Trapped Flux Measurements and Thermal Boundary Resistance Analysis for an ECR film

Thin Film Workshop 2016

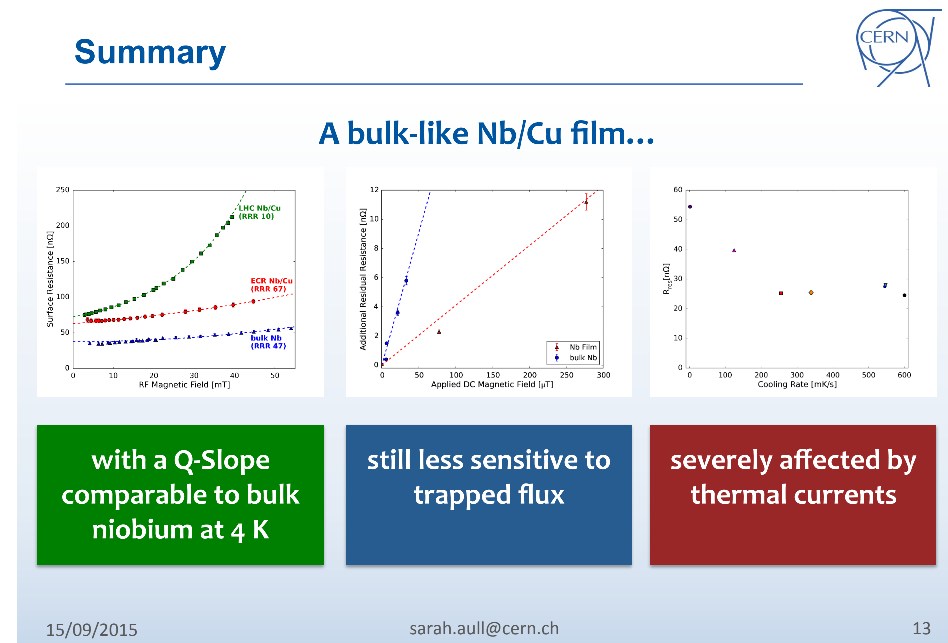
Sarah Aull

Acknowledgements to
A. Miyazaki, W. Venturini Delsolaro and the HIE-Isolde team (CERN)
A.-M. Valente-Feliciano (JLab)

Where we left at SRF 2015

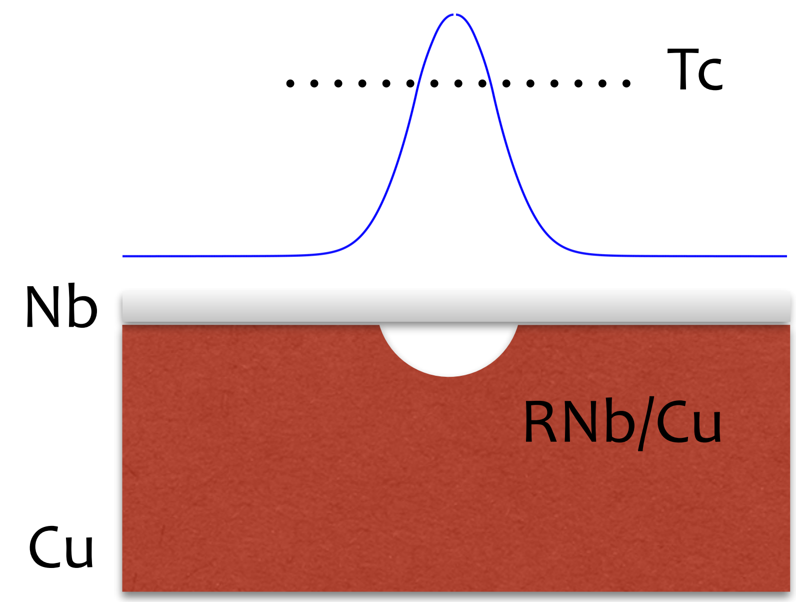
First Nb/Cu coating by energetic condensation showed

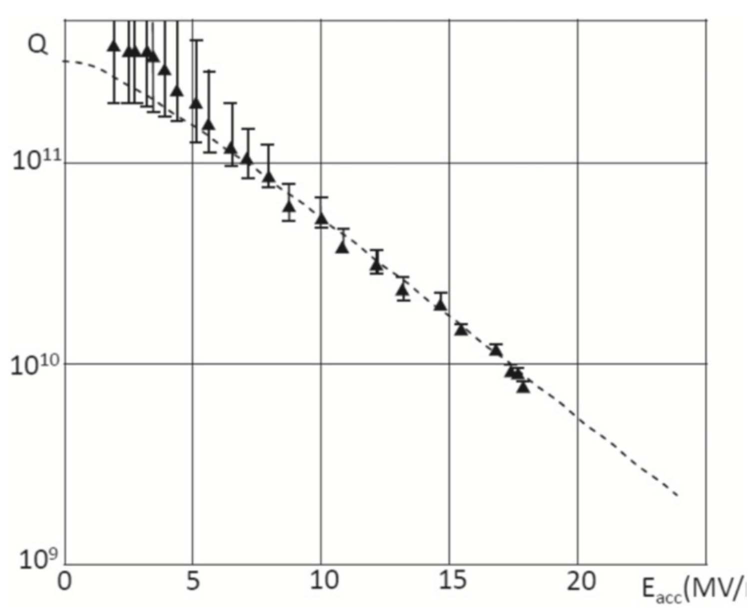
- a strongly mitigated Q-slope
- (still) low trapped flux sensitivity
- strong dependence on the cool down dynamics

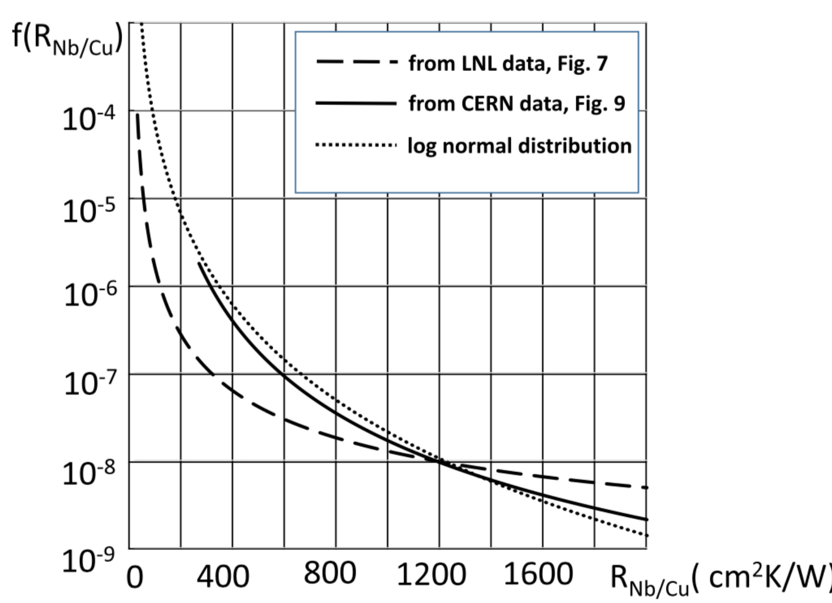


Thermal Boundary Resistance Model

- Small defects at the Nb-Cu interface lead to microscopic quenches which cause the Nb\Cu Q-slope.
- *$Q(E_{acc})$* curve can be converted into a distribution function of thermal contact resistances.







Integration yields detached surface area:

$$I = \int f\left(R_{\mathrm{Nb/Cu}}\right) dR_{\mathrm{Nb/Cu}}$$

V Palmieri and R Vaglio,
Supercond. Sci. Technol. 29 (2016) 015004

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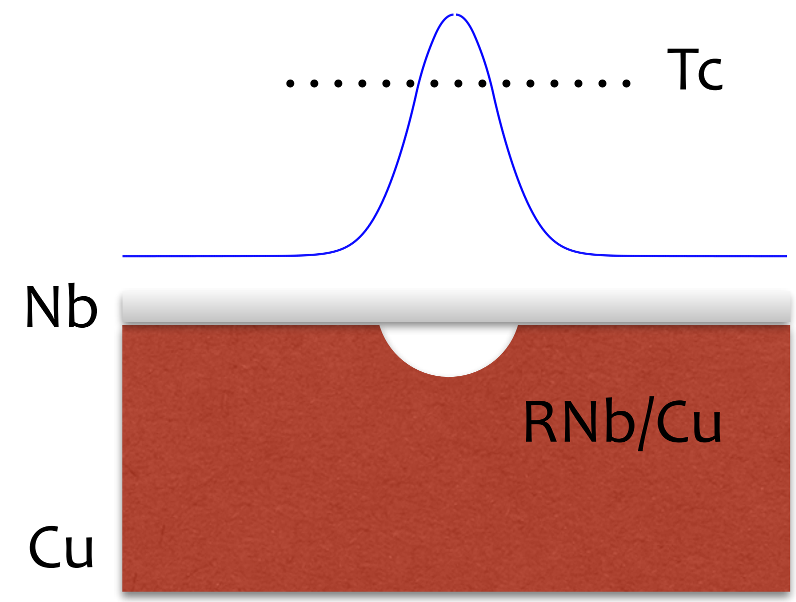

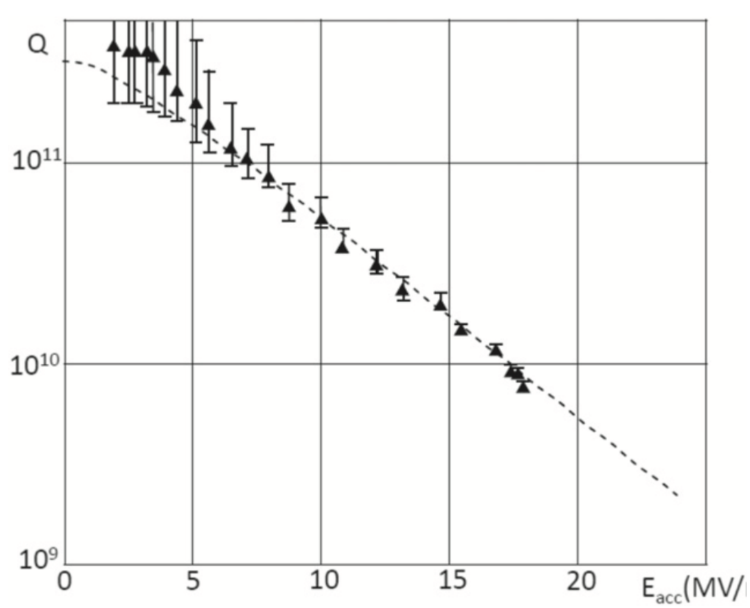

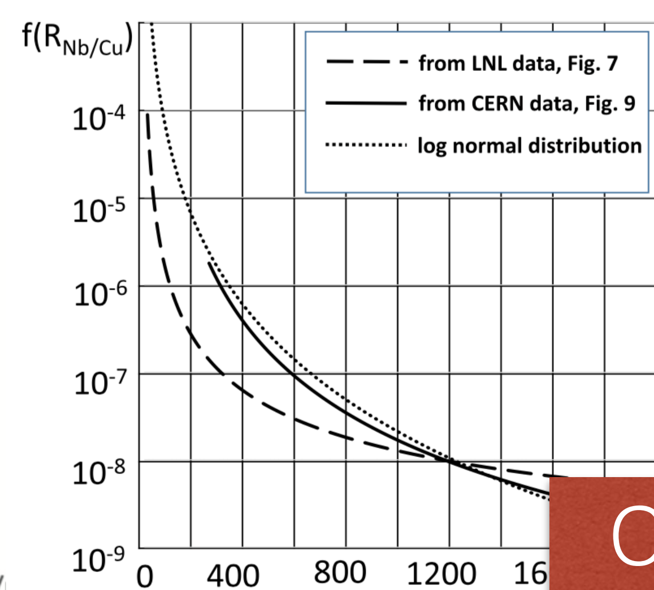

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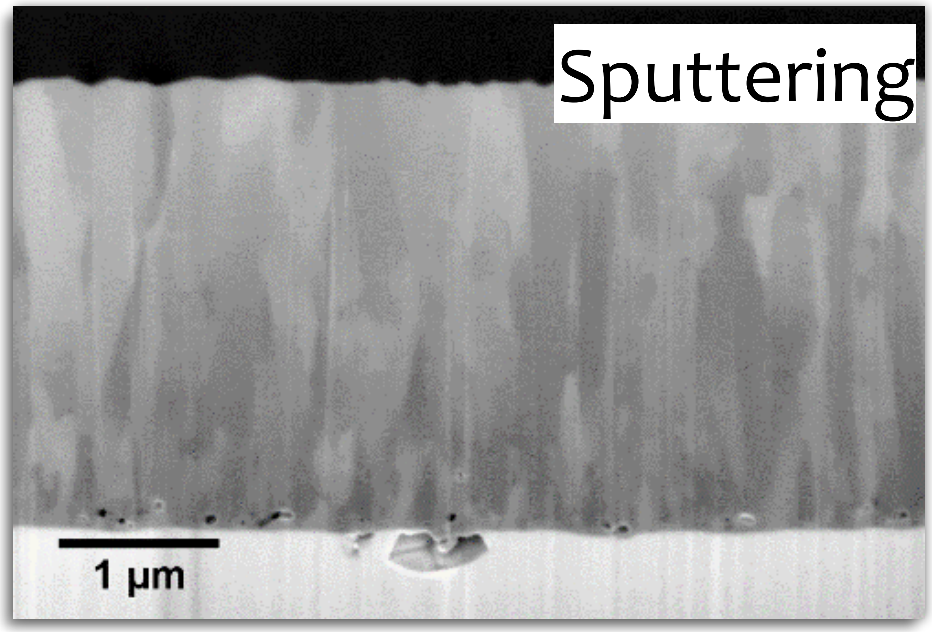
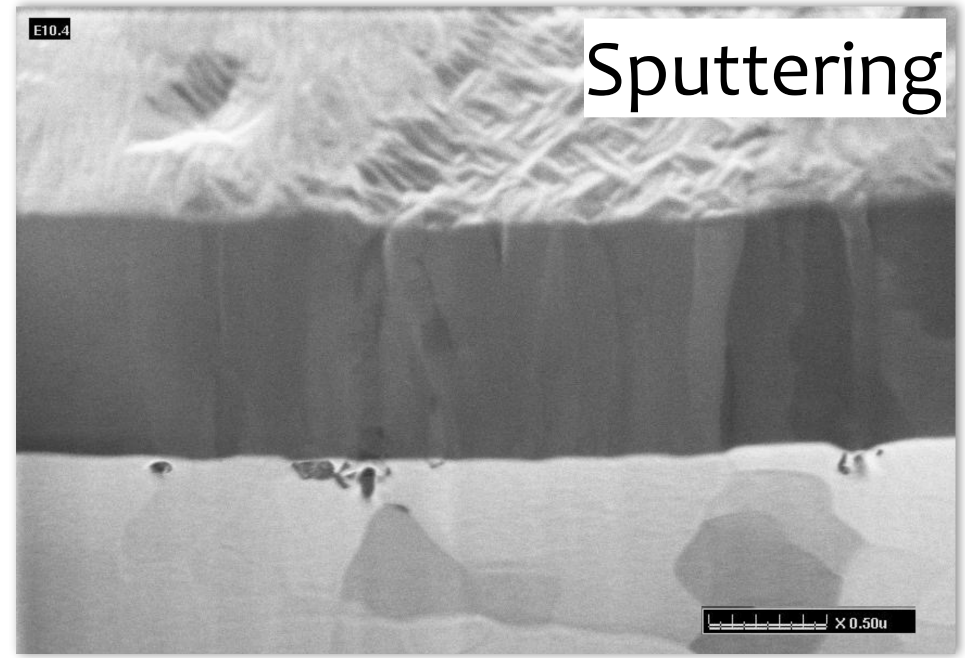
Conversion is not a fit

Difficult to test experimentally

Examples of Detached Surfaces

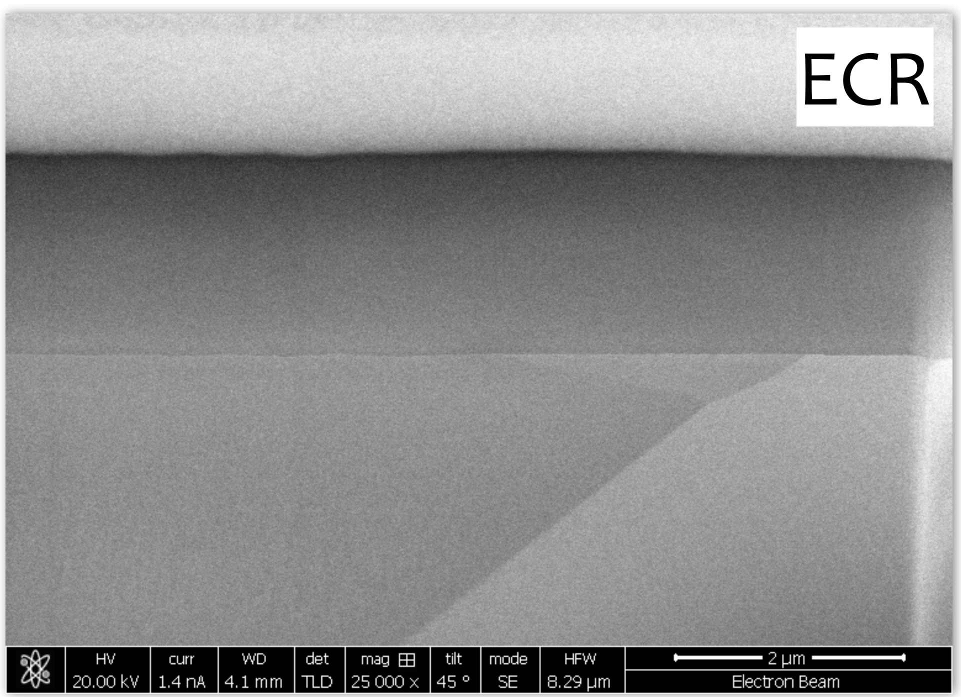
Courtesy B. Barbora

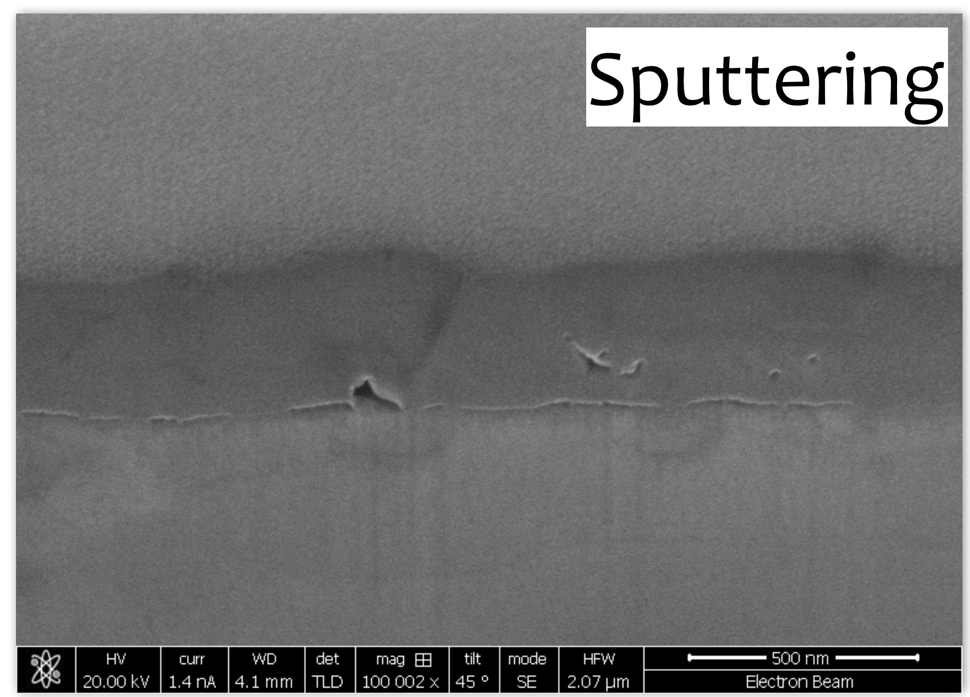




Courtesy P. Jacob

Courtesy R.Valizadeh

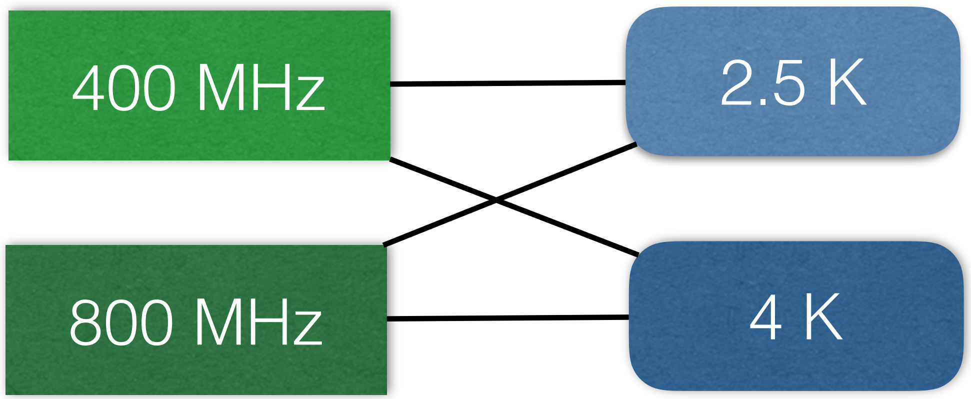




Courtesy R.Valizadeh

Thermal Contact Resistance of the ECR1

- Compare TBR analysis for RF measurements on the ECR coating at different temperatures and frequency combinations.



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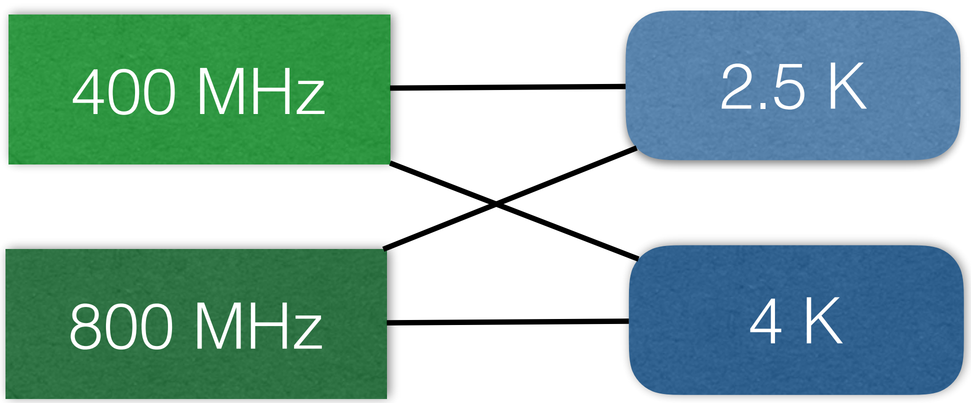

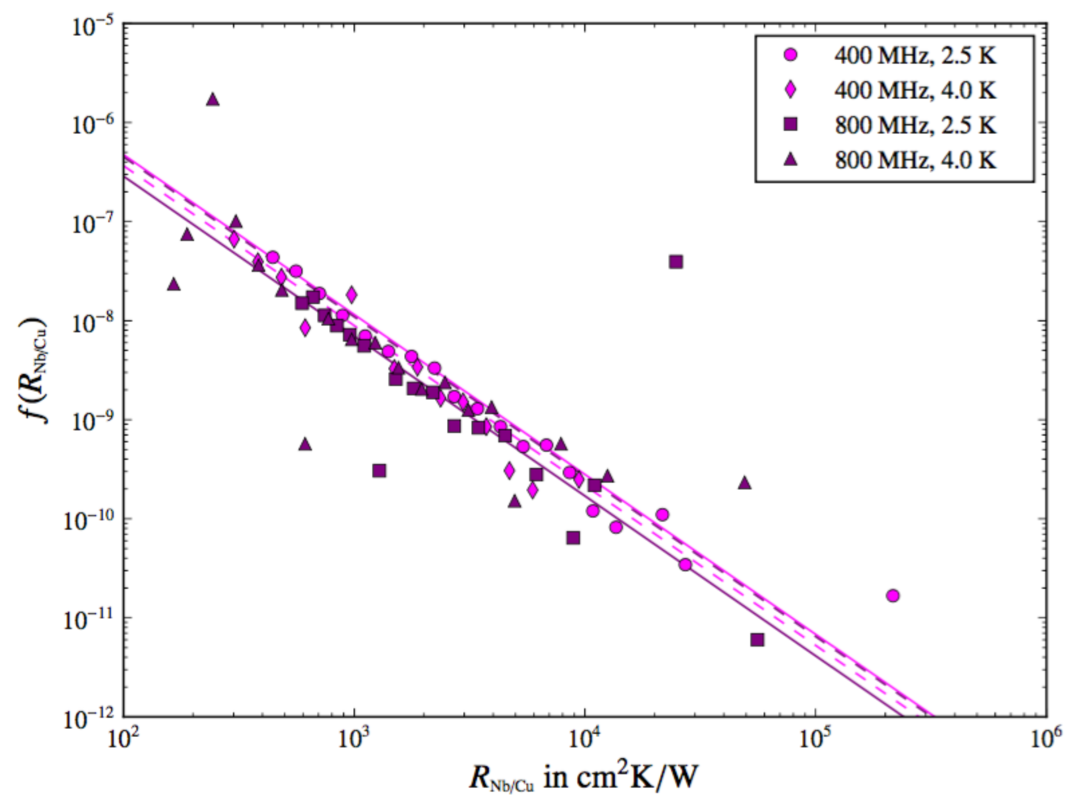

Detached surface area:

$$I = \int f\left(R_{\mathrm{Nb/Cu}}\right) dR_{\mathrm{Nb/Cu}}$$

$I = (3.4 \pm 0.7)\, 10^{-5} \ll (10^{-3} - 10^{-4})$

	f_{res}	T	Fraction of detached film
ECR Nb/Cu	400 MHz	2.5 K	3.3×10^{-5}
		4.0 K	3.1×10^{-5}
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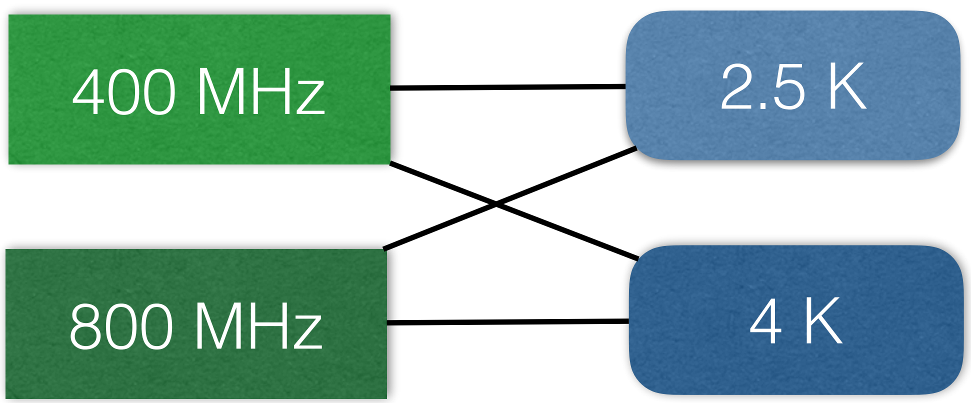

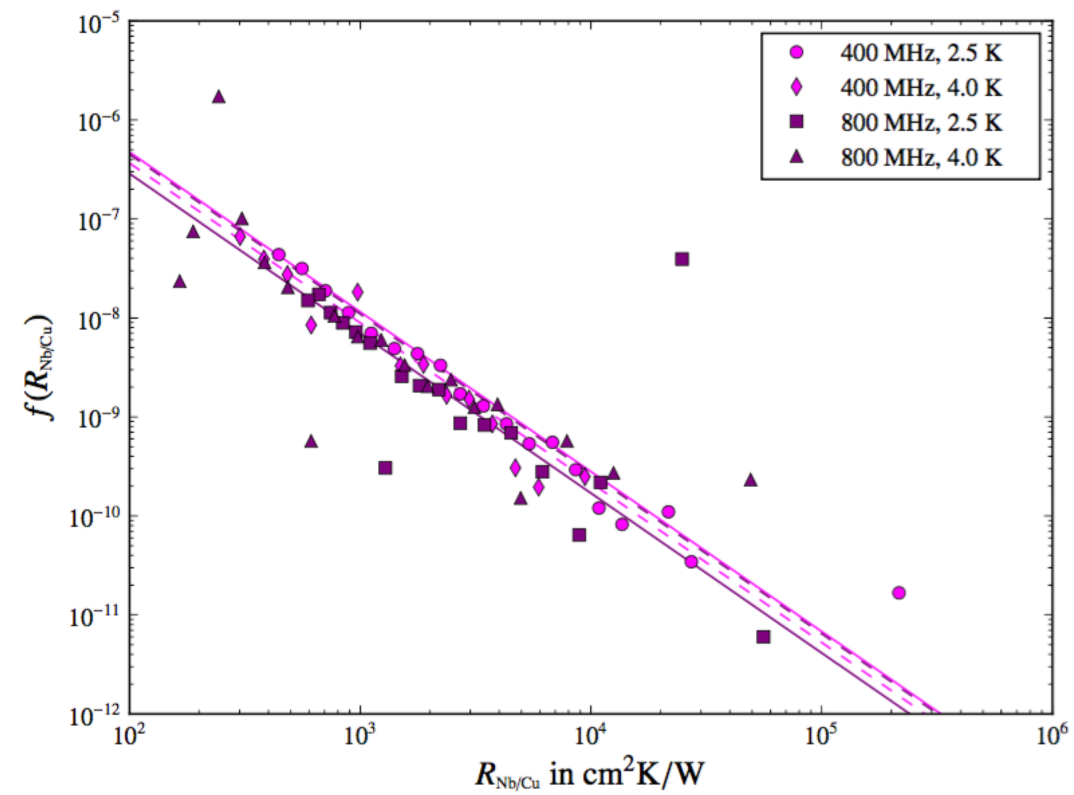

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Same result for all curves supports validity of TBR model

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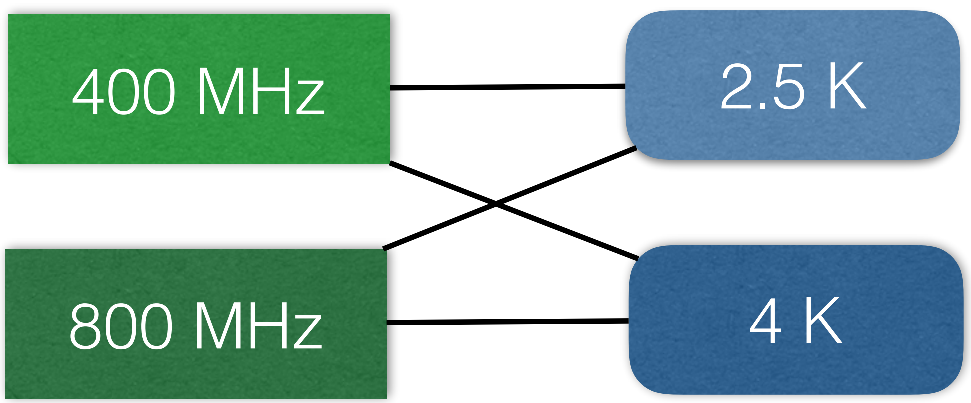
Testing the Thermal Contact Resistance Model

- Compare TBR analysis for RF measurements on bulk Nb reference at different temperatures and frequency combinations.



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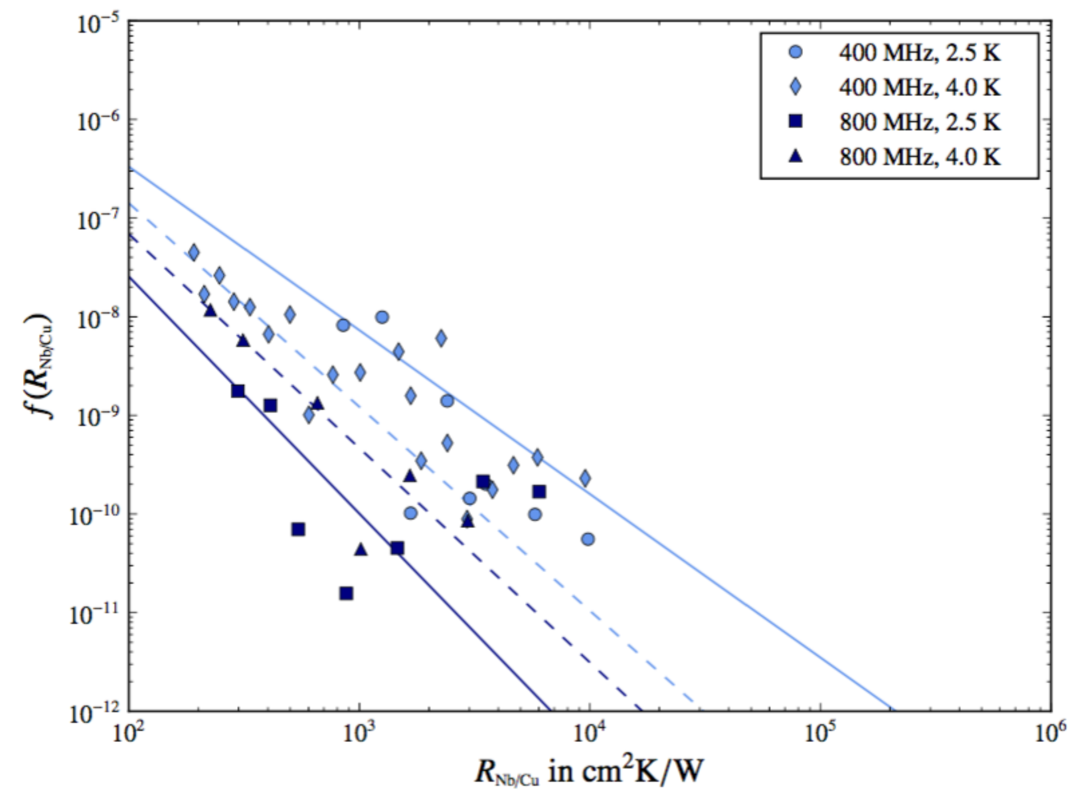

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bulk Nb	400 MHz	2.5 K	3.1×10^{-6}
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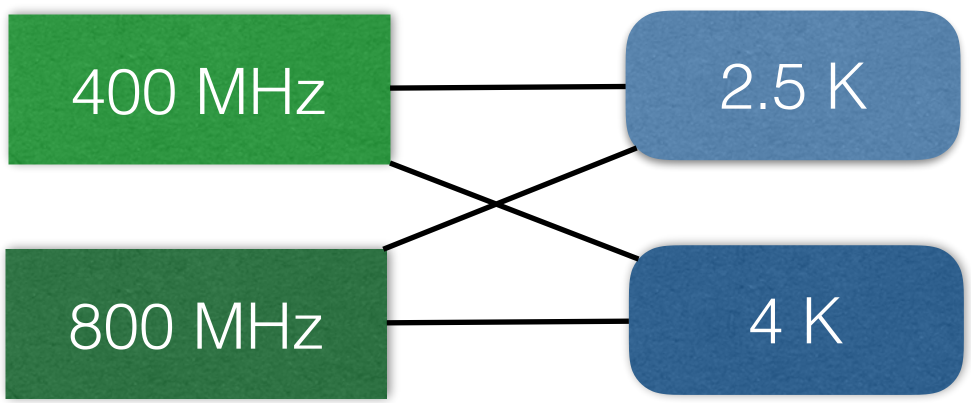

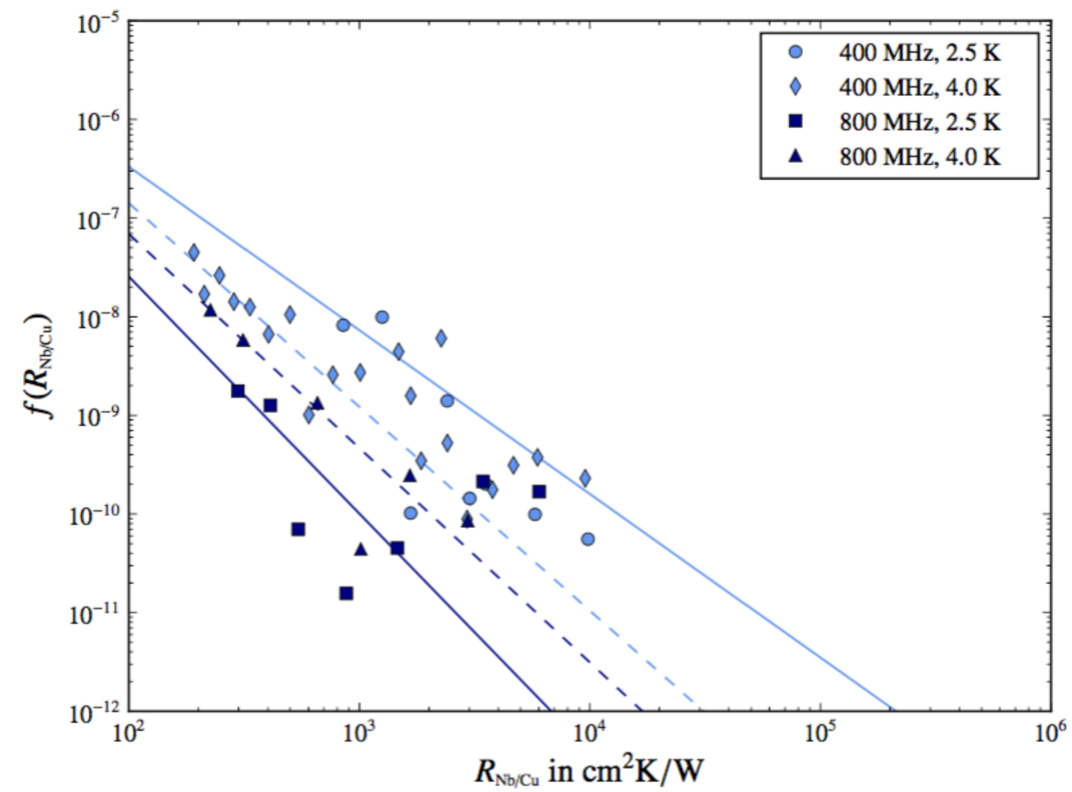

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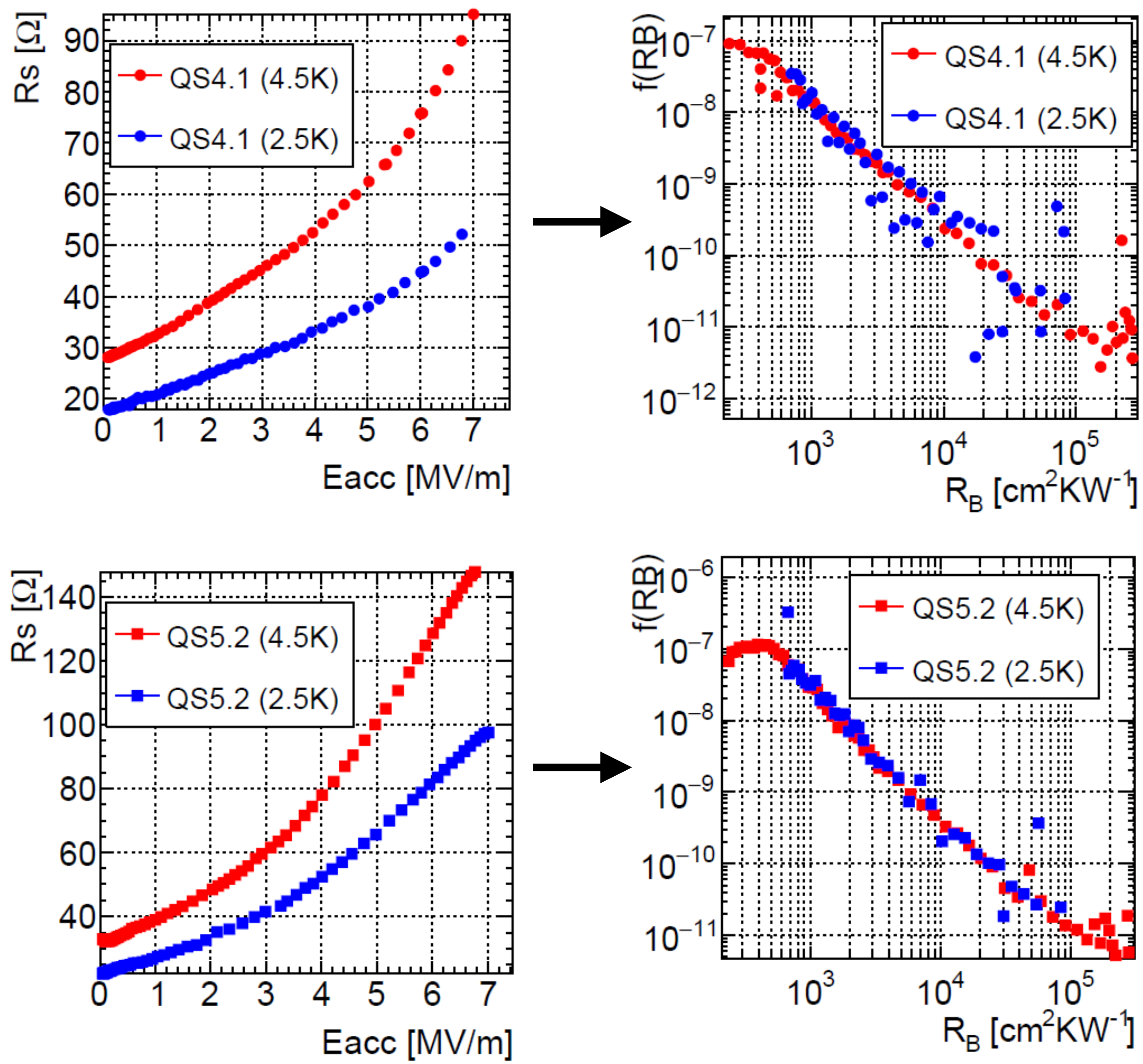
No meaningful result for bulk Nb ✓

TBR Analysis for HIE-Isolde

Compare Q(E) at 2.5 K and 4.5 K:

HIE-Isolde cavities shown also same distribution function for for different temperatures



Courtesy Akira Miyazaki (CERN)

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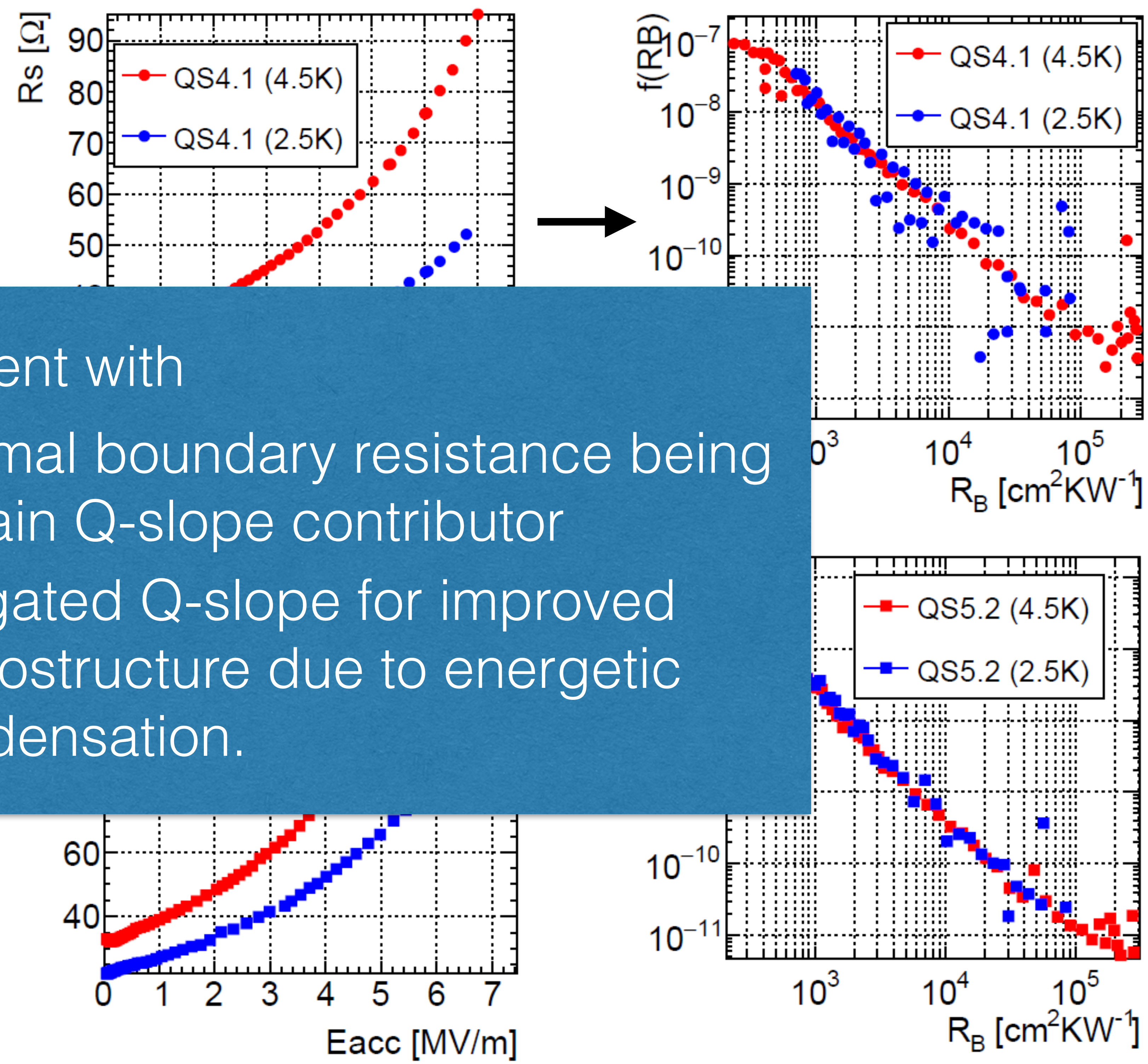


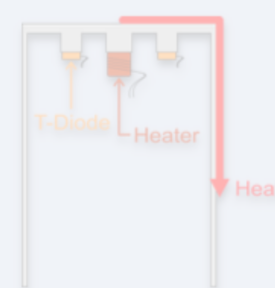
Consistent with

- thermal boundary resistance being a main Q-slope contributor
- mitigated Q-slope for improved microstructure due to energetic condensation.

Courtesy Akira Miyazaki (CERN)

Cool Down Dynamics: Thin Film Workshop 2014

Comparison between QPR, 1.3 GHz and HIE Isolde

		RRR	Geometry	Cooling	Grain size
Quadrupole Resonator: ECR	Lower R_S for fast cooling with T gradient	53	disc 	conduction	tens of microns
1.3 GHz: HIPIMS	Lower R_S for fast cooling with small T gradient	21	elliptical	Bath cooled	30 nm
HIE Isolde: Diode sputtering	Lower R_S for small T gradients	15	QWR 	conduction	200 nm – 1 µm depending on thickness

Unknown
Influence of grain size
Influence of geometry
Thermal currents
Influence of stress
Oxidation
Roughness
…

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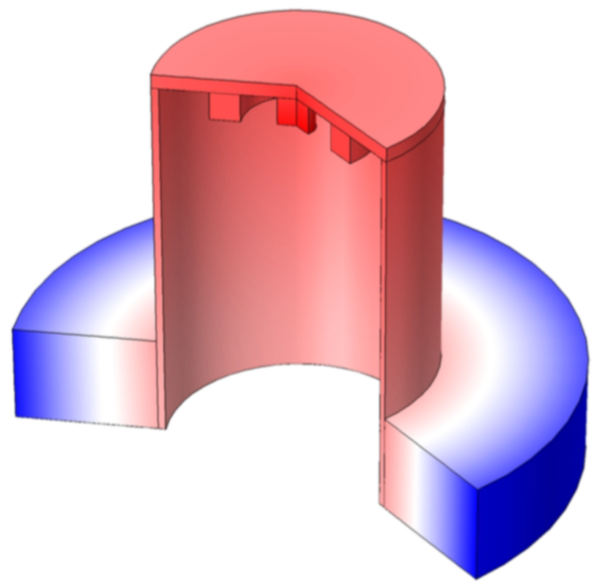
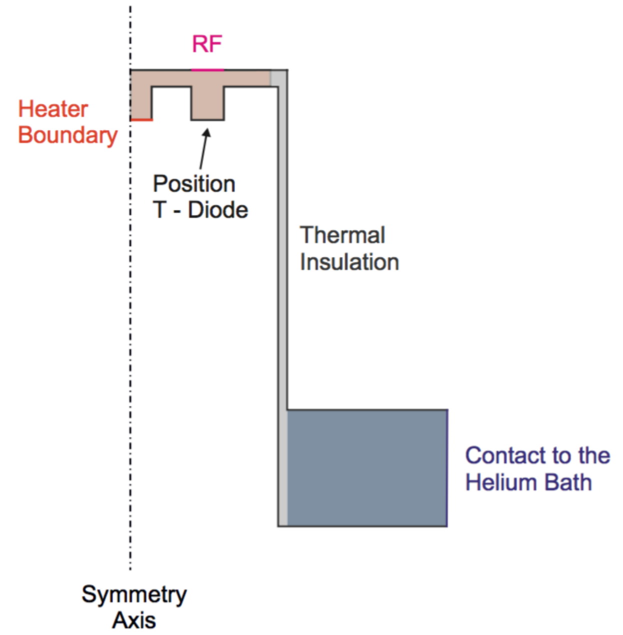
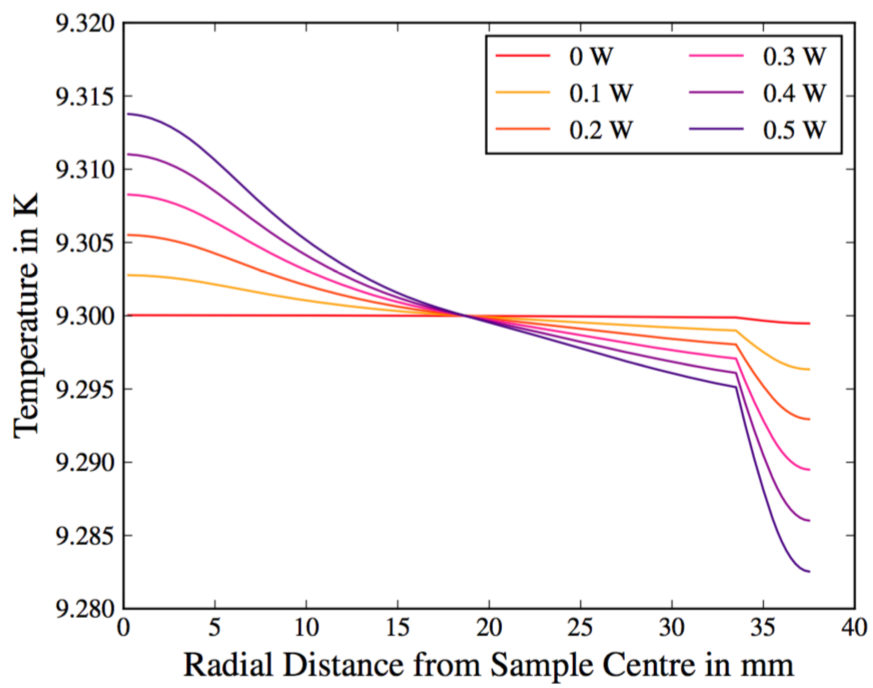
Simulation of Cool Down Dynamics

- Heat transfer simulation with COMSOL to study cool down dynamics in the Quadrupole Resonator geometry.
- Temperature dependent material properties for Nb, Cu and stainless steel.







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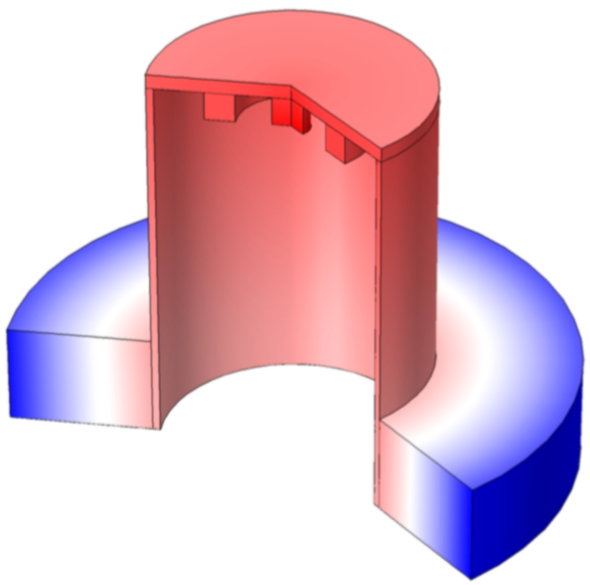

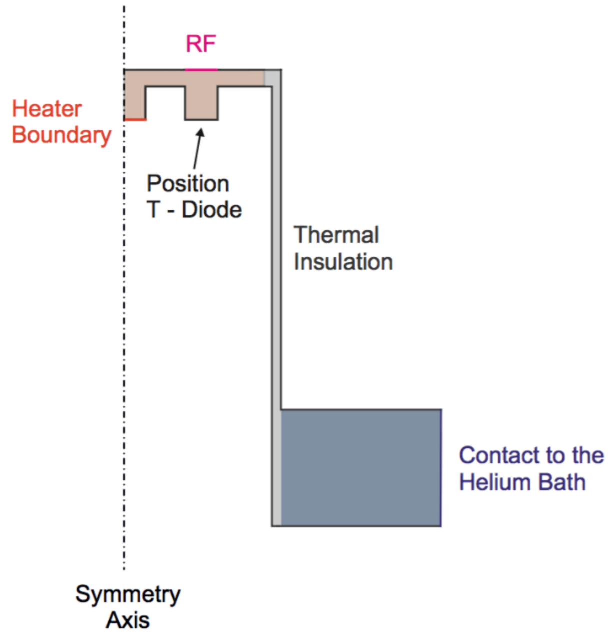

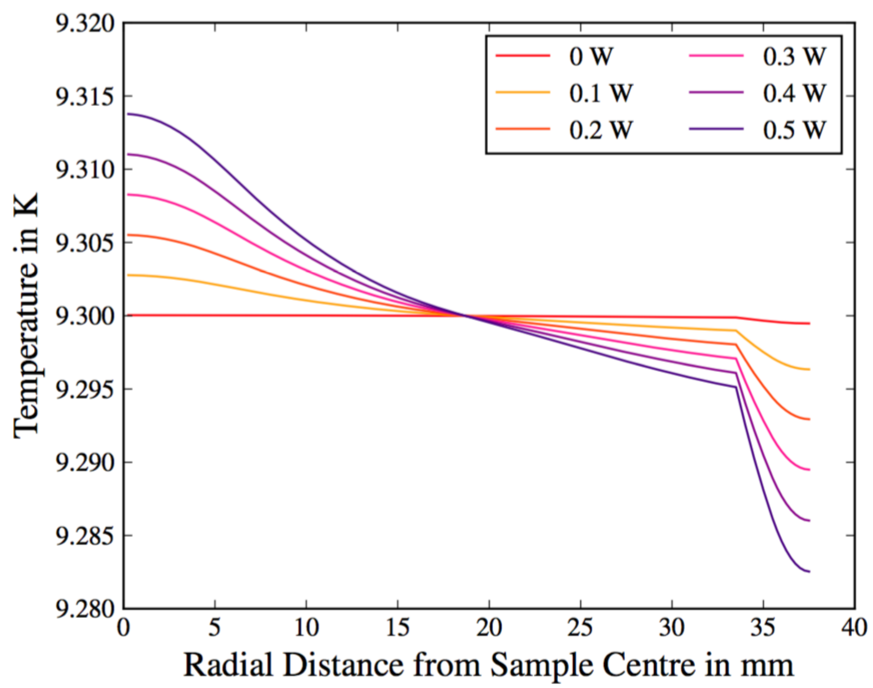

the slower the cool down, the bigger the temperature gradient across the surface

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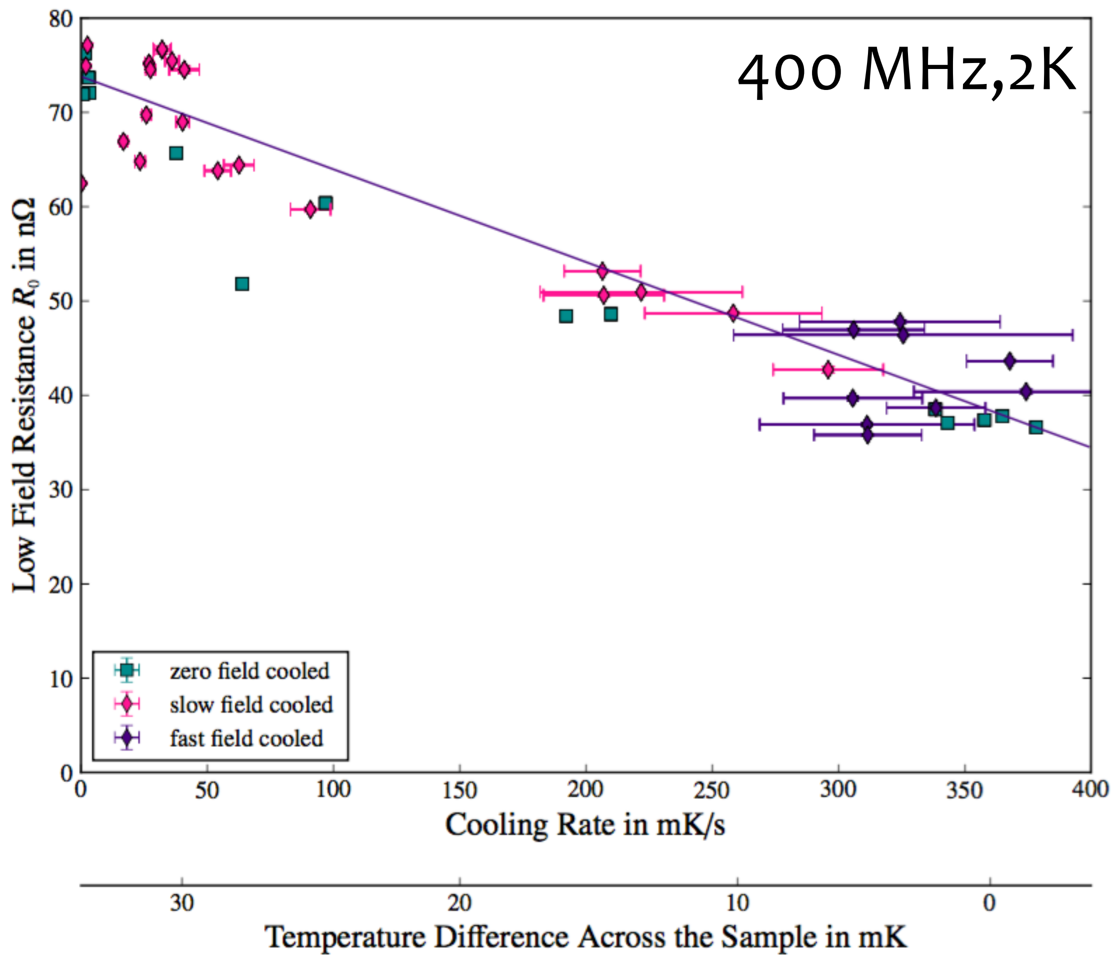
Influence of Cool Down

- The low field surface resistance increases for slow cooling, resp. large(r) temperature gradients
- The higher the low field resistance, the stronger the Q-slope.
- The influence of an ambient field is negligible.



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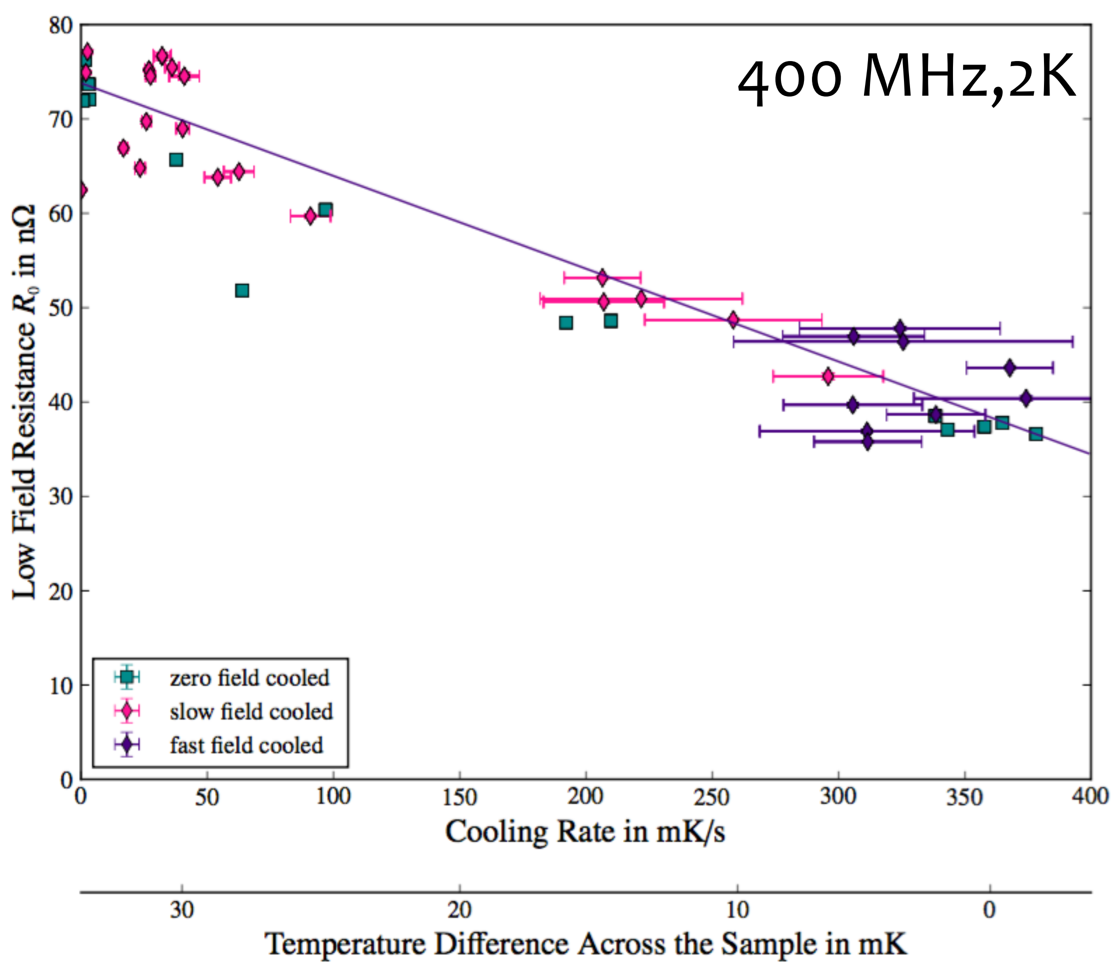
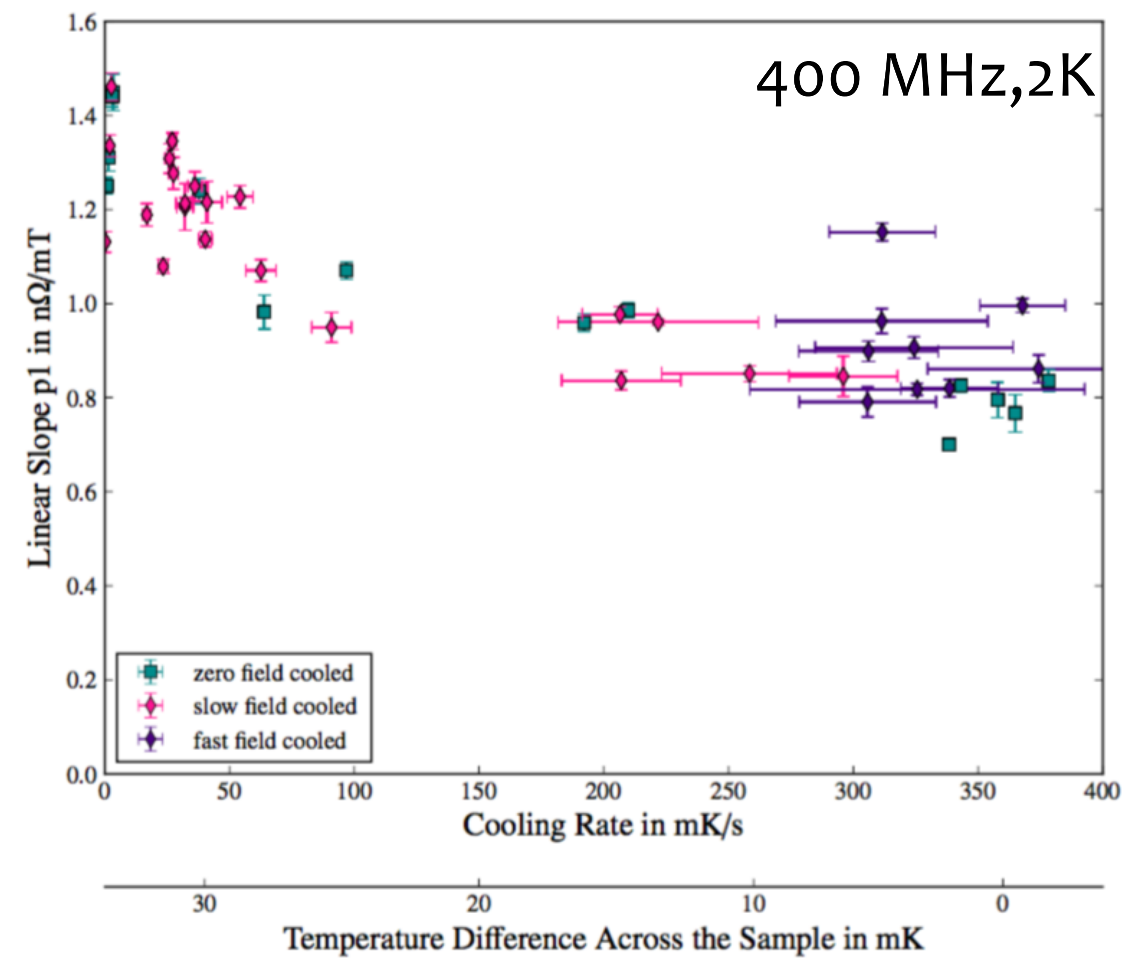
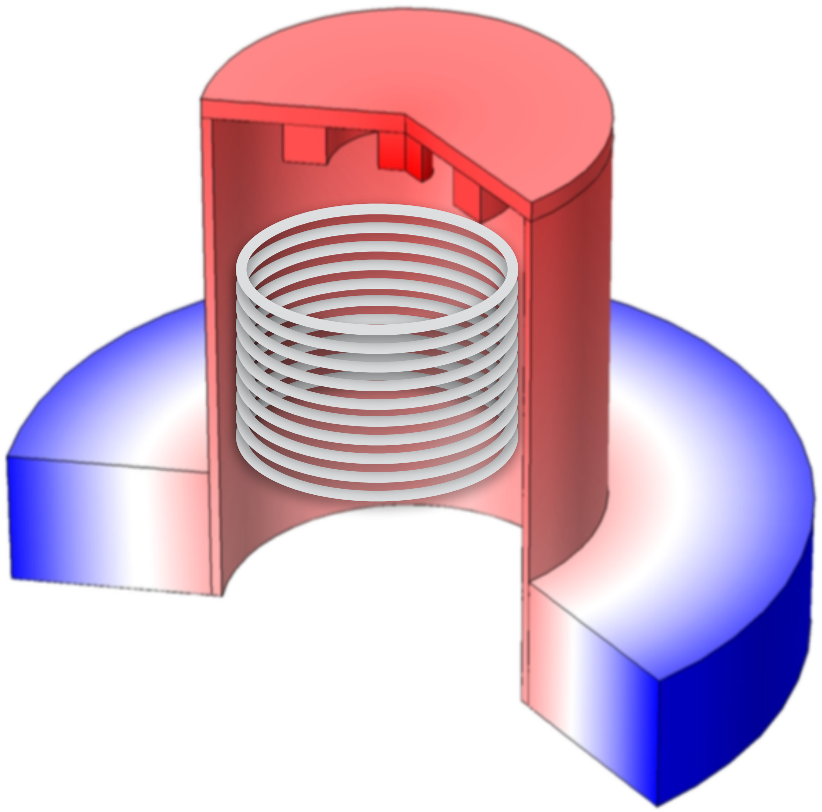




Flux Trapping or Flux Expulsion?

A solenoid under the sample allows trapped flux studies.



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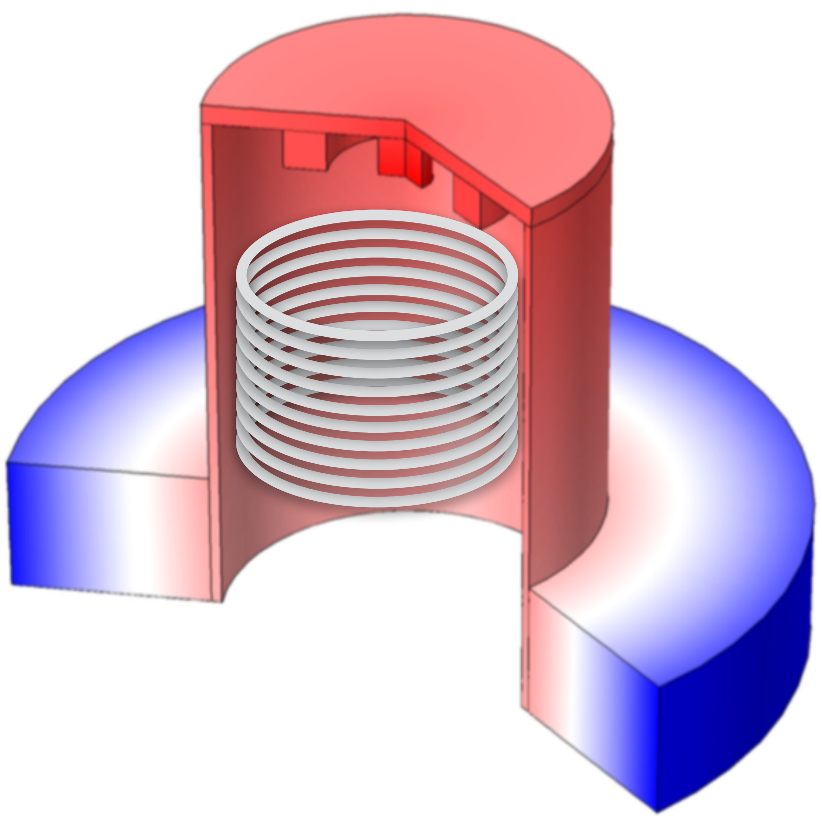
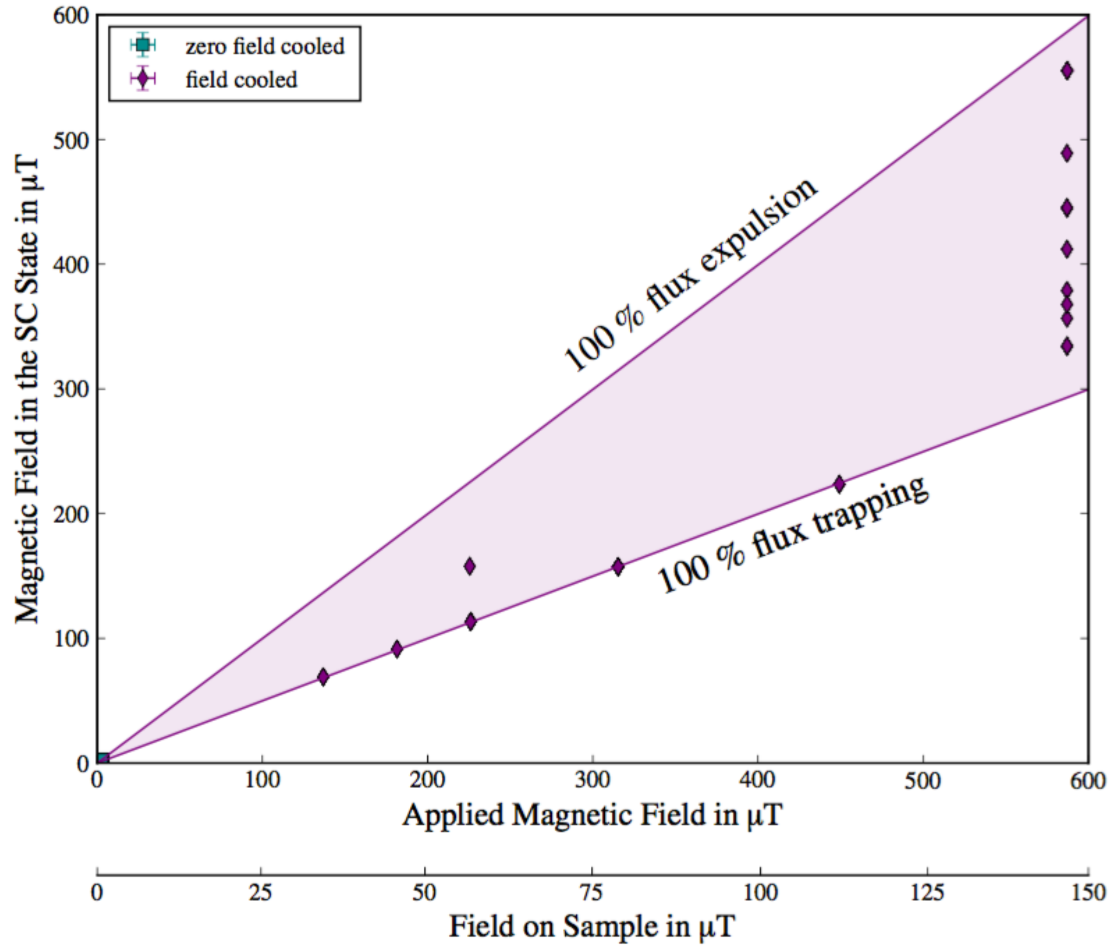
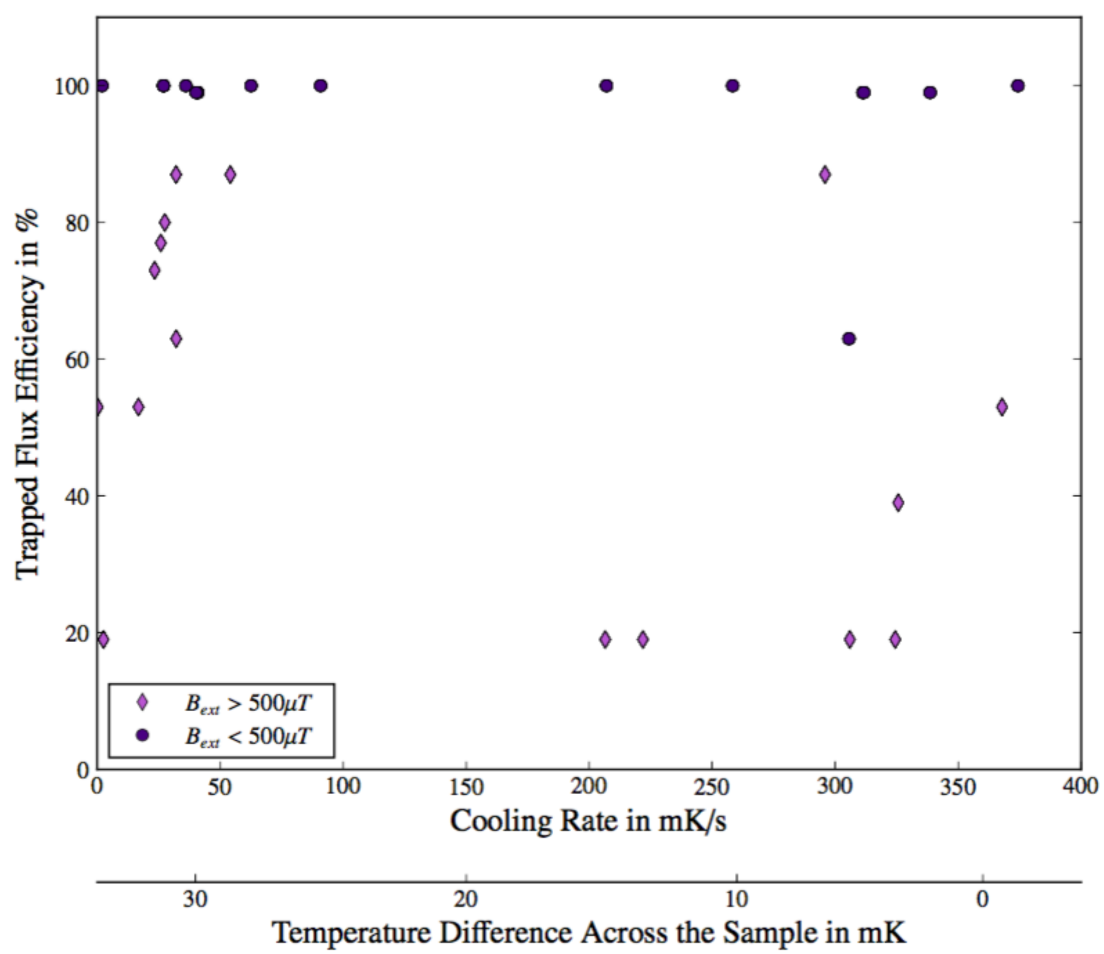
All ambient field is trapped up to a threshold field above which field can be expelled





Flux Trapping

- Below the threshold field, all field is trapped independently of cool down dynamics.
- The dependence on cool down dynamics is significantly stronger than losses due to trapped flux.



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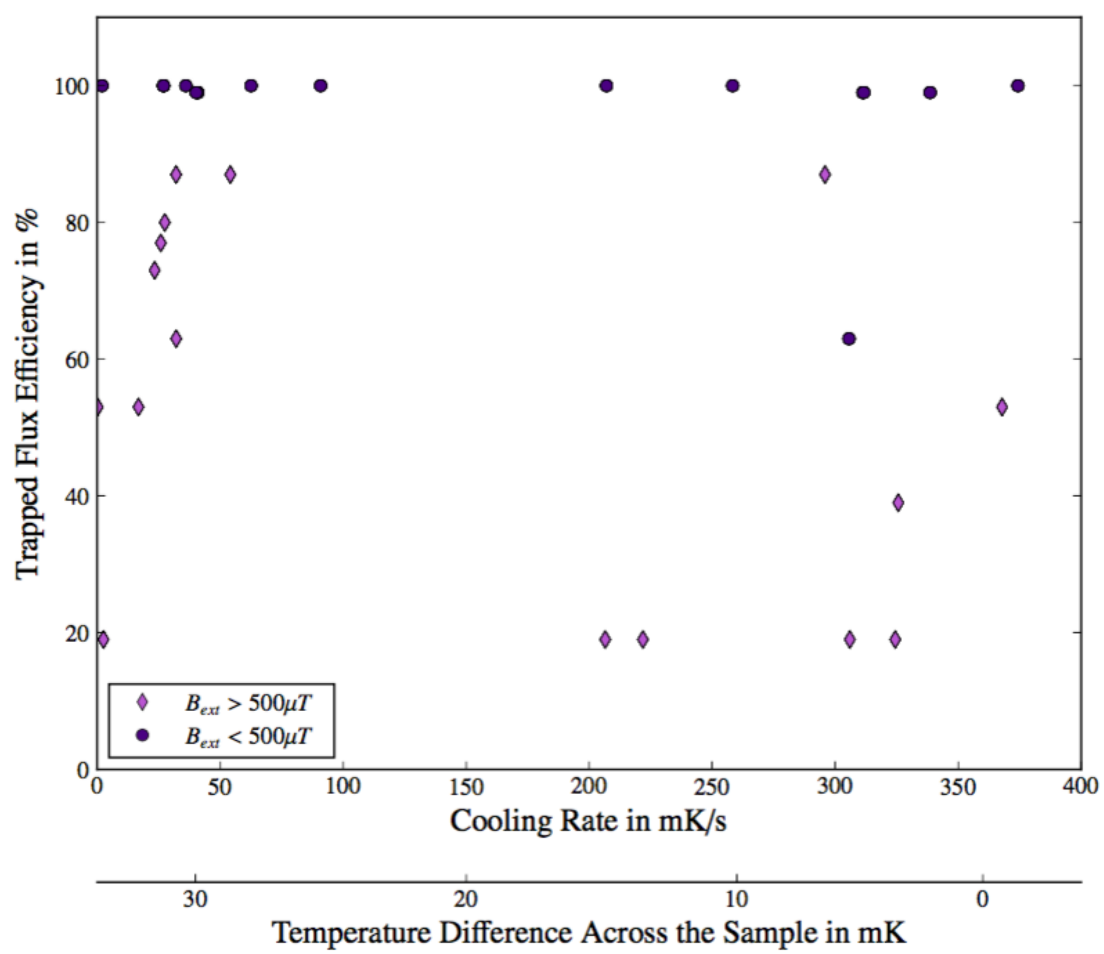
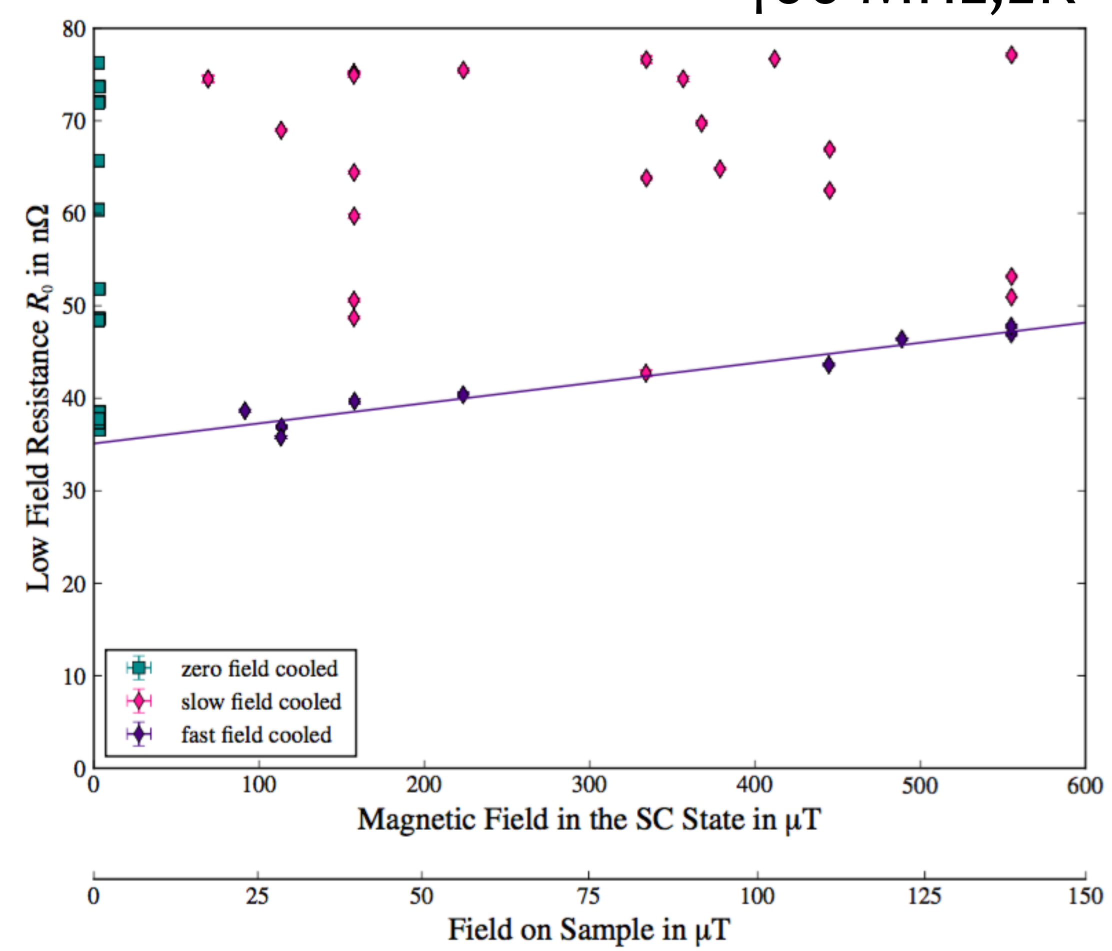


400 MHz,2K



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- The dependence on cool down dynamics is significantly stronger than losses due to trapped flux.
- ECR coating still shows low trapped flux sensitivity

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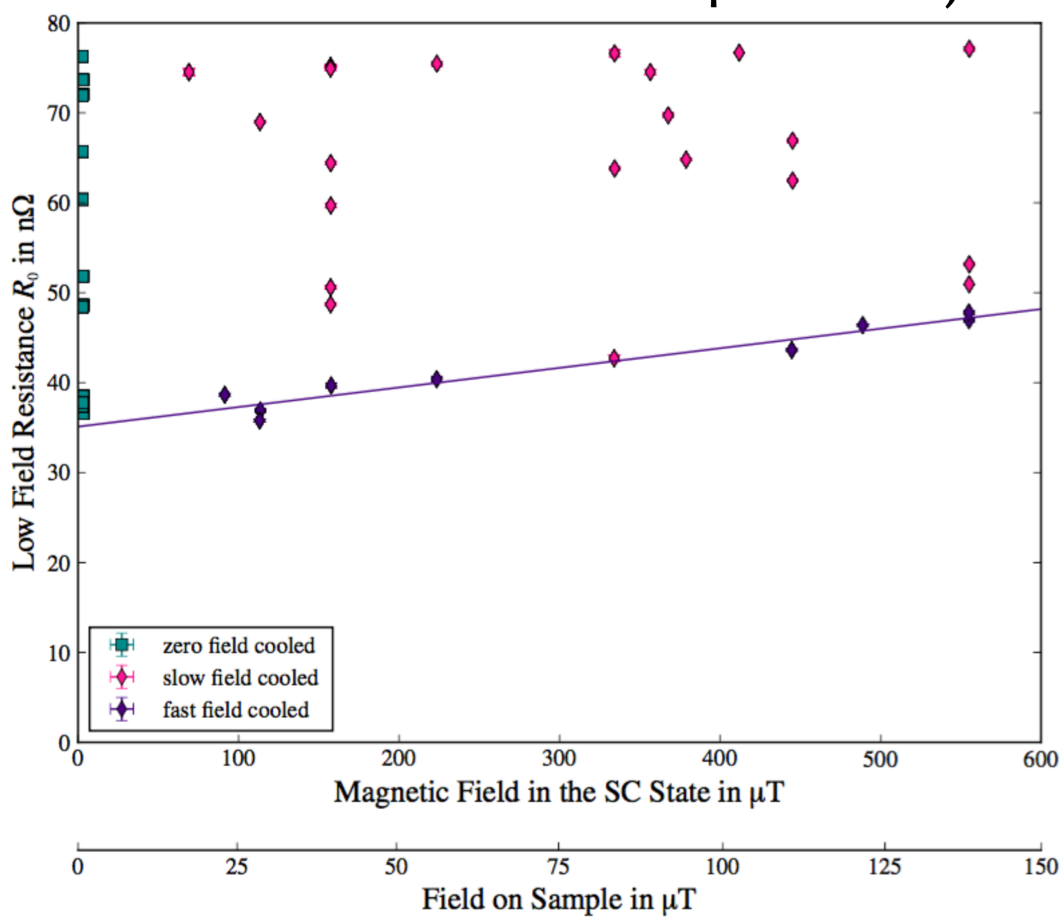

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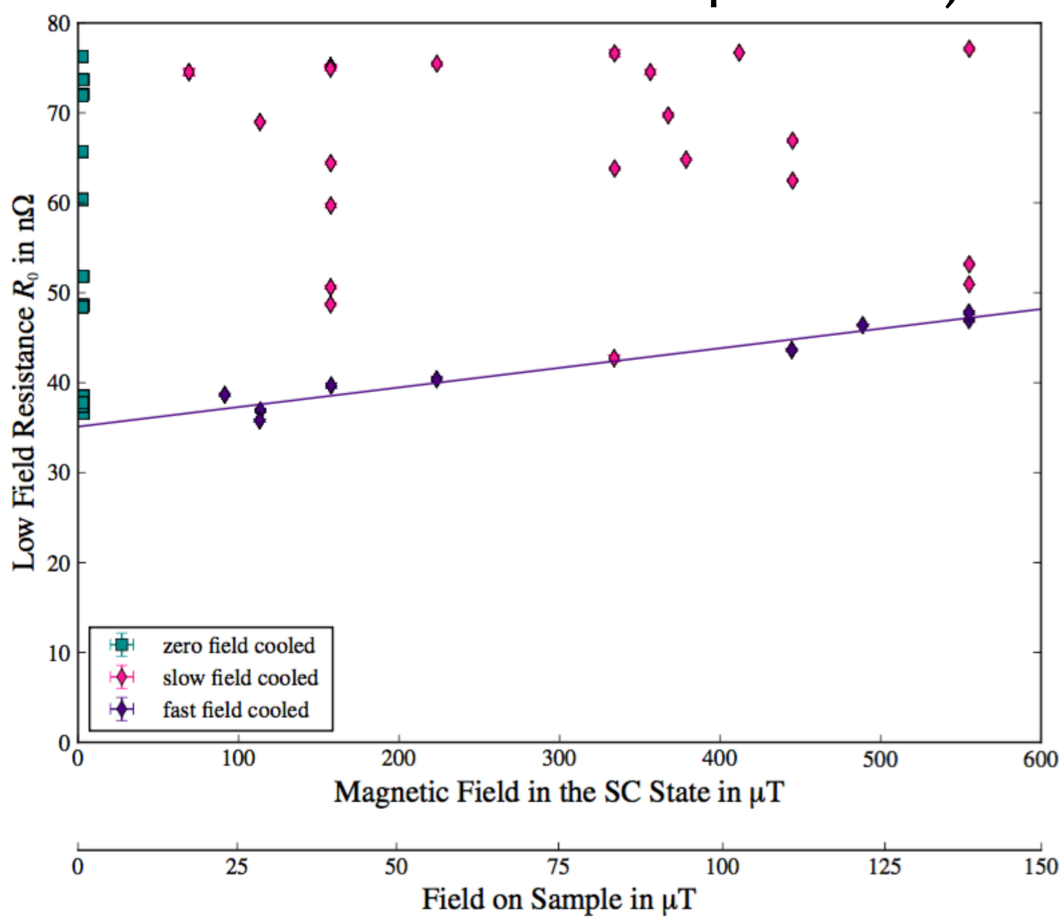

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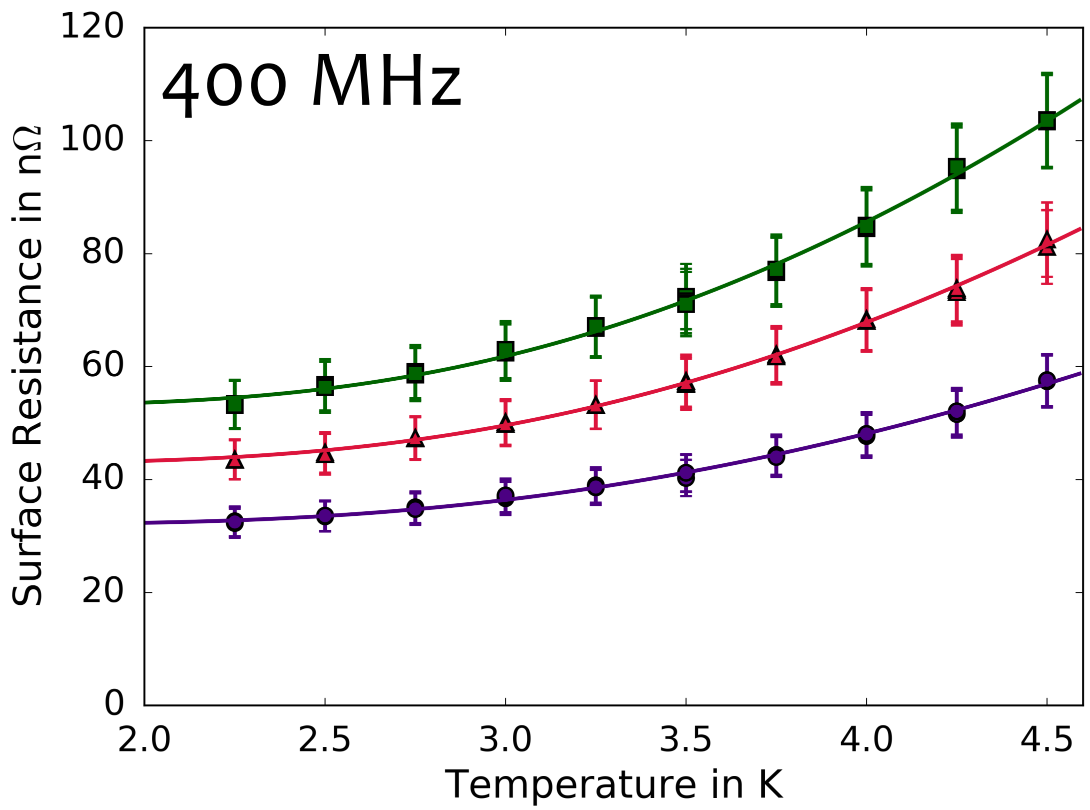
What causes the strong surface resistance dependence on cool down dynamics?

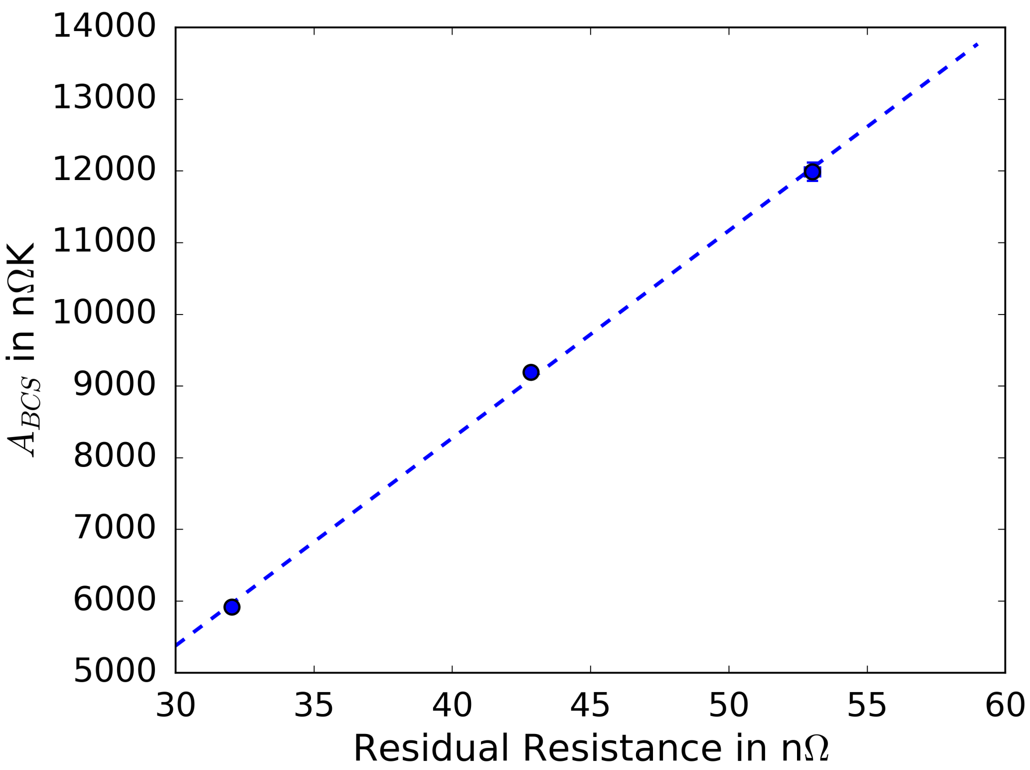
ECR2

- Measure $R_S\,(400\,\mathrm{MHz}, 10\,\mathrm{mT}, T)$ for three different thermal cycles.
- Fit with $R_S\,(T) = \frac{A_{BCS}}{T}\exp\left(\frac{\Delta}{k_B T}\right) + R_{res}$
- Find unchanged superconducting gap —> re-run fit with common Δ



Effect of Thermal Cycling

- BCS factor strongly increases with residual resistance
- $A_{\mathrm{BCS}} \sim \omega^2 \cdot \ell \cdot \lambda\,(T,\ell)^{3-4}$
- Hint towards strong magnetic fields? Due to thermal currents?



Conclusion

- Analysis of various RF data in combination with FIB-SEM supports that adhesion plays the key role in curing the Q-slope in Nb/Cu.
- Consistent picture for Nb/Cu: Temperature gradients when crossing T_c increase low field surface resistance.
- Magnetic flux expulsion only above threshold field.
- No correlation (so far) between cool down rate/temperature gradient and amount of flux expulsion.
- Effect of temperature gradient significantly stronger than trapped flux.
- Thermal cycling appears to change the effective penetration depth.