Integrated Electro-Thermal Model for Quench Simulation in YBCO Tapes.

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Outline

• Tape configurations and physical properties
• Problem statement
• Quench process in YBCO 2G conductors
• Existing models in the literature and their limitations
• Effect of current diffusion on quench dynamic
• From tape to device quench modelling
• Key parameters
• Proposed improved model
• Preliminary qualitative results and future work
American Superconductor - Tape Configurations

- Multi-layer configuration
- Physical properties strongly dependant on temperature

American Superconductor 344 - Copper-stabilized second generation HTS wire
- 0.2 mm * 4.35 mm
- 70 A @77K (minimum)

American Superconductor S344 - Stainless steel-stabilized second generation HTS wire
- 0.150 mm * 4.33 mm
- 60 A @77K (minimum)
Other Configurations

- Major manufacturers are American Superconductor, Sumitomo, EHTS, THEVA
- All have different configurations in terms of:
  - Layer thickness
  - Stabilization layer
  - Current density
- Maximum length achieved is 322 m by Sumitomo
# EHTS Tapes Available

## YBCO Coated Tapes

<table>
<thead>
<tr>
<th>Architectural Properties</th>
<th>YHT-HC Standard Tape</th>
<th>YHT-HC Tape with Optimized Quench Behavior</th>
<th>YHT-HC Tape with High 2D-Homogeneity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>stainless steel, thickness 100 µm or 50 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HTS film</td>
<td>YBCO, thickness 0.5 ... 3 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protection layer</td>
<td>silver or gold, thickness 0.2 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu Shunt layer</td>
<td>20µm thick</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Electrical Properties

- **Temperature:** 77 K, 0 T

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering current density</td>
<td>300 ... 1000 A/mm²</td>
</tr>
<tr>
<td>Critical currents</td>
<td>135 A in 4 mm wide tape, 350 A in 10 mm wide tape, 1000 A in 40 mm wide tape</td>
</tr>
</tbody>
</table>

### Mechanical Properties

- **Temperature:** 300 K

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial tensile strength</td>
<td>650 MPa</td>
</tr>
<tr>
<td>Critical bending radius</td>
<td>9 mm</td>
</tr>
<tr>
<td>Critical torsion</td>
<td>30 ang. deg. per cm-length (4mm wide tape @ 40N axial force)</td>
</tr>
</tbody>
</table>

### Typical Dimensions

- **Thickness:** 0.105 mm or 0.05 mm
- **Width:** 4.10 or 40 mm
- **Unit lengths:** 40 m @ 4mm wide tape

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*EHTS Tapes Available at CHATS AS 2006, Berkeley, CA, Sept. 5-7*
The Problem

• Why is quench a problem in 2G wires?
  – Normal zone propagation velocity too slow 1-10 mm/s
  – Hot spot T could be very high and destructive
  – Non uniformity of material properties
  – Not yet well understood

• Stabilization and quench protection are VERY important
  – Quench development appears to be a 3D phenomenon from experiment (because it is so slow that turn to turn diffusion matters)
  – Need 3D simulation tool to analyze quench and develop protection schemes
Problem: quench propagation in 2G tapes

Normal zone

Buffer is highly resistive: how much current goes into Ni layer?
Existing Models

- Chyu – Oberly – first study (1990)
- Iwasa – 1D steady state
- Fu – 1D lumped circuit – no magnetic coupling
- Ishiyama – 1D current sharing
- Iwasa – copper stabilized
- Vysotsky – scaling theory
Existing Models (2)

- Stadel – electrical field distribution due to hot spot
- No electrical breakdown to be expected

Figure 1. Cut-Out of simulated allocation of the electrical field in the model. The dimension of the electrical field is given in V/m.
One dimensional model

Temperature uniform across the tape

Nickel and silver in parallel

Simple formula for the joule loss

Solder only considered for the transverse resistance

Silver and copper not in parallel

Inductive effects negligible

Existing Models (5) : Universal scaling

- Uniform temperature along the tape
- Power law for the superconductor
- Based on equilibrium theory
- Analytical solution relative to the tape heating

Lumped electrical parameters model coupled with a discrete (electrical equivalent) thermal model
- Tape uniform along the length
- Tape divided into $N_L$ layers and $N_s$ sectors along the length
- Each layer sector has different thermal and electromagnetic properties
- Electrical coupling through electrical contact resistances and mutual induction coefficients
- Thermal coupling through thermal contact resistances
- Joule losses and temperature dependent properties link the two models
N-layer tape: lumped parameters electrical circuit model

Existing Models (6) : Lumped Parameters Model
Models Comparison with Experiments

• Temperature simulations are accurate
• Large discrepancies for voltage

Iwasa et Al.

Ishiyama, et Al.
Conclusion on Models

- Presented models have been validated on dedicated experiments
- Current models cannot predict quench or recovery
- Tape is considered equipotential which is not the case in reality
- Models are limited to single tape

- Need to do better.
# Typical Tape Configuration

<table>
<thead>
<tr>
<th>Material</th>
<th>$C_p$ (J/m$^3$.K)</th>
<th>$K$ (W/K)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$\mu/\mu_0$</th>
<th>$\sigma$ (Ω.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>65</td>
<td>1.5 e+6</td>
<td>8960</td>
<td>1</td>
<td>7.8 e-9</td>
</tr>
<tr>
<td>Silver</td>
<td>80</td>
<td>0.7 e+6</td>
<td>10490</td>
<td>1</td>
<td>7.55 e-9</td>
</tr>
<tr>
<td>Ni</td>
<td>30</td>
<td>0.4 e+6</td>
<td>8880</td>
<td>1240</td>
<td>2.5 e-8</td>
</tr>
</tbody>
</table>

30 K

<table>
<thead>
<tr>
<th>Material</th>
<th>$C_p$ (J/m$^3$.K)</th>
<th>$K$ (W/K)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$\mu/\mu_0$</th>
<th>$\sigma$ (Ω.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>230</td>
<td>0.6 e+6</td>
<td>8960</td>
<td>1</td>
<td>8.6 e-9</td>
</tr>
<tr>
<td>Silver</td>
<td>170</td>
<td>0.45 e+6</td>
<td>10490</td>
<td>1</td>
<td>8.31 e-9</td>
</tr>
<tr>
<td>Ni</td>
<td>150</td>
<td>0.2 e+6</td>
<td>8880</td>
<td>1240</td>
<td>2.8 e-8</td>
</tr>
</tbody>
</table>

77 K

| Tape length (cm) | 14 |
| Tape width (cm) | 1  |
| $d_{cu}$ (μm)   | 50 |
| $d_{ag}$ (μm)   | 3  |
| $d_{YBCO}$ (μm) | 1  |
| $d_{Ni}$ (μm)   | 75 |
| $I_c$ (77 K) (A) | 146 |
| $n$ (77 K)      | 21 |
Diffusivity and Time Constants

• If homogeneous material considered for each layer
  – Thermal:
    \[
    \alpha \left[ \frac{m^2}{s} \right] = \frac{k}{\rho C_p}
    \]

  – Magnetic:
    \[
    K = \frac{\sigma}{\mu}
    \]

• How do they compare?

\[
\frac{L^2}{\alpha} = \frac{\rho C_p L^2}{k}
\]

\[
\frac{L^2}{K} = \frac{L^2 \mu}{\sigma}
\]
Effect of Current diffusion

- Diffusion time constants

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal diffusivity</th>
<th>Electromagnetic diffusivity</th>
<th>Thermal time constant</th>
<th>Electromagnetic time constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>2.58</td>
<td>6.21 e-3</td>
<td>9.71 E-10</td>
<td>4.03 E-7</td>
</tr>
<tr>
<td>Silver</td>
<td>0.834</td>
<td>6.01 e-3</td>
<td>1.08 E-11</td>
<td>1.5 E-9</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.5</td>
<td>1.6 E-5</td>
<td>3.75 E-9</td>
<td>3.51 E-4</td>
</tr>
</tbody>
</table>

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<th>Electromagnetic diffusivity</th>
<th>Thermal time constant</th>
<th>Electromagnetic time constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>0.291</td>
<td>6.84 E-3</td>
<td>8.59 E-9</td>
<td>3.65 E-7</td>
</tr>
<tr>
<td>Silver</td>
<td>0.252</td>
<td>6.61 E-3</td>
<td>3.57 E-11</td>
<td>1.36 E-9</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.15</td>
<td>1.8 E-5</td>
<td>3.75 E-8</td>
<td>3.13 E-4</td>
</tr>
</tbody>
</table>

Time constants almost independent from temperature

Normal zone propagates at a few mm/s

Diffusion occurs in Ni layer and has to be taken into account
• Normal zone velocity in the same order of magnitude as current diffusion in Nickel layer!
Effect of Current diffusion (3)

- If model is 2D and tape considered infinite, how does current go into the Ni layer?

Current diffused in Ni layer much slower than in copper

- Current diffusion in Nickel has to be taken into account
- At beginning of quench, current can not develop in Ni and dissipates more losses than expected
Proposed Model for FEA Simulations

- FEA simulation
  - YBCO layer considered as a boundary condition
  - YBCO layer considered to have infinite resistance when T increases
  - Current diffusion in Ag and Cu neglected
  - Current diffusion in Nickel taken into account
Preliminary Qualitative Results

- Experiments show that current transfers on longer lengths into substrate
- This can only be explained by diffusion

- Typical sampling time in experiment around 1 ms
- Snapshot at t=1ms shows that current redistribution has already happened
  - What happens before?
  - What is driving the quench?
Edge Effects in Quench Development

- Layers may be in contact on the side

![Diagram of layers and current flow]

- Current is forced into Cu and Ni layers
- Current cannot diffuse fast into Ni
- More heat generated in copper while current goes "slowly" in buffer

Problem is not 2d but 3d (even for single tape)
From Tape to Device

- Quench in a coil will be different than in an isolated tape sample:
  - Magnetic coupling between winding layers
  - Heat transfer from one layer to another
- Quench simulation in coils is required to develop protection systems

Quench propagates in 3D by heat transfer and magnetic coupling between layers
Key Parameters

- Thermal and electrical characteristics of each of the materials forming layers
- Electrical contact resistance between layers
- Thermal contact resistance between layers
- Thermal and electrical diffusivity vs. temperature

- This implies to develop model with the help of experimental data
Promising Techniques to Speed Up Quench Propagation

- Implement contacts to force current to go into substrate
- Current density is increased at contacts thus generating more heating

Conclusion and Future Work

• LTS protection techniques do not work. Need 3D model to develop transition protection
• Current diffusion in the substrate may have an important role in quench dynamics
• Contacts on side between layers have to be taken into account and require a 3D model
• Model development needs to be closely linked to experimental testing
• Tape model cannot be applied to quench propagation in devices. 3D approach is required to simulate interaction between layers