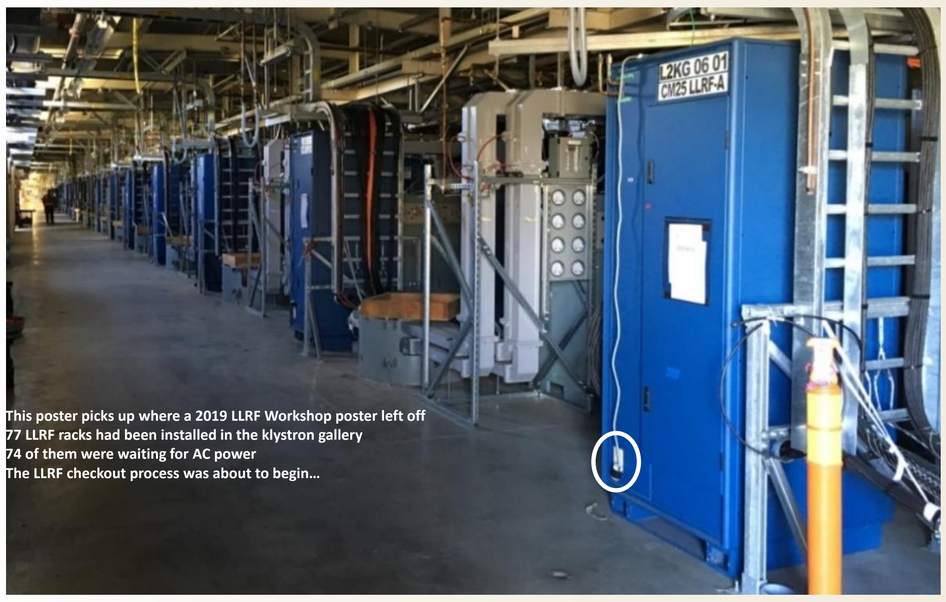
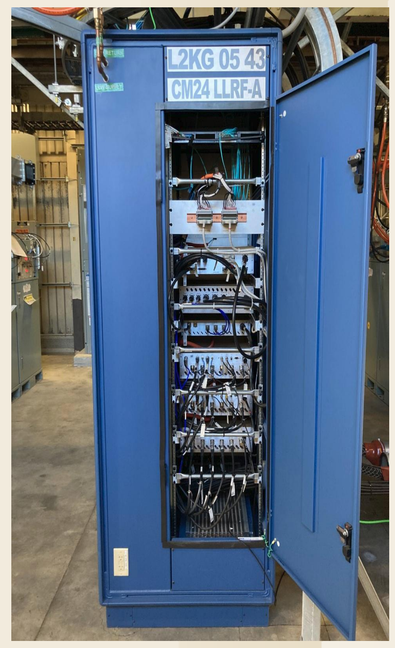
LCLS-II RF System Checkout Lessons Learned

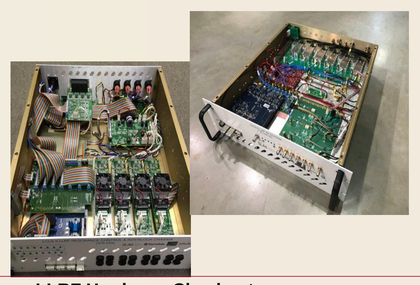
Andrew Benwell, Jing Chen, Jorge Diaz-Cruz, Sonya Hoobler, Rick Kelly, Andre McCollough, Mark Petree, Alex Ratti, SLAC, Menlo Park, CA 94025, USA
Brian Chase, Josh Einstein, Ed Cullerton, Fermi, Batavia, IL, 60510 | Ramakrishna Bachimanchi, Curt Hovater, JLAB, Newport News, VA 23696, USA
Larry Doolittle, Gang Huang, Shree Murthy, Carlos Serrano, LBNL, Berkeley, CA 94720, USA



This poster picks up where a 2019 LLRF Workshop poster left off
77 LLRF racks had been installed in the klystron gallery
74 of them were waiting for AC power
The LLRF checkout process was about to begin…

- LLRF Component Count
- LCLS – II is composed of 35 superconducting cryomodules each with eight 1.3 GHz
- Single Source Single Cavity architecture chose for precision field control in CW mode operation
- SSSC enables precise field control per cavity, but dramatically increases RF system component count
- One 186 MHz RF Gun – 1 normal conducting cavity with 2 SSAs and 2 RF controllers
- One 1300 MHz Buncher – 2 normal conducting cavities with 4 SSAs and 4 RF controllers
- 280 1300 MHz Superconducting Cavities each with 1 SSA and 1 RF Controller
- 16 3.9 GHz Superconducting Cavities each with 1 SSA and 1 RF Controller
- 77 total LLRF racks, each rack contains entire field control system for 4 superconducting cavities (half cryomodule)
- 236 RF field control chassis (RFS or PRC)
- 74 cryomodule cavity resonance control chassis
- 78 power distribution chassis
- 84 LO timing distribution chassis
- 3,850 fiber optic connections (in the
- LLRF racks alone)

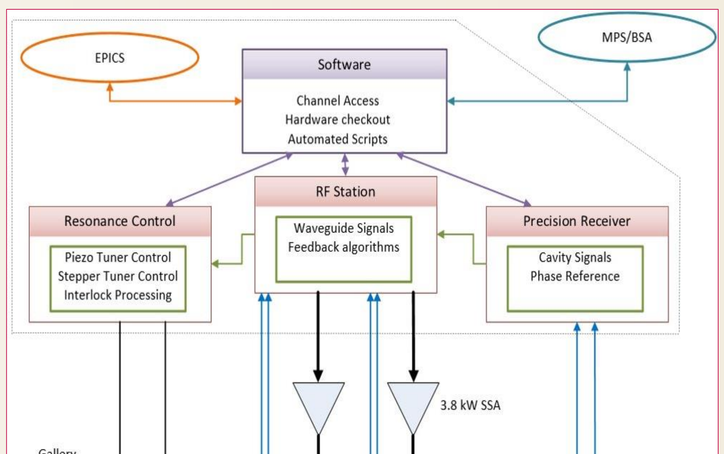




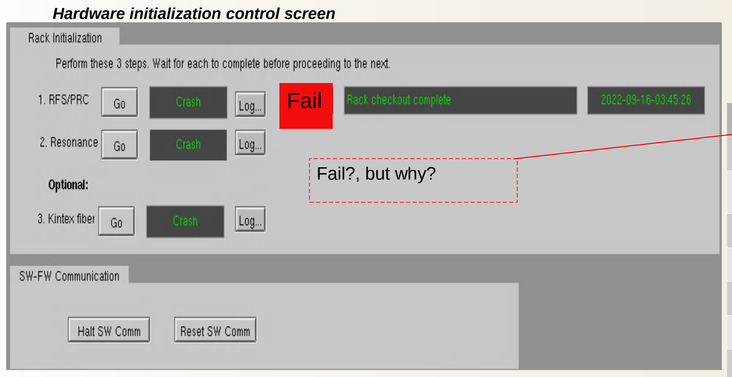
Field Initialization & Rack Checkout

- After energization, before RF hardware checks every rack must undergo:
- Network configuration of carrier card FPGAs
- Automated rack checkout process
  - Loads latest stable firmware over network
  - Checks standard board level diagnostics
  - Check chassis communication routing

- Rack Checkout Steps and Checks
- Get board information
- Configure QF2 oscillators with frequency 1300/7 MHz
- Check QSFP mapping and status
- Program kintex 7
- Configuring Kintex fiber network connection
- Beginning lcls2_rack_helper.py for Rack A
- RFS/PRC Setup: Initialize RFS and PRC
- SEL_WAVE_BEG: Initialize DSP registers
- ICC LOCK: RFS <-> PRC (ICC) link configuration
- CRC_CHECKN: RFS <-> PRC (ICC) link CRC check
- LINK_MAP: RFS <-> PRC (ICC) link map
- DAC BIST: RFS DAC data integrity check
- STATION_CHECK: RFS output check
- SEL_WAVE_TEST:
- SEL_WAVES: RFS waveform readout test
- GET_RAW_ADCS: Raw ADC readout
- CRC_CHECKN: RFS <-> PRC (ICC) link CRC check
- CC: RFS <-> RES (Chitchat) link configuration
- SEL_ENABLE: Initialize SEL registers
- Beginning Timing Check
- Check Forward PRL input signal
- Check Reverse PRL input signal
- Lock to PRL
- Rack checkout complete!



Hardware initialization control screen



Fail?, but why?

Rack Checkout Result	# of times
PASS	168441
FAIL	90750
Total	**259191**

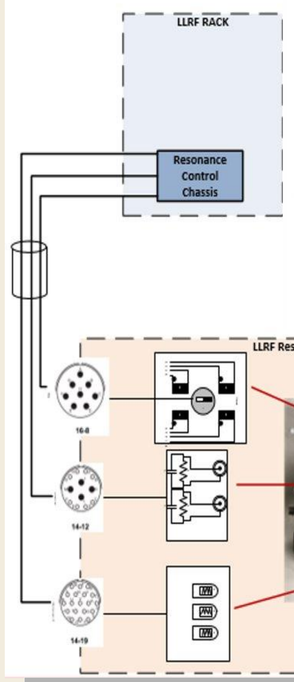
Failure mode	Error count	Issue
SEL_ENABLE	48084	firmware development issue
SEL_WAVE_TEST	14859	firmware development issue
timeout	6189	Networking problem
STATION_CHECK	4141	firmware development issue
CRC_CHECKN	2657	Inter-chassis fiber network problem
Setup	2621	network timeout during setup
frequency	2385	wrong timing frequency
LINK_MAP	2016	Inter-chassis fiber network problem
information	1939	internal PCB problem
oscillators	634	problem setting board oscillator
BUFR	502	problem reading buffer
Kintex	420	Problem with Kintex configuration
mmcm	281	firmware clocking issue
LO_LEVEL	138	clock too low
QSFP	49	cannot read values from transceiver
GET_RAW_ADCS	32	problem reading ADC buffer

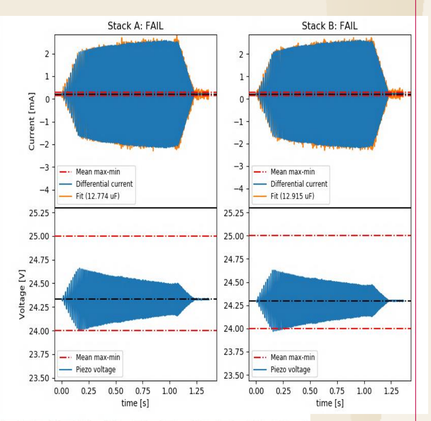
- From August 2021 to October 2022, rack checkout was run ~ 260 thousand times over 74 LLRF racks
- 8 times per night for every available LLRF rack
- Failure modes were counted and analyzed for improvements
- As new features were developed, rack checkout was updated
- Automated rack checkout extremely valuable to determine failure modes

LLRF Hardware Checkout

After the Rack Control System is ready, a combination of EPICS and custom test boxes were used for testing all LLRF hardware

- Long haul cable controls checks into test box
- Piezo control with capacitive load
- Stepper control with test motor
- Stepper tuner limit interlocks with test switches
- Temperature interlocks with RTD loads
- RF calibration with using EPICS interface (ensures proper signal routing)
- ADC calibration in back of eac
- Heliax cable calibration



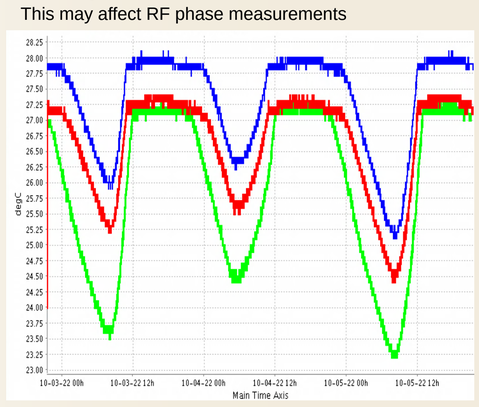


Common problems discovered during hardware checkout	Number found/reason
Heliax swapped	Too many to count
Heliax through the wrong penetration	15 (bad documentation)
Poor multi-pin termination	> 100
Poor heliax termination	Dozens and counting
Piezo tuner disengaged in CM	3 completely (5 single)
Stepper tuner problem in CM	1 motor heats with no tuning
Limit Switches stuck open in CM	1 (suspected)
RTD bad in CM	4
Failed rack checkout – poor fiber connection	Too many to count
Disconnected cable inside chassis	7
Low LO	Failed LO couplers
PRL signal unstable	> 20 and still investigating
Poor LLRF chassis linearity	8 – failing amplifiers
Failed fiber patch panels	5

3 things discovered during checkout that cause problems:

1. Better water temperature stabilization is needed

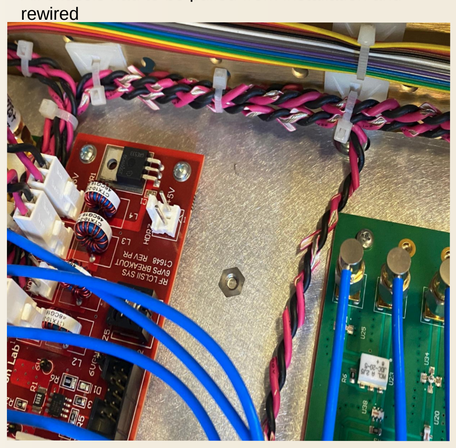
Water doesn't stay warm enough on cold nights to stay within regulation
This may affect RF phase measurements



2. Waveguide pressure digital readbacks would save time during troubleshooting

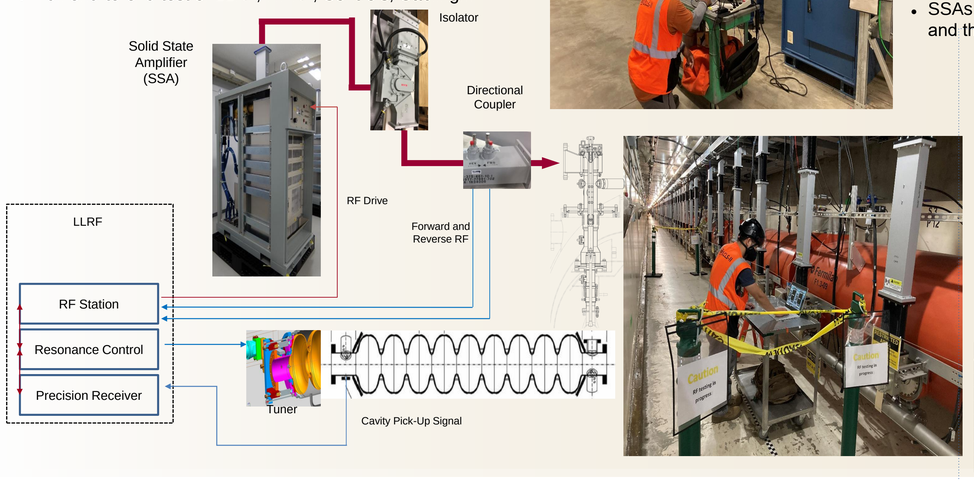
When RF trips, we often have to drive 2 miles to look at analoge waveguide pressure panels

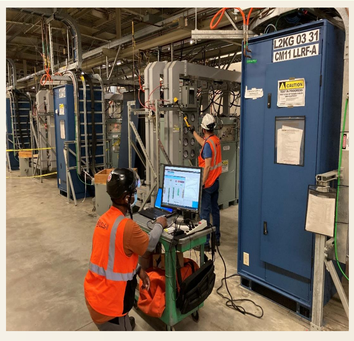
3. LLRF Chassis wire insulation began degrading in more than 50% of LLRF chassis
Suspected counterfeit insulation
All chassis had to be pulled from installation and rewired



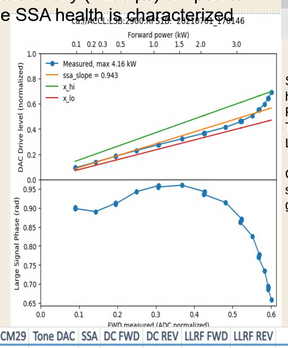
HPRF to warm cavities – a final RF check

- During Summer 2021, every RF System was fully energized to test RF integration
- Possibly the only time personnel can access the accelerator with HPRF energized
- Calculated normal conducting cavity voltage of about < 10 kV in this mode
- Full end-to-end test of LLRF, HPRF, Controls, Cabling...





- HPRF test
- LLRF drives SSAs at 400 W to warm CM cavities
- Waveguide non-ionizing radiation (NIR) surveys
- Power measurements are made at the directional couplers
- SSAs are briefly (<200 µs) chirped to 4 kV and the SSA health is characterized



SSA at CM29, cavity 5 is healthy
Peak RF power: 4.2 kW
Total phase slew: 0.2 rad
LLRF will not over drive SSA

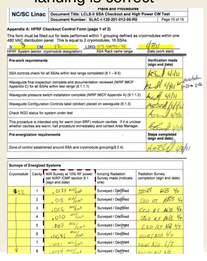
Calibration error of reverse signal at CM29, cavity 6 is greater than 5%

CM29	Tone DAC	SSA	DC FWD	DC REV	LLRF FWD	LLRF REV		FWD Error	REV Error
1	5790	404	394	397	389	387		1.27	2.52
2	5490	402	380	363	370	358		2.63	1.38
3	6100	400	389	387	386	380		0.77	1.81
4	5700	400	360	362	353	344		1.94	4.97
5	5675	402	395	374	387	370		2.03	1.07
6	6200	398	401	388	398	368		0.75	5.15
7	6090	405	337	346	338	341		0.30	1.45
8	5500	402	382	374	377	376		1.31	0.53

Failure type	Number found
Swapped SSA permit Cables	78 cases
Swapped RF heliax	Many (fixed immediately)
Low RF drive	28 chassis
Failed SSA electronics	18 failed interlock PCB 1 failed Control Unit 2 Failed Amplifier modules
Calibration error > 5%	>50 cases
Poor water flow	often

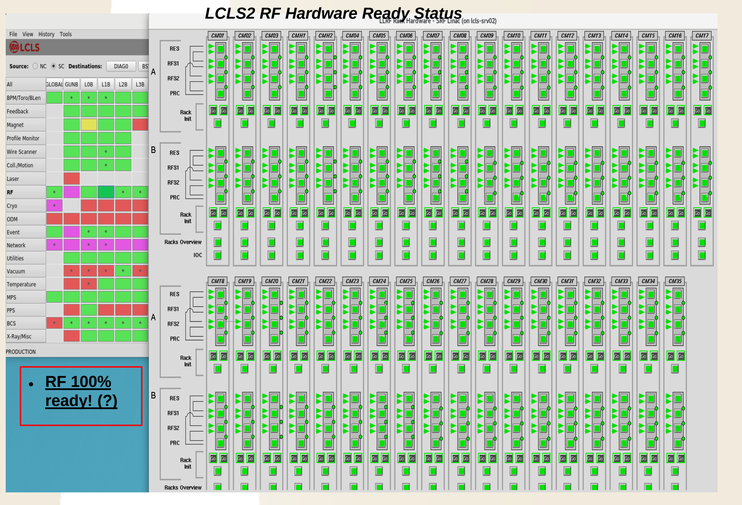
Successful HPRF test outcomes worth noting:

- SSA permit to LLRF is functional
- SSA drive cable is correctly mapped
- LLRF drive signal is correct
- LLRF – EPICS mapping is correct
- SSA – EPICS mapping is correct
- RF Heliax cable mapping to CM landing is correct



- LLRF System Checkout finished in April 2022, but LLRF system development continued leading to more troubleshooting
- 100% ready status for hardware was achieved 10/04/2022

LCLS2 RF Hardware Ready Status



This work was supported by the LCLS-II project and the U.S. Department of Energy, contract DE-AC02-76SF00515