Towards optimisation of multi-pulse, multi-temperature pulsed field magnetisation of bulk high-temperature superconductors

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Outline

• Pulsed field magnetisation (PFM)
• Modelling trapped field capability
  • Simulating field-cooling (FC) & zero-field-cooling (ZFC) magnetisation
• Modelling PFM & multi-pulse PFM
  • Electromagnetic & thermal considerations
  • Simulating multiple magnetic field pulses
• Main results & conclusions
Pulsed Field Magnetisation

- PFM technique: compact, mobile, relatively inexpensive
- Issues: $B_{\text{trap \ [PFM]}} < B_{\text{trap \ [FC], \ [ZFC]}}$
  - Temperature rise $\Delta T$ due to rapid movement of magnetic flux
- Record PFM trapped field: 5.2 T @ 29 K
  - Top surface of 45 mm diameter Gd-Ba-Cu-O
- Record trapped field by FC: 17.6 T @ 26 K
  - Centre of 2 x 25 mm diameter Gd-Ba-Cu-O
Pulsed Field Magnetisation

• Many considerations for PFM:
  • Pulse magnitude, pulse duration, temperature(s), number of pulses, type of magnetising coil(s), use of ferromagnetic materials
  • Dynamics of magnetic flux during PFM process
Pulsed Field Magnetisation

• Many considerations for PFM:
  • Pulse magnitude, pulse duration, temperature(s), number of pulses, type of magnetising coil(s), use of ferromagnetic materials
  • Dynamics of magnetic flux during PFM process
  • Multi-pulse PFM: effective in increasing trapped field/flux


Modelling Trapped Field Capability

Model #1
- Stationary
- Comsol Multiphysics 5.2a
  - 2D axisymmetric
  - AC/DC module
  - Magnetic Field (mf) interface
  - External Current Density node
- No flux creep
- Time taken: ~ 2-3 seconds

Model #2
- Time-dependent
- Comsol Multiphysics 5.2a
  - 2D axisymmetric
  - AC/DC module
  - Magnetic Field Formulation (mfh) interface
  - $E$-$J$ power law, $E \propto J^n$ (flux creep)
- Apply + remove background field
- Time taken: ~ 1-2 hours
Modelling Trapped Field Capability

**$J_c(B, T)$ characteristics**

- Measured from a small specimen taken from representative sample: GdBa$_2$Cu$_3$O$_7$ (15wt% Ag)
- Input into model using direct interpolation of experimental data, i.e., look-up table
- Can dramatically speed up model
- Can also use fitting equation for fishtail effect in (RE)BCO materials:

$$J_c(B) = J_{c1} \exp\left(-\frac{B}{B_L}\right) + J_{c2} \frac{B}{B_{\text{max}}} \exp\left[\frac{1}{y} \left(1 - \left(\frac{B}{B_{\text{max}}}\right)^y\right)\right]$$
Modelling Trapped Field Capability

Results

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Magnetisation</th>
<th>Time</th>
<th>Trapped Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>77 K</td>
<td>FC</td>
<td>t = 0 min</td>
<td>1.544 T</td>
</tr>
<tr>
<td></td>
<td>ZFC [5 T]</td>
<td>t = 10 min</td>
<td>1.263 T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = 20 min</td>
<td>1.223 T</td>
</tr>
<tr>
<td>65 K</td>
<td>FC</td>
<td>t = 0 min</td>
<td>3.826 T</td>
</tr>
<tr>
<td></td>
<td>ZFC [10 T]</td>
<td>t = 10 min</td>
<td>3.256 T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = 20 min</td>
<td>3.158 T</td>
</tr>
<tr>
<td>50 K</td>
<td>FC</td>
<td>t = 0 min</td>
<td>7.449 T</td>
</tr>
<tr>
<td></td>
<td>ZFC [20 T]</td>
<td>t = 10 min</td>
<td>6.577 T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = 20 min</td>
<td>6.405 T</td>
</tr>
</tbody>
</table>

79% 82.5% 86%
PFM Modelling Framework

Electromagnetic properties modelled as Model #2 (ZFC); magnetising fixture assumed as solenoid coil:

\[ I_{\text{pulse}}(t) = N \cdot I_0 \frac{t}{\tau} \exp \left( 1 - \frac{t}{\tau} \right) \quad \tau = 15 \text{ ms} \]

Thermal behaviour needs to be modelled during PFM; governing equations:

\[ \rho \cdot C \frac{dT}{dt} = \nabla \cdot (k \nabla T) + Q \]

\[ Q = E \cdot J \]

Heat source, coupling with EM model + \( J_c(B, T) \)

\( \rho = \) mass density (bulk 5900 kg/m\(^3\), indium 7310 kg/m\(^3\))

\( C = \) specific heat (measured, temperature-dependent)

\( k = \) thermal conductivity:

\( \kappa_{ab} = 20 \text{ W/(m·K)}, \ \kappa_c = 4 \text{ W/(m·K)}, \ \kappa_{\text{indium}} = 0.5 \text{ W/(m·K)} \)
PFM Single Pulse Results

- $t = 120 \text{ s} \rightarrow$ flux creep relaxation & cooling back to operating temp.

- Percentage of ZFC($t = 20 \text{ min}$):
  - 77 K 85%
  - 65 K 49%
  - 50 K 29%

- Four specific cases as initial conditions for 2$^{nd}$ pulse:
  - Partially-magnetised (PM), so-called 'M-shaped' profile
  - Under-magnetised (UM)
  - Fully-magnetised (FM)
  - Over-magnetised (OM)
For all $T$, trapped field after 2nd pulse exhibits two particular characteristics:
1) Increased trapped field, $B_t$, when the bulk is fully magnetised; maximum value when the 1st pulse results in full magnetisation
2) Increased activation field: applied field, $B_{app}$, required to fully magnetise the sample
PFM 2\textsuperscript{nd} Pulse: Magnetic Flux Penetration

- Why does this occur?
  - More difficult for magnetic flux to penetrate the sample due to existing trapped field
  - Existing, induced supercurrent flows in opposite direction
PFM 2\textsuperscript{nd} Pulse: Thermal Behaviour

- Why does this occur?
  - Reduced dynamic movement of flux = lower temperature rise for equivalent next pulse
  - Can examine the average temperature, $T_{\text{ave}}$, during & after PFM:

![Graph showing average and maximum temperature over time for different conditions.](Image)
Similar results are found for the 3rd pulse; however, increase in $B_t$ is marginal, suggesting saturation has been reached.
PFM: Towards Multi-Pulse, Multi-Temperature

77 K → 65 K → 50 K

- At $t = +120$ s, temperature is lowered to next temperature ($-0.5$ K/s)
- Fully magnetised (FM) cases as initial conditions
- Maximum trapped field, $B_{t,max}$, slightly less than for multiple pulses at constant $T$
- More investigations & optimisation needed!
Summary

- A 2D axisymmetric finite element method based on the $H$-formulation was extended to investigate multi-pulse PFM.
- An increase in the trapped field, $B_t$, can be achieved after a 2\textsuperscript{nd} pulse:
  - This is maximised when the 1\textsuperscript{st} pulse results in full magnetisation; and
  - An increased applied field is necessary for the 2\textsuperscript{nd} pulse.
- This occurs because:
  - It is more difficult for the magnetic flux to penetrate the already-magnetised sample.
  - There is a lower temperature rise from the reduced dynamic movement of flux.
- A 3\textsuperscript{rd} pulse results in a marginal increase in $B_t$.
- Preliminary multi-pulse, multi-temperature investigation showed similar, but slightly lower, $B_t$. 