Effect of striating coated conductors on reducing shielding-current-induced fields in pancake coils exposed to normal magnetic fields

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Motivation and objective

Motivation

- The striation of a coated conductor to divide its superconductor layer into filaments is one of the approaches to reduce the magnetization, i.e. shielding-current-induced field (SCIF).
- The striation is effective to reduce the magnetization, i.e. SCIF, only after the decay of the coupling current, which is the shielding current flowing through superconducting filaments and normal conductor between them.

Objective

- Characterization of shielding-current-induced fields in pancake coils wound with striated and copper-plated coated conductors, which are more robust against local defect and local normal transition exposed to normal magnetic fields
Sample configuration and numerical method
Configuration and sample pancake coil and coils generating cusp field

Cusp magnetic field is generated a pair of DPs.

The magnetic field is shaped by two iron rings.

All experiments and calculations were done at 30 K.

A normal magnetic field is applied to the sample PC.

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Model and method analyses

Governing equation

\[ \nabla \times \left( \frac{1}{\sigma} \nabla \times nT \right) \cdot n + \frac{\partial}{\partial t} \left( \frac{\mu_0 t_s}{4\pi} \int_{S'} \frac{\nabla \times n'T'}{r^3} \times r \cdot n \, dS' + B_{\text{ext}} \cdot n \right) = 0 \]

\( E-J \) characteristics

\[ \sigma = \frac{J}{E} = \left( \frac{J_c (B_n)}{E_0 J^{n-1}} \right)^n \]
\[ J_c (B_n) = J_{c0} \frac{B_0}{B_0 + B_n} \]

H-matrices with low-rank approximation

N. Tominaga et al.: Tue-Af-Po2.10-11
Specifications of conductors and coils; temporal profiles of applied magnetic field

### Specifications of coated conductor

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>4.0 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.94 mm</td>
</tr>
<tr>
<td>Superconductor thickness ( t_s )</td>
<td>1.7 µm</td>
</tr>
<tr>
<td>Gap between SC filaments ( w_g )</td>
<td>50 µm</td>
</tr>
<tr>
<td>Number of SC filaments</td>
<td>4</td>
</tr>
</tbody>
</table>

### Specifications of pancake coils

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius</td>
<td>55 mm</td>
</tr>
<tr>
<td>Number of turns</td>
<td>54.2</td>
</tr>
<tr>
<td>Conductor length</td>
<td>20 m</td>
</tr>
<tr>
<td>Separation between turns</td>
<td>25 µm</td>
</tr>
</tbody>
</table>

### Graphs

**30 K 20 m not striated**

**30 K 20 m striated**

**Updated data as of 26/8/17**

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Total measured magnetic field

Total measured magnetic field
when 500 mT of normal field is applied.

30 K 20 m Not-striated

30 K 20 m Striated
Shielding-current-induced field (SCIF) in measured magnetic field

500 mT of applied magnetic field – total measured magnetic field

30 K 20 m Not-striated

30 K 20 m Striated

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Measured and calculated SCIF

- The difference between the measured and calculated SCIF is a couple of millitesla
- Offsets of instruments and/or misalignment of Hall sensor can result in this level of error.

30 K 20 m Not-striated

30 K 20 m Striated

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Fitting measured data to calculated data by offset

**Not-striated**

- $I = 20\ m$
- $T = 30\ K$
- $n = 50$

**Striated**

- $I = 20\ m$
- $T = 30\ K$
- $n = 50$
- $\sigma_{ii} = 5.69 \times 10^8\ S/m$, $G_{ii} = 1.93 \times 10^8\ S/m$

**4 insulated filaments**

- $I = 20\ m$
- $T = 30\ K$
- $n = 50$

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Explanation of decay of SCIF in \textit{not striated} conductor with single time constant

\begin{equation}
\Delta B(t) = \Delta B_0 + \Delta B_1 \exp\left(-\frac{t}{\tau_1}\right)
\end{equation}

<table>
<thead>
<tr>
<th>Not-striated</th>
<th>$\Delta B_0$</th>
<th>$\Delta B_1 / \tau_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l = 20 \text{ m}, T = 30 \text{ K}$</td>
<td>3.17 mT</td>
<td>32.5 mT / 1.32 $\times 10^6$ s</td>
</tr>
</tbody>
</table>
Current lines in *not striated* conductor

$t = 0$ s (reaching flat top)

$t = 1000$ s

$t = 10000$ s

$t = 25000$ s

20 m, 30 K  40 A/line

Inner end  Outer end  Inner end
Explanation of decay of SCIF in *not striated* conductor with two time constants

\[ \Delta B(t) = \Delta B_0 + \Delta B_1 \exp(-t/\tau_1) + \Delta B_2 \exp(-t/\tau_2) \]

<table>
<thead>
<tr>
<th>Not-striated</th>
<th>$\Delta B_0$</th>
<th>$\Delta B_1 / \tau_1$</th>
<th>$\Delta B_2 / \tau_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l = 20$ m, $T = 30$ K</td>
<td>3.17 mT</td>
<td>32.4 mT / $2.02 \times 10^6$ s</td>
<td>0.662 mT / 935 s</td>
</tr>
</tbody>
</table>
Current lines in *striated* conductor

$t = 0$ s (reaching flat top)

$t = 1000$ s

$t = 10000$ s

$t = 25000$ s

20 m, 30 K, 25 A/line

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Explanation of decay of SCIF in various conductor with multiple time constants

\[ \Delta B(t) = \Delta B_0 + \Delta B_1 \exp(-t/\tau_1) + \Delta B_2 \exp(-t/\tau_2) + \Delta B_3 \exp(-t/\tau_3) + \Delta B_4 \exp(-t/\tau_4) \]

<table>
<thead>
<tr>
<th></th>
<th>Not-striated</th>
<th>Striated</th>
<th>4 insulated filaments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(l=20\text{ m}, \ T=30\text{ K})</td>
<td>(l=20\text{ m}, \ T=30\text{ K})</td>
<td>(l=20\text{ m}, \ T=30\text{ K})</td>
</tr>
<tr>
<td>(\Delta B_0)</td>
<td>3.17 mT</td>
<td>4.38 mT</td>
<td>0.00 mT</td>
</tr>
<tr>
<td>(\Delta B_1/\tau_1)</td>
<td>32.4 mT / 2.02 (\times 10^6) s</td>
<td>19.8 mT / 3.00 (\times 10^5) s</td>
<td>14.4 mT / 1.22 (\times 10^6) s</td>
</tr>
<tr>
<td>(\Delta B_2/\tau_2)</td>
<td>0.662 mT / 935 s</td>
<td>5.47 mT / 8660 s</td>
<td>0.468 mT / 2587 s</td>
</tr>
<tr>
<td>(\Delta B_3/\tau_3)</td>
<td></td>
<td>2.94 mT / 1020 s</td>
<td>0.415 mT / 241 s</td>
</tr>
<tr>
<td>(\Delta B_4/\tau_4)</td>
<td></td>
<td></td>
<td>0.297 mT / 22.3 s</td>
</tr>
</tbody>
</table>
Summary

- We calculated SCIF in pancake coils exposed to normal magnetic field and compared with experimental results.
  - Pancake coil wound with not striated coated conductor
  - Pancake coil wound with striated and copper-plated coated conductor

- Measured temporal behaviors of SCIF are explained well by calculations.

- The measured and calculated SCIFs are with multiple time constants, which can be explained by the calculated and visualized current lines.