LCLS-II Status

LLRF Workshop 2022

Andy Benwell

U.S. DEPARTMENT OF ENERGY | Stanford University

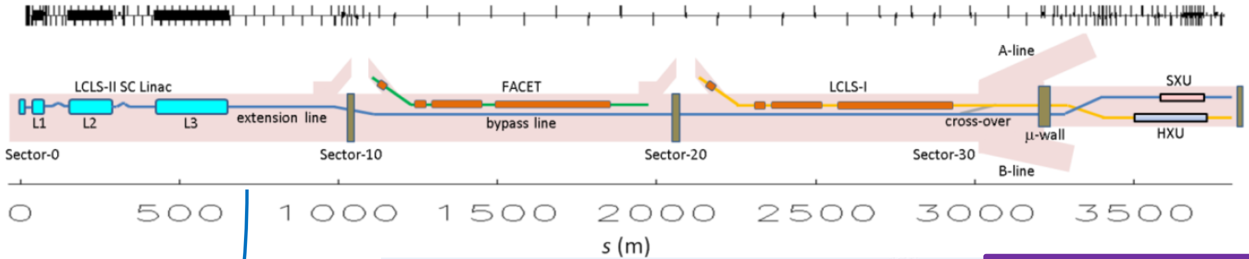
SLAC NATIONAL ACCELERATOR LABORATORY

- SLAC is developing an upgrade of its <u>Linac Coherent Light Source (LCLS)</u> that will be at the forefront of X-ray science.
- LCLS-II will provide a major jump in capability:
  - Increasing from 120 pulses per second to **1 million pulses per second**.
  - Enabling researchers to perform experiments in a wide range of fields that are currently impossible.
  - The unique capabilities of LCLS-II will yield a host of discoveries to advance technology, new energy solutions and our quality of life.

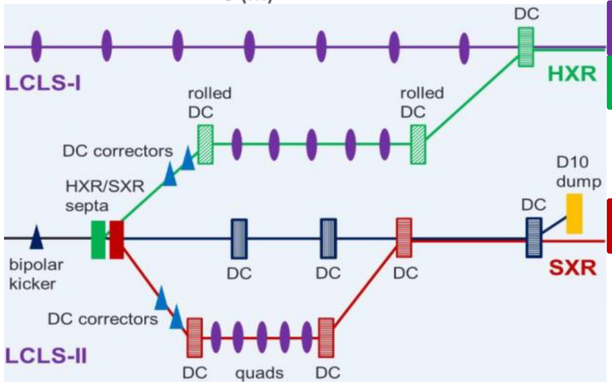

Remove SLAC Linac from Sectors 0-10
New Injector and New Superconducting Linac
LCLS-II
New Cryoplant
SLAC
BERKELEY LAB
Argonne
Fermilab
Jefferson Lab
Existing Bypass Line
New Transport Line
Two New Undulators And X-Ray Transport
Reconfigure Near Experiment Hall

LCLS-II (LLRF 2017)

- The Linac Coherent Light Source (LCLS-II), in Menlo Park, CA is designed produce a 4 GeV electron beam at high repetition rate (up to 1 MHz) for Soft X-ray (SXU) and Hard X-ray (HXU) Undulators
- In order to accomplish this, SLAC will install 280 1.3 GHz superconducting RF cavities in the first third of the 2-mile accelerator housing
- Superconducting RF is new for SLAC – much partner lab help is needed!



2 - 4.5 GeV, 1 MHz electron source

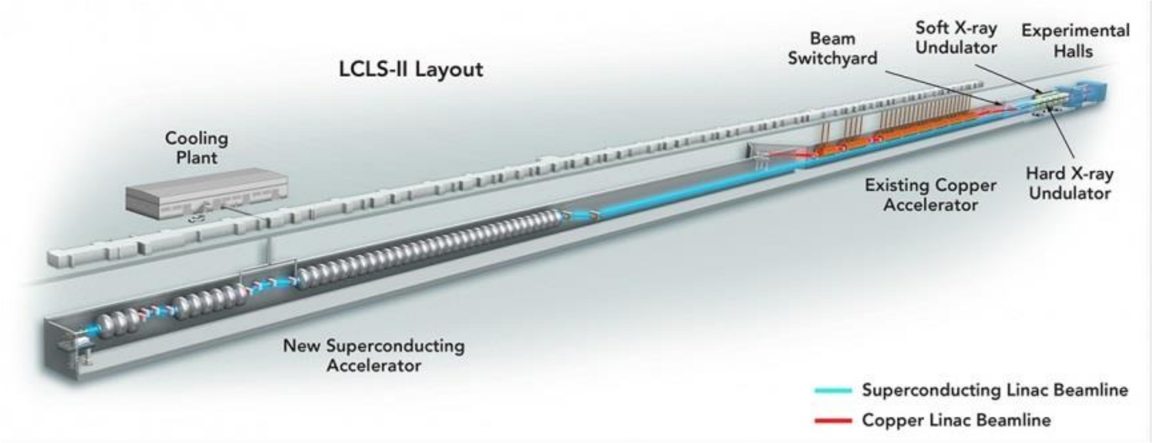


4 – 13 keV photons, 120Hz

1 – 5 keV photons, 1 MHz

0.2 – 1.3 keV photons, 1MHz

LCLS – II (LLRF 2019)



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- In order to accomplish this, SLAC is installing 280 1.3 GHz SRF cavities and 16 3.9 GHz SRF cavities in the first third of the 2-mile accelerator housing
- Superconducting RF is new for SLAC – we have benefitted greatly from the LLRF collaboration

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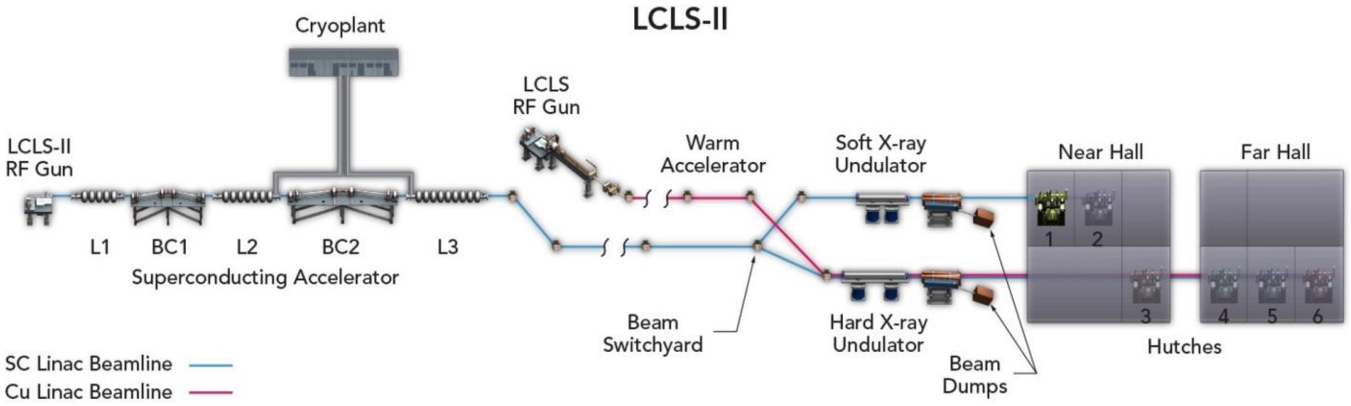
LCLS – II (LLRF 2022)



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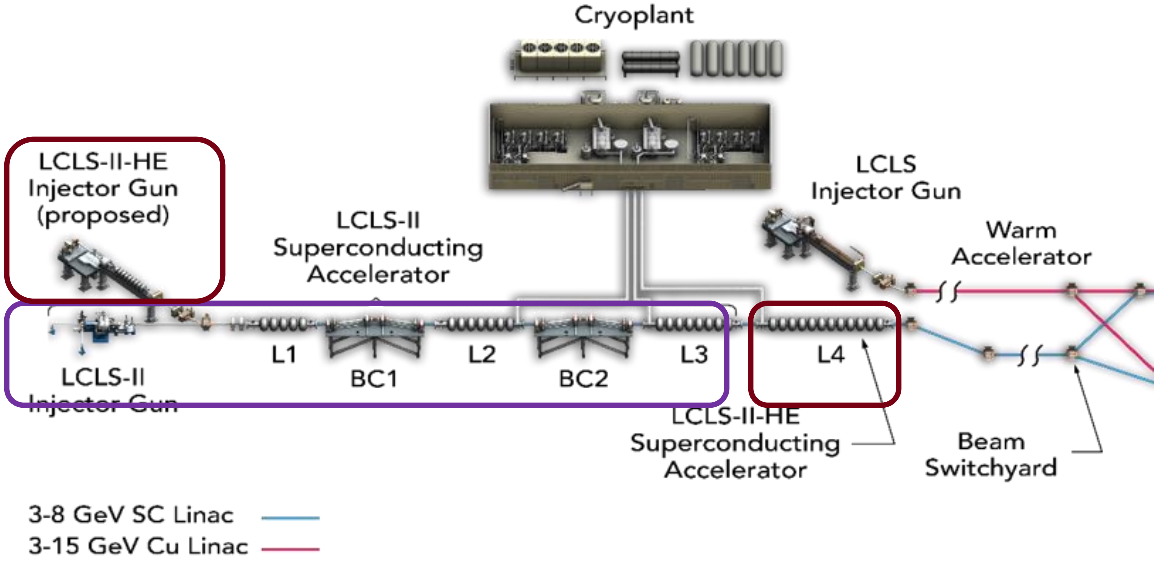
- To accomplish this, SLAC is installing 280 1.3 GHz SRF cavities and 16 3.9 GHz SRF cavities in the first third of the 2-mile accelerator housing
- We have now run SRF cavities at SLAC – and we are grateful for all the help from our colleagues!

LCLS-II HE (LLRF 2022)

- LCLS-II HE is a high energy upgrade to the LCLS-II linac
- 23 new cryomodules added to the LCLS-II SRF linac
- 5 total linac segments, the first four (L0-L3) accelerating the beam to 4 GeV
- New final section (L4) accelerating the remaining beam to 8 GeV
- 46 new LLRF rack systems to regulate 23 new cryomodules



LCLS-II Technical Parameters

Key equipment	Threshold	Objective
Variable gap undulators	2 (soft and hard x-ray)	2 (soft and hard x-ray)
Superconducting linac-based FEL system		
Superconducting linac electron beam energy	3.5 GeV	≥ 4 GeV
Electron bunch repetition rate	93 kHz	929 kHz
Superconducting linac charge per bunch	0.02 nC	0.1 nC
Photon beam energy range	250–3,800 eV	200–5,000 eV
High repetition rate capable end stations	≥ 1	≥ 2
FEL photon quantity		> 10^{11} @ 3,800 eV

Parameter	LCLS-II
# 1.3 GHz CMs	35
Operating Gradient	16 MV/m
Required Q_0 at Operating Gradient	2.7×10^{10}

LCLS-II (HE) RF Requirements

- RF field regulation at > 0.1 Hz
  - **0.01°** RMS in phase
  - **0.01%** RMS in amplitude
- RF regulation assumes
  - < 1% beam current fluctuation
  - < 10 Hz microphonic detuning
- Resonance Control regulation
  - **< 1Hz** Piezo tuner setting accuracy

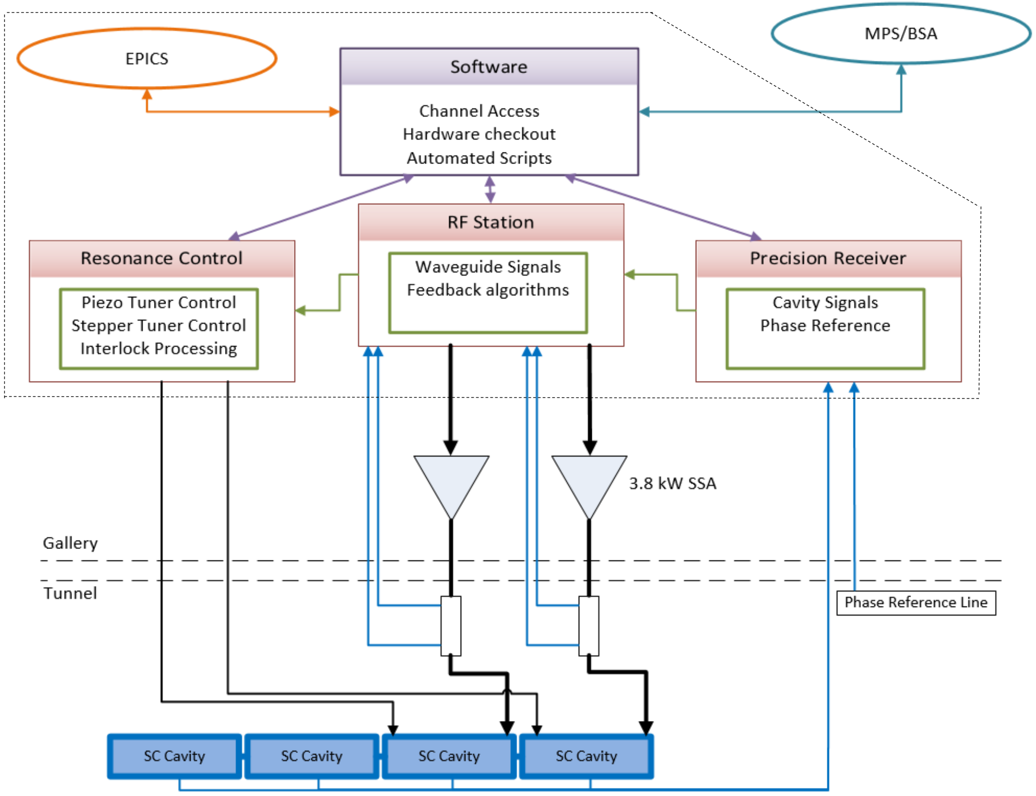
HE Linac Changes

- New high gradient SRF Gun
- L2 and L3 gradient increased
- L2 and L3 cavity QL increased (manually)
- L4 – new, with high gradient

Section	# of CM	# of Cavities	Minimum Gradient [MV/m]	QL	SSA Power [KW]
SRF Gun	-	1	20		6
L0	1	8	16.3	4.1e7	3.8
L1	2	16	13.6	4.1e7	3.8
L2	12	96	**15.5 -> 16**	**4.1e7->6.0e7**	3.8
L3	20	160	**15.5 -> 16**	**4.1e7->6.0e7**	3.8
L4	23	184	**20.8**	**6.0e7**	**7.0**

Scope: LLRF System Architecture

- **Hardware/Firmware**
  - **Precision Receiver Chassis (PRC)**
    - Exclusively for cavity signals
    - Fiber communication for **high Isolation** necessary for 0.01°/0.01%
  - **RF Station (RFS)**
    - Generates independent RF signal for 2 cavities
    - Forward, Reverse and SSA Drive signals
    - Detune frequency calculation, PI loop control
  - **Resonance Control**
    - Piezo Tuner Control
    - Stepper Motor Control
    - Temperature Monitoring
    - Interlock processing
- **Software**
  - Automated Scripting
    - Cavity and System Characterization
  - Smooth transition between modes
  - Channel Access
- **EPICS**
  - All control displays and waveform readouts
  - Cavity control interface
    - Modes of Operation
  - Hardware health



Early Testing Opportunities

- Cryomodule test facilities at FNAL and JLab used for LCLS-II LLRF for testing CMs

- Mandate for system to be as close to production as possible
  - All modes of operation (SEL, SELAP, Pulsed)
  - SSA and LLRF control
  - User interfaces
  - Calibration routines
  - Tuning scripts

- Cryomodules controlled by physicists, operators and LLRF
- experts

- Because of this, the LLRF controls system software and firmware were very mature for LCLS-II Commissioning

FNAL CMTF

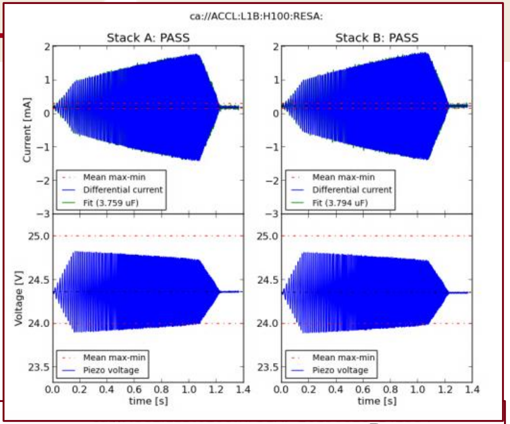
Jlab LERF Gallery

How to run? - Characterize System and Go

5 “easy” steps

1. Piezo tuner health check (expect ~ 3.5 uF)
2. SSA calibration
3. Chirp detune scan
   - Immediately “find” cavity and enter SEL
4. Pulsed SEL calibration
   - Measures loaded Q
   - Calculates cavity scale factor, based on energy integration
5. Piezo tuner gain scan

1.



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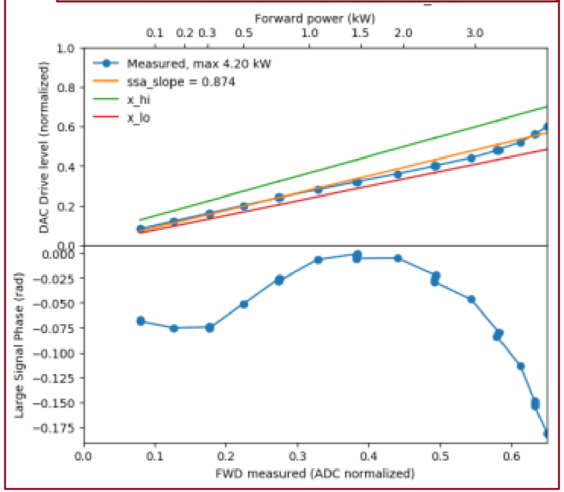
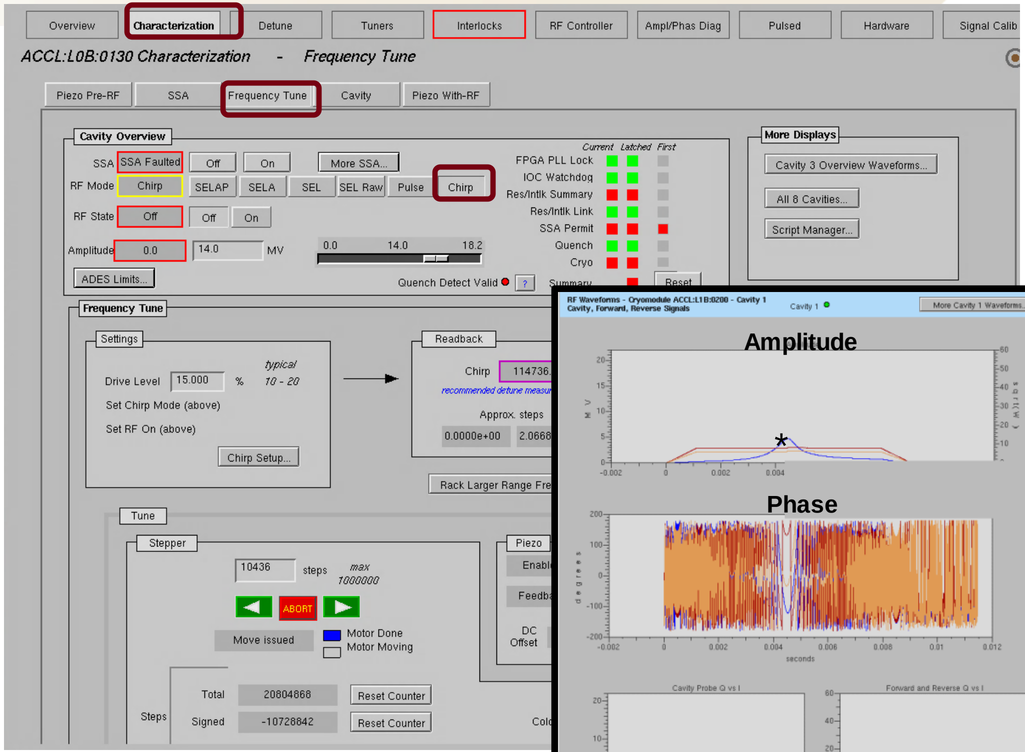
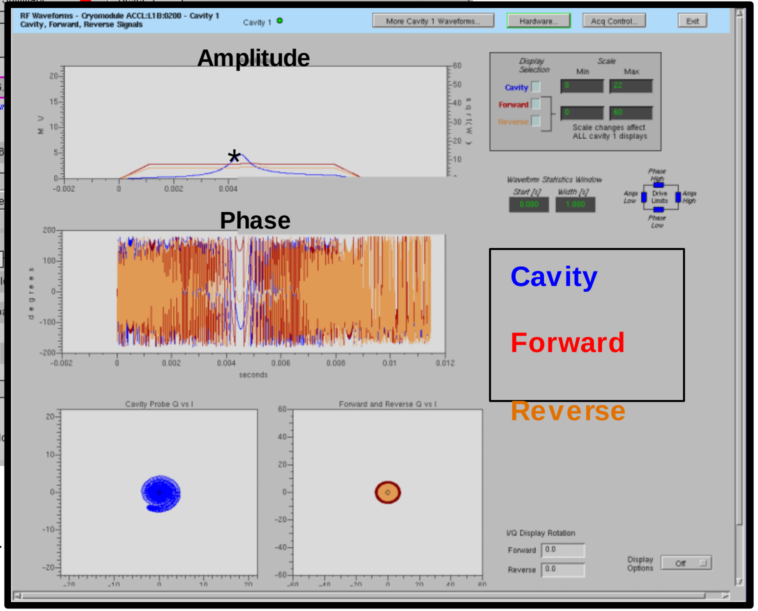


3 Chirp Detune Scan

Fast frequency scan of the SRF cavity

- Perform quick frequency sweep (like a network analyzer)
- Immediately “find” cavity in frequency domain
- User can tune the cavity to the nominal frequency (1300 MHz) with stepper tuners during chirp
- Frequency scan range as wide as 1 MHz to find various modes of cavity
  - Set 7pi/9, 8pi/9 mode digital filter frequency



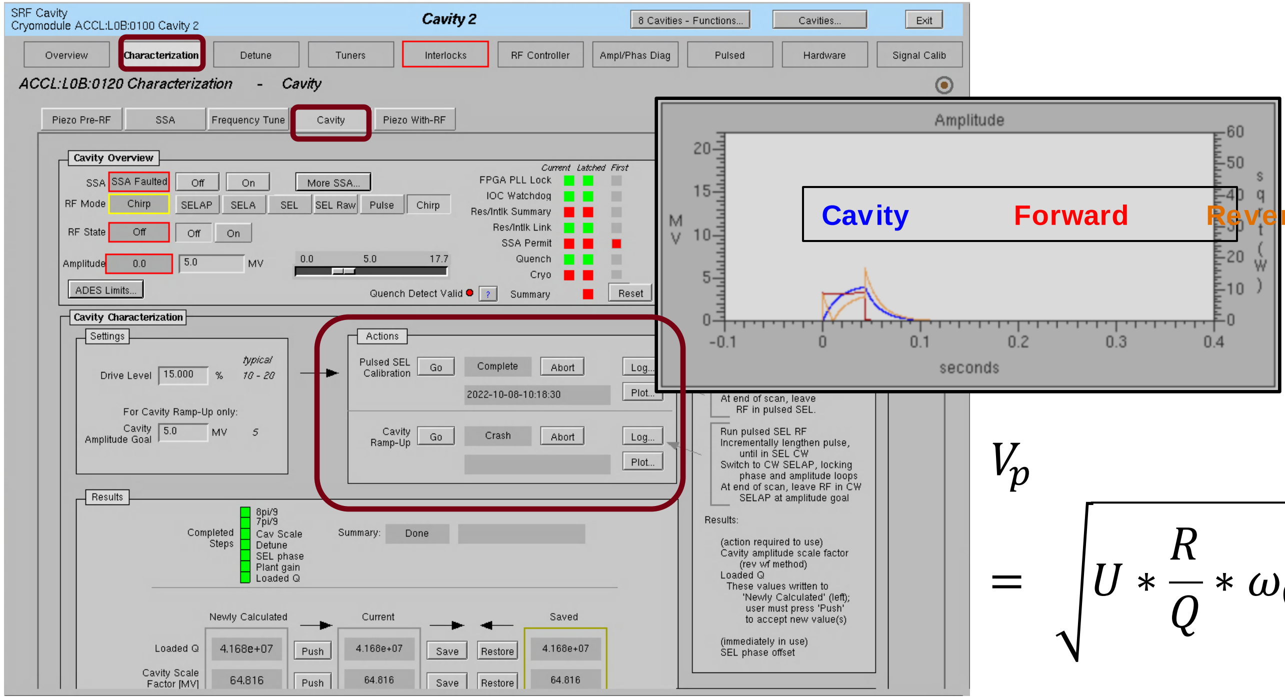


*This is a chirp of a low Q cavity emulator

4 Cavity Characterization

Run pulsed mode to generate a series of cavity waveforms for analysis

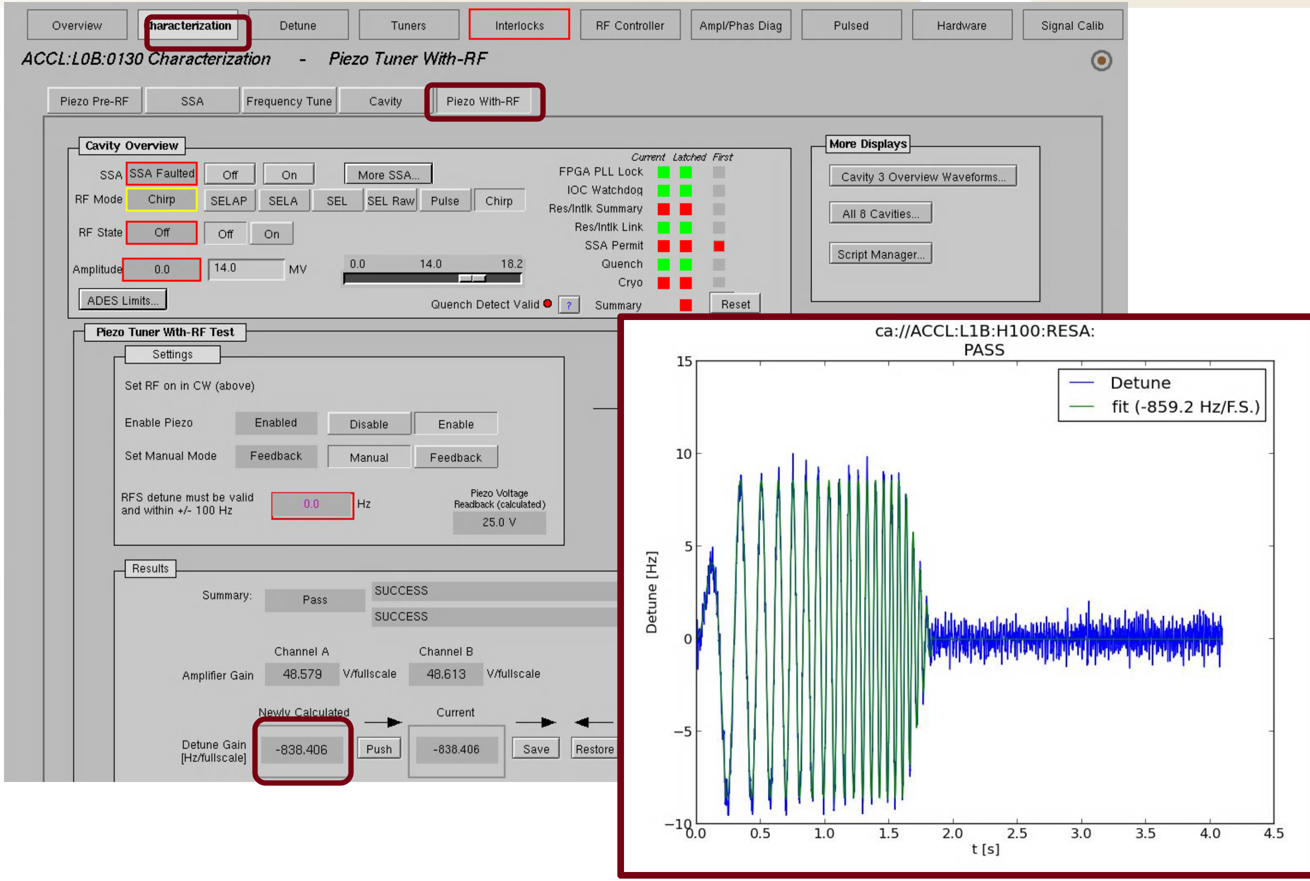
- Measure Loaded Q based on decay time
- Calculate **cavity scale factor**, based on the energy integration of the reverse power



$$V_p = \sqrt{U * \frac{R}{Q} * \omega_0}$$

5 Piezo Tuner Detuning Gain

- Piezo tuner excited a fraction of full scale
- Measurement made with RF on
- Detune gain saved and set for piezo tuner feedback



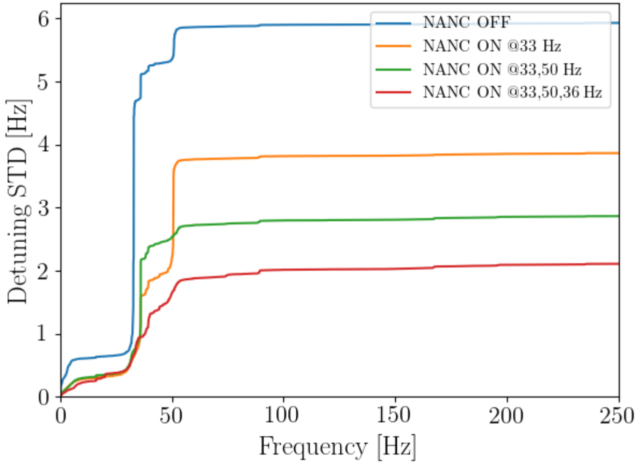
LCLS-II LLRF System – usable modes of operation

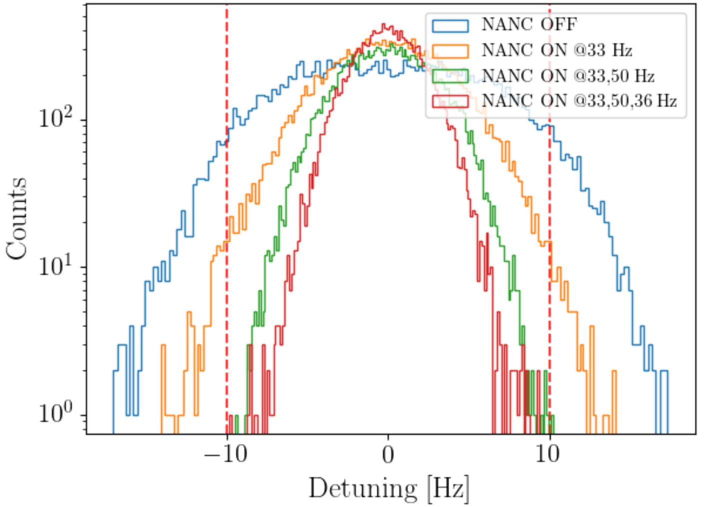
mode	description
SEL (Self Excited Loop)	RF system tracks the cavity frequency in open loop, no phase or amplitude regulation
SELA (Amplitude)	RF system tracks the cavity frequency while maintaining cavity amplitude with feedback loop parameters
SELAP (Phase)	RF system runs at nominal frequency while maintaining cavity amplitude and phase If detuning is temporarily beyond regulation parameters, RF will temporarily enter SELA to maintain cavity gradient
Chirp	Frequency sweep over 100 kHz (now up to 1Mz) within one waveform to quickly measure detune Used during characterization to find 7pi/9, 8pi/9, and pi mode
Pulsed	Pulsed RF, currently only in SEL (no phase lock)
Tone	Open loop forward power without tracking frequency. Used for SSA characterization and expert troubleshooting
Integrator (on)	Piezo tuner feedback loop enabled. Tunes cavity based on RF detune calculation

Fun New Tools

- Active Resonance Control (ARC) using Narrowband Active Noise Control (NANC)
- Compensation for frequencies from 0 to ~500 Hz using the piezo tuner
- Reduction in cavity detuning is ~9 dB
- NANC adapts automatically for drifts and changes in microphonics disturbances.
- Up to 4 different microphonics frequencies can be compensated using totally independent NANC components

Andrea Bellandi, Jorge Diaz

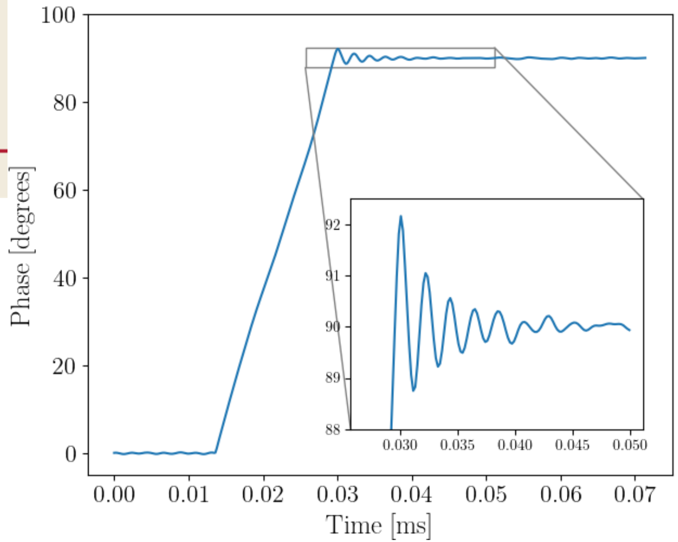


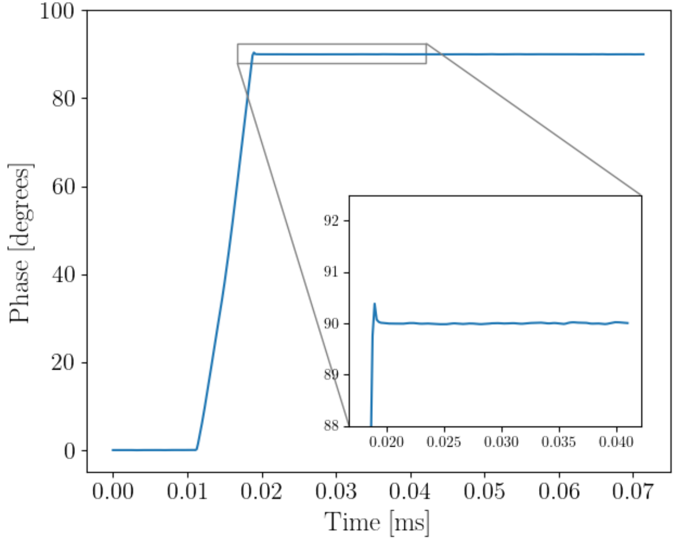


Fun New Tools

- Gain Optimization
- Script to set LLRF field control gains, P & I, for A & Φ
- Extend the cavity open-loop half-bandwidth from tens of Hz to KHz.
- Controller zero at a fraction of the new bandwidth to reduce steady state error
- Good results so far…
  - Less overshoot
  - Reduced oscillation and settling time
  - Faster response

Larry Doolittle, Jorge Diaz





LCLS-II Installation Layout

- 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
- 1536 heliax cables
- 3,850 fiber optic connections (in the LLRF racks alone)

LLRF System Hardware Checkout

- Procedure scope:
  - Rack energization
  - Chassis network configuration
  - Automated chassis communication checks (chassis – network, and chassis to chassis)
  - Distributed clock and signal balancing
  - Calibration and evaluation of PRL signal
  - Cryomodule resonance control system
  - RF heliax routing and calibration
  - CM cable connections and torqued
  - EPICS monitoring of system health
  - Vacuum system interlock checks
  - Precision timing system fiber links
  - Machine Protection System fiber links

HPRF to Warm Cavities Checkout – Summer 2021

1. LLRF controls SSAs to 400 W to warm CM cavities
2. Waveguide non-ionizing radiation (NIR) surveys
3. Power measurements are made at the directional couplers
4. SSAs are briefly (<200 µs) chirped to 4 kW and the SSA health is characterized

Issues discovered during HPRF checkout include:

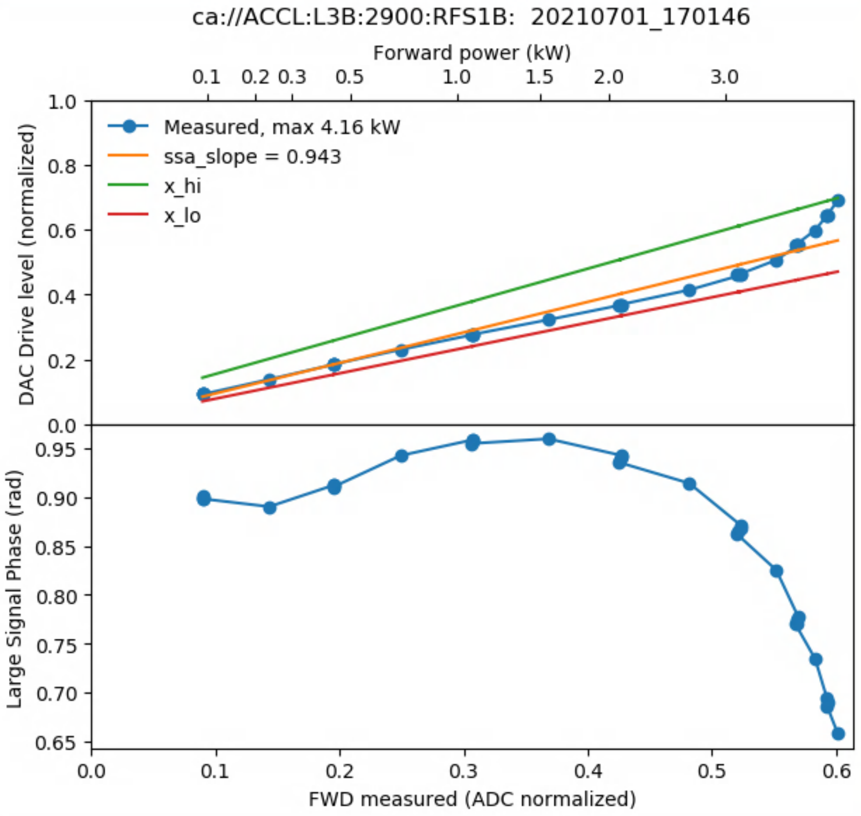
- Swapped permit cables
- Swapped RF heliax
- Low RF drive
- Poor water flow
- failed SSA electronics components
- Calibration error > 5%

Typical Test Results – Warm HPRF

- 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%

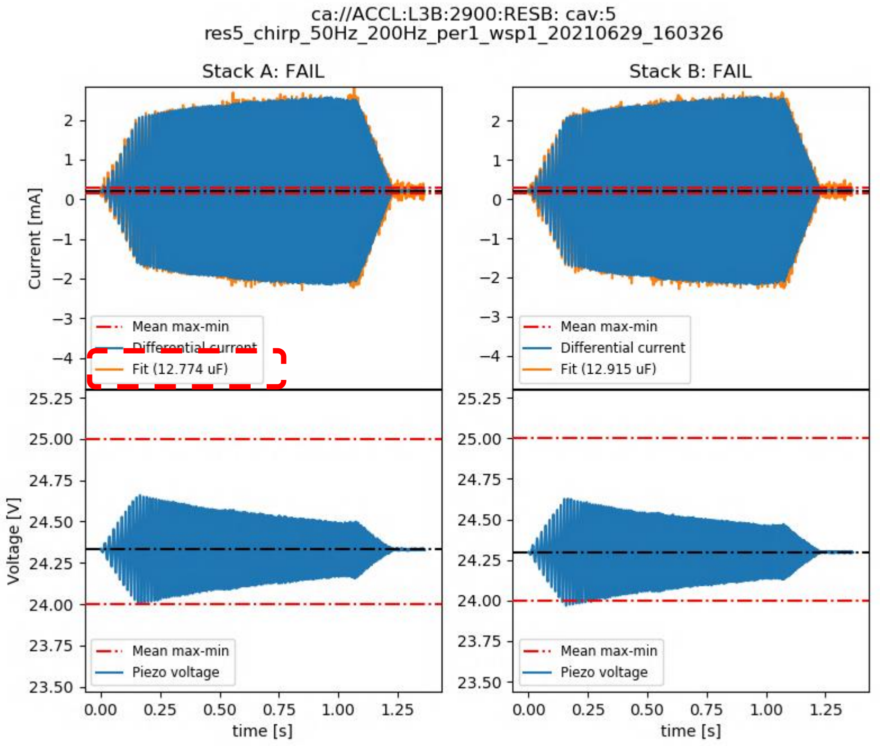
CM29	Tone DAC	SSA	DC FWD	DC REV	LLRF FWD	LLRF REV		FWD Error	REV Error
1	5790	404	394	397	389	387		1.27	2.52
2	5490	402	380	363	370	358		2.63	1.38
3	6100	400	389	387	386	380		0.77	1.81
4	5700	400	360	362	353	344		1.94	4.97
5	5675	402	395	374	387	370		2.03	1.07
6	6200	398	401	388	398	368		0.75	5.15
7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



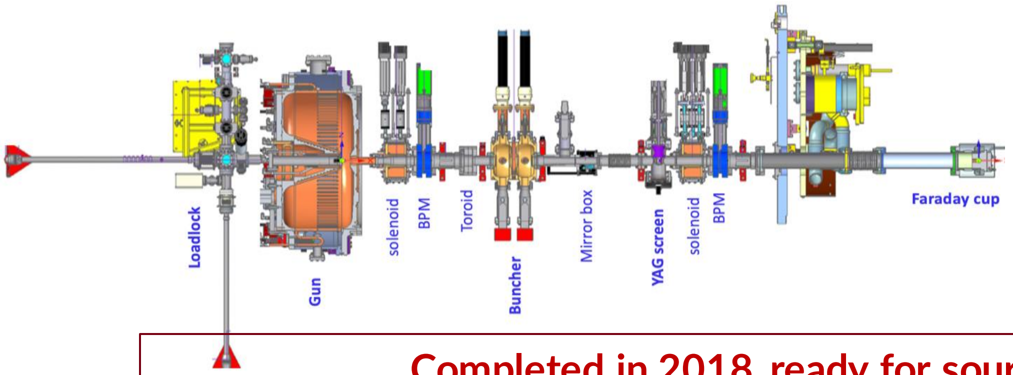
Typical Results – Warm Piezo

Other system test results 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
- Piezo tuner capacitance is correct for a warm cavity
    - ~ 13 uF



Electron Gun and NC Beam Line Installation



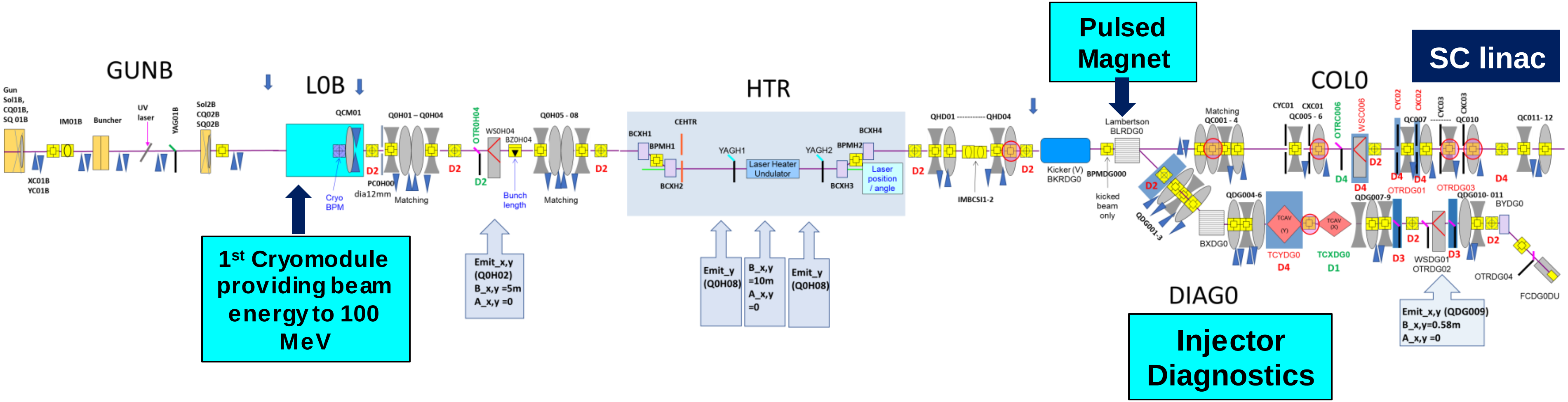
Electron Gun cavity

Completed in 2018, ready for source commissioning

- Electron source beamline was built by LBNL (APEX Gun)
- Laser system was manufactured by Amplitude:
  - Oscillator operates at 46.43MHz
  - Modulator selects pulse rate from 0 to 1MHz
  - Conversion from IR to UV is 8-20%
- Commissioned e-source (2018-2020), including several upgrades (e.g. tuners, additional collimators)

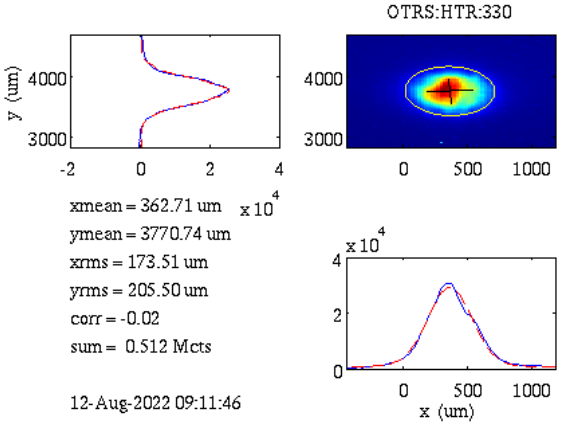
Parameters	Nominal
Gun energy (keV)	750
Gun cathode gradient (MV/m)	19.5
Cathode QE	> 0.5%
Laser energy (μJ) on the cathode	0.3 μJ
Maximum bunch repetition rate (MHz)	0.93
Nominal bunch charge (pC)	100
Initial beam current (μA)	30

100 MeV Injector Commissioning, August 2022



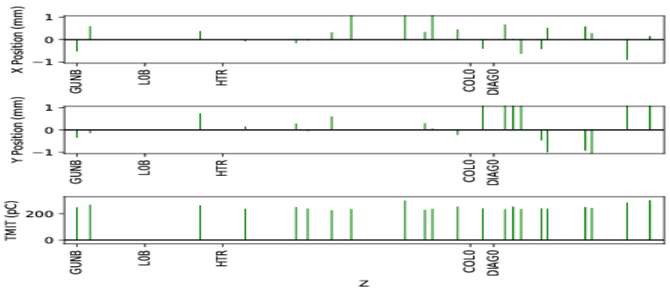
- Established beam through CM01
- Optimize to design specifications (emittance, charge, transmission)
- Conduct beam containment system (BCS) certification
  - Calibration of Beam Safety System devices at high repetition rate and bunch charge
  - Average beam current and beam loss monitoring

100 MeV Injector Performance

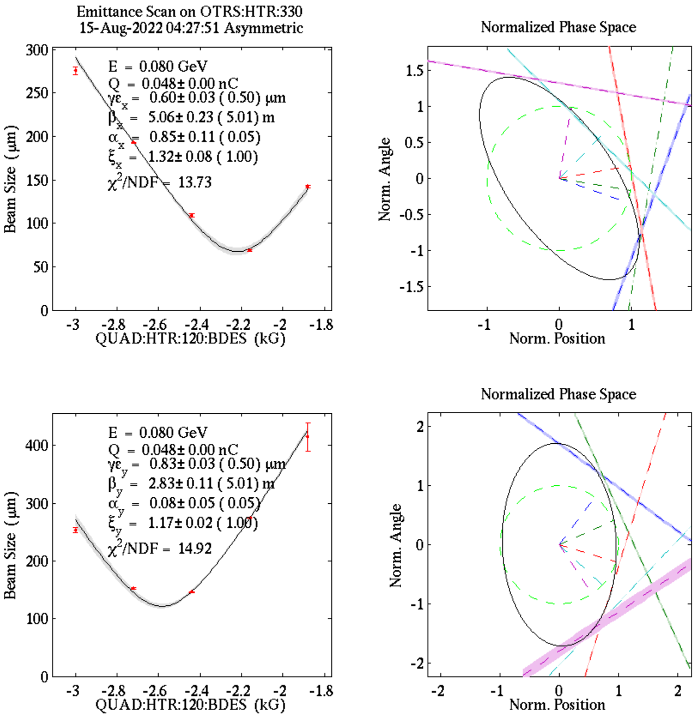


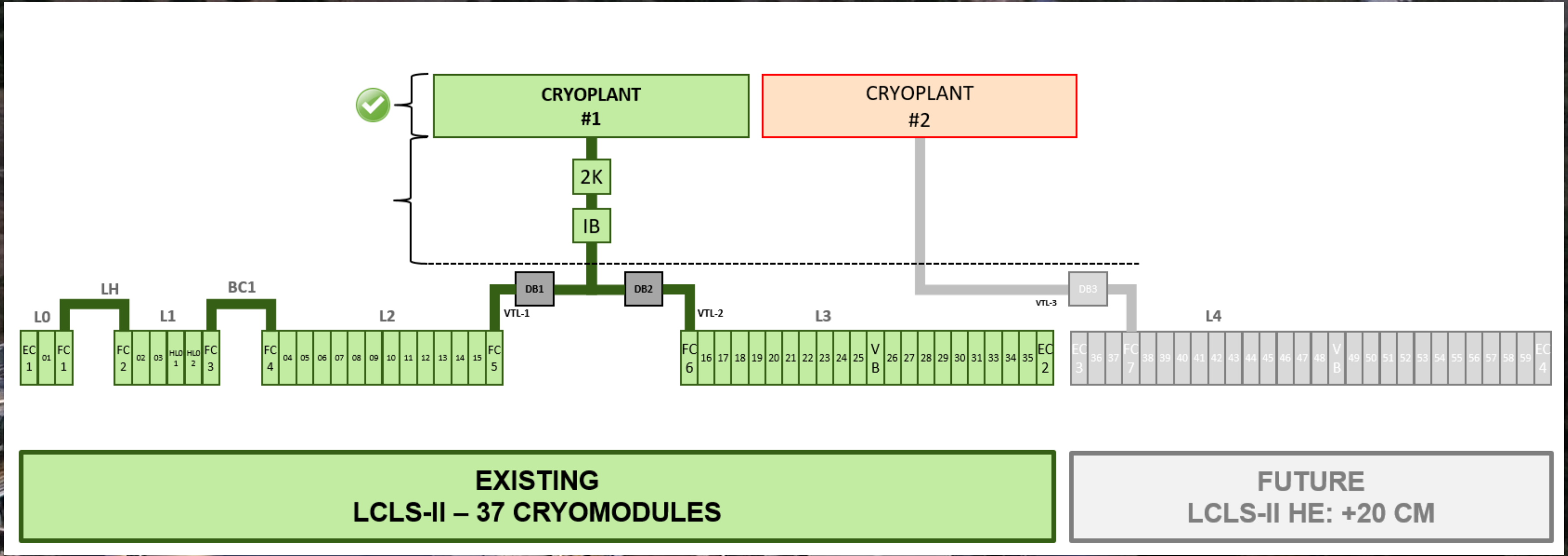
100 MeV electron beam image

Injector electron beam orbit 250 pC, 100% transmission



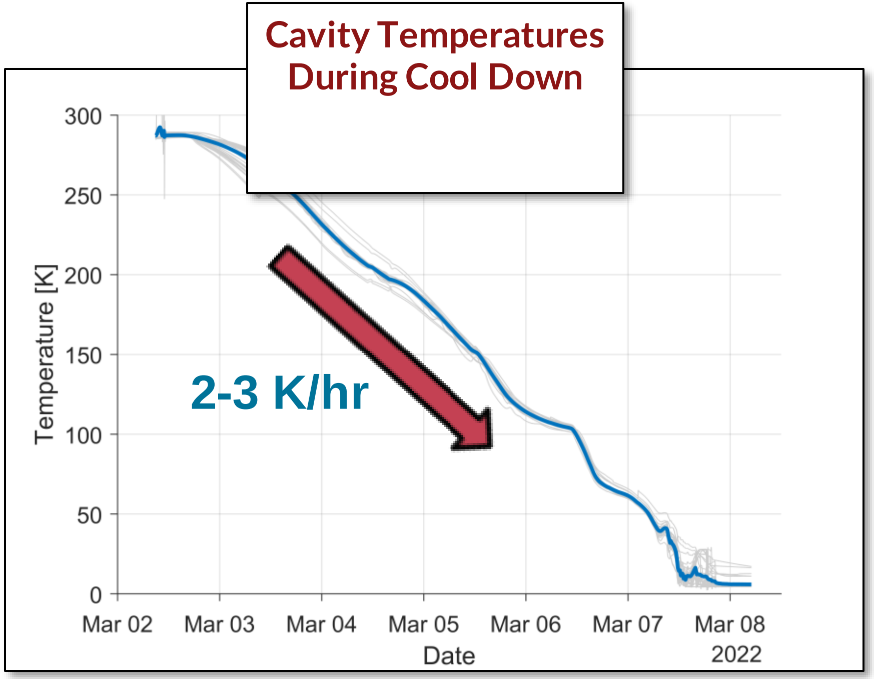
Excellent Injector emittance: 0.6x0.8 μm





Plan to fully commission and operate LCLS-II with 1 of 2 installed cryoplants

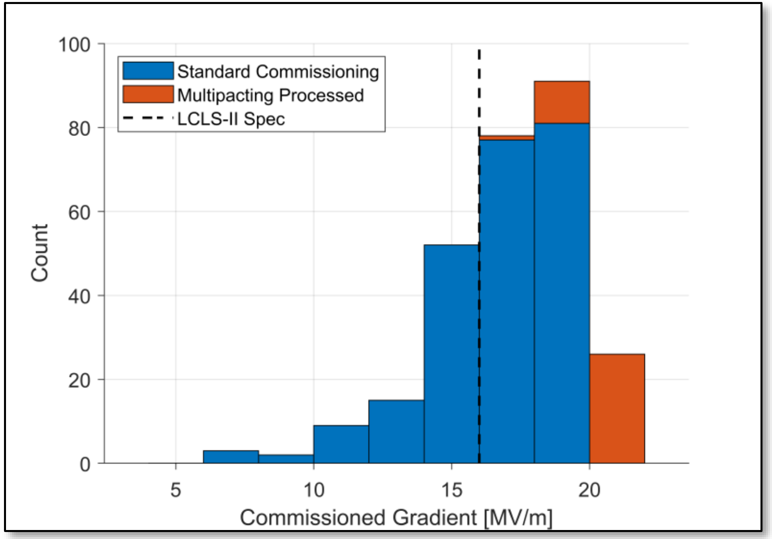
Cool Down & Pump Down to 2 K



- Cool down of the entire linac was completed in **~5 days!**
- A rate of 2-3 K/hour was maintained over that duration
- Cool down was **near-fully automated** by the cryogenic controls system
- After multiple attempts, stable operation at 2 K was achieved **only 11 days later**

Overall SRF Commissioning Status

Gradient Performance

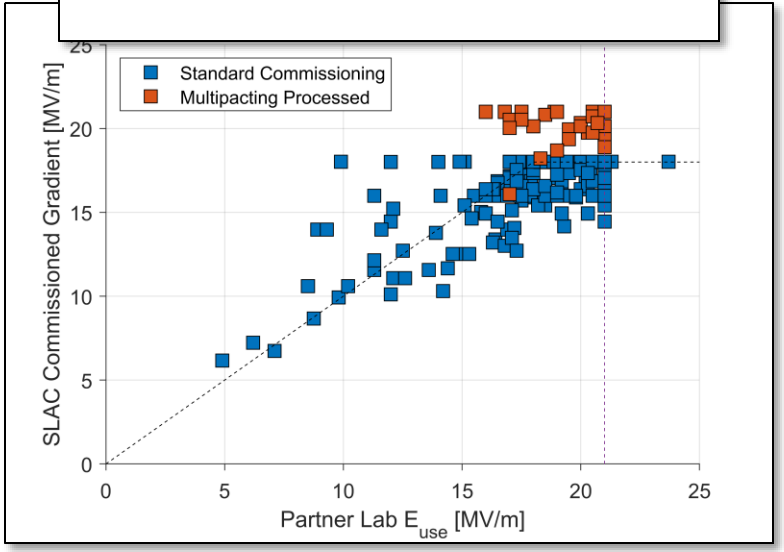


- Cryomodule commissioning has been very successful
- 97% of installed cavities fully operational (planned 94%)
- Majority of testing included an admin limit of 18 MV/m
- Total commissioned voltage **exceeds design by >20%**

Total Commissioned Cavity Voltage: 4.9 GV

Gradient Performance

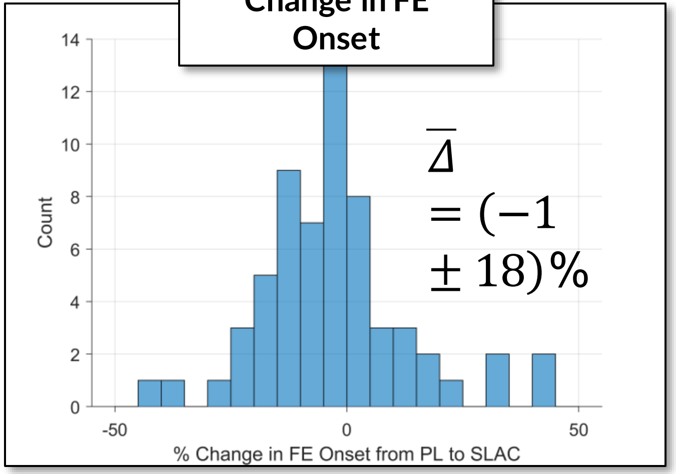
Comparison with Acceptance Test



Admin limits:
- 18 MV/m in commissioning
- 21 MV/m in acceptance test

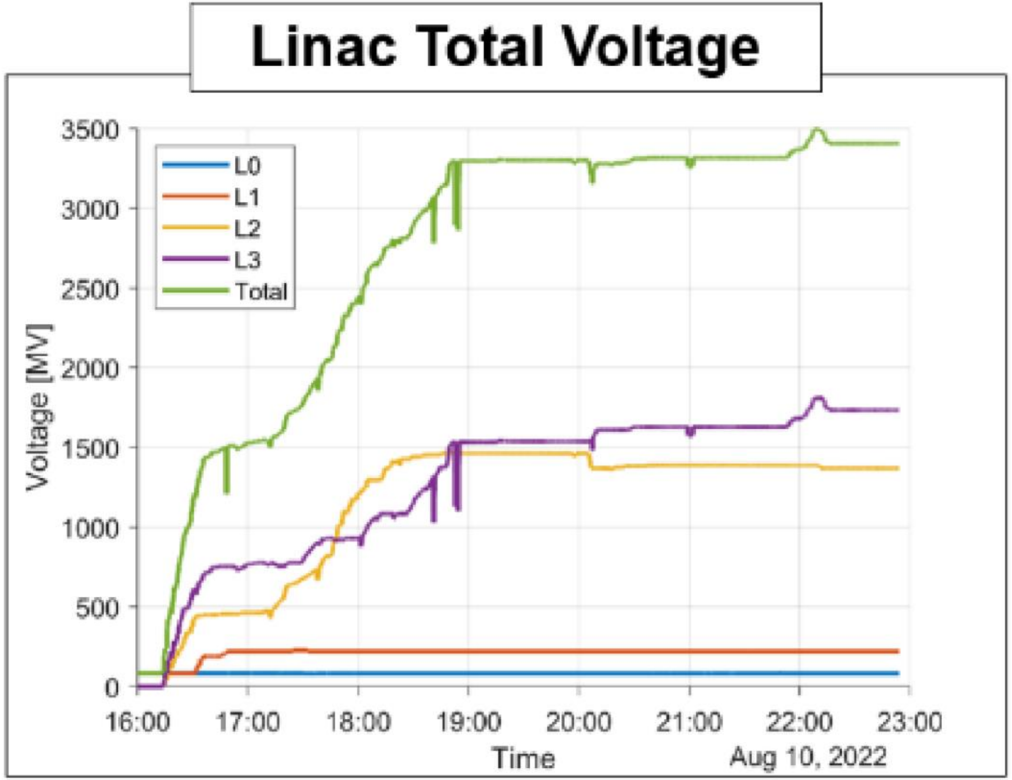
- Gradient performance is in line with CM acceptance test measurements at FNAL and Jlab
- **No observable change in field emission onsets or magnitude from installation**
- Multipacting processing resulted in ~3 MV/m gain in stable gradient

Change in FE Onset

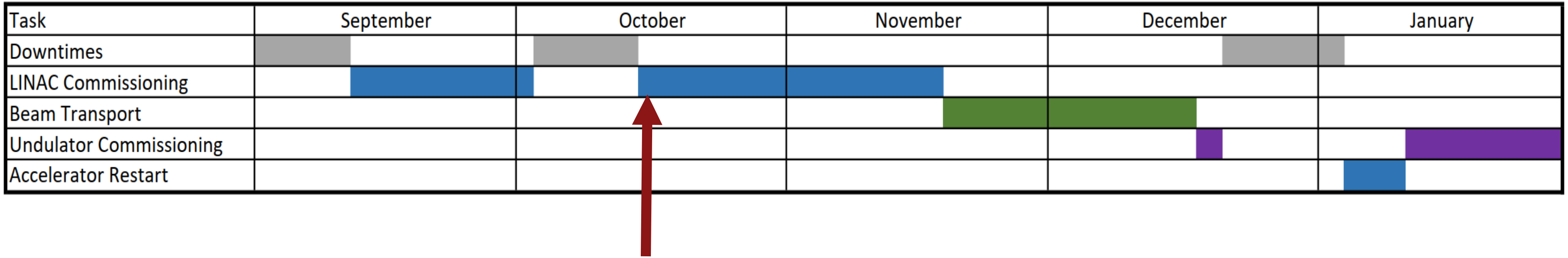


Linac Total Voltage

- First full SRF linac run 8/10/22
- LCLS-II powered on all of the 1.3 GHz cavities
- Demonstrated that controls systems for LLRF and cryogenic systems are working well
- All cavities powered on in less than 30 minutes
- Maximum achievable energy reached in ~3 hours
- Total energy: 3.495 MV



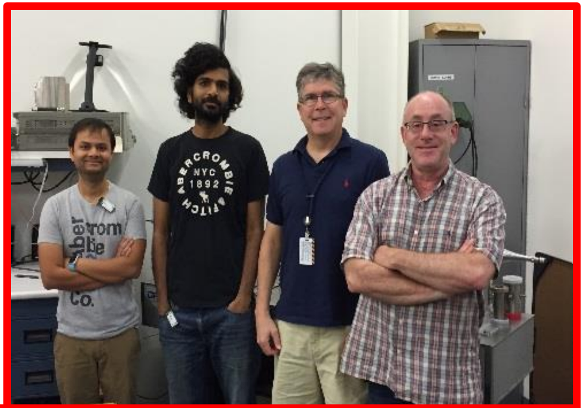
Schedule Outlook



Linac Commissioning for 4 GeV has begun (10/6/2022)

1st Light Milestone is anticipated in January of 2023

Special thanks to the entire LCLS-II collaboration for all their hard work to make this possible!



Fermilab

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CORNELL UNIVERSITY FOUNDED A.D. 1865

BERKELEY LAB
Lawrence Berkeley National Laboratory

Argonne NATIONAL LABORATORY

Jefferson Lab

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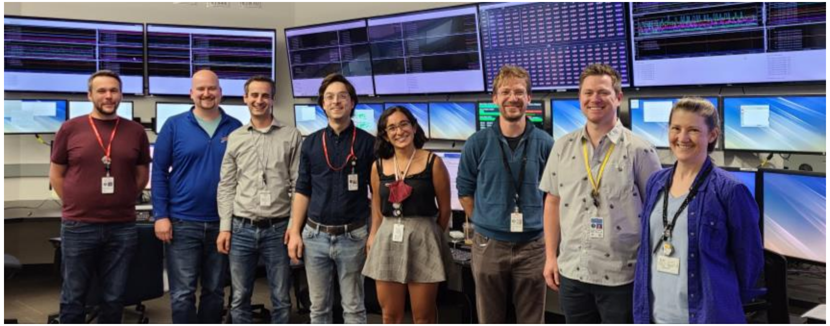

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Thank you for your time