SRF 2023 GRAND RAPIDS

Status of Cavity and Cryomodule Production for LCLS-II-HE

Mattia Checchin on behalf of LCLS-II-HE project

Deputy Cryomodule Systems Manager

LCLS-II-HE project

26 June 2023

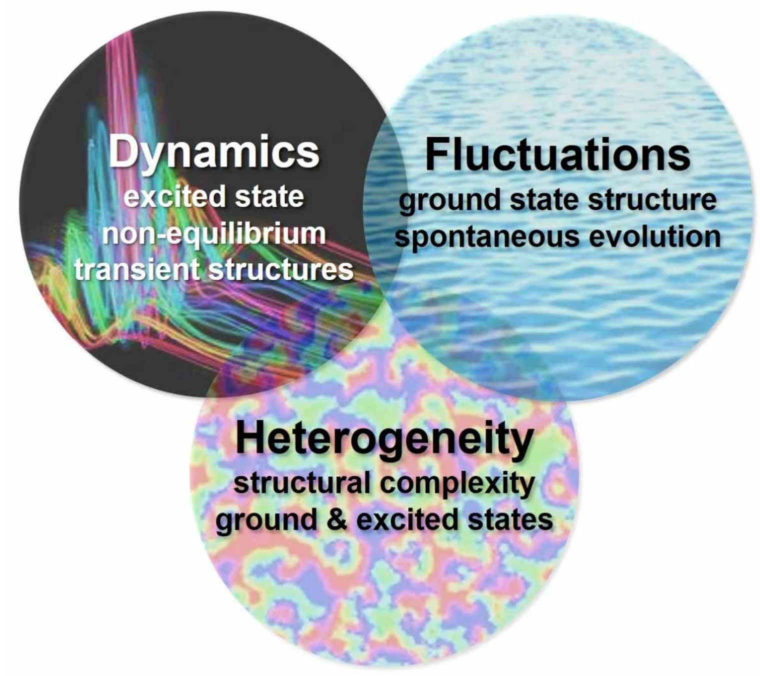
SLAC NATIONAL ACCELERATOR LABORATORY

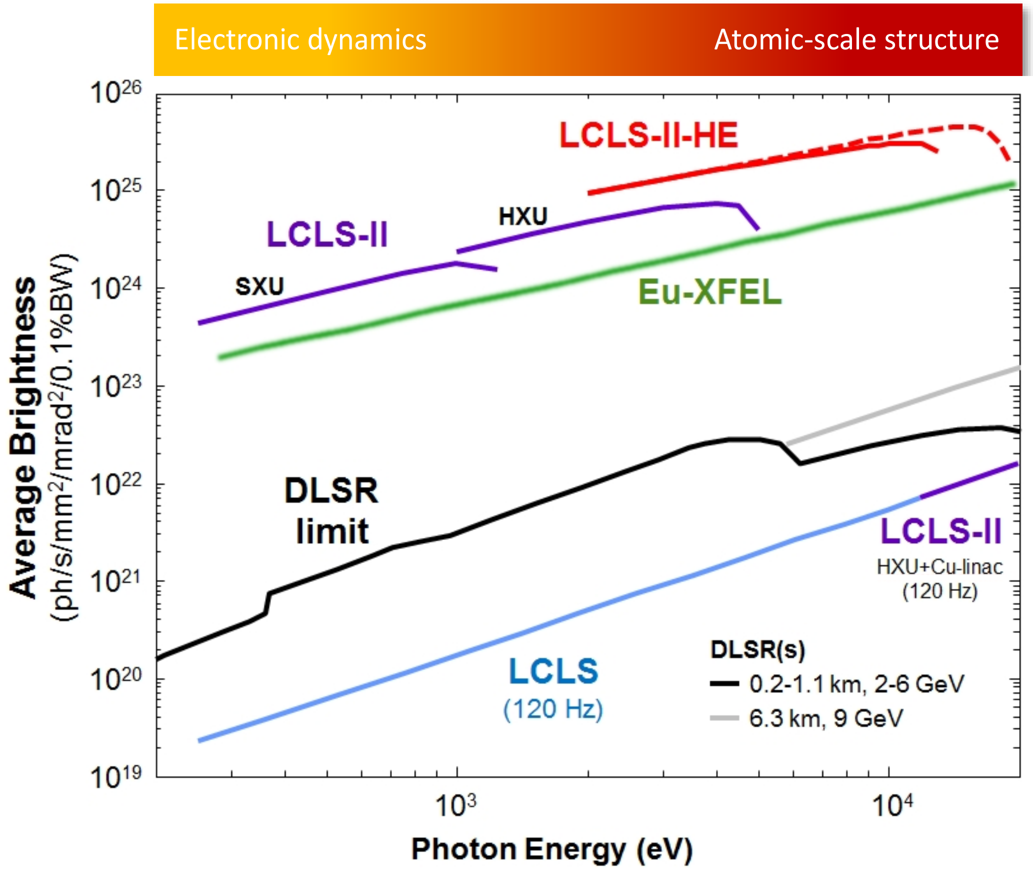
Stanford University | U.S. DEPARTMENT OF ENERGY

LCLS-II-HE mission

Deliver the ability to observe and understand the structural dynamics of complex matter at the atomic scale with hard x-rays, at ultrafast timescales, and in operational environments

- LCLS-II-HE provides high-rate, FEL radiation at Ångström wavelengths





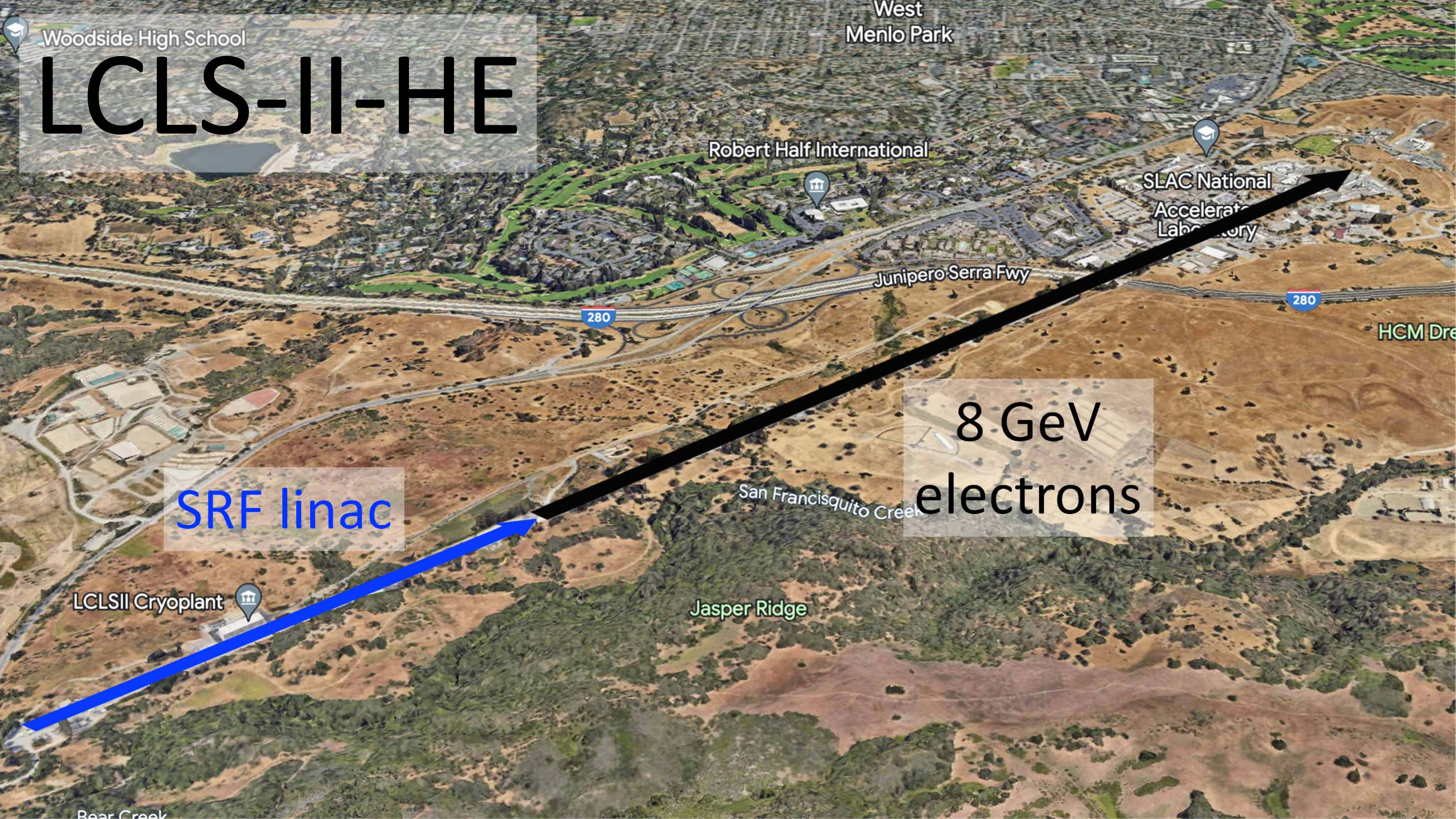
LCLS-II-HE


Woodside High School
West Menlo Park
Robert Half International
SLAC National Accelerator Laboratory
Junipero Serra Fwy
280
280
HCM Dre
San Francisquito Creek
Jasper Ridge
LCLSII Cryoplant
Bear Creek

LCLS-II-HE


West
Menlo Park
Woodside High School
Robert Half International
SLAC National
Accelerator
Laboratory
Junipero Serra Fwy
280
280
HCM Dre
SRF linac
San Francisquito Creek
LCLSII Cryoplant
Jasper Ridge
Bear Creek

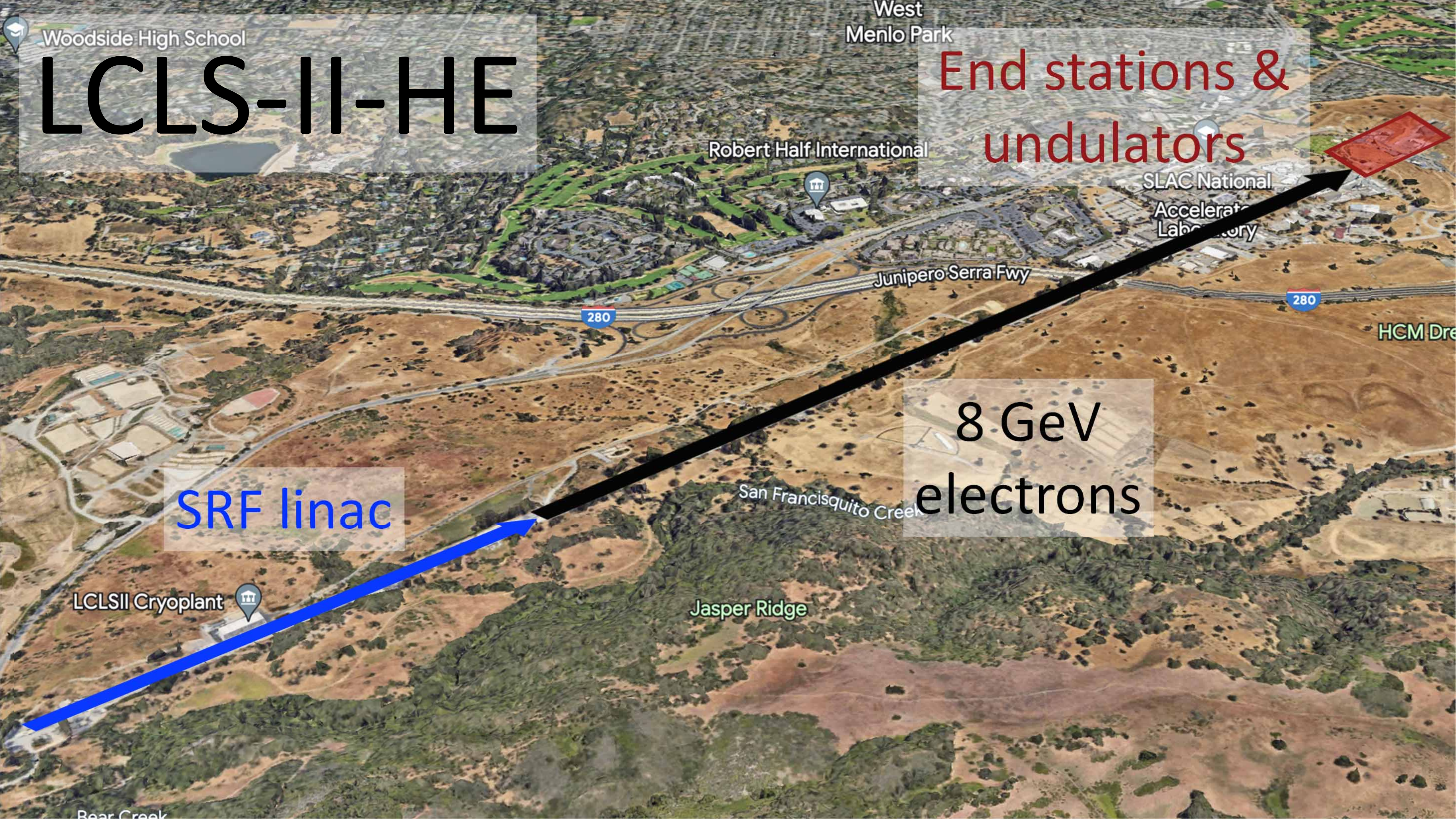
LCLS-II-HE



SRF linac

8 GeV electrons

LCLS-II-HE



End stations & undulators

8 GeV electrons

SRF linac


LCLSII Cryoplant
San Francisquito Creek

LCLS-II

SRF linac
(35 CMs)

LCLS-II


CP1 & CP2
LCLSII Cryoplant
SRF linac
(35 CMs)
San Francisquito Creek

LCLS-II-HE

Add 23 CMs
to the SRF linac

LCLS-II-HE

Add 23 CMs to the SRF linac

New helium transfer line

LCLS-II-HE

Add 23 CMs
to the SRF linac

New helium
transfer line

LEI tunnel

LCLS-II-HE

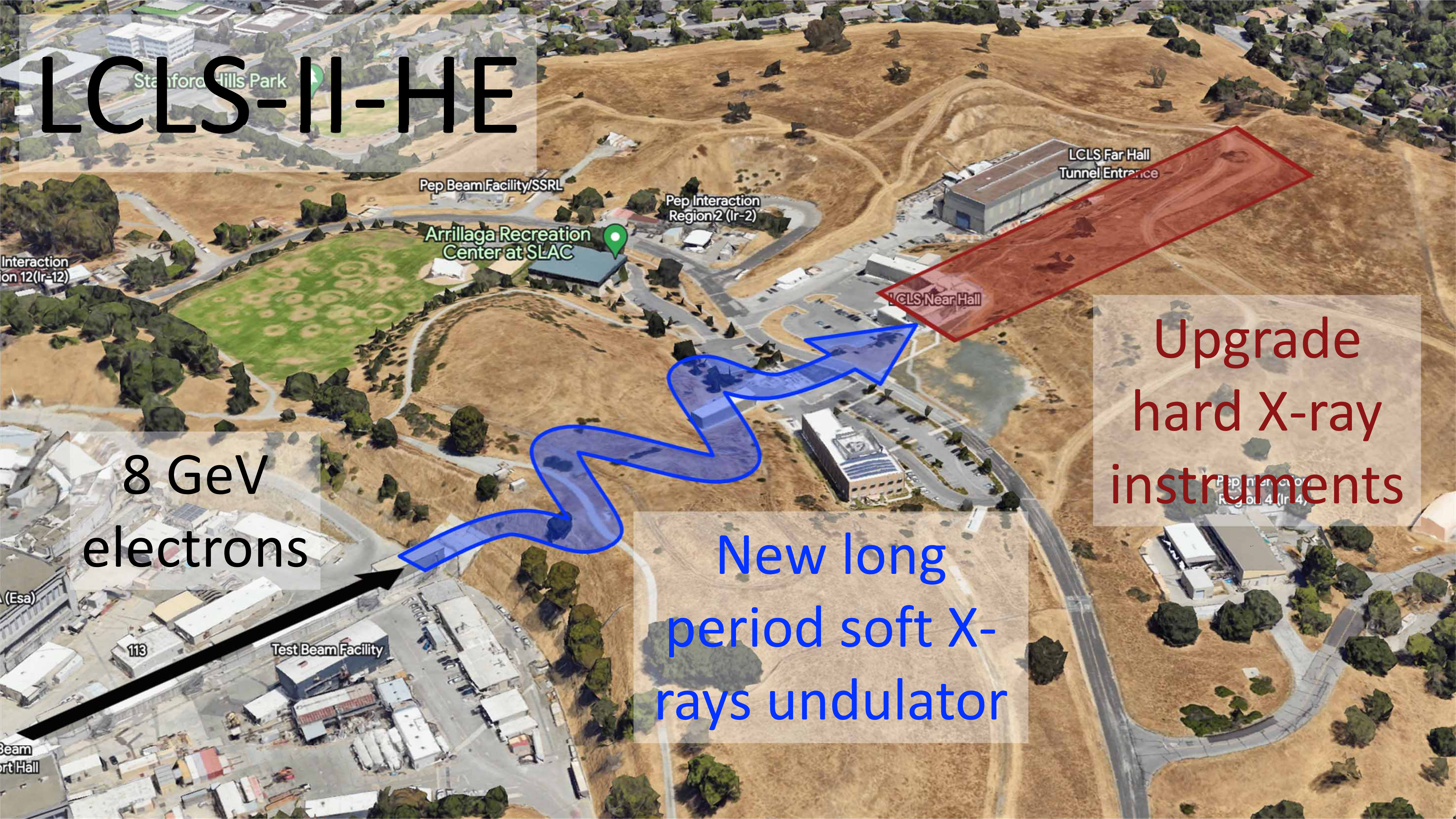
8 GeV electrons

LCLS-II-HE

8 GeV electrons

New long period soft X-rays undulator

LCLS-II-HE

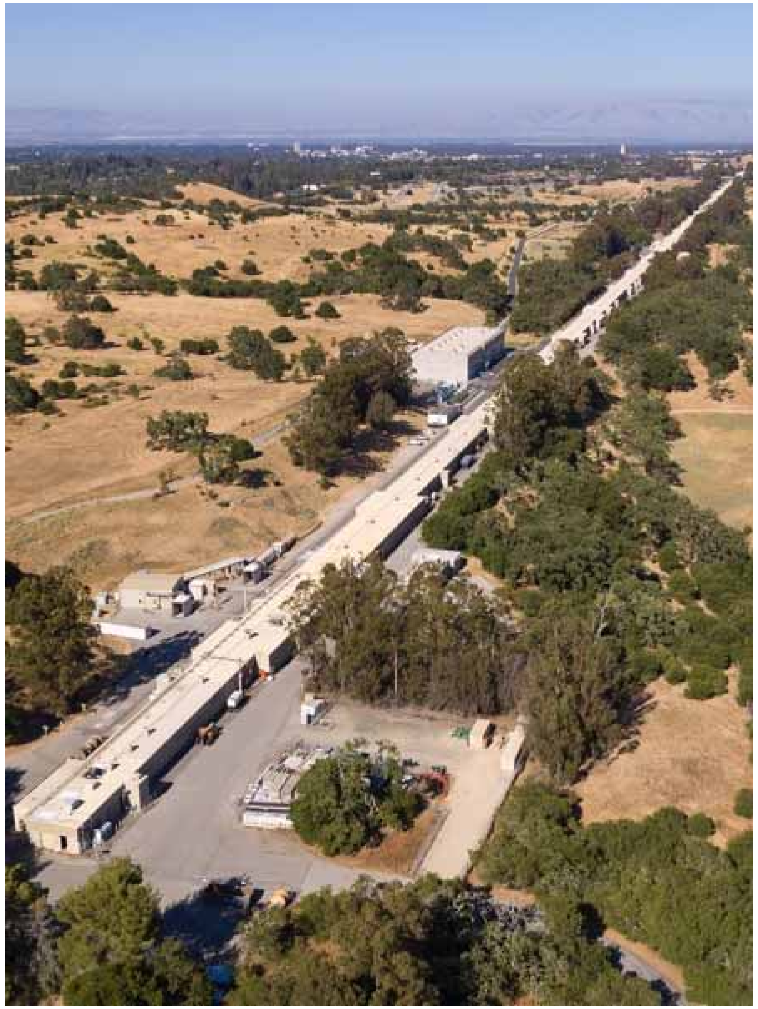


8 GeV electrons

New long period soft X-rays undulator

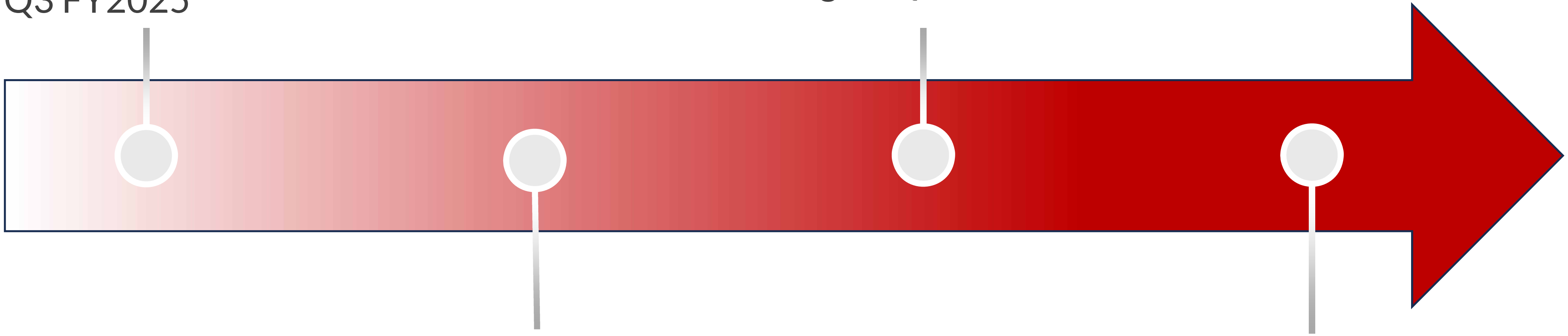
Upgrade hard X-ray instruments

LCLS-II-HE project collaboration



SLAC NATIONAL ACCELERATOR LABORATORY	• Accelerator and FEL Design & Installation • High Power RF, low-level RF, and Controls • X-ray instrument design & installation
Fermilab	• High Q0 & High Gradient R&D • Cryomodule design and cryomodule production • Buncher Cavity Cryomodule design
Jefferson Lab EXPLORING THE NATURE OF MATTER	• High Q0 & High Gradient R&D • Cryomodule production
BERKELEY LAB	• Accelerator Physics • Undulator design & procurement
FRIB	• SRF Gun Design & Prototype Demonstration
CORNELL UNIVERSITY	• High Q0 & High Gradient R&D
Argonne NATIONAL LABORATORY HZDR	• SRF Gun Design & Prototype Demonstration

LCLS-II-HE summary timeline



Completion of CM production

- Q3 FY2025

CM Installation

- Q4 FY2025 to Q4 FY2026
- LCLS-II long down time

Commissioning

- Q1 FY2027 to Q1 FY2028
- First light: Q2 FY2027

CD-4

- Early finish: Q2 FY2028
- Completion: Q2 FY2030

LCLS-II-HE cavity and cryomodule requirements

Objective: increase beam energy from 4.0 to 8.0 GeV

- 23 new cryomodules added to existing 35

Quantity	LCLS-II Cavities 4 GeV operation	LCLS-II Cavities 8 GeV operation	HE Cavities 8 GeV operation	Unit
Number of 1.3 GHz cavities	280	280	184	
Minimum average cavity Q_0 at nominal E_{acc}	2.7	2.7	2.7	10^{10}
Nominal average operating gradient	15.7 in L2-3	16.9 in L2-3	20.8	MV/m

High-Q/High-gradient R&D

R&D program following LCLS-II project to improve nitrogen doping recipe and surface processing (2018-2020)

- Research collaboration between SLAC, Fermilab, Jefferson Lab, Cornell University
- Increase cavity gradient without degrading Q_0
- Improve uniformity of performance with tighter QA

Incorporating lessons learned from LCLS-II

- Furnace contamination: recurring issue that led to significant amount of rework
- EP temperature: lower & more stable temperatures correlated with higher quench fields
- Flux expulsion: different material batches require different treatment
- In-person vendor oversight: necessary solve issues in a timely manner

LCLS-II-HE improved cavity processing

LCLS-II

Bulk EP → High T baking → Doping (2/6) → Final EP

High T baking + Doping (2/6): Same run

LCLS-II-HE

Bulk EP 1 → High T baking → Bulk EP 2 (last portion cold) → Doping (2/0) → Final EP (all cold)

Additional changes:

- Continuous RGA spectrum during furnace runs
- Continuous monitoring of temperatures during electropolishing runs
- Sort cavity half-cell material by required heat treatment temperature

1

Cavity production and qualification

Vertical test acceptance criteria

- **Gradient: $E_{acc} \geq 23$ MV/m**
- **Quality factor: $Q_0(21\ \mathrm{MV/m}) \geq 2.5\times10^{10}$**
  - VT stainless steel flange R = 0.8 nΩ
- HOM coupling: $Q_{ext} > 2.7\times10^{11}$
- HOM power: $P_{HOM}(21\ \mathrm{MV/m}) < 1.7$ W
- Field emission: no detectable FE up to quench
- Frequency: f = 1300.25 ± 0.10 MHz
- Field probe coupling: $2.5 \times 10^{11} < Q_{ext} < 7.0 \times 10^{11}$
- Multipacting: fully processed before final Q vs E curve
- 7π/9 mode: avoid mode buildup → quick measurements

Cavities vertical test results

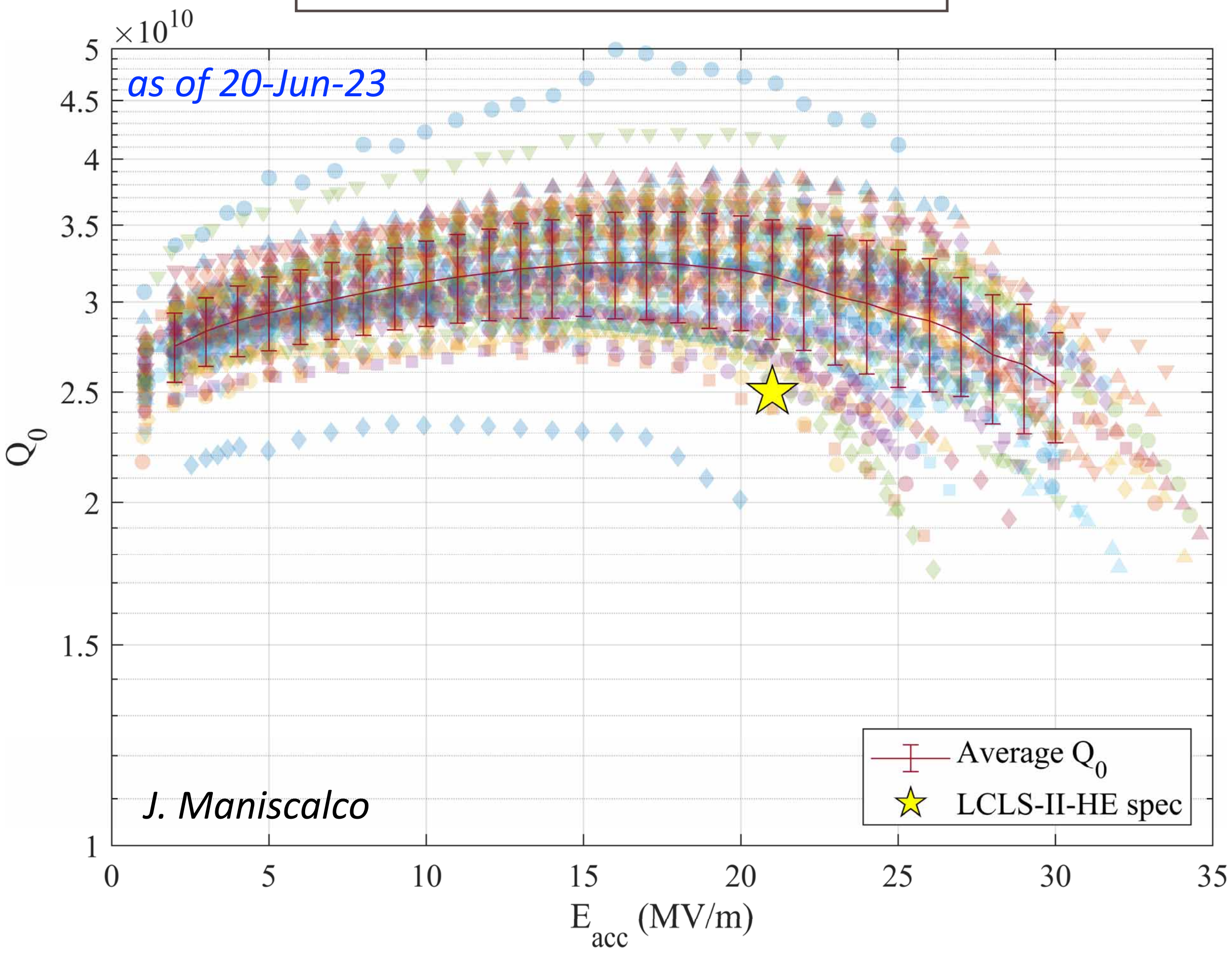
High-Q/High-gradient R&D outcome

- LCLS-II-HE incorporates the state-of-the art processing to achieve high-Q and high-gradient
- In average, cavities exceed both Q-factor and accelerating gradient

Industrialization of the process

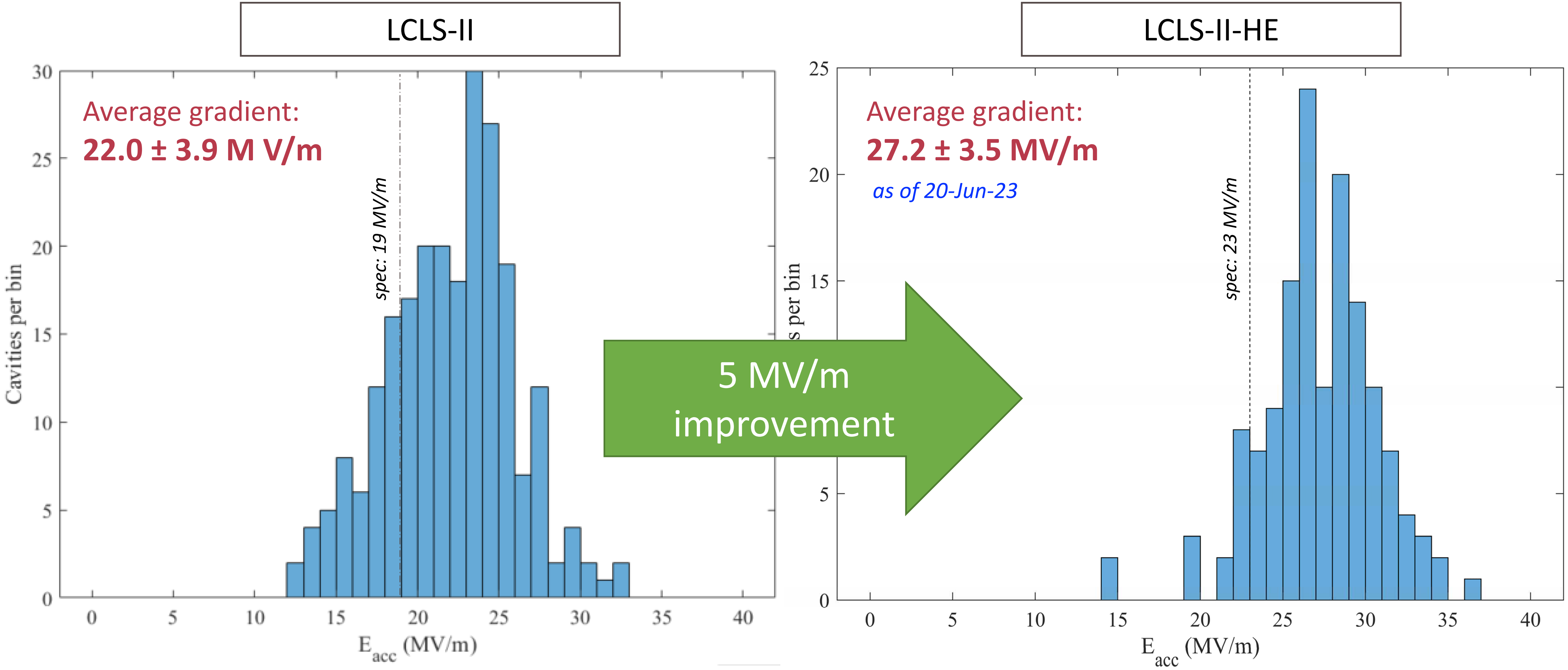
- Technology transfer to industry was successful
  - Constant communication with vendor and in-person oversight by project SMEs
- Major issues
  - He vessel bellows damage and non-conformities
  - Higher yield loss than anticipated for eddy current scanning qualification of raw Nb material

All cavities with no FE



See J. Maniscalco poster MOPMB072

HE cavities vs LCLS-II: accelerating gradient in VT



LCLS-II

Average gradient:
22.0 ± 3.9 M V/m

LCLS-II-HE

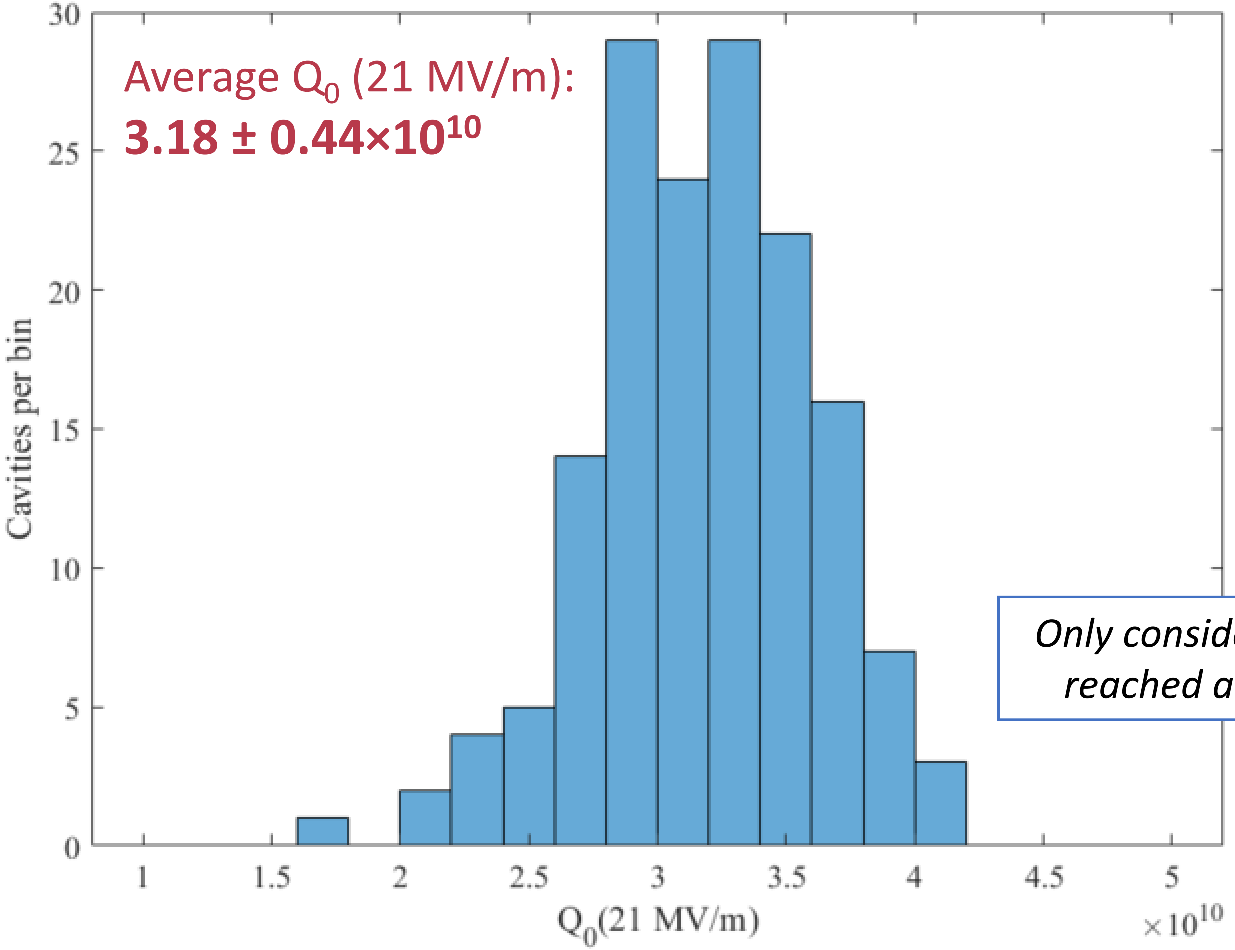
Average gradient:
27.2 ± 3.5 MV/m
as of 20-Jun-23

5 MV/m improvement

Slide adapted from J. Maniscalco

HE cavities vs LCLS-II: quality factor in VT

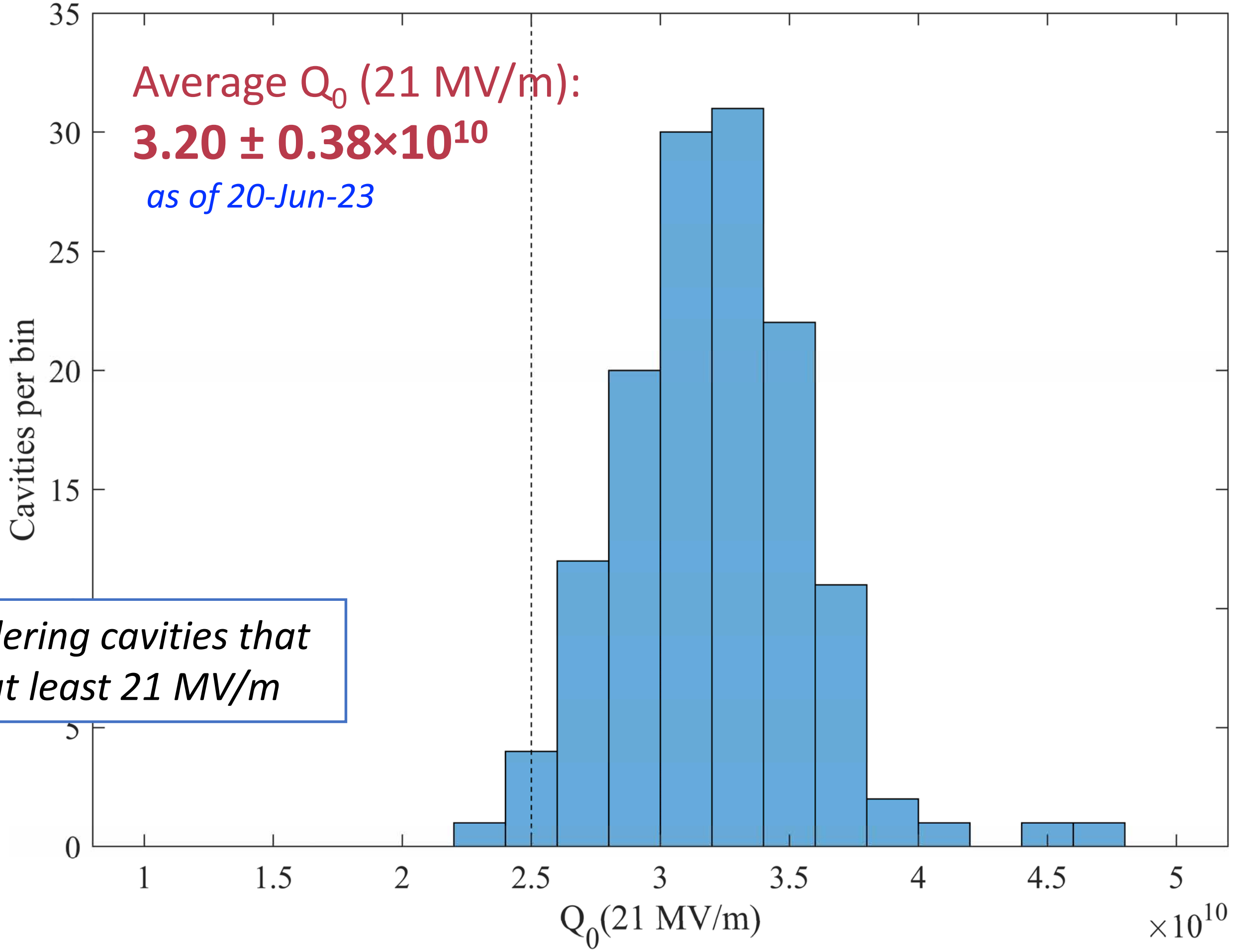
LCLS-II



Average Q_0 (21 MV/m):

$3.18 \pm 0.44\times10^{10}$

LCLS-II-HE



Average Q_0 (21 MV/m):

$3.20 \pm 0.38\times10^{10}$

as of 20-Jun-23

Only considering cavities that reached at least 21 MV/m

Slide adapted from J. Maniscalco

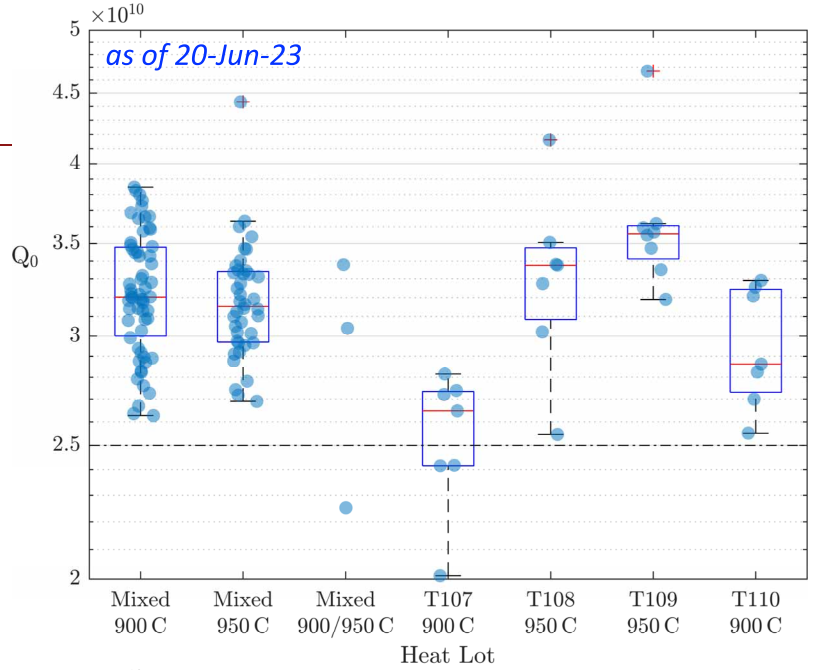
Quality factor by heat lot

High T baking temperature selection

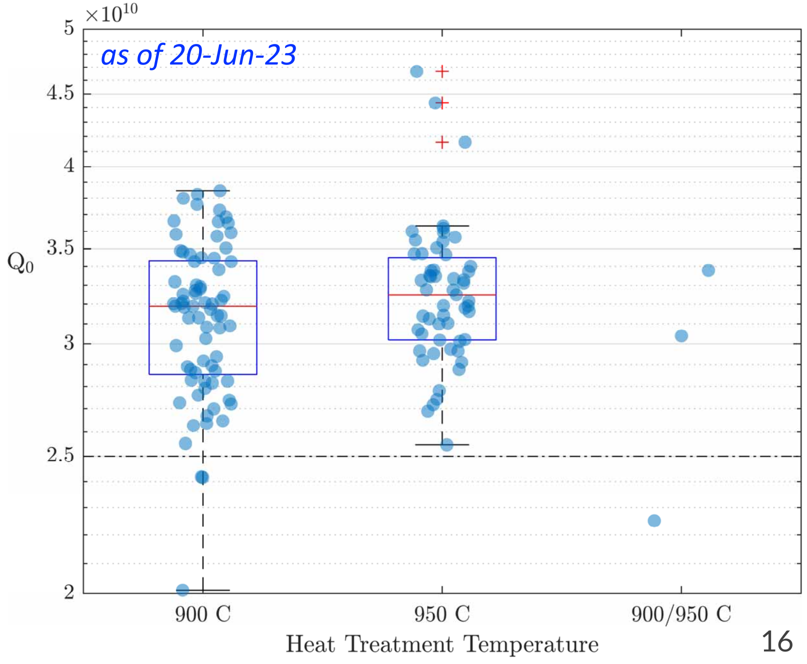
- Single cells cavities were manufactured for each material lot
- Flux expulsion studies on single cells identified the correct heat treatment temperature for each lot

Material segregation strategy has been successful

- Lots treated at higher temperature generally show higher Q_0 (better flux expulsion)
- Mixed 900 °C lot cavities have higher Q_0 than single lot cavities at same temperature
- High Q_0 also for mixed 900/950 °C cavities with pre-treated subassemblies



as of 20-Jun-23



as of 20-Jun-23

See J. Maniscalco poster WEPWB120

Yield and qualification statistics

As received statistics:

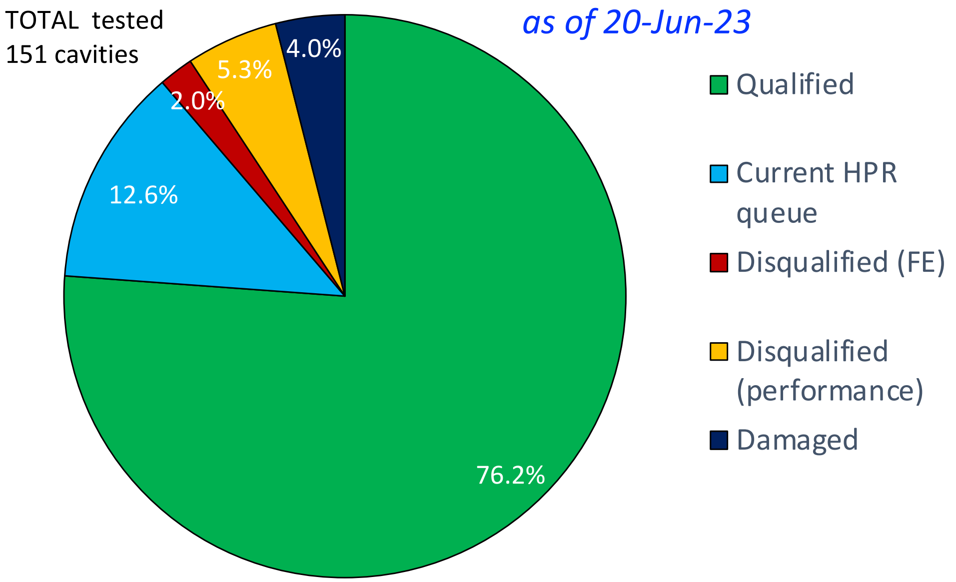
- Cavities delivered: **156**
- Cavities tested: **151**
  - Qualified: **76.2%**
  - HPR queue: **12.6%**
  - Disqualified: **7.3%**
  - Damaged: **4.0%**

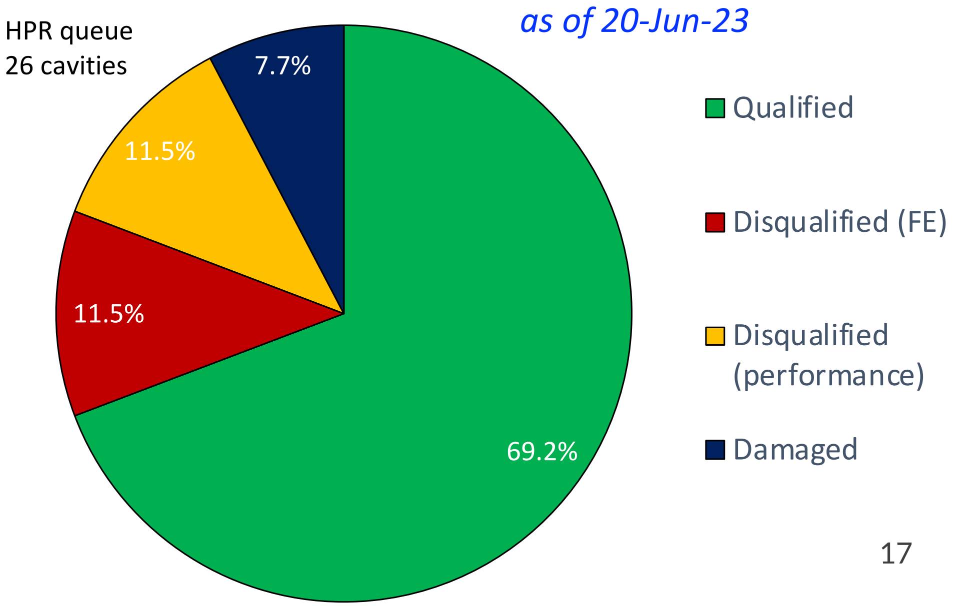
Field emission statistics:

- Cavities with FE from vendor: **26%**
- Qualification rate of cavities after HPR at PLs: **69.2%**

Forecast:

- Total yield loss by the end of the project: **13.6%**





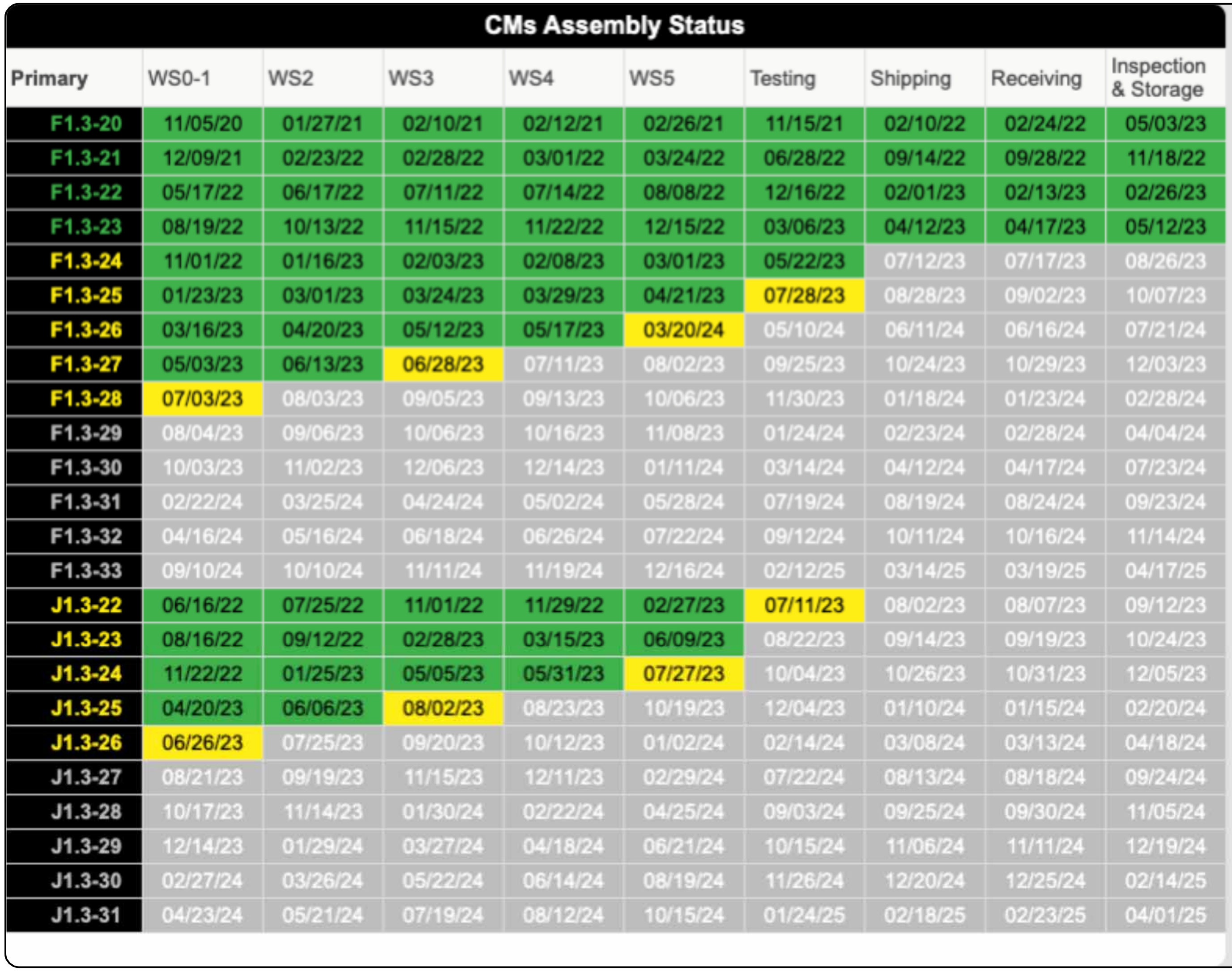
2

Cryomodule assembly and test

Cryomodule production status & schedule

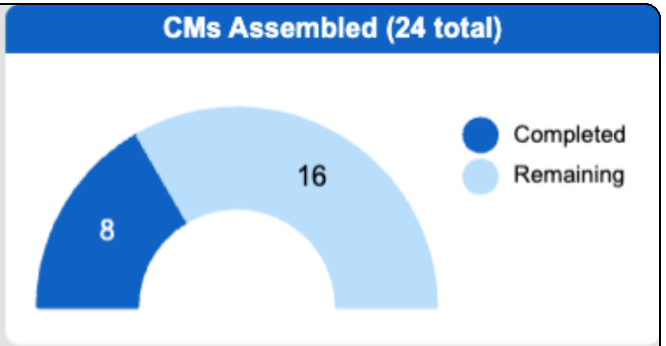
Fermilab

Jefferson Lab

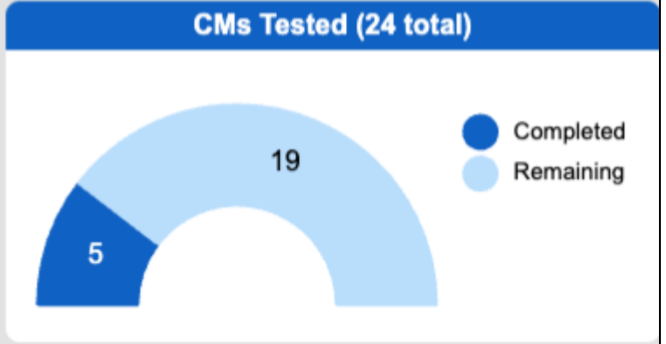


CMs Assembly Status

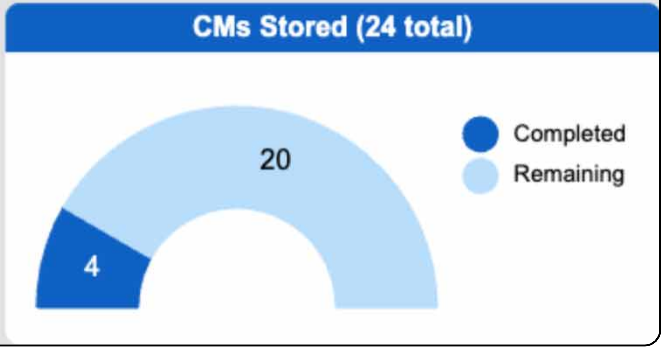
Primary	WS0-1	WS2	WS3	WS4	WS5	Testing	Shipping	Receiving	Inspection & Storage
F1.3-20	11/05/20	01/27/21	02/10/21	02/12/21	02/26/21	11/15/21	02/10/22	02/24/22	05/03/23
F1.3-21	12/09/21	02/23/22	02/28/22	03/01/22	03/24/22	06/28/22	09/14/22	09/28/22	11/18/22
F1.3-22	05/17/22	06/17/22	07/11/22	07/14/22	08/08/22	12/16/22	02/01/23	02/13/23	02/26/23
F1.3-23	08/19/22	10/13/22	11/15/22	11/22/22	12/15/22	03/06/23	04/12/23	04/17/23	05/12/23
F1.3-24	11/01/22	01/16/23	02/03/23	02/08/23	03/01/23	05/22/23	07/12/23	07/17/23	08/26/23
F1.3-25	01/23/23	03/01/23	03/24/23	03/29/23	04/21/23	07/28/23	08/28/23	09/02/23	10/07/23
F1.3-26	03/16/23	04/20/23	05/12/23	05/17/23	03/20/24	05/10/24	06/11/24	06/16/24	07/21/24
F1.3-27	05/03/23	06/13/23	06/28/23	07/11/23	08/02/23	09/25/23	10/24/23	10/29/23	12/03/23
F1.3-28	07/03/23	08/03/23	09/05/23	09/13/23	10/06/23	11/30/23	01/18/24	01/23/24	02/28/24
F1.3-29	08/04/23	09/06/23	10/06/23	10/16/23	11/08/23	01/24/24	02/23/24	02/28/24	04/04/24
F1.3-30	10/03/23	11/02/23	12/06/23	12/14/23	01/11/24	03/14/24	04/12/24	04/17/24	07/23/24
F1.3-31	02/22/24	03/25/24	04/24/24	05/02/24	05/28/24	07/19/24	08/19/24	08/24/24	09/23/24
F1.3-32	04/16/24	05/16/24	06/18/24	06/26/24	07/22/24	09/12/24	10/11/24	10/16/24	11/14/24
F1.3-33	09/10/24	10/10/24	11/11/24	11/19/24	12/16/24	02/12/25	03/14/25	03/19/25	04/17/25
J1.3-22	06/16/22	07/25/22	11/01/22	11/29/22	02/27/23	07/11/23	08/02/23	08/07/23	09/12/23
J1.3-23	08/16/22	09/12/22	02/28/23	03/15/23	06/09/23	08/22/23	09/14/23	09/19/23	10/24/23
J1.3-24	11/22/22	01/25/23	05/05/23	05/31/23	07/27/23	10/04/23	10/26/23	10/31/23	12/05/23
J1.3-25	04/20/23	06/06/23	08/02/23	08/23/23	10/19/23	12/04/23	01/10/24	01/15/24	02/20/24
J1.3-26	06/26/23	07/25/23	09/20/23	10/12/23	01/02/24	02/14/24	03/08/24	03/13/24	04/18/24
J1.3-27	08/21/23	09/19/23	11/15/23	12/11/23	02/29/24	07/22/24	08/13/24	08/18/24	09/24/24
J1.3-28	10/17/23	11/14/23	01/30/24	02/22/24	04/25/24	09/03/24	09/25/24	09/30/24	11/05/24
J1.3-29	12/14/23	01/29/24	03/27/24	04/18/24	06/21/24	10/15/24	11/06/24	11/11/24	12/19/24
J1.3-30	02/27/24	03/26/24	05/22/24	06/14/24	08/19/24	11/26/24	12/20/24	12/25/24	02/14/25
J1.3-31	04/23/24	05/21/24	07/19/24	08/12/24	10/15/24	01/24/25	02/18/25	02/23/25	04/01/25



CMs Assembled (24 total)

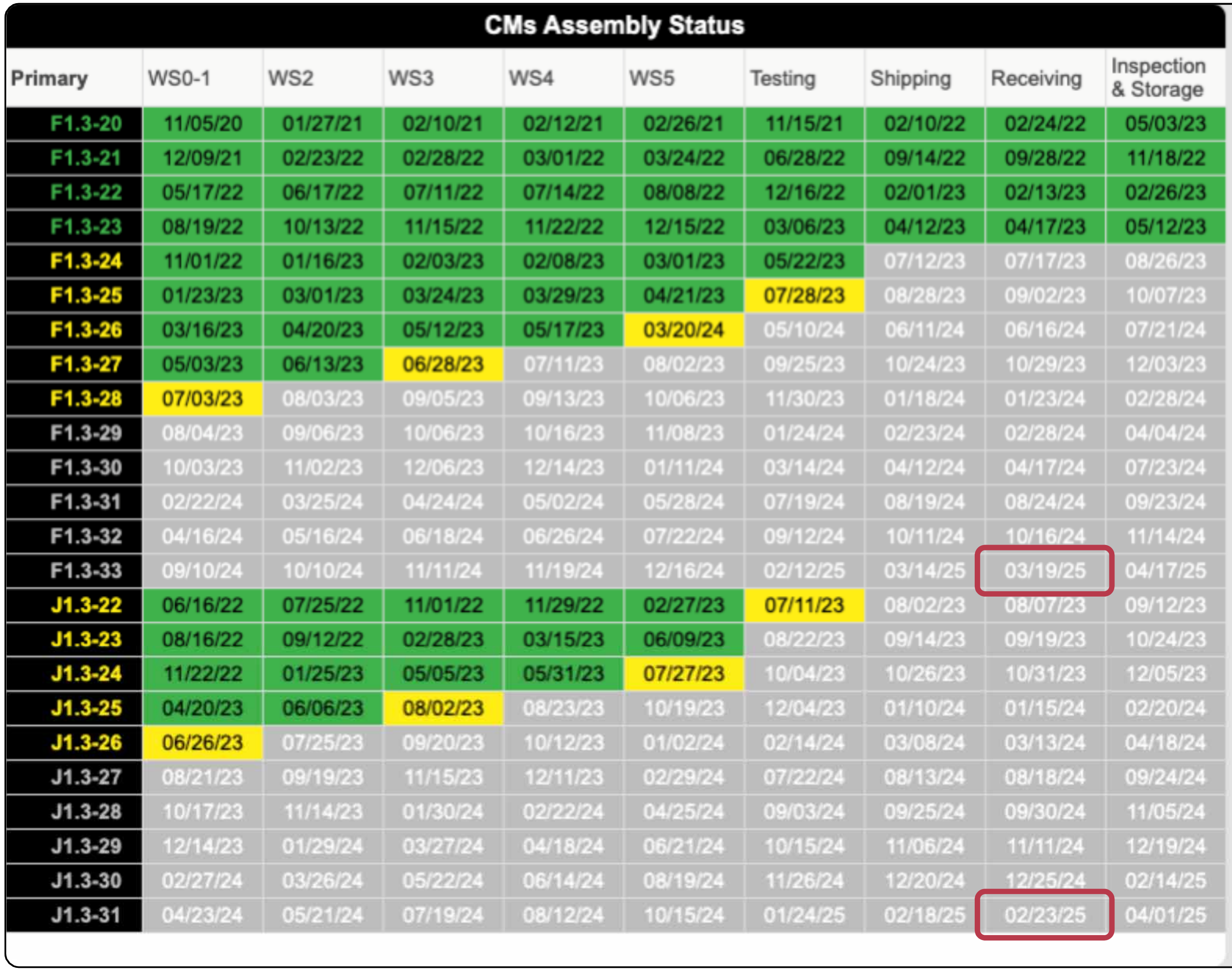


CMs Tested (24 total)



CMs Stored (24 total)

Cryomodule production status & schedule

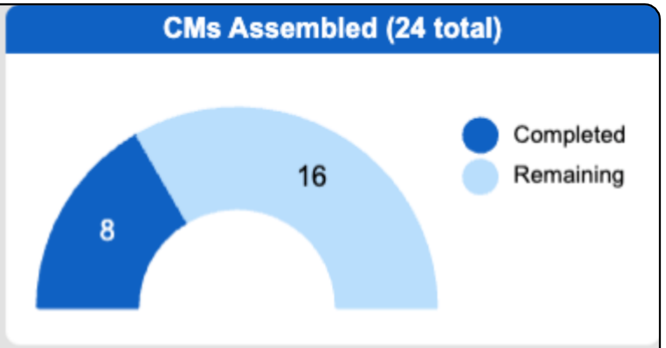


Fermilab: F1.3-20 to F1.3-33

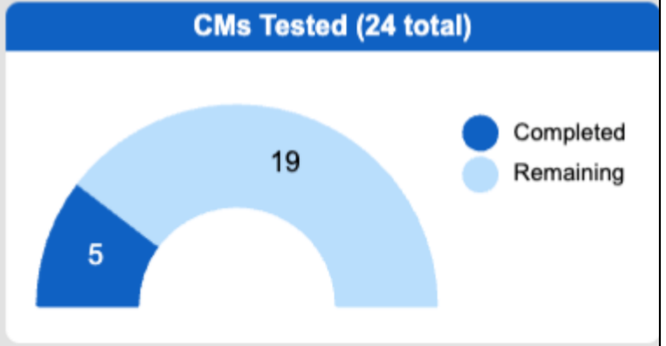
Jefferson Lab: J1.3-22 to J1.3-31

CMs Assembly Status

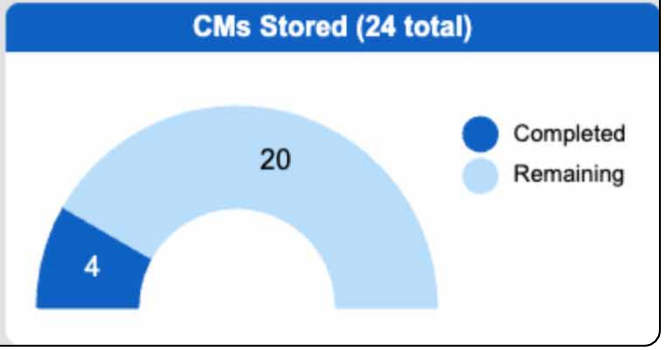
Primary	WS0-1	WS2	WS3	WS4	WS5	Testing	Shipping	Receiving	Inspection & Storage
F1.3-20	11/05/20	01/27/21	02/10/21	02/12/21	02/26/21	11/15/21	02/10/22	02/24/22	05/03/23
F1.3-21	12/09/21	02/23/22	02/28/22	03/01/22	03/24/22	06/28/22	09/14/22	09/28/22	11/18/22
F1.3-22	05/17/22	06/17/22	07/11/22	07/14/22	08/08/22	12/16/22	02/01/23	02/13/23	02/26/23
F1.3-23	08/19/22	10/13/22	11/15/22	11/22/22	12/15/22	03/06/23	04/12/23	04/17/23	05/12/23
F1.3-24	11/01/22	01/16/23	02/03/23	02/08/23	03/01/23	05/22/23	07/12/23	07/17/23	08/26/23
F1.3-25	01/23/23	03/01/23	03/24/23	03/29/23	04/21/23	07/28/23	08/28/23	09/02/23	10/07/23
F1.3-26	03/16/23	04/20/23	05/12/23	05/17/23	03/20/24	05/10/24	06/11/24	06/16/24	07/21/24
F1.3-27	05/03/23	06/13/23	06/28/23	07/11/23	08/02/23	09/25/23	10/24/23	10/29/23	12/03/23
F1.3-28	07/03/23	08/03/23	09/05/23	09/13/23	10/06/23	11/30/23	01/18/24	01/23/24	02/28/24
F1.3-29	08/04/23	09/06/23	10/06/23	10/16/23	11/08/23	01/24/24	02/23/24	02/28/24	04/04/24
F1.3-30	10/03/23	11/02/23	12/06/23	12/14/23	01/11/24	03/14/24	04/12/24	04/17/24	07/23/24
F1.3-31	02/22/24	03/25/24	04/24/24	05/02/24	05/28/24	07/19/24	08/19/24	08/24/24	09/23/24
F1.3-32	04/16/24	05/16/24	06/18/24	06/26/24	07/22/24	09/12/24	10/11/24	10/16/24	11/14/24
F1.3-33	09/10/24	10/10/24	11/11/24	11/19/24	12/16/24	02/12/25	03/14/25	03/19/25	04/17/25
J1.3-22	06/16/22	07/25/22	11/01/22	11/29/22	02/27/23	07/11/23	08/02/23	08/07/23	09/12/23
J1.3-23	08/16/22	09/12/22	02/28/23	03/15/23	06/09/23	08/22/23	09/14/23	09/19/23	10/24/23
J1.3-24	11/22/22	01/25/23	05/05/23	05/31/23	07/27/23	10/04/23	10/26/23	10/31/23	12/05/23
J1.3-25	04/20/23	06/06/23	08/02/23	08/23/23	10/19/23	12/04/23	01/10/24	01/15/24	02/20/24
J1.3-26	06/26/23	07/25/23	09/20/23	10/12/23	01/02/24	02/14/24	03/08/24	03/13/24	04/18/24
J1.3-27	08/21/23	09/19/23	11/15/23	12/11/23	02/29/24	07/22/24	08/13/24	08/18/24	09/24/24
J1.3-28	10/17/23	11/14/23	01/30/24	02/22/24	04/25/24	09/03/24	09/25/24	09/30/24	11/05/24
J1.3-29	12/14/23	01/29/24	03/27/24	04/18/24	06/21/24	10/15/24	11/06/24	11/11/24	12/19/24
J1.3-30	02/27/24	03/26/24	05/22/24	06/14/24	08/19/24	11/26/24	12/20/24	12/25/24	02/14/25
J1.3-31	04/23/24	05/21/24	07/19/24	08/12/24	10/15/24	01/24/25	02/18/25	02/23/25	04/01/25



CMs Assembled (24 total)



CMs Tested (24 total)



CMs Stored (24 total)

CM assembly and storage

24 cryomodules are being assembled at the partners labs

- Leveraging same assembly lines, test facilities, and personnel from LCLS-II assembly
- 13 CMs + vCM assembled at Fermilab
- 10 CMs assembled at Jefferson Lab

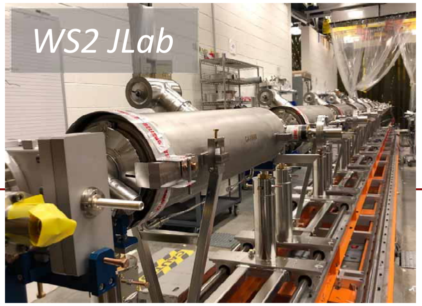
Standardized assembly procedures and tooling at the two labs

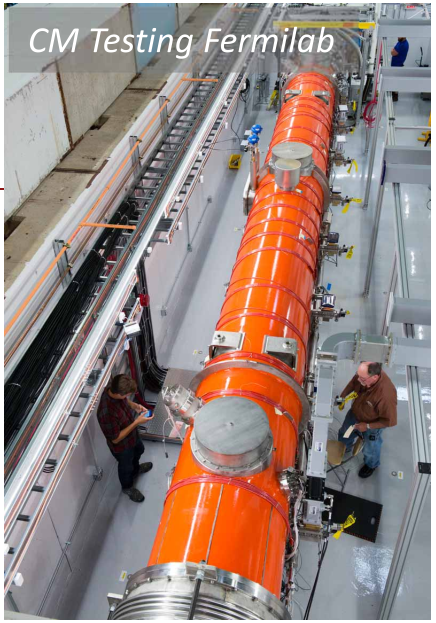
- String kept under vacuum throughout production
- Same nitrogen venting/purging system and procedure for cavity string assembly

Storage on-site at SLAC

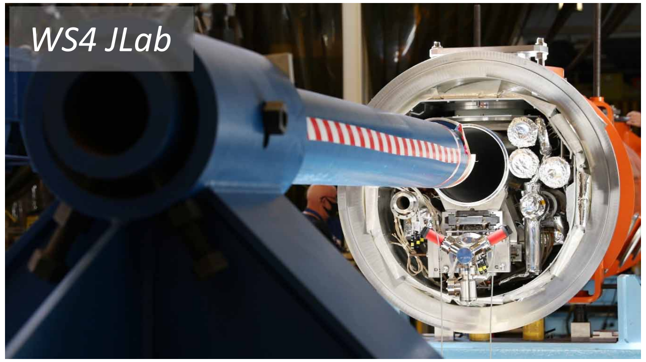
- 4 dedicated buildings


WS1 Fermilab

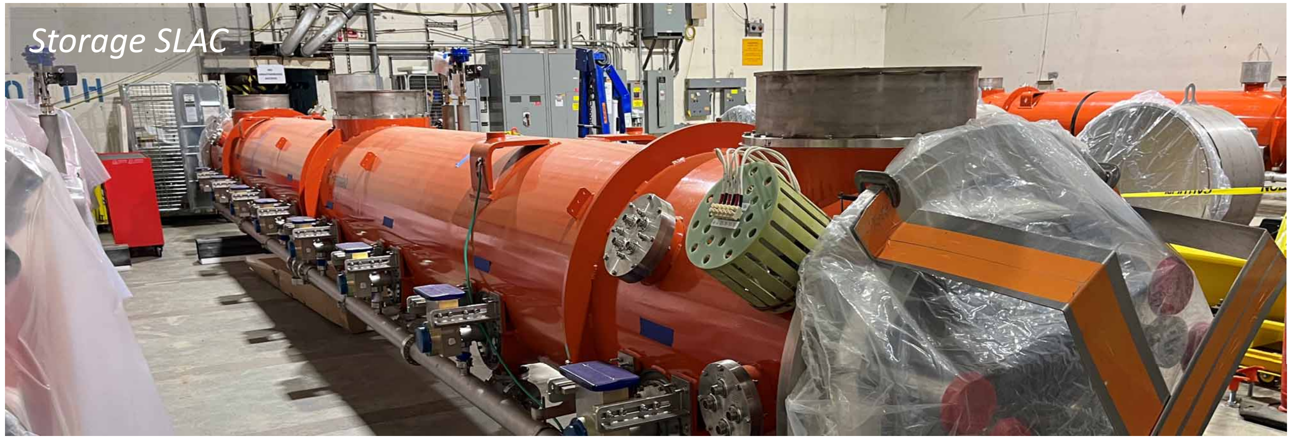

WS2 JLab


CM Testing Fermilab


WS3 Fermilab


WS4 JLab


WS5 JLab


Storage SLAC

See J. Kaluzny MOPMB064 and D. White MOPMB074 posters

Cryomodule test acceptance criteria

Usable gradient per cavity: $\geq$ 20.8 MV/m

- The maximum gradient at which the following 3 conditions are met:
  - Radiation level below 50 mRad/hr,
  - Cavity runs stably for one hour (no MP quenches, no trips)
  - 0.5 MV/m below the quench field

Usable CW voltage: $\geq$ 173 MV

- The total CW voltage of 8 cavities running at their usable gradient in GDR/SELAP mode
  - Captured dark current: $\leq$ 30 nA
  - Magnets at nominal operation current
  - CM runs stably for one hour (no MP quenches, no trips)

Stability test: Each CM shall operate in GDR/SELAP mode at usable voltage with magnet on for at least 10 h or until the coupler is in thermal equilibrium with 90% operating time, whichever is less

Dynamic heat load at 2 K: $\leq$ 137 W at usable voltage (equivalent to average $Q_0 \geq 2.7\times10^{10}$)

Static heat load at 2 K: $\leq$ 7 W

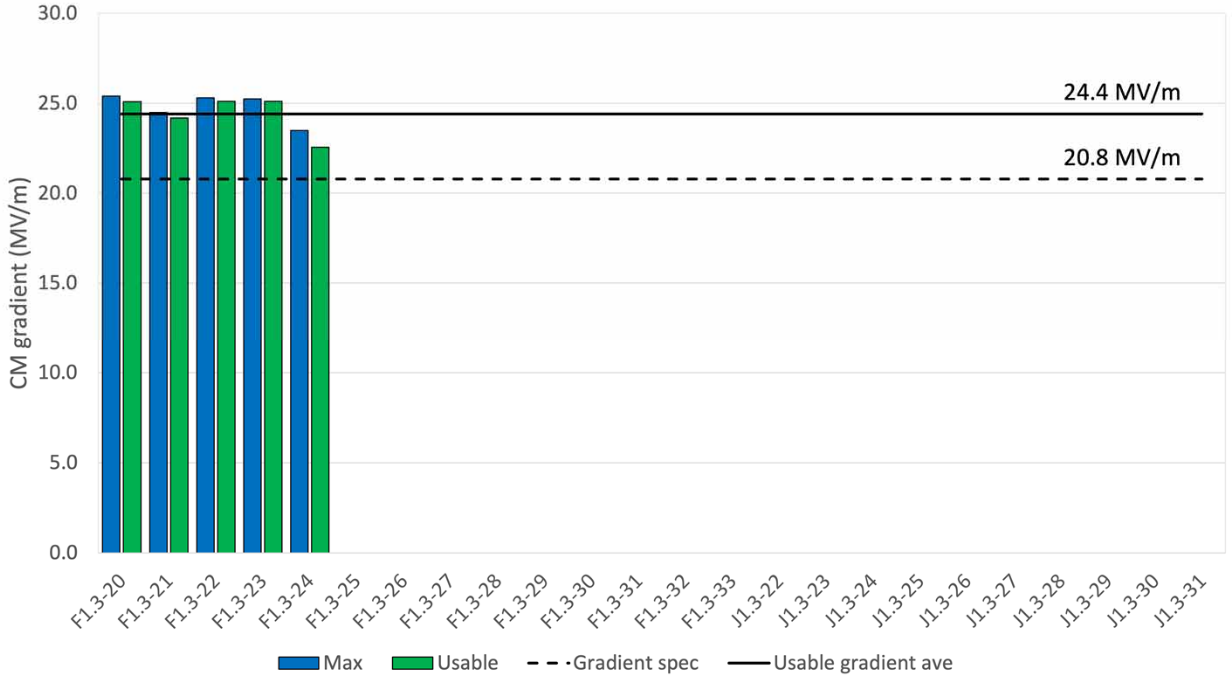
Cavity microphonics: $<$ 10 Hz peak-to-peak

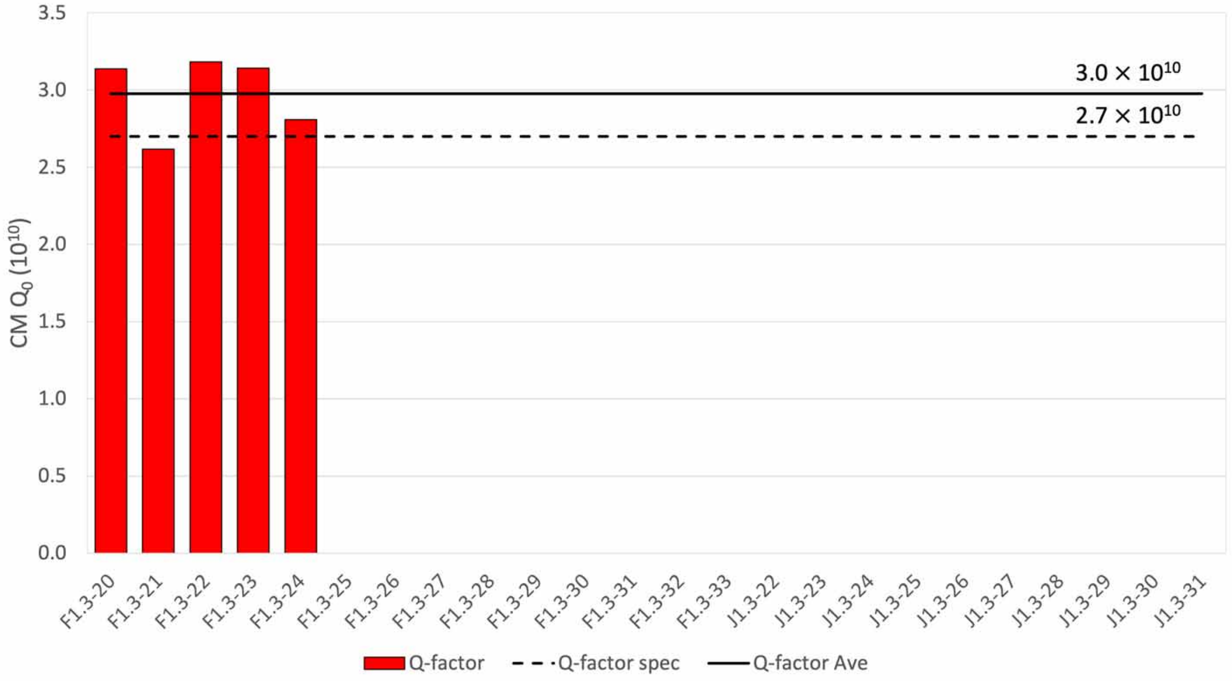
- With JT valve regulating liquid level

CM test results

5 cryomodules assembled and fully tested

- Average **usable gradient is 24.4 MV/m (202.6 MV)**
- Average **Q_0 is 3.0×10^{10} @ 173 MV**
- All CMs exceed gradient specification
- F1.3-21 does not meet Q_0 specification
  - Assembled using 6 remediated LCLS-II cavities
- F1.3-24 string had a leaky bellow between cavity 5 and 6
  - Bellow was replaced in cleanroom, but process introduced particles
  - Gradient reach limited by FE in cavity 5 and 6
- J1.3-22 had a preliminary test
  - Test interrupted because of cryoplant maintenance
  - All cavities exceeded gradient spec
  - No FE observed
  - Beamline leak developed during thermal cycling



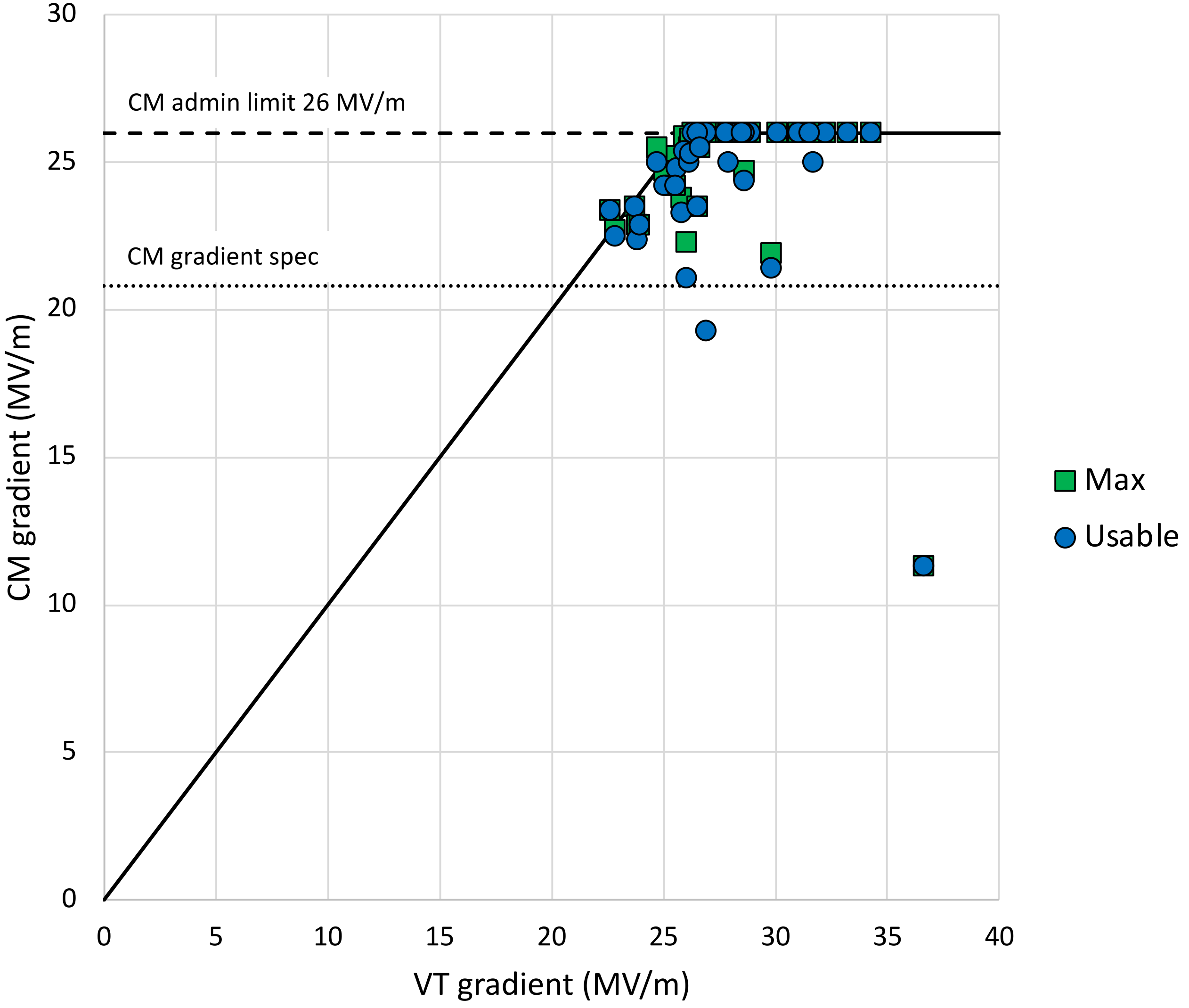


See J. Maniscalco MOPMB072 and A. Cravatta MOPMB063 posters

CM test vs VT: gradient

Minimal gradient degradation

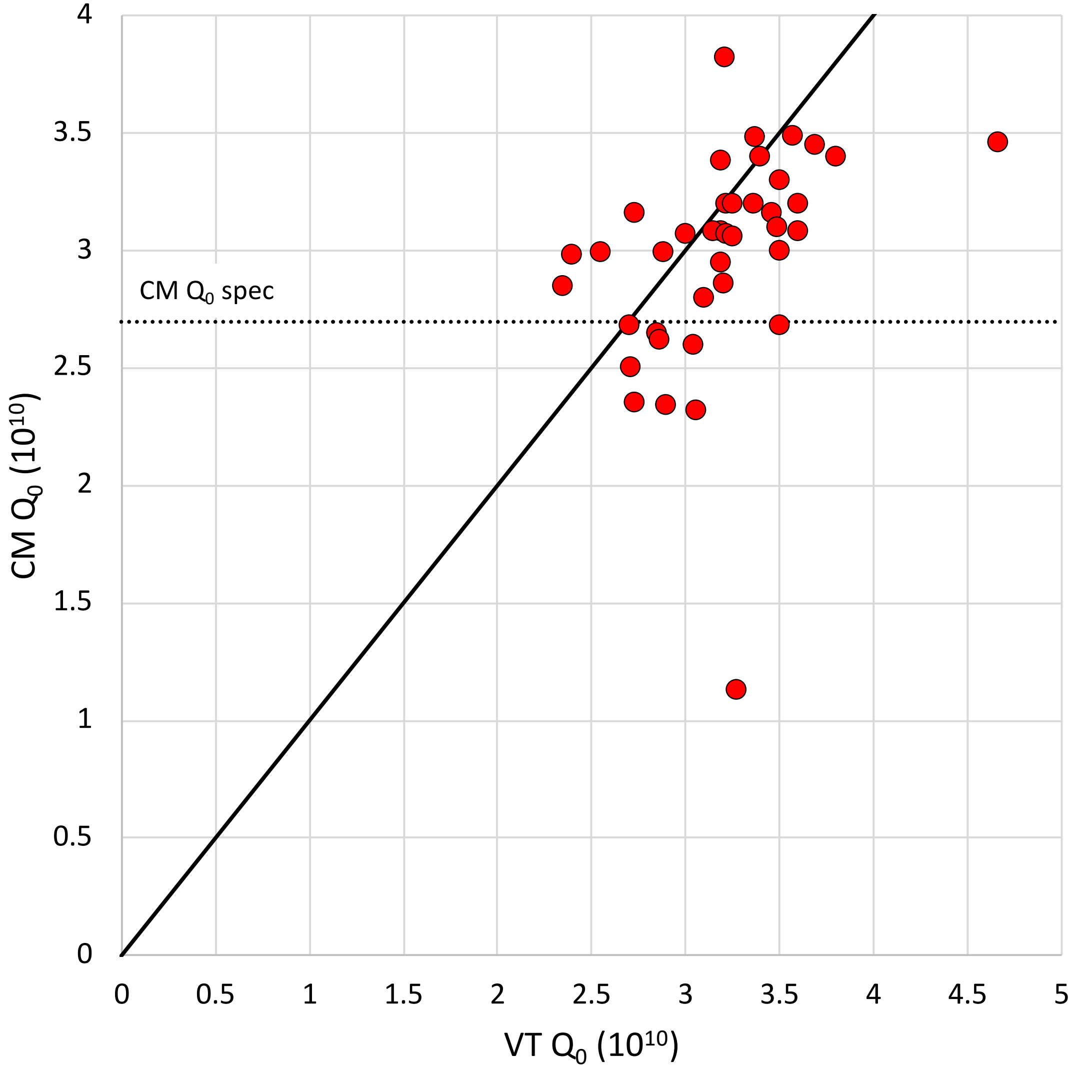
- Many cavities are limited by the administrative limit (26 MV/m)
- Usable gradient and max gradient very close to each other in most of cases
- Just two cavities do not meet gradient specification
  - Cavities 5 and 6 in F1.3-24
  - Limited by FE
  - Issue during string assembly – leaky bellow between cavities had to be replaced



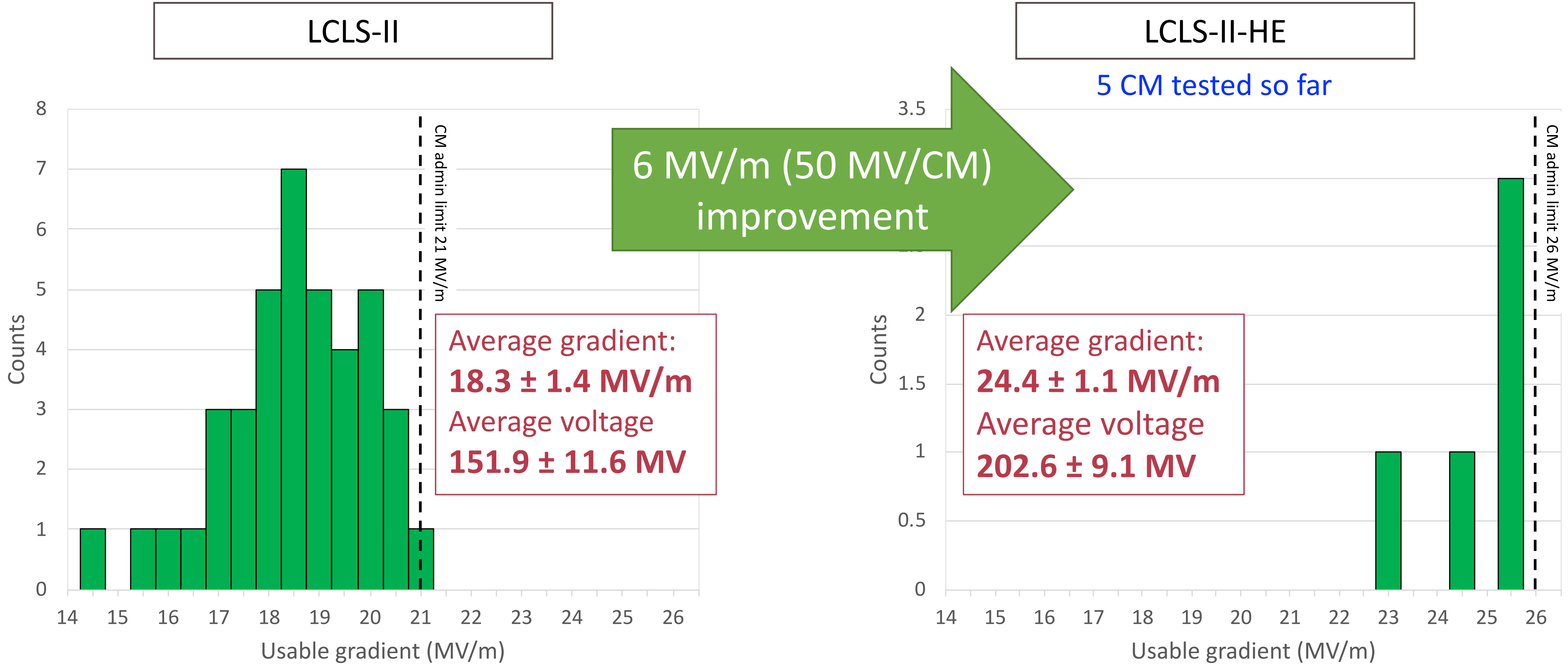
CM test vs VT: Q-factor

Some Q-factor degradation

- Q_0 degraded with respect to vertical test
  - Average degradation not due to FE: 4 nΩ
  - Likely related to trapped flux
    - Even after demag, the magnetic field environment in the CM is not ideal
    - Thermal currents always present in CMs due to components thermalized at different temperatures
- 10 cavities do not meet Q_0 specification
  - 2 are just below the Q_0 spec
  - 6 are remediated LCLS-II cavities assembled in F1.3-21 string
  - Largest Q-factor degradation due to FE
    - Cav 6 in F1.3-24



HE vs LCLS-II CM test: usable gradient



5 CM tested so far

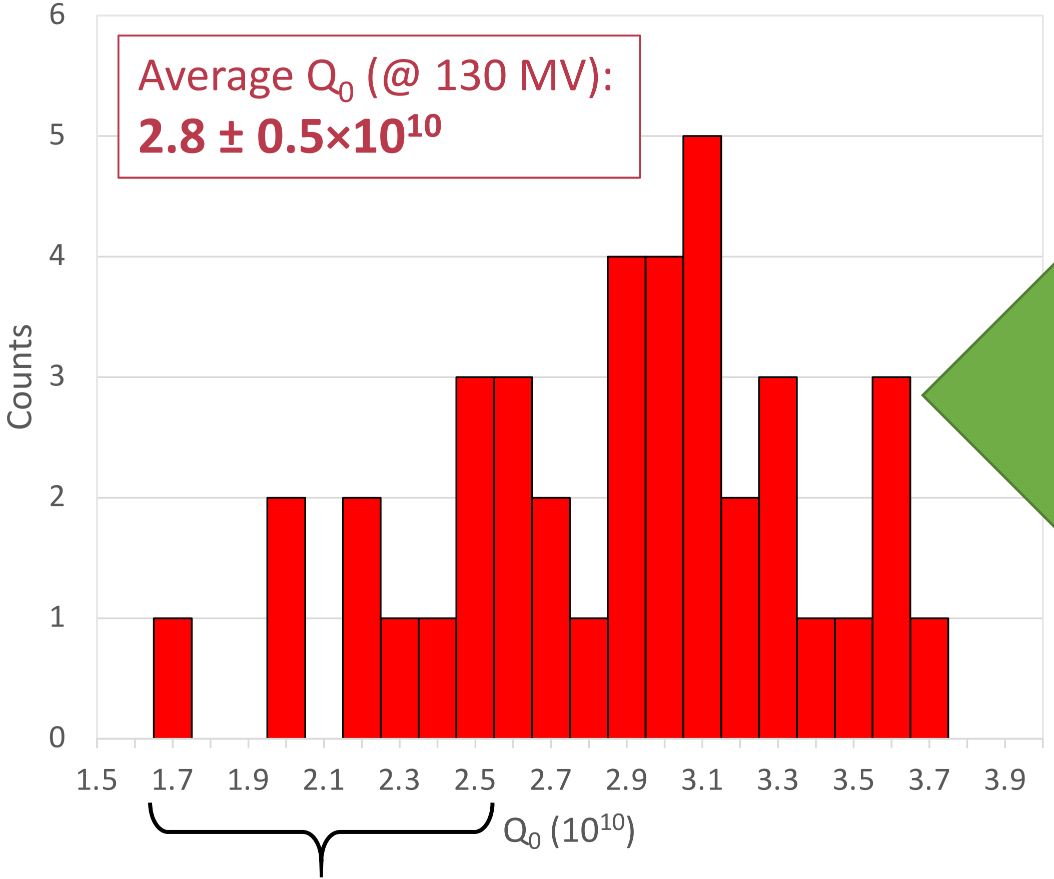
6 MV/m (50 MV/CM) improvement

Average gradient:
18.3 ± 1.4 MV/m
Average voltage
151.9 ± 11.6 MV

Average gradient:
24.4 ± 1.1 MV/m
Average voltage
202.6 ± 9.1 MV

HE vs LCLS-II CM test: Q-factor

LCLS-II



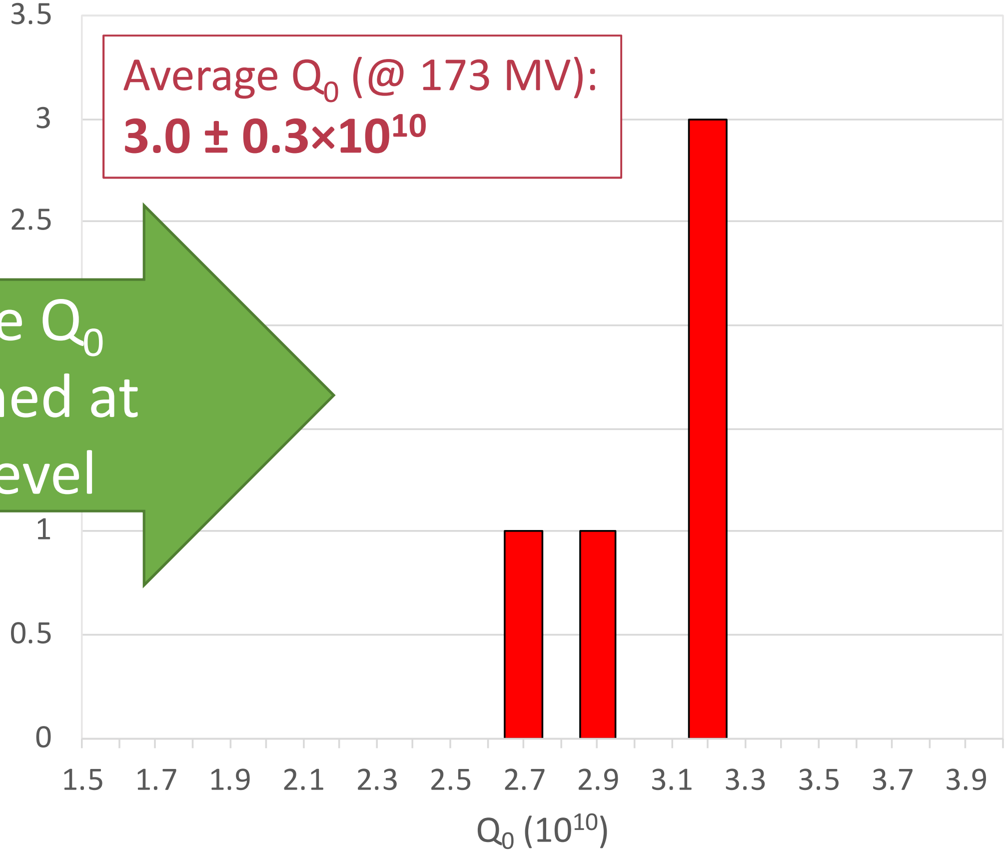
Average Q_0 (@ 130 MV):
$2.8 \pm 0.5 \times 10^{10}$

Mostly CMs tested after slow cooldown

Average Q_0 maintained at same level

LCLS-II-HE

5 CM tested so far



Average Q_0 (@ 173 MV):
$3.0 \pm 0.3 \times 10^{10}$

HE vs LCLS-II CM test: field emission

LCLS-II-HE

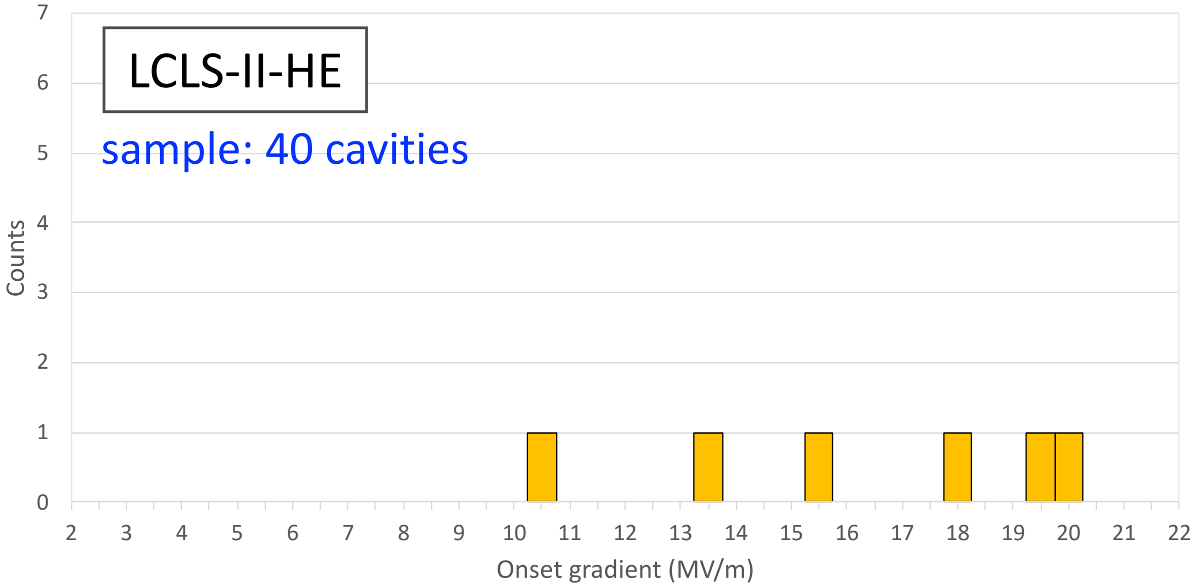
- **15.0% of cavities with FE** during CM test (6 cavities out of 40)
- **Average onset: 16.03 ± 3.8 MV/m**
- Admin limit 26 MV/m

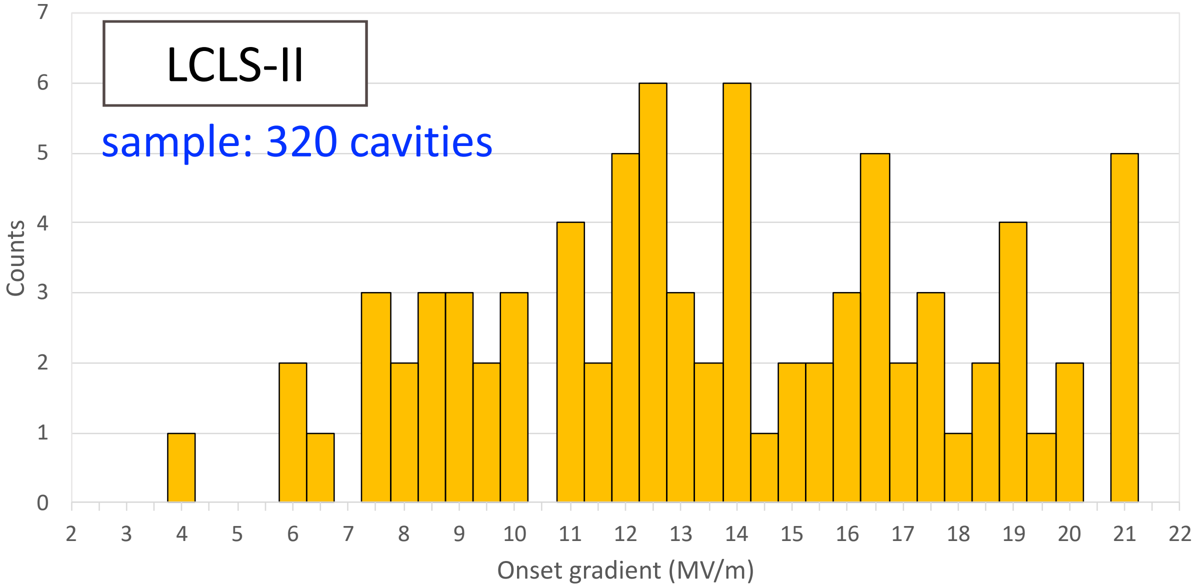
LCLS-II

- **25.3% of cavities with FE** during test CM (81 cavities out of 320)
- **Average onset: 13.4 ± 4.3 MV/m**
- Admin limit 21 MV/m

FE-free qualification criteria outcome

- **10.3% less FE cavities** in CM testing than LCLS-II





3

Summary

Lessons learned

No-FE qualification criteria in VT is good practice to get FE-free CMs

- Less FE observed in CM testing compared to LCLS-II even if admin limit is higher (26 MV/m vs 21 MV/m)

He vessel leak check after vertical test qualification

- In two occasions leaks discovered at He vessel welds after string completion
  - Likely due to thermal cycling during VT
- In-situ repair is possible

Cavity disconnection from string can be problematic and source of particles

- F1.3-24 is a good example. Leaking bellow between cavities lead to string disassembly between cavity 5 and 6
  - Strong FE in CM testing on both cavities
- Preferred path is to completely rebuild the string from scratch with newly qualified cavities

Helium vessel bellow is a weak spot in the design

- Damage on bellows was recorded in several instances
  - Damage during shipping, at the partner labs, and on as received bellows at cavity vendor
- Bellows protection does not always guarantee protection during handling

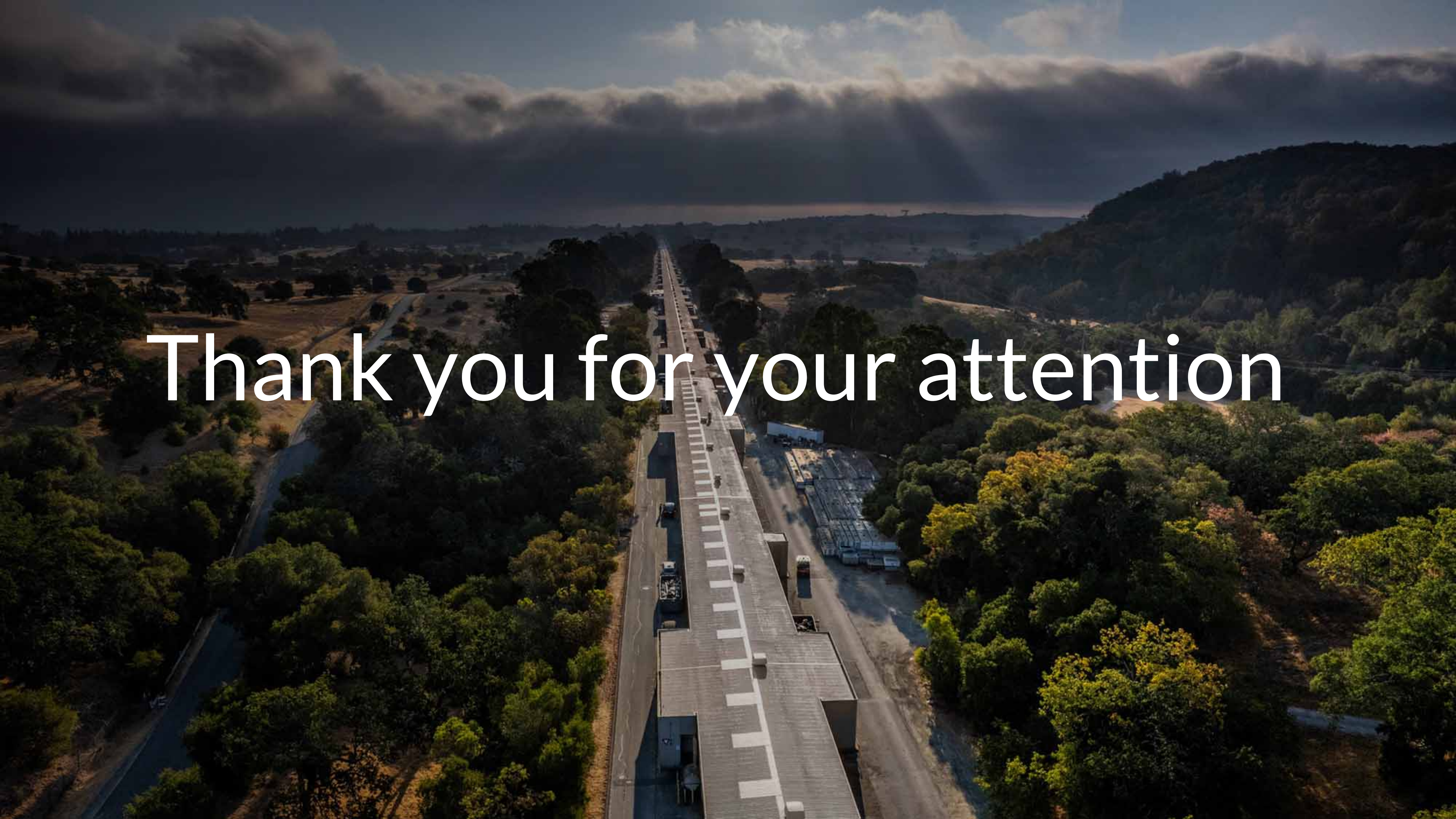
Conclusions

Cavities qualification is proceeding without obstacles

- In average, cavities **outperform VT qualification criteria**
  - New surface processing is delivering the expected results
  - Material segregation by heat lot good practice to maintain high-Q in CM testing

CM assembly and test are underway

- In average, the CMs tested so far **outperform LCLS-II-HE specifications**
  - Average voltage: **202.6 MV**
  - Average Q_0: **3.0×10^{10} @ 173 MV**
- 15% of cavities are field-emitting in CM testing
  - FE-free qualification criteria in VT is delivering the expected results

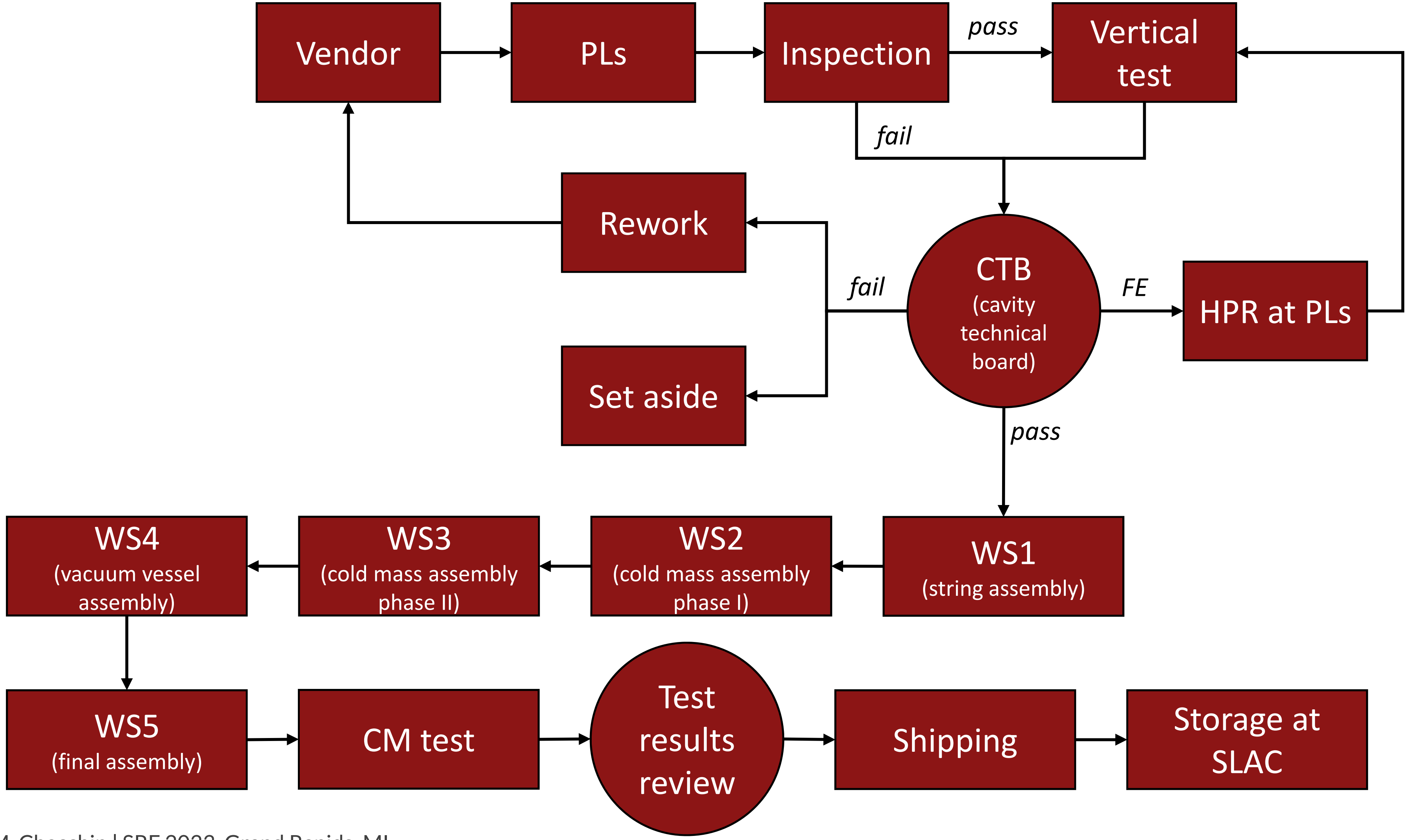


Thank you for your attention

4

Backup

Cavity qualification and cryomodule assembly and test flowchart



Vendor

PLs

Inspection

pass

Vertical test

fail

Rework

fail

CTB (cavity technical board)

FE

HPR at PLs

Set aside

pass

WS4 (vacuum vessel assembly)

WS3 (cold mass assembly phase II)

WS2 (cold mass assembly phase I)

WS1 (string assembly)

WS5 (final assembly)

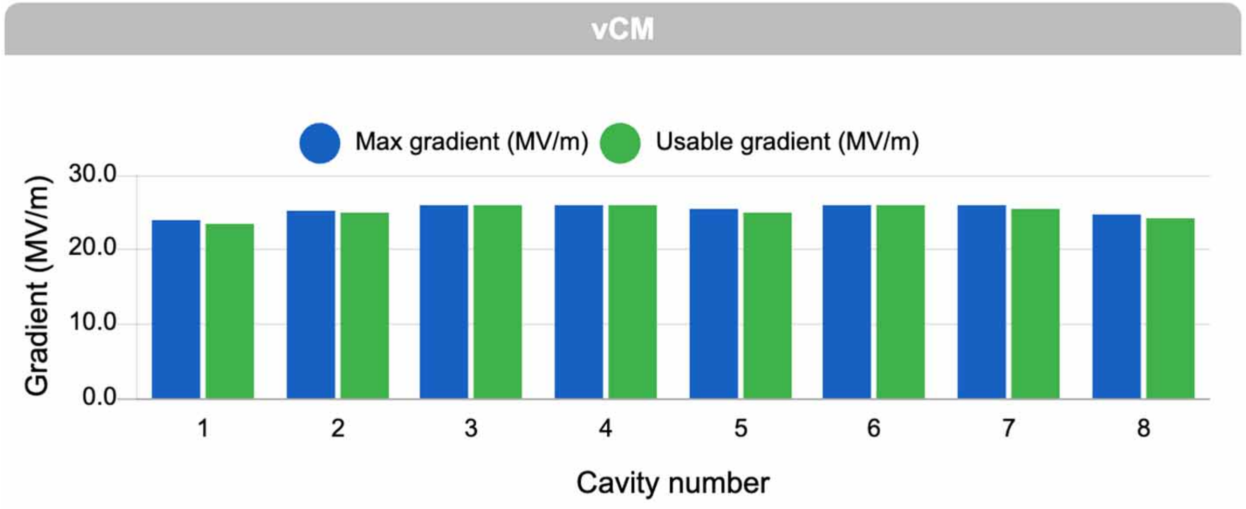
CM test

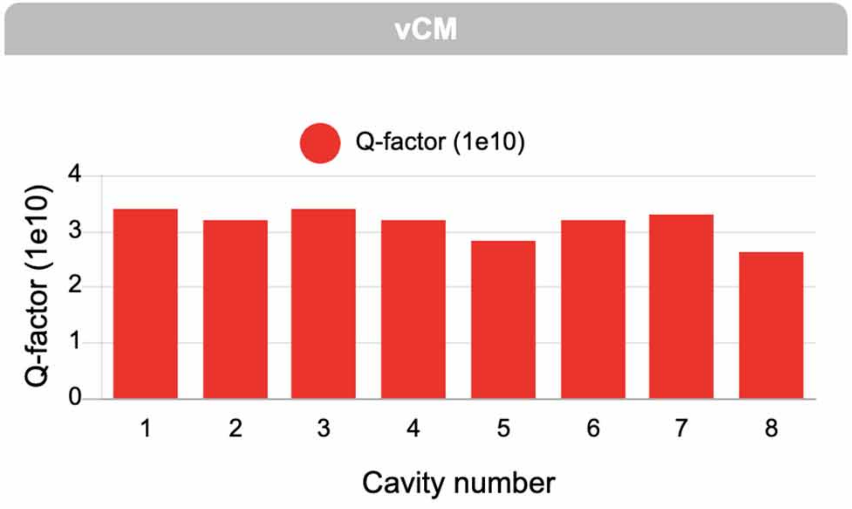
Test results review

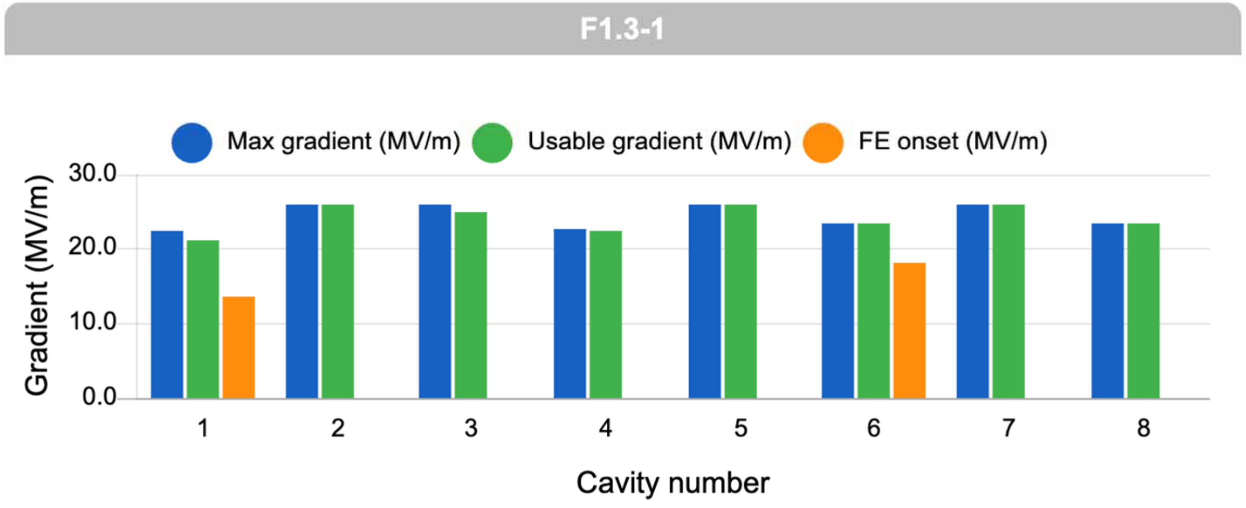
Shipping

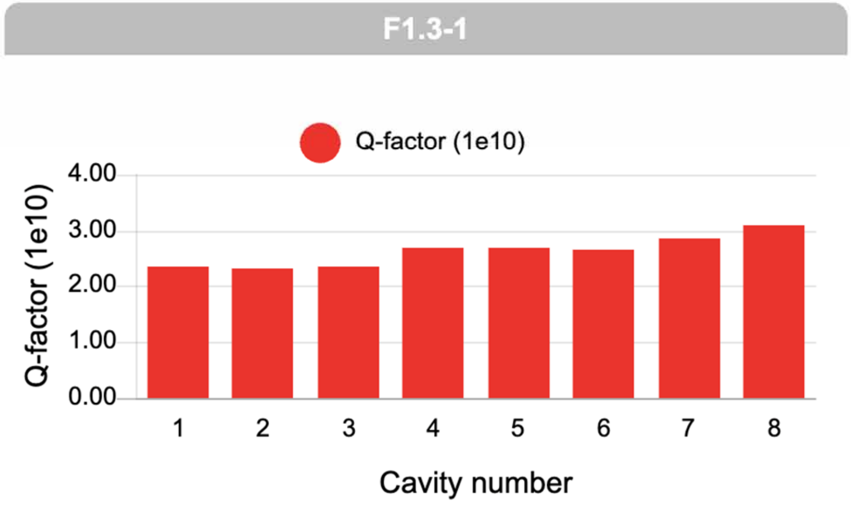
Storage at SLAC

CM test results - detailed


vCM

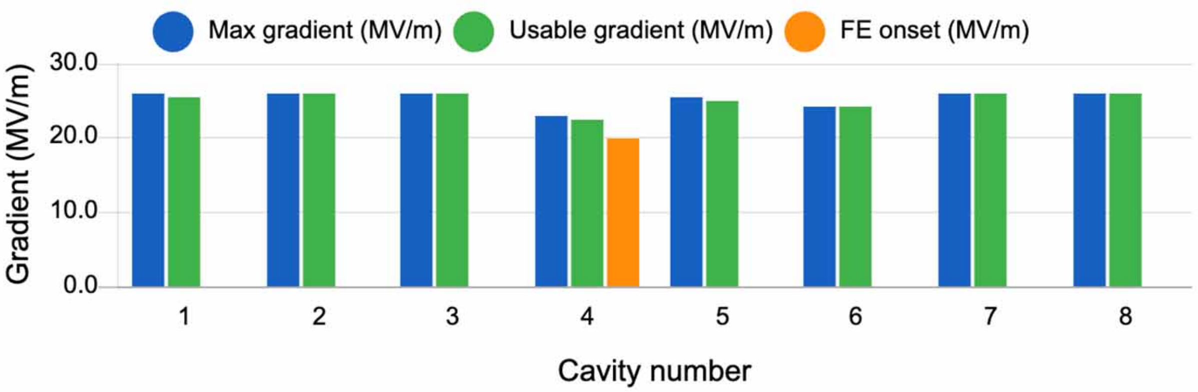

vCM


F1.3-1

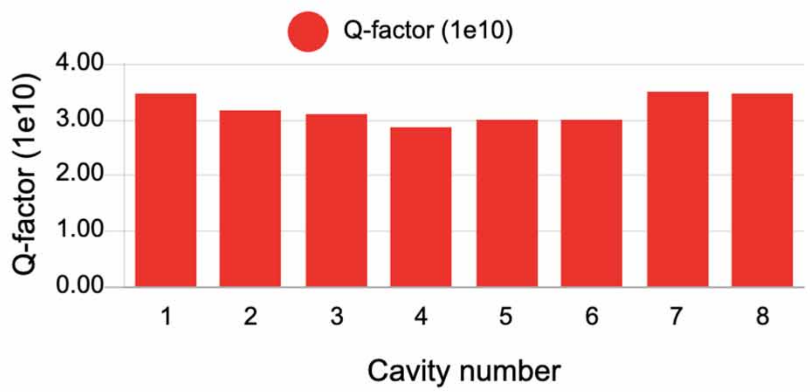

F1.3-1

CM test results - detailed

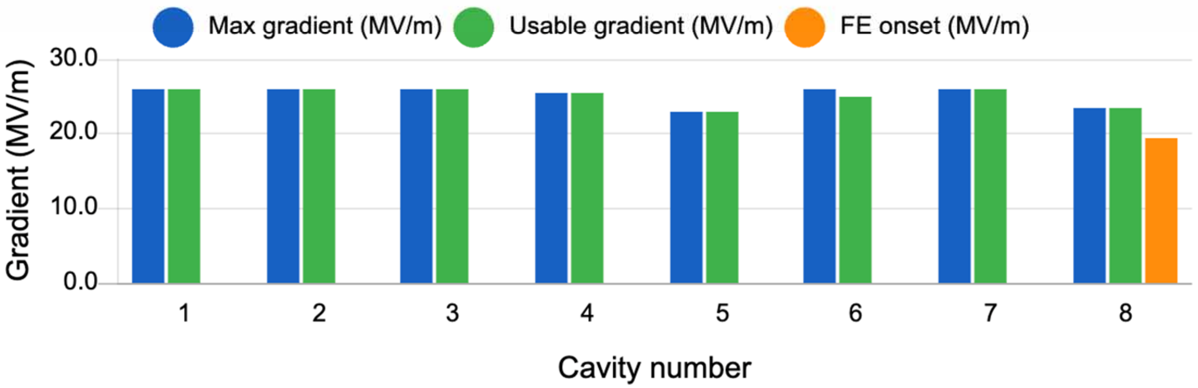
F1.3-2



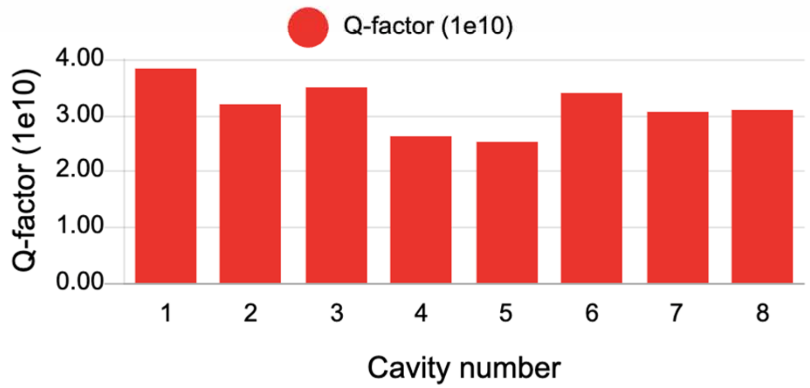
F1.3-2



F1.3-3



F1.3-3



CM test results - detailed