LCLS-II-HE Cavity and Cryomodule Test Progress

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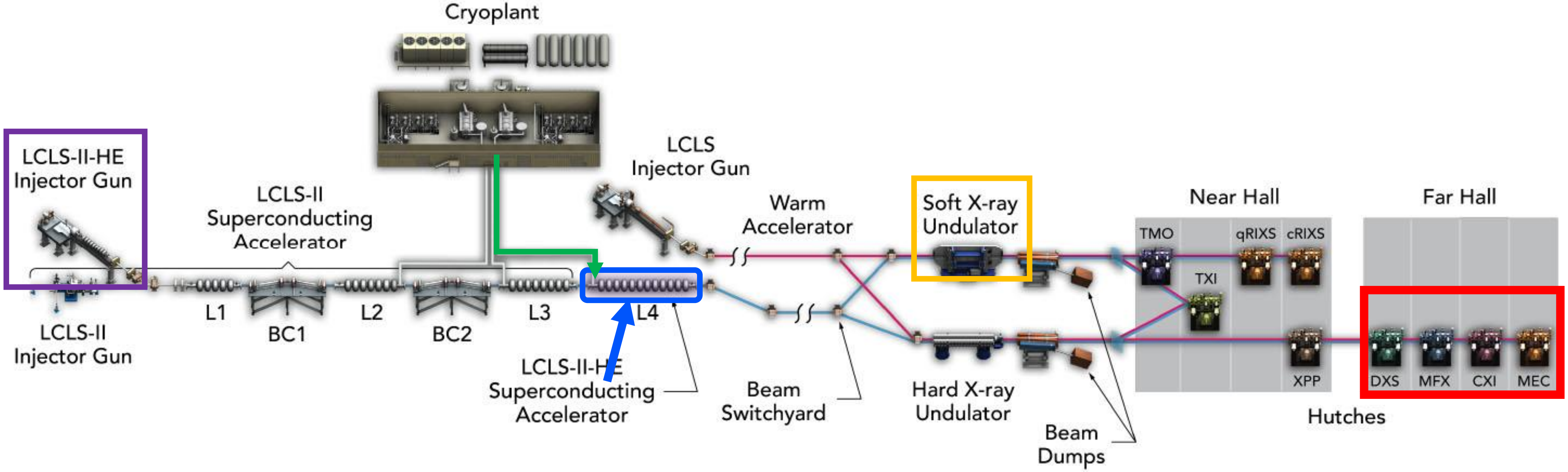
5 December 2023

LCLS-II-HE project scope



1. <u>Add 23 additional cryomodules (L4 linac) to increase the LCLS-II accelerator energy to 8 GeV.</u>
2. Install new cryogenic distribution box and transfer line between the cryoplant and the new L4 linac.
3. Upgrade soft X-ray undulator for 8 GeV operation.
4. Upgrade the LCLS Hard X-ray endstations for MHz beam and data rates.
5. Develop conceptual design of a Low Emittance Injector including a tunnel design; also fund construction of a prototype high-gradient SRF gun for the LEI.

LCLS-II-HE SRF plan overview

- Building on the success of LCLS-II cavity production to meet higher performance requirements
  - $E_{acc} \geq 23$ MV/m
  - Quality factor: $Q_0(21\ \mathrm{MV/m}) \geq 2.5\times10^{10}$ (in vertical test)
  - No field emission accepted in vertical test
- Improvements to LCLS-II cavity production strategy
  - Updated nitrogen doping recipe following R&D program
  - Expanded process reporting requirements (QA/QC)
  - Frequent in-person visits to cavity supplier
- Cavity acceptance testing at Fermilab and Jefferson Lab
  - Cavities tested as-is from vendor (static vacuum)
  - HPR as needed to recover from field emission

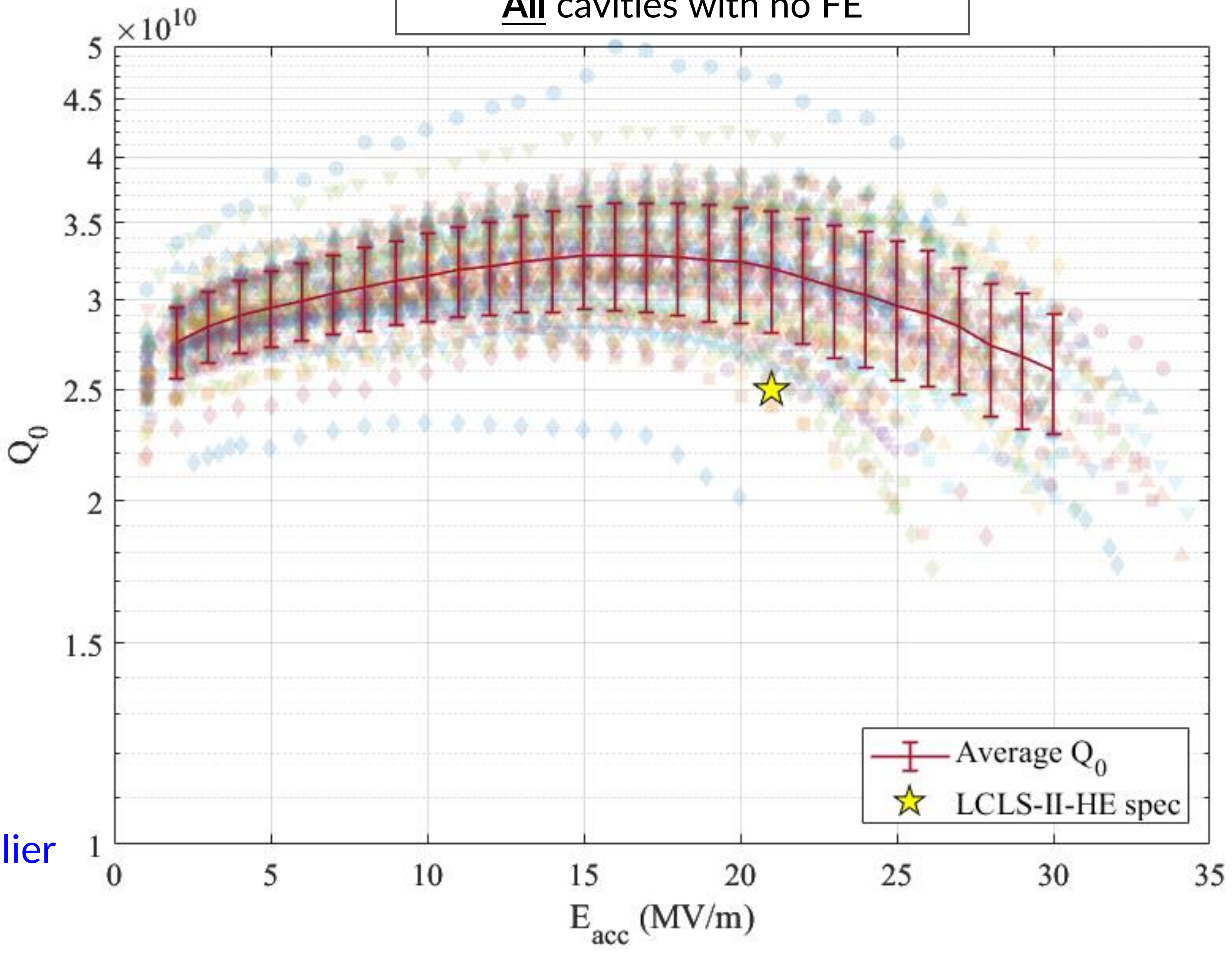
Vertical test performance so far – as of Dec. 1, 2023

167 cavities tested, of which:

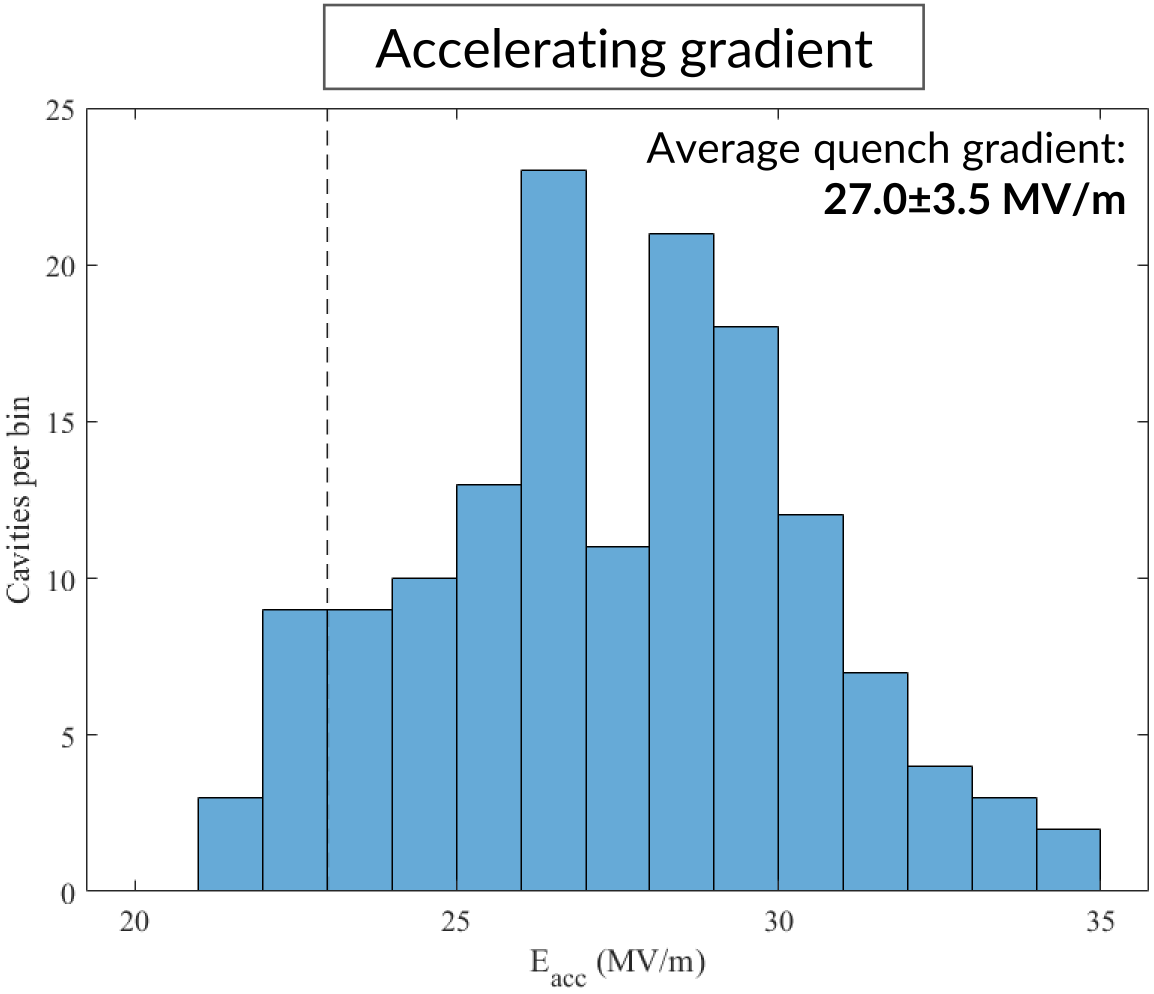
- 132 qualify (79%)
  - 109 as received
  - 12 after 1 rerinse
  - 11 after 2+ rerinses
- 8 placed "on hold" (marginal E_{acc}) (4.8%)
  - 7 with marginal E_{acc}
  - 1 with marginal Q0
- 9 disqualified (5.8%)
  - 4 with low Eacc
  - 1 with low Q0
  - 3 with persistent FE
  - 1 with HOM scratch
- 11 undergoing other rework (6.6%)
  - 7 bellows damage
  - 4 surface rework at labs
- 6 awaiting re-test after high-pressure rinse to mitigate field emission (3.6%)

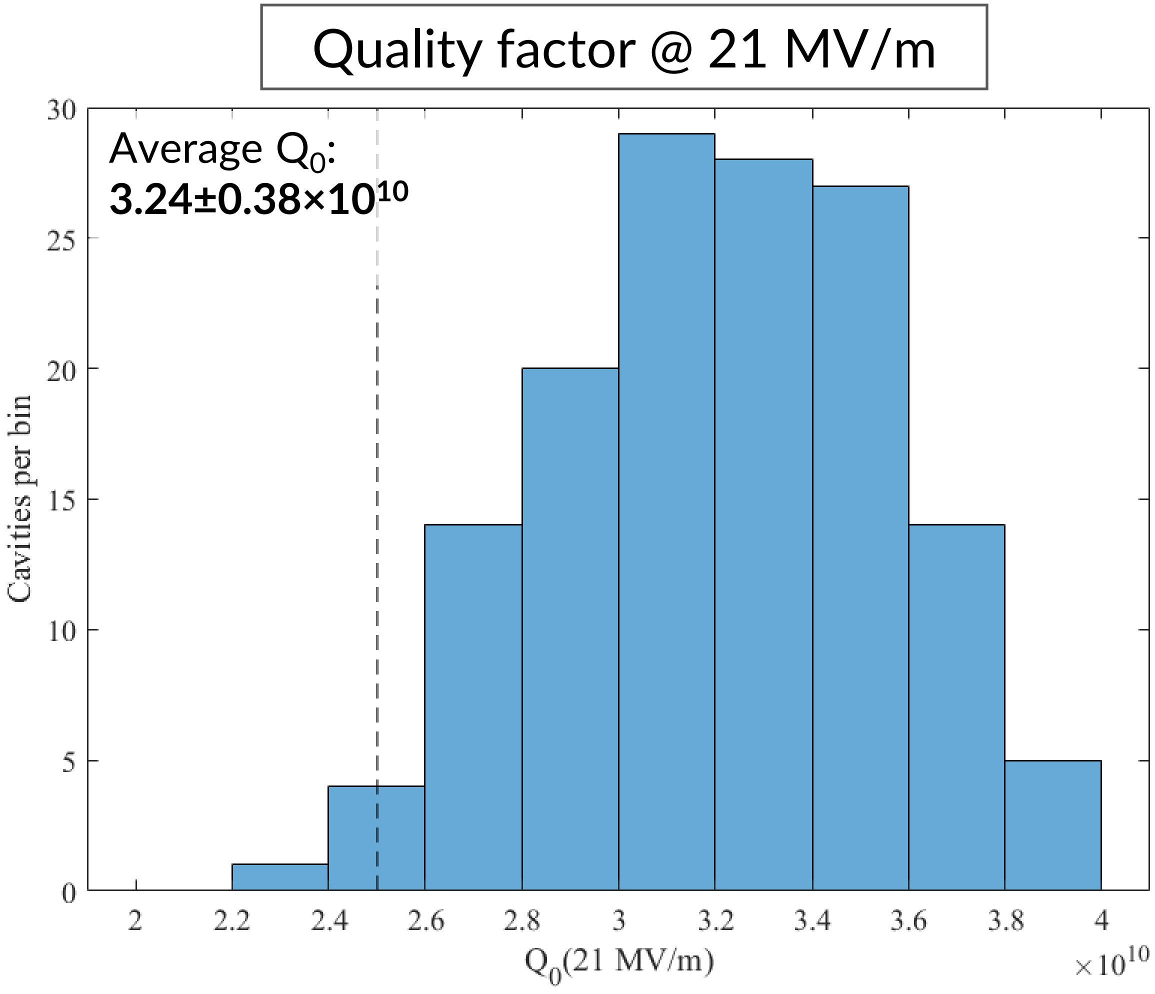
- 13 of the above recently sent back to the supplier for repair/rework

All cavities with no FE



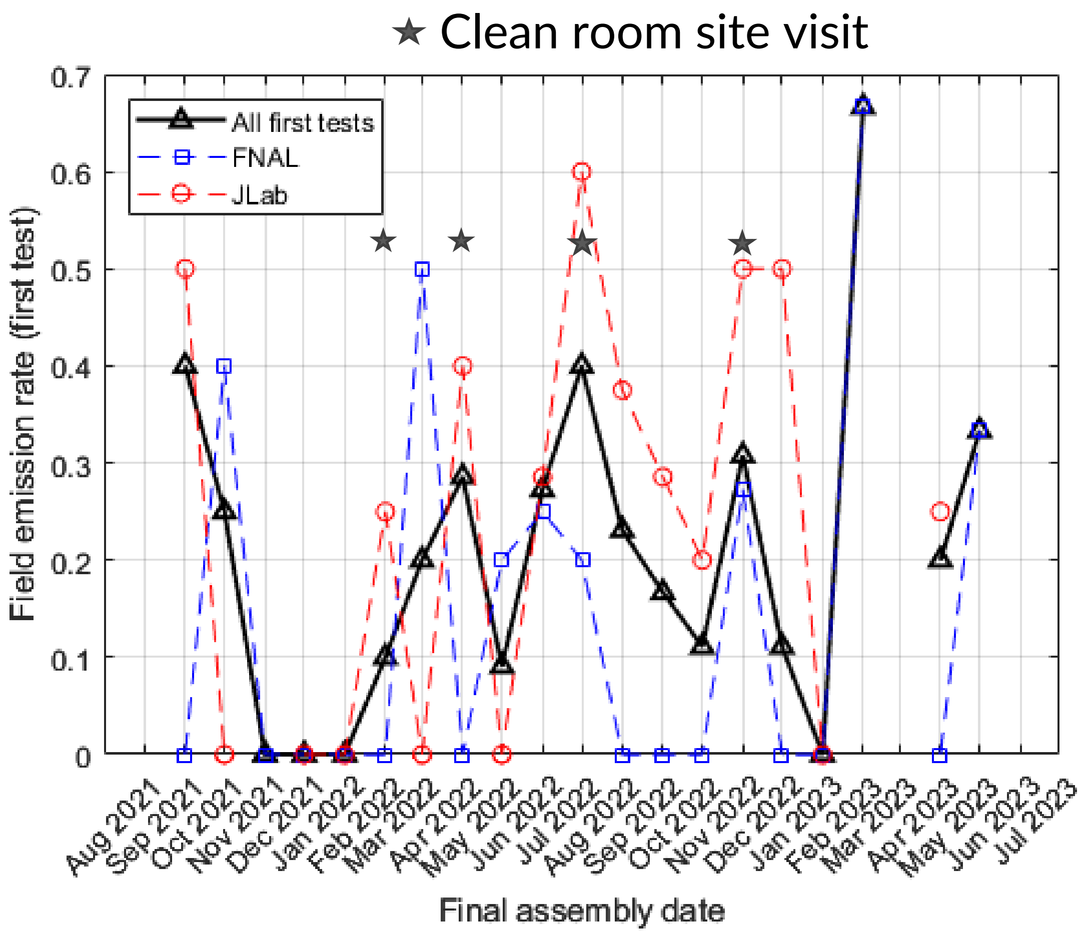
Vertical test performance so far – E_{acc} and Q_0





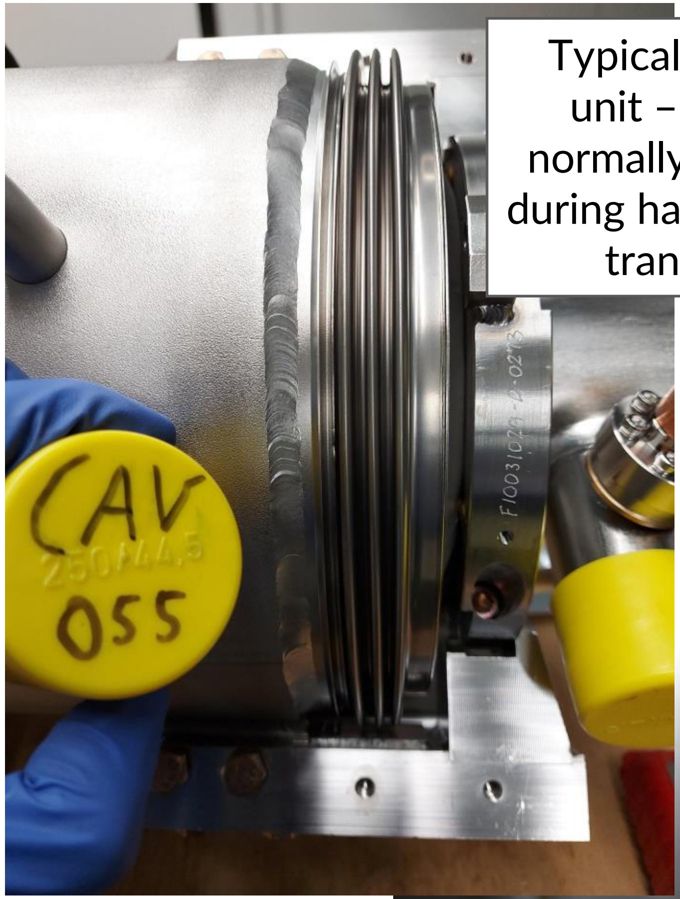
Cavity production challenges – field emission radiation

- Early and continuing issue
  - 40% of initial cavities had FE in first vertical test
  - Has been a recurring issue, similar long-term average rate to LCLS-II (20%)
    - Higher E_{acc} for LCLS-II-HE means we are likely cleaner now than in earlier project
  - High pressure rinsing (HPR) has removed FE in some cavities (29 of 38 so far)
  - Some FE may be due to issues at labs
- Site visits
  - Initial visit to evaluate clean room practices & recommend changes
  - Periodic follow-on site visits
- Rework at cavity supplier
  - 2 FE cavities included in rework plan

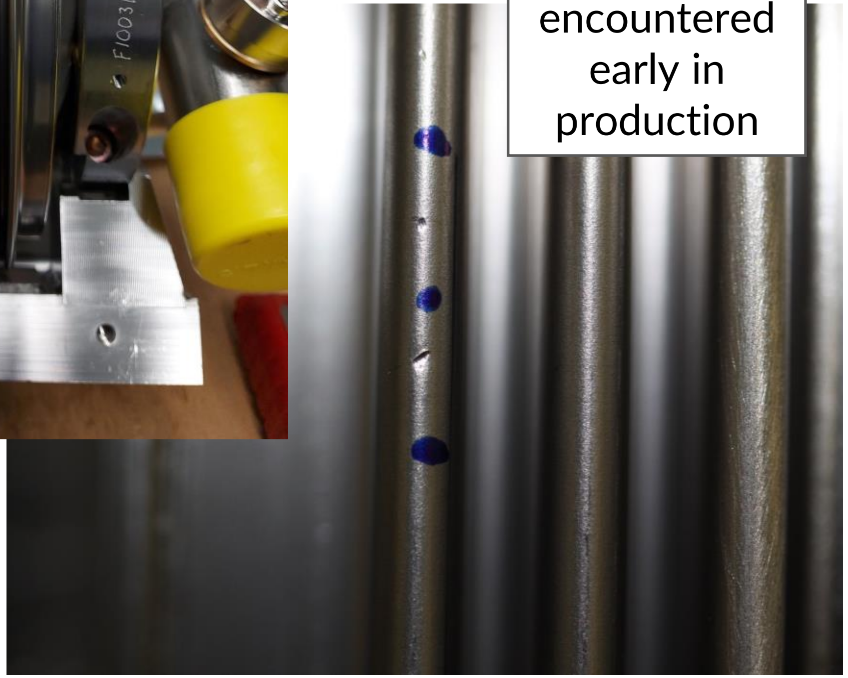


Cavity production challenges – bellows damage

- Damage at supplier and laboratory to ~8% of cavities
  - Delicate external bellows is a weak point in the LCLS-II/LCLS-II-HE cavity design
  - Problem early in production despite using incumbent vendor (“rusty” technicians; loss of expertise/training)
  - Damage also caused due to mishandling at the laboratories
- Schedule and cost impact
  - Several months total delay to shore up deficient procedures at supplier and lab
  - Cost to repair cavities damaged after receipt
- Mitigations effective but imperfect
  - External covers and retraining only go so far



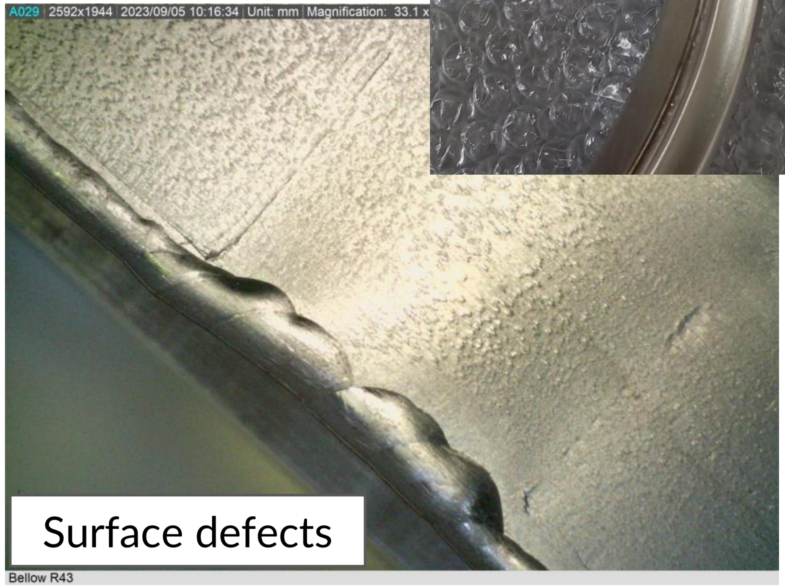
Typical bellows unit – covers normally installed during handling and transport



Damage encountered early in production

Cavity production challenges – further bellows issues

- Incumbent bellows supplier not willing to continue supply
  - Cavity supplier could not reach an agreement with incumbent supplier
- Quality issues with new supplier
  - Many months of prototyping and QA/QC to produce acceptable parts
  - Titanium supply chain issues caused further delays
  - Parallel effort to identify another supplier took very long, quality issues resolved first.
- Good quality achieved after 5-6 months
  - Additional QC in place at cavity supplier



Cavity production challenges – weak vacuum

- Cavities found in a state of "weak vacuum" at time of string assembly
  - Vacuum well below atmosphere but above acceptance level (1e-3 – 1e-1 torr)
  - 9 cavities encountered so far (7 FNAL, 2 JLab)
  - All > 3.5 months with static vacuum
  - 7 had last vacuum pulled at supplier; 2 at labs
- Root cause study in progress
  - Strongly suspected: VAT right angle valves
    - Not rated for cryogenic use; known to develop intermittent leaks
    - Does anyone know of a different valve type that is rated for particle-free UHV *and* cryo use?
  - Also suspected: other re-used cavity accessories (burst disks, etc.)
  - Leak checking has been inconclusive
  - Ongoing "sleeper" issue – likely that this will be encountered again as work continues

Cryomodule assembly and testing in progress

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	08/16/23	08/21/23	10/13/23
F1.3-25	01/23/23	03/01/23	03/24/23	03/29/23	04/21/23	08/10/23	12/06/23	12/11/23	01/31/24
F1.3-26	03/05/24	04/04/24	05/06/24	05/14/24	05/22/24	08/22/24	09/23/24	09/28/24	11/01/24
F1.3-27	05/03/23	06/13/23	07/11/23	07/14/23	08/07/23	10/30/23	01/17/24	01/22/24	02/28/24
F1.3-28	07/27/23	08/25/23	09/19/23	09/21/23	10/30/23	12/20/23	02/29/24	03/05/24	04/10/24
F1.3-29	12/13/23	01/18/24	02/20/24	02/28/24	03/22/24	05/14/24	06/13/24	06/18/24	07/25/24
F1.3-30	01/25/24	02/27/24	03/28/24	04/05/24	04/30/24	07/03/24	08/02/24	08/07/24	11/01/24
F1.3-31	02/29/24	03/26/24	05/06/24	06/06/24	06/14/24	07/10/24	08/23/24	08/28/24	11/15/24
F1.3-32	04/16/24	06/14/24	07/17/24	07/25/24	08/19/24	12/03/24	01/07/25	01/12/25	02/11/25
F1.3-33	07/16/24	08/15/24	09/17/24	09/25/24	10/18/24	01/28/25	02/27/25	03/04/25	04/02/25
J1.3-22	07/19/24	08/16/24	10/14/24	11/04/24	03/03/25	04/14/25	05/06/25	05/11/25	06/17/25
J1.3-23	08/16/22	09/12/22	02/28/23	03/15/23	07/31/23	11/17/23	01/09/24	01/15/24	02/19/24
J1.3-24	11/22/22	01/25/23	05/05/23	05/31/23	10/17/23	01/10/24	02/02/24	02/07/24	03/15/24
J1.3-25	04/20/23	06/05/23	09/20/23	10/19/23	01/09/24	02/23/24	03/18/24	03/23/24	04/26/24
J1.3-26	07/13/23	08/28/23	11/27/23	01/04/24	03/07/24	04/18/24	05/10/24	05/15/24	06/21/24
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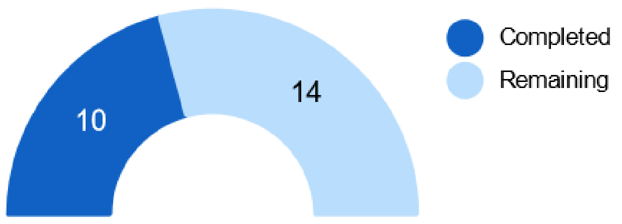
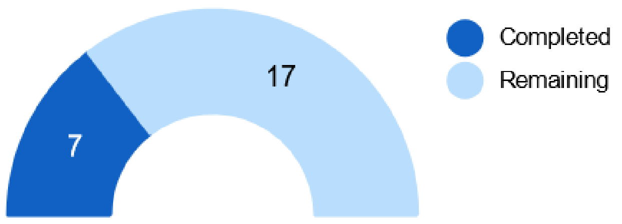
J1.3-28	12/08/23	01/22/24	03/19/24	04/09/24	06/28/24	10/08/24	10/30/24	11/04/24	12/12/24
J1.3-29	01/30/24	02/28/24	04/24/24	05/23/24	08/26/24	11/19/24	12/13/24	12/18/24	02/07/25
J1.3-30	03/27/24	04/24/24	06/20/24	07/22/24	10/22/24	01/16/25	02/10/25	02/15/25	03/24/25
J1.3-31	05/22/24	06/20/24	08/16/24	09/17/24	12/19/24	03/03/25	03/25/25	03/30/25	05/05/25

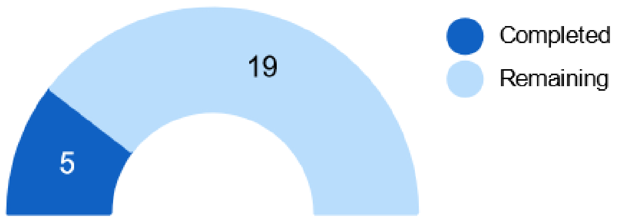
CMs Assembled (24 total)



CMs Tested (24 total)



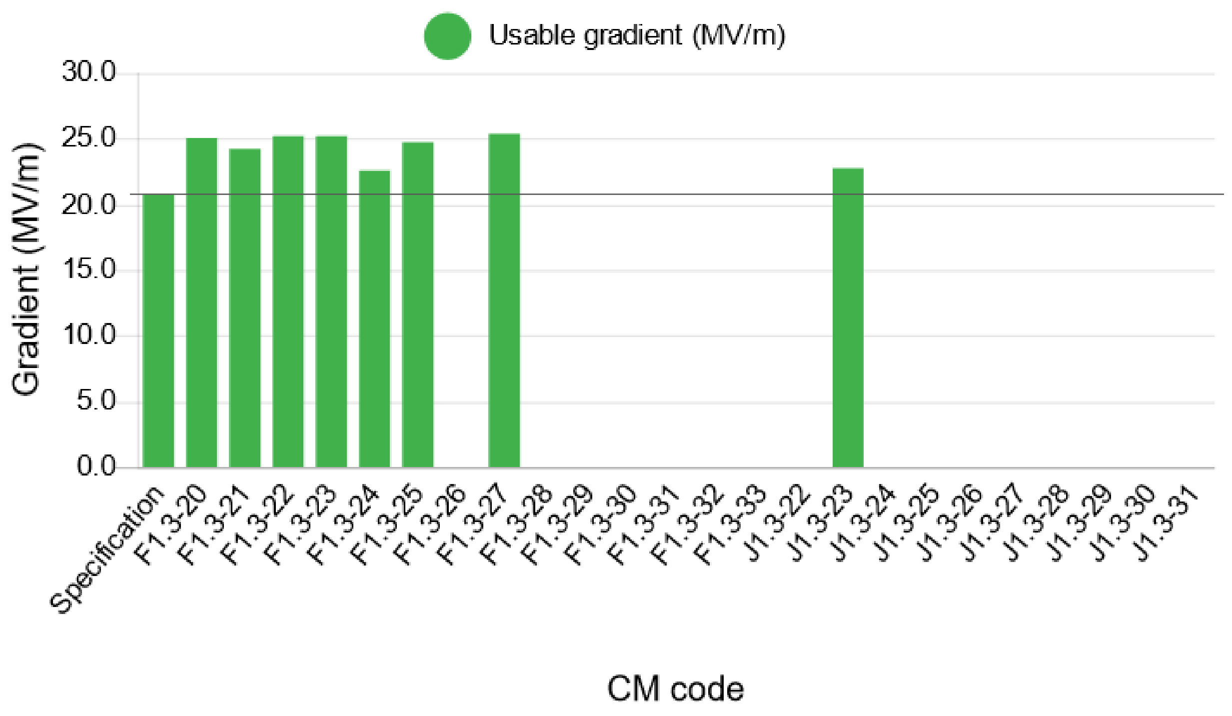
CMs Stored (24 total)



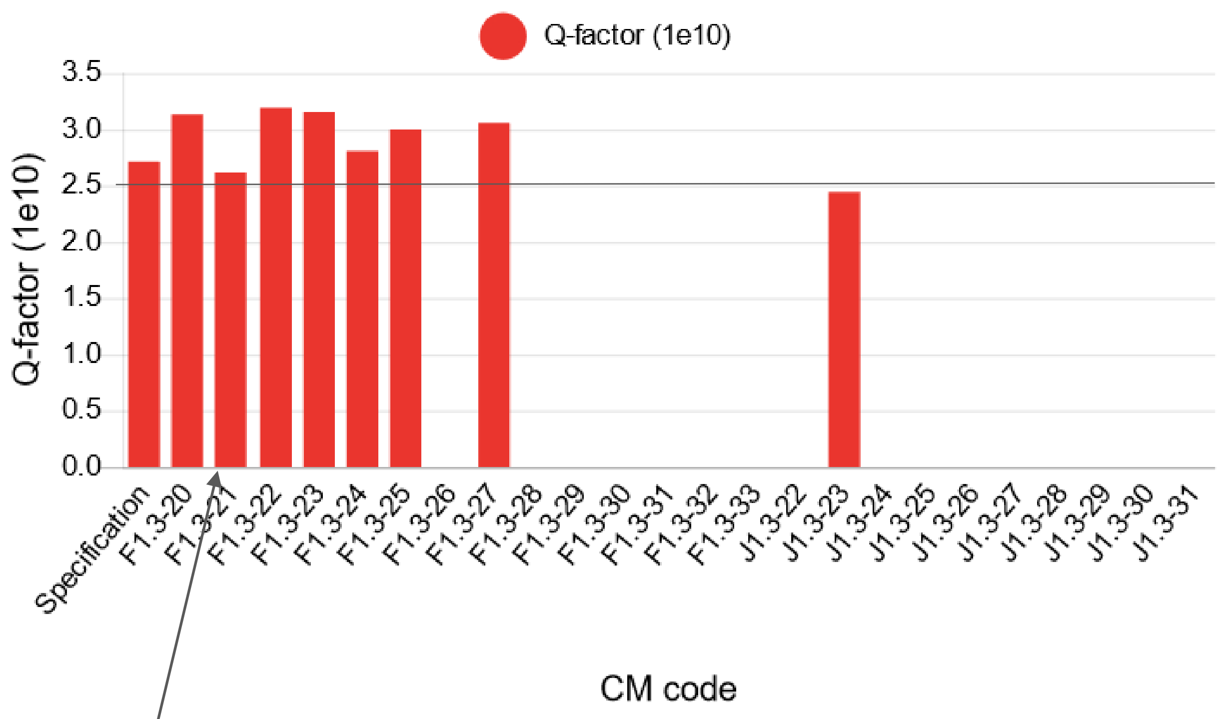
Cryomodule assembly and testing in progress

Average Usable Gradient (MV/m)	Average Usable Voltage (MV)	Average Q-factor (1e10)
24.3	203	2.9

CMs Usable Gradient Summary

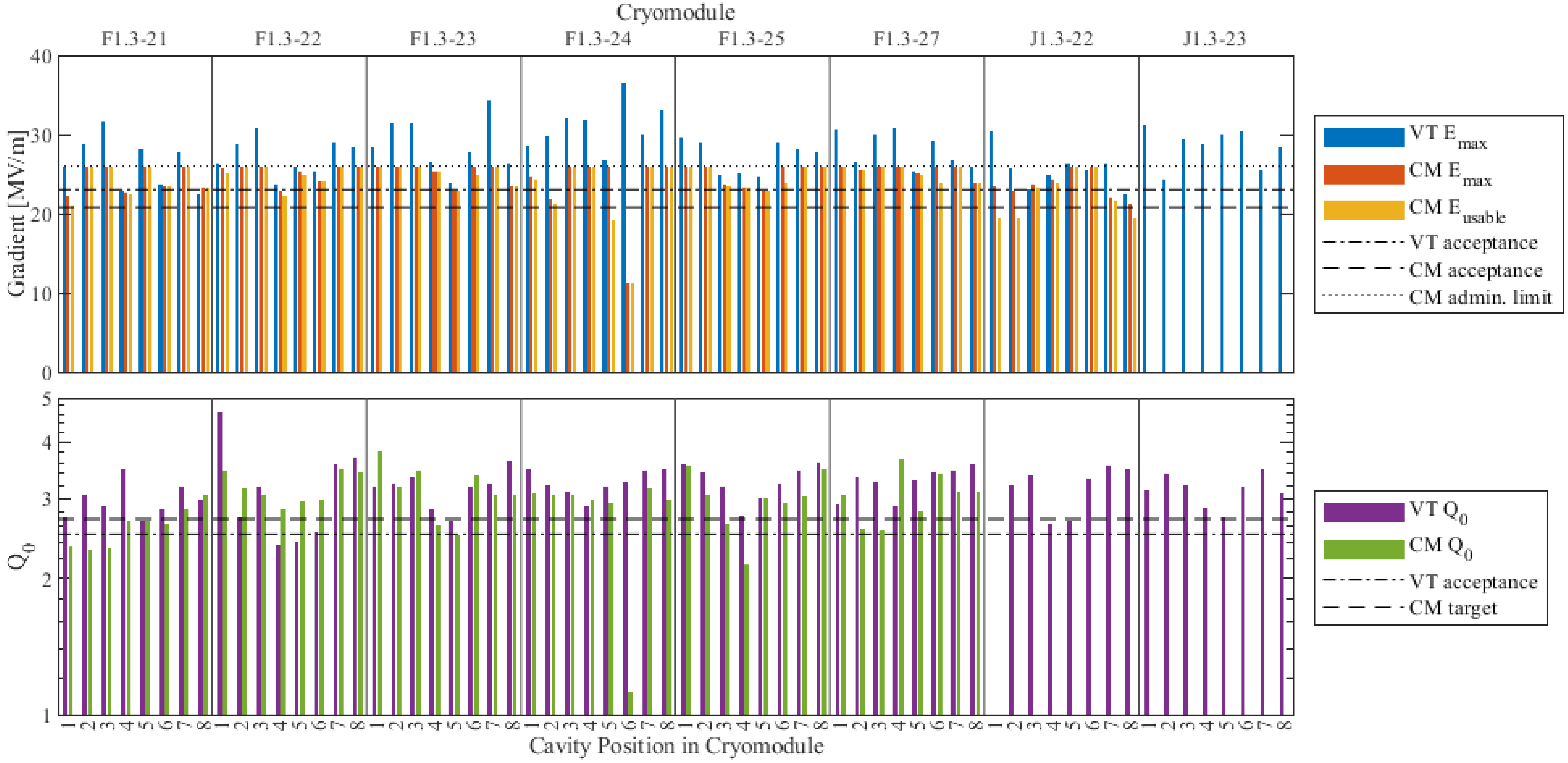


CMs Q-factor Summary



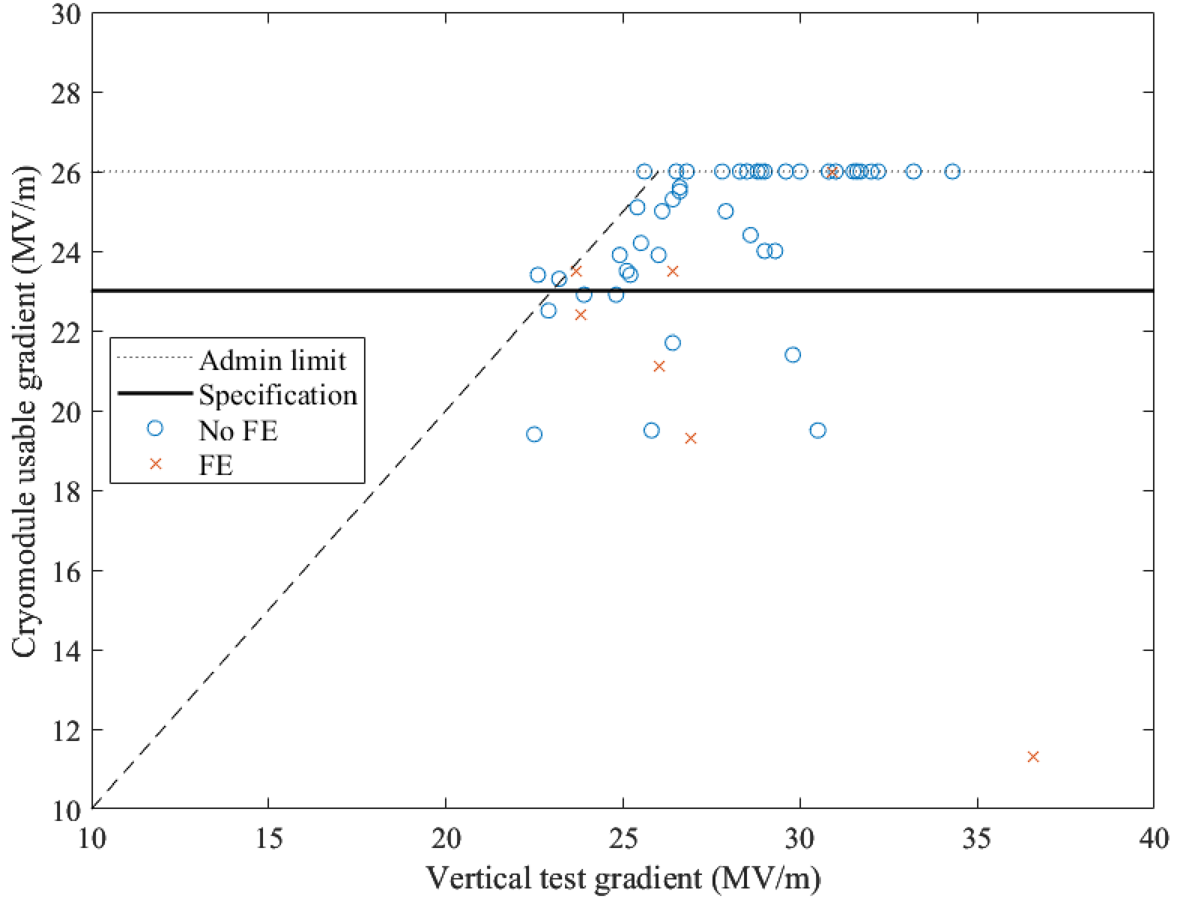
F1.3-21 built using recovered LCLS-II cavities

Cavity performance in cryomodules

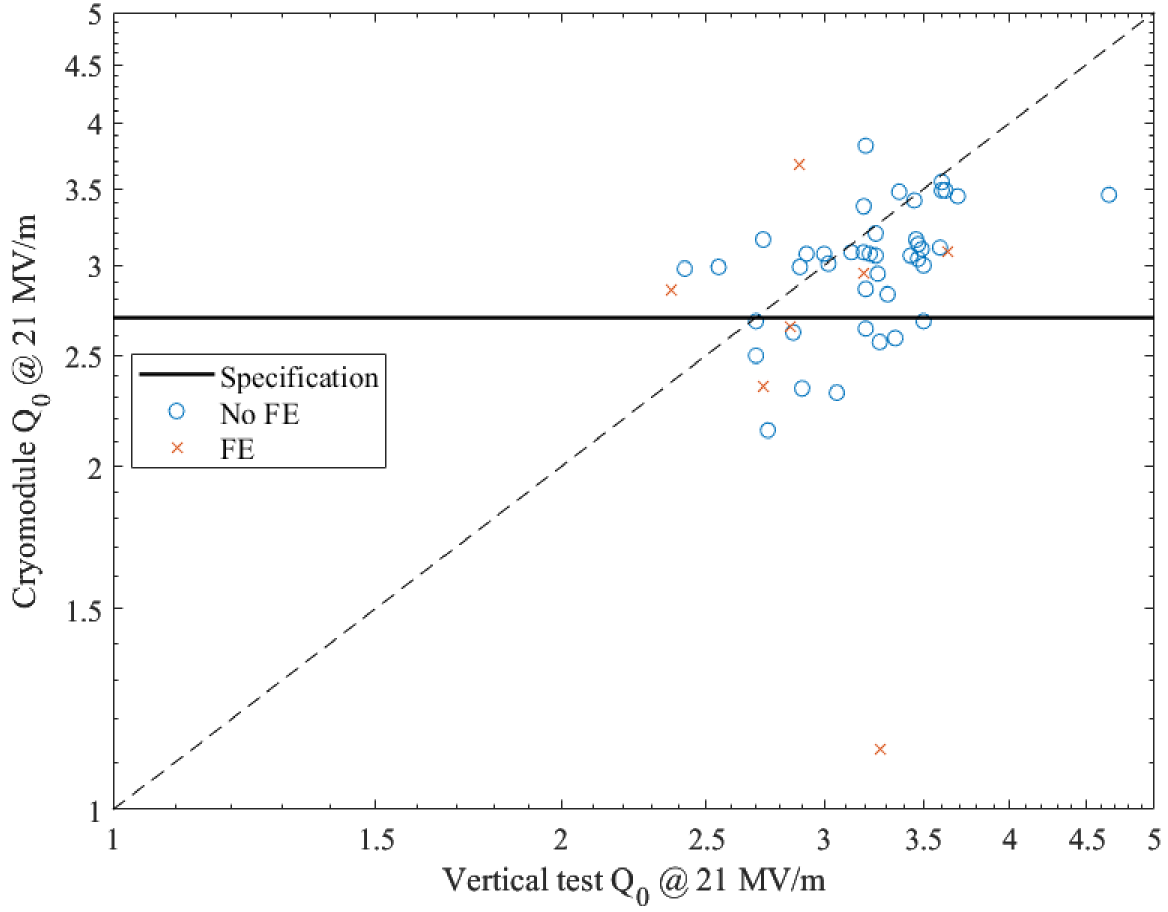


Cavity performance in cryomodules

Accelerating gradient



Quality factor @ 21 MV/m



ΔE_{acc} = 2.7±2.8 MV/m

Excluding field emission and administrative limits

ΔQ_0 = 2.1±3.8×10^9

Cryomodule issues

- Field emission encountered in approximately 13% of cavities
  - 2 worst cases caused by off-normal work to repair damaged beamline bellows
  - No root cause determined for other cases
  - No captured dark current detected so far, only X-rays
- Partial rebuilds to correct other issues
  - Another case of damaged beamline bellows
    - Lessons learned from first case → revised disassembly scheme & requalification of cavities
  - Beamline leak
    - Leak localized to field probe feedthrough; full rebuild required
    - Leak only appeared after > 6 thermal cycles! Will be investigated after disassembly.
  - Chipped FPC ceramics
    - Rebuild required
  - We are taking a conservative approach, prioritizing quality over schedule.

Outlook

- 13 of 192 production cavities remaining to be delivered
  - Final delivery coming in May 2024
- 13 rework cavities to be delivered Dec 2023 – Feb 2024
- Vertical test qualification to continue through June/July 2024
- Cryomodule assembly and test to continue through mid 2025
- Installation scheduled to start Summer 2025

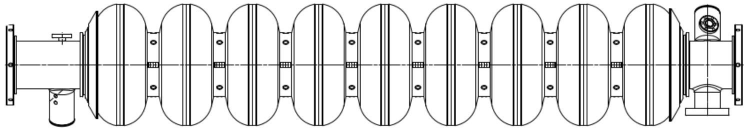
Thank you

Backup slides

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

Bare 1.3 GHz LCLS-II/LCLS-II-HE cavity



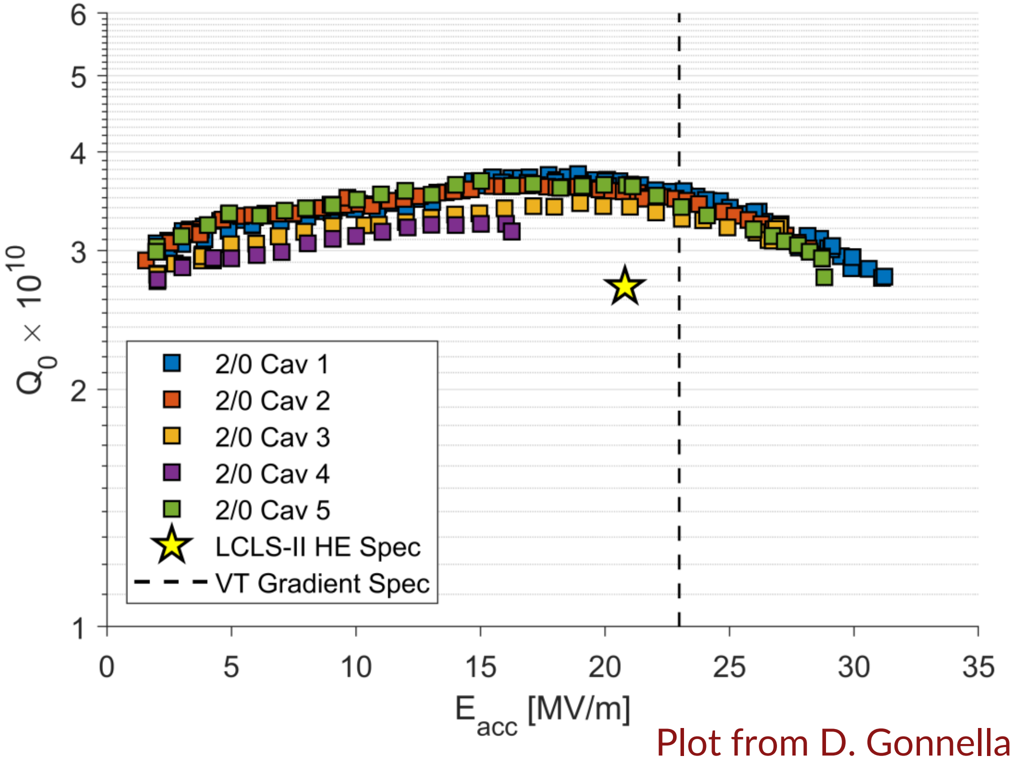
Quantity	LCLS-II Cavities	LCLS-II Cavities in HE	HE Cavities in HE	Unit
Number of 1.3 GHz cavities	280	280	193†	
Minimum average cavity Q_0 at nominal E_{acc}	2.7	2.7	2.7	10^{10}
Vertical test qualifying gradient	19		23	MV/m
Assumed fraction of failed cavities	6	3	6	%
Nominal average operating gradient	15.7 in L2-3	16.9 in L2-3	20.8	MV/m
Vertical test field emission onset min.	17.5		No FE allowed	MV/m
Maximum CM captured dark current	10	10	30	nA

† includes injector CM (8) and BCC (1)

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
    - Challenge: long lag between vendor activities and cavity tests (2-3 month minimum)
- New "2N0" recipe chosen
  - Update to LCLS-II "2N6" recipe
  - R&D results:
    - 4 of 5 cavities exceeded 30 MV/m
    - Average Q_0(21 MV/m) ≈ 3.5×10^{10}

2N0 R&D results (9-cell cavities)



Plot from D. Gonnella

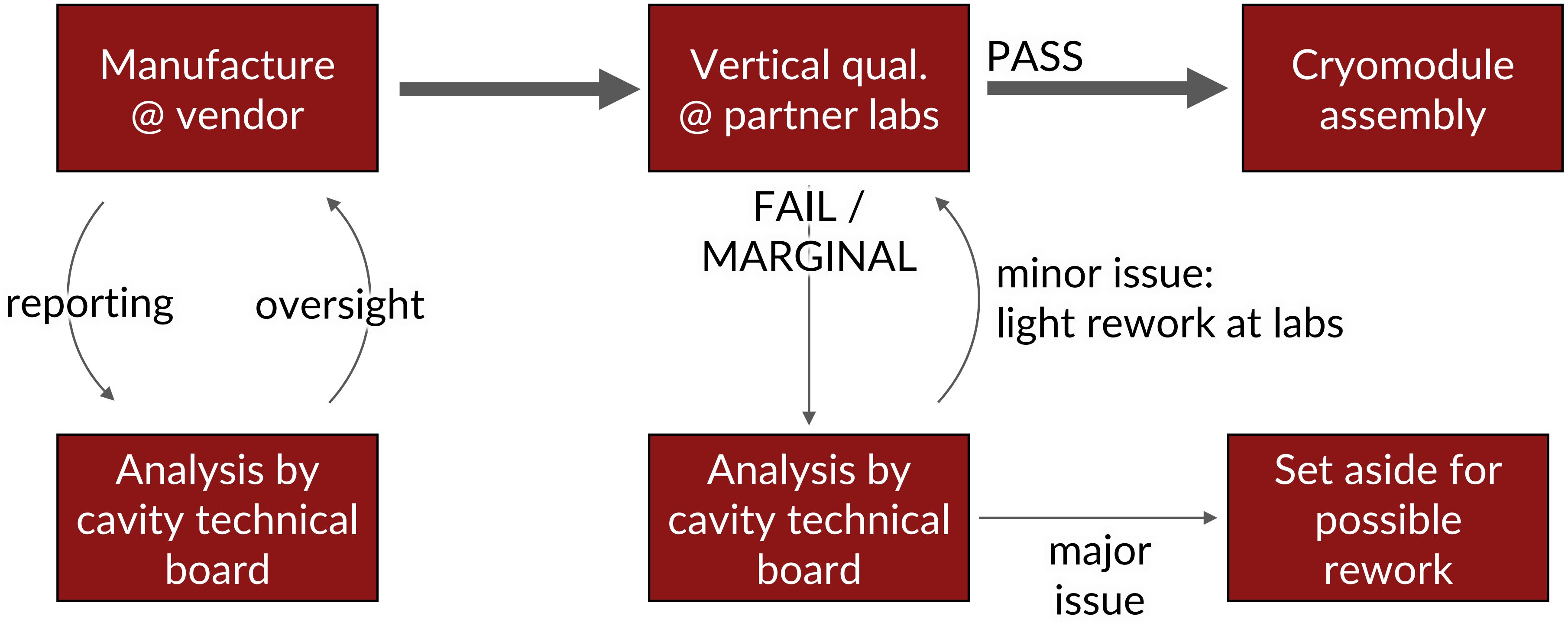
LCLS-II-HE recipe

LCLS-II	LCLS-II-HE
Bulk EP	Bulk EP 1
High Temperature Furnace Treatment & Doping (2N6)	High Temperature Furnace Treatment
	Bulk EP 2 (last portion cold)
	Doping (2N0)
Fine EP	Fine EP (all cold)

- Additional changes:
  - Require continuous RGA spectrum during furnace runs
  - Require continuous monitoring of temperatures during electropolishing runs
  - Sort cavity half-cell material by required heat treatment temperature

LCLS-II-HE cavity scope

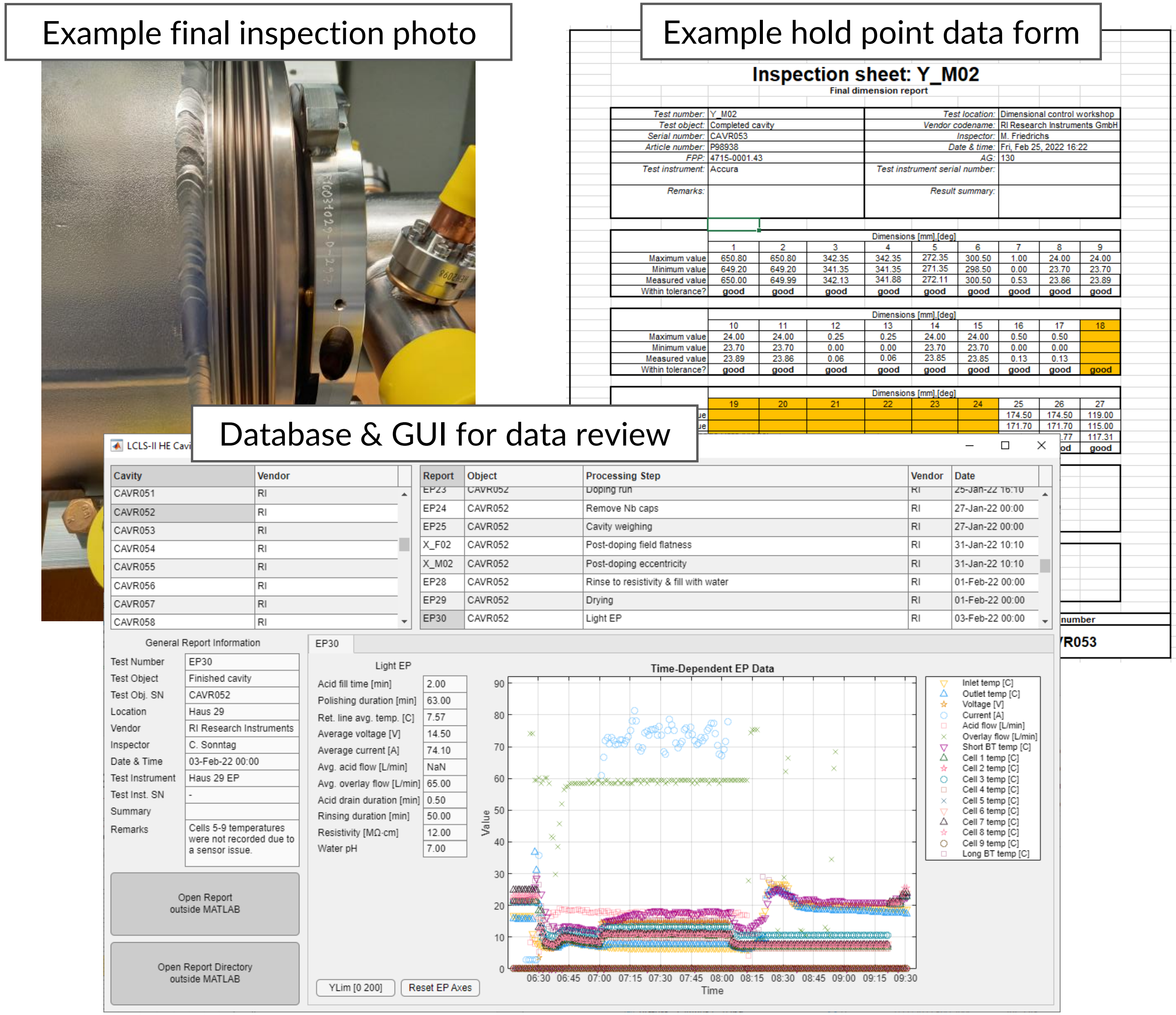
- 10 qualification + 168 main production + 24 additional cryomodule cavities ordered from an industrial vendor in Europe, following competitive bid process
  - Qualification cavities went into "verification cryomodule" (vCM)
- Cavity qualification testing overseen by Cavity Technical Board (CTB)



CTB: SRF experts from SLAC, JLab, and FNAL

Cavity hold point data (some examples)

- Mechanical measurements
  - CMM reports
  - Eccentricity
- Frequency & field measurements
  - Passband modes
  - 9x9 field flatness measurements
- Process data
  - Furnace temps and RGA
  - EP temps, voltage, current
  - Assembly particle counts
- Other inspections
  - Final visual inspection
  - Weld reports
- ~16 MB per cavity + photos



LCLS-II-HE cavity timeframes

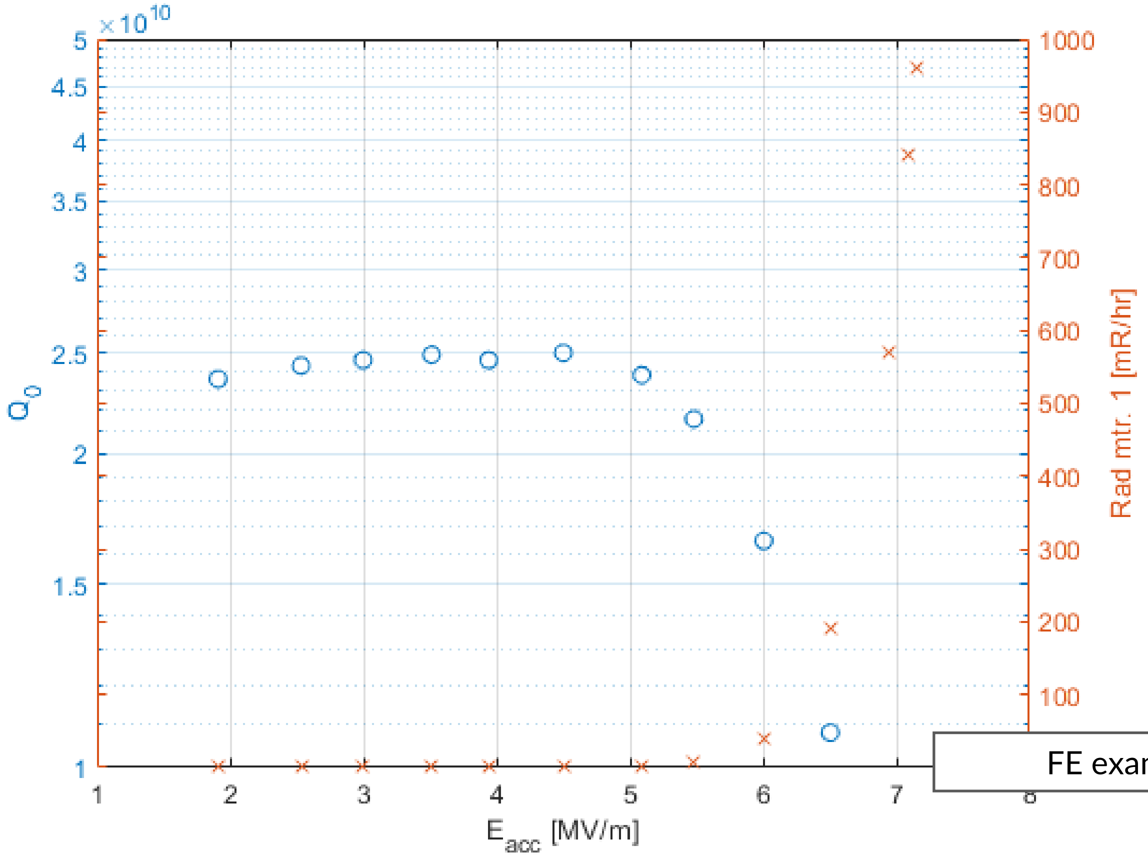
- Mechanical fabrication begins: t=0
- Bare 9-cell cavity complete: 6 months
  - Hold Point 1 data submitted and reviewed
- Steps through doping: +1 month
  - Hold Point 2 data submitted and reviewed
- Steps through final assembly: +1.5-2 months
  - Hold Point 3 data submitted and reviewed
- Shipping: +2 weeks
- First vertical test: +1 week – 3 months
  - Prioritization scheme in place to ensure new and old cavities tested
- High pressure rinse and retest: +1-2 months

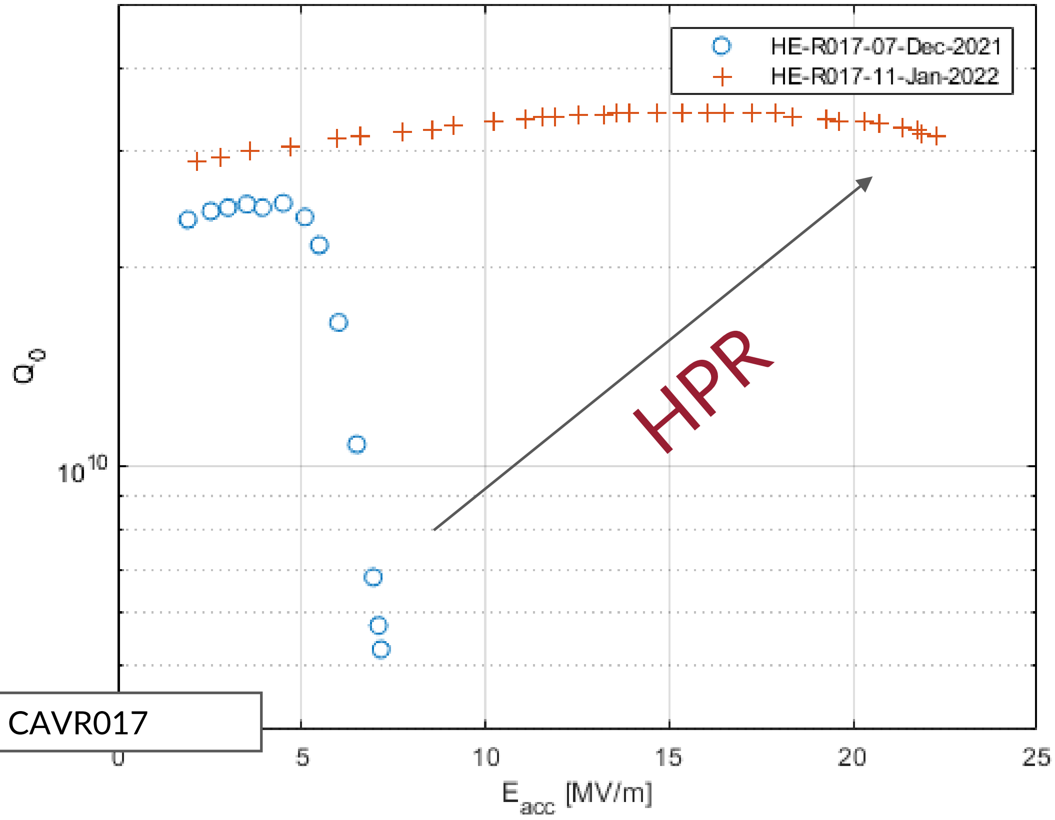
Timely review of process/hold point data is crucial for identifying production issues

Vertical qualification testing – requirements

- Gradient: $E_{acc} \geq 23$ MV/m
- Quality factor: Q_0(21 MV/m) $\geq 2.5\times10^{10}$
  - VT stainless steel flange R = 0.8 nΩ
- HOM coupling: $Q_{ext} > 2.7e11$
- HOM power: P_{HOM}(21 MV/m) < 1.7 W
- Field emission: no detectable FE up to quench
- Frequency: f = 1300.25±0.10 MHz
- Field probe coupling: $2.5\times10^{11} < Q_{ext} < 7.0\times10^{11}$
- Multipacting: *fully processed before final Q vs. E*
- 7π/9 mode: *avoid mode buildup → quick measurements*

High pressure rinse to mitigate field emission





FE example: CAVR017