LCLS-II HE Status and R&D

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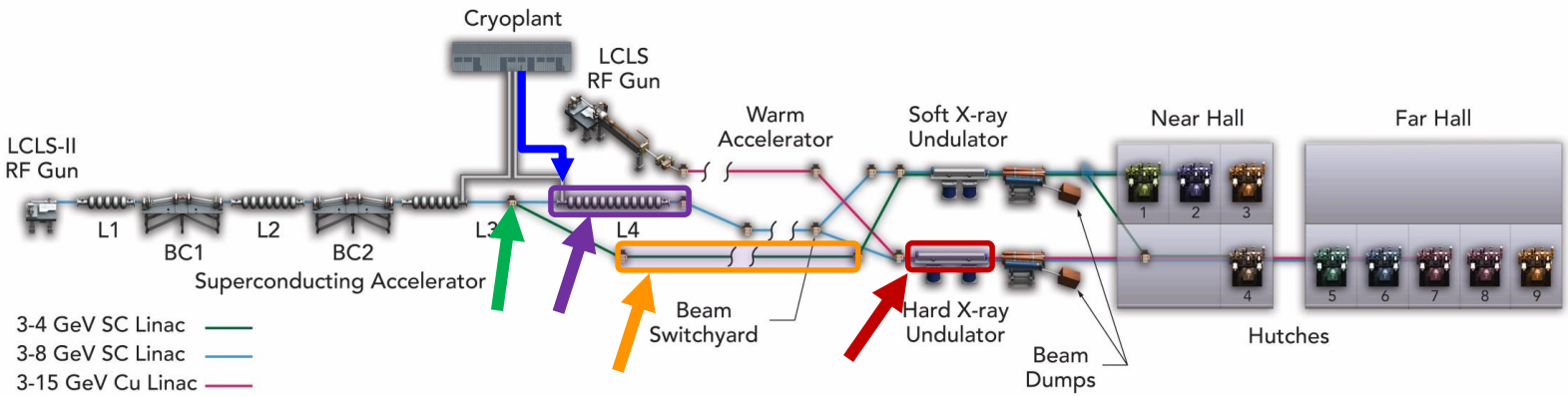
SLAC NATIONAL ACCELERATOR LABORATORY

Fermilab Jefferson Lab

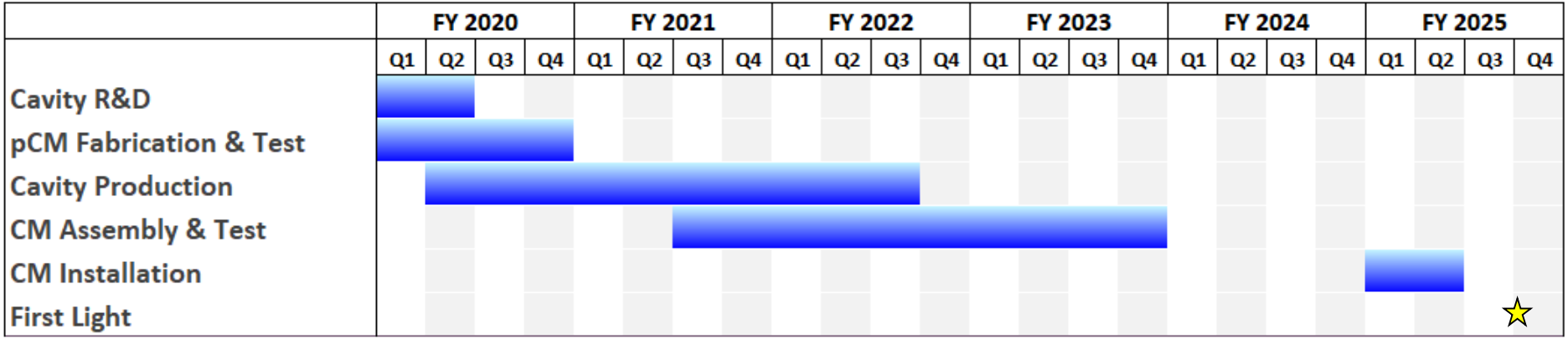
U.S. DEPARTMENT OF ENERGY | Stanford University

LCLS-II HE Scope



1. Add 20 additional cryomodules (L4 linac) to increase the LCLS-II accelerator energy to 8 GeV.
2. Install new cryogenic distribution box and transfer line between the cryoplant and the new L4 linac.
3. Add low-energy extraction point at 3.8 GeV to enable quasi-independent operation of the soft-X-ray and hard-X-ray programs.
4. Use existing transport line to bypass downstream linacs and install new dump in the beam switch yard
5. Install high rep-rate Hard X-ray Self Seeding capability in the hard X-ray undulator

LCLS-II HE Project Schedule



- Cavity production begins early in the new year
- Prototype cryomodule will be tested next summer with new recipe cavities
- CM assembly begins early 2021

LCLS-II HE Requirements

1.3-GHz Superconducting Cavities	LCLS-II	LCLS-II-HE	Unit
Cavities per cryomodule	8	8	-
Active length 1.3-GHz cavity	1.038	1.038	m
1.3 GHz LCLS-II Style Cavities	280	280	-
1.3 GHz LCLS-II-HE Style Cavities	**--**	**160**	**-**
Specified average cavity Q_0	> 2.7	> 2.7	10^{10}
~~Specified LCLS-II cavity *qualifying* gradient~~	~~13~~	~~13~~	~~MV/m~~
~~Specified LCLS-II cavity average *operating* gradient~~	~~16~~	~~18~~	~~MV/m~~
Specified LCLS-II-HE cavity *qualifying* gradient	**--**	**23**	**MV/m**
Specified LCLS-II-HE cavity average *operating* gradient	**--**	**20.8**	**MV/m**
~~Specified LCLS-II cavity field emission *onset*~~	~~17.5~~	~~17.5~~	~~MV/m~~
Specified LCLS-II-HE cavity field emission *onset*	**--**	**--**	**MV/m**
Max. RF power per 1.3-GHz LCLS-II cavities	4.2	4.2*	kW
Max. RF power per 1.3-GHz LCLS-II-HE cavities	**--**	**7.0**	**kW**
RF cavity detuning (see avg. current)	10	10	Hz

- The Q_0 specification is the same as in LCLS-II, but at 21 MV/m
- ***Qualifying* gradient** in vertical test is 23 MV/m
- ***Cutoff* gradient** will be defined at the conclusion of the R&D program
  - Follows the logic from LCLS-II gradient definitions Cavities that do not reach qualifying gradient can still be used as long as an average of 21 MV/m in the CM can be achieved

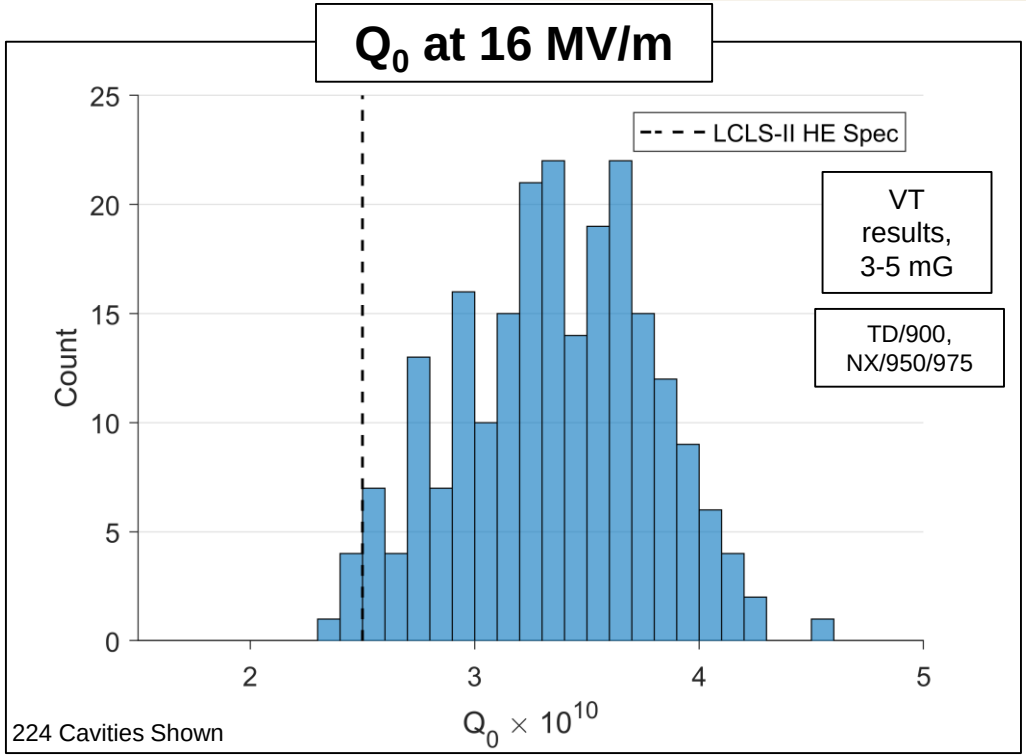
LCLS-II and LCLS-II HE Requirements

Parameter	LCLS-II	LCLS-II HE
# 1.3 GHz CMs	35	20
Operating Gradient	16 MV/m	20.8 MV/m for new CMs 18 MV/m for old CMs
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}**

LCLS-II Results: Q_0 at HE Gradient

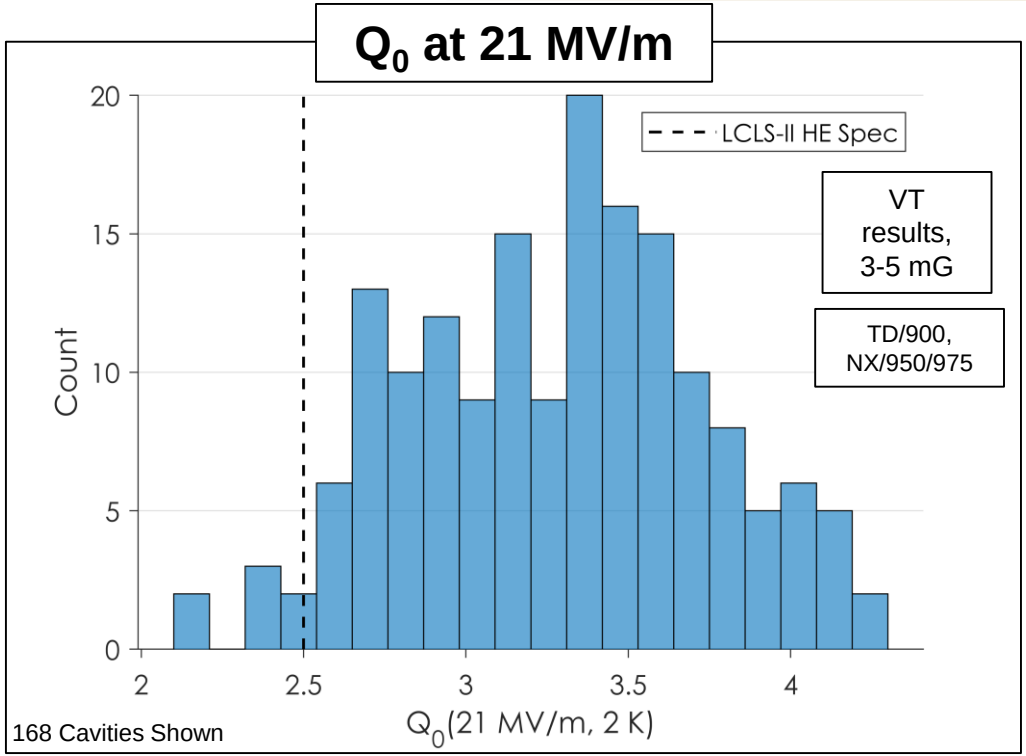


Gradient	$<Q_0>$
16 MV/m	3.3×10^{10}

- Nearly all cavities made with "good" material have Q's above the LCLS-II spec at 16 MV/m

Note that the spec has been adjusted to 2.5×10^{10} to account for flange losses present in VT

LCLS-II Results: Q_0 at HE Gradient

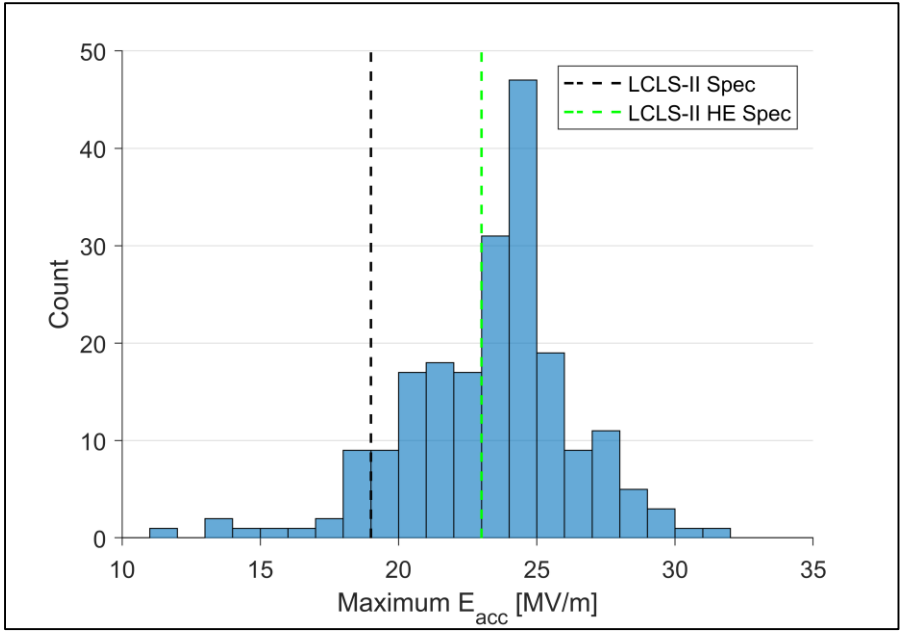


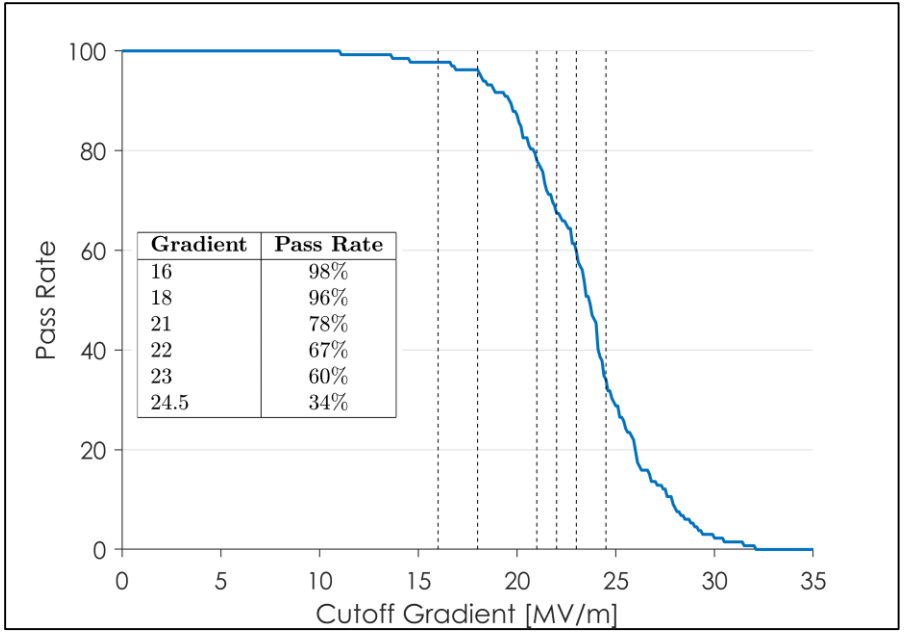
Gradient	$\langle Q_0 \rangle$
16 MV/m	3.3×10^{10}
21 MV/m	3.2×10^{10}

- Nearly all cavities made with "good" material have Q's above the LCLS-II spec at 16 MV/m
- Of the cavities that make it to 21 MV/m, all except for 2 have a Q_0 higher than 2.5×10^{10} at 21 MV/m
- Q_0 in LCLS-II cavities is more than sufficient for HE

Note that the spec has been adjusted to 2.5×10^{10} to account for flange losses present in VT

LCLS-II Results: Gradient





Gradient	Pass Rate
16	98%
18	96%
21	78%
22	67%
23	60%
24.5	34%

Only 60% of LCLS-II cavities exceed the HE VT Gradient Specification

While the average LCLS-II cavity meets HE requirements, the distribution needs to be shifted

Cavity R&D Goals

- In order to meet the requirements of LCLS-II HE, an R&D effort is being carried out
  We will develop a cavity processing method to consistently produce cavities that reach **23 MV/m** in VT with a Q_0 of **2.7×10^{10} at 21 MV/m**
- This effort is being carried out by the three labs that participated in the original LCLS-II R&D: FNAL, JLab, and Cornell University

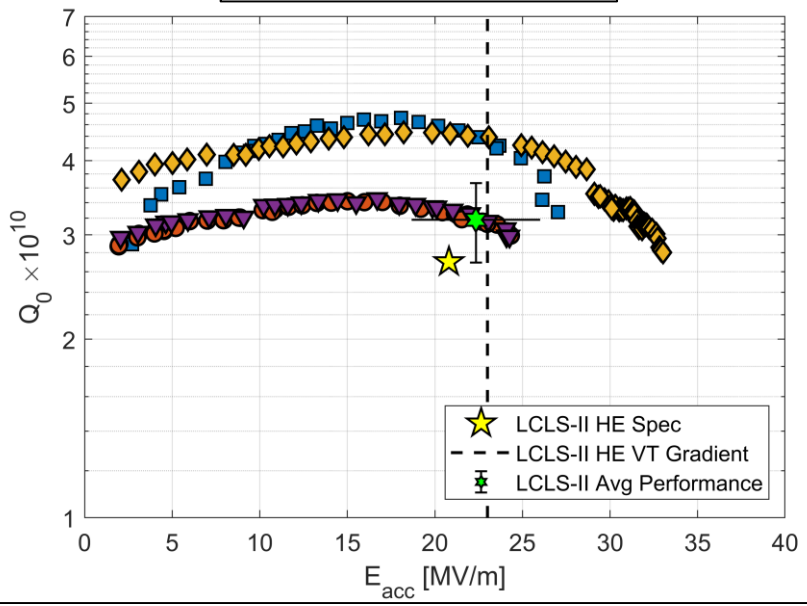
Cavity R&D Program

The cavity R&D program was a 3 prong approach:

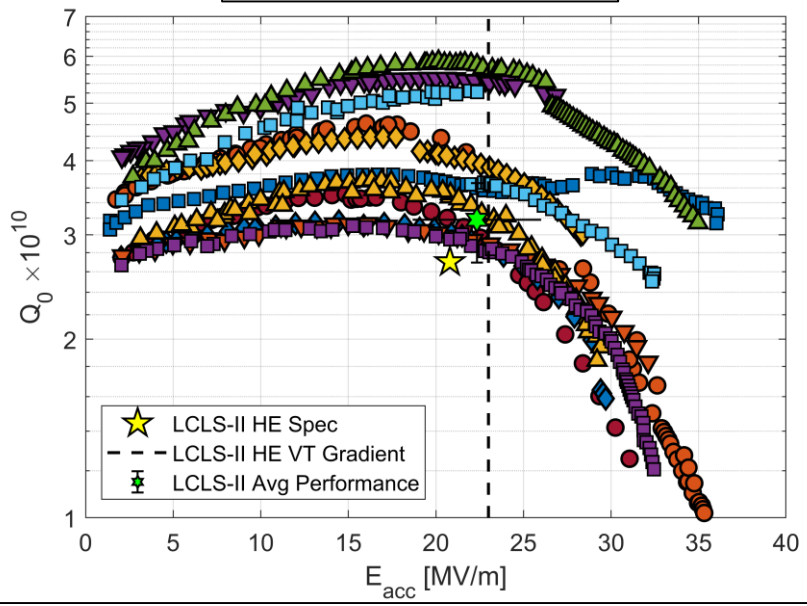
- Development of light nitrogen-dopings (FNAL)
- Development of longer anneal time dopings (JLab)
- Explore the nitrogen- infusion parameter space (Cornell)

Single-Cell Results

2/0 Cavities

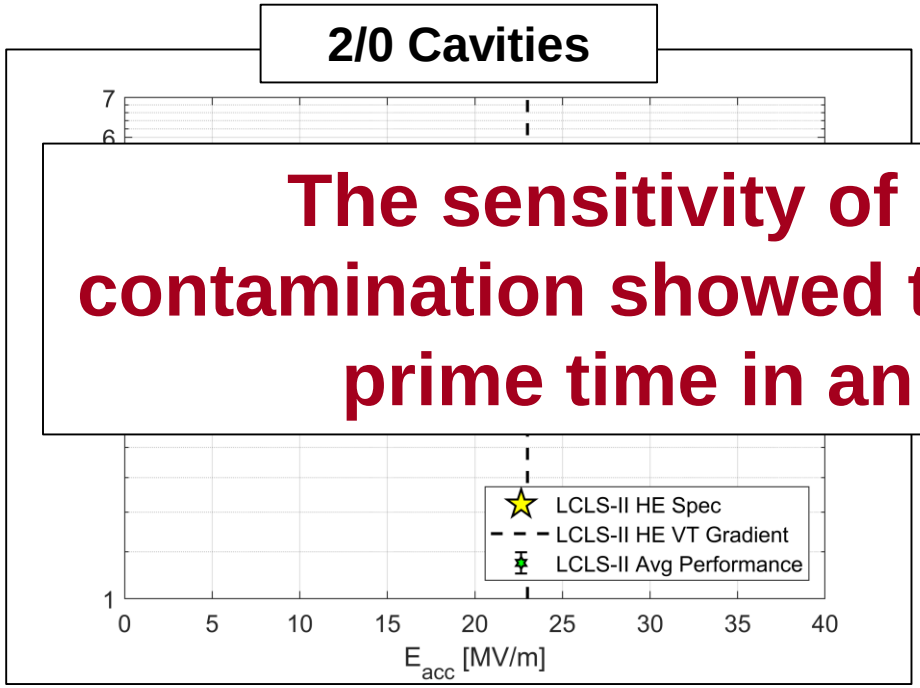


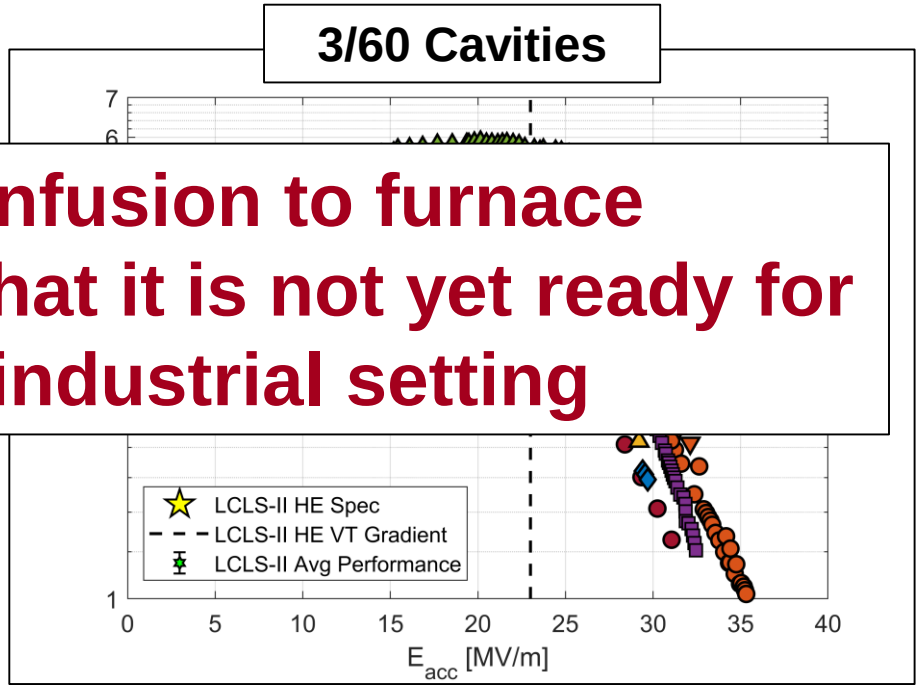
3/60 Cavities



Nearly all single-cell cavities passed LCLS-II HE specification

Single-Cell Results



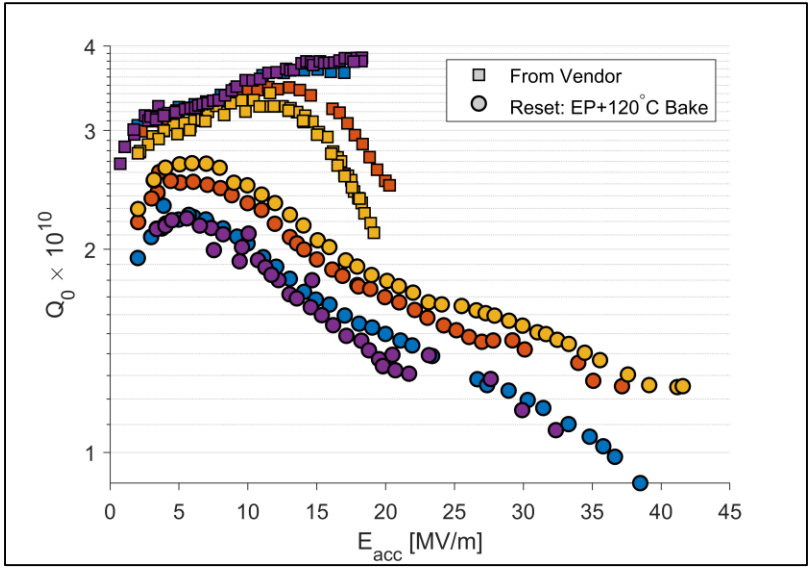


The sensitivity of infusion to furnace contamination showed that it is not yet ready for prime time in an industrial setting

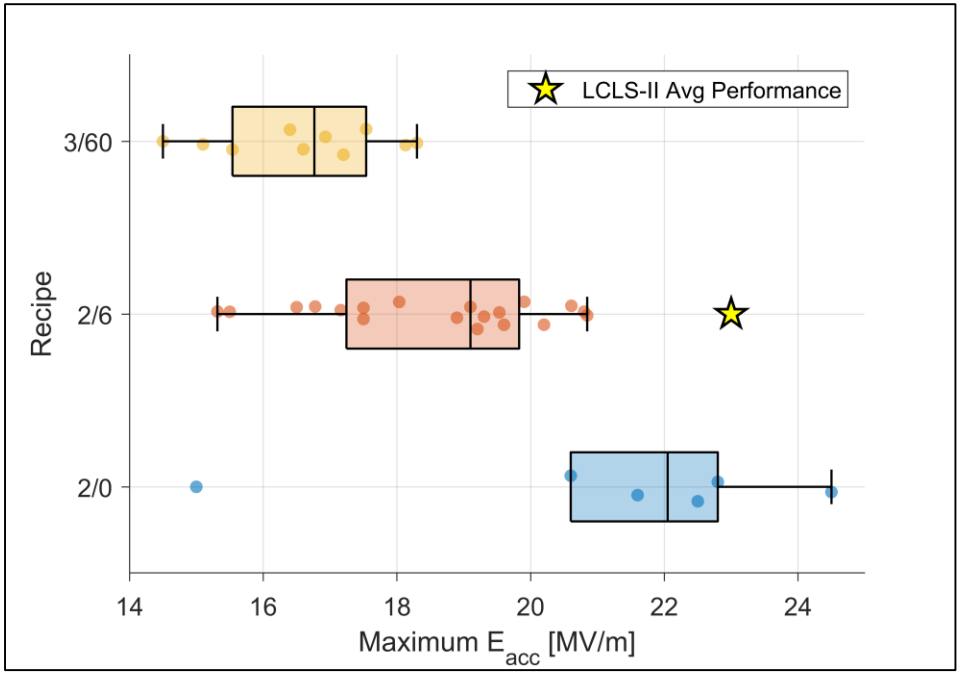
Nearly all single-cell cavities passed LCLS-II HE specification

Transition to 9-cells

- Success on single-cell motivated testing out the new recipes on 9-cells
- 16 cavities were prepared at the cavity vendors with the new recipes
- Unfortunately, results were less than stellar, however upon reset, the cavities showed excellent un-doped performance
- This led into investigations into improving process control during key steps

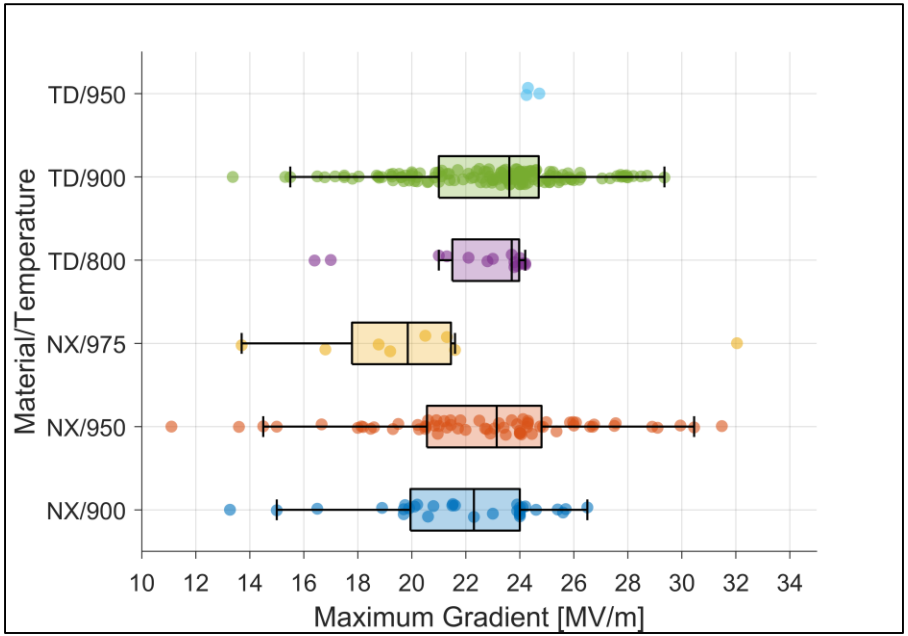


Results of First Round of 9-Cells with New Recipes



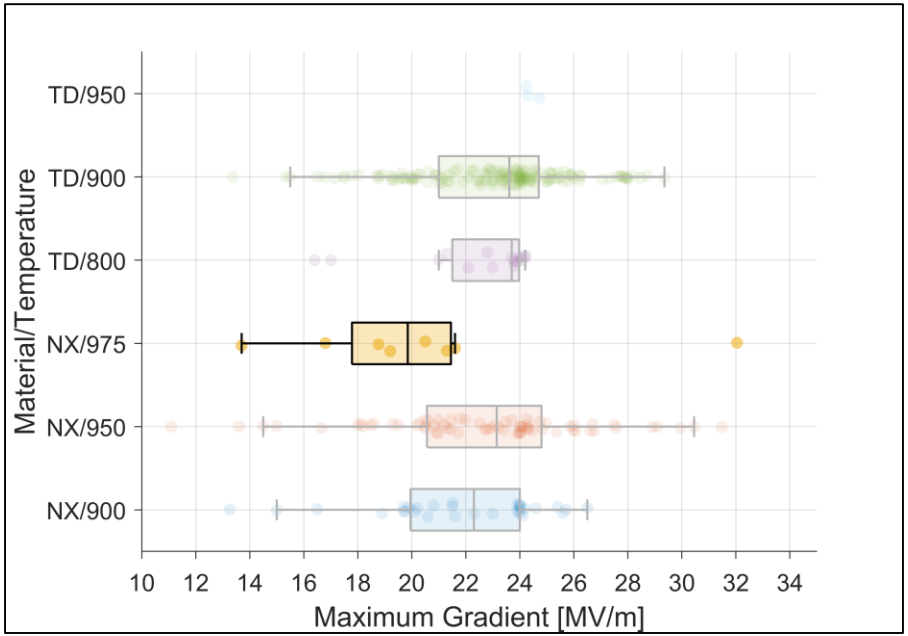
- All 16 of the 9-cell cavities performed worse than expected
- Performance was highly dependent on the exact recipe
- Those treated with LCLS-II 2/6 recipe also performed significantly worse than the LCLS-II average
- Suggests that there was a fundamental issue with the cavities, not the recipe:
  - Either cavity fabrication, EP, or furnace contamination
- Remediation path is in development for use of these cavities in production

Concerns of Furnace Contamination @ High Temperatures



- **NO CORRELATON** between niobium manufacturer and quench field
- Typically no correlation between heat treatment temperature and quench field has been observed

Concerns of Furnace Contamination @ High Temperatures

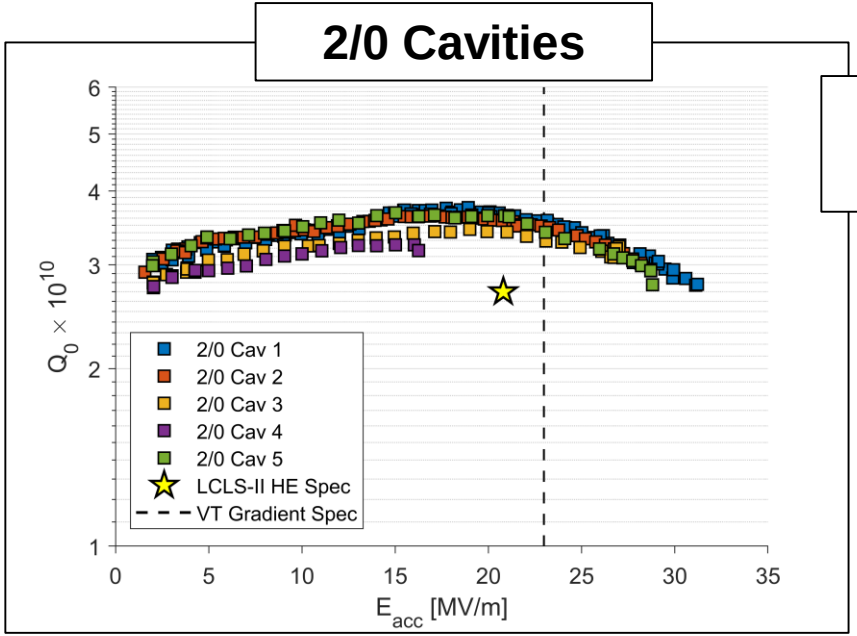


- **NO CORRELATON** between niobium manufacturer and quench field
- Typically no correlation between heat treatment temperature and quench field has been observed
- However, cavities treated **ABOVE 950°C** in one vendor's furnace showed a statistically significant **drop in quench field**
  - Suggests presence of contamination that outgasses above 950°C
  - Likely contributed to some lowering of quench field in cavities shown on last slide

Cold EP

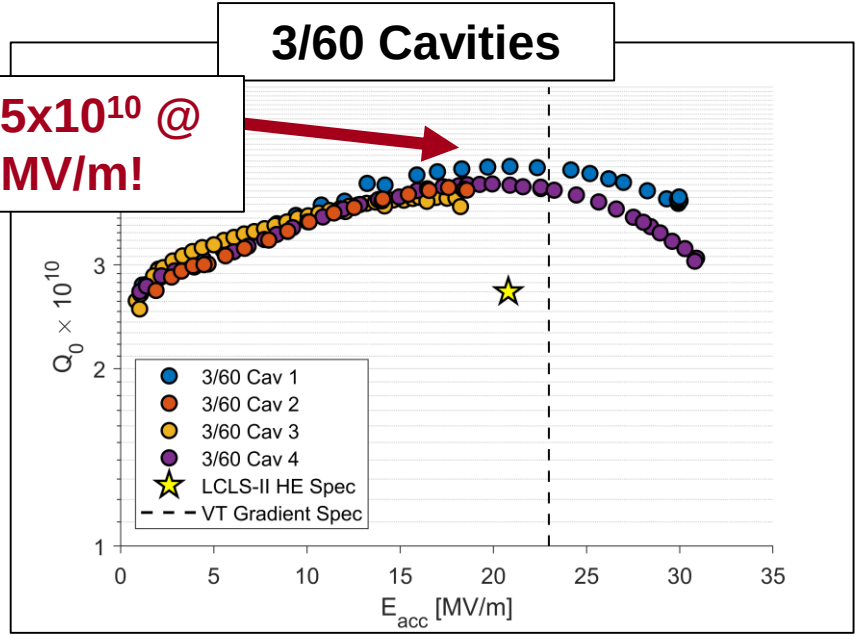
- The key to achieving good performance in 9-cells is now understood to be related to performing very cold EP's
  - This is necessary for the last part of the bulk and the final EP after nitrogen-doping
- For more details see *A. Palczewski* "Electropolishing Studies on N-doped Surfaces - current understanding" in this workshop

9-Cell Results



4 out of 5 2/0 9-cells exceed HE requirements by a large margin!

Q_0>4.5x10^{10} @ 21 MV/m!

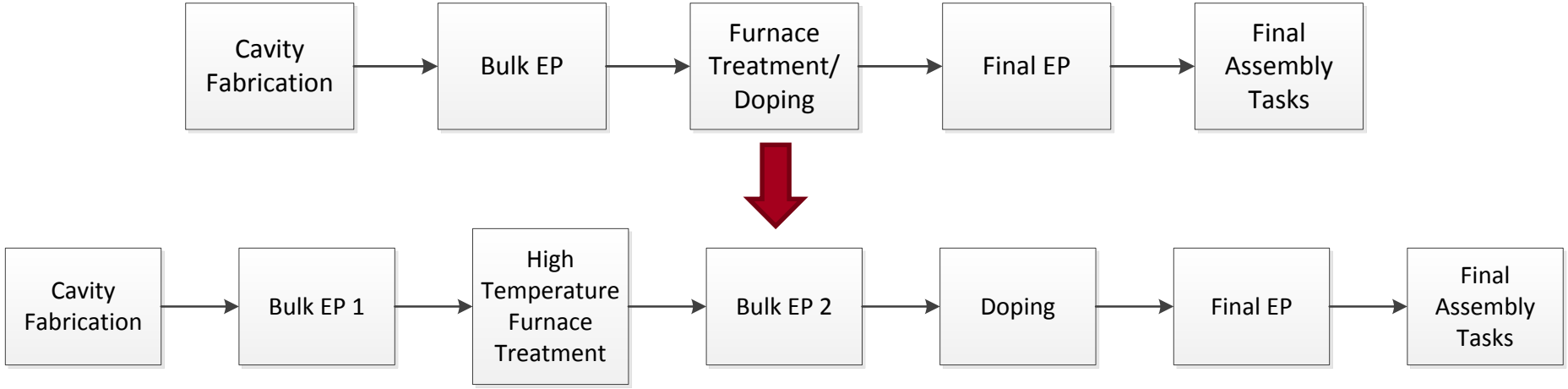


2 out of 4 3/60 9-cells exceed HE requirements with unprecedented Q_0 and gradient

Procedural Modifications from Lessons Learned

Lessons learned from LCLS-II & HE R&D will result 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
- Additional bulk EP and furnace step to reduce chance of furnace contamination



Looking Forward

- The HE R&D program has demonstrated excellent results on single and 9-cell cavities
- It is extremely important to keep control over EP parameters and furnace contamination in order to reach high gradients with high Q_0
- We continue to push the bulk niobium performance boundaries
- Within the next 6 months we will gather additional statistics on 9-cells prepared with the new recipes at FNAL and JLab and on cavities prepared at RI
- Cavity and cryomodule production for HE will begin at the beginning of 2020

Questions?