LCLS-II SRF commissioning and early operational experience

ERL2024 KEK, WG-3

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September 27, 2024

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Outline

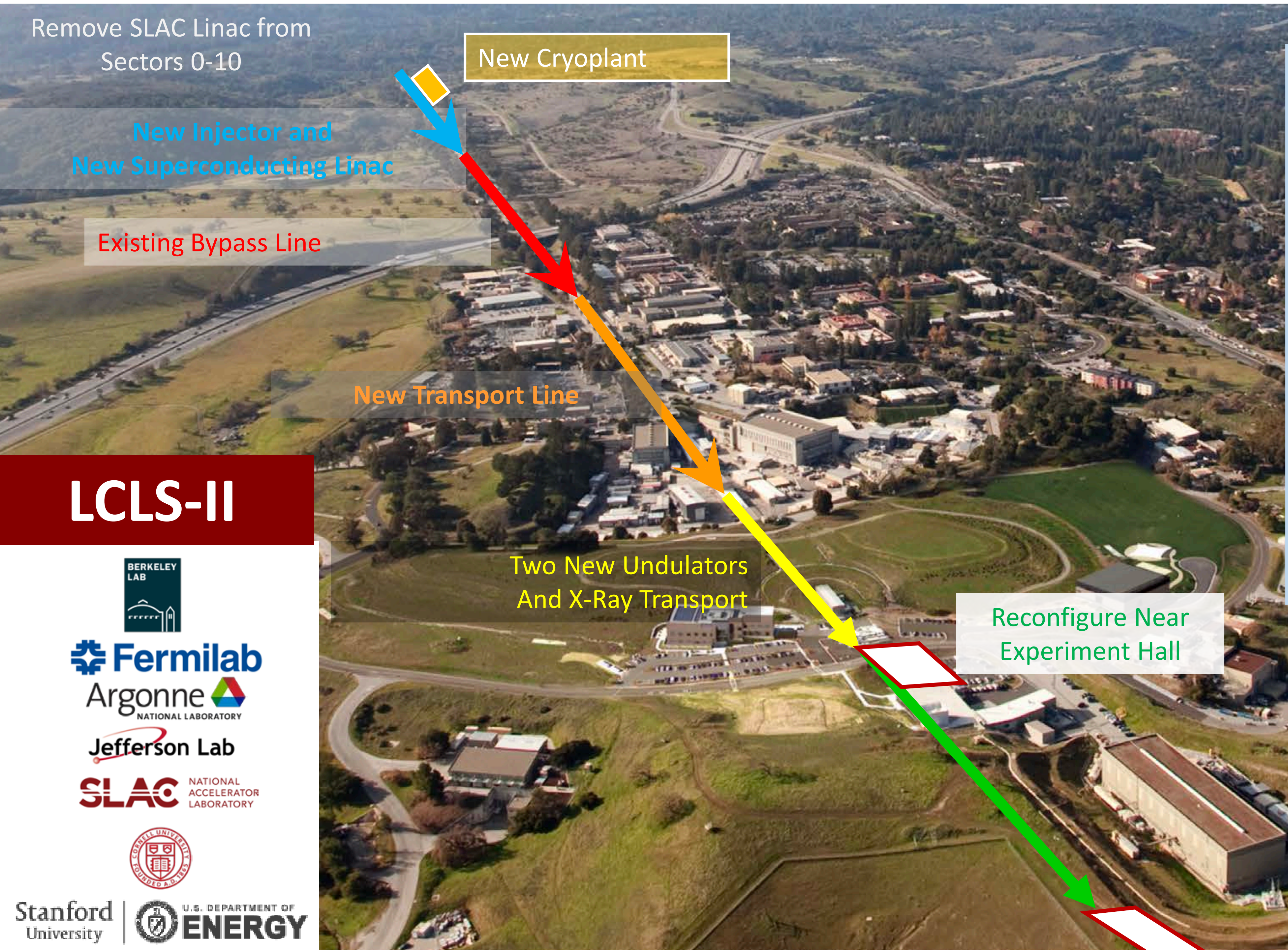
Facility Overview

SRF commissioning

Early operational experience

Outlook

Summary



LCLS-II

LCLS-II design features:

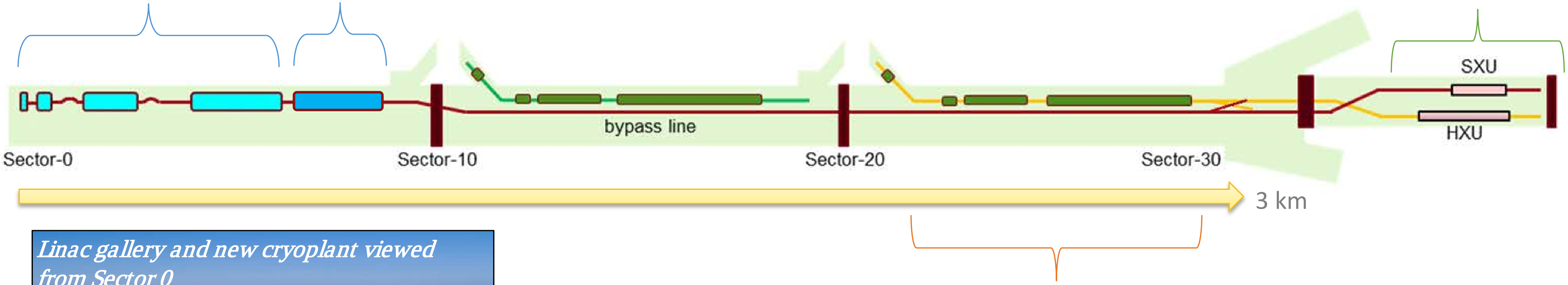
- *CW VHF gun*
- *CW SRF linac*
- *Support MHz-rate*
- *Two undulator lines*
- *Pulsed magnetic kicker*
- *Long (2km) bypass line*
- *Machine protection and beam loss control*

LCLS FEL complex based on normal and superconducting Accelerators

Superconducting Linac
4 GeV, High
rep-rate, CW RF

Future 8 GeV
extension
(LCLS-II-HE)

**Soft and Hard X-ray
Variable Gap
Undulators (VGUs)**



Normal Conducting Linac
3.5-17 GeV,
120 Hz Pulsed RF

LCLS-II Key Performance Parameters - KPPs

Performance Measure	Threshold (5 kW beam)	Objective (120 kW beam)	Measurements
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 ✓	$\geq$ 4 GeV	Spectrometer bend (magnet strength, screen)
Electron bunch repetition rate	93 kHz ✓	929 kHz	BPM's, laser rate
Superconducting linac charge per bunch	0.02 nC ✓	0.1 nC ✓	Toroid, Faraday cup
Photon beam energy range	250–3,800 eV ✓	200–5,000 eV	Absorption edges, spectrometer
High repetition rate capable end stations	$\geq$ 1 ✓	$\geq$ 2 ✓	N/A
FEL photon quantity (10^{-3} BW) per bunch	$5\text{x}10^8$ (10x spontaneous) @2,500 eV ✓	> 10^{11} @ 3,800 eV	Gas energy monitor, GMD, Spectrometer
Normal conducting linac-based system			
Normal conducting linac electron beam energy	13.6 GeV ✓	15 GeV ✓	Spectrometer bend (magnet strength, screen)
Electron bunch repetition rate	120 Hz ✓	120 Hz ✓	BPM's, laser rate
Normal conducting linac charge per bunch	0.1 nC ✓	0.25 nC ✓	Toroid, Faraday cup
Photon beam energy range	1–15 keV ✓	1–25k eV ✓	Absorption edges, spectrometer
Low repetition rate capable end stations	$\geq$ 2 ✓	$\geq$ 3 ✓	N/A
FEL photon quantity (10^{-3} BW[a]) per bunch	10^{10} (lasing @ 15 keV) ✓	> 10^{12} @ 15 keV	Gas energy monitor, GMD, Spectrometer

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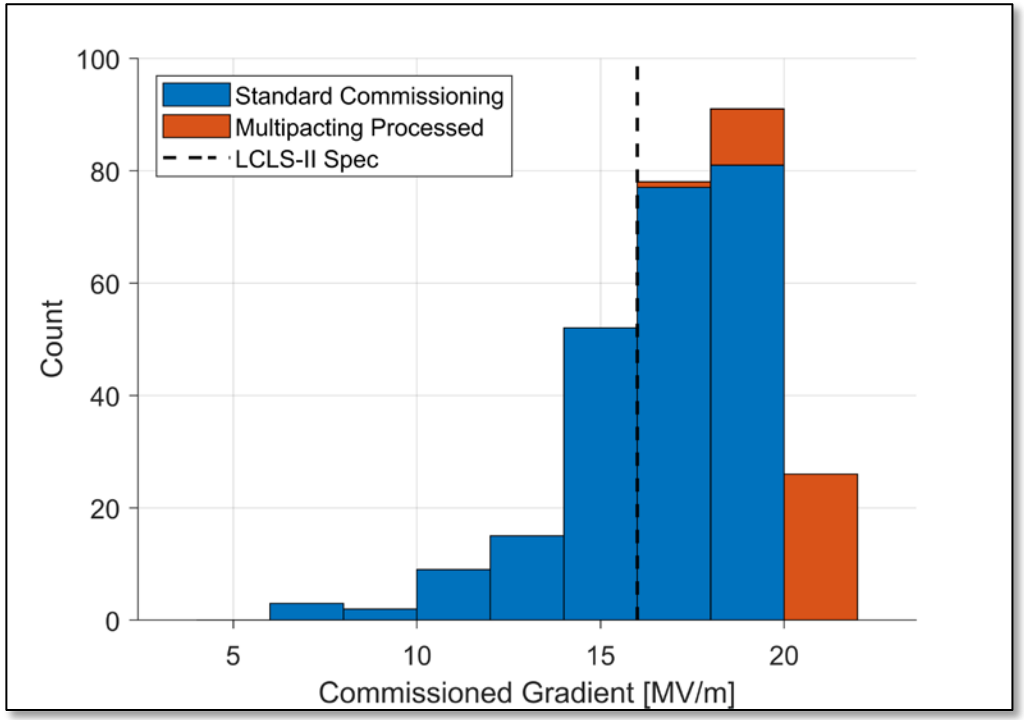
SRF Commissioning

SRF commissioning was very successful

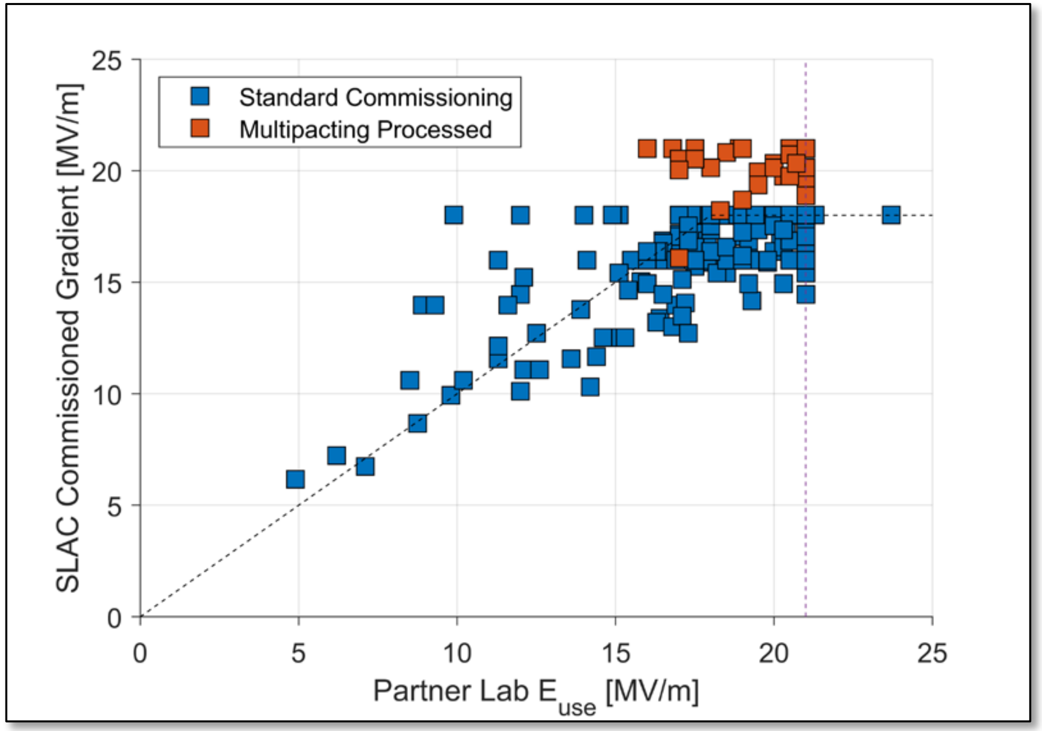
- 97% of all cavities fully operational (planned for 94%)
- Total commissioned (summed individual cavity) voltage exceeded design by >20% and reached 4.8GV
- No significant change in field emission observed with respect to cryomodule acceptance tests at partner labs

Gradient Performance



Gradient Performance

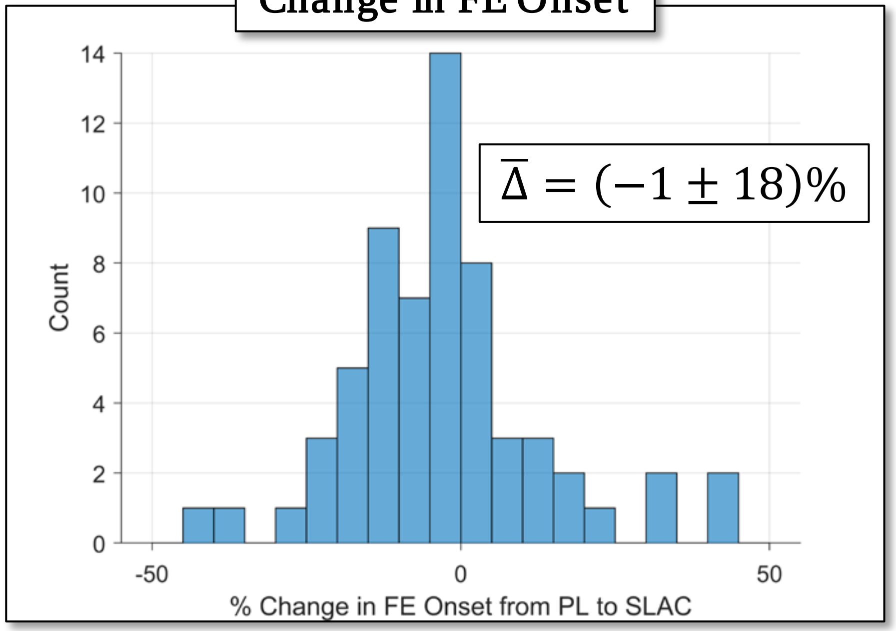
Comparison with Acceptance Test



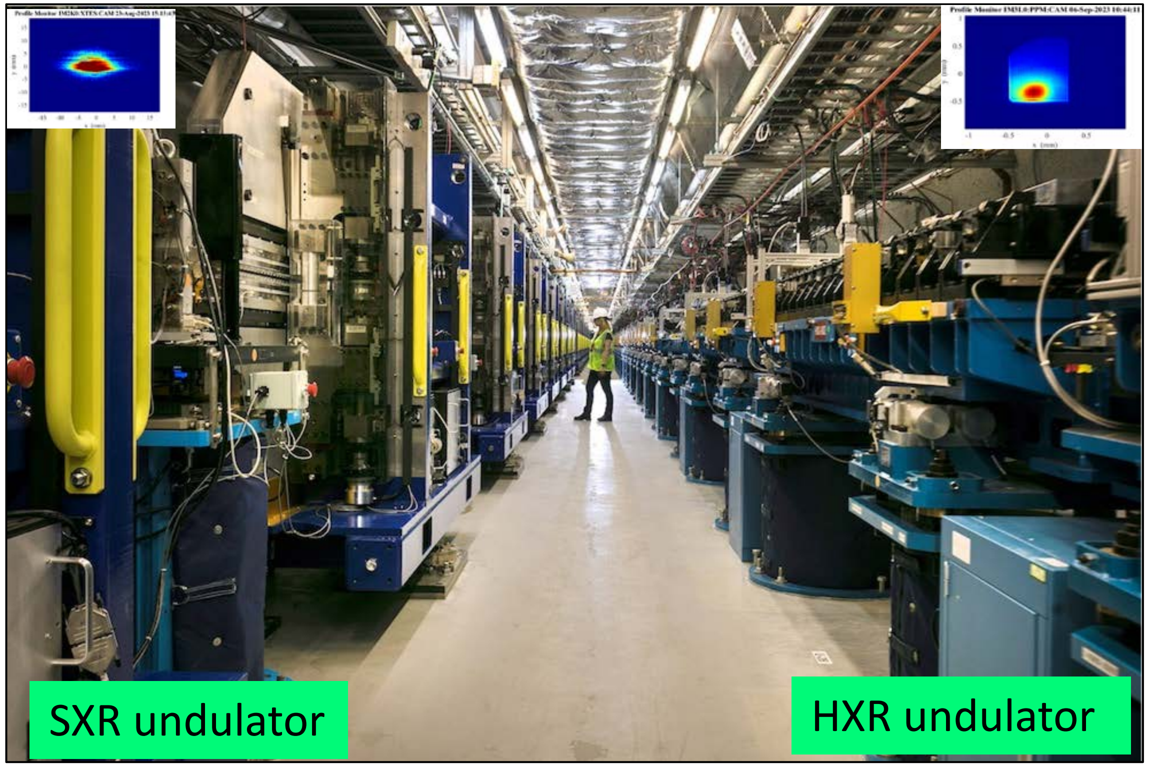
Admin limits:
- 18 MV/m in commissioning
- 21 MV/m in acceptance test

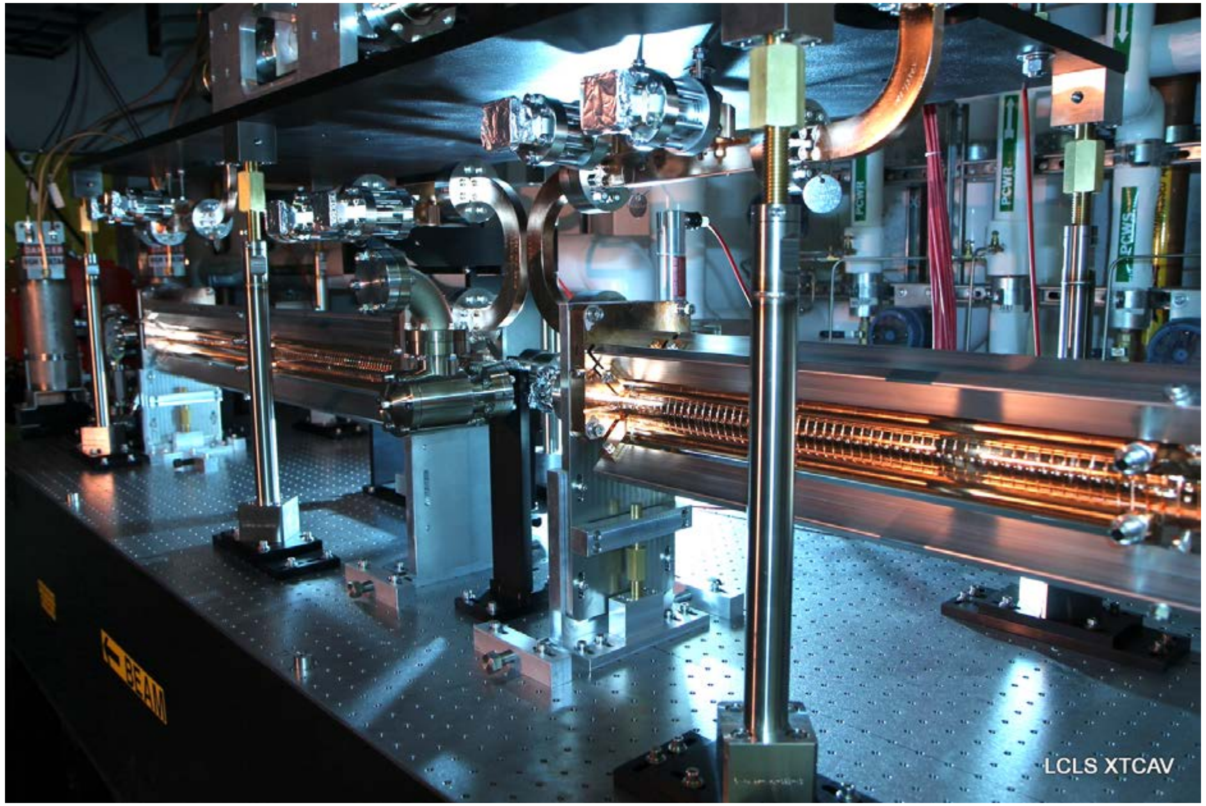
- Gradient performance is in line with CM acceptance test measurements at FNAL and Jlab
- **No observable change in field emission onsets or magnitude from installation**
- Multipacting processing resulted in ~3 MV/m gain in stable gradient

Change in FE Onset



Undulator and FEL commissioning





XTCAV and XTCAVB to support commissioning

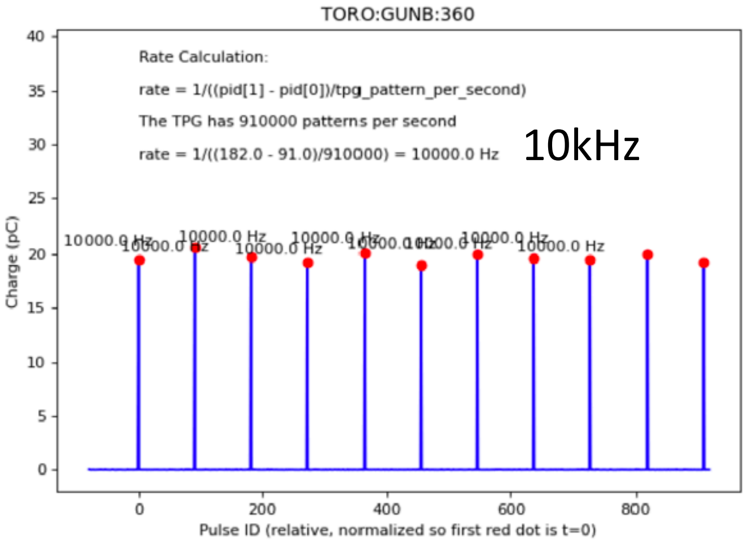
- Beam-based alignment with Cu-linac beam;
- E-beam transverse and longitudinal optimization;
- Beam loss control; Undulator tapering;
- GMD, spectrometer, XTCAV measurement.

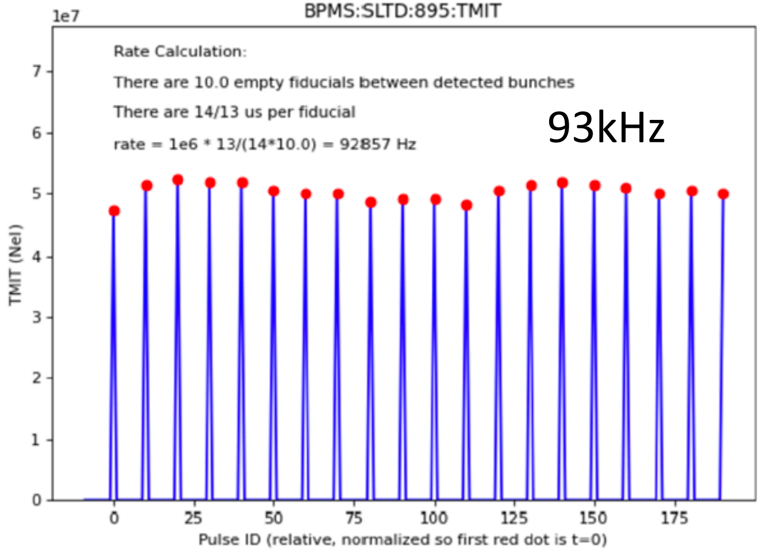
First lasing with SC-linac beam, SXR line, 8/23/2023; HXR line, 9/6/2023

Beam Repetition Rate

- Achieved **10 kHz beam rate on 12/9/2022.**
- **Achieved 93 kHz (6/7/2023)**
  - **→ Project Threshold Milestone**
- ***Initial science program operates at 8.25 kHz.***

- While ramping up the beam rate:
  - Diagnostic devices response
  - Feedback system response
  - Machine protection system
  - Beam loss monitor display
  - Beam dump and cooling water temperature response
  - Verify actual beam rate with Toroid or BPM BSA data





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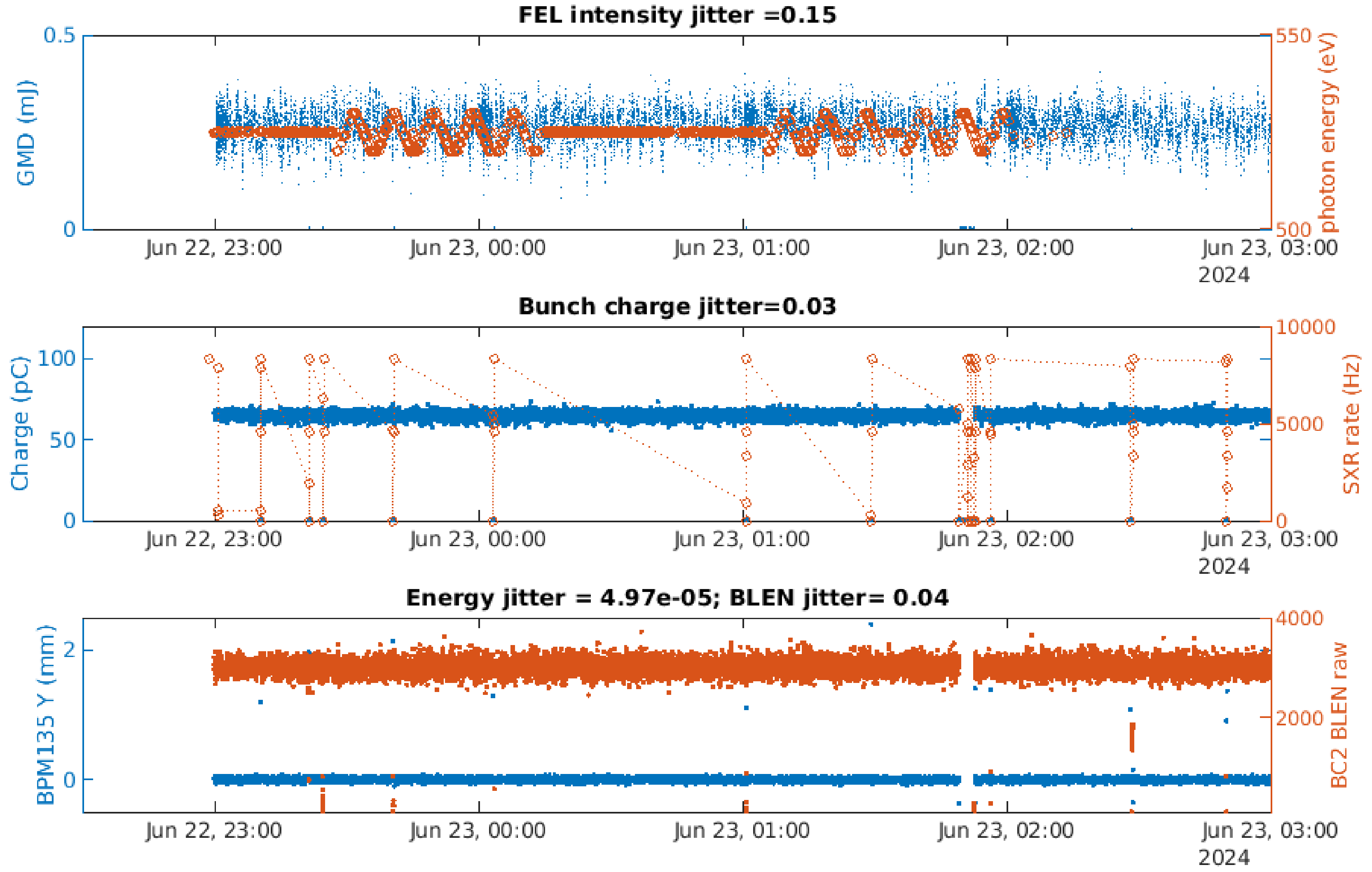
Beam Stability



6/23/2024
65pC, 8kHz, 530eV:
operation data in 4 hours

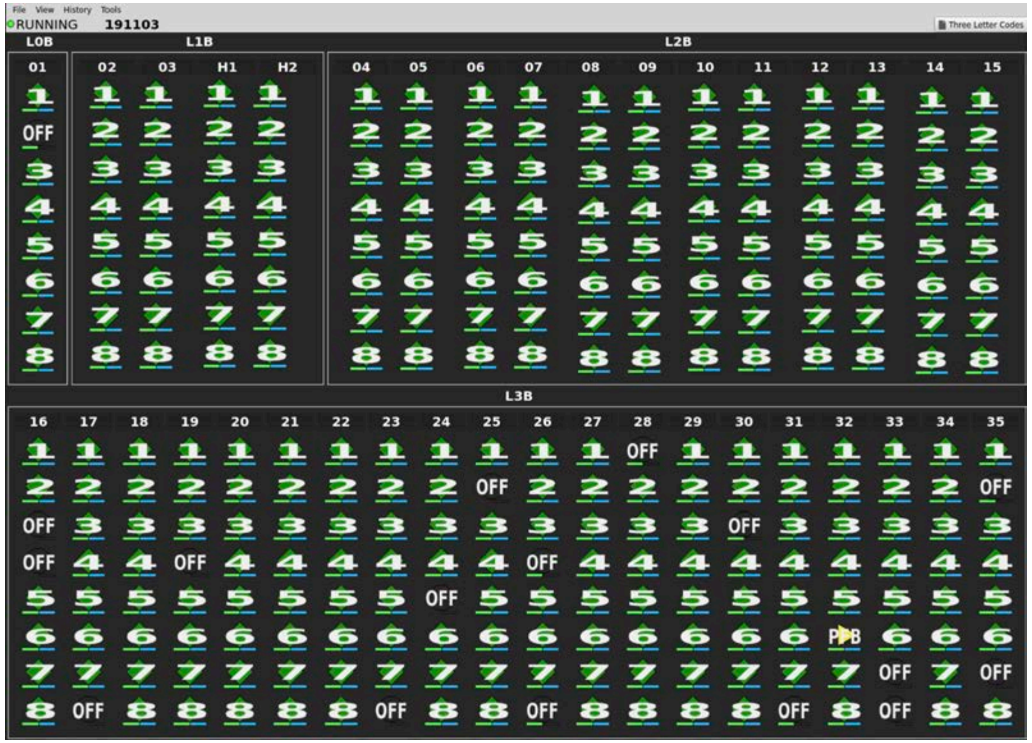
Design jitter specs (rms):

charge jitter: 1.5%,
energy jitter: 1e-4,
peak current jitter: 4%,
arrival time jitter: 20 fs.

With the 3rd cathode

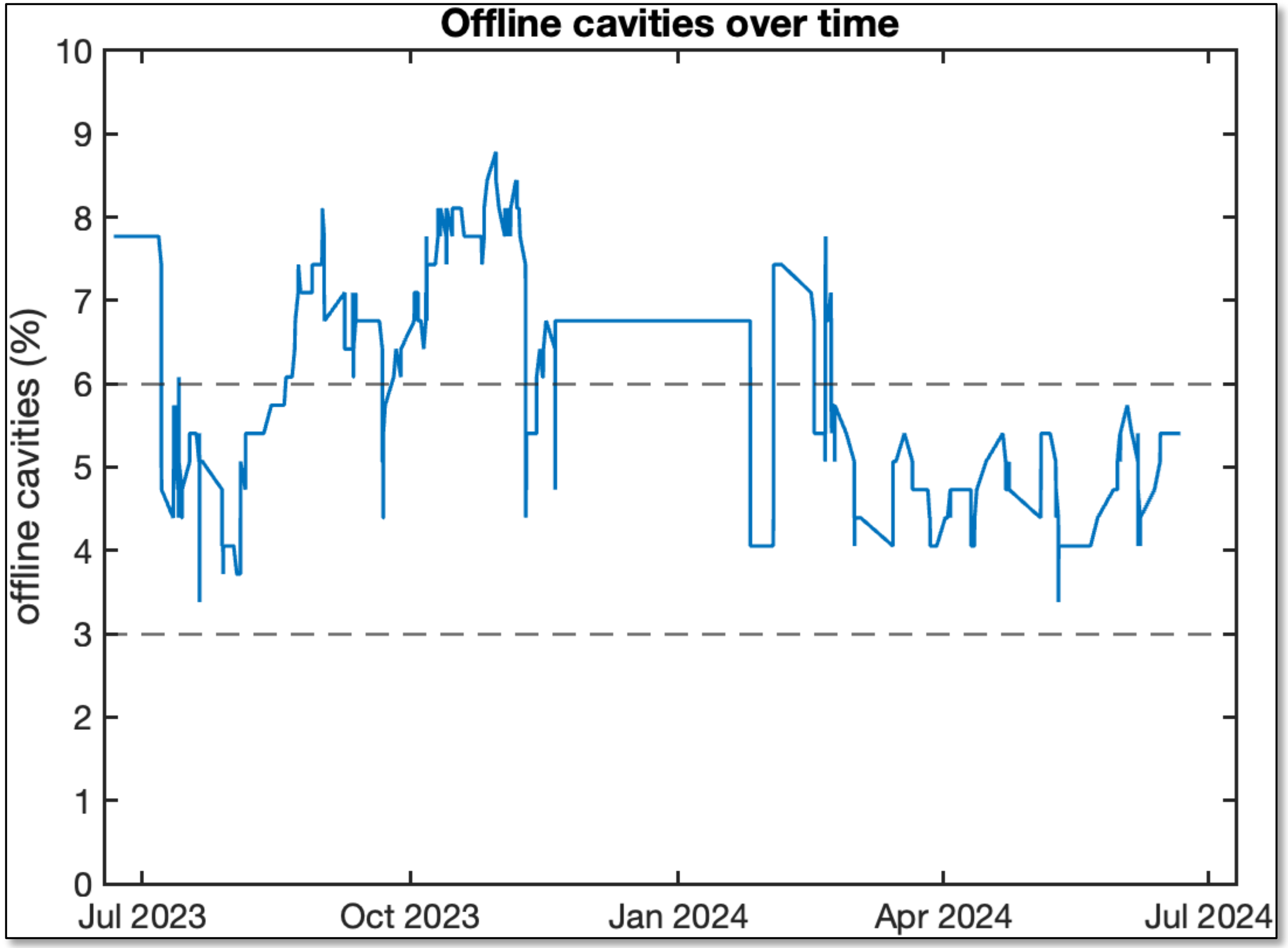
Cavity availability

- After initial commissioning only 3% of cavities non-operational (problems inside the CM that need room temperature warm-up)
- No additional cavities with problems inside cryomodule since then
- All new problems related to LLRF system, cables/ connections or SSAs
- Individual Solid State Amplifiers allow to take single cavities with intermittent problems offline for maintenance
- Generally enough amplitude overhead to compensate for cavities being repaired while the linac is running or during maintenance periods



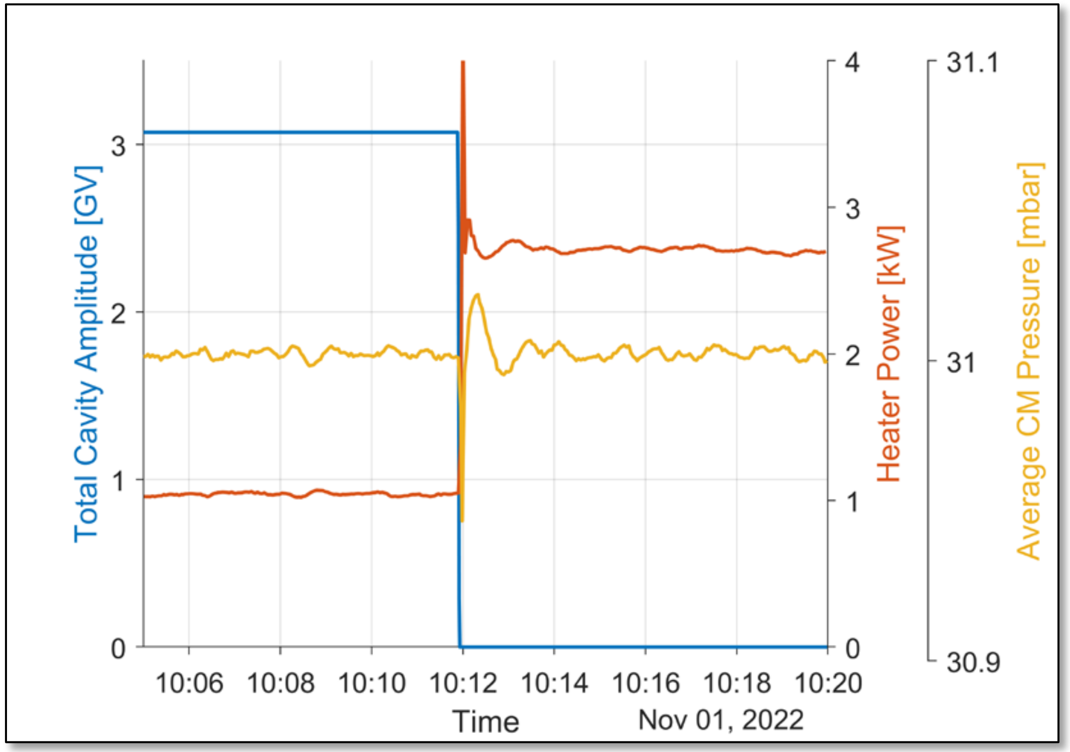
Offline cavities over time

- During operation cavities with problems are taken offline to be fixed later.
- Repair during maintenance periods or parasitically (if possible)
- 9 cavities (3%) offline due to long term issues
  - power coupler: 2x
  - Tuner (stepper/piezo/limit switch): 7x
  - Will require linac warm-up
- Remaining cavities mostly RF-system related



Cryogenic system is very robust

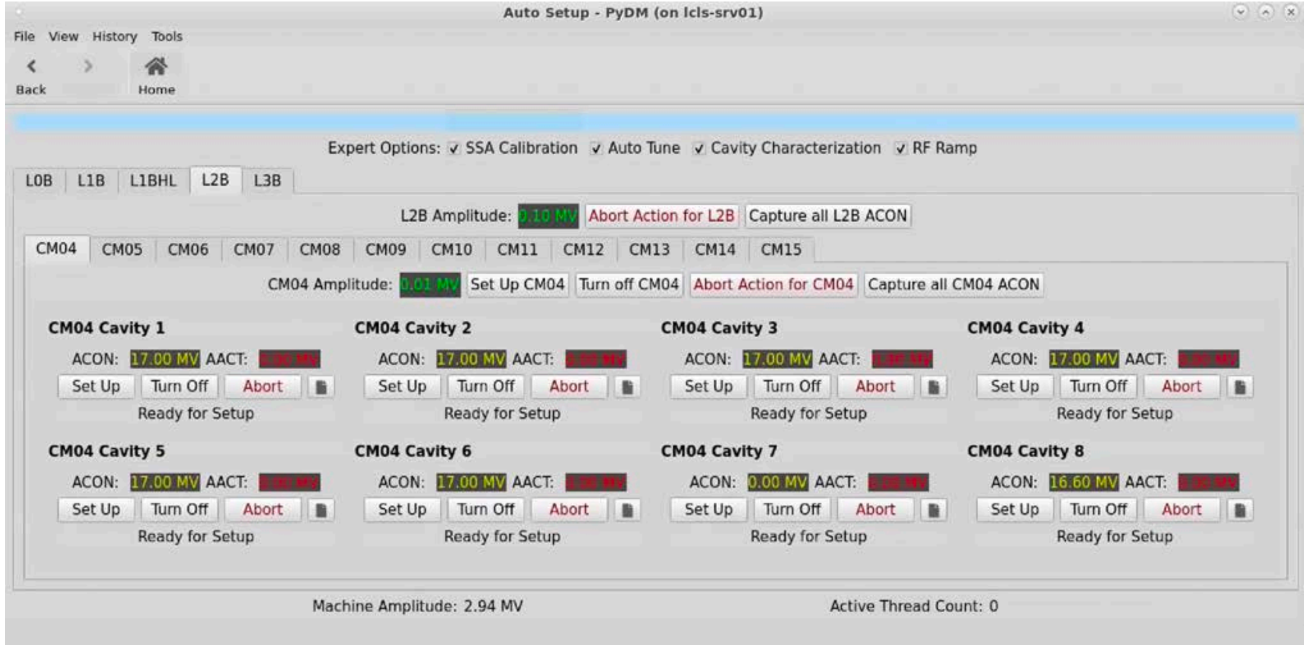
- Electric heaters on underside of cavity helium vessels to compensate for change in RF heatload
- Control loop regulates linac helium pressure by adjusting electric heaters to keep return pressure to cold compressors stable
- Even in cases of sudden loss of all RF heat [e.g. shut-off by Personal Protection System (PPS)] feedback keeps cold compressors stable and recovers pressure within minutes



Software development and automation

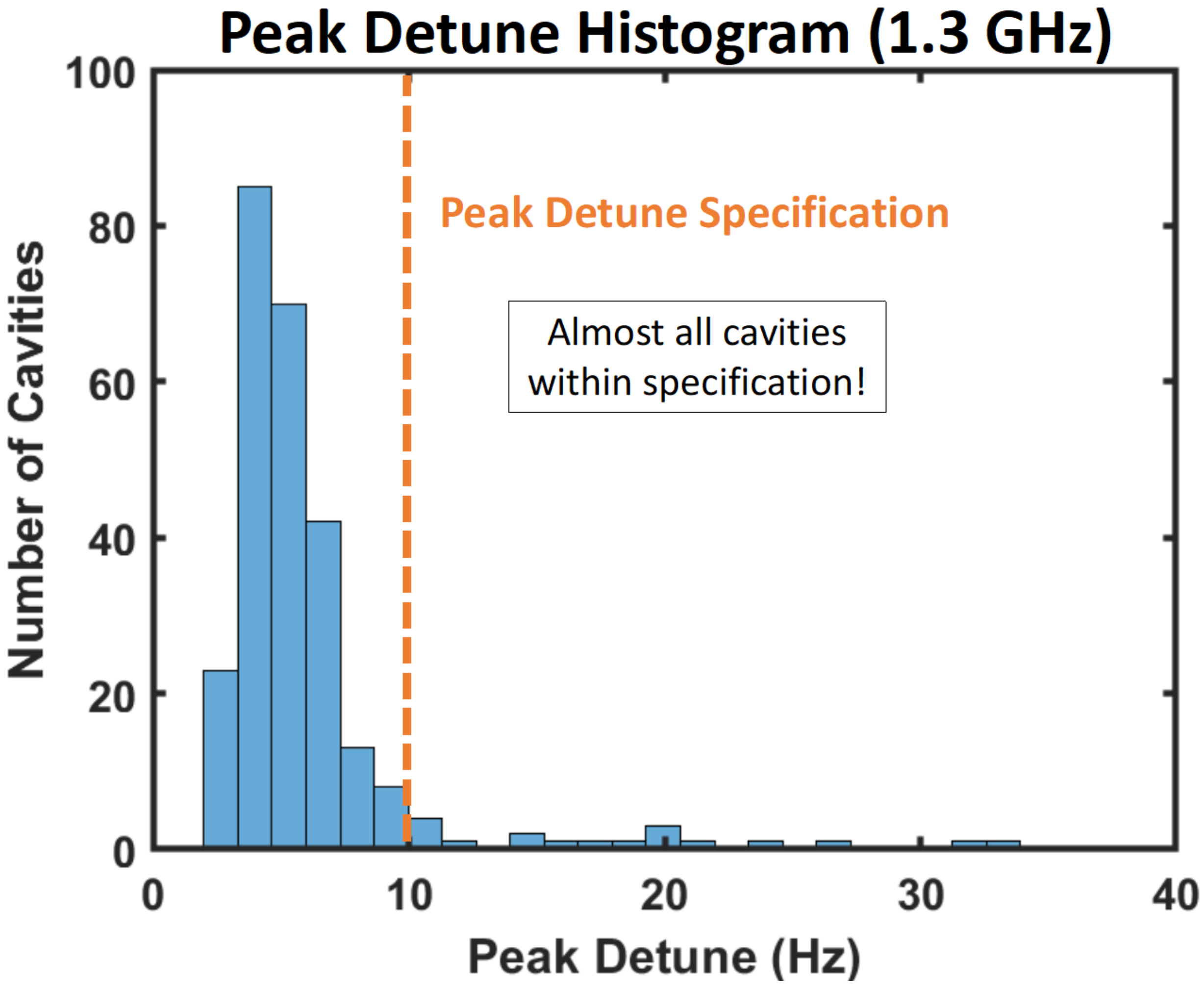
Auto Setup GUI

- Push-button tool for initial set-up or to address cavities that have become unstable
- Building heavily on software framework developed for and since initial linac commissioning
- Simplified interface on top of expert screens for ease of operator use
  - Automated sequence of steps, some level of error handling and checking if values are within set boundaries
- Start of the whole linac (e.g. after maintenance days) CM by CM within 30min - 1h, depending on number of parallel instances
- Recent infrastructure improvement cut down to less than 5min, true single button



Microphonics

- Overall microphonics levels are very good
  - 94% of cavities within specification of +/-10Hz
- Only two cavities are currently amplitude limited due to microphonics
- Biggest source of excessive microphonics are cooldown valve leaks
- More details by R. Porter at SRF2023: MOPMB081



L3 insulating vacuum

Upstream linac section

- L3 string is separated into section upstream and downstream of insulating vacuum break
- L3 upstream string exhibits higher than expected static heatload and increased insulating vacuum pressure
  - Suspect leak from helium process pipe into insulating vacuum space
  - Partially mitigated by doubled pump capacity

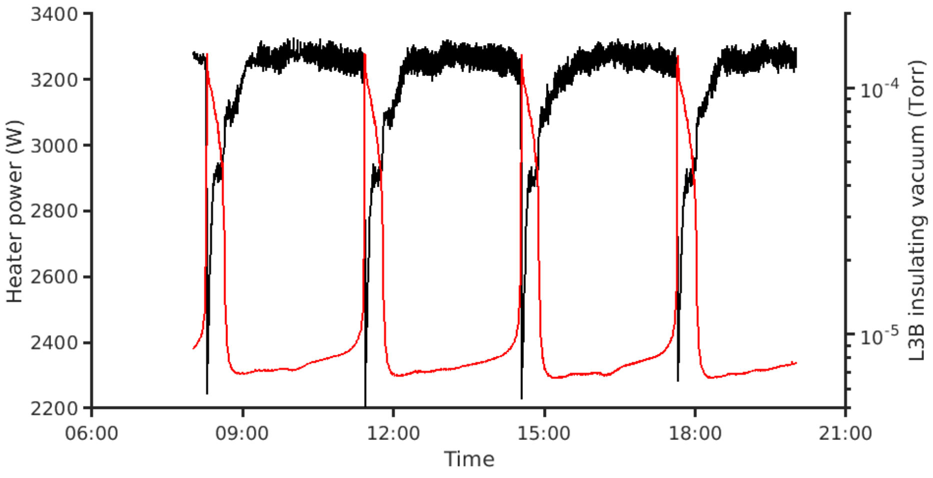
	EXPECTED CM STATIC	OBSERVED CM STATIC (Initial)	OBSERVED CM STATIC (with Additional Pump)
LO-L2	9 W / CM → 150 W	9 W / CM → 150 W	9 W / CM → 150 W
L3-UPSTREAM	9 W / CM → 90 W	47 W / CM → 470 W	17 W / CM → 170 W
L3-DOWNSTREAM	9 W / CM → 90 W	16 W / CM → 160 W	16 W / CM → 160 W
TOTAL CM STATIC	**330 W**	**800 W**	**500 W**

Added Pumps →

L3 insulating vacuum

Downstream section

- L3 downstream string insulating vacuum pressure has oscillating behavior
  - Oscillation period is dependent on whether RF is on (~1.5h) or off (~3h)
  - Global heater feedback reacts in response to change in static heatload
  - Suspect leak in cooldown line of one of the later CMs (~CM33-34)
  - Most notable consequence is HOM couplers on some cavities to start (over-) heating
    - Decreased cavity amplitudes slightly to accommodate



New Field Emission in CM01

- CM01 has specific cavity amplitude requirements for optimal injector performance and linac beam quality
  - Cryomodule with high max amplitudes and without field emission was chosen for this location
  - For best emittance preservation cavity 1 runs at low amplitude (6.5MV) and cavity 2 is chosen to be off

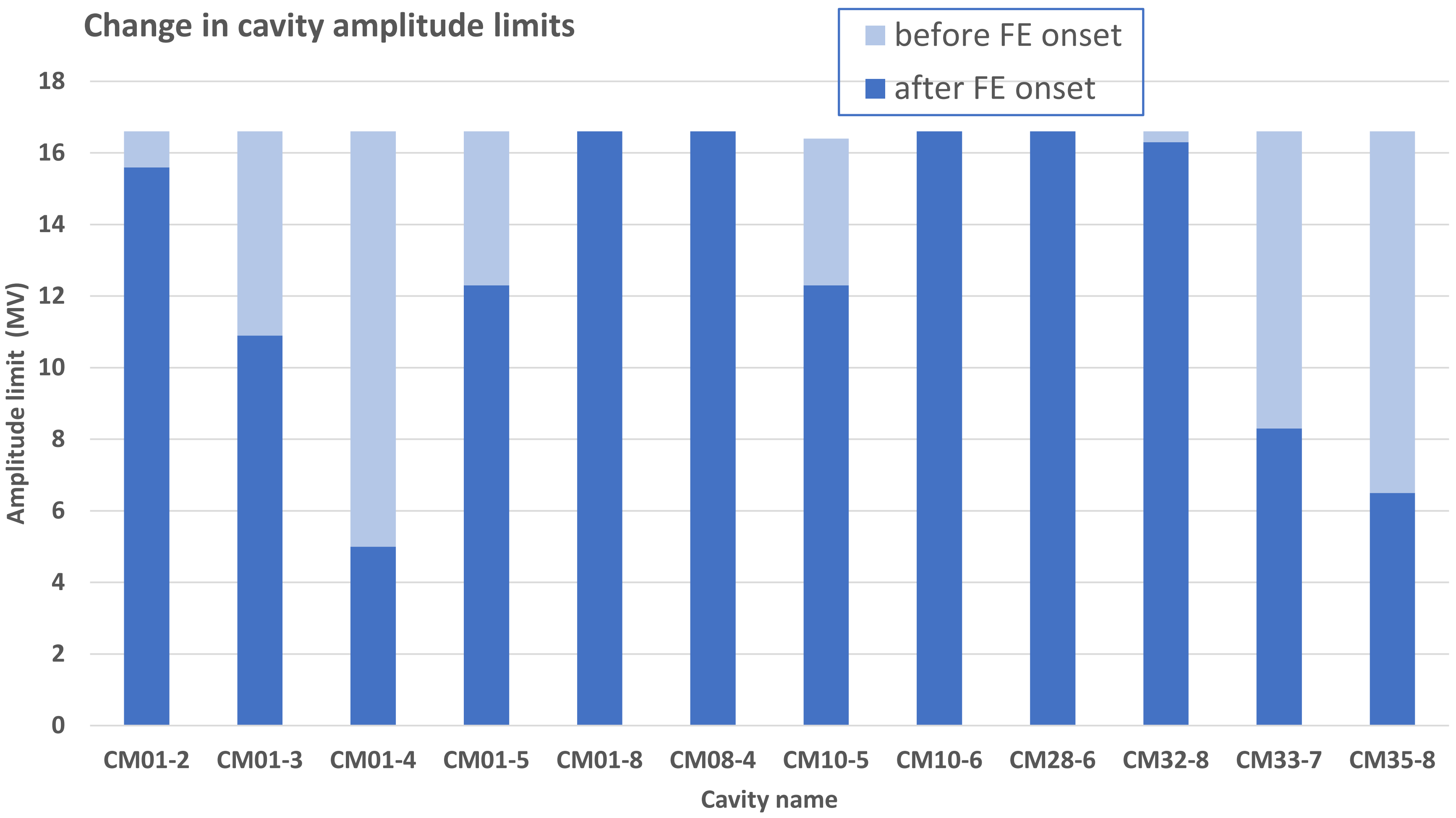
- Prompted by unexplained high signals on beam loss monitors in injector moved radiation monitors next to CM01 and re-characterized field emission
  - Found field emission in cavities 2, 3, 4, 5

- No specific events in beamline vacuum that would explain particle migration or gas bursts

CM01: Path forward

- Will keep monitoring field emission levels in CM01 on a regular basis
- Started re-characterization campaign for all other CMs (moving one set of sensors every maintenance period)
- Assessing impact on injector performance
  - Just at the lower edge of required energy for laser heater operation while keeping cavities below 50mR/hr when turning on cavity 2
  - Seems feasible as long as FE does not get worse
- Looking for mechanisms that would explain pattern with highest radiation in the middle of the CM
- Long term solutions (both would need room temperature warm-up and significant work):
  - Replace cryomodule with spare
  - Perform in-situ plasma processing

Change in cavity amplitude limits due to Field Emission (FE)



Total cavities in linac	296
Cavities re-characterized for FE	128 (43%)
Cavities with change in FE characteristics	12 (4%)
Number of affected CMs	7 (out of 16 re-characterized)
Cavities where the change impacts operational setpoint	7 (2%)

Total amplitude lost over whole linac: 45.4 MV

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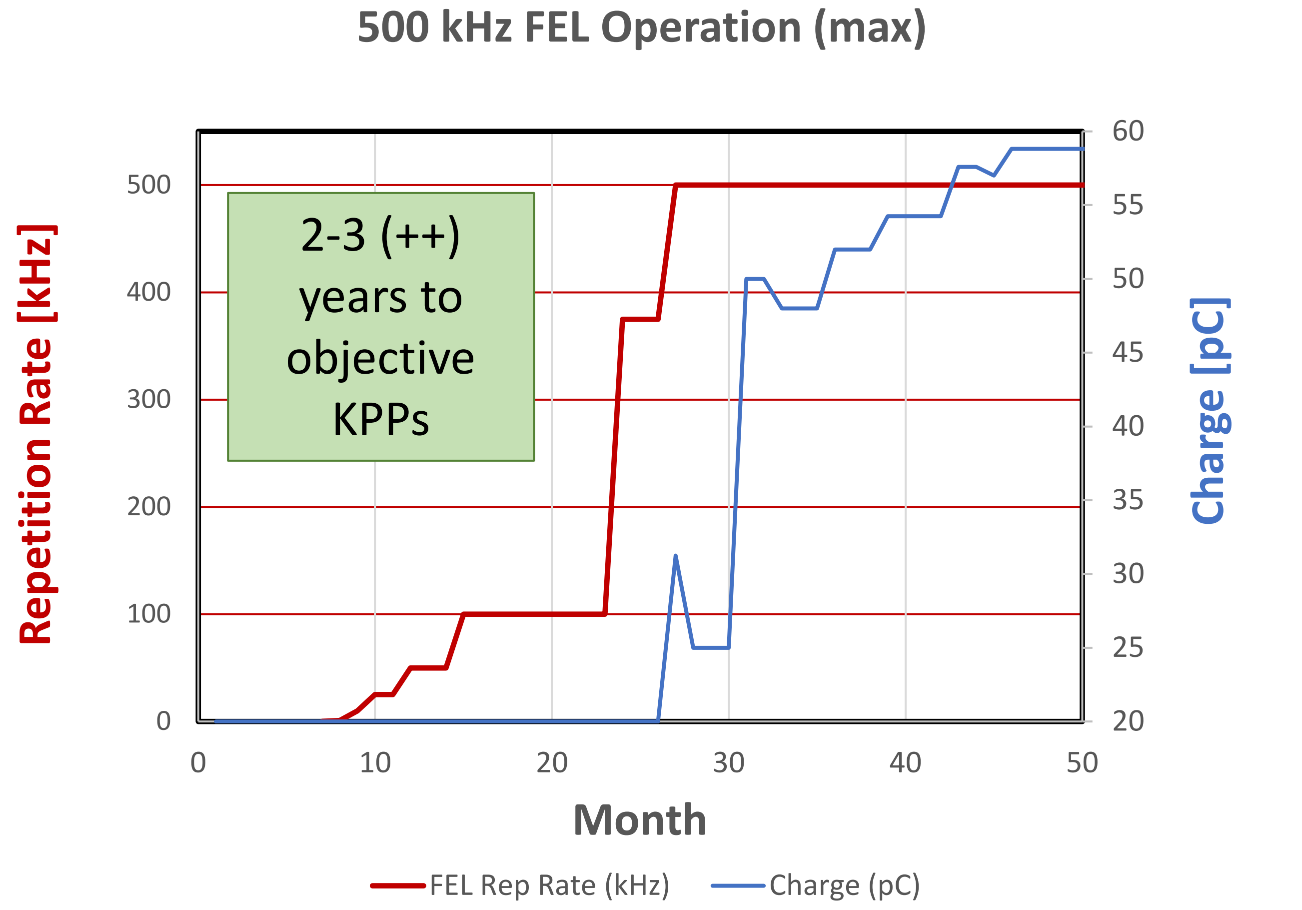
Ramp-up Plan for 500 kHz FEL Operation – 120 kW Limit

- Current beam power limit is 5 kW (safety system limitation)
- Ramp – up to full performance is governed by safety system functionality, RP surveys, beam loss minimization.
- Process to achieve KPP's will take 2-3 (+) years and will be integrated into user program.
- Repetition Rate and Bunch charge can be traded to maintain a specific beam power.
- Critical concern is undulator dose rate → prevention of radiation damage of magnetic material.



Ramp-up is governed by beam power considerations, management of beam losses.

LCLS-II-HE Construction is underway

Double the electron energy of the accelerator (4 ➔ 8 GeV)

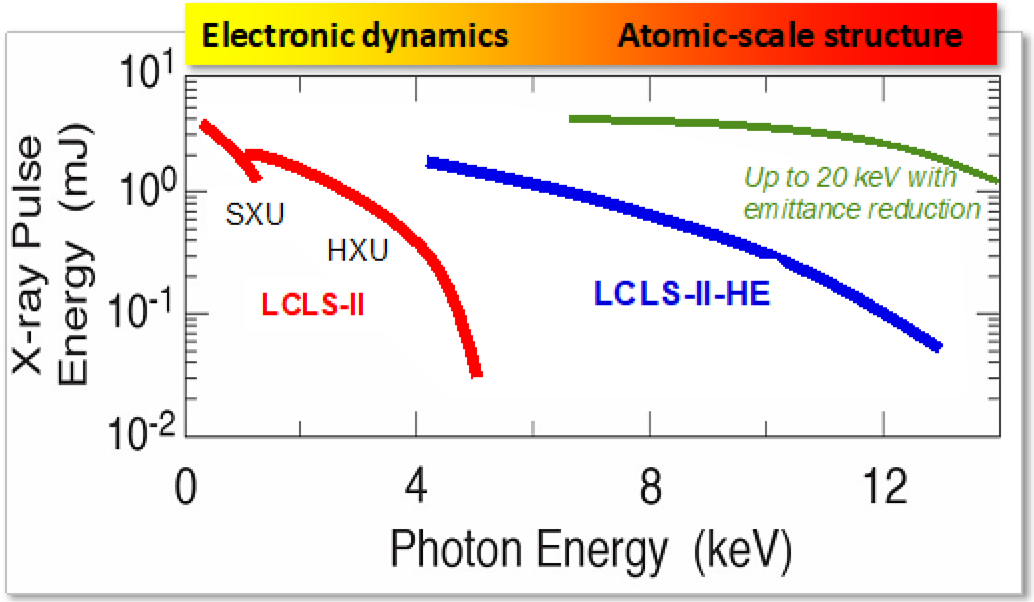
- Extends X-ray energy range from 5 keV to 12.8 keV

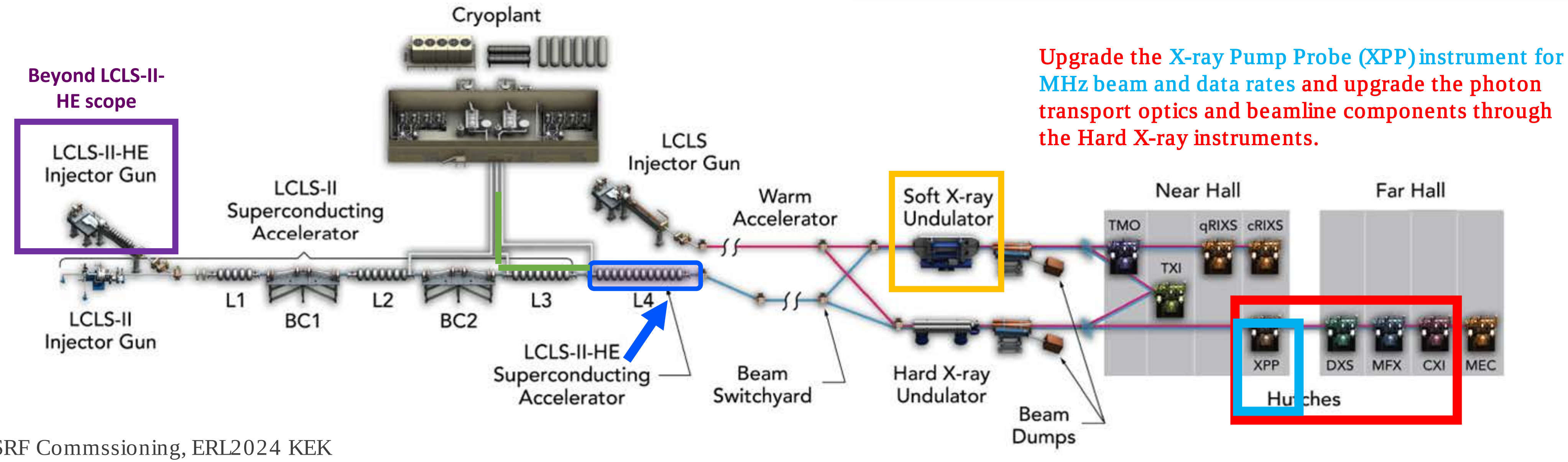
Provide a dual source X-ray capability

- Delivers simultaneous soft X-ray and hard X-ray beams at high repetition rate

Provide specialized instrument for unique new source

- Delivers optimized measurement capabilities and enables science immediately after accelerator commissioning





Summary

- LCLS-II SRF commissioning has been a successfully completed and threshold key performance parameters have been met
- Early operations of SRF systems are going well (beam stability, microphonics, cavity availability) with some issues (new field emission in CM01, insulating vacuum in L3 string)
- Next year will be spent delivering beam to users in parallel to further beam performance improvement and beam power ramp up
- Getting ready of LCLS-II-HE installation