Presentation of master thesis

Investigation of thermo-magnetic instability in superconducting NbN thin-films by automated real-time magneto-optical imaging

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Outline

Introduction
- General superconductivity
- Important topics for this thesis
- Goals for this thesis

Experimental methods and setup
- The magneto-optical imaging [MOI] method
- MOI experimental setup

Results and discussion
- Automation of setup
- Flux dynamics
- Phase diagram

Summary
What is a superconductor?

Basic properties

$T \leq T_c$

- No electrical resistivity
- Meissner effect

$B_c, J_c$ Critical magnetic field and current density
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Critical magnetic field and current density
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- Fundamental length-scales:
  \( \xi \): Coherence length
  \( \lambda_L \): London penetration depth

- Type I and Type II
- (Abrikosov) vortices and pinning
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Critical state model

- The Bean model
- Thin-film superconductors
- Discontinuity lines (d-lines)
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Thermo-magnetic instability

- Meta stable state
- Avalanche
- Big avalanche
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Goals for this thesis

Investigate thermo-magnetic instabilities in NbN thin-film superconductors, at a wide range of magnetic fields and temperatures by:

- Automated real-time experiments
  - Design program in LabView to control experimental setup
- Automated processing of images
  - Develop an algorithm in Matlab for graphical recognition of magnetic flux avalanches,
  - and another for deciding the threshold fields for the formation of flux avalanches
- Construct a phase diagram showing the threshold fields as a function of temperature
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The magneto-optical imaging [MOI] method

Faraday rotation

- Polarization plane of linearly polarized light is rotated in a dielectric medium, induced by a magnetic field.
- Angle of rotation ($\Theta_F$) is decided by magnetic field (B), thickness of medium (d) and the Verdet constant (V).

$$\theta_F = V \cdot d \cdot H$$
The magneto-optical imaging [MOI] method
Magneto-optical indicator film

- Bismuth-substituted ferrite garnet sensor film
  - 5 mm gadolinium gallium garnet (GGG) substrate
  - 5 µm bismuth substituted yttrium iron garnet (Bi:YIG)
  - 0.1 µm mirror layer (often aluminium)
The magneto-optical imaging [MOI] method
Magneto-optical imaging technique

- Linearly polarization of high intensity light
- Sent through MOI-film and reflected back
- Filtered by analyser, only rotated light passes
- We have a visualization of the magnetic field passing through the MOI-film
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MOI experimental setup

sample

- Niobium Nitride (NbN) thin-film superconductor (Senapati et al. 2006)
  - Size: 2.4 mm × 4.8 mm
  - Thickness: 2000 Å
  - Grown on a single crystal (100) magnesium oxide (MgO)
- Mounted on sample-holder, with MOI film on top
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equipment

1. He-flow cryostat with resistive coils above and below
2. 12bit digital output camera, 1.4Mpixel resolution
3. Leica DMRM polarization research microscope
4. Power supply
5. Temperature controller
LabView: CEFA4.vi

Automation of setup

- Initialization
- Control
  - Increase and decrease field
  - Acquire image
  - Adjust exposure time
- Termination
LabView: CEFA4.vi

Automation of setup

• Initialization

• Control
  ▶ Increase and decrease field
  ▶ Acquire image
  ▶ Adjust exposure time

• Termination

• Front panel
Matlab
Algorithm for graphical recognition of magnetic flux avalanches

- Two adjacent images are subtracted
  - Difference image
    - “Noise filter”
    - 16bit (12bit) to 8bit conversion
    - Only new flux avalanches
- Divide image into 23x23 pixel squares
Matlab

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Algorithm for graphical recognition of magnetic flux avalanches

- Are there any dendritic flux avalanches?
  - Calculate light intensity in each square
  - Intensity above threshold gives “1” (white)
- If two adjacent squares have a “1”, we have an avalanche
- Lowest and highest B-field giving flux avalanches are recorded, both for increasing and decreasing fields
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Flux dynamics

Size of flux avalanches

- Increase in size with increasing applied field
- Decrease in size with decreasing applied field
- Increase in size with increasing temperature
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Sample-spanning flux avalanches

- Sample-spanning avalanches at $T \geq 7$ K
- Increasing applied field; avalanche filling most of the superconductor with vortices
- Decreasing applied field:
  - Second discontinuity line forms
  - Vortex avalanches draining these high vortex density areas
Flux dynamics

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![Image of flux dynamics](image-url)
Flux dynamics

Secondary flux avalanches

- Avalanches seem to cross the central d-line, but only with decreasing applied field
  - No inertia or Lorentz force to do this
  - Primary avalanche reaching the d-line triggers secondary avalanches on the other side
  - These avalanches drain the second d-line into central d-line
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Phase diagram

Hysteretic behaviour

- Experiments carried out for
  - $T=4\,\text{K} - 10\,\text{K}$, $\Delta T=1\,\text{K}$
  - Plus $T=8.5\,\text{K}$ and $T=9.5\,\text{K}$

- Increasing field phase diagram
- Decreasing field phase diagram
- Hysteretic behaviour between $T=7\,\text{K}$ and $9.5\,\text{K}$
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Increasing field phase diagram

Decreasing field phase diagram

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Phase diagram
Threshold field and critical current density

- Functional dependance of $B^{th}$ on $J_c$: $B^{th} = B^{th}(J_c)$
- Magnetic field profile
- Higher $J_c$ gives higher $B^{th}_2$
- No hysteresis for $T<7$ K

$^a$Yurchenko et.al. 2007
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Yurchenko et al. 2007
Summary

- **Automated real-time MOI experiments** and **Automated processing of MO-images** makes the investigation of thermo-magnetic instabilities more precise and efficient.
- A number of **flux-dynamic effects** have been observed.
- A phase diagram of the threshold fields as a function of temperature shows a **hysteretic behaviour** for the upper thresholds ($B_{2}^{th}$) for $T=7$ K to $T=9.5$ K

**Outlook**
- More quantitative studies of the threshold field hysteresis.
- Studies are needed on correlation between ramp rate and threshold fields in different superconducting materials.
- The tools developed in this thesis is well suited for continued studies of thermo-magnetic instabilities.
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