HIGH Q_0 RESEARCH: THE DYNAMICS OF FLUX TRAPPING IN SC NIOBIUM

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SRF 2013 Paris, Tuesday, 24 September 2013

QUEST FOR HIGH Q_0: RESIDUAL RESISTANCE ELIMINATION

$$G / Q_0 = R_{surface} = R_{BCS}(f, T) + R_{residual}(?)$$

- Trapped vortices under rf field (up to 100% of ambient field)
- Lossy oxides or metallic hydrides on surface
- Grain boundaries
- Precipates
- Generation of hypersound
- Localized electron surface states
- ...

→ Surface treatment,
Bake out

TRAPPED VORTICES UNDER RF FIELD

Reduction of trapped vortices

- Shielding (earth field)
- Can we reduce pinning centers? Impact niobium material properties the trapping behavior?
- Are there additional ways to optimize Meissner effect?
- Do temperature gradients generate trapped flux?

Impact of trapped vortices on losses

$$R_{residual} \propto B_{applied}$$

⟶ *Phys Rev B 87, Gurevich and Ciovati (2012)*

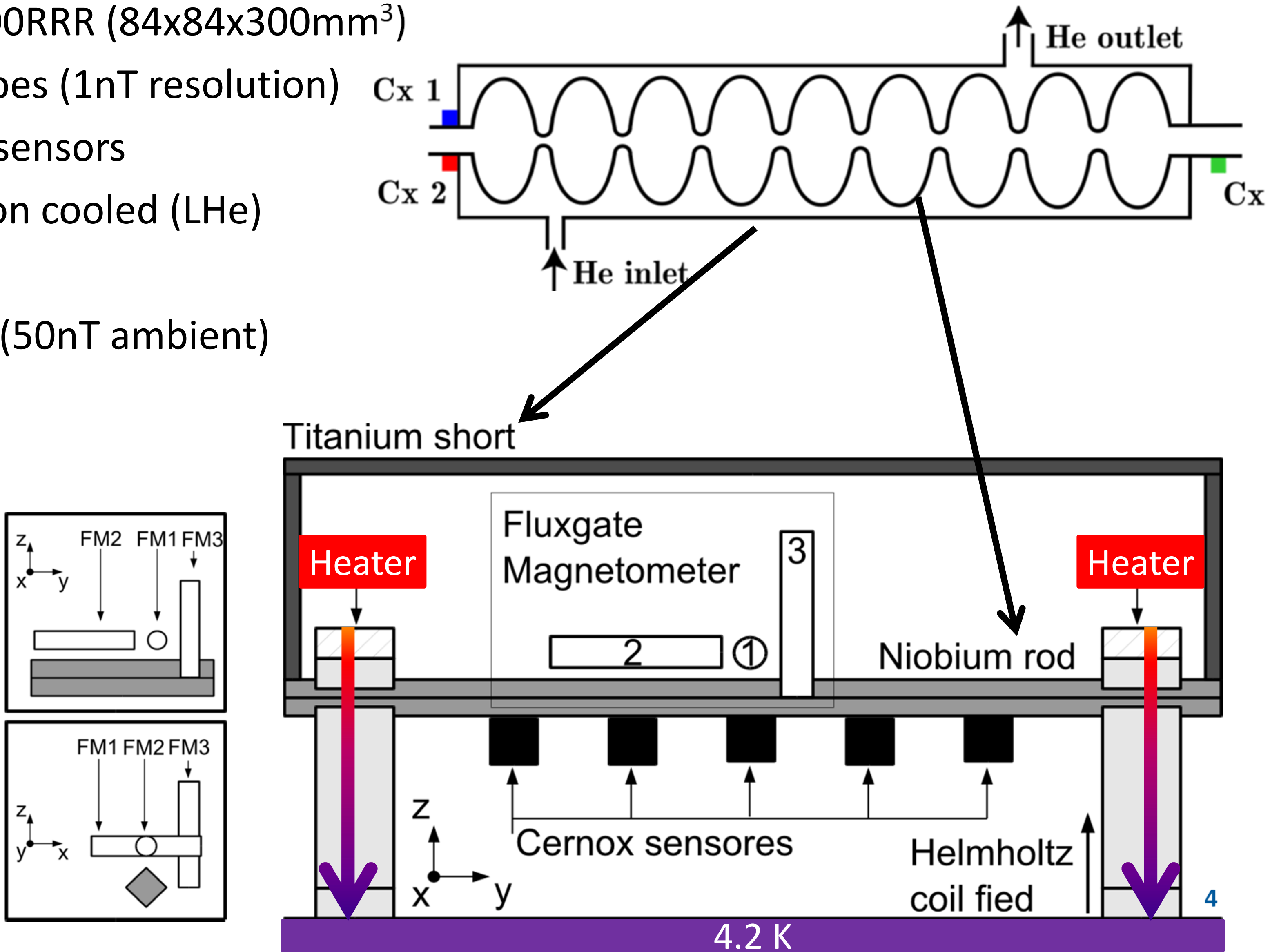
Empiric: 1µT⇔3.5nΩ (TESLA)

⟶ *Phys. Rev. STAB 3, B. Aune, et al. (2000)*

⟶ *Vogt, Kugeler and Knobloch, PRSTAB (accepted for publication, Sept. 11, 2013)*

MODEL SYSTEM

- Mimics thermoelectric properties of cavity-tank system
- Nb rod 300RRR (84x84x300mm^3)
- 3 FM probes (1nT resolution)
- 7 Cernox sensors
- Conduction cooled (LHe)
- 2 heaters
- Shielding (50nT ambient)



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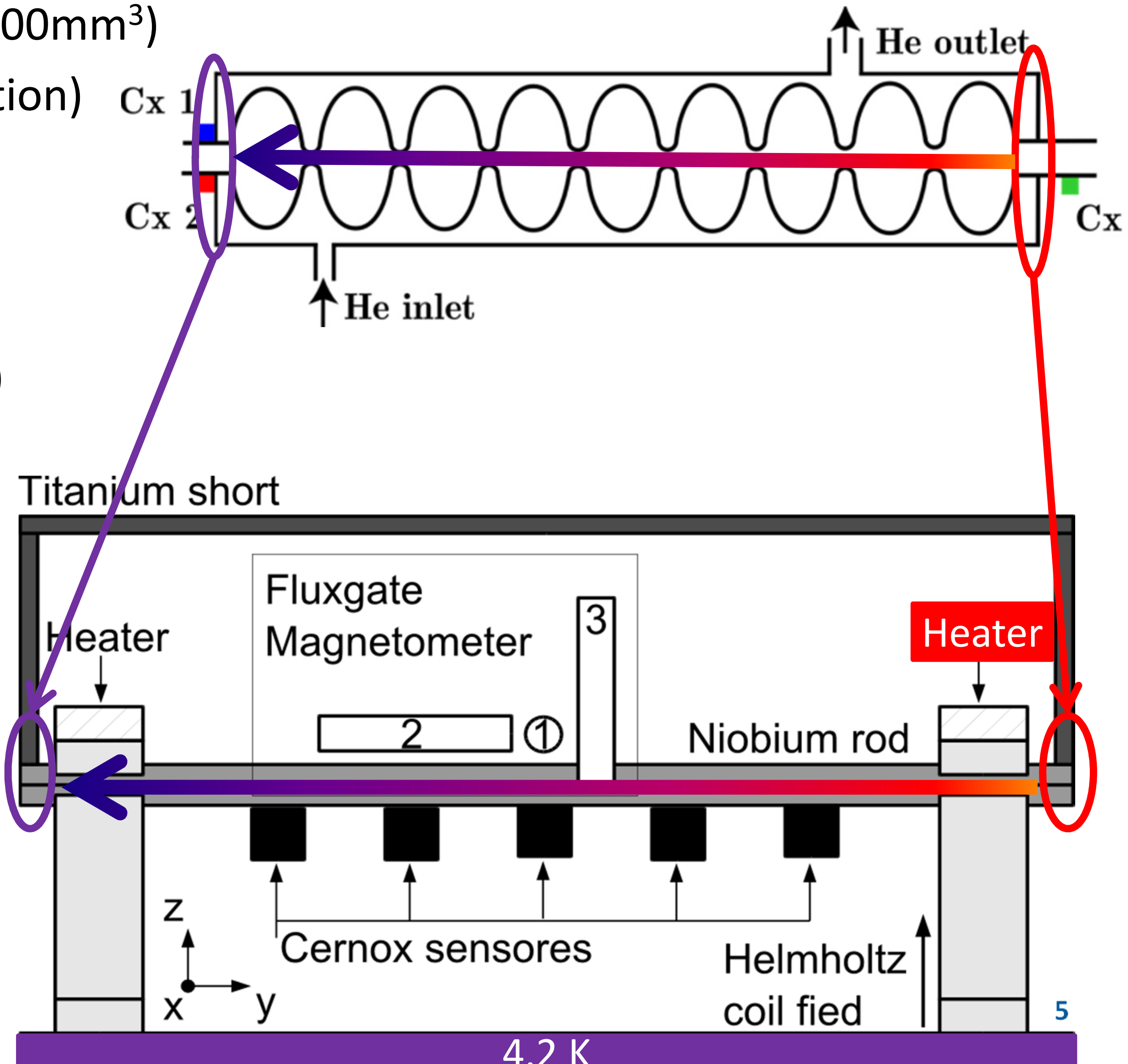
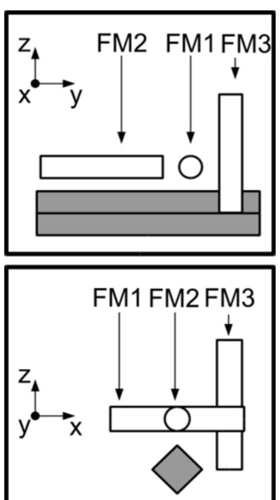
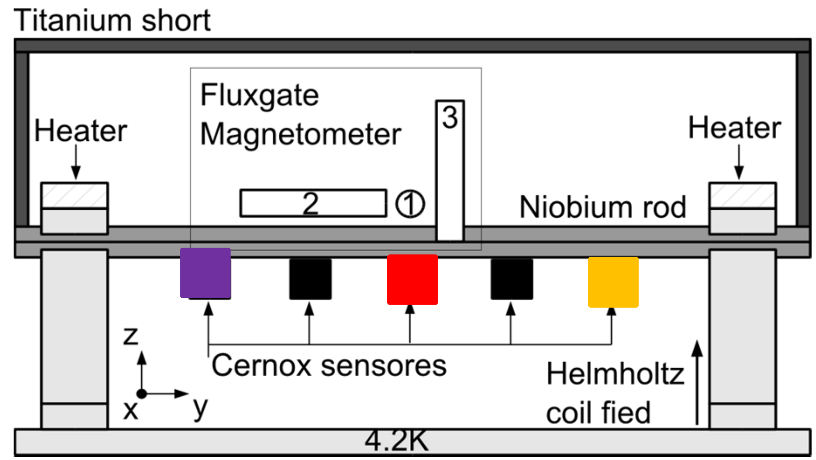
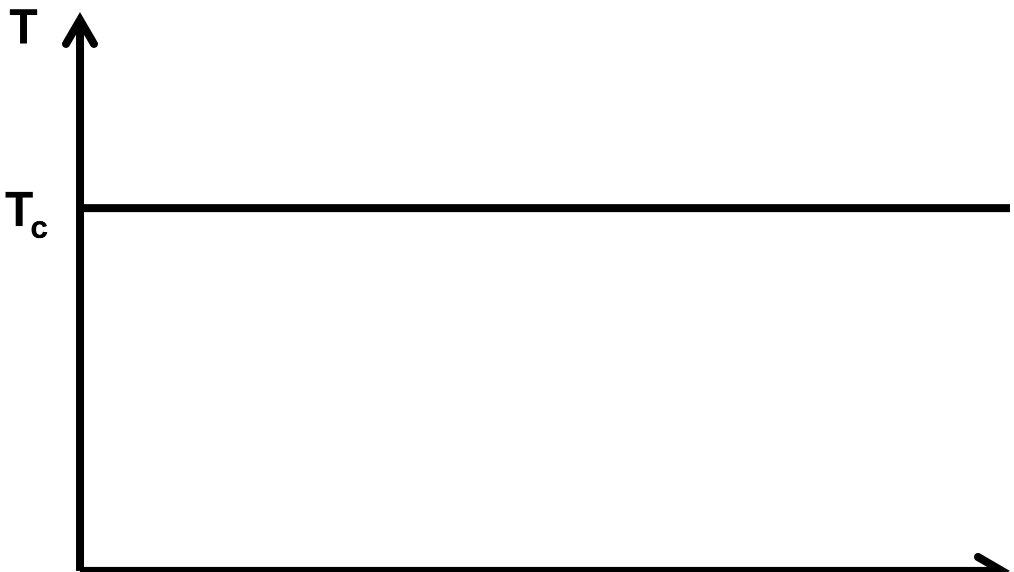




MODEL SYSTEM: THERMOCURRENTS





Two contact points on different temperatures

Level of trapped flux correlates with ΔT at the instance of phase Transition. Thermoelectric effect:

$$B \leftrightarrow I = \Delta V / R = \Delta S \cdot \Delta T / R$$

Thermopower of System $\Delta S = S_{Nb} - S_{Ti}$

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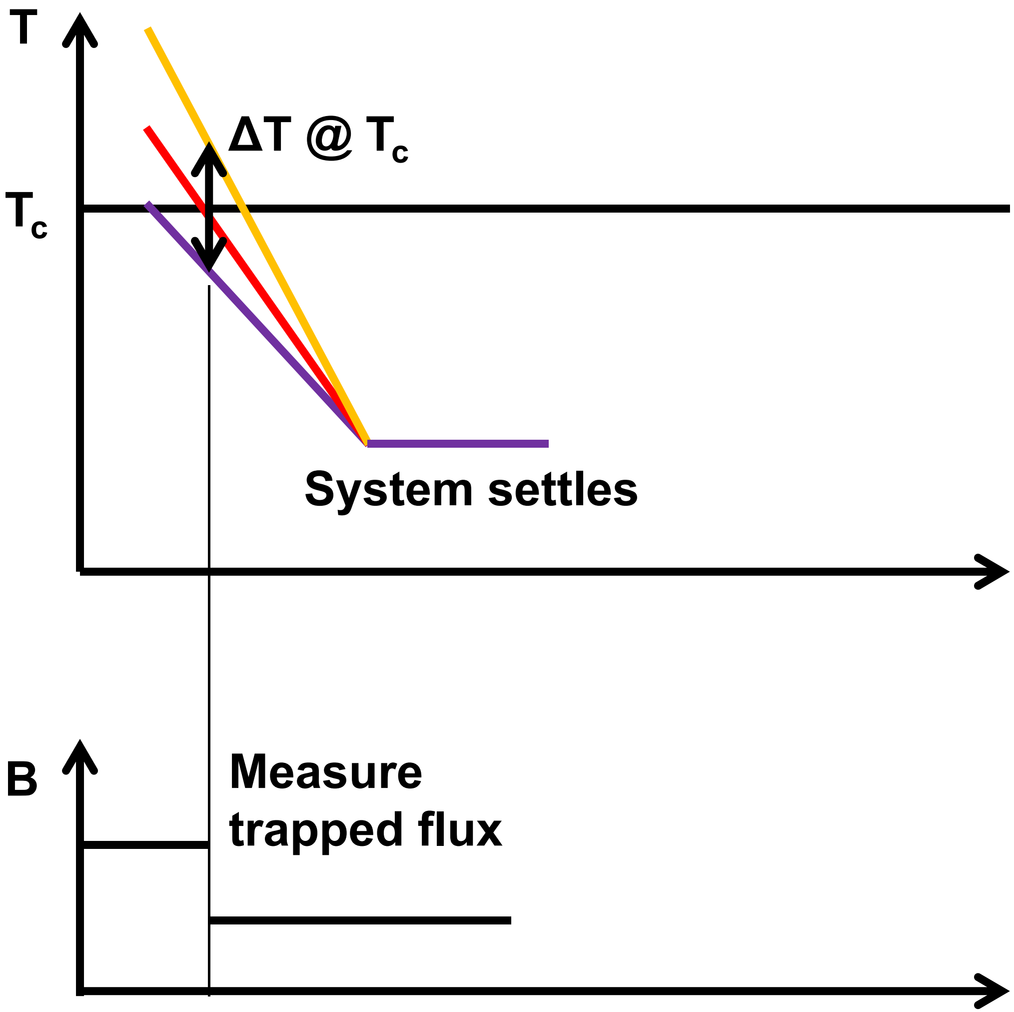

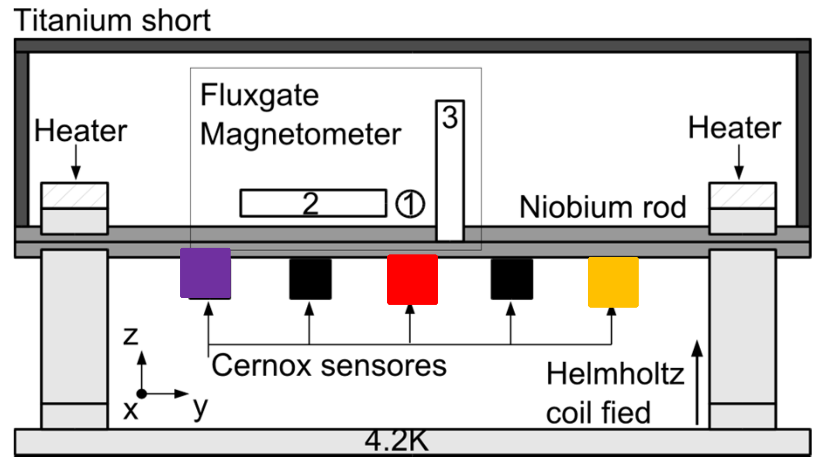

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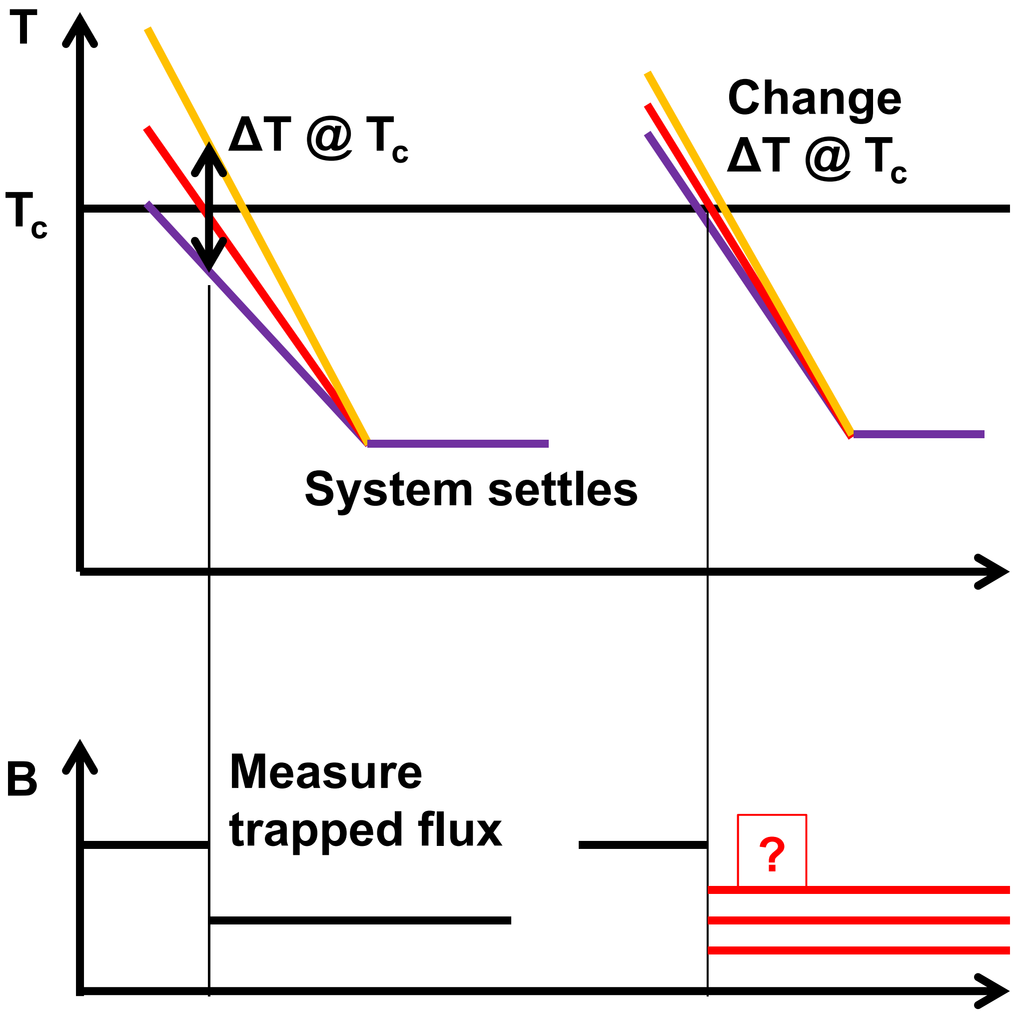

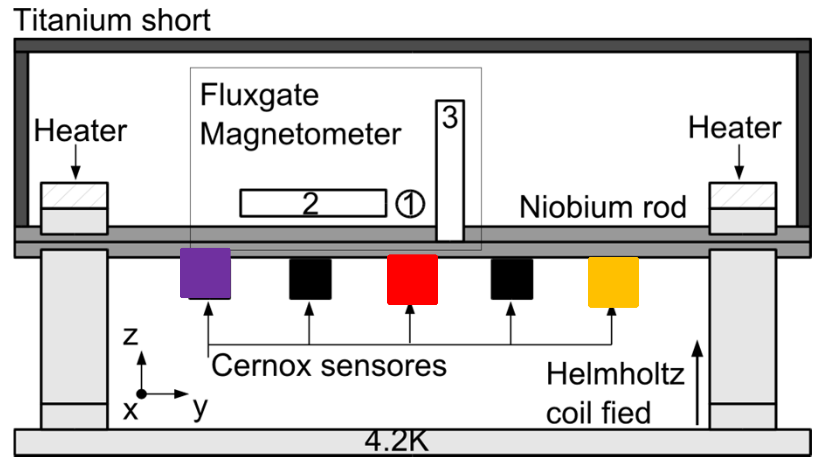

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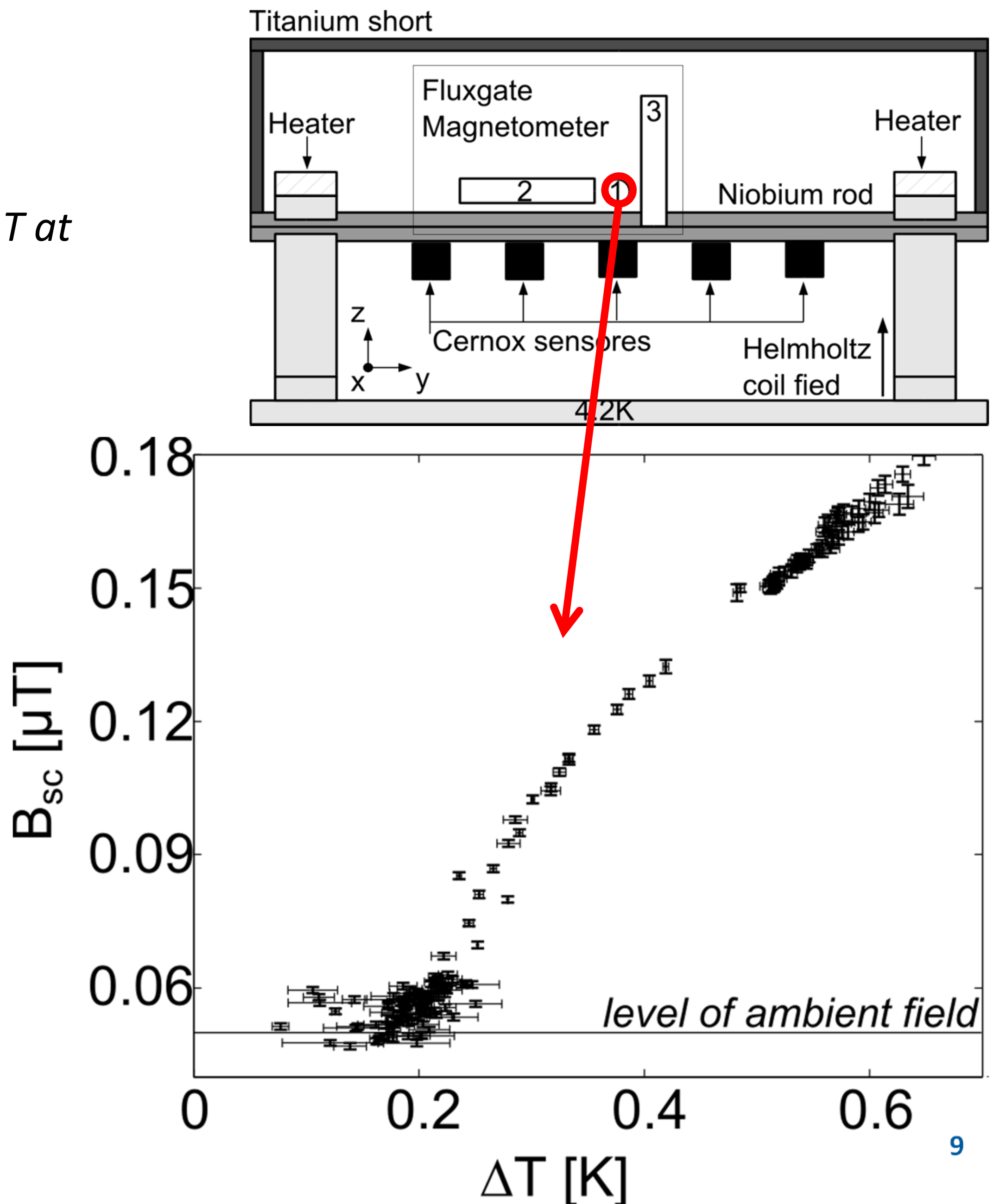
- **Measure temperature difference during phase transition of Nb rod**
- **System settles**
- **Measure trapped flux**



MODEL SYSTEM: THERMOCURRENTS

- **Two contact points on different temperatures**

Level of trapped flux correlates with ΔT at the instance of phase Transition. Thermoelectric effect:

B ↔ I = ΔV / F

Thermopower of Sy

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  during phas
- **System settles**
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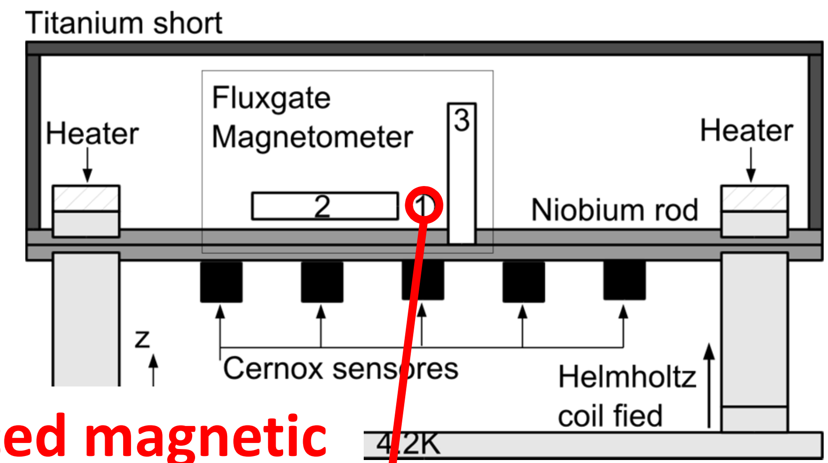
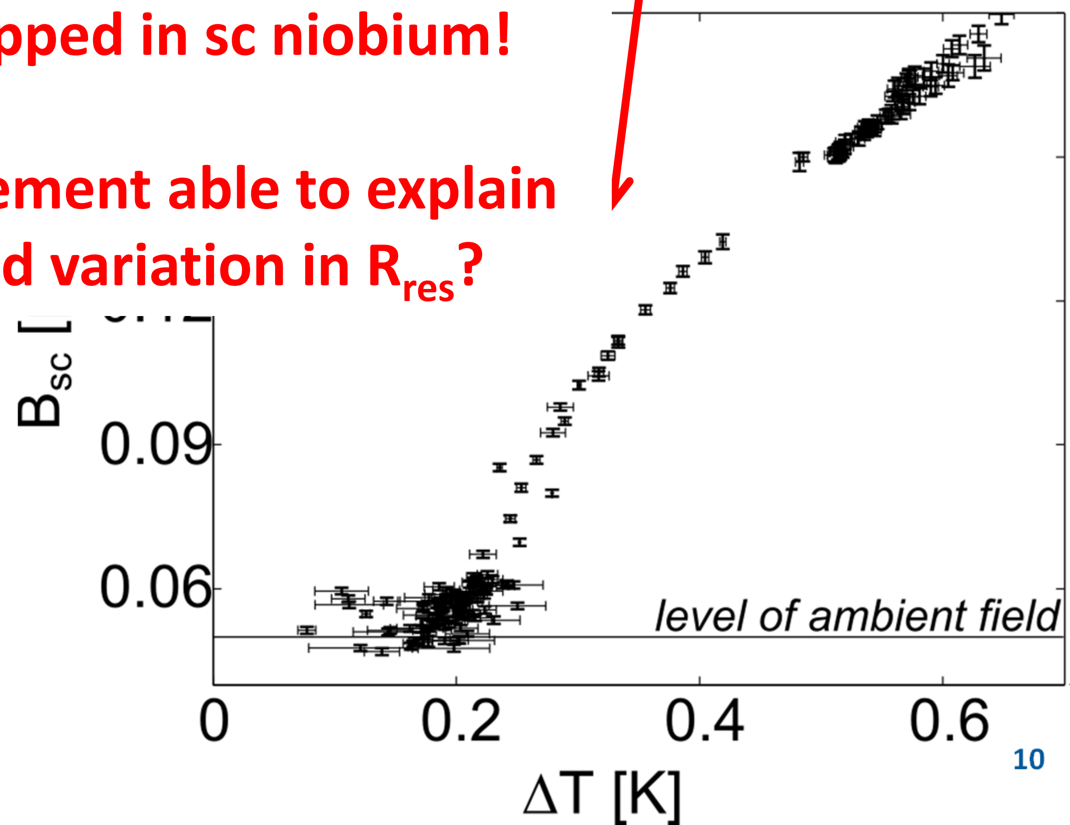
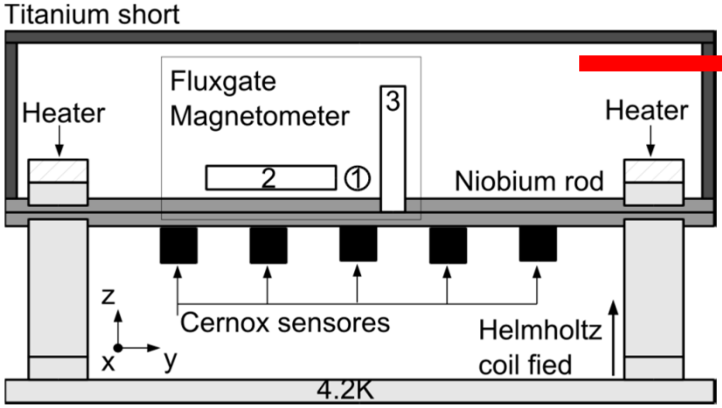


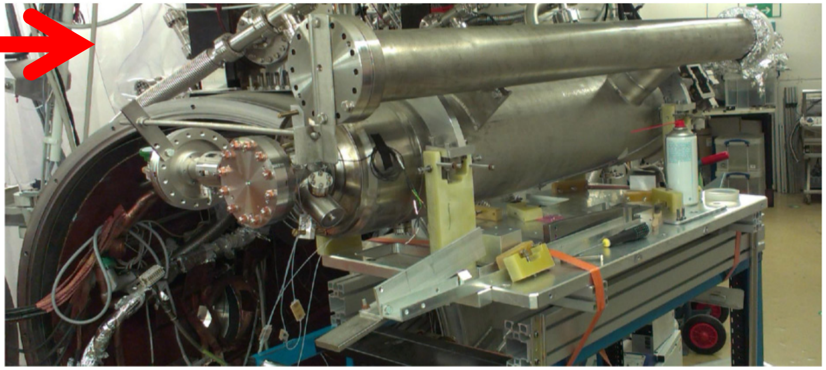
Thermoelectrically induced magnetic field gets trapped in sc niobium!

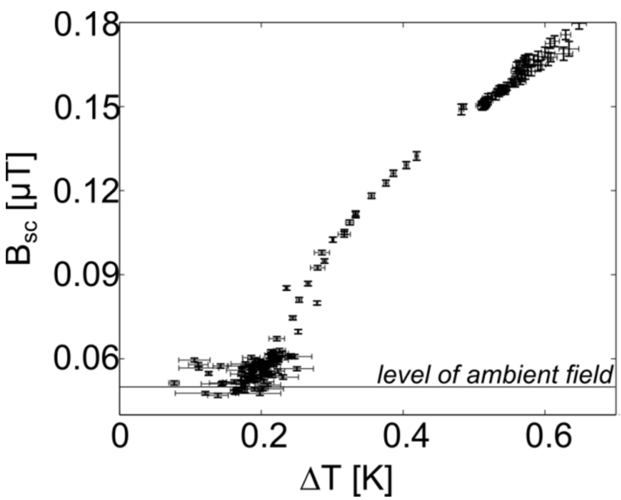
Is this measurement able to explain the observed variation in R_{res}?

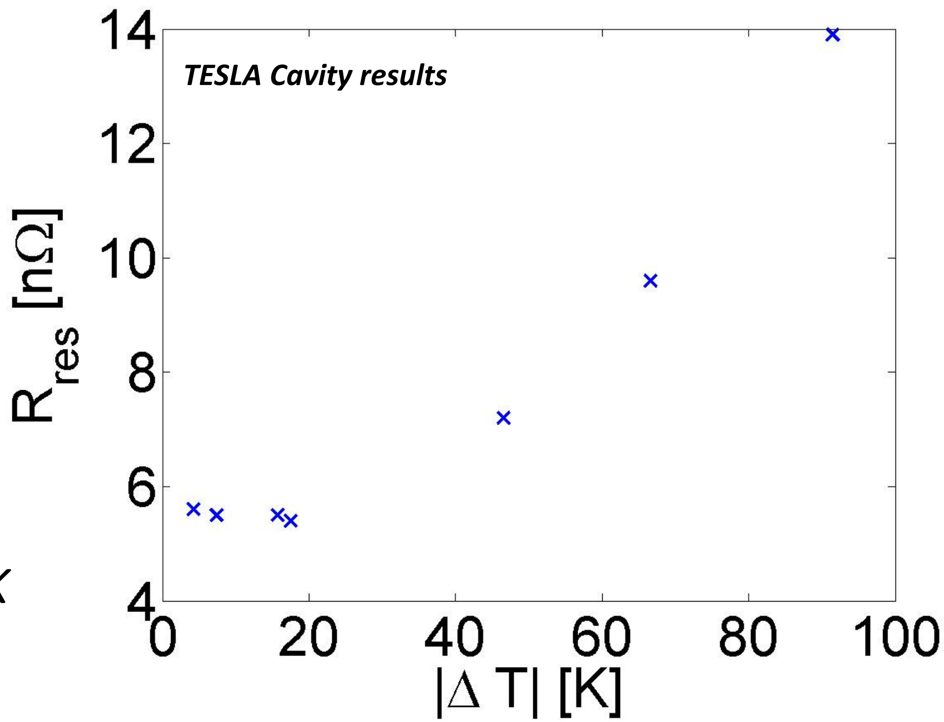


MODEL SYSTEM VS. DRESSED CAVITY: TEST 1









Model system: *B = 0.12μT* for *ΔT = 0.6K*

0.12μT trapped in a TESLA Cavity:

→ $\Delta R_{res} = 0.4n\Omega$

⟶ *Kugeler, Vogt and Knobloch, SRF2013, TUIOA01*

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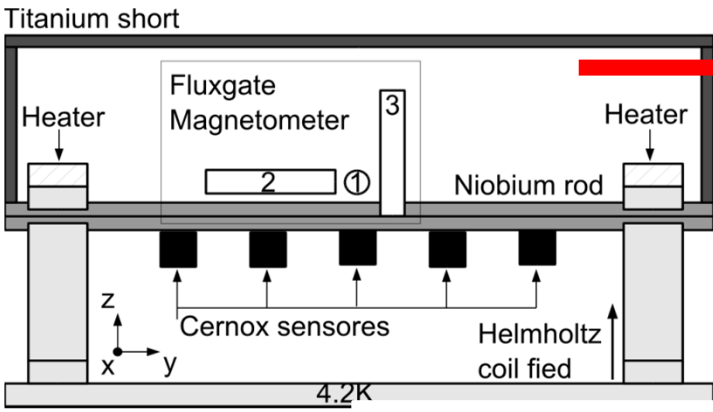
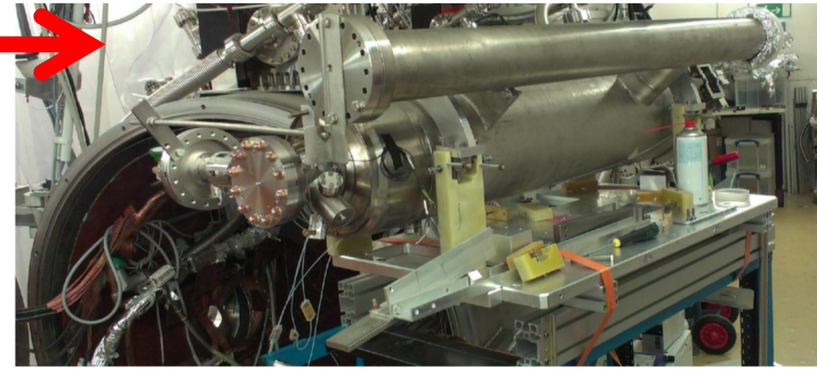
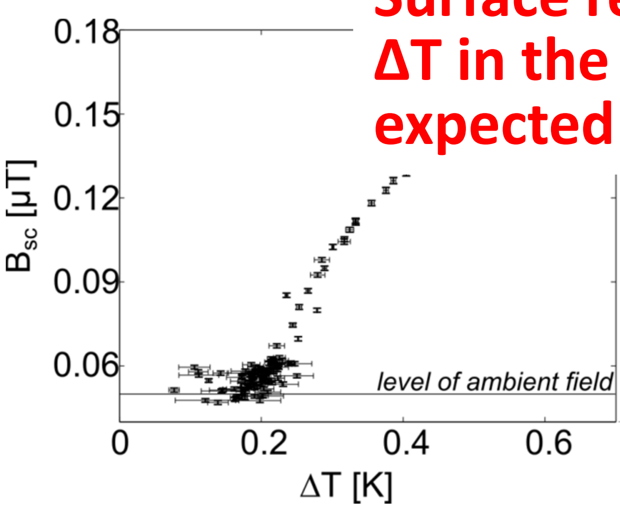
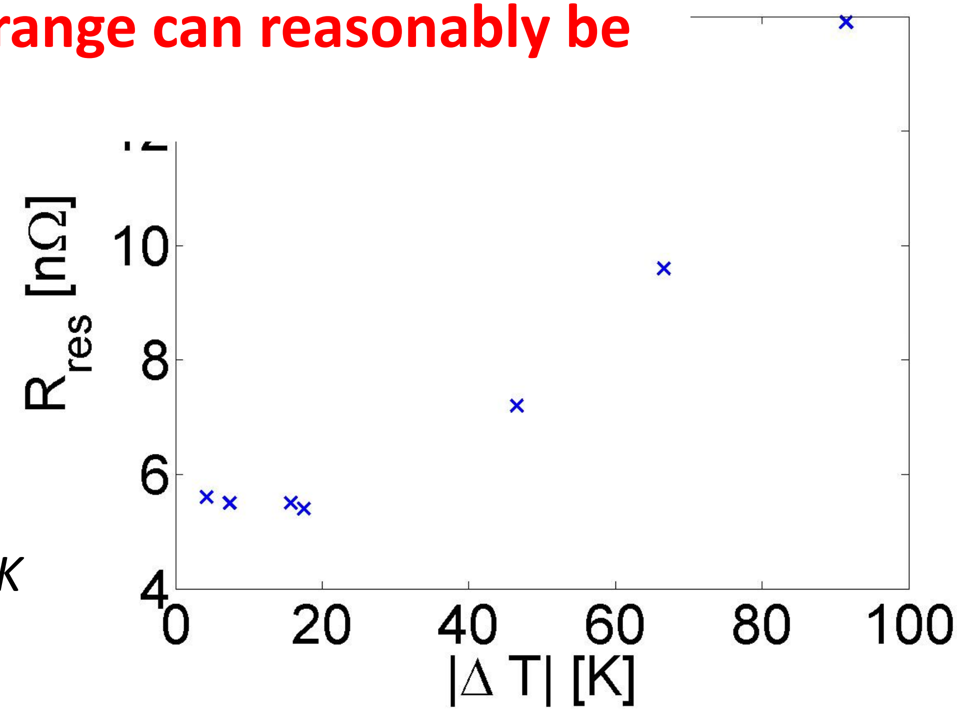






Surface resistance in the 10 nΩ range for ΔT in the 10's K range can reasonably be expected!



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MODEL SYSTEM VS. DRESSED CAVITY: TEST 2

Is this measurement able to explain the observed variation in R_{res}?

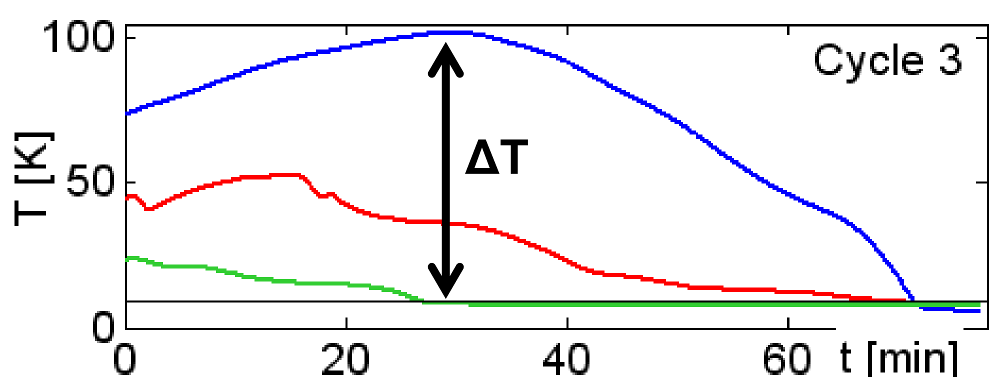
$$B \leftrightarrow I = \Delta V / R = \Delta S \cdot \Delta T / R$$

Thermopower: **$\Delta S \approx 10\mu V/K$**
Literature is not consistent for titanium.
Independent measurement performed in HoBiCaT.

Parameter of cavity-tank system @10K:
$R \approx 100\mu\Omega$ (dominated by titanium tank)

→ *J. Milck, Tech. Rep., Hughes Aircraft Company (1970)*

$$= 10\mu V/K \cdot 100K / 100\mu\Omega = 1A$$



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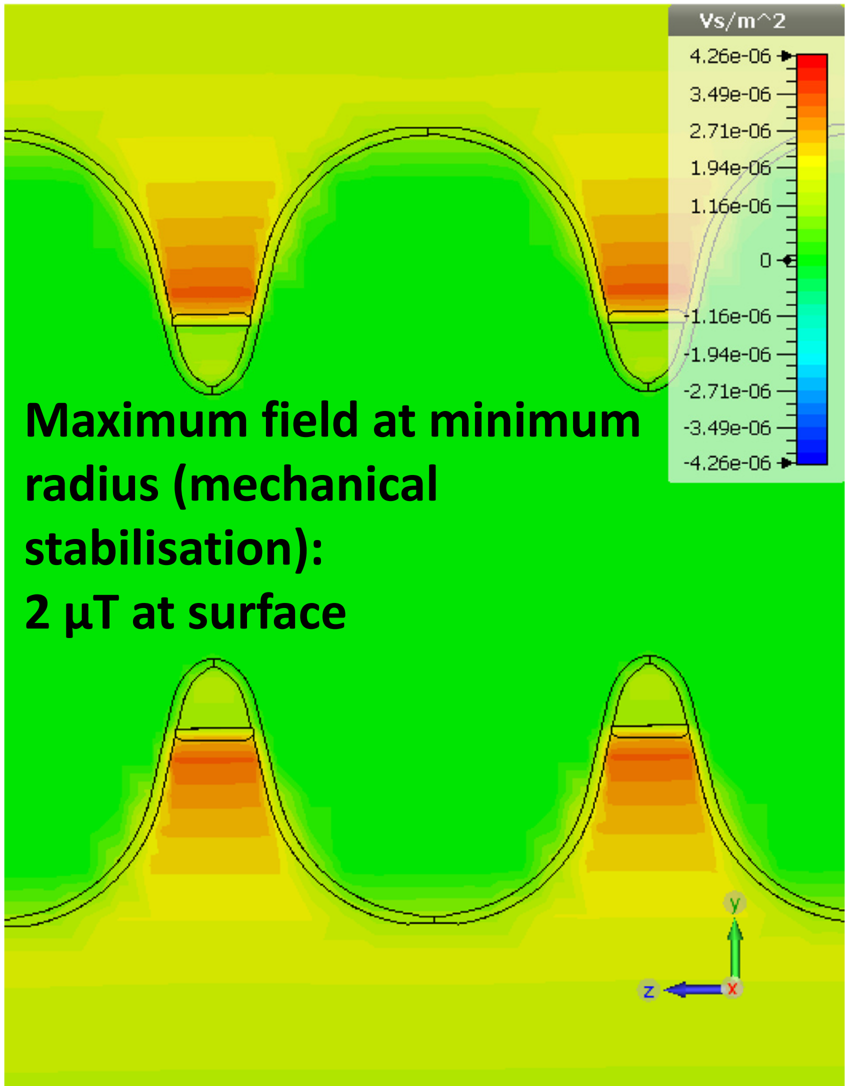
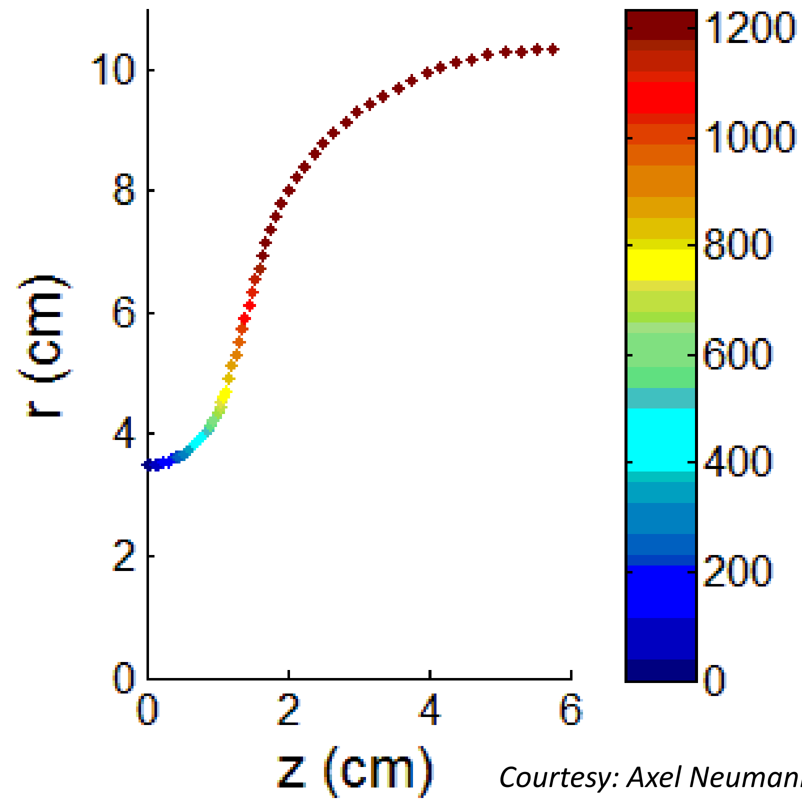


Maximum field at minimum radius (mechanical stabilisation):
2 µT at surface

TESLA half cell, TM_{010} π–mode, surface H-field



Courtesy: Axel Neumann

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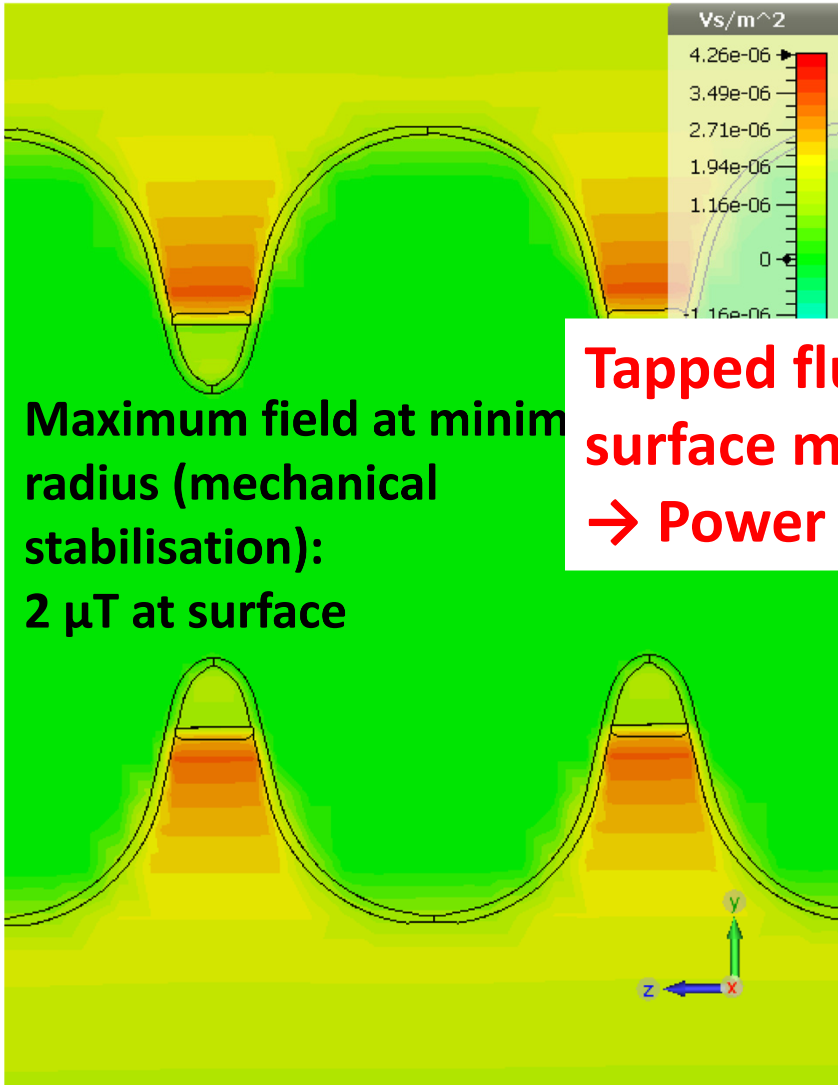

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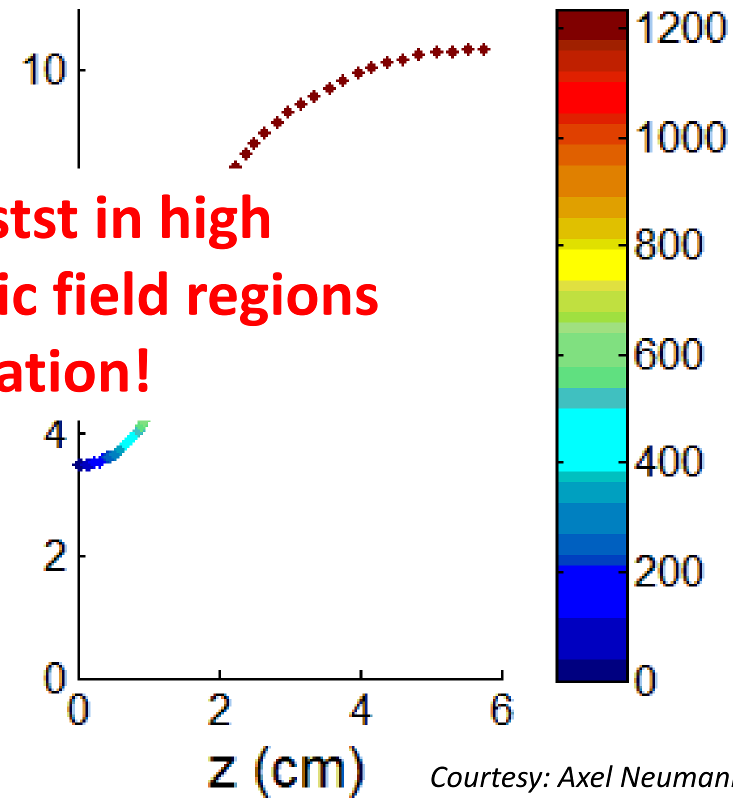

Tapped flux existst in high surface magnetic field regions
→ Power dissipation!

Courtesy: Axel Neumann

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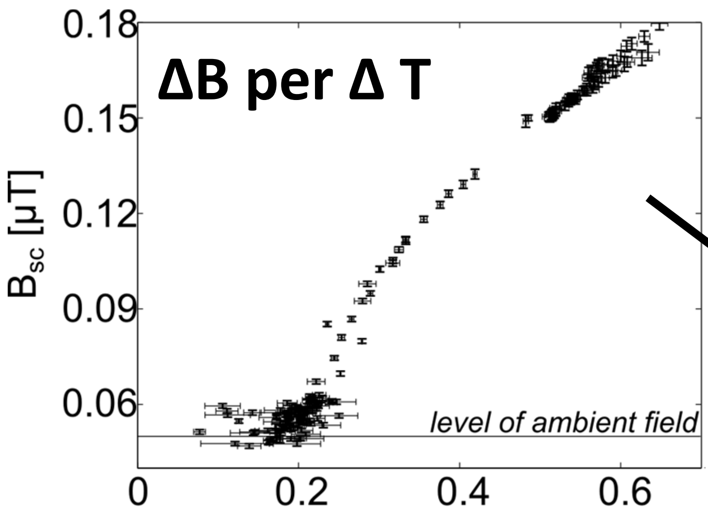
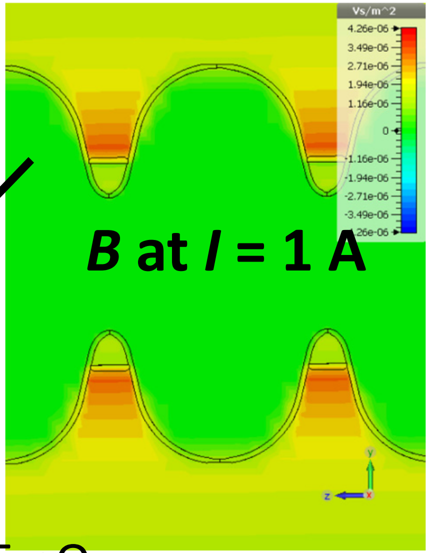
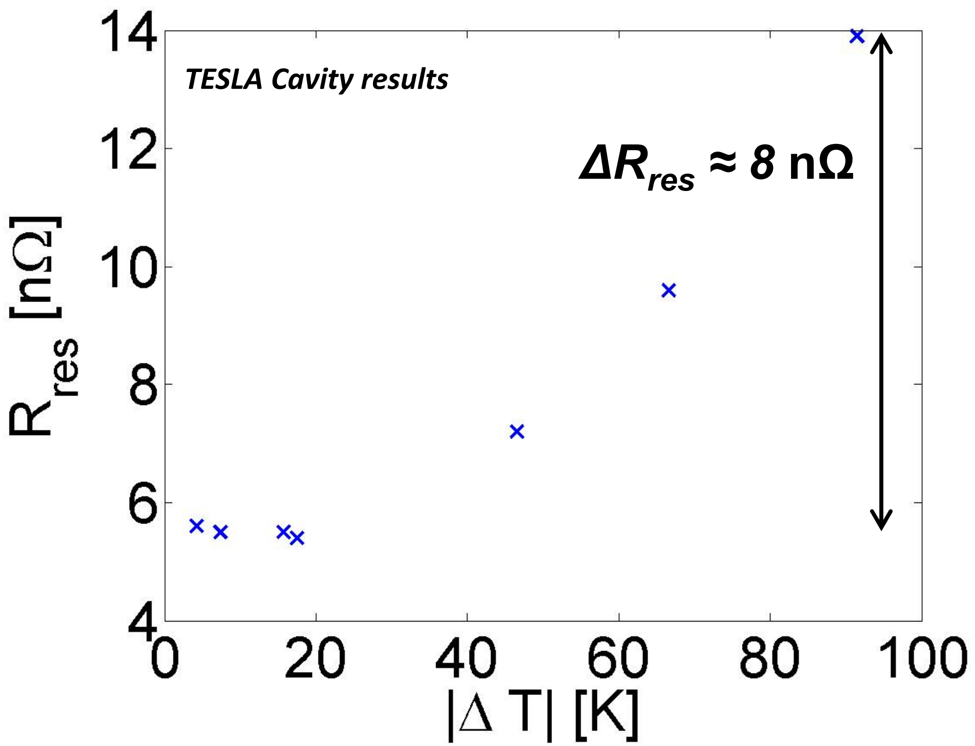




2 μT trapped flux
for ΔT = 100K

1 μT↔3.5 nΩ

cause **7 nΩ** additional
surface resistance



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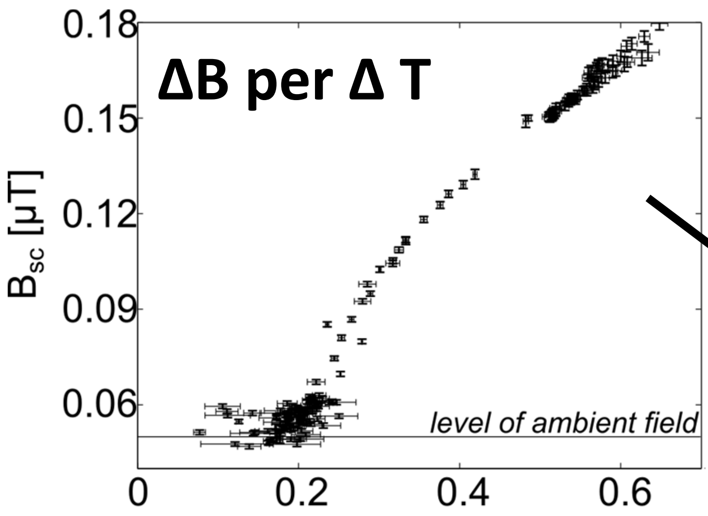

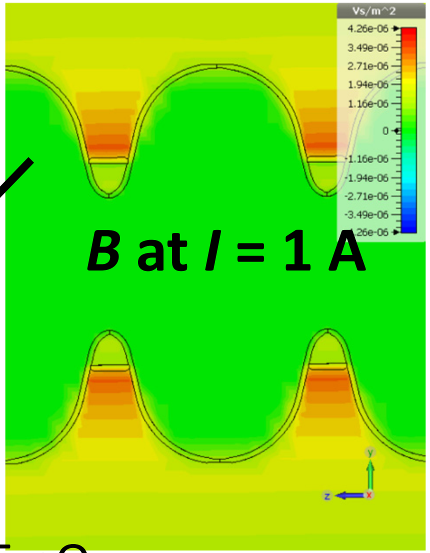

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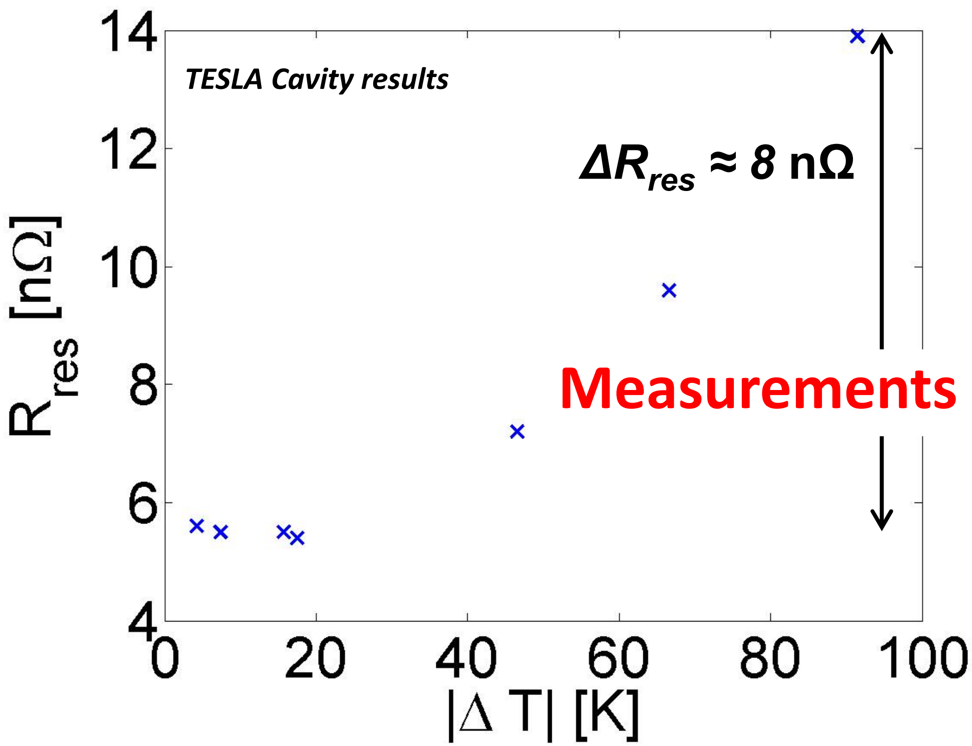

Measurements are consistent!

TRAPPED VORTICES UNDER RF FIELD

Reduction of trapped vortices

- Shielding (earth field)
- Do temperature gradients generate trapped flux?
- Can we reduce pinning centers? Impact niobium material properties the trapping behavior?
- Are there additional ways to optimize Meissner effect?

Impact of trapped vortices on losses

$$R_{residual} \propto B_{applied}$$

⟶ *Phys Rev B 87, Gurevich and Ciovati (2012)*

Empiric: 1µT↔3.5nΩ (TESLA)

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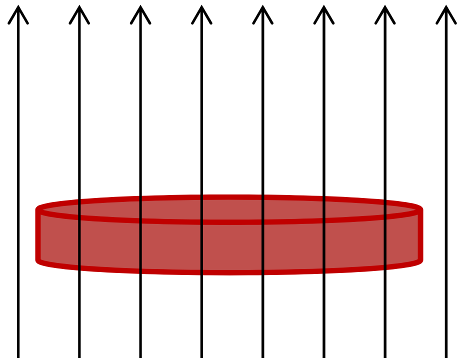
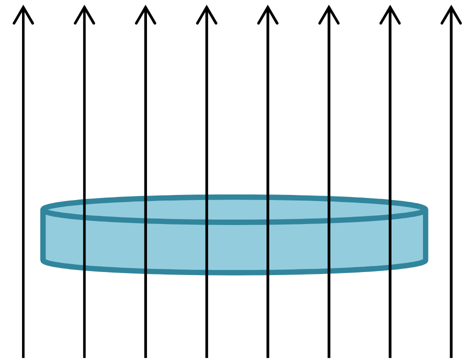
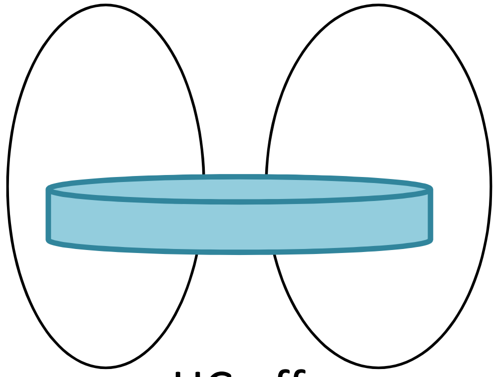
FLUX TRAPPING IN DISK-SHAPED NIOBIUM SAMPLES



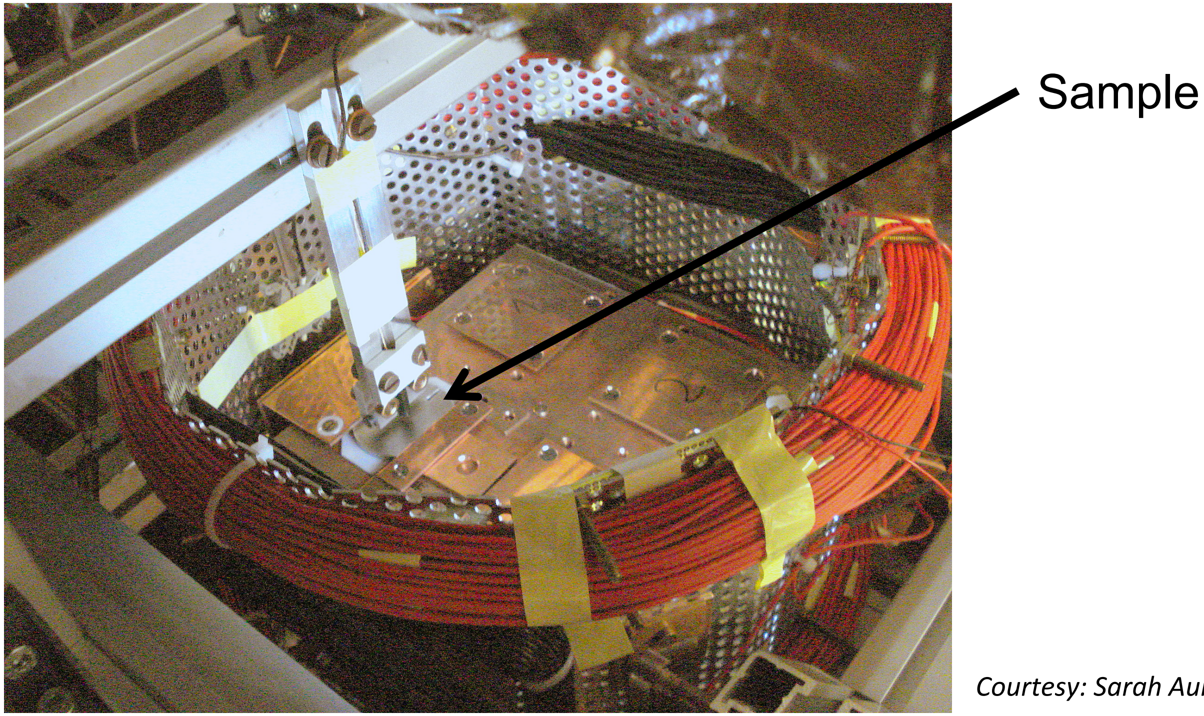
Helmholtz coil applies magnetic field



Field cooled



HC off,
Measure magnetization



Courtesy: Sarah Aull

FLUX TRAPPING IN DISK-SHAPED NIOBIUM SAMPLES (≈300RRR)

#	Crystal structure	Treatment	Fraction of trapped flux
1	Polycrystalline	None	100%
2	Polycrystalline	BCP	100%
3	Polycrystalline	BCP + 800°C bake out	$(83.1 \pm 0.8)\%$
4	Single crystal	BCP	$[(72.9 + 0.1\,\ln v) \pm 0.8]\%$
5	Single crystal	BCP + 800°C bake out	$[(61.6 + 1.3\,\ln v) \pm 0.8]\%$
6	Single crystal	BCP + 1200°C bake out	$[(42.1 + 0.13\,\ln v) \pm 0.6]\%$

→ *Aull, Kugeler and Knobloch, PRSTAB 15, 062001 (2012)*

depends on cooling rate $v = \Delta T/\Delta t$

Consistant with results that Q's of large grain cavities are greater.
For example W. Singer, MOIOA03: "Large grain cavities on average have 60% higher Q"

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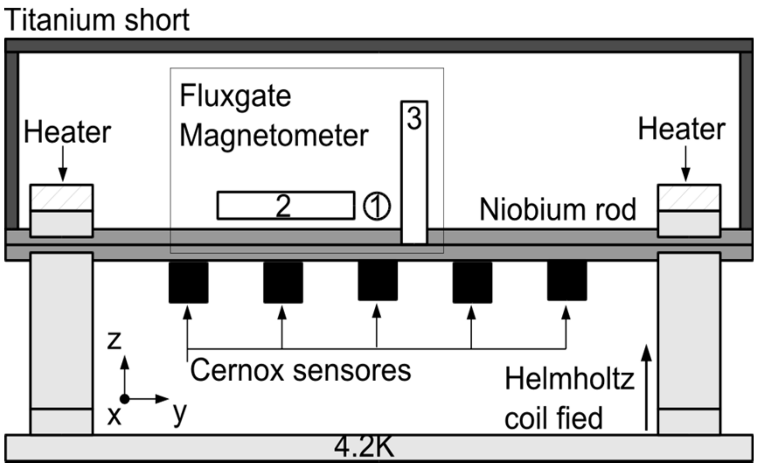
COOLING RATE

- Ambient field increased to 3µT (0.3µT in FM1 direction)
- Vary cooling rate during isothermal cooldown (max ΔT < 0.1K)
- Slower transition supports Meissner effect
- Logarithmic correlation



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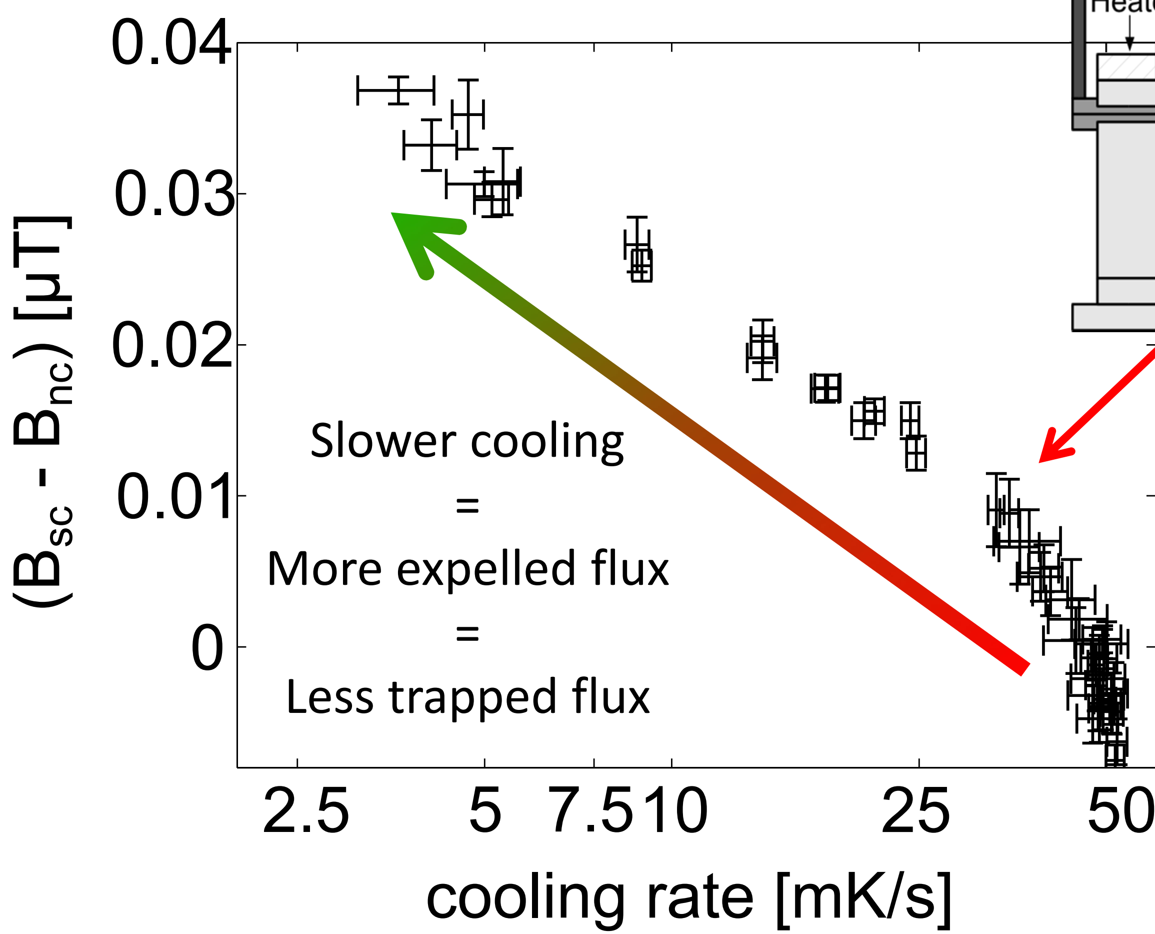

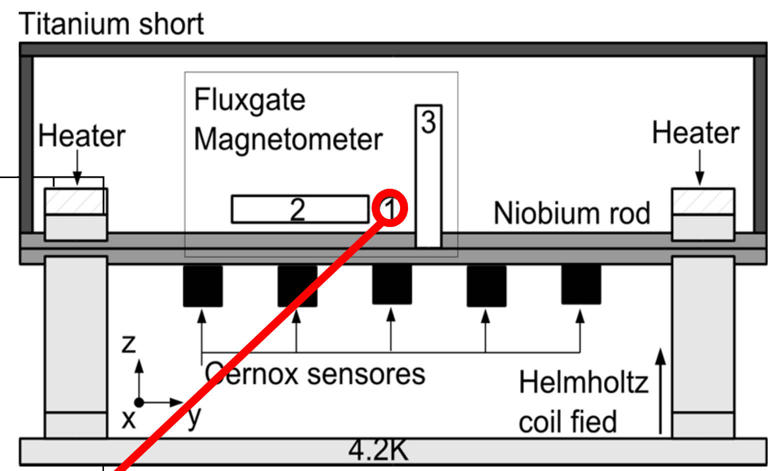

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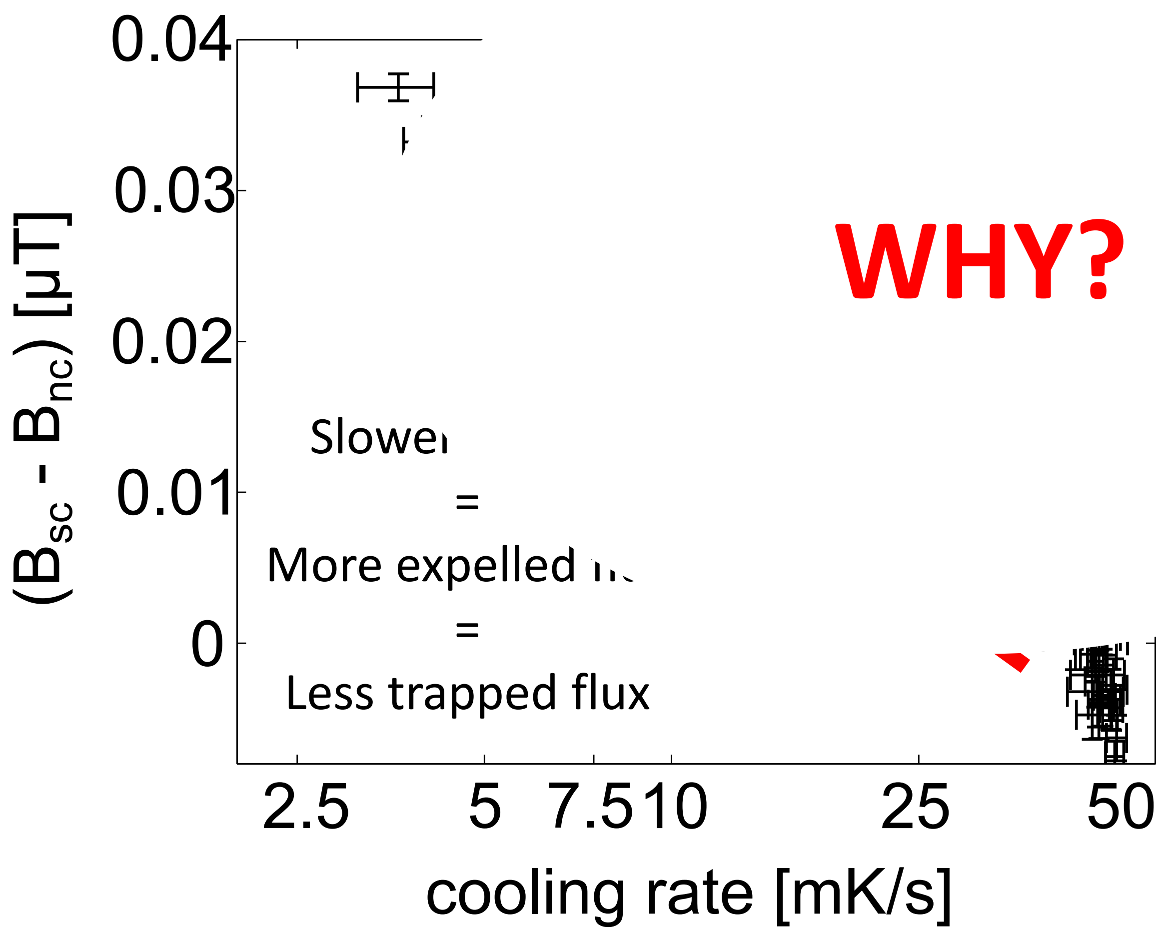
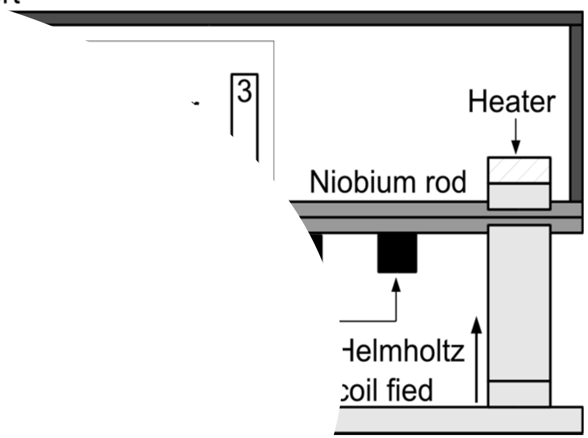
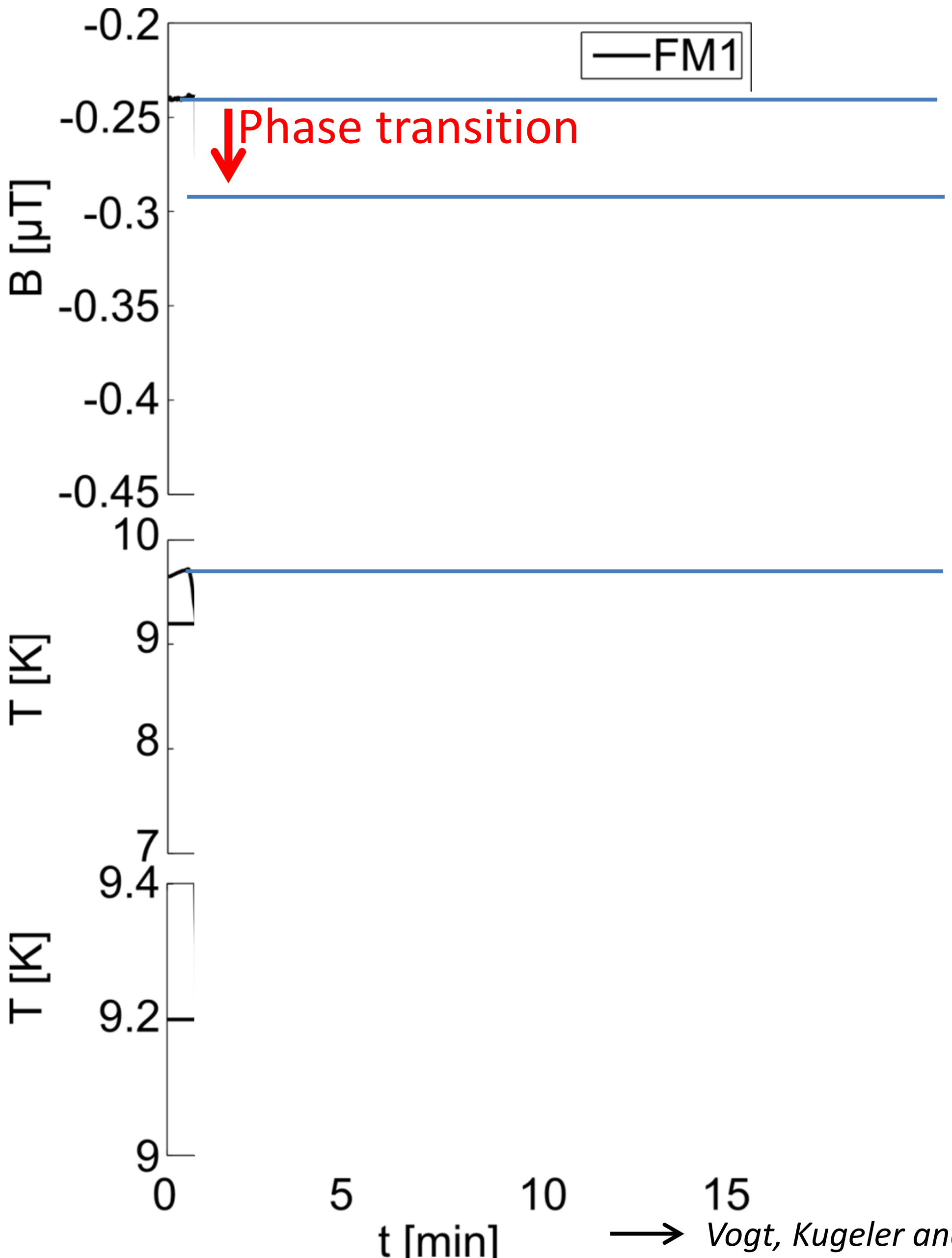


WHY?



INCREASED FLUX MOBILITY CLOSE TO TRANSITION TEMPERATURE



Level ambient field

Initially expelled flux:
$\Delta B \approx 50nT$

Starting temperature of rod

→ *Vogt, Kugeler and Knobloch, IPAC2013, WEPWO004*

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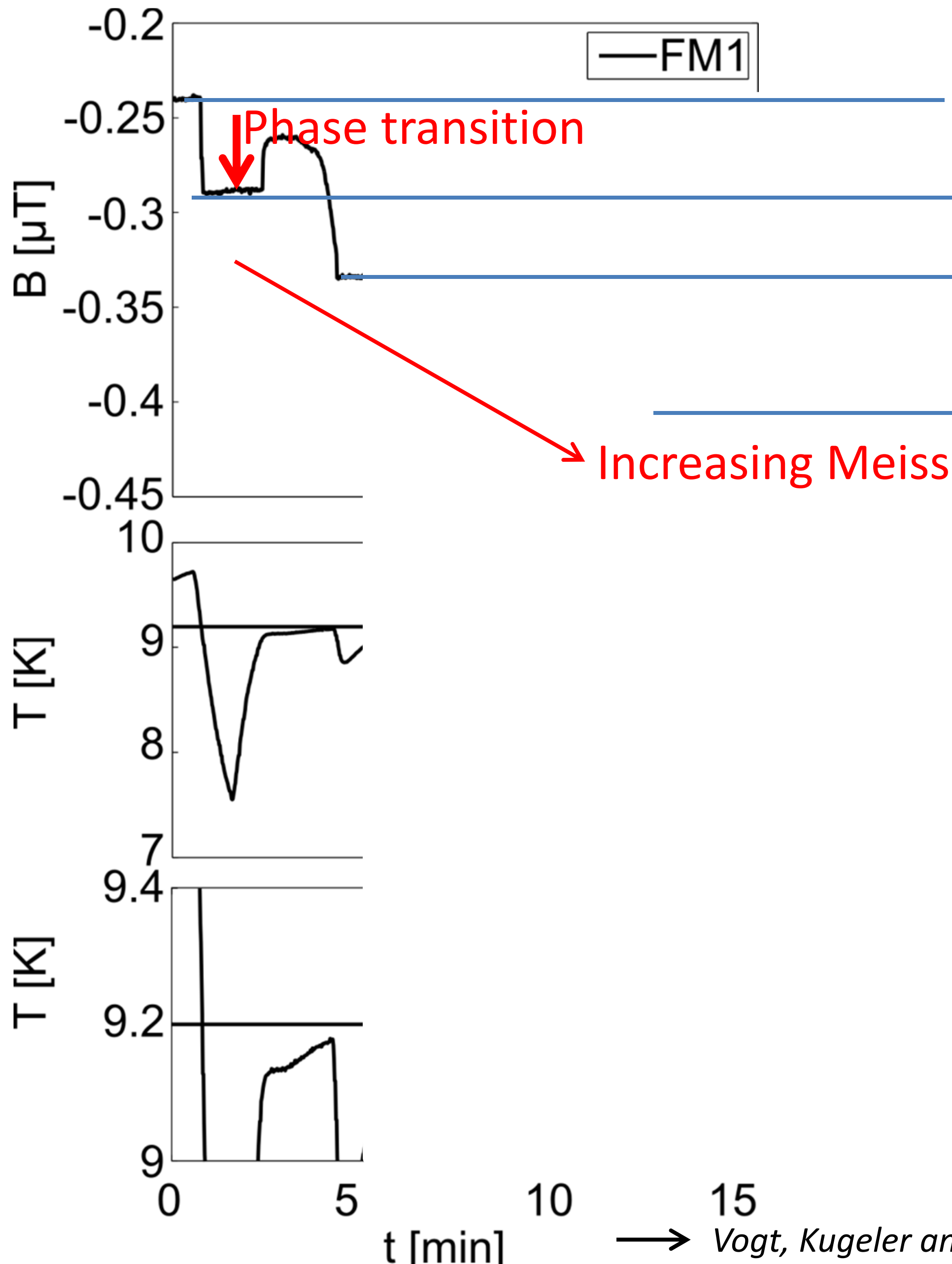


Level ambient field

Initially expelled flux:

ΔB ≈ 50nT

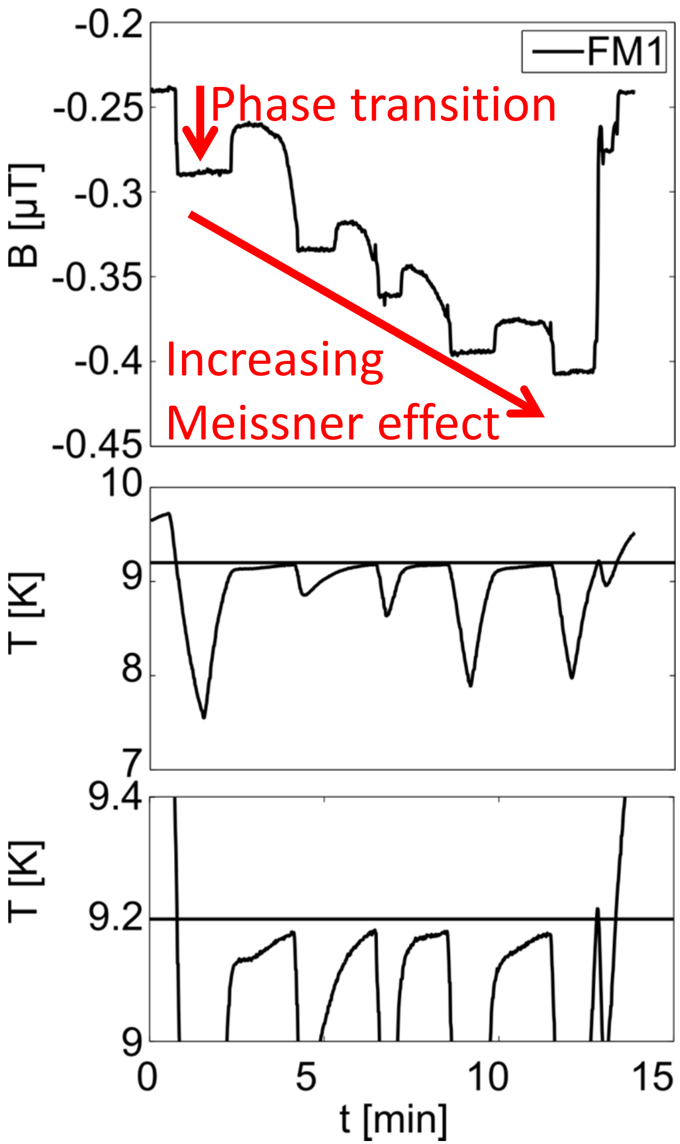
Increased expelled flux

4 × more flux expelled

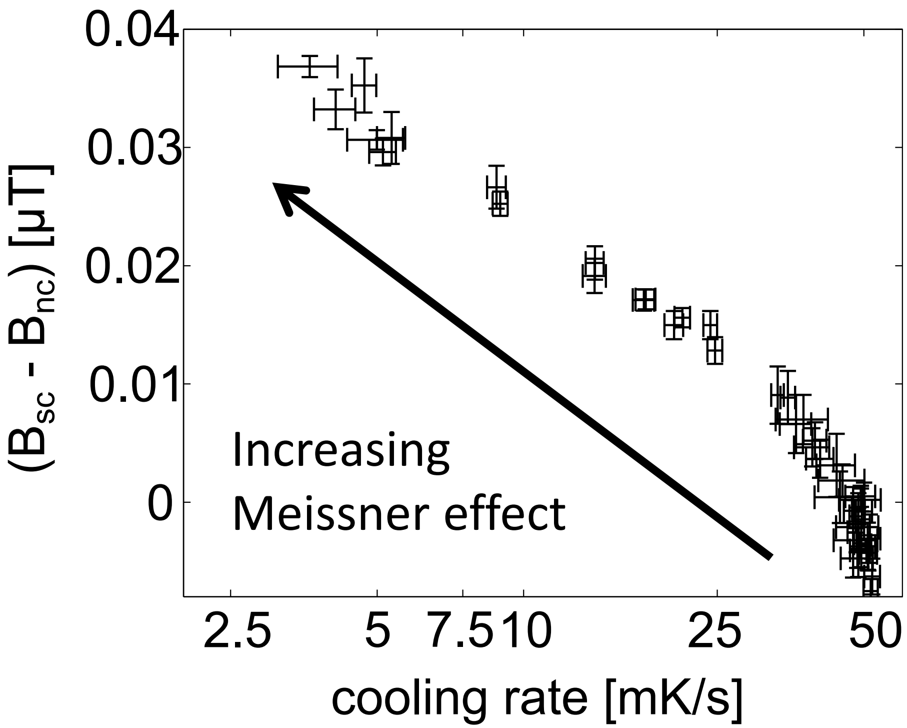
Increased flux mobility close to transition temperature

→ *Vogt, Kugeler and Knobloch, IPAC2013, WEPWO004*

INCREASED FLUX MOBILITY CLOSE TO TRANSITION TEMPERATURE



Slower coolingrate = niobium longer in region with increased flux mobility



Sarah Aull et al., SRF2013, WEIOC01
RF measurements demonstrate that R_s is impacted by the cooling rate

SUMMARY

Do temperature gradients generate trapped flux?	Thermoelectrically induced magnetic fields exist and get trapped in sc niobium.	Avoid temperature gradients as you transition to the SC state!
Can we reduce pinning centers? Impact niobium material properties the trapping behavior?	Material defects and contaminants affect trapped flux	Use large grain material and/or high temperature treatment!
Are there additional ways to optimize Meissner effect?	Flux shows increased mobility close to transition temperature	Decrease cooling rate near T_c to take advantage of increased flux mobility!

- Cavity cooldown without ΔT (time to settle before transition or add cycling)
- Cool slowly and smoothly through T_c

→ *Vogt, Kugeler and Knobloch, PRSTAB (accepted for publication, Sept. 11, 2013)*

THANK YOU FOR YOUR ATTENTION

Acknowledgement:

Hans-Peter Vogel and Peter vom Stein (RI), Peter Kneisel and Rong-Li Geng (J Lab), Enzo Palmieri (INFN-Legnaro) for providing the samples.

To our engineers André Frahm, Michael Schuster, Sascha Klauke, Dirk Pflückhahn, Stefan Rotterdam, Axel Hellwig for patient support and

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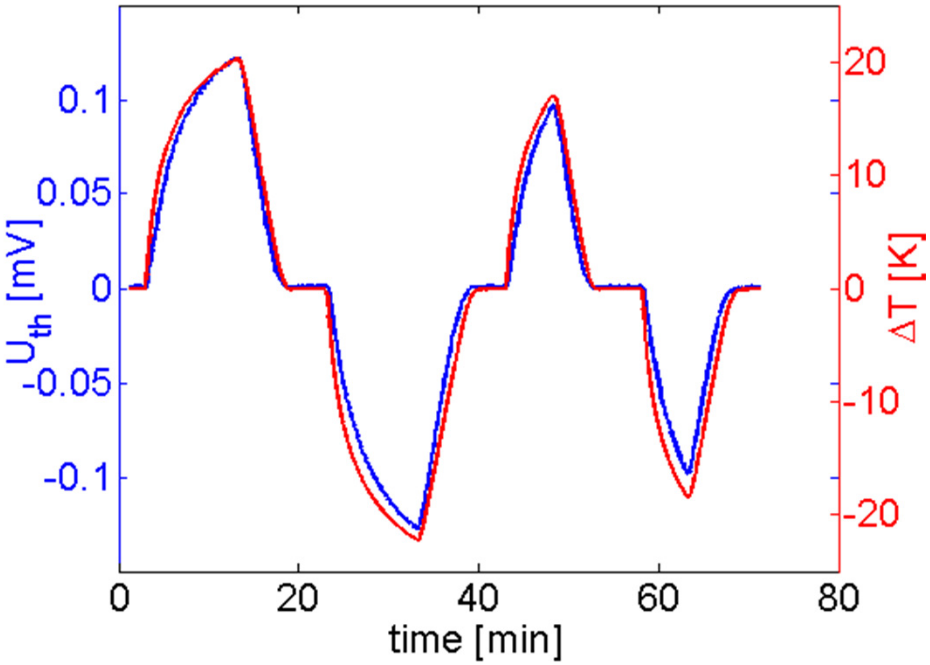
Is this measurement able to explain the observed variation in R_{res}?

$$B \leftrightarrow I = \Delta V / R = \Delta S \cdot \Delta T / R$$

Thermopower **ΔS ≈ 10µV/K**
Literature is not consistent



Parameter of cavity-tank system @10K:
R ≈ 100µΩ (dominated by titanium tank)

→ *J. Milck, Tech. Rep., Hughes Aircraft Company (1970)*