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

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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
- Precipitates
- 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?

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

Impact of trapped vortices on losses

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

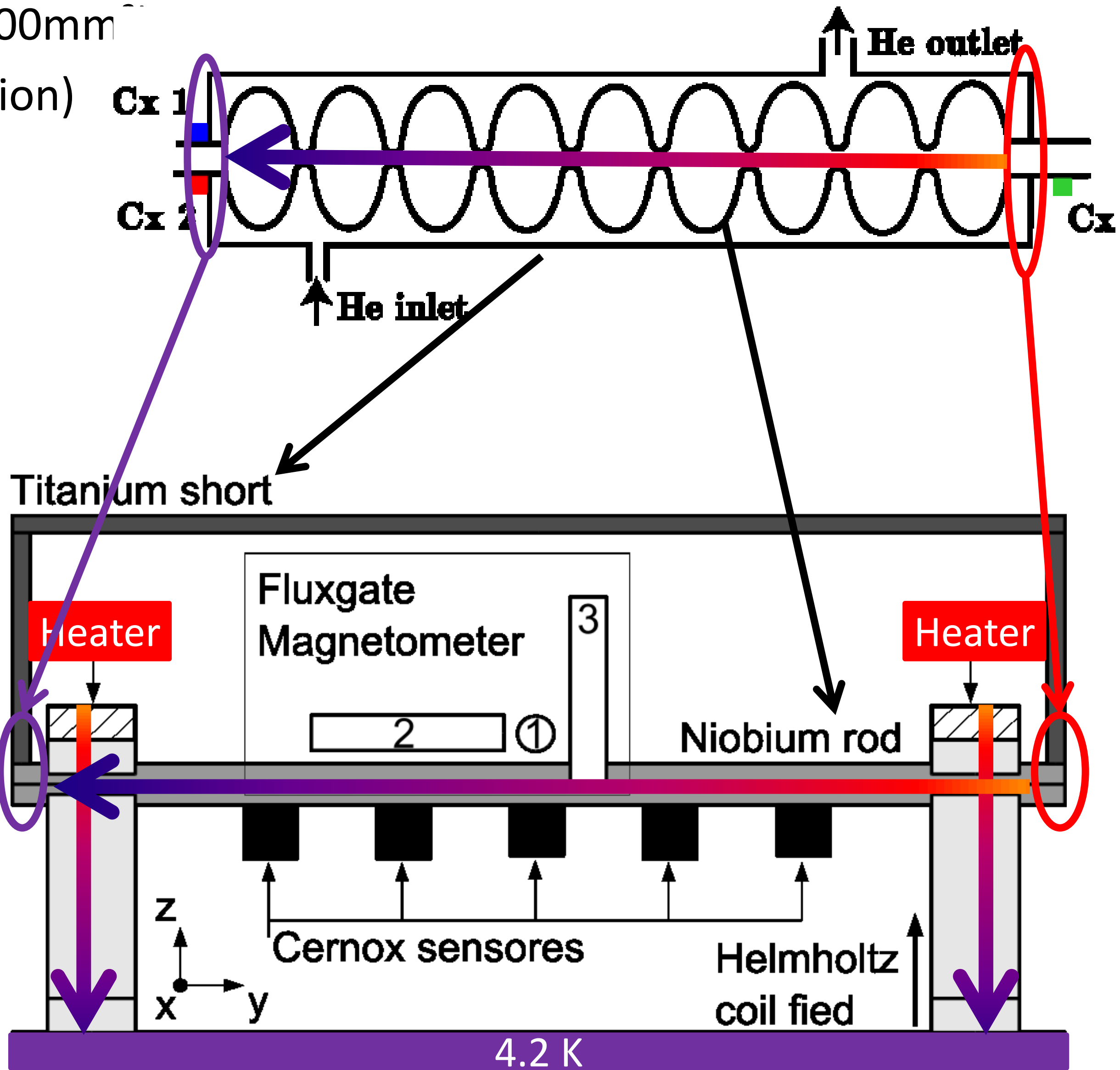
→ *Phys Rev B 87, Gurevich and Ciovati (2012)*

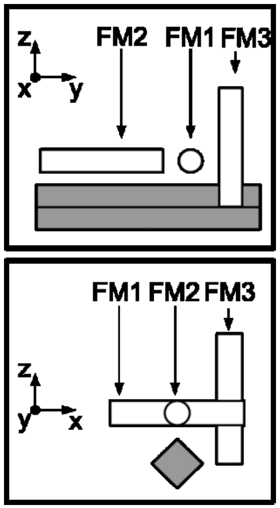
Empiric: 1µT⇔3.5nΩ (TESLA)

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

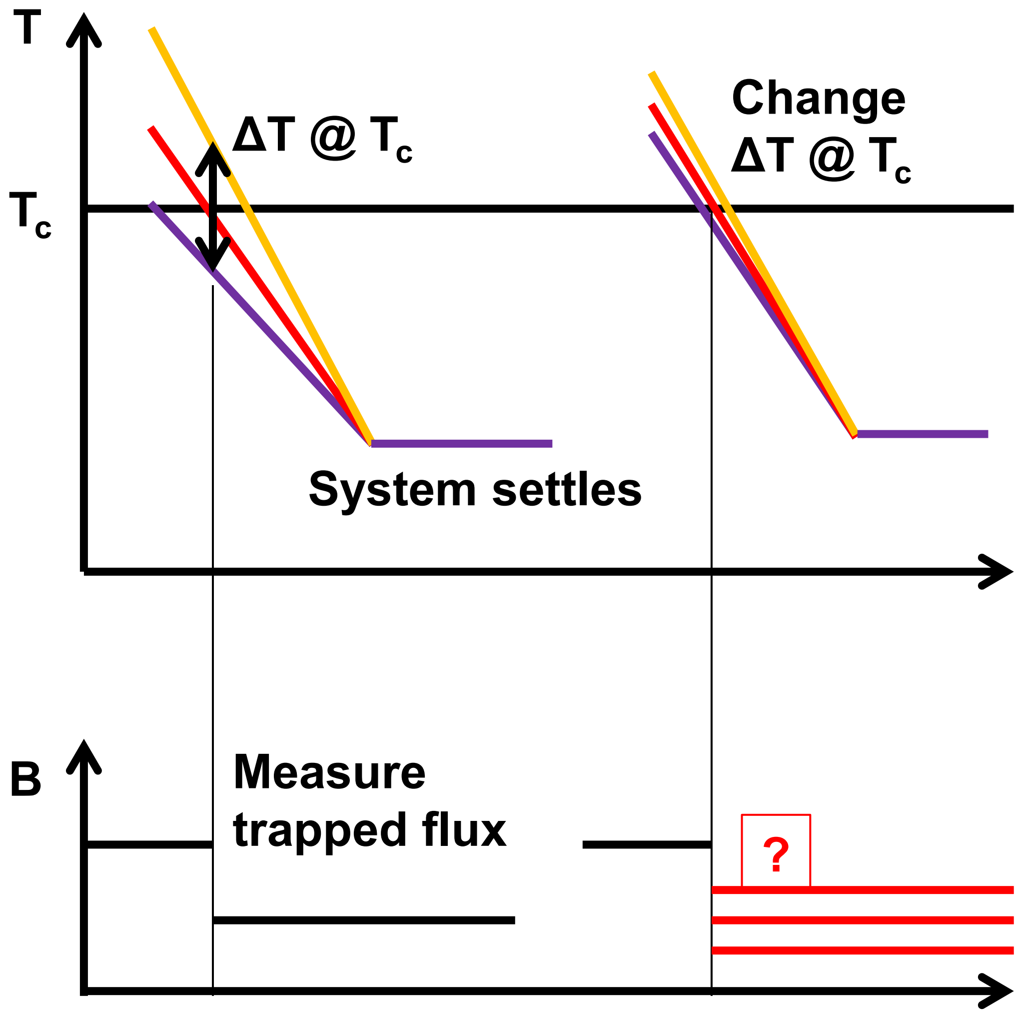
MODEL SYSTEM

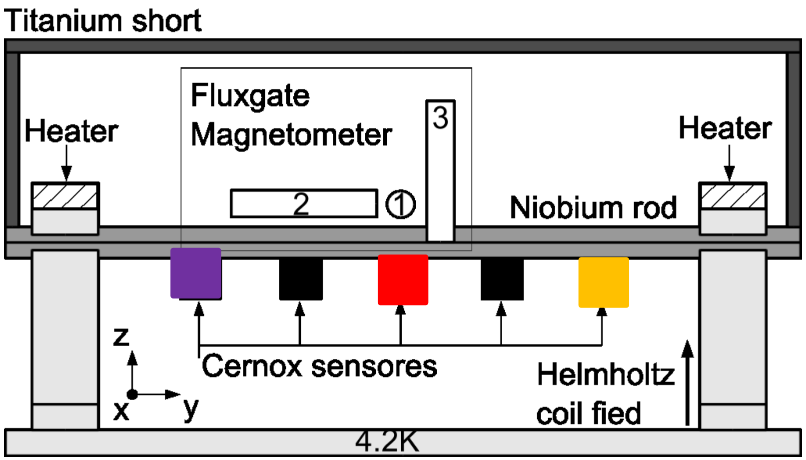
- Mimics thermoelectric properties of cavity-tank system
- Nb rod 300RRR (84x84x300mm
- 3 FM probes (1nT resolution)
- 7 Cernox sensors
- Conduction cooled (LHe)
- 2 heaters
- Shielding (50nT ambient)





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 $\Delta S = S_{Nb} - S_{Ti}$

MODEL SYSTEM: THERMOCURRENTS

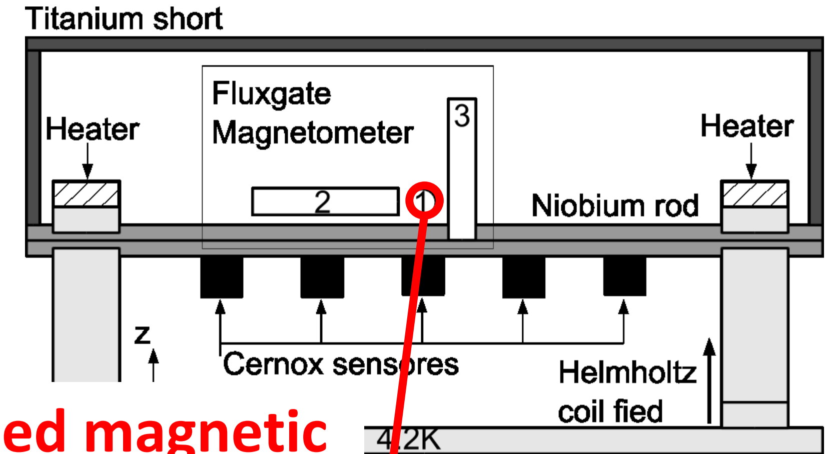
- **Two contact points on different temperatures**

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

B ↔ I = ΔV / R

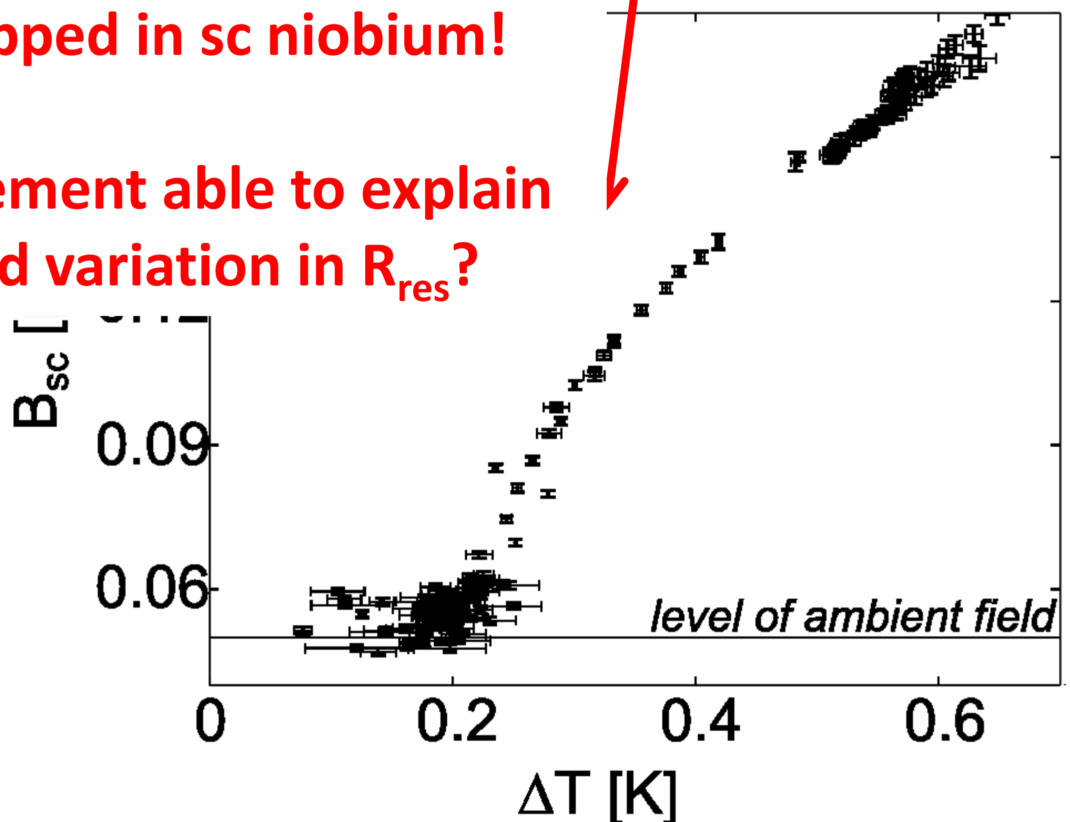
Thermopower of Sy

- **Measure te during phas**
- **System settles**
- **Measure trapped flux**

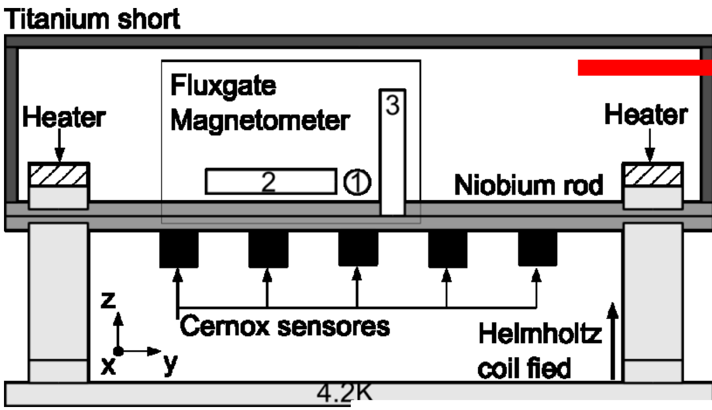


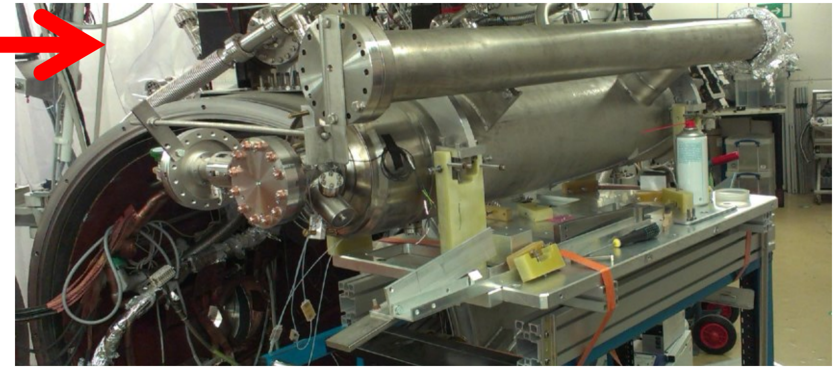
Thermoelectrically induced magnetic field gets trapped in sc niobium!

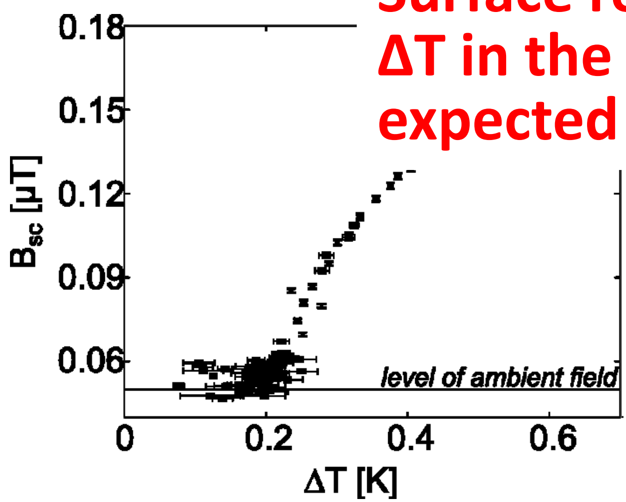
Is this measurement able to explain the observed variation in R_{res}?



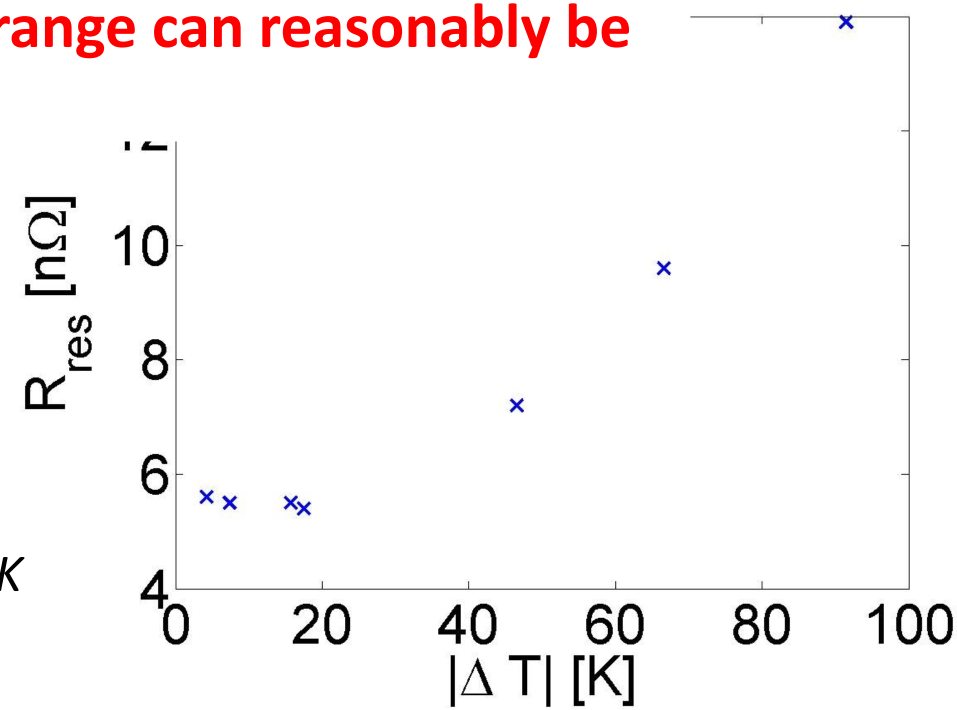
MODEL SYSTEM VS. DRESSED CAVITY: TEST 1







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



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

0.12µT trapped in a TESLA Cavity:

→ $\Delta R_{res} = 0.4 n\Omega$

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

MODEL SYSTEM VS. DRESSED CAVITY: TEST 2

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

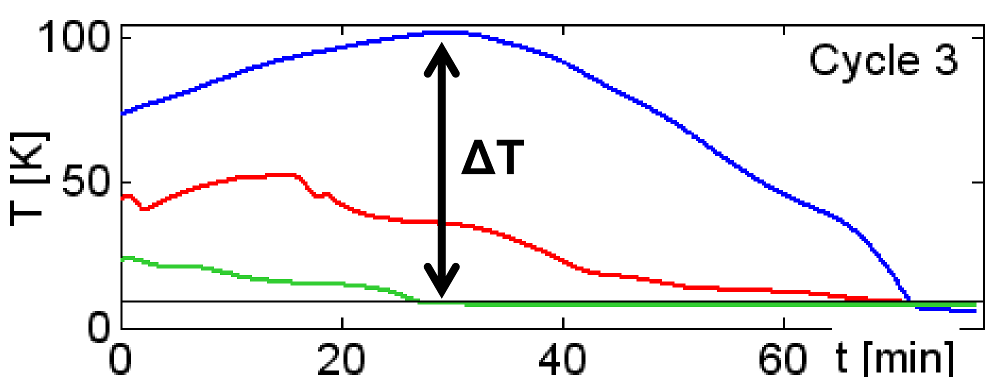
$$B \leftrightarrow I = \Delta V / R = \Delta S \cdot \Delta T / R$$

Thermopower: **ΔS ≈ 10µV/K**
Literature is not consistent for titanium.
Independent measurement performed in HoBiCaT.

Parameter of cavity-tank system @10K:
R ≈ 100µΩ (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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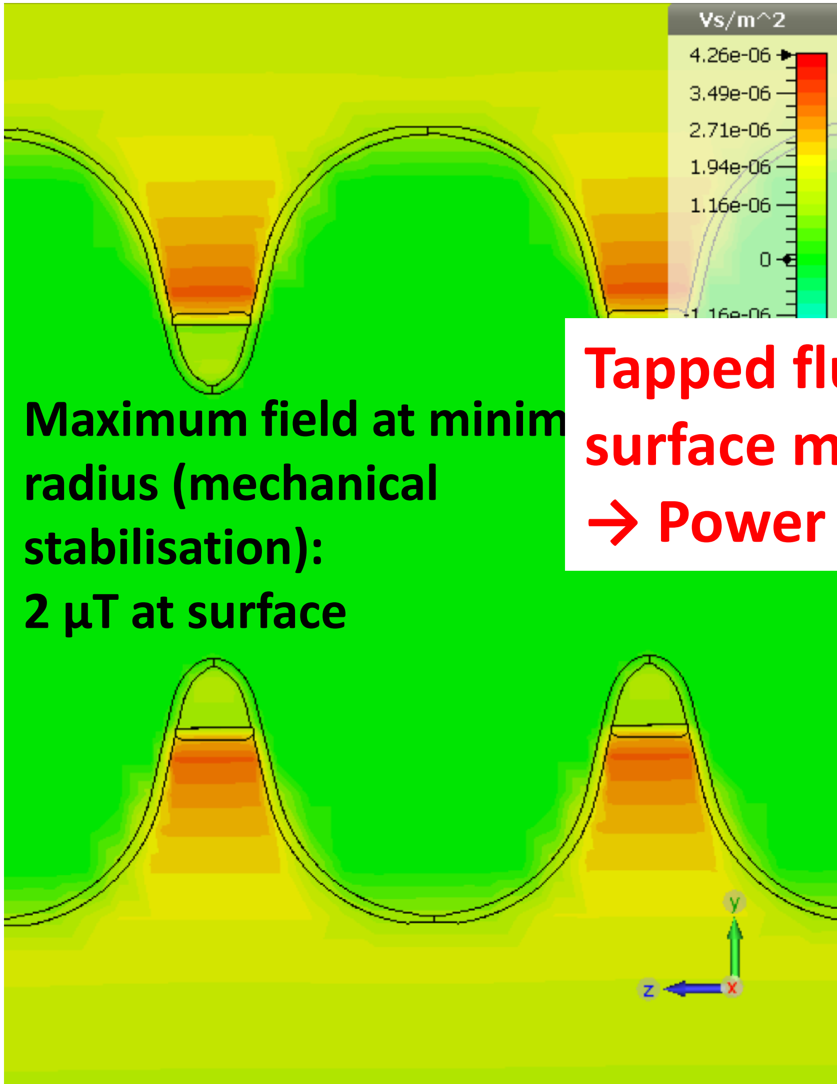
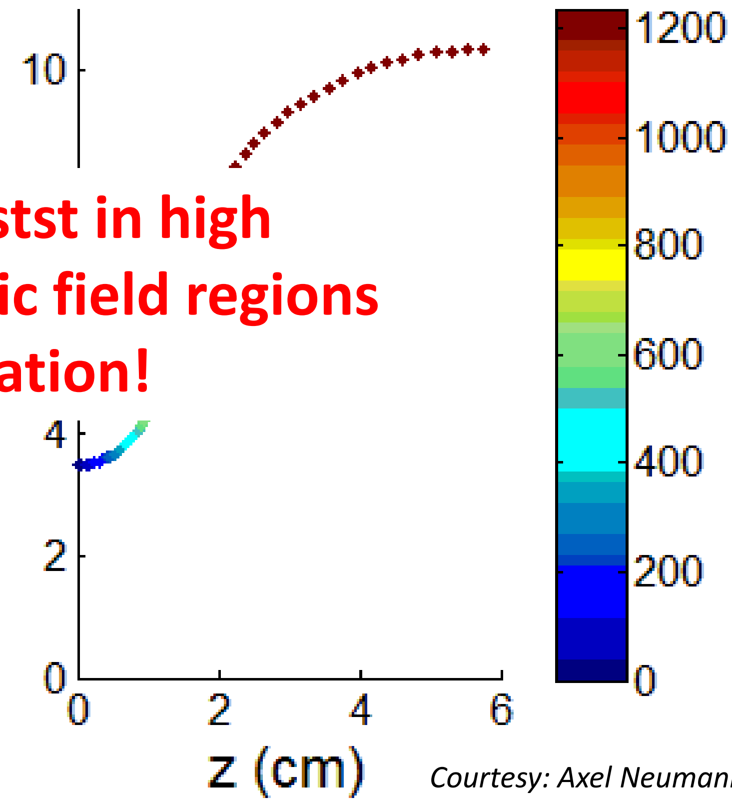


Maximum field at minimum radius (mechanical stabilisation):
2 µT at surface

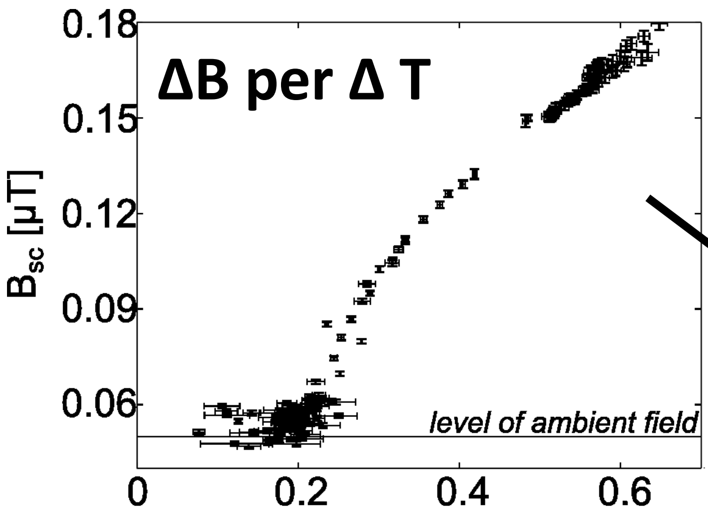
TESLA half cell, TM_{010} π–mode, surface H-field

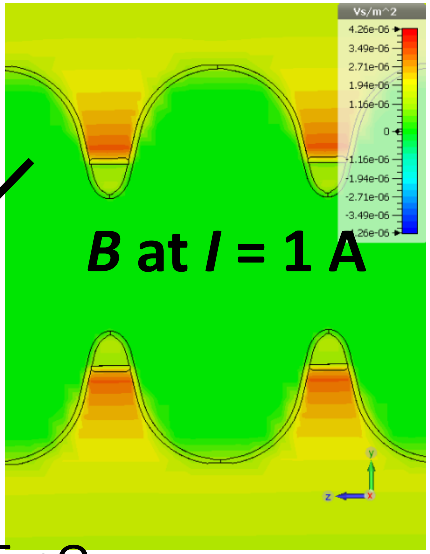


Tapped flux existst in high surface magnetic field regions
→ Power dissipation!

Courtesy: Axel Neumann

MODEL SYSTEM VS. DRESSED CAVITY: TEST 2

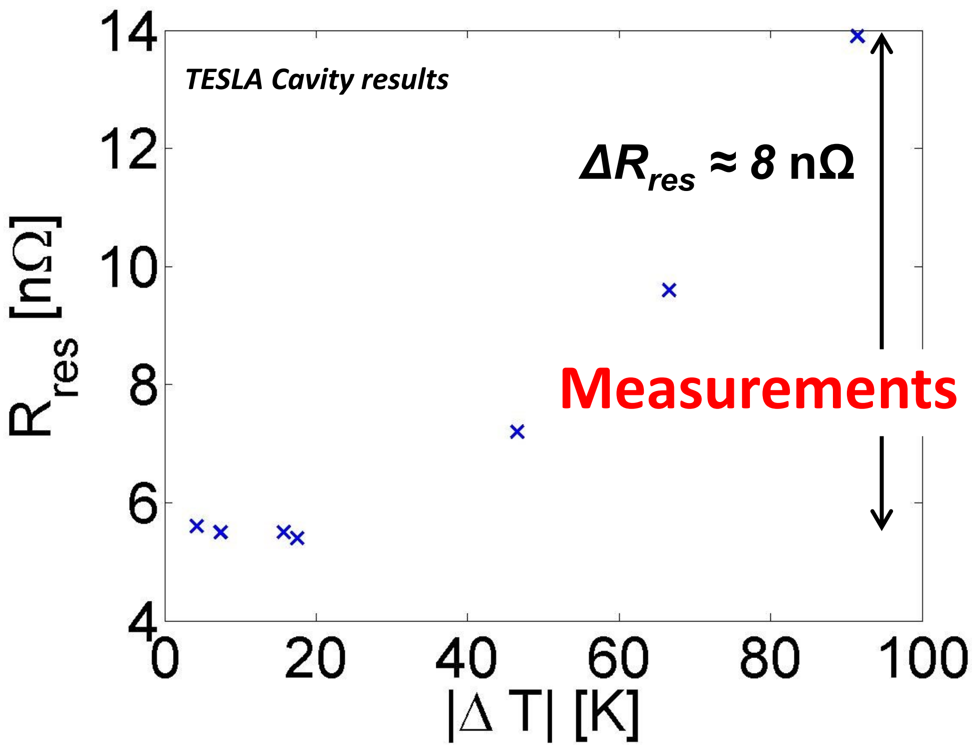




2 μT trapped flux
for ΔT = 100K

1 μT↔3.5 nΩ

cause **7 nΩ** additional
surface resistance



Measurements are consistent!

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Reduction of trapped vortices

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Impact of trapped vortices on losses

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

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Empiric: $1\mu T \Leftrightarrow 3.5 n\Omega$ (TESLA)

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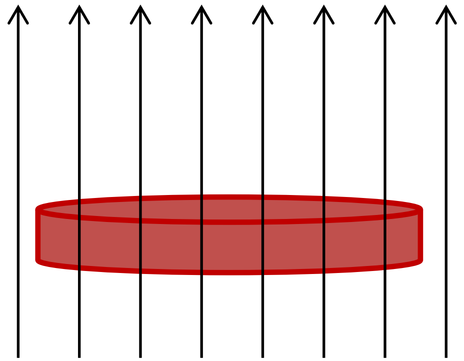
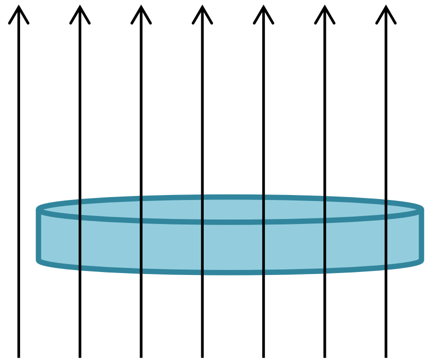
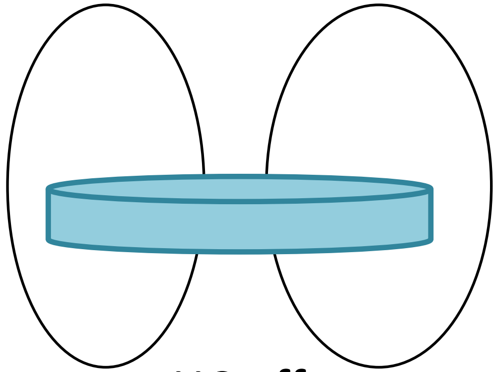
FLUX TRAPPING IN DISK-SHAPED NIOBIUM SAMPLES



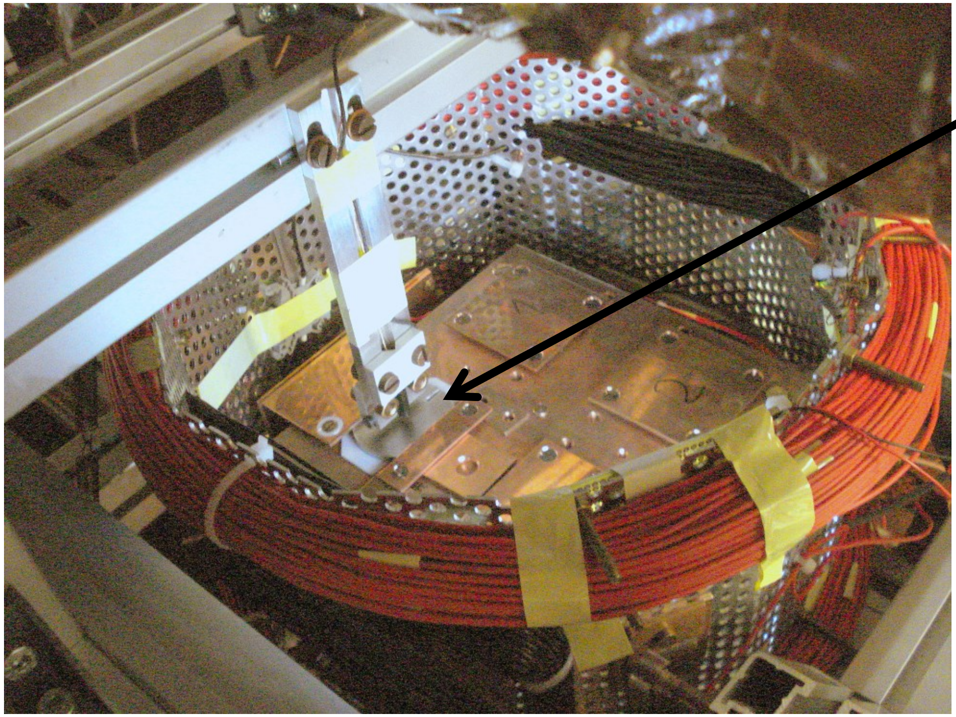
Helmholtz coil applies magnetic field



Field cooled



HC off,
Measure magnetization



Sample

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 ± 0.8)%
4	Single crystal	BCP	[(72.9 + 0.1 lnv) ± 0.8]%
5	Single crystal	BCP + 800°C bake out	[(61.6 + 1.3 lnv) ± 0.8]%
6	Single crystal	BCP + 1200°C bake out	[(42.1 + 0.13 lnv) ± 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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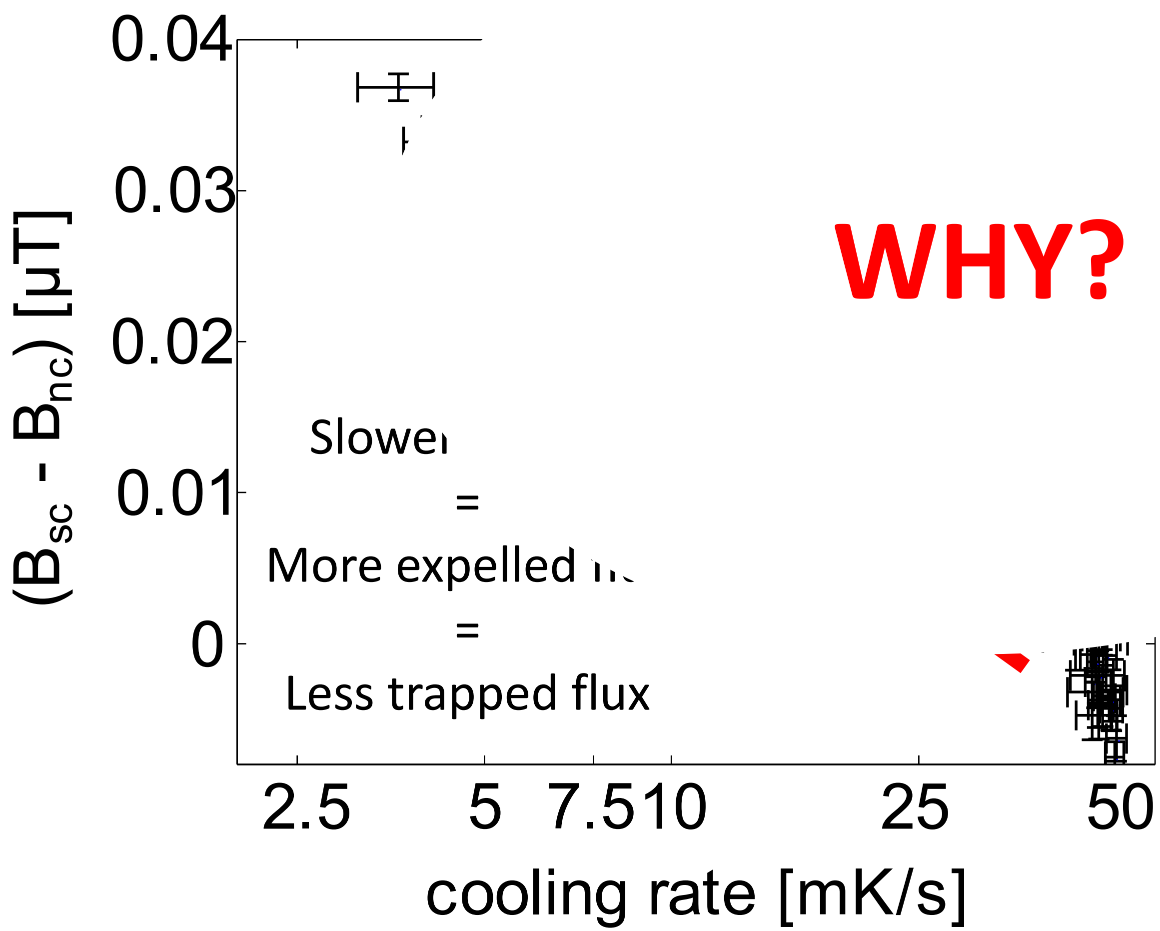
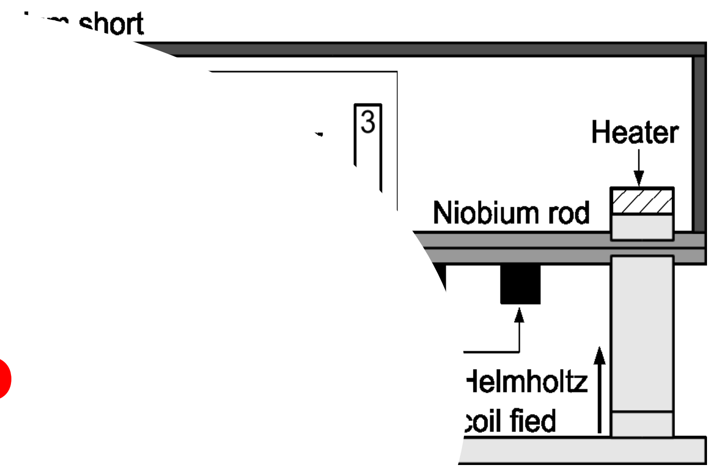
COOLING RATE

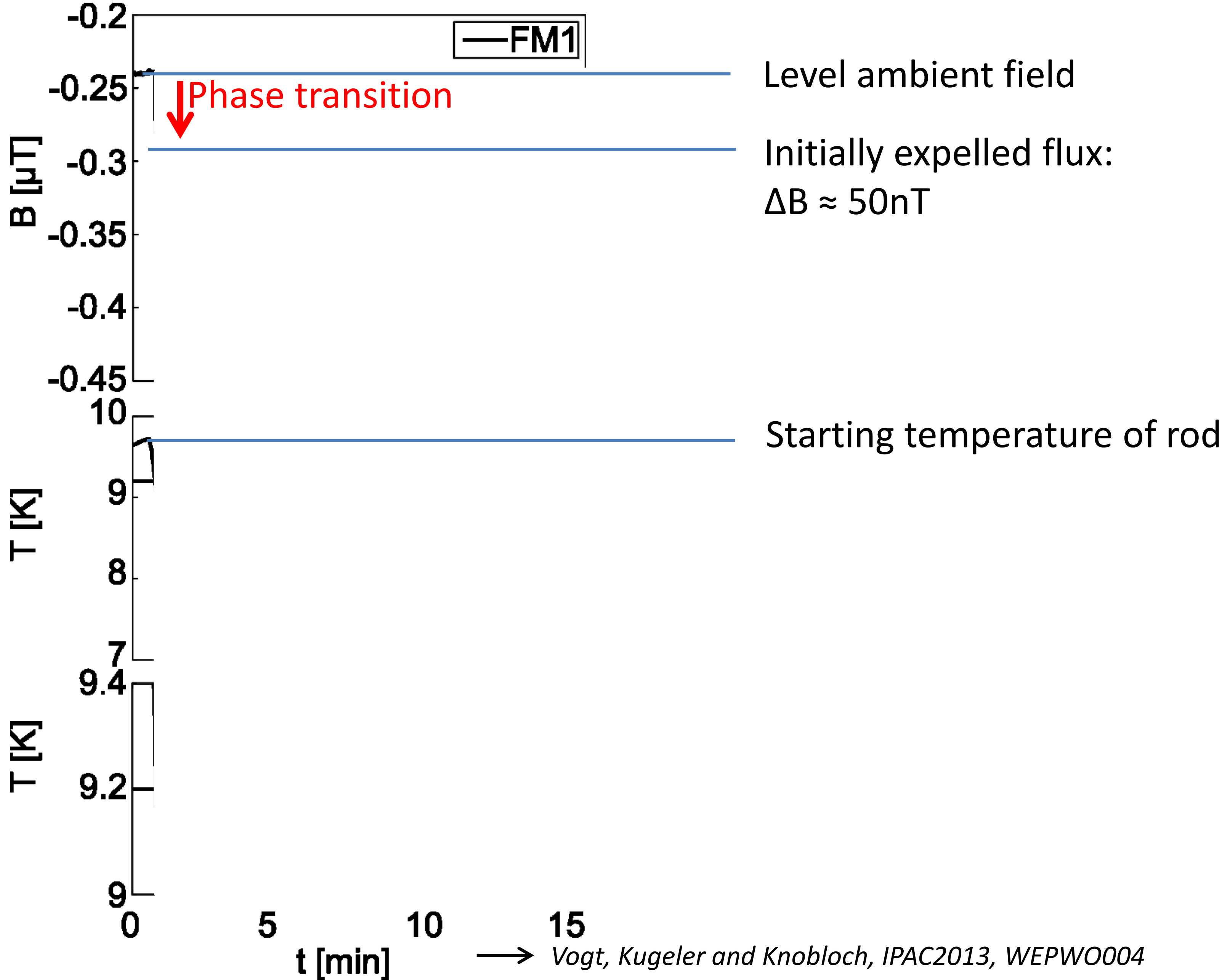
- Ambient field increased to 3µT (0.3µT in FM1 direction)
- Vary cooling rate during isothermal cooldown (max ΔT < 0.1K)
- Slower transition supports Meiss…
- Logarithmic correlation



WHY?



INCREASED FLUX MOBILITY CLOSE TO TRANSITION TEMPERATURE



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

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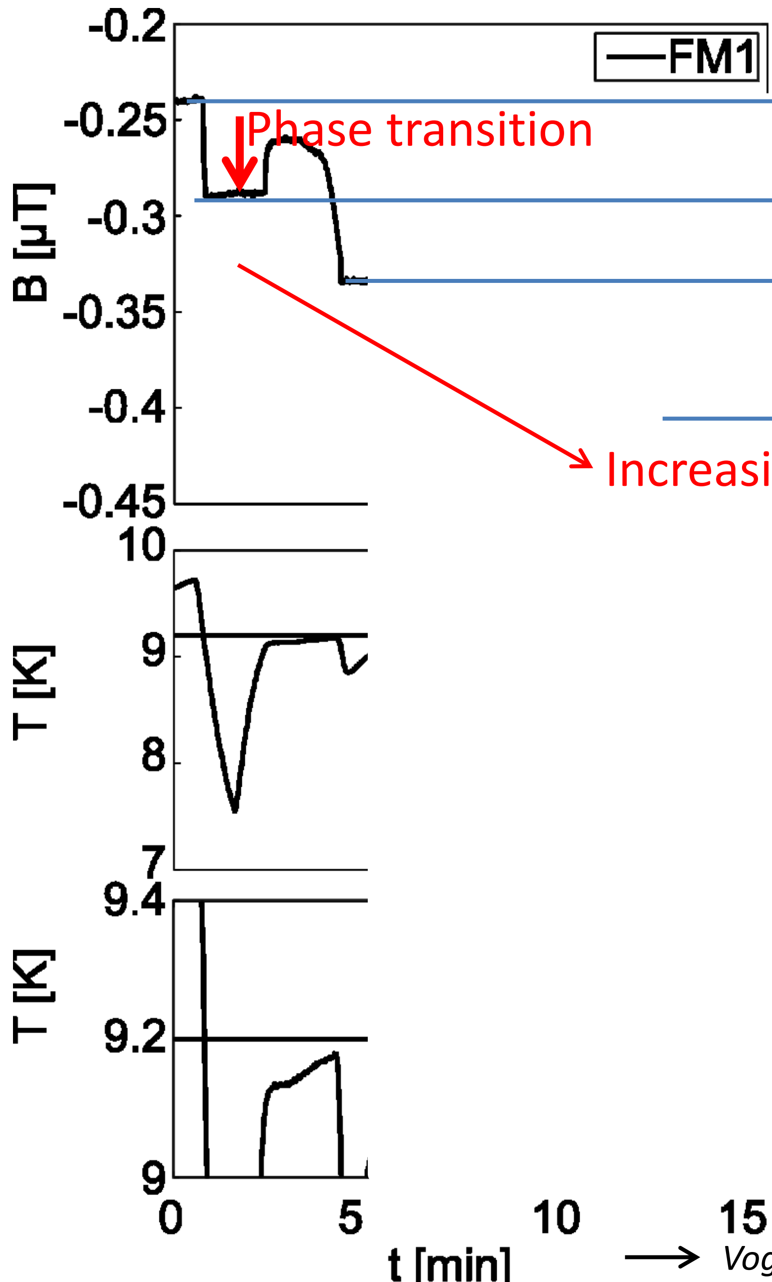


Increasing Meissner effect

Level ambient field

Initially expelled flux:

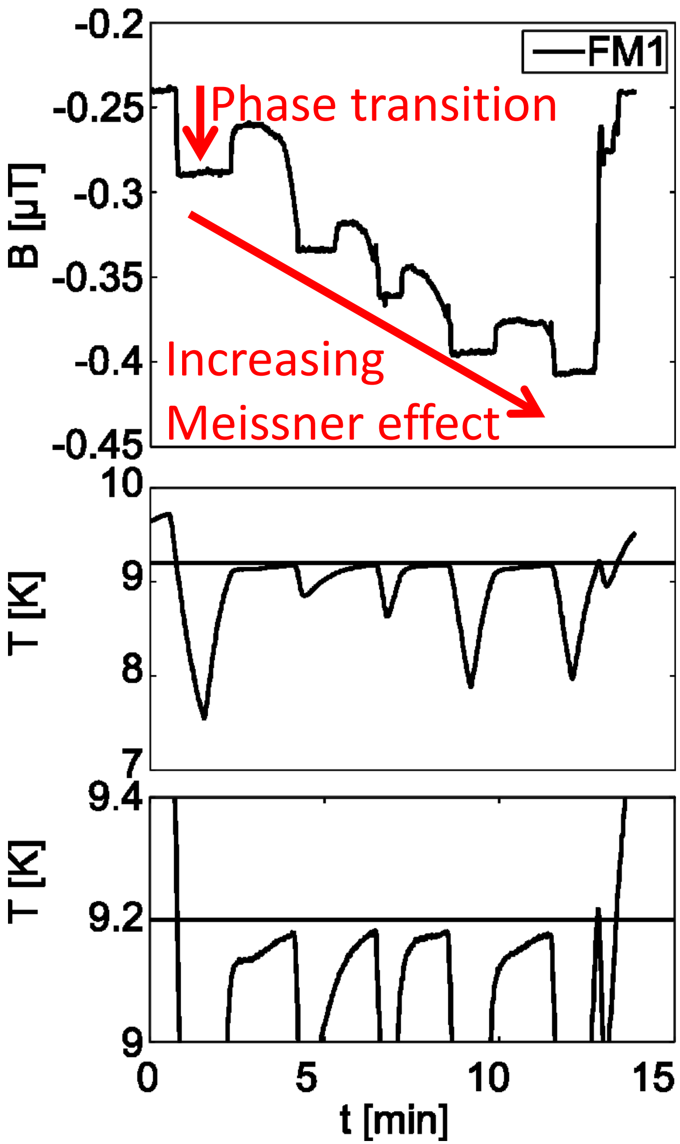
ΔB ≈ 50nT

Increased expelled flux

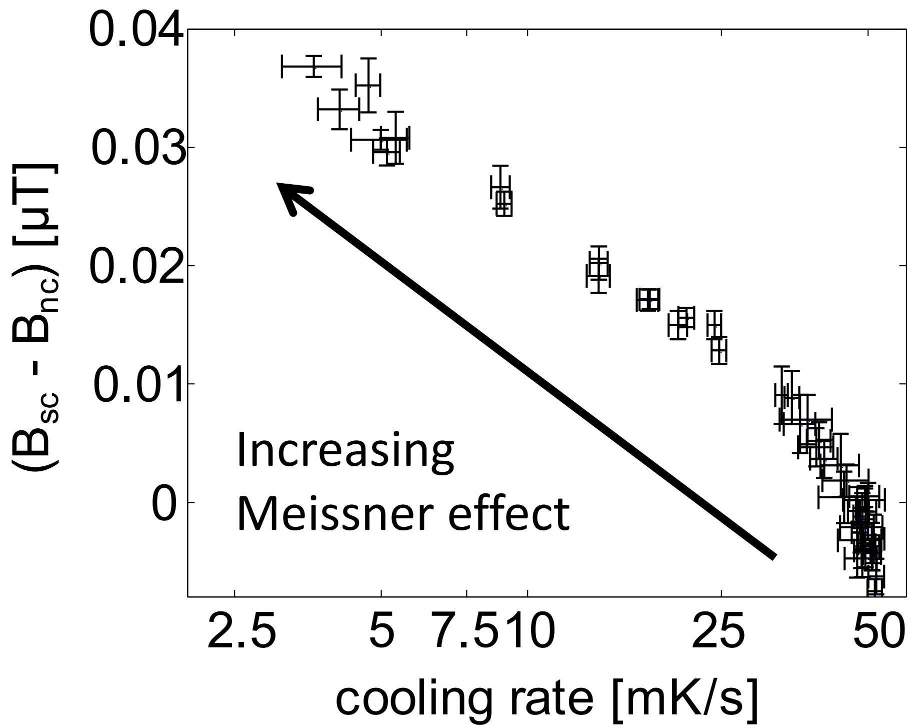
4 × more flux expelled

Increased flux mobility close to transition temperature

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



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

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