The Field-Dependent Surface Resistance of Doped Niobium:

New Experimental and Theoretical Results

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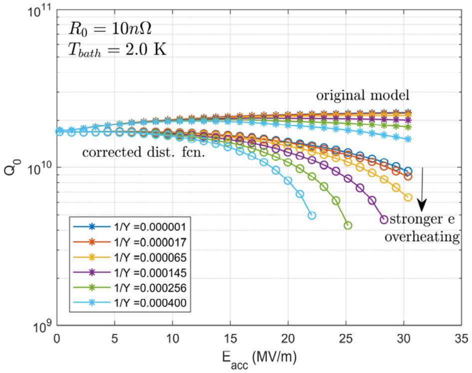

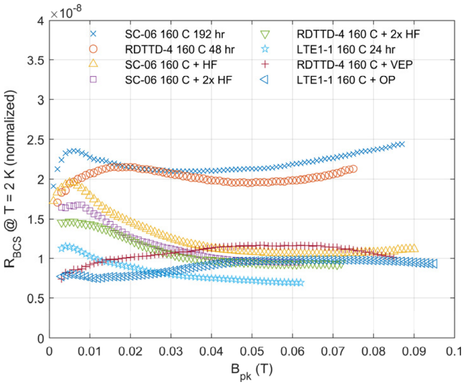

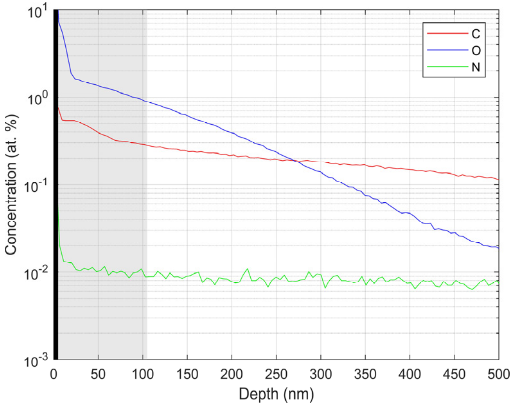

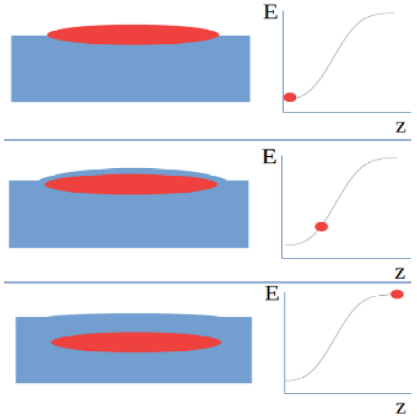

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Overview

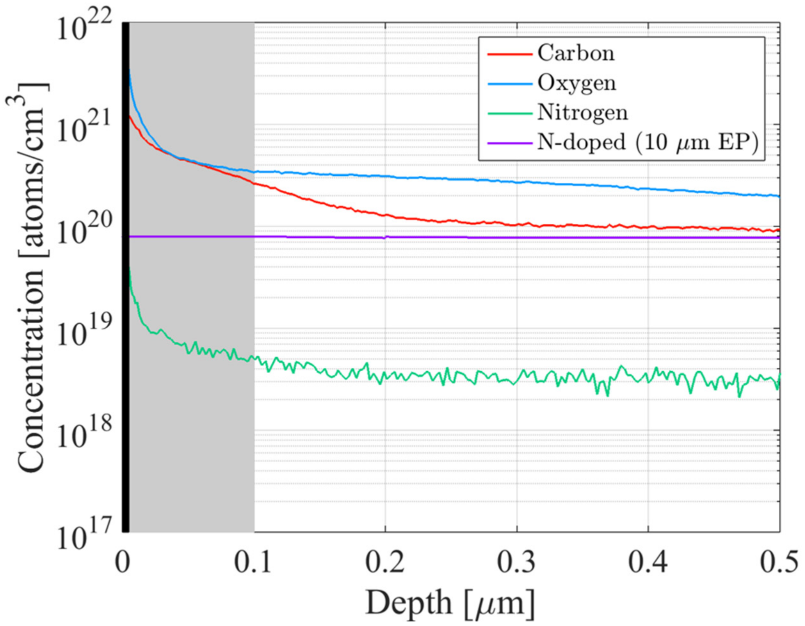
- Nitrogen infusion and surface removal studies
- Thermal modeling of SRF cavities
- Assessment of anti-Q-slope models

Nitrogen infusion and surface removal studies

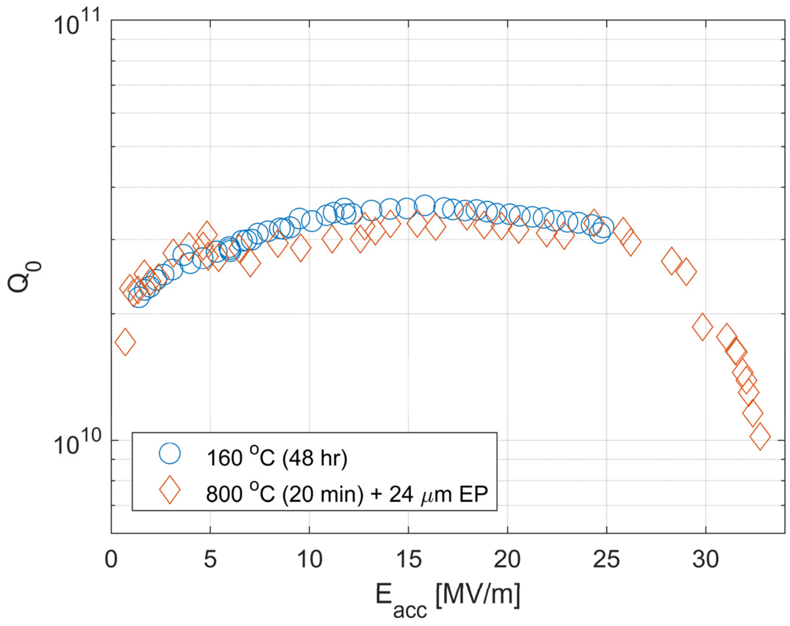
Determining the role of nitrogen and other impurities

N-infusion

Impurity content:



RF performance:



Strikingly similar RF behavior despite differences in impurities!

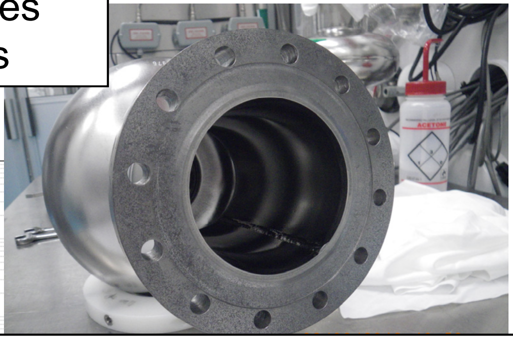
N-infusion

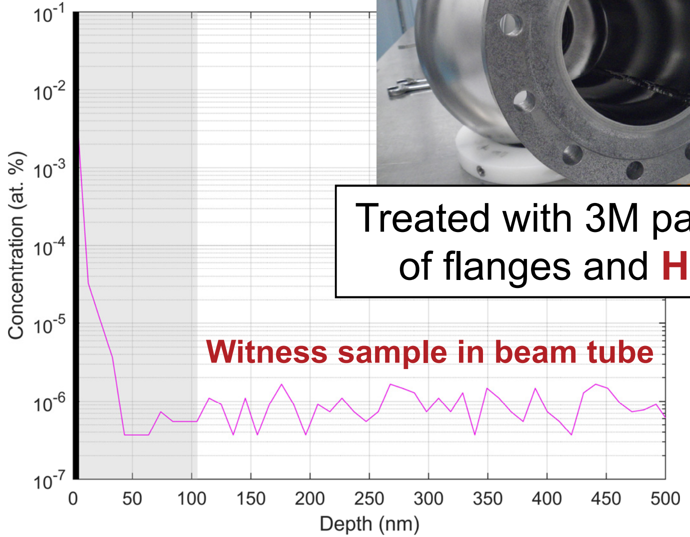
Treatment:

- Reset VEP
- 800 °C UHV degas (3 hrs)
- 160 °C UHV stabilization step (3 hrs)
- 160 °C infusion step (1-7 days)
- Optional post chemistry

Cavity	160 °C N_2 time + post trtmnt.
SC-06	**4.5 days**
SC-06	… + HF rinse
SC-06	… + 2^{nd} HF rinse
RDTTD-4	**48 hours**
RDTTD-4	… + 2x HF rinse
RDTTD-4	… + 100 nm cold VEP
LTE1-1	**24 hours**
LTE1-1	… + 54 nm oxypolish

Titanium contamination observed for cavities with NbTi flanges

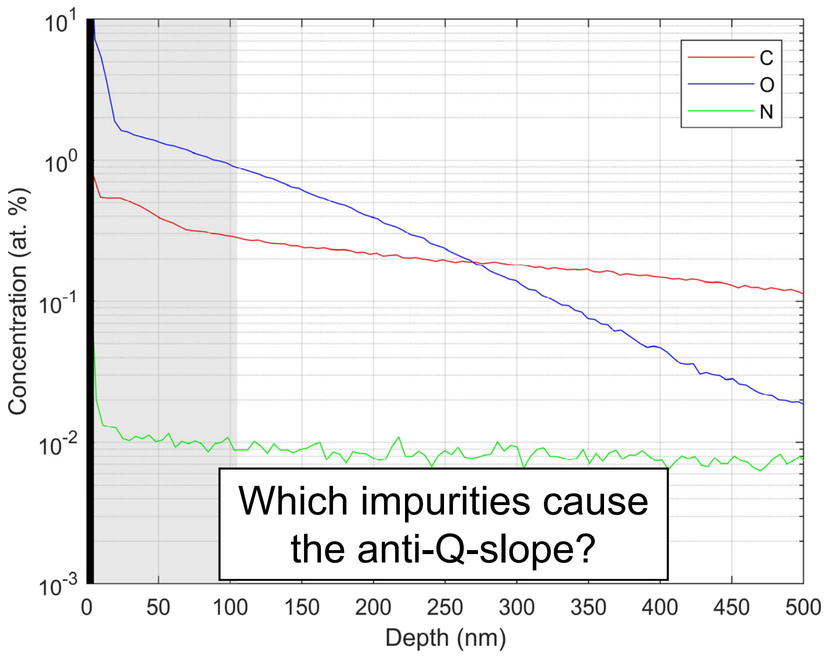


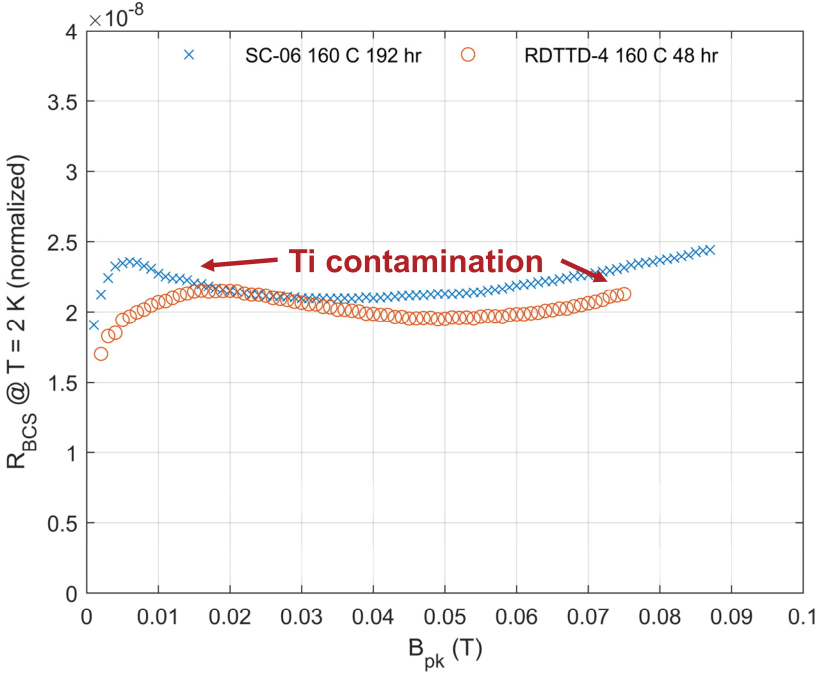


Treated with 3M pad scrubbing of flanges and **HF rinsing**

N-infusion

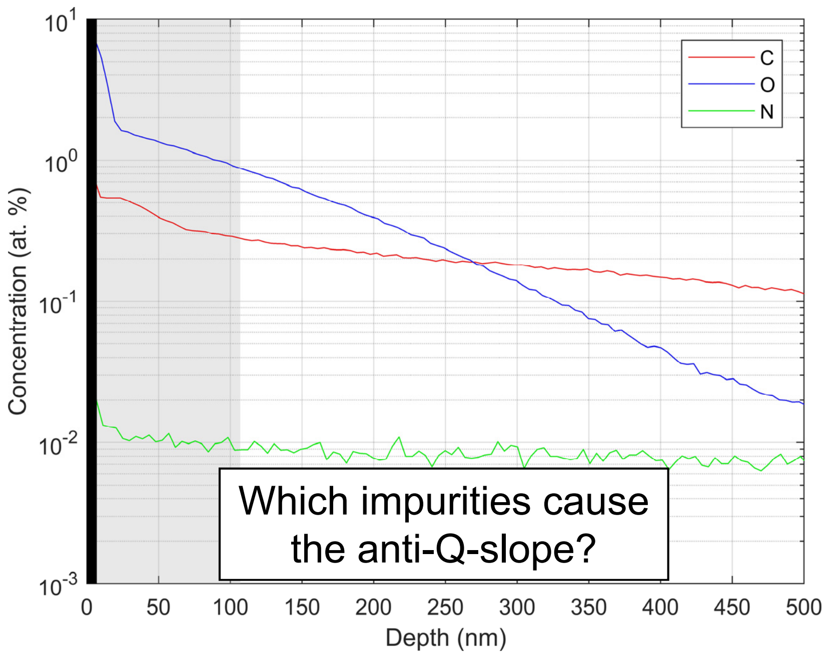
- **Ti-contaminated** cavities have **no anti-Q-slope**

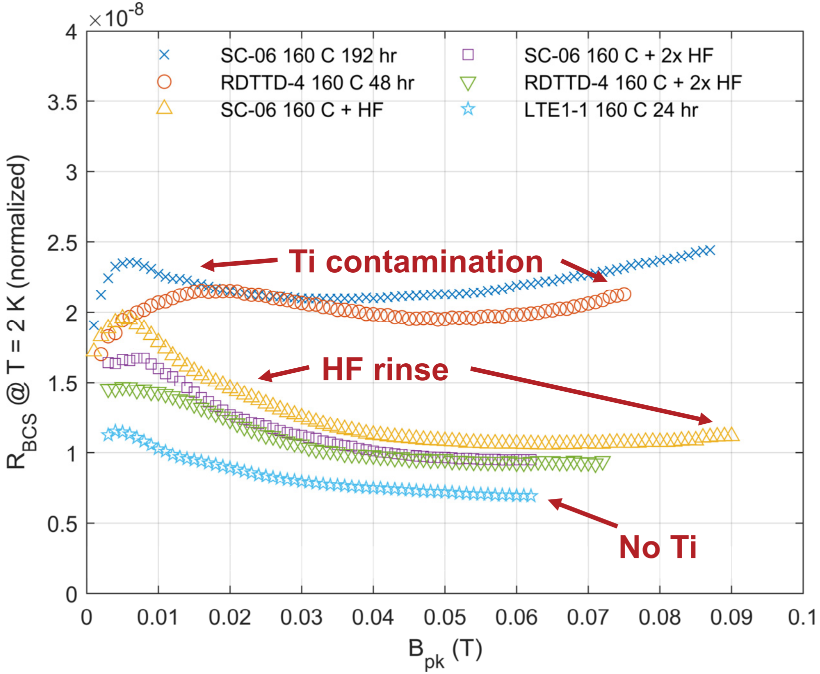




N-infusion

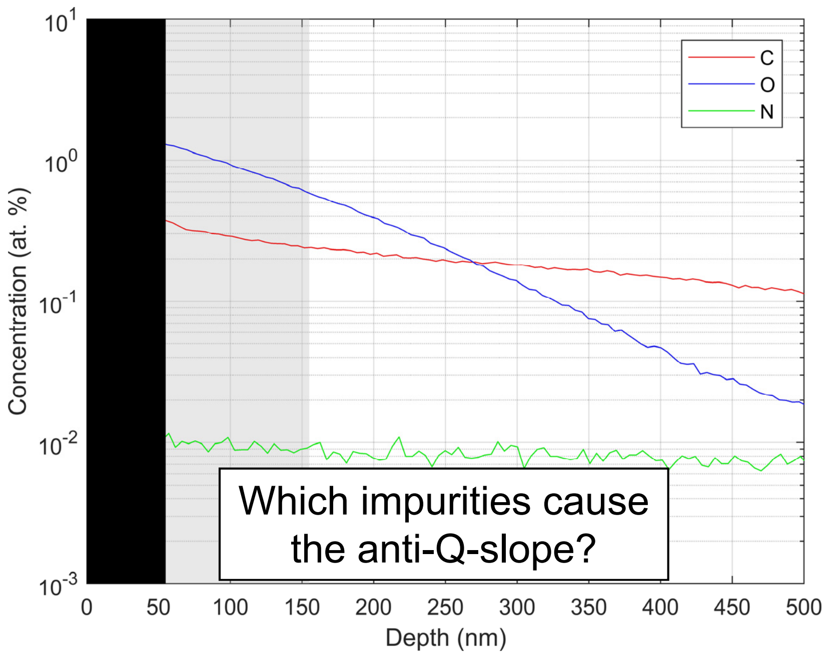
- **Ti-contaminated** cavities have **no anti-Q-slope**
- **HF rinsing** (<5 nm removal) **restores anti-Q-slope**

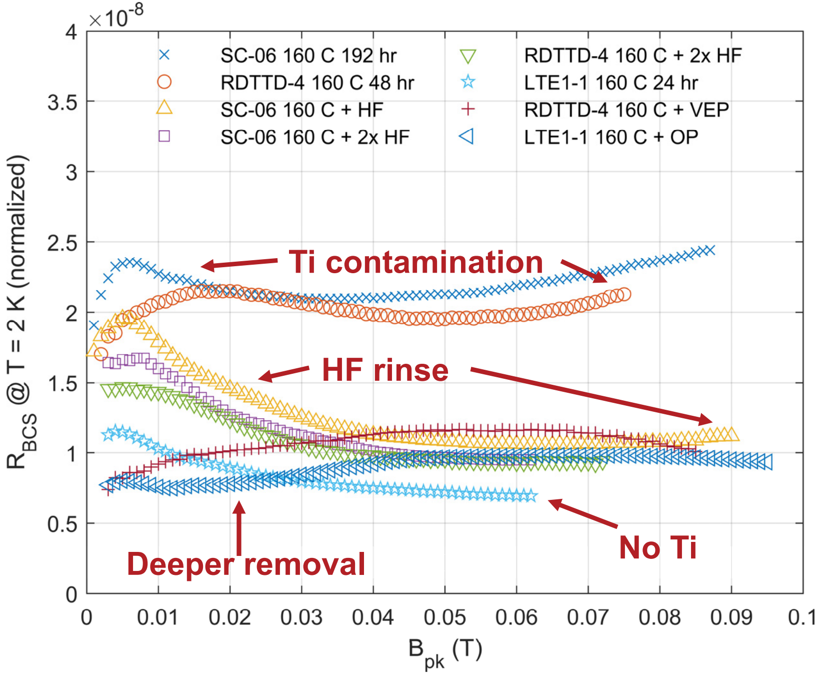




N-infusion

- **Ti-contaminated** cavities have **no anti-Q-slope**
- **HF rinsing** (<5 nm removal) **restores anti-Q-slope**
- **Deeper removal** (>50 nm) **removes anti-Q-slope**



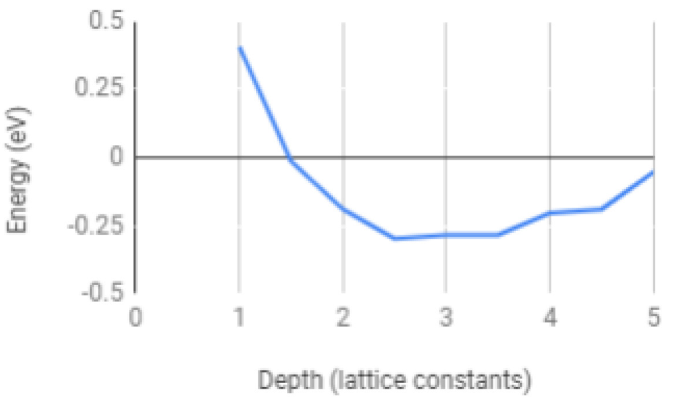


N-infusion

Lessons learned:

- Infusion time has **little effect** on **anti-Q-slope** magnitude
- Physics **very near the surface** is important for **the anti-Q-slope**!
- AQS in infused cavities is sensitive to **surface contamination**…
  May be cured by **HF rinsing**
- **High impurity concentration near surface**
  likely linked to **anti-Q-slope** – is N the most important?

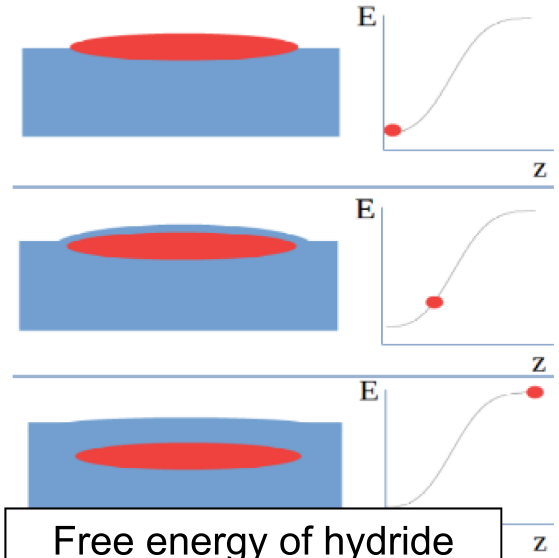
N suppression of hydrides – see N. Sitaraman TUP045



Free energy of interstitial nitrogen impurities

Niobium hydrides preferentially form **on or near surface**

Nitrogen occupies available interstitial sites and **prevents hydride formation**

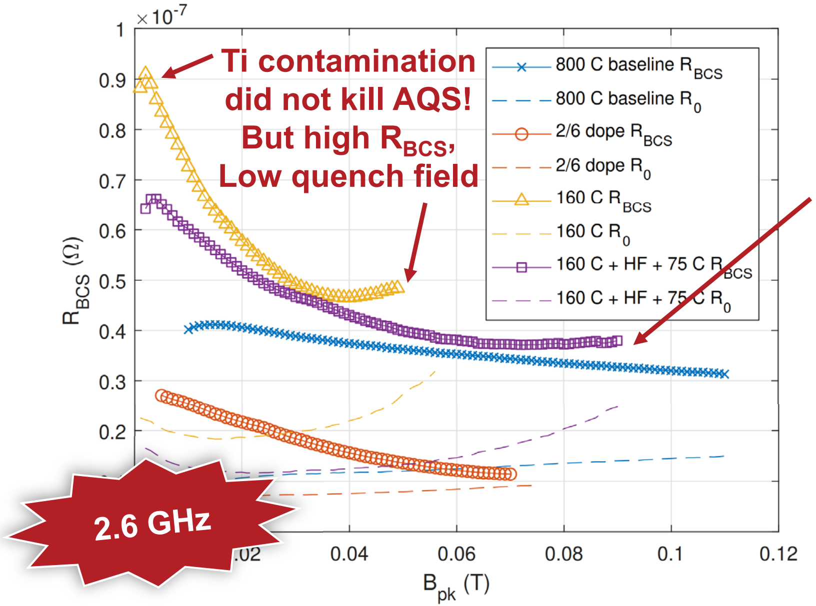


Free energy of hydride platelet formation

2.6 GHz

- **Anti-Q-slope** even in **800 °C baseline test**!
- Lowest R_{BCS}, best AQS in **2/6 N-doped test** → Q_0(2 K, 20 MV/m) = 1.5×10^{10}
- **N-infused** cavities: **strong anti-Q-slope** but **high R_{BCS}**

comparable to 3×10^{10} at 1.3 GHz



Coming soon: more treatments, more frequencies

Cavity	Treatment protocol
STE1-1	800 °C baseline
STE1-1	2/6 N doping
STE1-1	160 °C N infusion (48 hours)
STE1-1	… + HF rinse + 75 °C UHV (6 hours)

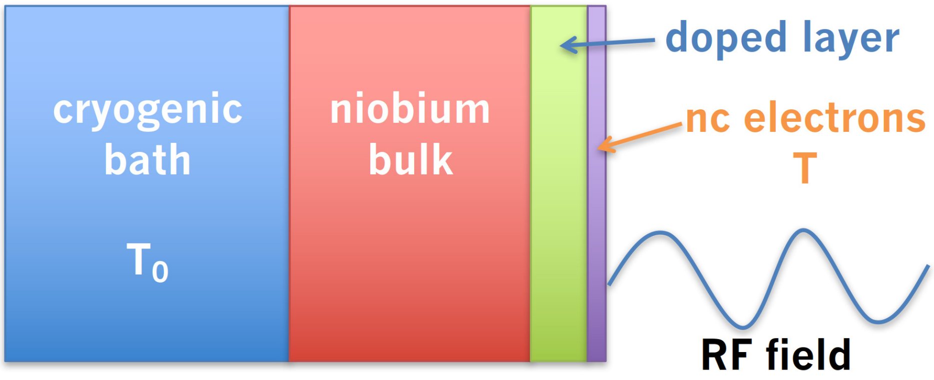
Thermal modeling of SRF cavities with quasiparticle overheating

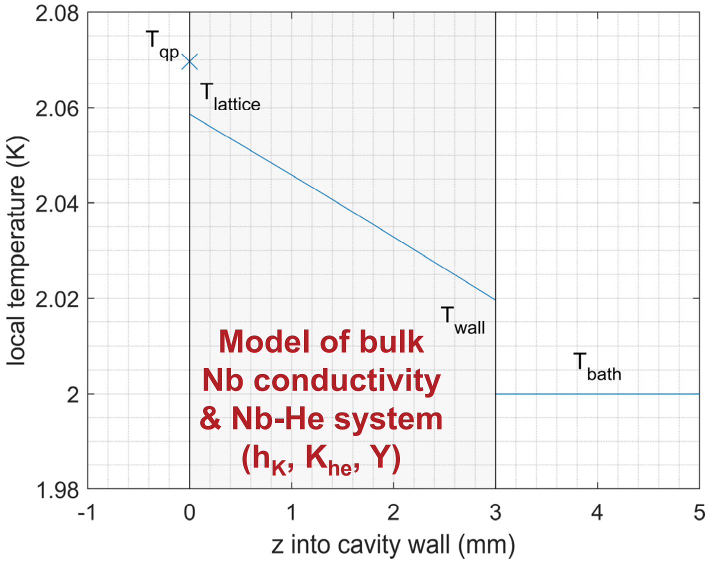
Theoretical calculations with
real cavity parameters

Thermal modeling

quasiparticle overheating = important thermal effect

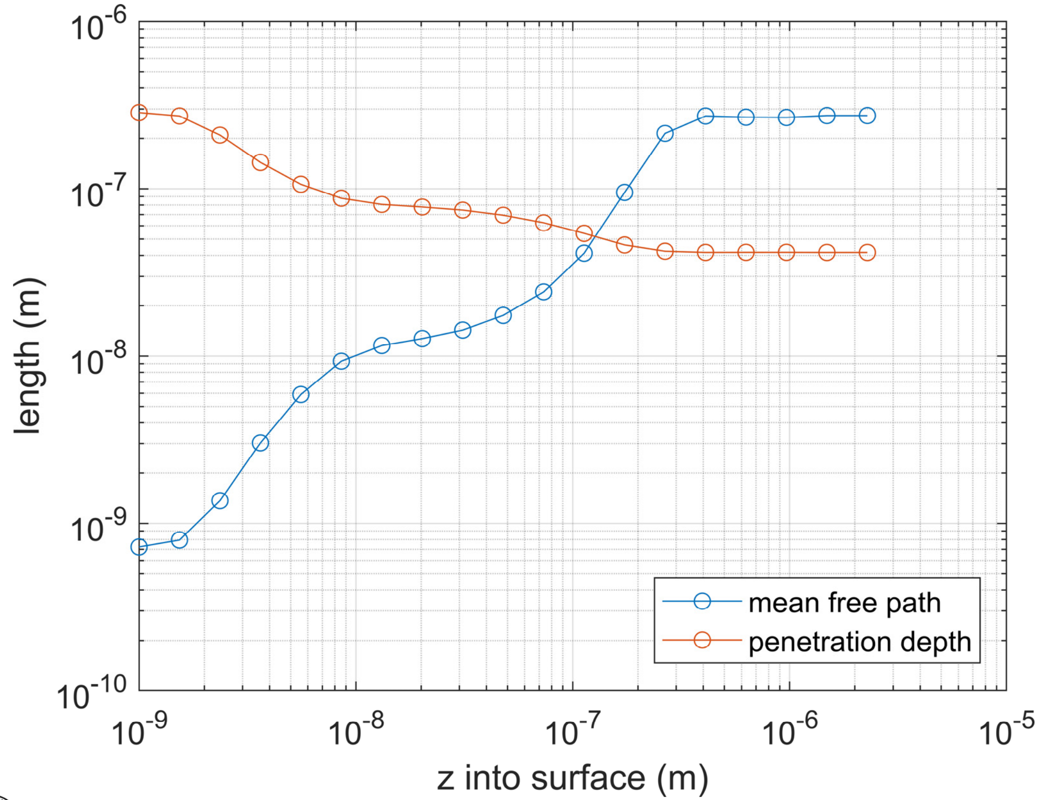
$$T - T_0 = \alpha' \frac{1}{2} H_{\mathrm{a}}^2 R_{\mathrm{BCS}}(H_{\mathrm{a}}, T) = \alpha' \frac{P_{\mathrm{diss}}}{\mathrm{area}}$$





Thermal modeling

Infused cavities → **depth-dependent material parameters**



1) Calculate local quasiparticle conductivity from material parameters, ansatz T_{qp}

Can use any **local** R_S model

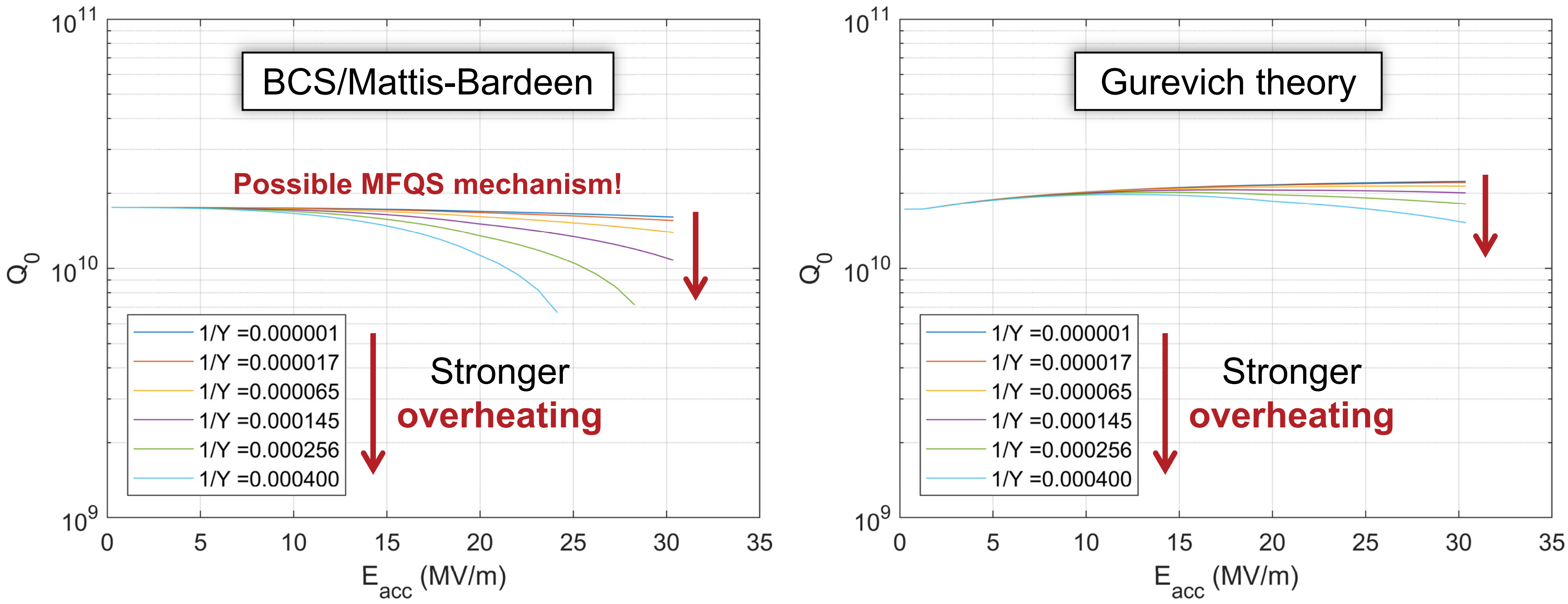
2) Integrate quasiparticle conductivity to get $R_s(T_{qp})$

$$R_S \propto \int_0^\infty \frac{\sigma_{qp}(z)}{\lambda(z)} \exp\left(-\frac{2z}{\lambda(z)}\right) dz$$

3) Calculate self-consistent T_{qp} given overheating simulation (h_K, K_{he}, **e-ph efficiency Y**)

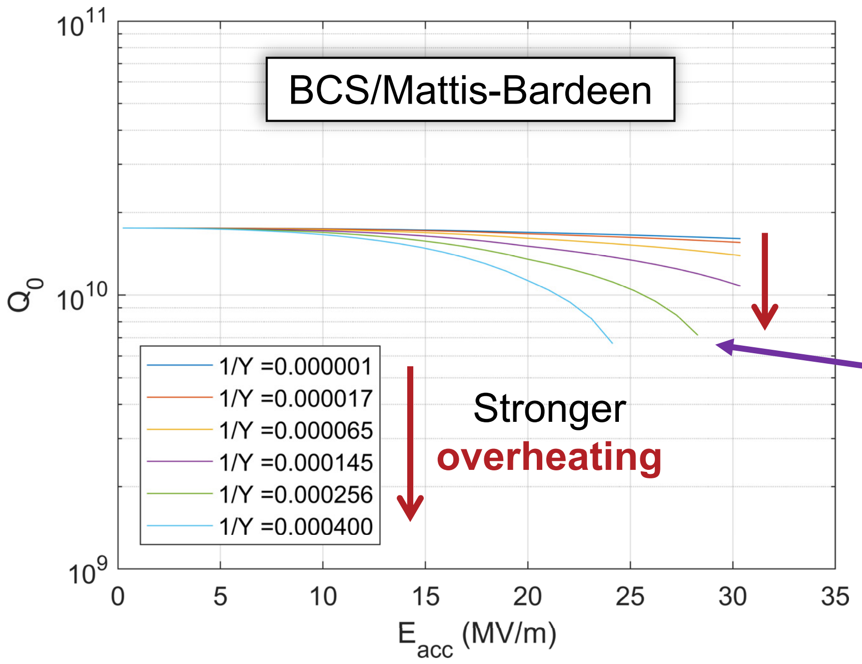
Thermal modeling

Example results of thermal simulations:



Thermal modeling

Example results of thermal simulations:

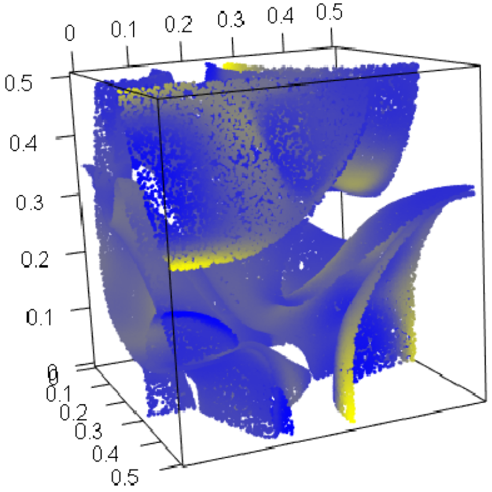


Emergent properties from simulation:

- Thermal Q-slope / mediation of anti-Q-slope
  - **Thermal runaway quench** (not just when $T_{lattice}$ reaches T_c !)

Thermal modeling

Next plans: *ab initio* picture of quasiparticle overheating using **density functional theory**

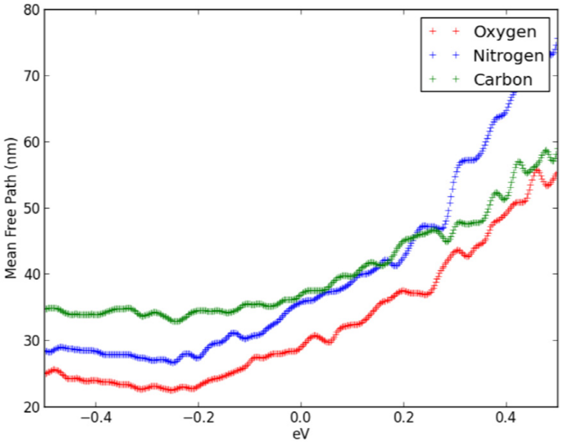


Impurity	Mean free path @ 1 % at.	
	DFT	experiment
H	782 nm	~100 nm
C	38 nm	~10 nm
N	34 nm	~10 nm
O	28 nm	~10 nm

Promising early results!

Next investigate **inelastic scattering** for contribution to **quasiparticle overheating**

See **N. Sitaraman TUP045**



Assessing models of the field-dependent surface resistance

Finding the source of the anti-Q-slope

Assessing R_s models

Several models proposed for field-dependent surface resistance, esp. anti-Q-slope:

1. Weingarten model
   - Small pockets of poor SC with proximity effect

W. Weingarten, IEEE Trans. App. Sup. 28 (2018).

2. Goldie/Withington model
   - Non-thermal qp distribution function

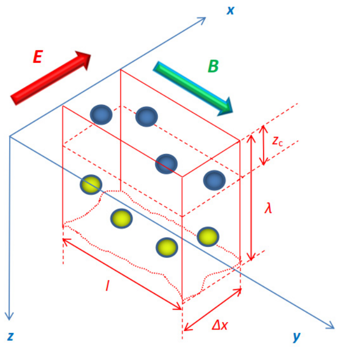
D. J. Goldie & S. Withington, Sup. Sci. Tech. 26 (2013).

3. Gurevich model
   - Smearing qp density of states to lower σ_{qp}

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

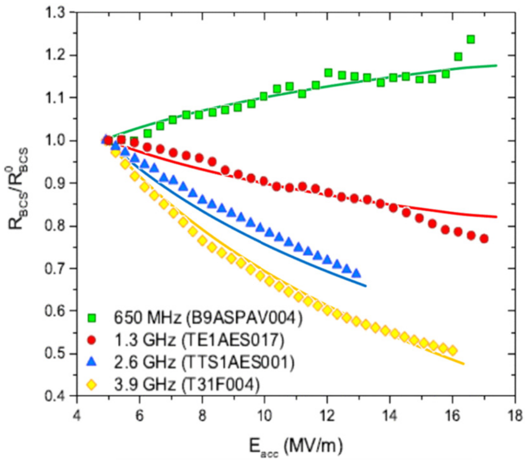
Assessing R_s models

1. Weingarten model



- Doped niobium forms disordered composite of weak superconductor dispersed in good niobium
- As field increases, weak SC pockets go NC… But are small and become proximity-coupled SC
- Quasiparticle conductivity is decreased in a ω-dependent manner

Agreement with expt. (Martinello *et al*. 2018)



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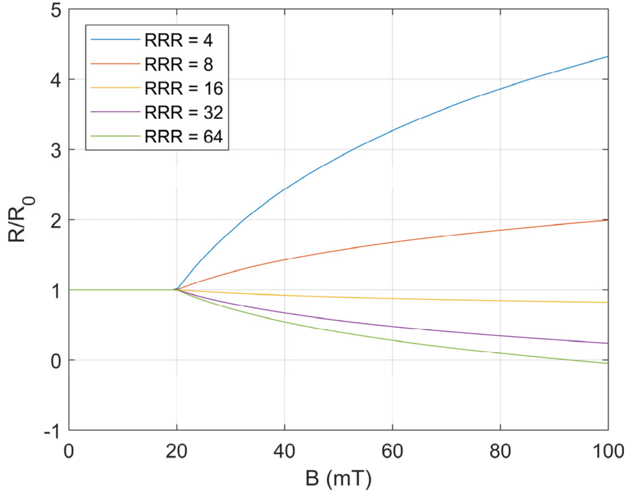


However…

- Model predicts the **wrong dependence on mean free path!**
- Possible physics issues
  - Two-fluid model
  - Proximity effect argument not rigorous
  - Many finely-tuned parameters

Assessing R_s models

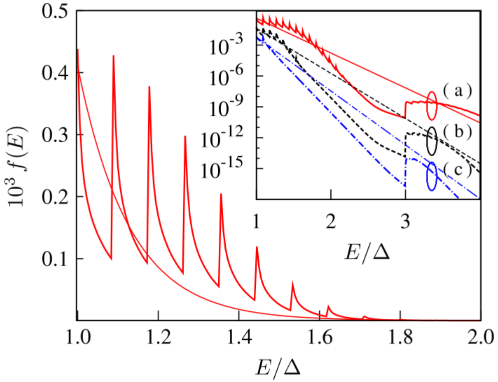
2. Goldie/Withington model

$$R_{\text{BCS}} \propto \int_{\Delta}^{\infty} N(\epsilon)N(\epsilon+\hbar\omega)\,[f(\epsilon)-f(\epsilon+\hbar\omega)]\,d\epsilon.$$

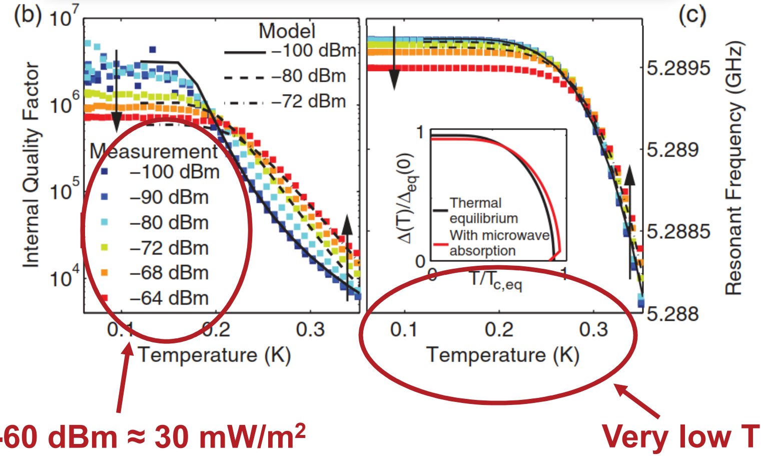
Increased distribution function at high E

- Non-thermal distribution function of quasiparticles has higher value at higher ε, reducing R_{BCS} integral
- Experimental results seem to confirm the model

D. J. Goldie & S. Withington, Sup. Sci. Tech. 26 (2013).



P. J. de Visser, *et al*. PRL 112 (2014).



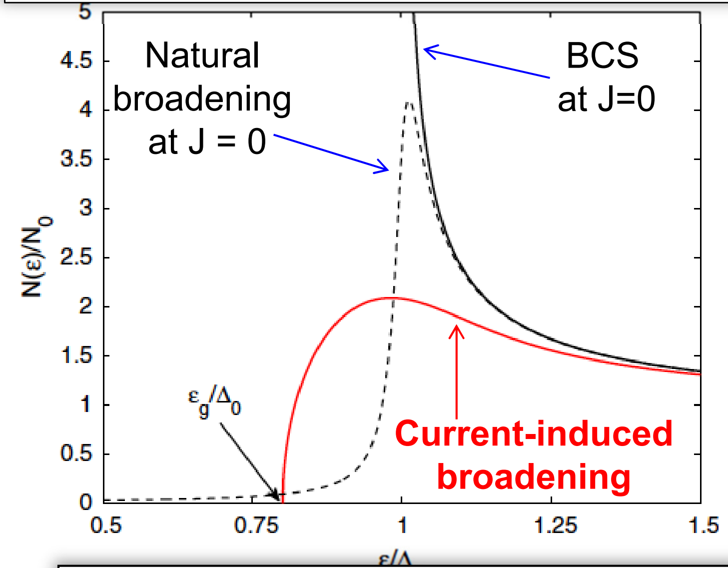
- Physics may not apply to typical SRF conditions:
  - Model relies on quantum effects where $\hbar\omega \approx k_B T$, **near 60 mK** for 1.3 GHz cavities; also needs $\hbar\omega > \Delta_0$
  - Also relies on **very low power levels** / fields
- Model makes **no connection to doping**, impurity content, κ_{GL}, etc.

Assessing R_s models

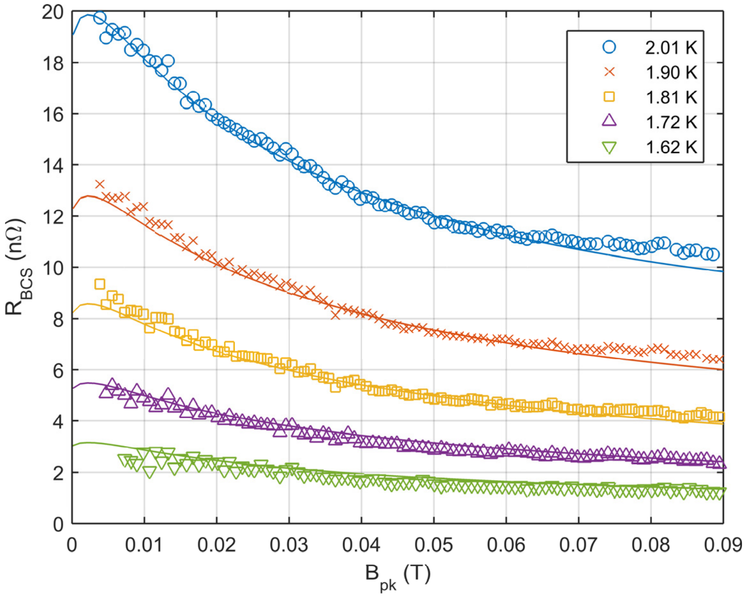
3. Gurevich model (strong RF case)

$$R_{BCS} \propto \int_{\Delta}^{\infty} N(\epsilon)N(\epsilon+\hbar\omega)[f(\epsilon)-f(\epsilon+\hbar\omega)]\,d\epsilon.$$

Large decrease in DOS due to surface currents



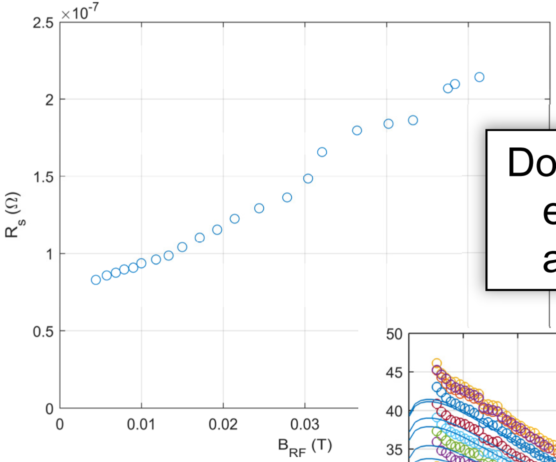
A. Gurevich, Phys. Rev. Lett. 113 (2014).



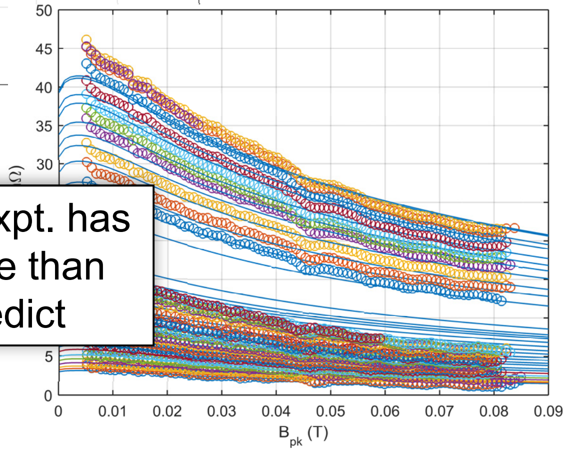
- Good agreement with experiment at **1.3 GHz** for **doped cavities**
- Good agreement as well with **1.3 GHz infused cavities**

Assessing R_s models

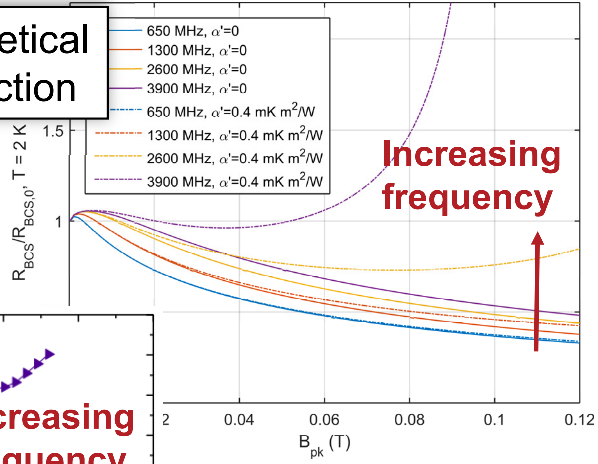
However: Poor agreement at higher and lower frequency
Theory predicts **wrong frequency dependence**

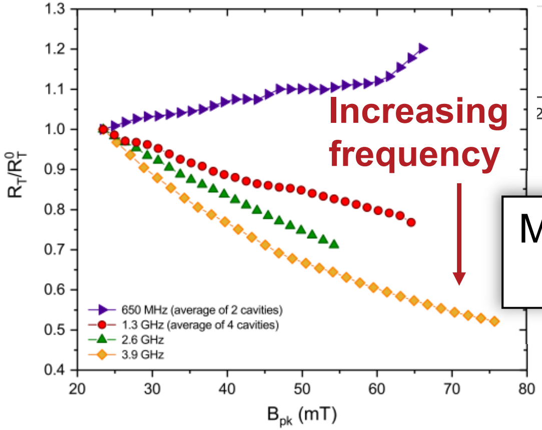


Doped 500 MHz expt. has no anti-Q-slope



Doped 2.6 GHz expt. has steeper decrease than theory can predict





M. Martinello *et al.*, PRL 121 (2018).

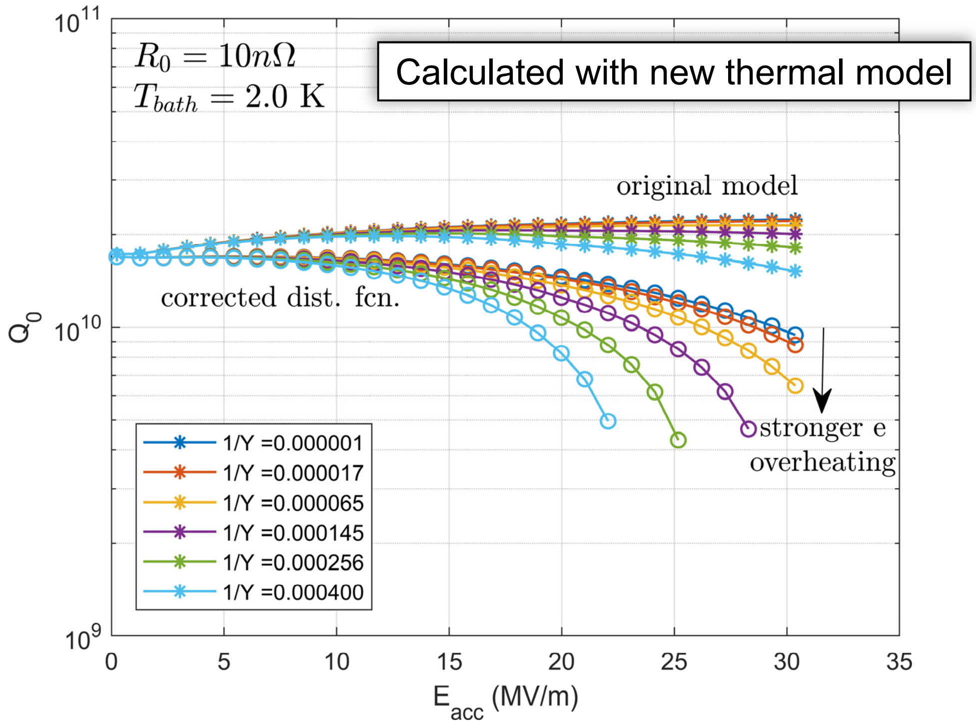
Assessing R_s models

Further issues: possible physics error in distribution function

- **Theory assumes qp distribution function** f(ε) at arbitrary time *t* is equal to the *zero-field* distribution – the assumption is **not properly justified**

- **Correcting this assumption** and replacing the distribution function with a stationary field-averaged distribution **negates the anti-Q-slope prediction**!

This correction does not affect the "weak RF" DC magnetic field case



Assessing R_s models

Several models proposed for field-dependent surface resistance, esp. anti-Q-slope:

✖ Weingarten model
- Small pockets of poor SC with proximity effect

✖ Goldie/Withington model
- Non-thermal qp distribution function

✖ Gurevich model
- Smearing qp density of states to lower σ_{qp}
- **Currently under refinement/improvement**

No satisfying anti-Q-slope models!

Time to inspire our theorist partners…

Forthcoming **CBB** work using Floquet basis (for periodically driven quantum systems)
Stay tuned!

Conclusions

Thank you for your attention!

Nitrogen infusion studies:

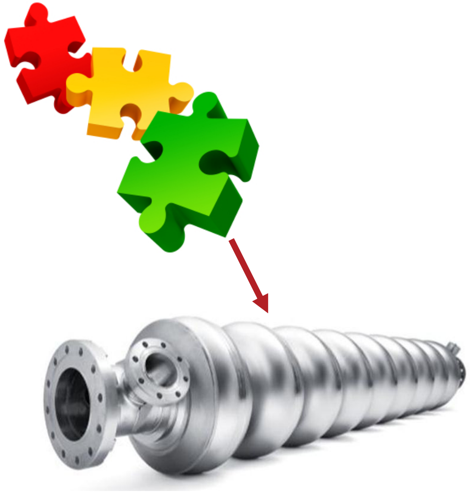
Physics within first ~20 nm quite important for the anti-Q-slope

Thermal modeling of SRF cavities:

Robust simulation of R_s with quasiparticle overheating

Assessment of anti-Q-slope models:

No satisfying theories currently! Stay tuned for work from **CBB**



see also:
- **N. Sitaraman TUP045**
- **M. Ge TUP051**

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High frequency cavity development supported under NSF award PHY-1734189.