Leveraging Experience from Production, Commissioning, & Early Operations of LCLS-II and HE for ILC

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On behalf of the LCLS-II Collaboration

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LCWS2023
INTERNATIONAL WORKSHOP ON LINEAR COLLIDERS

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

What questions can LCLS-II answer for ILC?

1. **Gradient**
   - Can we build cavities that achieve gradients required for ILC?
   - If we achieve those high gradients in vertical test, can they be preserved in the installed linac?
2. **Q_0**
   - Can we build cavities that achieve high Q_0?
   - Can we achieve the required cool downs to maintain high Q_0 in the linac?

Outline

LCLS-II Facility Overview, Scope, and Parameters

SRF Cavity & Cryomodule Production

LCLS-II Installation Experience

Cool Down and Q_0 Performance of the Superconducting Linac

SC Linac Commissioning

Summary

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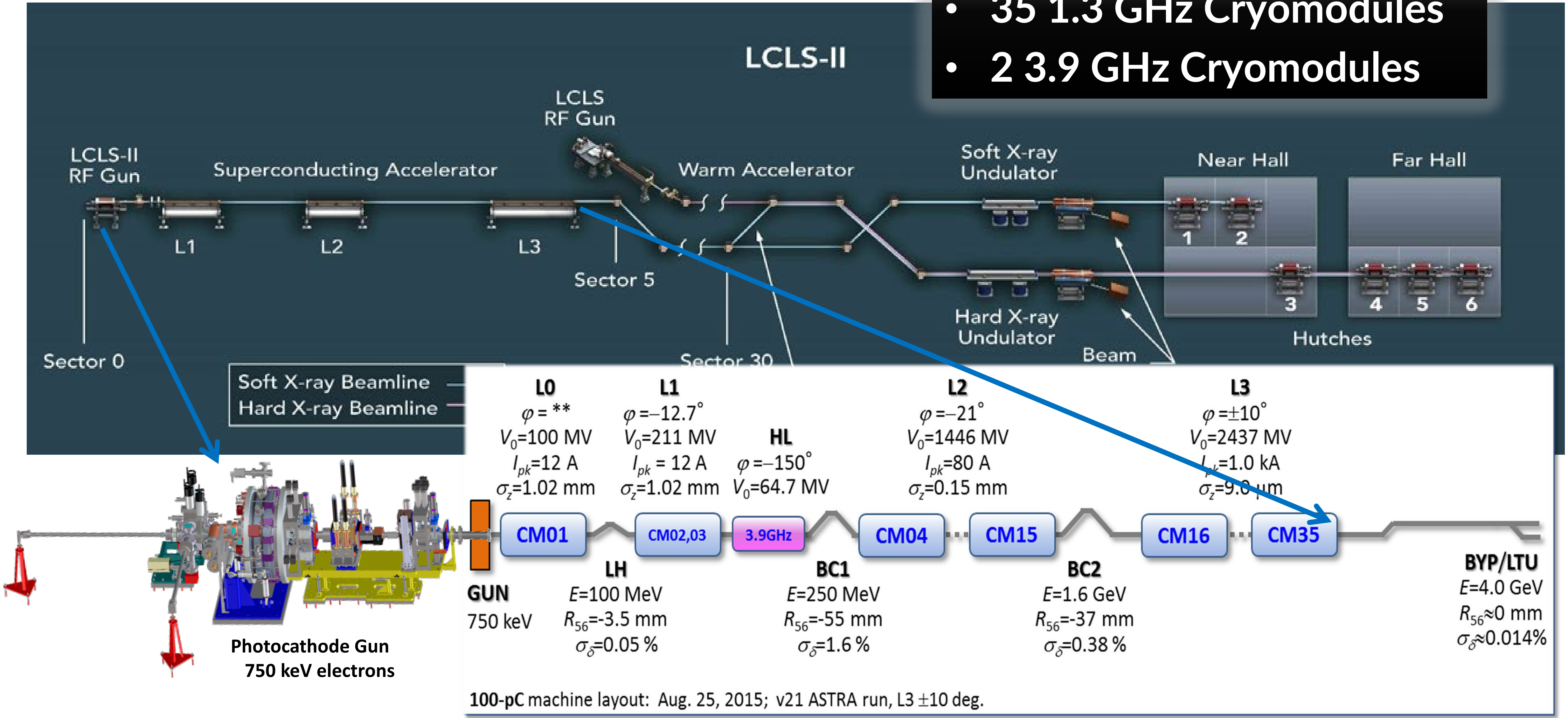
LCLS-II Facility Overview, Scope, and Parameters

- 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.


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

Linac & FEL Layout

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



LCLS-II Technical Parameters

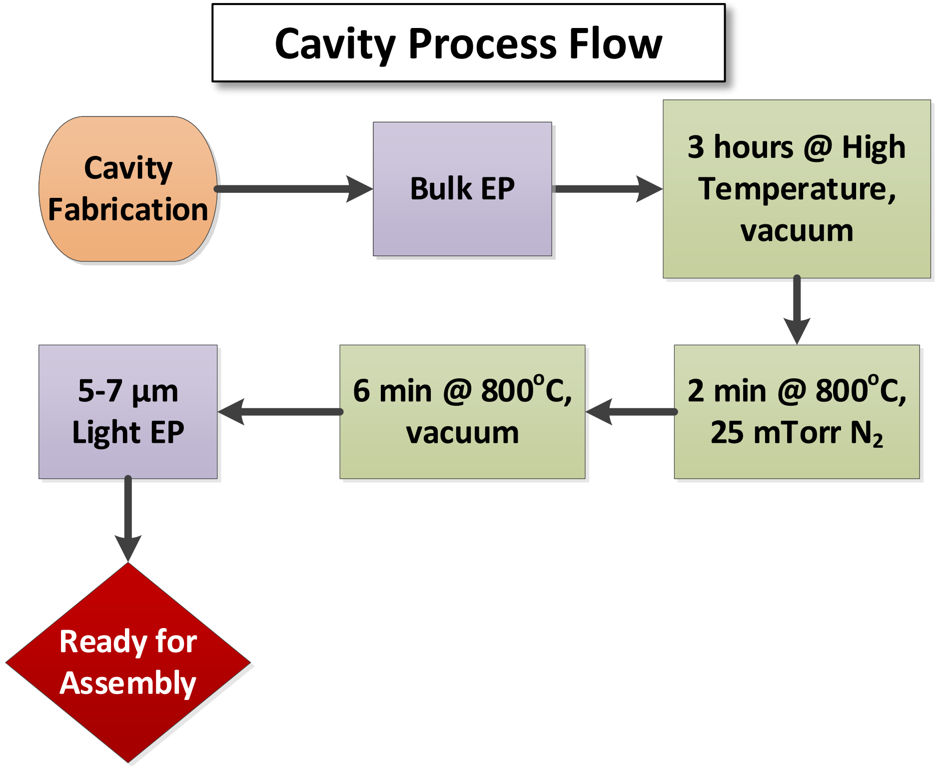
Performance Measure	Threshold	Objective
Variable gap undulators	2 (soft and hard x-ray)	2 (soft and hard x-ray)
Superconducting linac-based FEL system		
Superconducting linac electron beam energy	3.5 GeV	≥ 4 GeV
Electron bunch repetition rate	93 kHz	929 kHz
Superconducting linac charge per bunch	0.02 nC	0.1 nC
Photon beam energy range	250–3,800 eV	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

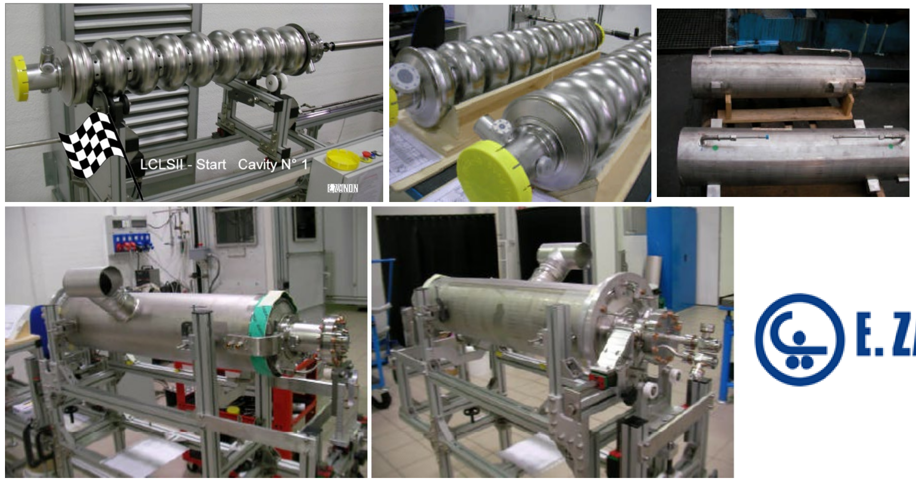
2

SRF Cavity & Cryomodule Production

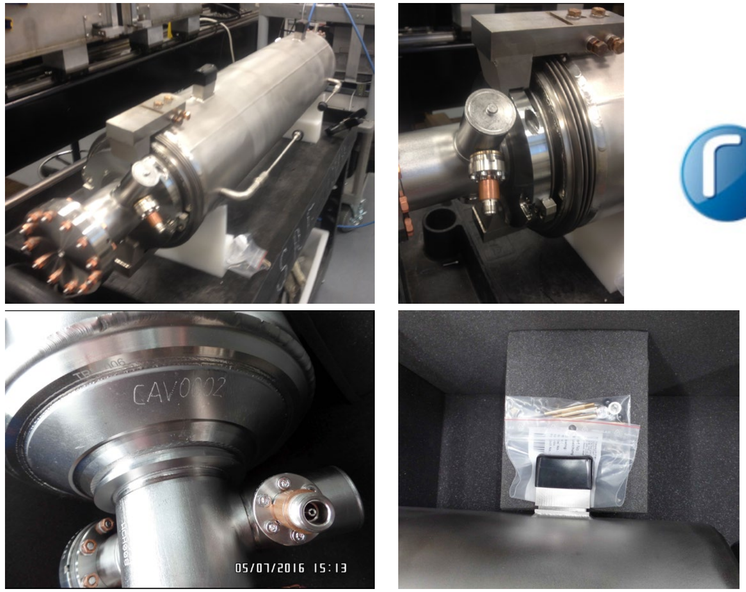
Cavity Fabrication



- In order to meet the high-Q_0 requirements, the cavities were produced with “Nitrogen-doping”
- Cavities were manufactured at RI and Zanon and shipped to Fermilab and Jefferson Lab for acceptance testing

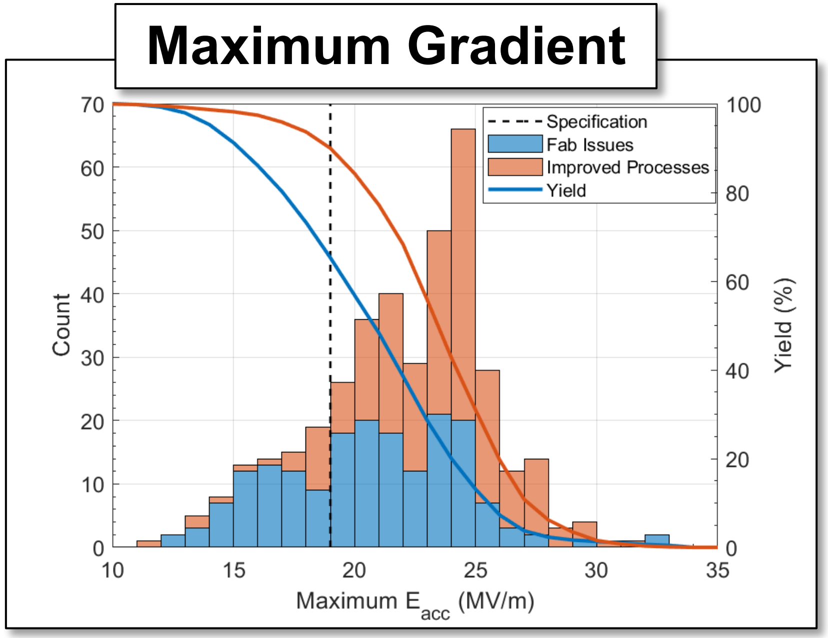


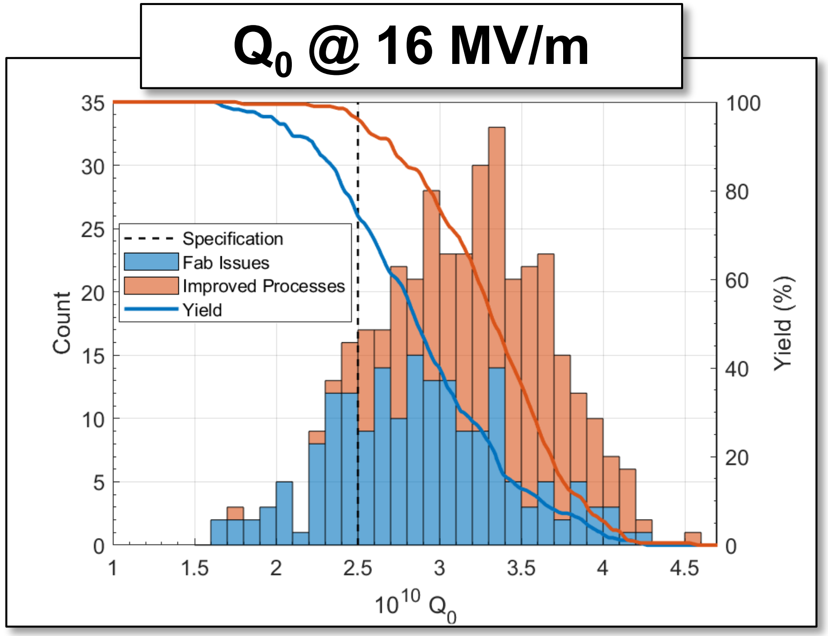
E. ZANON



research instruments

LCLS-II Cavity Performance

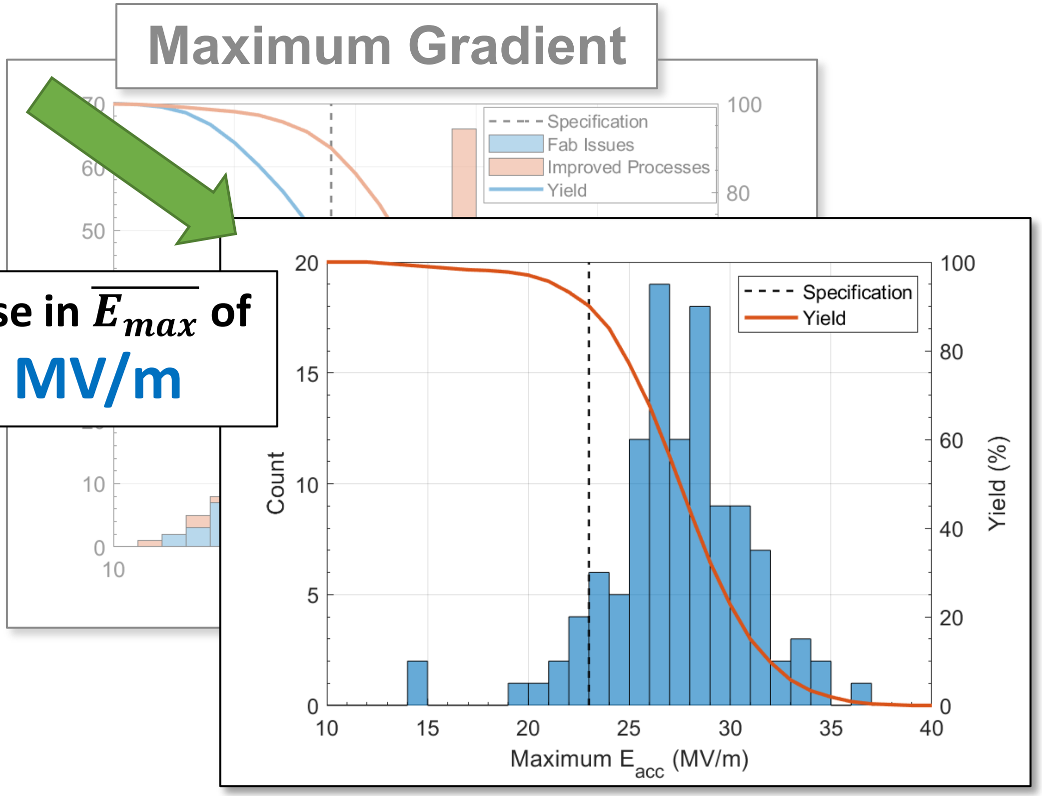




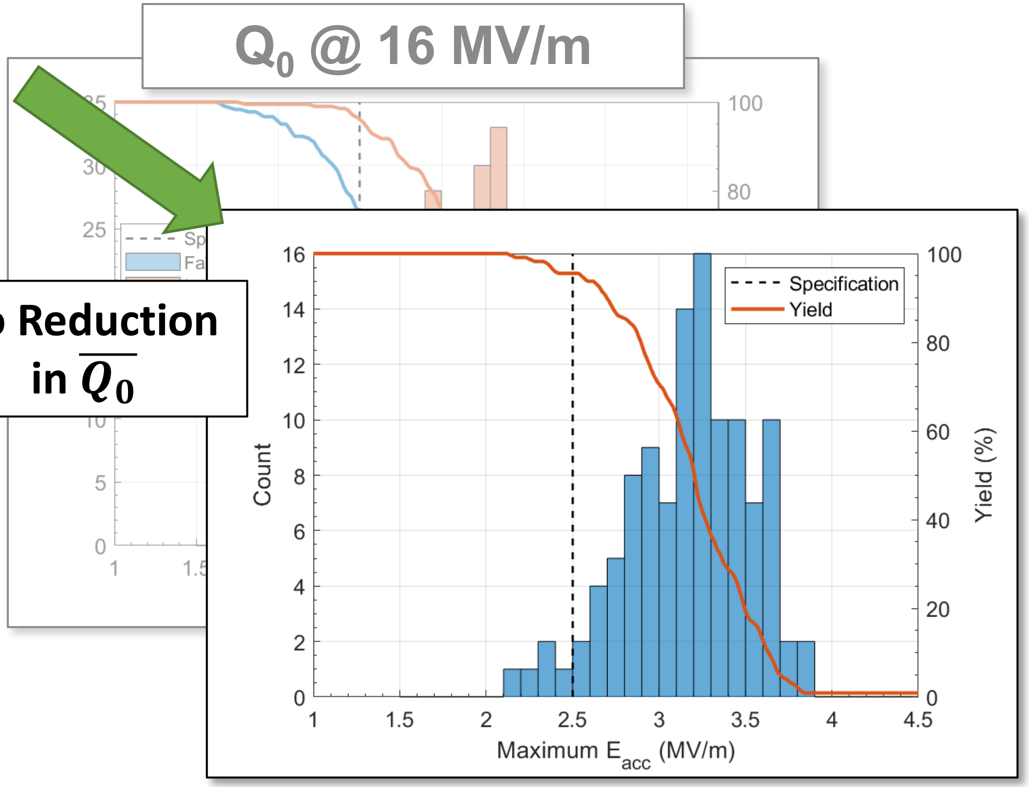
- Gradient performance typically exceeded the LCLS-II requirements in VT
- Significant improvements to processes were made throughout production which led to an increased yield
- New processes led to an average maximum gradient of **23±3 MV/m**

- Q_0 performance from the production doped cavities was excellent
- A change in heat treatment temperatures resulted in improved flux expulsion which led to consistently higher Q_0
- Able to achieve an average Q_0 of **$(3.3\pm0.4)\times10^{10}$** at 16 MV/m and 2 K

Further Improvement for LCLS-II-HE



Increase in $\overline{E_{max}}$ of **>5 MV/m**

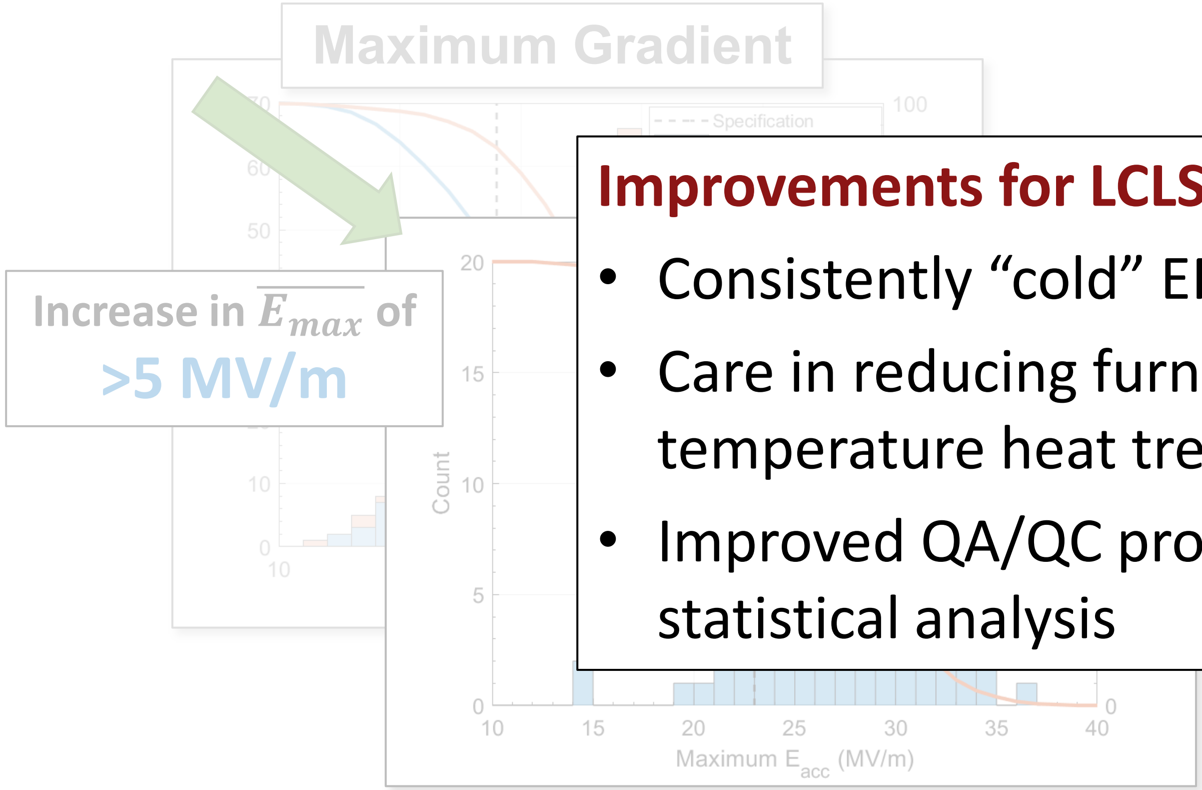


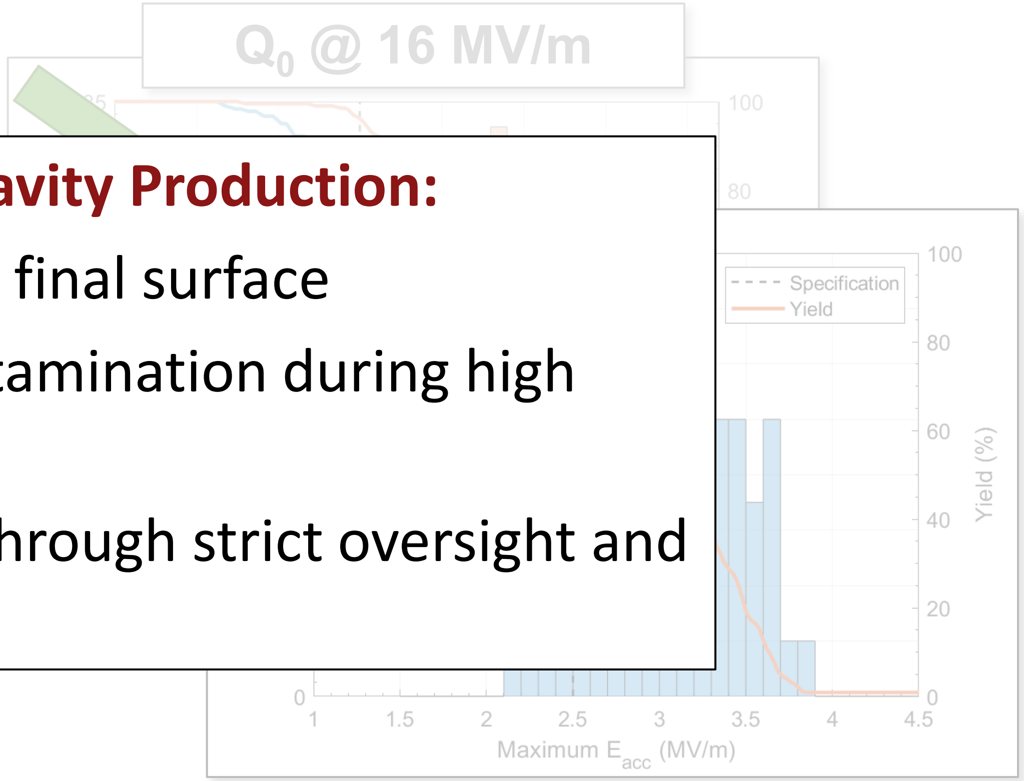
No Reduction in $\overline{Q_0}$

Lessons learned from LCLS-II production and LCLS-II-HE R&D led to significant improvement in gradient performance while maintaining high Q_0

For additional details, see J. Maniscalco's presentation

Further Improvement for LCLS-II-HE





Improvements for LCLS-II-HE Cavity Production:

- Consistently "cold" EP for the final surface
- Care in reducing furnace contamination during high temperature heat treatment
- Improved QA/QC processes through strict oversight and statistical analysis

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1. **Gradient**
   - Can we build cavities that achieve gradients required for ILC? **We're getting there**
   - If we achieve those high gradients in vertical test, can they be preserved in the installed linac?
2. **Q_0**
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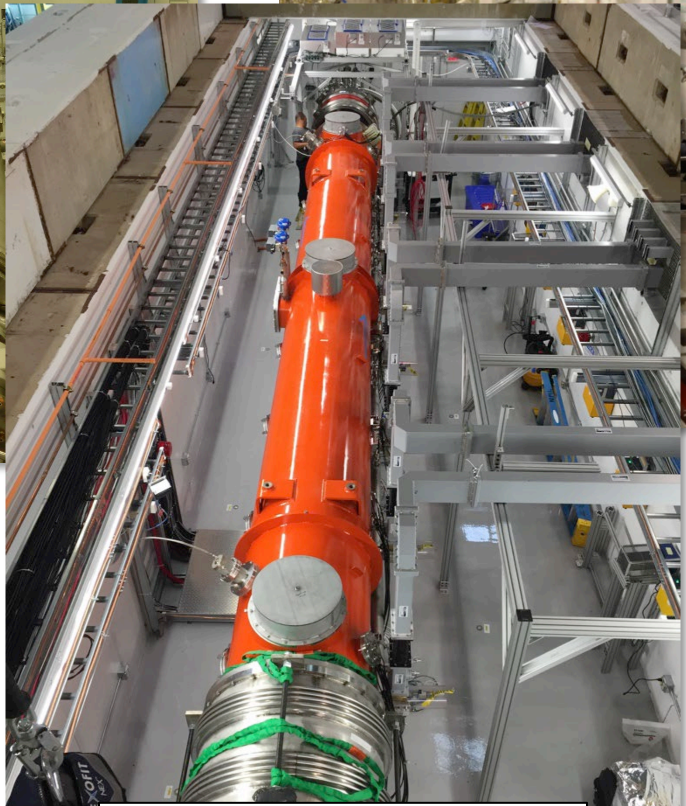
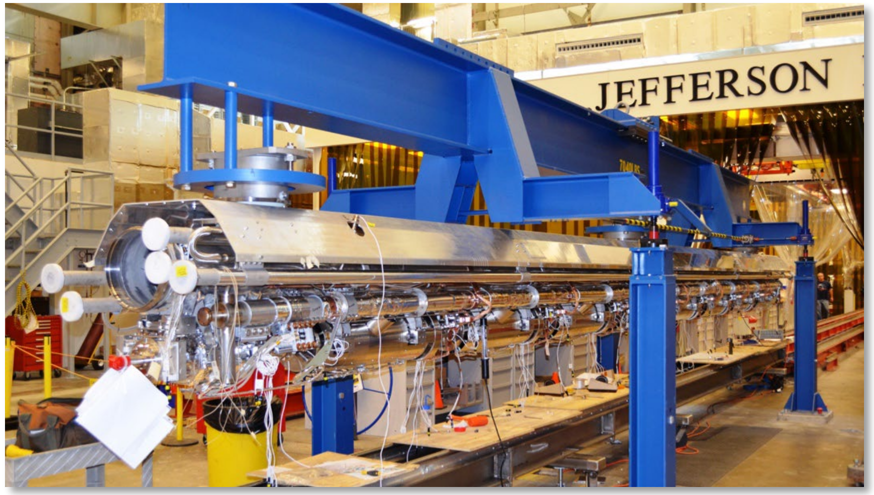
Cryomodule Production

String Assembly



CM Testing

Cryomodule Construction



- Cryomodules were constructed at Fermilab and Jefferson Lab
- Each CM was tested at the respective lab following construction
- Results were typically excellent and exceeded the LCLS-II requirements

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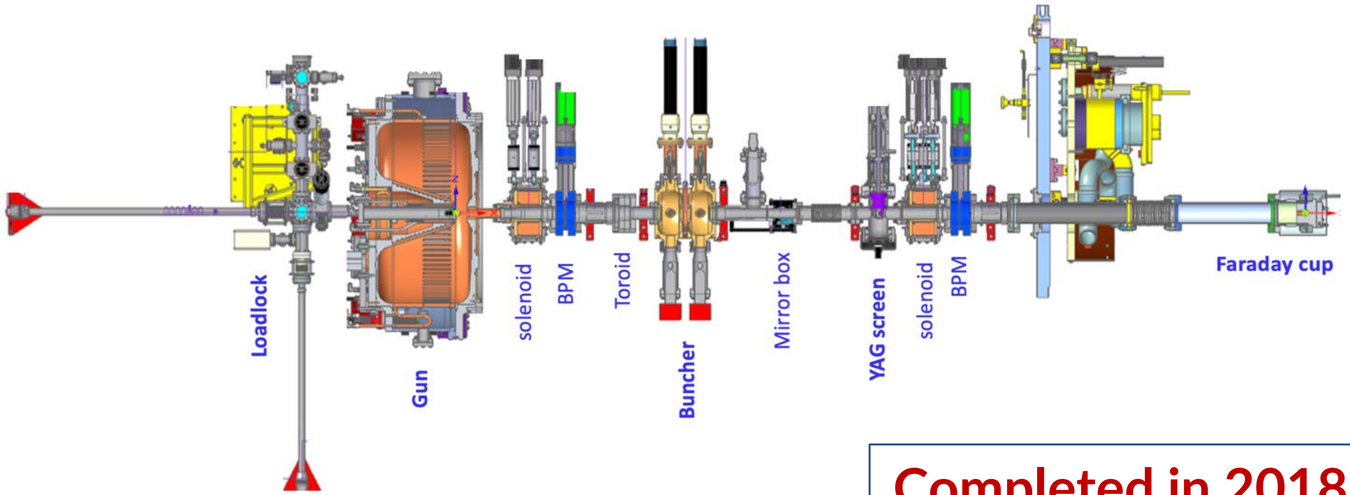
LCLS-II Installation Experience

Cryomodule Installation

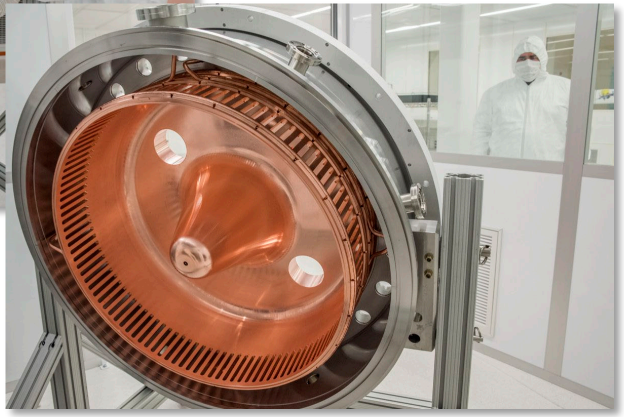
Last CM (spare) Delivered in May 2021

CM Installation Complete February 2021

Electron Gun and NC Beam Line Installation



Completed in 2018



Electron Gun cavity

- 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

Undulator Installation

Vertical Variable Gap SXR Undulator

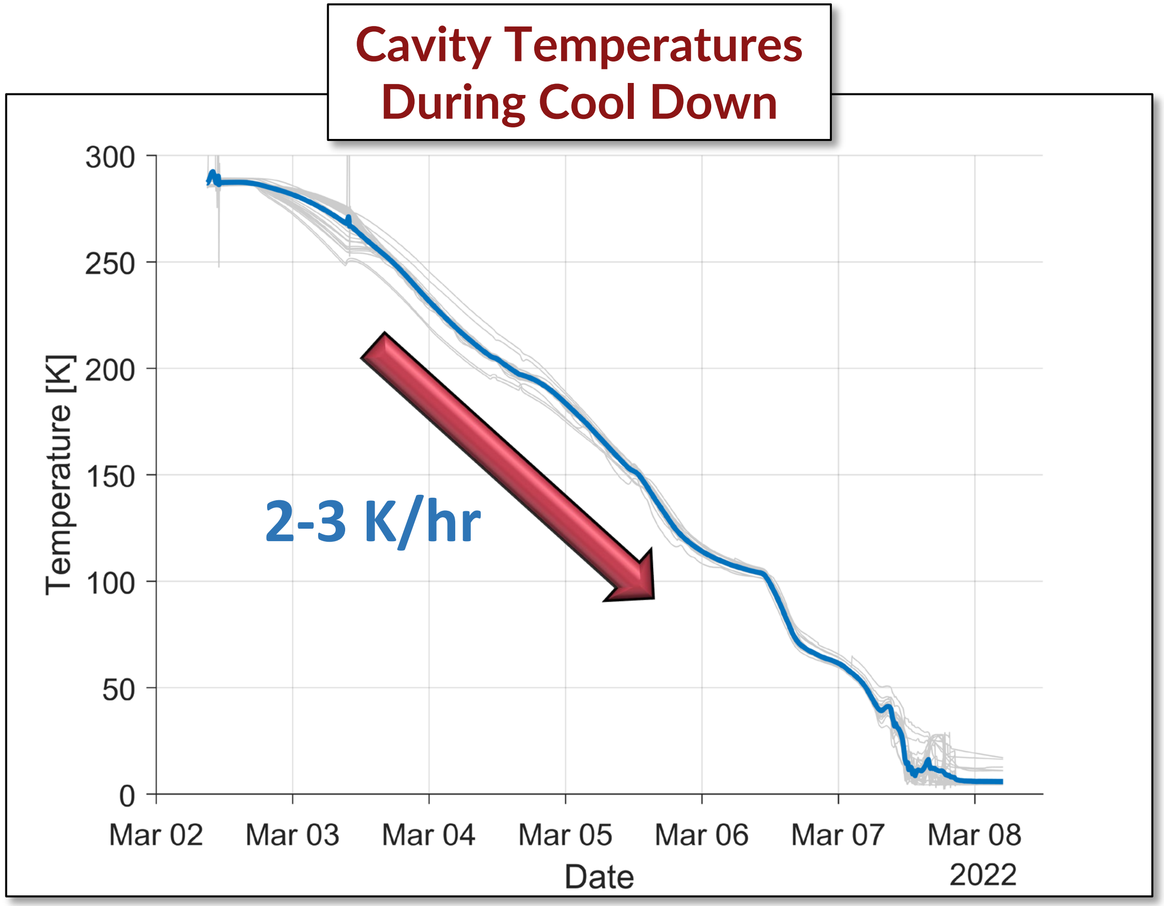
Horizontal Variable Gap HXR Undulator

Delivery of X-Rays to Instruments Began in 2020

4

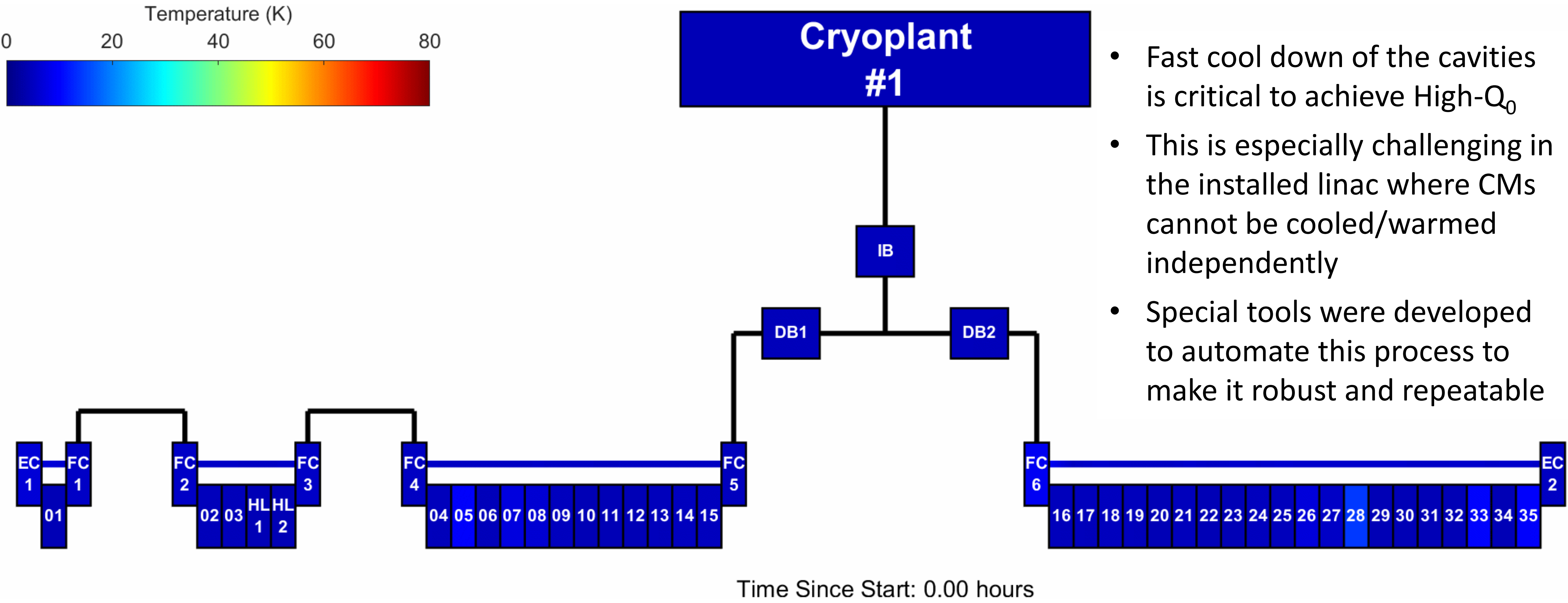
Cool Down and Q_0 Performance of the Superconducting Linac

Cool Down & Pump Down to 2 K



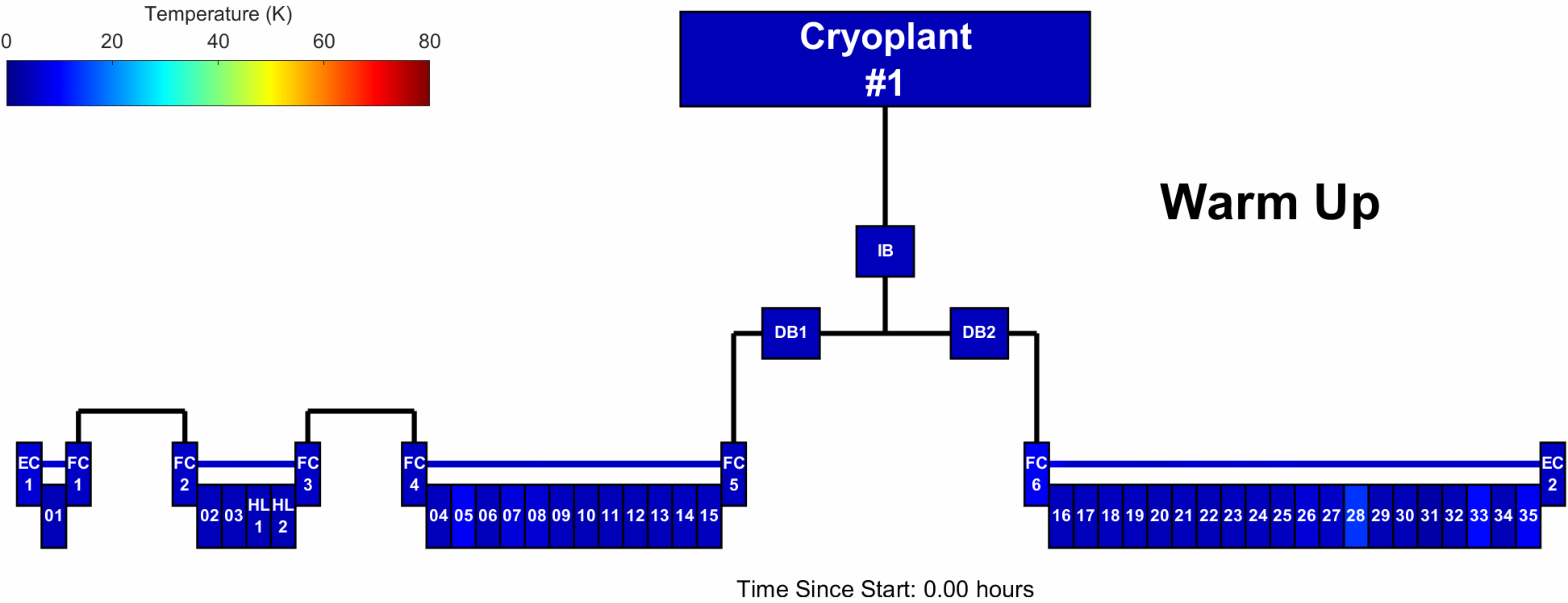
- Cool down of the entire linac was completed in **~5 days!**
- A rate of 2-3 K/hour was maintained over that duration
- Cool down was **near-fully automated** by the cryogenic controls system
- After multiple attempts, stable operation at 2 K was achieved **only 11 days later**

Fast Cool Down

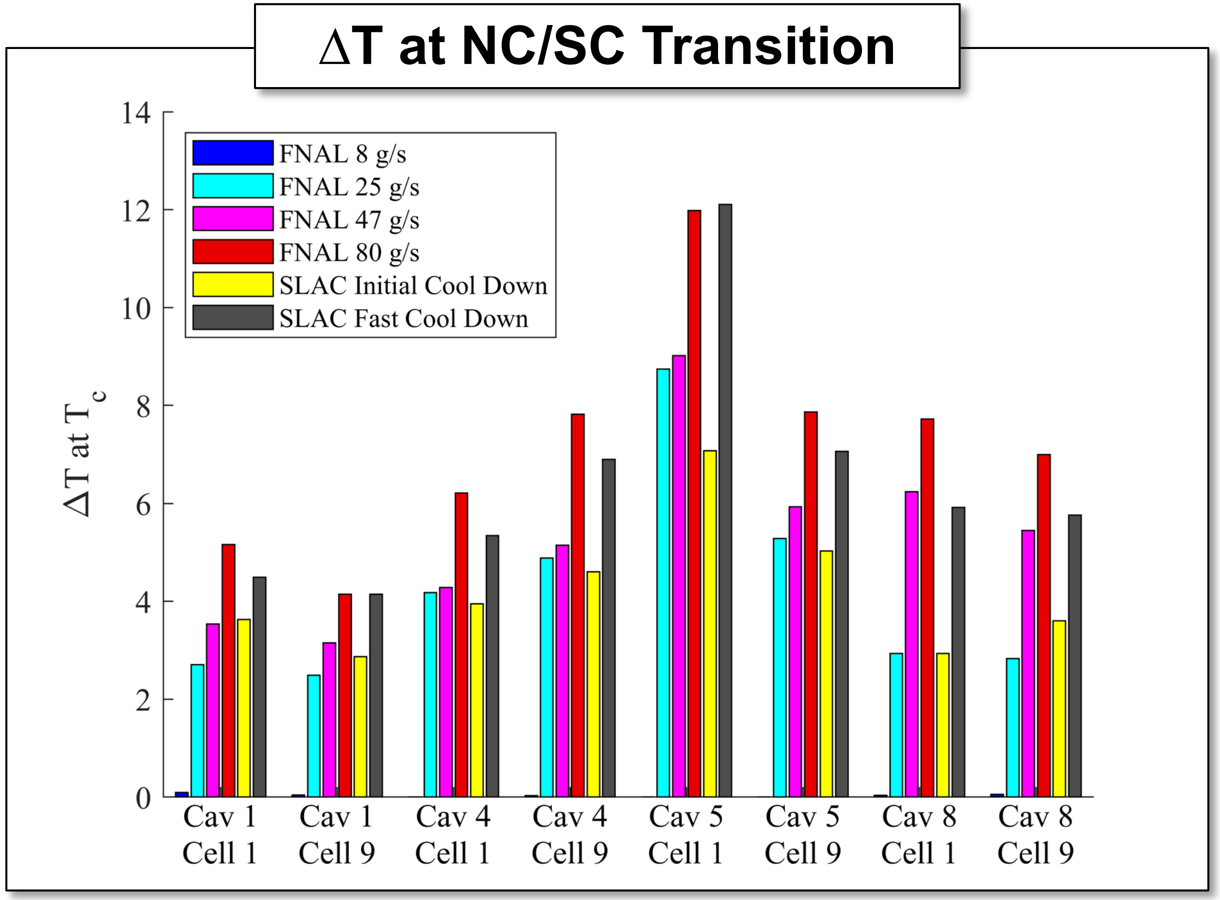


- Fast cool down of the cavities is critical to achieve High-Q_0
- This is especially challenging in the installed linac where CMs cannot be cooled/warmed independently
- Special tools were developed to automate this process to make it robust and repeatable

Fast Cool Down



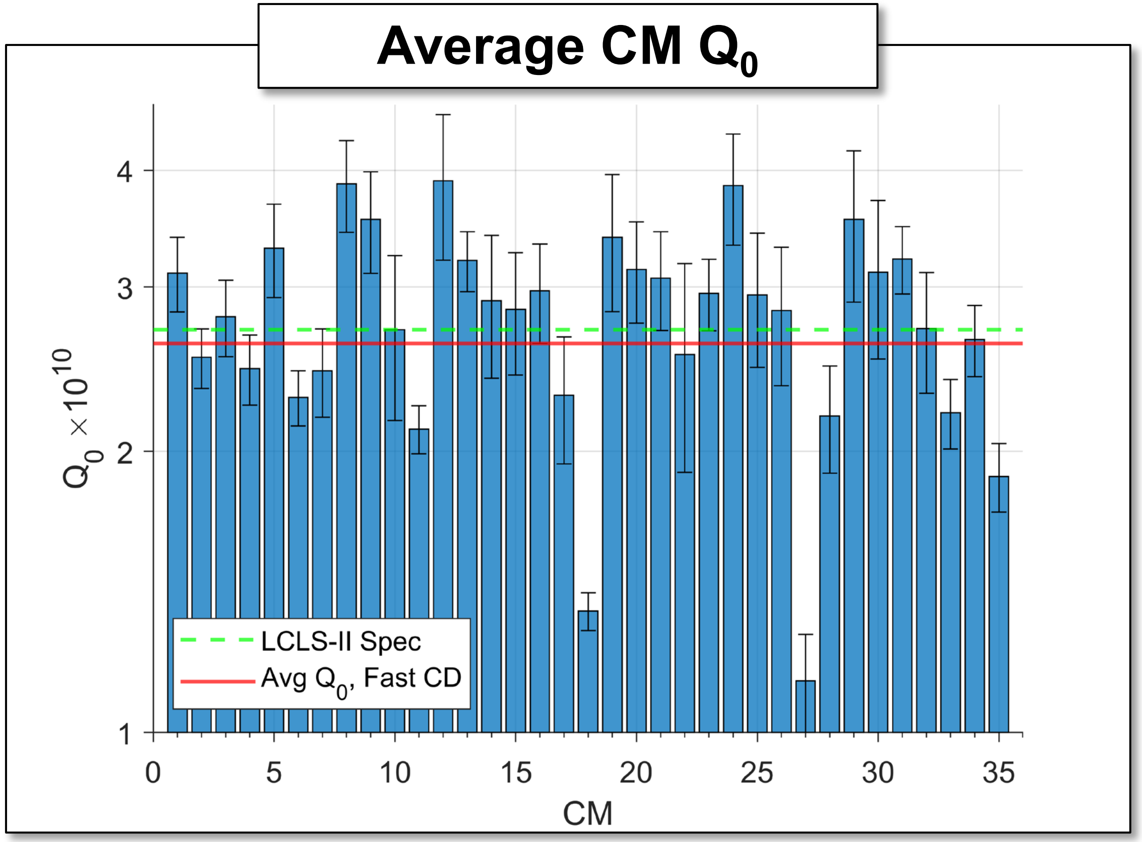
Fast Cool Down Results



- 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
- We are routinely able to achieve similar temperature gradients across the cavities to what was achieved at FNAL

Sufficient cool downs for High Q_0 achieved at SLAC

Q_0 of the Installed Cryomodules



- Full CM average Q_0 results look promising
- Across the linac an average of $2.6\text{x}10^{10}$ has been observed
- Low performers can likely be improved by additional CM degaussing

Demonstrates High Q_0 in an installed linac for the first time

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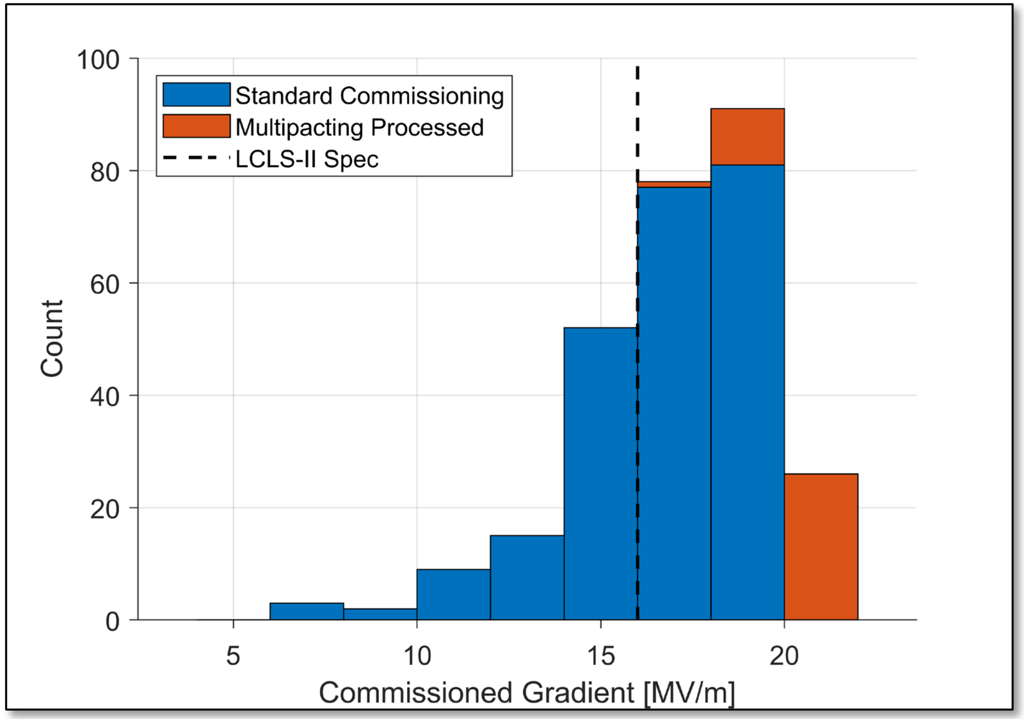
5

SC Linac Commissioning

Overall SRF Commissioning Status

Gradient Performance

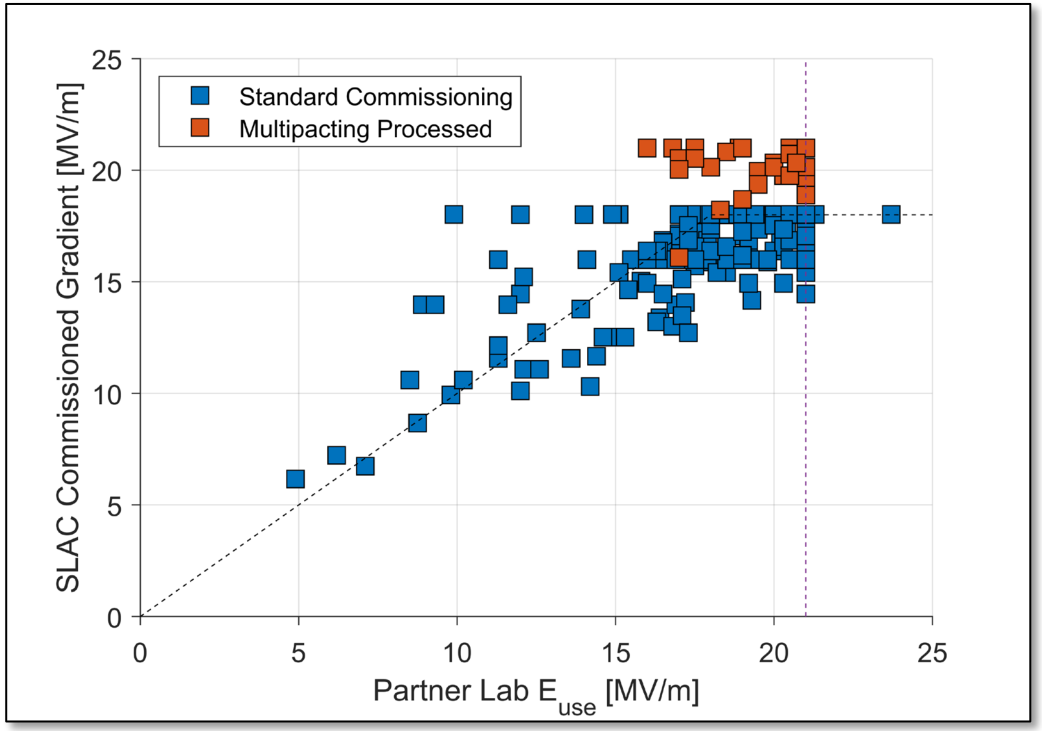


- Cryomodule commissioning has been very successful
- 97% of installed cavities fully operational (planned 94%)
- Majority of testing included an admin limit of 18 MV/m
- Total commissioned voltage **exceeds design by >20%**

Total Commissioned Cavity Voltage: 4.9 GV

Gradient Performance

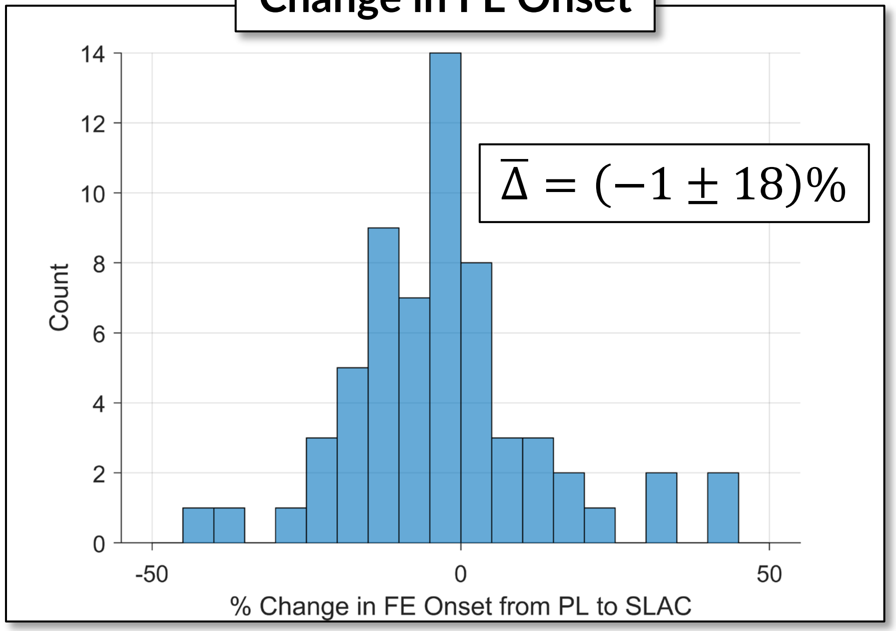
Comparison with Acceptance Test



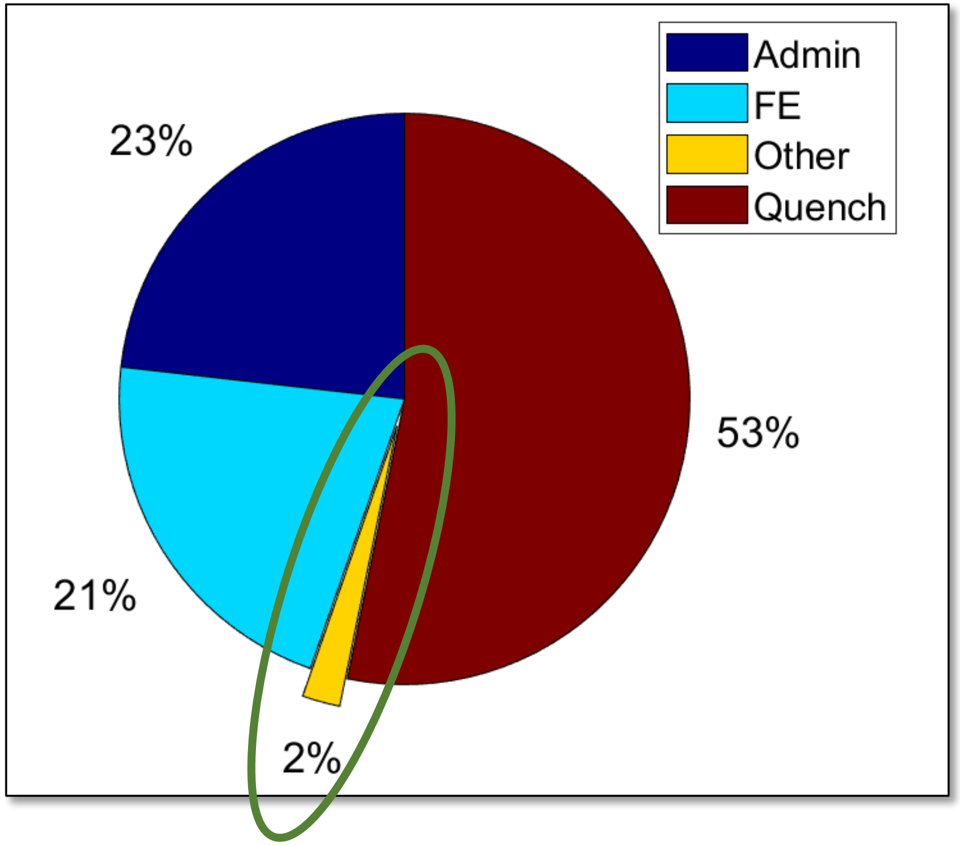
- Gradient performance is in line with CM acceptance test measurements at FNAL and Jlab
- **No observable change in field emission onsets or magnitude from installation**

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

Change in FE Onset



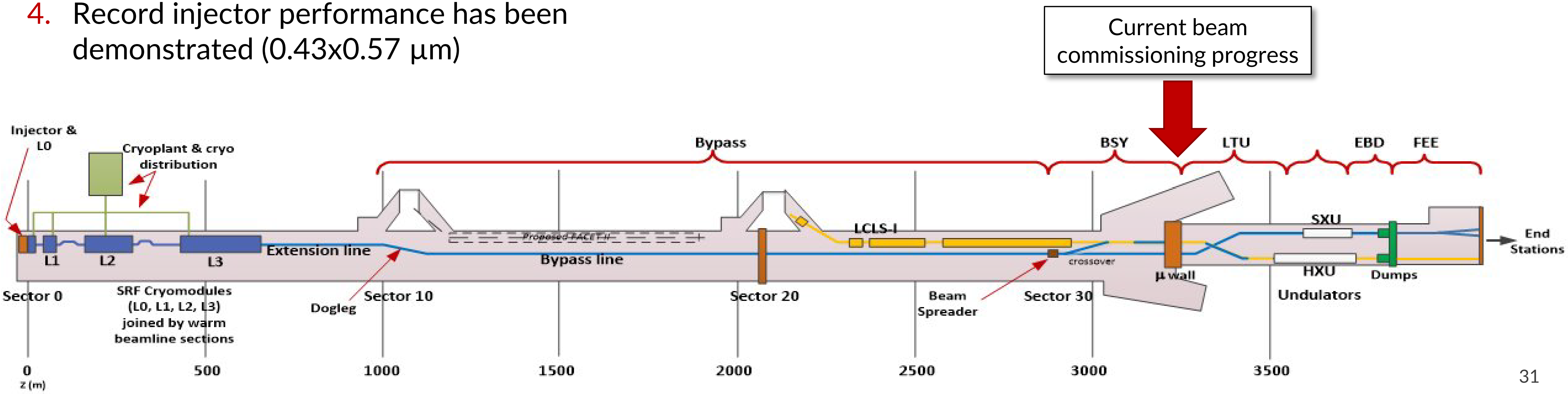
Cavity Limitations



- 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 warm and cold end couplers
  - 4 cavities: tuners not functioning properly
  - It is expected that all 6 of these cavities could be repaired *in situ* at room temperature

Accomplishments: Beam Commissioning

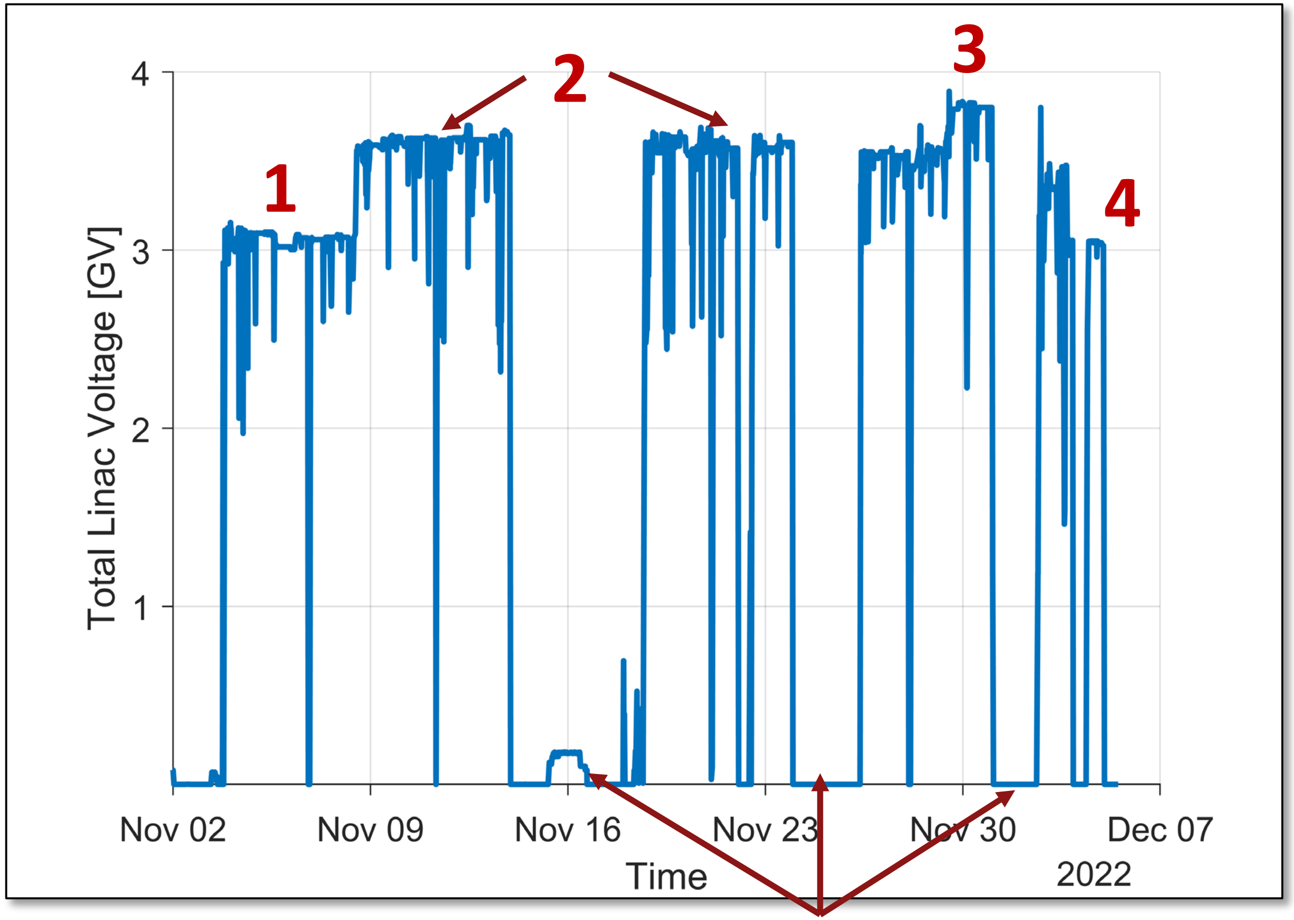
1. Established the first-time beam through the three main SC linac sections (L1B, L2B, and L3B) on 10/7 -10/9
2. Beam energy is characterized at the Sector-7 “dogleg” beamline area with the bending dipole magnets
3. 3.5 GeV beam transported to BSY dump (all CMs powered) on 11/8
4. Record injector performance has been demonstrated (0.43x0.57 μm)
5. Demonstration of critical beam control and diagnostics:
   - Emittance measurements
   - Screen and camera functionality
   - Cavity phasing
   - Chicane control
   - BPM data and beam orbit analytics
   - Beam energy measurements
6. Demonstration of repetition rate of 10 kHz on 12/9 (93 kHz required for threshold KPP)



Demonstration of 3.5 GeV Beam

1. Stable 3 GeV beam to BSY achieved on 10/28
2. Stable 3.5 GeV beam (on crest) to BSY achieved on 11/8
   - Ran stably through end of November
3. 3.5 GeV beam with L1 and L2 phasing at end of November
4. Lowered to 3 GeV for remaining beam tasks until December break

Total Cavity Voltage



Planned Shutdowns

6

Summary

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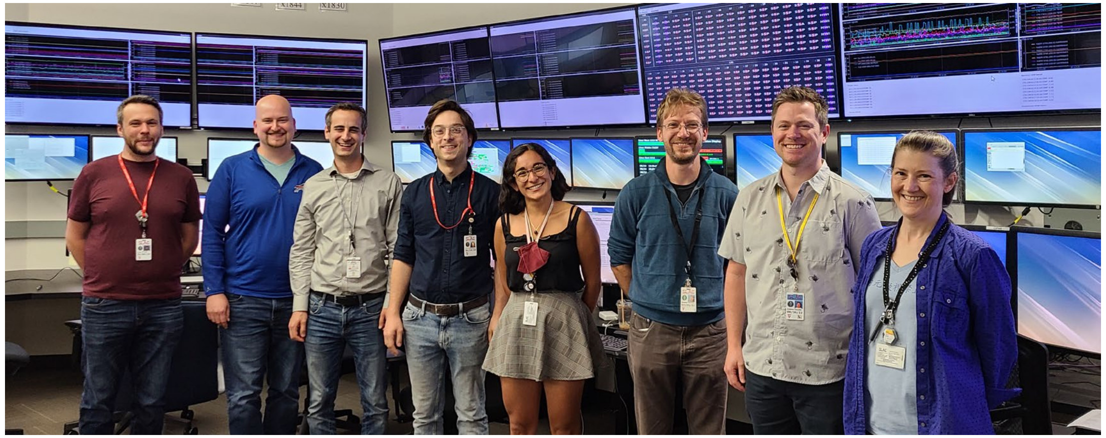
Summary

- LCLS-II production and commissioning has progressed well
- We can reliably produce cavities, install them in cryomodules, and install those cryomodules in a linac all while maintaining excellent gradient and Q_0 performance
- LCLS-II-HE has further improved upon the cavity and CM performance first demonstrated in LCLS-II
- The future is BRIGHT!



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

Thanks for your attention!

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