The Importance of the Electron Mean Free Path for Superconducting Radio-Frequency Cavities

James Maniscalco
SRF 2017, Lanzhou, China

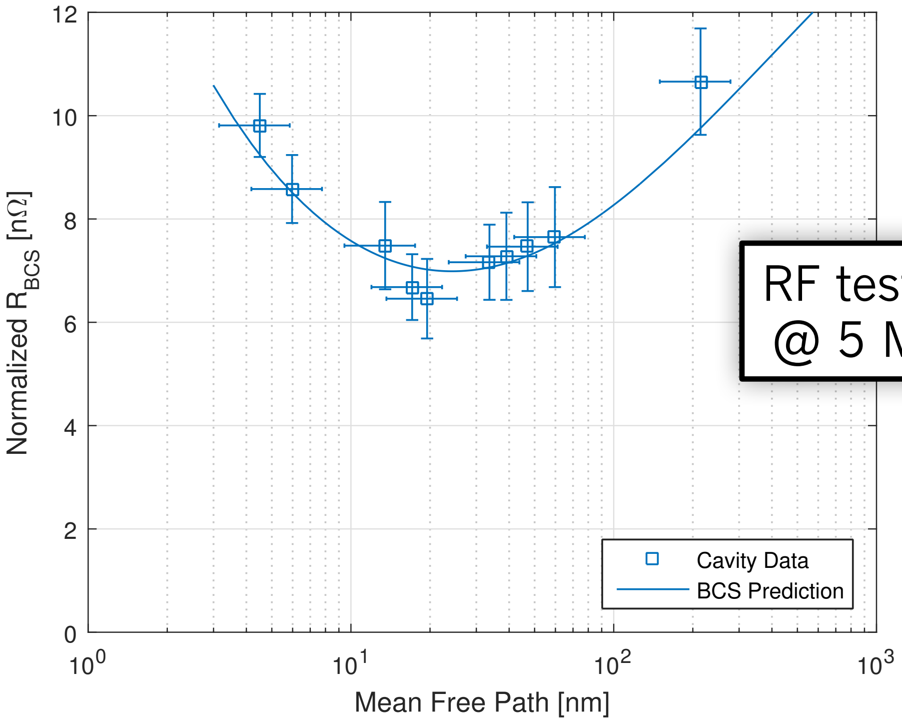
"The importance of the electron mean free path for superconducting radio-frequency cavities"

Journal of Applied Physics **121**, 2017 – J. T. Maniscalco, D. Gonnella, M. Liepe

Impurity-Doping Observations

- Classic observation: minimum in R_{BCS} vs. **mean free path**

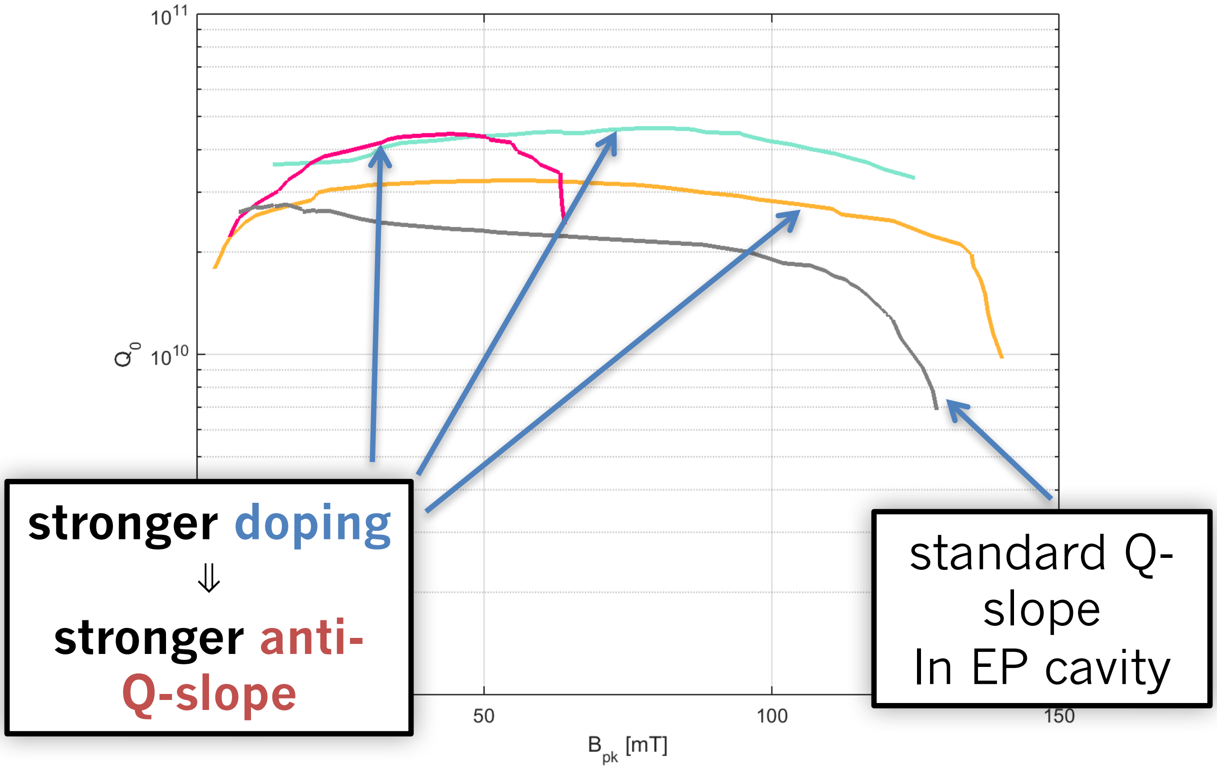
stronger doping
⇓
more impurities
⇓
shorter mean free path



RF test data @ 5 MV/m

Impurity-Doping Observations

- Recent observation: **anti-Q-slope** from **impurity doping**



Impurity-Doping Observations

- Low-field minimum comes from BCS theory
- Recent theory offers explanation for **anti-Q-slope**
  - A. Gurevich (ODU): current-induced smearing of energy gap causes field-dependent reduction in surface resistance

Background: Gurevich Theory

- Strong RF magnetic fields excite screening currents on superconducting surface which modify density of states of quasiparticles (unpaired electrons)
- Decreases R_S for sufficiently sharp gap peak

"Reduction of Dissipative Nonlinear Conductivity of Superconductors by Static and Microwave Magnetic Fields"

A. Gurevich, PRL **113**, 087001 (2014)

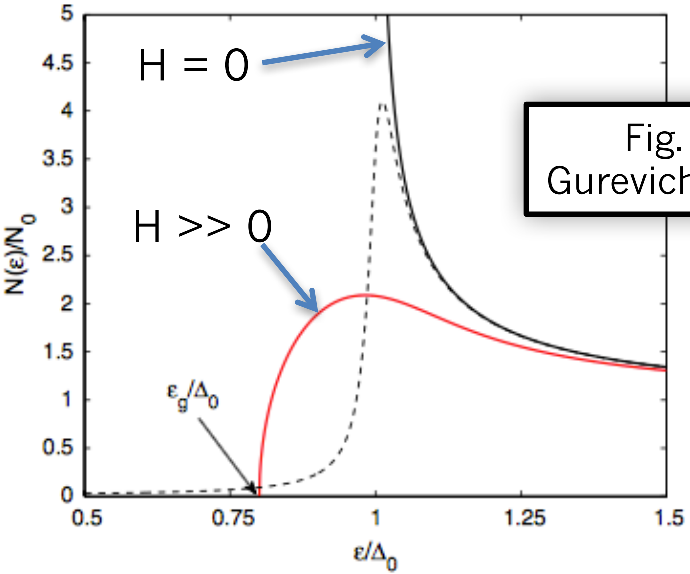


Fig. 2, Gurevich 2014

Background: Gurevich Theory

- **Doping** connection: doping Nb sharpens gap peak?
  - Early results indicated more uniform energy gap on surface, but need more systematic data

Blue: undoped Nb
Red: high-T doped Nb

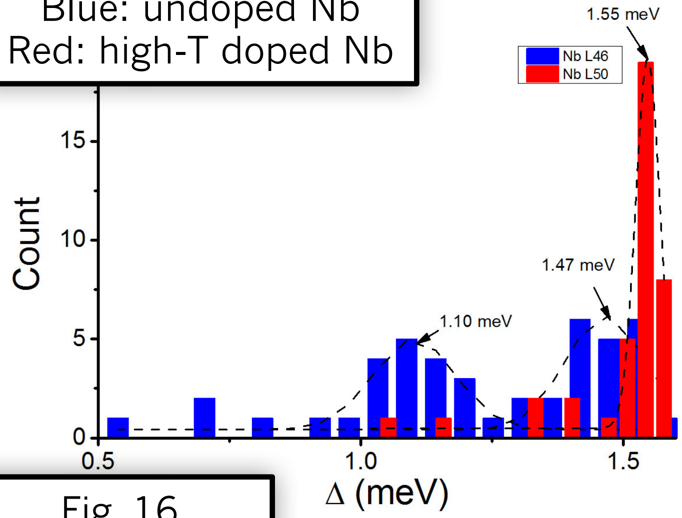


Fig. 16, Dhakal 2013

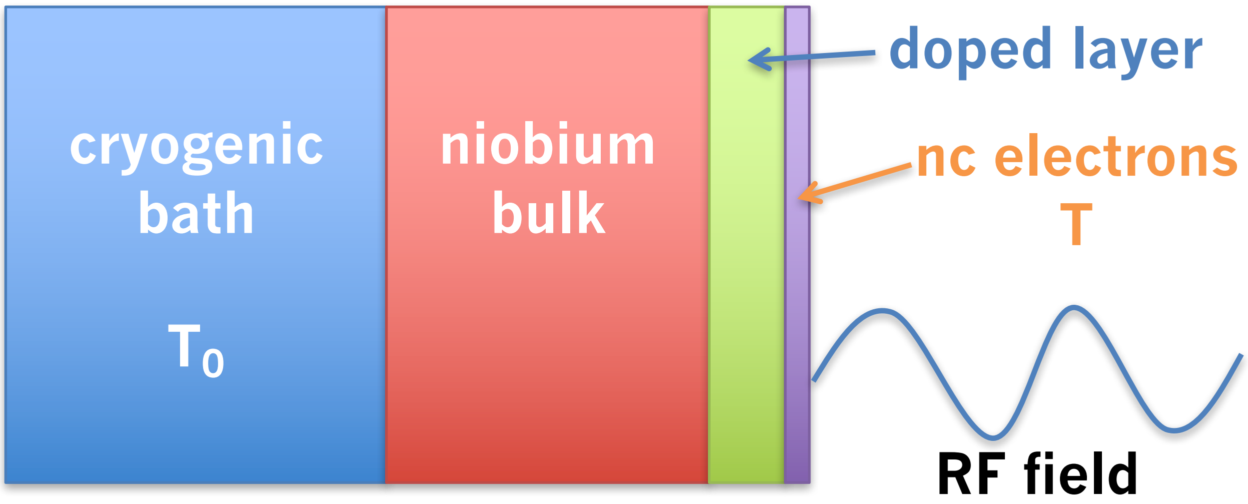
"Effect of high-temperature heat treatments on the quality factor of a large-grain superconducting radio-frequency niobium cavity"

P. Dhakal *et al.*, PRST-AB **16**, 042001 (2013)

Background: Gurevich Theory

- Quasiparticle **overheating**

$$T - T_0 = \alpha' \frac{1}{2} H_{\mathrm{a}}^2 R_{\mathrm{BCS}}(H_{\mathrm{a}}, T) = \alpha' \frac{P_{\mathrm{diss}}}{\mathrm{area}}$$



Background: Gurevich Theory

- Quasiparticle **overheating**

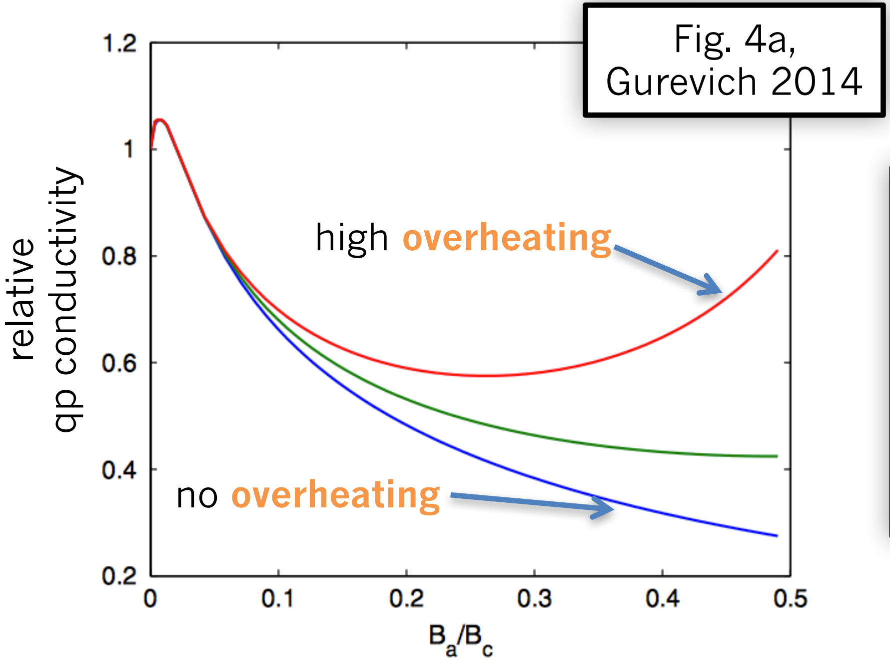
$$T - T_0 = \alpha' \frac{1}{2} H_\mathrm{a}^2 R_\mathrm{BCS}(H_\mathrm{a}, T) = \alpha' \frac{P_\mathrm{diss}}{\mathrm{area}}$$

$$\alpha' = \left(\frac{1}{Y} + \frac{d}{\kappa} + \frac{1}{h_\mathrm{K}} \right)$$

Y (e⁻-phonon energy transfer) dominates, can be dependent on **mean free path**

properties of bulk, **do not change** with **doping**

Background: Gurevich Theory



Gurevich theory does not consider **mean free path**,

leaves **overheating** as free parameter

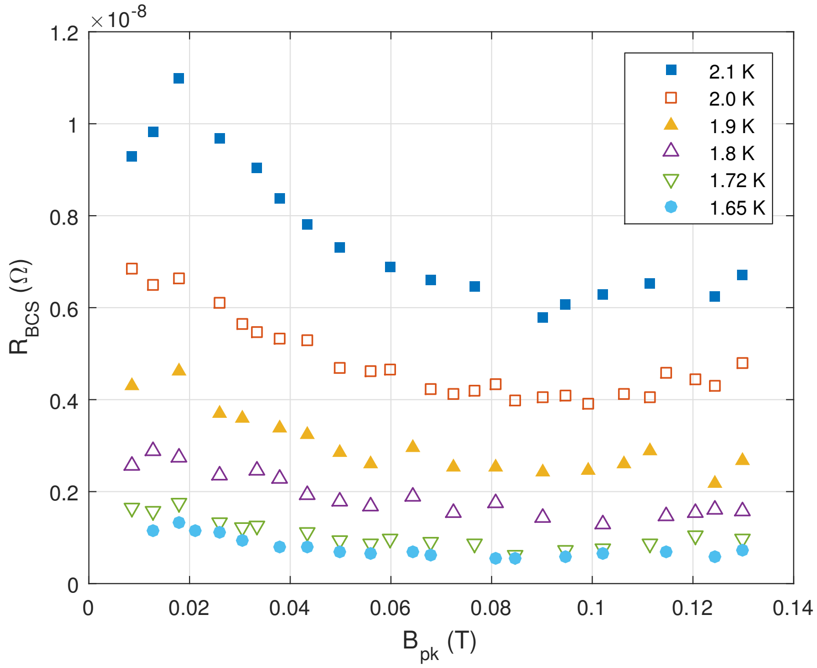
– Magnitude of R_{BCS} reduction controlled by **quasiparticle overheating**

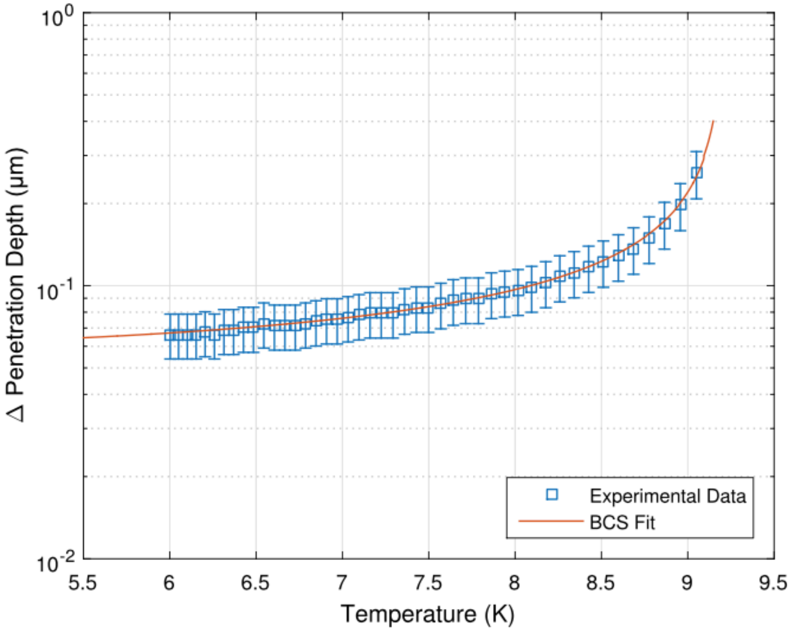
Experimental Parameters

- 1.3 GHz **Nitrogen-doped** TESLA single-cell niobium cavities
- Prepared with **varied doping recipes** to achieve a range of **electron mean free paths** **from 4 nm to over 200 nm**
- CW RF tests at Cornell

RF Test Results and Analysis

- Extract **mean free path**, $R_{BCS}(H, T)$



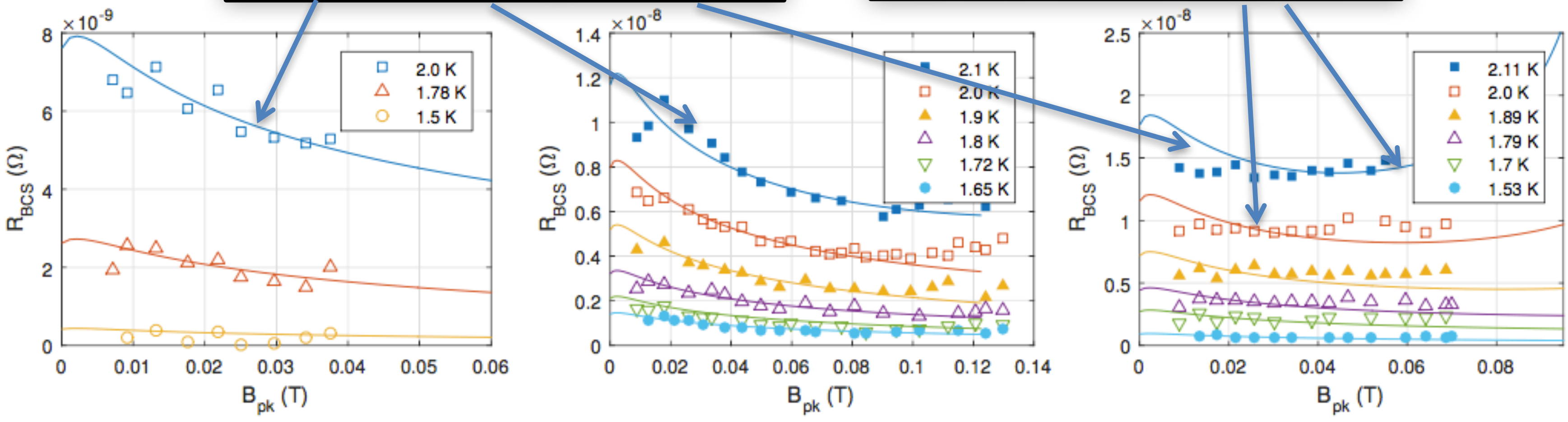


RF Test Results and Analysis

- Fit Gurevich theory to experimental data
  - α' as free fitting parameter

Increasing **mean free path**, increasing **α'**

Theory needs expansion to predict outside **dirty limit**

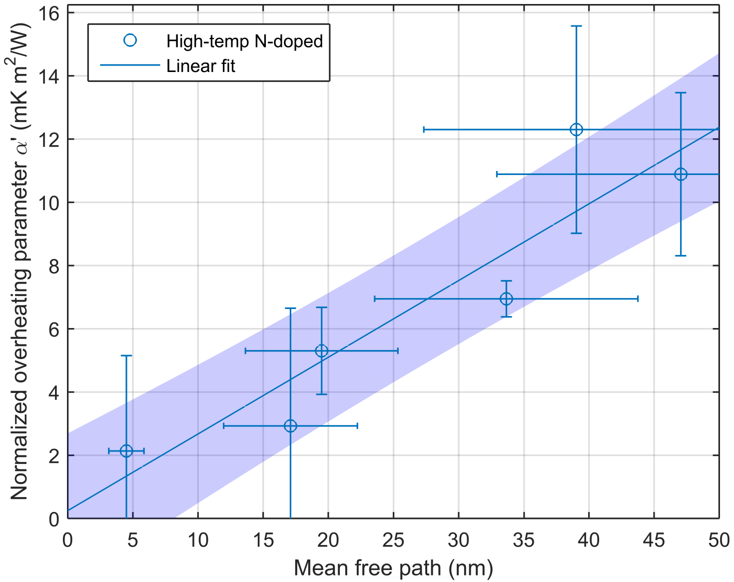


mfp = 4.5 nm

mfp = 34 nm

mfp = 213 nm

The Mean Free Path



stronger **doping**

⇓

lower **mean free path**

⇓

lower **overheating**

⇓

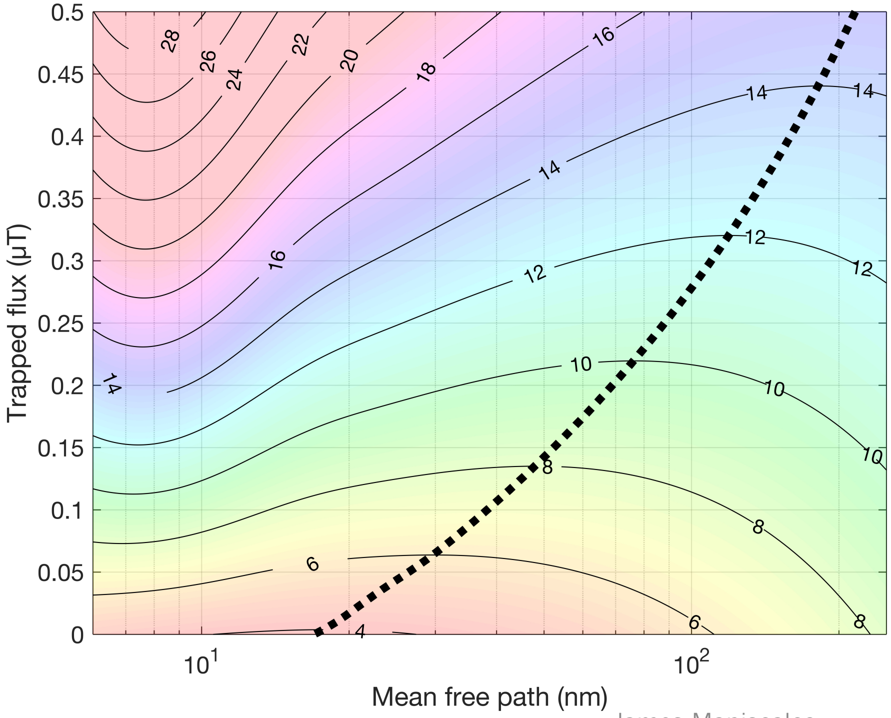
stronger **anti-Q-slope**

Overheating depends strongly on **mean free path!**

→ This is what connects **impurity doping** to observed strength of **anti-Q-slope**

Optimal Doping Level

- Optimizing the mean free path
  - Account for sensitivity of R_0 to trapped flux



At right:

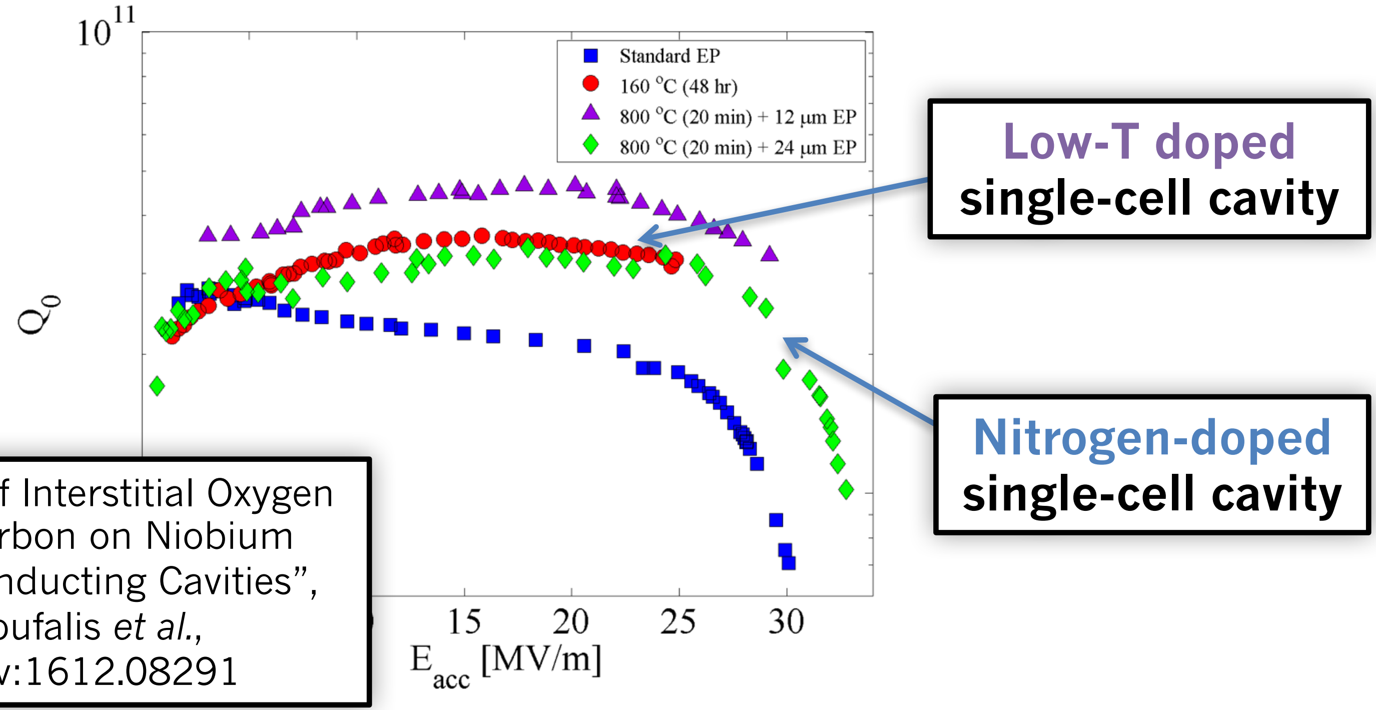
$R_S = R_0 + R_{BCS}$ at 68 mT (16 MV/m), 2K
LCLS-II spec gradient

Low-Temperature Doping

- New tests: **Low-temperature impurity-doped** 1.3 GHz TESLA niobium cavities
- Simpler **doping procedure** – no post-doping chemical etching
- Different impurities – high levels of C, O
- CW RF tests at Cornell

Low-Temperature Doping

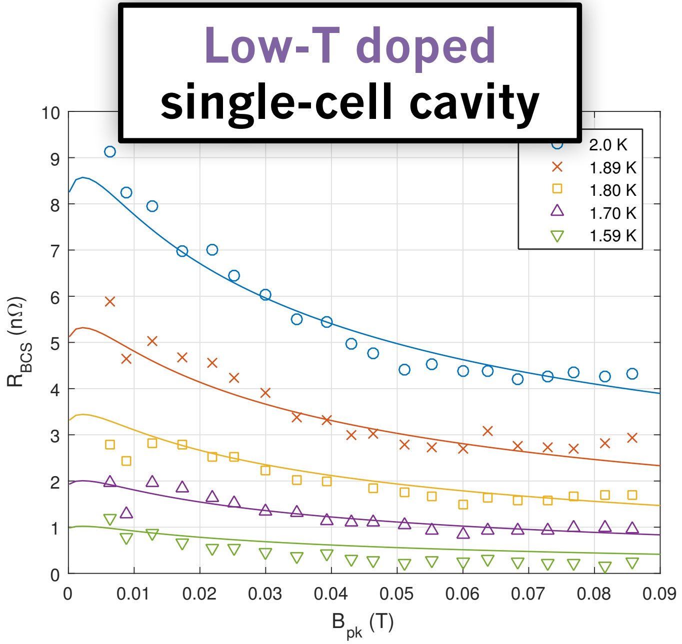
- Similar RF performance to **N-doped** cavities

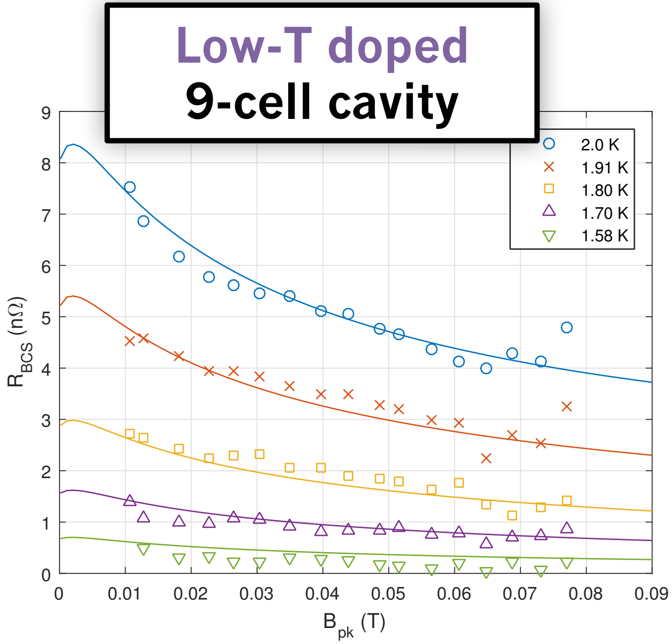


"Effects of Interstitial Oxygen and Carbon on Niobium Superconducting Cavities", Koufalis *et al.*, arXiv:1612.08291

Low-Temperature Doping

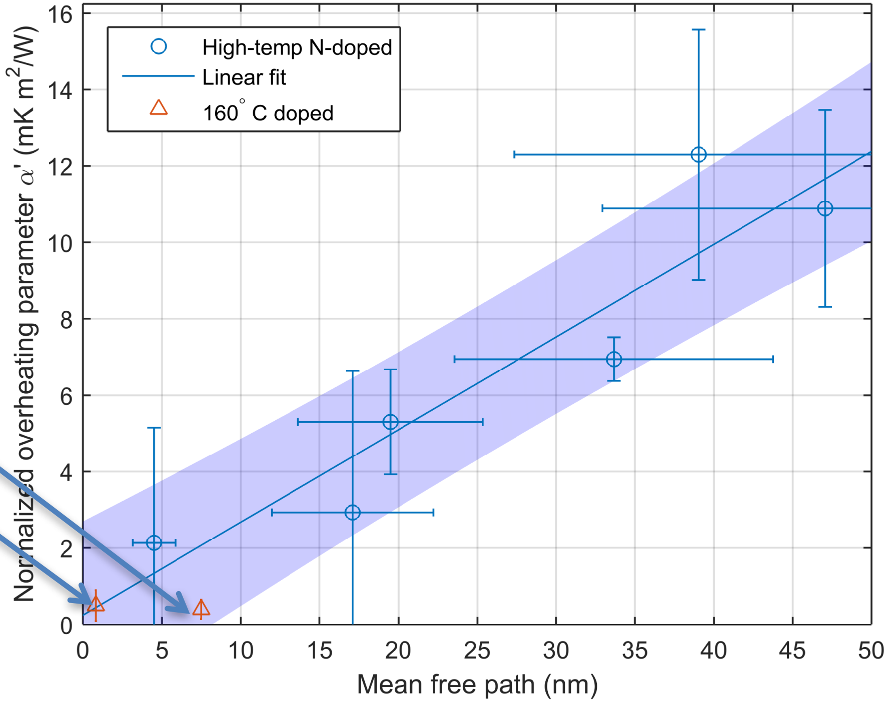
- Fit using same procedure as before
  - Single α' for all temperatures





Low-Temperature Doping

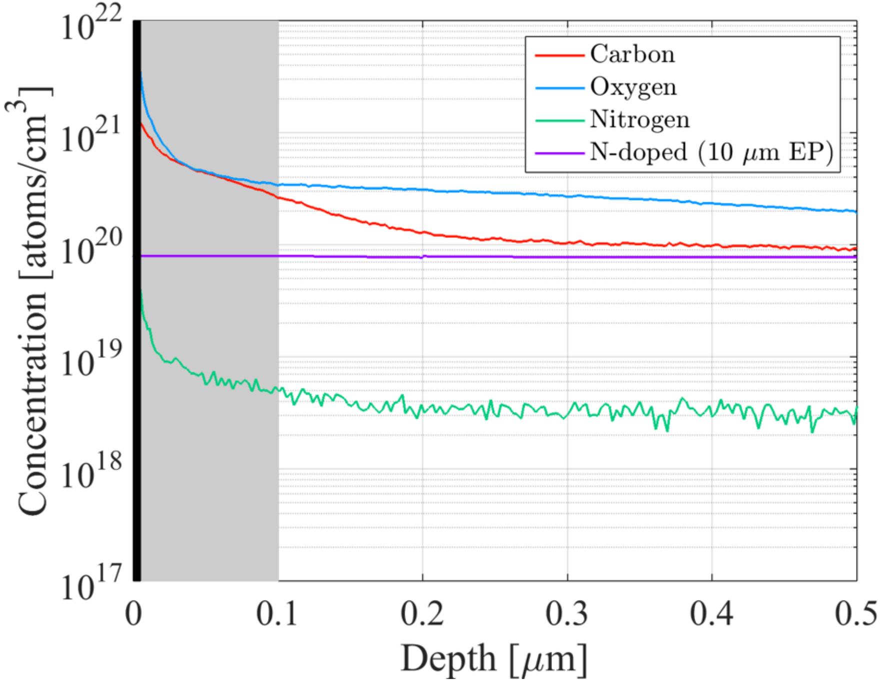
- Good agreement with **N-doping** model



New results from **Low-T doping**

Low-Temperature Doping

- Drastic differences in RF penetration layer
  - How does this change the physics?



Conclusions

- Theoretical link between **doping level**, **mean free path**, **quasiparticle overheating** and the **anti-Q-slope**

- Promising/interesting early results with **low-T doping**

Thank you for your attention!

- References / further reading:

  - J. T. Maniscalco, D. Gonnella, and M. Liepe, J. Appl. Phys. **121**, 043910 (2017). http://aip.scitation.org/doi/10.1063/1.4974909
  - A. Gurevich, Phys. Rev. Lett. **113**, 087001 (2014). http://link.aps.org/doi/10.1103/PhysRevLett.113.087001
  - P. N. Koufalis, D. L. Hall, M. Liepe, and J. T. Maniscalco, arXiv:1612.08291 (2016).
  - J. T. Maniscalco, F. Furuta, D. L. Hall, P. N. Koufalis, M. Liepe, IPAC 2017 (WEPVA145).
  - This conference: **TUPB009, THPB004, THPB005, THPB006**

Backup: Terms and Equations

$$R_s = R_0 + R_{BCS}$$

$T = T_{electron}$ = temperature of quasiparticles
T_0 = cryogenic bath temperature

α' = normalized overheating parameter
Y = electron-phonon energy transfer rate
κ = thermal conductivity
d = thickness of cavity wall
h_K = Kapitza interface conductance

P_{diss} = power dissipated in cavity walls

Backup: Cavity Preparations

- Nitrogen-doped 1.3 GHz TESLA single-cell niobium cavities
  - Prepared with a range of electron mean free paths from 4 nm to over 200 nm
    - 100 μm vertical electropolish (VEP) "reset"
    - 800 ºC in vacuum, 3 h, "outgassing"
    - 800-990 ºC in 4-8 Pa (30-60 mTorr) N_2, 5-30 min
    - 5-40 μm VEP to determine "doping level", quantified by electron mean free path (deeper etch reveals cleaner layer)
- Low-T doping at 120-160º C
    - chemical reset and outgassing bake phase
    - 48 h bake with nitrogen gas, impurities at ppm level
    - 48-168 h anneal in vacuum