LCLS-II-HE High Q_0 & Gradient R&D Program, First CM Test Results, and CM Plasma Processing Results

Dan Gonnella *for the LCLS-II HE Collaboration*

SLAC National Accelerator Laboratory

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SLAC NATIONAL ACCELERATOR LABORATORY

Cornell University

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U.S. DEPARTMENT OF ENERGY

Stanford University

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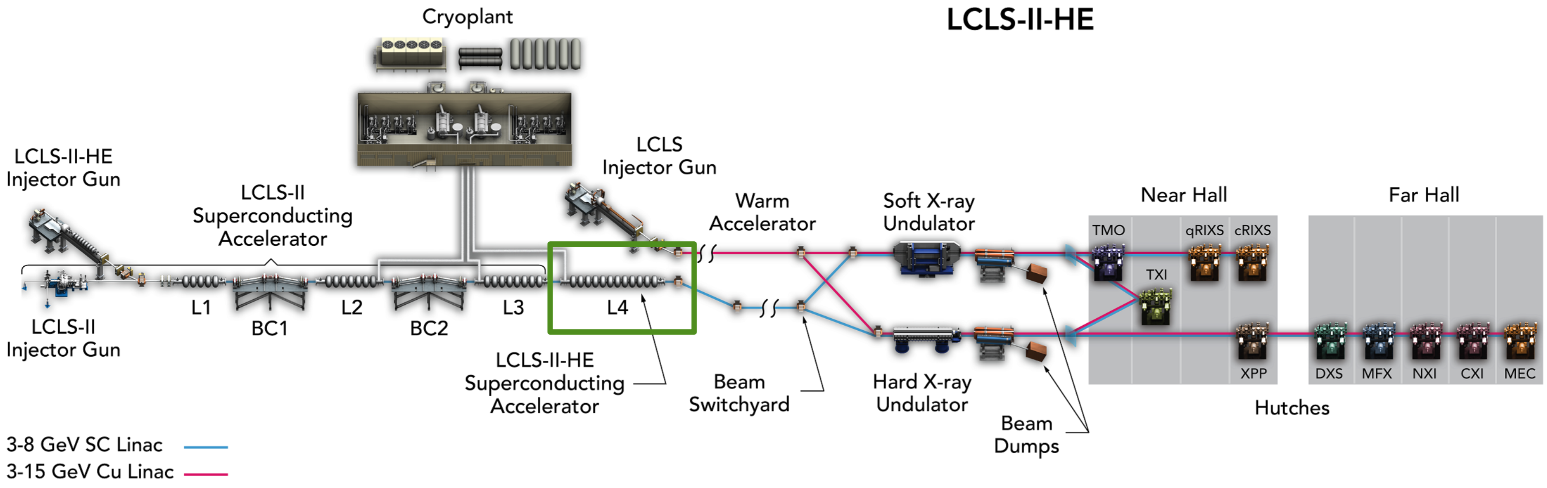
Outline

- LCLS-II HE: Overview and Requirements
- High Gradient and Q_0 R&D
- Cryomodule Results
- Plasma Processing on the HE vCM
- Conclusions & Outlook

LCLS-II-HE: Overview and Requirements



- LCLS-II-HE will expand the superconducting linac with an additional 24 cryomodules (23 in L4 and 1 with the new injector)
- These cryomodules will extend the energy reach of the machine to 8 GeV
- In order to meet this energy gain, the state-of-the-art for SRF cavities needs to pushed significantly

LCLS-II and LCLS-II-HE Requirements

Parameter	LCLS-II	LCLS-II-HE
# 1.3 GHz CMs	35	24
Operating Gradient	16 MV/m	20.8 MV/m
Required Q_0 at Operating Gradient	2.7×10^{10}	2.7×10^{10}

LCLS-II is constructing two 4 kW cryoplants @ 2 K

- Operation at **4 GeV** for LCLS-II can be achieved with a **Q_0 of 1.2×10^{10}**
- Single-cryoplant operation of LCLS-II is a necessary condition for the success of HE
- Operating at **8 GeV** for LCLS-II HE requires an average **Q_0 of 2.7×10^{10}**

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VT Acceptance Gradient	**19 MV/m**	**23 MV/m**

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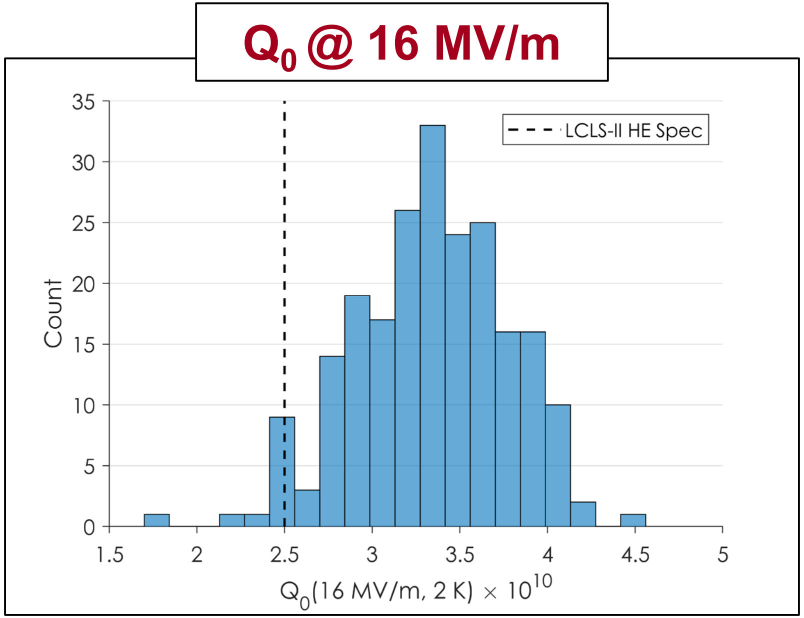
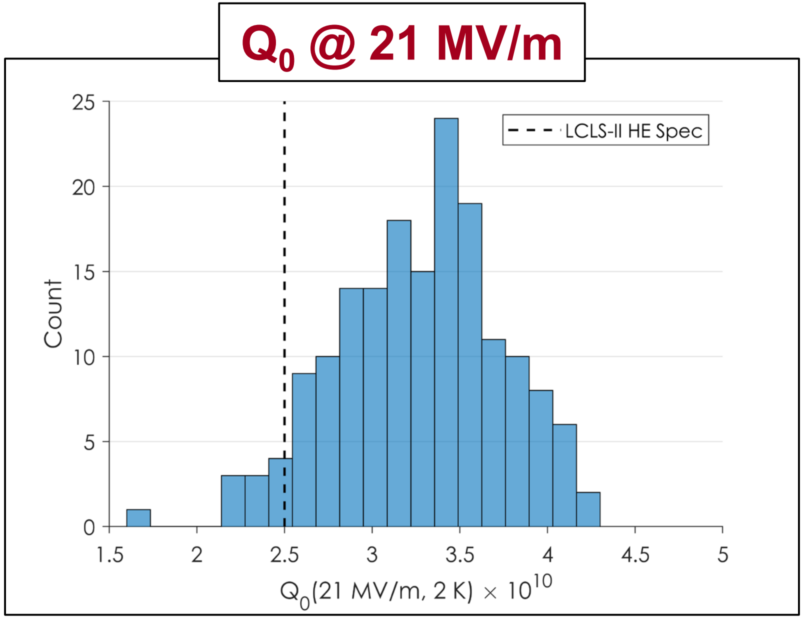
LCLS-II Vertical Test Performance vs Needs of HE

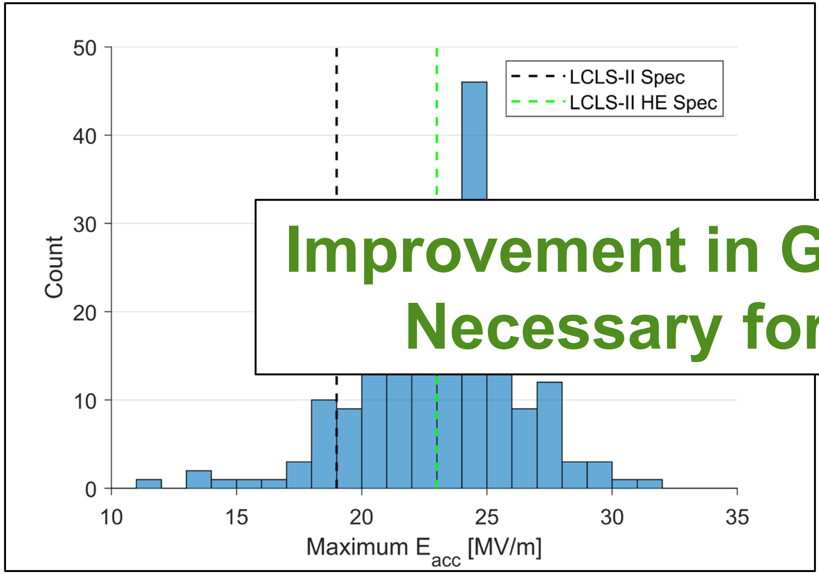


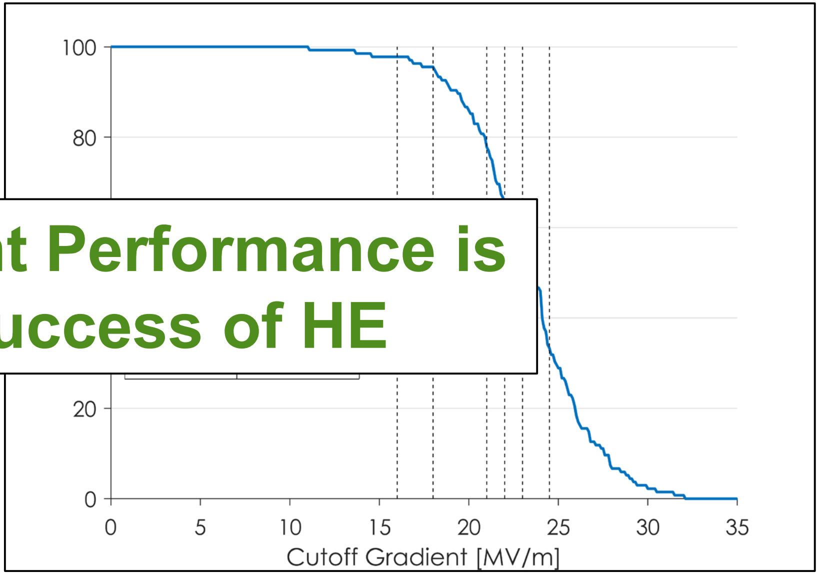


Q_0 performance for LCLS-II cavities at both 16 and 21 MV/m exceeds the requirements of LCLS-II-HE

Gradient	Q_0 @ 2 K
16 MV/m	3.3×10^{10}
21 MV/m	3.3×10^{10}

LCLS-II Performance





Improvement in Gradient Performance is Necessary for the Success of HE

- Nearly all cavities *with improved processes* passed LCLS-II specification
- *Only* 57% of cavities exceed the HE acceptance gradient of 23 MV/m

The Path to Higher Gradients and High Q_0

In order to meet the requirements of LCLS-II-HE, an R&D program was launched which focused on two main areas:

1. Development of a new cavity doping recipe which would maintain high Q_0 while increasing the average quench gradient

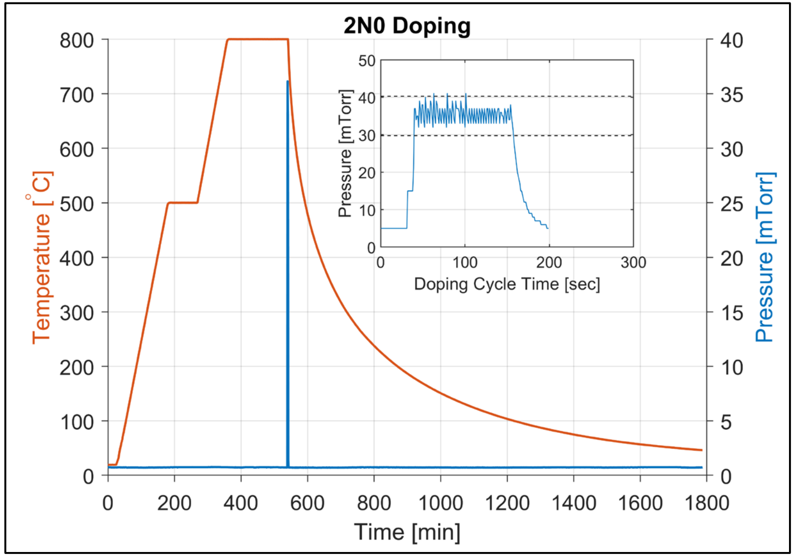
2. Conduct a thorough dissection of the cavity production process and implement lessons learned from LCLS-II and improve QA processes

Improve Quench
Don't Hurt Q_0

Smaller spread in cavity performance

Major Changes from LCLS-II Process

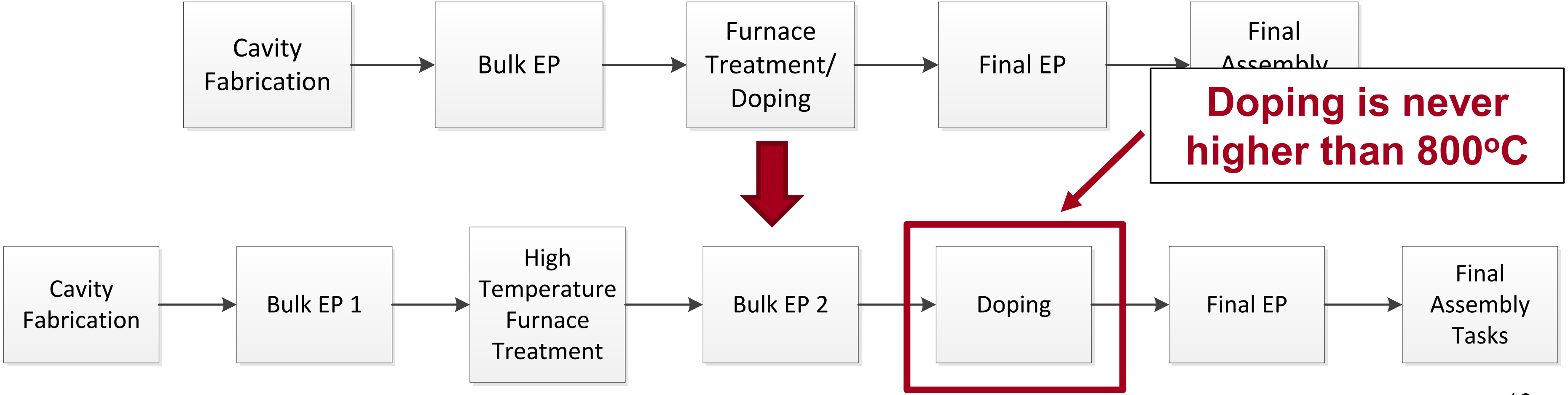
- New nitrogen-doping recipe identified from R&D on single and 9-cells
- 2N0 nitrogen-doping recipe vs 2N6 to improve quench field without impact to Q_0



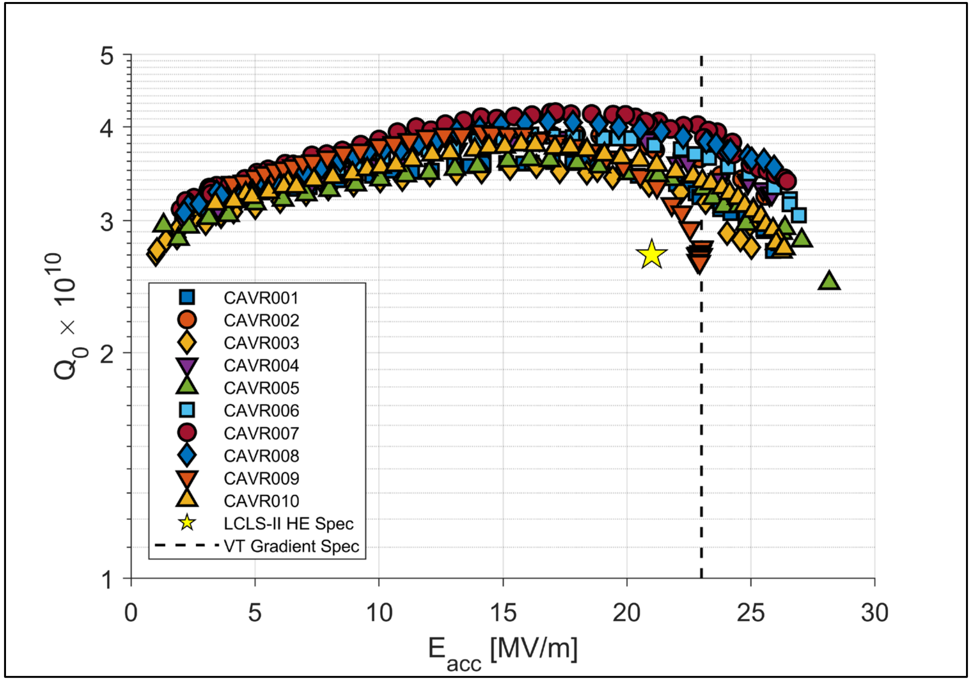
Changes to Cavity Process Flow

Lessons learned from LCLS-II & HE R&D has resulted in two main changes to the cavity production process:

- Last portion of bulk EP and all of final EP must be done at “cold” temperatures
- An additional bulk EP and furnace step with increased RGA monitoring was added to reduce the chance of furnace contamination



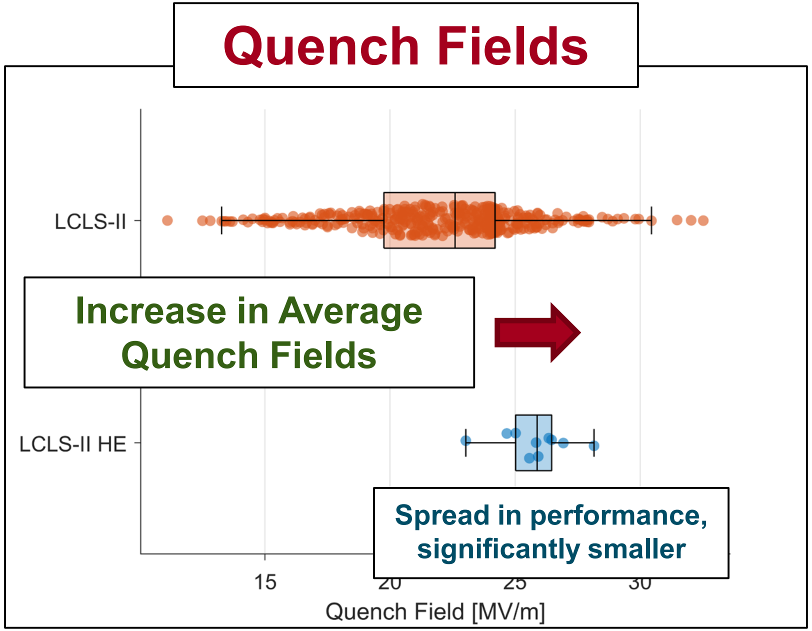
Industry Produced 9-Cells with New Processes

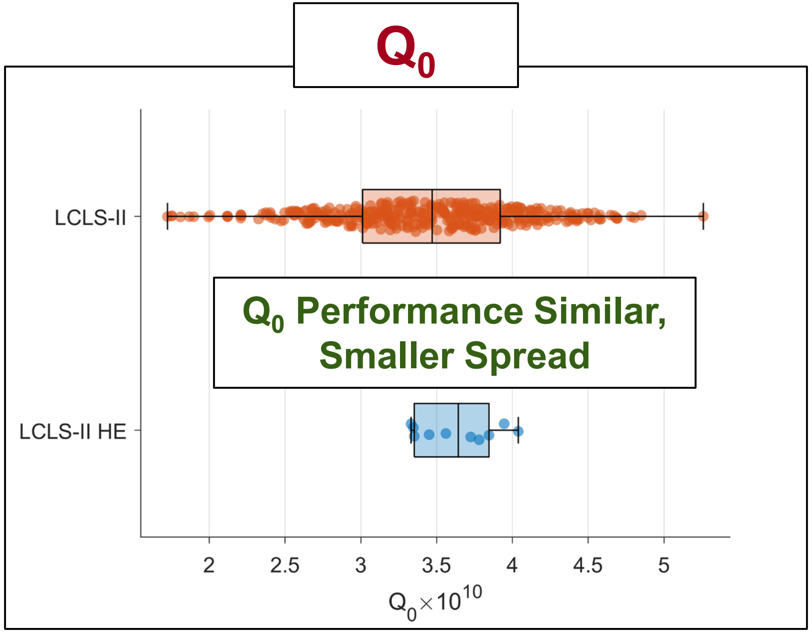


$\langle E_{acc} \rangle$ = 25.9 MV/m
$\langle Q_0 \rangle = 3.6 \times 10^{10}$

- LCLS-II-HE commissioned the construction of 10 9-cell cavities from industry, produced with the 2N0 recipe for use in a *verification* cryomodule
- The improved processes described here and many more were implemented in the production
- All of the cavities passed the HE specification!
- Improvement of >3 MV/m compared with the LCLS-II average!
- High number of 2N0 statistics motivates the decision to **use 2N0 in production**

Comparison with LCLS-II

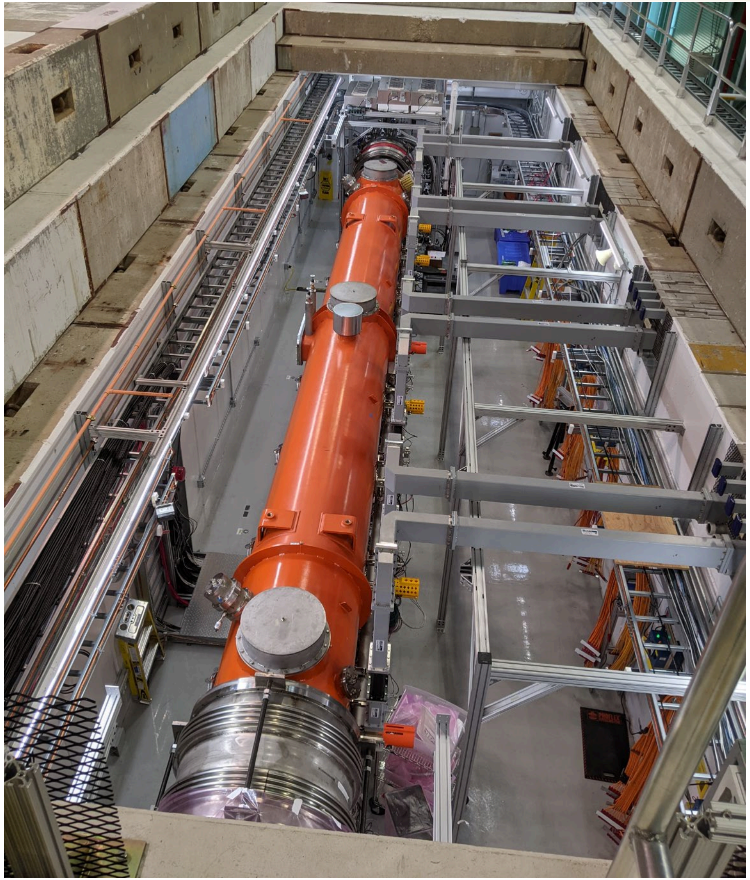




R&D Goals:

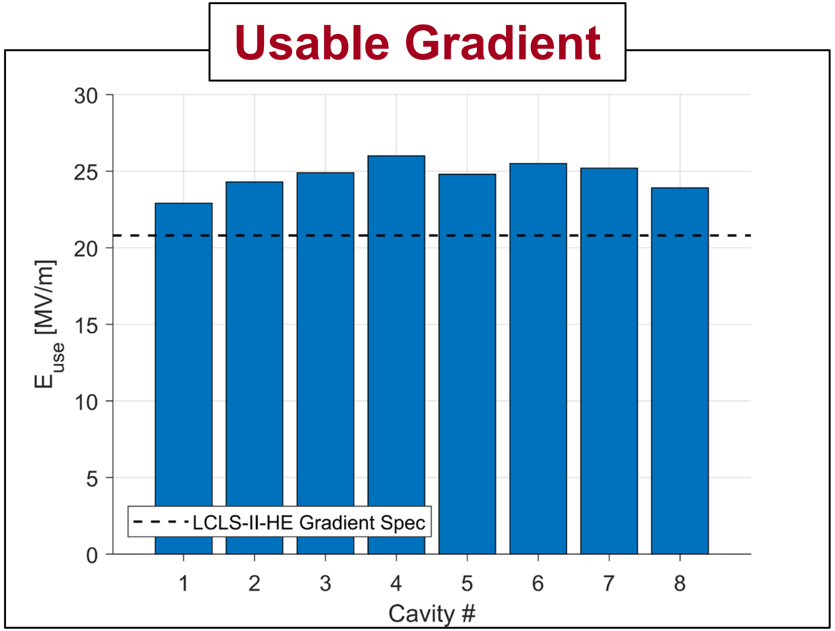
- ✓ Improve quench, don't hurt Q_0
- ✓ Smaller spread in cavity performance

First HE Cryomodule with 2N0 Cavities

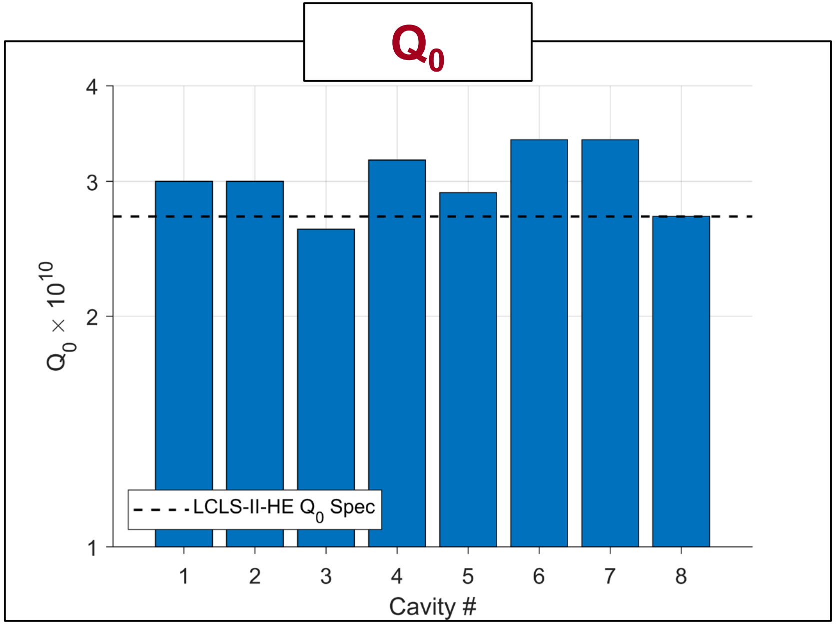


- 8 of the 10 industrial produced 9-cell cavities were assembled into the **HE vCM**
- Tested at FNAL last Summer/Fall

First HE Cryomodule Results

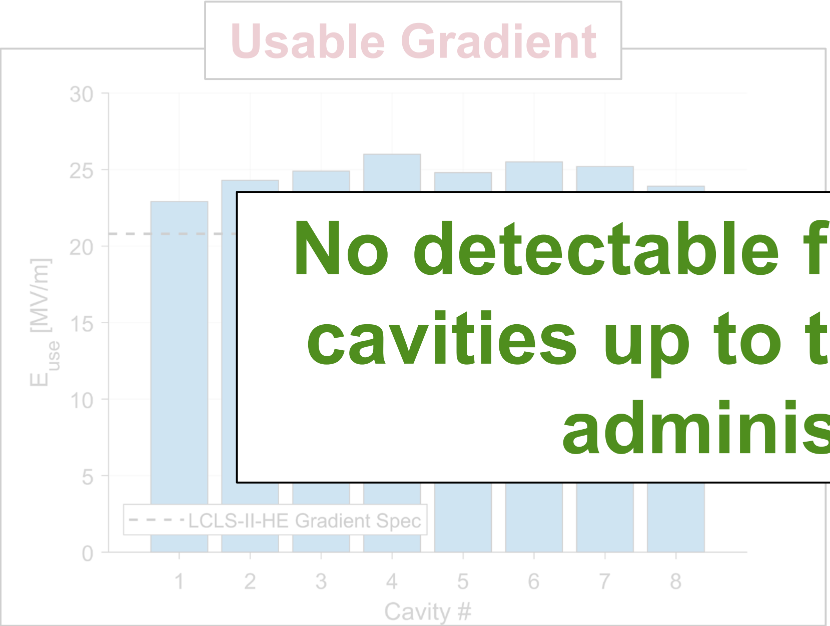


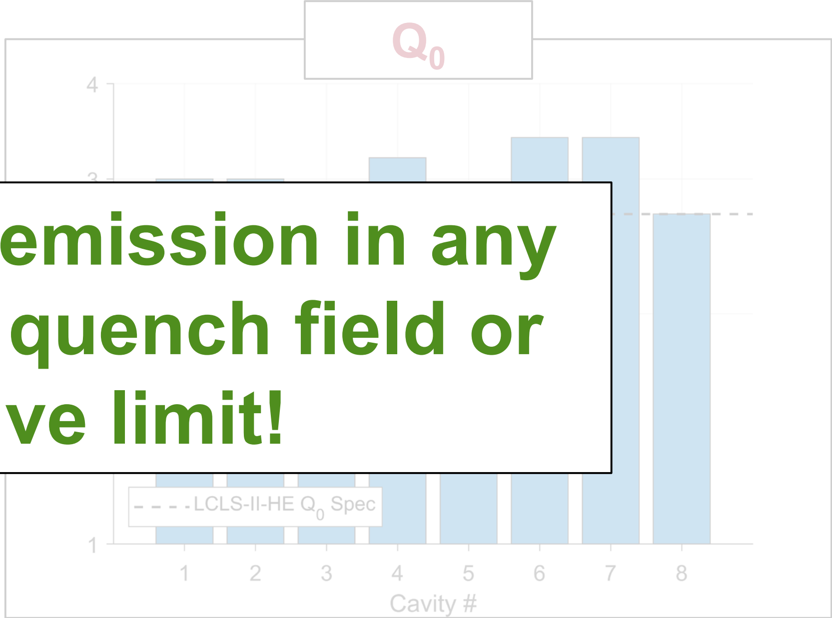
Gradient results are excellent with all cavities operating stably above the HE operating gradient



Q_0 performance has shown an average of **3×10^{10} at 21 MV/m!**

First HE Cryomodule Results



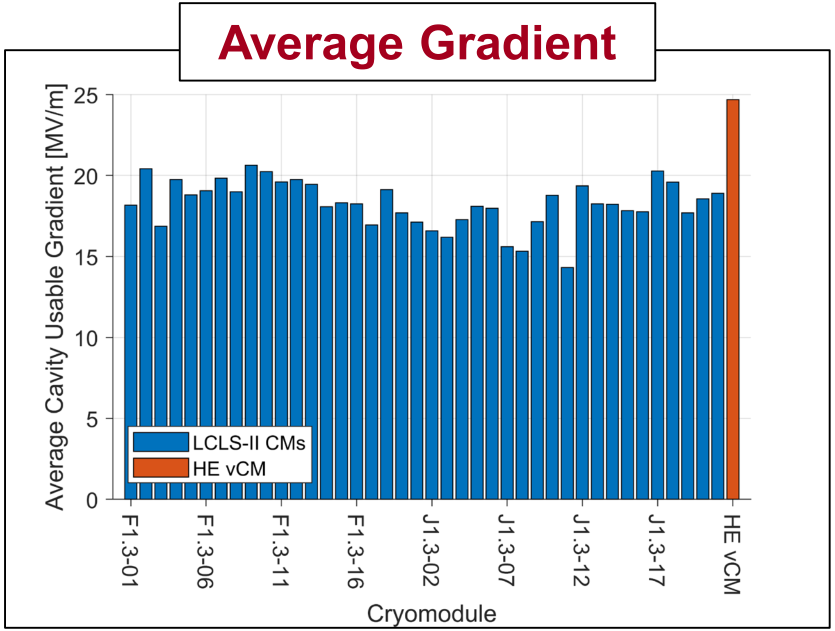


No detectable field emission in any cavities up to their quench field or administrative limit!

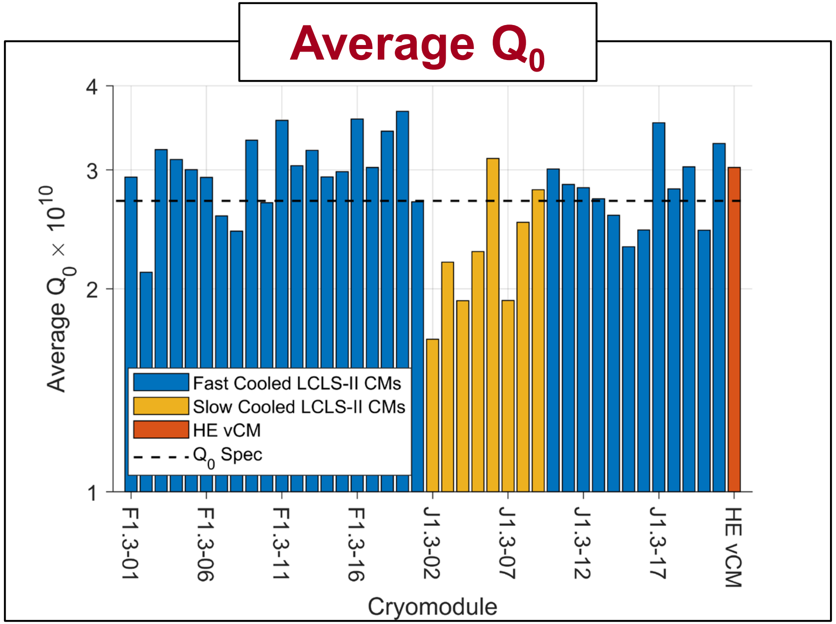
Gradient results are excellent with all cavities operating stably above the HE operating gradient

Q_0 performance has shown an average of **3×10^{10} at 21 MV/m!**

Comparison with LCLS-II CMs



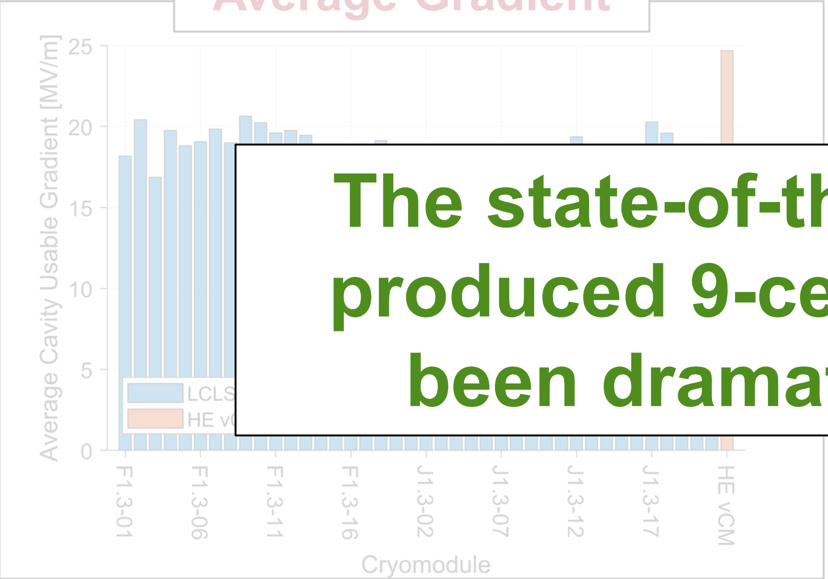
Gradient performance exceeded all LCLS-II modules!



Average Q_0 in line with the best LCLS-II modules!

Comparison with LCLS-II CMs

Average Gradient



Average Q_0

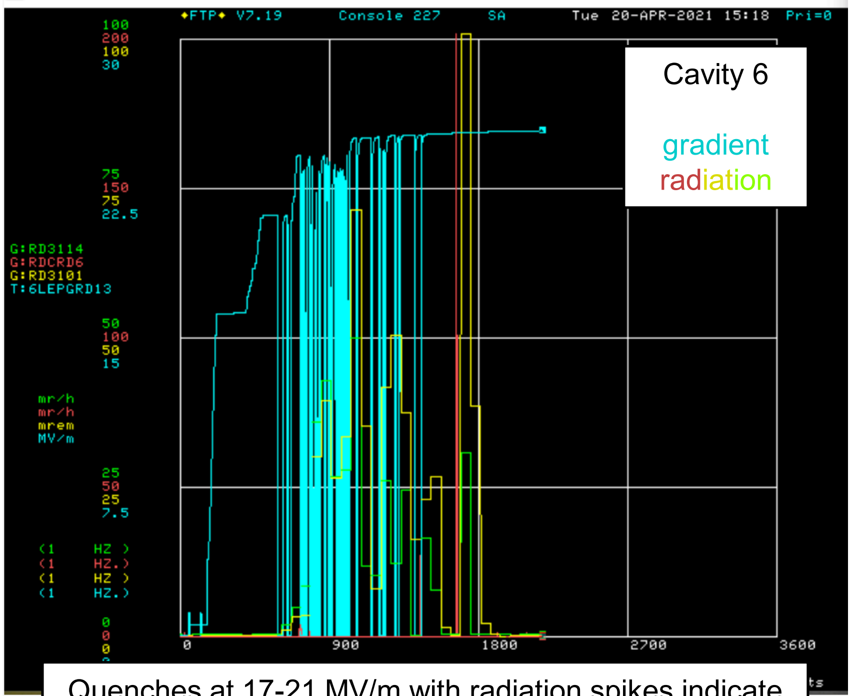
The state-of-the-art for industrial produced 9-cell SRF cavities has been dramatically improved!

Gradient performance exceeded all LCLS-II modules!

Average Q_0 in line with the best LCLS-II modules!

Multipacting in the vCM

- A number of cavities showed multipacting in the range of 17-21 MV/m during the initial power rise
- Example on one cavity:
  - Initial rise to 16 MV/m with no quenches
  - Dozens of quenches encountered on each cavity during push to 21 MV/m
    - Generally increasing field and time to quench
  - Stable operation achieved after many quenches
- Significant impact on testing, commissioning, and operation of LCLS-II-HE



Quenches at 17-21 MV/m with radiation spikes indicate multipacting; increase of quench gradient followed by stable operation indicates MP processing

Extended Unit Test

- Part of vCM test plan was an extended unit test – try to operate all 8 cavities in SELAP at nominal module voltage 173 MV
- SLAC operators travelled to Fermilab and took shifts so that at least one operator would be in the control room 24/7
- Duration: 12 days

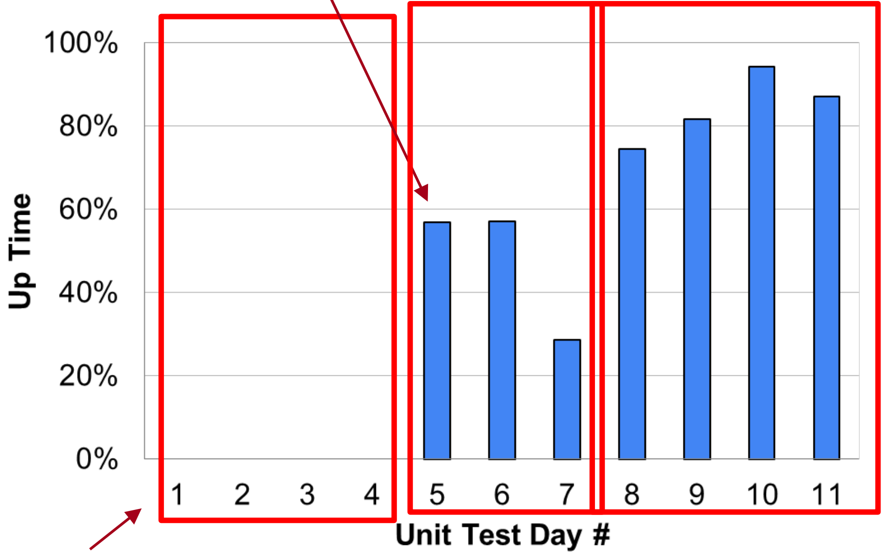
SLAC visiting operators: Sebastian Aderhold, Bob Legg, Janice Nelson, James Maniscalco, Lisa Zacarias
FNAL RF operators: Andrew Cravatta, Sam Posen

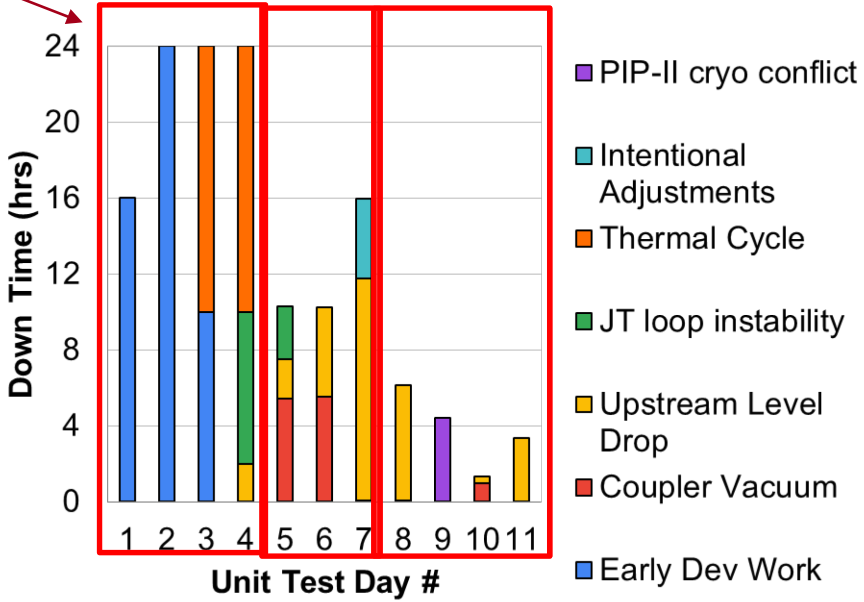
Up Time / Down Time Statistics

First few days spent building understanding how to deal with cryo limitations, LLRF issues, etc. – key also for unit testing in production

First time with all 8 cavities in SELAP was on Friday of 1st week

2nd week had uptime higher than ~80% starting Monday





First day was Monday 6/7/21

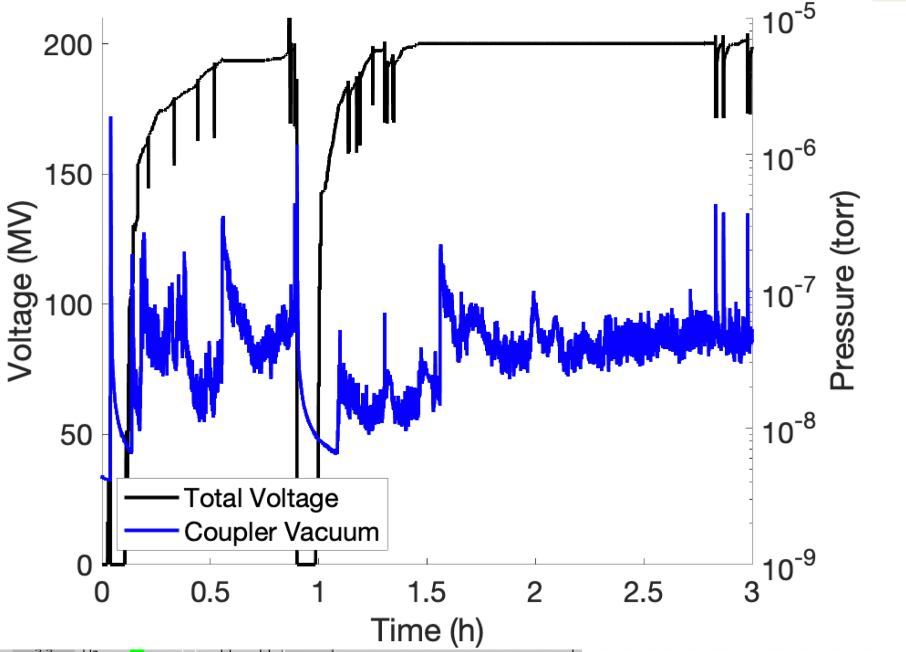
Plots courtesy of Sam Posen

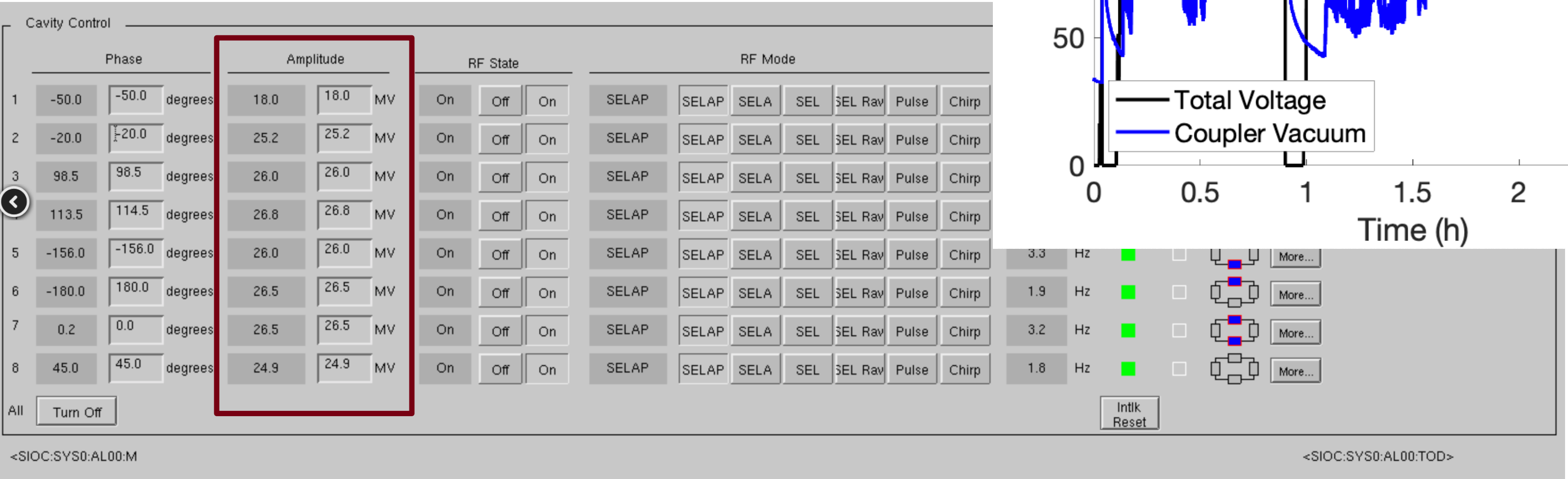
Push for Module Voltage in GDR

Total voltage: 200.0 MV

Average Gradient: 24.1 MV/m

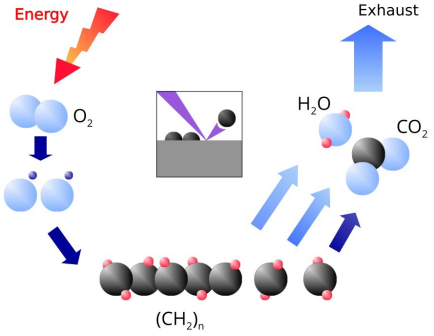
Duration >1 hour (ended by cavity quench when pushing more)

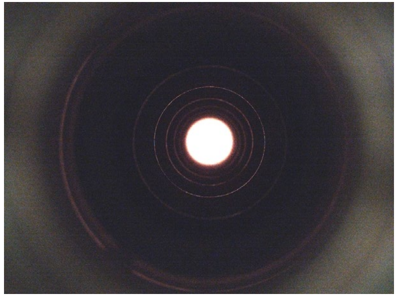




Plasma Processing Applied to LCLS-II-HE vCM

- Procedure can be applied at **room temperature *in-situ***, using the hardware present in the cryomodule: can address **field emission mitigation without CM disassembly.**
- Plasma processing developed for LCLS-II 1.3GHz cavities showed successful results in preserving N-doped cavity performance and FE mitigation
- Now applied for the first time to 1.3GHz cryomodule: LCLS-II-HE vCM





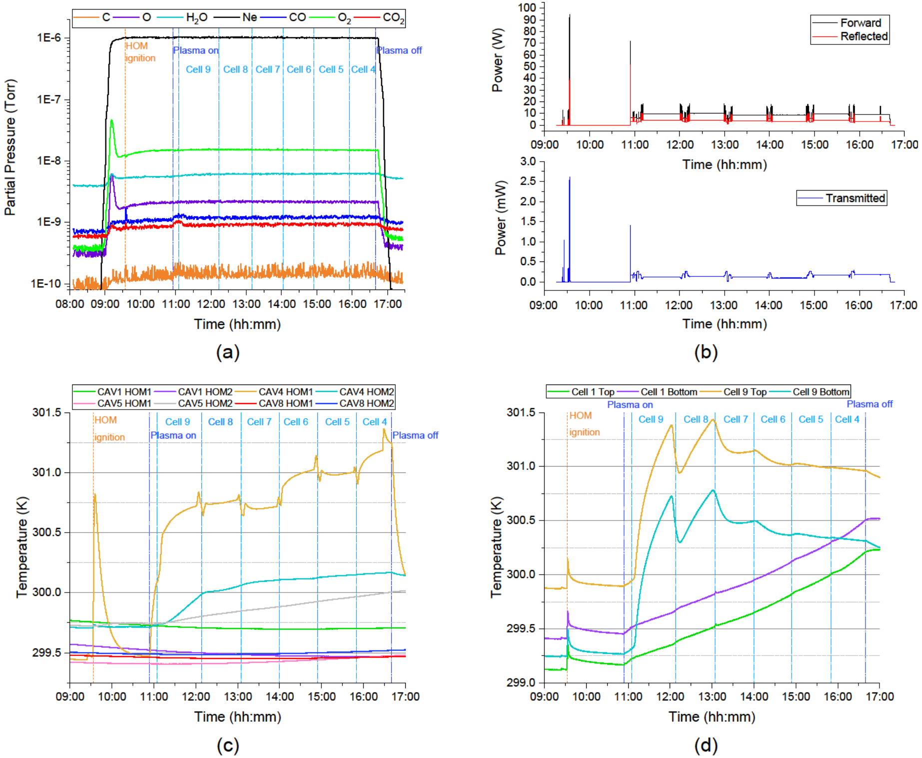

Vacuum cart –
Downstream

RF system,
computers

P. Berrutti et al., J. Appl. Phys. 126, 023302 (2019)
B. Giaccone et al., Phys. Rev. Accel. Beams 24, 022002 (2021)

Plasma Processing Applied to LCLS-II-HE vCM

- Risk analysis and mitigation strategy to scale procedure from single cavity to entire cavity string
- New vacuum cart to avoid pressure instabilities
- Plasma processing applied to 4 out of 8 vCM cavities: CAV1-4-5-8
  - The 4 cavities were instrumented with additional temperature sensors on the cavity surface and HOM cables



Example of experimental data collected during plasma processing of CAV4:

a) RGA data
b) Forward, reflected and transmitted power measured on the CAV4 HOM1 and HOM2
c) HOM cables temperature profile measured on of all 4 instrumented cavities
d) Temperature profile of CAV4 He vessel sensors

B. Giaccone, P. Berrutti, M. Martinello, et al.: Plasma cleaning of LCLS-II-HE verification cryomodule cavities. Preprint on Arxiv

Effect of Plasma Processing on Multipacting in vCM

	Before Plasma Processing				After Plasma Processing			
Cavity #	Max E_{acc} [MV/m]	Usable E_{acc} [MV/m]	Q_0 @ 21MV/m, 2K	MP quenches	Max E_{acc} [MV/m]	Usable E_{acc} [MV/m]	Q_0 @ 21MV/m, 2K	MP quenches
1	**23.4**	**22.9**	**3.0E+10**	**Y**	**23.8**	**23.3**	**3.4E+10**	**N**
2	24.8	24.3	3.0E+10	Y	25.2	24.7	3.2E+10	Y
3	25.4	24.9	2.6E+10	Y	26.0	26.0	3.4E+10	Y
4	**26.0**	**26.0**	**3.2E+10**	**Y**	**26.0**	**26.0**	**3.2E+10**	**N**
5	**25.3**	**24.8**	**2.9E+10**	**Y**	**25.5**	**25.0**	**2.8E+10**	**N**
6	26.0	25.5	3.4E+10	Y	26.0	26.0	3.2E+10	Y
7	25.7	25.2	3.4E+10	Y	25.9	25.4	3.3E+10	Y
8	**24.4**	**23.9**	**2.7E+10**	**Y**	**24.7**	**24.2**	**2.6E+10**	**N**
Avg	25.1	24.7	3.0E+10		25.3	25.1	3.1E+10	
Total	209	205			210	208		

Before P.P. performance: S. Posen, et al. *arXiv:2110.14580* (2021)

RF test after plasma processing demonstrated that:

- **vCM performance** is **preserved**
- Plasma processing did not introduce any contamination: vCM **still FE-free**

Plasma processing procedure is fully validated

Plasma processing **can eliminate multipacting:**

- **the 4 plasma processed cavities do not exhibit any MP quenches,** contrary to the other 4 cavities

We could **address both FE and MP**, decreasing CM testing time, the commissioning time and increasing the reliability during machine operations.

B. Giaccone, P. Berrutti, M. Martinello, et al.: Plasma cleaning of LCLS-II-HE verification cryomodule cavities. Preprint on Arxiv

Conclusions & Outlook

- LCLS-II-HE R&D has demonstrated excellent performance in 9-cell cavities from vertical test through cryomodule test
- The HE vCM showed excellent performance with an average gradient of >25 MV/m!
- Plasma processing has been demonstrated on a full CM string and shown to “do no harm” to FE rates as well as reduce the impact of multipacting
- First production cavities have arrived at the partner labs – look for first results in the next conference/workshop!

Acknowledgments

Special thanks to the LCLS-II HE collaboration at multiple labs around the US and to our cavity vendors in Europe!

Thanks for your attention!