LCLS-II Commissioning

Dan Gonnella, SRF Group Leader
On behalf of the LCLS-II Collaboration

29 August 2022

LINAC2022 LIVERPOOL

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Outline

LCLS-II Facility Overview, Scope, and Parameters

Installation

NC Linac Based Commissioning

Cryogenic Systems & Cool Down

SRF and Cryomodule Commissioning

SC Beam Commissioning

Summary

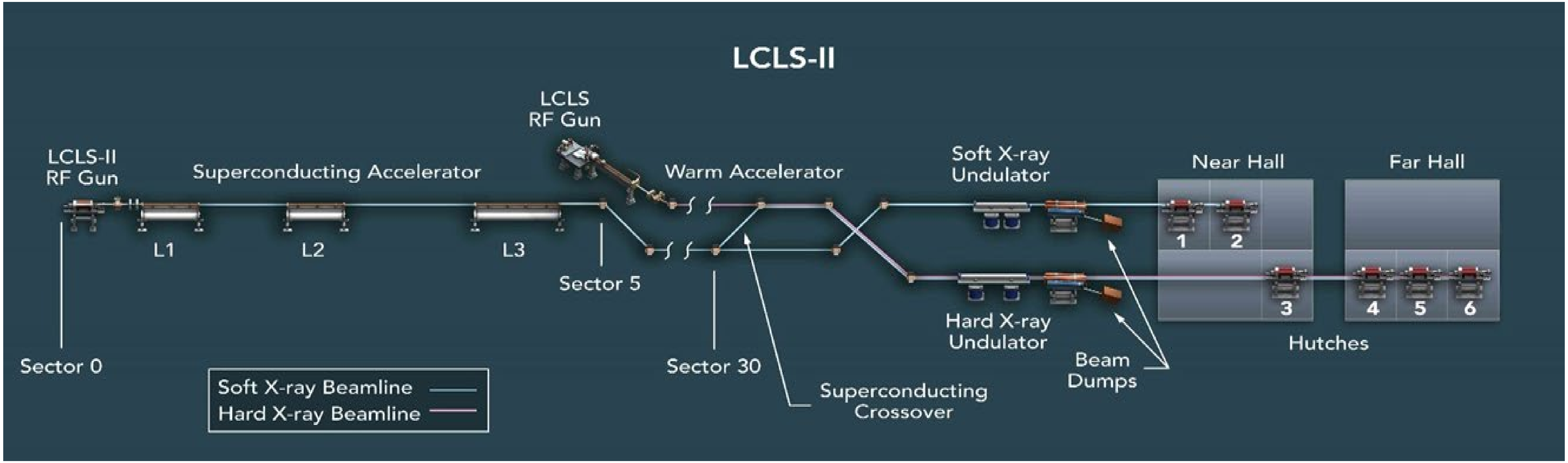
1

LCLS-II Facility Overview, Scope, and Parameters

- SLAC is developing an upgrade of its [Linac Coherent Light Source (LCLS)]() 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.

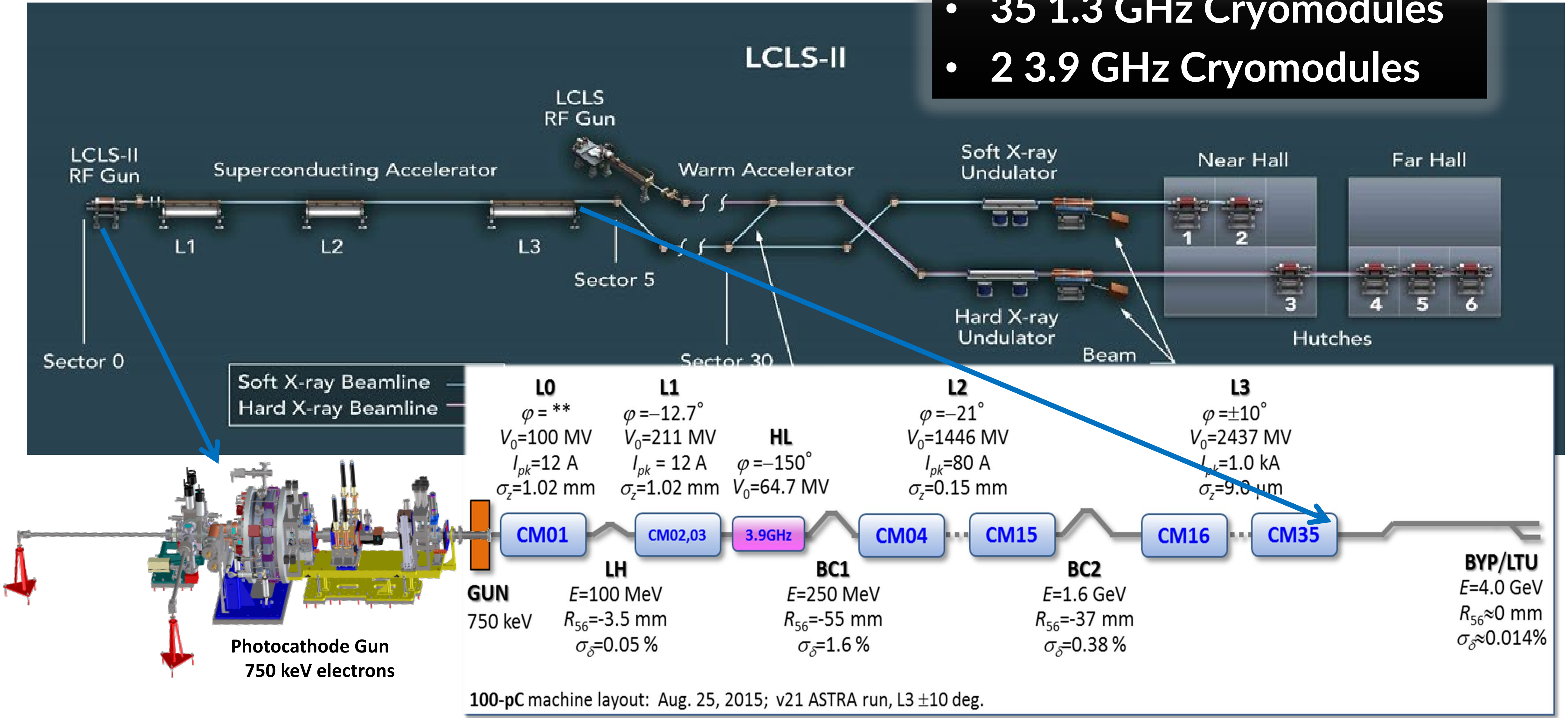

Remove SLAC Linac from Sectors 0-10
New Injector and New Superconducting Linac
New Cryoplant
LCLS-II
SLAC NATIONAL ACCELERATOR LABORATORY
BERKELEY LAB
Argonne NATIONAL LABORATORY
CORNELL UNIVERSITY FOUNDED A.D. 1865
Fermilab
Jefferson Lab
Existing Bypass Line
New Transport Line
Reconfigure Near Experiment Hall
Two New Undulators And X-Ray Transport

Linac & FEL Layout



Linac & FEL Layout

- **RF Photocathode Gun**
- **35 1.3 GHz Cryomodules**
- **2 3.9 GHz Cryomodules**



LCLS-II Technical Parameters

Performance Measure	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^{-3} BW) per bunch	$5x10^{8}$ (10x spontaneous) @2,500 eV	> 10^{11} @ 3,800 eV
Normal conducting linac-based system		
Normal conducting linac electron beam energy	13.6 GeV	15 GeV
Electron bunch repetition rate	120 Hz	120 Hz
Normal conducting linac charge per bunch	0.1 nC	0.25 nC
Photon beam energy range	1–15 keV	1–25k eV
Low repetition rate capable end stations	≥ 2	≥ 3
FEL photon quantity (10^{-3} BW[a]) per bunch	10^{10} (lasing @ 15 keV)	> 10^{12} @ 15 keV

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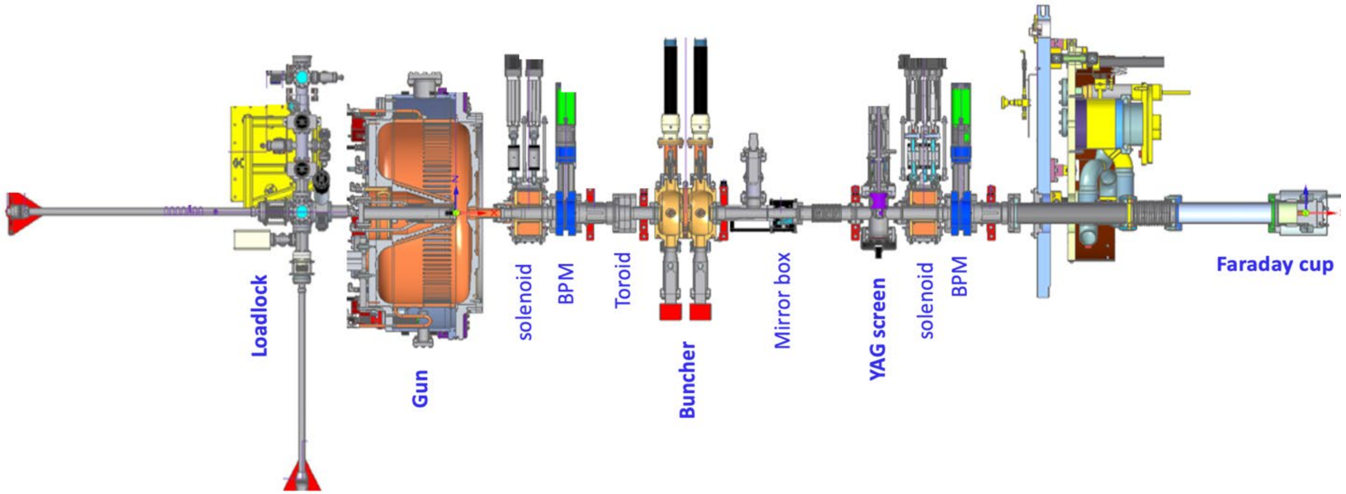
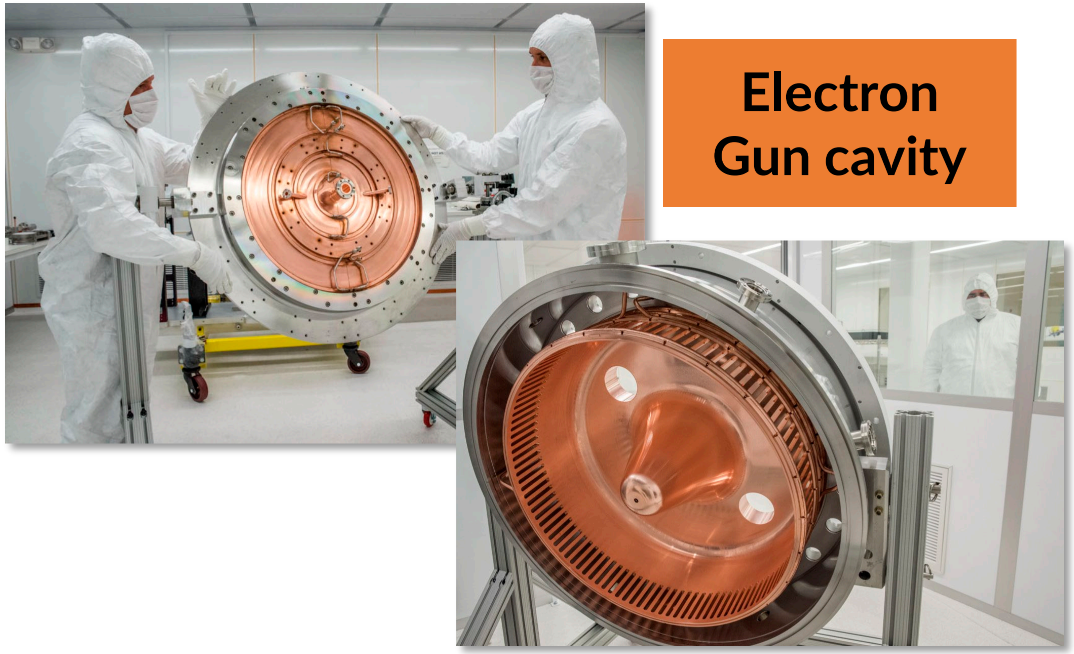
Parameter	LCLS-II
# 1.3 GHz CMs	35
Operating Gradient	16 MV/m
Required Q_0 at Operating Gradient	2.7×10^{10}

2

Installation

Electron Gun and NC Beam Line Installation

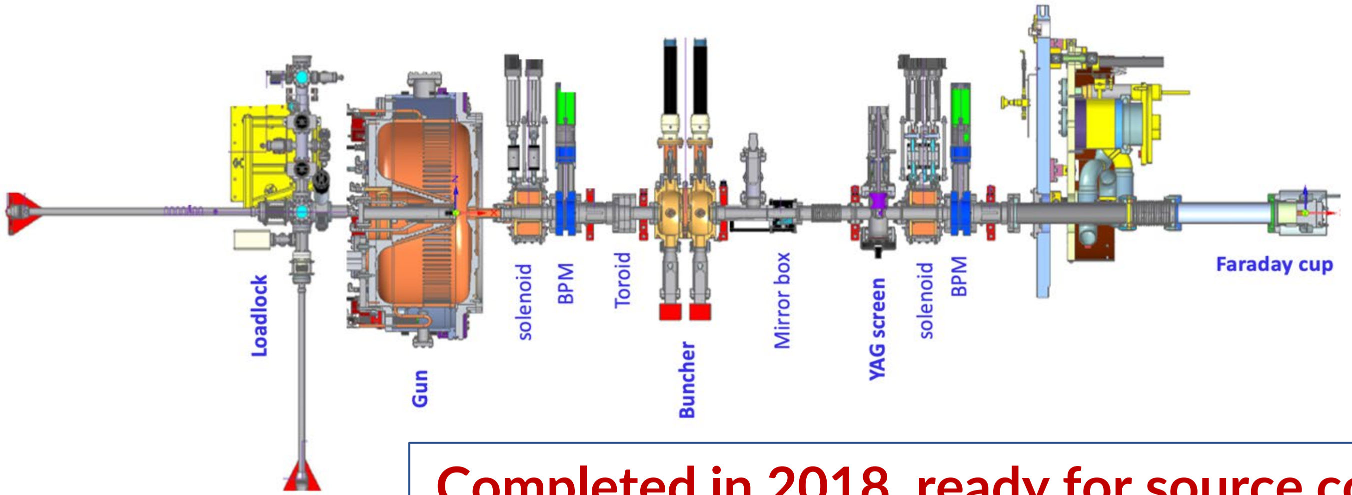




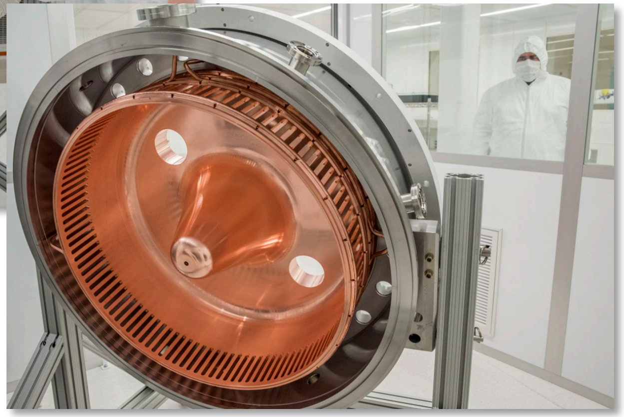
Electron Gun cavity

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

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)

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Cryomodule Installation

Last CM (spare) Delivered in May 2021

Cryomodule Installation

Last CM (spare) Delivered in May 2021

CM Installation Complete February 2021

Undulator Installation

Vertical Variable Gap SXR Undulator

Horizontal Variable Gap HXR Undulator

Delivery of X-Rays to Instruments Began in 2020

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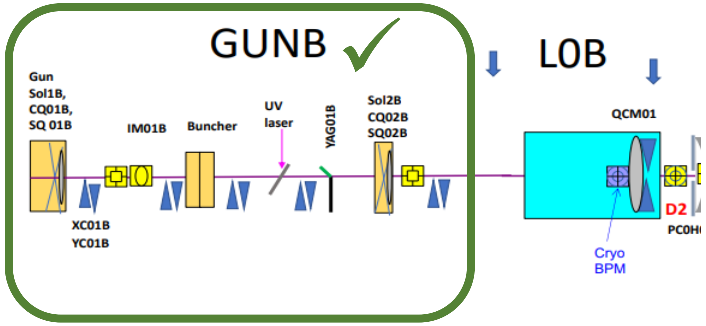
NC Linac Based Commissioning

Completed Scope – NC Based Commissioning

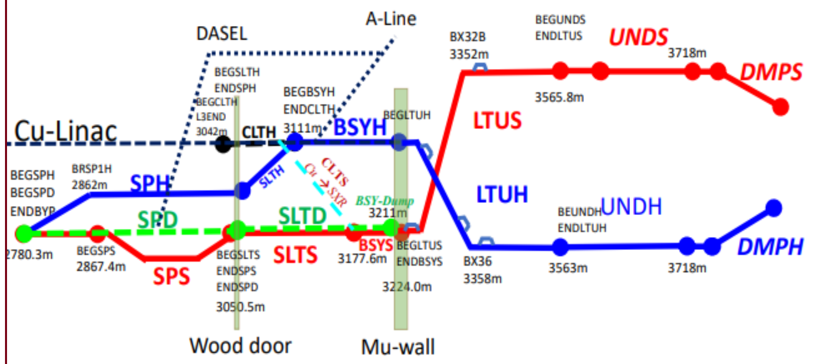
Electron Gun

- 750 keV Gun and laser system fully commissioned
- Low energy beamline (LEB)
- Loadlock for photocathode swaps



Beam Transport

- Linac to Undulators (LTUS, LTUH)
- CLTS (Ops) beamline allowed early commissioning of SXR systems:
  - Beam Transport
  - Undulators and Instruments



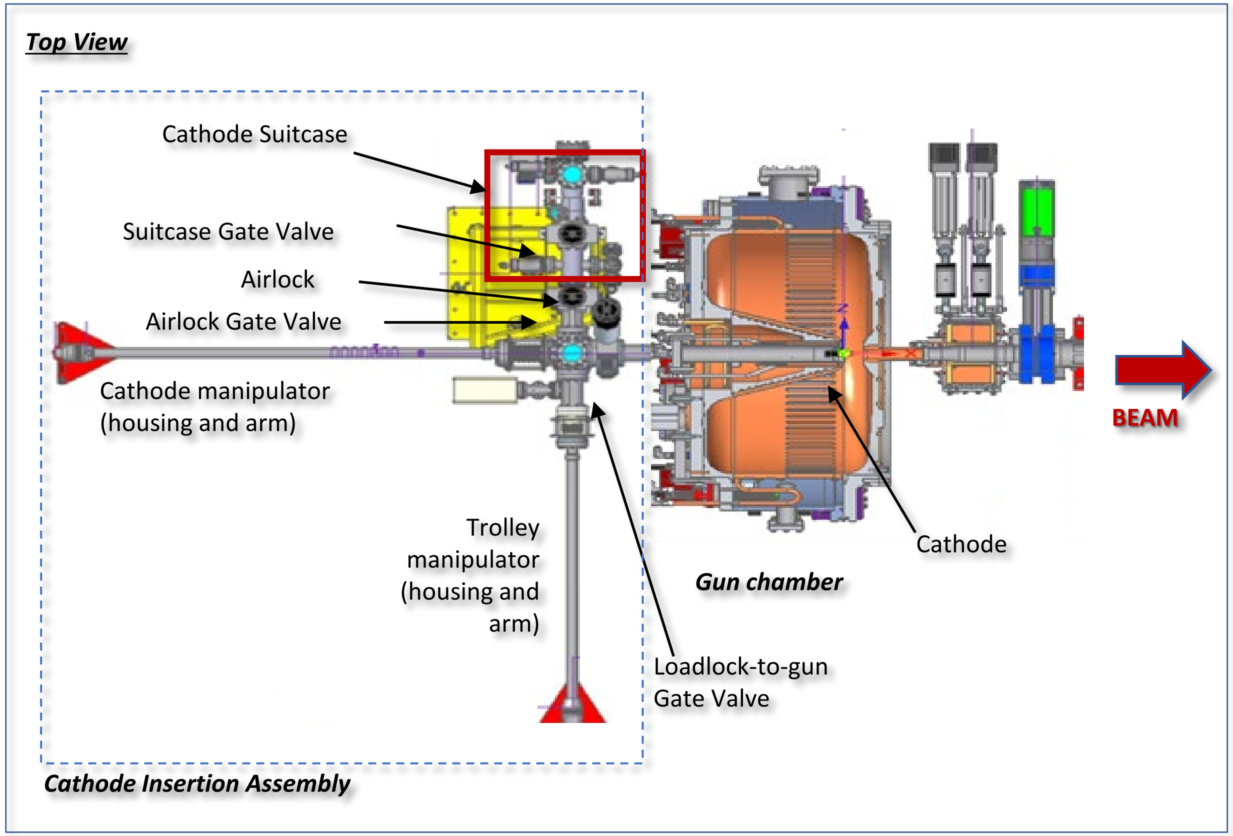
Undulators

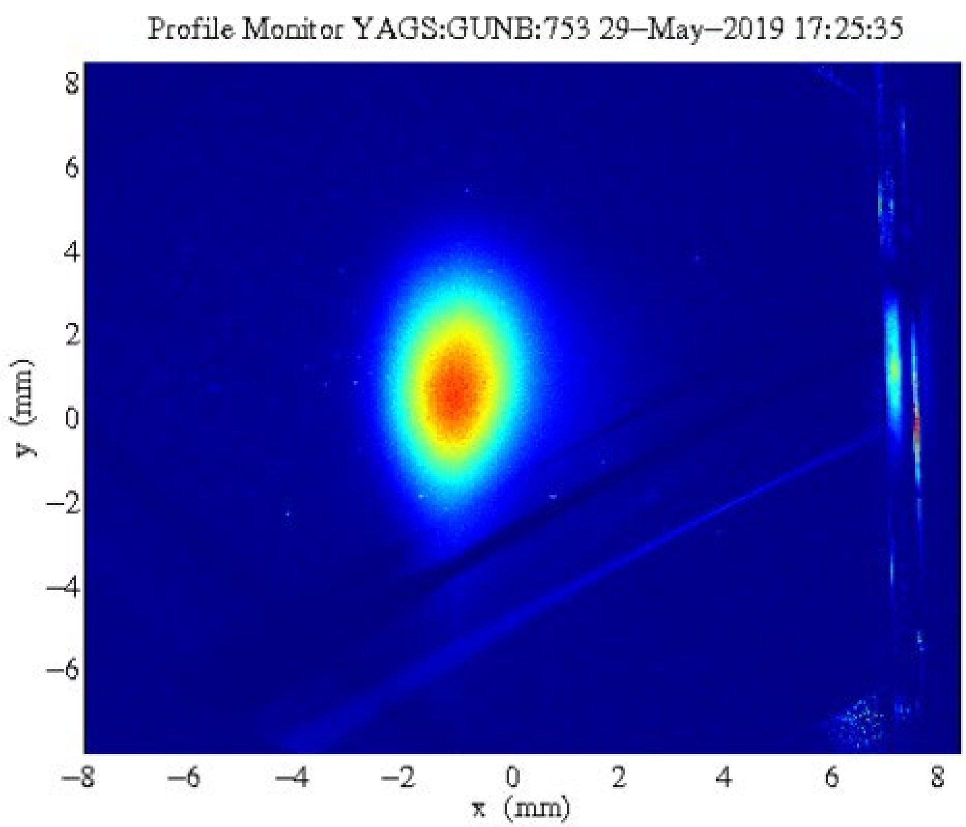
- HXR Undulator
- SXR Undulator
- HXRSS-II
- SXRSS-II (Ops)

Cu-Linac operation allowed commissioning of warm beamline systems, undulators, and instruments

SLAC

Early Injector Commissioning Completed in 2018





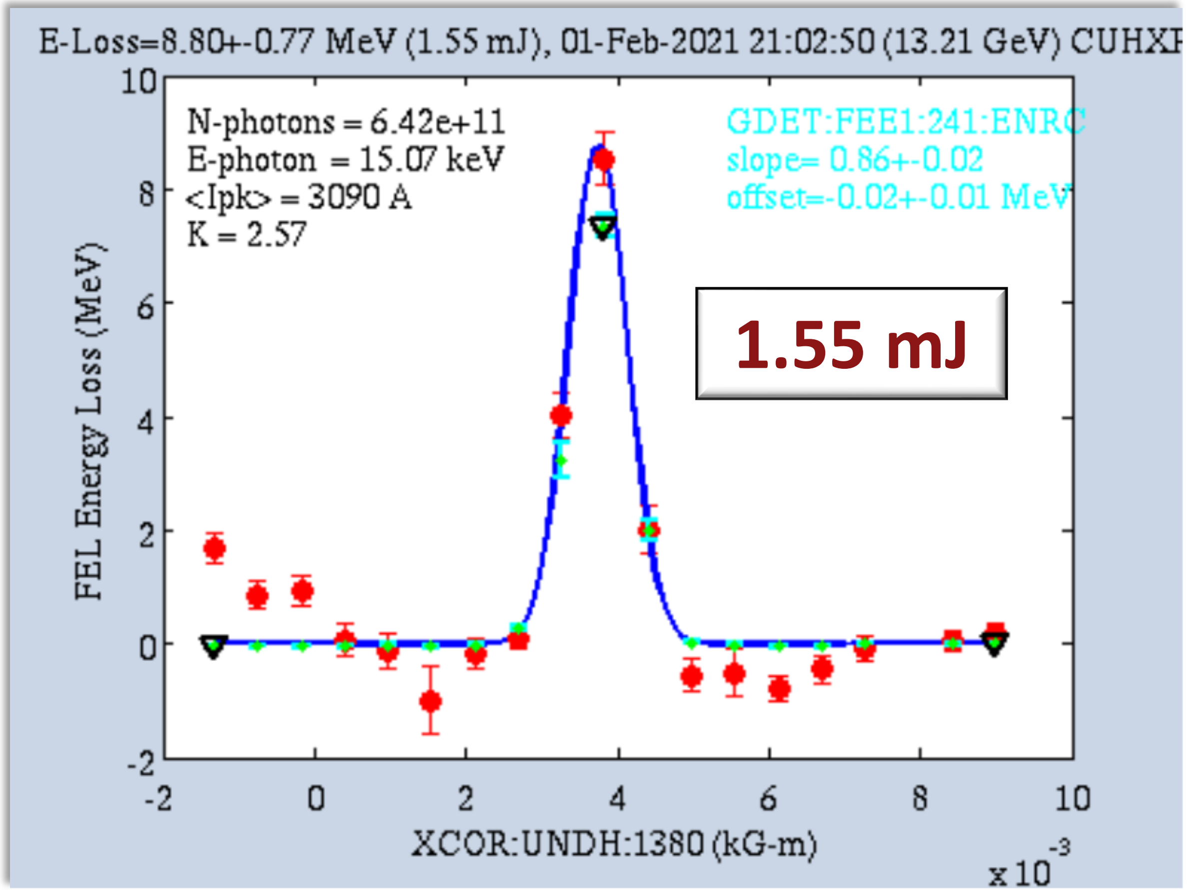
F. Zhou et al, "First Commissioning of the LCLS-II CW Injector Source," presented at IPAC '19, Melbourne, Australia, May 2019, TUPTS106

Table 1: Major LCLS-II Injector Beam Requirements

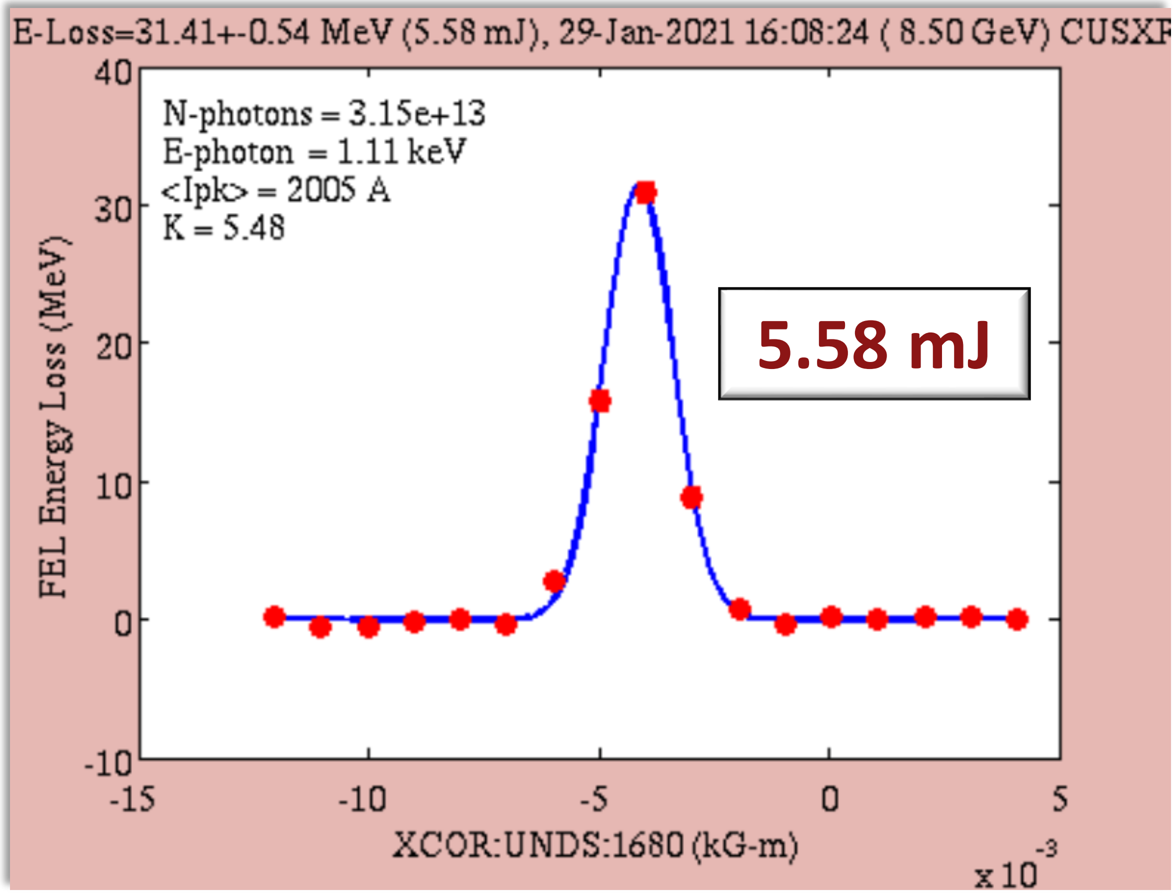
Parameter	Nominal
Gun energy (keV)	750
Bunch repetition rate (MHz)	0.93
Bunch charge (pC)	100
Peak current (A)	12
Slice emittance (µm.rad)	0.4

NC Linac Based Undulator Performance

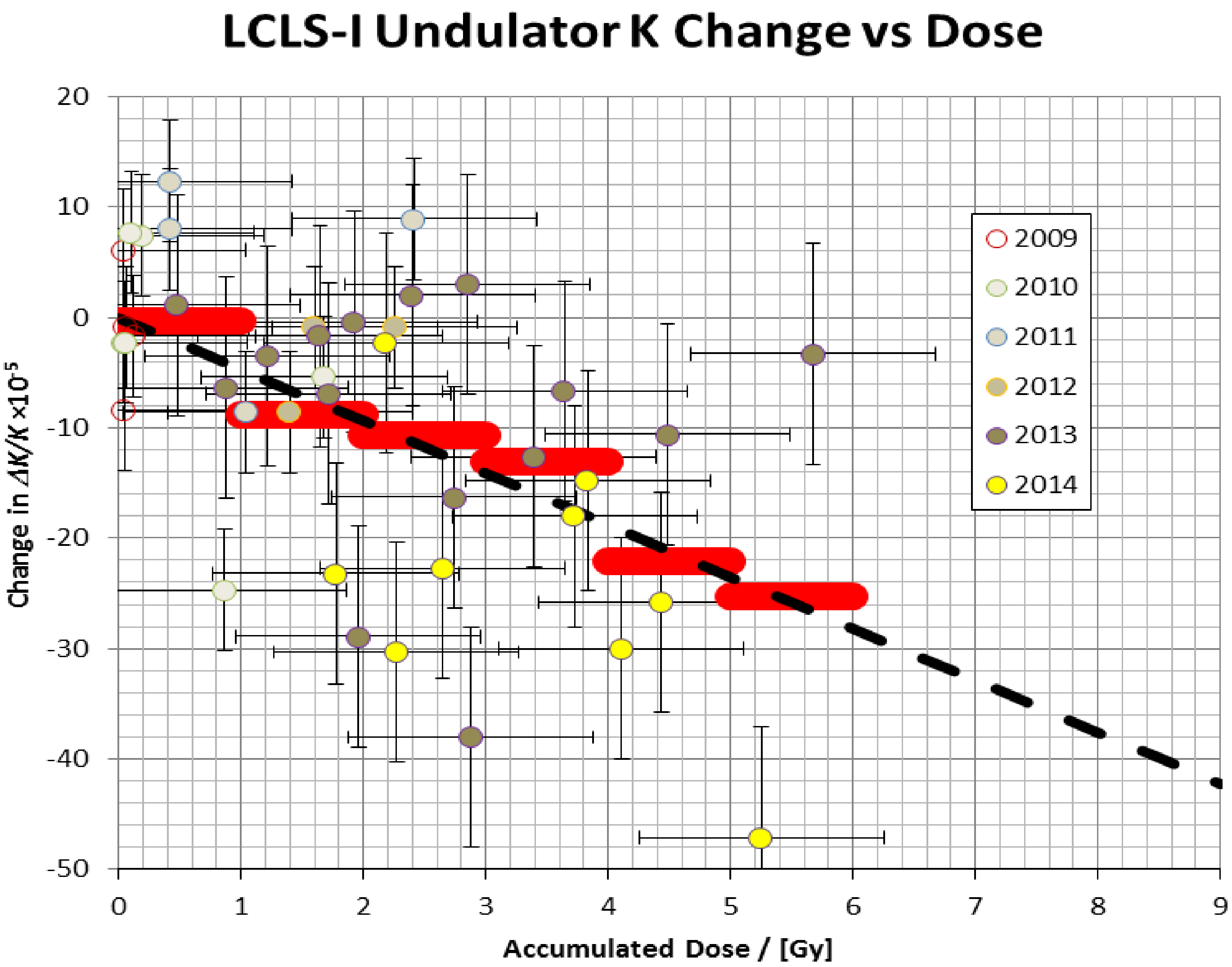
HXR Achieved Photon Number



SXR Achieved Photon Number

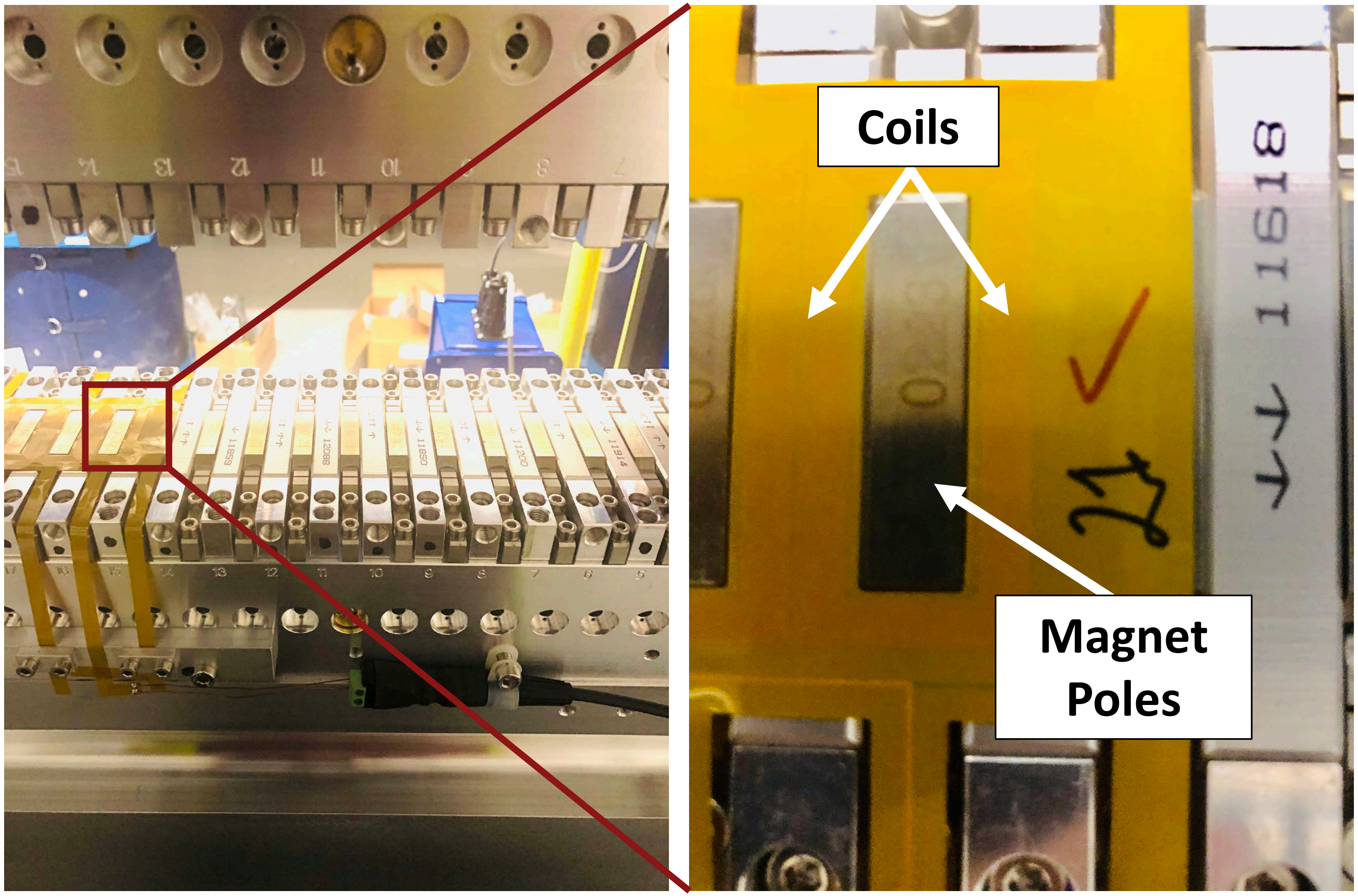


Undulator Demagnetization



- Degradation of undulator magnetization from radiation dose is a concern for LCLS-II operation
- Primary source of radiation dose is background radiation
    - Beam steering errors do not contribute significantly due to MPS
- Rough measurement of demagnetization per radiation does completed for LCLS-I
- Expected to require undulator swaps for long term beam operation for LCLS-II
- **Direct measurements of radiation does (RADFETs) planned for LCLS-II**

In-Situ Undulator Radiation Damage Measurement



Developing system to measure the change in magnetization of an undulator *in situ*

Currently being tested in SXR

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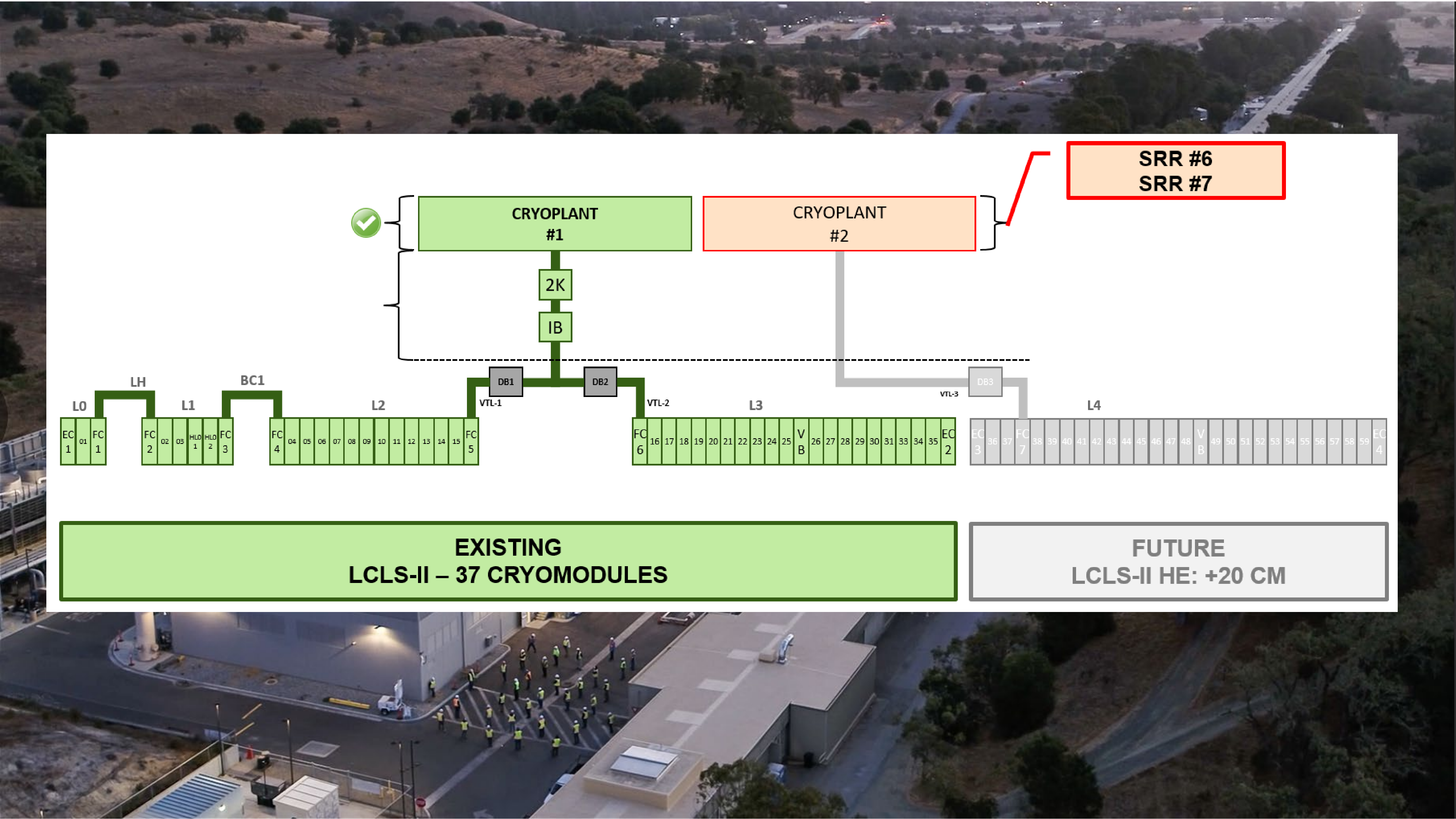
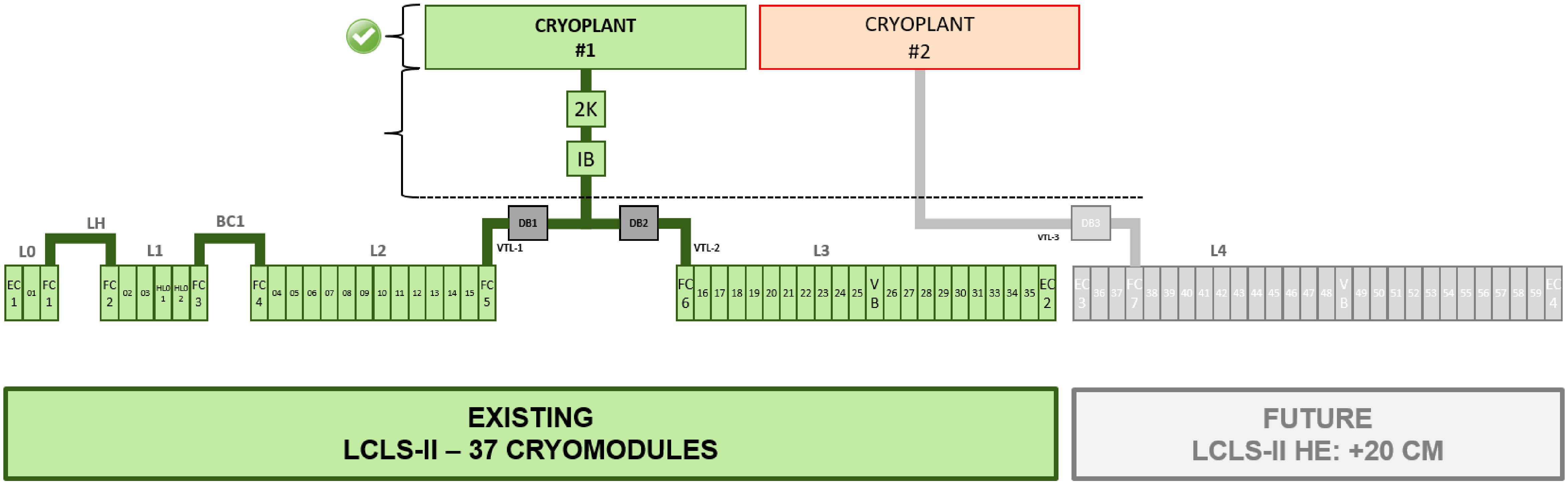
Cryogenic Systems & Cool Down


SRR #6
SRR #7
CRYOPLANT #1
CRYOPLANT #2
2K
IB
DB1
DB2
DB3
VTL-1
VTL-2
VTL-3
L0
LH
L1
BC1
L2
L3
L4
EC 1
01
FC 1
FC 2
02
03
HL0 1
HL0 2
FC 3
FC 4
04 05 06 07 08 09 10 11 12 13 14 15
FC 5
FC 6
16 17 18 19 20 21 22 23 24 25
V B
26 27 28 29 30 31 33 34 35
EC 2
EC 3
36 37
FC 7
38 39 40 41 42 43 44 45 46 47 48
V B
49 50 51 52 53 54 55 56 57 58 59
EC 4
EXISTING
LCLS-II – 37 CRYOMODULES
FUTURE
LCLS-II HE: +20 CM



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

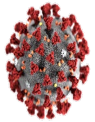
Cryoplant Commissioning Process

~ 30 Months

UTILITIES
- Electricity
- Control Network
- Water
- Air
- Nitrogen
- Helium

AUXILIARIES
- Recovery compressor
- Gas Analyzer
- Purifier

COMPRESSORS



4K Cold Box

LINAC Ready

LINAC @ 4 K

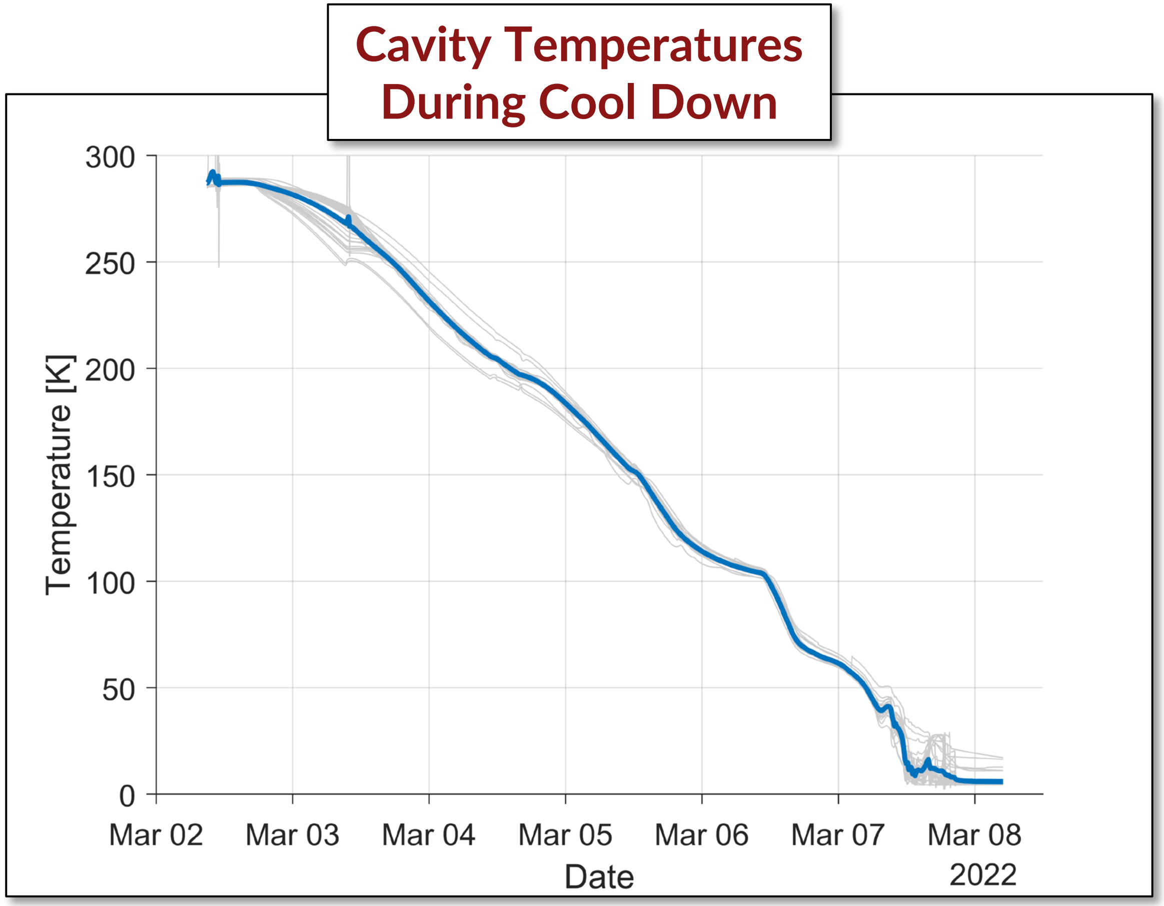
Cool Down

LINAC @ 2 K

2 K Pump Down

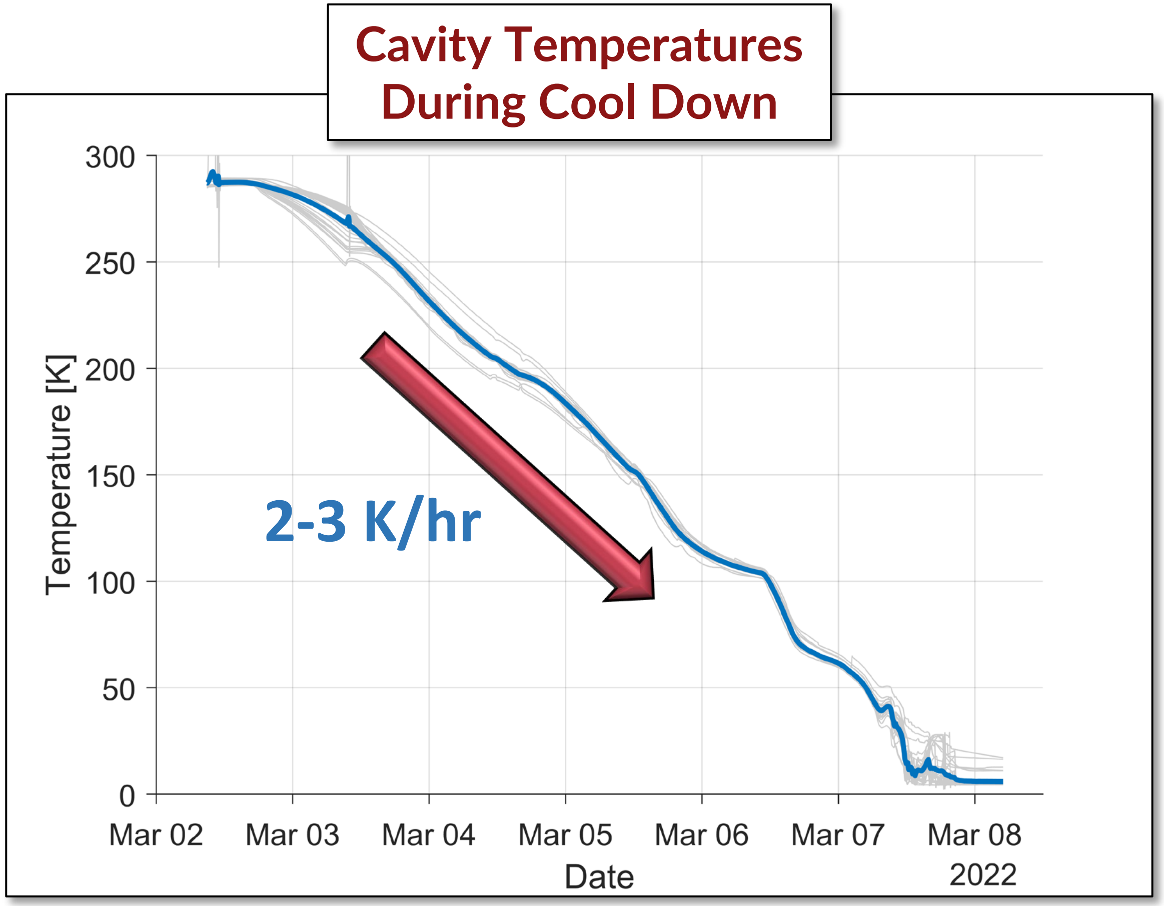
Aug. 15th 2019	4 mths	Dec. 15th 2019	3 mths	Mar. 15th 2020	10 mths	Jan. 15th 2021	7 mths	Oct. 15th 2021	2.5 mths	Jan. 1st 2022	3 mths	Mar. 30th 2022	1.5 mths	May 15th 2022

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**

Cool Down & Pump Down to 2 K



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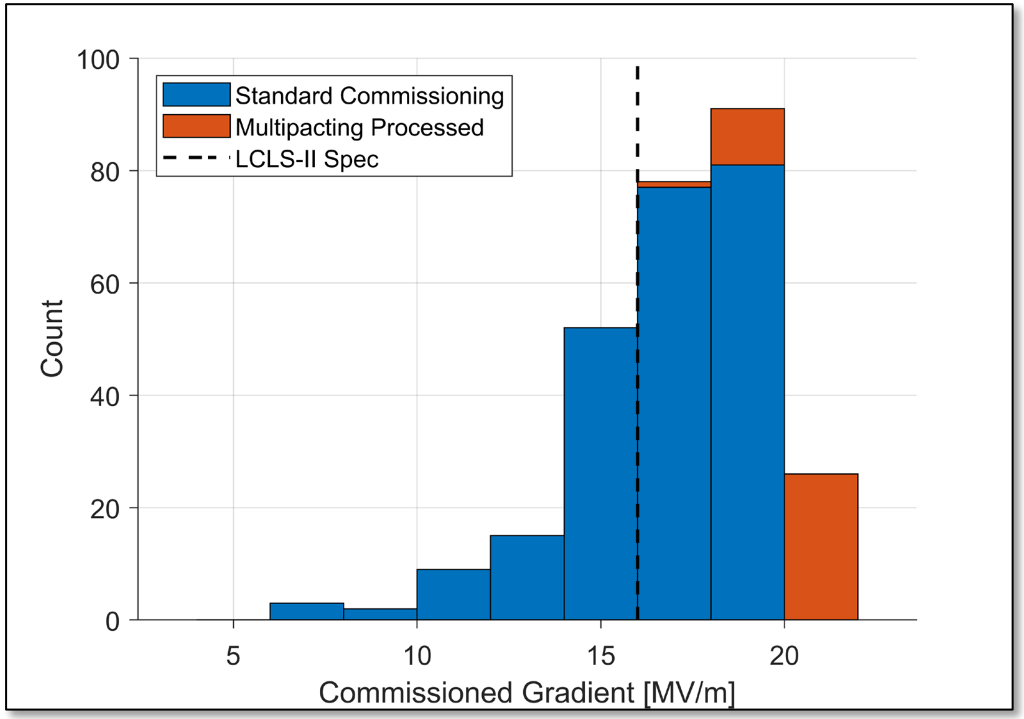
SRF and Cryomodule Commissioning

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%**

Overall SRF Commissioning Status

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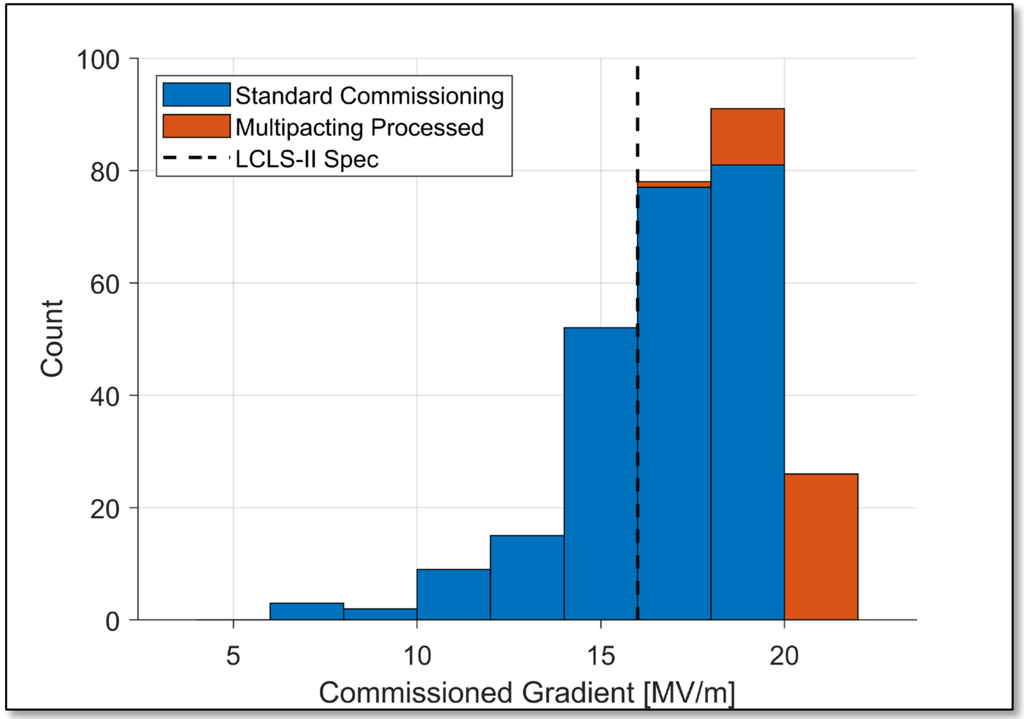

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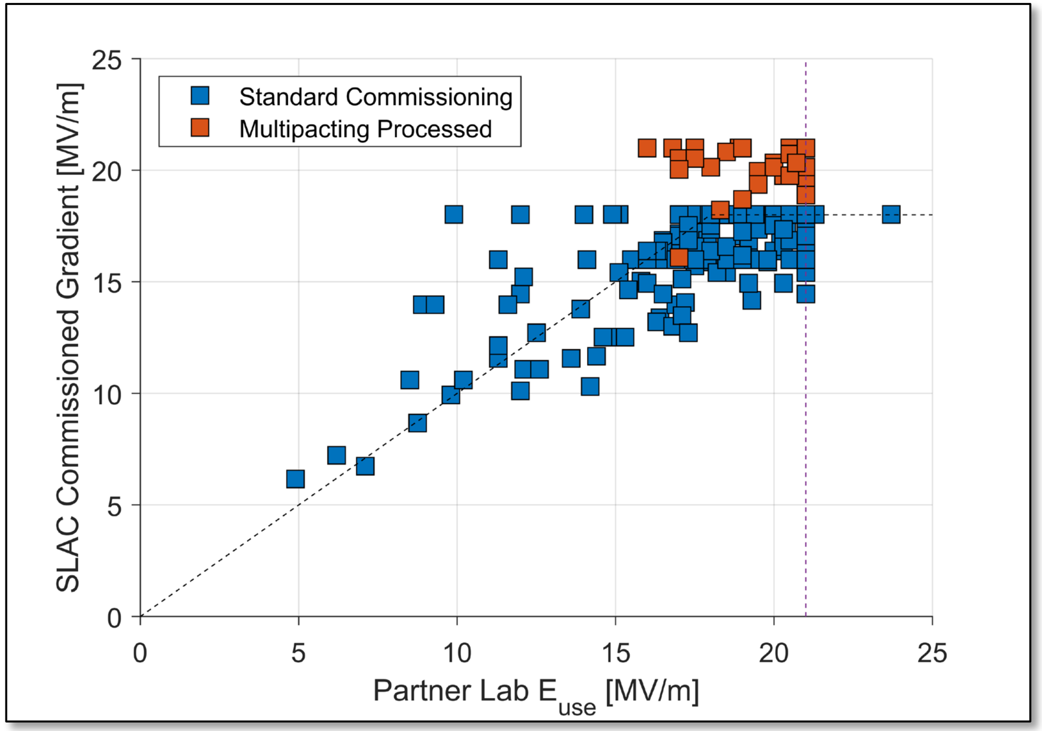
Total Commissioned Cavity Voltage: 4.9 GV

Gradient Performance

Comparison with Acceptance Test



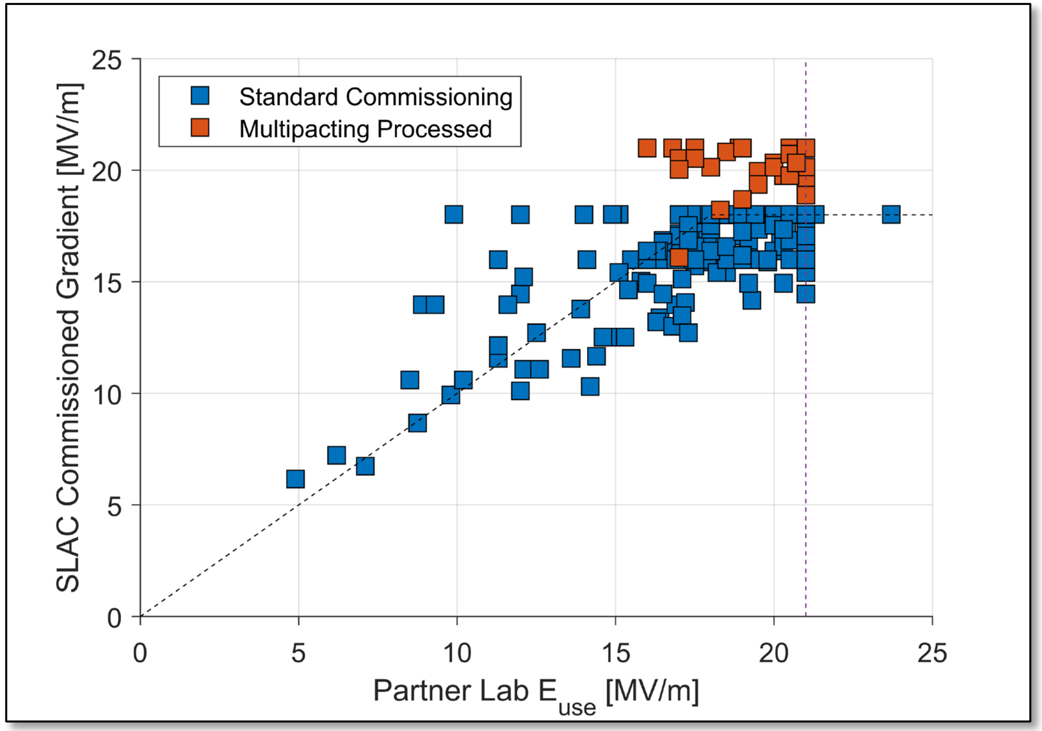
Admin limits:

- 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

Gradient Performance

Comparison with Acceptance Test



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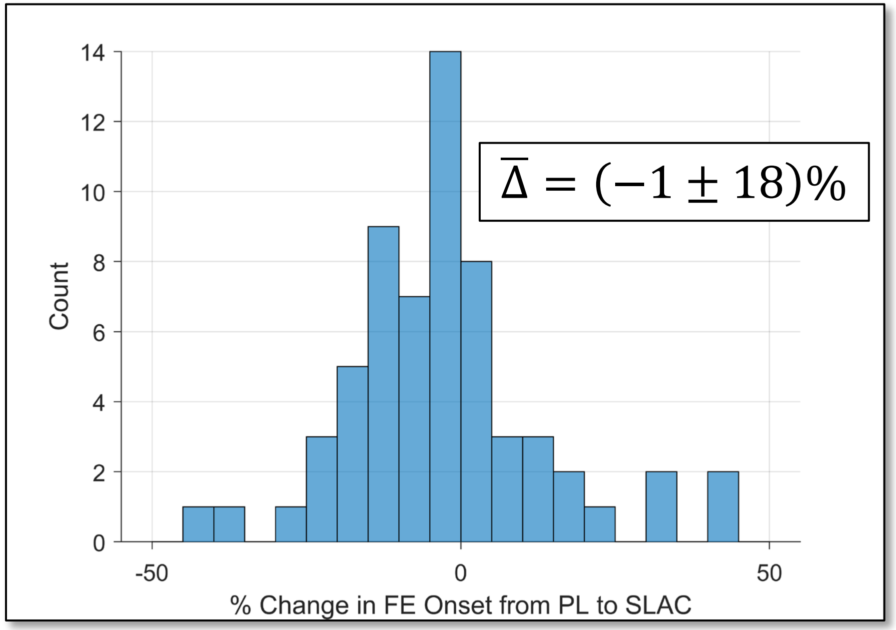

Gradient Performance

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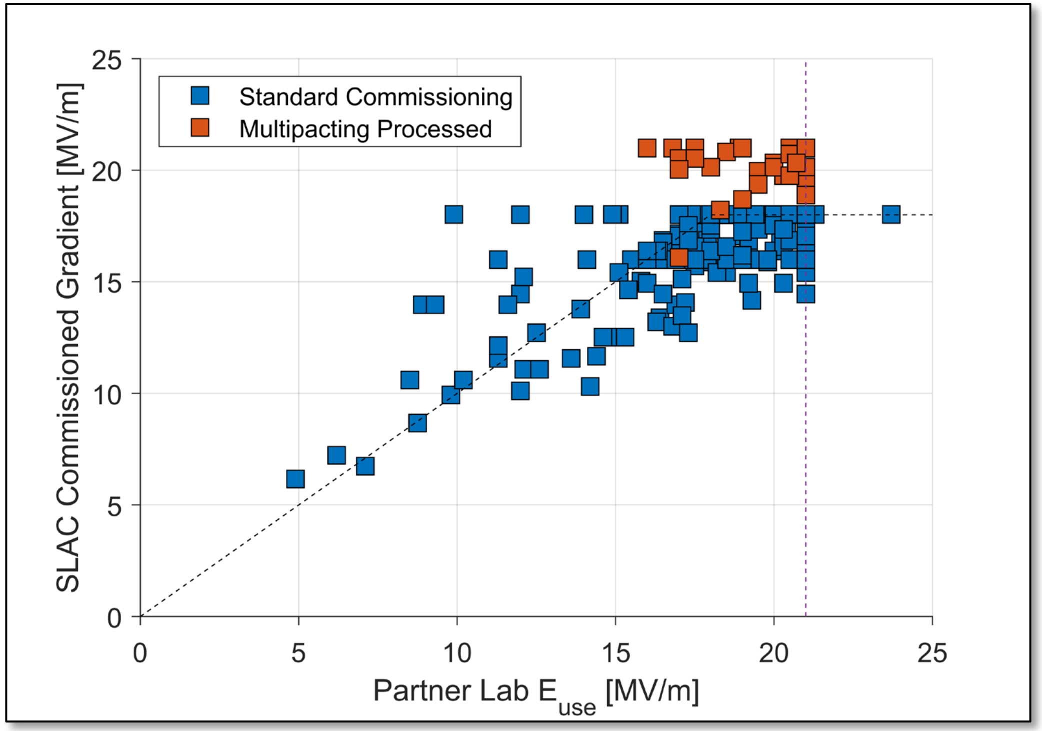

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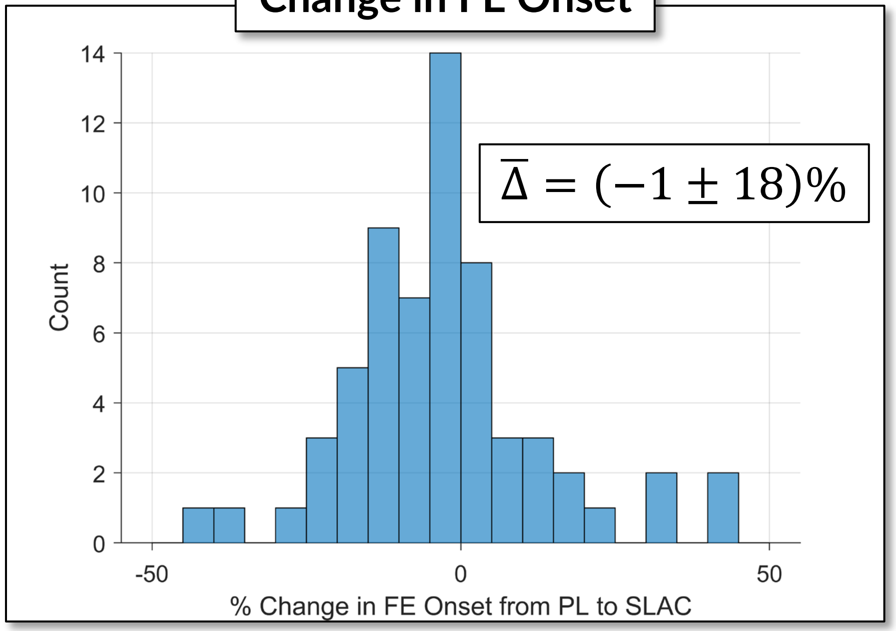
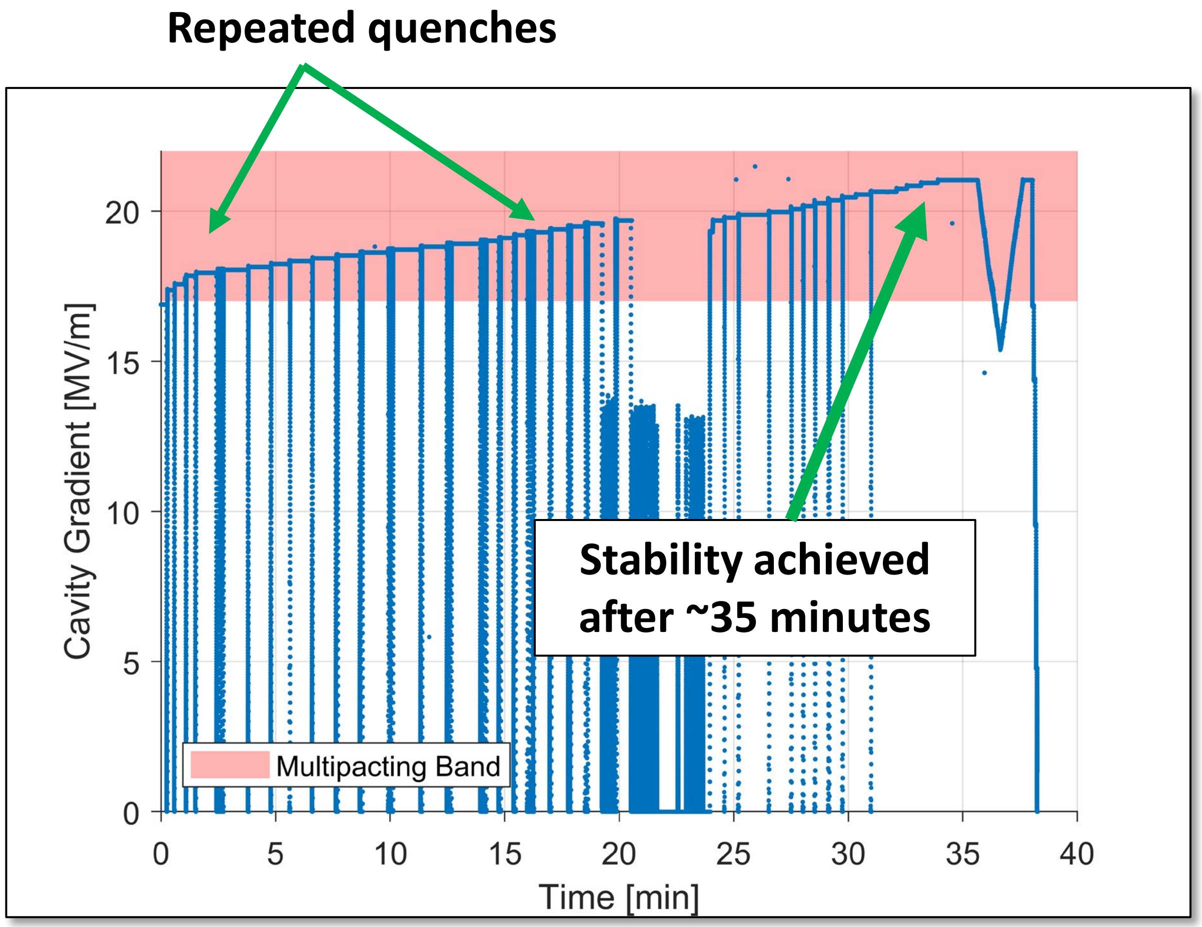
Change in FE Onset



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

Multipacting Processing

- Multipacting identified as a gradient limitation for LCLS-II cavities late in CM production
- Observed as a short term stability at gradient in the band of 17-23 MV/m
- Processing techniques developed and tested by LCLS-II-HE team and applied to a subset of cavities in the installed linac
  - Consists of repeatedly quenching the cavity in CW mode with limited time (few seconds) for recovery

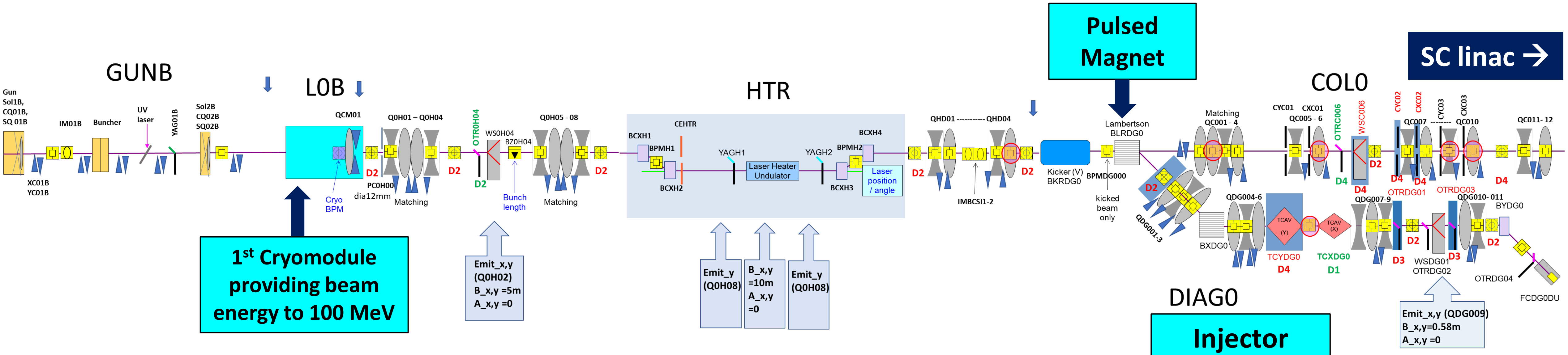


Average gradient gain of ~3 MV/m observed in 37 cavities processed

6

SC Beam Commissioning

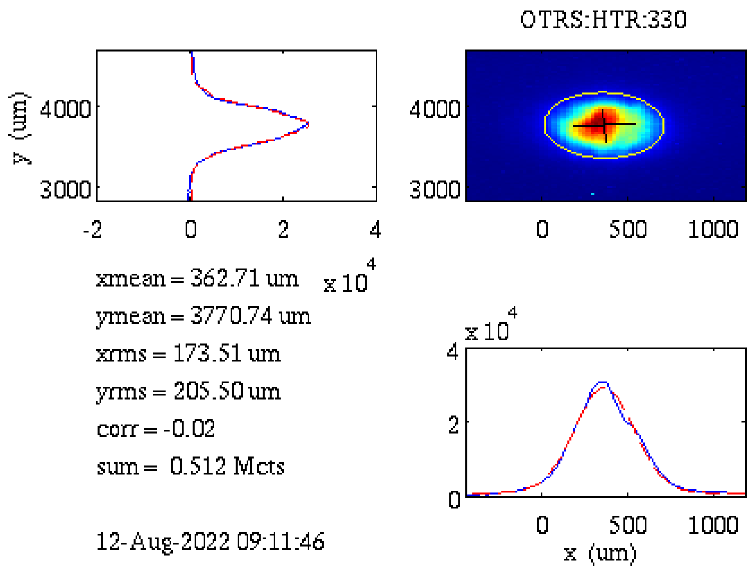
100 MeV Injector Commissioning Nearing Completion



Goals of Injector Commissioning:

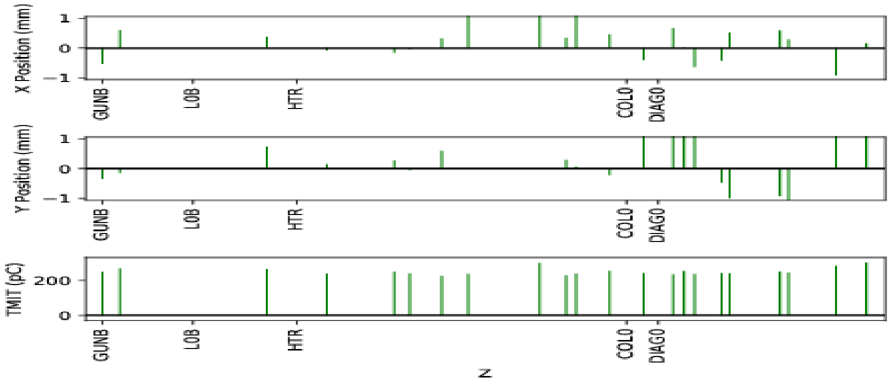
- Establish beam and optimize to design specifications (emittance, charge, transmission)
- Conduct beam containment system (BCS) certification
  - Calibration of Beam Safety System devices at high repetition rate and bunch charge
  - Beam current and beam loss monitors

100 MeV Injector Performance

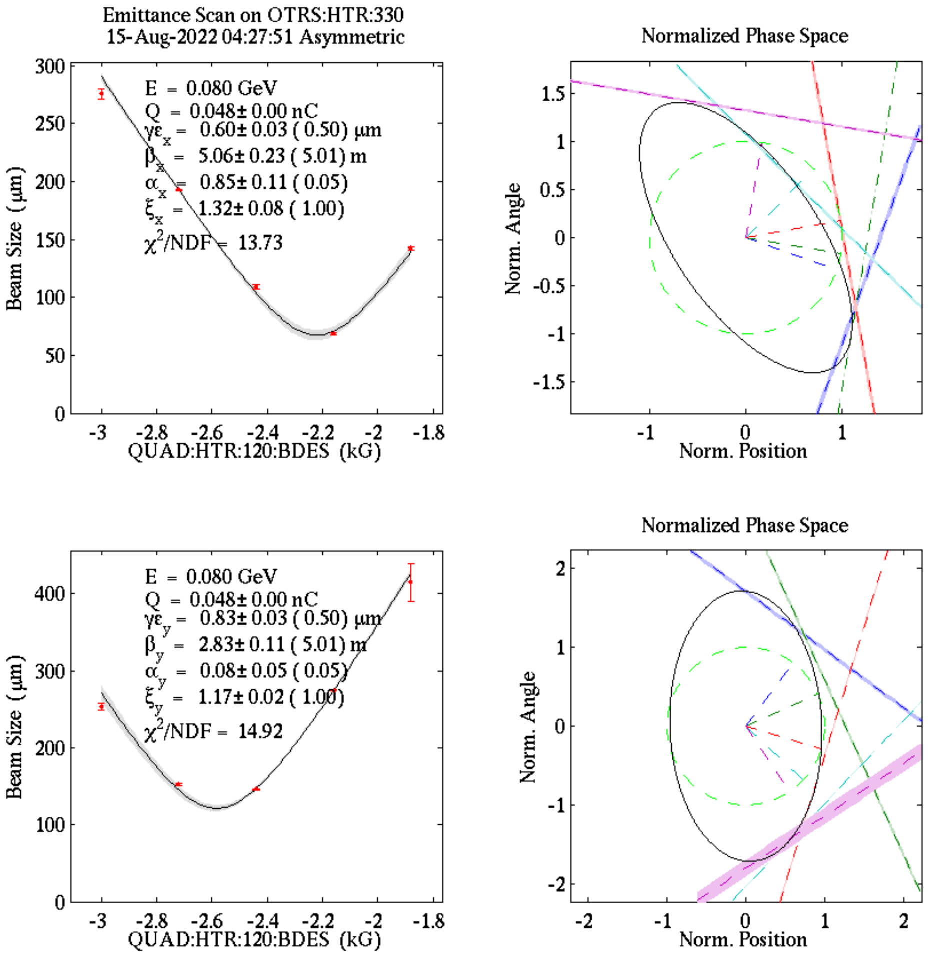


100 MeV electron beam image

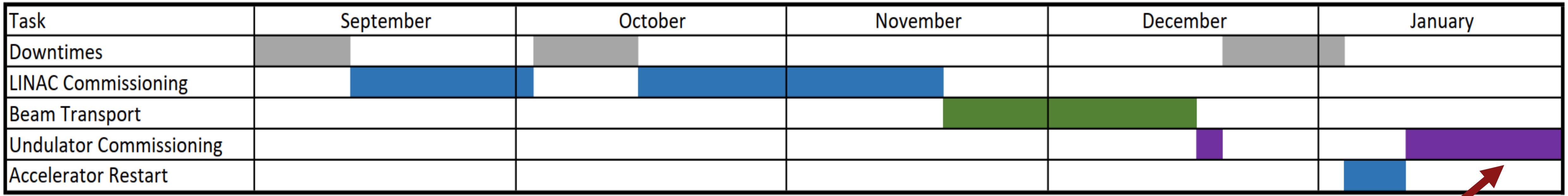
Injector electron beam orbit 250 pC, 100% transmission



Excellent Injector emittance: 0.6x0.8 µm



Schedule Outlook

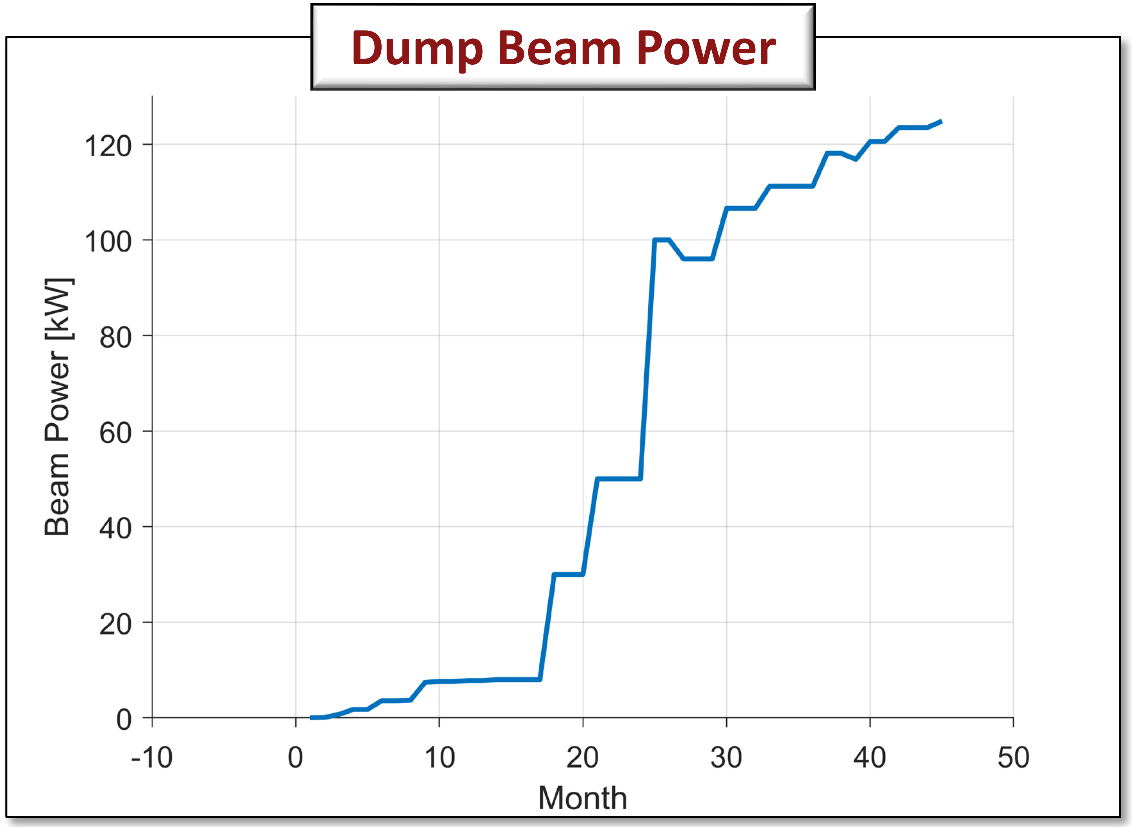


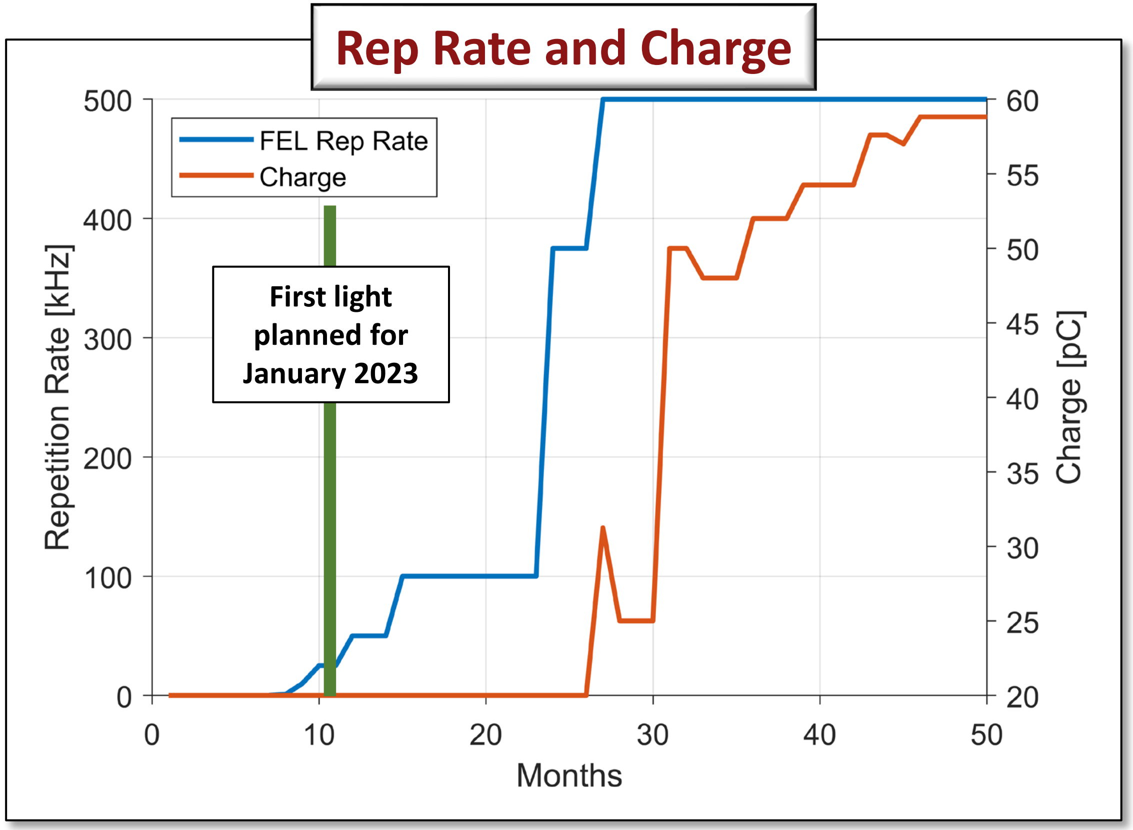
1st Light Milestone is anticipated in January of 2023

→Achievement of Threshold KPPs ←

→Ready to begin routine delivery of x-rays to the instruments ←

Ramp- Up Plan for 500 kHz FEL Operation

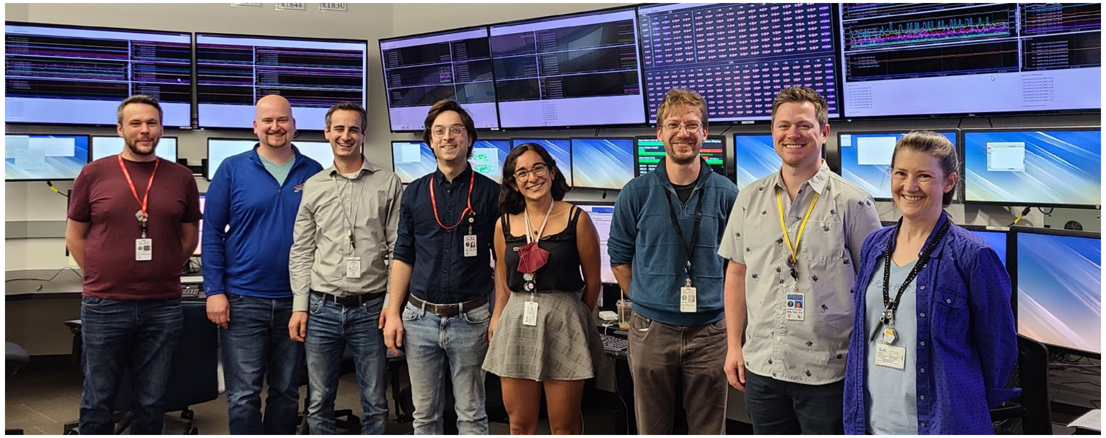




- Conservative and slow beam power ramp-up to full performance ensures safe beam operation
- Objective KPPs will be reached after ~2 years following gun restart (March/April 2024)

Summary

- LCLS-II commissioning is progressing well
- Undulator and beamline systems were commissioned with the copper linac
- Cool down of the superconducting linac went very smoothly and was complete in May 2022
- Injector and 100 MeV commissioning has produced a **beam of excellent quality**
- Cryomodule performance has been excellent, showing **no degradation to cavity performance** from installation at SLAC
- The next few months will be very exciting!



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

Thanks for your attention!

SLAC NATIONAL ACCELERATOR LABORATORY

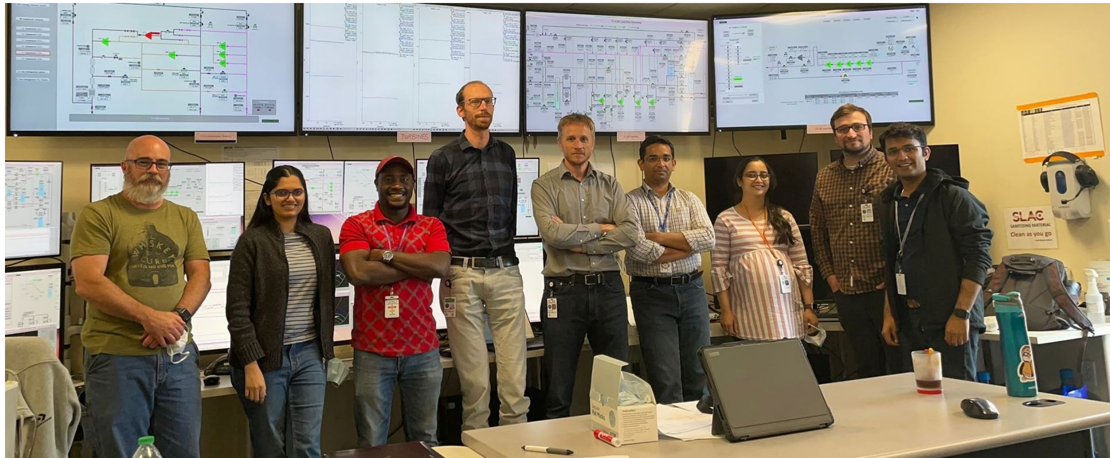
Fermilab

Argonne NATIONAL LABORATORY

CORNELL UNIVERSITY FOUNDED A.D. 1865

BERKELEY LAB Lawrence Berkeley National Laboratory

Jefferson Lab



SLAC