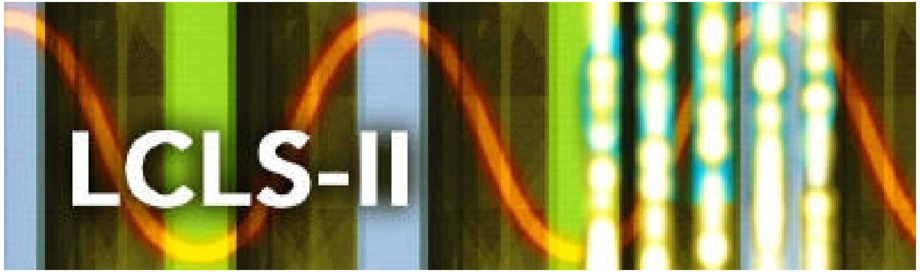

Industrial Cavity Production:

Lessons Learned to Push the Boundaries of Nitrogen-Doping

Dan Gonnella *for the LCLS-II and LCLS-II HE Collaboration*

SLAC National Accelerator Laboratory

July 5, 2019

SRF 19 DRESDEN

U.S. DEPARTMENT OF ENERGY | Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

Cornell University

BERKELEY LAB

Argonne NATIONAL LABORATORY

Fermilab

Jefferson Lab

Outline

SLAC

- Introduction – the Need for High Q_0
- LCLS-II Cavity Production Overview
- Lessons Learned from Cavity Production
- Nitrogen-Doping in the Future: LCLS-II HE
- Conclusions

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LCLS-II and LCLS-II HE Requirements

Parameter	LCLS-II	LCLS-II HE
# 1.3 GHz CMs	35	
Operating Gradient	16 MV/m	
Required Q_0 at Operating Gradient	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

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}

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- Operation at **4 GeV** for LCLS-II can be achieved with a **Q_0 of 1.2×10^{10}**
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- Operating at **8 GeV** for LCLS-II HE requires an average **Q_0 of 2.7×10^{10}**

LCLS-II and LCLS-II HE Requirements

SLAC

Parameter	LCLS-II	LCLS-II HE
# 1.3 GHz CMs	35	20

Achieving Q_0's of at least 2.7×10^{10} required significant improvement and great care in previous industrial cavity performance

LCLS-II is constructing two 4 kW cryoplants

- 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
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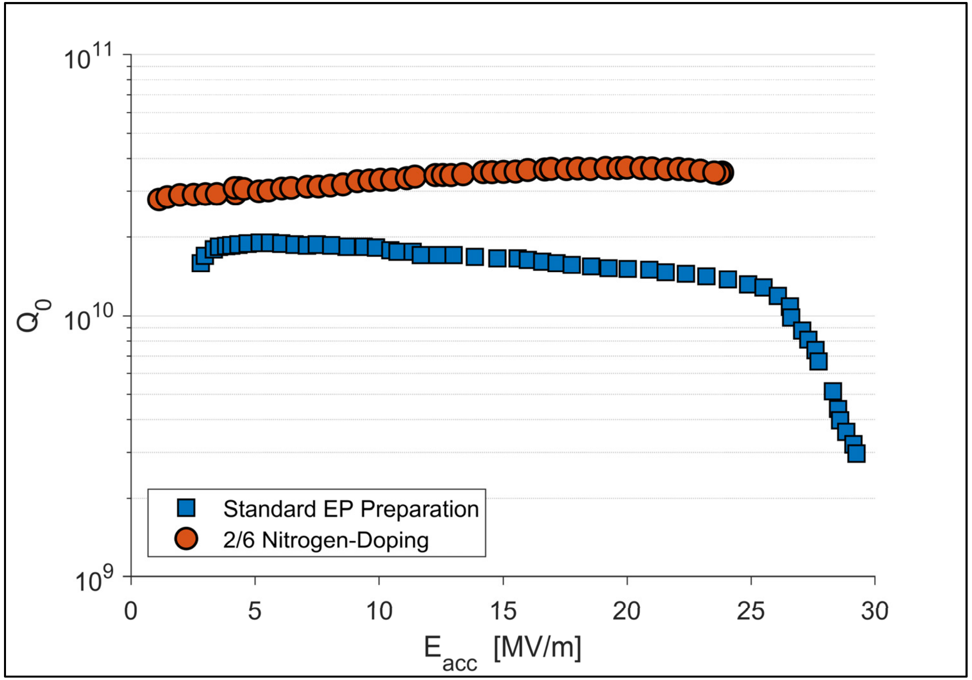
2/6 Nitrogen-Doping



- Cavities prepared with EP typically show Q_0~$1.5x10^{10}$ at medium fields with quench fields ~25-30 MV/m
- 2/6 Nitrogen-doping on average:
  - increases the Q_0 by 100-200%
  - Lowers the quench field by ~20-30%

LCLS-II Cavity Order

- To facilitate the construction of **36 Cryomodules** (34 production + 2 prototypes), **264 9-cell cavities** were ordered
  - This order was split 50/50 between RI and Zanon – previous success with XFEL
  - Material was split ~50/50 between Tokyo Denkai (TD) and Ningxia (NX)
  - Additionally **16 prototype cavities** were used (produced by AES with Wah-Chang material during ILC R&D studies)
- Midway through production additional cavities were ordered to allow for a total of **40 CMs** to be built and to account for cavity yield losses
  - This brings the total cavities purchased to **373**
  - These cavities were prepared with the 2/6 nitrogen-doping and were required to reach the LCLS-II specifications of:

$$\mathbf{Q_0 \geq 2.7\times10^{10} \text{ at } 16\ MV/m}$$

$$\mathbf{E_{max} \geq 19\ MV/m}$$

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LCLS-II cavity requirements push the state-of-the-art considerably compared with XFEL and previous projects using similar SRF technology

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  - These cavities were prepared with the 2/6 nitrogen-doping and were required to reach the LCLS-II specifications of:

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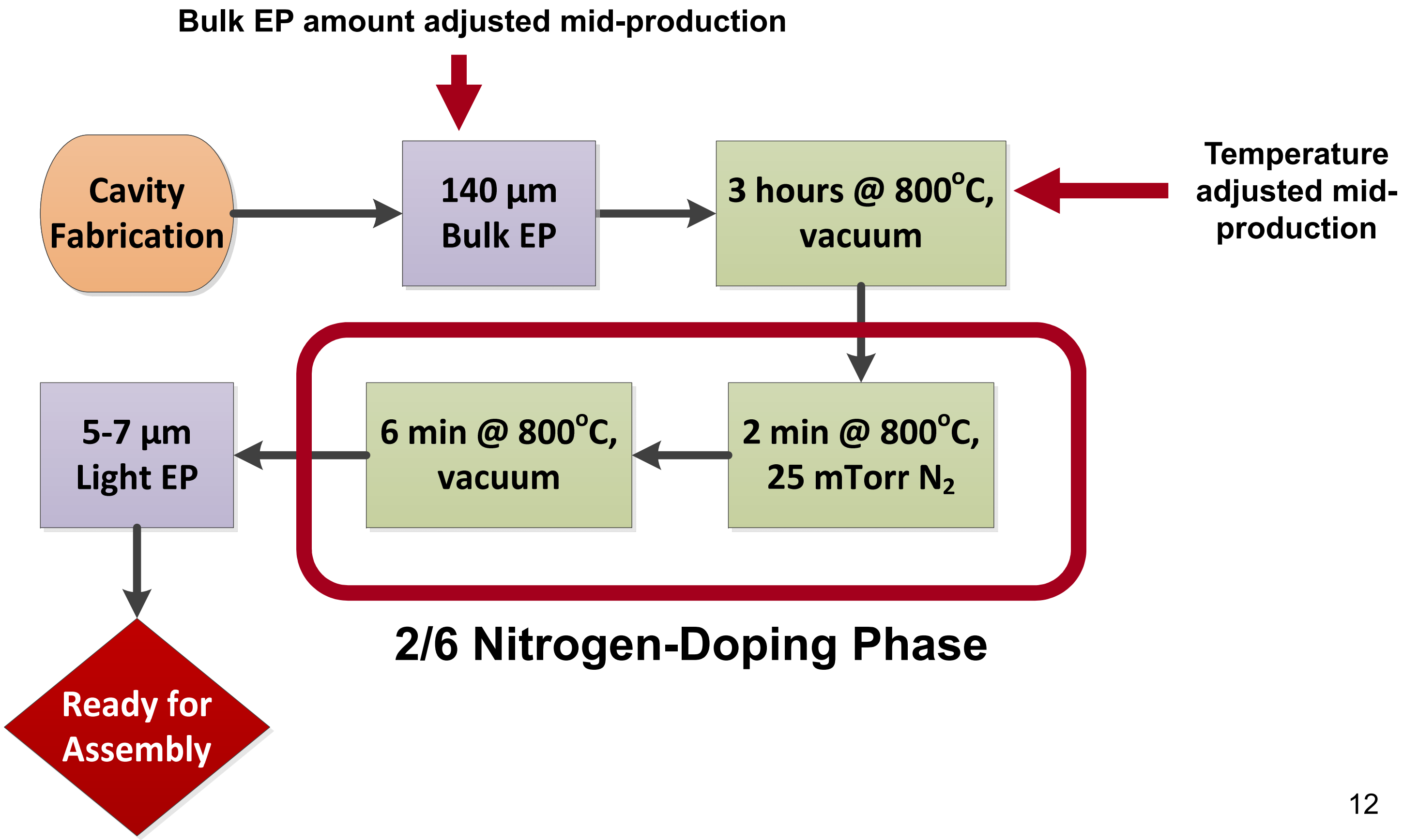
Baseline LCLS-II Cavity Preparation



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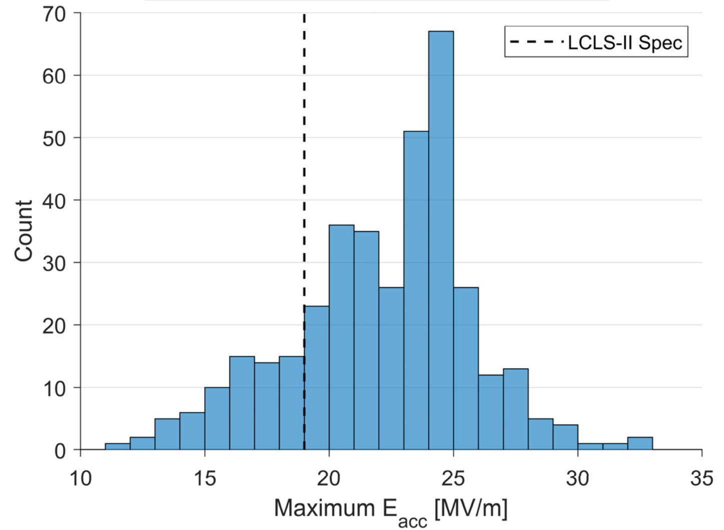
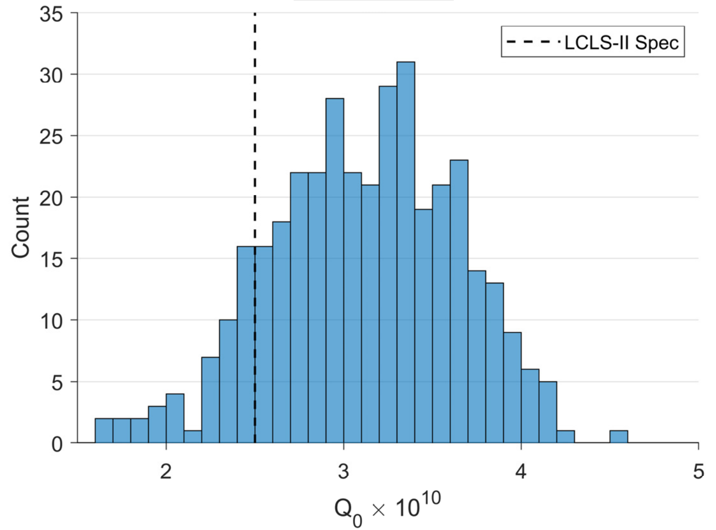
Overall Cavity Performance

Gradient Reach



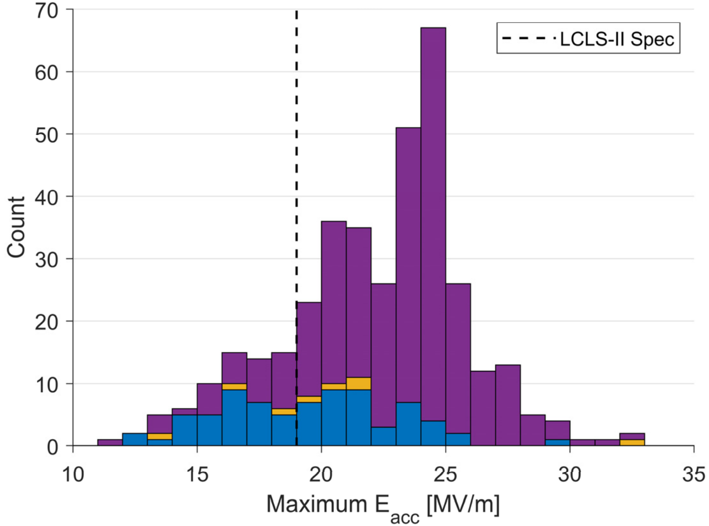
Q_0



Overall performance has been very good – cavities typically exceed requirements

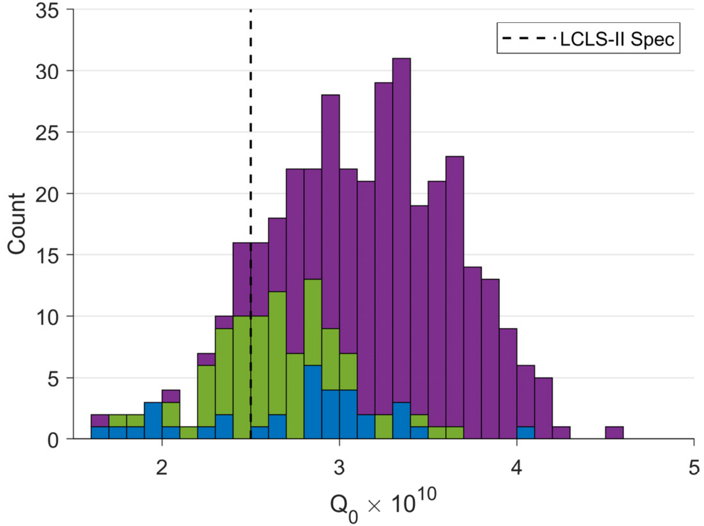
Overall Cavity Performance

Gradient Reach



- Poor fabrication techniques at EZ
- Furnace contamination at high temperatures
- Good procedures

Q_0



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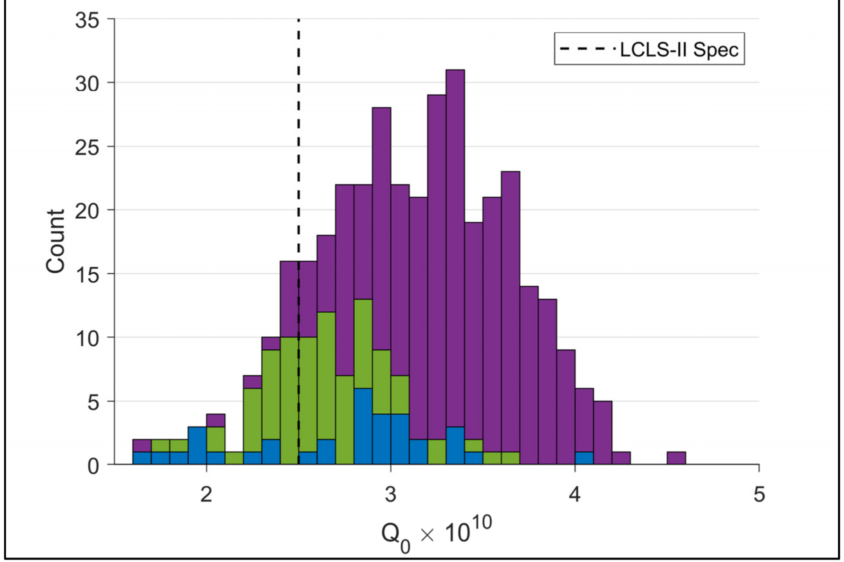
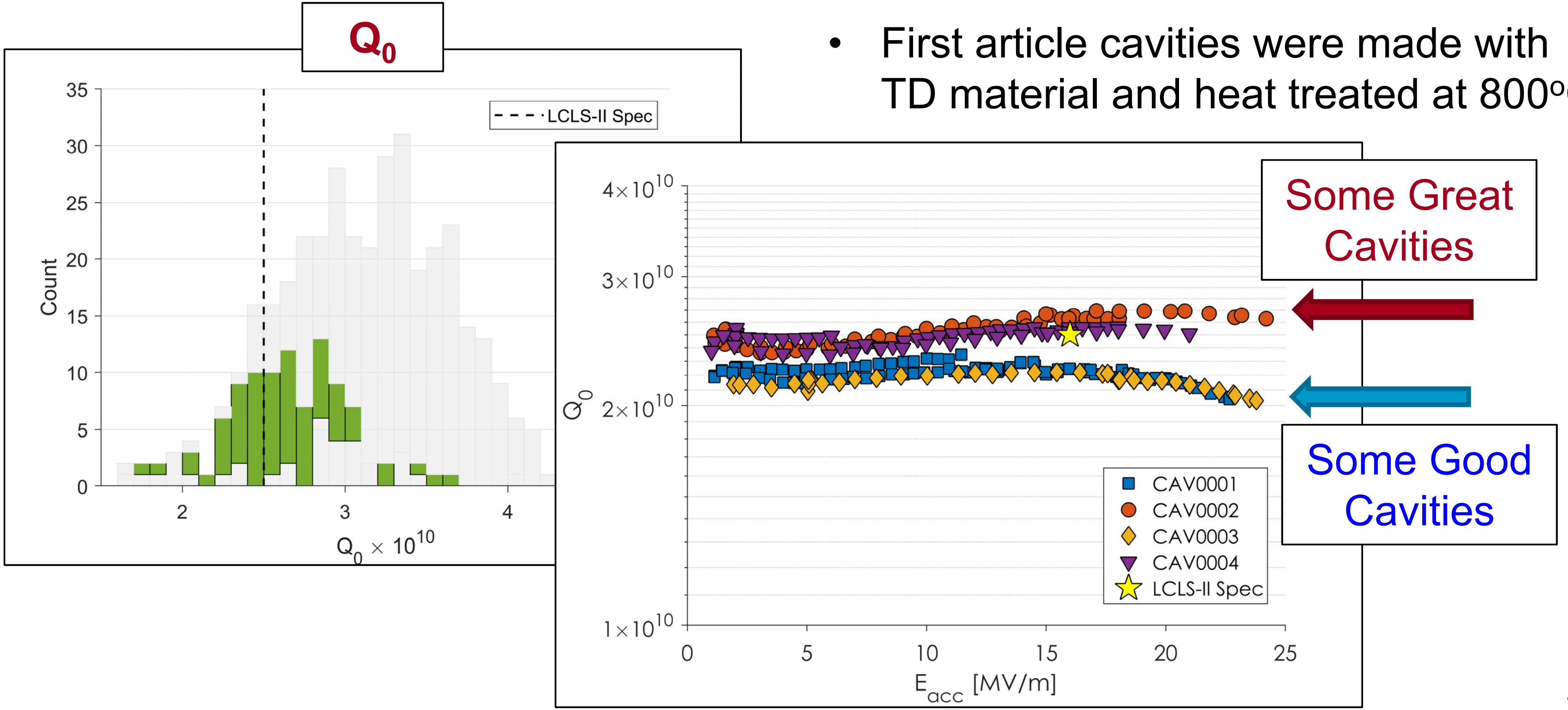
Lesson Learned: Q_0 and Flux Expulsion

Q_0



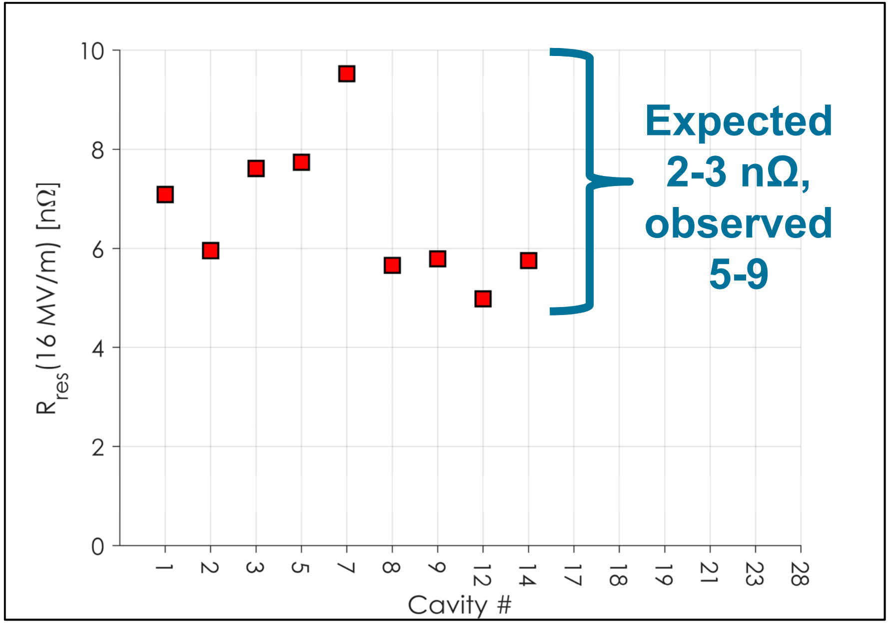
Lesson Learned: Q_0 and Flux Expulsion

- First article cavities were made with TD material and heat treated at 800°C



Lesson Learned: Q_0 and Flux Expulsion

- First article cavities were made with TD material and heat treated at 800°C
- Low Q_0 was attributed to flux trapping causing high residual resistance



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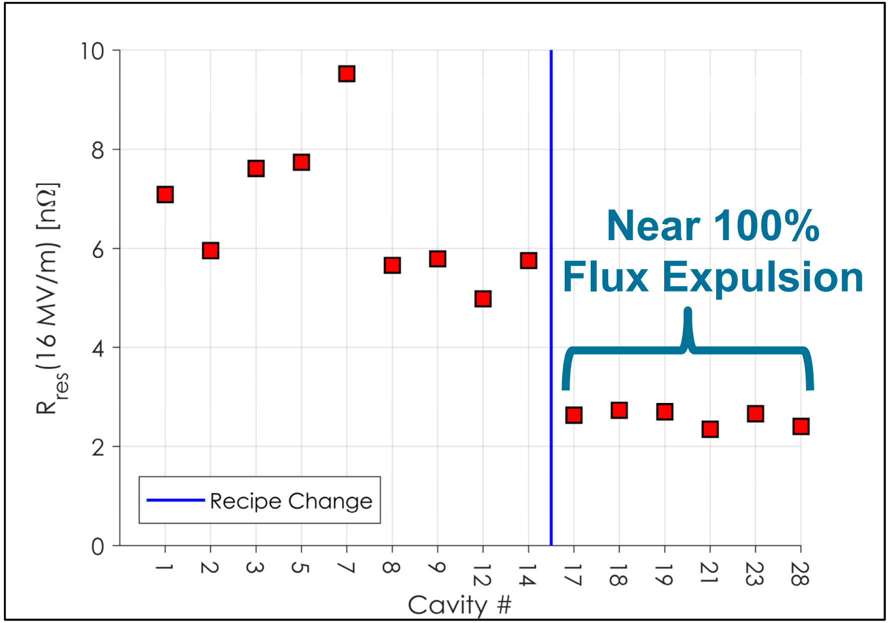
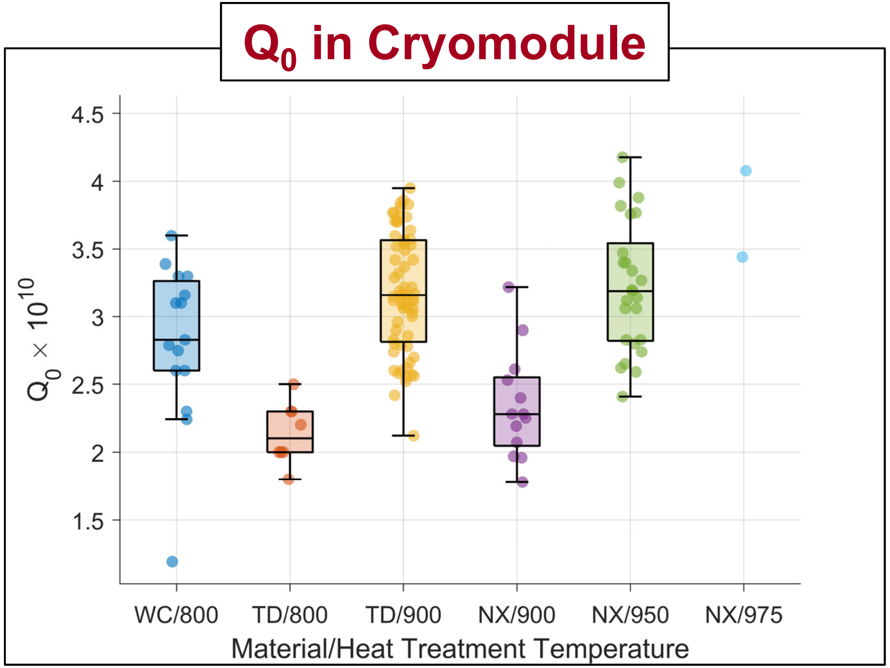


Lesson Learned: Q_0 and Flux Expulsion

- First article cavities were made with TD material and heat treated at 800ºC
- Low Q_0 was attributed to flux trapping causing high residual resistance
- Increase of the heat treatment temperature to 900ºC improved flux expulsion
- It was later found that material from different vendors did not respond to the same heat treatment temperatures
  - NX material typically required higher temperatures for the same flux expulsion
  - Some TD material required higher temperatures



Midway through production: single-cell cavities were built for remaining material batches and material was sorted prior to cavity construction

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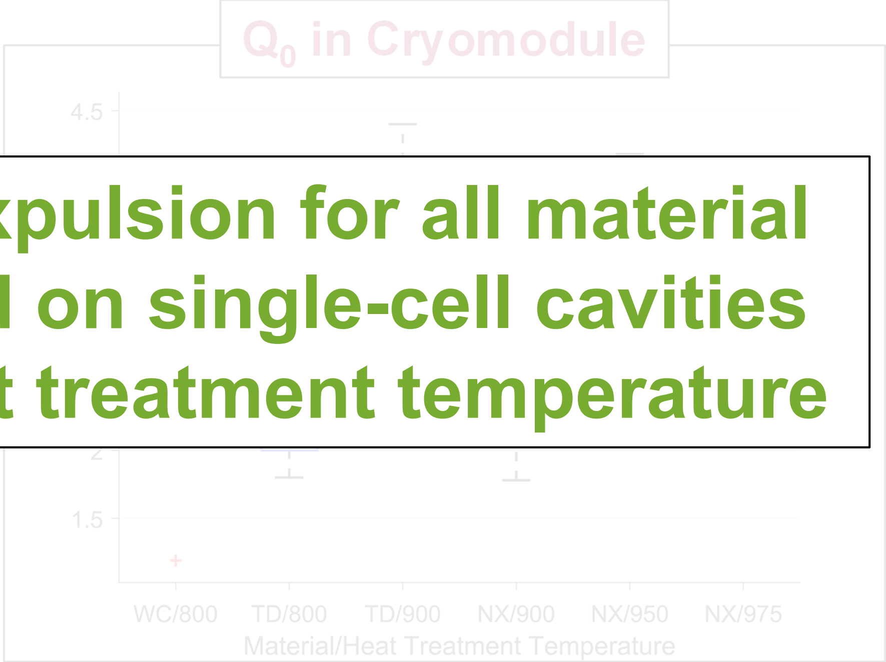
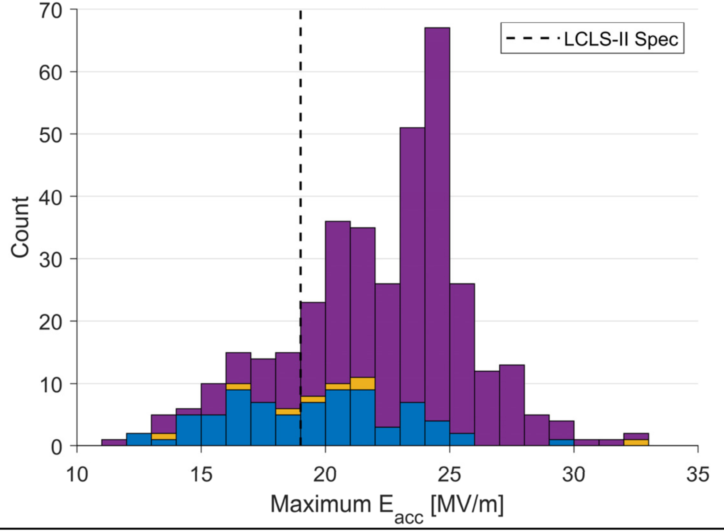


Lesson Learned: Flux expulsion for all material batches must be verified on single-cell cavities to determine correct heat treatment temperature

Midway through production: single-cell cavities were built for remaining material batches and material was sorted prior to cavity construction

Overall Cavity Performance

Gradient Reach



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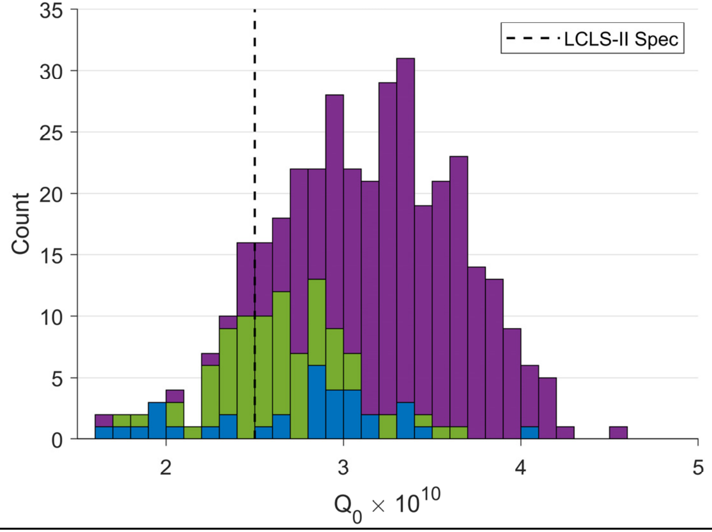
Q_0



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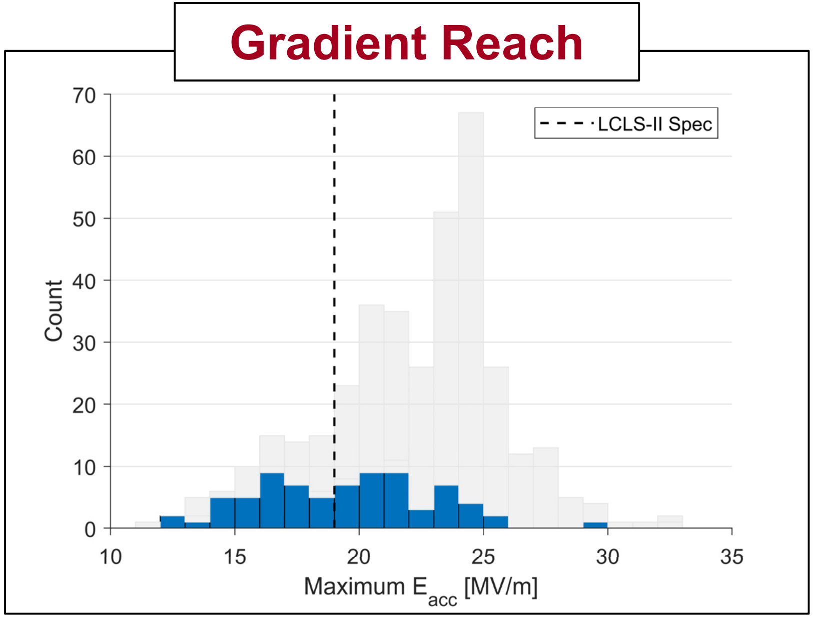
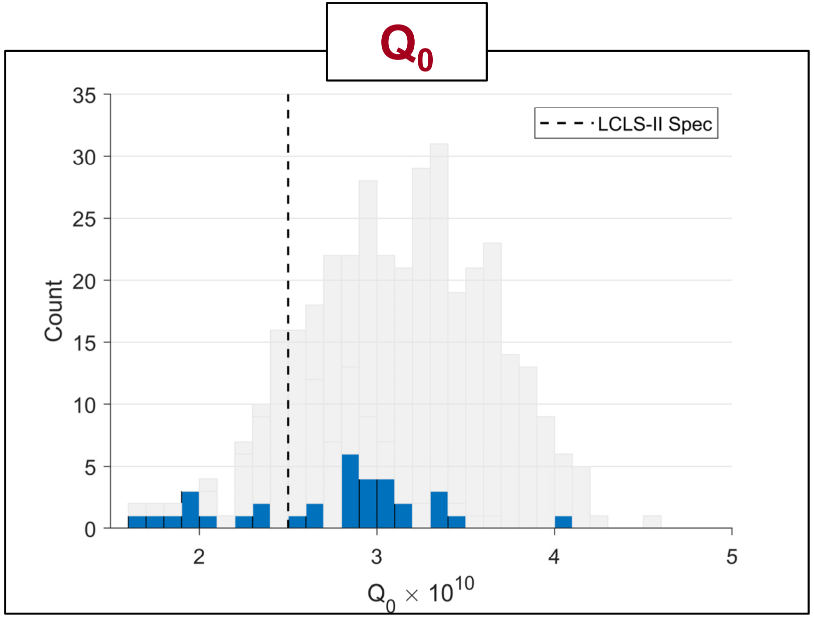
Overall Cavity Performance

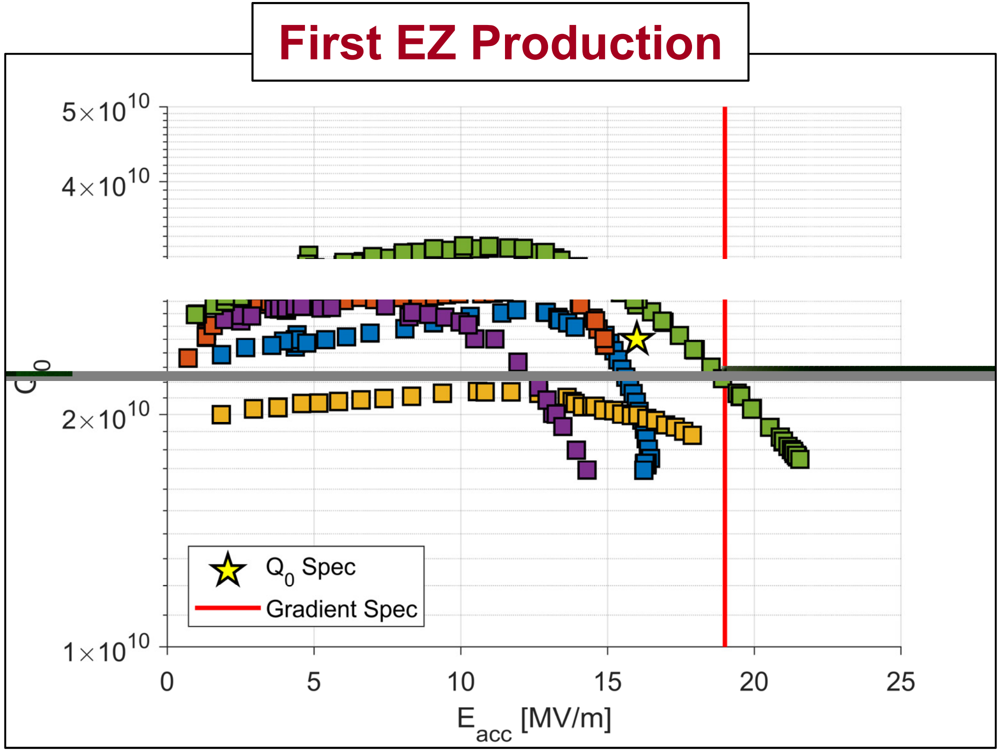


- **Poor fabrication techniques at EZ**
- **Furnace contamination at high temperatures**
- **Good procedures**



- **Poor fabrication techniques at EZ**
- **Insufficient heat treatment to improve flux expulsion**
- **Procedures Improved**

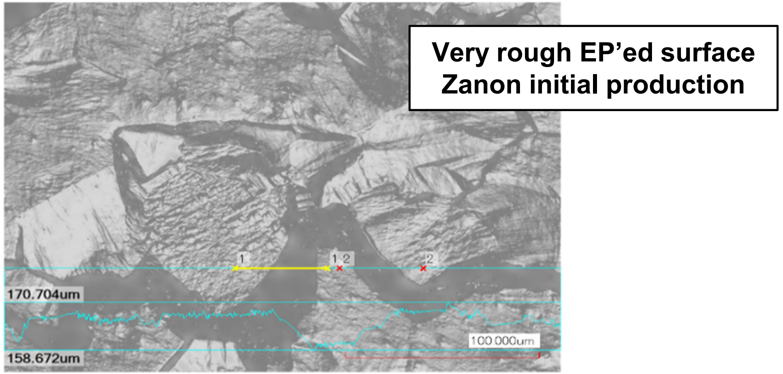
Lesson Learned: Fabrication Techniques at EZ



- First nitrogen-doped cavities produced by EZ for LCLS-II showed low quench fields and a strong Q-slope above 13 MV/m

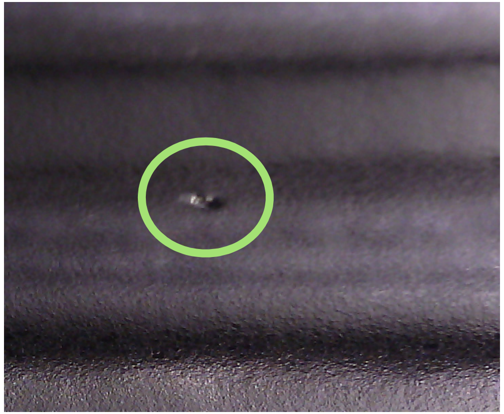
- Production was placed on hold at EZ and a full audit of fabrication procedures was undertaken

Lesson Learned: Fabrication Techniques at EZ



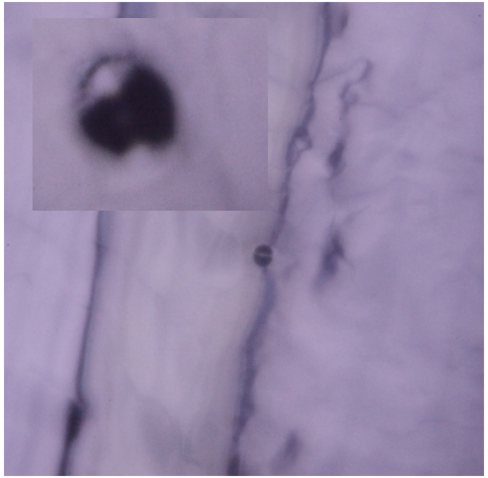
- Incomplete transfer of new EP technology to EZ resulted in etching, which in turn caused rough surfaces for the first ~25 cavities
- EP procedures improved via on-site presence by JLab staff

- Incorrect cell polishing prior to welding
- Whole-cell grinding with aggressive tooling resulted in the burial of normal conducting media
- Corrected through thorough vetting of procedures and retraining by JLab and SLAC staff



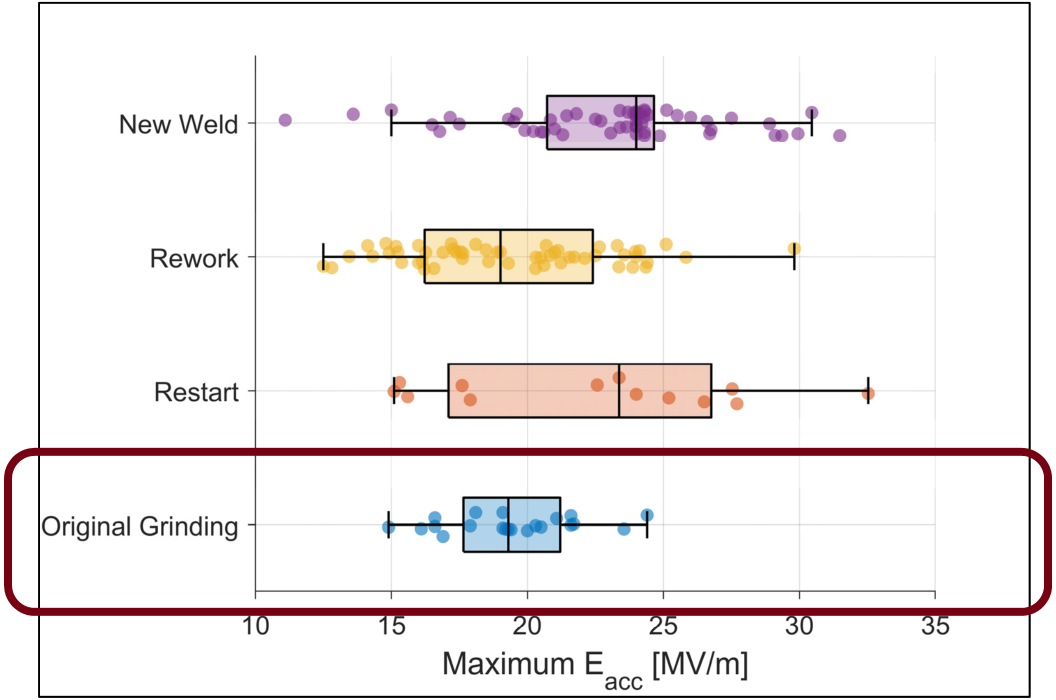
Lesson Learned: Fabrication Techniques at EZ

- LCLS-II contract did not forbid weld splatter
- Many of the first ~70 cavities had internal and external weld splatter
- **This is not acceptable for high performing cavities as the splatter is highly correlated to cat eye defects**
- Improved through multi-week, hands-on training and review during weld stack-up, and weld prep machining



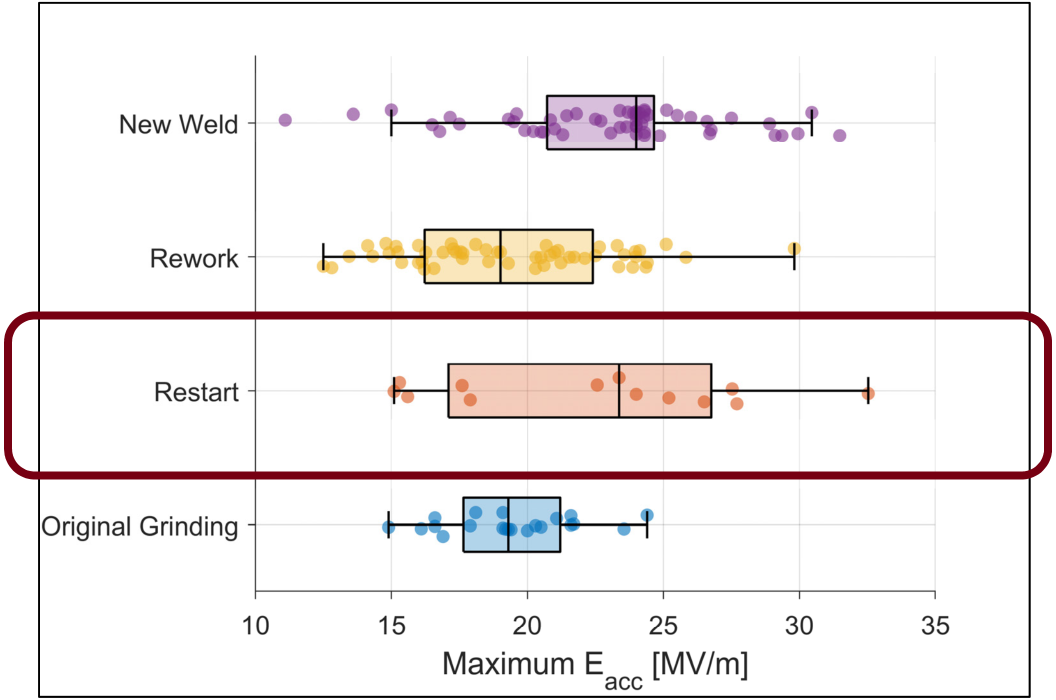
- ~70 cavities produced by EZ for LCLS-II required rework
- These cavities were in various states of production and required different rework paths
- Typically involved BCP to attack normal conducting media

Lesson Learned: Fabrication Techniques at EZ



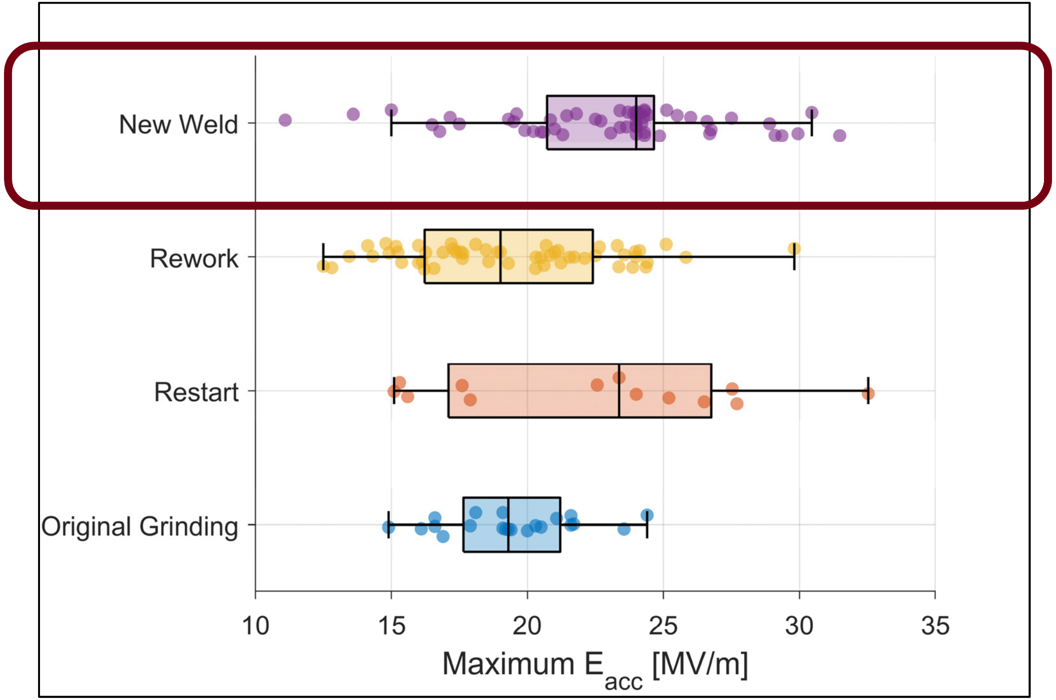
Lesson Learned: Fabrication Techniques at EZ

SLAC



- Repair of EP and grinding procedures improved gradient performance moderately

Lesson Learned: Fabrication Techniques at EZ



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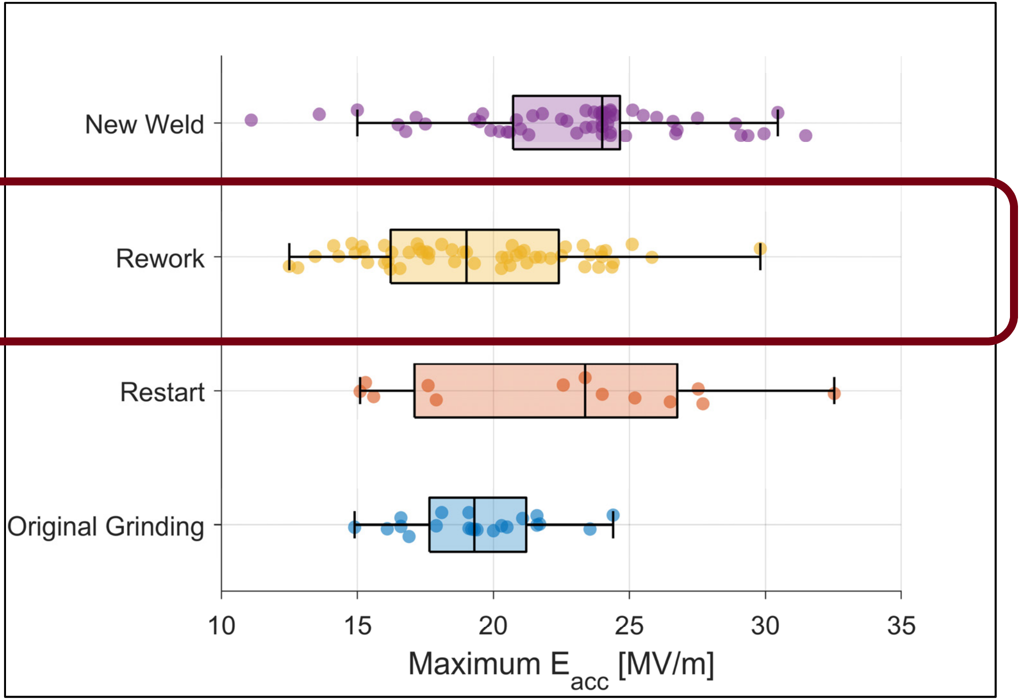

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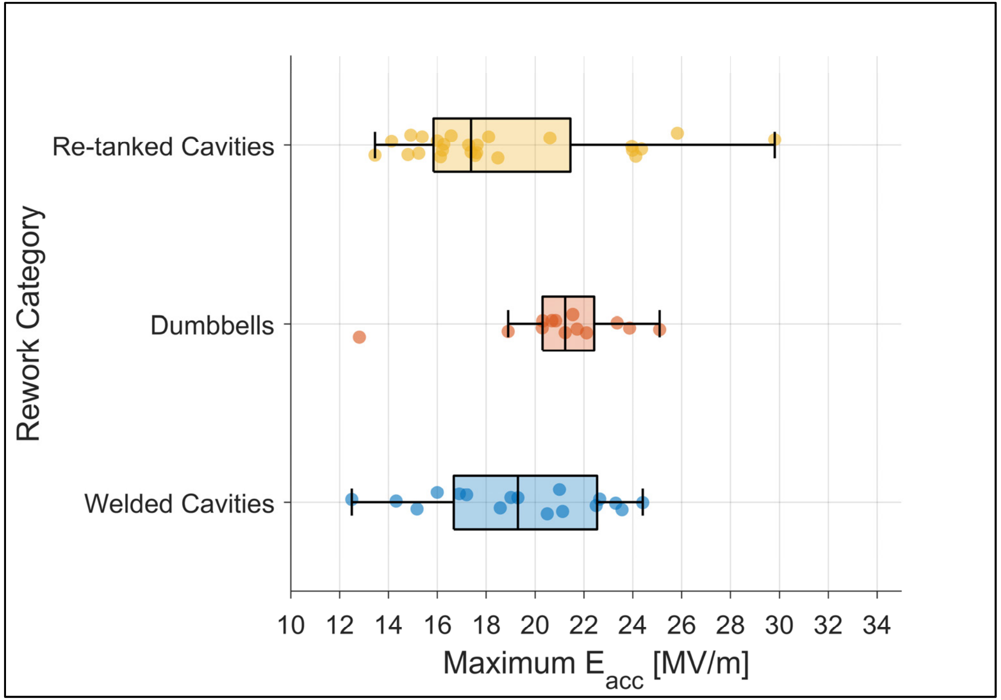

- Repair of EP and grinding procedures improved gradient performance moderately
- Improvement of weld stackup procedures resulted in cavities with performance in line with RI
- Rework had ~50% success
    - Cavities which were already fabricated had lower chance of rework success compared with dumbbells

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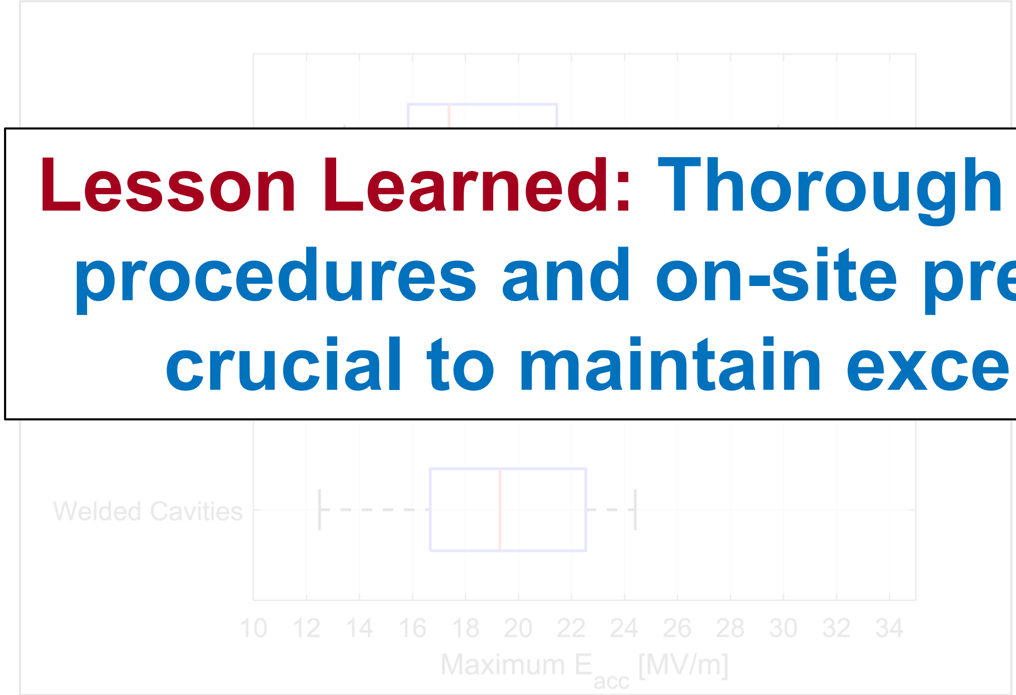
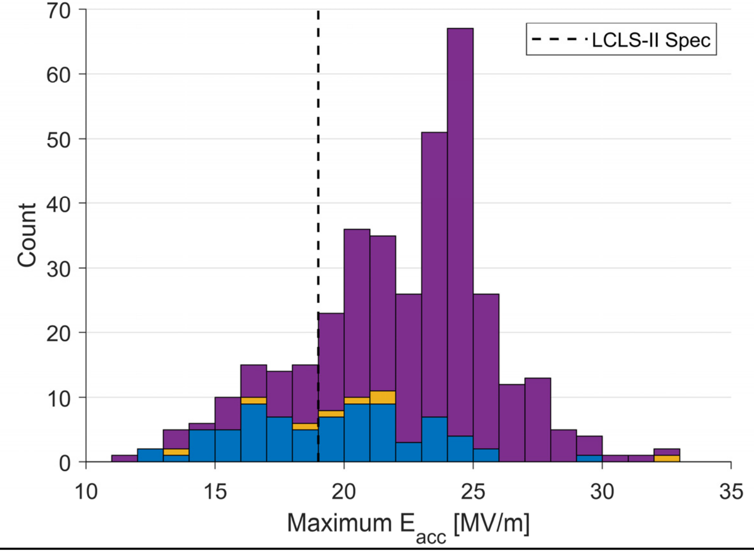


- Repair of EP and grinding procedures improved gradient
  - Cavities which were already fabricated had lower chance of rework success compared with dumbbells

Lesson Learned: Thorough vetting of fabrication procedures and on-site presence at vendors is crucial to maintain excellent performance

Lesson Learned: Furnace Contamination

Gradient Reach



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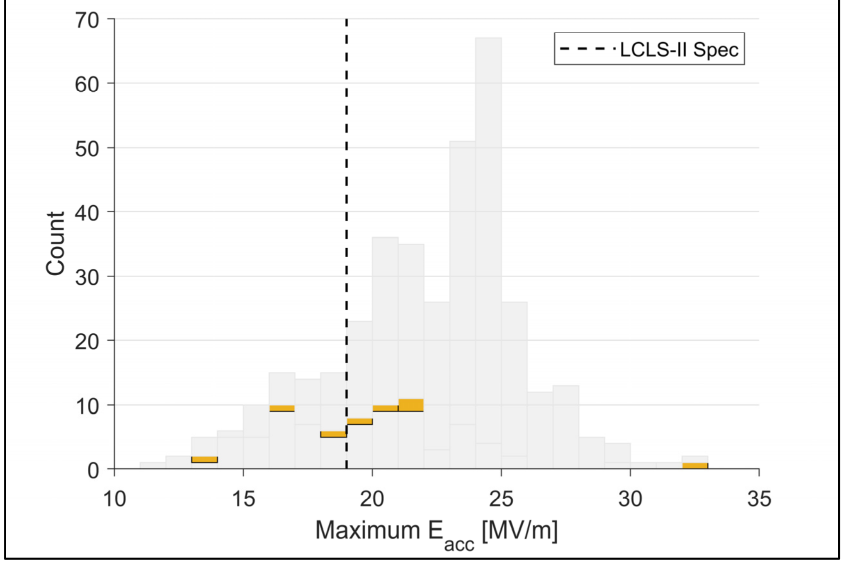

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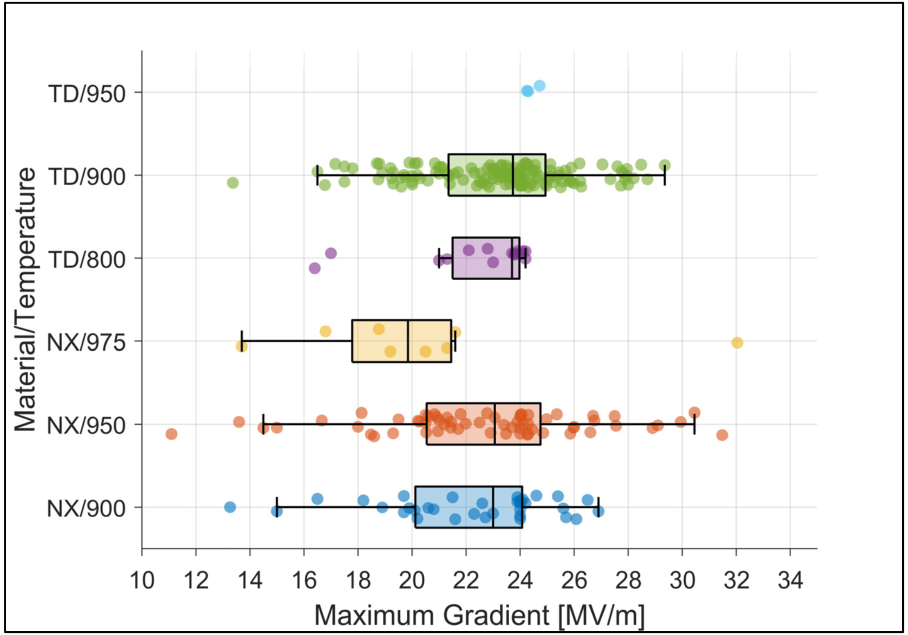

- **NO CORRELATON** between niobium manufacturer and quench field
- Typically no correlation between heat treatment temperature and quench field has been observed

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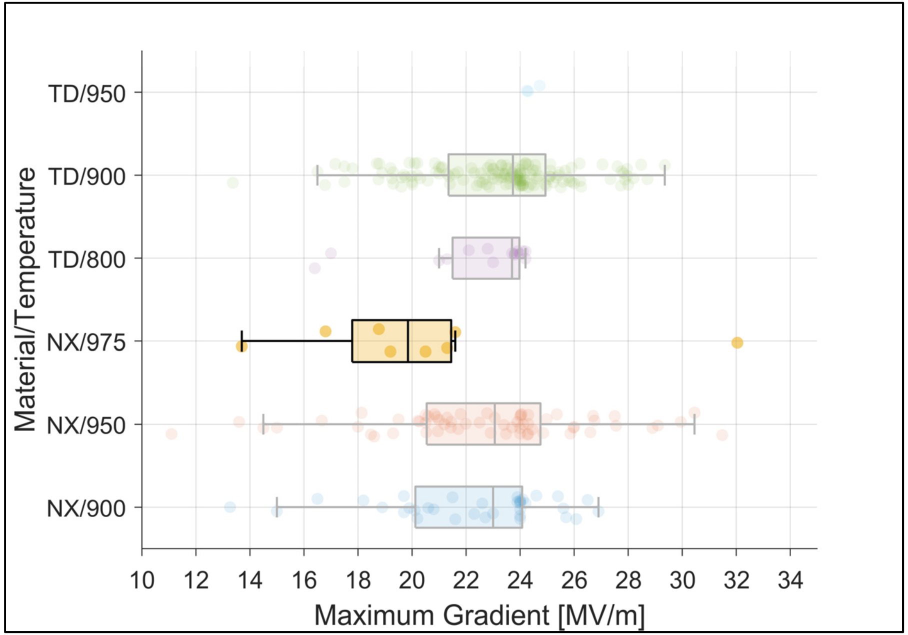

- **NO CORRELATON** between niobium manufacturer and quench field
- Typically no correlation between heat treatment temperature and quench field has been observed
- However, cavities treated **ABOVE 950°C** in RI's furnace showed a statistically significant **drop in quench field**
    - Suggests presence of contamination that outgasses above 950°C

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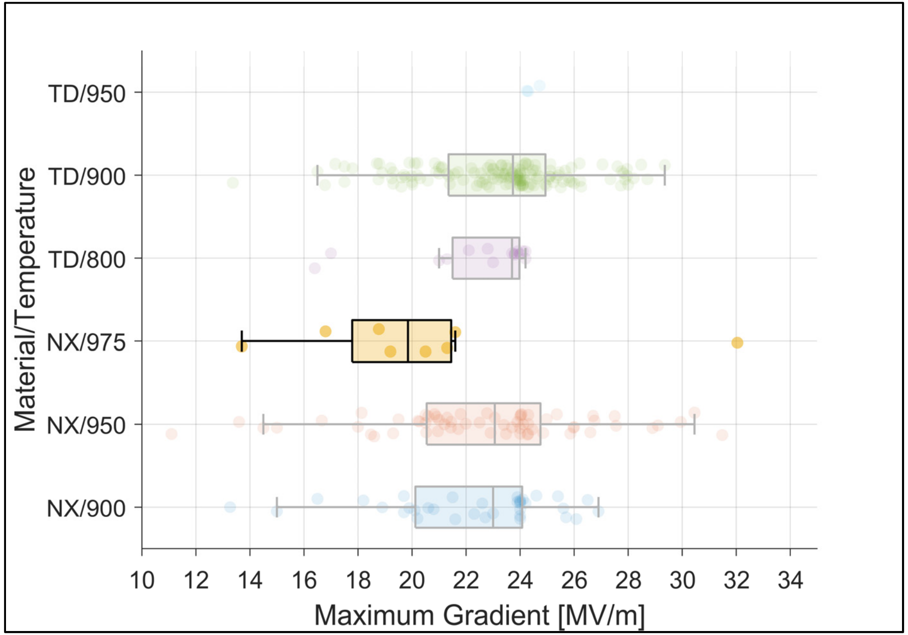

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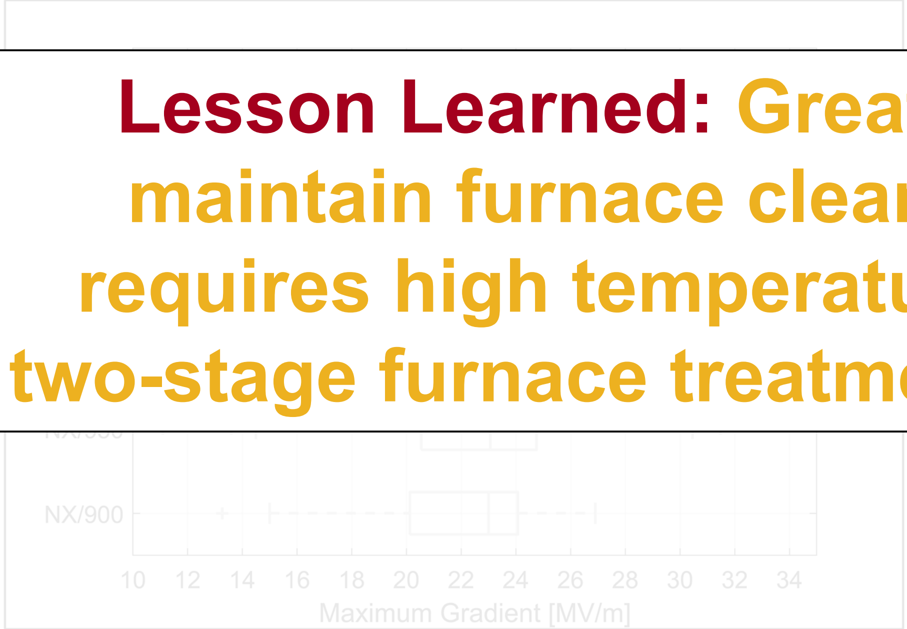
- Likewise, EZ's furnace was found to be contaminated near the end of production and is in the process of being rehabilitated

Lesson Learned: Furnace Contamination

Lesson Learned: Great care must be taken to maintain furnace cleanliness – when high Q_0 requires high temperature treatment consider a two-stage furnace treatment cycle with EP between



- NO CORRELATON between niobium manufacturer and quench field
  - contamination that outgasses above 950ºC
- Likewise, EZ's furnace was found to be contaminated near the end of production and has since been rehabilitated

Overall Cavity Performance

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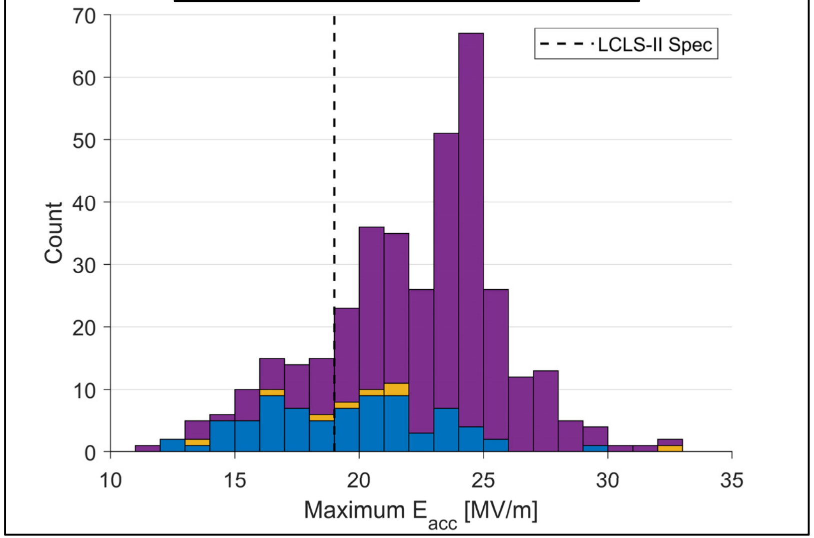

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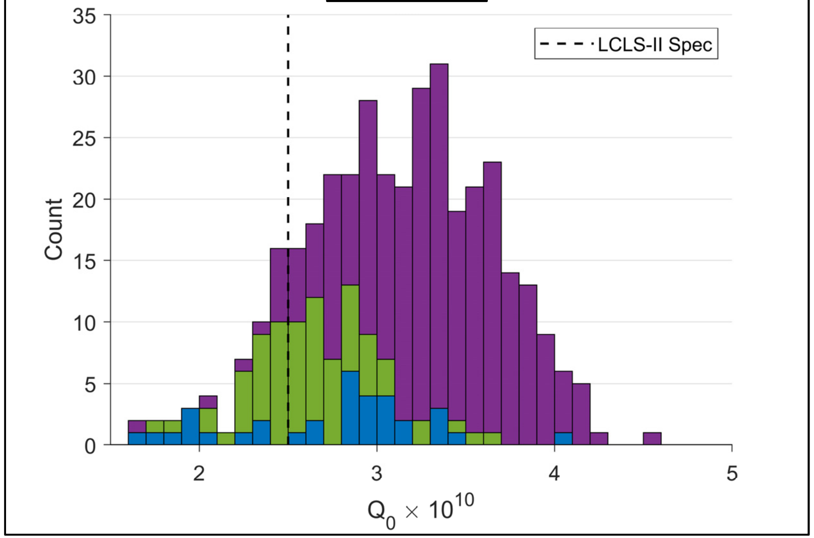
Q_0



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Overall Cavity Performance

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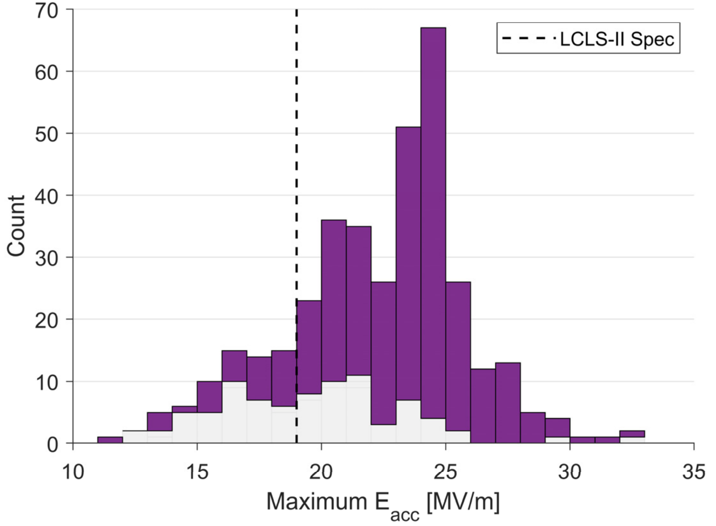

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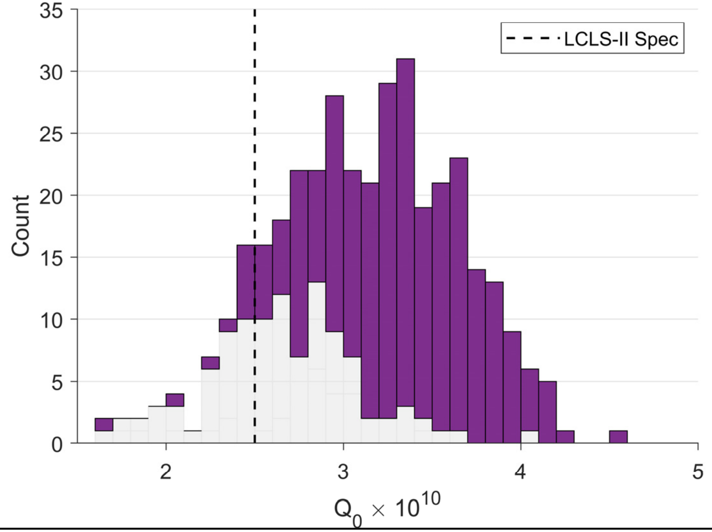
Q_0



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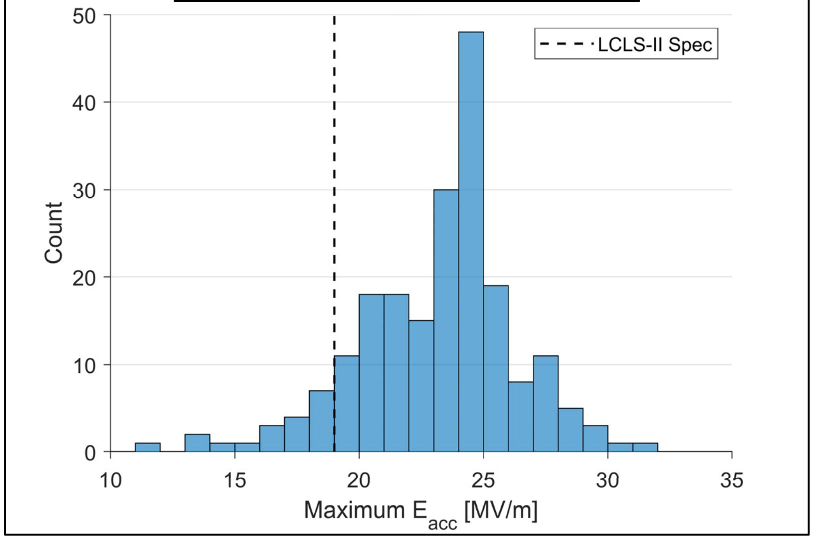
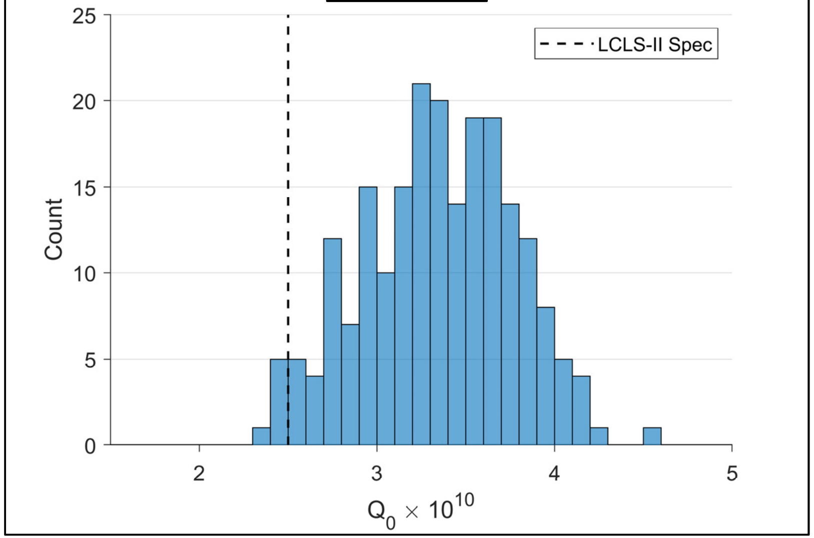
Improved Cavity Performance

Gradient Reach



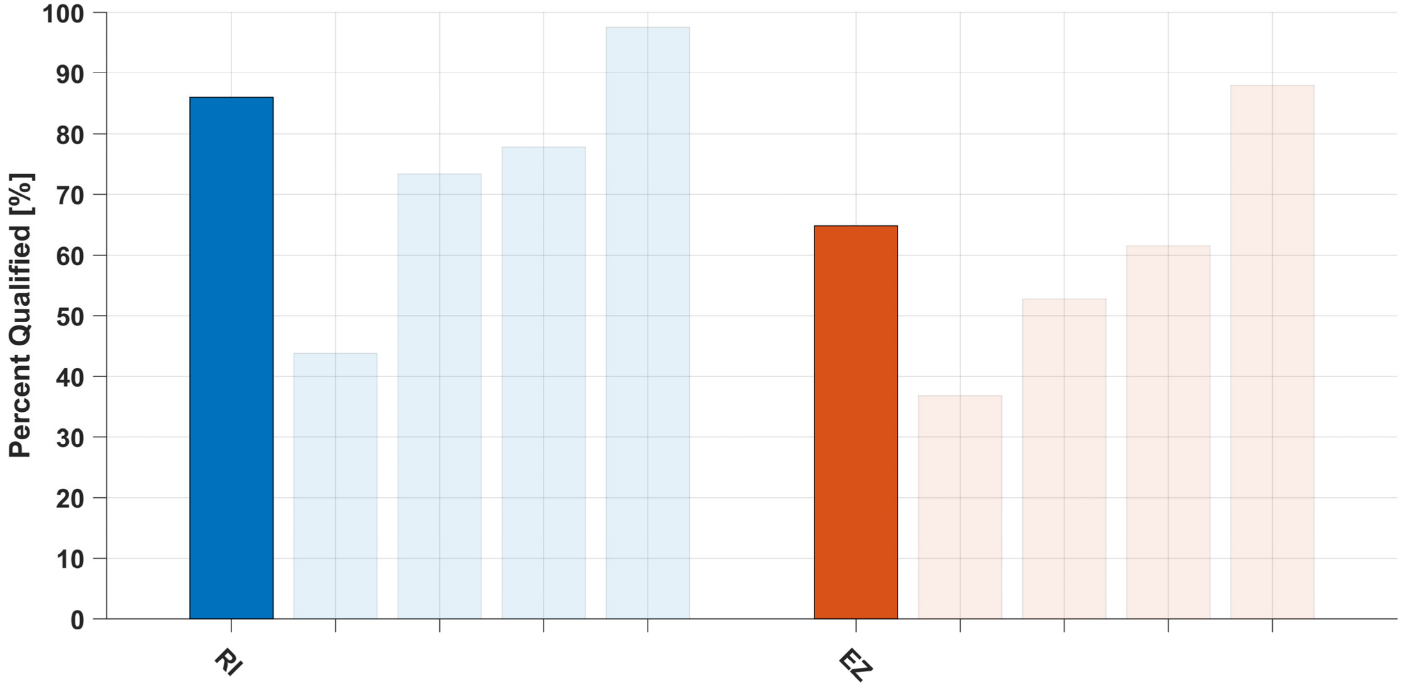
Q_0



Both vendors now produce excellent nitrogen-doped cavities

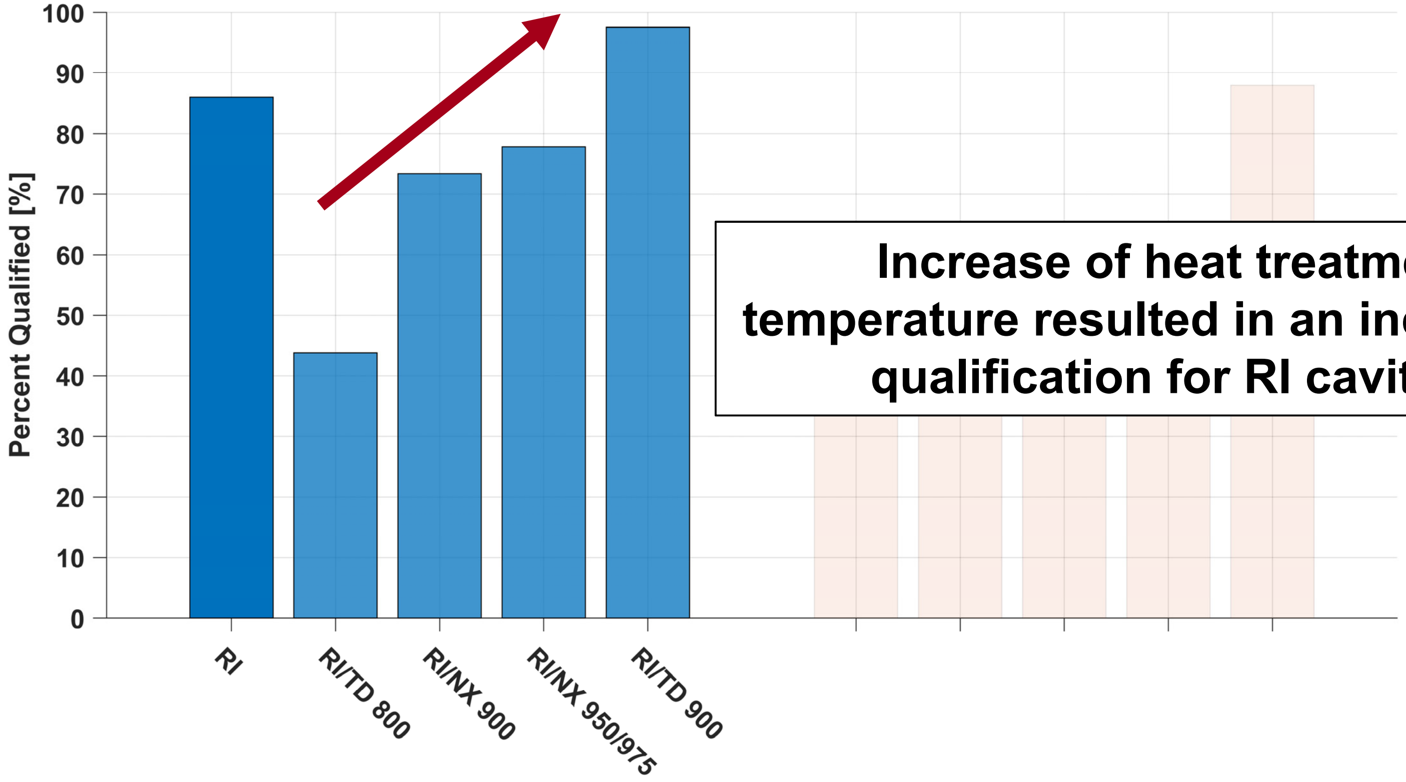
Parameter	Value
$\langle E_{acc} \rangle$	23.1 MV/m
$\langle Q_0 \rangle$	3.3×10^{10}

LCLS-II Cavity Qualification



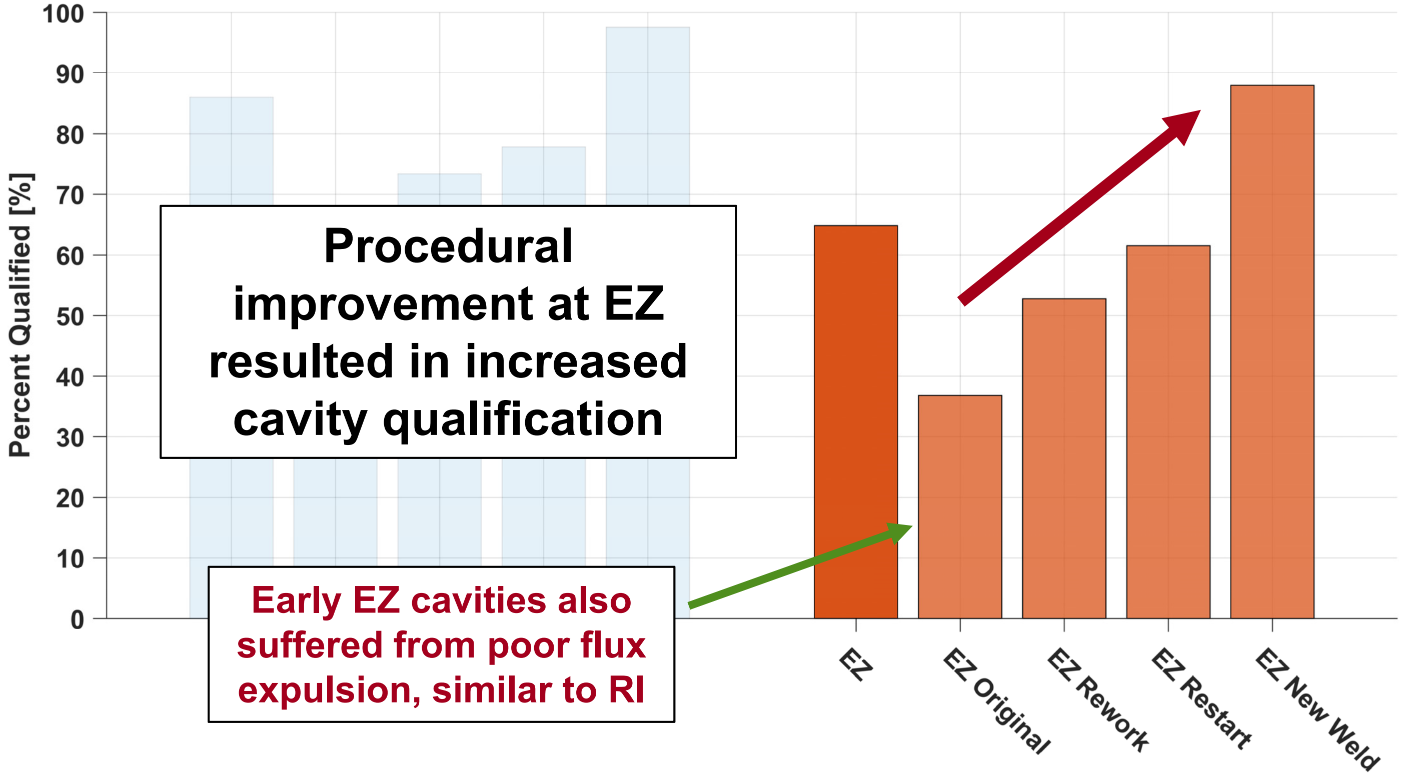
Qualification: $E_{quench} \geq 19$ MV/m, $Q_0(16 \text{ MV/m}, 2 \text{ K}) \geq 2.5\times10^{10}$

LCLS-II Cavity Qualification



Increase of heat treatment temperature resulted in an increase in qualification for RI cavities

LCLS-II Cavity Qualification



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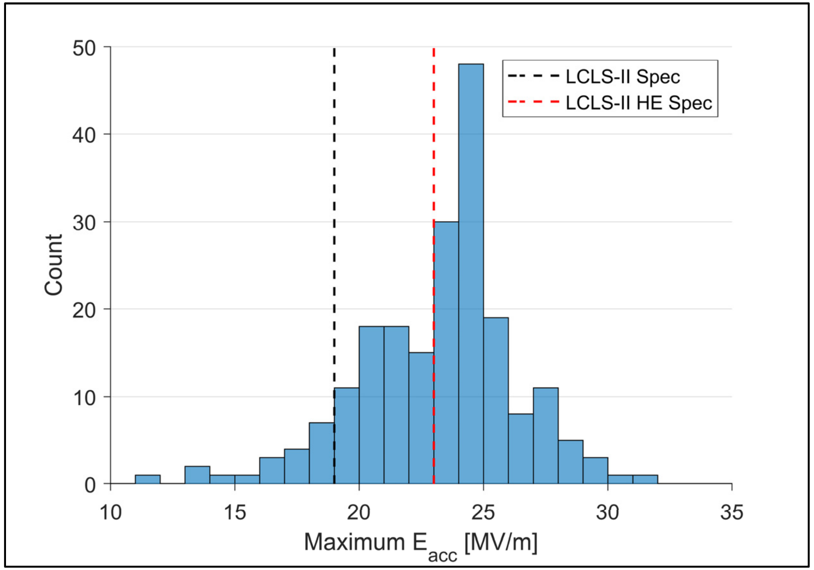
LCLS-II HE Requirements, *Again*

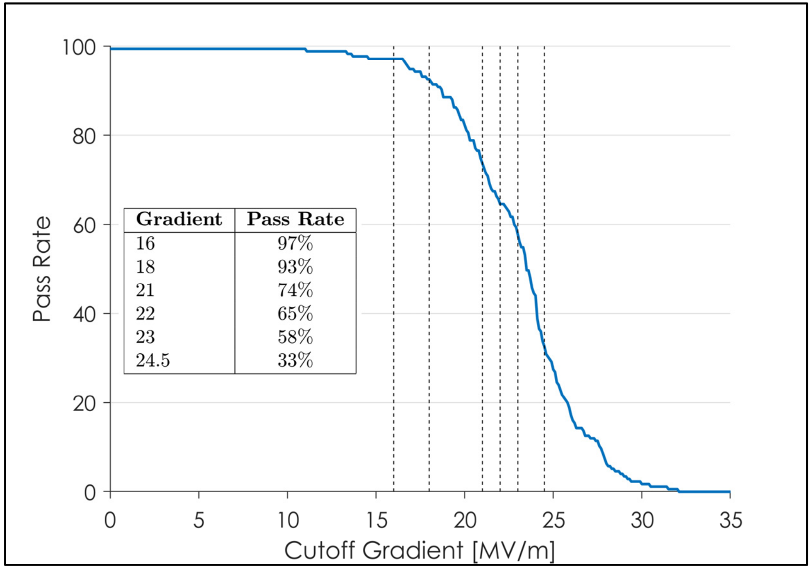
- LCLS-II asked: “can we operate at medium fields with high Q_0?”
- XFEL asked: “can we operate at high fields (low to mid 20s)?”

WHY NOT BOTH?

- LCLS-II HE will operate at high fields **WITH** high Q_0
- Cavities in the linac will operate at 20.8 MV/m
- In VT, these cavities are required to achieve 23 MV/m with a **Q_0 of 2.7×10^{10} at 21 MV/m**

2/6 Doping and LCLS-II HE



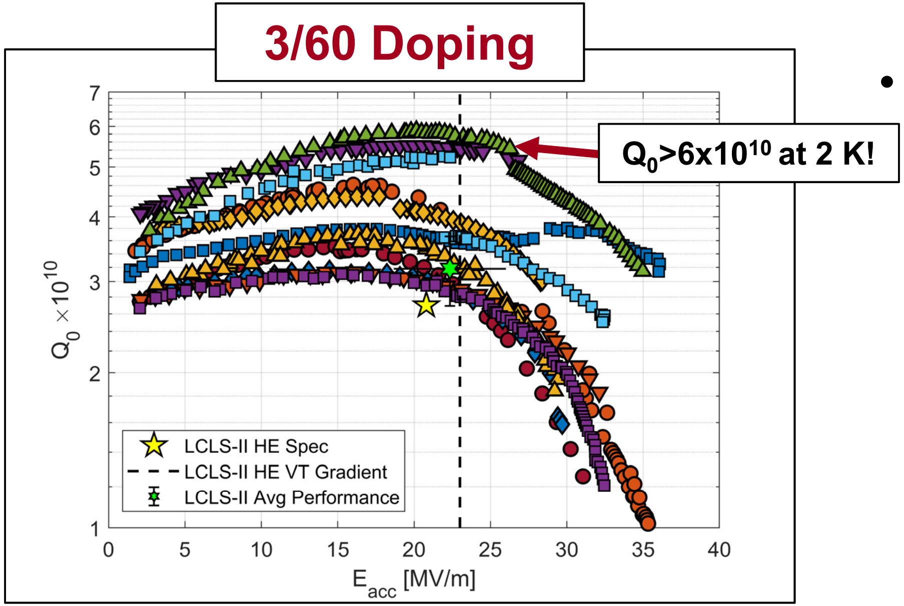


~42% of LCLS-II cavities do not meet the LCLS-II HE vertical test specification

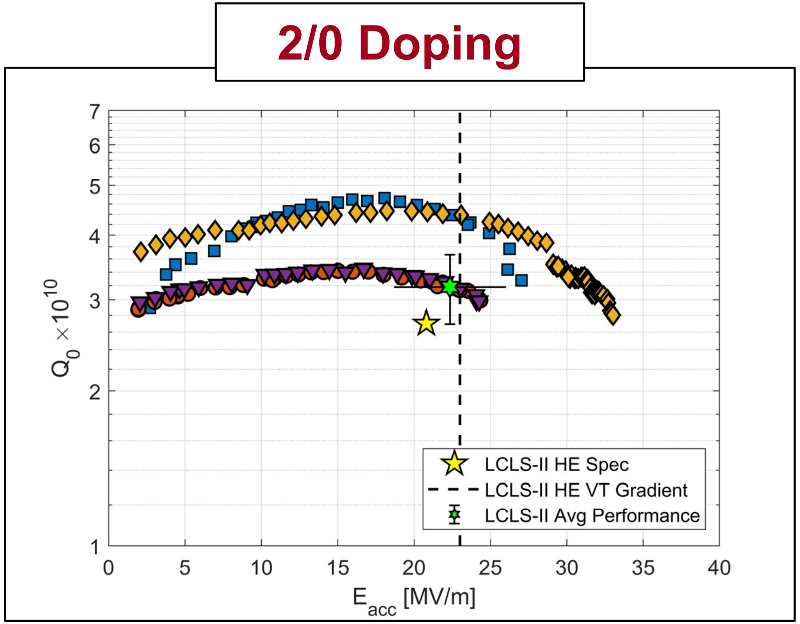
A change to the doping is required

Pushing the Boundaries of Nitrogen-Doping

SLAC

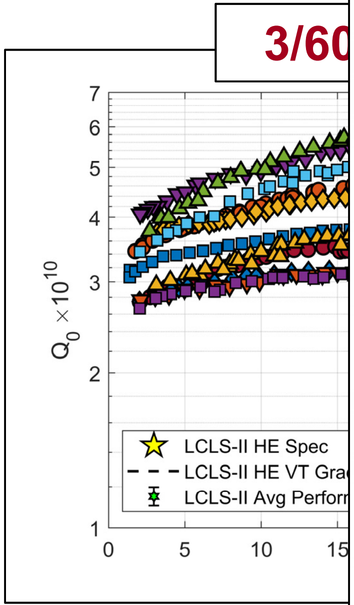


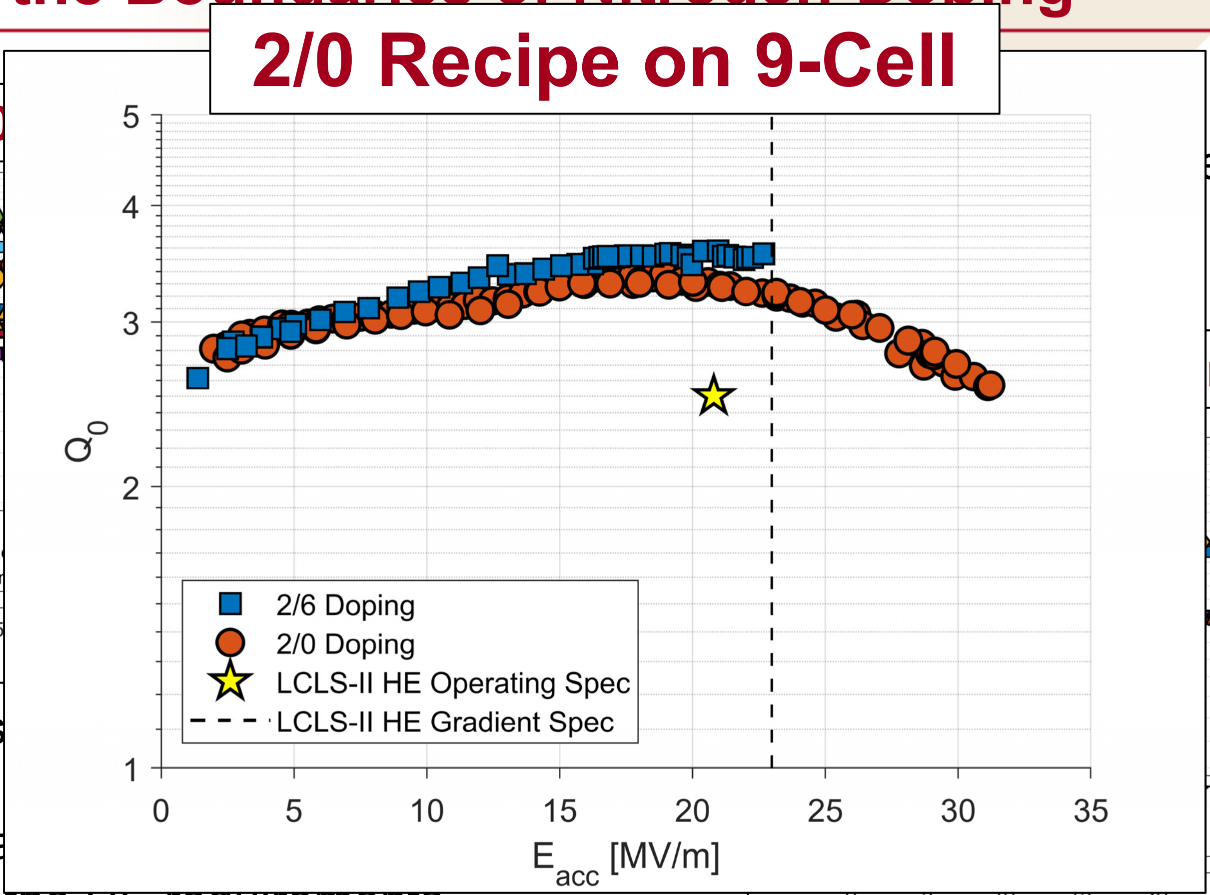
- Two new doping recipes have been explored: 3/60 and 2/0

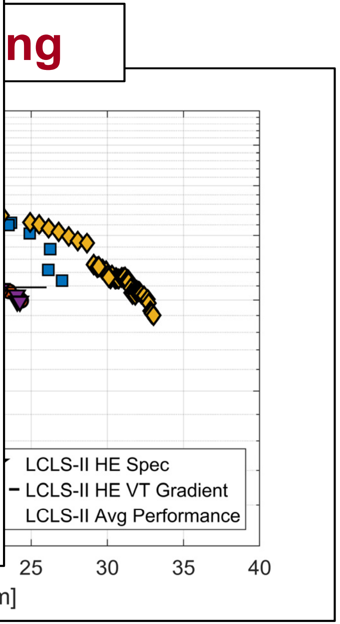


- Both recipes have shown excellent progress on single-cells
  - Nearly all single-cell cavities tested exceed the HE requirements

Pushing the Boundaries of Nitrogen-Doping







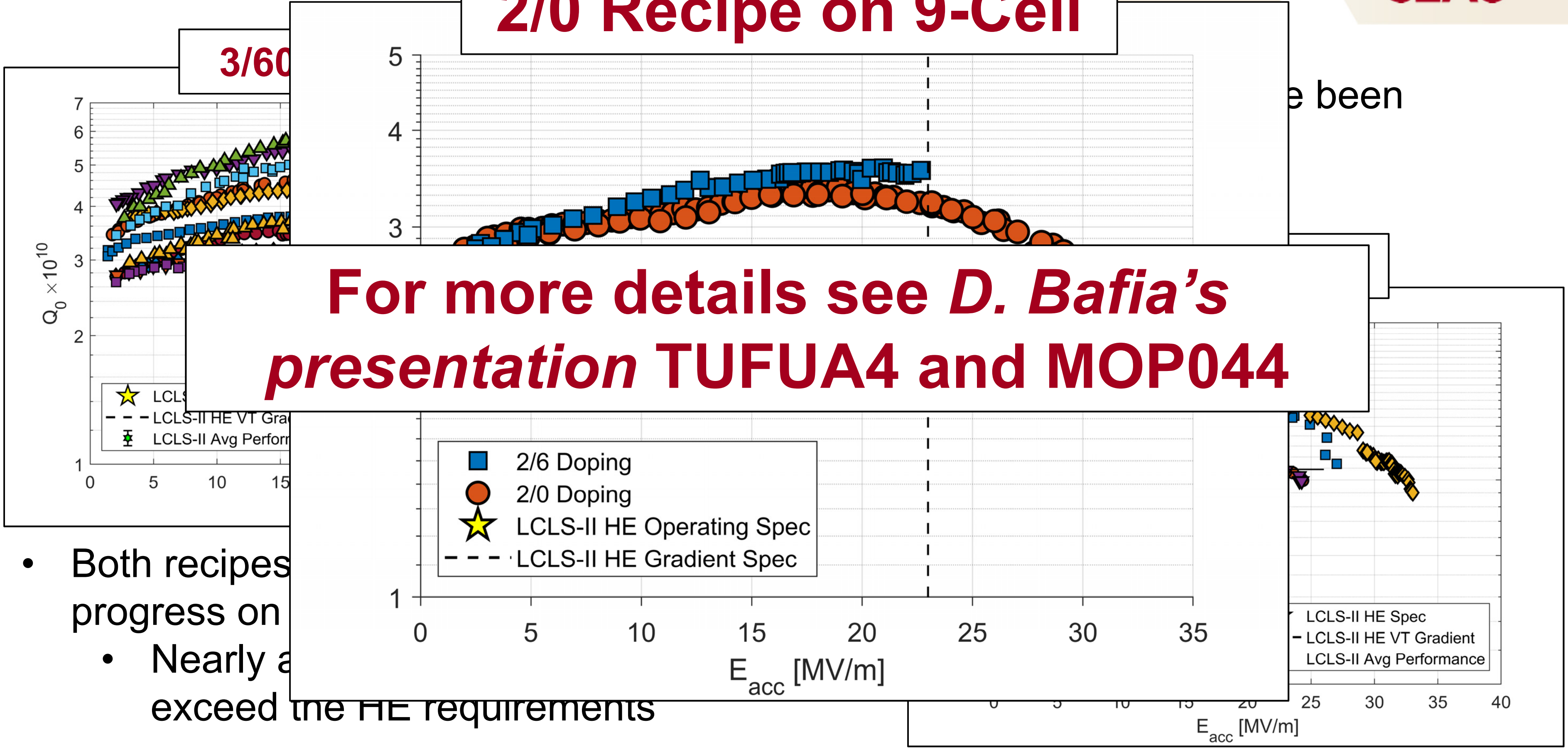
e been

- Both recipes
  progress on
  - Nearly a
    exceed the HE requirements

Pushing the Boundaries of Nitrogen-Doping

SLAC

2/0 Recipe on 9-Cell



For more details see *D. Bafia's presentation* TUFUA4 and MOP044

- Both recipes ...
  progress on ...
  - Nearly a...
    exceed the HE requirements

Outline

- Introduction – the Need for High Q_0
- LCLS-II Cavity Production Overview
- Lessons Learned from Cavity Production
- Nitrogen-Doping in the Future: LCLS-II HE
- Conclusions

Conclusions

- LCLS-II cavity production has resulted in nearly 400 nitrogen-doped cavities produced by industry and performance has been excellent but there have been important lessons learned:
  - **Flux expulsion for all material batches must be verified on single-cell cavities to determine correct heat treatment temperature**
  - **Thorough vetting of fabrication procedures and on-site presence at vendors is crucial to maintain excellent performance**
  - **Great care must be taken to maintain furnace cleanliness**
- The strict requirements of nitrogen-doping laid bare issues that had not manifested in earlier projects
- **With project oversight, cavity vendors can produce cavities that achieve $Q_0 > 3\times10^{10}$ at 2 K with good gradient reach**
  - **High Q_0 SRF Cavity production is moving towards industrialization**
- LCLS-II HE will continue to push the boundaries of nitrogen-doping and pursue a cavity recipe which produces high Q_0 with higher gradient reach
  - Early results have been exceptional

Acknowledgments

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

Thanks for your attention!