HZB Helmholtz Zentrum Berlin

STUDY OF THE DYNAMICS OF FLUX TRAPPING IN DIFFERENT SRF MATERIALS

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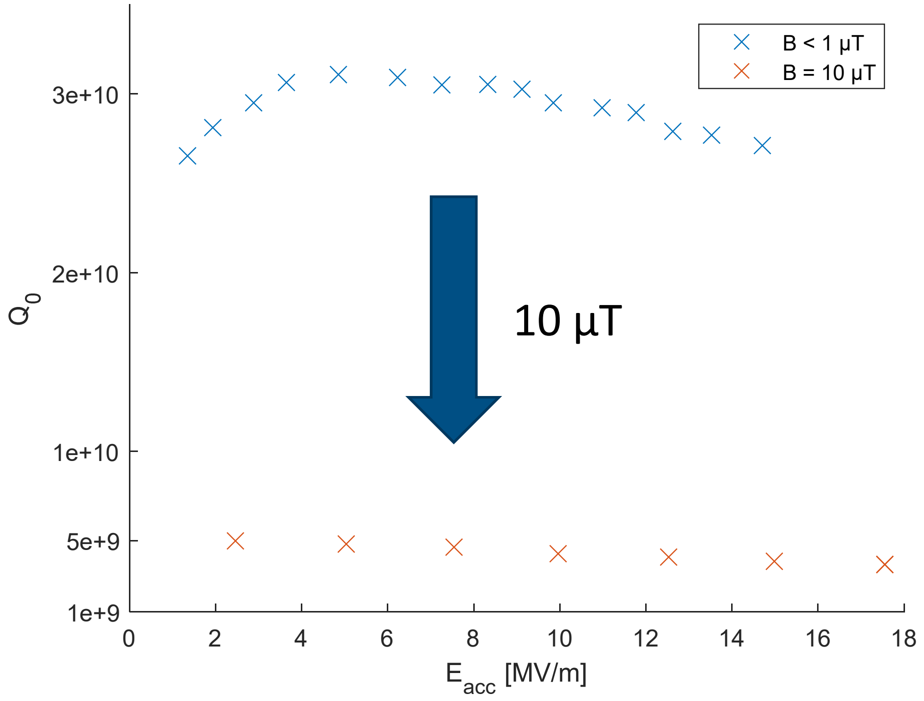
SRF
Grand Rapids, USA

Brief recap: Why do we care about trapped flux?

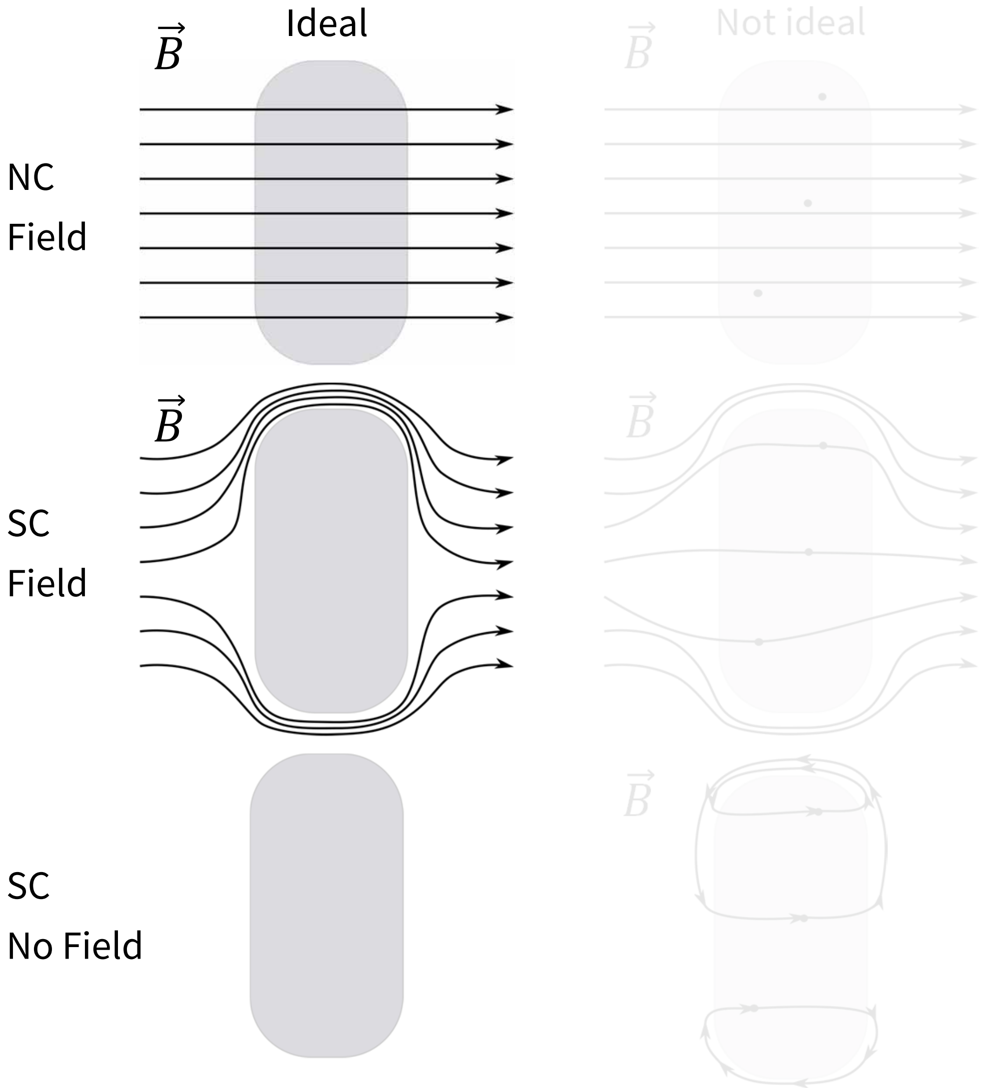
- Trapped flux reduces Q_0 in SRF cavities
- Double magnetic shielding reduces ambient Earth magnetic field from 50 µT to < 1 µT
- But it is impossible to completely shield off all magnetic fields
- Magnetic shielding in expensive
- Shielding does not reduce intrinsic fields caused by thermo currents
- Find a way to reduce flux trapping efficiency

ambient Earth magnetic field = 50 µT



Trapped Flux: What is it?

- When cooling down a Type I superconductor in an external magnetic field, it will transition into the *Meissner* state. In this state all magnetic field is expelled.
- However, there are small defects in the material which *pin* the quantized magnetic field lines and prevent them from being pushed out
- The pinned flux lines oscillate in the RF field and cause losses in the cavity wall [1]



[1] Gurevich, A. and Ciovati, G., Effect of vortex hotspots on the radio-frequency surface resistance, *Phys. Rev. B*, 2013

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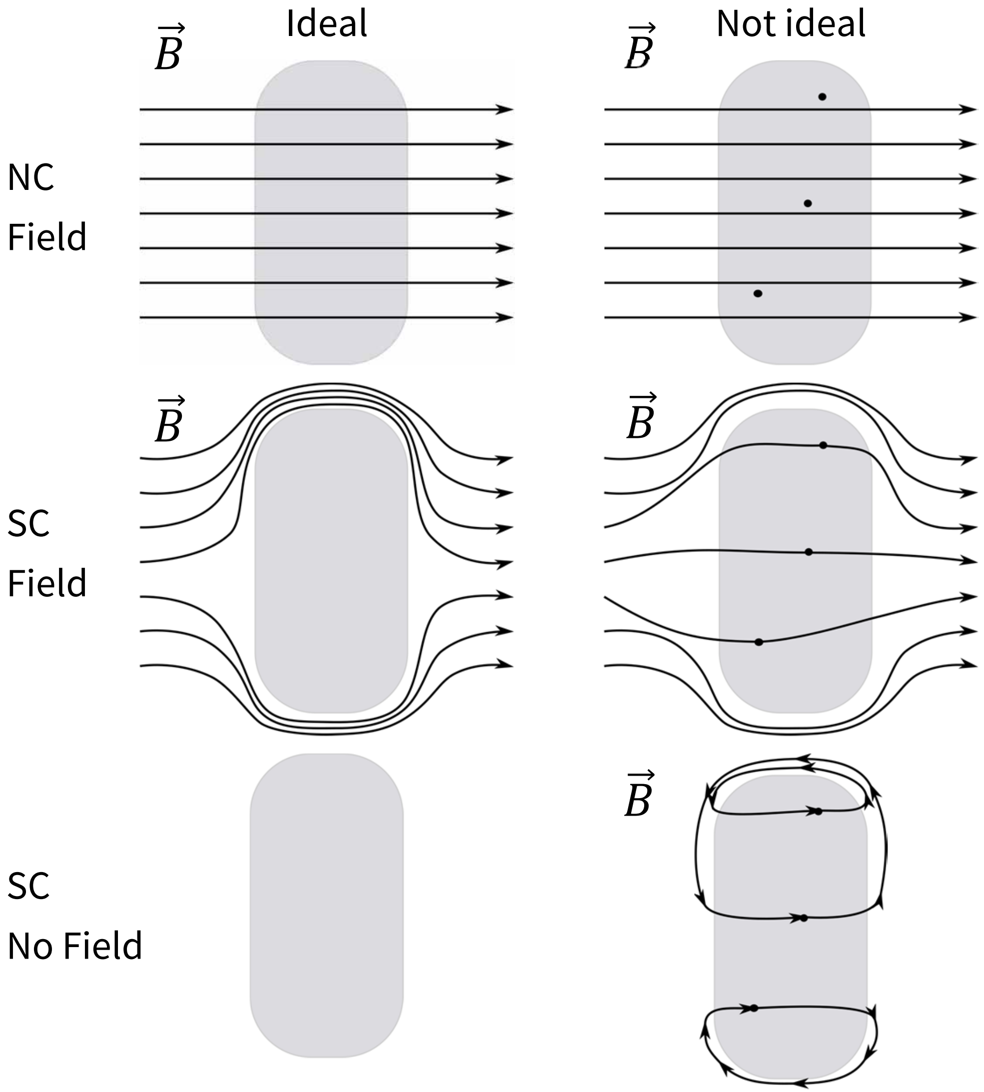

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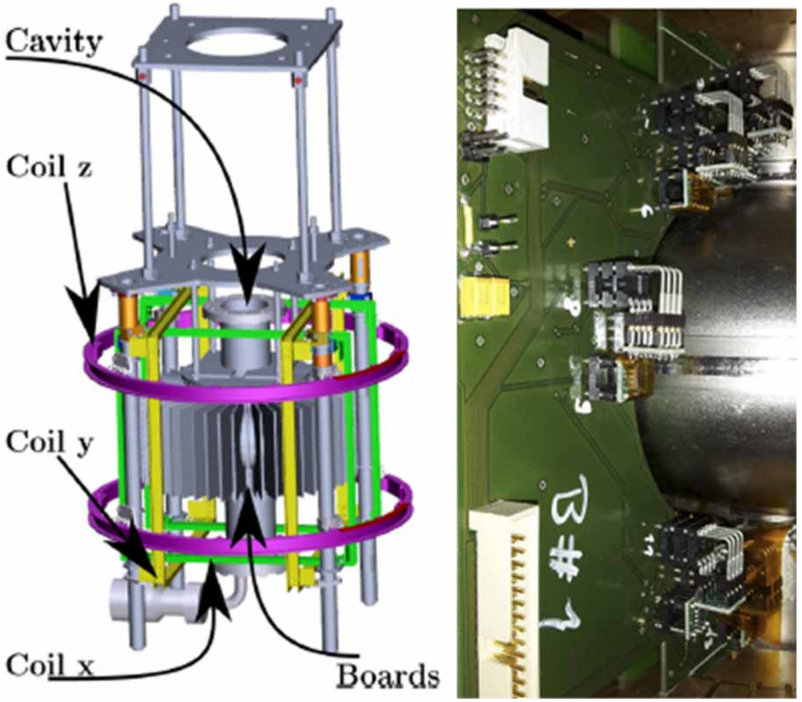
CONCEPT – USE FLAT SAMPLES

- We want to understand trapped flux in more detail, before trying to minimize it

- To understand trapped flux, we need control parameters which might have an influence on it:
    - Temperature gradient
    - Cooldown rate
    - Ambient magnetic field
    - Impact of geometry (demagnetization factor, shape anisotropy)
    - Material & treatment

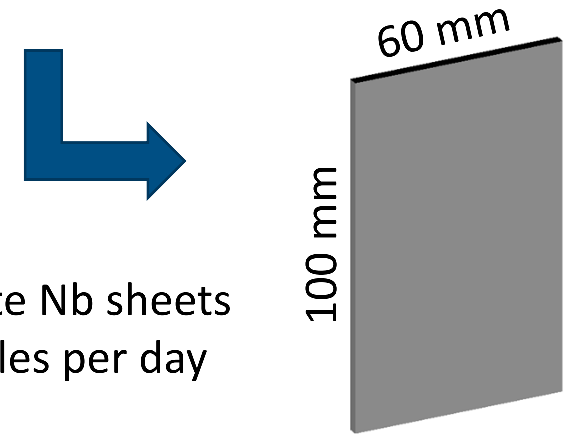
Use samples instead of cavities

- Better Control of the parameters
- More cooling cycles possible (~300/day instead of ~3-4/day)
- Less material needed and treatments are easier to apply
- Easier geometry



AMR based magnetometry system developed at HZB for cavities in 2017 ~ 3-4 cycles per day

Investigate Nb sheets ~300 cycles per day

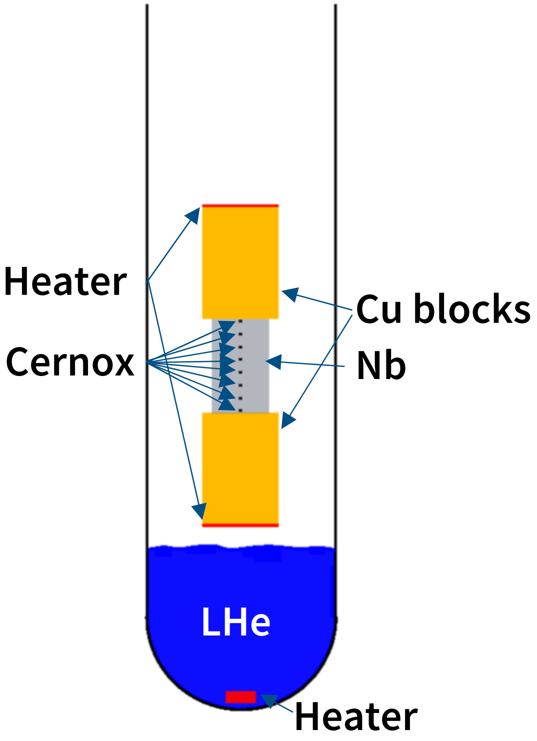


EXPERIMENTAL INFRASTRUCTURE

- Small glass cryostat
- Filled from helium Dewar
- No magnetic shielding
- Active field compensation with two Helmholtz coils and one solenoid
- Minimum flux density at location of reference sensors: < 15 nT (Earth magnetic field ~ 50 µT)
- Maximum flux density: 190 µT

EXPERIMENTAL SETUP

- Sample (100x60x3)mm, clamped in copper blocks at either end
- Dual heaters on the end of the blocks allow for precise control of temperature gradient and cooldown rate
- Blocks move electric heaters away from sample, this reduces magnetic fields from the heaters at the sample
- Setup is suspended above liquid helium bath
- Heater in helium is used to control helium gas flow
- 8 Cernox sensors measure temperature distribution across sample
- Multiple AMR sensors for magnetic field measurements
- grouping of 3 sensors to measure field vector in 3d
- 15 AMR sensor groups measure magnetic field just above the sample



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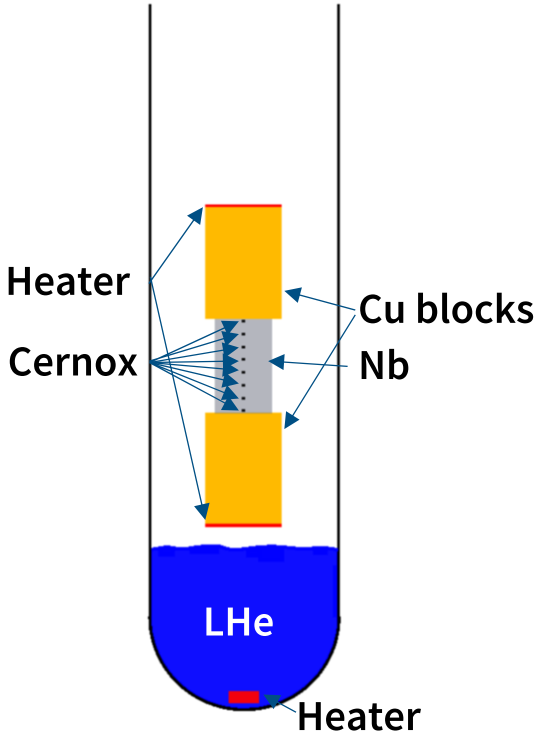
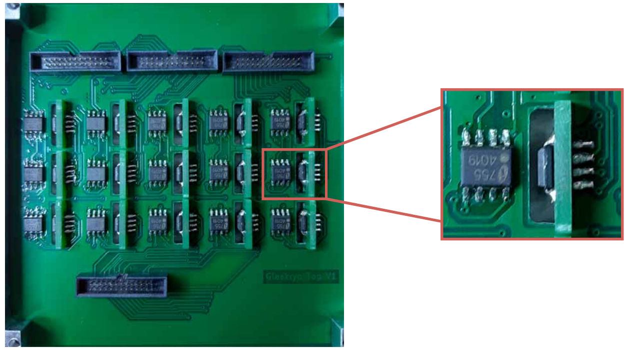
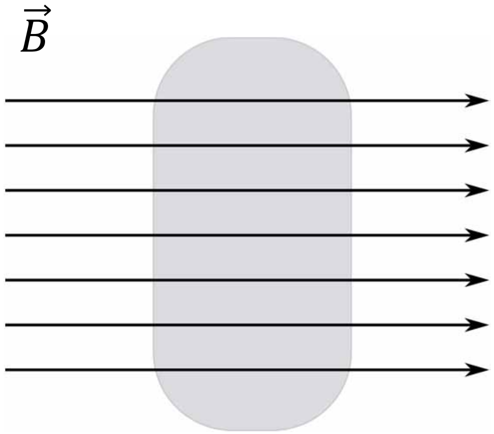




10.1 K

A TYPICAL COOLDOWN

- Apply external field B_{ext} = 100 µT
- Set Temperature gradient across sample (∇T = 0.06 K/cm)
- Lower Sample temperature at top and bottom simultaneously
- After Sample is fully superconducting, remove external field B_{ext} = 0 µT
- Measure trapped flux



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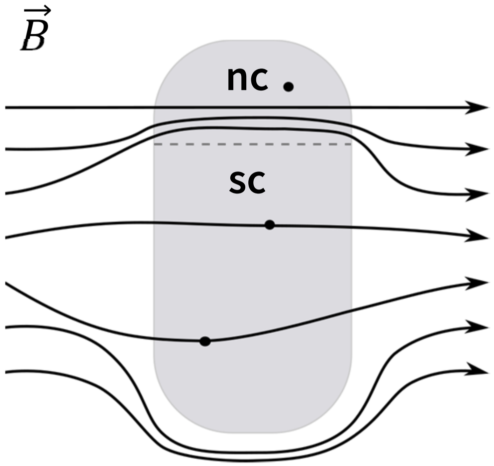

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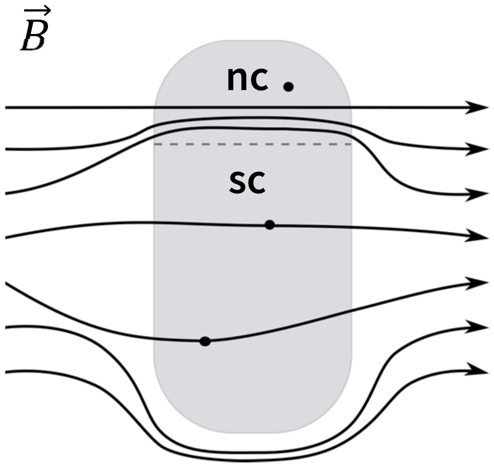

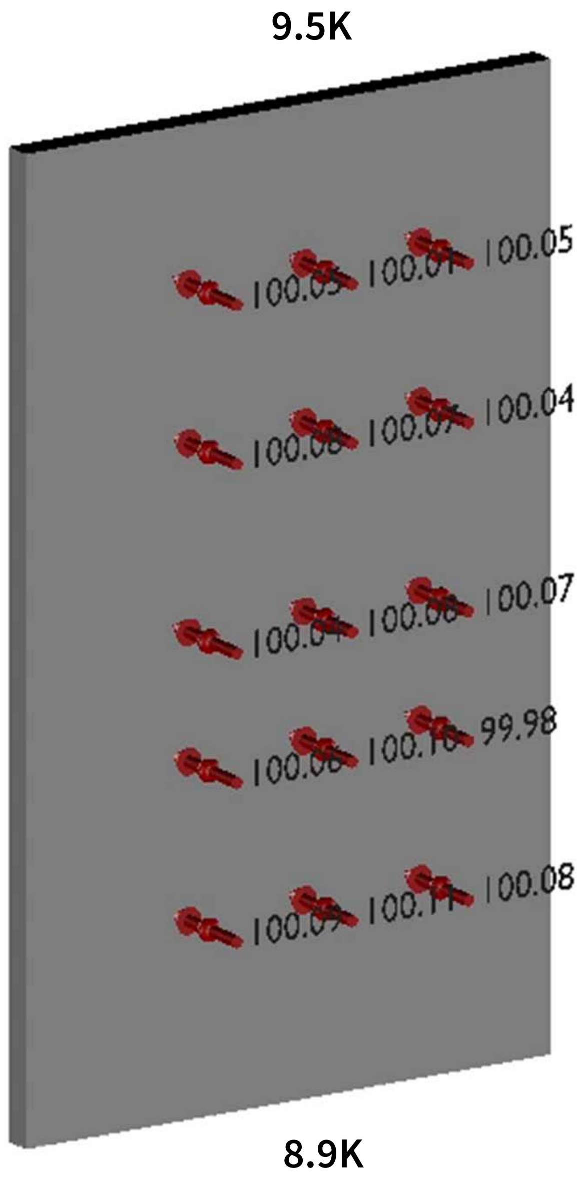

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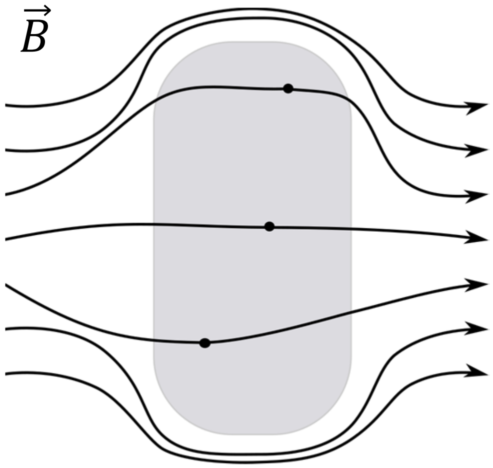

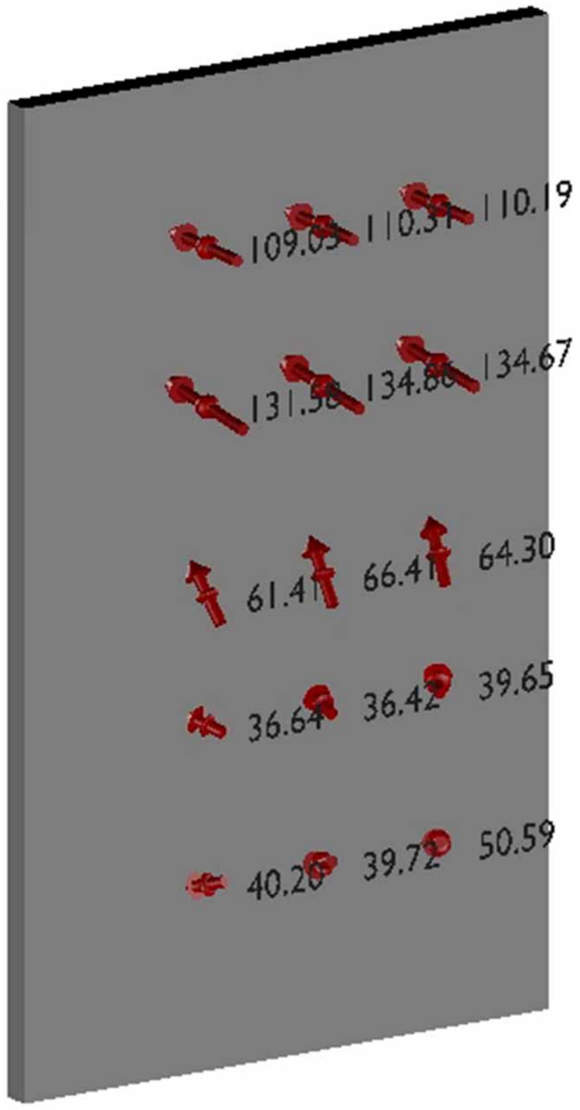

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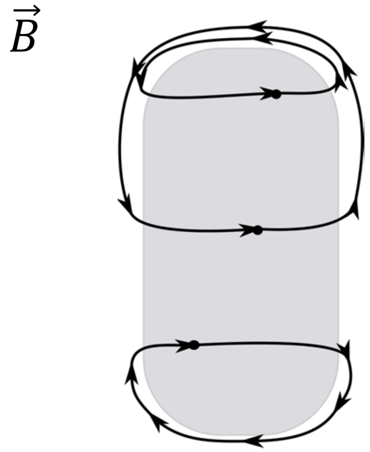
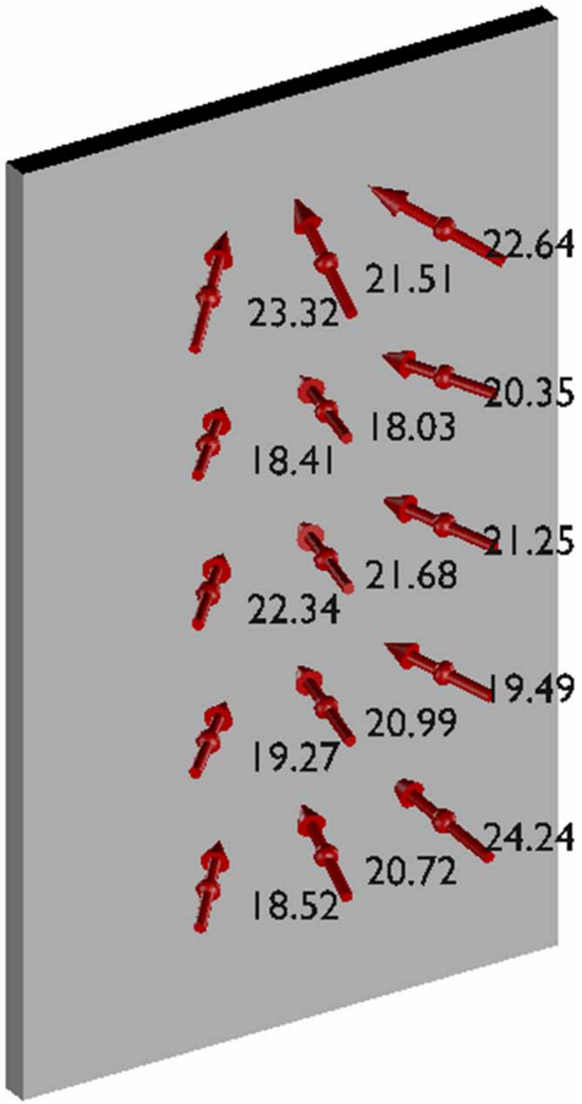
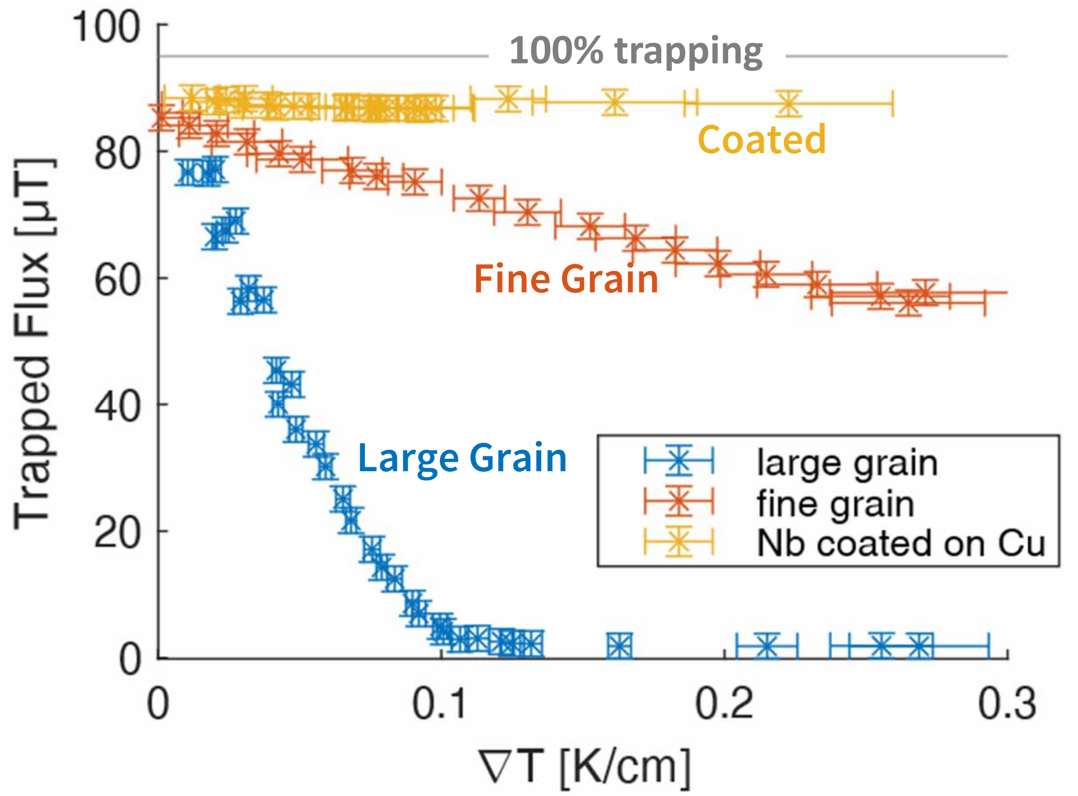




TRAPPED FLUX VS TEMPERATURE GRADIENT

- **Vary temperature gradient while keeping external magnetic field and cooldown rate constant**
  - B_{ext} = 100 µT
  - dT/dt = 0.07 K/s
- **Comparison of three samples**
  - Nb large-grain (untreated)
  - Nb fine-grain (untreated)
  - Nb coated on Cu (4 µm)



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- **Large grain material allows near 100% flux expulsion**
- **No effect for coated sample**

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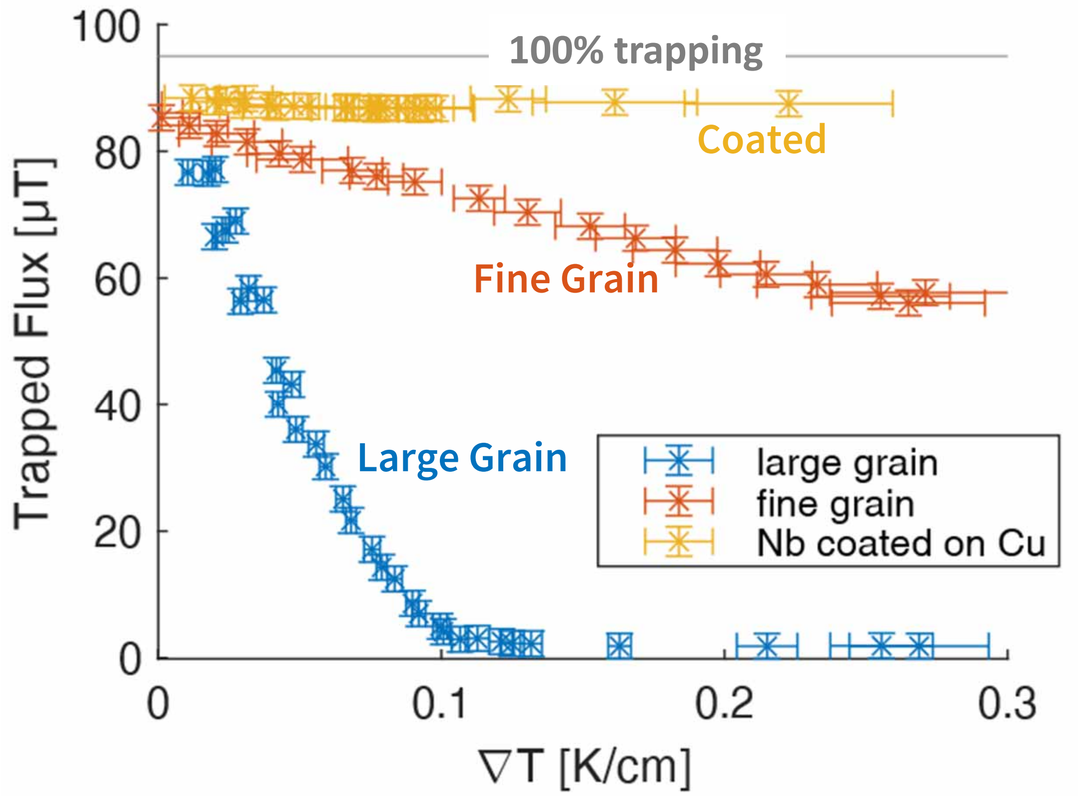

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Nearly full expulsion with untreated large-grain
Thin film is sufficient to have nearly full trapping

TRAPPED FLUX VS AMBIENT FIELD

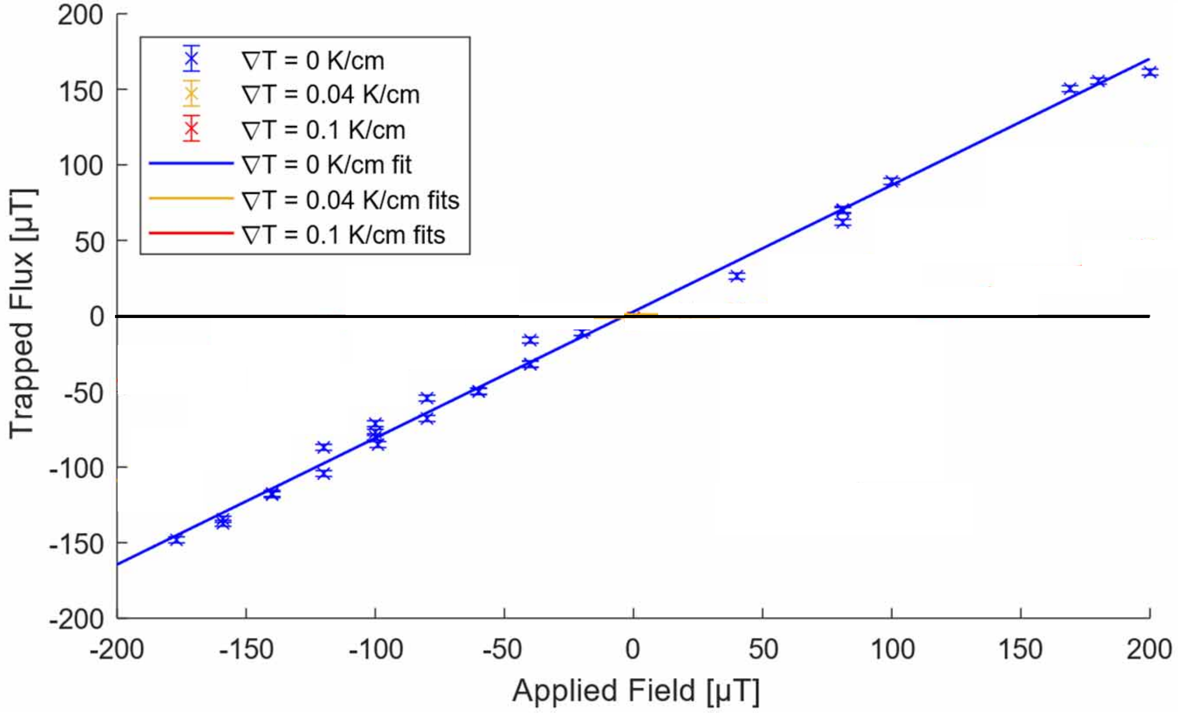
Large-grain Nb sample

- **Vary magnetic field strength with constant temperature gradient and cooldown rate**
- **Change Temperature gradient for different measurement runs**

  Large grain sample
  dT/dt = 0.07K/s
  ∇T = 0 K/cm; 0.04 K/cm; 0.1 K/cm

- **Flux is not trapped below a gradient-dependent threshold field**
- **Above threshold the dependence is linear**
- **Slope decreases with increasing temperature gradient**

- **This threshold behavior is not observed in fine-grain sample**



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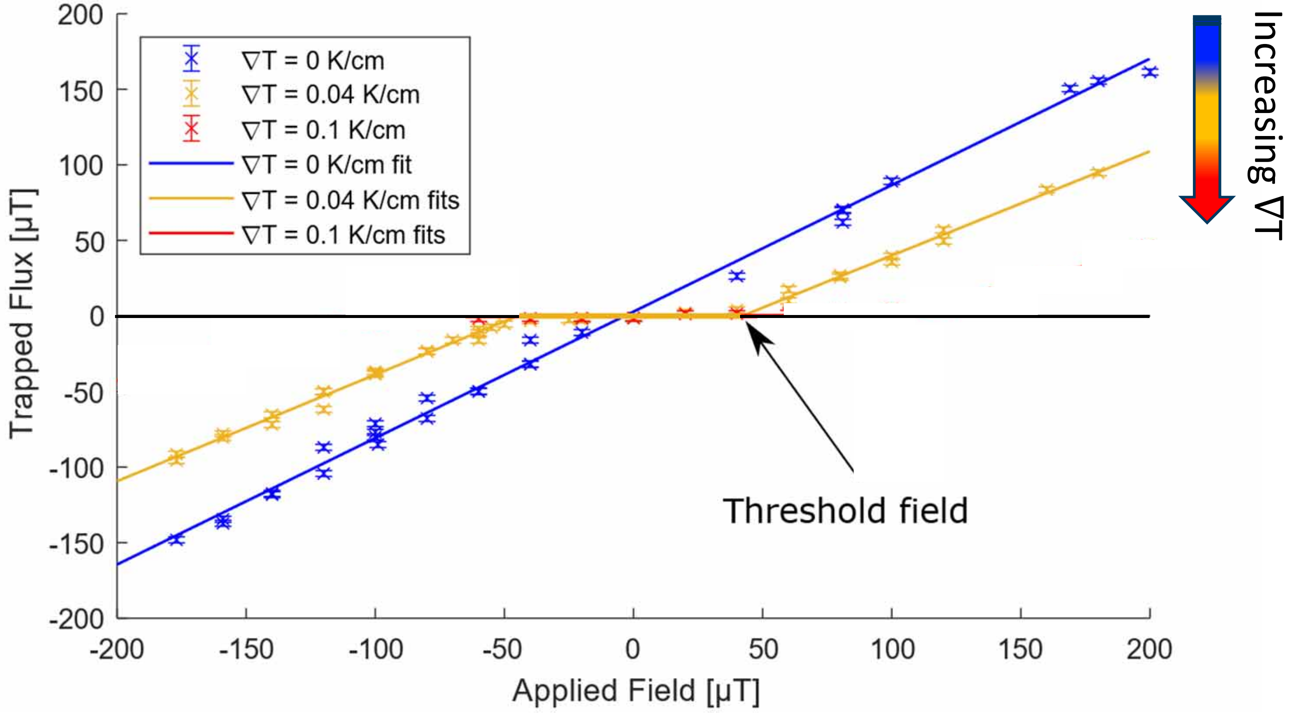

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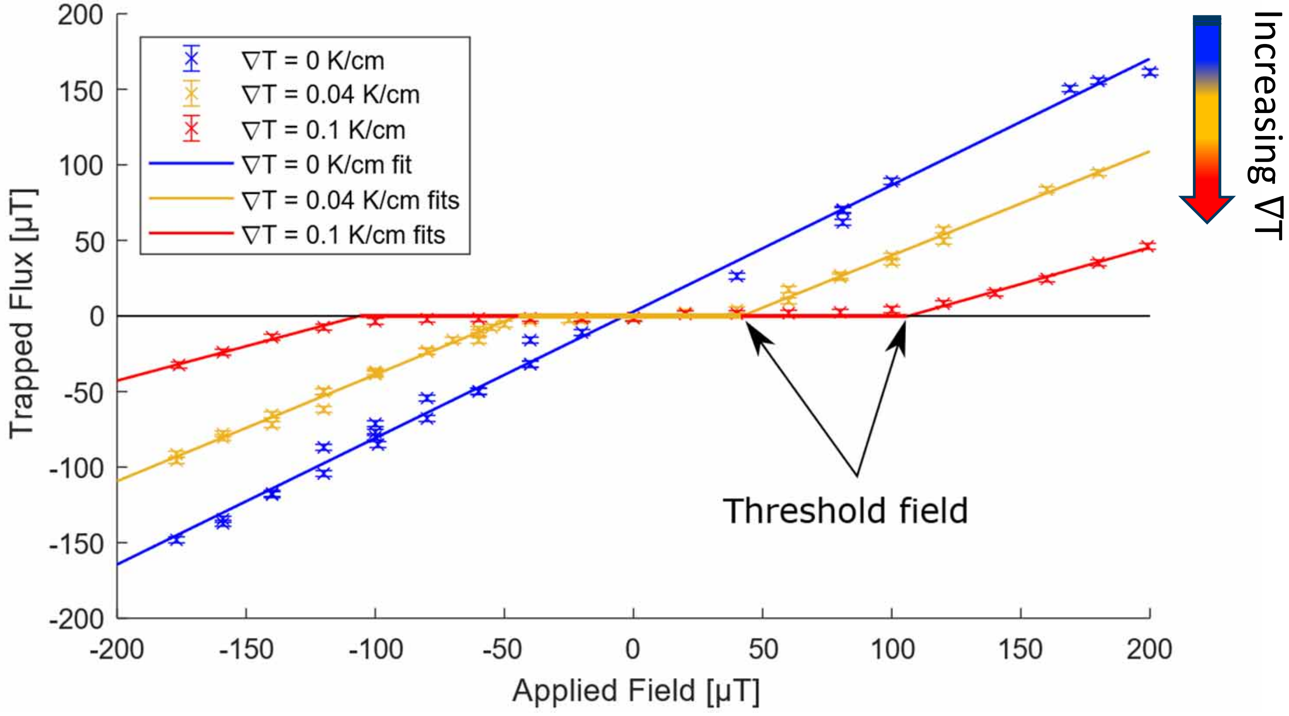

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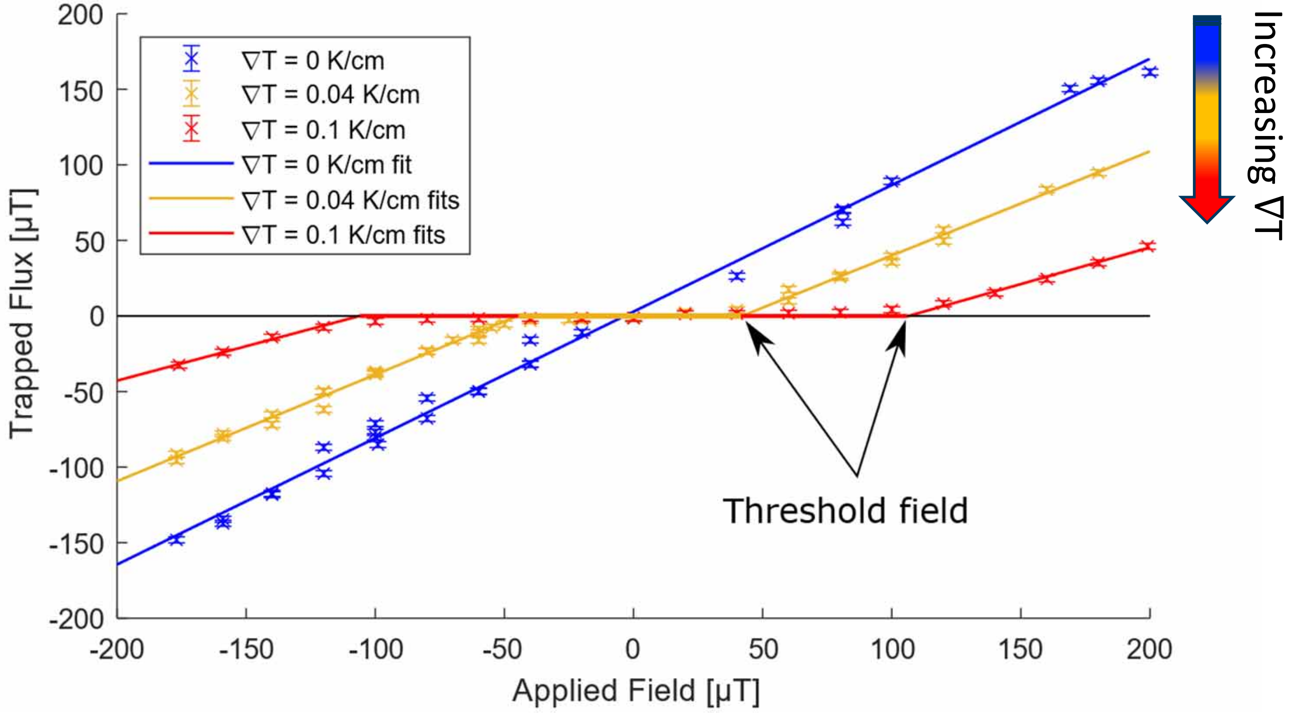

Temperature gradient dependent threshold field

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TRAPPED FLUX VS COOLDOWN RATE

Large-grain Nb sample

- **Vary cooldown rate while keeping temperature gradient and external magnetic field constant**
- **Alter temperature gradient for different measurement series**

  Large grain sample

  B_{ext} = 100 µT

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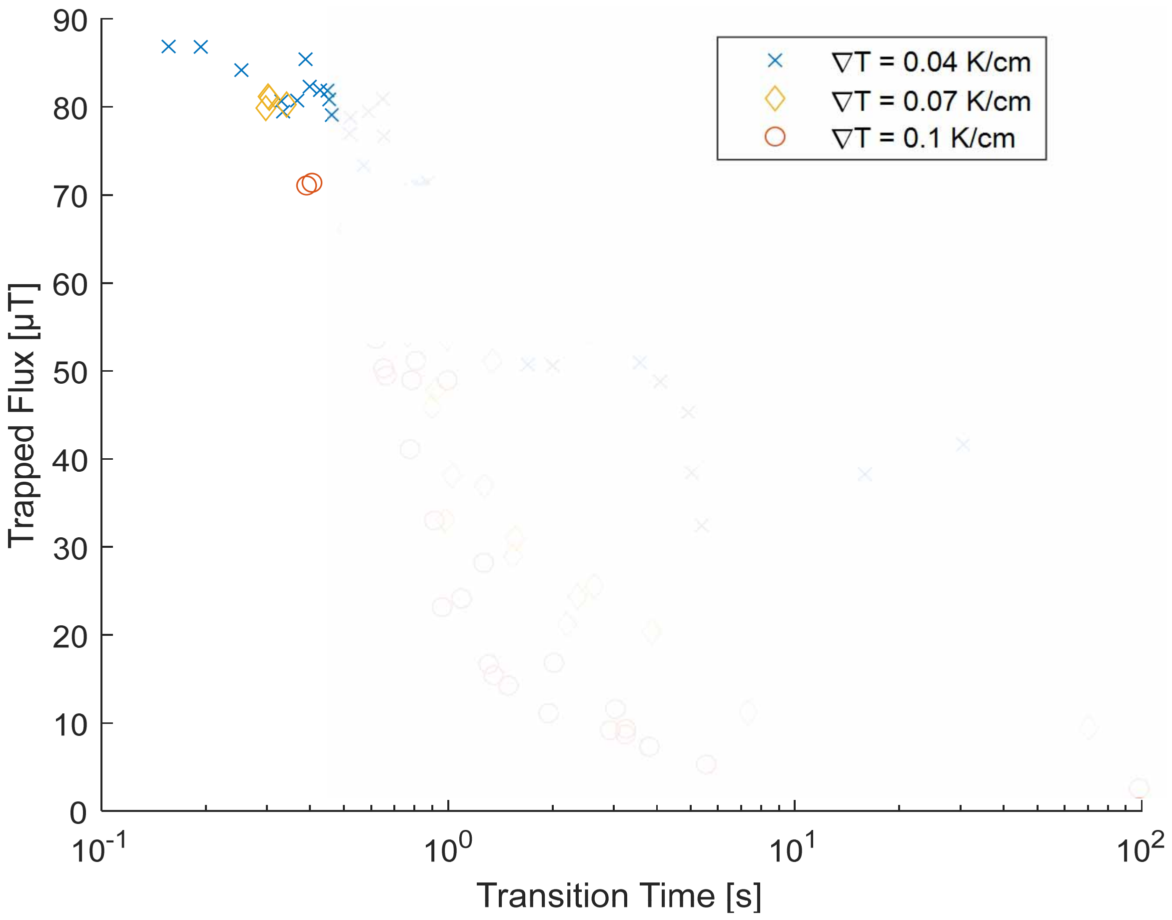
- **Increasing Trapped Flux with decreasing Transition Time**
- **No difference after ~10s**



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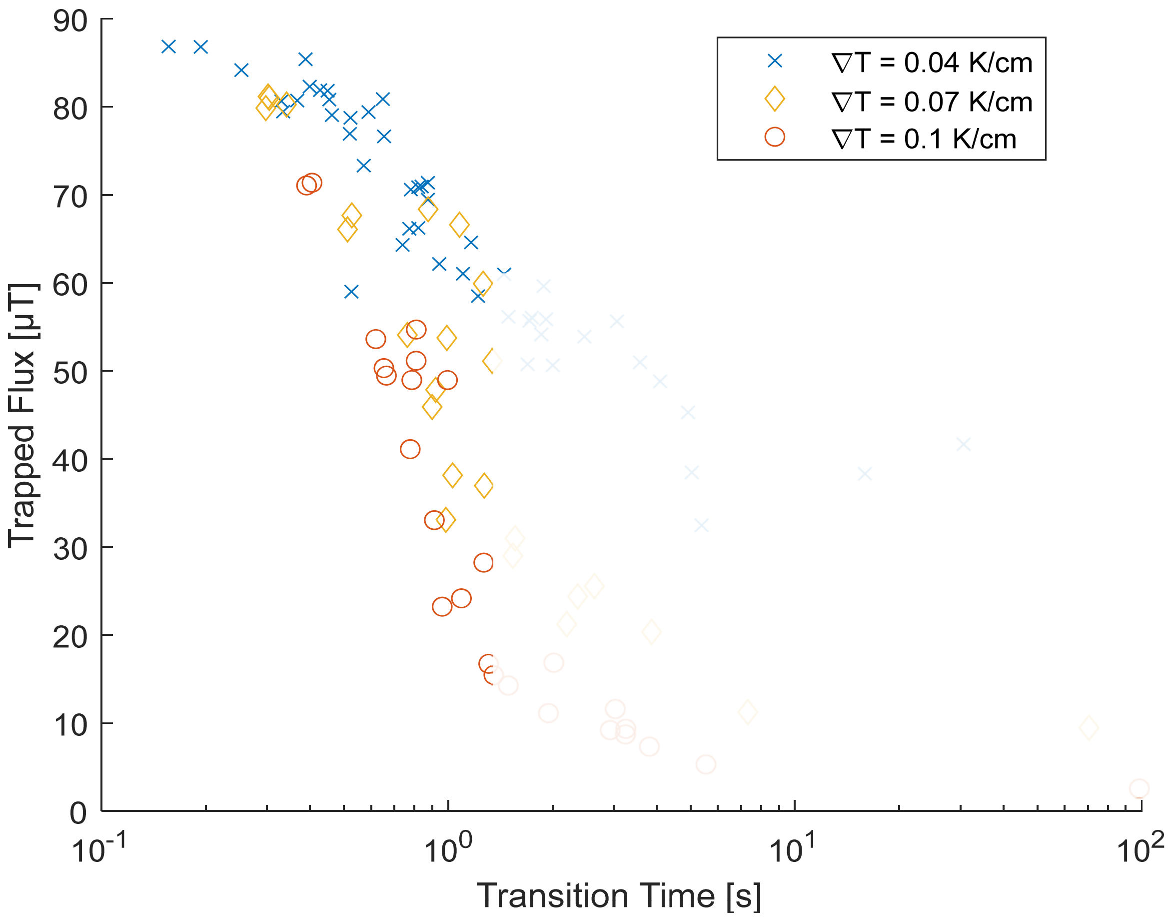

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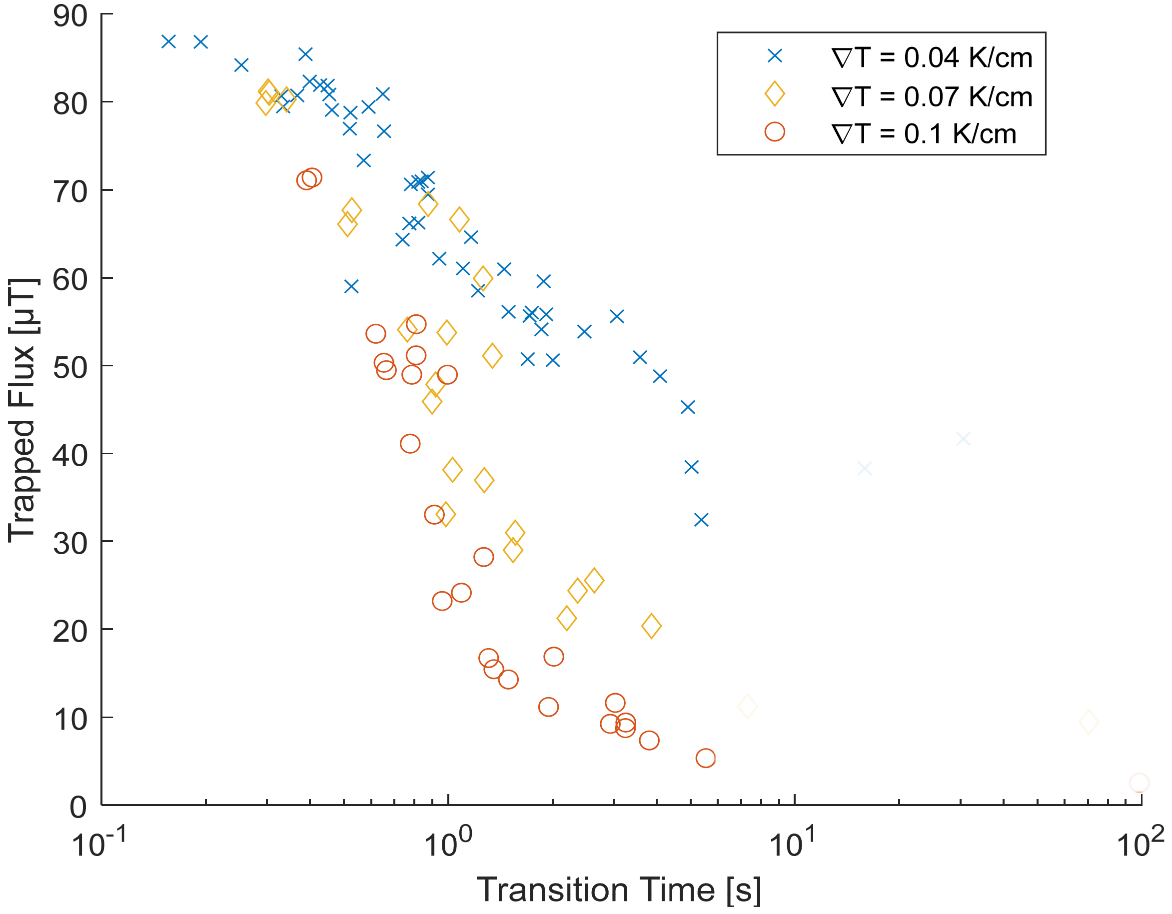

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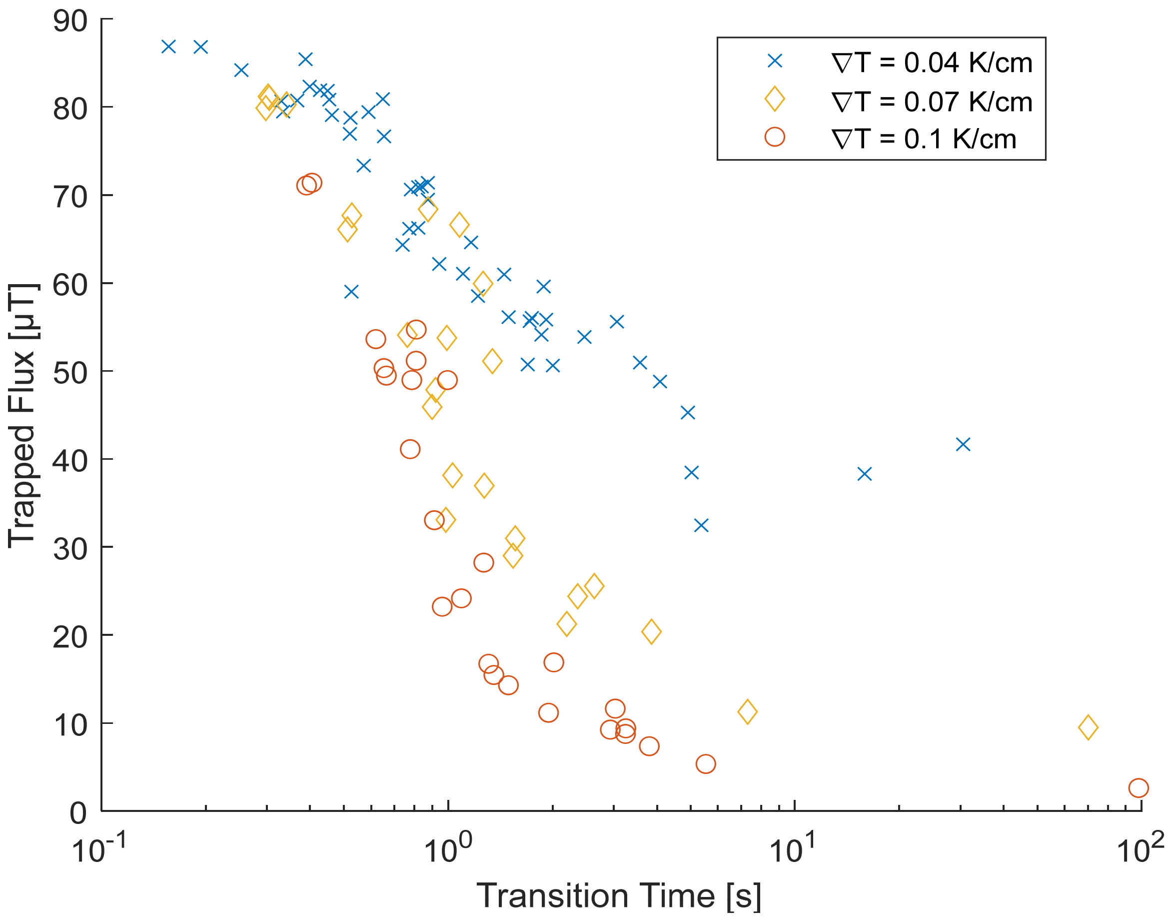

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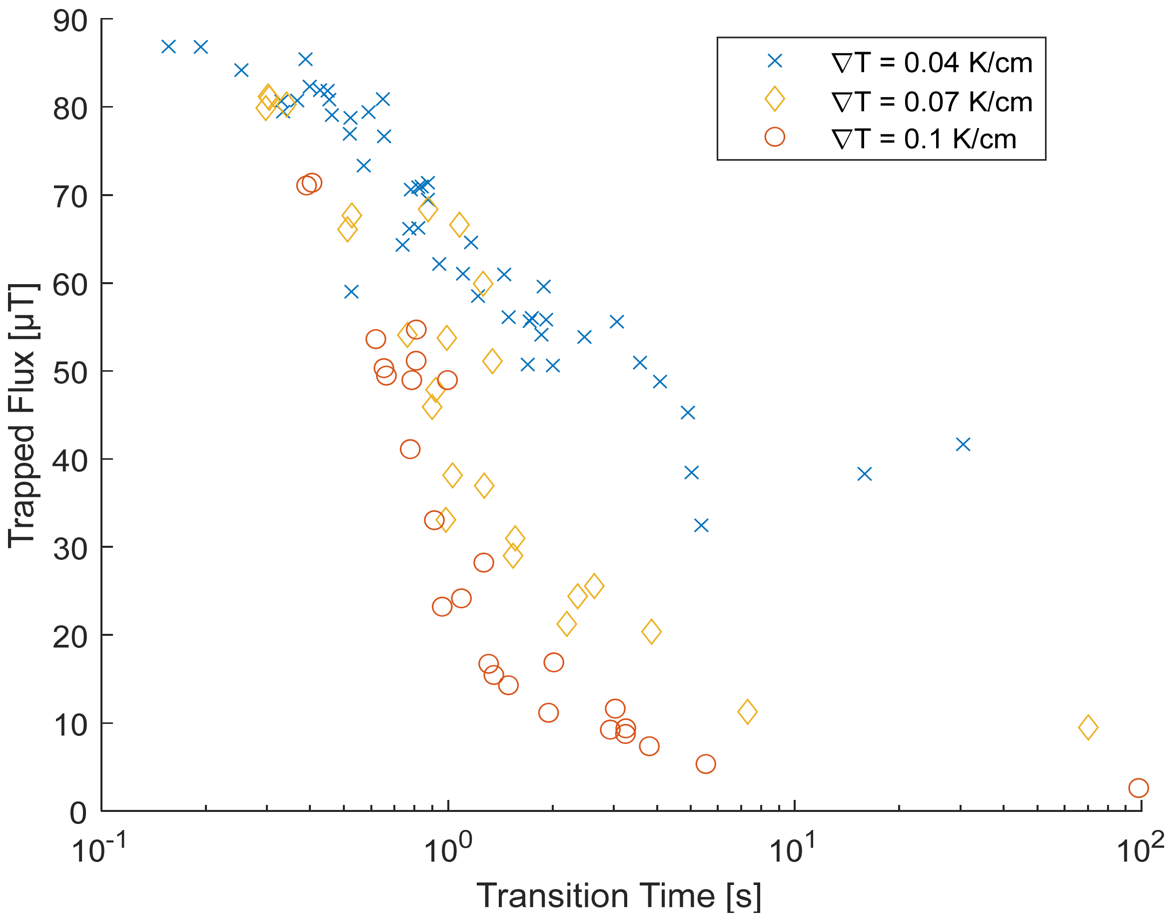
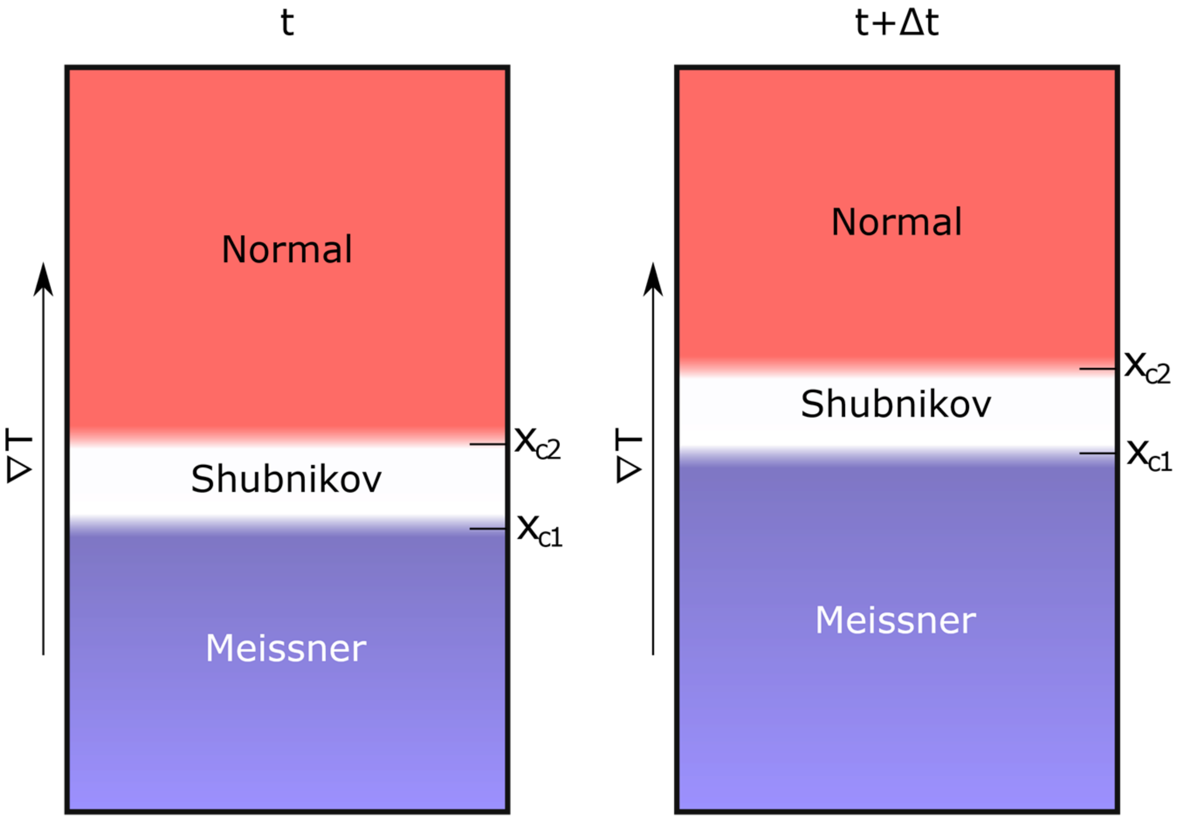


Too fast cooldowns degrade flux expulsion

BASE MODEL

More details on Poster TUPTB002

- **Describes trapped flux in dependence of temperature gradient and external magnetic field**
- **During Cooldown sample is in three states simultaneously**
- **Quantized flux lines establish at x_{c2}**
- **In Shubnikov phase flux are pushed towards Meissner state at x_{c1} by the thermal force $f_{th} = a\, \nabla T$ [2]**
- **Mechanism at x_{c1} unclear at the moment:**
  - Flux lines are trapped if they are at pinning center when x_{c1} reaches them, otherwise they are expelled
  - Thermal force can push flux lines over pinning centers if $f_{th} > f_p$



[2] R. P. Huebener, "Superconductors in a temperature gradient," *Supercond. Sci. Technol.*, vol. 8, no. 4, pp. 189–198, 1995

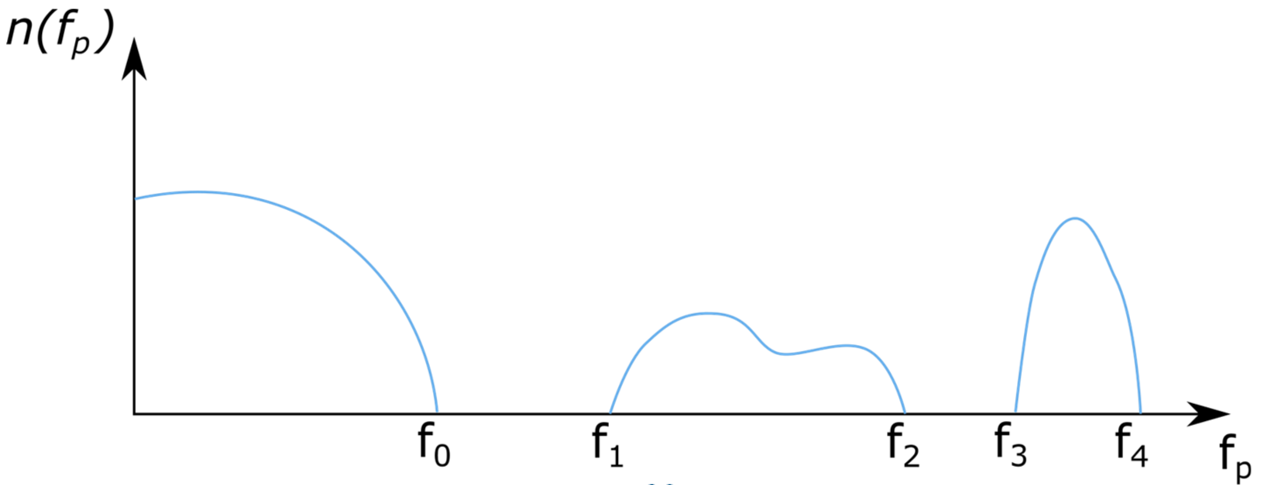
BASE MODEL

More details on Poster TUPTB002

- Introduce distribution function $\boldsymbol{n(f_p)}$ describing probability of flux line to interact with pinning center with $\boldsymbol{f_p}$
- $\int_0^\infty \boldsymbol{n(f_p)\mathrm{d}f_p = 1}$
- Calculate ratio of expelled flux lines

$$r(\nabla T) = \int_{f_p<f_{th}} n(f_p)\mathrm{d}f_p$$

- Two assumptions
  1. $f_0 < f_{th\,max} < f_1$
  2. $n(f_p < f_0) = n_0 = const.$



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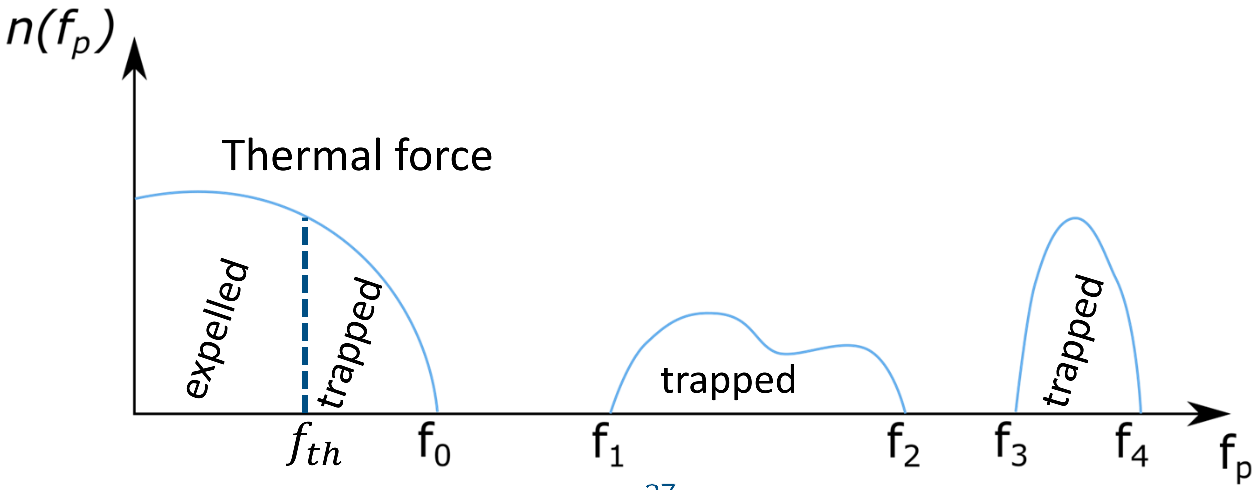

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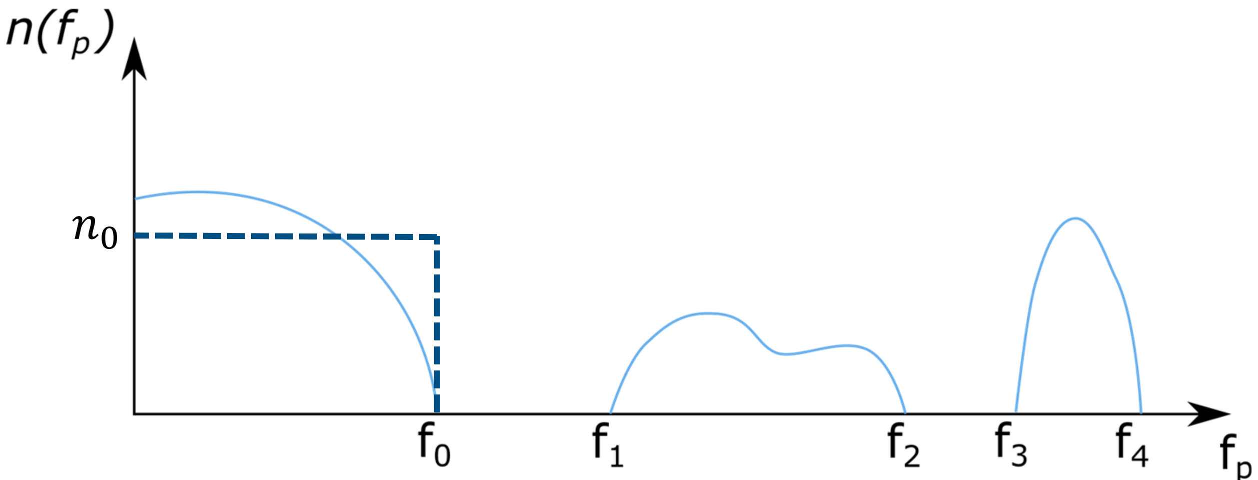

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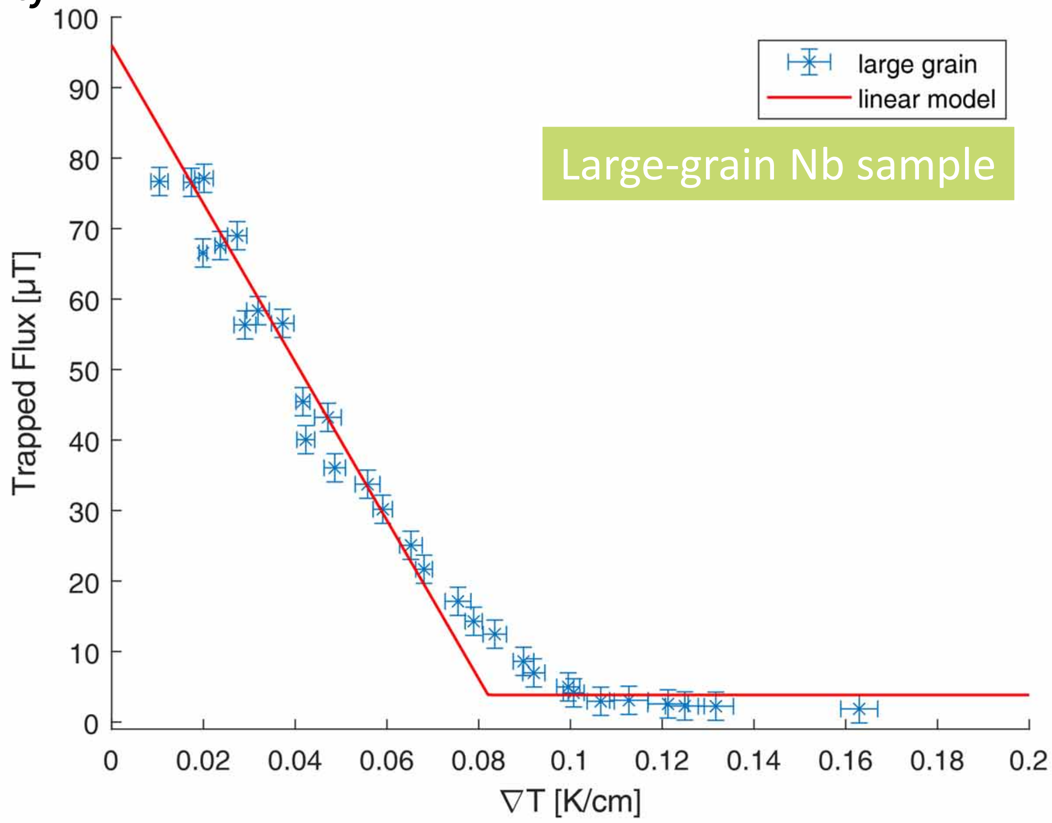
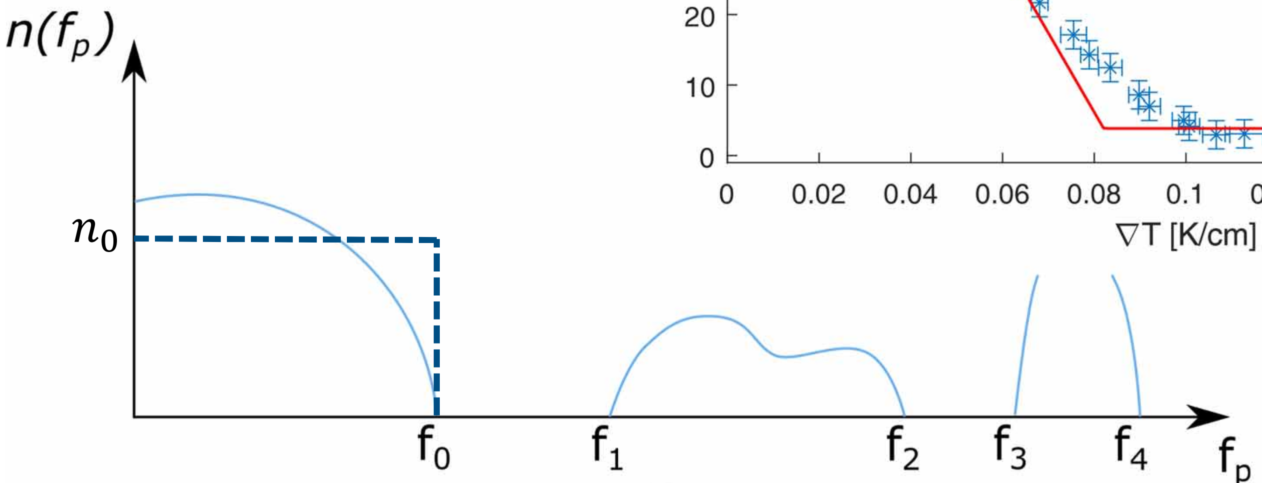
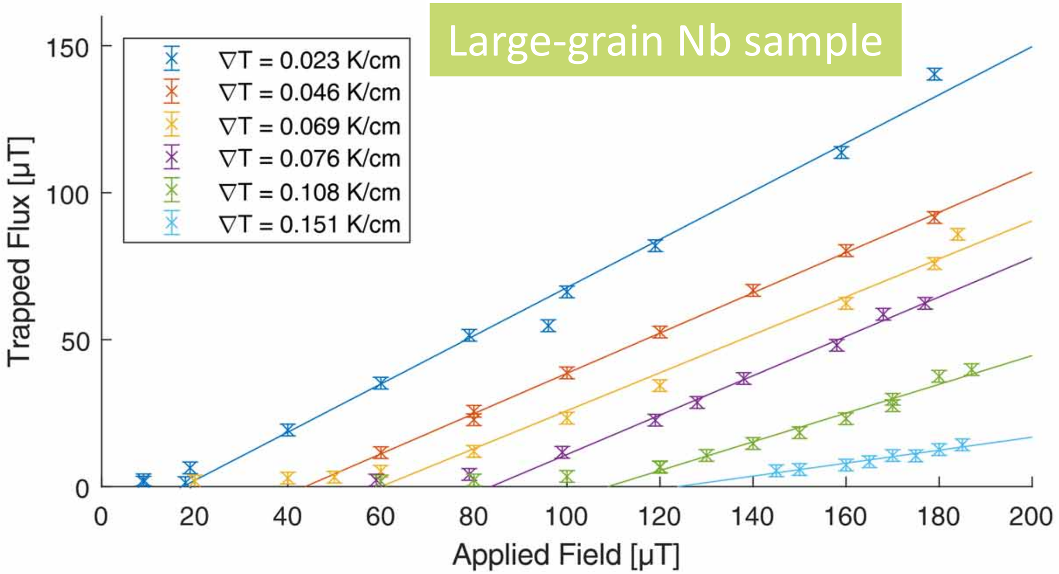




More details on Poster TUPTB002

REFINED MODEL

- Linear fits of trapped flux versus external field data
- Plot slope, x-axis, and y-axis crossing versus temperature gradient
- Slope and x-axis crossing show linear dependency on temperature gradient
- => y-axis crossing must have quadratic dependency on temperature gradient



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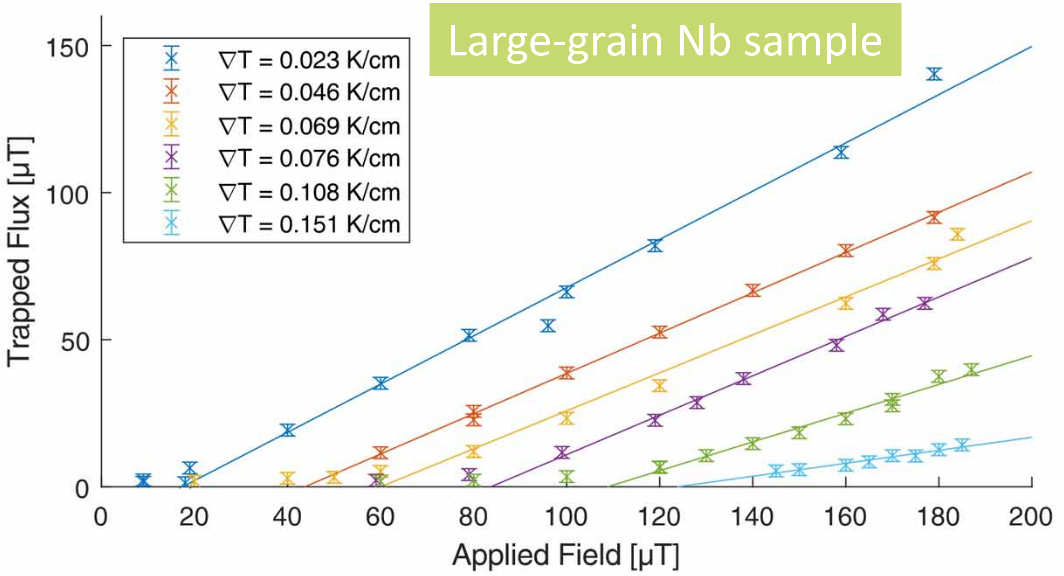

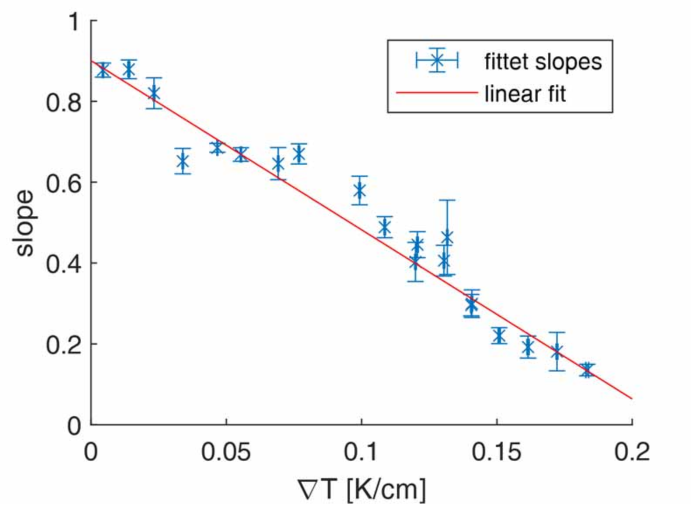

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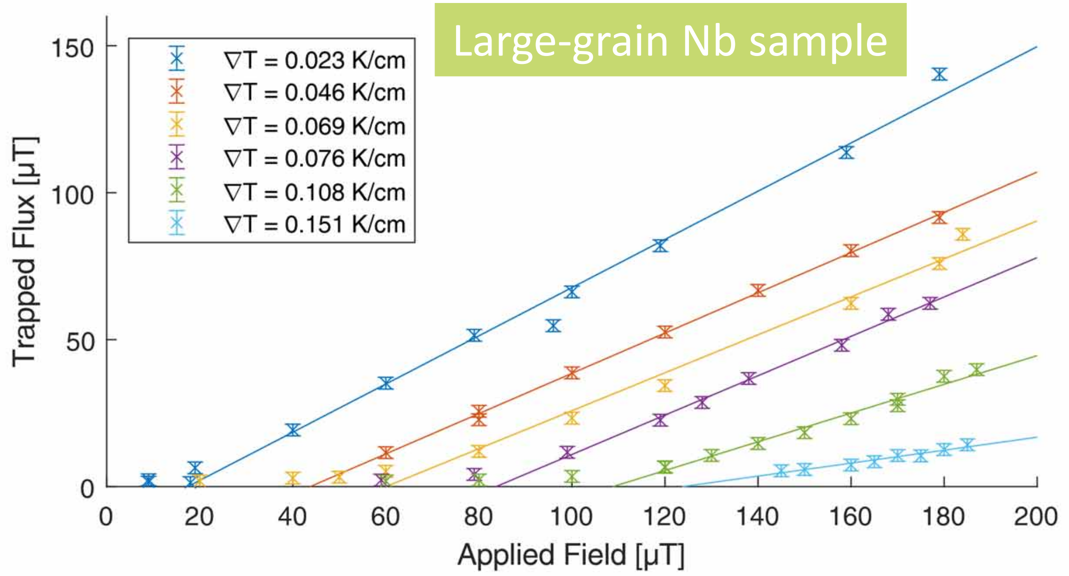

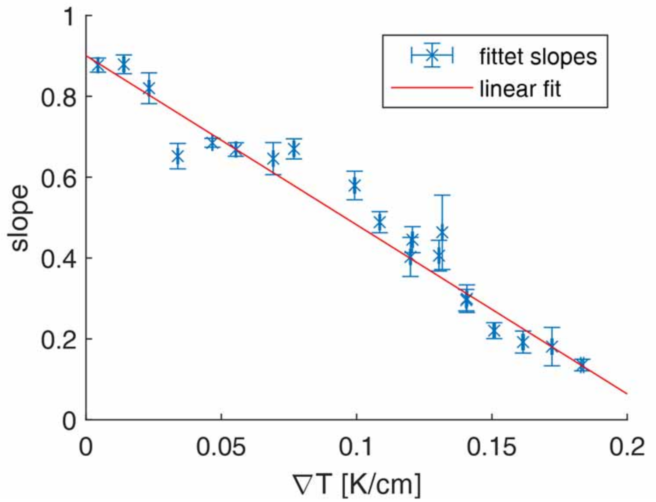

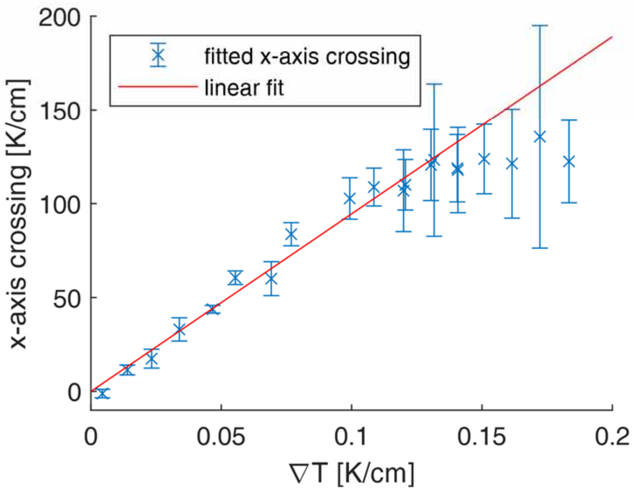

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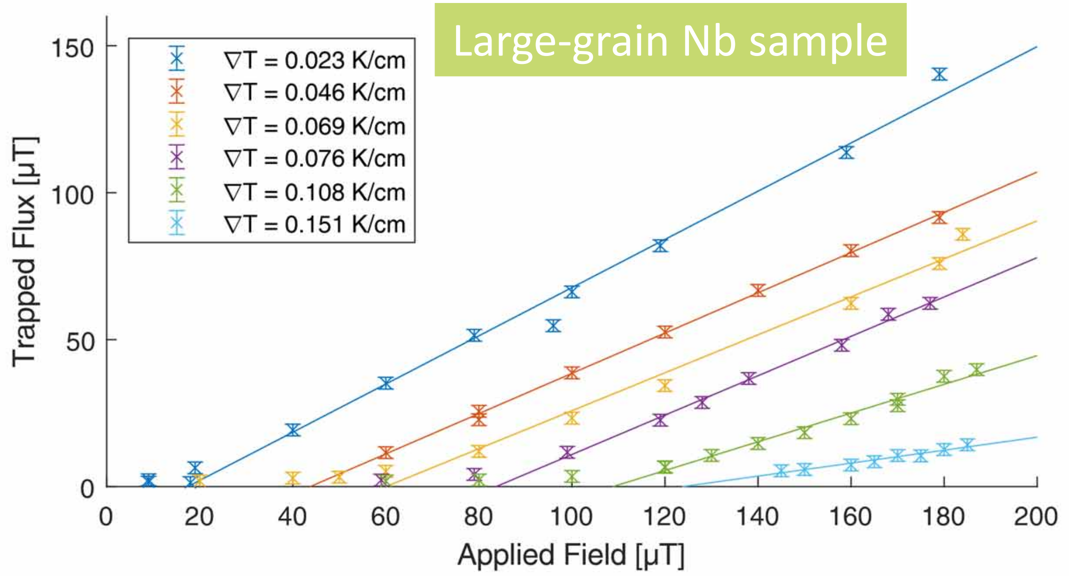
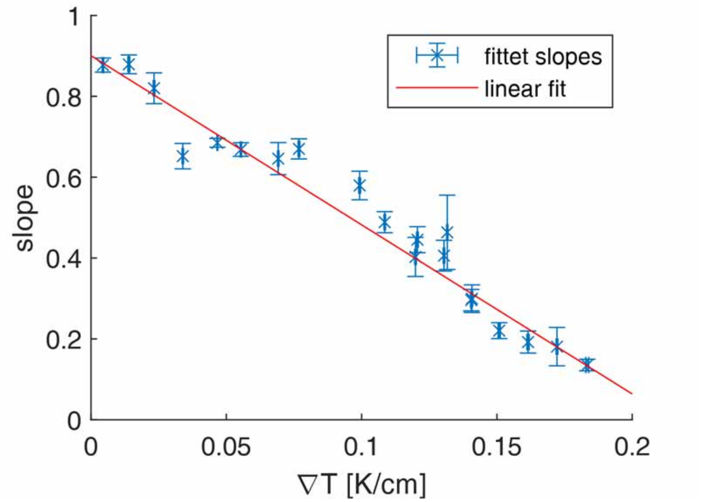
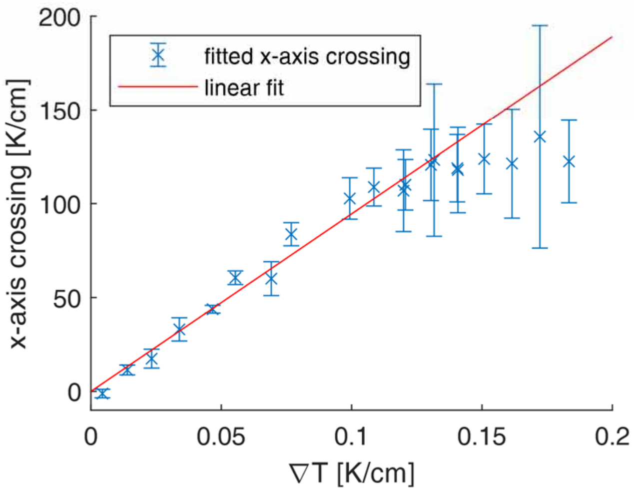
More details on Poster TUPTB002

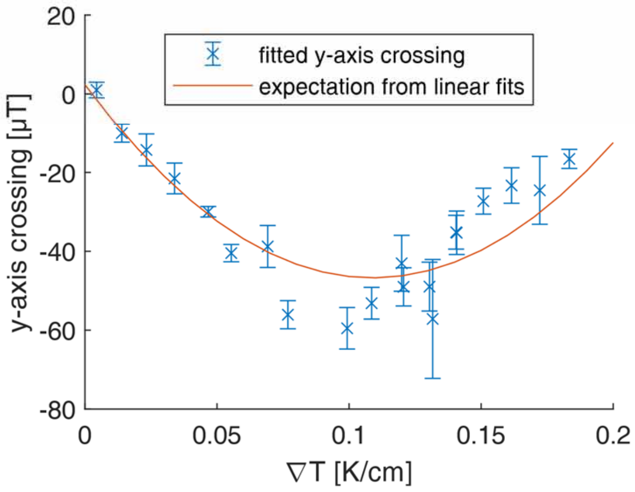
REFINED MODEL

- Linear fits of trapped flux versus external field data
- Plot slope, x-axis, and y-axis crossing versus temperature gradient
- Slope and x-axis crossing show linear dependency on temperature gradient
- => y-axis crossing must have quadratic dependency on temperature gradient







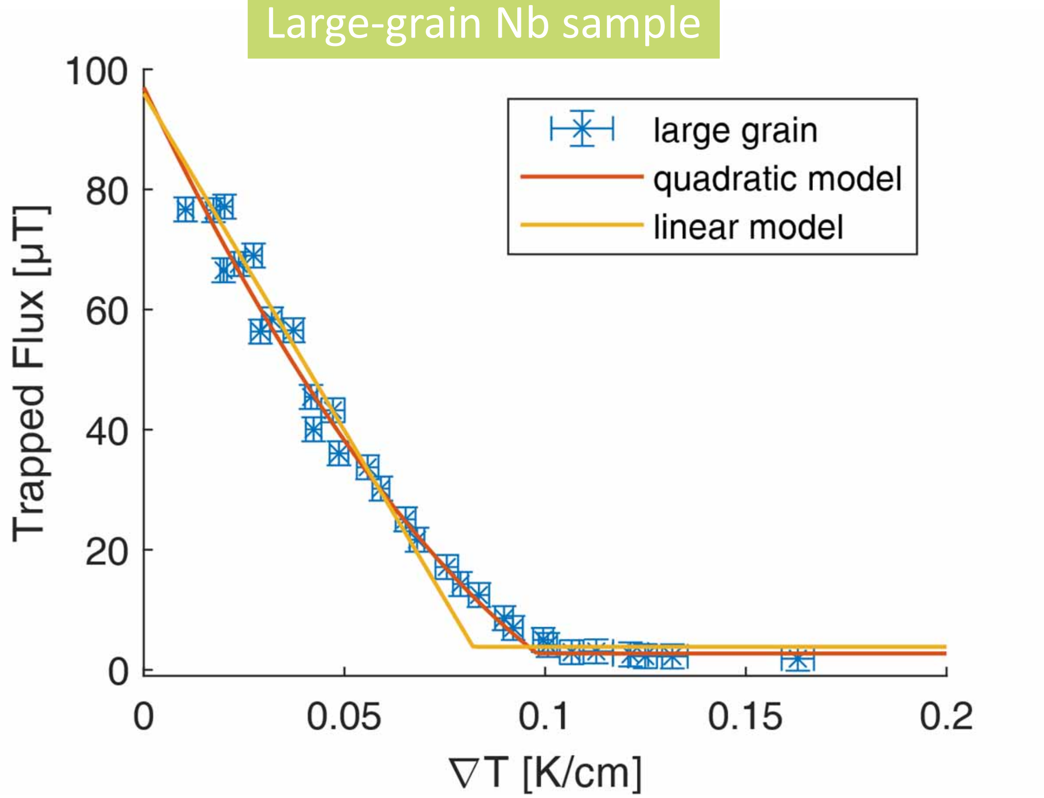


REFINED MODEL

More details on Poster TUPTB002

- **Quadratic term results in a quadratic correction term in the model**

Large-grain Nb sample

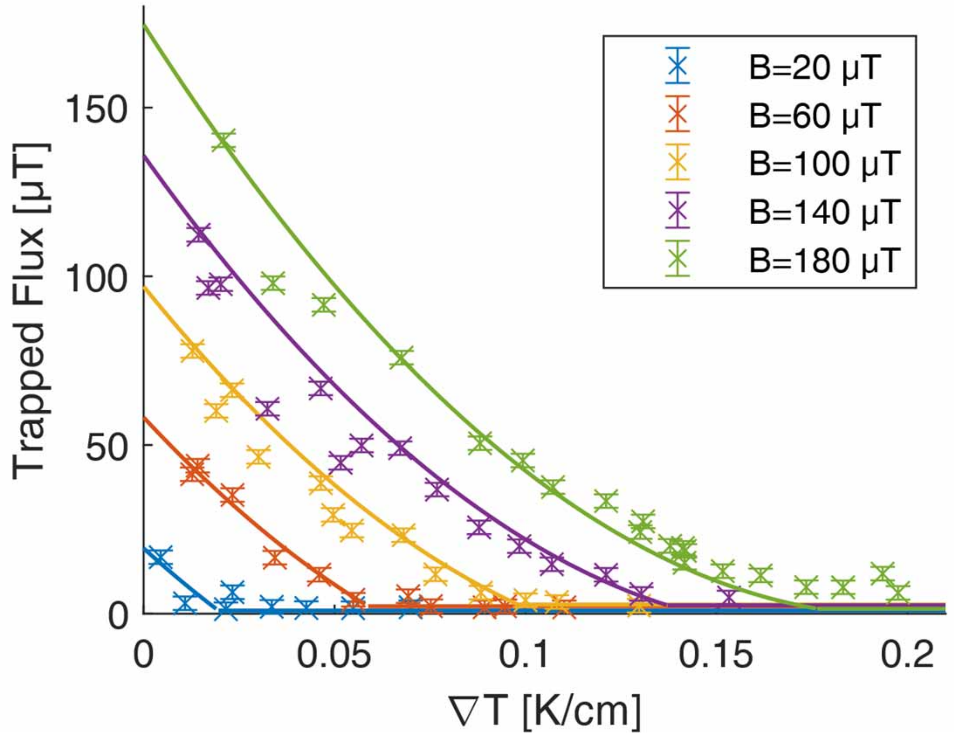


REFINED MODEL

More details on Poster TUPTB002

- Quadratic term results in a quadratic correction term in the model
- Obtained fit parameters can be used to predict trapped flux at different external flux densities

Large-grain Nb sample

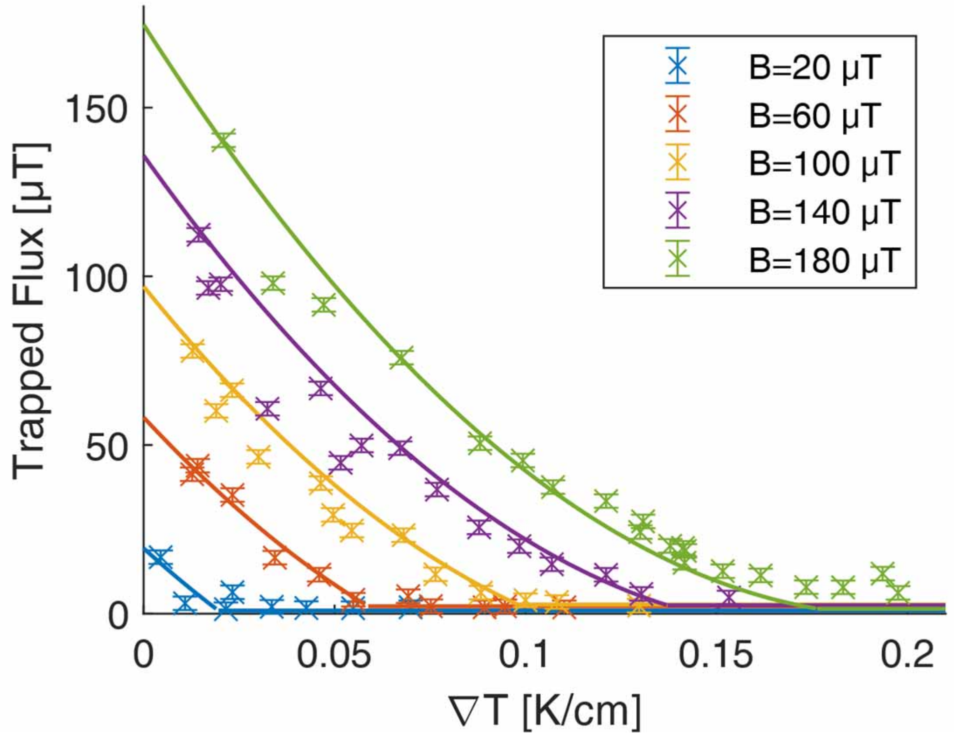


REFINED MODEL

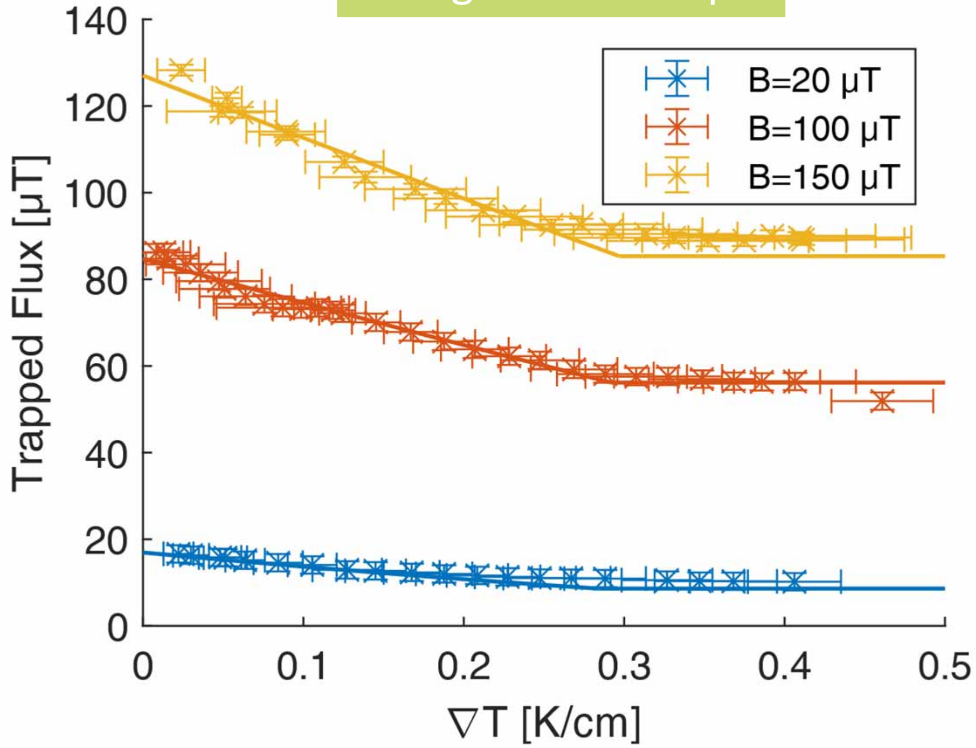
More details on Poster TUPTB002

- **Quadratic term results in a quadratic correction term in the model**
- **Obtained fit parameters can be used to predict trapped flux at different external flux densities**

Large-grain Nb sample



Fine-grain Nb sample



CONCLUSION

Temperature Gradient / Material

- Better expulsion at higher gradients
- Large grain expels flux much more efficiently than fine grain
- Above 0.1 K/cm all flux is expelled in large grain sample

External magnetic field

- Depending on temperature gradient, flux is only trapped above threshold field
- Linear dependency above threshold field

Cooldown speed

- Flux needs time to exit the superconductor

Model

- Agrees well with data, and correctly predicts trapped flux at different external flux densities
- Still open questions regarding dynamics at Meissner phase front, and origin of threshold field.

OUTLOOK

- Investigate different materials (N infused Nb, Nb3Sn, multilayer) and treatments (surface- and heat treatment)
- Develop model further and address open questions
- Develop methods to decrease trapped flux