LCLS-II Commissioning

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On behalf of the LCLS-II Collaboration

12 June 2024

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Outline

LCLS-II Overview

Installation & Cool Down

SRF Cavity Commissioning

Challenges

Summary & Outlook

LCLS-II Overview


LCLS RF Gun
LCLS-II RF Gun
Superconducting Accelerator
Warm Accelerator
Soft X-ray Undulator
Near Hall
Far Hall
L1
L2
L3
Sector 5
1
2
3
4
5
6
Hard X-ray Undulator
Hutches
Sector 0
Sector 30
Beam Dumps
Superconducting Crossover
Soft X-ray Beamline
Hard X-ray Beamline

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	0–5,000 eV
High repetition rate capable end stations	≥ 1	≥ 2
FEL photon quantity (10^{-3} BW) per bunch	5x10^8 (10x spontaneous) @2,50	> 10^{11} @ 3,800 eV
Normal conducting linac-based syst		
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

Achieved

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# 1.3 GHz CMs	35
Operating Gradient	16 MV/m
Required Q_0 at Operating Gradient	2.7x10^{10}

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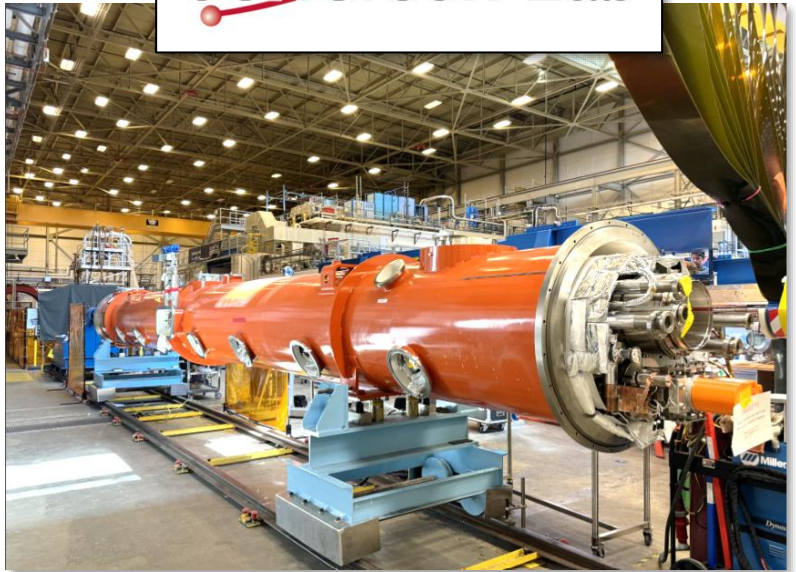
Cryomodules constructed at PLs

1.3 GHz cryomodules were constructed at Fermilab and Jefferson Lab

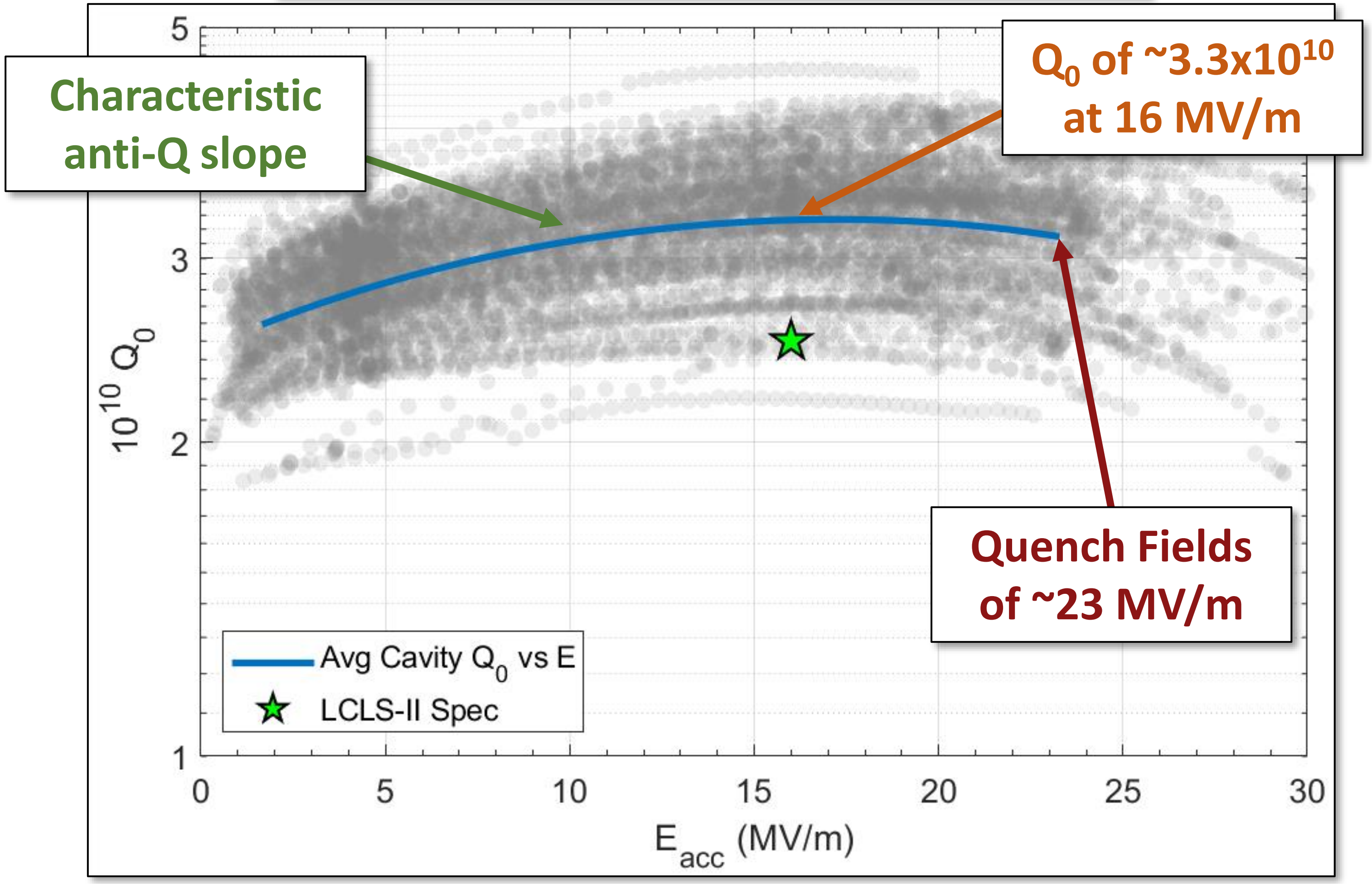
Fermilab

Jefferson Lab



Nitrogen-Doping for LCLS-II

Average Q_0 vs E Performance



Characteristic anti-Q slope

Q_0 of ~3.3×10^{10} at 16 MV/m

Quench Fields of ~23 MV/m

- LCLS-II constructed **373 nitrogen-doped 1.3 GHz cavities**
- All cavities were produced with the **2/6 nitrogen-doping** protocol
- Significant procedural improvements were made along the way to achieve reliable good performance

(flux expulsion, fabrication techniques)

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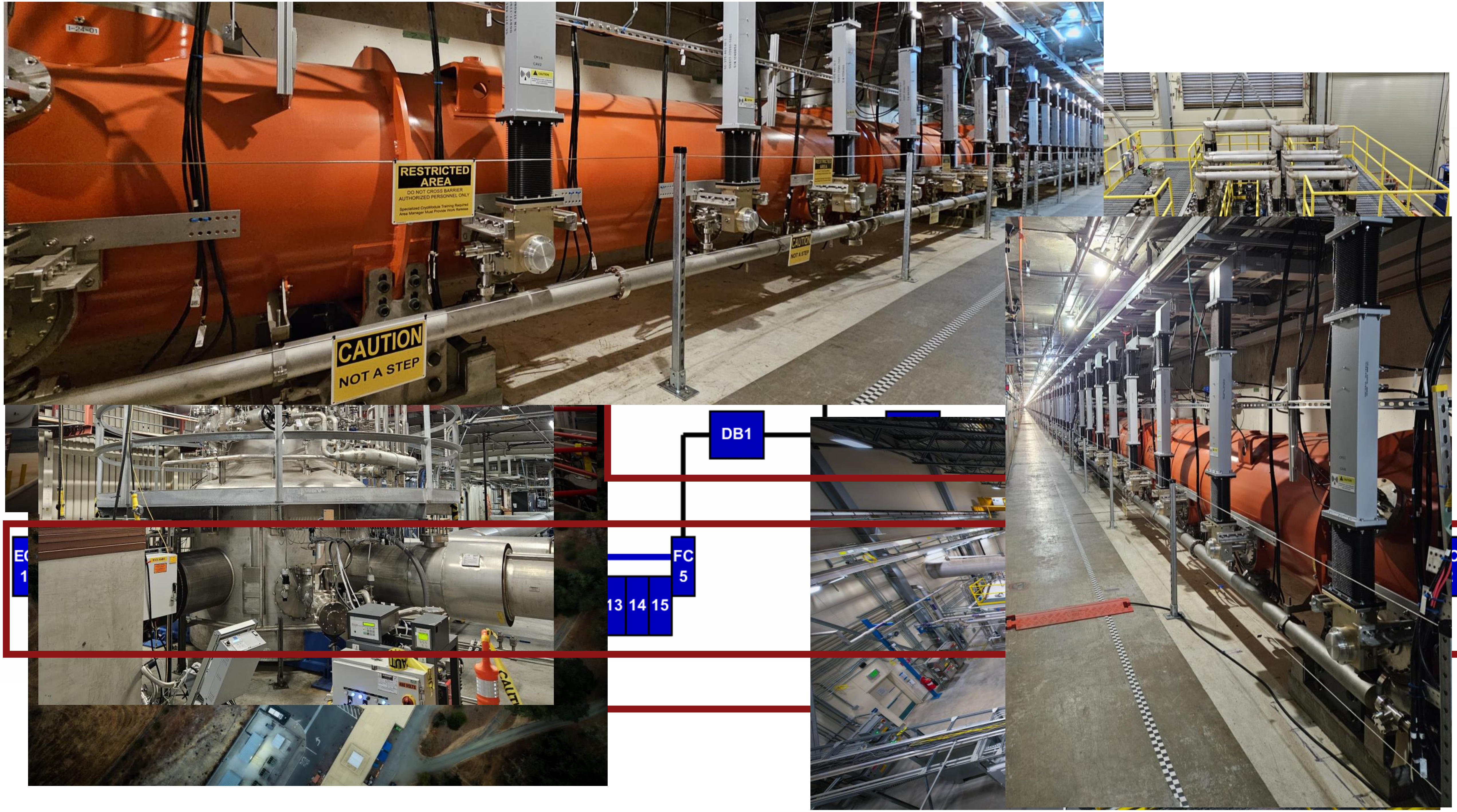
Installation & Cool Down

Cryomodule Installation

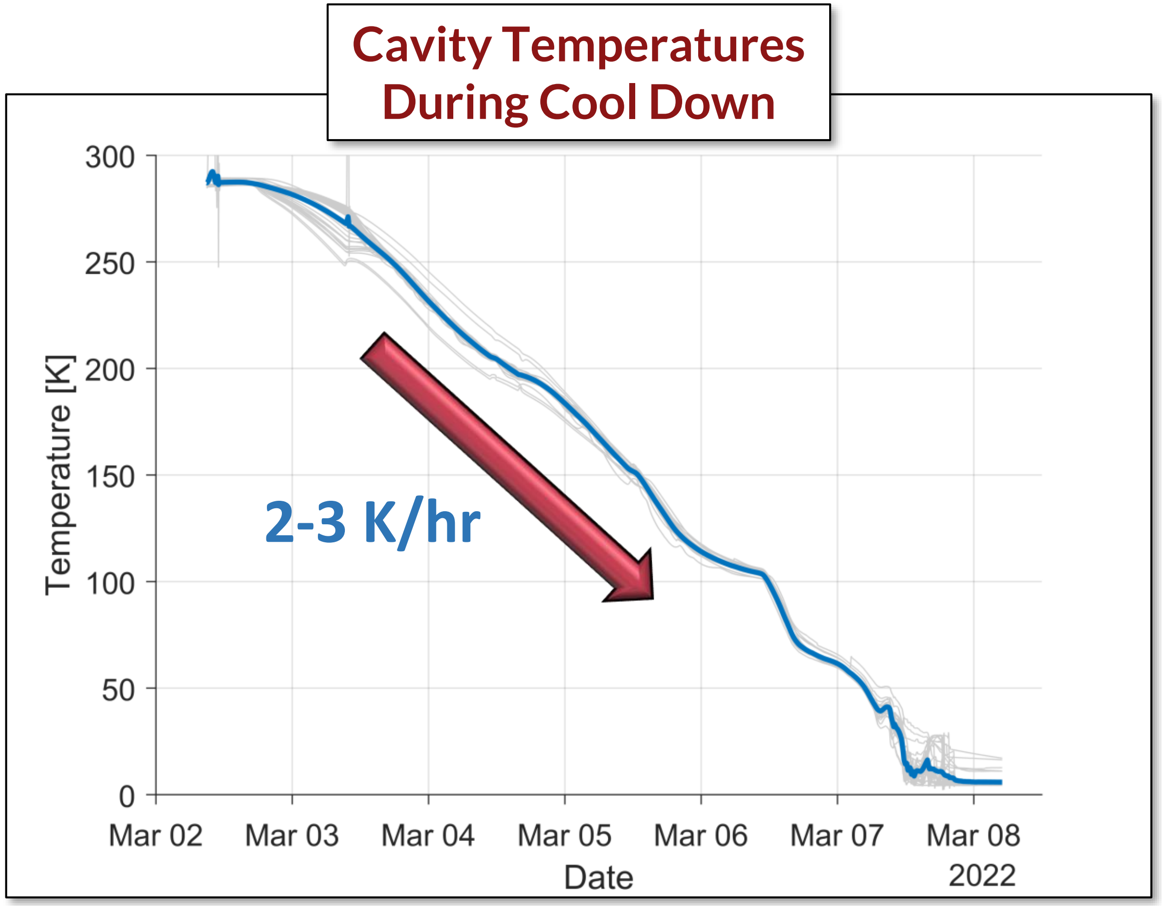
Last CM (spare) Delivered in May 2021

CM Installation Complete February 2021


1-24-01
RESTRICTED AREA
DO NOT CROSS BARRIER AUTHORIZED PERSONNEL ONLY
Specialized CryoModule Training Required Area Manager Must Provide Work Release
CAUTION
NOT A STEP
DB1
FC 5
13
14
15
EC 1

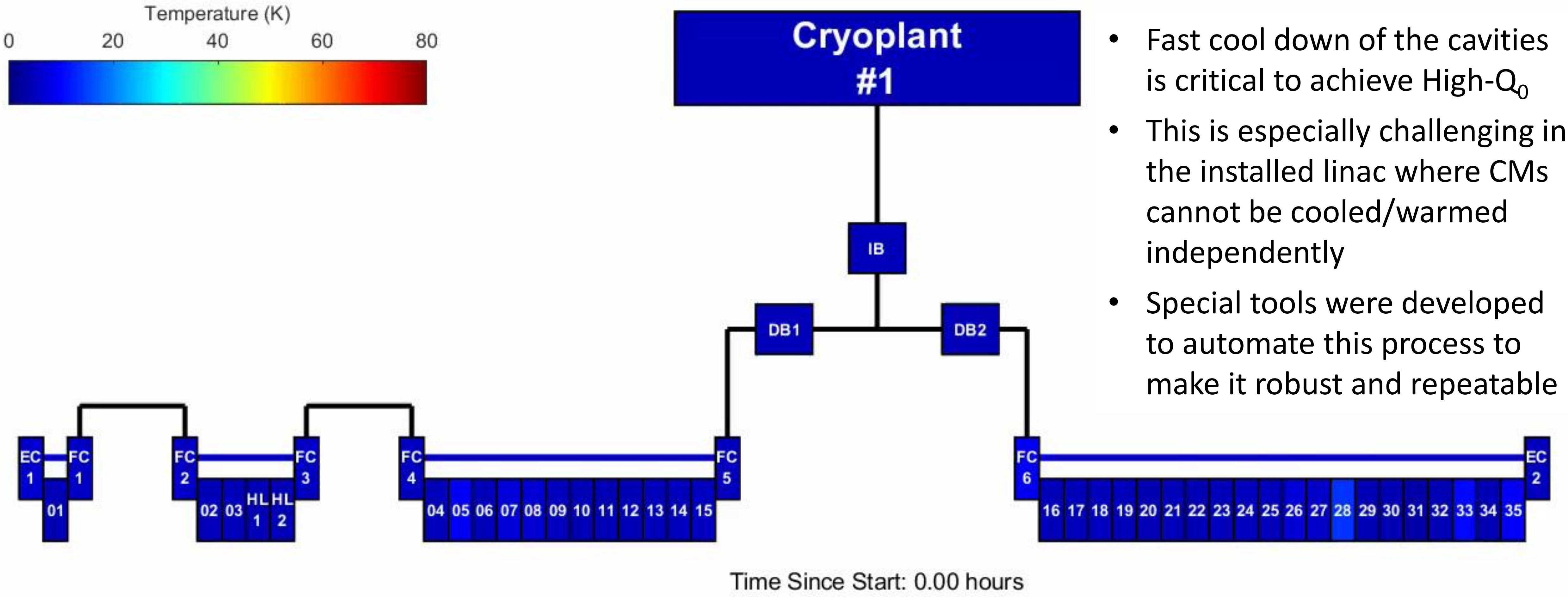
Cool Down & Pump Down to 2 K

Cavity Temperatures During Cool Down



- 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
  - CD valves were used to maintain rate and safe temperature gradients across the linac
- After multiple attempts, stable operation at 2 K was achieved **only 11 days later**

Fast Cool Down



Time Since Start: 0.00 hours

- Fast cool down of the cavities is critical to achieve High-Q_0
- This is especially challenging in the installed linac where CMs cannot be cooled/warmed independently
- Special tools were developed to automate this process to make it robust and repeatable

Coloring based on *actual* temperature data during FCD

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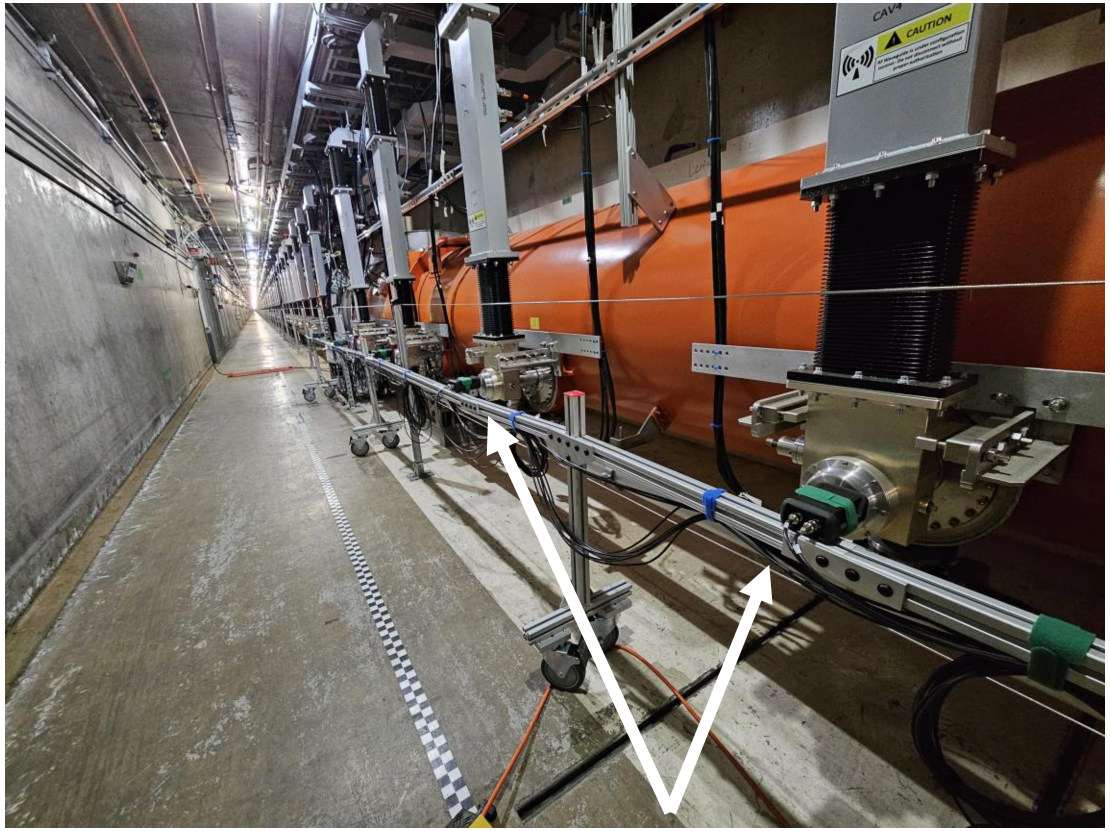
SRF Cavity Commissioning

Cavity Commissioning Process

Each individual cavity went through an identical checkout process:

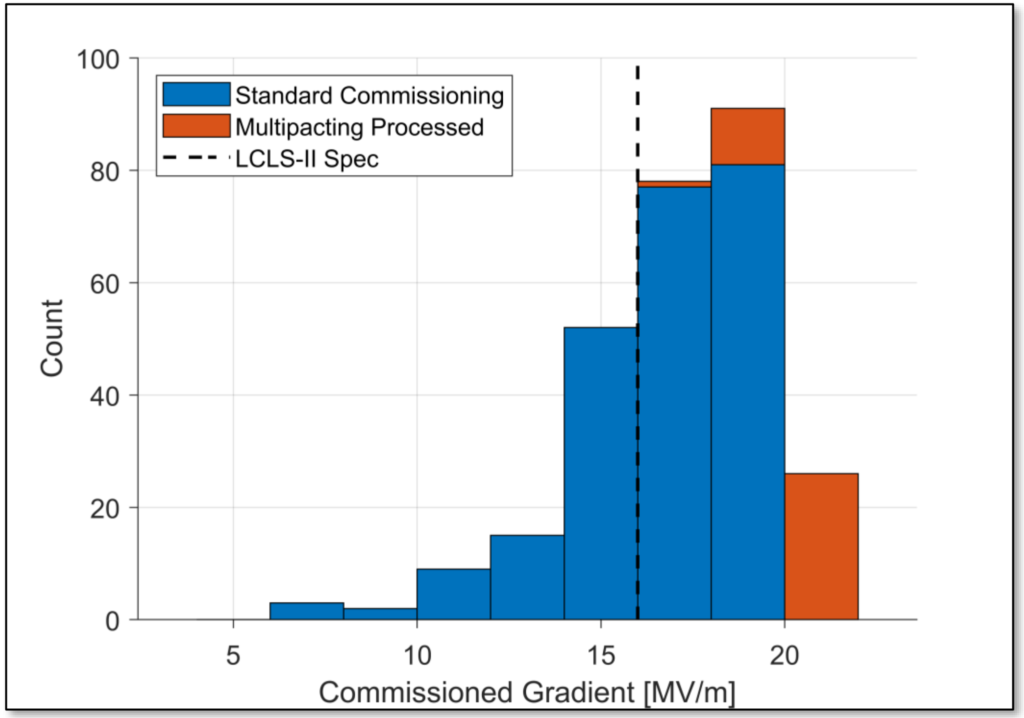
1. Checkout of support systems (SSAs, LLRF, etc.)
2. Checkout of auxiliary components (tuner, piezos, coupler, etc.)
3. Gradient and field emission characterization
4. Individual and full CM stability demonstration
    - 1 hour run for single cavities to define usable gradient
    - 12 hour full CM test



Placement of radiation sensors is similar but *not identical* to placement during CM acceptance testing

Overall SRF Commissioning Status

Gradient Performance

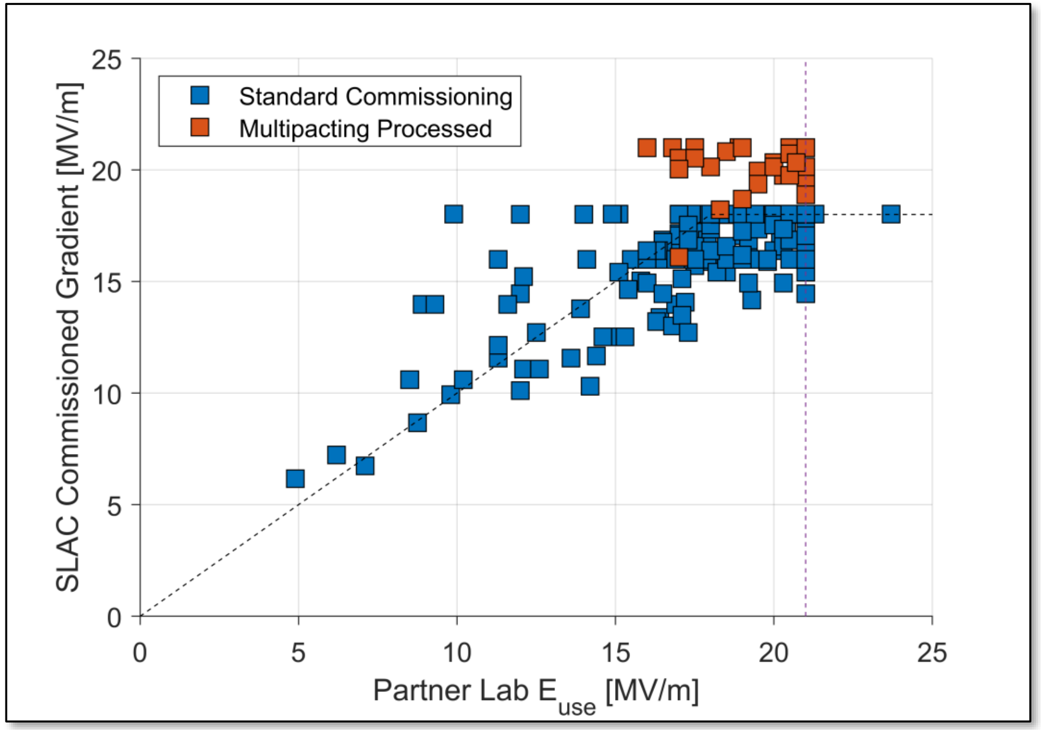


- Cryomodule commissioning has been very successful
- 97% of installed cavities fully operational (planned 94%)
- Majority of testing included an admin limit of 18 MV/m
- Total commissioned voltage **exceeds design by >20%**

Total Commissioned Cavity Voltage: 4.9 GV

Gradient Performance

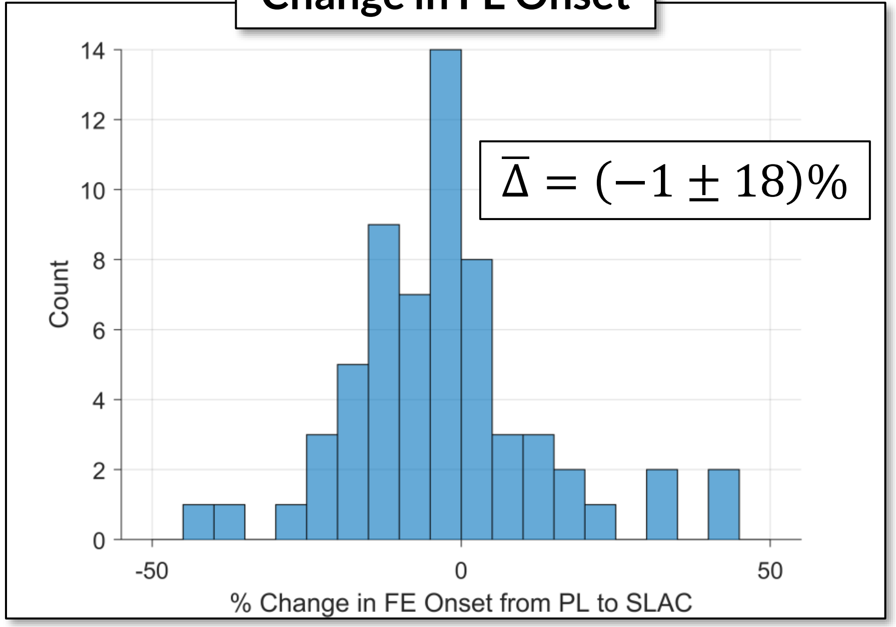
Comparison with Acceptance Test



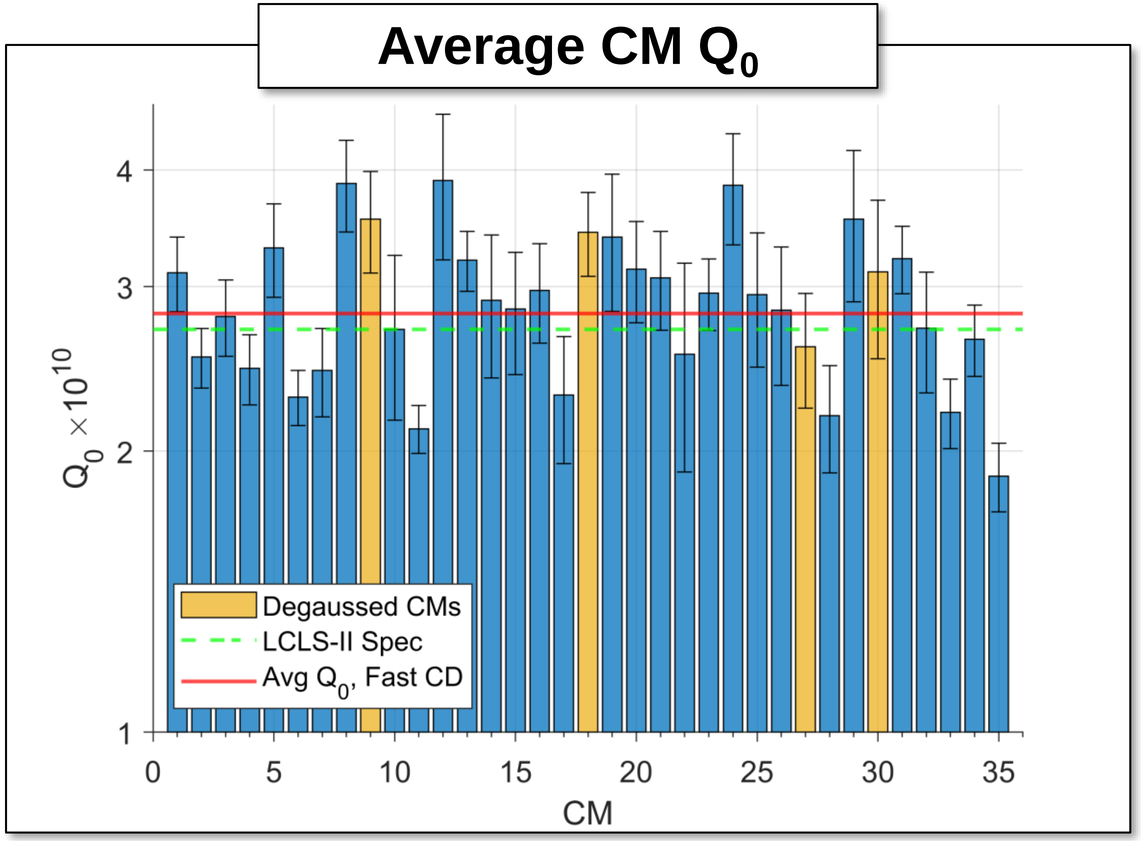
Admin limits:
- 18 MV/m in commissioning
- 21 MV/m in acceptance test

- 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**
  - **Remarkable achievement by the SLAC installation team**

Change in FE Onset



Q_0 in the Linac

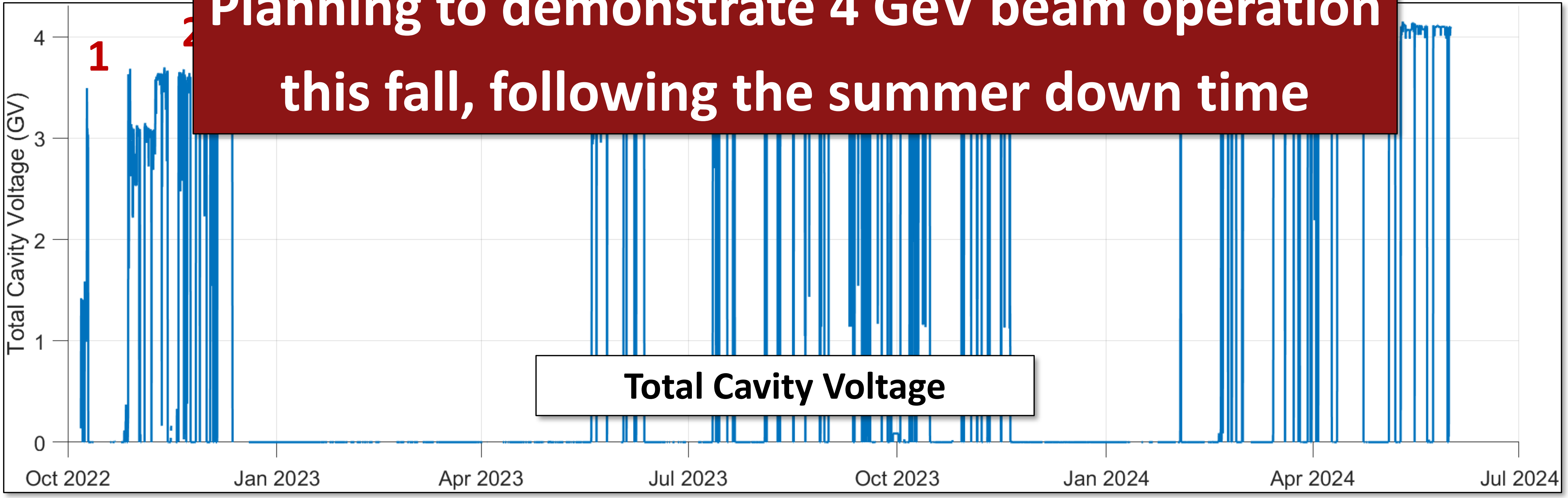


- Due to the strong coupling in the CM, Q_0 is measured cryogenically
- Full CM average Q_0 results look promising
- Across the linac an **average of 2.8×10^{10}** has been observed, **exceeding the spec** of 2.7×10^{10}
- Low performers can likely be improved by additional CM degaussing

Demonstrates High Q_0 in an installed linac for the first time

Demonstration of Beam Energy

1. Stable 3 GeV beam to BSY achieved in October 2022
2. 3.5 GeV beam with design cavity phases demonstrated at end of November 2022
3. 3.5 GeV used for most of the beam commissi
4. 3.75 GeV beam demonstrated in September 2023 to facilitate lasing
5. Beam energy lowered to 3.5 GeV since September with higher headroom to facilitate commissioning and user programs



Planning to demonstrate 4 GeV beam operation this fall, following the summer down time

Total Cavity Voltage

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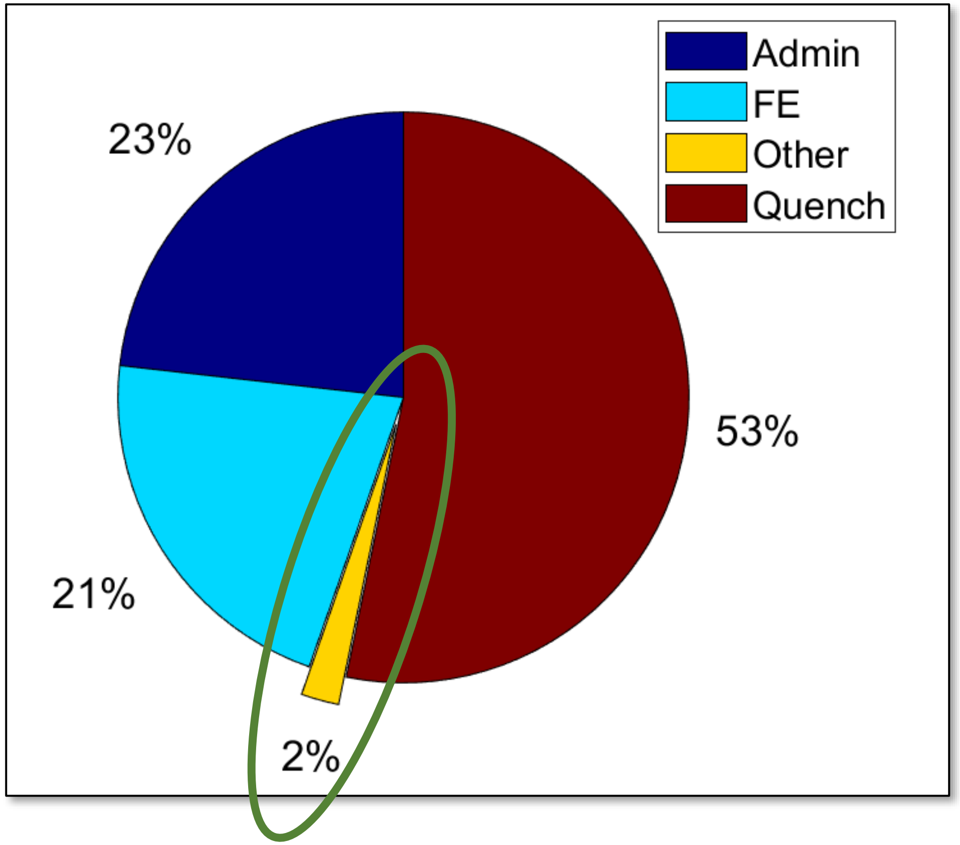
Challenges

Cavity Limitations

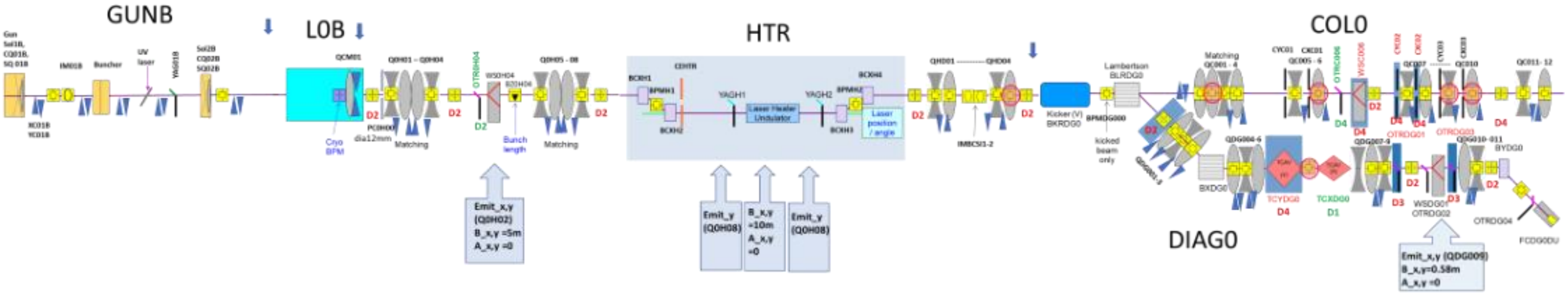


80% of cavities reach ≥16 MV/m

- The majority of cavities were limited by quench below the admin limit of 18 MV/m
  - It is suspected that many of these are limited by multipacting which could be processed
- About one-quarter of the cavities reached the admin limit
- About one-fifth of the cavities were limited by field emission
- The remaining 2% of cavities are unable to be used:
  - 2 cavities: poor contact between coupler warm and cold ends
  - 4 cavities: tuners not functioning properly
  - It is expected that all 6 of these cavities could be repaired *in situ* at room temperature

New Field Emission in CM01

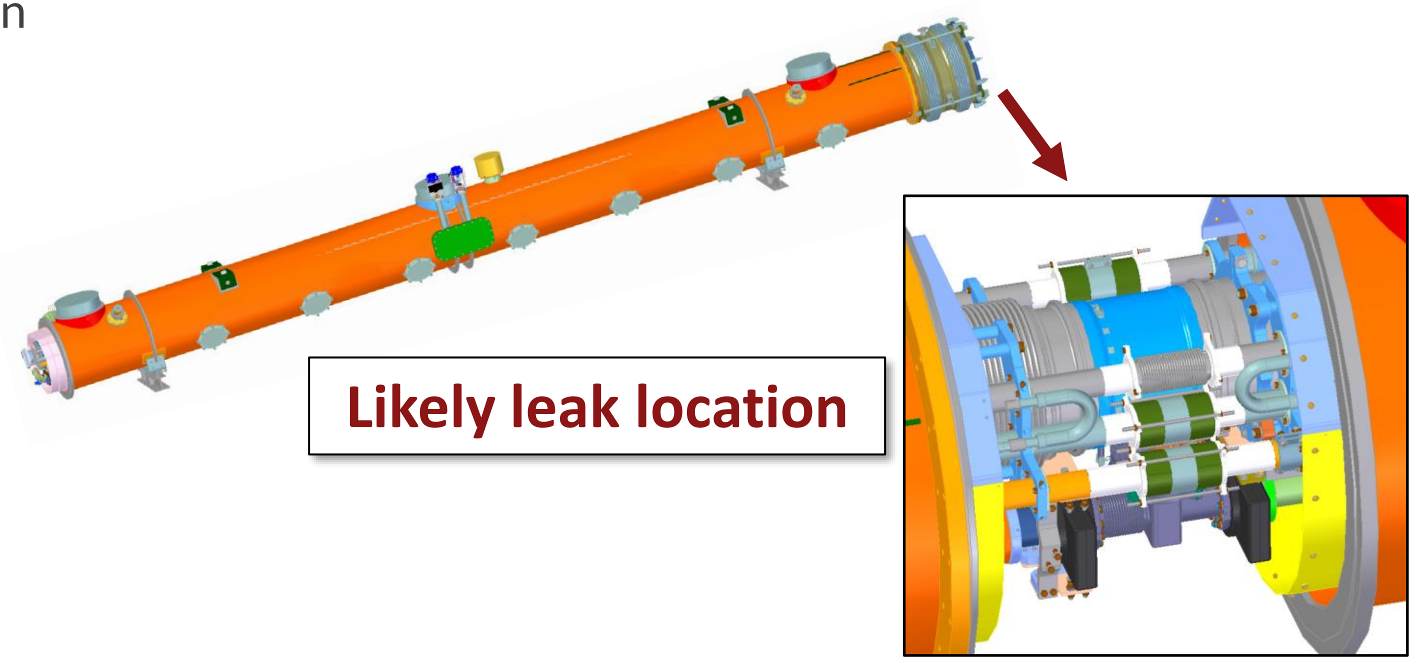
- During commissioning, CM01 was field emission free (no radiation) and operated at ~100 MeV
  - Specific amplitudes are required for optimal injector performance and beam quality
- In October 2023, **new field emission was found** in four cavities in CM01, suggesting contamination was introduced
- **Exact cause is currently unknown:** no specific events in beamline vacuum were found that would explain particle migration or gas bursts
- Operating energy has been reduced to ~80 MeV
  - ➢ Required to run below the optimal energy for the laser heater



Static Heat Load

- One of the cryomodule strings, consisting of 20 CMs shows significantly higher static heat loads than were expected
- This is in part due to a leak from the cryogenic system to the insulating vacuum of the cryomodules
- Overall, an additional 200 W of static heat has been observed compared with what was expected
- While this limits the overall cryogenic capacity, the **beam energy program has not been impacted**
- Plans are underway to repair this issue during an extended down period starting in summer 2025

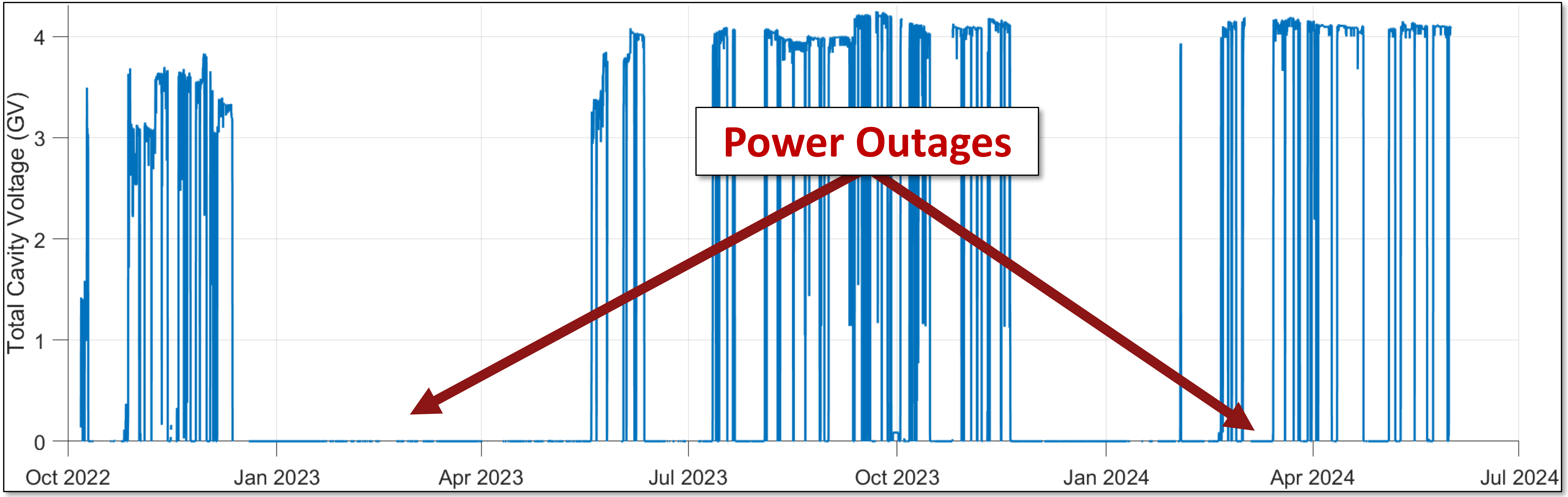
	Expected Static Heat Load	Observed Static Heat Load
LO-L2	9 W / CM → 150 W	9 W / CM → 150 W
L3-UPSTREAM	9 W / CM → 90 W	17 W / CM → 170 W
L3-DOWNSTREAM	9 W / CM → 90 W	16 W / CM → 160 W
TOTAL CM STATIC	**330 W**	**500 W**



Likely leak location

Power Outages

- SLAC has experienced three site-wide power outages since LCLS-II commissioning began
- Combined with the static heat load issues, uncontrolled warm up of the linac occurred in each of these instances
- This results in loss of helium and risk of damage to CMs
- In the most serious case, in March of 2023, the linac warmed to room temperature
- Additionally, multiple public safety power shutoff threats have resulted in shutting the beam program down out of an abundance of caution



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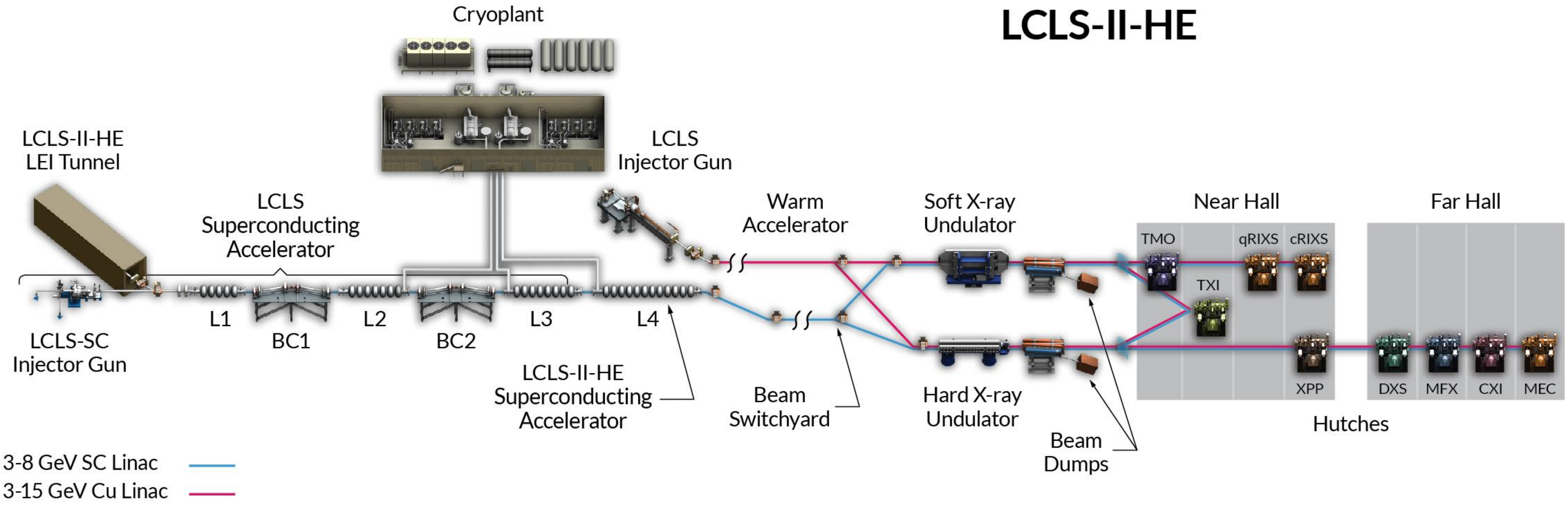
Summary & Outlook

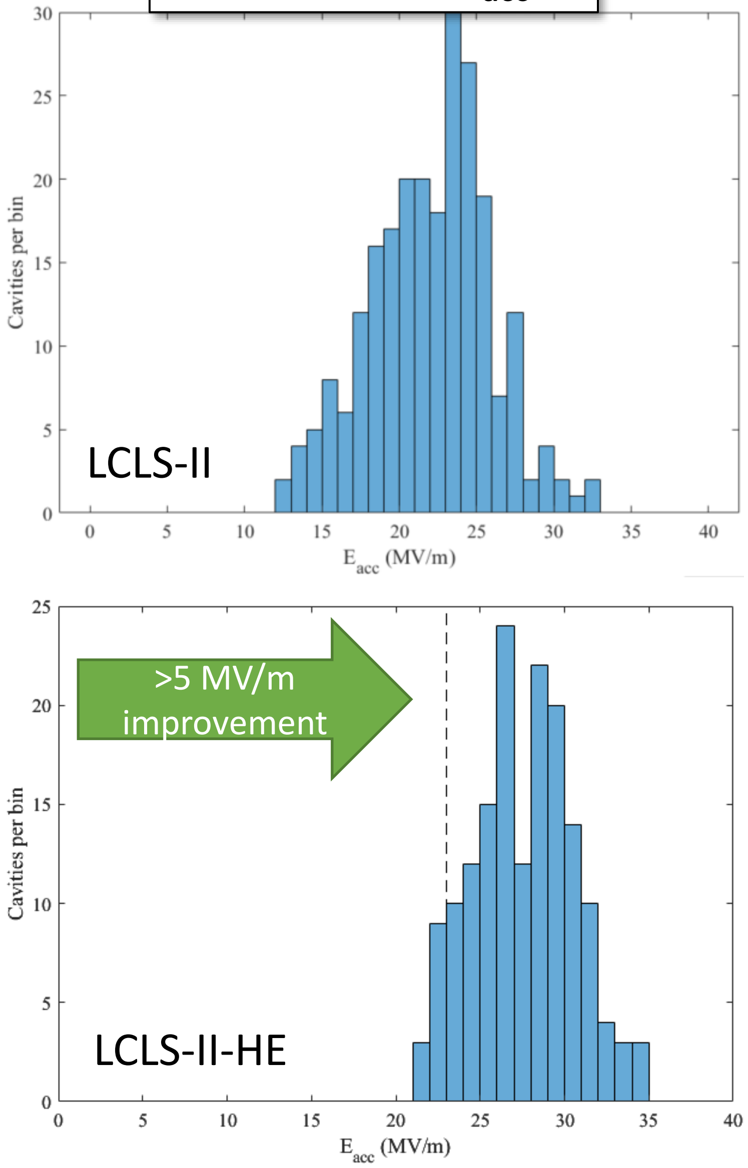
Up Next: LCLS-II-HE



1. **Add 23 additional cryomodules (L4 linac) to double the LCLS-II accelerator energy: 4 GeV to 8 GeV**
2. **Install new cryogenic distribution box and transfer line between the cryoplant and the new L4 linac**
3. **New long period soft X-ray undulator**
4. **Upgrade XPP instrument & hard X-ray photon beamlines for high average power and MHz beam rates**
5. **Construct new tunnel for future Low Emittance Injector (LEI)**
6. **Develop prototype SRF gun for the LEI**

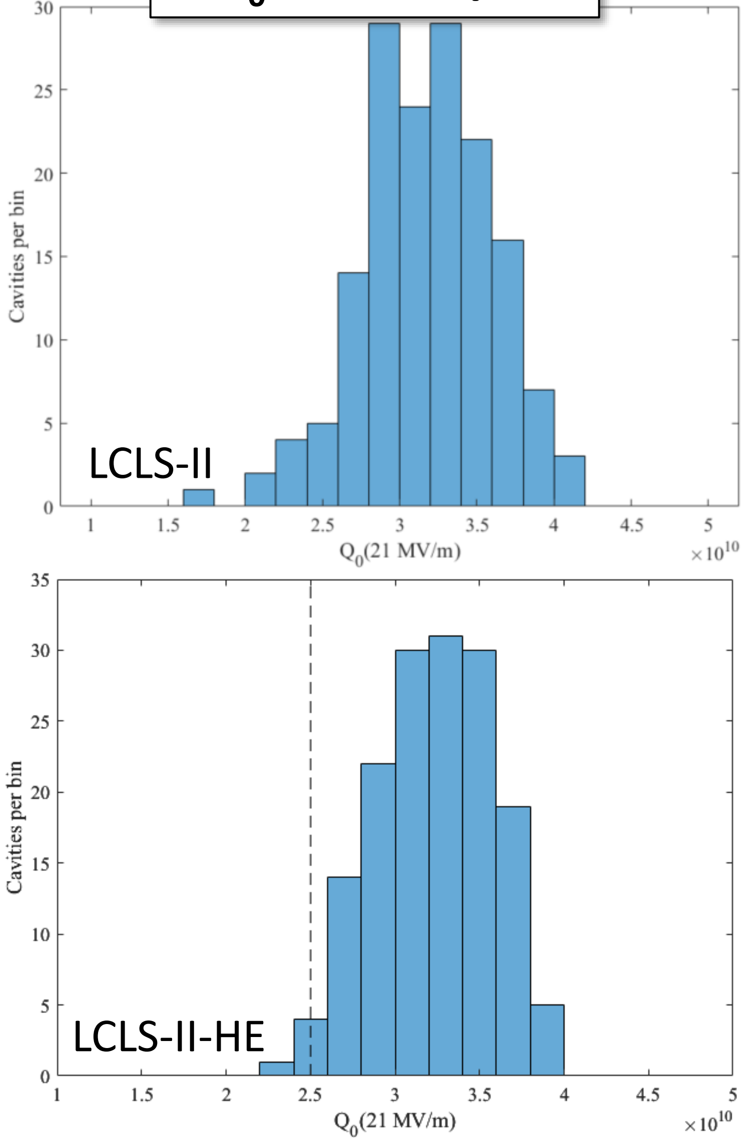
LCLS-II-HE Cavity Performance

Maximum E_{acc}



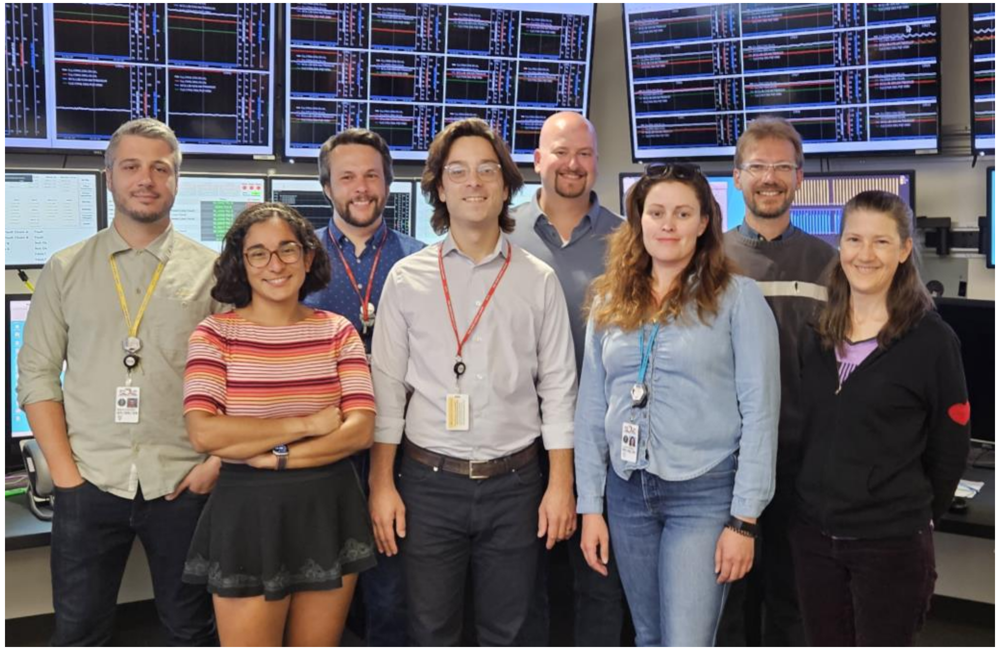
- LCLS-II-HE implemented lessons learned and additional SRF R&D to further improve cavity performance
- Demonstrated >5 MV/m improvement in gradient on average
- Q_0 is preserved and has significantly fewer cavities below specification

Q_0 at 21 MV/m



Summary

- LCLS-II project commissioning is now complete and the SC Linac is facilitating user science
- Cavity performance has been excellent with **NO DEGRADATION FROM INSTALLATION**
- Average Q_0 exceeds the LCLS-II specification and demonstrates **high-Q_0 in an installed linac for the first time**
- Challenges were encountered along the way but the linac is running stably to support the science program
- LCLS-II-HE will further increase the performance of the SC Linac in the next couple of years



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

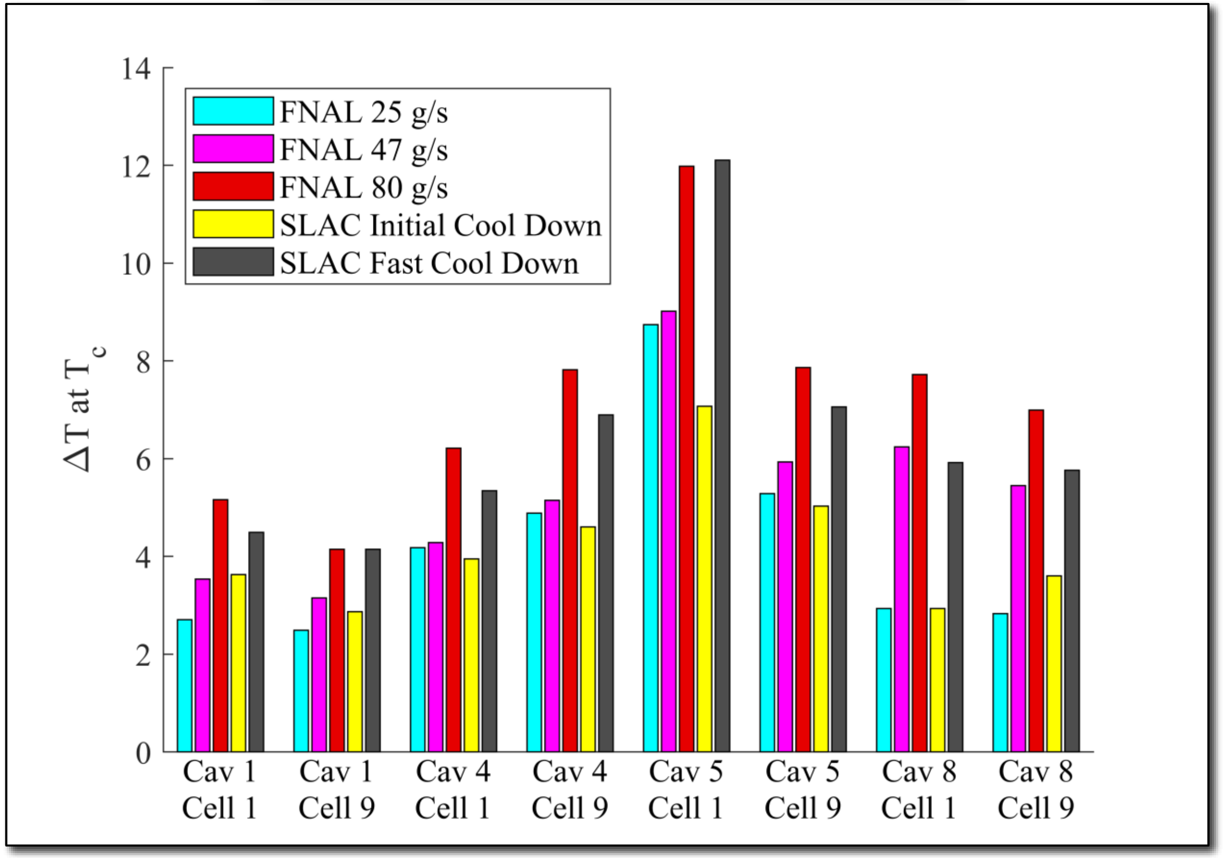
BERKELEY LAB
Lawrence Berkeley National Laboratory

Jefferson Lab

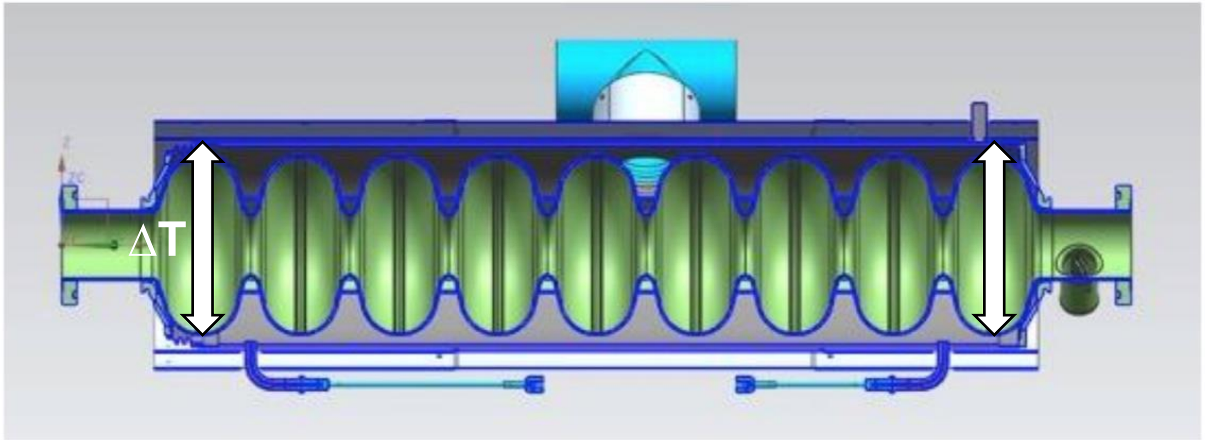
Backup

Fast Cool Down Results

ΔT at NC/SC Transition



- What we really care about is the **cool down *gradient*** not the *rate* – faster usually means larger gradients
- Two installed CMs have temperature sensors located on the cavity cells
- Gradients from the SLAC fast cool down and testing at FNAL could be compared to gauge how “successful” we were
- Non-optimized cool down results in lower ΔT than achieved



Sufficient cool downs for High Q_0 achieved at SLAC