Dynamic Study of Field and Current Distribution in Multifilamentary YBCO Thin Films

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Motivation

- High-temperature superconductors (HTS) have many potential applications
  - Most promising ones: YBa$_2$Cu$_3$O$_7$
    - Thin films
    - Very high aspect ratio (width/thickness): 1,000 – 10,000
    - AC losses still too high
    - Filamentarization
      - What is the dynamic?
- How can we predict their behavior?
  - Analytical models are too simplified
  - FEM
    - Numerically challenging
      - HTS have highly non-linear current-voltage relation
      - High aspect ratio (high number of FEM nodes)
The model (2-D)

- Faraday’s law: \( \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \)
- Non-linear resistivity for the superconductor:
  - \( \rho(J) = \frac{E_c}{J_c} |J/J_c|^{n-1} \)
  - \( n = 25-50 \)
- Magnetic field components as state variables:
  - \( J \) derived from \( H \) by differentiation
  - \( E = \rho J \)
- Transport current: integral constraint
- External field: boundary conditions
- Edge elements

\[ E \sim J^n \]
Power losses in multifilamentary YBCO films

- **Hysteresis losses**

  \[ Q_{hv}^{st} \approx I_c \cdot E_\perp = I_c w_n Bf \]

- **Coupling losses**

  \[ Q_{vn}^{st} \propto \frac{|E_\perp|^2}{\rho} W d_n = 2 \frac{(BfL)}{\rho} d_n W \]

- **Total losses**

  \[ Q = Q_{hv}^{st} + Q_{vn}^{st} \approx Iw_n Bf + 2 \frac{(BfL)}{\rho} d_n W \]

- **Loss reduction (high \( \rho \))**

  \[ \frac{\langle Q_{st}^{st} \rangle_V}{\langle Q \rangle_V} \approx \frac{1}{N} \]

  \[ w_n = \frac{W}{N} \]
Simulation of 6 rectangular filaments
- Dimensions: 120 µm x 300 nm
- 60,000 mesh nodes
- 90,000 degrees of freedom

Magnetic field evaluated 1 µm above sample
- As in experiments

Physical parameters
- $J_c = 3 \times 10^{11}$ A/m²
- AC current: 8 A @ 1000 Hz
- DC field 5 mT
Motivation for TRMOI

- TRMOI offers:
  - High spatial and temporal resolution (sub-µm, pico-second)
  - Dynamical study of the vortex movement
  - Qualitative and quantitative -> current density evolution
  - Manipulation of vortices

Leidere PRL 93, 2642 (1993)
Johansen PRB 54, 16264 (1996)
Experimental setup

- Superconductor
- Garnet indicator
- He lamp
- CCD camera
- Polarizer
- Cryostat
- Solenoid
- Analyzer
- Microscope
- Laser
- AC Power Source
- PC
- Probe
- Solenoid
- He
- Cryostat
- AC Power Source
- Pump
- T ± δT
- Θ_{F} = αB
- H_a ± δH_a
- Laser pulse phase
- AC time
- Time
Multifilamentary YBCO Samples

YBCO thin film 250-300nm thick. 6 filaments obtained using etching.

YBCO thin film 1-3 mm thick. 7 filaments obtained using laser processing.
Experimental observation
TRMOI field and current profiles

$T = 40 \text{K}$  $H_a = 5 \text{mT}$  $I = 8 \text{A}$  $f = 1000 \text{Hz}$
Transport current per filament

- $B_e = 5 \text{ mT}$
- $I_{ac} = 8 \text{ Amps}$
- $f = 1000 \text{ Hz}$

<table>
<thead>
<tr>
<th>Filaments</th>
<th>Pos Int Current (A)</th>
<th>Pos Current Fit (A)</th>
<th>Neg Int Current (A)</th>
<th>Neg Current Fit (A)</th>
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</thead>
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<tr>
<td>Filament#1</td>
<td>-1.93</td>
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<td>-1.39</td>
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<td>Filament#6</td>
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<td>1.80</td>
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</table>
Magnetic field profiles

- Magnetic field profiles for different thicknesses:
  - 120/15 µm
  - 120/30 µm
  - 120/60 µm

- The graphs show the magnetic field strength (B, mT) and the phase angle (φ, deg) as functions of position (x, µm).

- The color bar on the right indicates the magnetic field strength range from 0 to 40 mT.
Current density profiles

- 120/15 µm
- 120/30 µm
- 120/60 µm

The diagrams illustrate the current density profiles with varying x (µm) values and φ (deg) for different configurations.
AC losses

![AC losses graph]

- separ 15
- separ 30
- separ 60
- separ 90

AC losses (W/m)

Time (s)
Conclusions

- Performed TRMOI measurements on YBCO multifilamentary films
- Developed FEM model in Comsol for studying current density and field profiles in HTS
  - Very good agreement with measurements
- Used model to study influence of inter-filament distance ("magnetic coupling")
  - Current/field profiles and AC losses change
- Model will be used to optimize geometry