Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

IPAC16

Impurity Doping of Superconducting Radio Frequency Cavities

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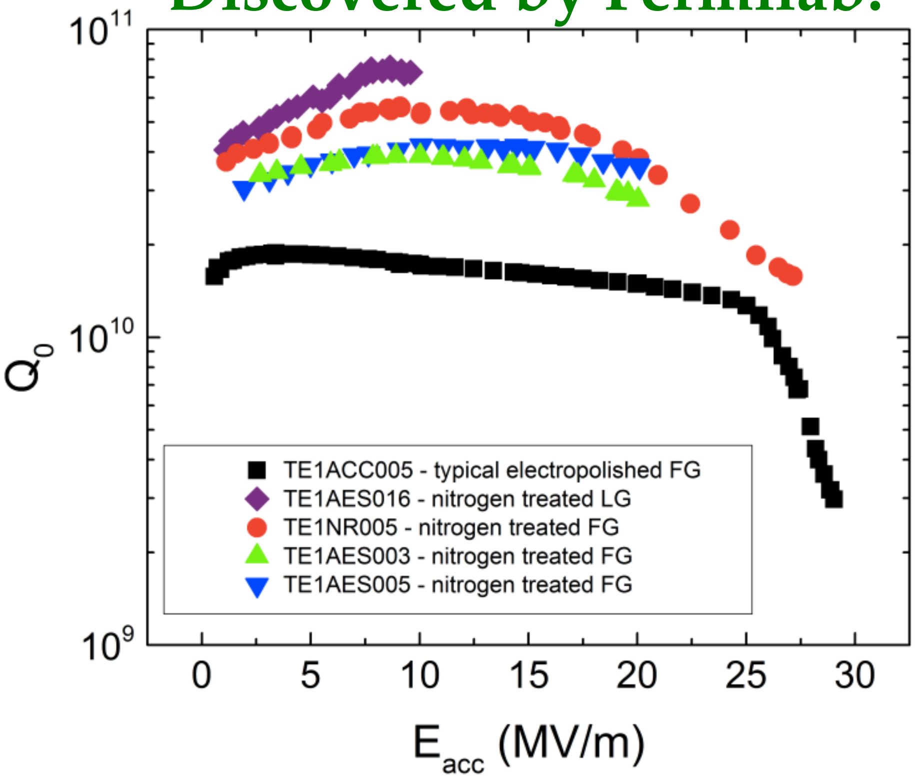
CLASSE facilities are operated by the Cornell Laboratory for Elementary Particle Physics (LEPP) and the Cornell High Energy Synchrotron Source (CHESS) with major support from the National Science Foundation.

Outline

- **Nitrogen doping**
  - Why dope?
  - Benefits of N-doping
  - Nitrogen Doping Process
  - Field dependence of surface resistance
  - Drawbacks of N-doping
- **Inert Dopants**
  - Why alternative dopants?
  - Argon
  - Helium

Discovered by Fermilab:



A. Grassellino et al. *Supercond. Sci. Tech.*, 26(102001), 2013.

$$Q_0 = \omega_0 U / P_c$$

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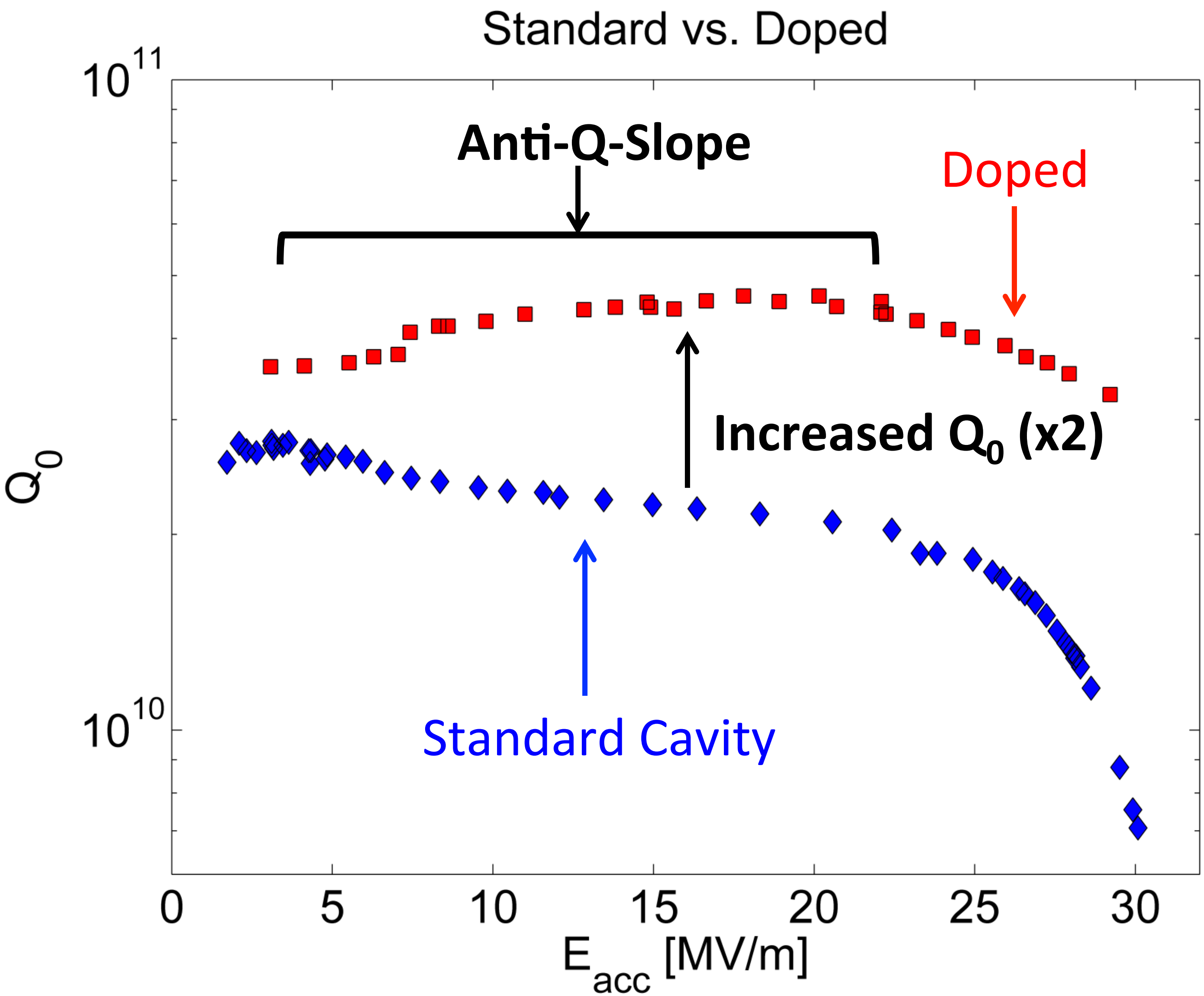
Why Dope?



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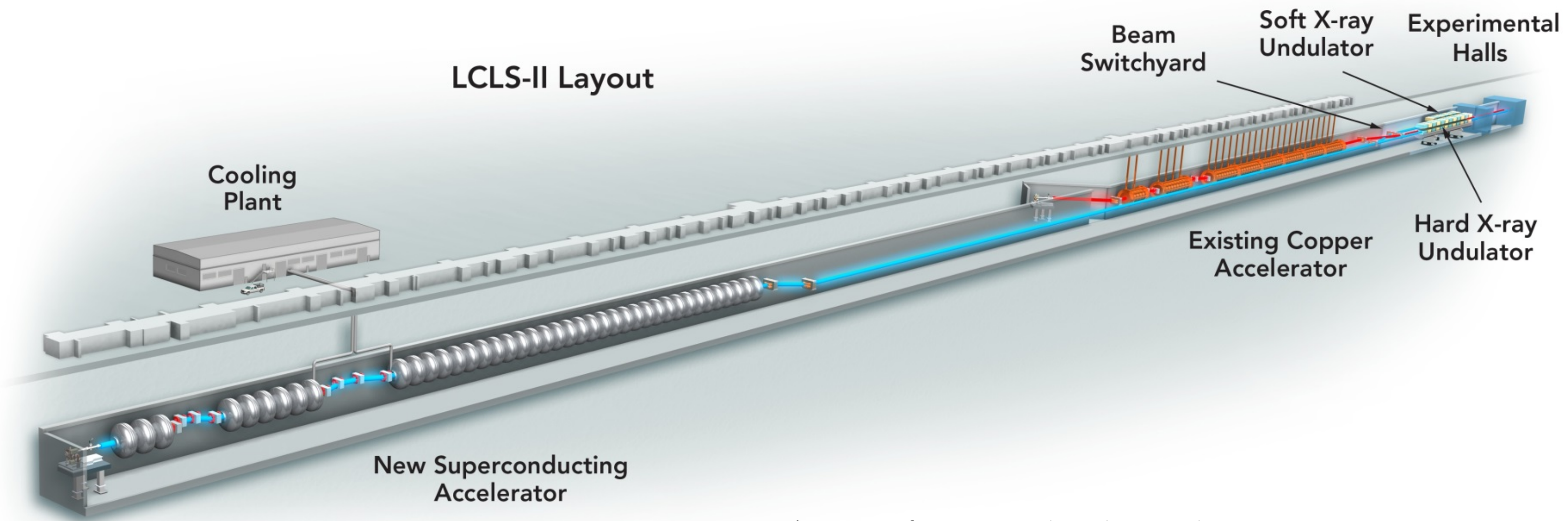
LCLS-II

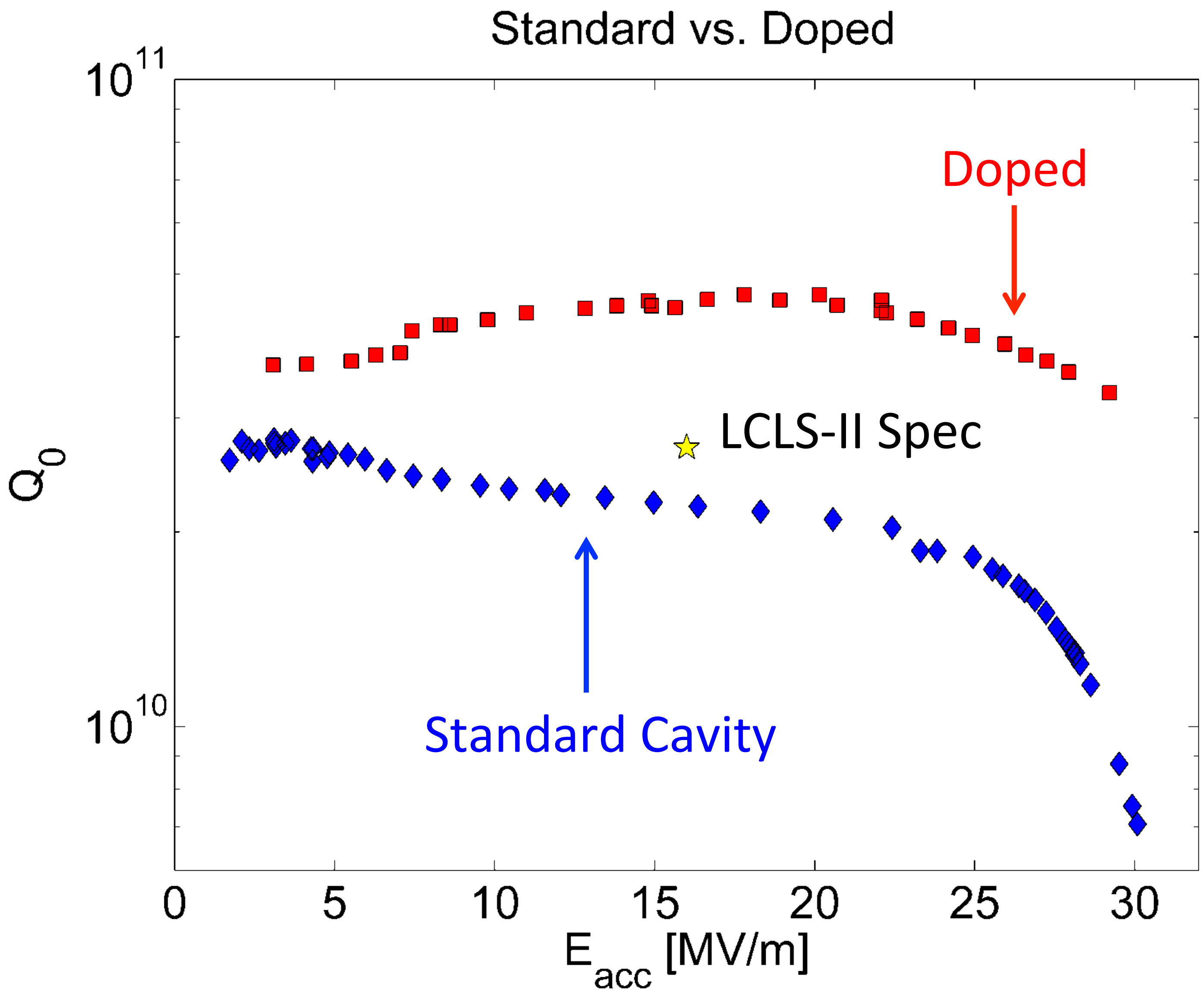
- N-doped 9-cell cavities
- Increased efficiency
- Lower operating costs

Cryogenic losses ~ $1/Q_0$

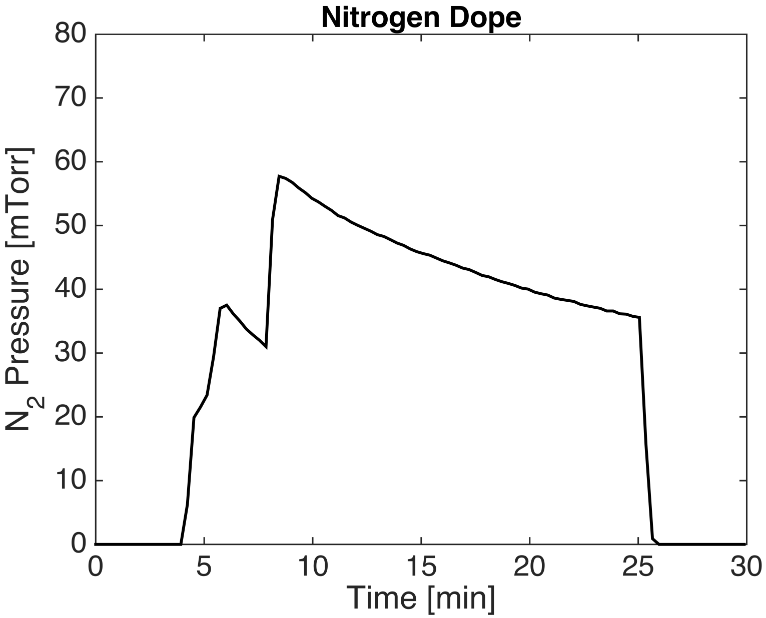


*Courtesy of SLAC National Accelerator Laboratory

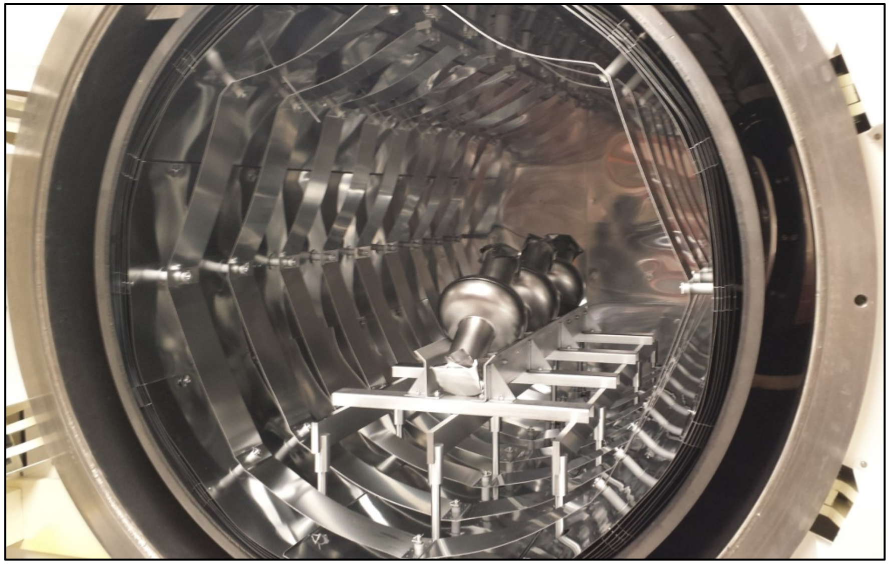
LCLS-II


Standard vs. Doped
10^11
10^10
Q0
0
5
10
15
20
25
30
Eacc [MV/m]
Doped
LCLS-II Spec
Standard Cavity

Nitrogen Diffusion



TM Vacuum Furnace



Recipe:

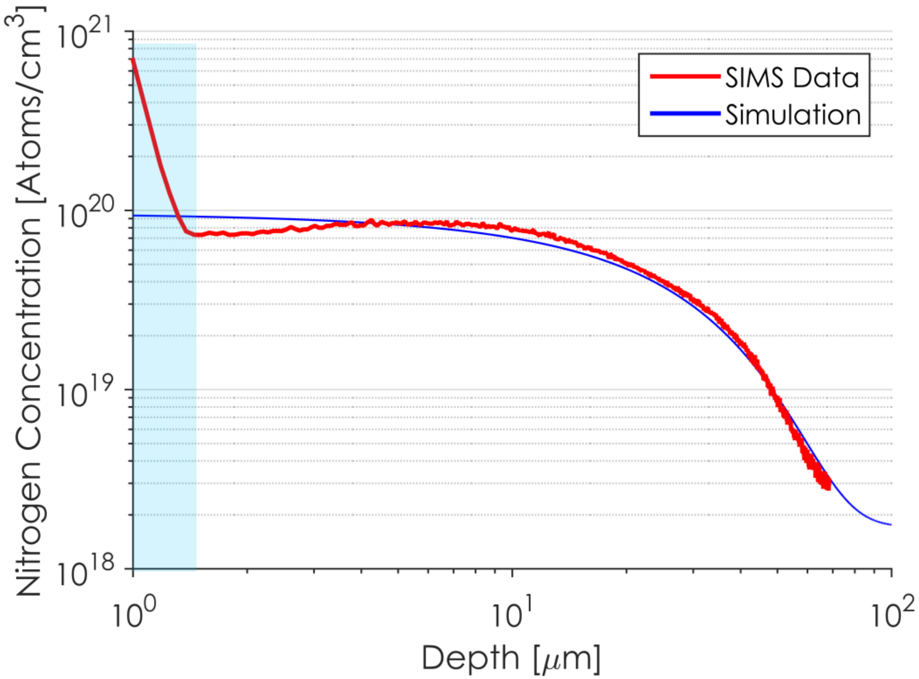
1. Dope
   - 800 °C / 20 mins / 60 mTorr N_2
2. Anneal Step
   - 800 °C / 30 mins / Vacuum

D. Gonnella et al. Nitrogen Treated Cavity Testing at Cornell. *Proceedings of LINAC14*, 2014.

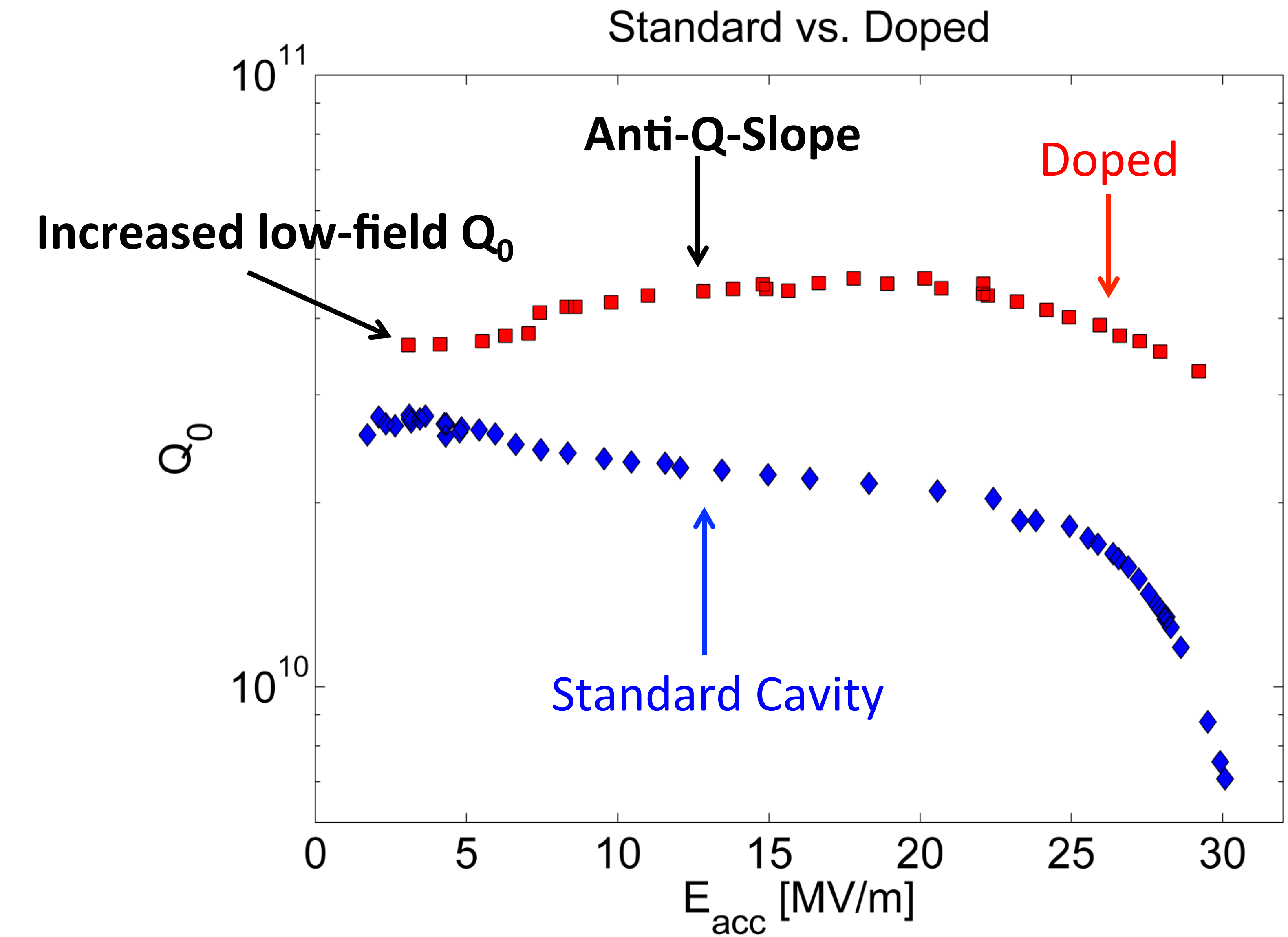
Nitrogen Diffusion

- Cavities doped in a vacuum furnace at high temperatures
- NbN forms on the surface of the cavity
- Nitrogen diffuses from the NbN layer into the Nb bulk as an interstitial
- Chemical etching is performed to remove the ***lossy*** NbN layer

WEPMR025



What is Nitrogen Doping?



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Surface Resistance

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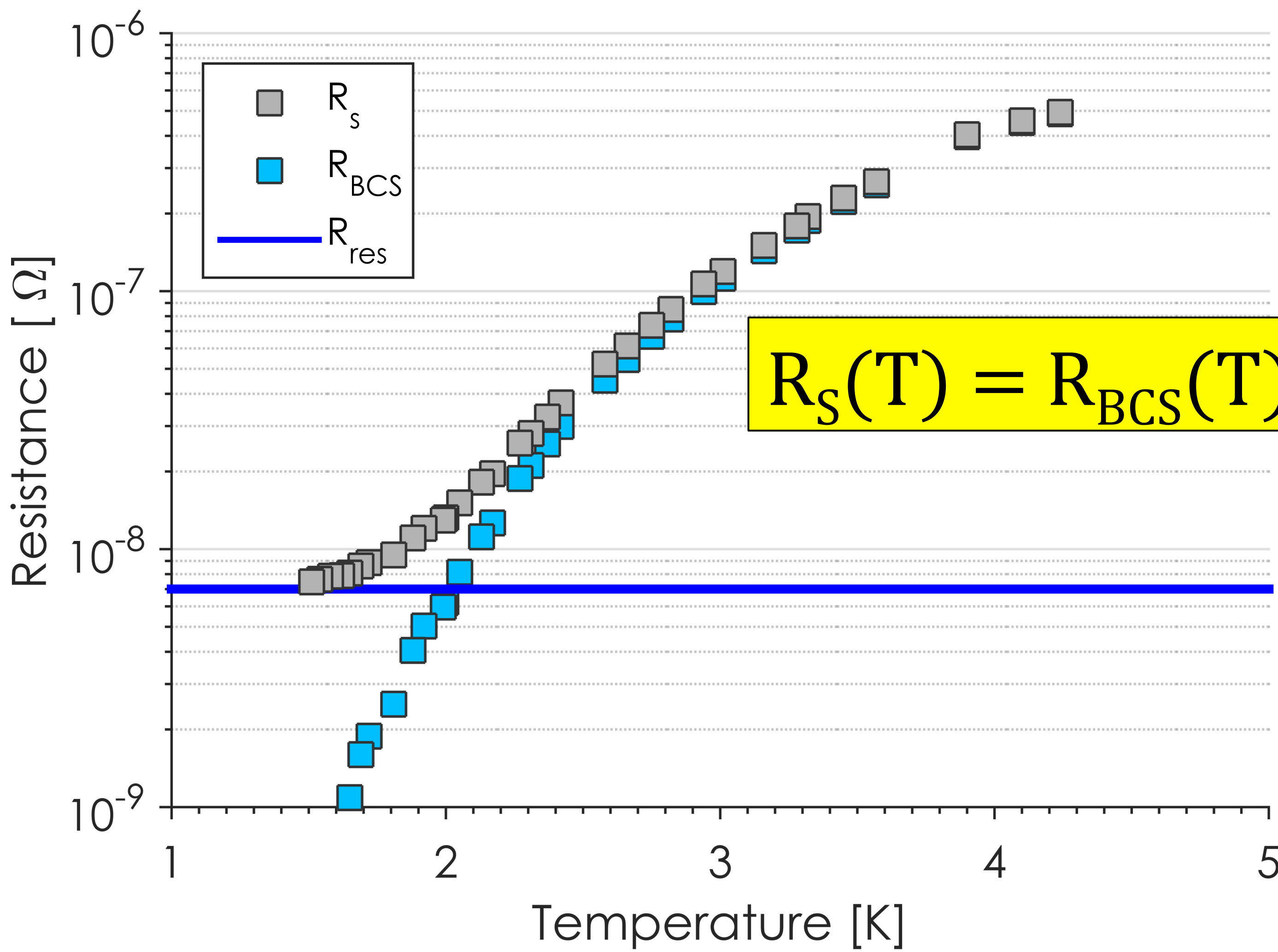
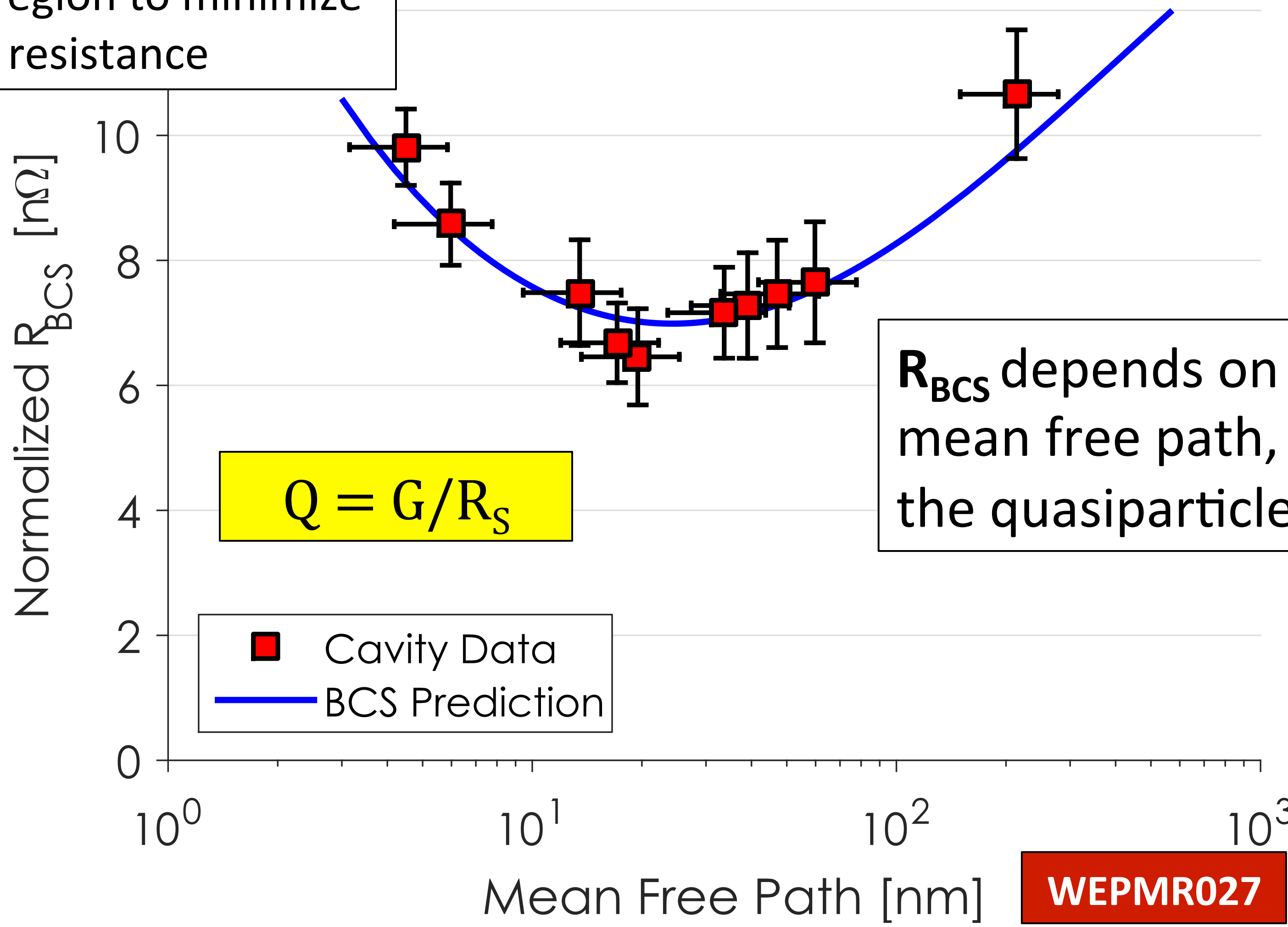


$$R_S(T) = R_{BCS}(T) + R_0$$

Low Field BCS Resistance

Nitrogen doping brings ***l*** to optimal region to minimize low field resistance



$$Q = G/R_S$$

R_{BCS} depends on the mean free path, ***l***, of the quasiparticles

WEPMR027

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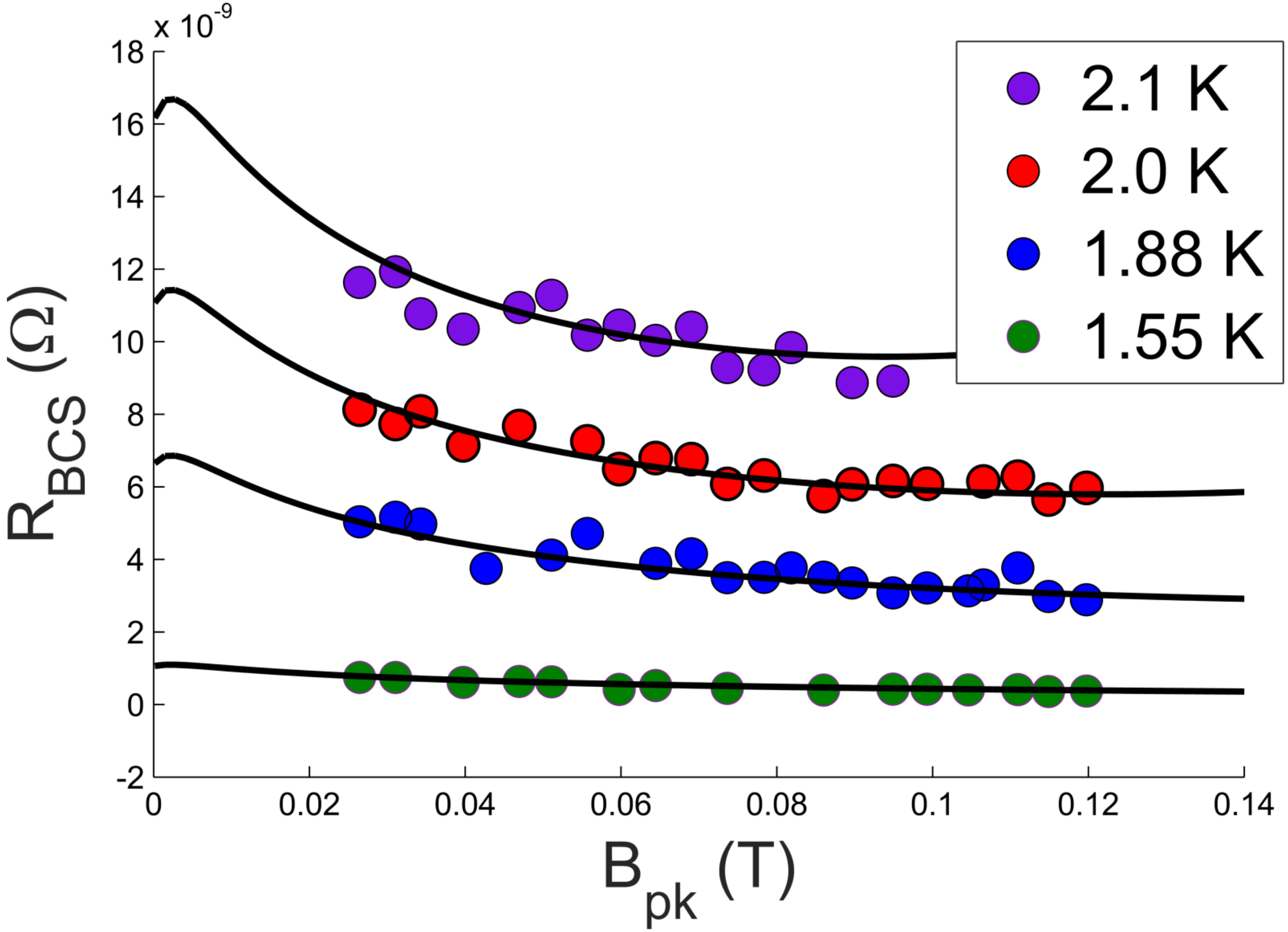
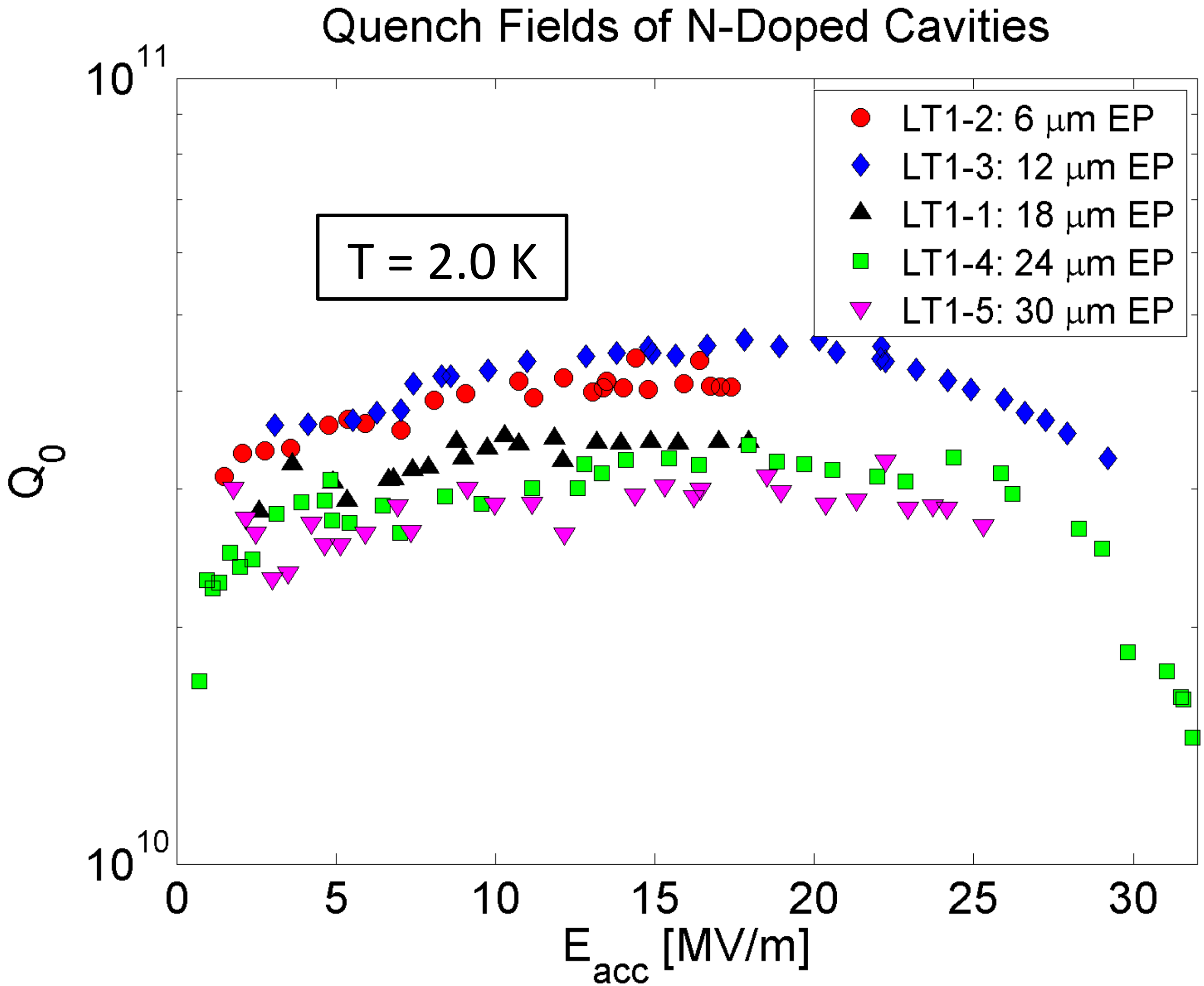
Field Dependence



A. Gurevich. Phys. Rev. Lett. 113:087001, Aug. 2014.

Quench Fields



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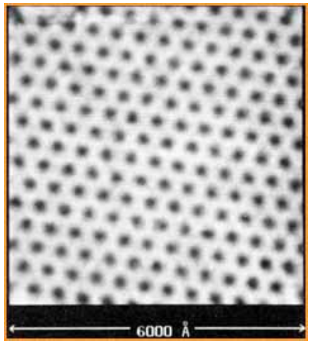
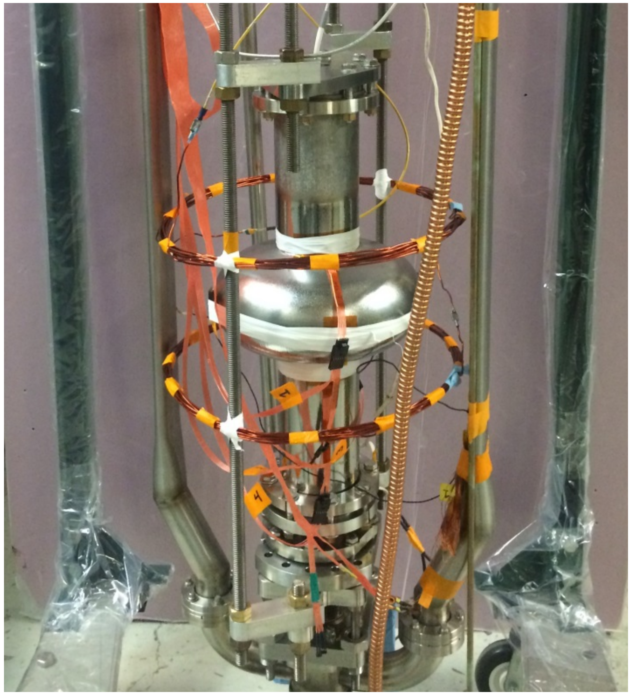
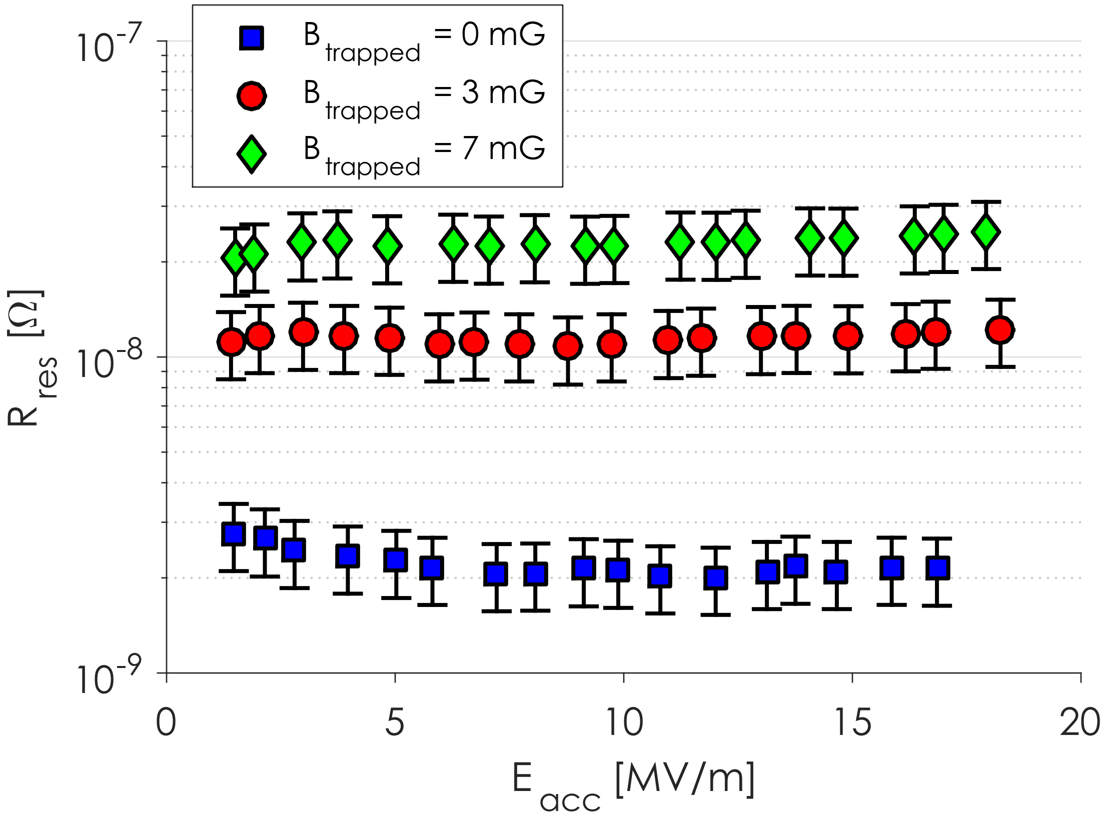
RF Losses from Trapped Magnetic Flux

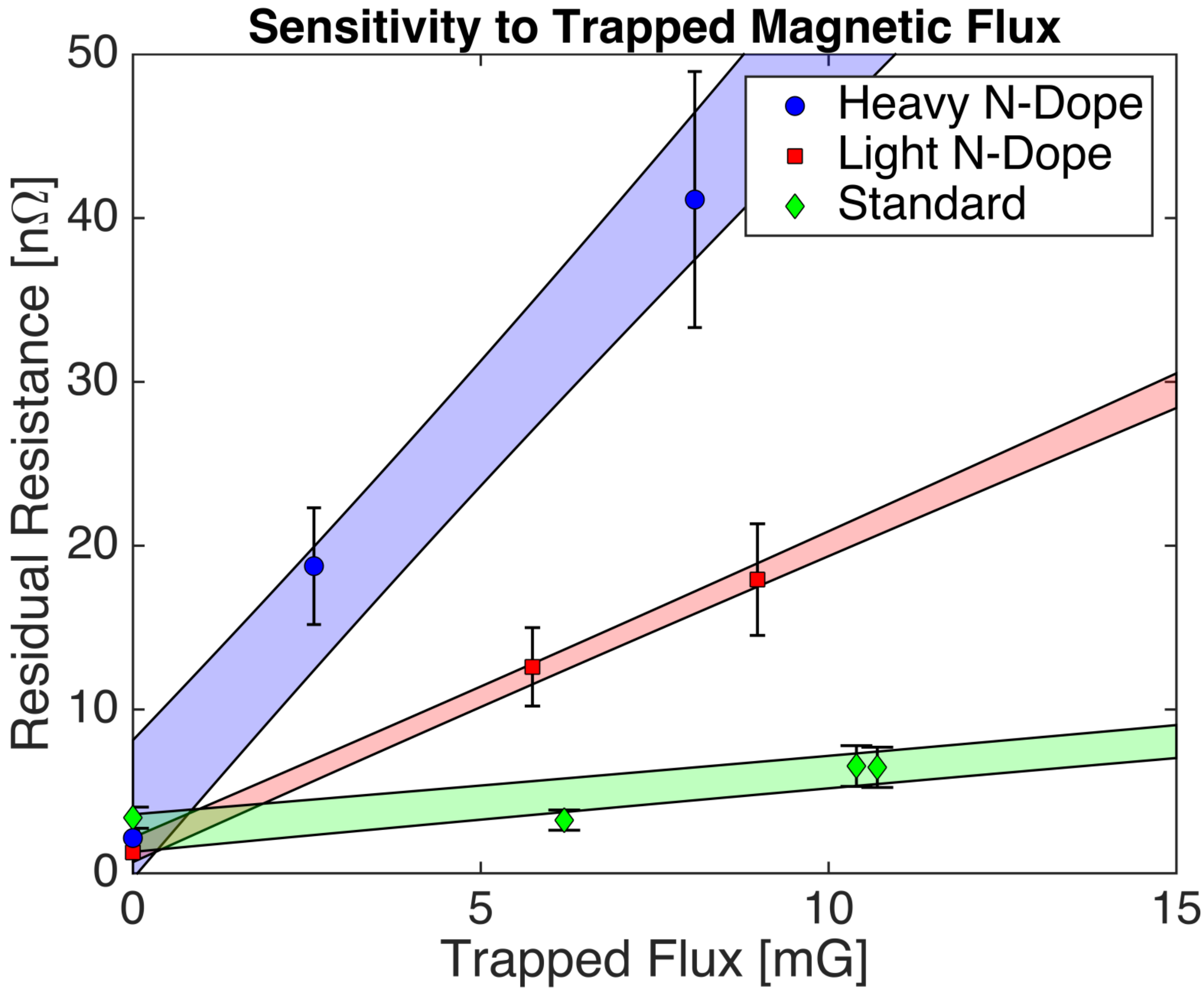


Phys. Rev. Lett., 62(114), 1989.





Flux Sensitivity



D. Gonnella et al., *Journal of Applied Physics*, 119(073904) 2016.

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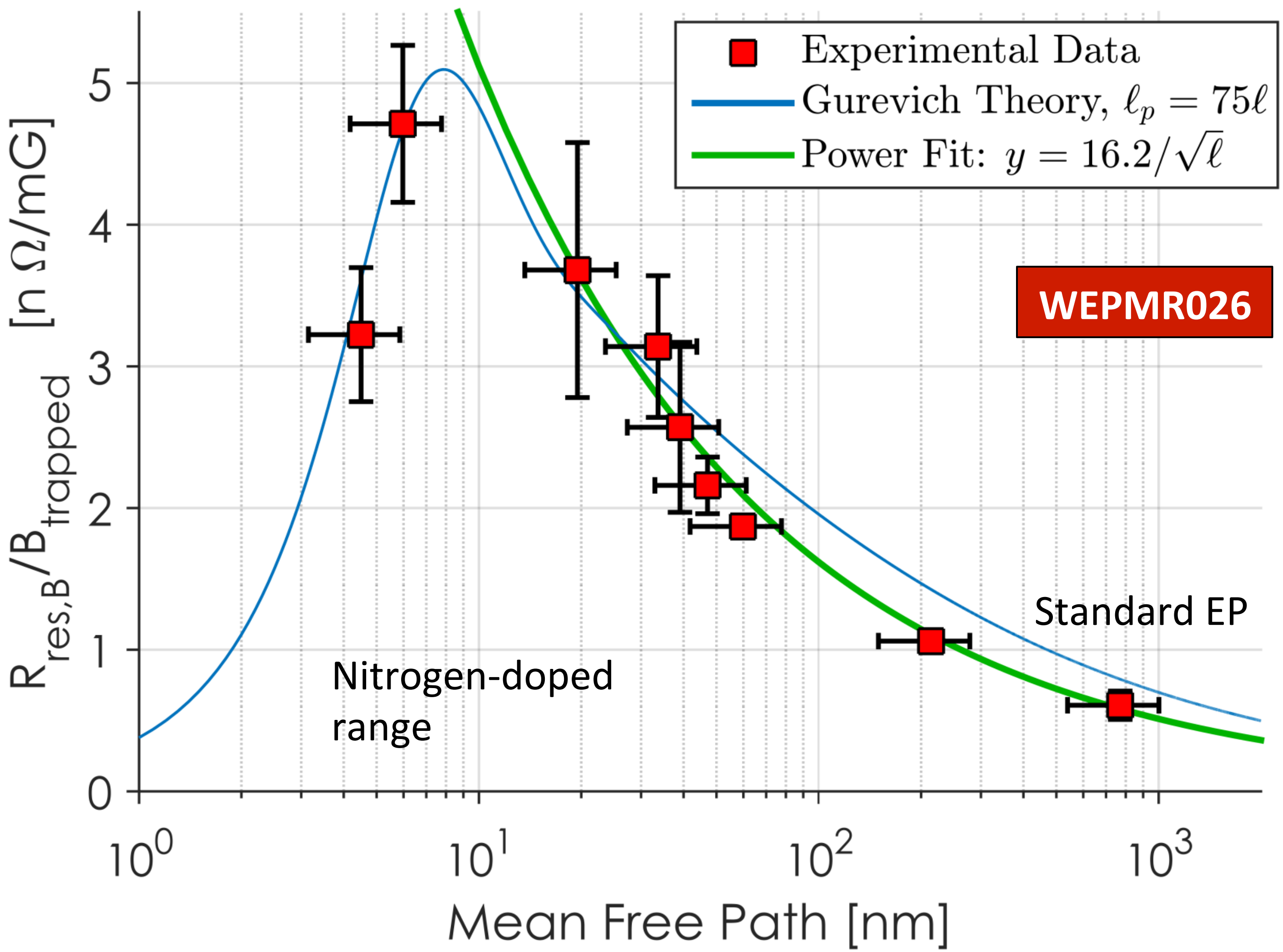
Flux Sensitivity



D. Gonnella et al., *Journal of Applied Physics*, 119(073904) 2016.

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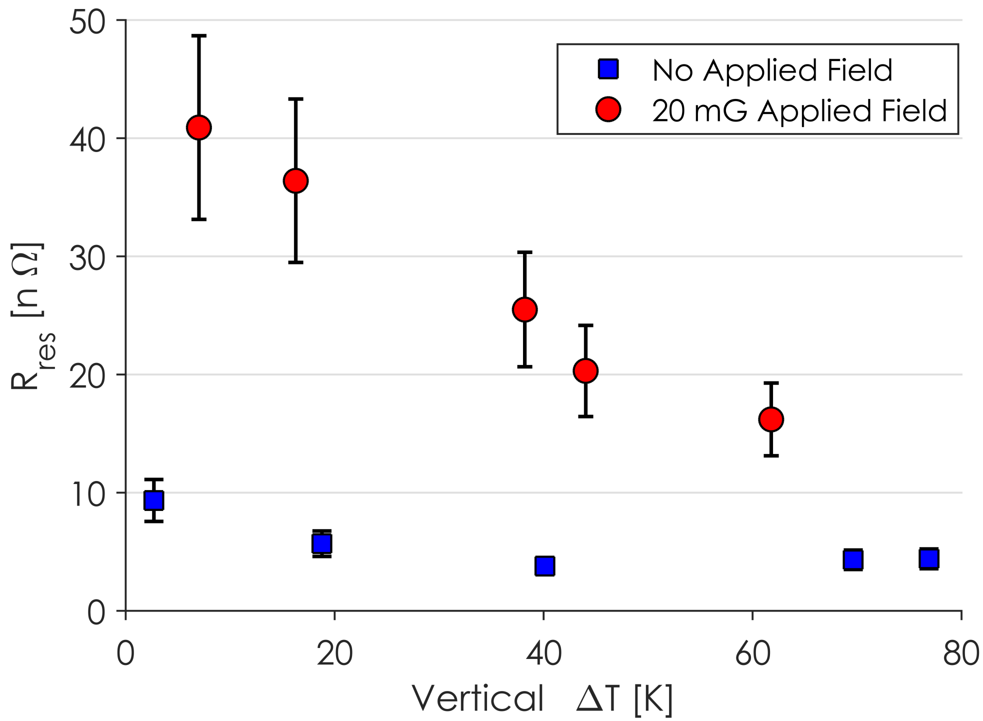
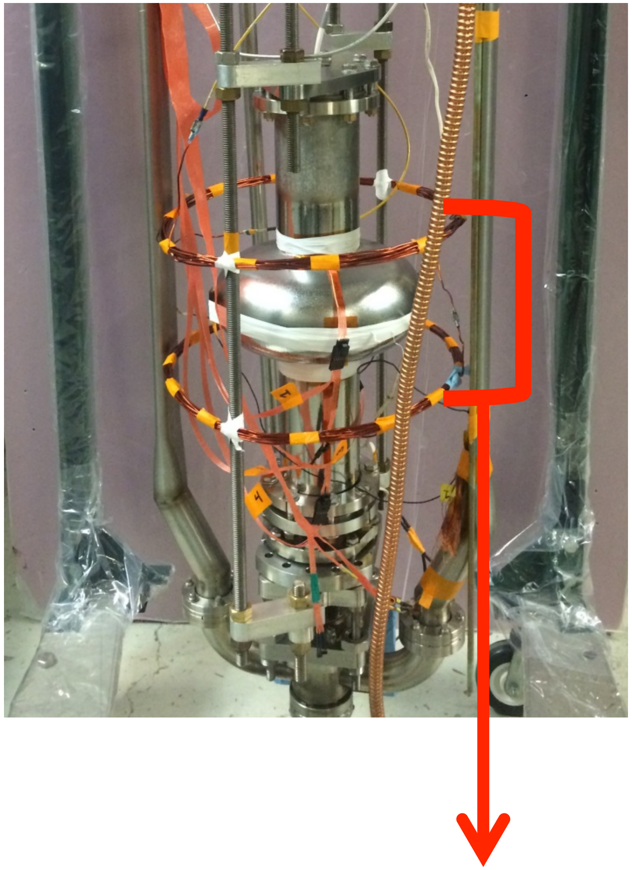
Solutions

- Ways around this sensitivity:
  - Good magnetic shielding
  - Very fast cooldowns
  - Compensation coils





Helmholtz coils

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  - Why dope?
  - Nitrogen Diffusion
  - Benefits of N-doping
  - Field Dependence of Surface Resistance
  - Limitations of N-doping
- **Inert Dopants**
  - Why alternative dopants?
  - Argon
  - Helium

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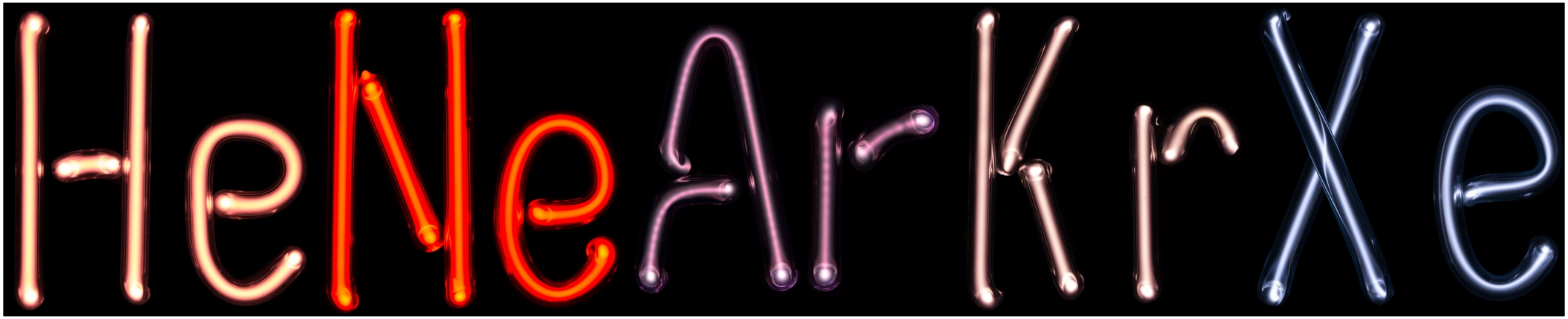
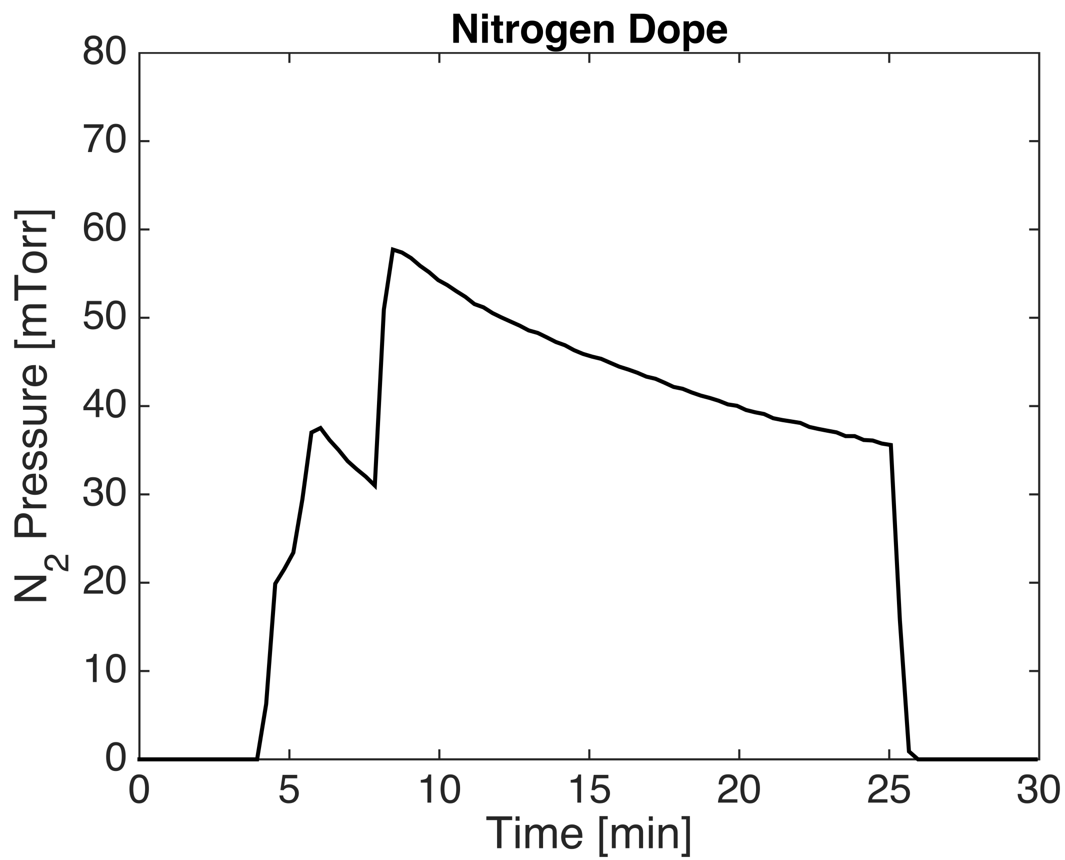
Beyond Nitrogen

- Nitrogen is only dopant that has been studied so far:
  - Nitrogen doping has yielded great results
  - Is Nitrogen the best dopant? Are there better dopants?
  - Inert doping could remove chemical etching from the process



Impurity Doping

Nitrogen doping so far:



Next Step →

Explore alternative dopants: He, Ne, Ar, …

D. Gonnella et al. Nitrogen Treated Cavity Testing at Cornell. *Proceedings of LINAC14*, 2014.

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Argon Doping

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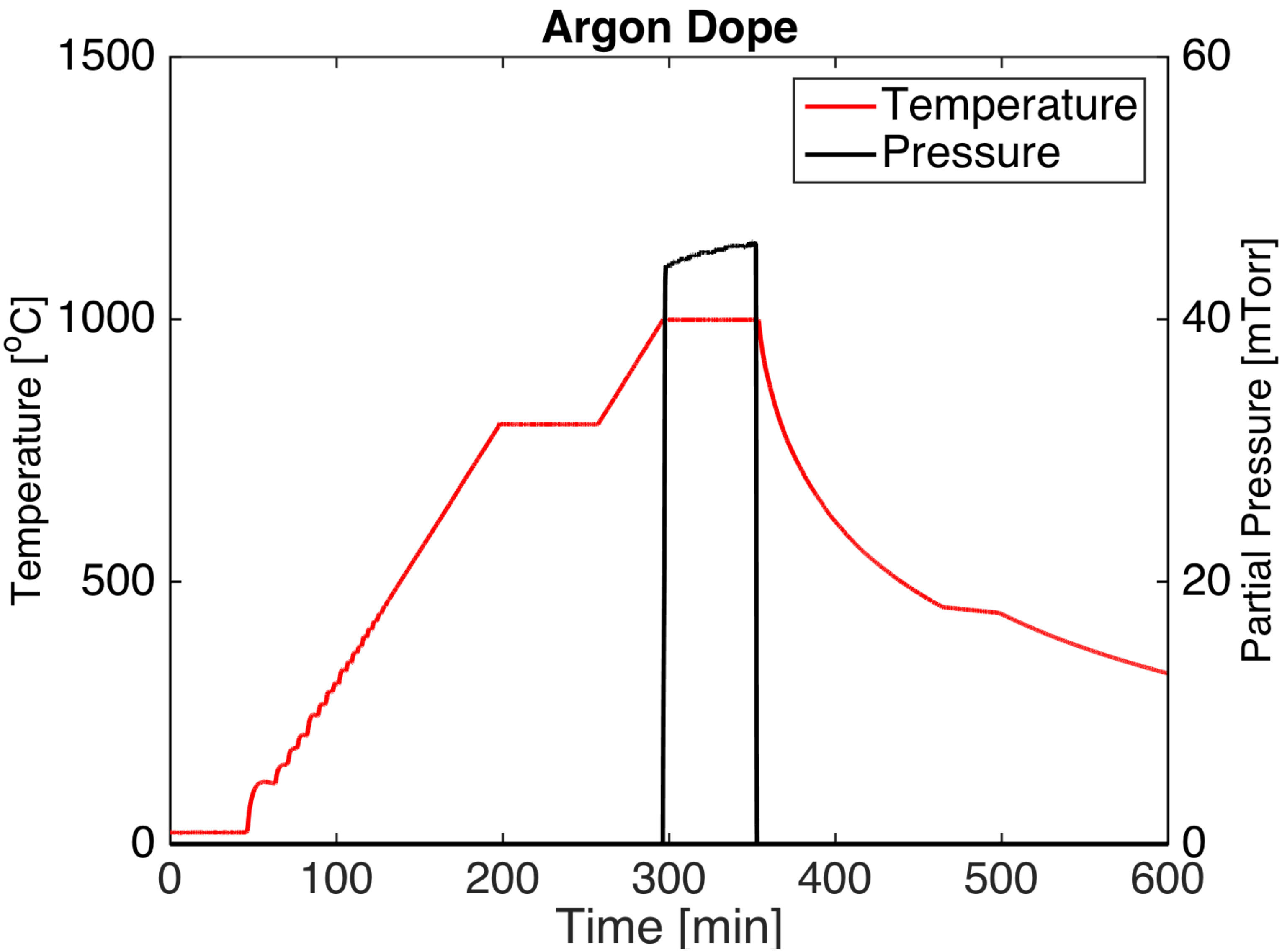
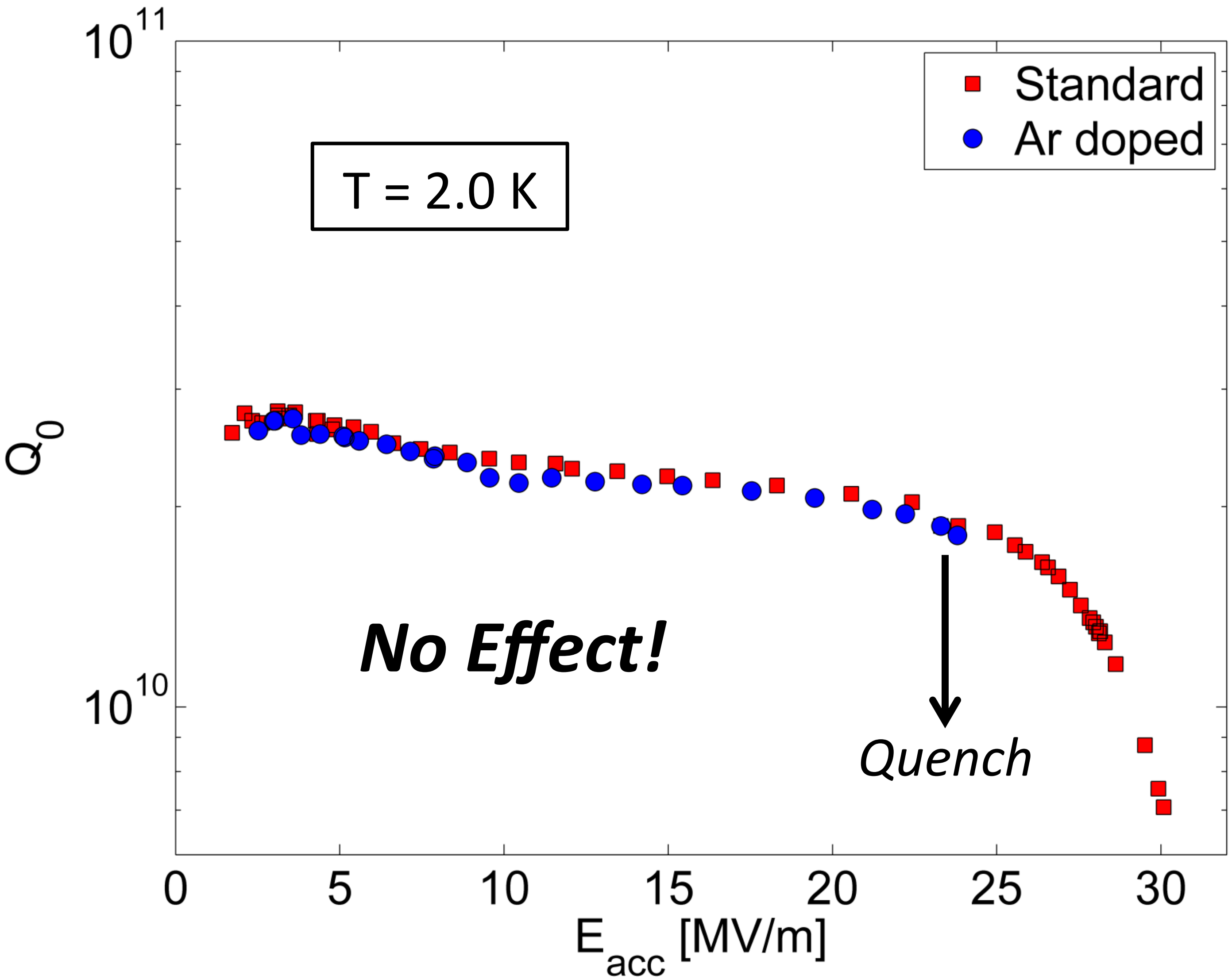
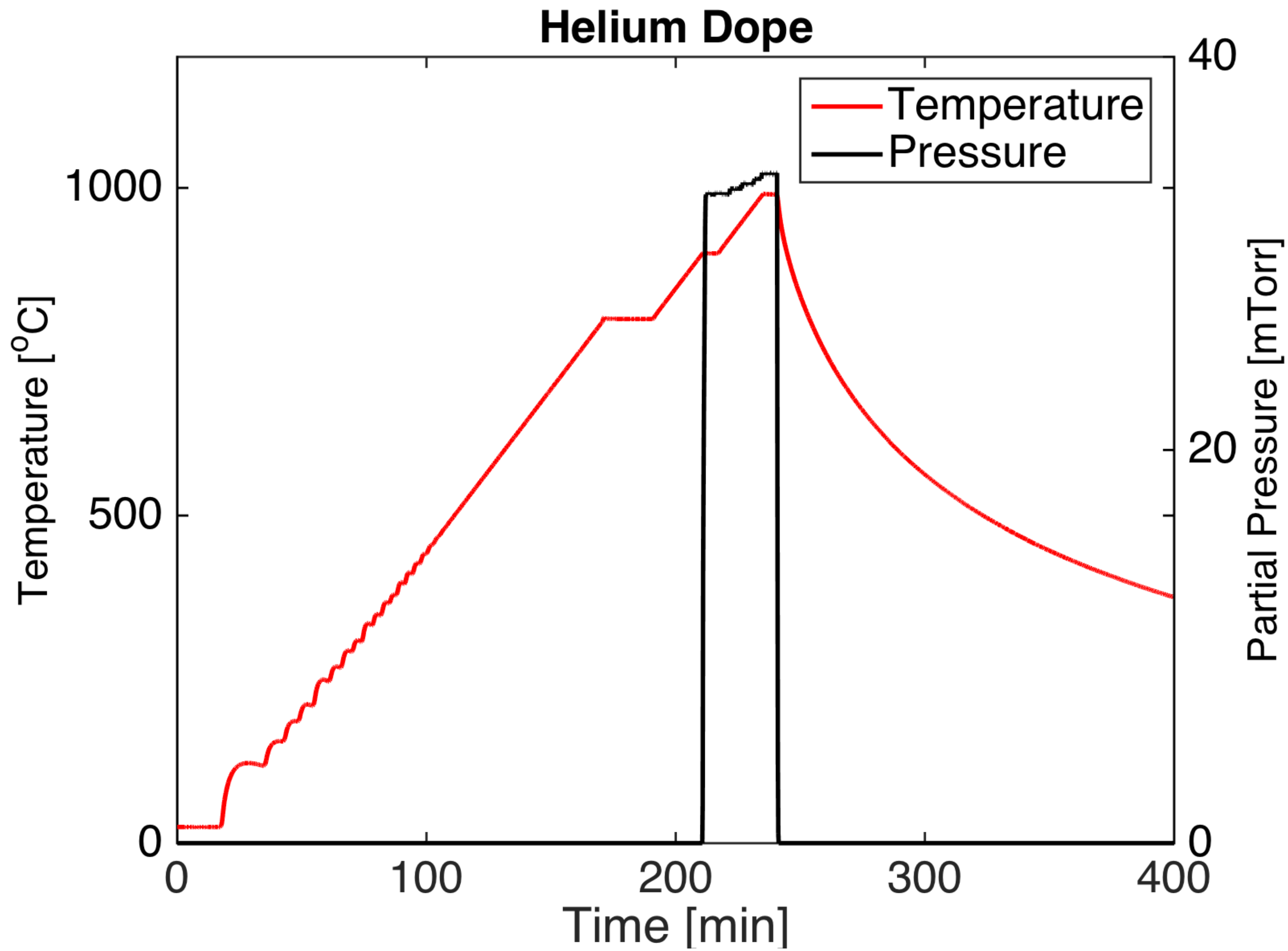


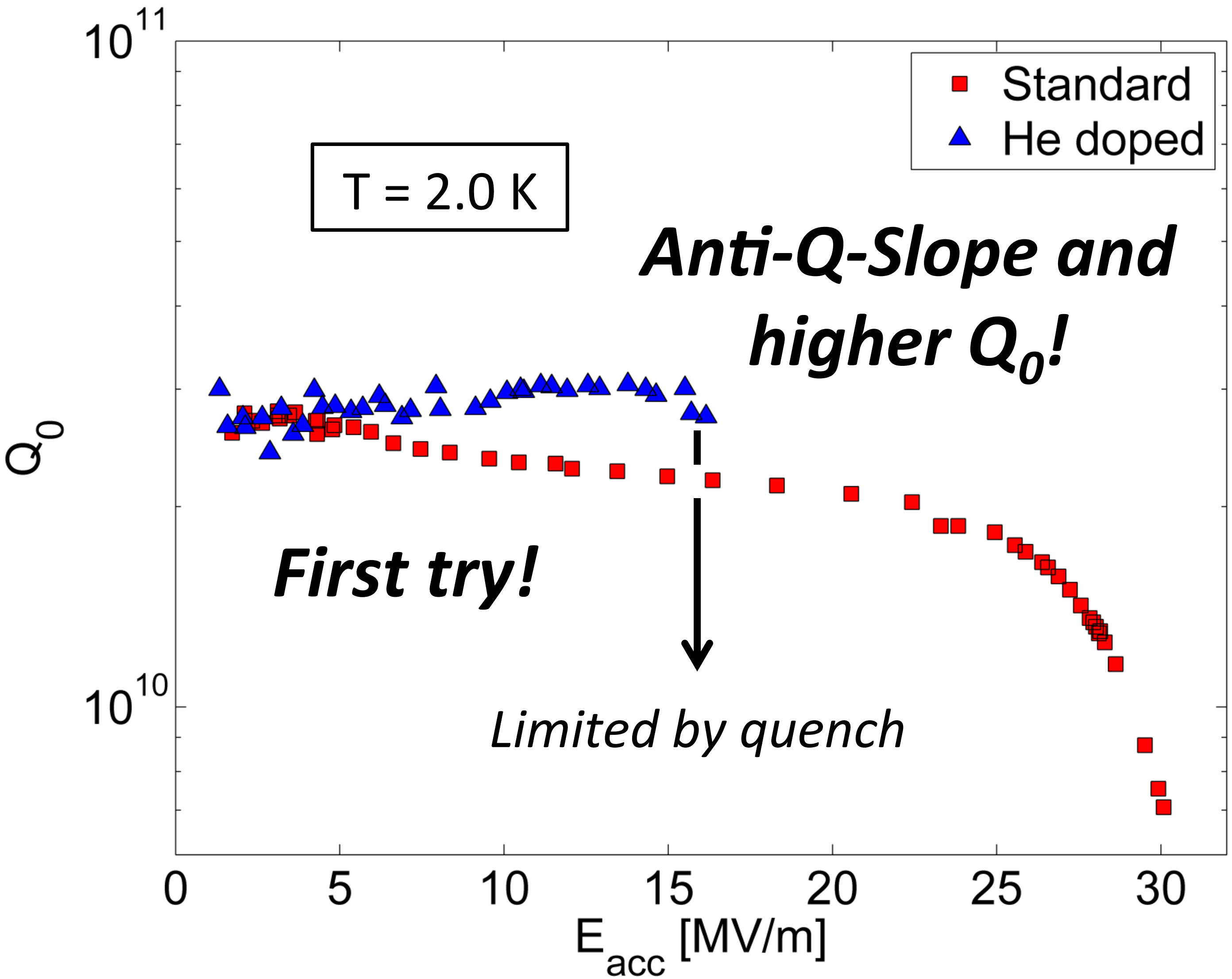
Argon Doping



Helium Doping



First He Dope!



Conclusion

- Nitrogen doping
  - Very well established method to increase Q_0
  - Significant progress understanding the science of N-doping
  - Drawbacks
    - Trapped flux sensitivity
    - Lower average quench fields
- Inert Doping
  - Argon had no effect
  - First results with helium are exciting
  - Effects similar to nitrogen
  - There is much to be done!

References & Acknowledgements

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H. Conklin, D. Gonnella, T. Gruber, D. L. Hall, J. J. Kaufman, M. Liepe, J. T. Maniscalco