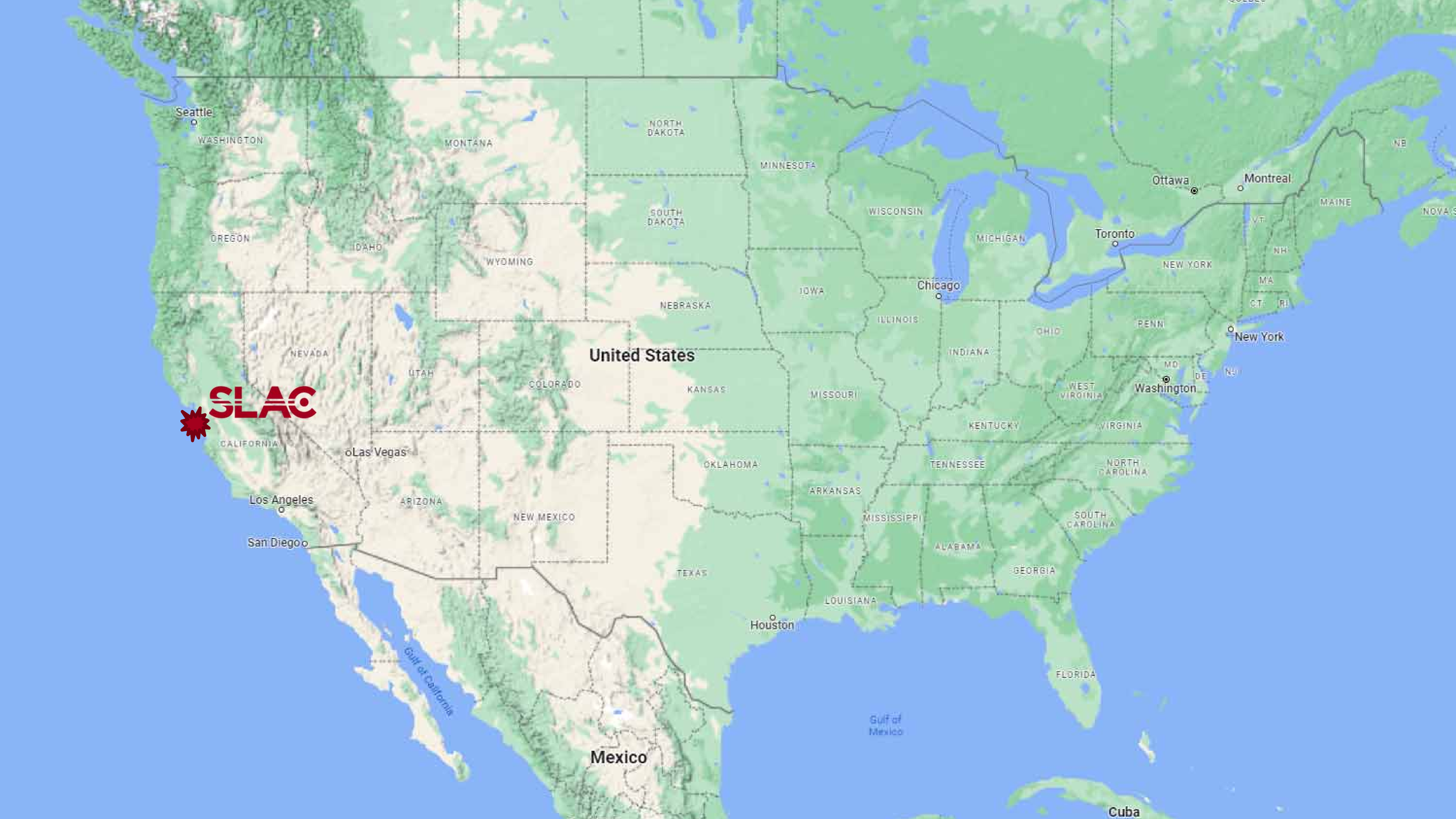
Commissioning and First Operation of the LCLS-II Linac

Dan Gonnella, SC-Linac-Physics Department Head
On behalf of the LCLS-II Collaboration

26 June 2023

Outline

LCLS-II Overview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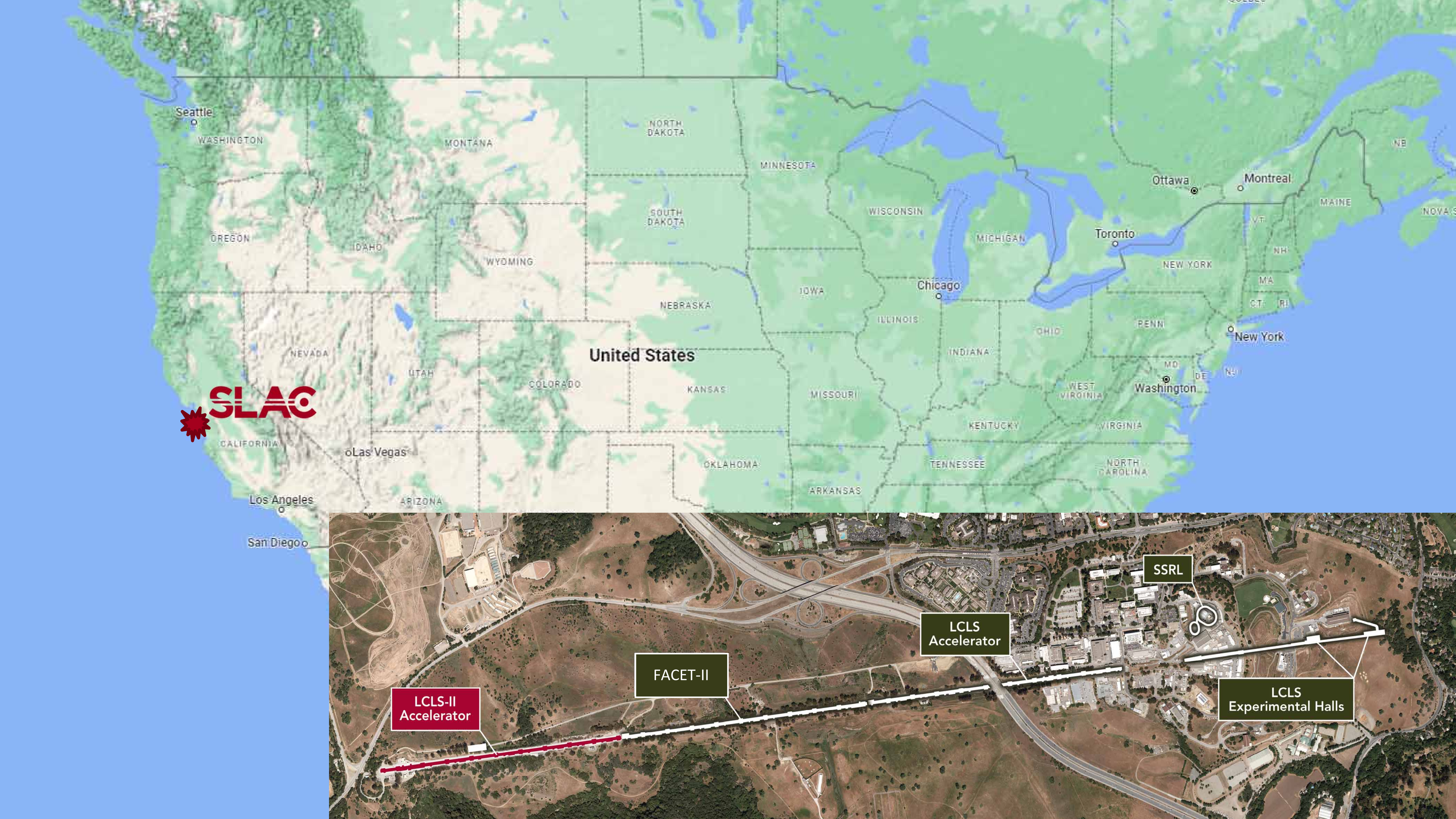
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LCLS-II Accelerator
FACET-II
LCLS Accelerator
SSRL
LCLS Experimental Halls


LCLS RF Gun
LCLS-II RF Gun
Superconducting Accelerator
Warm Accelerator
Soft X-ray Undulator
Near Hall
Far Hall
L1
L2
L3
Sector 5
Sector 0
Sector 30
1
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6
Hard X-ray Undulator
Beam Dumps
Hutches
Superconducting Crossover
Soft X-ray Beamline
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San Diego
SSRL
LCLS Accelerator
FACET-II
LCLS-II Accelerator
LCLS Experimental Halls

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	5×10^8 (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
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Achieved

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Operating Gradient	16 MV/m
Required Q_0 at Operating Gradient	$2.7x10^{10}$

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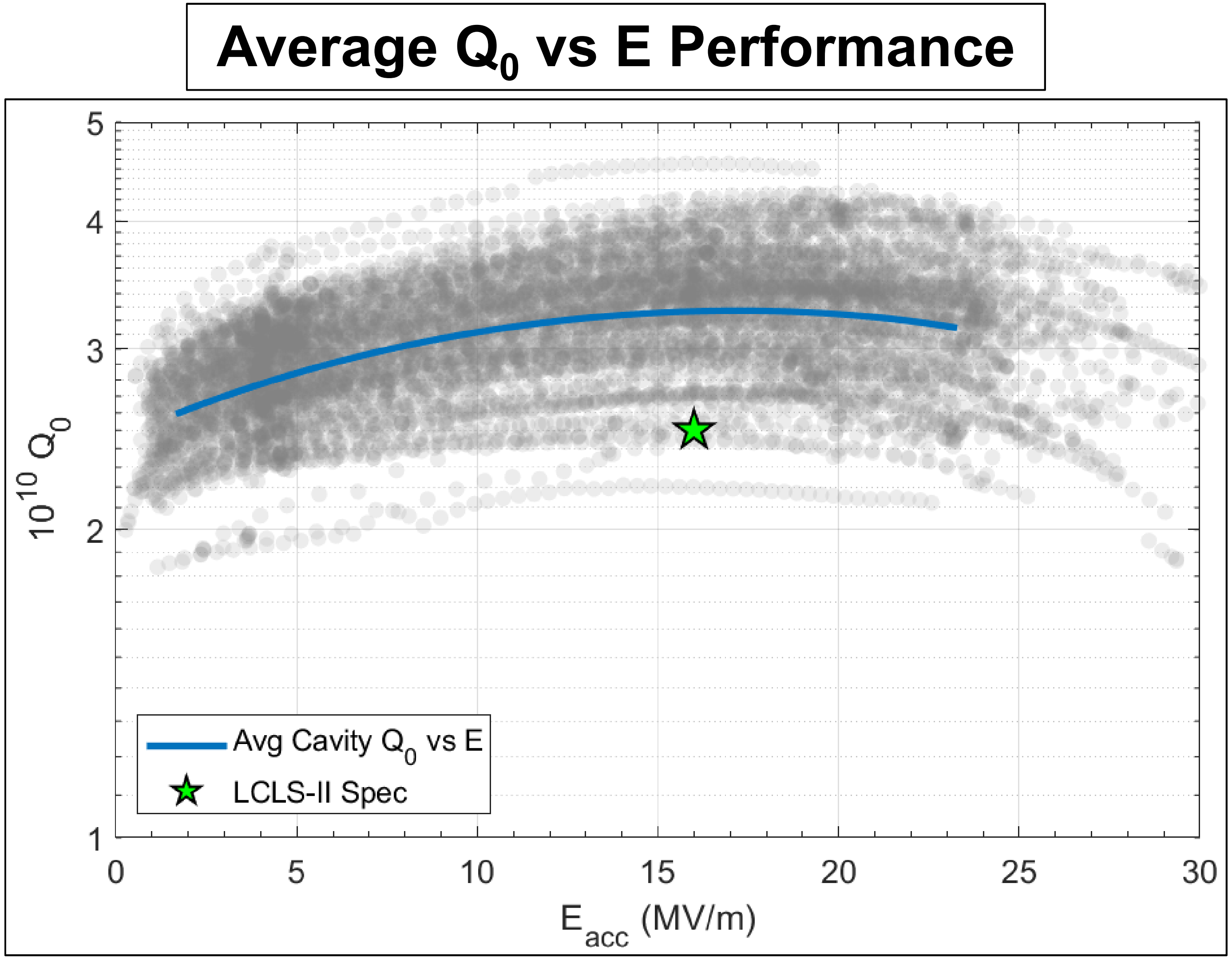
Nitrogen-Doping for LCLS-II

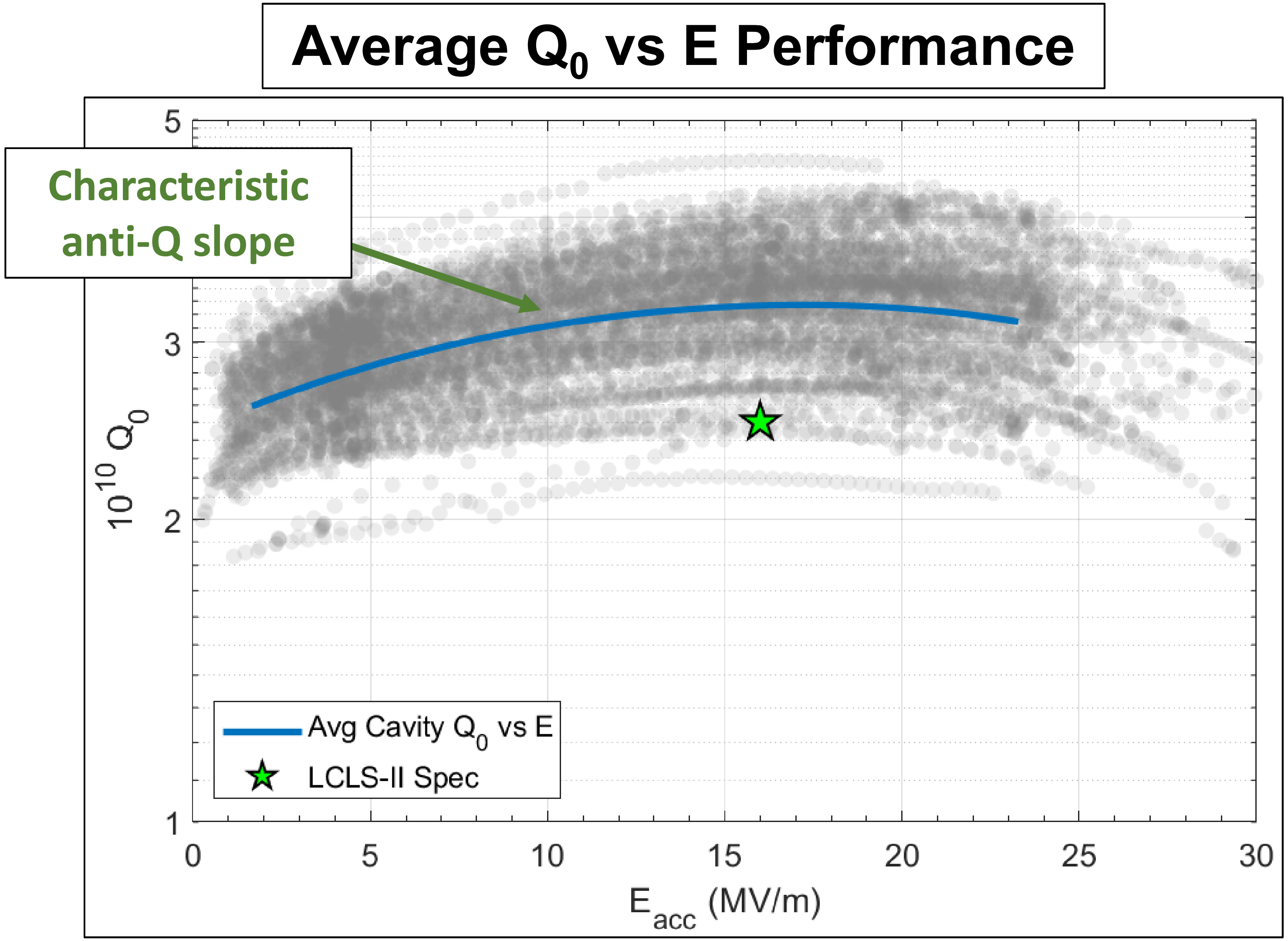


- LCLS-II constructed **373 nitrogen-doped 1.3 GHz cavities**
- All cavities were produced with the **2/6 nitrogen-doping** protocol
- Significant procedural improvements were made along the way to achieve reliable good performance

  (flux expulsion, fabrication techniques)

SLAC

Nitrogen-Doping for LCLS-II



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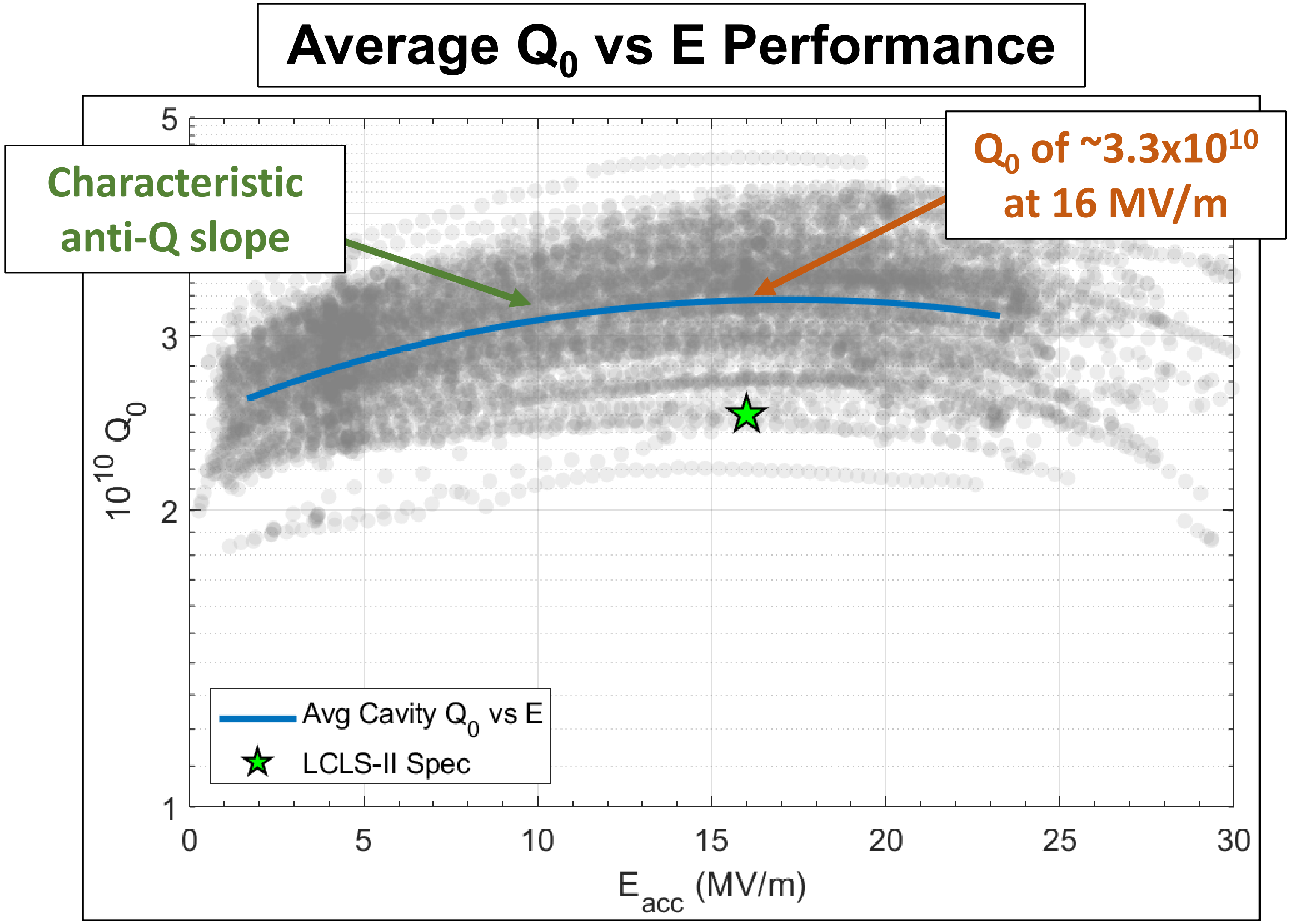

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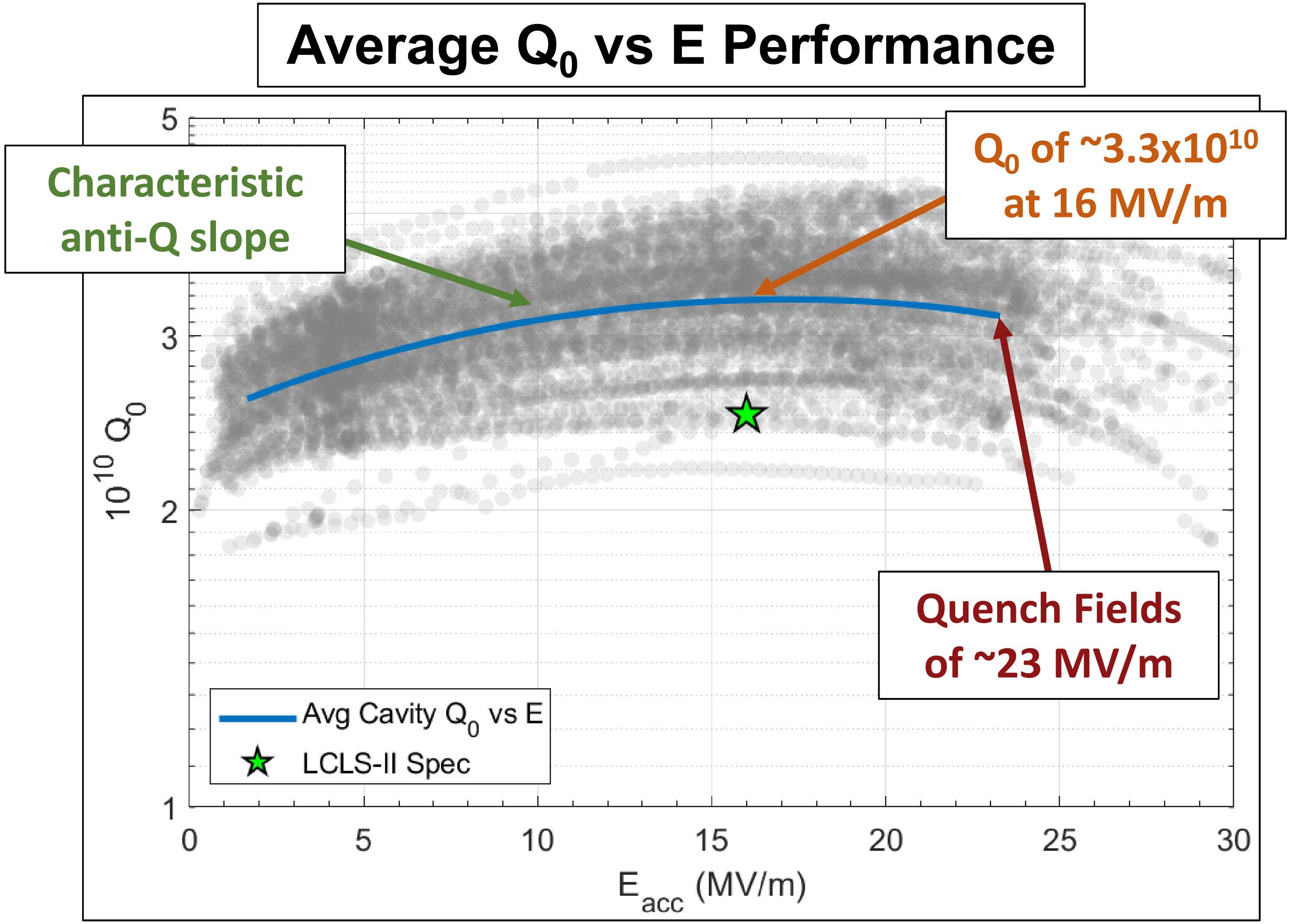

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2

Installation & Cool Down

Cryomodule Installation

Last CM (spare) Delivered in May 2021

For more details see D. White MOPMB089

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CM Installation Complete February 2021

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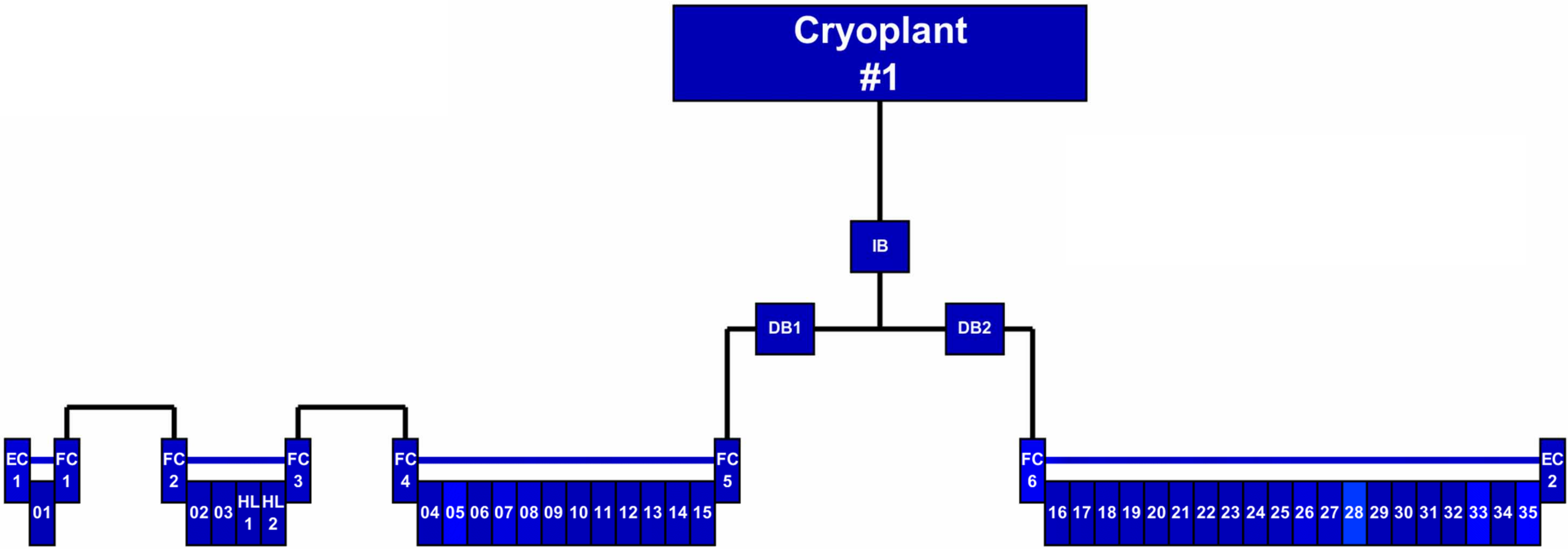
Linac-Cryoplant Schematic



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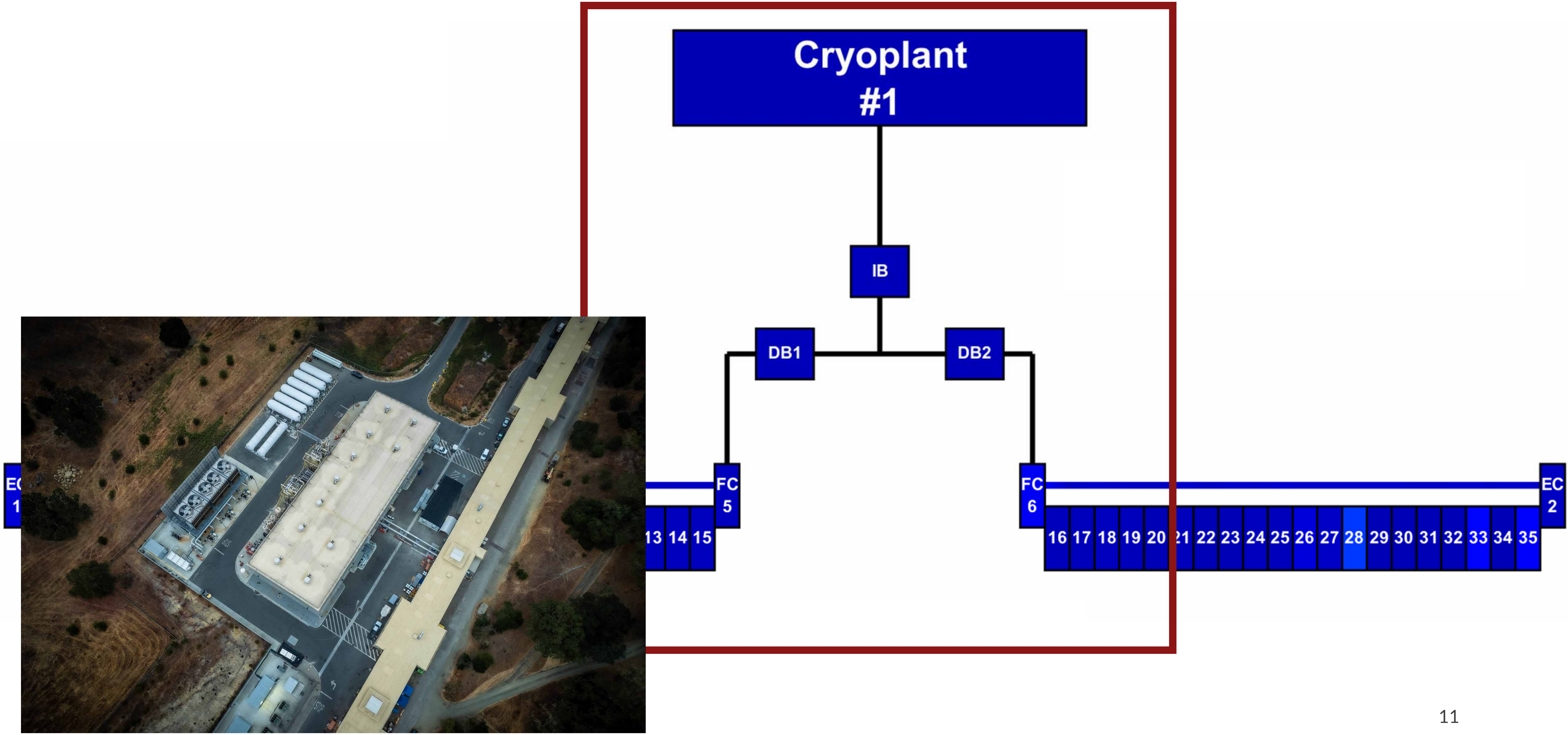

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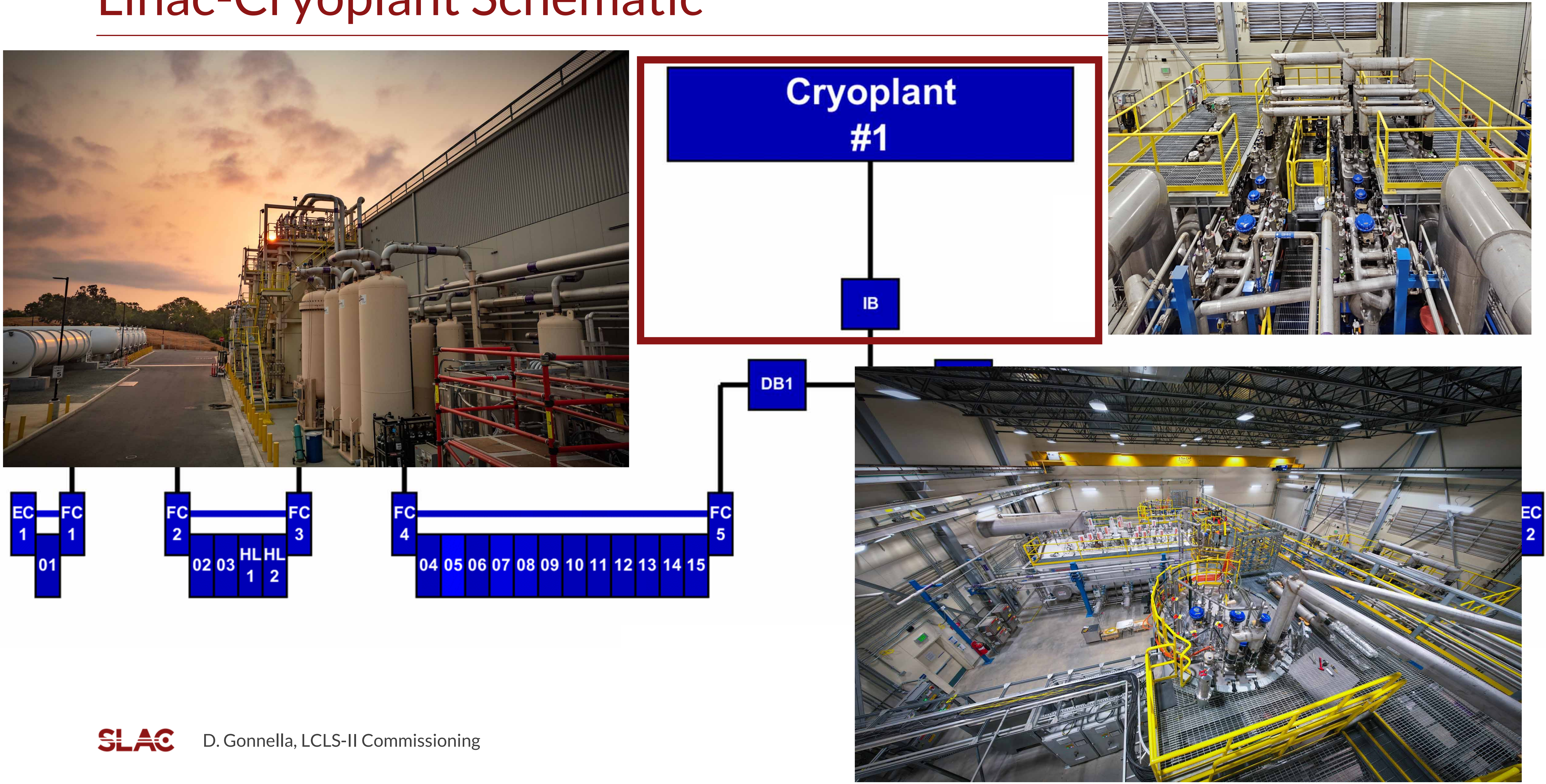

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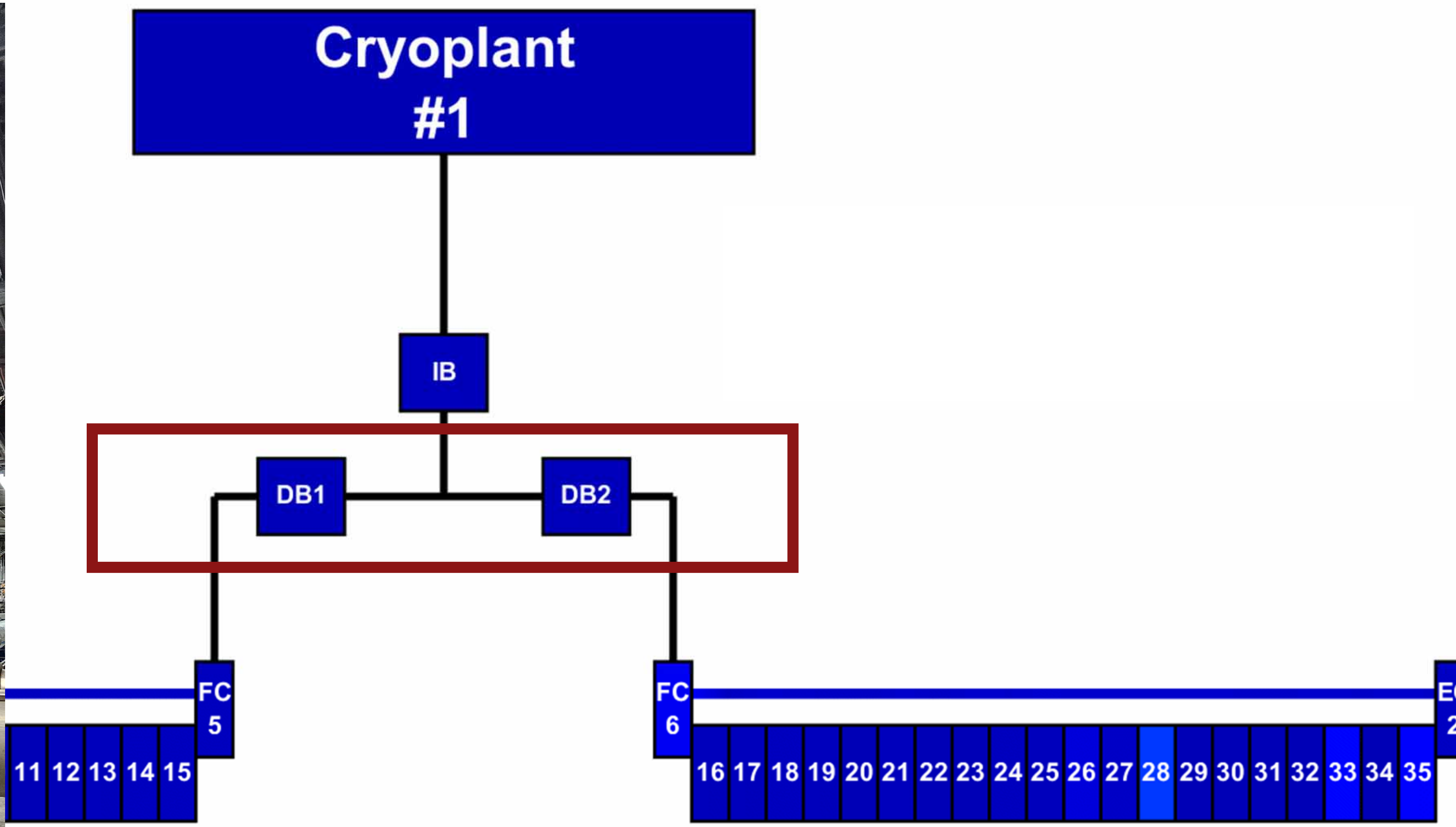
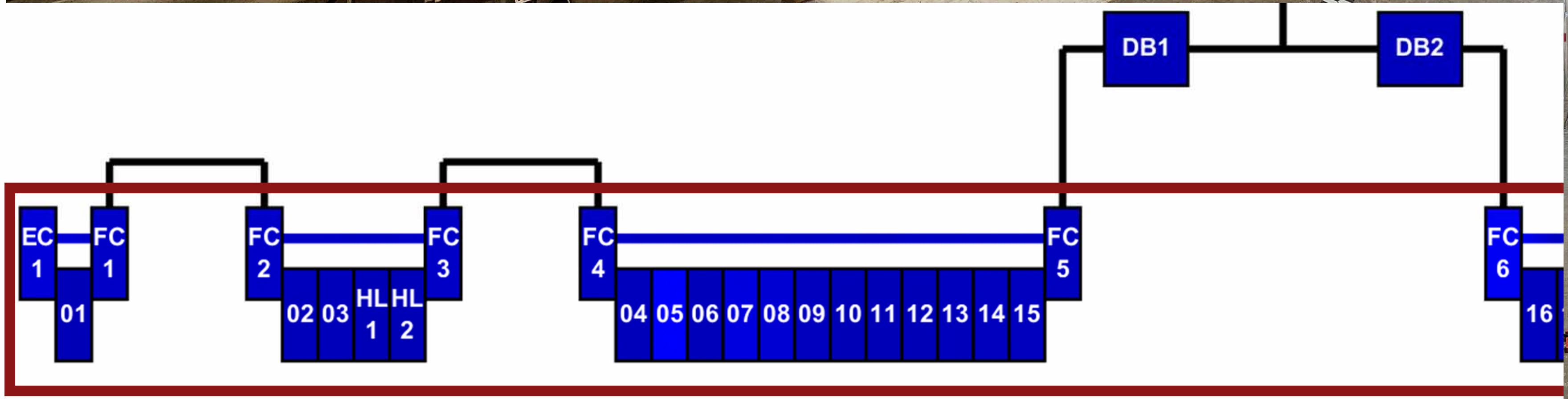



RESTRICTED AREA
DO NOT CROSS BARRIER
AUTHORIZED PERSONNEL ONLY
CAUTION
NOT A STEP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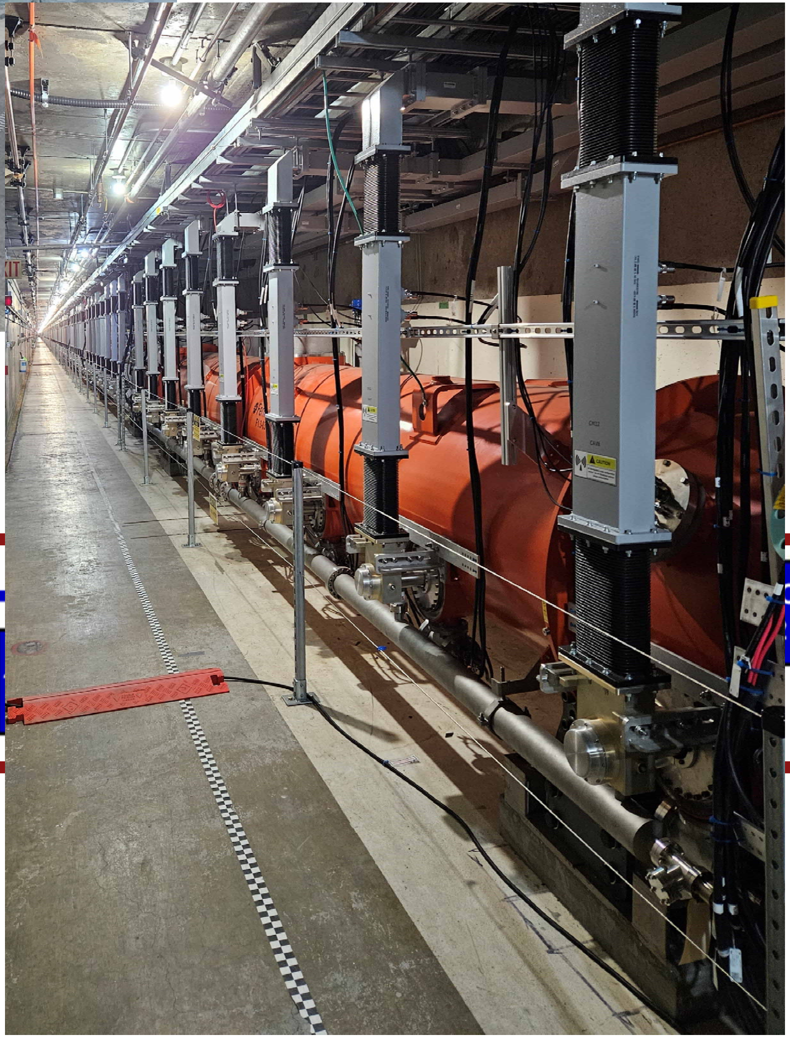
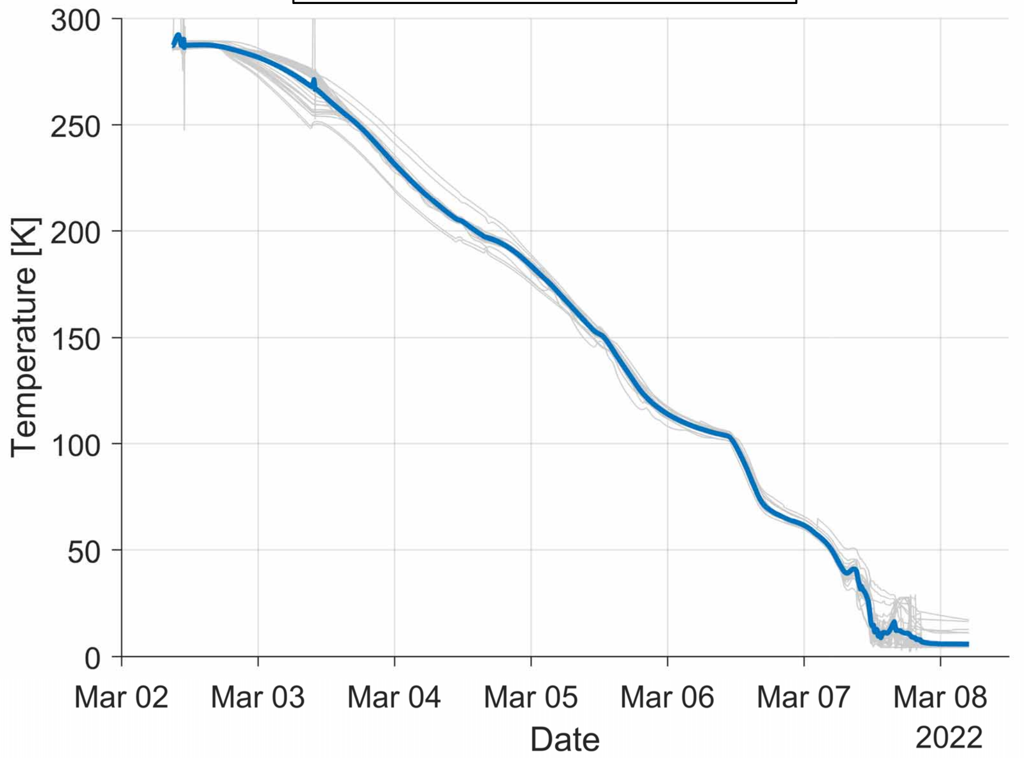


Cool Down & Pump Down to 2 K

Cavity Temperatures During Cool Down



For more details see MOPMB087

- Cool down of the entire linac was completed in **~5 days!**

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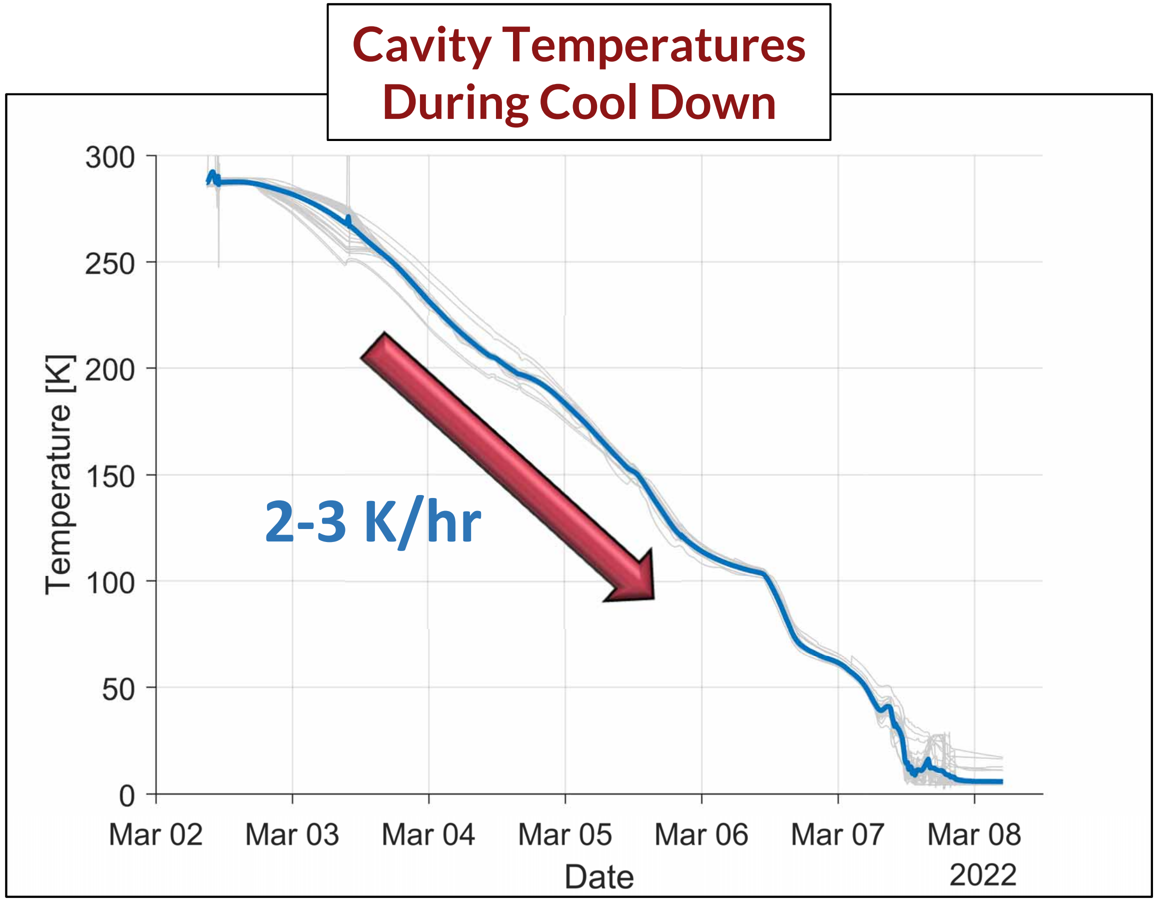

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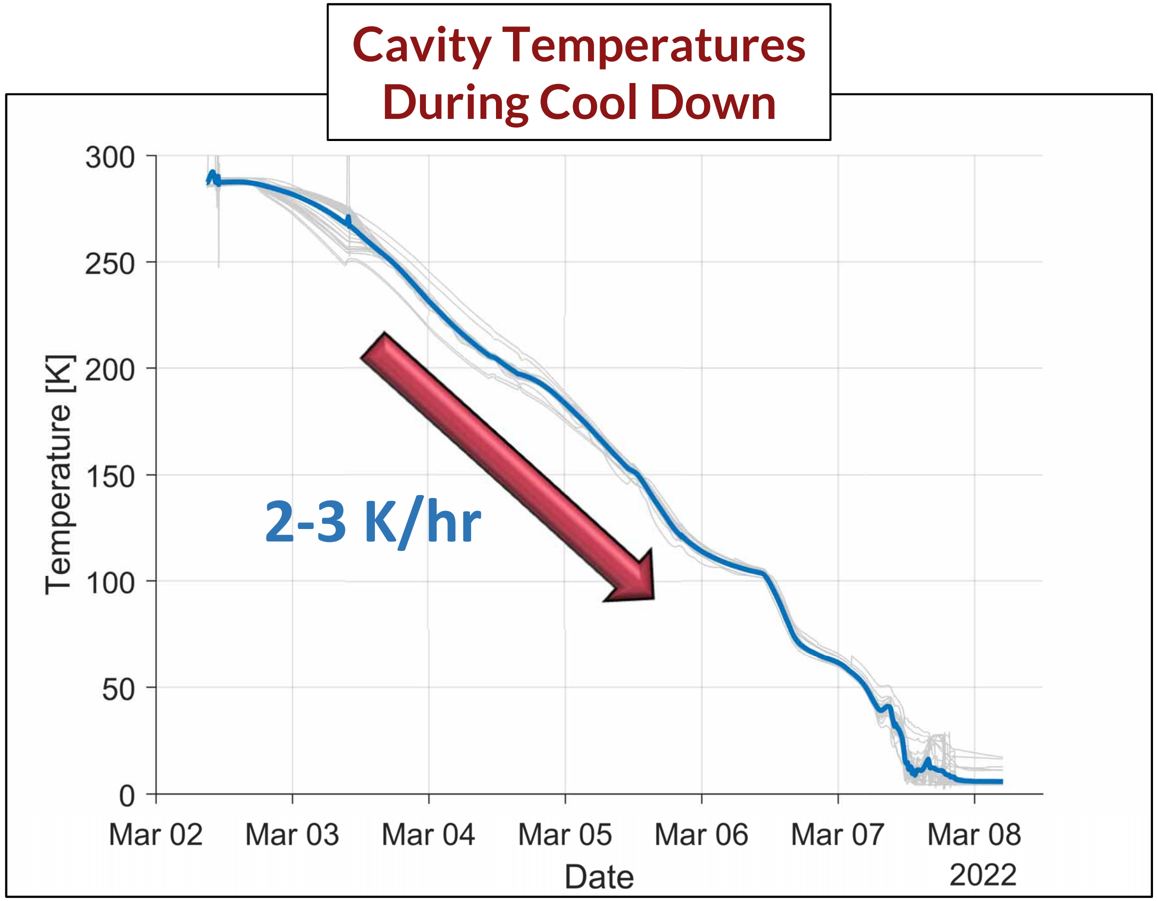

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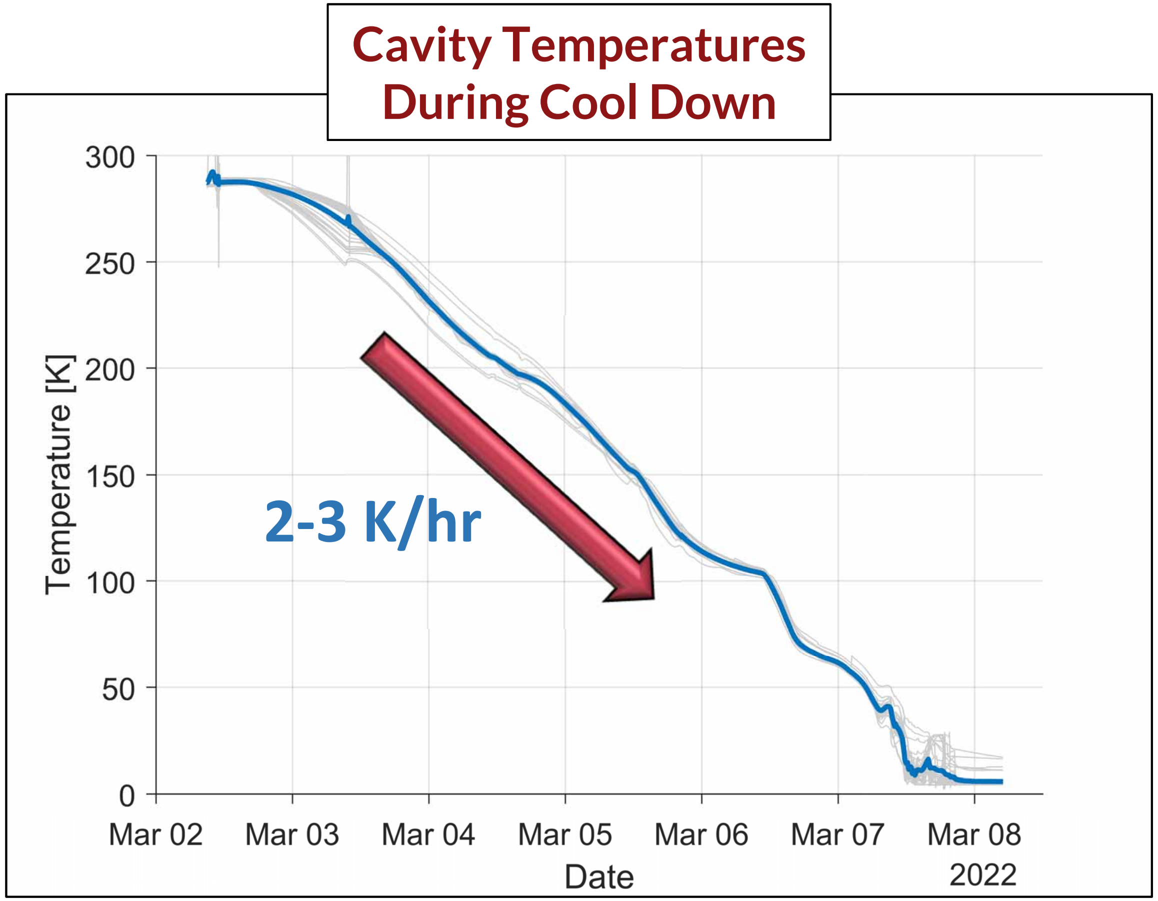

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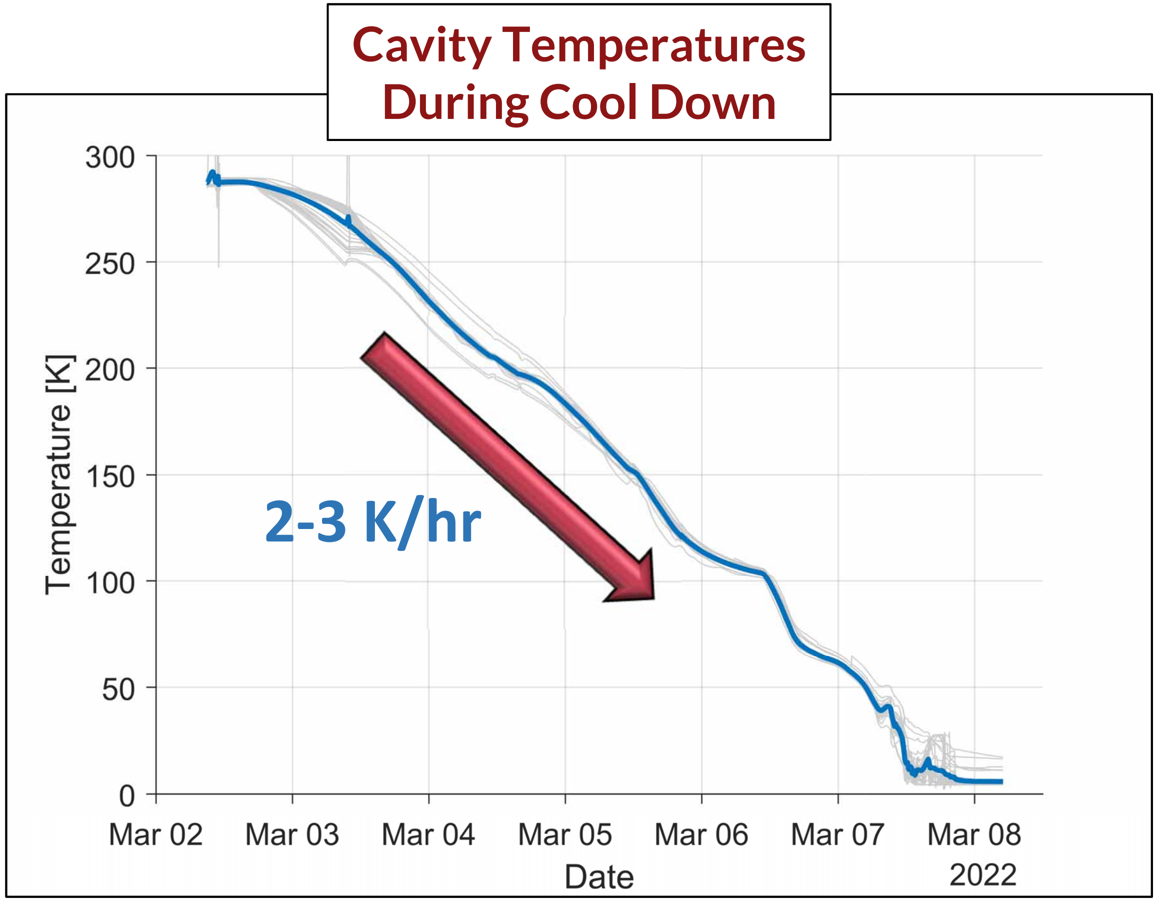

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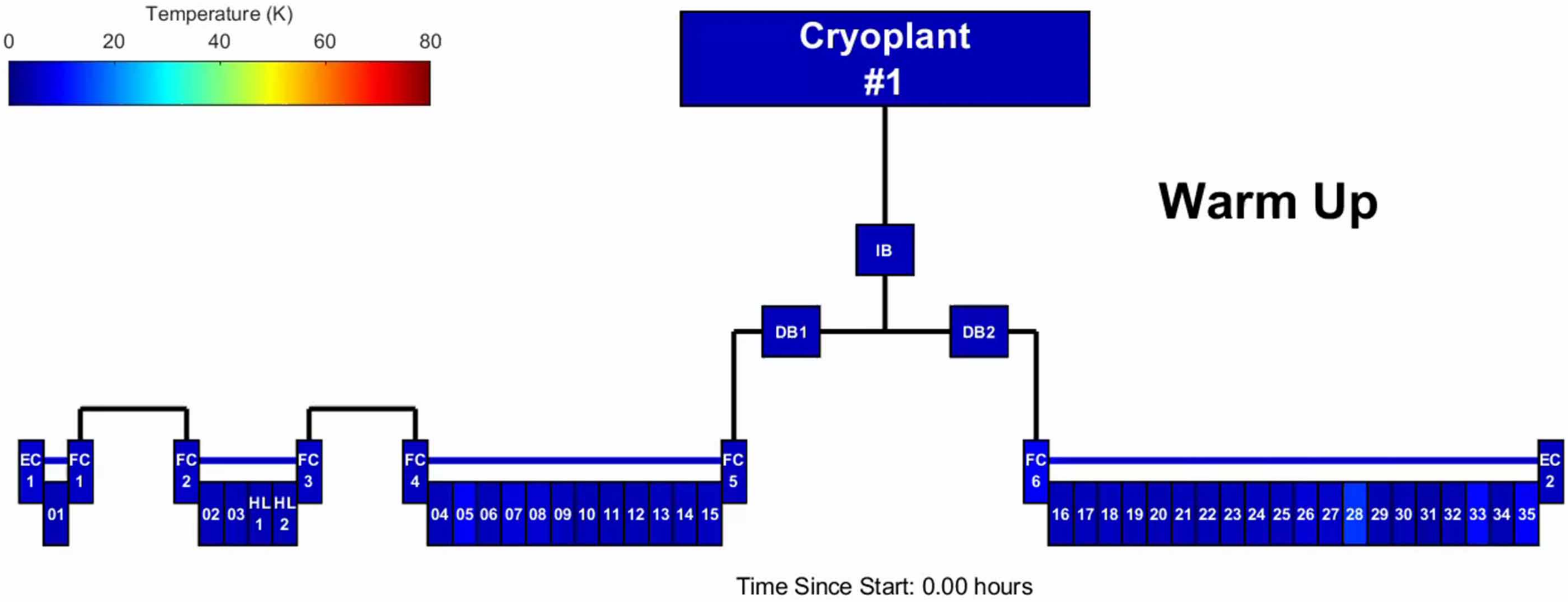
- Cool down was **near-fully automated** by the cryogenic controls system
  - CD valves were used to maintain rate and safe temperature gradients across the linac
- After multiple attempts, stable operation at 2 K was achieved **only 11 days later**

Fast Cool Down

- 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

Fast Cool Down



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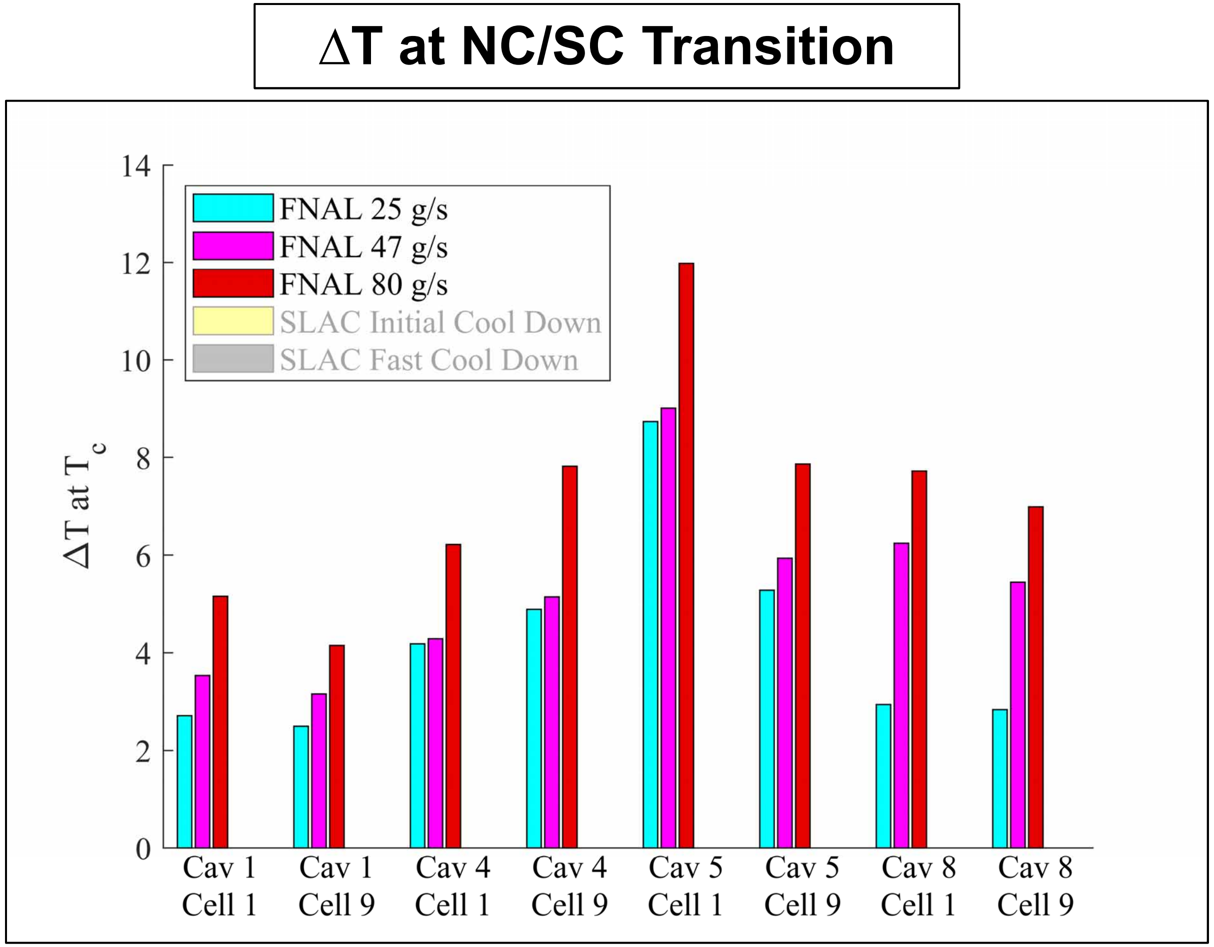
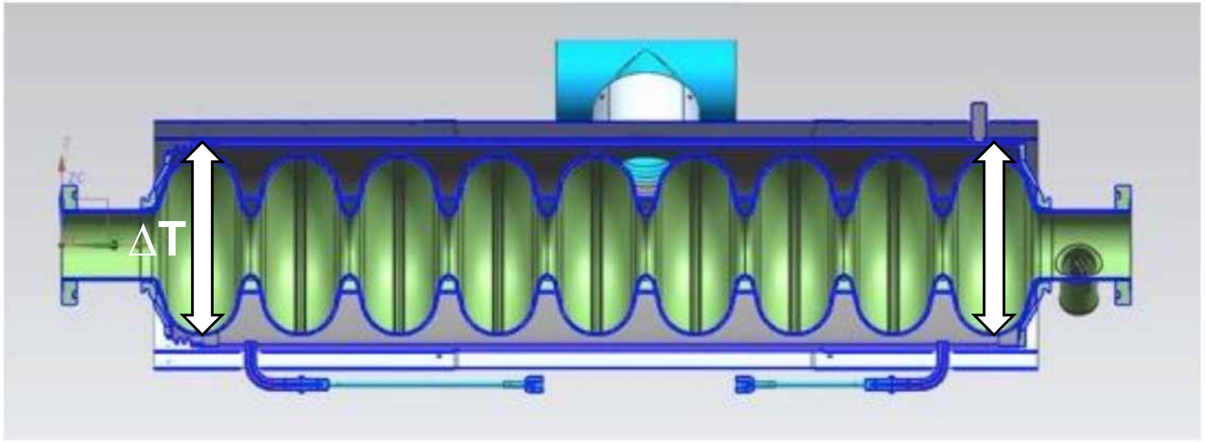
Fast Cool Down Results

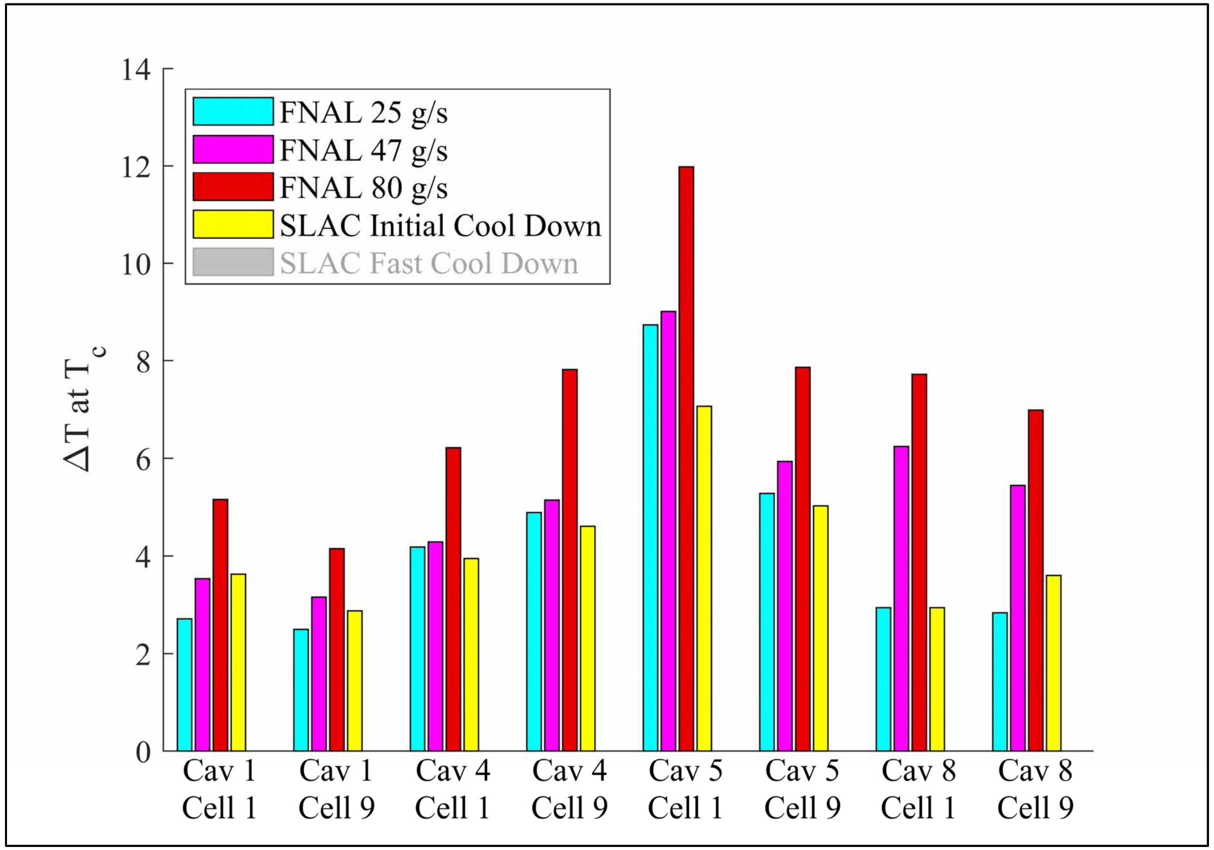


- What we really care about is the **cool down *gradient*** not the *rate* – faster usually means larger gradients
- Two installed CMs have temperature sensors located on the cavity cells
- Gradients from the SLAC fast cool down and testing at FNAL could be compared to gauge how "successful" we were



Fast Cool Down Results

ΔT at NC/SC Transition



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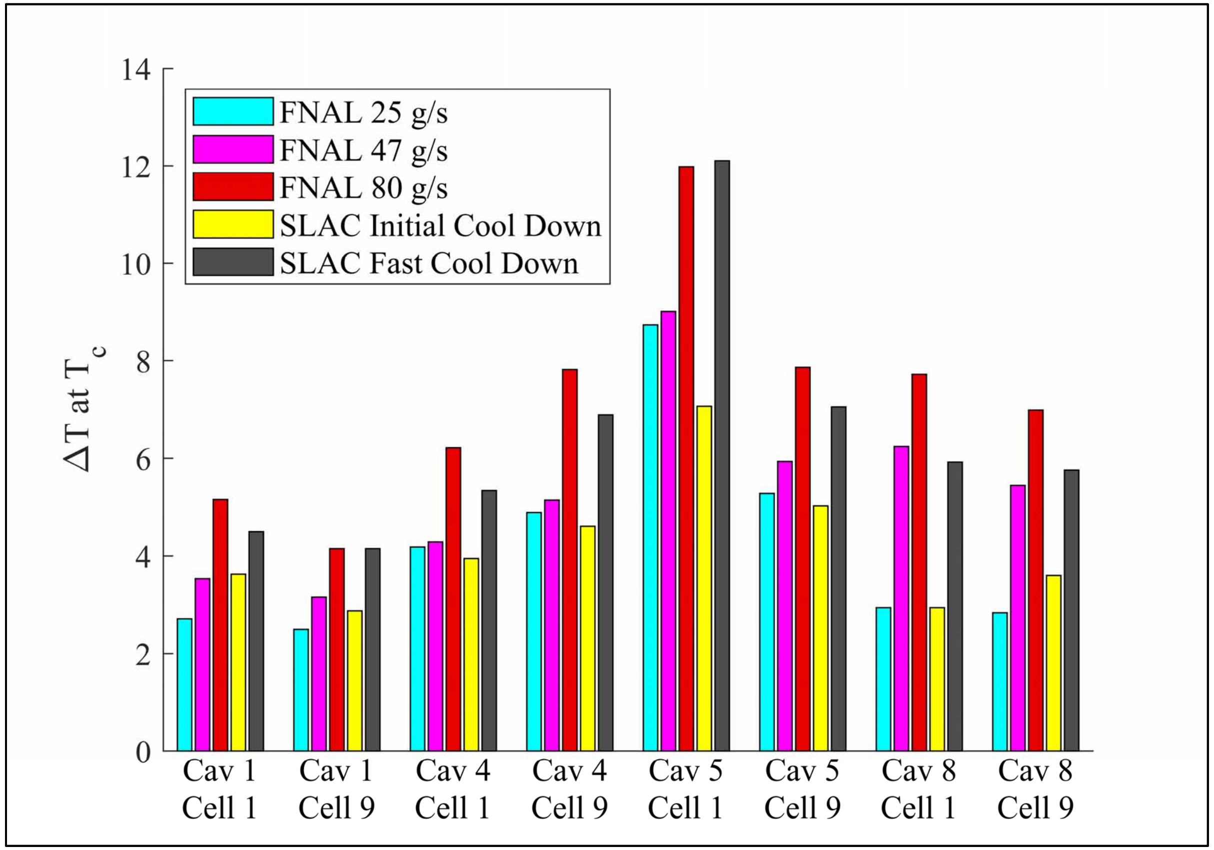

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Sufficient cool downs for High Q_0 achieved at SLAC

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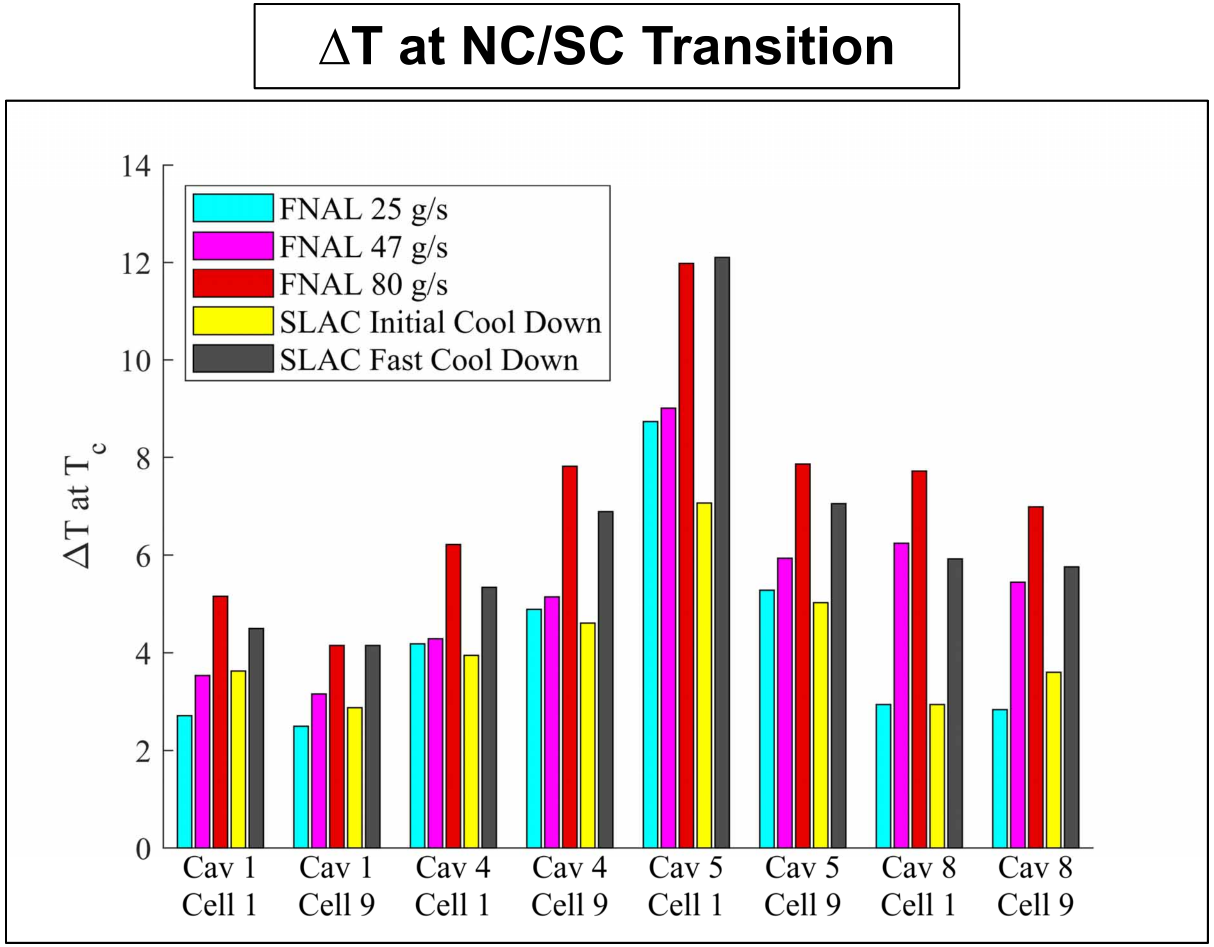

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- Non-optimized cool down results in lower ΔT than achieved at the test stands
- Fast cool down process produces similar gradients to FNAL CMTF
- We are now able to routinely achieve similar temperature gradients across the cavities to what was achieved during CM testing

Sufficient cool downs for High Q_0 achieved at SLAC

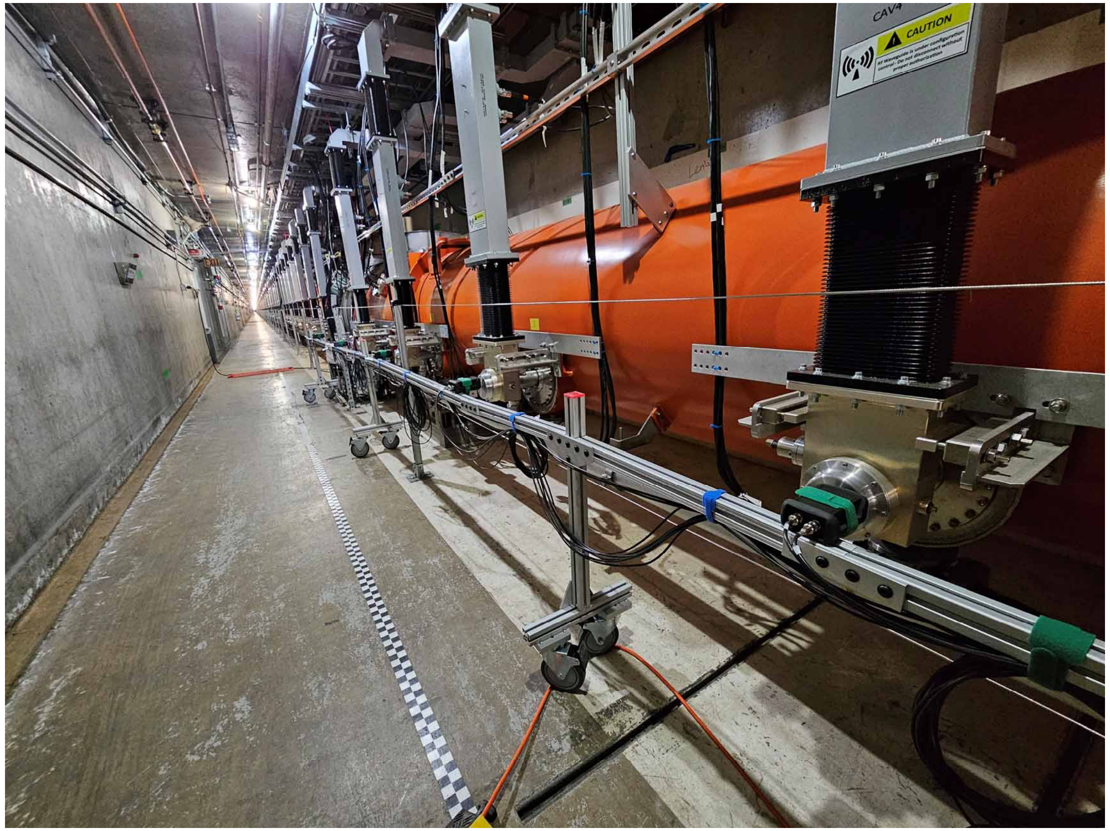
3

Cavity Commissioning Results

Cavity Commissioning Process

Each individual cavity went through an identical checkout process:

1. Checkout of support systems (SSAs, LLRF, etc.)



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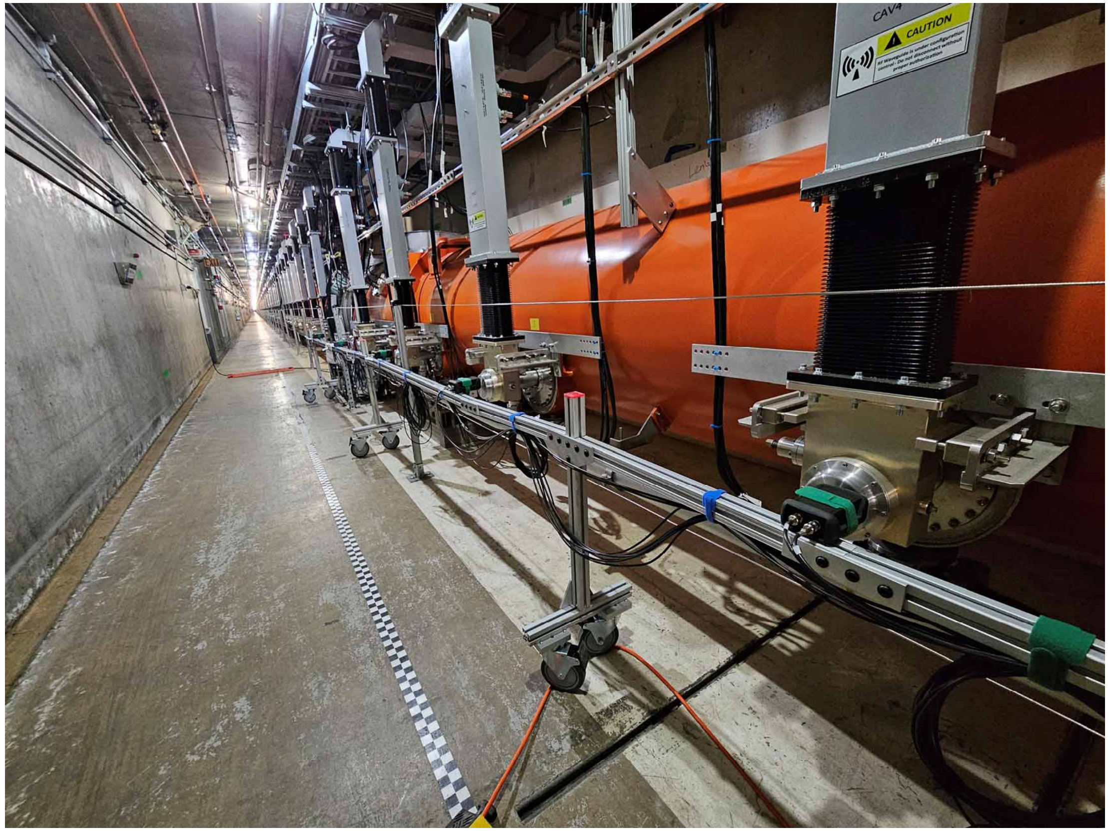

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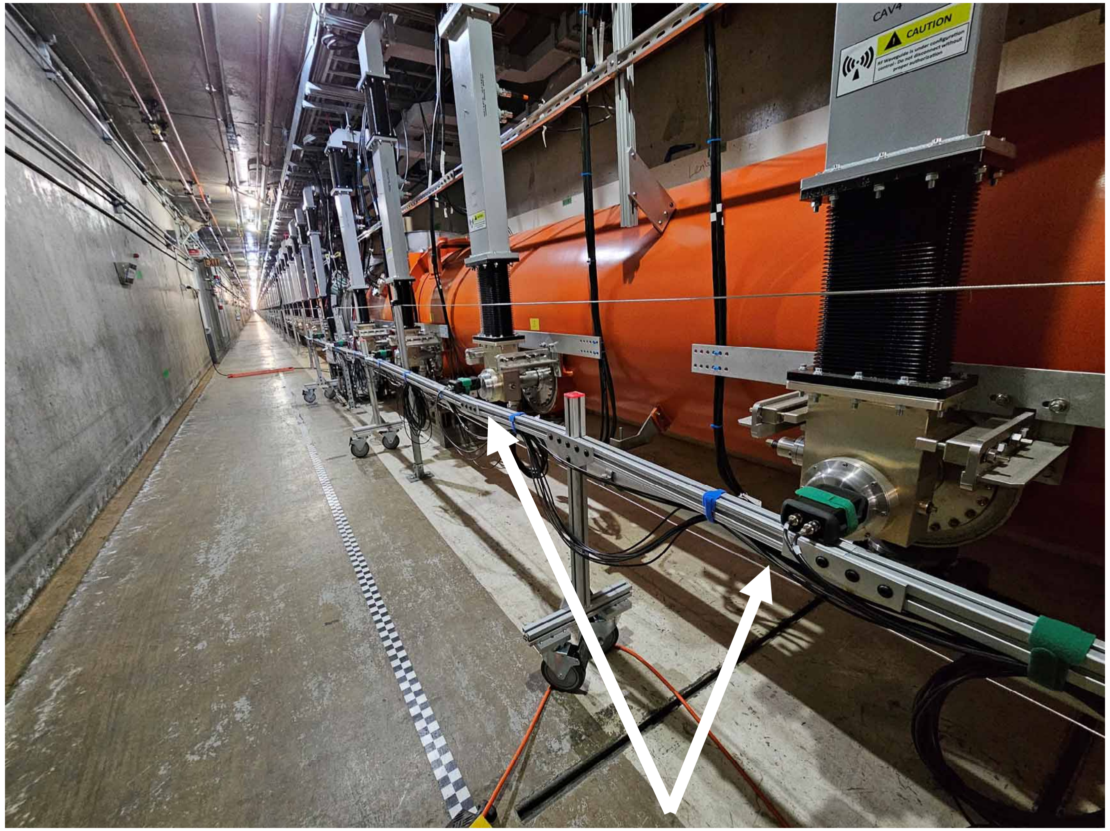

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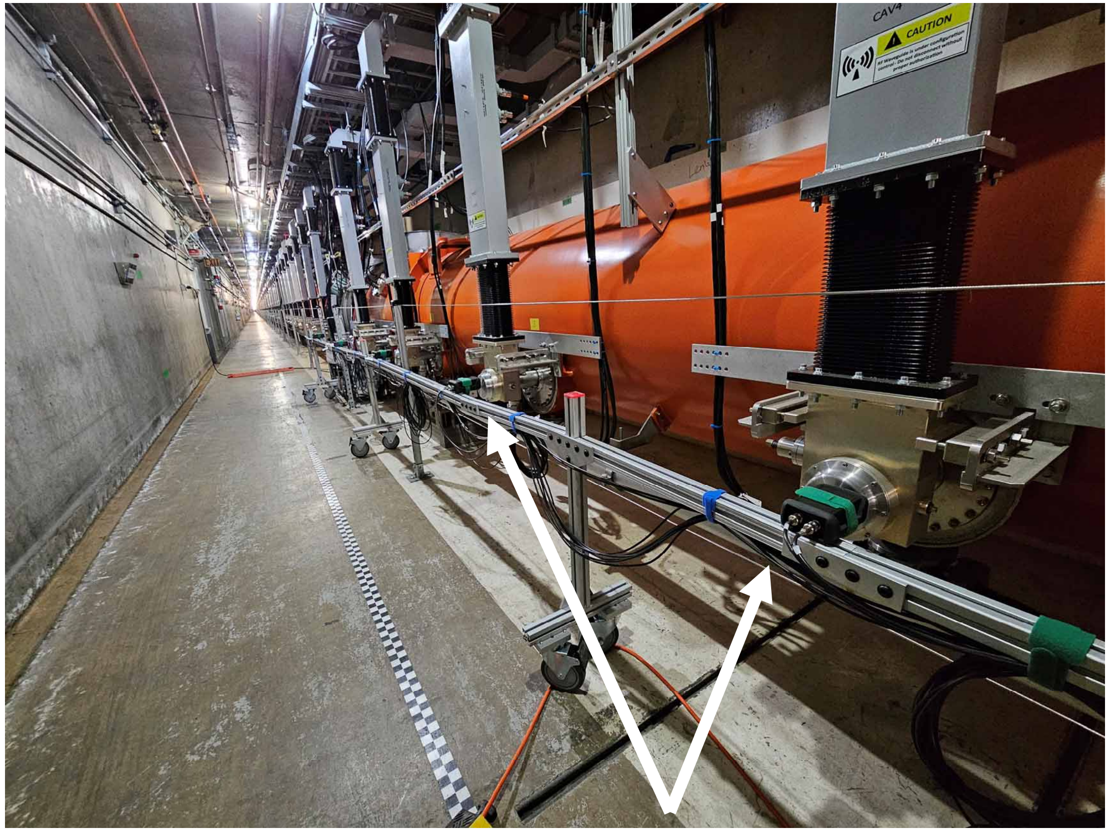
4. Individual and full CM stability demonstration
   - 1 hour run for single cavities to define usable gradient
   - 12 hour full CM test



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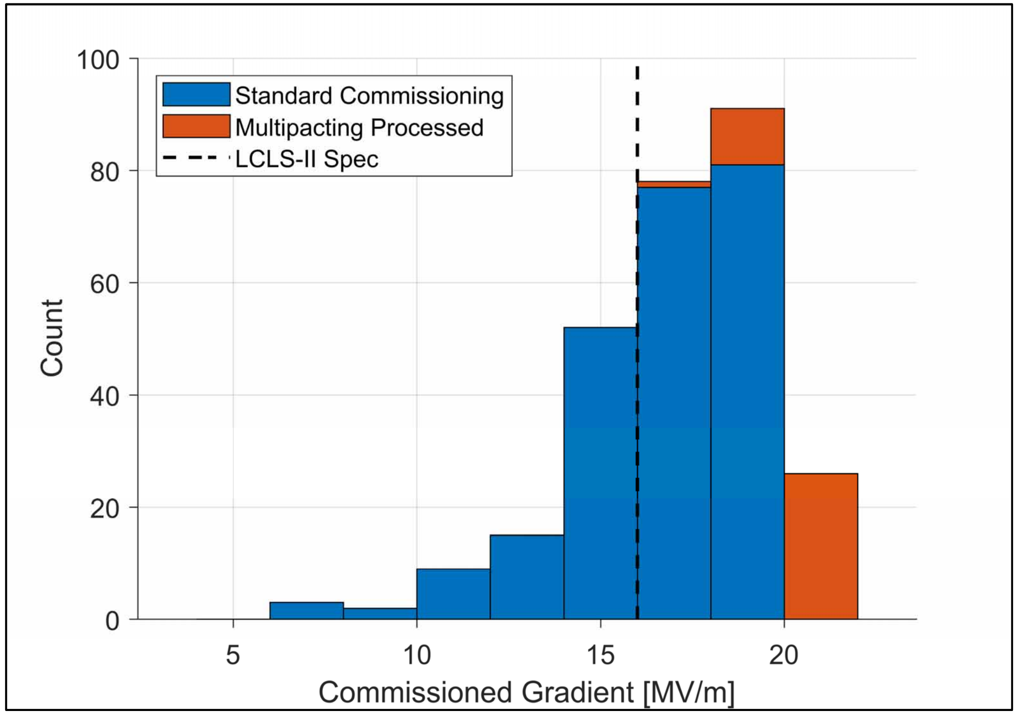
Overall SRF Commissioning Status

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

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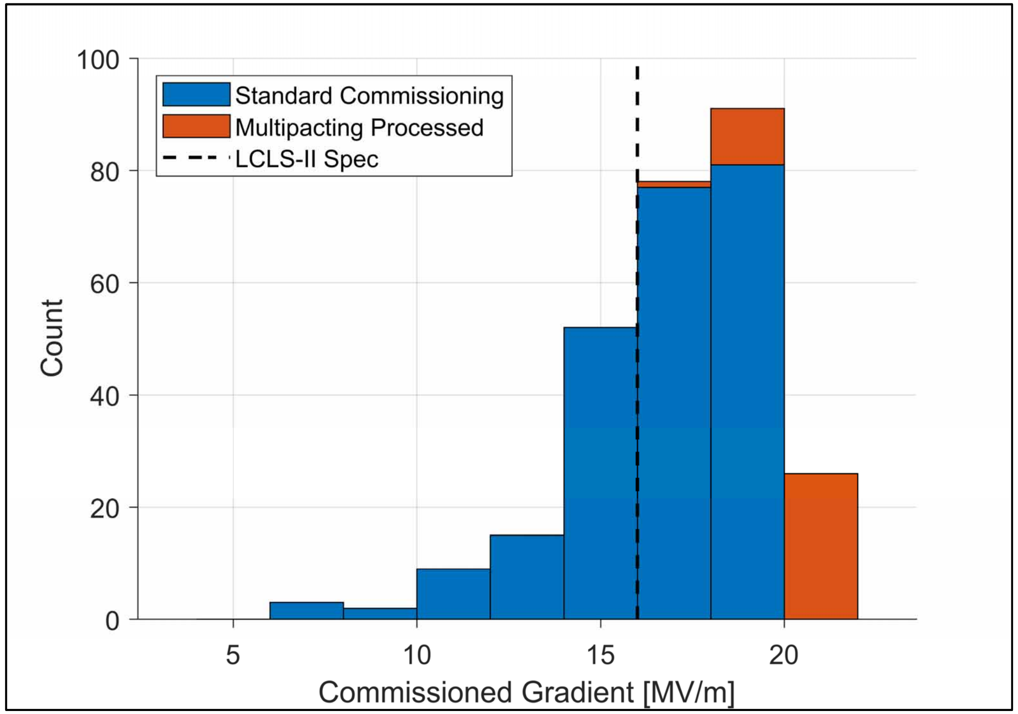

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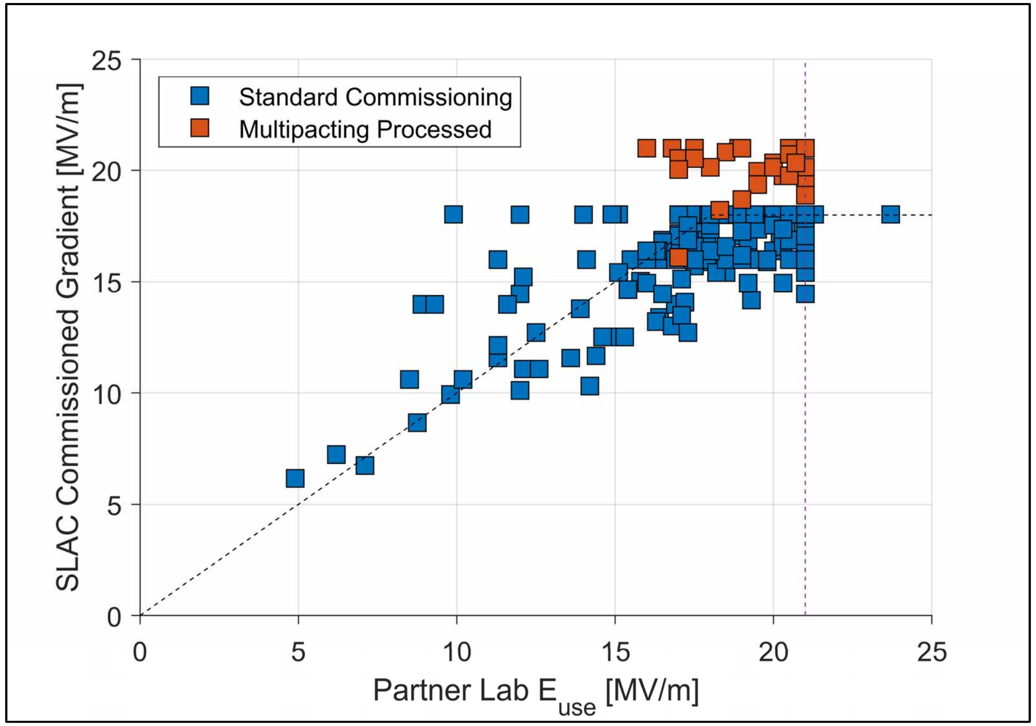
- Total commissioned voltage **exceeds design by >20%**

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

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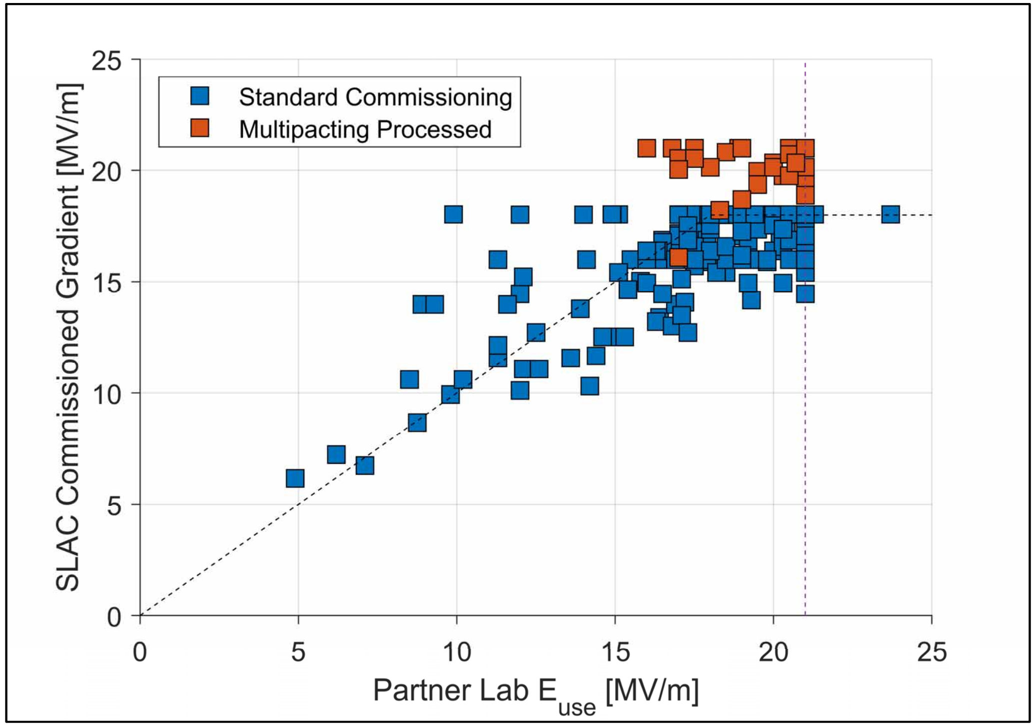

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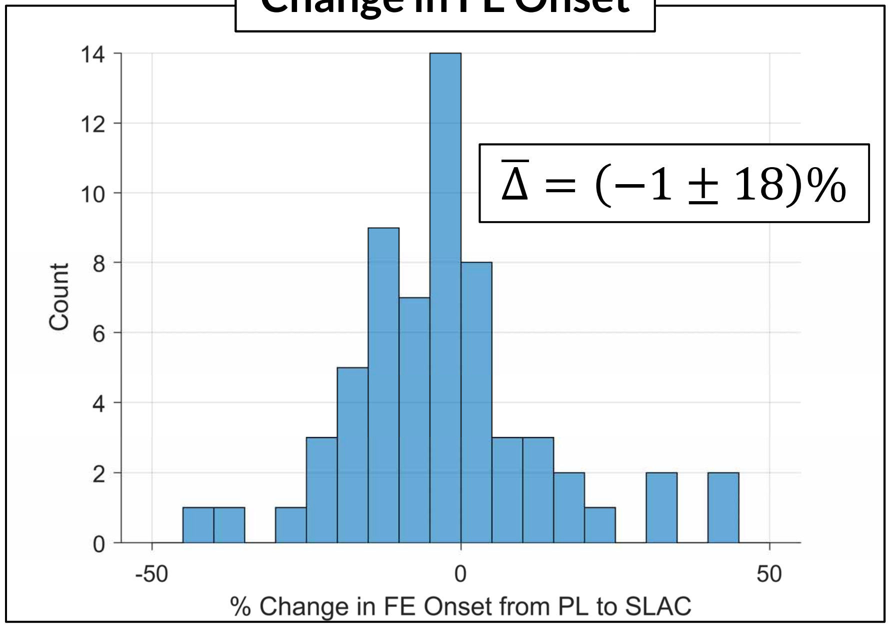
- Gradient performance is in line with CM acceptance test measurements at FNAL and JLab
- **No observable change in field emission onsets or magnitude from installation**
  - **Remarkable achievement by the SLAC installation team**

Change in FE Onset



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

For more details see A. Cravatta MOPMB063

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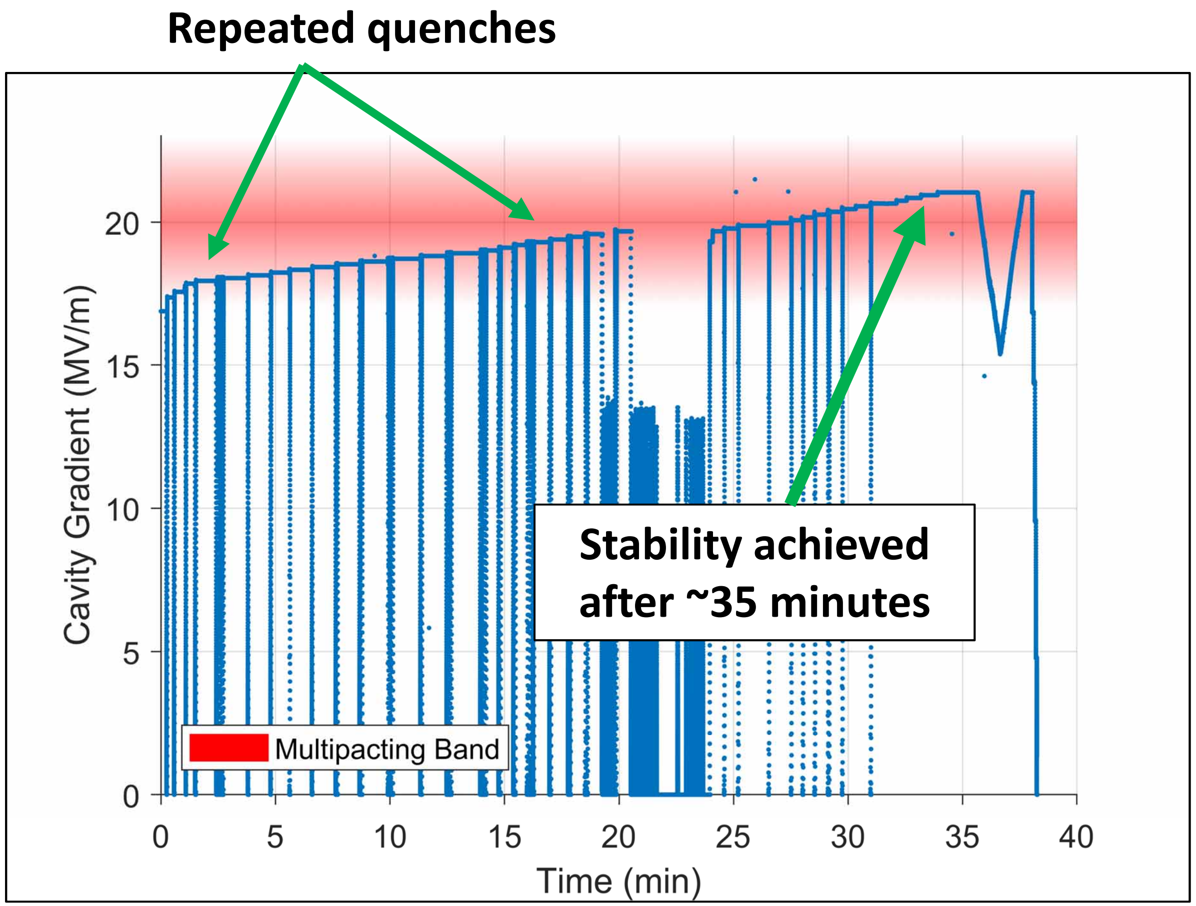
  - Consists of repeatedly quenching the cavity in CW mode with limited time (few seconds) for recovery



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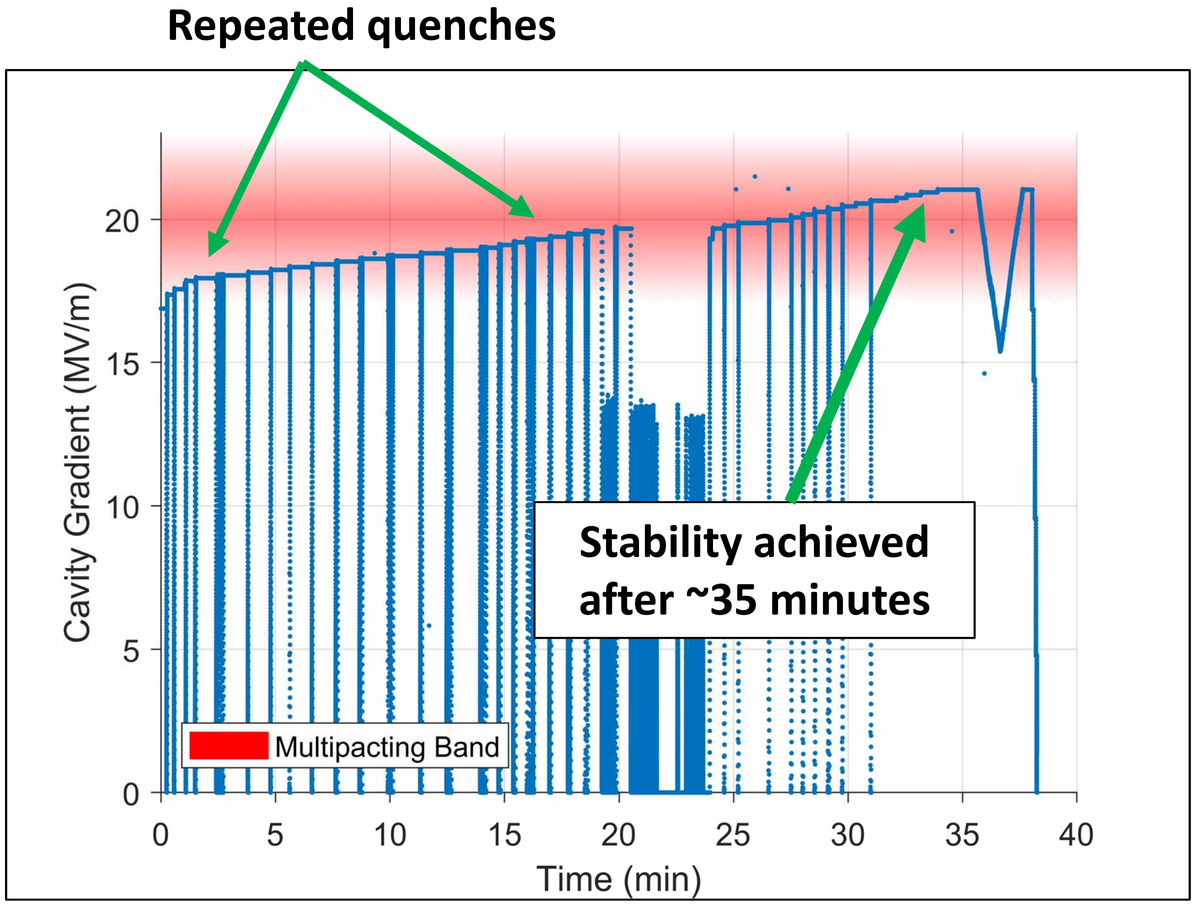

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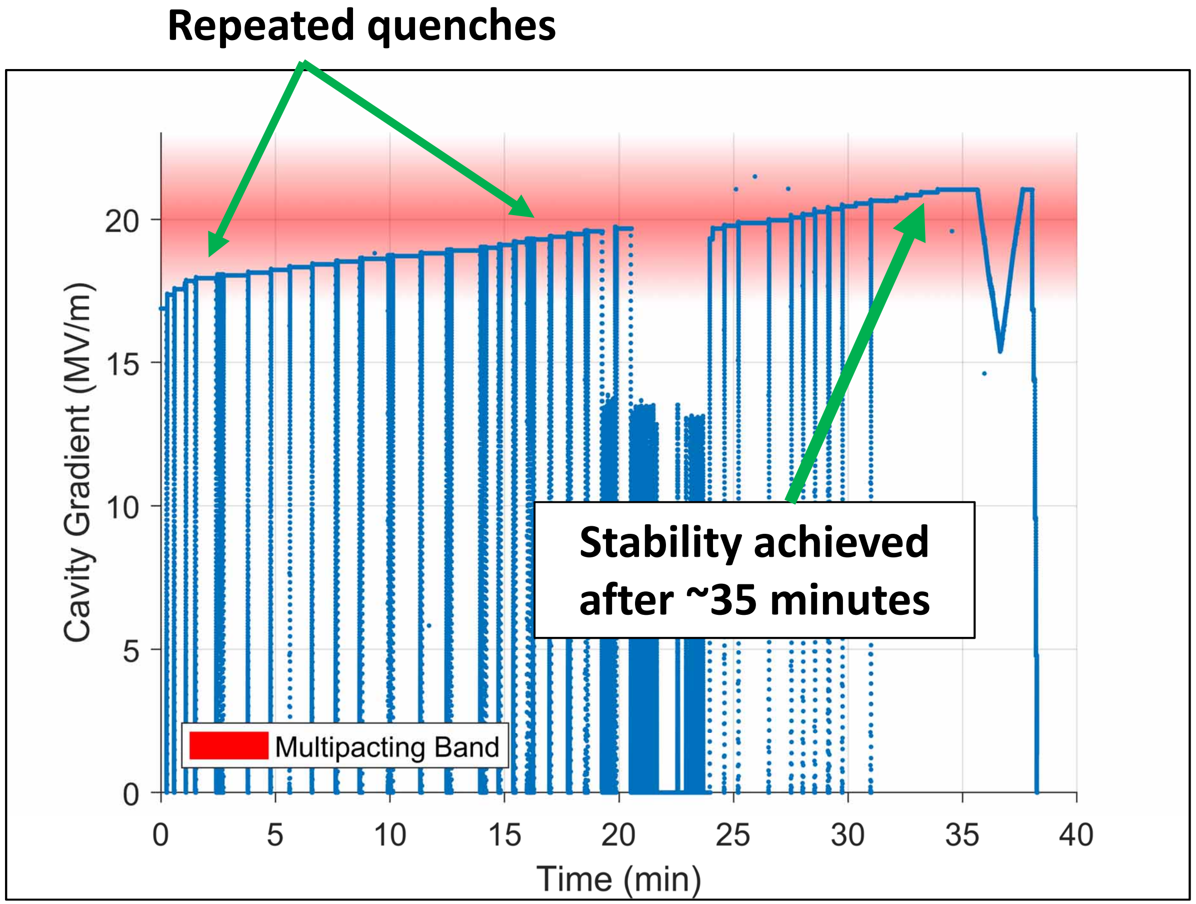
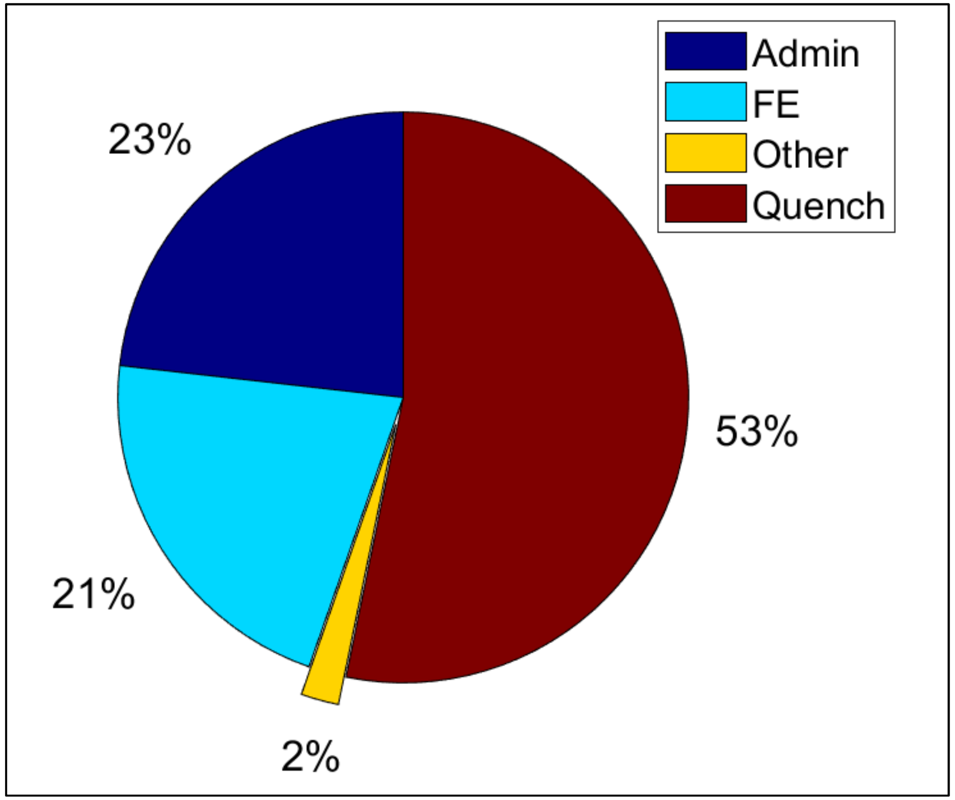


Average gradient gain of ~3 MV/m observed in 37 cavities processed

For more details see A. Cravatta MOPMB063

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
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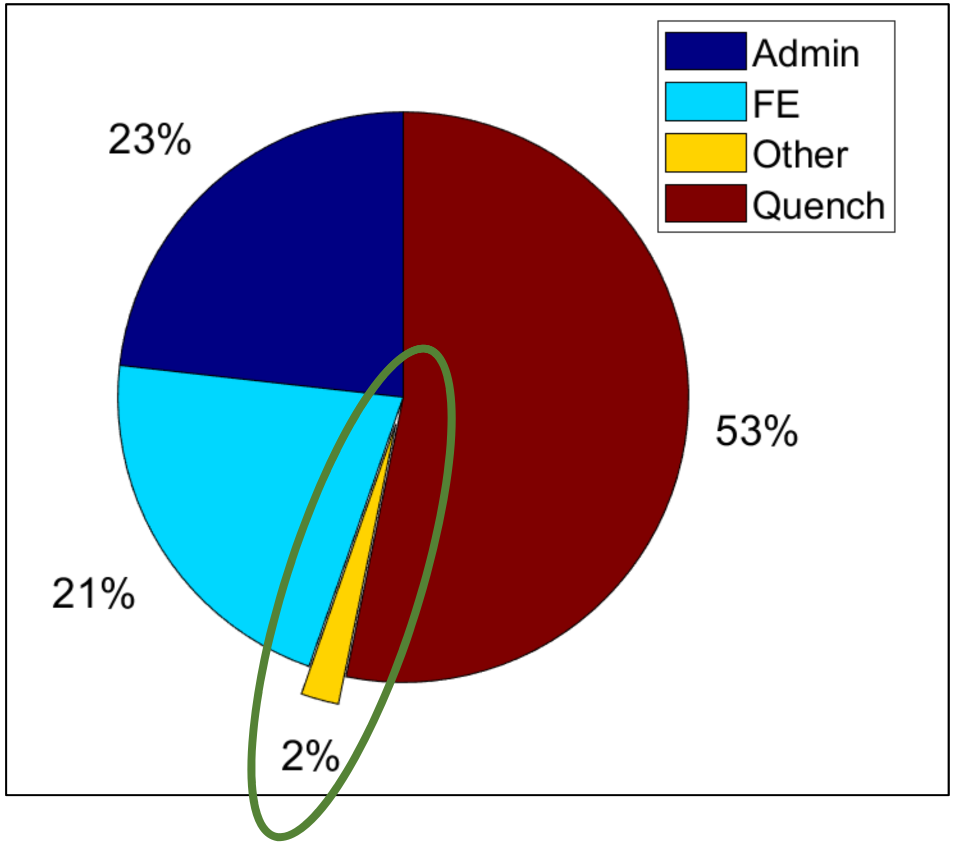

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- About one-quarter of the cavities reached the admin limit
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- The remaining 2% of cavities are unable to be used:
  - 2 cavities: poor contact between coupler warm and cold ends
  - 4 cavities: tuners not functioning properly
  - It is expected that all 6 of these cavities could be repaired *in situ* at room temperature

The Q_0 that was promised…

- Due to the strong coupling in the CM, Q_0 is measured cryogenically

For more details see L. Zacarias MOPMB090

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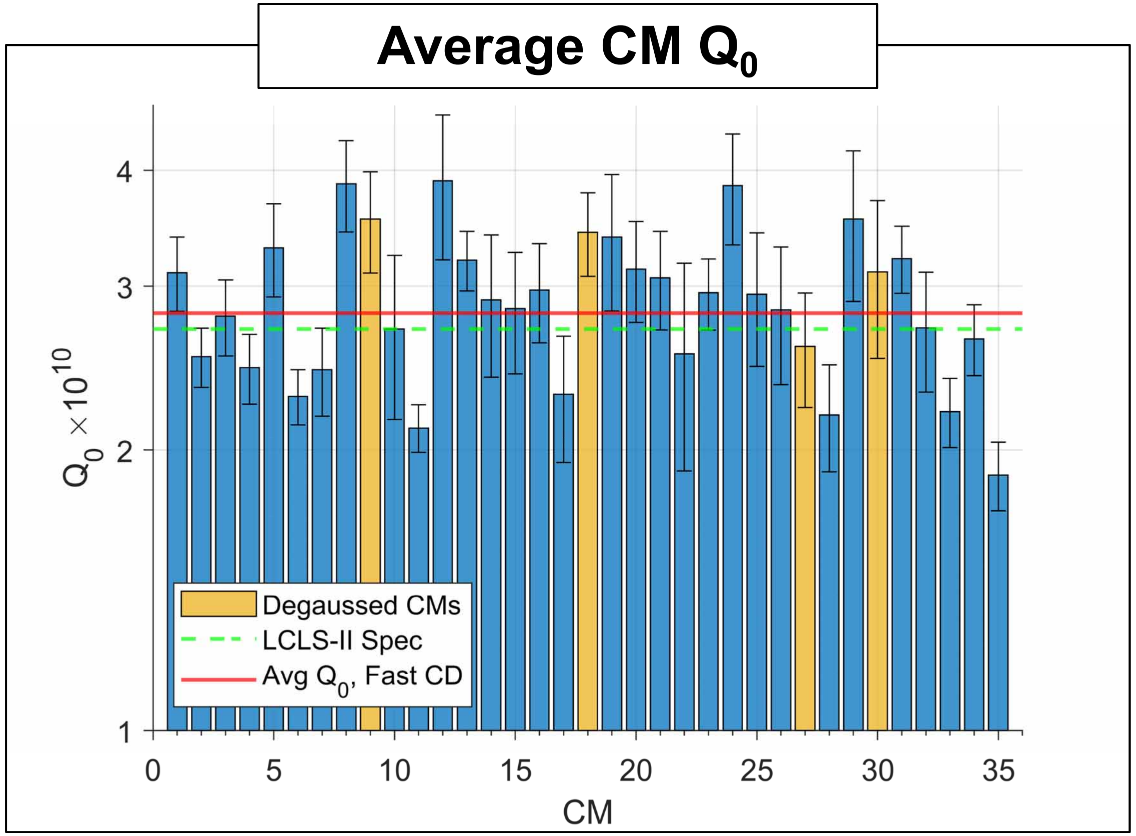

- Due to the strong coupling in the CM, Q_0 is measured cryogenically
- Full CM average Q_0 results look promising
- Across the linac an **average of 2.8×10^{10}** has been observed, **exceeding the spec** of 2.7×10^{10}

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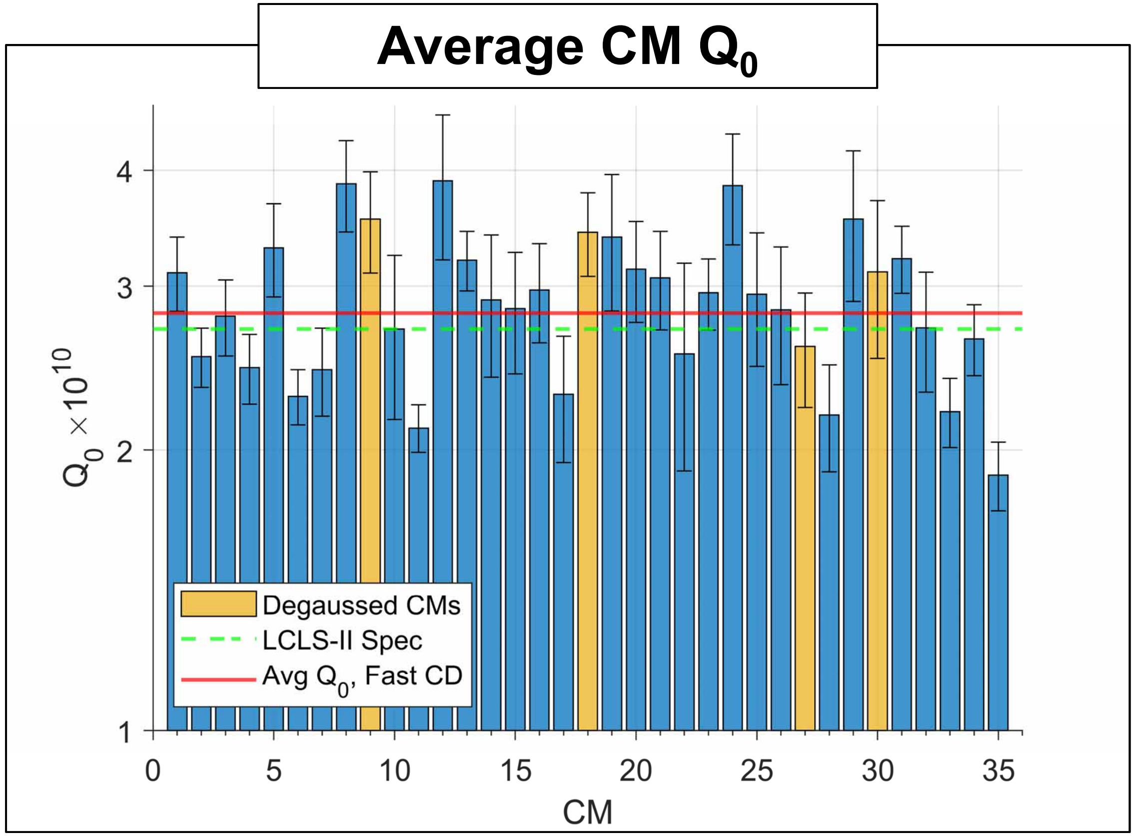

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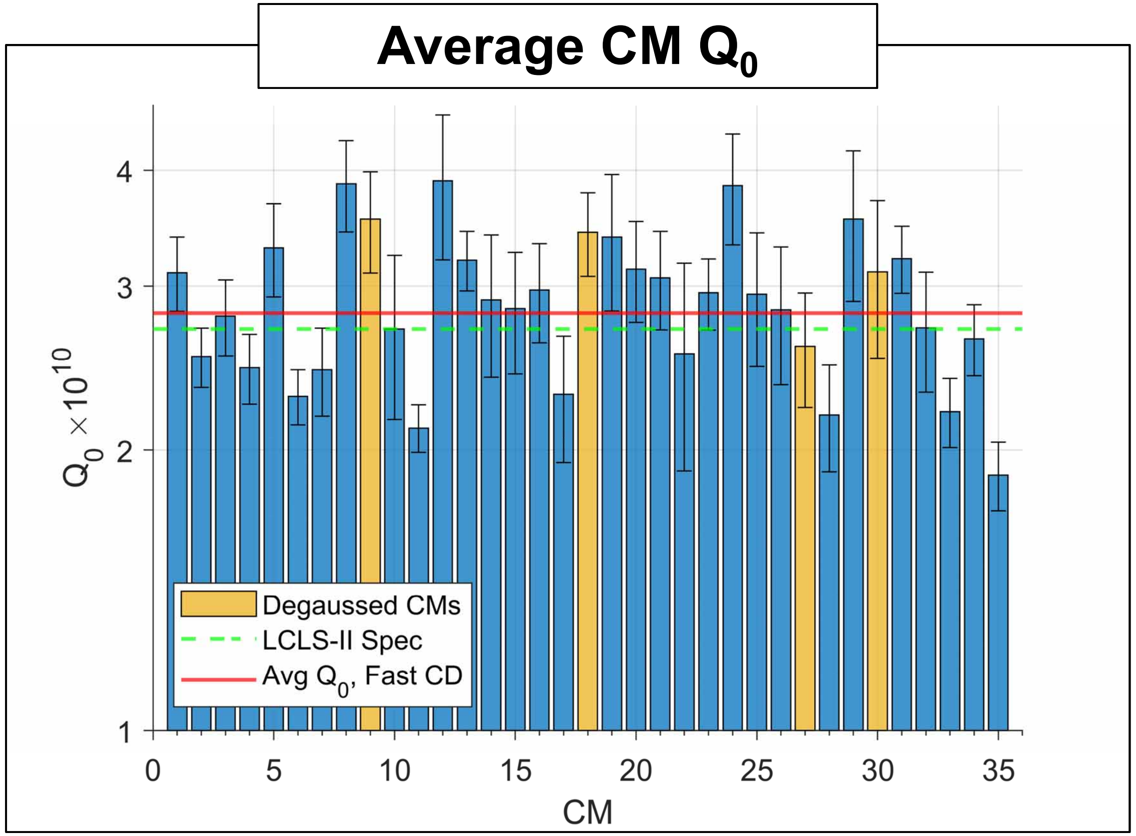

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Demonstrates High Q_0 in an installed linac for the first time

For more details see L. Zacarias MOPMB090

Effect of Degauss on Q_0

- The two worse cavities in terms of Q_0 were degaussed during the recent room temperature warm up

Cryomodule	Q_0 Before Degauss	Q_0 After Degauss	P_{diss} Savings at 16 MV/m
CM18	1.3×10^{10}		
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Nominal heat load for 1 CM: 80 W

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- Significant improvement in Q_0 was observed compared to before degaussing
- We have now degaussed 4 CMs, with an average Q_0 of $3.1x10^{10}$ compared to $2.7x10^{10}$ for those not degaussed
- **For HE, degaussing of all CMs, including already installed LCLS-II CMs NEEDS to be included in the plan**

Cryomodule	Q_0 Before Degauss	Q_0 After Degauss	P_{diss} Savings at 16 MV/m
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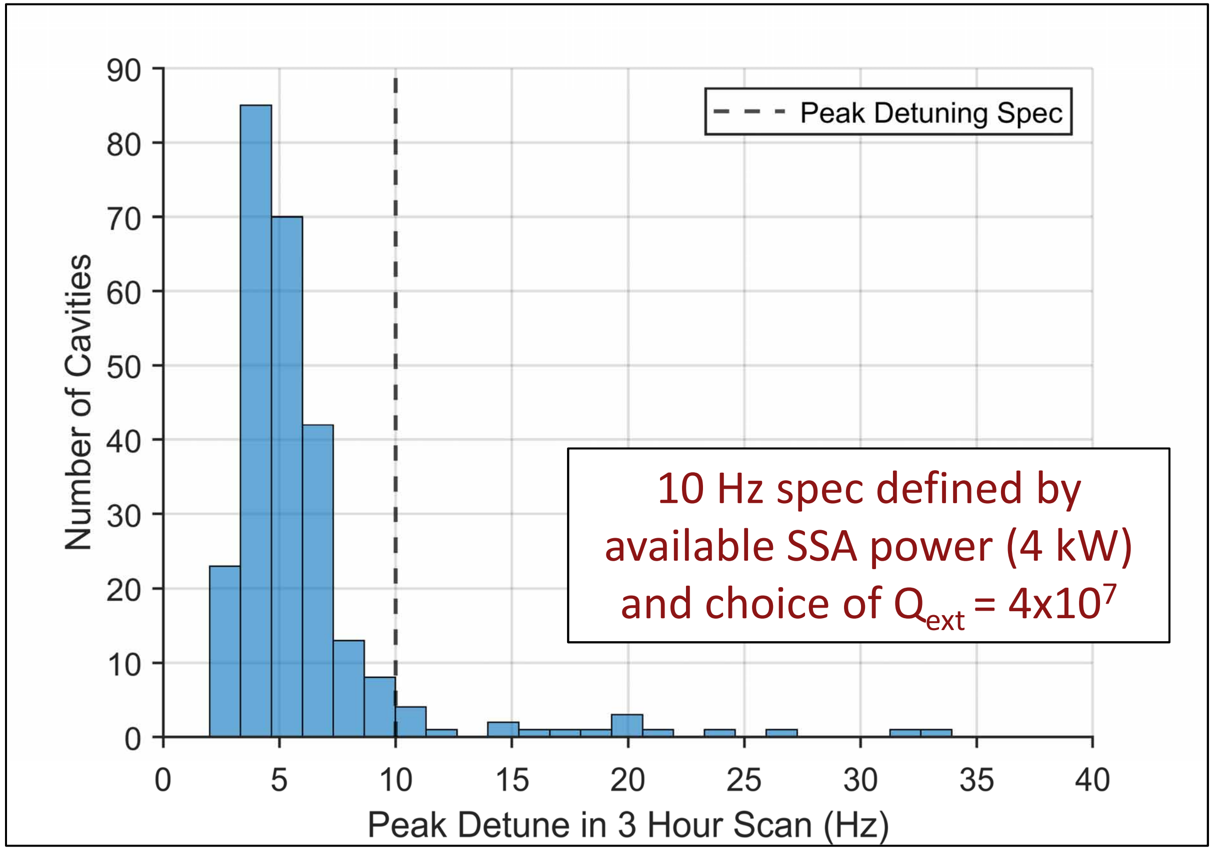
Microphonics Performance

Peak Detuning Over 3 Hours



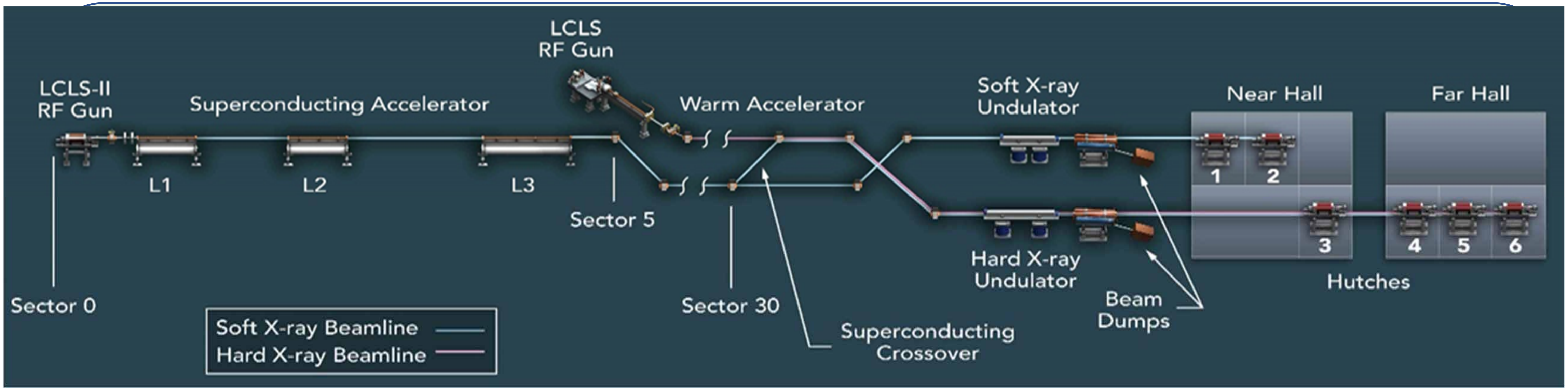
- Overall, microphonics performance in the linac has been excellent
- 94% of cavities show peak detuning below the 10 Hz specification
- Only 2 cavities currently have gradients limited by microphonics
- Primary source of gradient-limiting microphonics is leaky cool down valves

For more details see R. Porter MOPMB081

4

SC Linac & Beam Commissioning

Injector Beam Emittance



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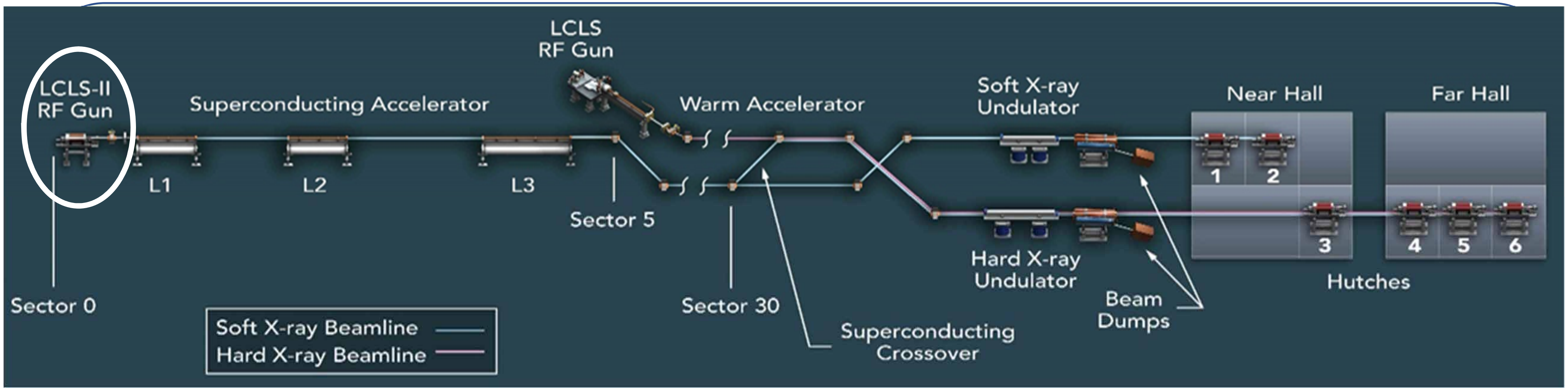

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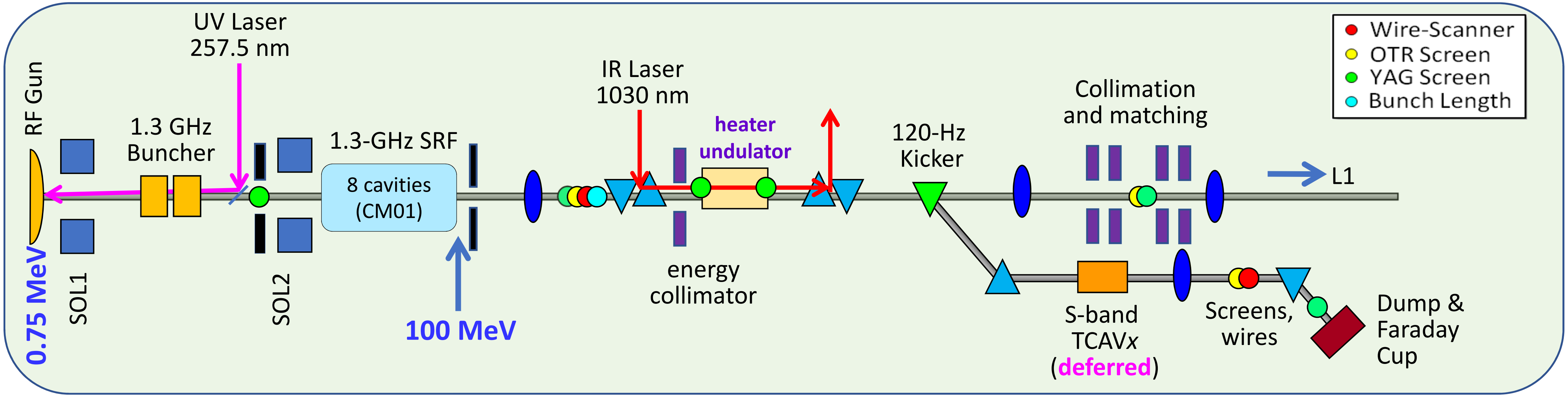

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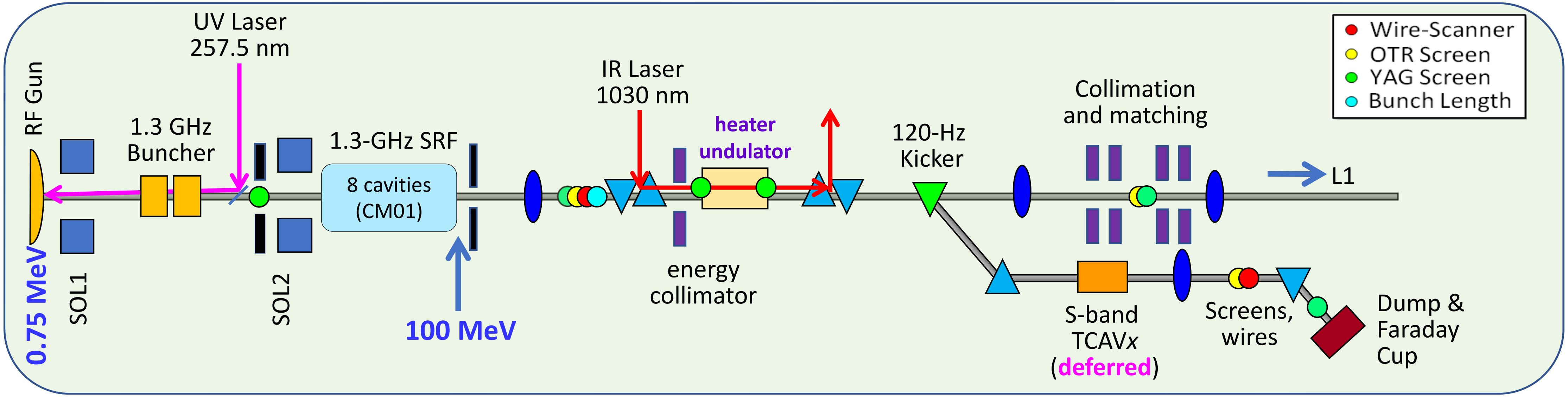
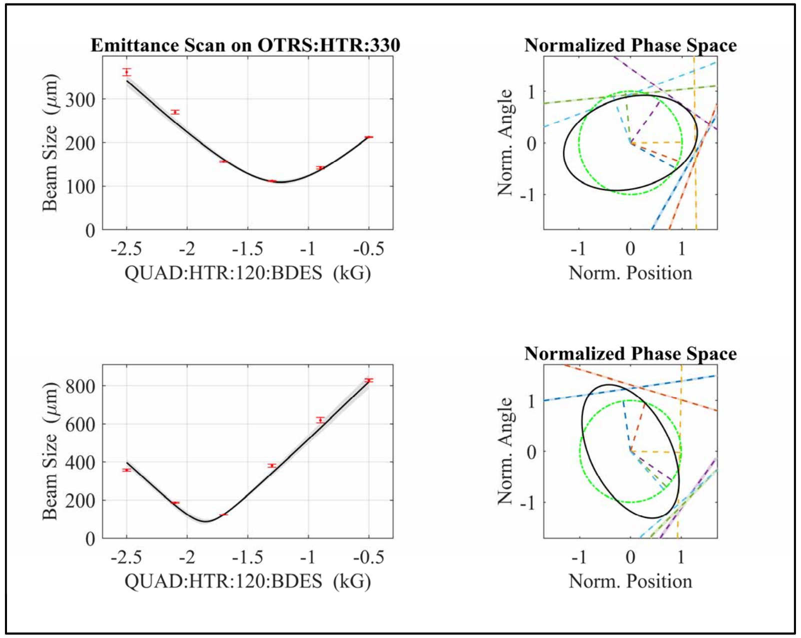




Dimension	Emittance (µm)
$\gamma\epsilon_x$	0.58 ± 0.02
$\gamma\epsilon_y$	0.56 ± 0.02

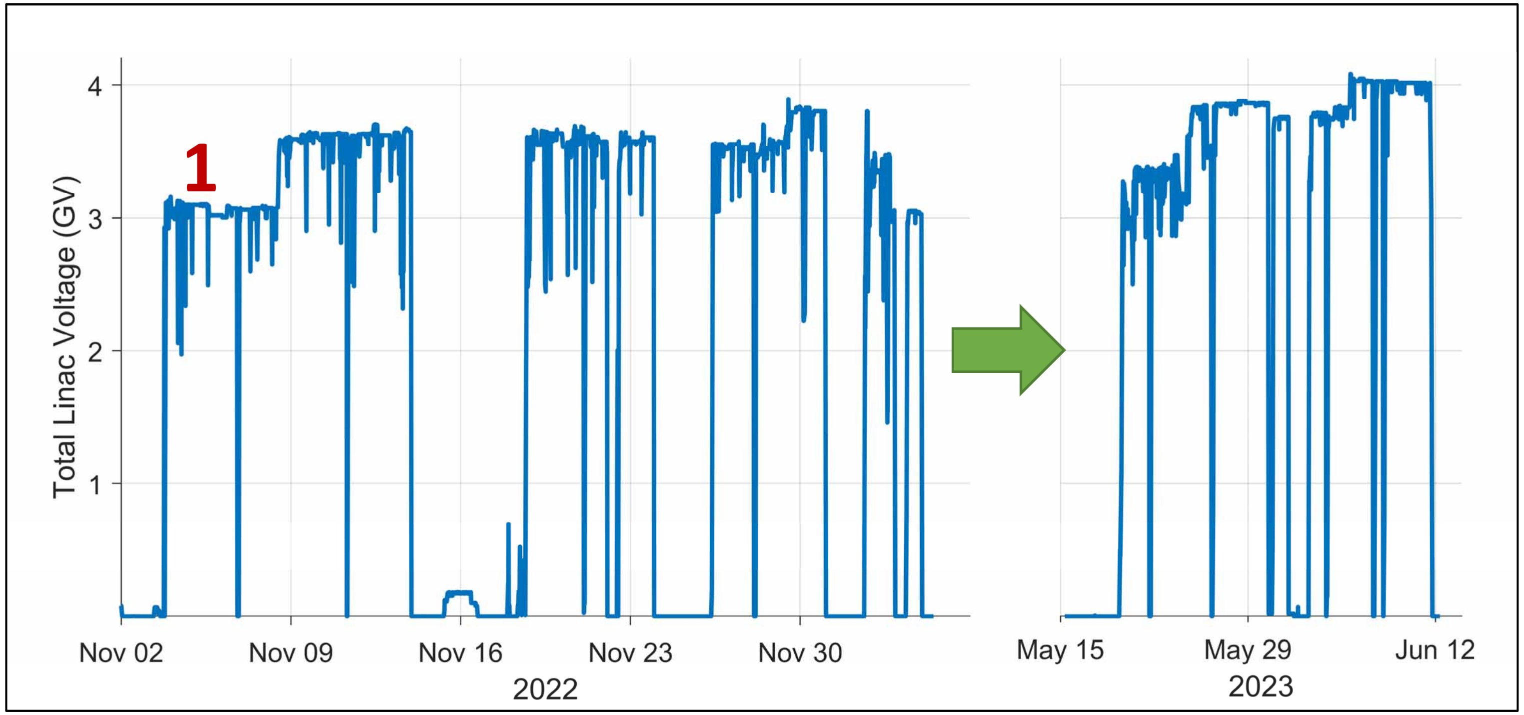
50 pC beam

Excellent Injector Emittance Achieved

Demonstration of 3.5 GeV Beam

1. Stable 3 GeV beam to BSY achieved on 10/28

Total Cavity Voltage



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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

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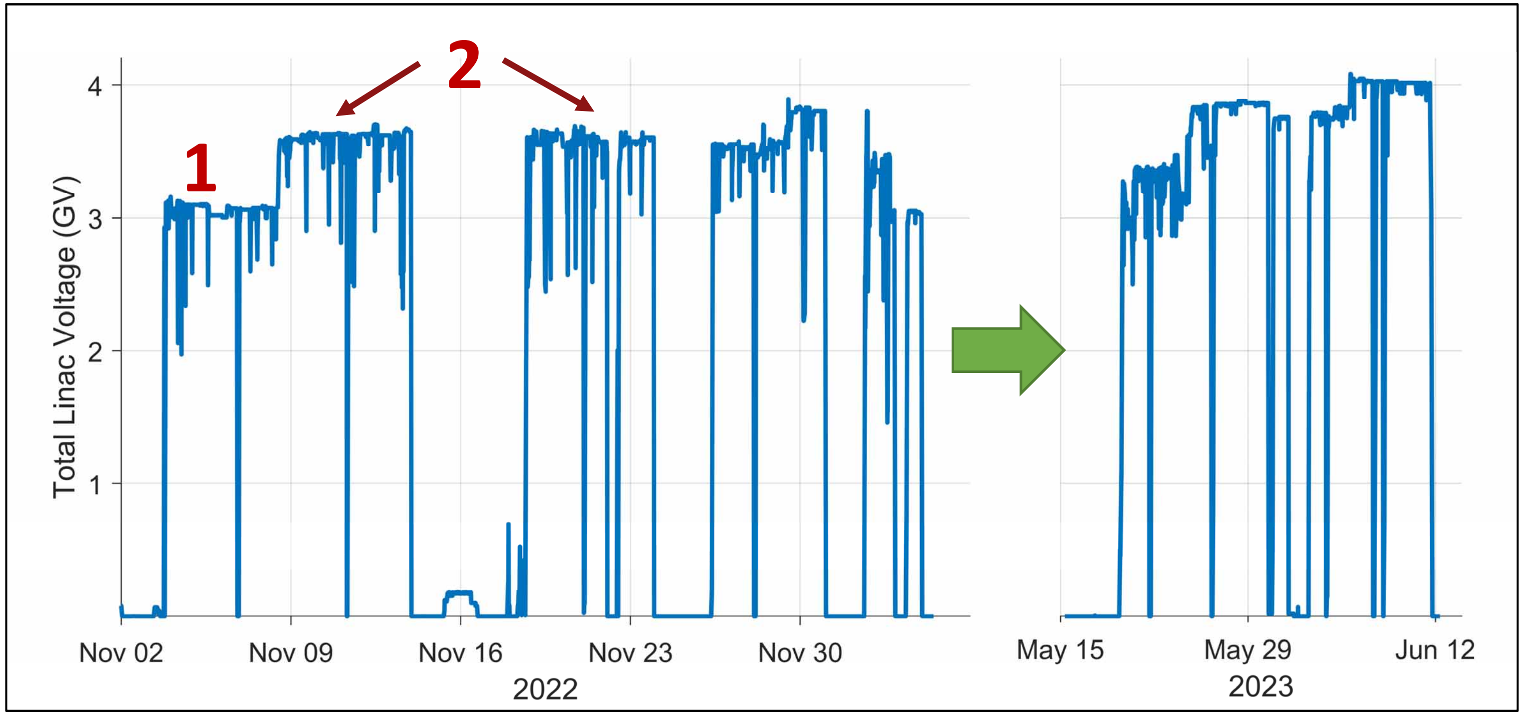

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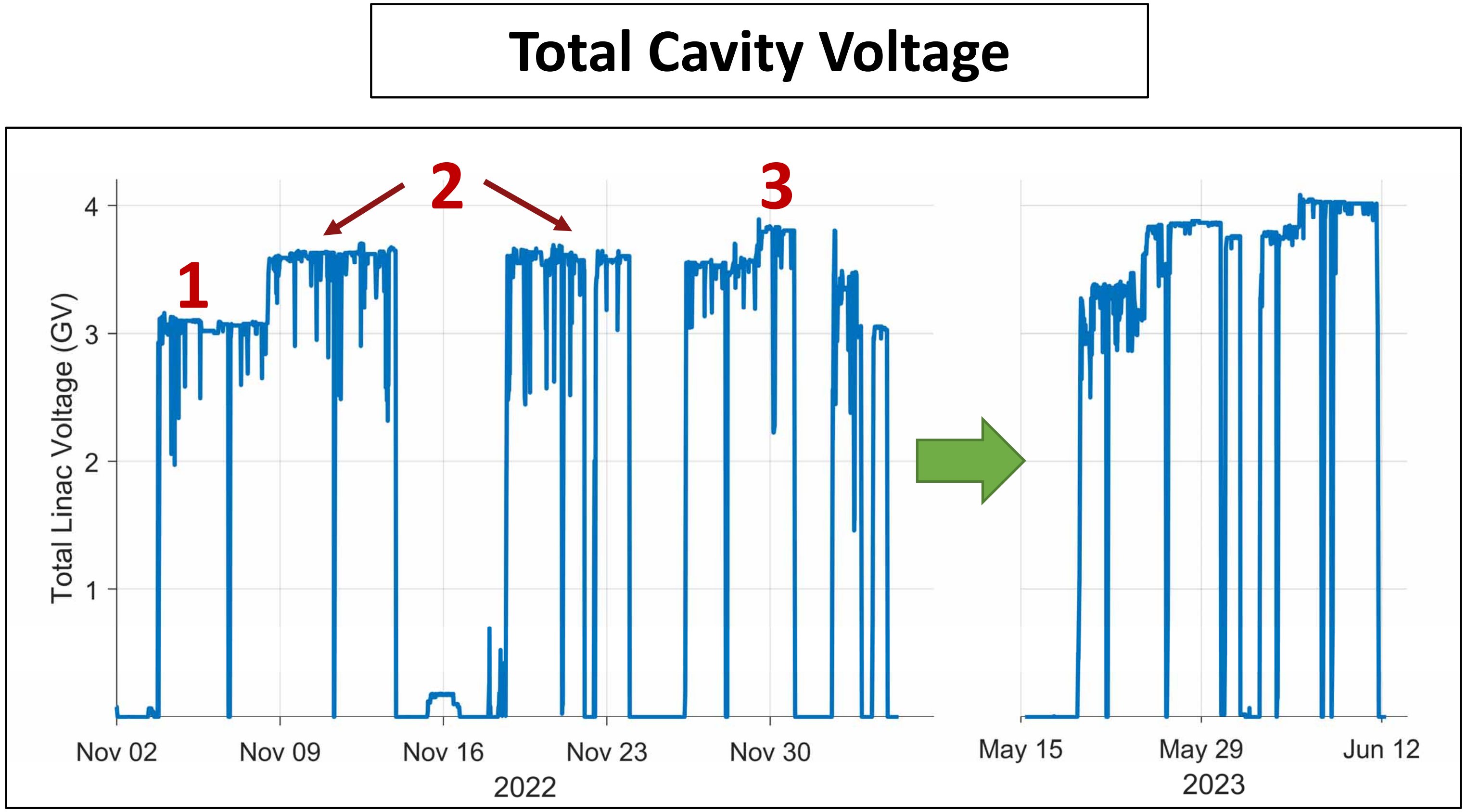

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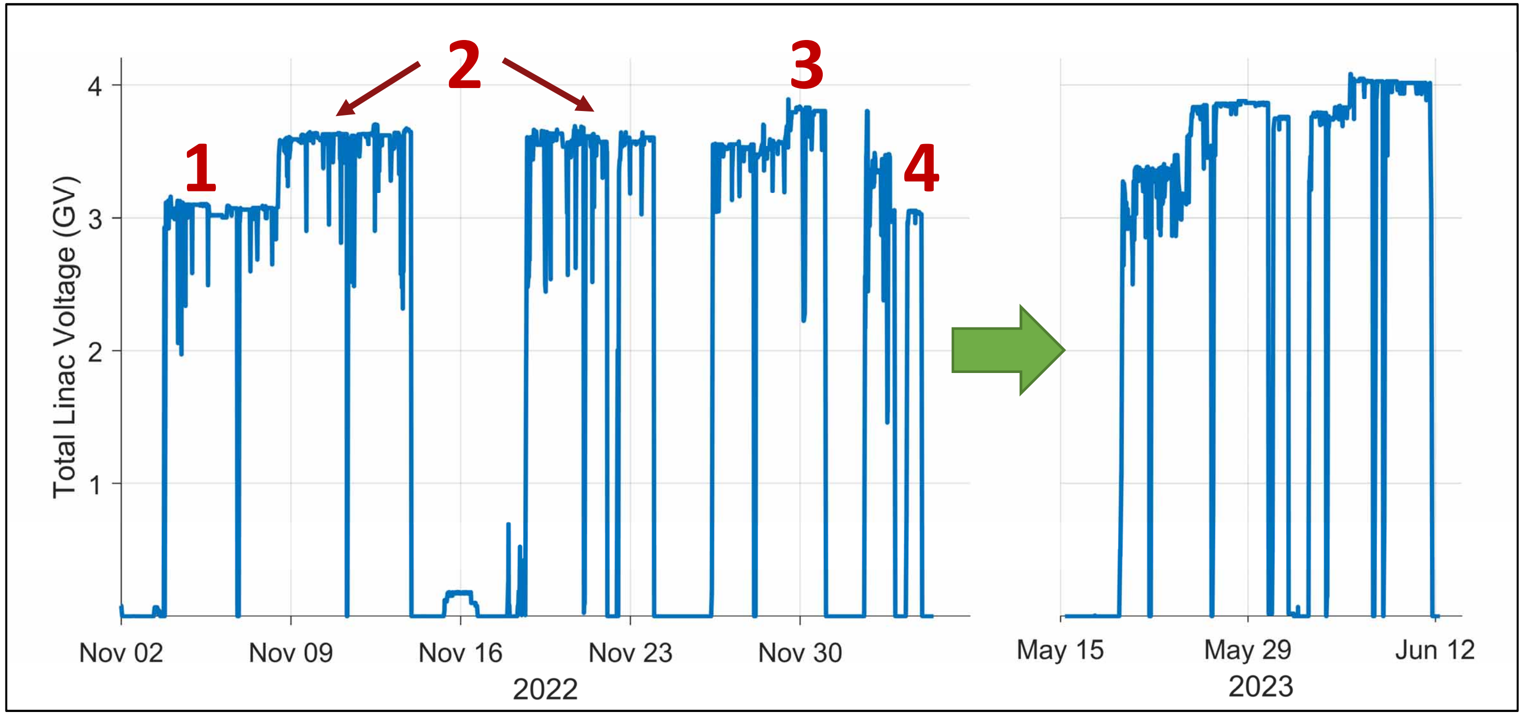

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5. Following restart in May 2023, 3.5 GeV beam has been used exclusively

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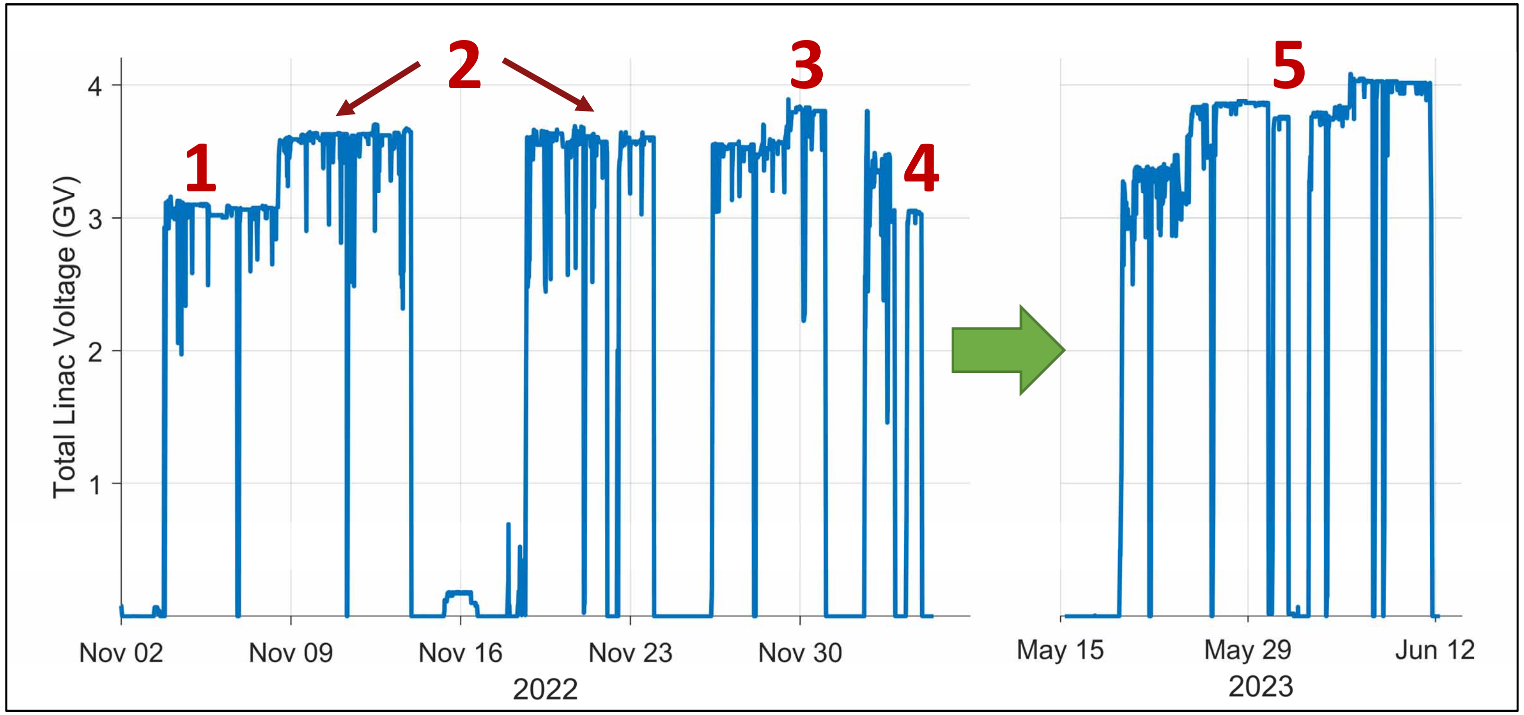
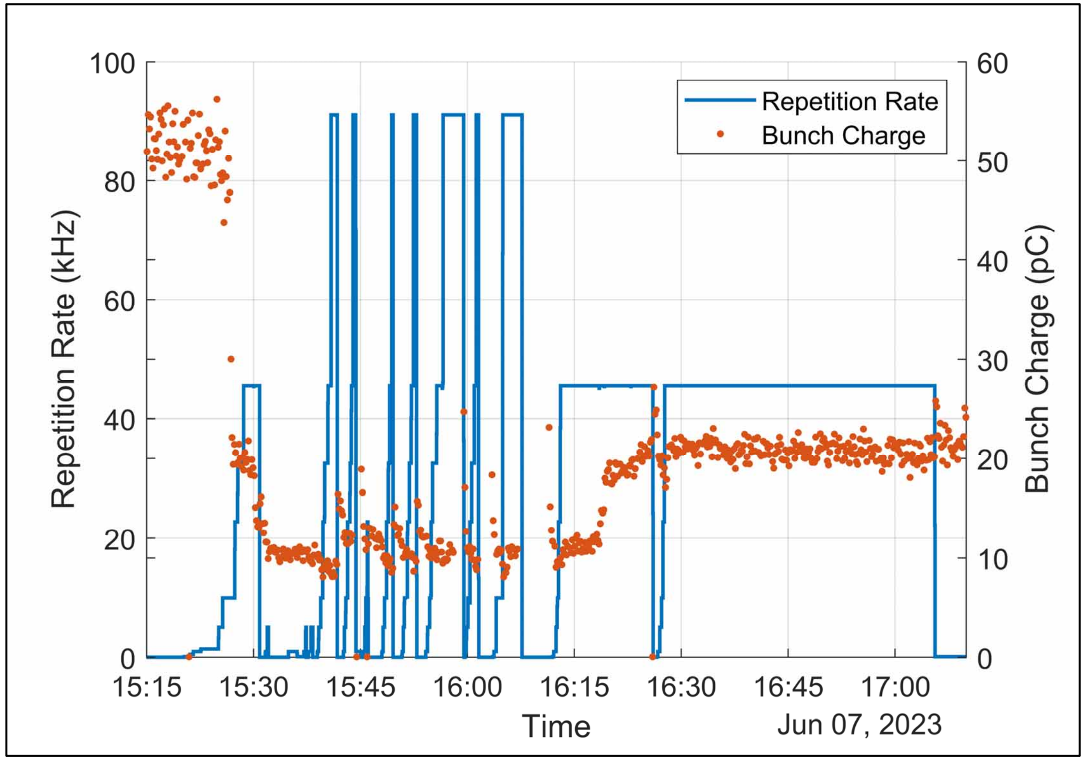
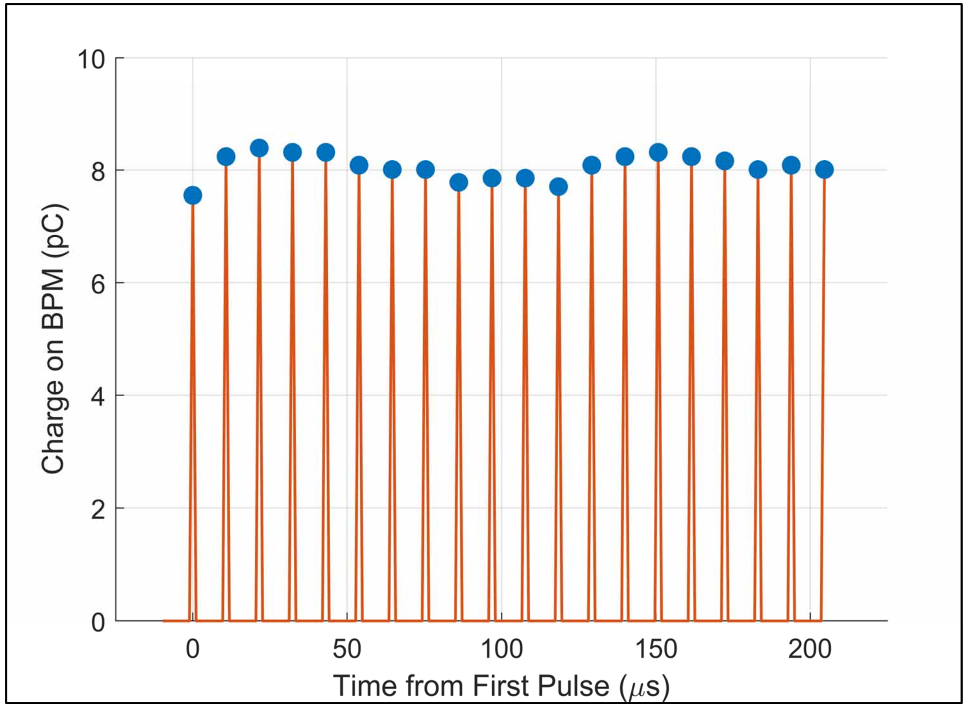


93 kHz Operation

- Repetition rate was ramped up to 93 kHz on 6/7 for the first time
- Subsequent measurements were carried out at half the rate but at same beam power for additional testing
- This was the last KPP for the linac



Pulse Spacing Measurement on Last BPM



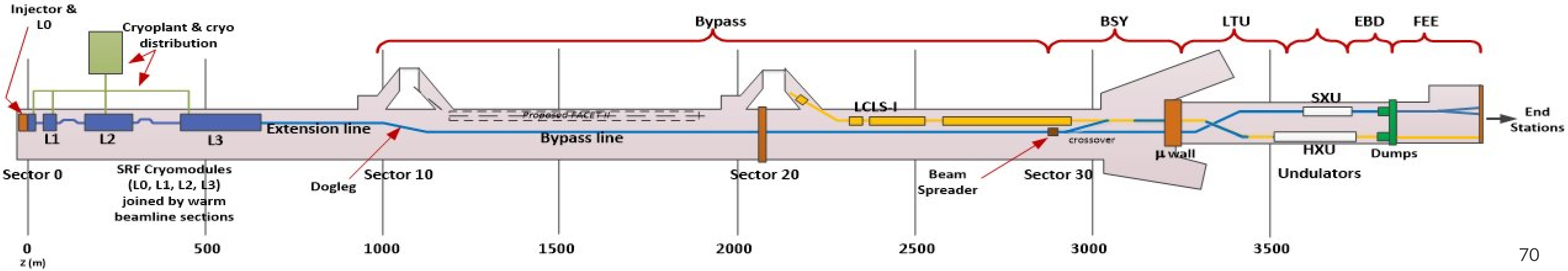
Spacing of ~10.7 µs between pulses demonstrates 93 kHZ

5

Summary & Outlook

SC Linac Commissioning Accomplishments & Remaining Tasks

Linac Commissioning



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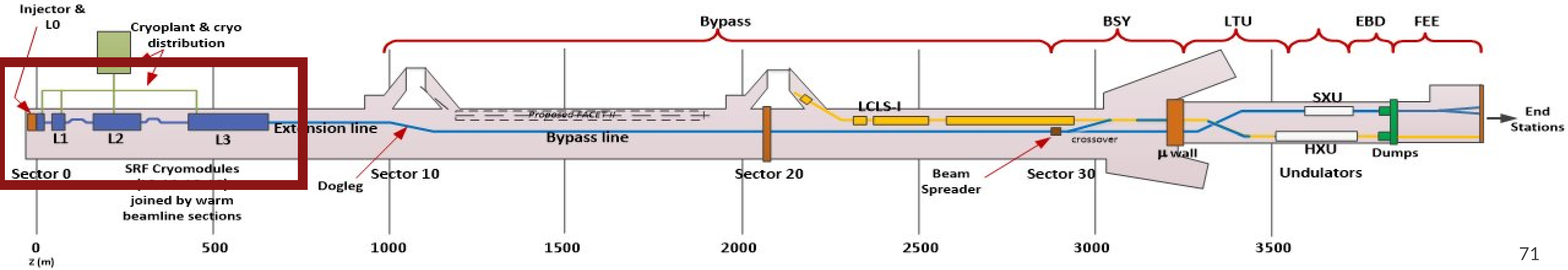

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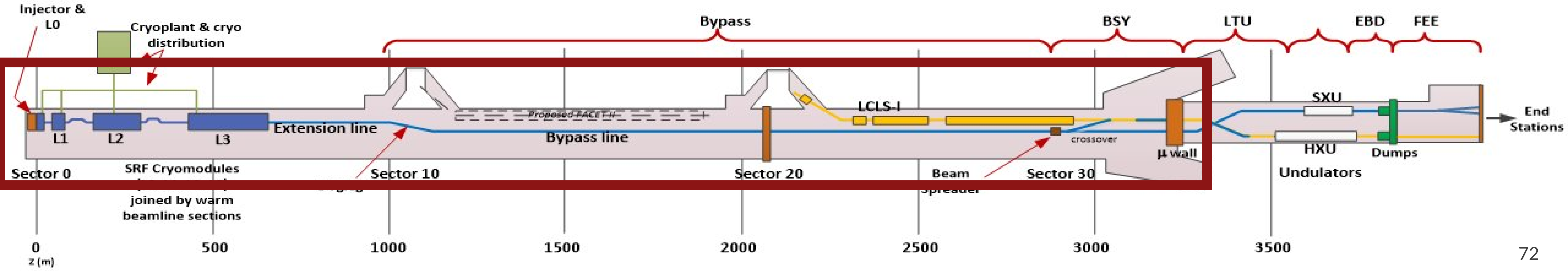

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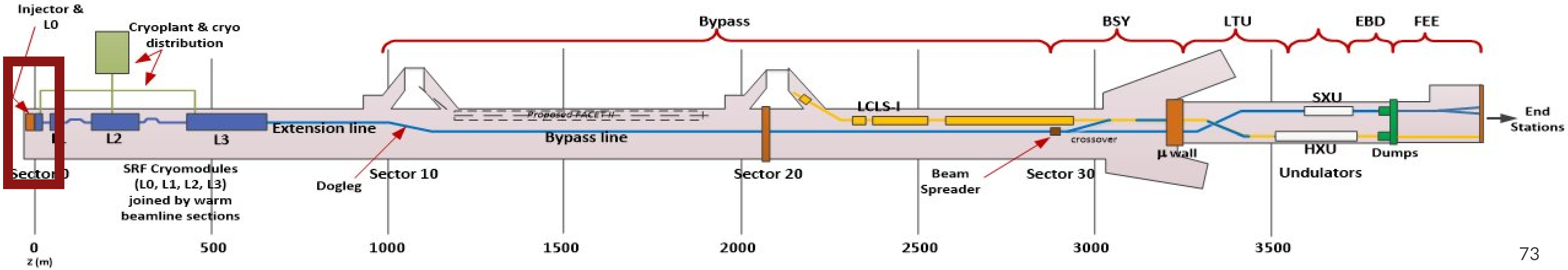

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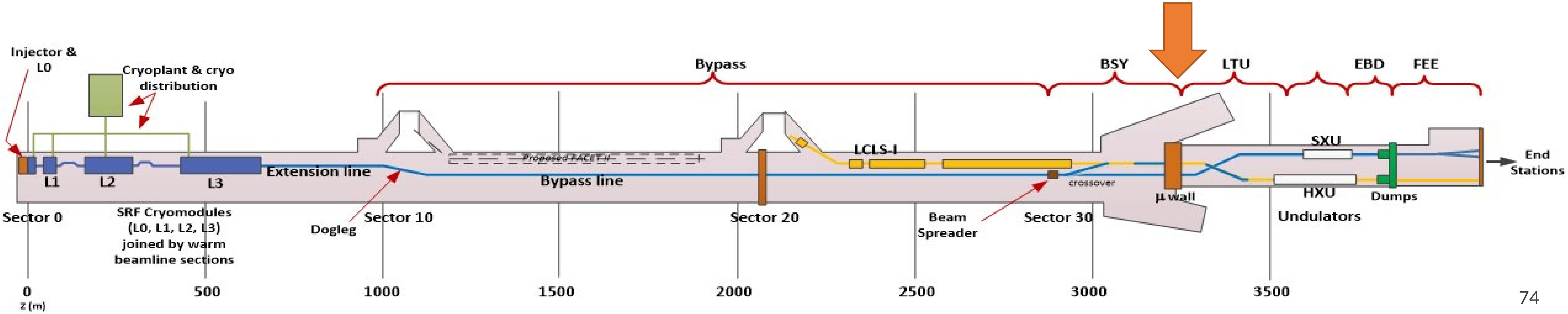

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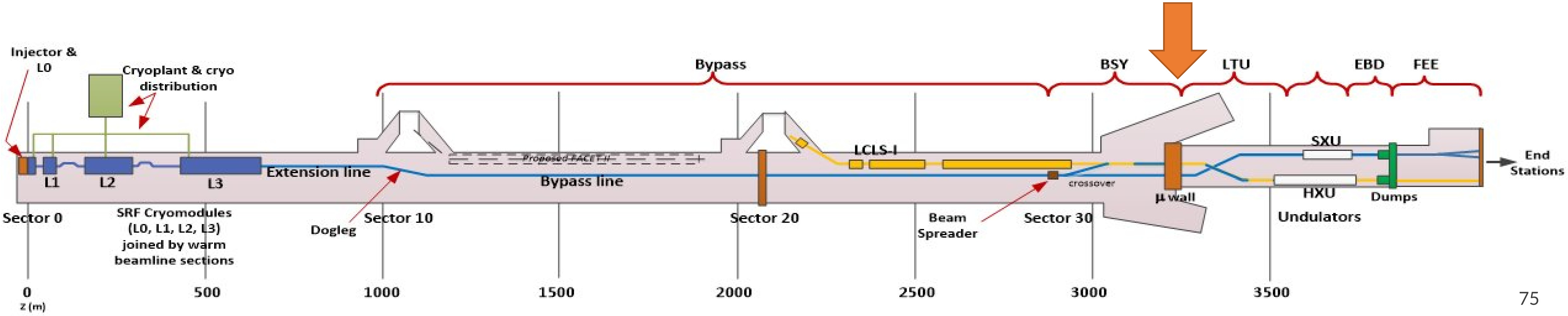

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Estimate to complete August 2023

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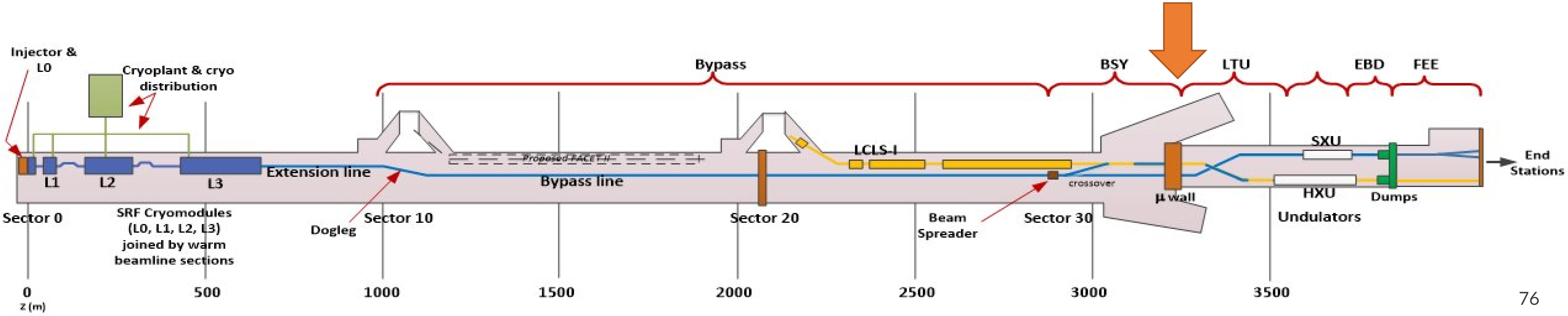

Summary

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- Average Q_0 exceeds the LCLS-II specification and demonstrates **high-Q_0 in an installed linac for the first time**
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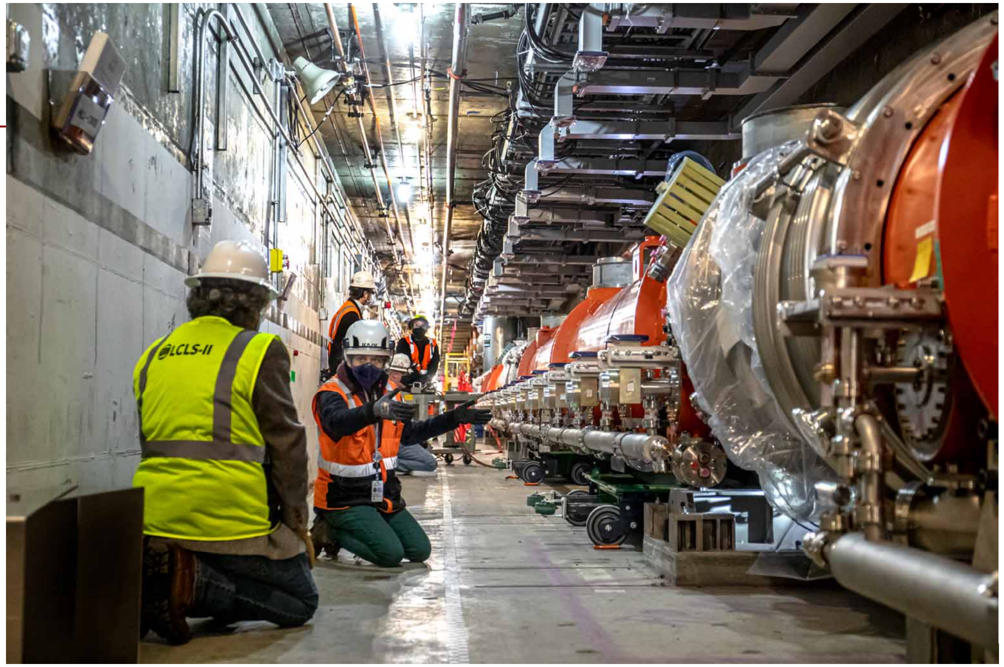
- This is only the beginning…

The Future of SRF at SLAC



2023

LCLS-II First Light

The Future of SRF at SLAC

2023-2025

LCLS-II Science

2023

LCLS-II First Light

The Future of SRF at SLAC

2023
LCLS-II First Light

2023-2025
LCLS-II Science

2025-2026
LCLS-II-HE Installation

2027
LCLS-II-HE First Light

2027+
LCLS-II-HE Science

The Future of SRF at SLAC

2023
LCLS-II First Light

2023-2025
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2025-2026
LCLS-II-HE Installation

2026-2028
SRF Facility Construction

2027
LCLS-II-HE First Light

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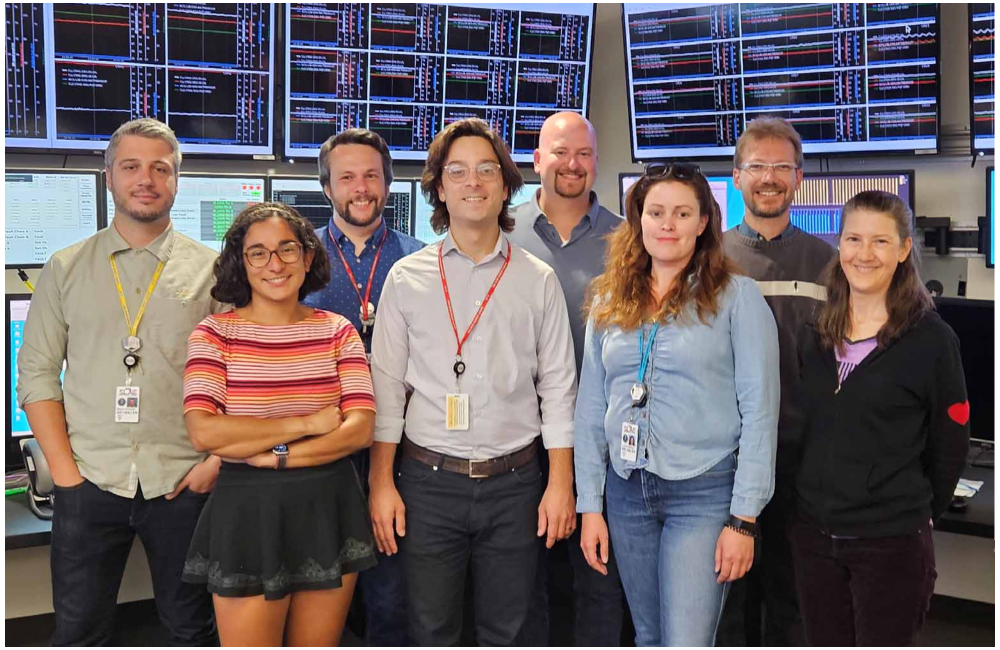
LCLS-II-HE Science

2028+
Fundamental SRF R&D



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