Results and New Insights from Vertical Testing of LCLS-II Production Cavities

Dan Gonnella
For the LCLS-II Project

Outline

- Overview of LCLS-II Cavity Requirements
- First Article Results
  - Change of Recipe
- R_{BCS} in Production Cavities
- Production Results
- Conclusions and Outlook

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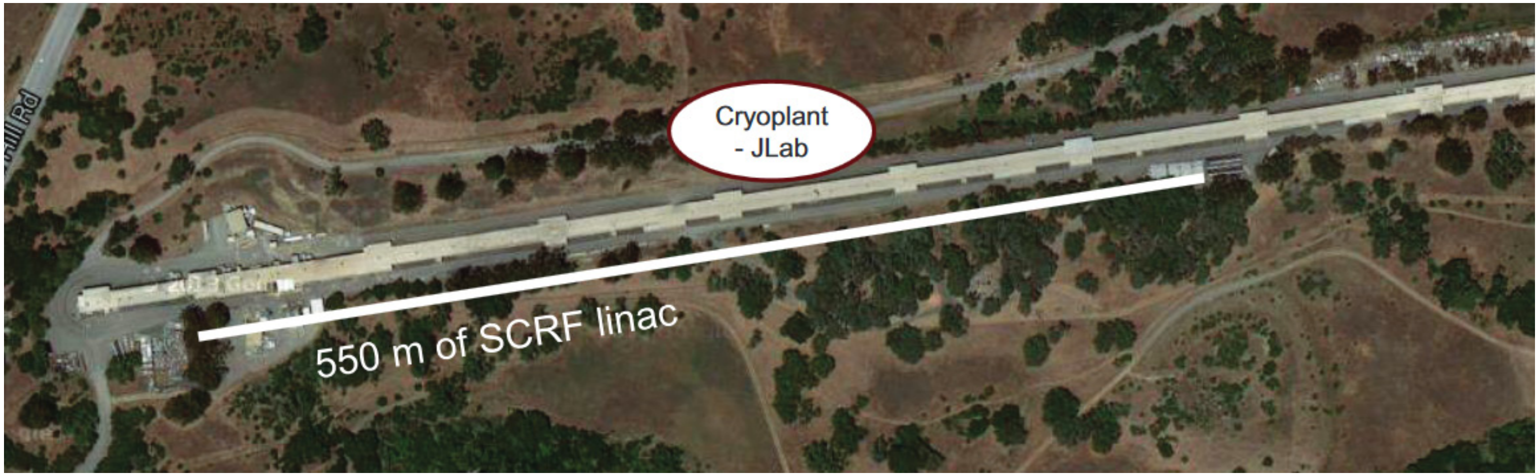
Introduction to LCLS-II

- The SRF linac is closely based on the XFEL/ILC/TESLA Design
- It consists of 35 cryomodules each with 8 cavities – total of 280 cavities



Introduction to LCLS-II

SLAC

- The SRF linac is closely based on the XFEL/ILC/TESLA Design
- It consists of 35 cryomodules each with 8 cavities – total of 280 cavities
- The 280 1.3 GHz 9-cell cavities have a very ambitious Q specification:

2.7×10^{10} at 16 MV/m and 2 K

Introduction to LCLS-II

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- It consists of 35 cryomodules each with 8 cavities – total of 280 cavities
- The 280 1.3 GHz 9-cell cavities have a very ambitious Q specification:

2.5×10^{10} at 16 MV/m and 2 K

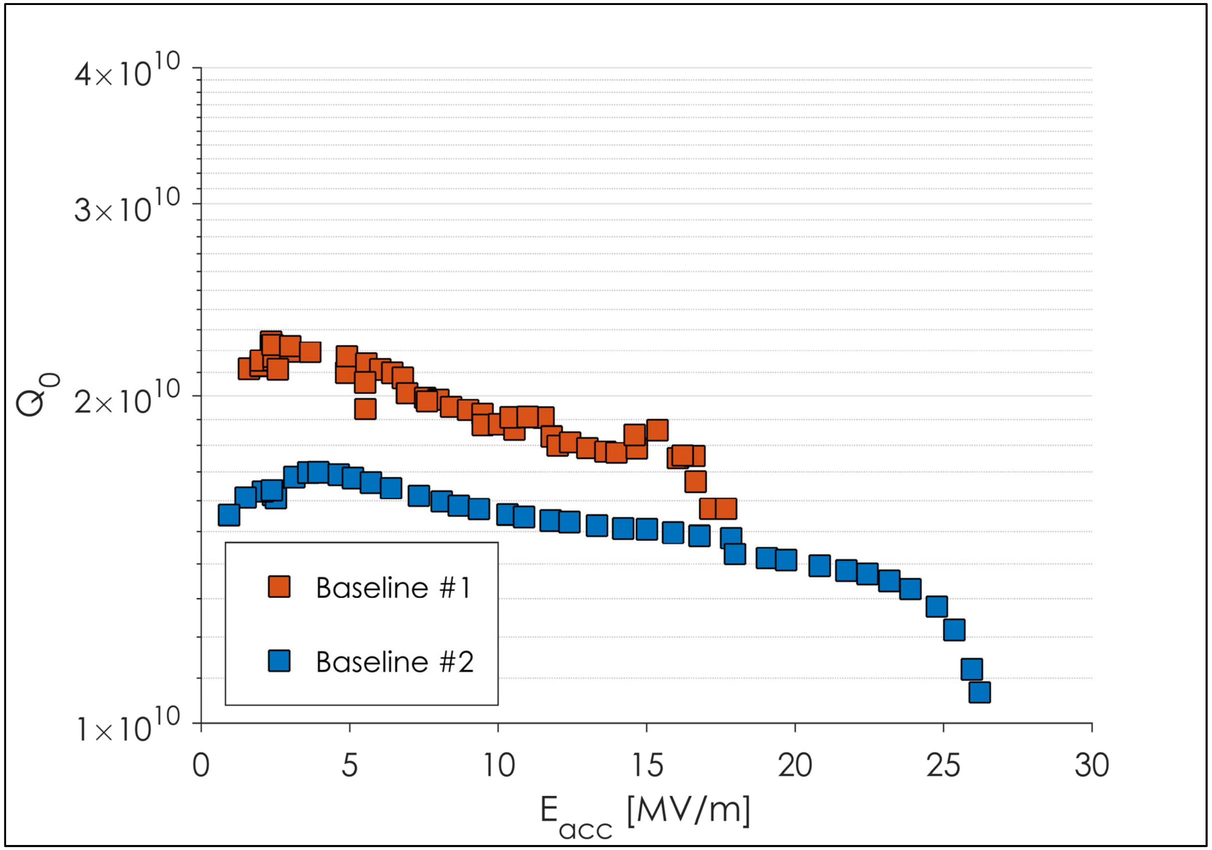
Q specification lowered in VT due to addition of stainless steel blank on short side of cavity – adds ~0.8 nΩ of R_{res}

- Additionally, cavities must reach 19 MV/m

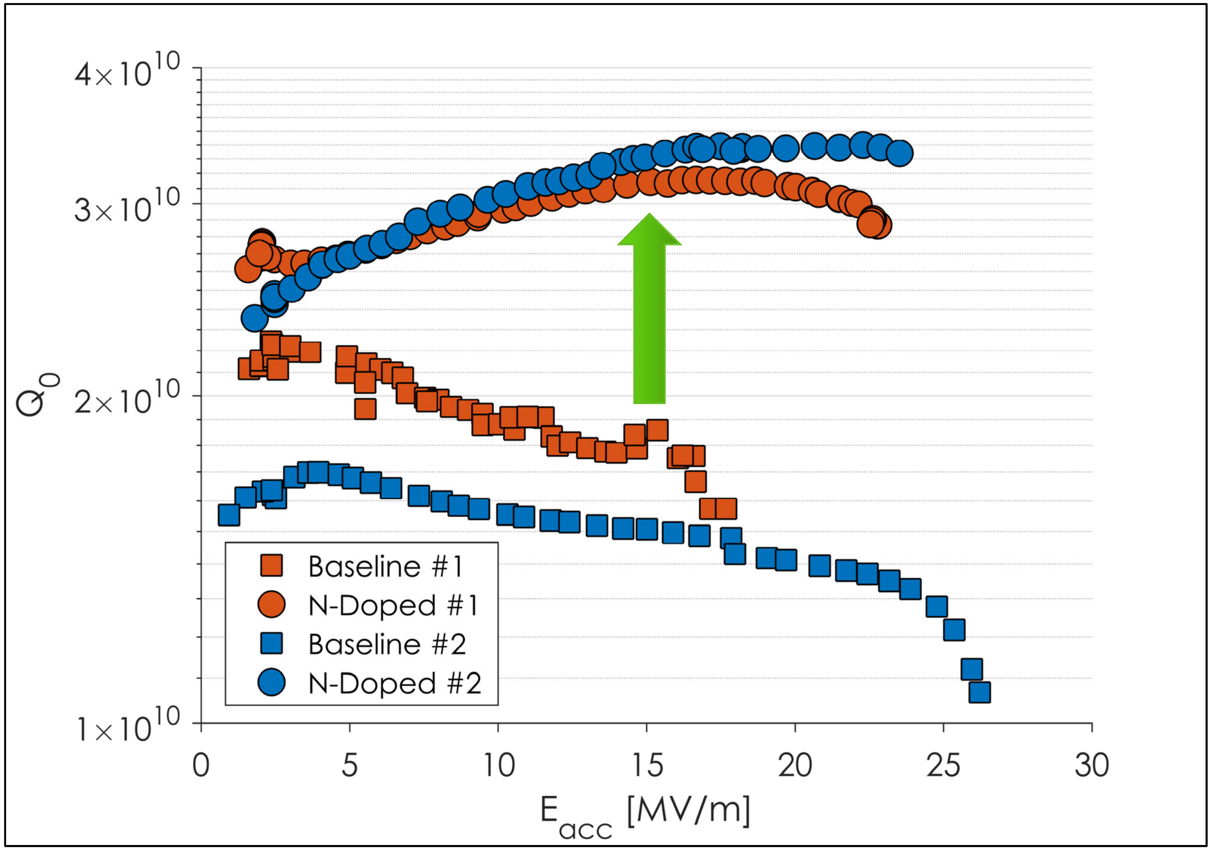
Cavity Preparation

- In order to achieve the ambitious Q specification, all 9-cell cavities for LCLS-II are prepared with nitrogen-doping
- Original recipe:
  - 140 µm bulk EP
  - 800^{o}C degas for 3 hours in vacuum
  - 2 minutes at 800^{o}C in 20-30 mTorr of N_2
  - 6 minutes at 800^{o}C in vacuum
  - 5-7 µm light EP
- Cavities are being produced by Research Instruments GmbH (RI) and Ettore Zanon S.p.a (EZ)
- Niobium was procured from Tokyo Denkai and OTIC Ningxia

Nitrogen-Doping Introduction



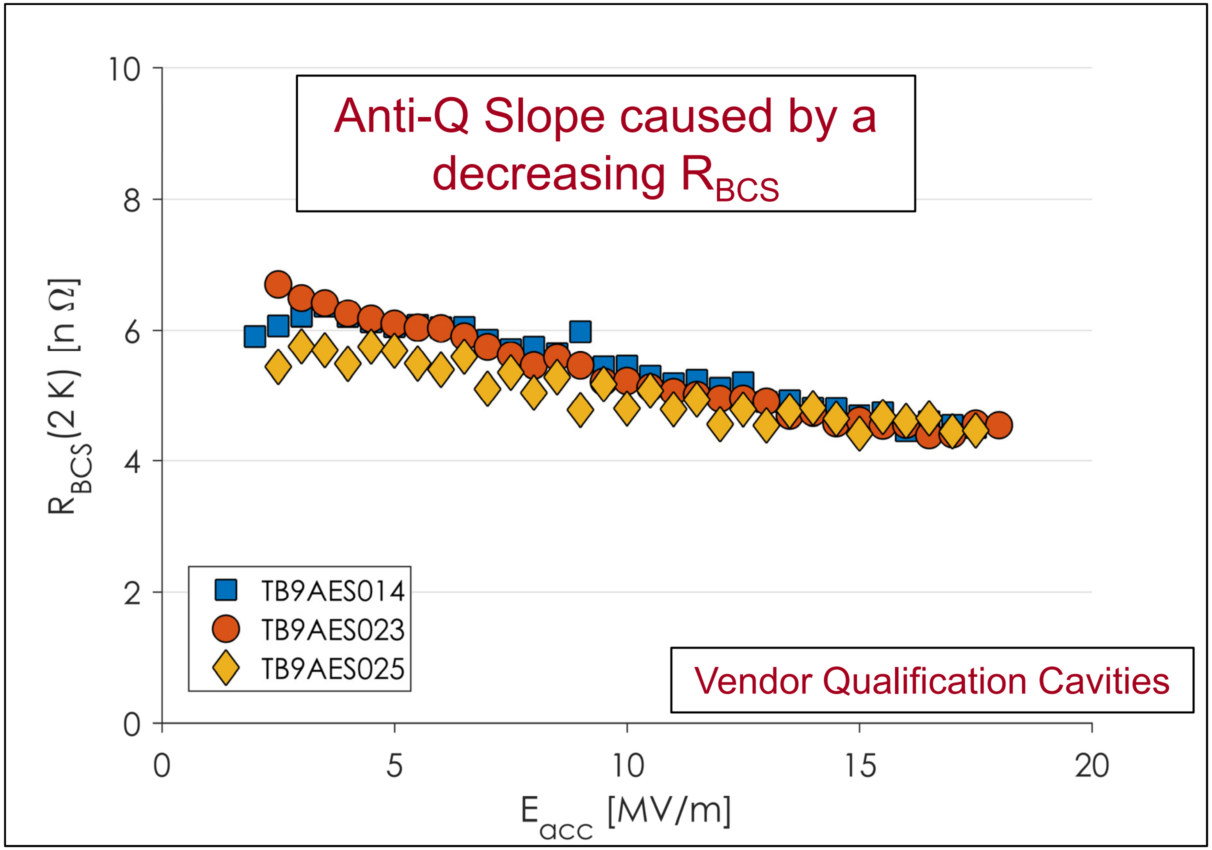
Nitrogen-Doping Introduction



- Q is improved by 2 mechanisms:
  - Higher starting Q_0
  - Anti-Q slope
- Both of these are a resulting of a changing R_{BCS}

Q_0's of >$3x10^{10}$
can consistently be produced

Anti-Q Slope

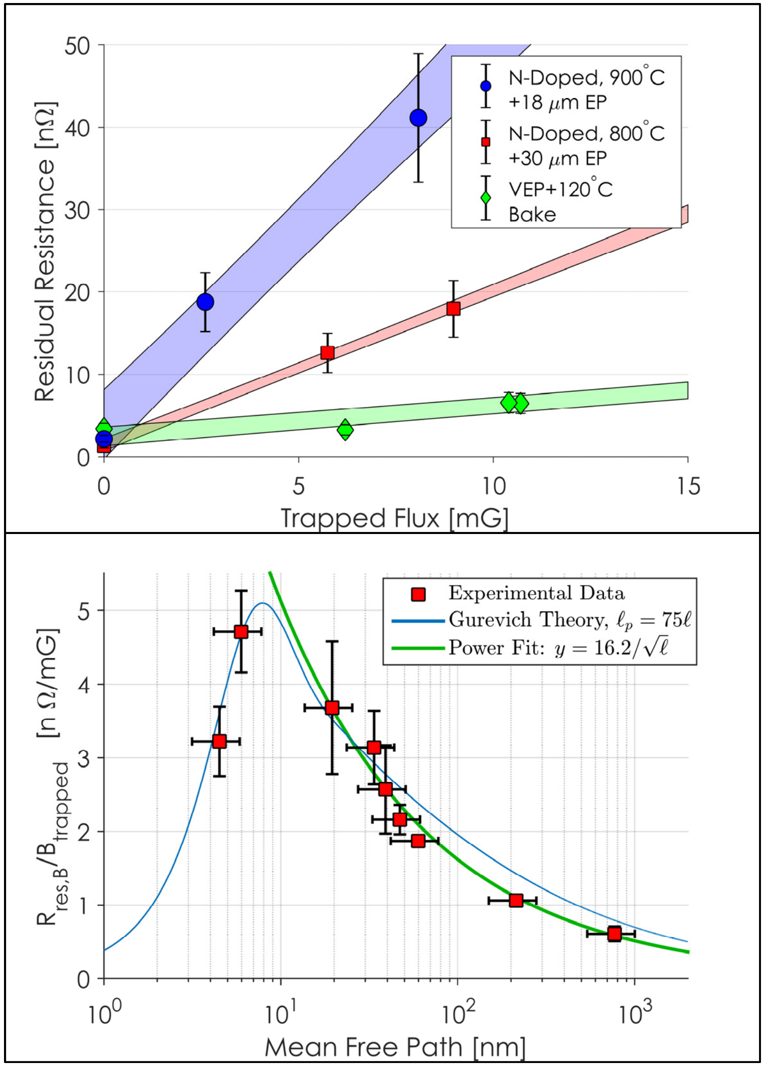


Anti-Q Slope caused by a decreasing R_{BCS}
Vendor Qualification Cavities
TB9AES014
TB9AES023
TB9AES025
R_{BCS}(2 K) [n Ω]
E_{acc} [MV/m]
0
2
4
6
8
10
0
5
10
15
20

Drawbacks of N-Doping

- Q_0 is significantly improved by the lowering of R_{BCS}
- There is a tradeoff however with R_{res}
- Nitrogen-doped cavities are more sensitive to losses from trapped magnetic flux
- For the same amount of trapped flux, a N-doped cavity will have a higher R_{res} than an un-doped cavity
  - 3.4x for the LCLS-II cavity recipe
- This requires efficient flux expulsion or small ambient magnetic fields to maintain high Q_0

See Also:
A. Palczewski TUXBA06
S. Posen TUXBA02
J. Maniscalco TUYAA01



Presented at SRF 2015 and J. Appl. Phys. 119:073904

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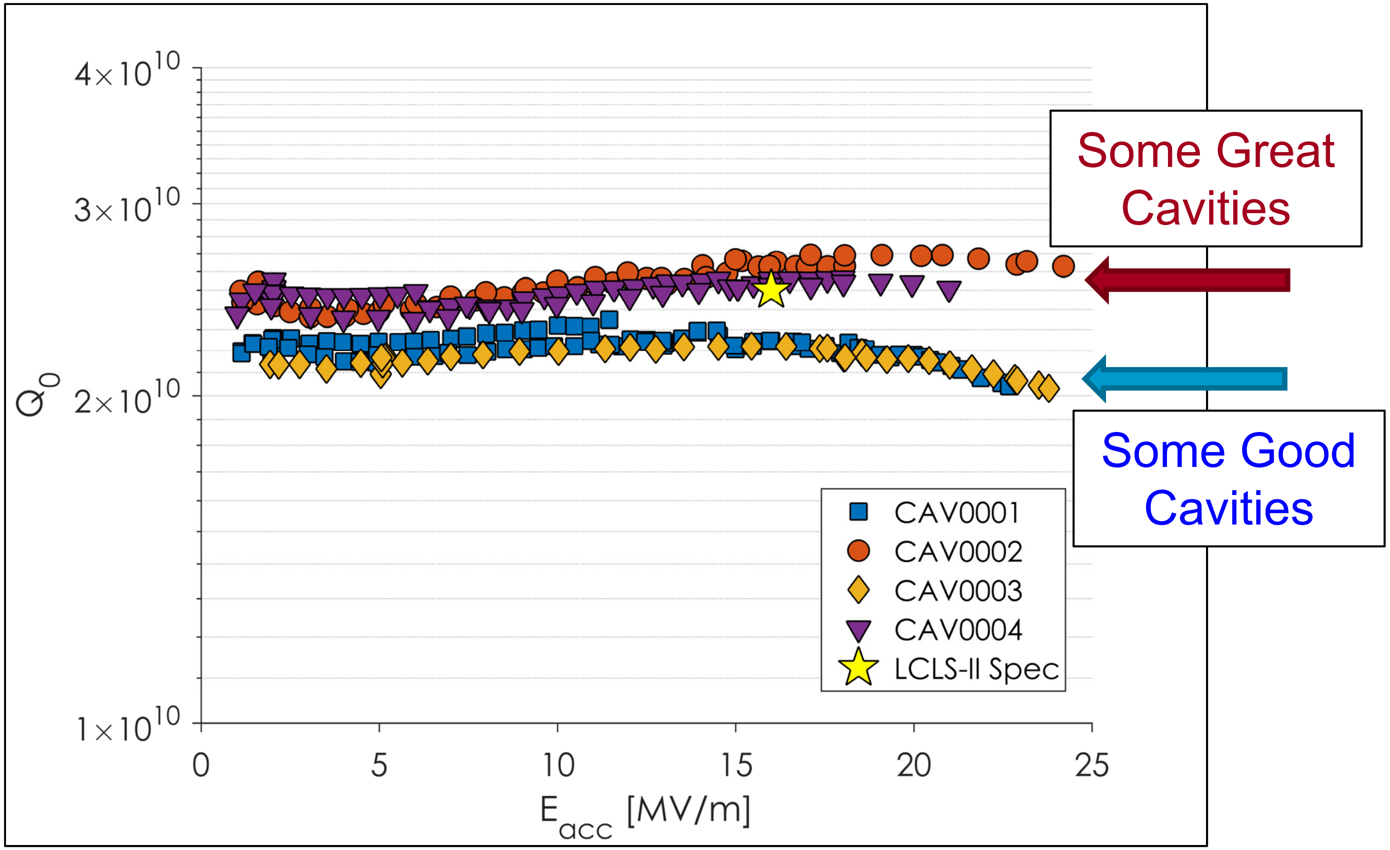
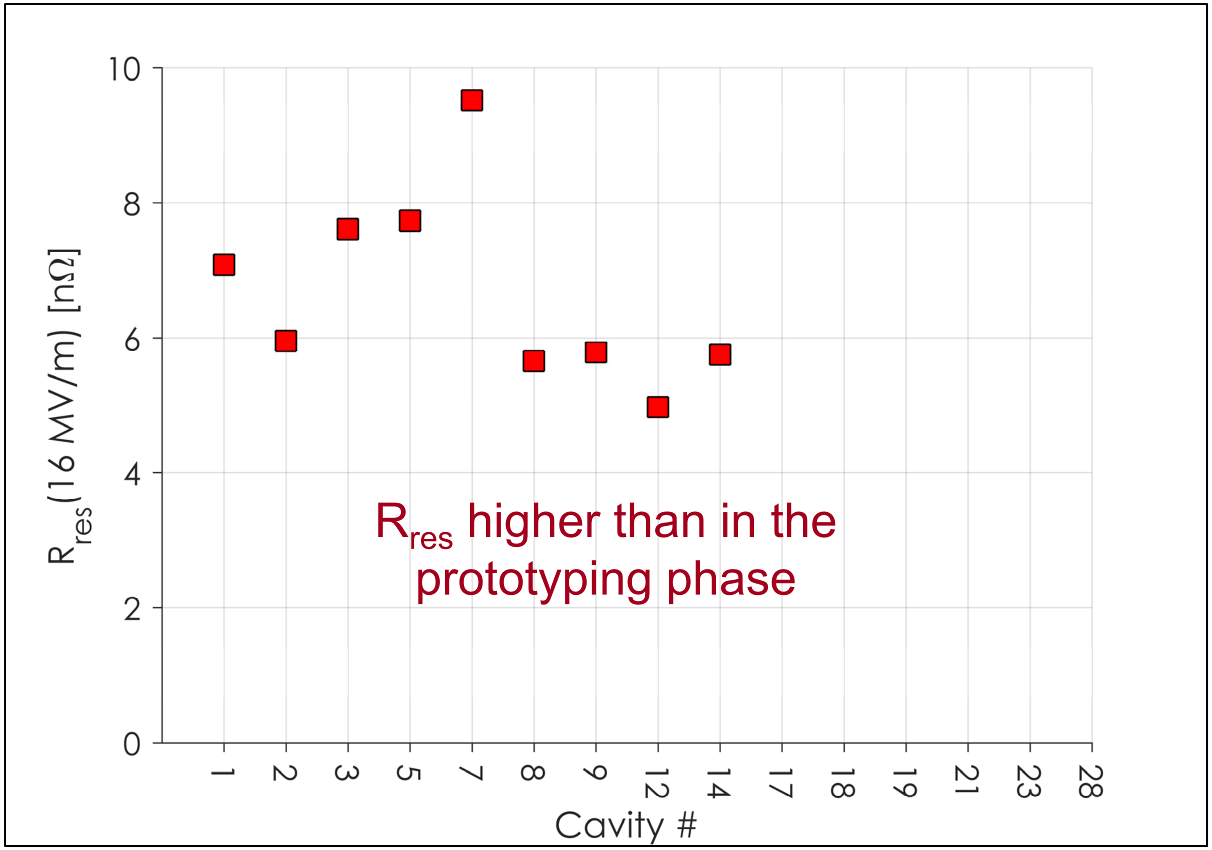
Q vs E for First Article Cavities



All these cavities tested in very low (0-1 mG) magnetic fields

Residual Resistance in First Articles



- Expected 2-3 nΩ, found 5-9 nΩ
- Spread is a result of differences in ambient magnetic fields

Issues with Original Recipe

- Material from both vendors showed worse flux expulsion when treated at 800°C in single-cell cavity tests than material used during the prototyping and R&D stage
  - All material meets specifications
- This means that magnetic field specifications would need to be tighter in order to minimize the need for efficient flux expulsion
- Cryomodule results thus far have shown ambient magnetic fields less than the LCLS-II CM Spec of 5 mG – further improvement on this would be difficult
- 140 µm bulk EP was insufficient to remove the damage layer, adding additional R_{res}

Worse flux expulsion is an independent phenomena from N-Doping – It impacts all cavity preparation methods

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Cavity Preparation

SLAC

- In order to achieve the ambitious Q specification, all 9-cell cavities for LCLS-II are prepared with nitrogen-doping
- Updated recipe:
  - **200** µm bulk EP
  - **900**^{o}C degas for 3 hours in vacuum
  - 2 minutes at 800^{o}C in 20-30 mTorr of N_2
  - 6 minutes at 800^{o}C in vacuum
  - 5-7 µm light EP

For additional information see:
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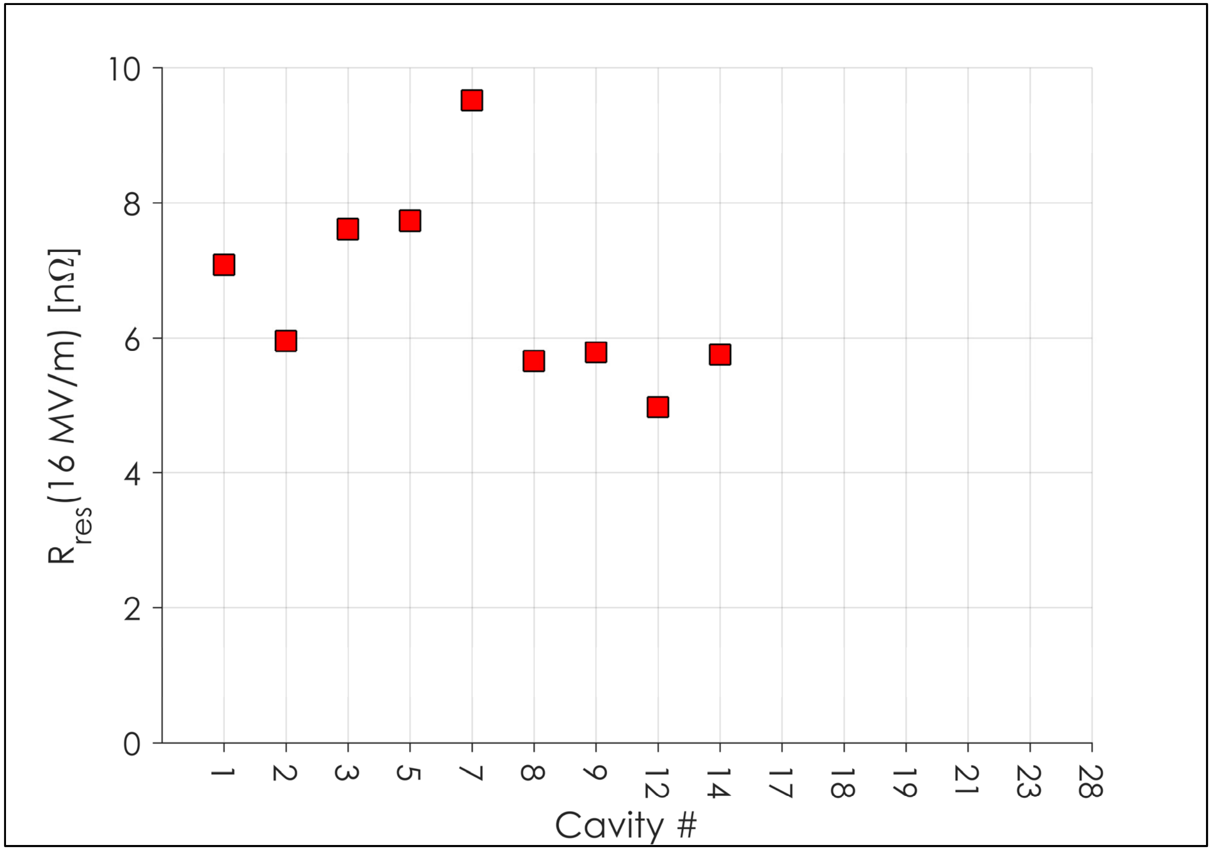
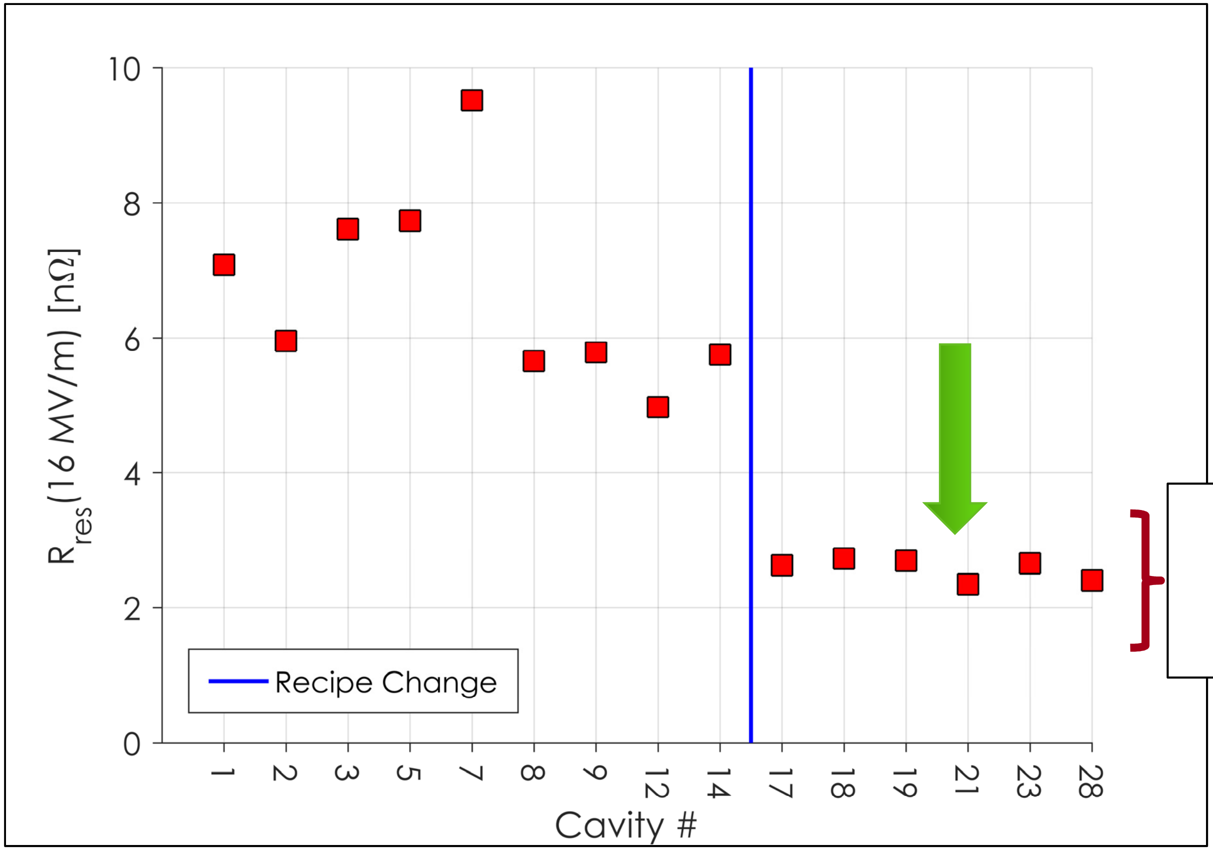
S. Posen TUXBA02

Residual Resistance in First Articles



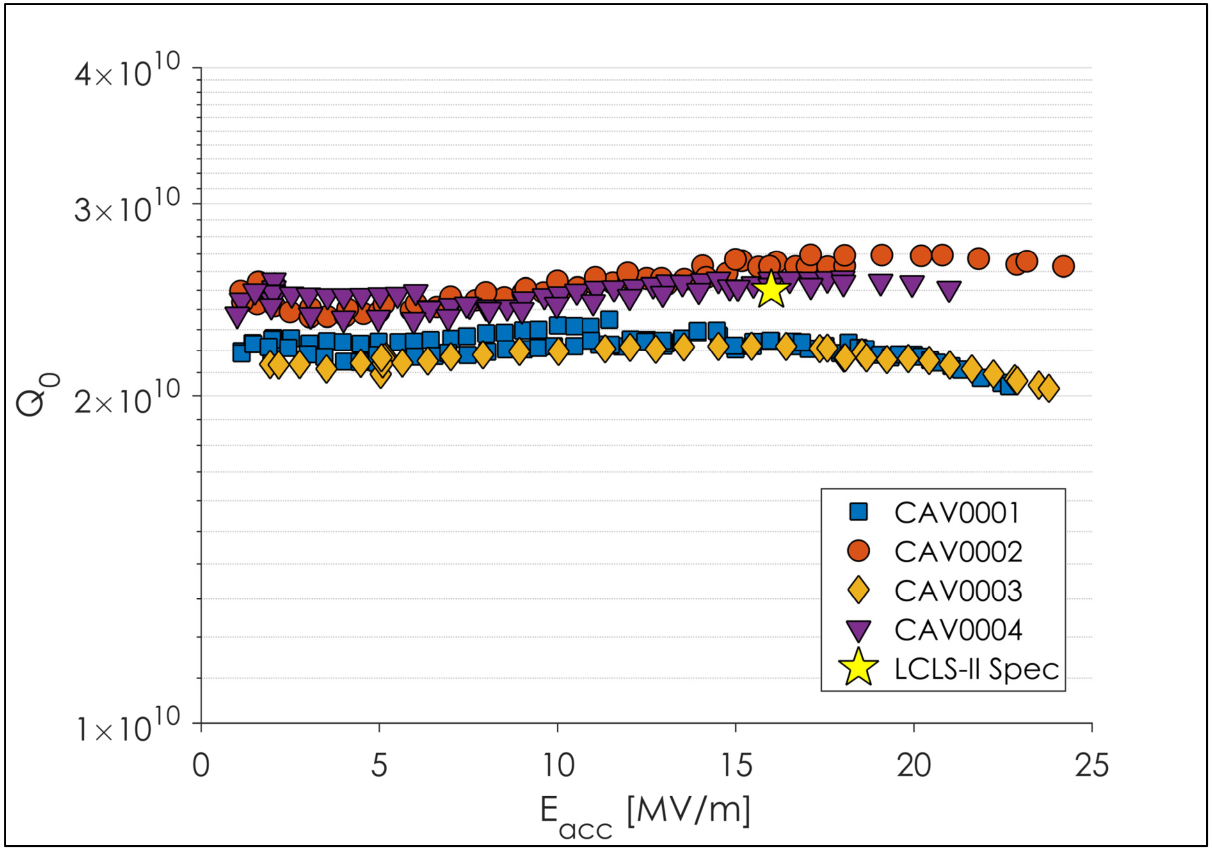
Residual Resistance After Recipe Change



Spread lower due to near 100% FE

After Increasing Bulk EP and Degas Temperature, R_{res} is consistently ~2 nΩ

Q vs E for First Article Cavities



Q vs E for First Article Cavities

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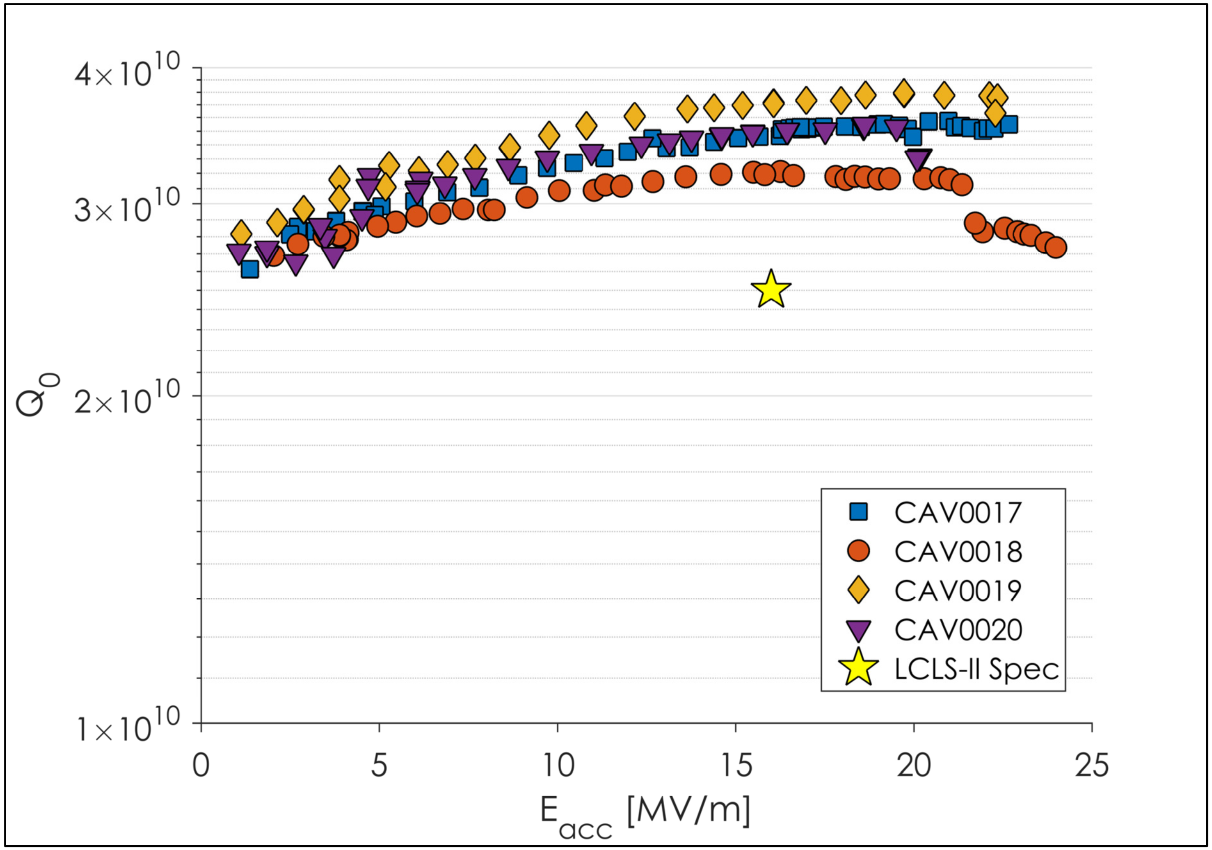
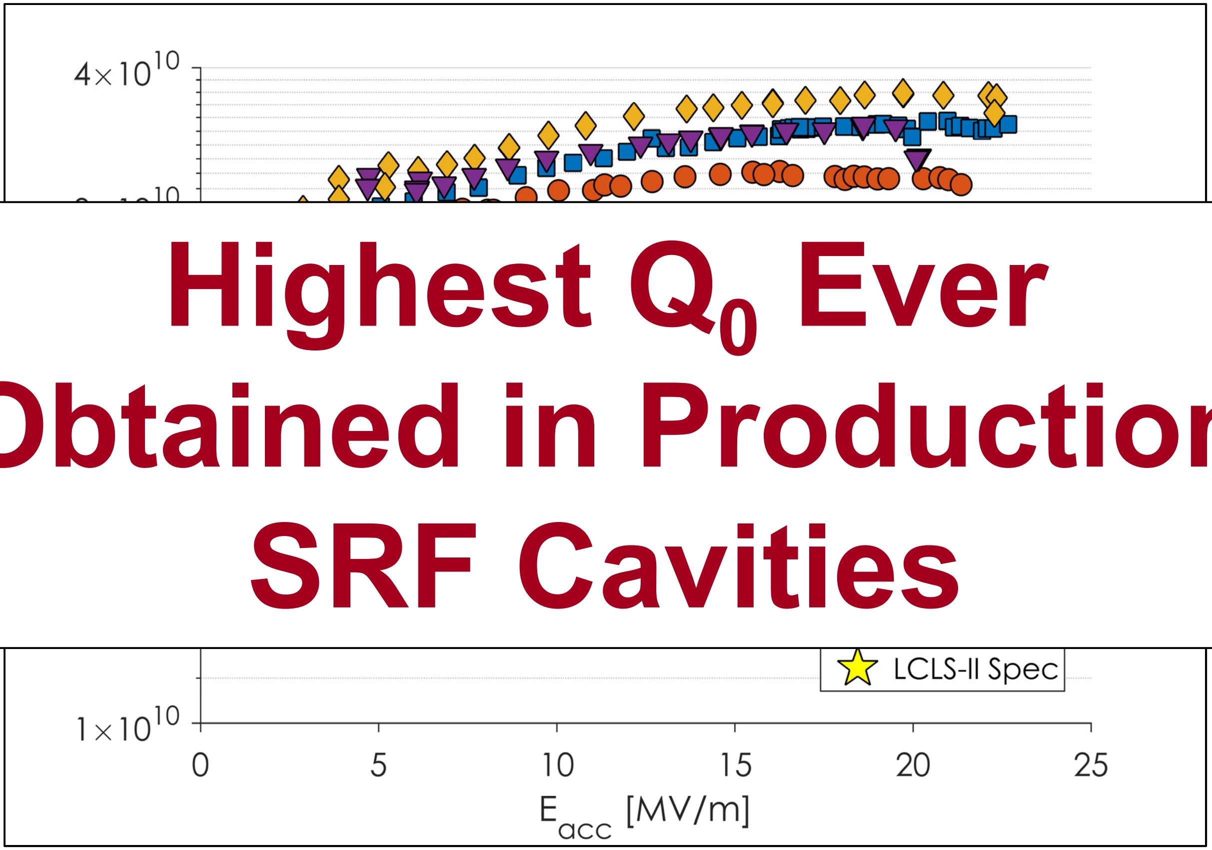


Cavities now consistently meet Q_0 specification

Q vs E for First Article Cavities



Highest Q_0 Ever Obtained in Production SRF Cavities

Cavities now consistently meet Q_0 specification

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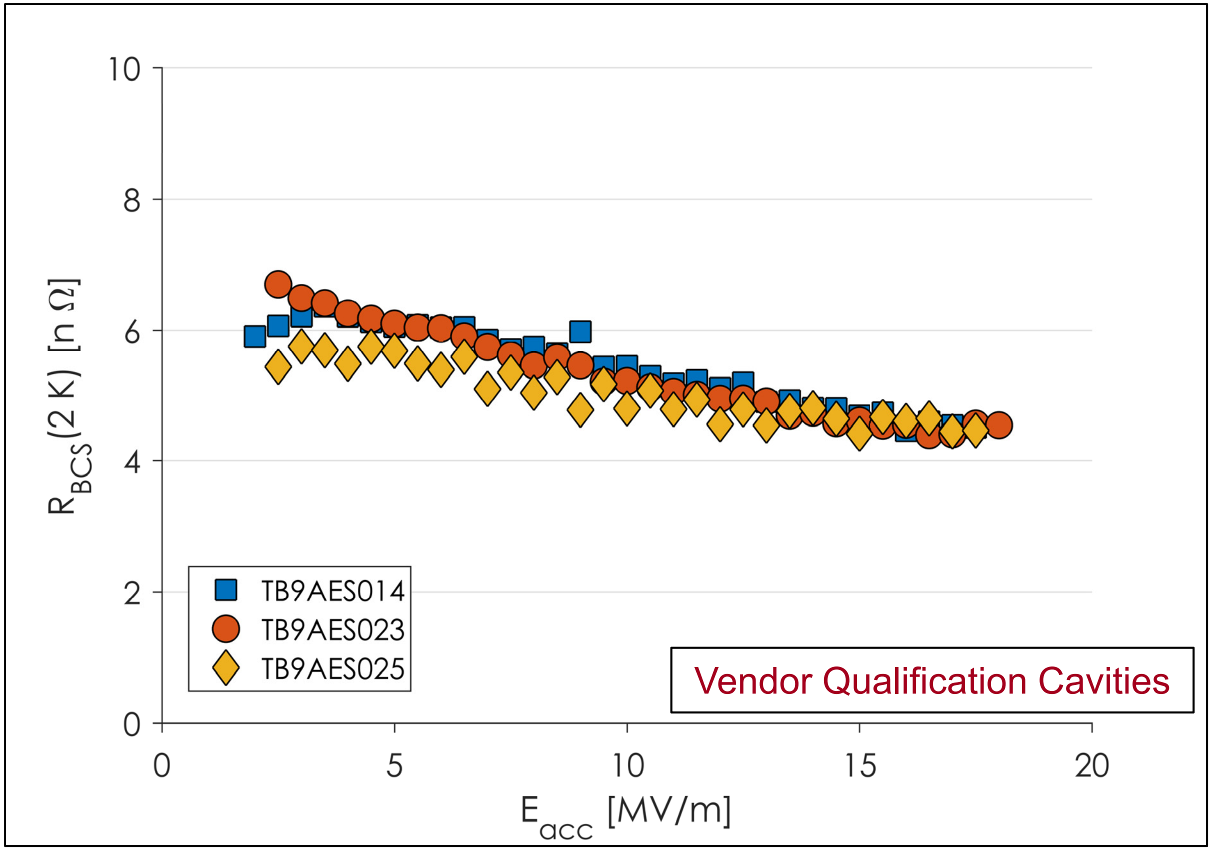
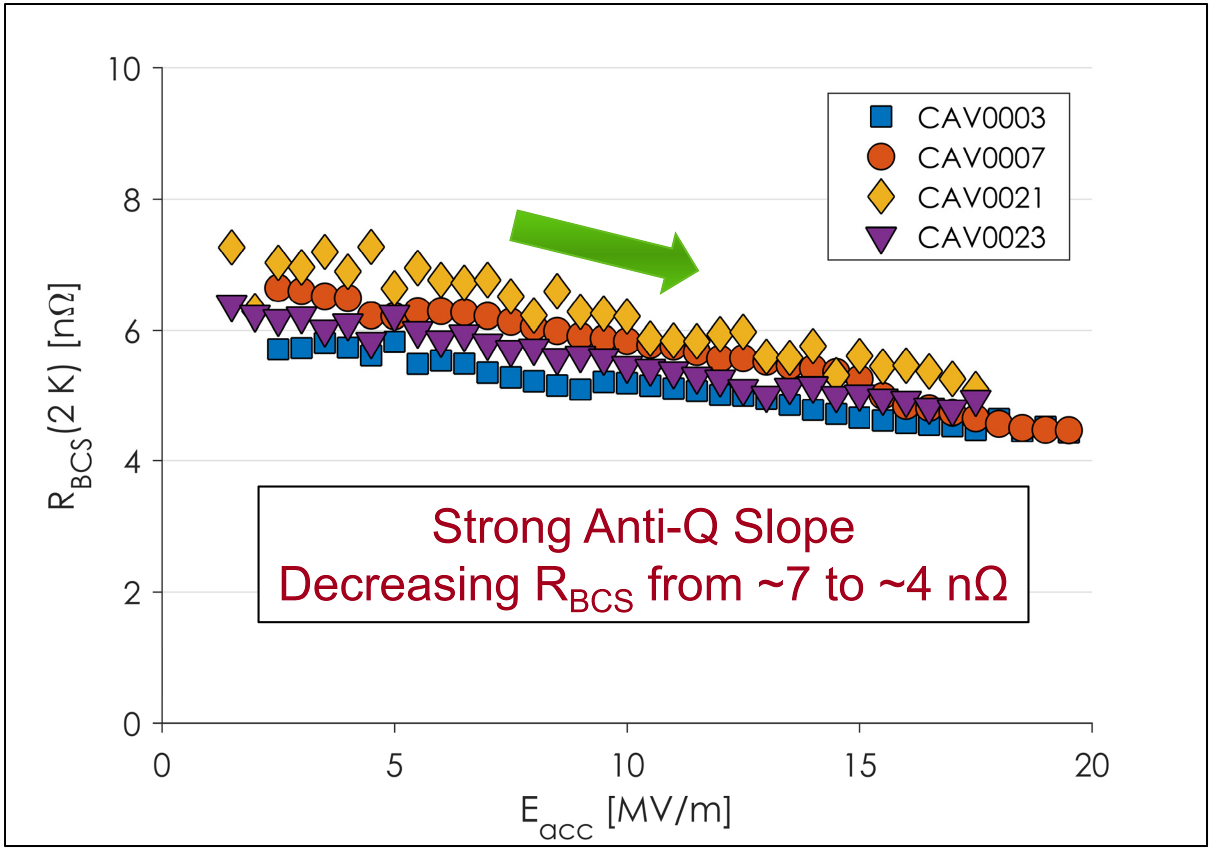
Reminder: Anti-Q Slope



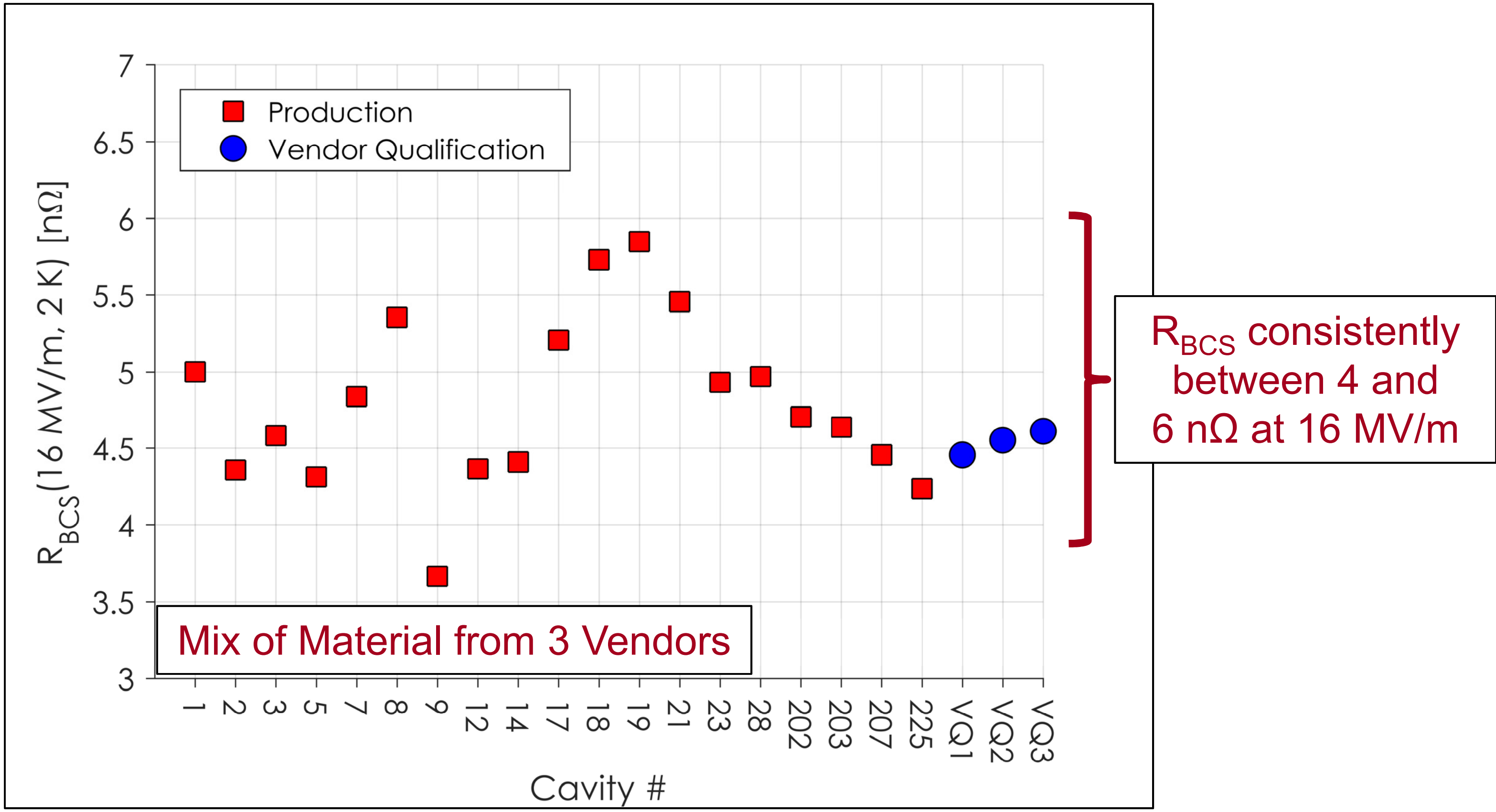
R_{BCS} in Production Cavities

SLAC



Production cavities show similar anti-Q slope to R&D cavities

R_{BCS} in Production Cavities



- R_{BCS} at 16 MV/m and 2.0 K is consistently 4-6 nΩ
- This is consistent with "2/6" N-Doping developed in the R&D phase of LCLS-II

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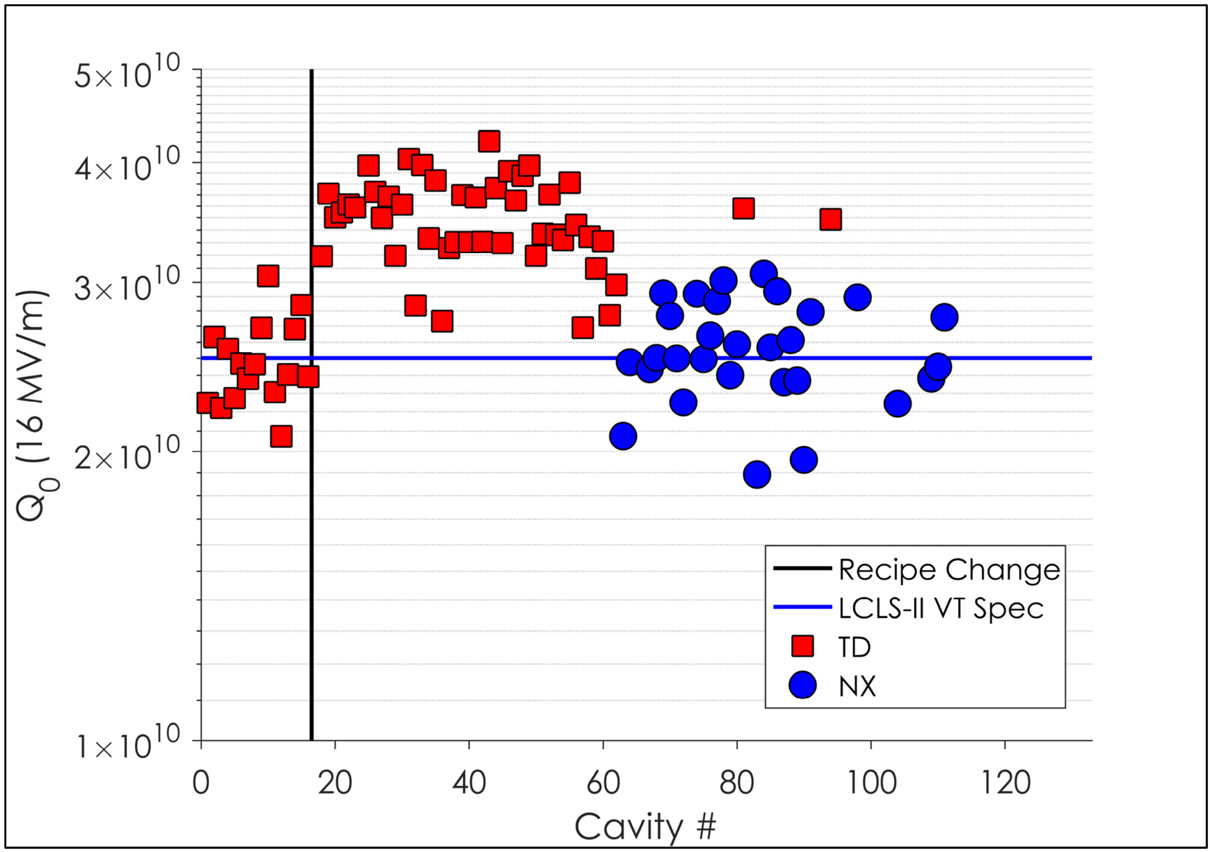
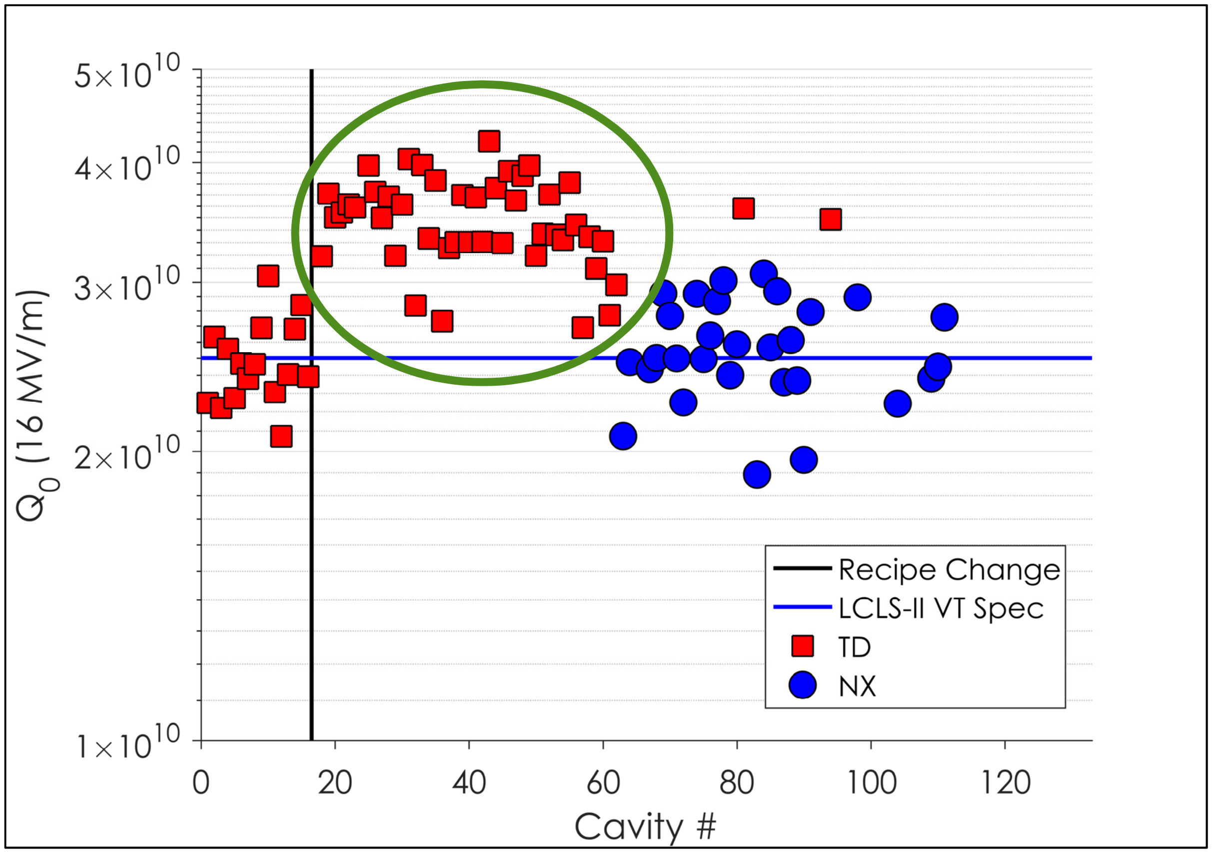
Vendor B Results



- Vendor B has completed fabrication of original order of 133 cavities
- 99 cavities have been tested so far at JLab and Fermilab

Vendor B Results



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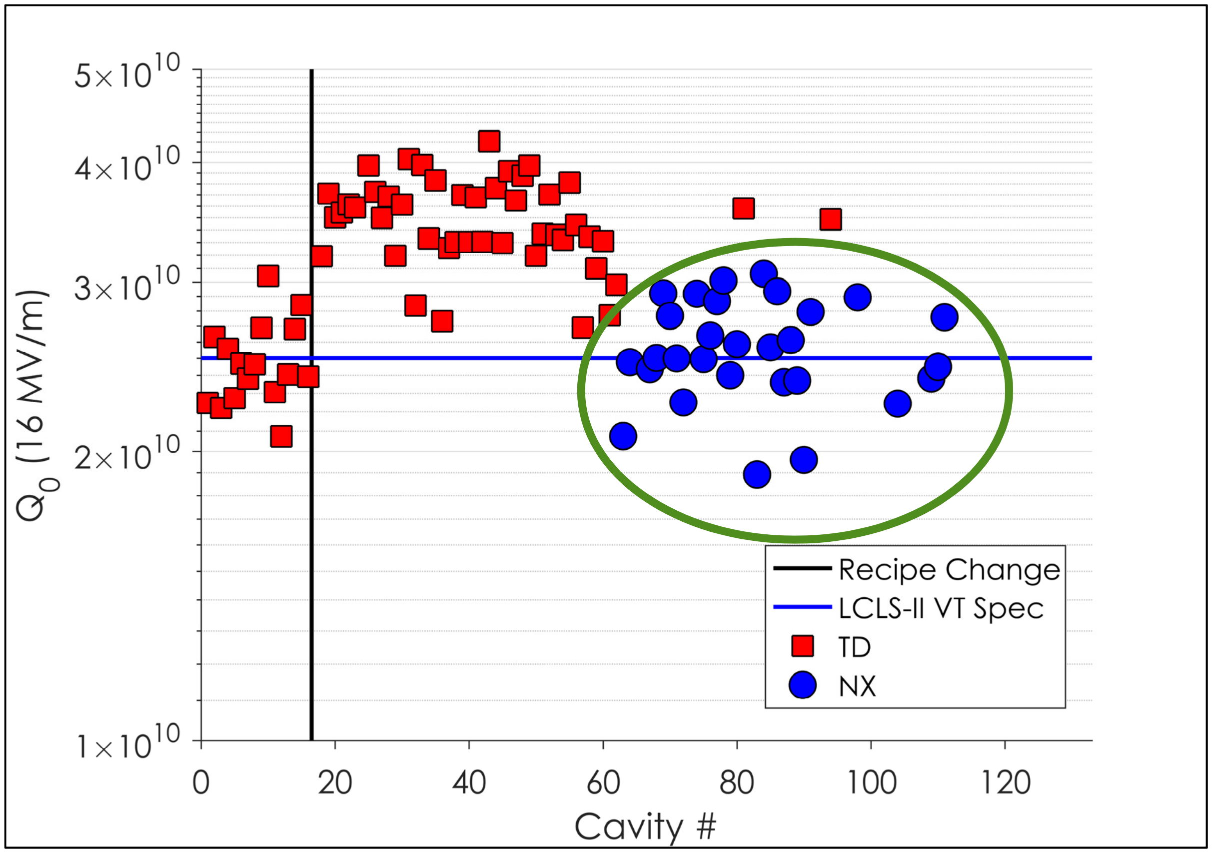
- TD Cavities 900/200 preparation consistently exceed LCLS-II spec

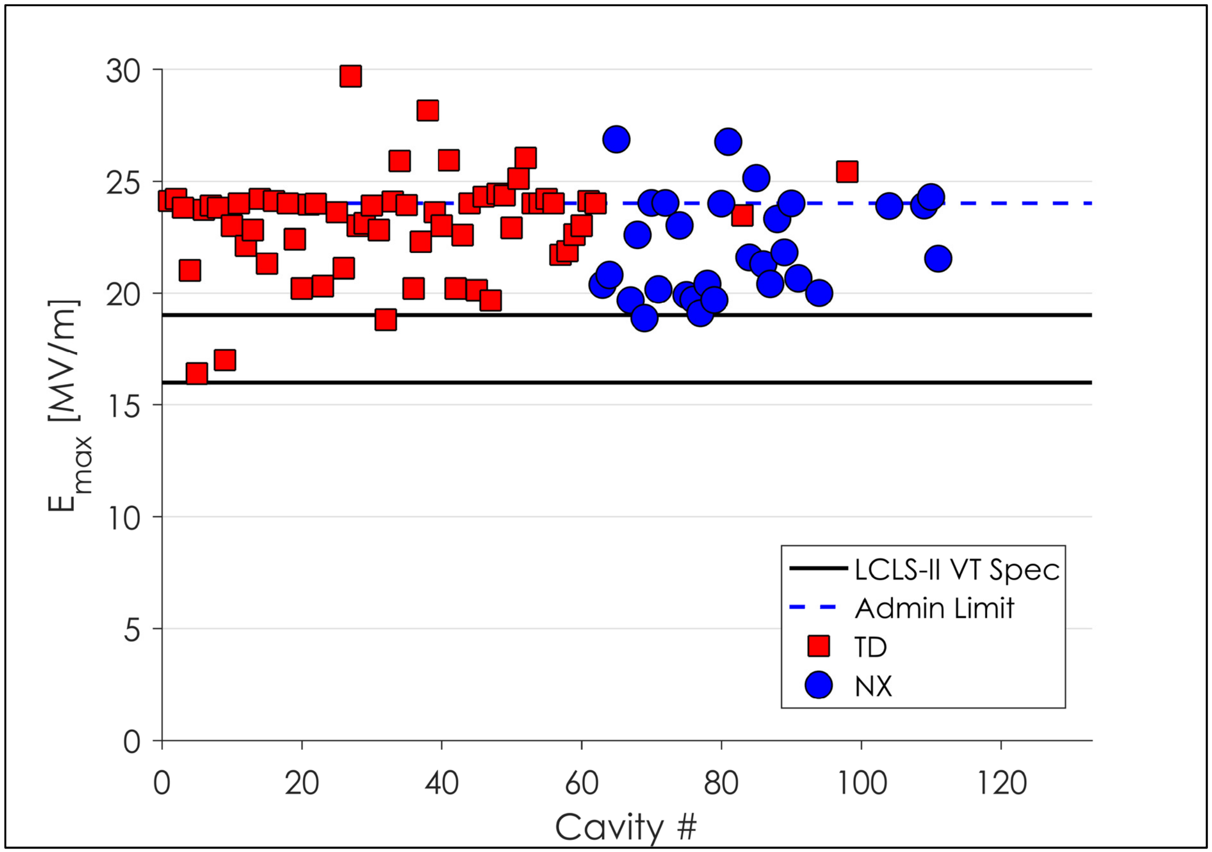
Vendor B Results

SLAC



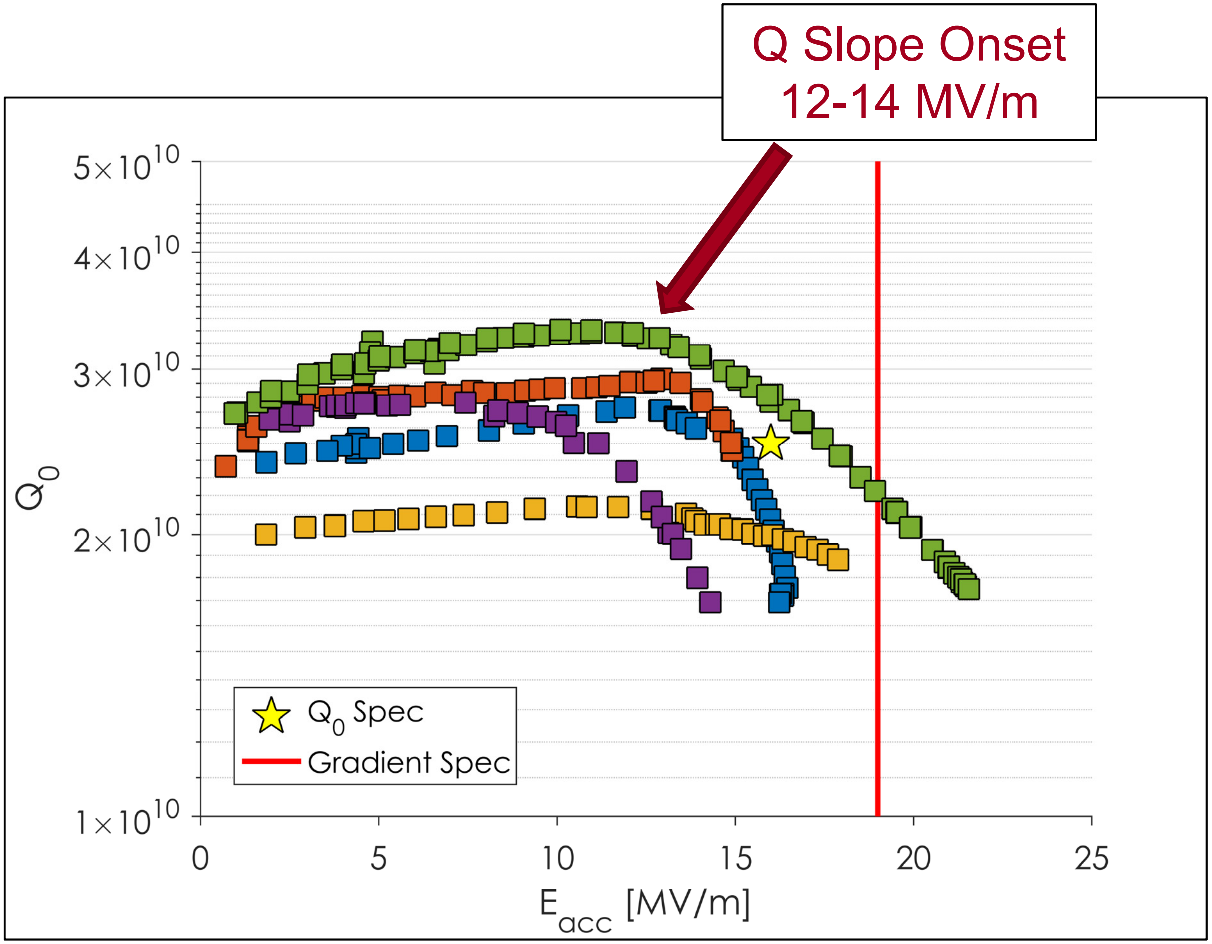
- Vendor B has completed fabrication of original order of 133 cavities
- 99 cavities have been tested so far at JLab and Fermilab
- TD Cavities 900/200 preparation consistently exceed LCLS-II spec
- NX Cavities have middling results with Q_0's ranging from 2 to $3x10^{10}$
  - Future NX cavities will be treated at 950°C – evidence suggests this improves Q_o

Vendor B Results



- JLab employs an administrative limit at 24 MV/m during VT
- Gradient reach has consistently exceeded specification throughout production

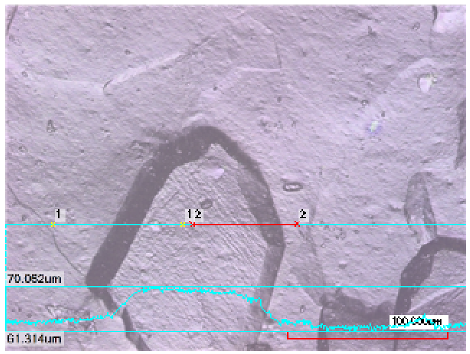
Vendor A Results

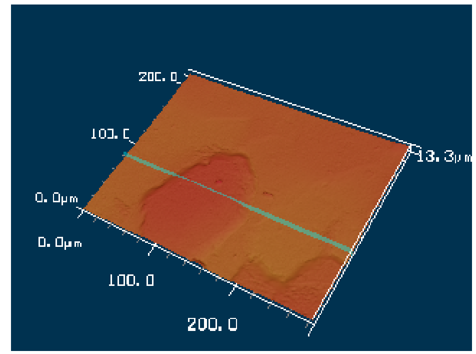


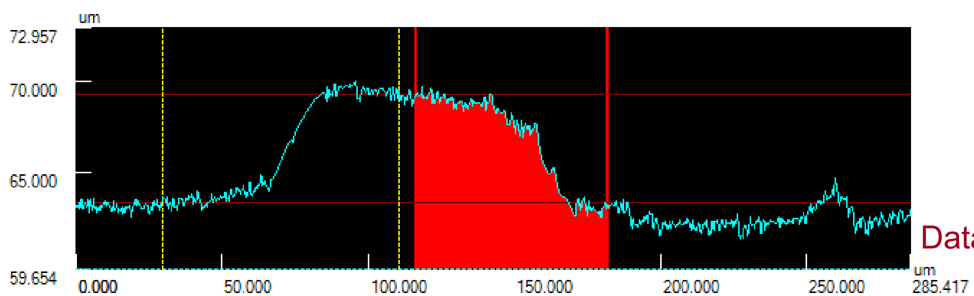
Subset of cavities, behavior observed in most

- Vendor A cavities were dominated by a strong Q slope with onset 12-16 MV/m
- This Q slope led to early quench and low Q at 16 MV/m

Vendor A – Surface Roughness



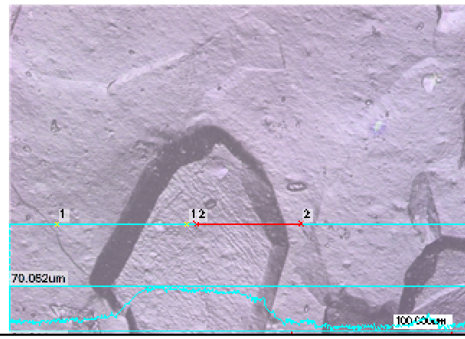


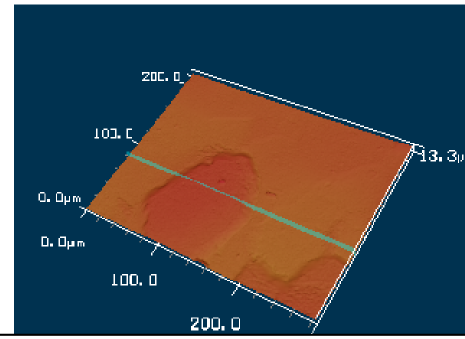


Data from Y. Trenikhina

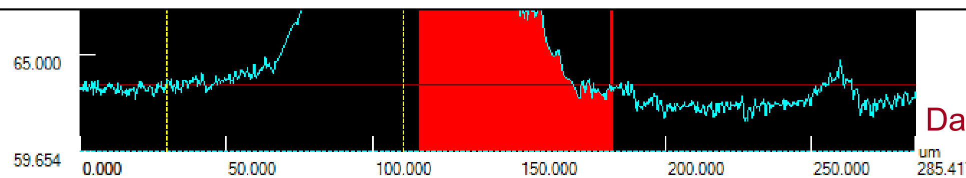
- EP at Vendor A was producing a very rough surface
- Roughness was as high as 15 μm
- It was found that EP temperature was leading to the EP no longer being in the “polishing regime” but in the “etching regime”

Vendor A – Surface Roughness





This Issue was Fixed



Data from Y. Trenikhina

- EP at Vendor A was producing a very rough surface
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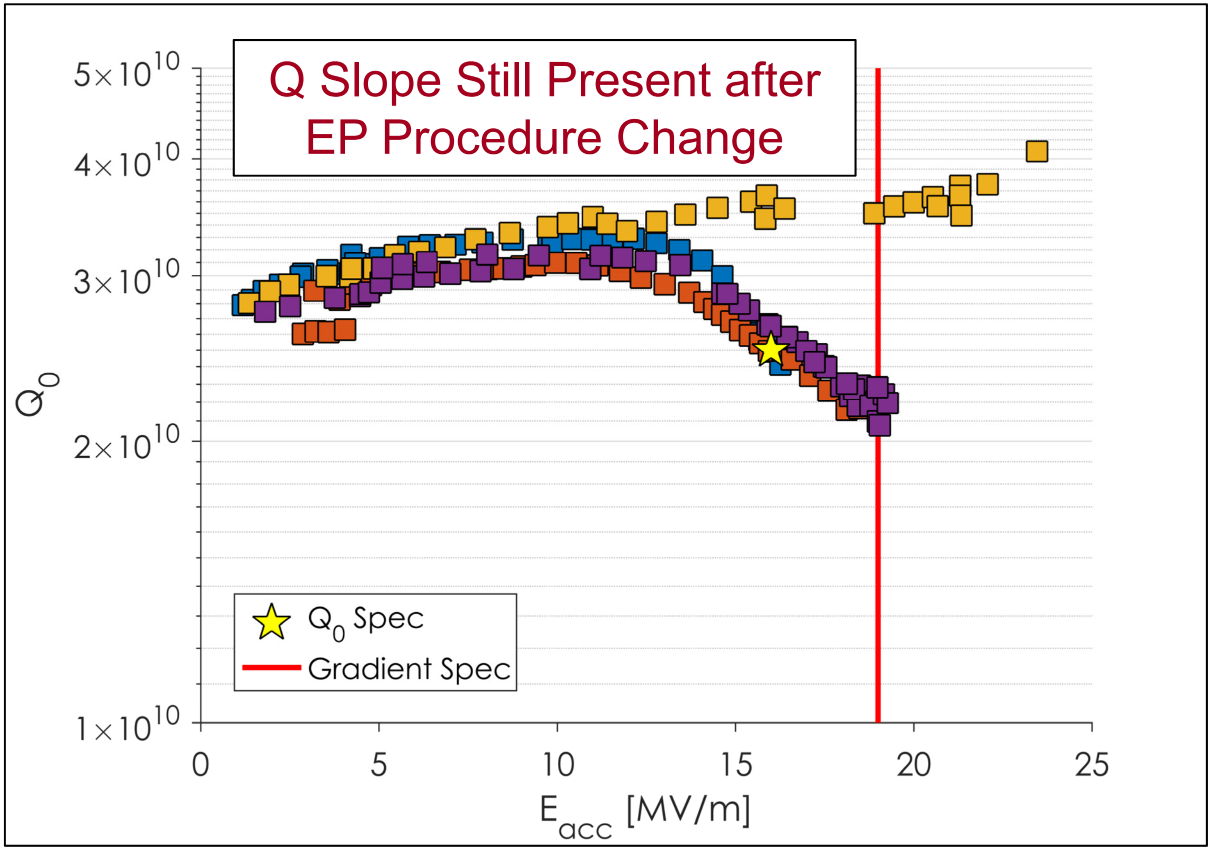
Vendor A – Surface Roughness

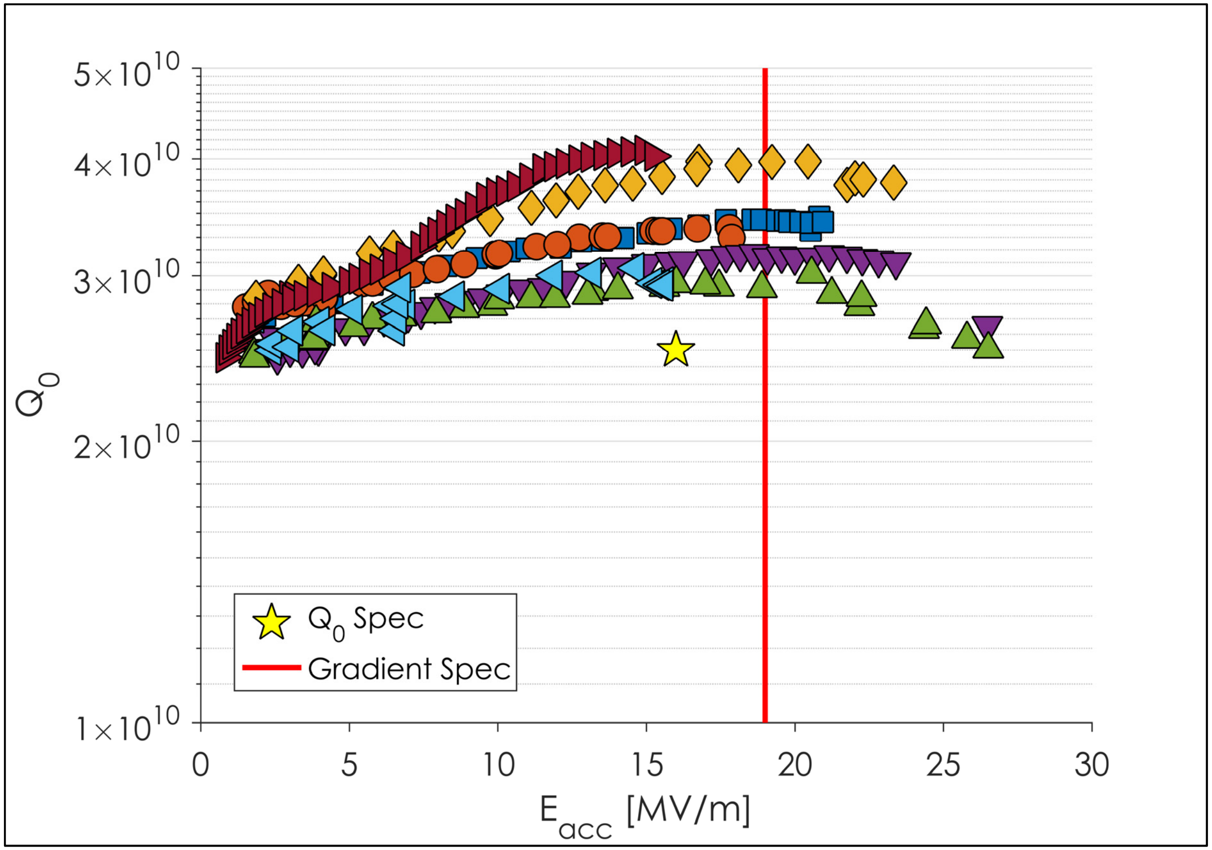


- 3 of 4 cavities with "New EP" still had strong Q slope
- Bad EP was not the cause of the performance issues

Vendor A – Grinding Technique

- Visual inspection of the interior of Vendor A cavities after fabrication showed the presence of many defects
- Some pits had visible normal conducting media embedded
- Theorized that aggressive grinding on the dumbbell surface led to the "burying" of media
- This normal conducting media would then be revealed after bulk EP
- All procedures were reworked with LCLS-II staff to improve the fabrication procedures

Vendor A – Restart



- 7 cavities have been tested so far after restart
- No evidence of Q slope that was seen before
- 2 of the 7 still have lower than ideal quench fields – may be related to expected spread

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Conclusions and Outlook

- Production of cavities for LCLS-II is well underway
- The original recipe used caused poor flux expulsion and higher residual resistance than expected leading to a recipe change
- With the new recipe TD cavities routinely reach >3×10^{10} at 16 MV/m
- NX cavities still produce middling results: all future NX cavities will be heat treated at higher temperature

Conclusions and Outlook

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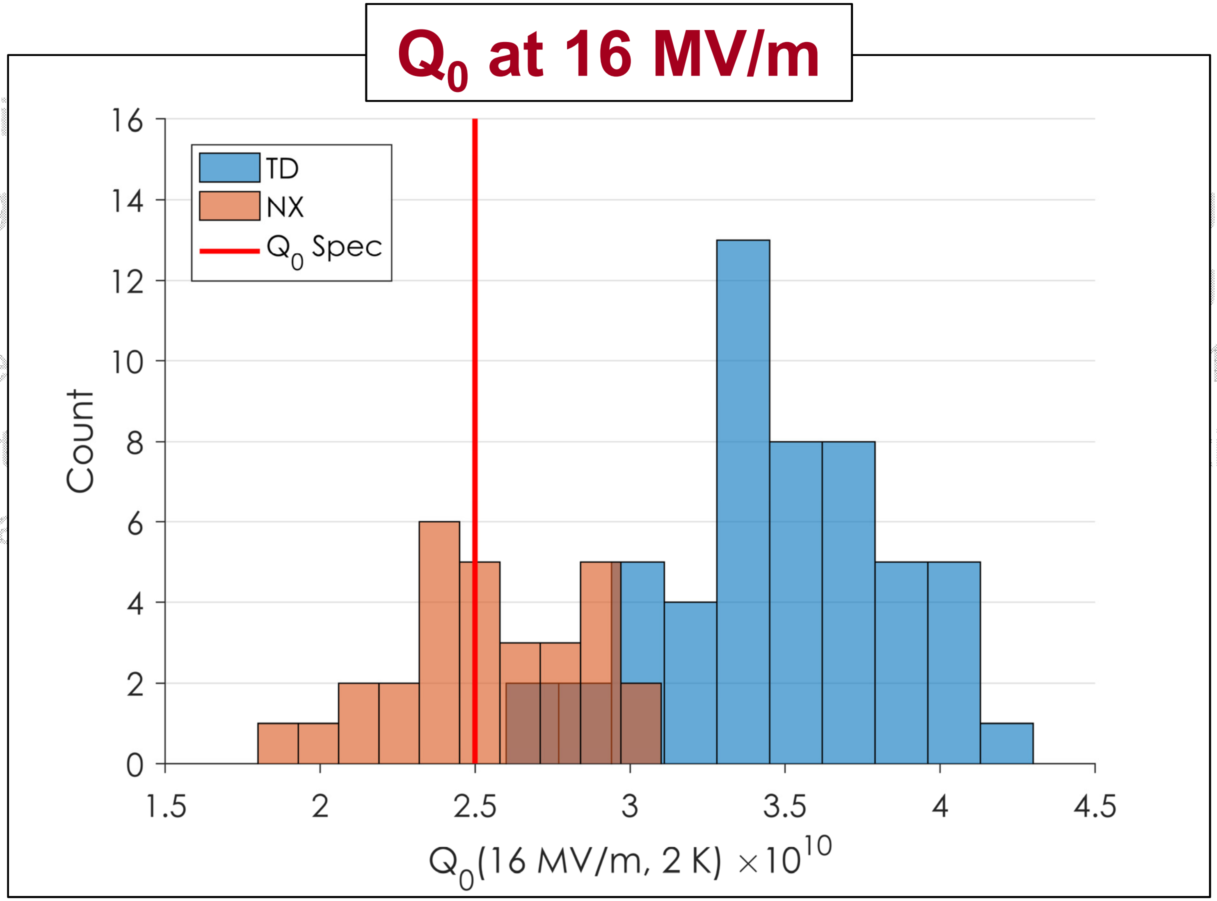

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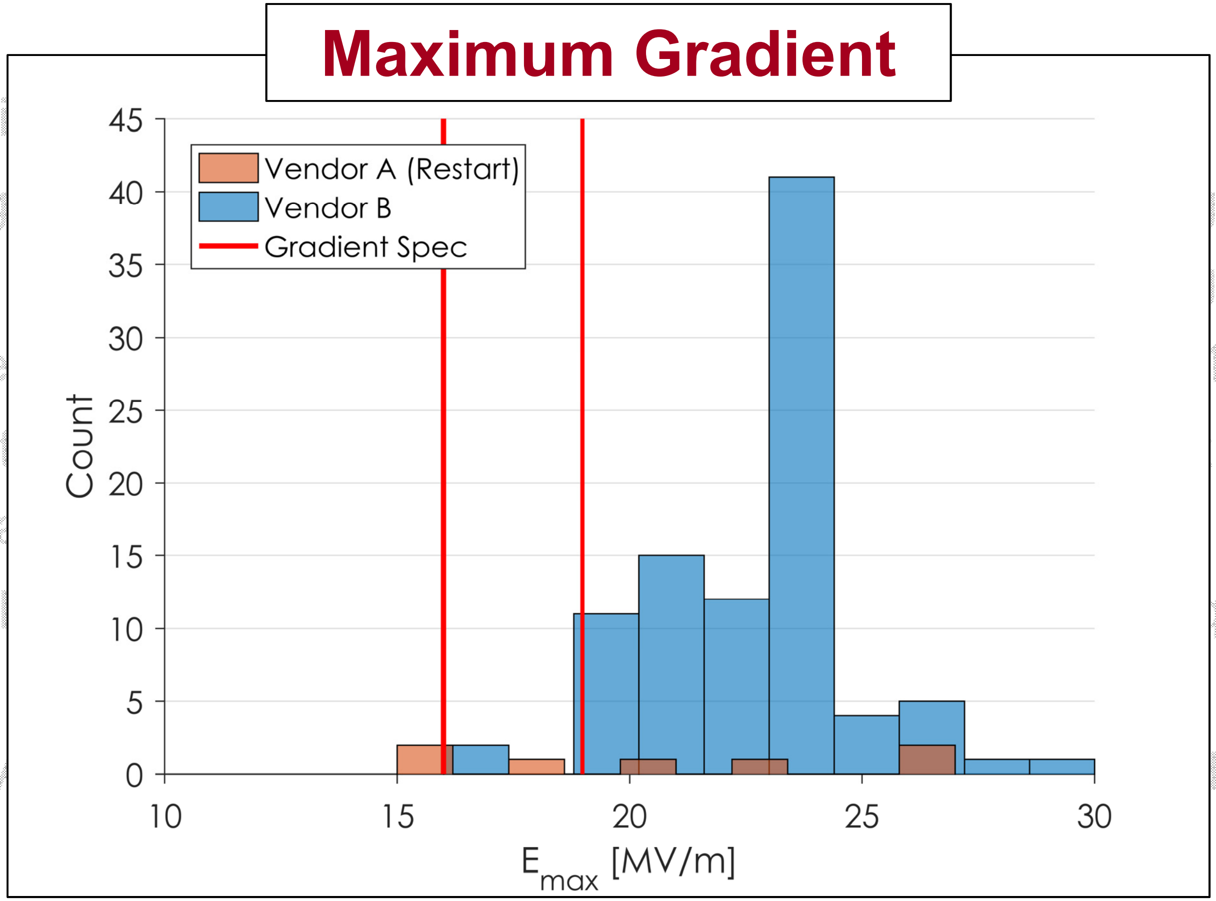
- The original recipe used caused poor flux expulsion and higher residual resistance than expected leading to a recipe change
- With the new recipe TD cavities routinely reach >3×10^{10} at 16 MV/m
- NX cavities still produce middling results: all future NX cavities will be heat treated at higher temperature
- Vendor B consistently produces cavities with great Q_0 and quench fields
- Vendor A has had issues with improper EP parameters, and a grinding technique that led to a strong Q slope
- LCLS-II staff oversight and rework at Vendor A has improved performance – Vendor A now produces good cavities

Conclusions and Outlook

SLAC



- Producti
- The orig ... gher residual ... ge
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Lessons Learned So Far

- When dealing with high Q_0 great care needs to be taken to maintain performance
- Flux expulsion is especially important in Nitrogen-Doped cavities
- Changes to cavity preparation recipe has been necessary at multiple stages to ensure performance is kept high
- In order to meet schedule demands, some cavities will have worse flux expulsion than others
  - Retreating all cavities is not a feasible option
- Project oversight at cavity vendors is important
- However when great care is taken…

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We Can Obtain World Record Q_0 in Production

Questions?