Optimization of High Temperature Nitrogen Doping

Daniel Bafia

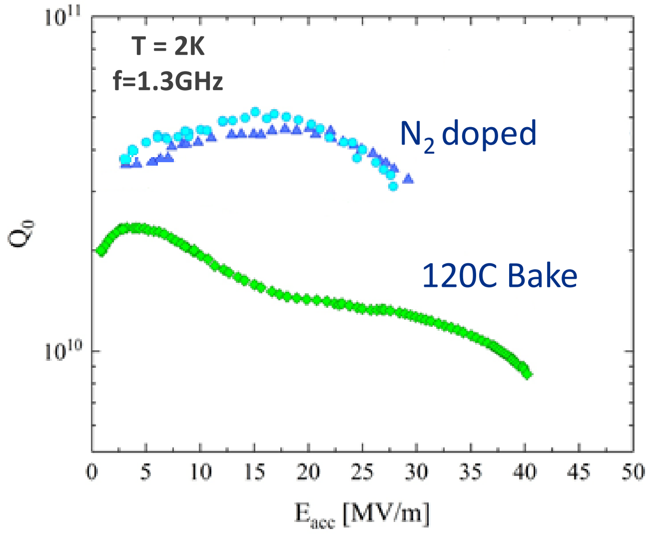
TTC/ARIES topical workshop on flux trapping and magnetic shielding

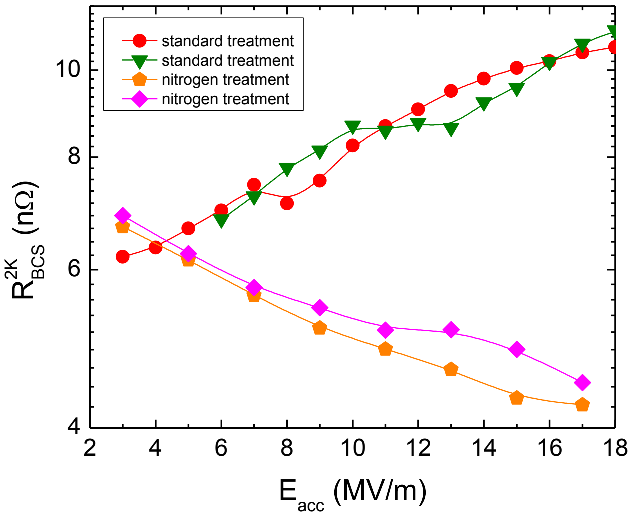
09 November 2018

Effects of High Temperature N-Doping on Cavity Performance

- Gives very high Q > 2-3 times higher than 120C bake
  - RF layer modified to have uniform **mean free path**
- Anti-Q slope phenomenon caused by the reversal of BCS dependence on the field

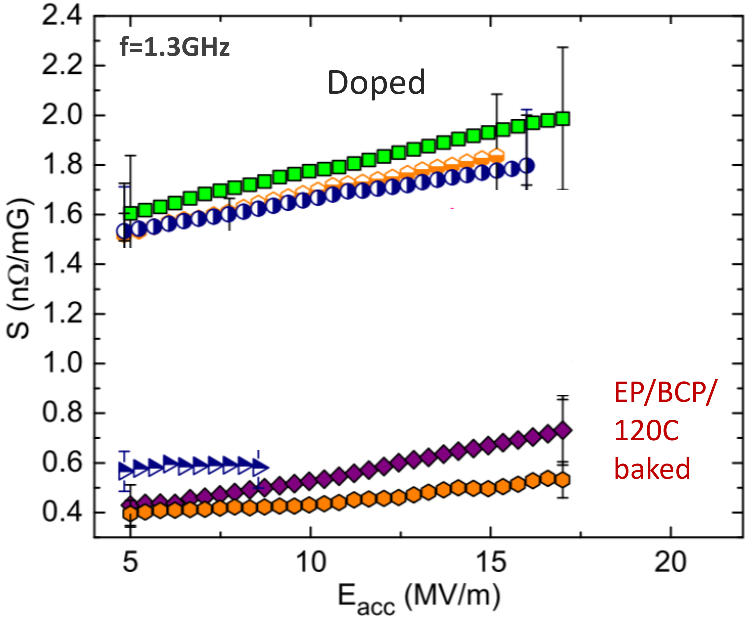
A. Grasselino et al, Superconductor Science and Technology, Volume 26, Number 10





Sensitivity to Trapped Magnetic Flux

- High temperature N-doping increases sensitivity to trapped flux compared to EP or EP bake



Plot adapted from M. Martinello et al, Appl. Phys. Lett. 109, 062601 (2016)

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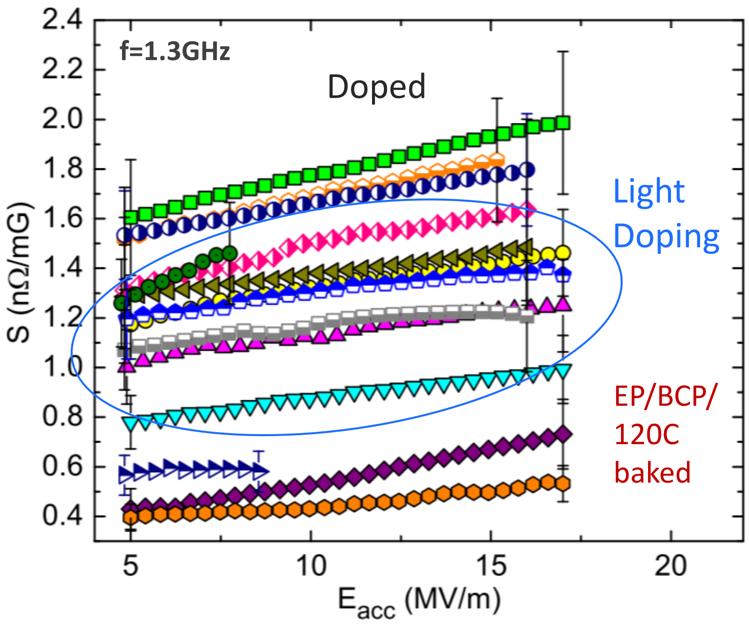
- **<u>However, this depends strongly on the level of doping</u>**
- Light doping leads to <u>lower</u> sensitivity than heavier doping
  - E.g., 2/6 doping used in LCLS-2



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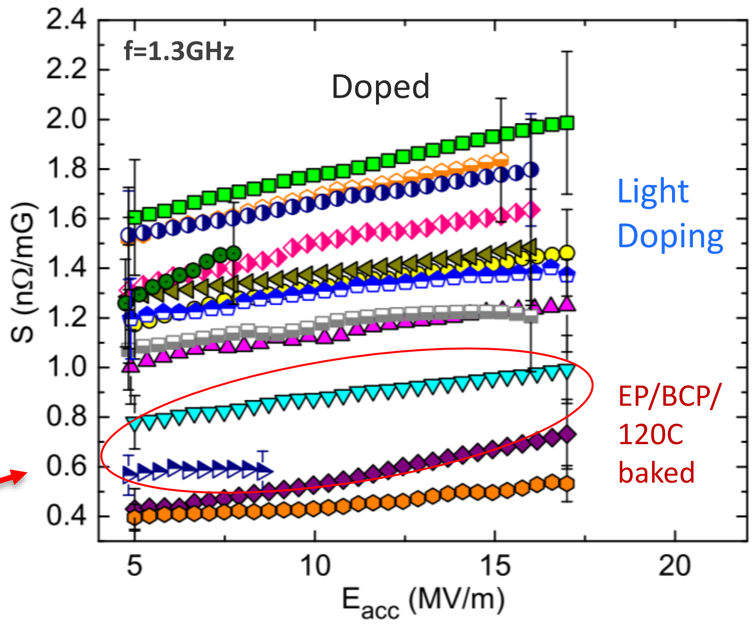
Can we improve further?



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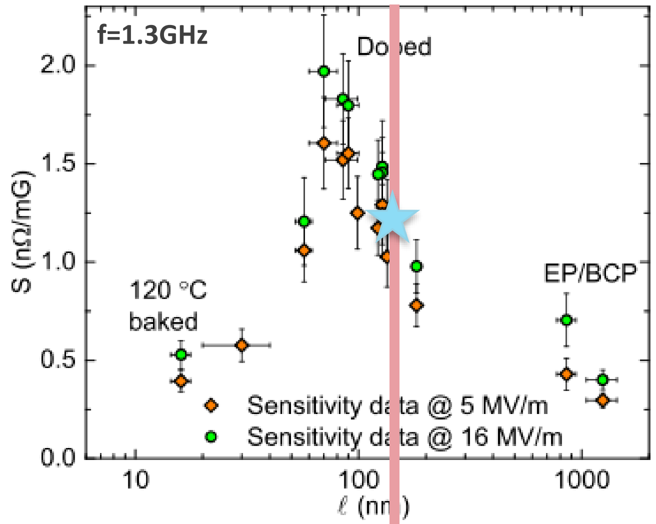
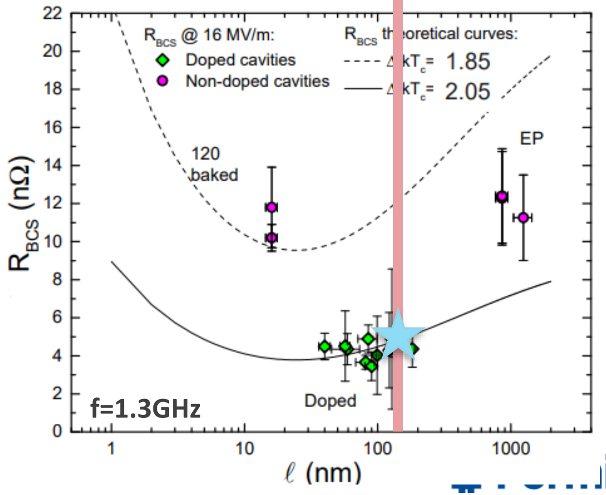
The Role of MFP

- Nitrogen doping allows to alter the surface MFP by varying the bake + EP recipe
- Some trend in MFP with sensitivity, BCS, and quench
  - However, not the only parameter





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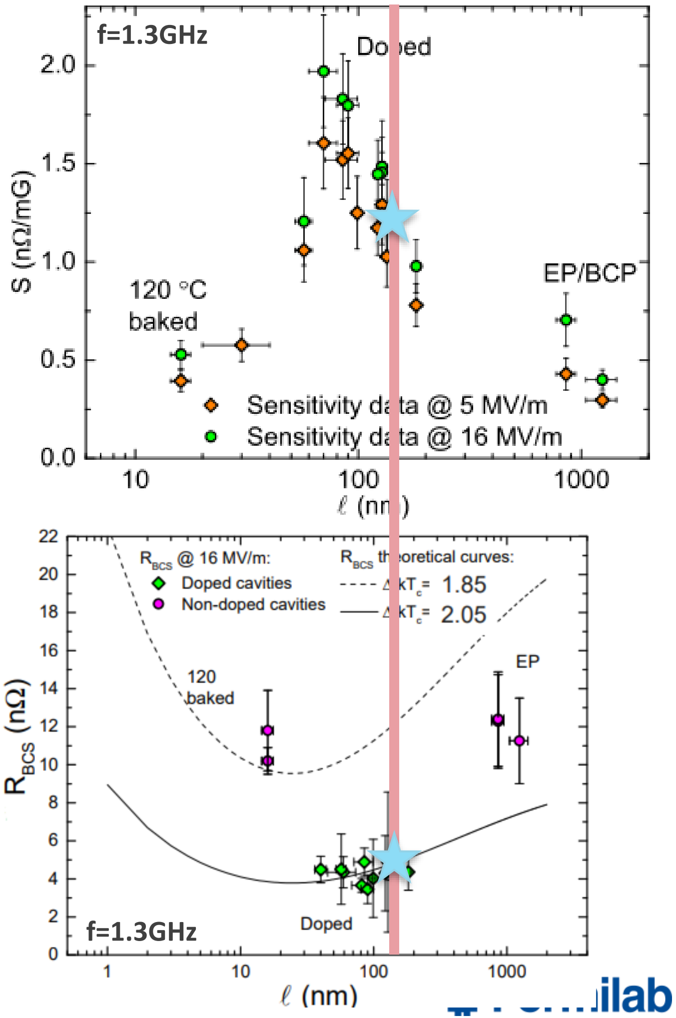
Q#1: How do we optimize the doping recipe to have low sensitivity and low BCS?



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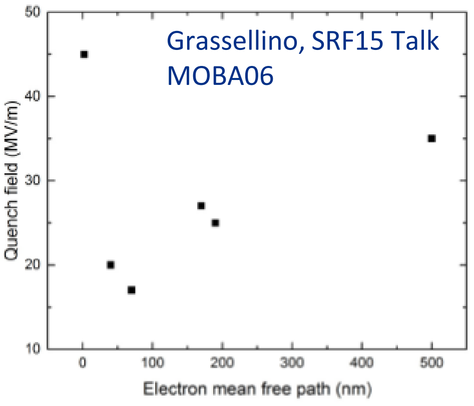
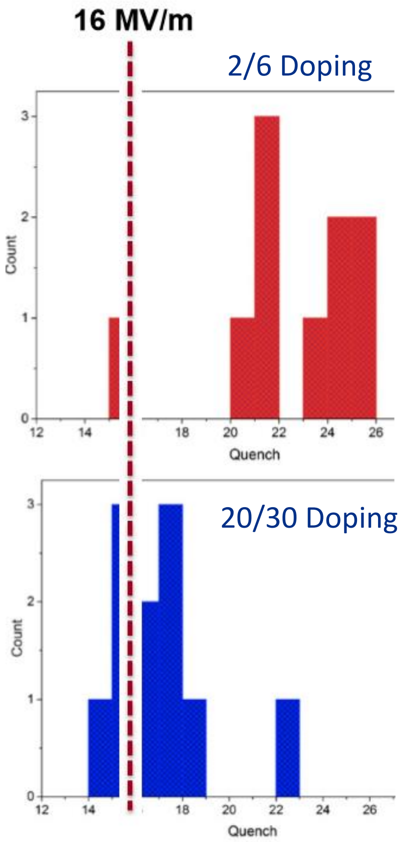


Q#2: How do we optimize the doping recipe to have high quench field?

20/30 recipe (~60-80 nm mean free path) tends to give lower quench than 2/6 (~100nm) (16MV/m vs 23MV/m)



Grassellino, SRF15 Proceedings MOBA06

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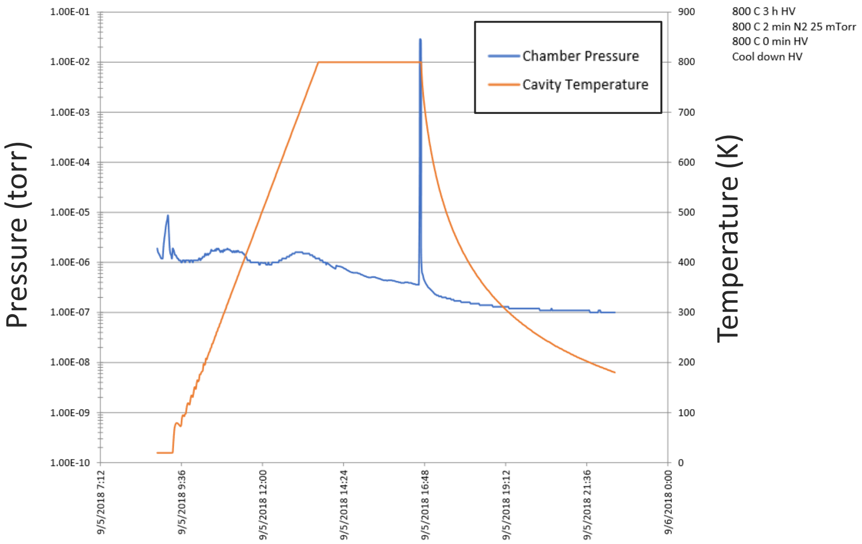
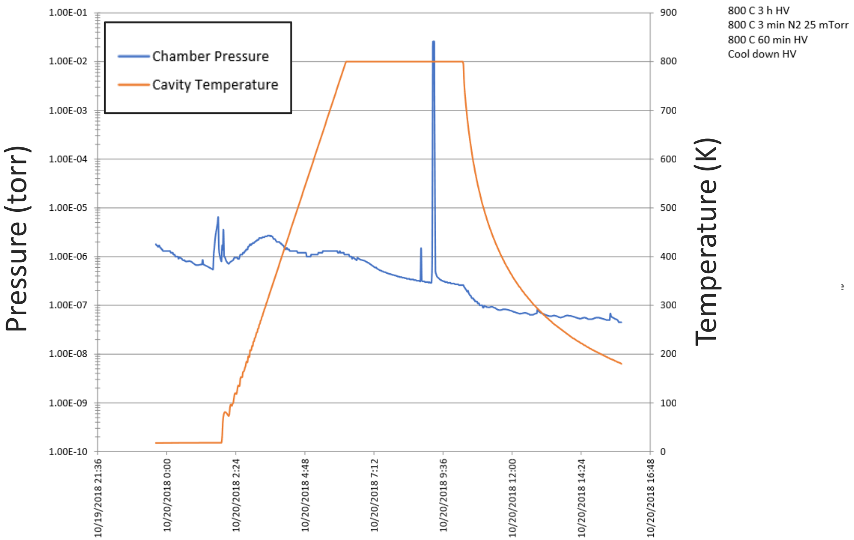
Exploring New Doping Recipes

- Using 3 cavities, we test sequential treatments with a 40μm EP surface reset in between
- Working in the context of Fermilab R&D and LCLS-II HE, we studied the following recipes:

2/0 Doping - Fermilab

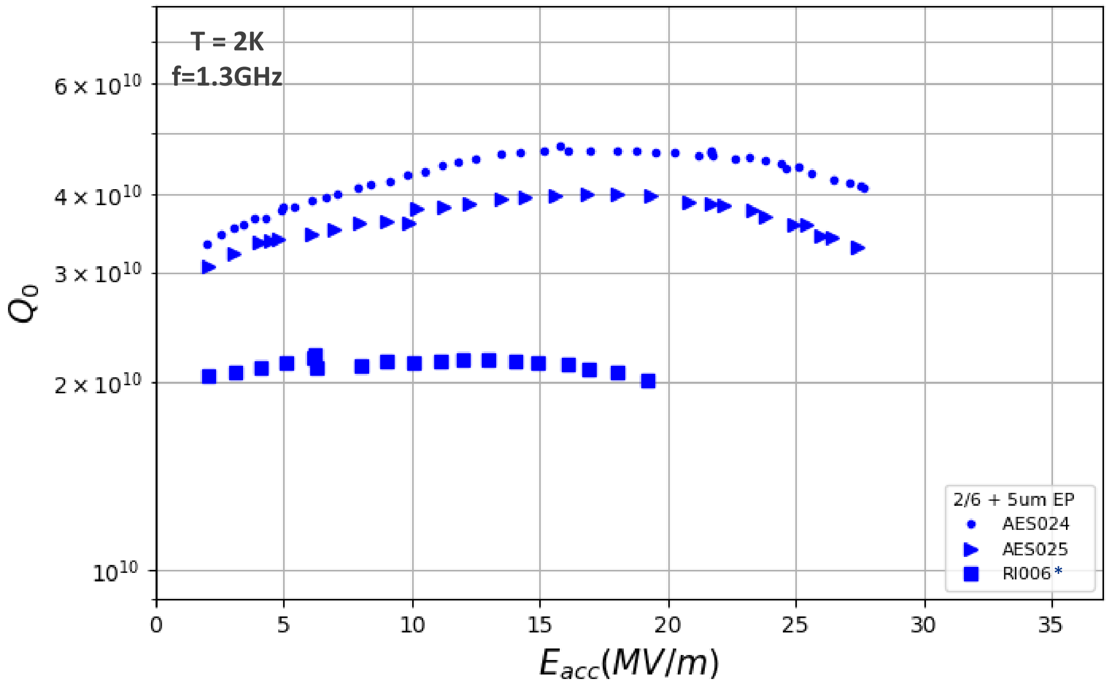


3/60 Doping - JLAB



Sequential Cavity Recipe Study: Test 1/3

2/6 + 5um EP (Baseline):



* RF test had a bad FG

LCLS-II-HE

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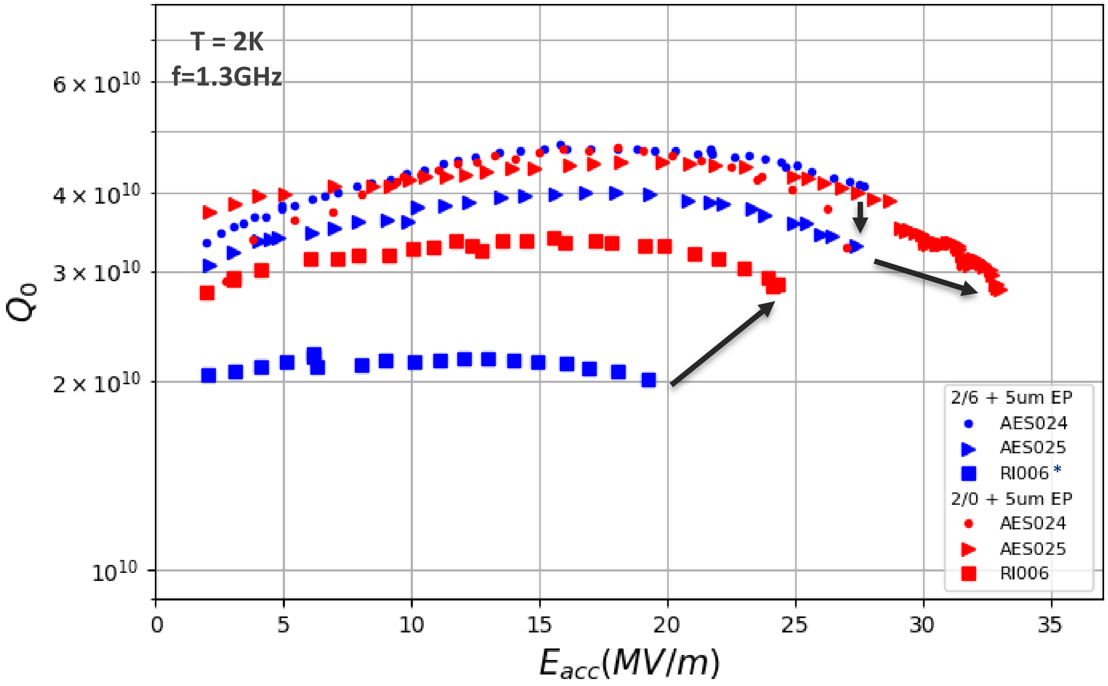

2/6 + 5um EP (Baseline):

+40um EP reset

2/0 + 5um EP:

- AES025 & RI006: higher Q and Quench increases by +6MV/m
- AES024 yields similar results

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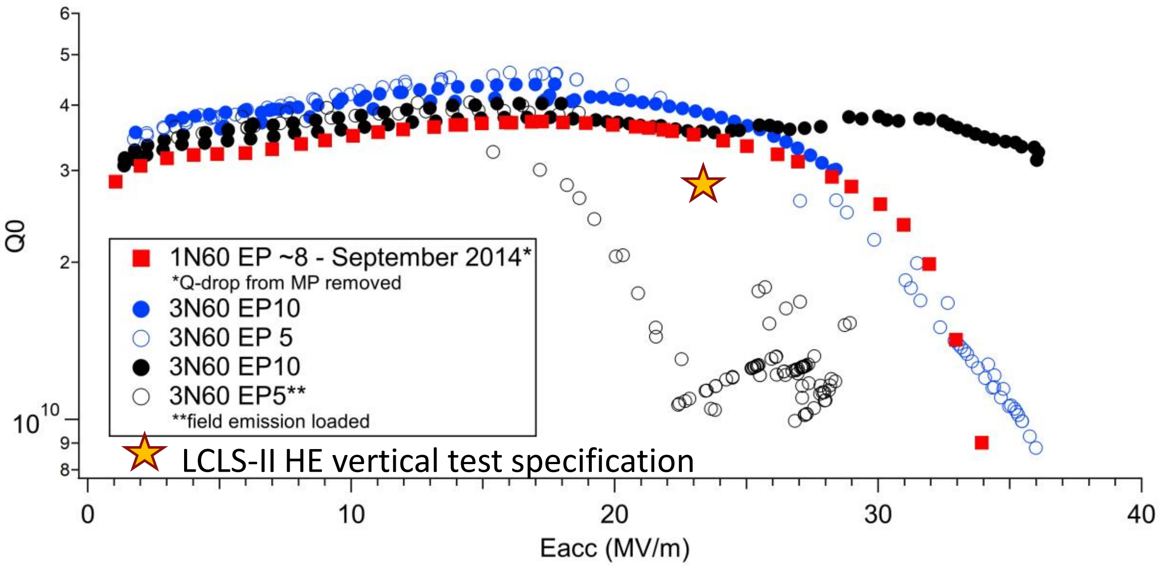
Low doping - long anneal R&D – Palczewski Jlab



- Initial 2014 recipe development by A. D. Palczewski and Charlie Reece, plot by A. D. Palczewski –Jefferson Lab (TJNAF).
- 2018 work financially supported by the LCLS-II HE project R&D.

**Dhakal and citation within https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.21.032001

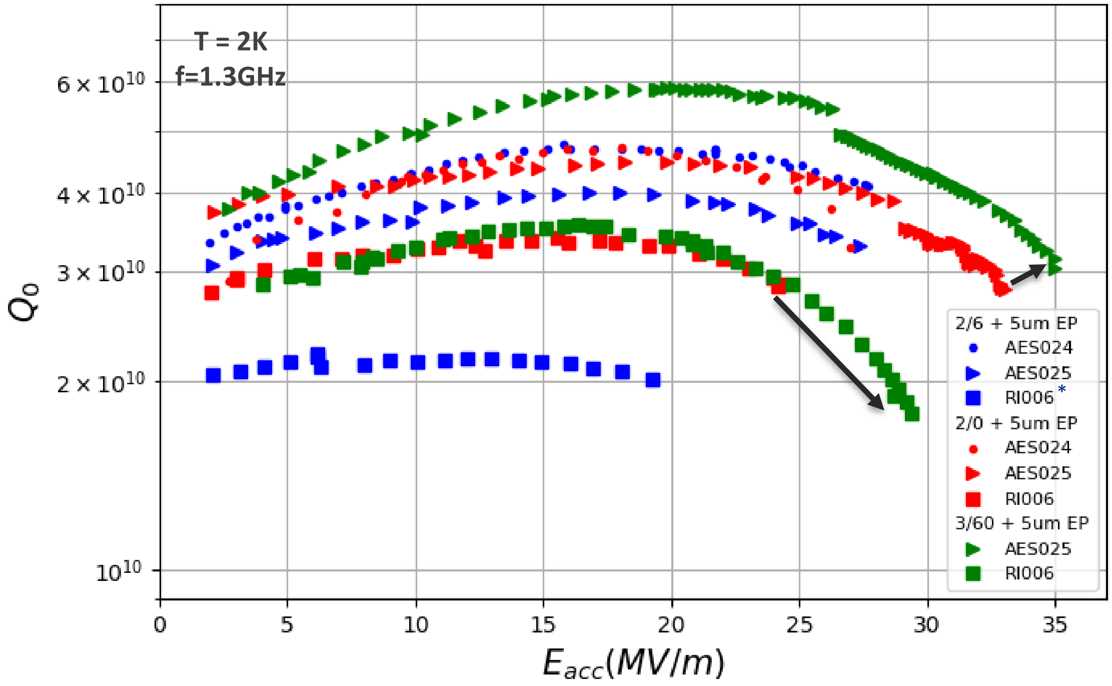
All work performed by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.

- Lower doping recipe first explored in 2014 at Jefferson Lab as a way to enhance the quench field – hypothesizing that lower doping increasing the mean free path compared to the 2n6 doping - increasing H_{sh} and therefore quench.
- Was the first demonstration of high Q doped cavity with quench field significantly above 30 MV/m
- 2018 result now possibly interpreted as hydrogen blocking deeper into the bulk - allowing greater quench field independent of mean free path.**
- Recipe successfully duplicated at FNAL under LCLS-II HE R&D collaboration.

LCLS-II-HE

Jefferson Lab

Sequential Cavity Recipe Study: Test 3/3



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3/60 + 5um EP:

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- AES025: Quench improves by additional +2MV/m, very high Q_0!

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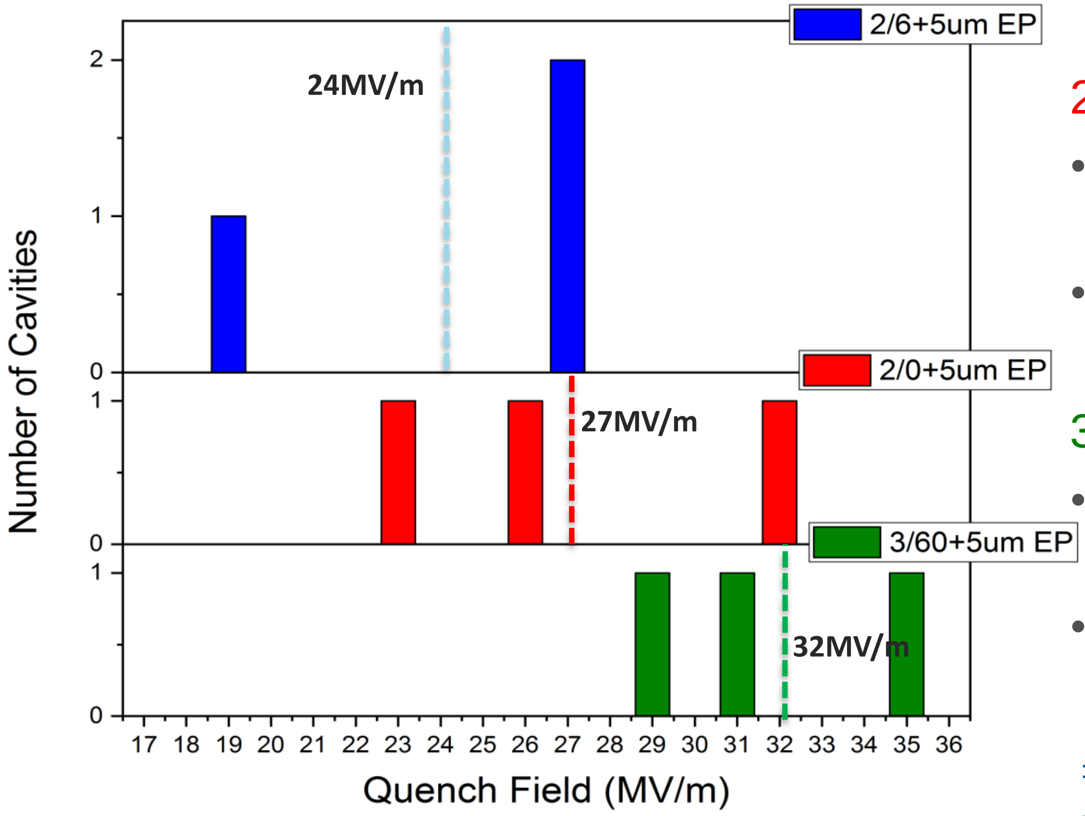

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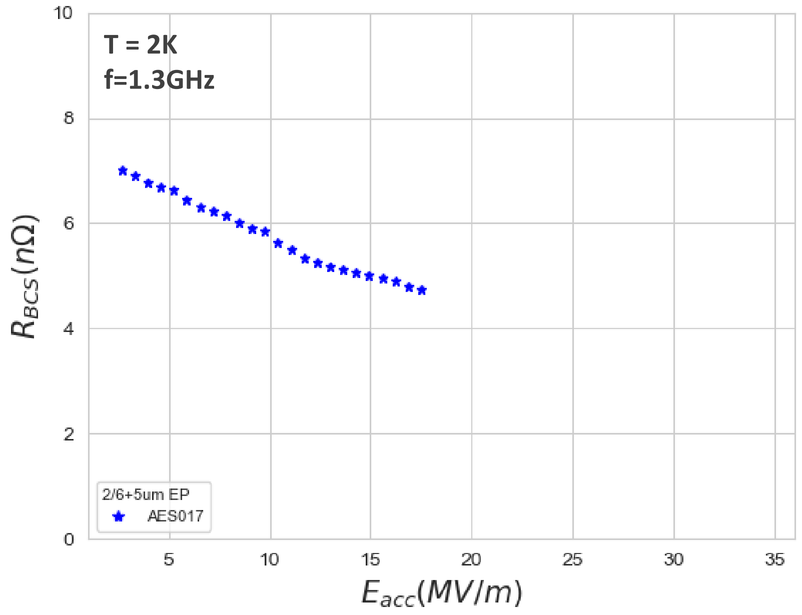
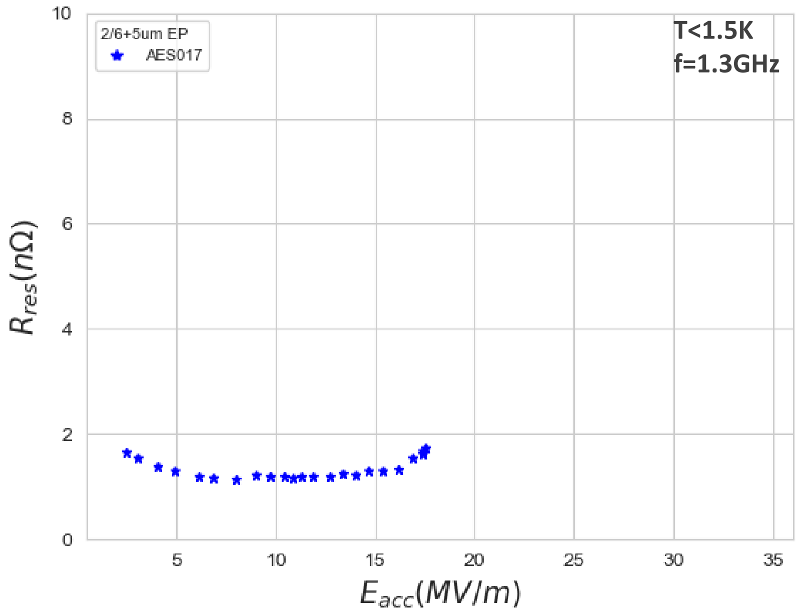
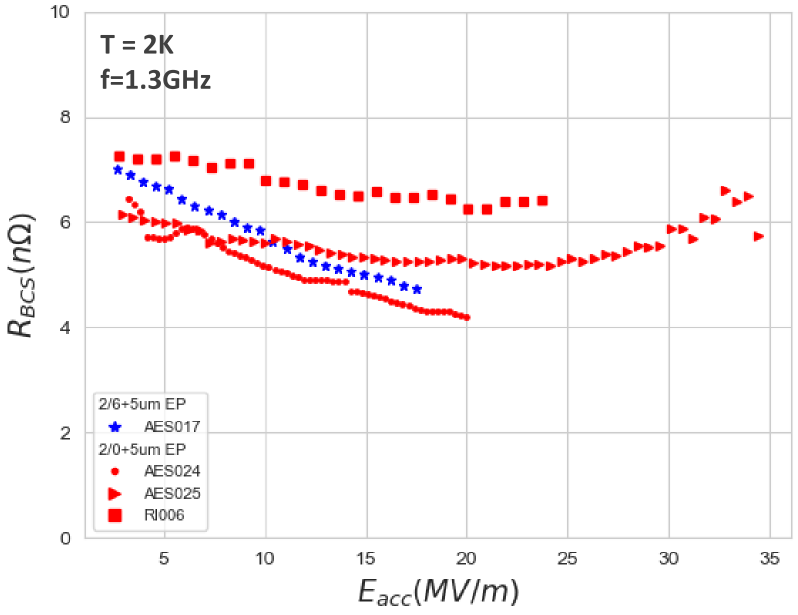
BCS and Residual Resistances of Sequential Recipe Study: (1/3)



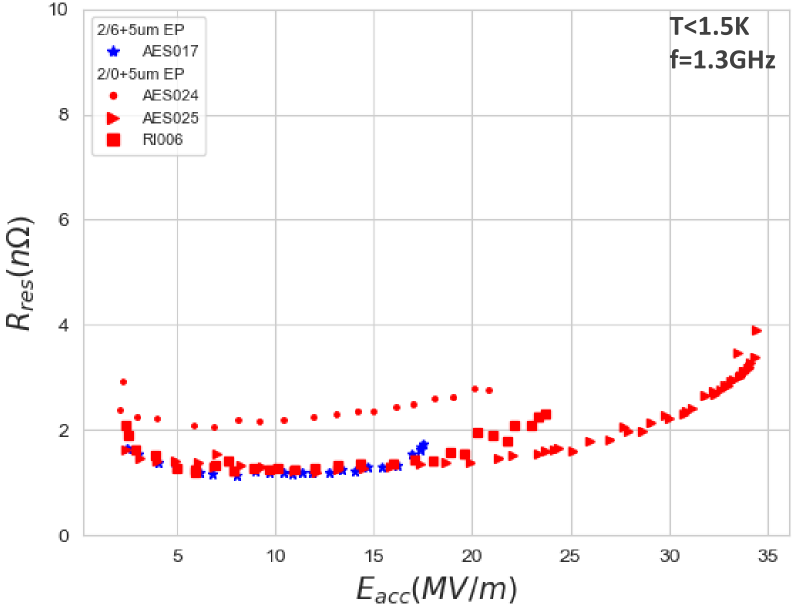


Typical BCS and residual of a 2/6 + 5um EP cavity

BCS and Residual Resistances of Sequential Recipe Study: (2/3)

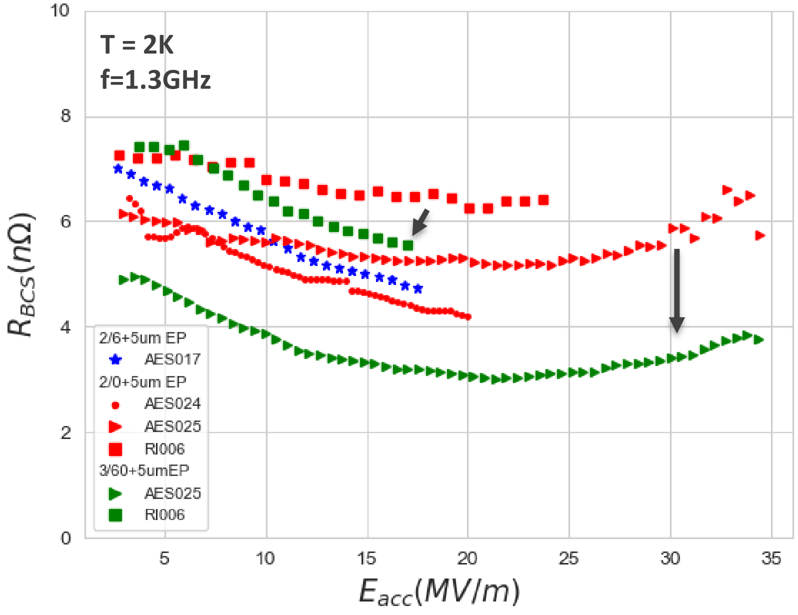


BCS of AES025 & AES024 similar to a typical 2/6 cavity

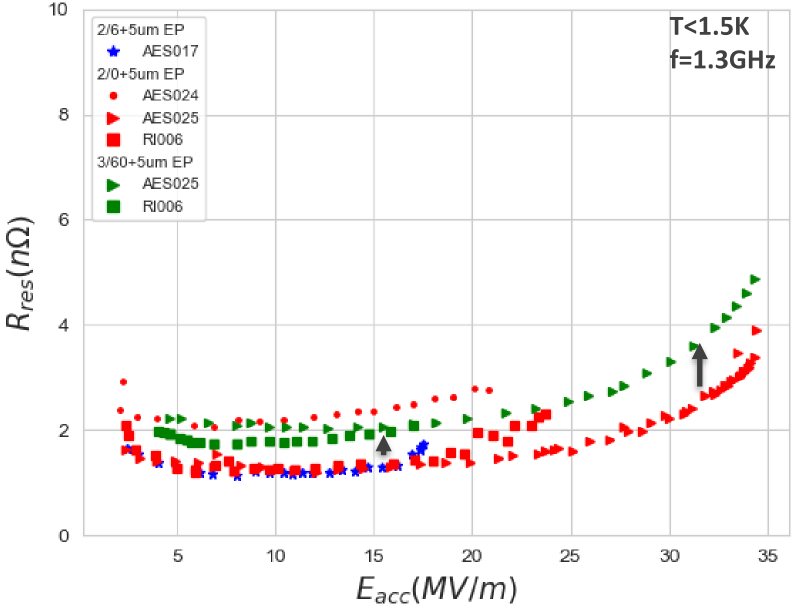


Residual resistance of AES024 is slightly larger

BCS and Residual Resistances of Sequential Recipe Study: (3/3)



3/60 + 5um EP cavities show lower overall BCS after 5MV/m



3/60 + 5um EP appears to increase residual

Takeaway: 3/60 + 5um EP tends to lower BCS

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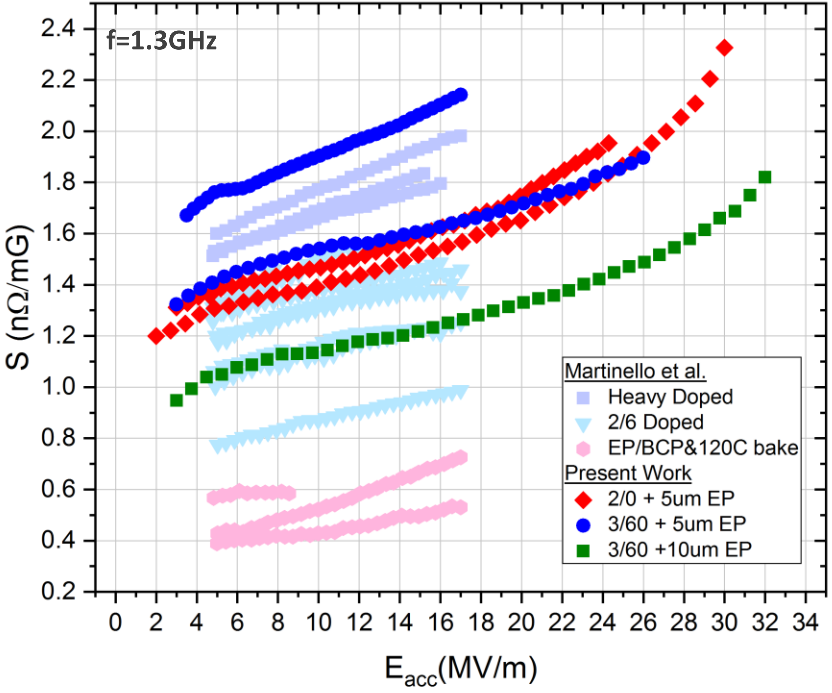
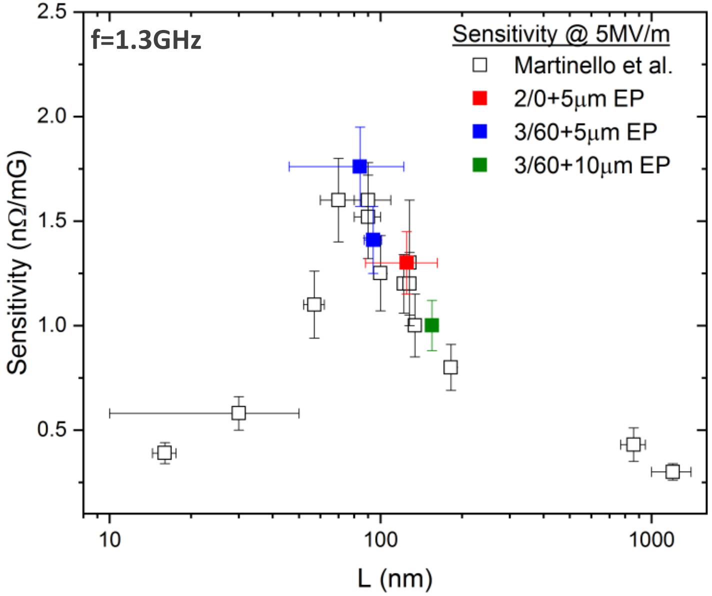
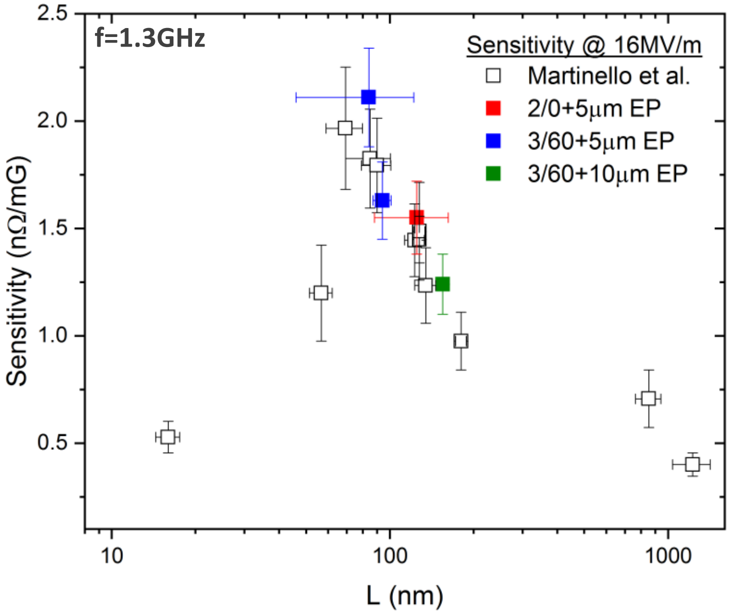
Comparison of Sensitivity for new Doping Recipes



- 2/0 + 5um EP gives results similar to that of 2/6 doped cavities
- 3/60 + 5um EP yields sensitivity closer to that of more heavily doped cavities
- 3/60 + 10um EP sensitivity characteristic to that of the lower branch of 2/6 doped cavities

Possible Trends in Sensitivity with MFP

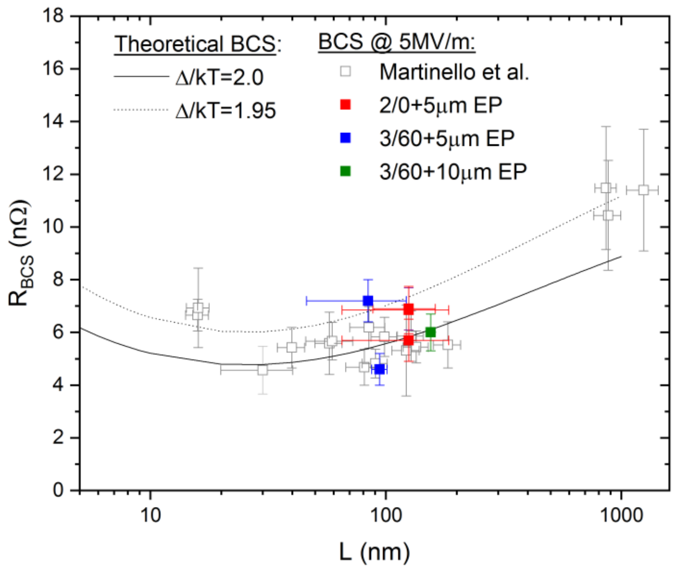


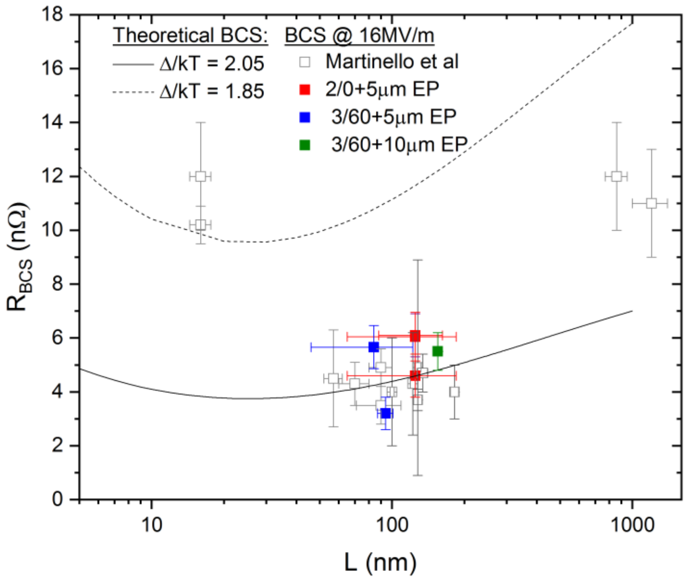


- Results in line with what was found in Martinello et al.
  - Sensitivity appears to have a non-monotonic dependence of the MFP at all fields with the largest values occurring at around 80nm

BCS Resistance: Experimental Data vs Theoretical Curves

- In line with previous findings – large advantage of doping comes at higher fields but **cannot** be explained only by MFP



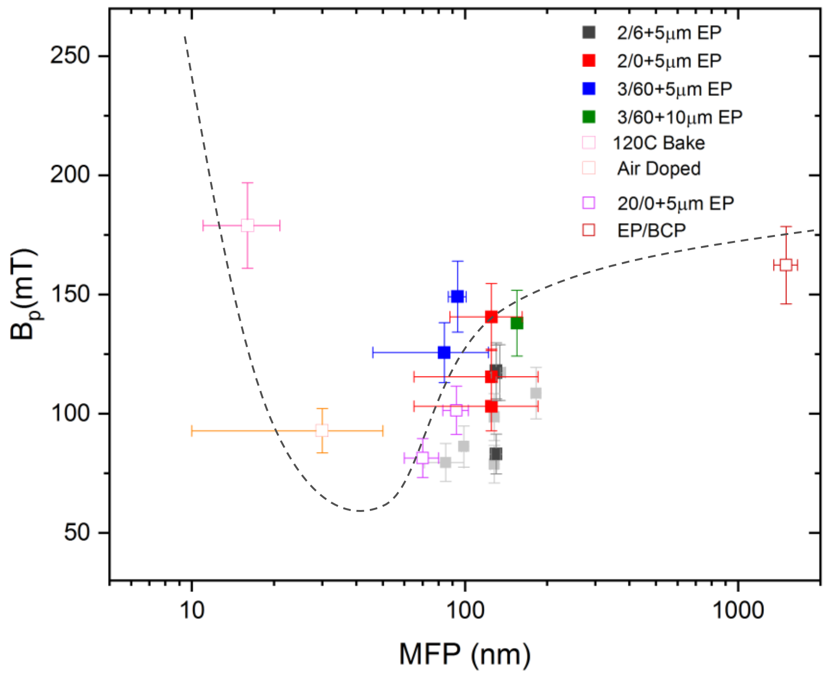


Gray points taken from M. Martinello et al, Appl. Phys. Lett. 109, 062601 (2016)

New data in color

Peak Magnetic Field with MFP

Dotted line serves as a guide for the eye



- On a wide scale, shape slightly resembles that of theoretical BCS vs L curves

Open squares: data points from M. Checchin talk @TTC RIKEN 2017, new data in solid color

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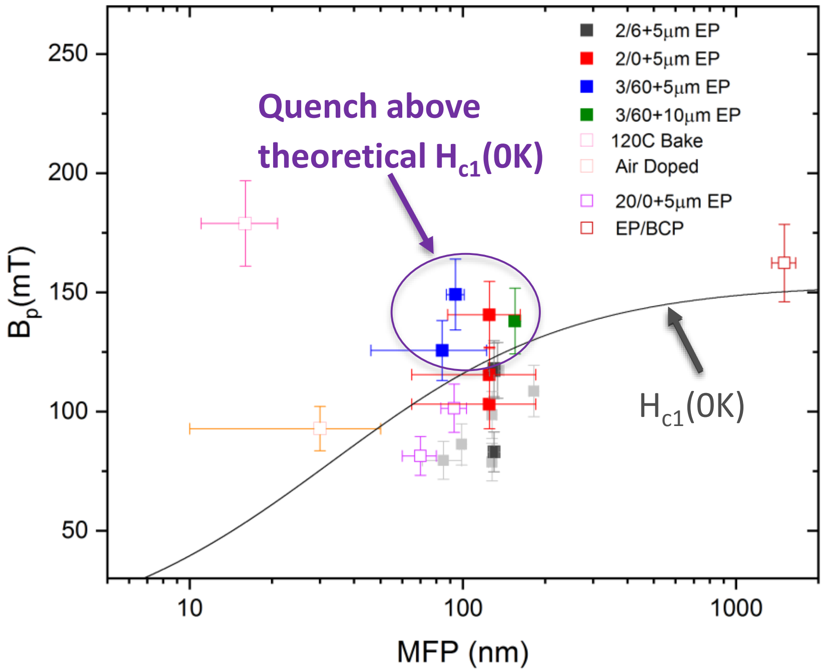

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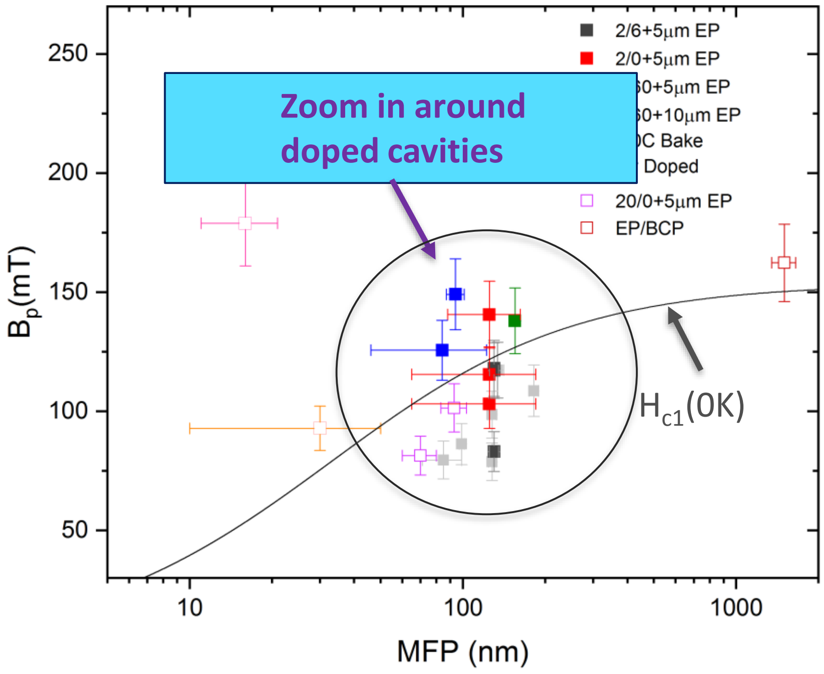

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Zoom in around nitrogen doped cavities

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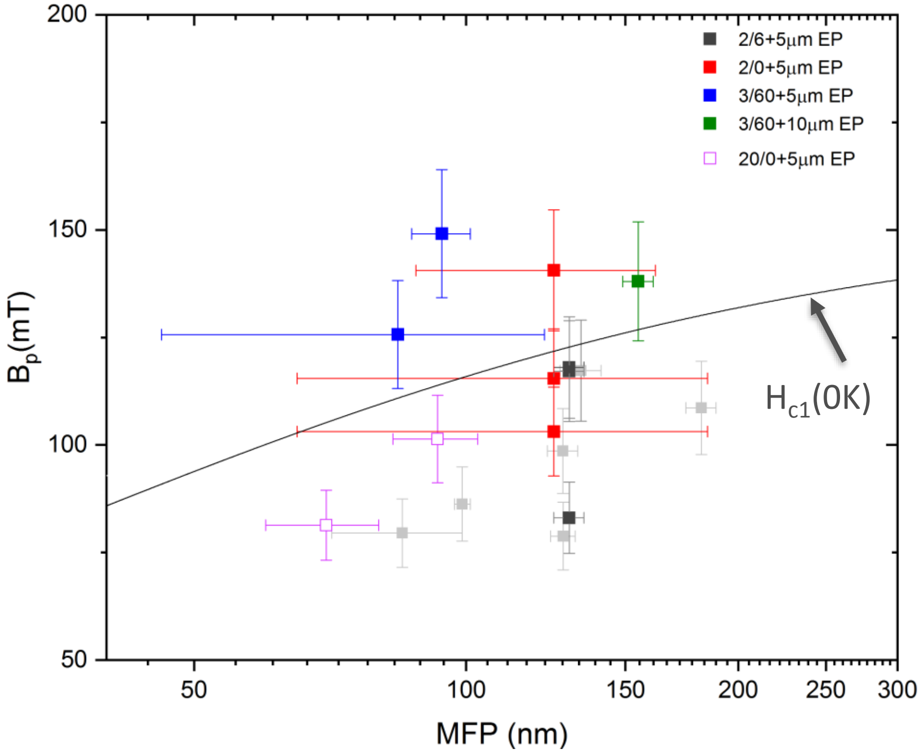
Peak Magnetic Field vs MFP – Nitrogen Doped Cavities



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Zoom in around nitrogen doped cavities

- MFP cannot explain any trend
  - Could be a bi-dimensional function of MFP and each recipe (gap?)

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Conclusion

- Very high Q values typical of doped cavities (**up to 6e10 at 2K, 1.3GHz**) can be achieved even with higher gradients **up to 35 MV/m** while maintaining or reducing sensitivity, (and not compromising on BCS surface resistance)
- New doping recipes confirm the previously obtained S vs MFP curve.
  - Maintain or improve the sensitivity to trapped magnetic flux.
- Quench fields above H_{C1}(0K) achieved
  - MFP is not the only parameter – trends observed per same recipe
- Sensitivity to trapped field, BCS and quench field are not fighting against each other:
  - 2/0+5 EP has higher quench field than 2/6+5 EP but same BCS and sensitivity
  - 3/60+10 EP has higher quench field than 2/6+5 EP, lower BCS and better sensitivity
  - Further studies are needed to find the optimal doping

Acknowledgments

LCLS-II HE Collaborators

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- Anna Grassellino
- Alexander Romanenko

Helpful discussions with:

- Mattia Checchin
- Martina Martinello