hot standby also being monitored;



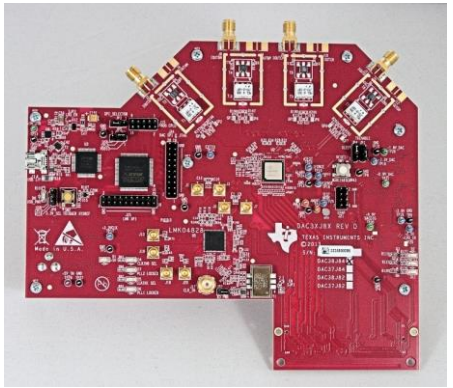
New LLRF Controller Hardware for Higher Frequency

- Field Programmable Gate Array (FPGA)
  - Xilinx Zynq UltraScale+ MPSoC: ZCU102
  - With two high pin count (HPC) FPGA mezzanine card (FMC) connectors
- Analog to Digital Converter (ADC)
  - TI ADS54J66
  - 900 MHz analog bandwidth
  - 4-ch, 14 bit
  - 500 mega-sample per second (MSPS)
  - JESD204B (high speed serial interface)
- Digital to Analog Converter (DAC)
  - TI DAC37J82
  - 2-ch, 16 bit
  - 1600 MSPS
  - JESD204B

Digital Board



ADC Evaluation Board



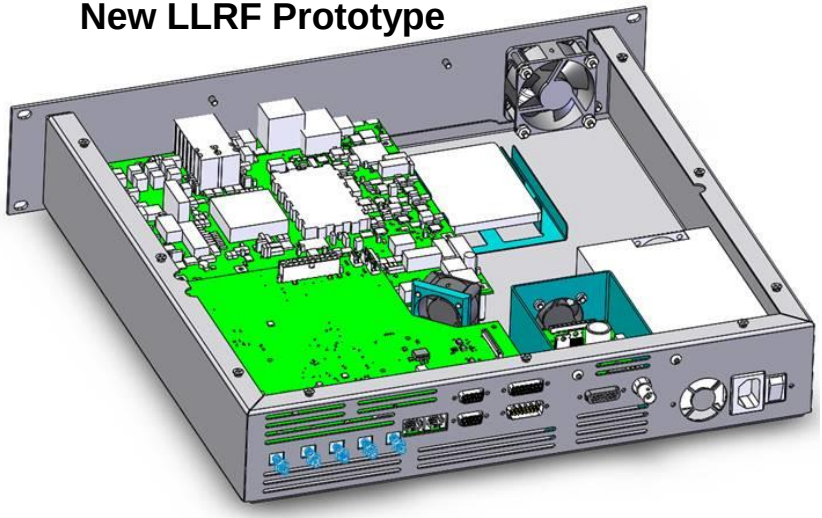
DAC Evaluation Board

New LLRF Controller Development

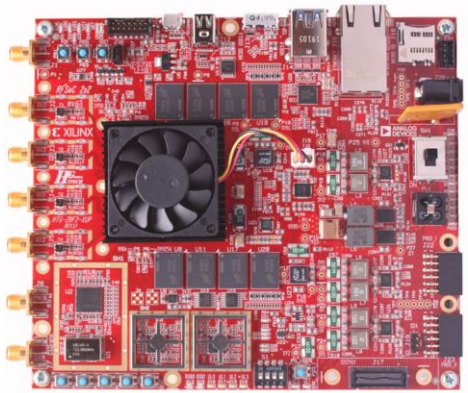
Poster 78, LLRF'22

- AMD-Xilinx Zynq UltraScale+ MPSoC
  - ZCU102 Evaluation Kit
  - Frequency supported
    - » 644 MHz FRIB upgrade cavity
      - 5-cell elliptical cavity
    - » 1.013 GHz room temperature cavity
      - MSU Ultrafast Electron Microscopy lab
  - On board Input / output controller (IOC)
    - » Less load per IOC
    - » Less network traffic
  - Large local storage
    - » 500 GB Solid State Drive (SSD)
- AMD-Xilinx Zynq UltraScale+ RFSoC
  - RFSoC Evaluation Kit
  - Potential application
    - » K500 SEE
    - » Cavity simulator

New LLRF Prototype



RFSoC Evaluation Kit



Summary

- FRIB linac was successfully commissioned by end of 2021
  - Cavity control performance meets specification with comfortable margin
- User operation started in May 2022
  - Completed three scientific user experiments so far
  - FSEE industrial user program runs in between
  - Next few years will focus on power ramp up
- More effort on making operation smooth
  - Automation
  - Spare parts management
  - Better user interface
  - Debugging tools development
  - Operator training
- New LLRF controller development started
  - MPSoC platform prototype is completed
  - RFSoC option is being explored