Mean-Free-Path Dependence of the Losses From Trapped Magnetic Flux in SRF Cavities

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Motivation

- It is well understood that to achieve optimal Q_0 performance, SRF cavities should be cooled in as small magnetic fields as possible.
- A rule of thumb is given in Padamsee: residual resistance will increase by 0.3 nΩ per mG of magnetic field.

Cavity Q_0	Q_0 in 10 mG, 0.3 nΩ/mG	ΔP_{diss} (0.3 nΩ/mG)	Q_0 in 10 mG, 1 nΩ/mG	ΔP_{diss} (1 nΩ/mG)
1×10^{10}	9×10^{9}	**11%**	7×10^{9}	**40%**
2.7×10^{10}	2.1×10^{10}	**29%**	1.4×10^{10}	**93%**

At lower Q_0's, the exact sensitivity didn't matter as much

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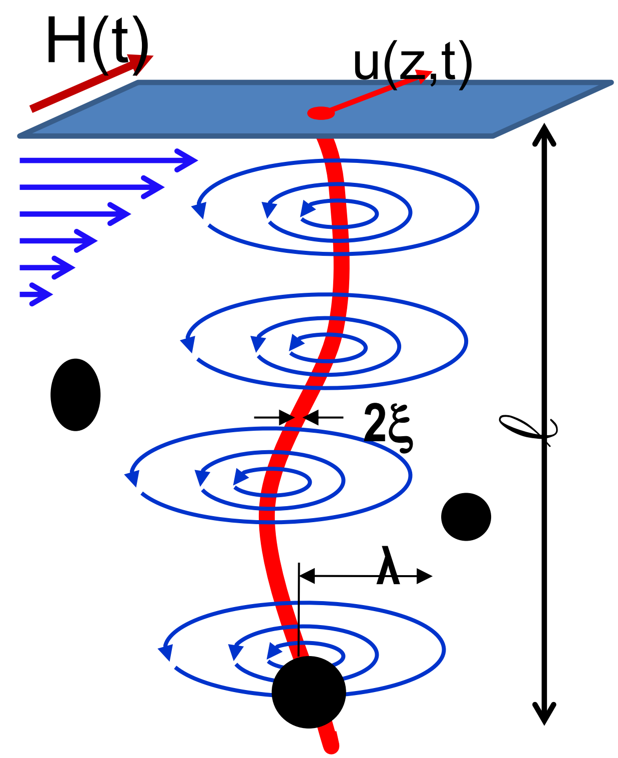
Motivation

Now that we are routinely dealing with higher Q_0's and new cavity preparation techniques:

- How does this ratio change depending on cavity preparation/material parameters?
  - Is there anything different about how doped cavities react to magnetic fields?

Theoretical Considerations

- A. Gurevich predicts a higher sensitivity to trapped flux with lower mean free path.
  - In the dirty limit $R_{res} \sim \frac{1}{\ell^3}$
- The exact theoretical dependence is heavily dependent on the material parameter space.



A. Gurevich, Vortex hotspots in SRF Cavities. 7th SRF Materials Workshop, Jlab, July 16, 2012

R_{res} vs ΔT

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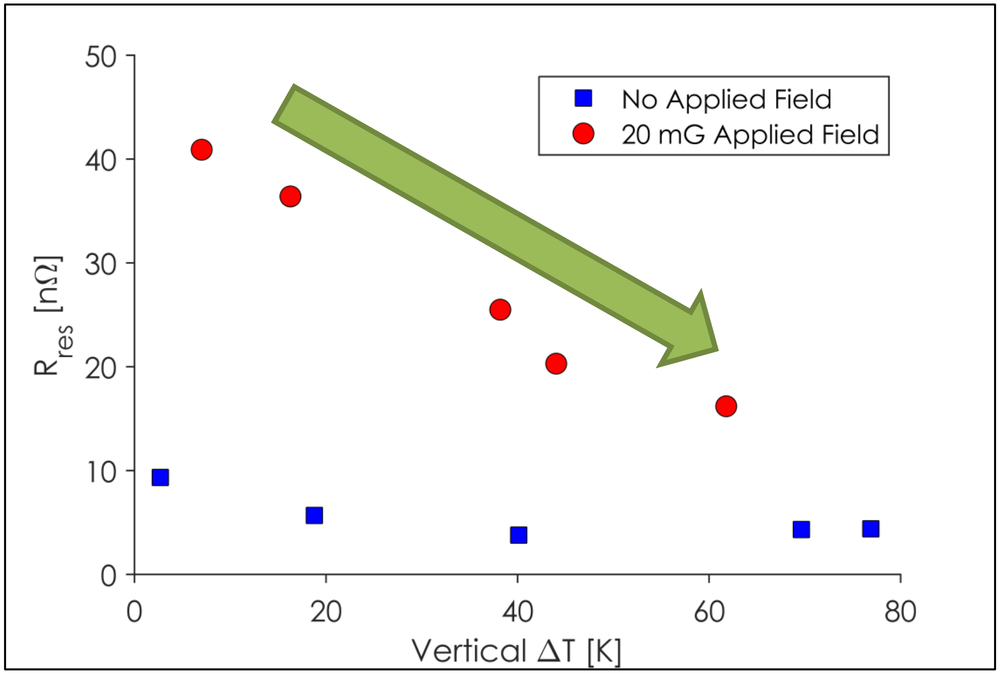
R_{res} vs $\Delta T_{vertical}$ in the Cornell HTC



- Romanenko et. al. first showed that residual resistance increased in nitrogen-doped cavities and 120°C baked cavities after a slow cool down.
- Recent results at Cornell and FNAL have further expanded upon these initial results.
- **Larger transverse spatial temperature gradients during cool down lead to** more efficient flux expulsion and **lower residual resistance.**

Large ΔT/Δx → Lower R_{res}

See MOBA08 and MOPB041

How then can we compare cavity sensitivities to magnetic fields while normalizing for cool down parameters?

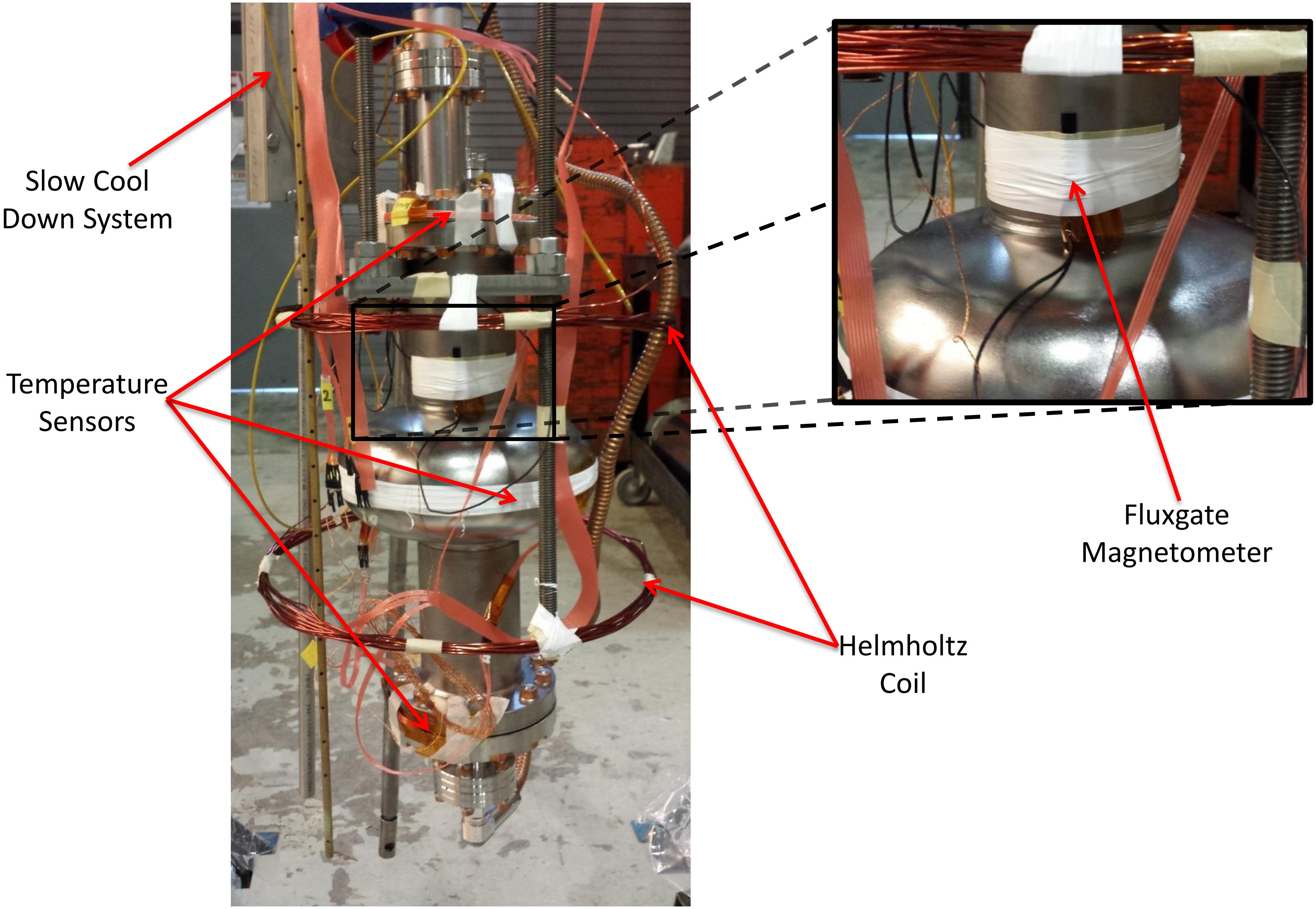
By normalizing to trapped magnetic flux:

- When a cavity becomes superconducting in a magnetic field, some of that field will be trapped in the cavity walls.
- This trapped magnetic field directly leads to additional residual resistance.

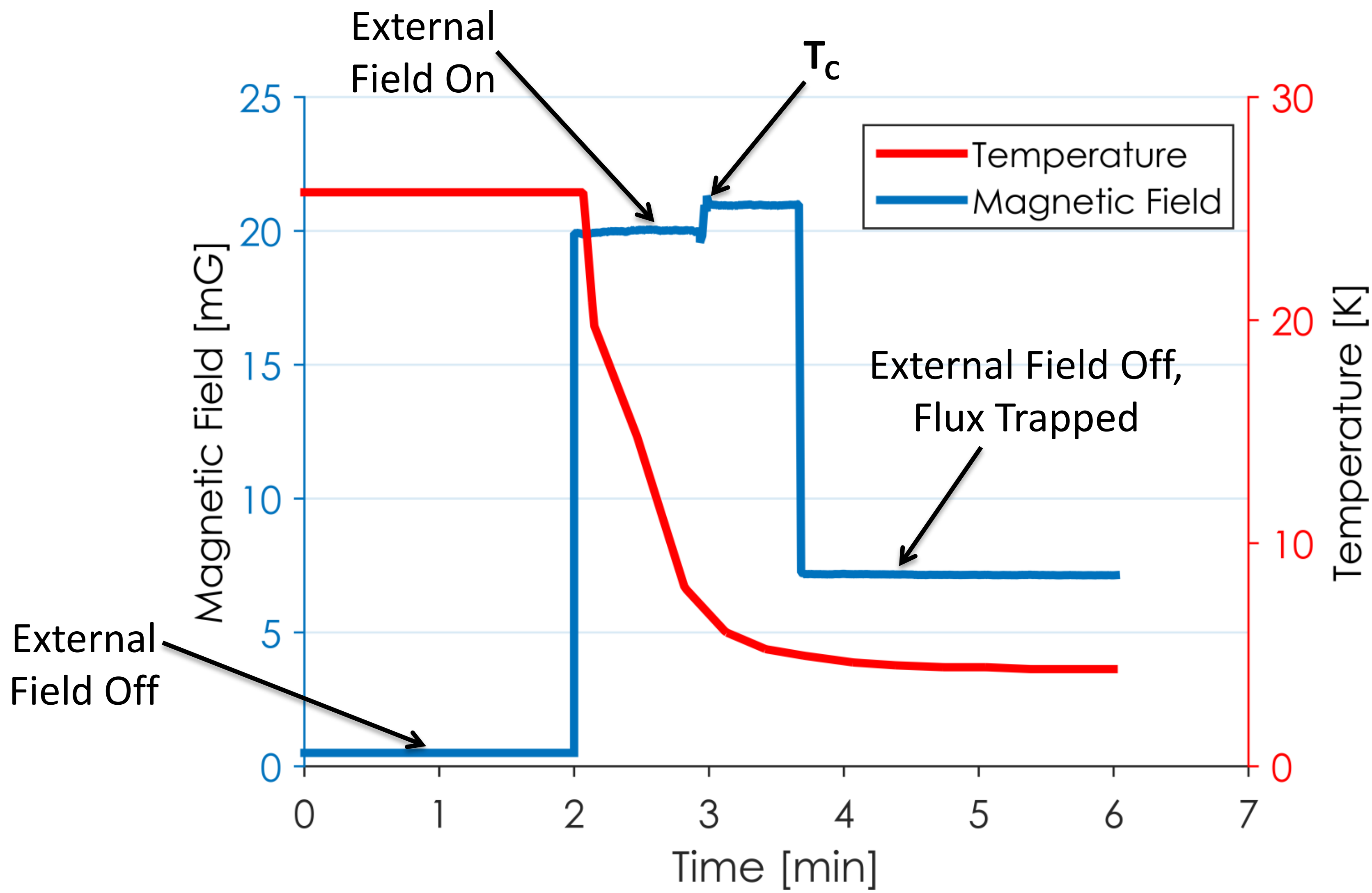
The Experiment

- Want to measure increase in R_{res} due to trapped flux as a function of material properties
  - 3 challenges:
    1. Control flux trapping/measure how much is trapped
    2. Measure R_{res} at low fields
    3. Extract material properties from RF surface impedance measurements

Experimental Setup



Fluxgate Measurements



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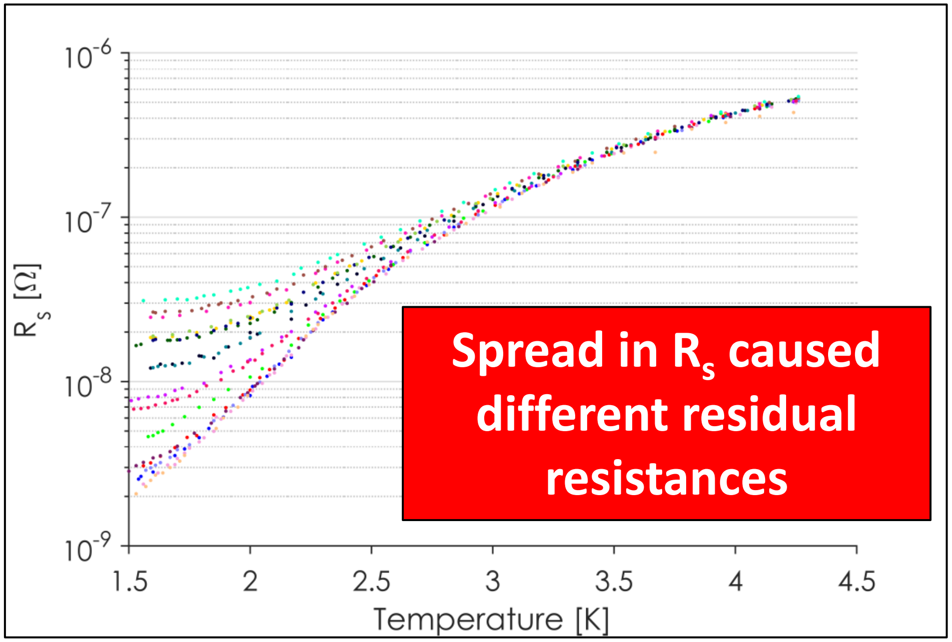
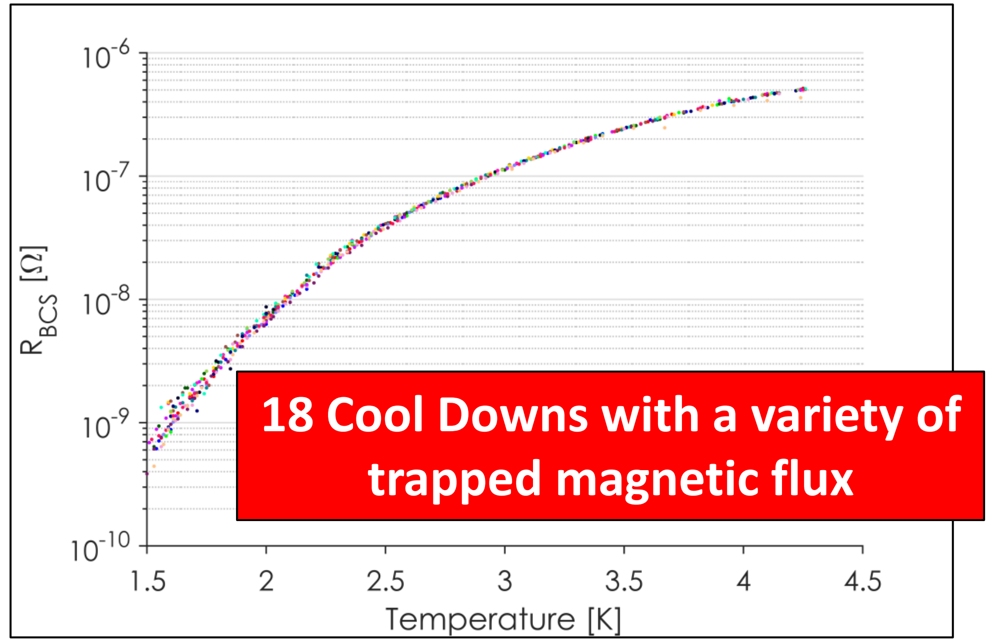
R_s vs T

Surface Resistance vs Temperature



BCS Resistance vs Temperature



- More trapped flux leads to higher surface resistance.
- This surface resistance increase is seen only in the temperature independent residual resistance.
- **Temperature dependent BCS resistance is unaffected** by trapped flux.

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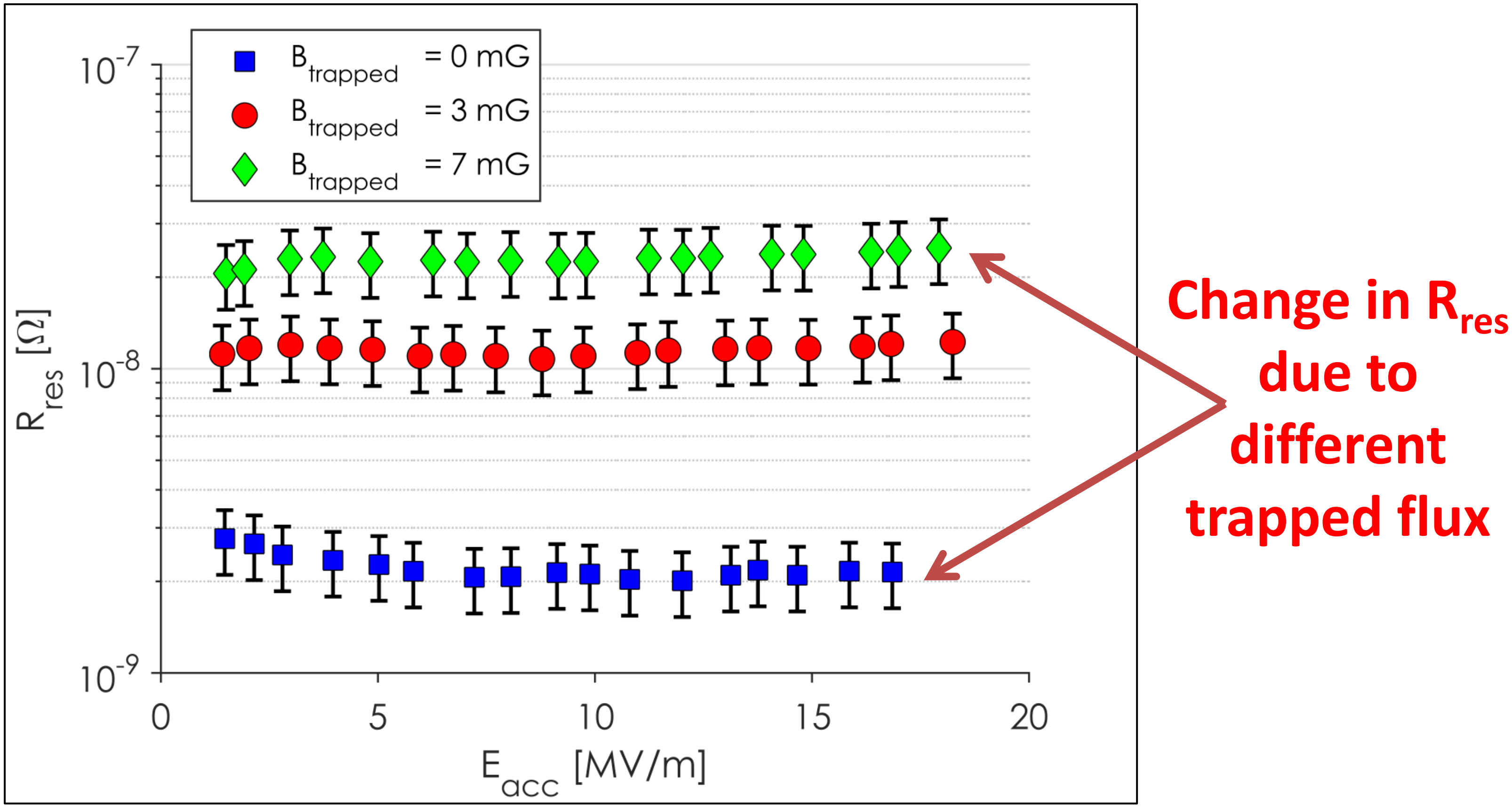
R_{res} vs RF Field



Residual resistance from trapped flux is independent of E_{acc} up to medium field

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Fitting of BCS Parameters

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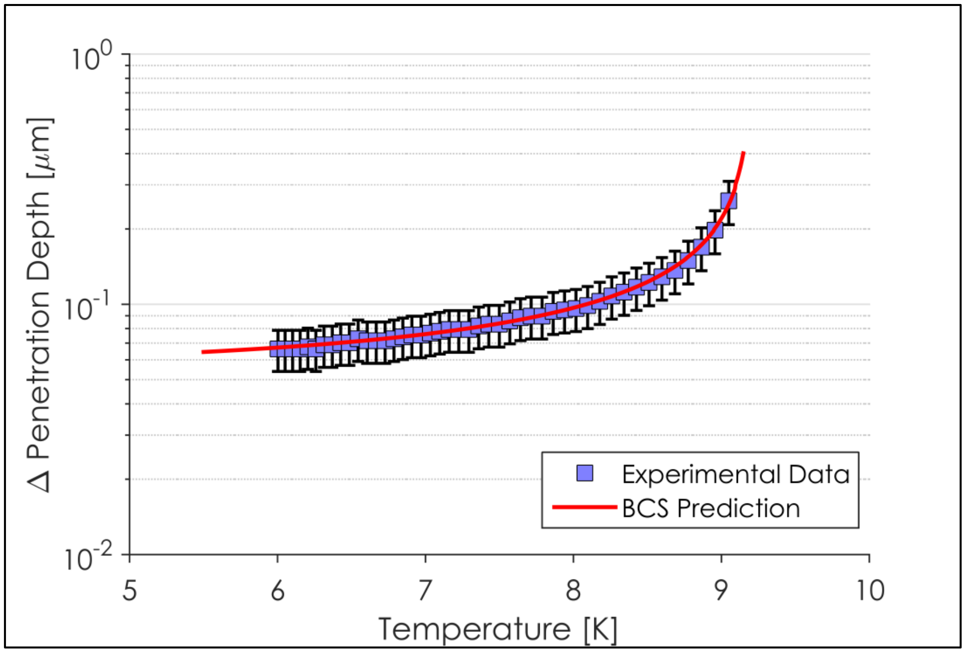
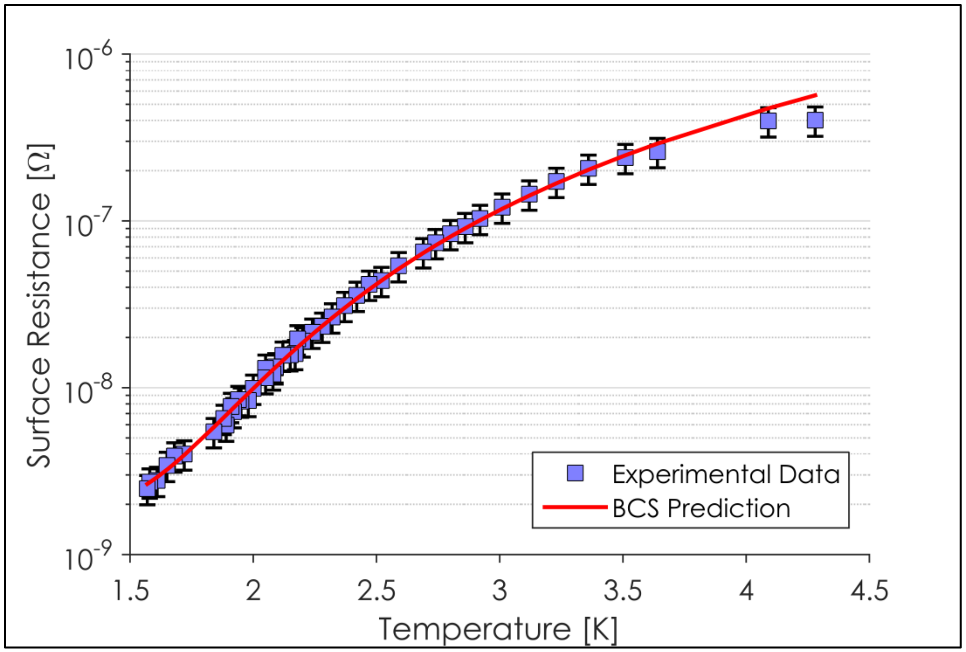
Penetration Depth vs Temperature



- Change in penetration depth is computed from change in resonance frequency.
- Penetration depth depends strongly on mean free path and T_c.
- This is fit using BCS theory **to extract mean free path** holding energy gap and residual resistance constant.

Surface Resistance vs Temperature



- Q_0 is sensitive to energy gap and residual resistance but not mean free path.
- Surface resistance vs temperature is fit using BCS theory to **extract energy gap and residual resistance** holding mean free path constant.

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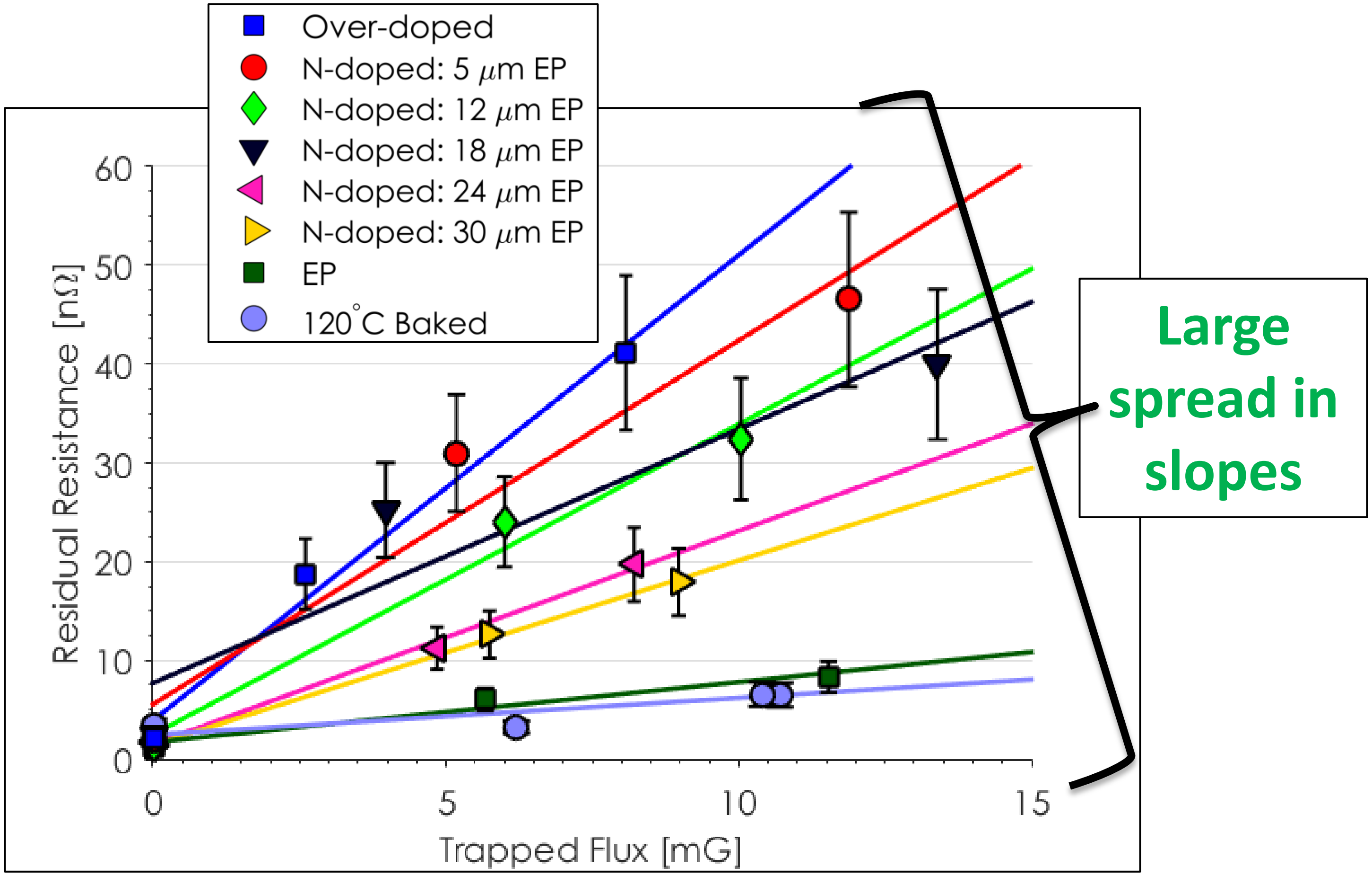
The Experiment

- 8 single-cell cavities were prepared with a variety of techniques.
  - 6 nitrogen doped cavities of varying doping levels
  - 2 "standard" treated cavities: one EP cavity and an EP+120^{0}C baked cavity

The Experiment

- Each cavity was cooled in a variety of magnetic fields leading to different amounts of trapped magnetic flux.
- Mean free path was extracted for each cavity.
- Sensitivity to trapped magnetic flux was found.

R_{res} vs Trapped Flux



Cavities with different preparations show very different sensitivities to trapped flux!

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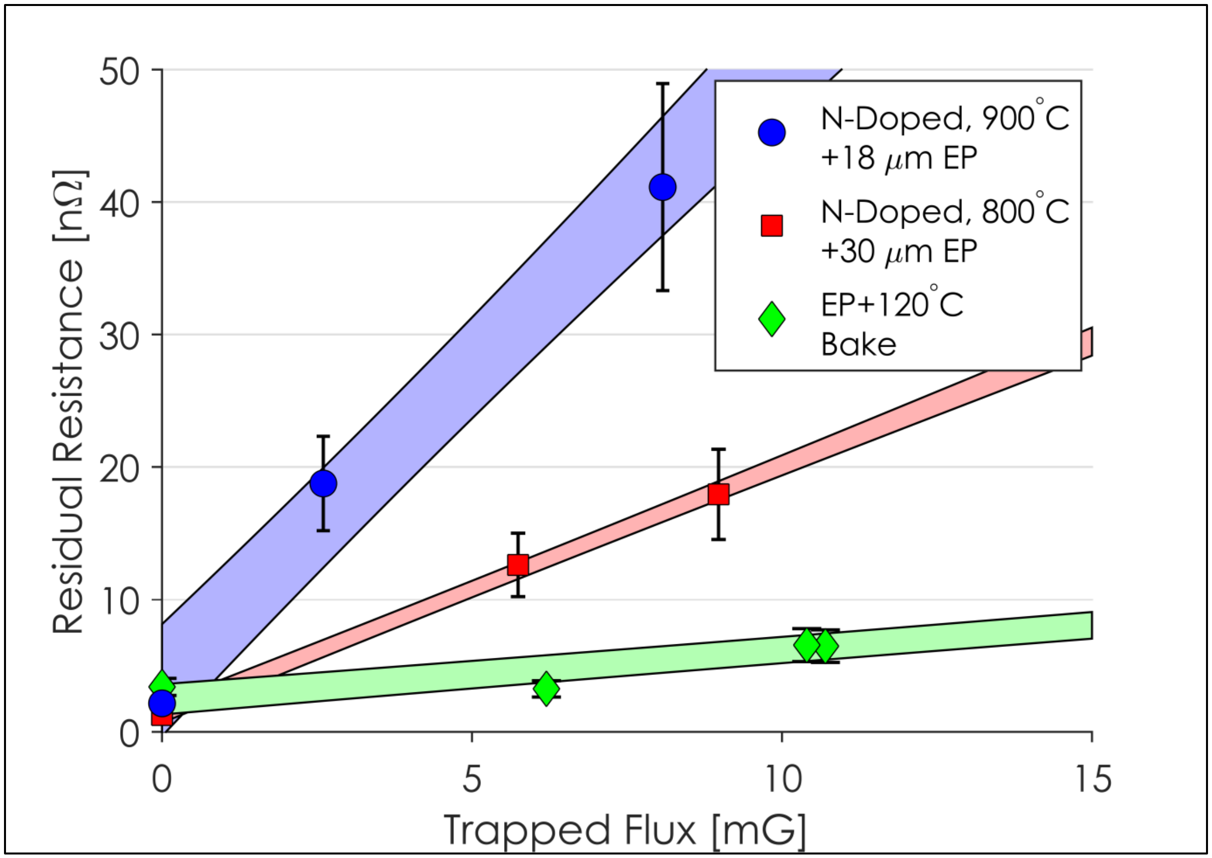
R_{res} vs Trapped Flux



- Stronger doping results in a higher sensitivity to trapped flux.
- All nitrogen-doped cavities tested showed a higher sensitivity than both the EP and EP+120°C baked cavities.

$$\text{Sensitivity parameter} = \frac{dR_{res}}{dB_{trapped}}$$

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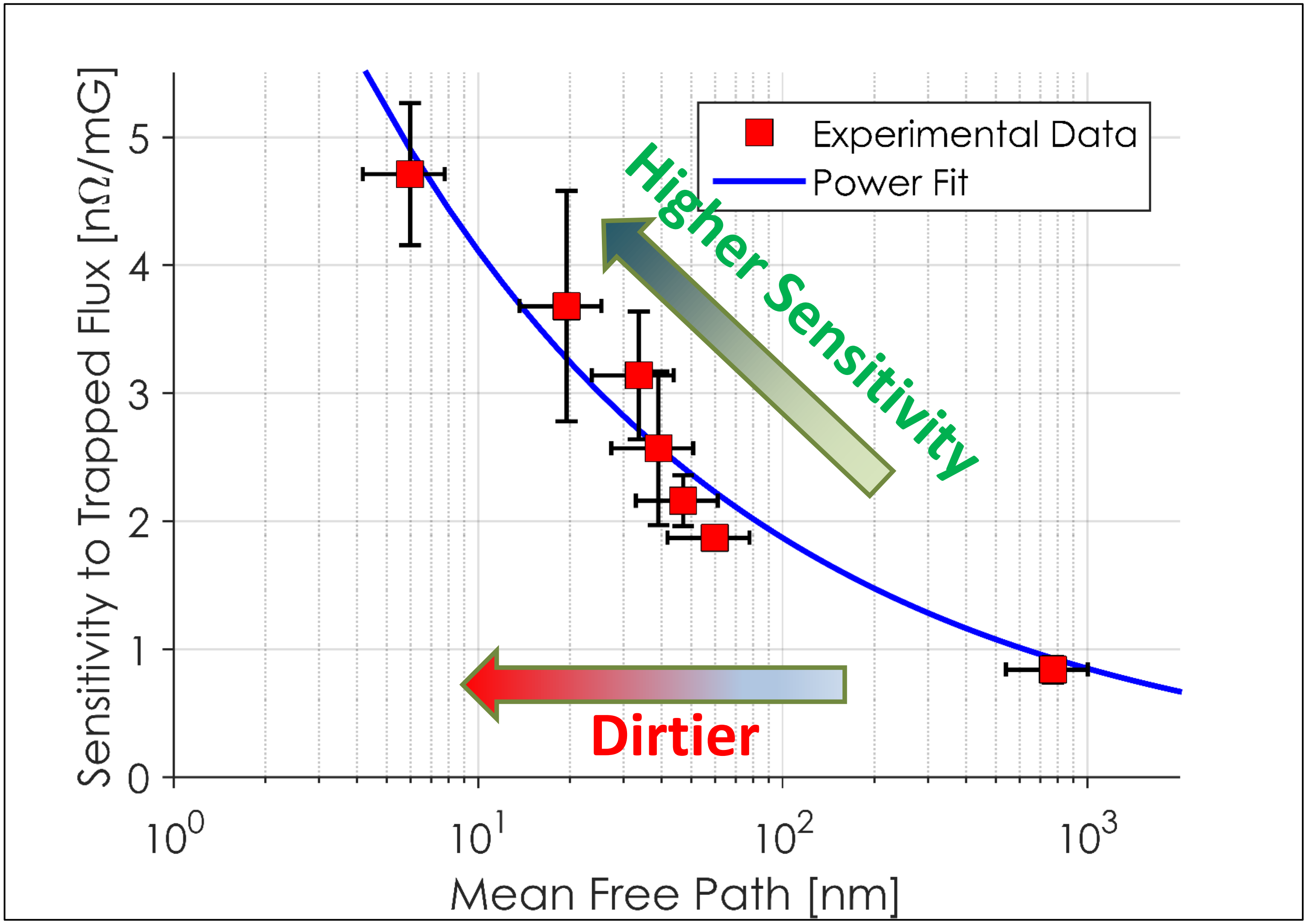
Results

N-Doping Temperature	Cavity	Mean Free Path [nm]	$\varepsilon/k_B T_c$	Sensitivity to Trapped Flux [nΩ/mG]
800°C	LT1-2	**19±6**	1.87±0.03	**3.7±0.9**
	LT1-3	**34±10**	1.91±0.03	**3.1±0.5**
	LT1-1	**39±12**	1.88±0.03	**2.5±0.6**
	LT1-4	**47±14**	1.89±0.03	**2.2±0.2**
	LT1-5	**60±18**	1.88±0.03	**1.87±0.08**
900°C	LT1-2	**6±2**	2.01±0.03	**4.7±0.6**
	NR1-3 (EP)	**770±230**	1.81±0.03	**0.8±0.1**
	NR1-3 (EP+120°C)	**120±36†**	1.96±0.03	**0.6±0.05**

† 120°C bake only affects a fraction of the RF penetration layer – mean free path is found effectively by averaging over the whole RF layer

Sensitivity vs MFP



Smaller mean free path results in higher sensitivity to trapped flux.

Conclusions

- This is the first systematic measurement of the dependence of residual resistance sensitivity to trapped magnetic flux on cavity preparation.
- Nitrogen-doped cavities have a **lower mean free path → higher sensitivity**
- These measurements explain why slow cool down affects nitrogen-doped cavities so much stronger than "standard" prepared cavities.

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