Analysis of Mean Free Path and Field-Dependent Surface Resistance

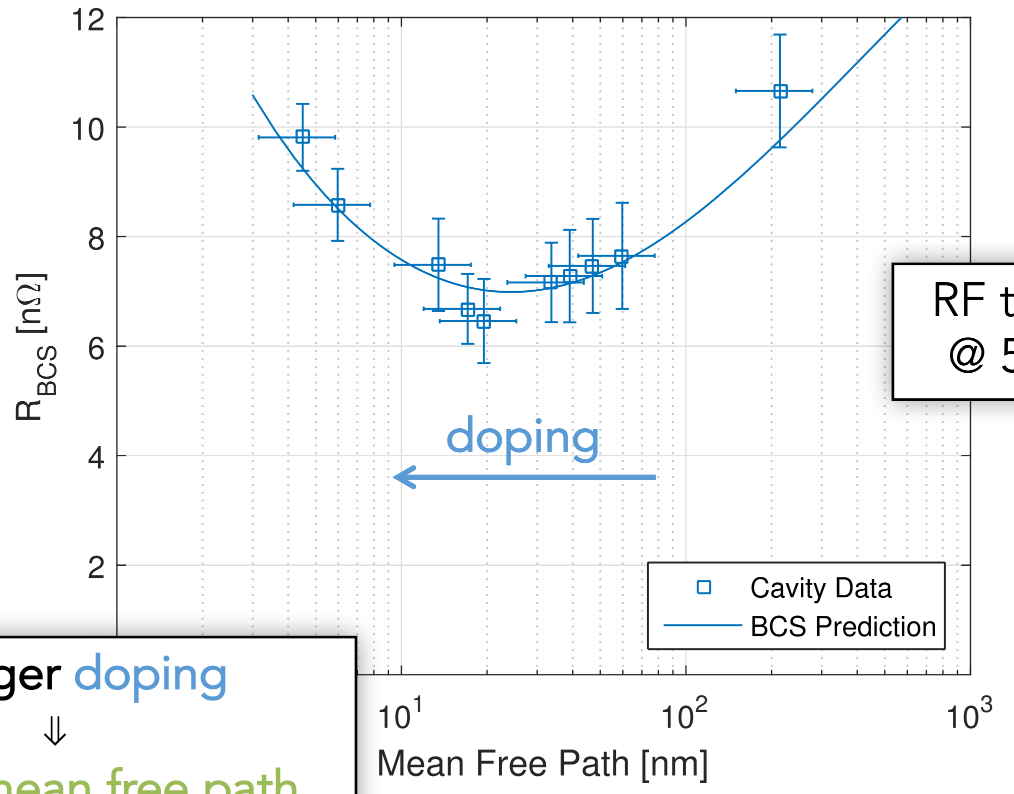
James T. Maniscalco

November 15, 2017

TTC Topical Workshop

Impurity-Doping Observations

- Classic observation:
  - Dope niobium, reach minimum in R_{BCS} vs. mean free path



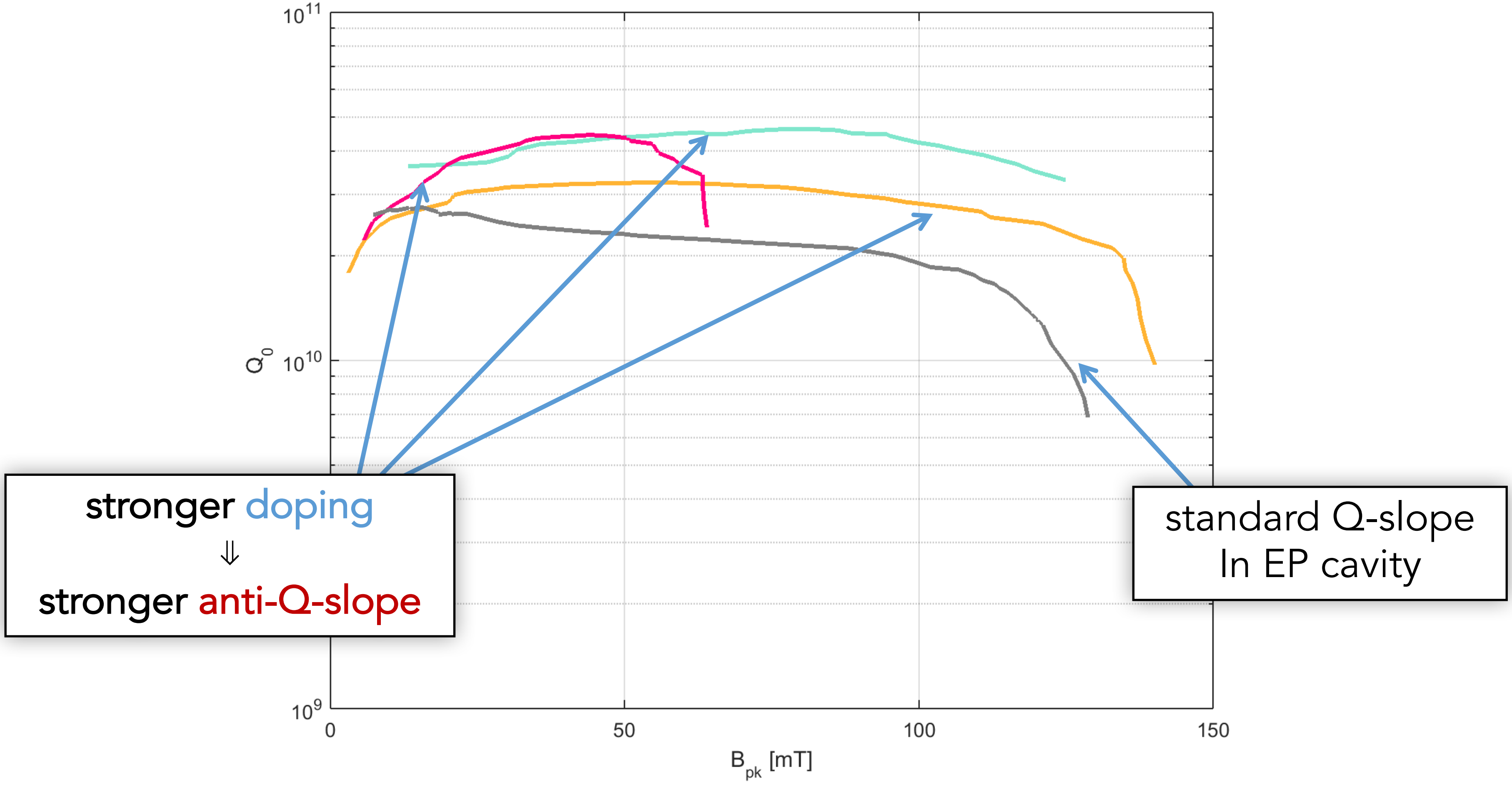
RF test data @ 5 MV/m

stronger doping
⇓
shorter mean free path

J. T. Maniscalco, D. Gonnella, and M. Liepe, J. Appl. Phys. **121**, 043910 (2017).

Impurity-Doping Observations

- "New" observation:
  - Dope niobium, see "anti-Q-slope"



Impurity-Doping Observations

- Most study of AQS has been phenomenological
  - Project-driven field – optimizing recipes, etc.

- Growing number of theoretical models

Background: Gurevich Theory

- Nonequilibrium superconductivity +
- Electron DOS modified by screening currents +
- Quasiparticle overheating

- New contribution: qp overheating ∝ mean free path

A. Gurevich, Phys. Rev. Lett. **113**, 087001 (2014).

Background: Gurevich Theory

- Quasiparticle overheating

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

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

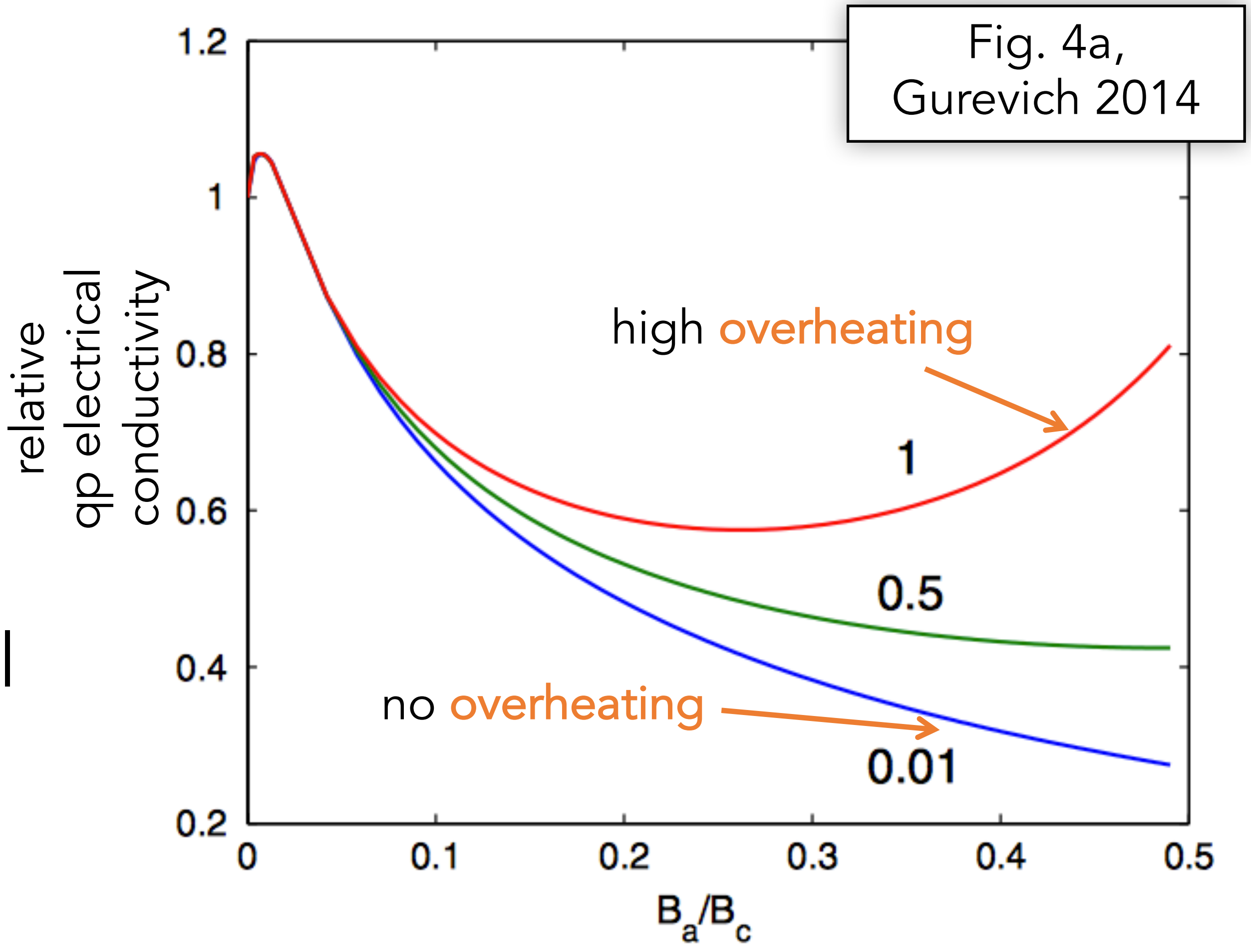
Y (e⁻-phonon energy transfer) **dominates**, can be dependent on mean free path

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

Background: Gurevich Theory

- Magnitude of R_{BCS} reduction controlled ("tuned") by quasiparticle overheating

- Overheating parameter **α** is theory's **only free parameter** (*i.e.* not controlled by material properties)

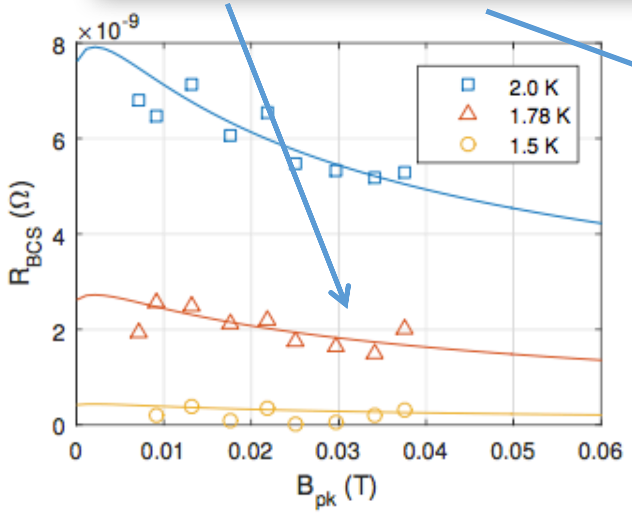


RF Tests and Analysis @ Cornell

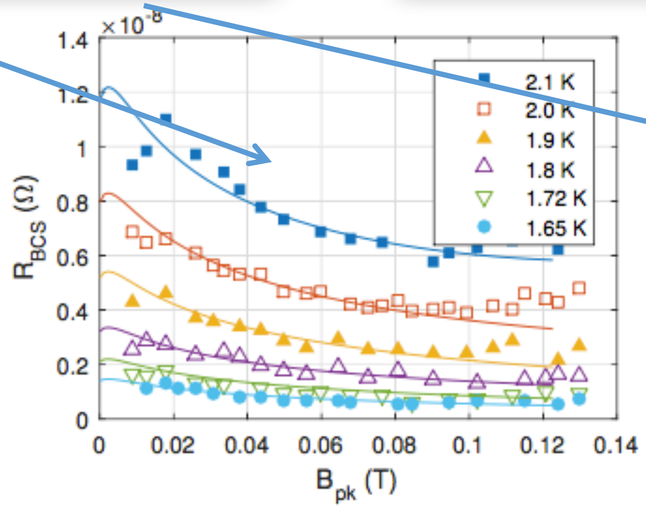
- CW RF tests, 1.3 GHz TESLA single-cells, N-doped
- Fit Gurevich theory to experimental data
  - α′ as free fitting parameter, mfp from RF fitting

Increasing mean free path, increasing α′

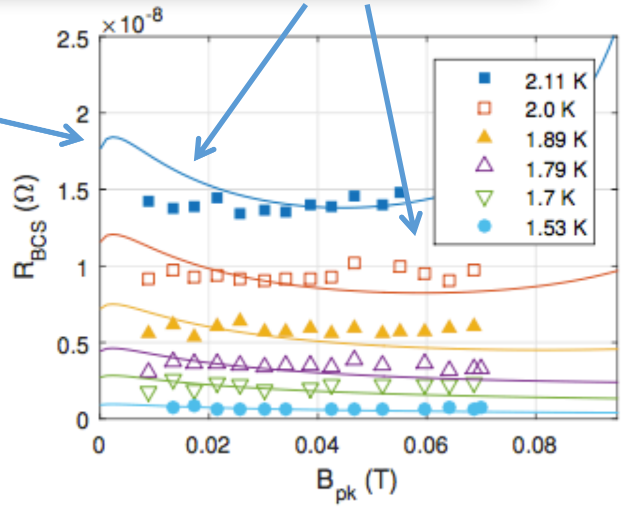
Theory needs expansion to predict outside **dirty limit**



mfp = 4.5 nm
α′ = 2.1 mK m^2/W



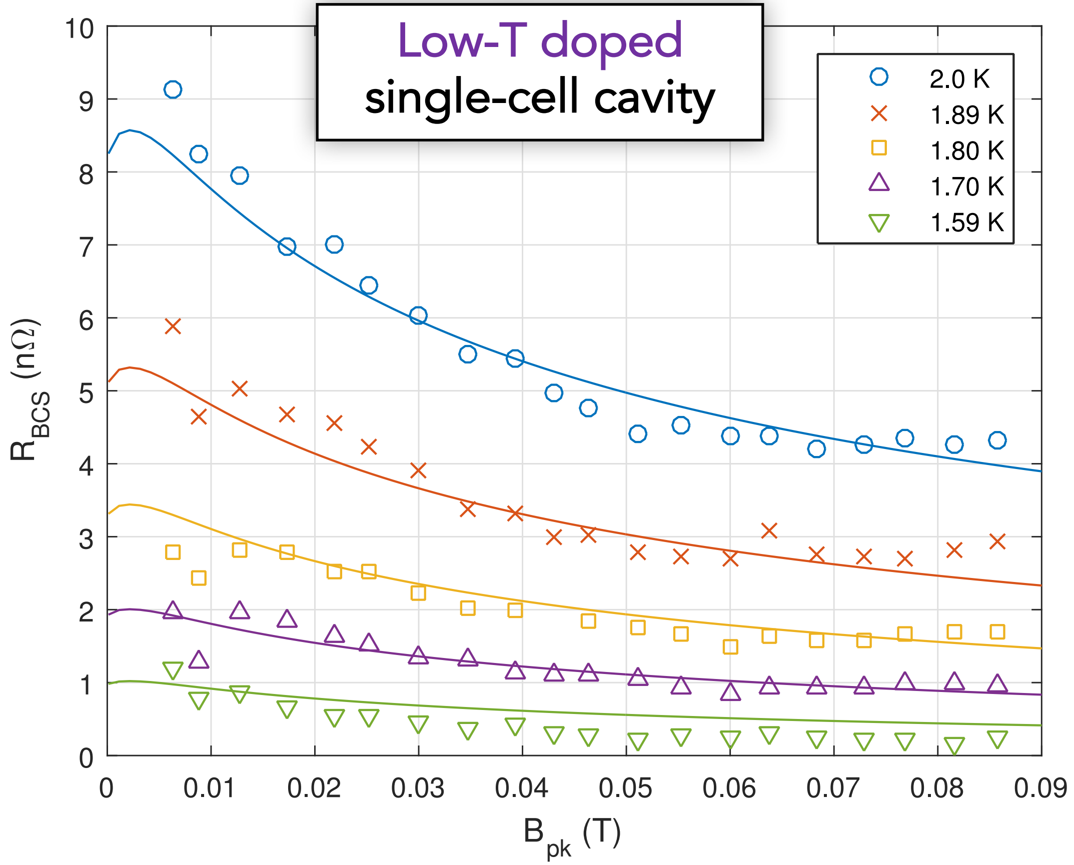
mfp = 34 nm
α′ = 7.0 mK m^2/W

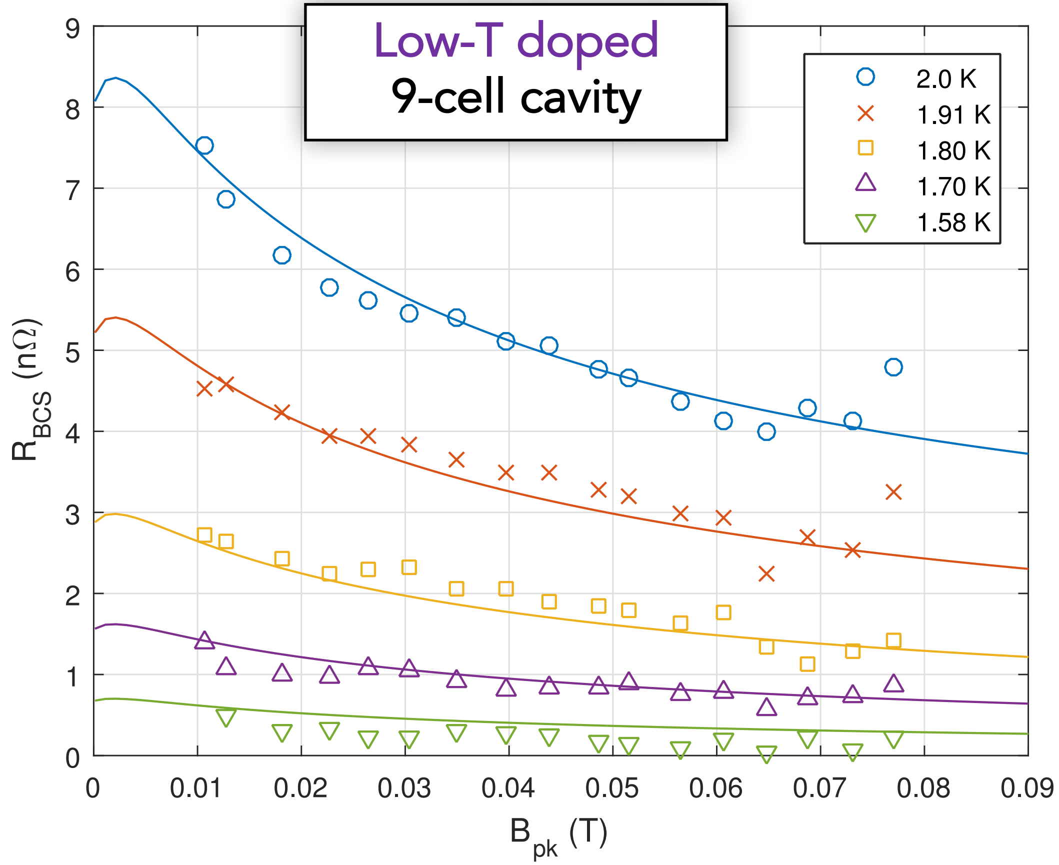


mfp = 213 nm
α′ = 17 mK m^2/W

RF Tests and Analysis @ Cornell

- CW RF tests, 1.3 GHz TESLA single-cells, Low-T-doped





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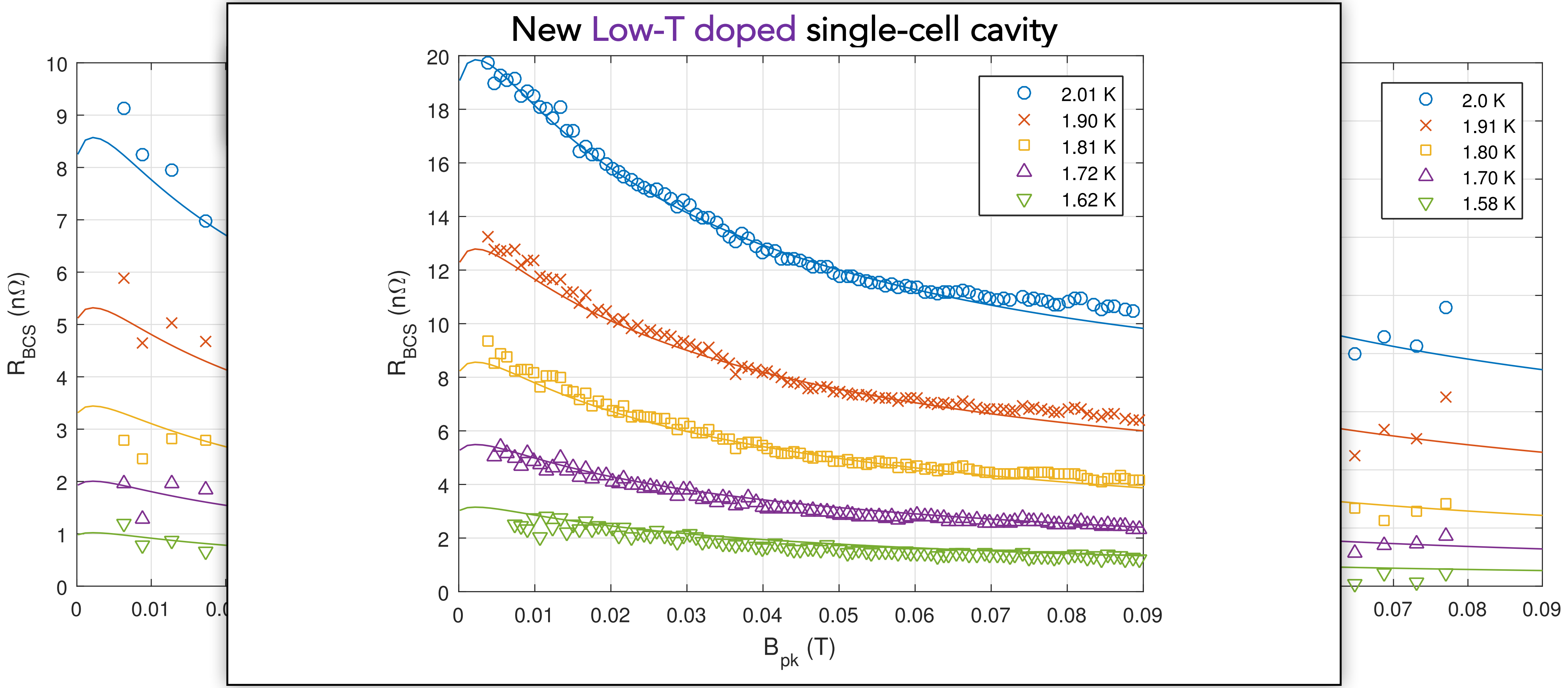
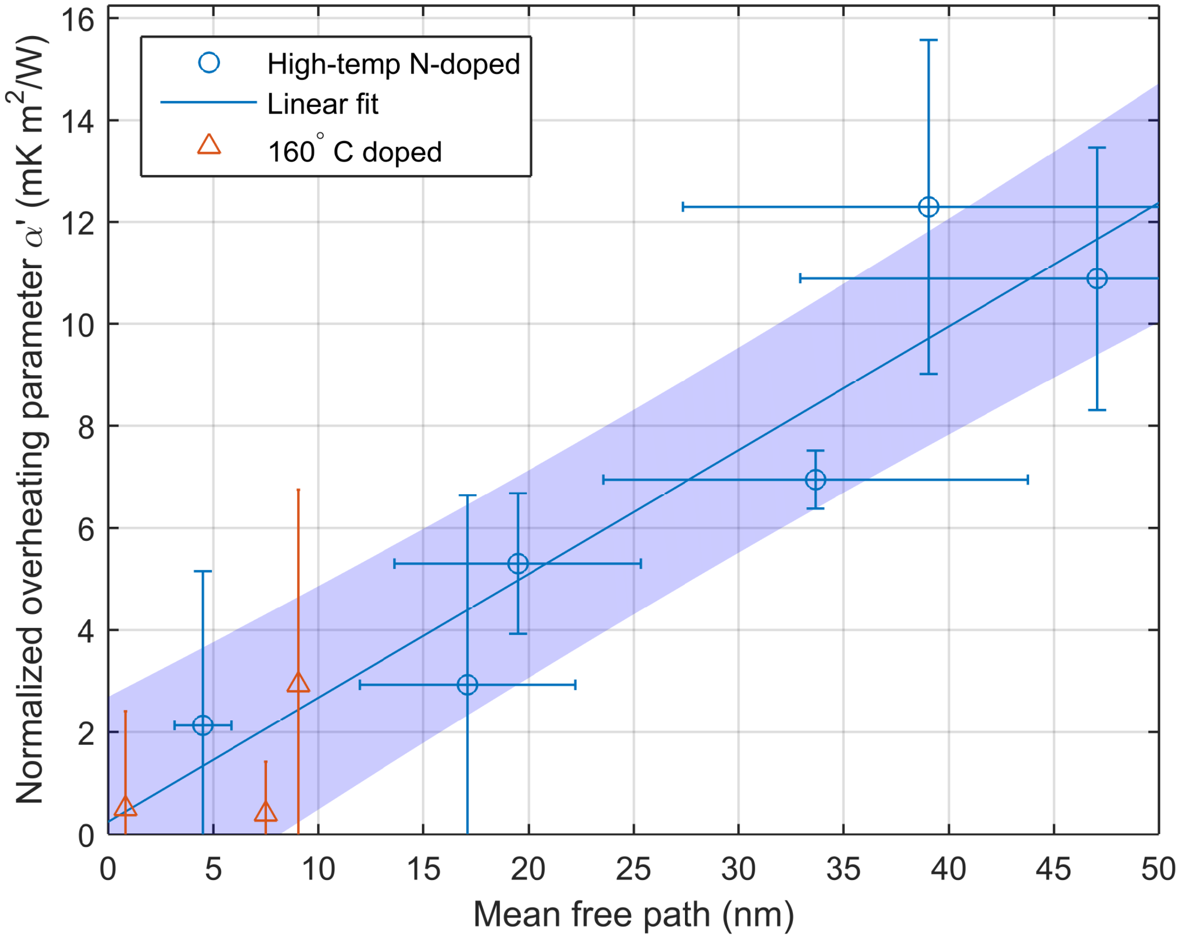


RF Tests and Analysis @ Cornell

- Linear dependence of α′ on mean free path (impurity content)



J. T. Maniscalco, D. Gonnella, and M. Liepe, J. Appl. Phys. **121**, 043910 (2017).

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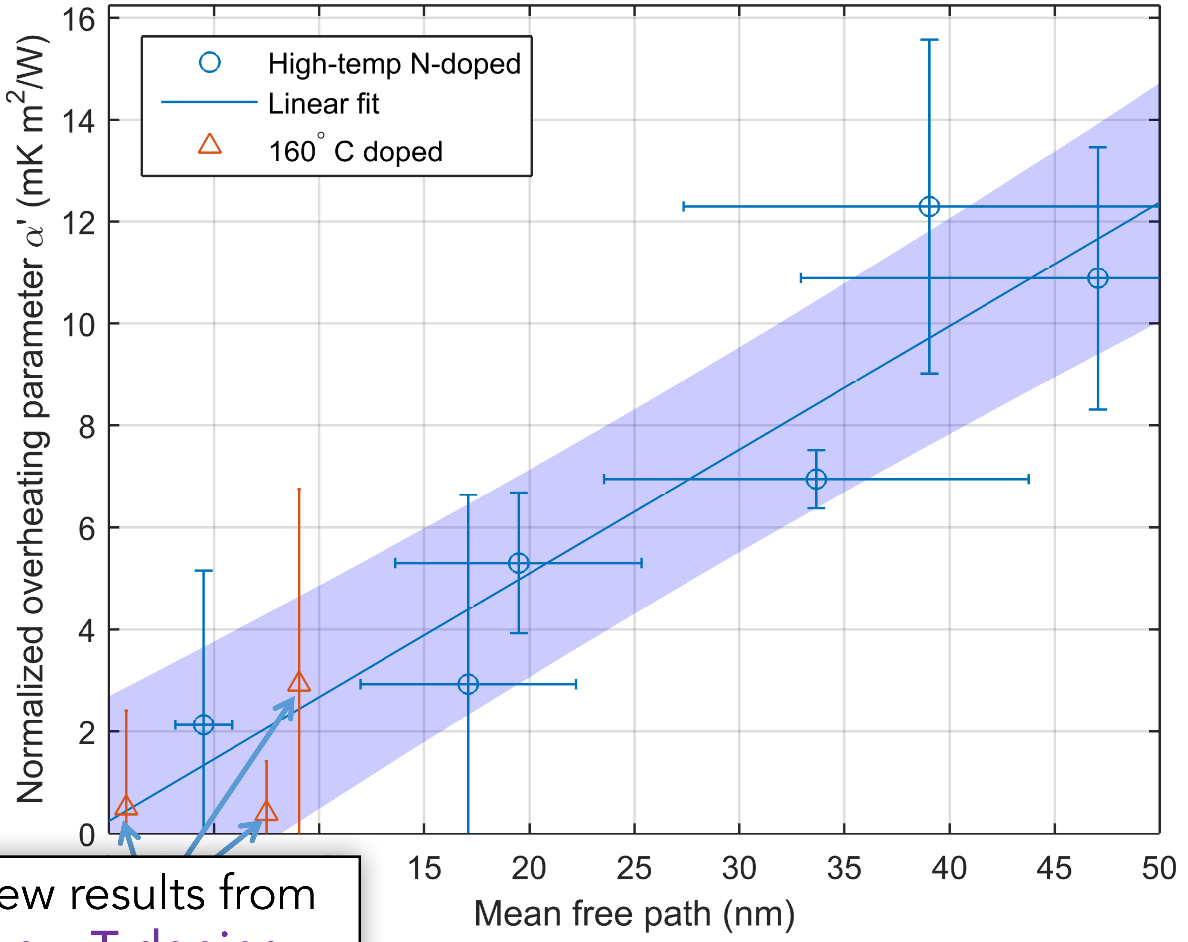
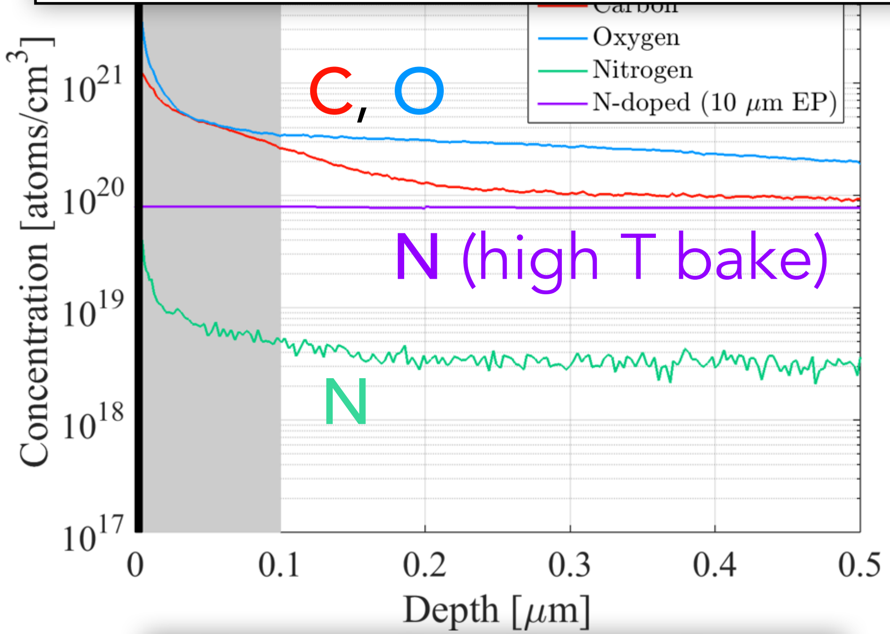


New results from
Low-T doping

Agreement remarkable due to **drastic differences** in RF penetration layer!

Not clear that nitrogen is still the culprit



P. N. Koufalis, D. L. Hall, M. Liepe, and J. T. Maniscalco, arXiv:1612.08291 (2016).

Limitations & Open Questions

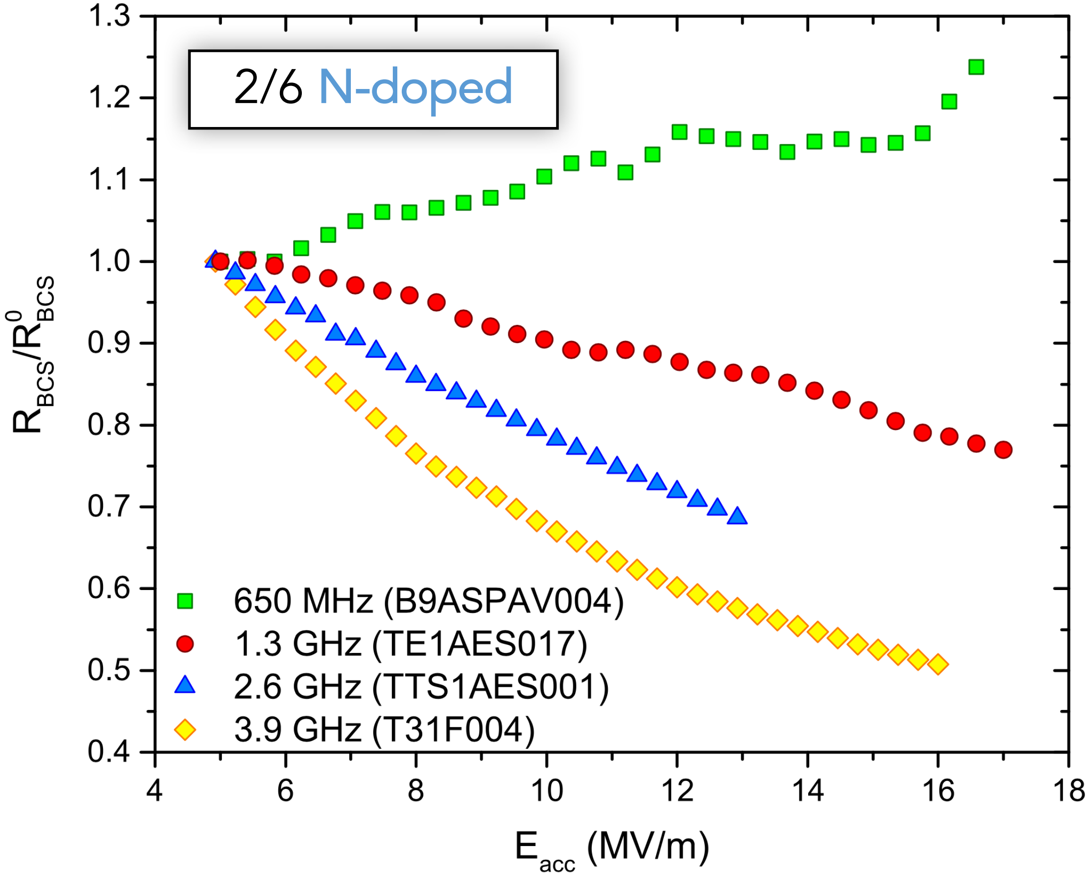
- Very high α′ yields results not (yet) observed in the lab
  - Linear approximation – is there a more appropriate form?

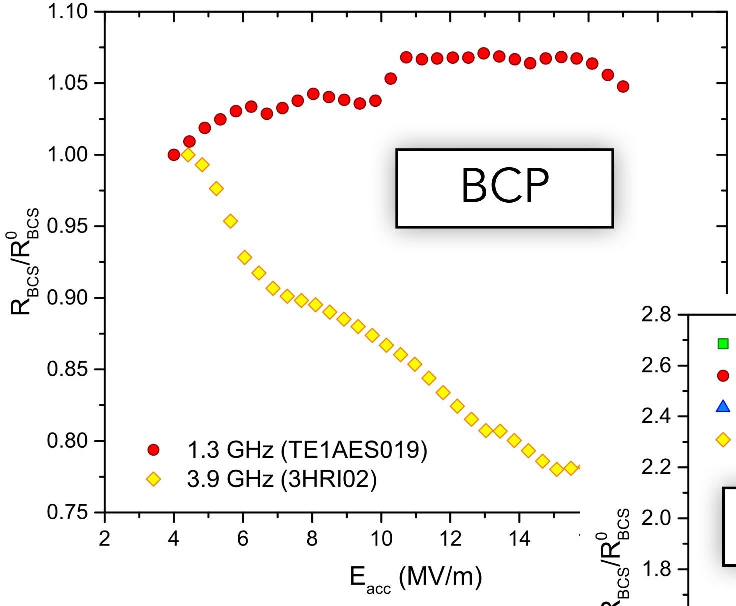
- Theory does not extend to clean niobium
  - Limited to mfp < 100 nm
  - **Same problem as above?** Long mfp gives high α′…

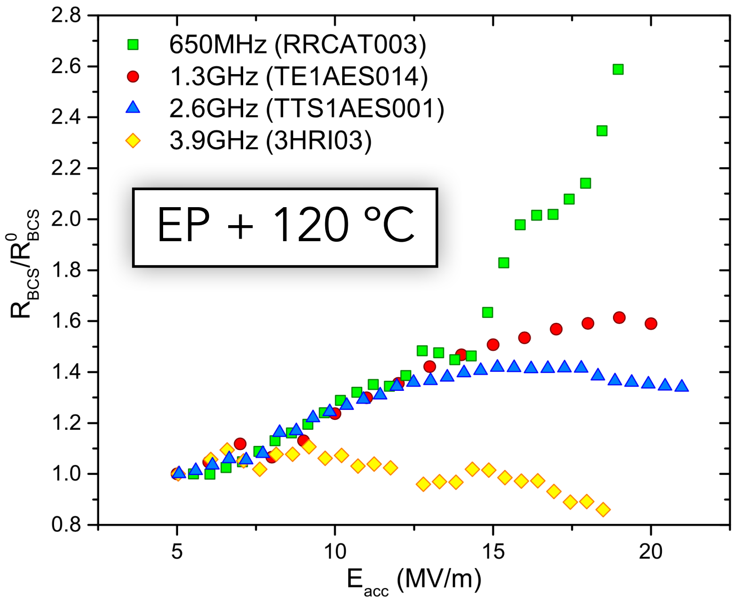
- How successful is the model at other frequencies?
  - High frequency SRF is a hot topic!
  - Lower construction costs, new optima of ω and T for new surfaces…

Doping High-Frequency Cavities

- New results from FNAL
  - Martinello *et al.* 2017 (arXiv: 1707.07582)

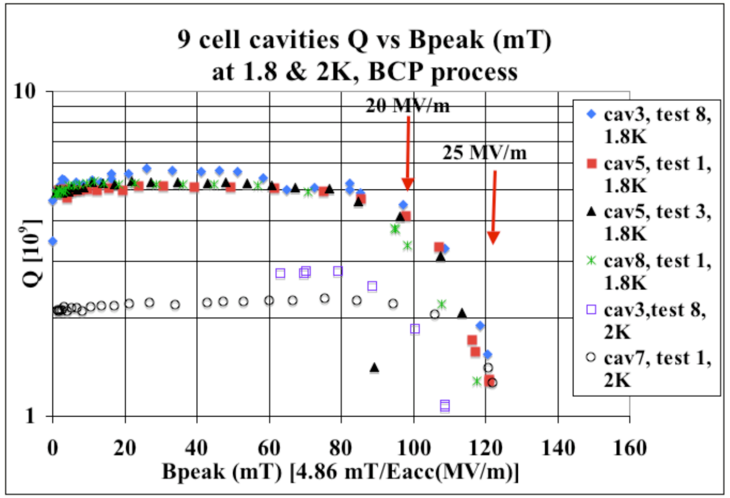


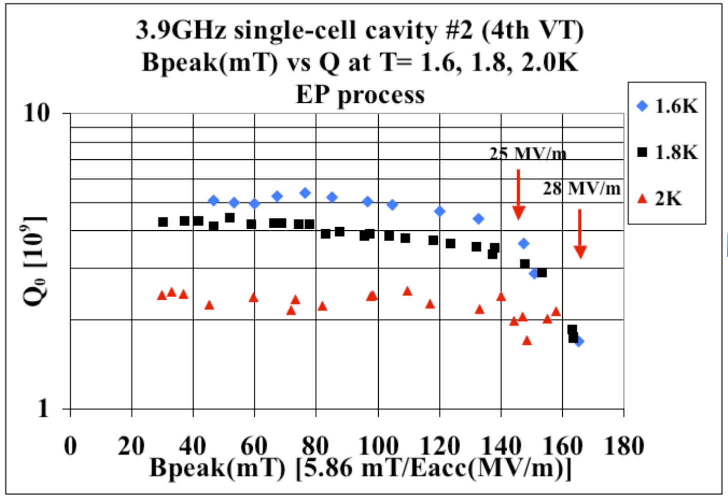




Doping High-Frequency Cavities

- BCP and EP + 120 °C: at odds with previous results?





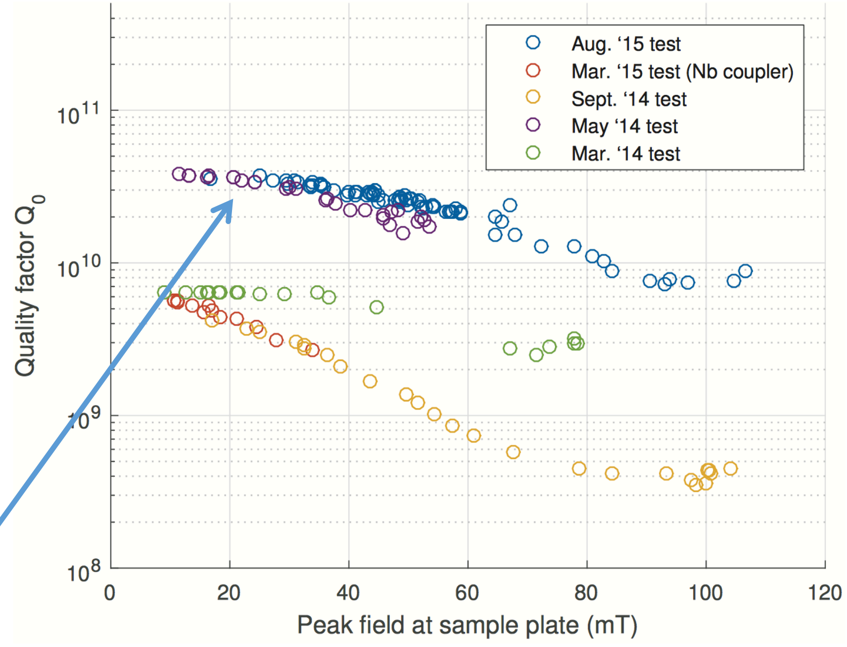
Edwards *et al.* (FNAL)
SRF 2009

BCP @ 3.9 GHz

EP + 120 °C
@ 3.9 GHz

Maniscalco *et al.*
SRF 2015

EP + 120 °C
@ 3.9 GHz



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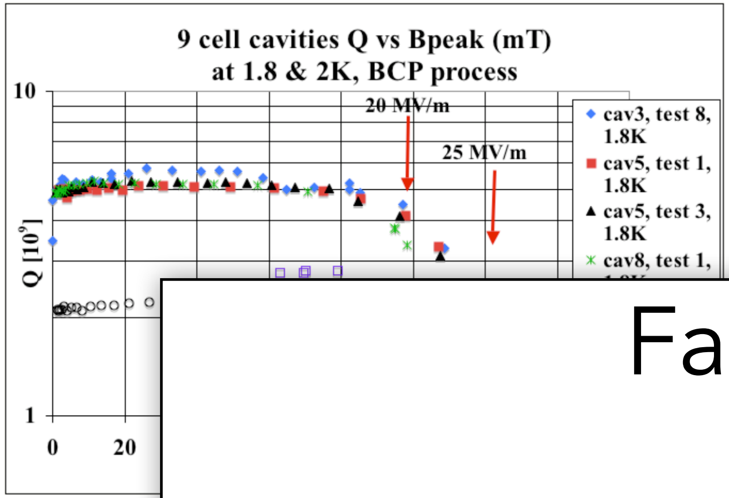

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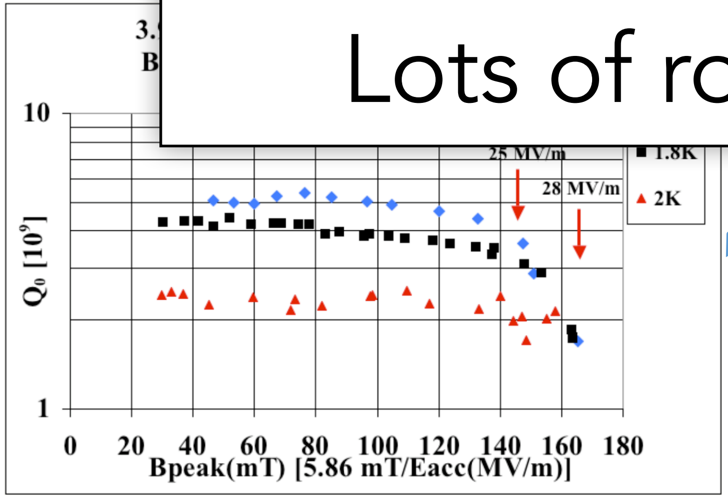
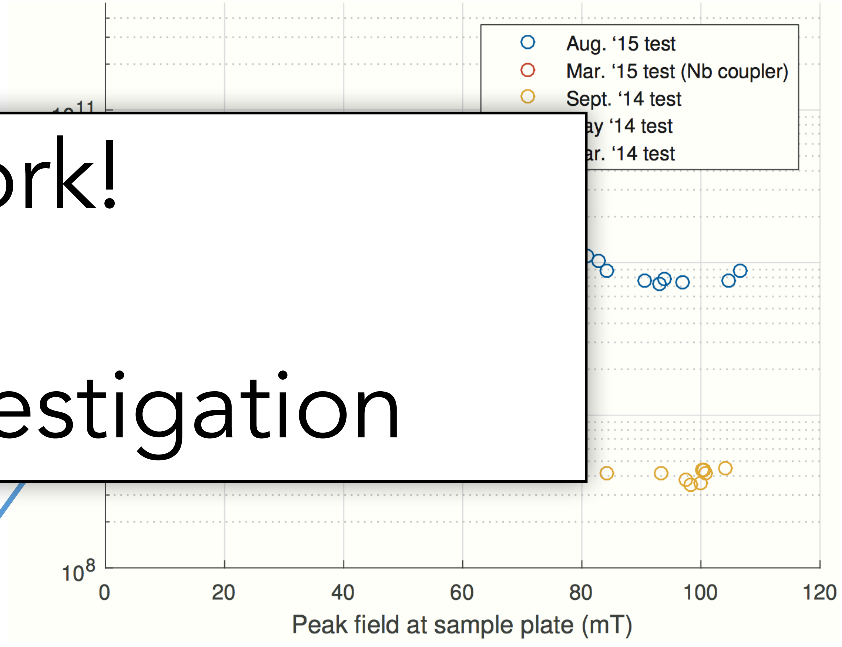


SRF 2015

EP + 120 °C
@ 3.9 GHz

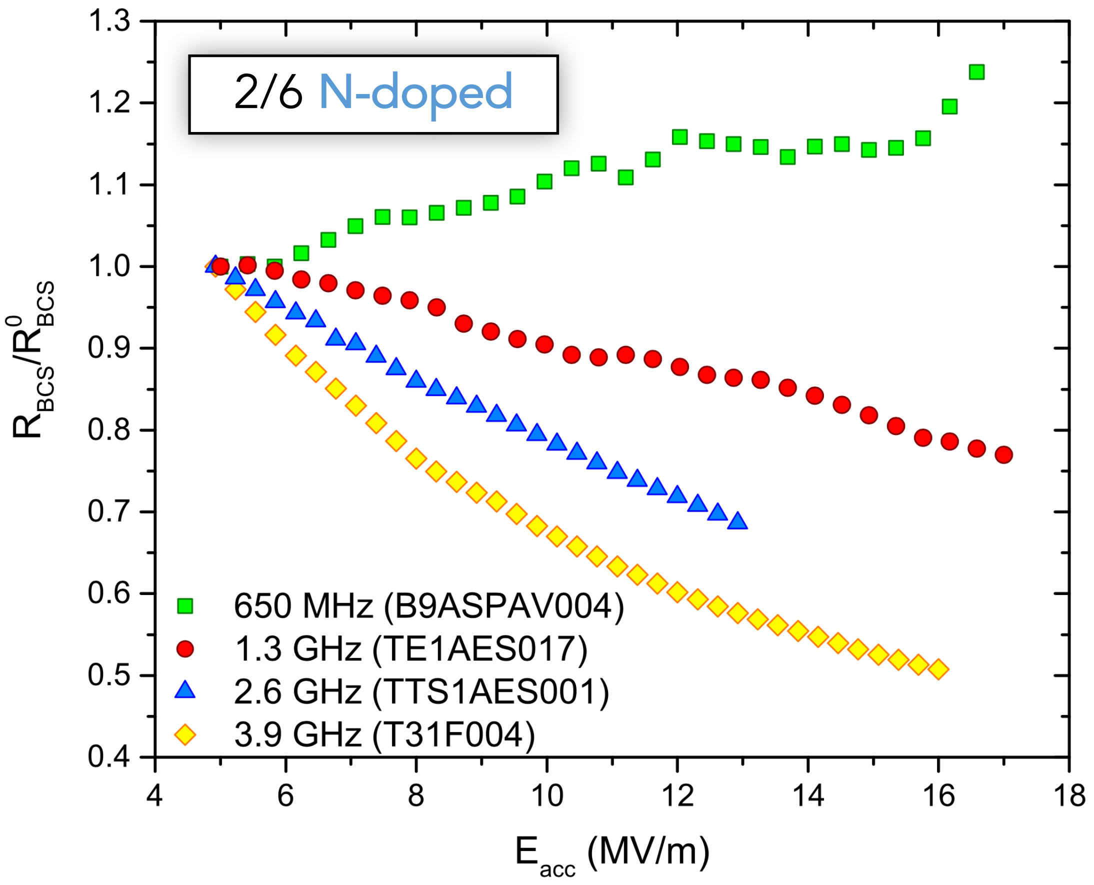


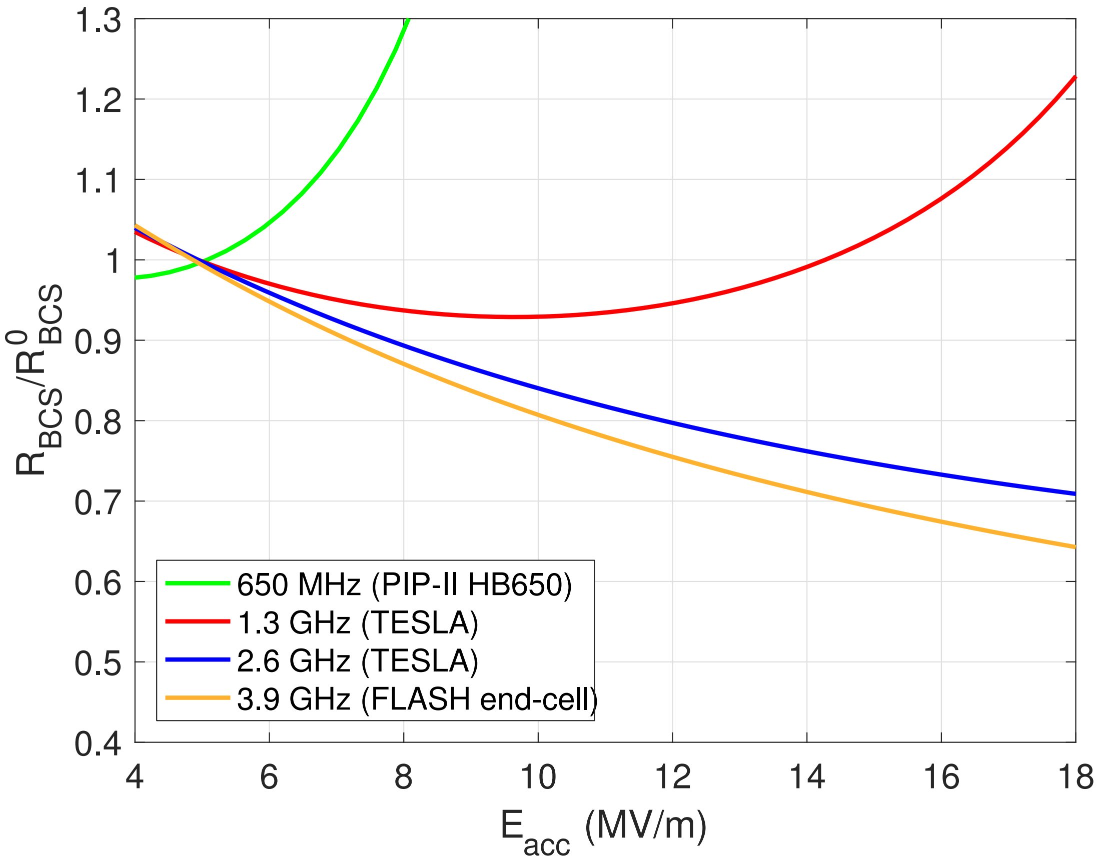
Fascinating new work!

Lots of room for more investigation

Doping High-Frequency Cavities

- How does our model hold up against new N-doping results?
  - Introduce an inverse dependence of **α′** on frequency (in this case ω^{-4}):





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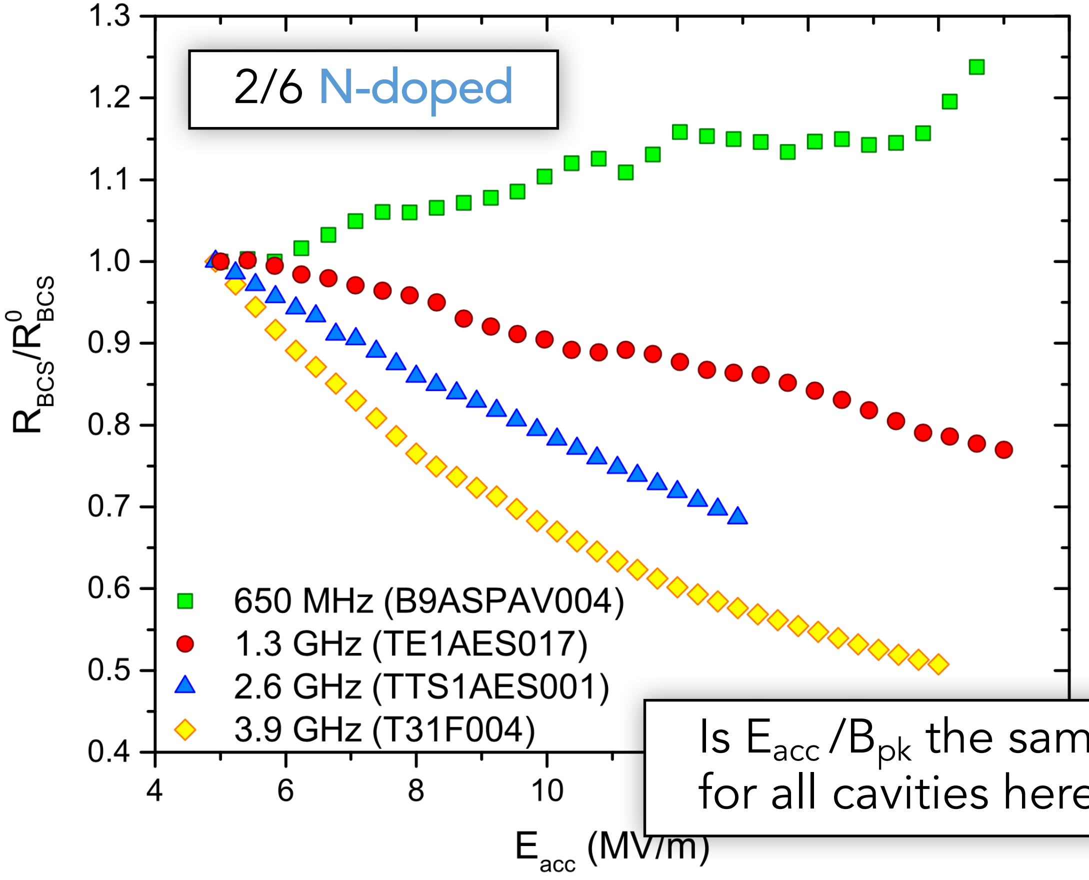
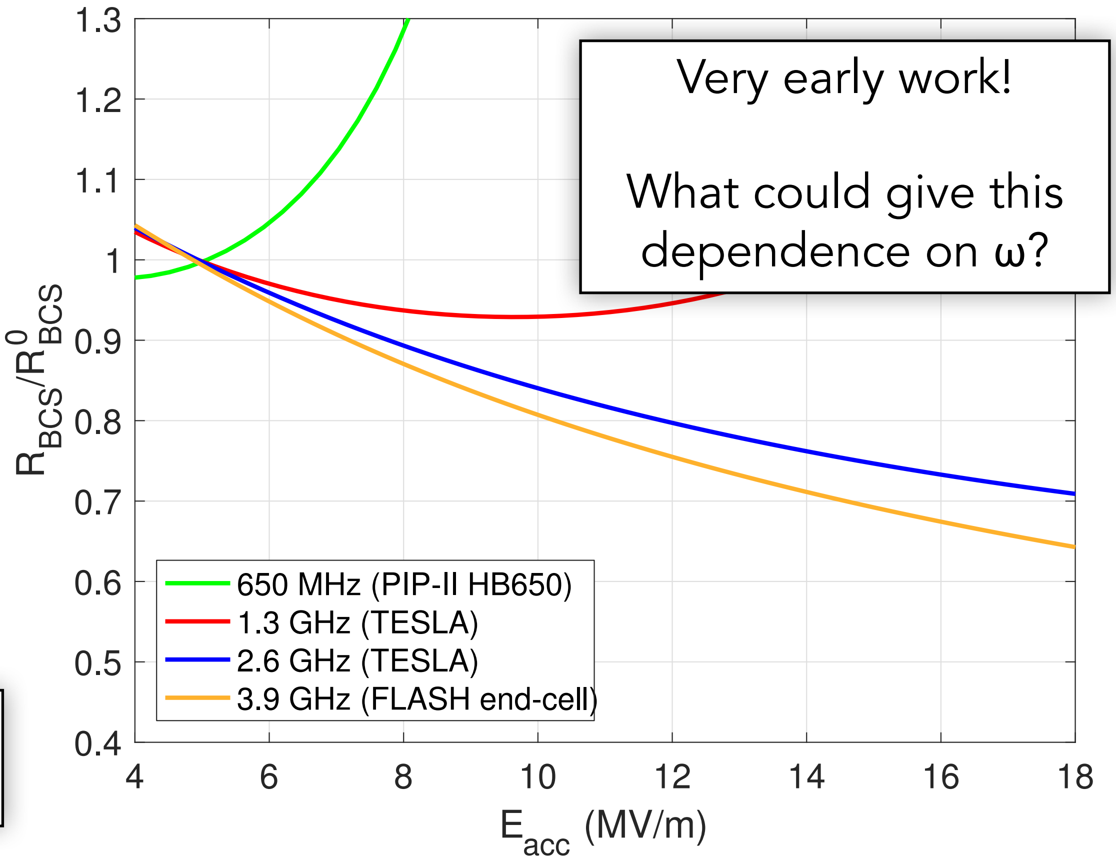


Is E_{acc}/B_{pk} the same for all cavities here?



Very early work!

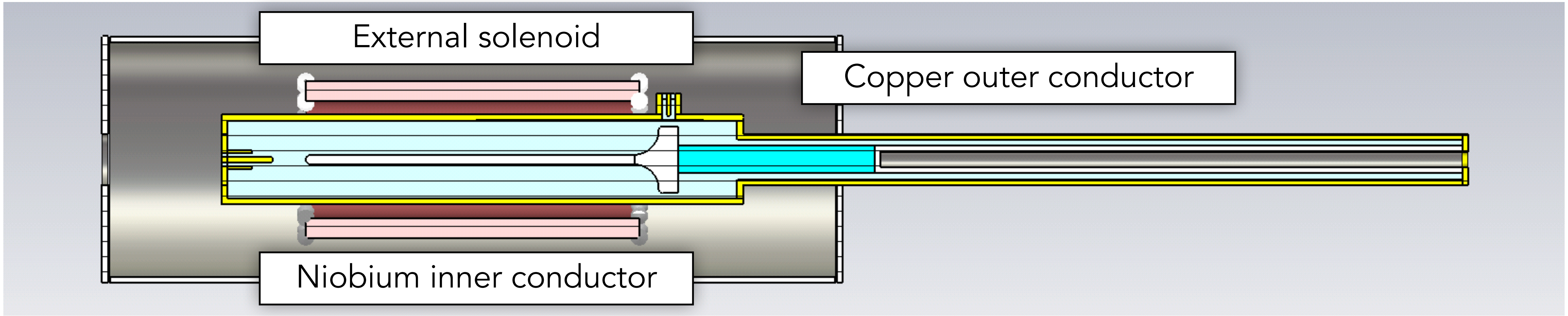
What could give this dependence on ω?

Other Models?

- Could this be the transition from equilibrium to nonequilibrium superconductivity?
  - Very lucky to have 1.3 GHz precisely at threshold!
  - Requires that τ_s (qp scattering time) is **between 0.12 and 0.24 ns**
    - Literature suggests longer times (**0.30-0.70 ns**), increasing with film thickness
    - Maybe cavity tests are *always* in nonequilibrium regime (as Gurevich suggests)
  - Requires that impurities drastically ***increase*** this characteristic time
    - No AQS (or very little) for clean cavities at 3.9 GHz
    - Literature suggests this time scale ***decreases*** as material gets dirtier
  - Requires that clean-limit τ_s is very short, < **0.04 ns**

Coaxial Resonator with Solenoid

- New apparatus in the works to test frequency dependence
  - Probing "simpler" physics of DC magnetic field superimposed on weak RF field

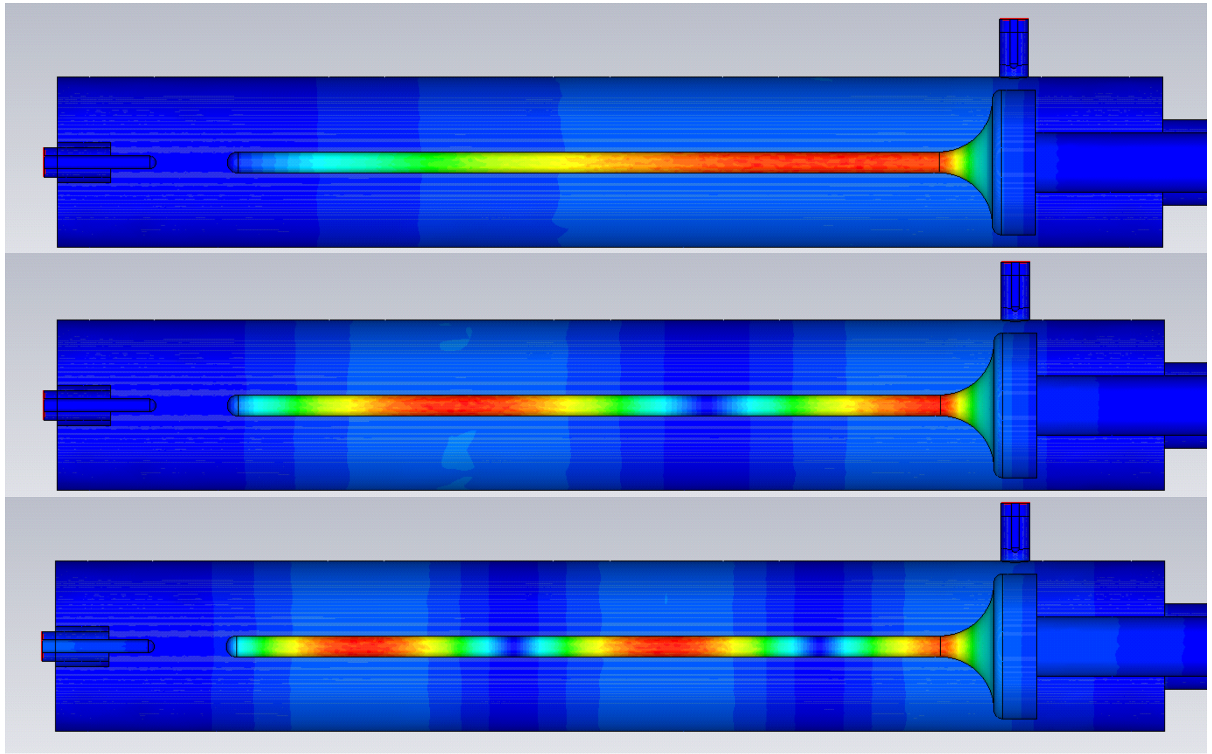


  - Test for DOS smearing (DC anti-Q-slope) vs. nonequilibrium transition (no DC anti-Q-slope)
  - Weak RF field → no qp overheating

J. T. Maniscalco, M. Liepe, R. D. Porter, SRF 2017.

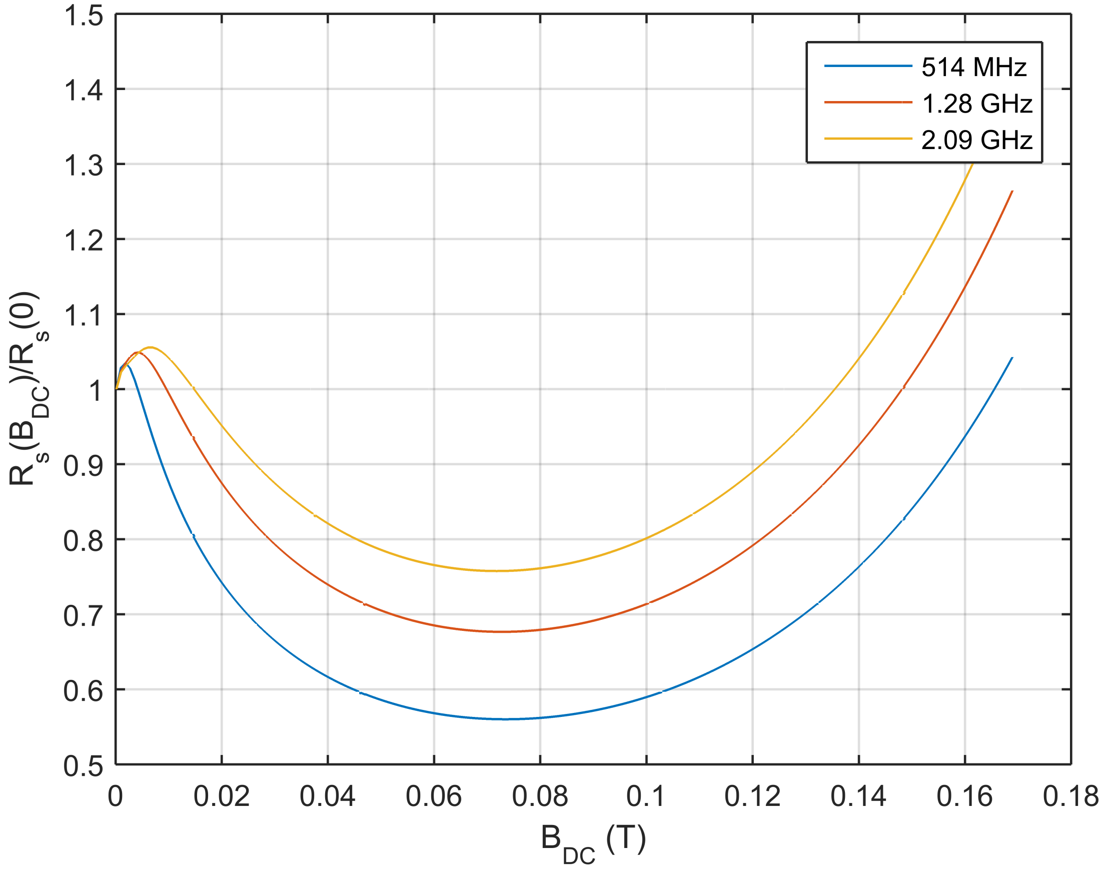
Coaxial Resonator with Solenoid

- Calorimetric measurements to extract R_s
  - Expect sensitivity between ± 2% and ± 15% depending on T, ω, P_{in}
- Three frequencies: ~500 MHz, ~1.3 GHz, ~2.1 GHz



Coaxial Resonator with Solenoid

- Expected measurements (by Gurevich theory):
  - Generally, **higher T** and **lower ω** have **larger relative decrease in R_s**



A Final Word

- Some requests for my fellow scientists…
  - Please show R vs. B, not R vs. E – magnetic field is the important one!
  - If you don't, please show B_{pk} / E_{acc} !
  - Please list material parameters (mfp, Δ, λ, ξ, T_c, …) so models can be tested against experimental data
  - Keep on discovering!

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. http://jacow.org/ipac2017/papers/wepva145.pdf
  - J. T. Maniscalco, M. Liepe, R. D. Porter, SRF 2017 pre-press (once available), contribution THPB005 (2017).
  - M. Martinello *et al.*, arXiv:1707.07582 (2017).
  - H. T. Edwards *et al.*, SRF 2009.

This work supported under NSF Award No. PHY-1549132, the Center for Bright Beams, and NSF Award No. PHY-1416318.

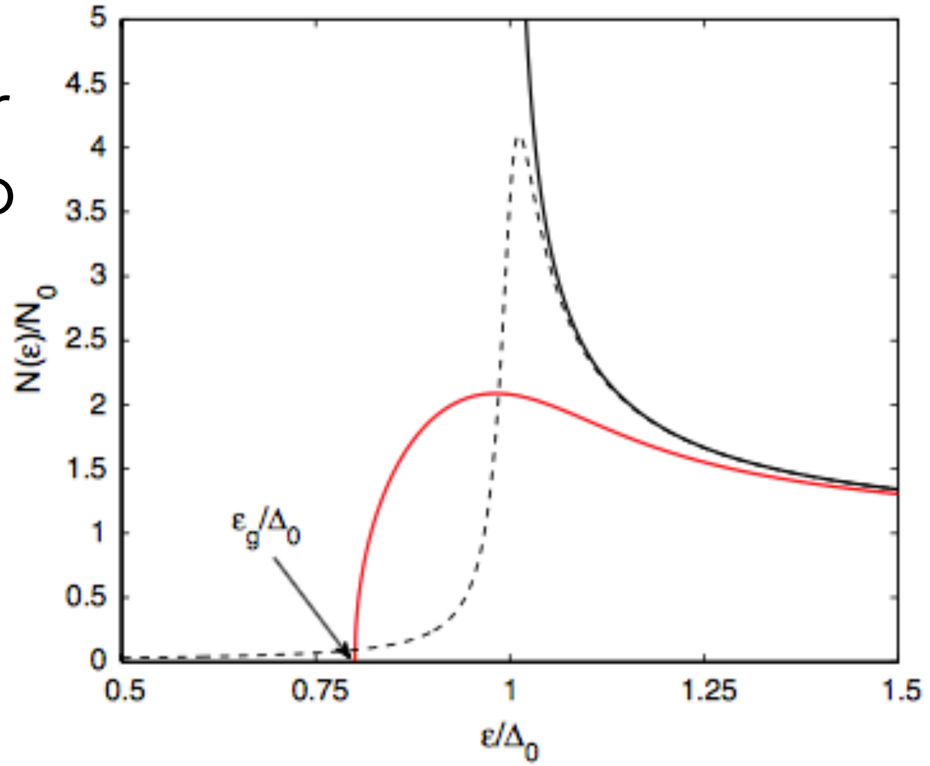
Backup Slides

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

- Nonequilibrium effects further suppress R_s



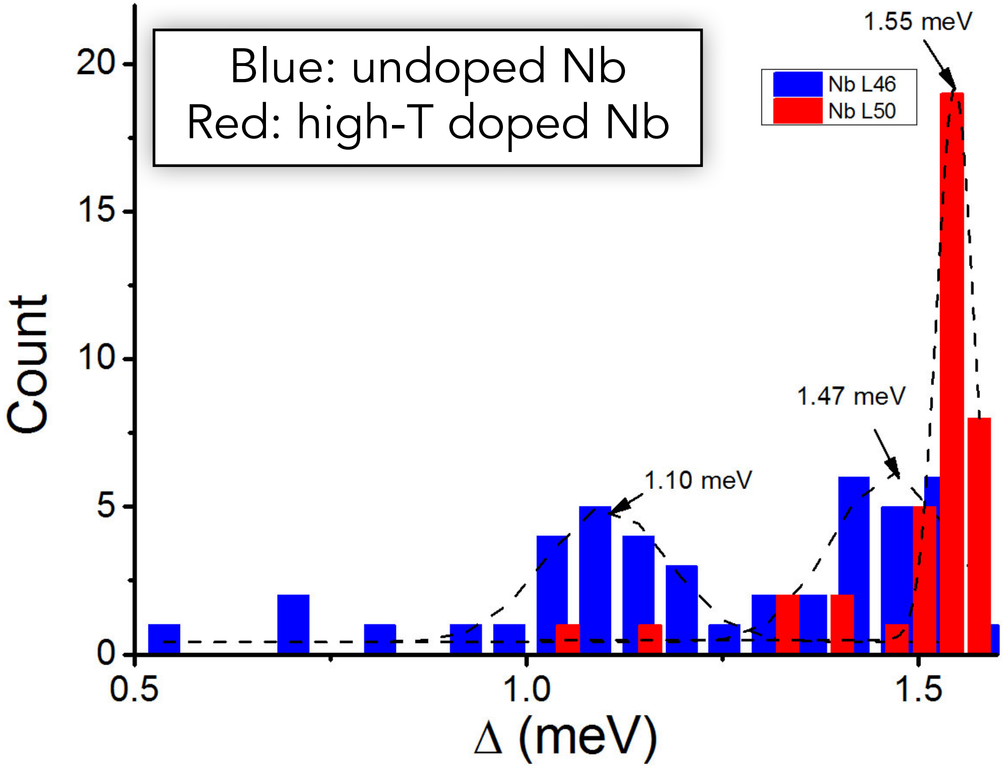
Reduction of Dissipative Nonlinear Conductivity of Superconductors by Static and Microwave Magnetic Fields

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

At left: Fig. 2, *ibid.*

Gurevich Theory

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



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

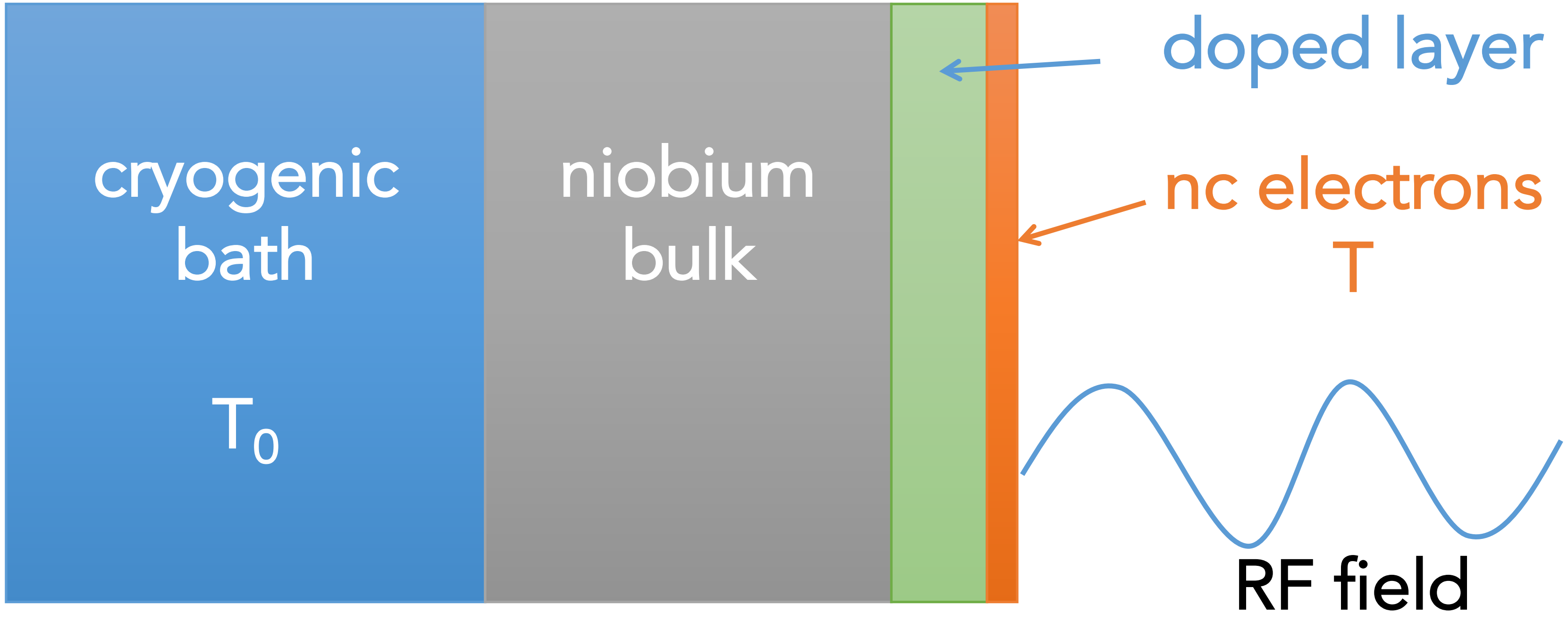
P. Dhakal *et al.*, PRST-AB **16**, 042001 (2013)

At left: Fig. 16, *ibid.*

Gurevich Theory

- Quasiparticle overheating

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



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

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

Terms and Equations

$$R_{\mathrm{s}} = R_0 + R_{\mathrm{BCS}}$$

$T = T_{electron}$ = 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

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 °C in vacuum, 3 h, "outgassing"
    - 800-990 °C 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 120-160° C
    - chemical reset and outgassing bake phase
    - 48 h bake with nitrogen gas, impurities at ppm level
    - 48-168 h anneal in vacuum