Development of REBCO superconducting coils for MRI operating in subcooled LN$_2$ at 65 K

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   Ac Loss Reduction by Scribing (AC)
   in Transformers with REBCO tapes
   in Motors with REBCO tapes (Trial)
   = Magnetization Reduction by Scribing (DC)

2. Scribing effect in
   Small Test Coils with REBCO Tapes for MRI

3. Summary
Ac loss reduction for ac use by scribing


Conventional Method for M & Ac Loss Reduction, i.e. Multifilamentization and Twisting, is not Applicable.

- Fine filaments
  - Reduction of pinning loss

- Twist & high-resistivity matrix
  - Reduction of coupling current loss

\[
W = \int B dH = \int M dH \propto J_c d_f B_m \quad \text{for } B_m > B_{fp}
\]
Ac loss reduction of superconducting thin tapes

Combination

- Multifilamentation by laser-scribing
- Special winding process

Laser scribing

Buffer layer: Insulator
⇒ Filaments are insulated with each other

Graph:
- $\mu_0 M_B$ [T/m$^3$ in SC] vs. $B$ [T]
- 5-filament
- 10-filament
- Reference

-1 0 1 2
-30 -20 -10 0 10 20 30 40

$w$

$\text{Ag}$

YBCO

Buffer layer

Hastelloy

$n=4$
Ac losses in 1-, 3-, 5-, 10- and 20-filament short straight tapes

Ac loss in a short tape is reduced by scribing in inverse proportion to the number of filaments as theoretically predicted. → Nearly perfect insulation among the filaments

Approximate expression of ac loss

\[ W = \frac{\alpha}{\gamma} B_m^\gamma \frac{w}{n} \]

\( \alpha, \gamma \): pin parameter

\( B_m \): magnetic field amplitude

\( n = 4 \)

Field Amplitude [T] vs. Ac Loss [J/m³ cycle] graph with various data points and non-scribed tape. The graph shows the relationship between field amplitude and ac loss for different filament numbers and tape configurations.
10-turn × 19-layer coil with 5mm wide 5-filament tape
Verification of ac loss reduction with small test transformers

The present 1/10 model transformer was reduced only in current capacity as compared with the designed 20 MVA one. So the applied magnetic field was lower than the penetration field of the GdBCO tape. Hence we made small test transformers and verified the ac loss reduction by our technique.

### Parameters of Test Transformers for Ac loss Reduction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>215 kVA</td>
</tr>
<tr>
<td>Number of phase</td>
<td>1</td>
</tr>
<tr>
<td>Rated Voltage (Pri./Sec.)</td>
<td>1075 V / 1075 V</td>
</tr>
<tr>
<td>Rated Current (Pri./Sec.)</td>
<td>200 A / 200 A</td>
</tr>
<tr>
<td>Load</td>
<td>5.4 W</td>
</tr>
<tr>
<td>Inner diameter (Prim. /Second.)</td>
<td>183 mm / 128 mm</td>
</tr>
<tr>
<td>Outer diameter (Prim. /Second.)</td>
<td>226 mm / 171 mm</td>
</tr>
<tr>
<td>Height (Prim. /Second.)</td>
<td>107 mm</td>
</tr>
<tr>
<td>Turn number of each winding</td>
<td>20 turn x 20 layer = 400</td>
</tr>
<tr>
<td>1turn voltage</td>
<td>2.69</td>
</tr>
<tr>
<td>Total length of GdBCO tapes</td>
<td>445 m</td>
</tr>
</tbody>
</table>

![Image of transformer](image1)

![Graph showing AC loss reduction](image2)

3Φ-66/6.9kV-2MVA SC Tr.
Fabrication Process of $3\phi$-66/6.9kV-2MVA superconducting transformer
3φ-66/6.9kV-2MVA superconducing transformer system

3φ-66/6.9kV-2MVA GdBCO transformer

Ne turbo-Brayton refrigerator system
Ne turbo-Brayton refrigerator system

Flow diagram of cooling system

- Turbo-compressor
- Ne gas
- Heat-exchanger
- Sub-cooler
- Pump
- GdBCO windings
- Pump unit
- Turbo-expander
- Turbo-Compressor
- Buffer tank of Ne gas
- Cold box
- Pump unit for the circulation of subcooled LN$_2$

Impeller of expander: 32 mm\(\phi\)
Impeller of compressor: 155 mm\(\phi\)
Insulation test: 350kV Impulse, 140kV AC excess voltage

LIWL: 350kV, Power frequency AC excess voltage withstand level: 140kV for 1 min.
Bath-cooled with LN$_2$ at 77K and rated operation

Injecting time was 39 hours.
Injected LN$_2$ 4450 L, reserved LN$_2$ 2800 L

Load loss (ac loss of the windings) : 27W; No load loss (iron loss): 8kW
Magnetization reduction for dc use by scribing


Uniformity of magnetic field under ppm order is required

Produced magnetic field by the induced shielding current disturbs the uniformity of original magnetic field in space.

Shielding current decays due to flux creep and/or flux flow.

Here magnetization, \( M \), is defined as the magnetic moment, \( m \), due to the induced shielding current per unit volume.

\[ M = \frac{\mu_0 I_c}{4hn} \]

\[ M = \frac{\mu_0 I_c}{4h} \]

\( \Rightarrow \) We can say \( M \) disturbs the uniformity of magnetic field in time and space.

\( \Rightarrow \) It is necessary to reduce \( M \) itself for the uniformity of magnetic field.
$M$ reduction = Ac Loss Reduction

$W = \int H \, dM = -\int M \, dH$

$M$ reduction is made by scribing & special winding.
Test Coils with Non-scribed GdBCO and Scribed EUBCO

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of tape</td>
<td>5 mm</td>
</tr>
<tr>
<td>Thickness of tape</td>
<td>112 µm</td>
</tr>
<tr>
<td>Length of tape</td>
<td>100 m, 30 m</td>
</tr>
<tr>
<td>Substrate</td>
<td>Hastelloy (100 µm)</td>
</tr>
<tr>
<td>Buffer layer</td>
<td>CeO₂+LaMnO₃+MgO+Y₂O₃+Gd₂Zr₂O₇</td>
</tr>
<tr>
<td>Superconducting layer</td>
<td>GdBaCuO (1.6 µm), EUBCO+BaHfO₃ (1.52 µm)</td>
</tr>
<tr>
<td>Number of filaments</td>
<td>1, 4</td>
</tr>
<tr>
<td>Ic of tape (@77K, s.f.)</td>
<td>219.5 A, &gt;300 A</td>
</tr>
<tr>
<td>Winding</td>
<td>Solenoid (19 turn / layer, 20 or 6 layers)</td>
</tr>
<tr>
<td>Hight of winding</td>
<td>102 mm</td>
</tr>
<tr>
<td>Inner diameter of winding</td>
<td>80 mm</td>
</tr>
<tr>
<td>Outer diameter of winding</td>
<td>86.0 , 81.8 mm</td>
</tr>
<tr>
<td>Bobbin</td>
<td>GFRP</td>
</tr>
<tr>
<td>Produced magnetic field</td>
<td>3.42 mT/A, 1.14 mT/A</td>
</tr>
<tr>
<td>Ic of coil (@77K)</td>
<td>75A, 140A</td>
</tr>
</tbody>
</table>
Experimental Setup (in background field by NbTi Magnet)
Variation of Current and Magnetic Field

- Voltage of shunt resistance [V]
  - t [sec]
  - Current
  - B [T]
  - Magnetic field at coil center
65K, 0.5T (GbBCO 100m, 19-turn, 20-layer)

\[ B [T] \]

- \( a_{2\_65K\_0.5T\_60A} \)
  - \( \tau_1 \): 11.009
  - Slope: \( 5.6113 \times 10^{-7} \)

- \( a_{2\_65K\_0.5T\_110A} \)
  - \( \tau_1 \): 14.53
  - Slope: \( 1.4275 \times 10^{-6} \)

- \( a_{2\_65K\_0.5T\_125A} \)
  - \( \tau_1 \): 11.199
  - Slope: \( 5.2171 \times 10^{-7} \)
65K, 0.5T (GbBCO 100m, 19-turn, 20-layer)

- For 80A, the magnetic field $B$ increases from 0.808 to 0.81 with a change rate of $2 \times 10^{-3}$.
- For 100A, the magnetic field $B$ increases from 0.882 to 0.884.
- For 120A, the magnetic field $B$ increases from 0.958 to 0.9778.
- For 125A, the magnetic field $B$ increases from 0.9774 to 0.9794.
65K, 0.5T (GbBCO 100m, 19-turn, 20-layer)
65K, 2T (GbBCO 100m, 19-turn, 20-layer)

- **a2_65K_2T_40A**
  - $\tau_1$: 10.352
  - Slope: $4.7733 \times 10^{-7}$

- **a2_65K_2T_70A**
  - $\tau_1$: 12.737
  - Slope: $1.0041 \times 10^{-6}$

- **a2_65K_2T_80A**
  - $\tau_1$: 10.084
  - Slope: $2.8663 \times 10^{-7}$
Analysis

\[ B_{\text{center}} = B_0 + B_1 \left( 1 - e^{-\frac{t}{\tau_1}} \right) + B_2 \left( 1 - e^{-\frac{t}{\tau_2}} \right) + \ldots \]

Contribution by each turn or each part

In the case of decay time constant \( \tau >> t \)

\[ B_i \left( 1 - e^{-\frac{t}{\tau_i}} \right) = B_i \left( 1 - \left( 1 - \frac{t}{\tau_i} \right) + \frac{1}{2!} \left( \frac{t}{\tau_i} \right)^2 - \frac{1}{3!} \left( \frac{t}{\tau_i} \right)^3 + \ldots \right) \]

\[ = B_i \frac{t}{\tau_i} \]

\[ B_{\text{center}} = B_0 + B_1 \left( 1 - e^{-\frac{t}{\tau_1}} \right) + B_2 t \]

Let us pay attention to decay time constant, \( \tau_1 \), and gradient of linear part, \( B_2 \)
65K, 0.5T (GbBCO 100m, 19-turn, 20-layer)

- a2_65K_0.5T_60A
  - $\tau_1$: 11.009
  - slope: $5.6113 \times 10^{-7}$

- a2_65K_0.5T_110A
  - $\tau_1$: 14.53
  - slope: $1.4275 \times 10^{-6}$

- a2_65K_0.5T_125A
  - $\tau_1$: 11.199
  - slope: $5.2171 \times 10^{-7}$
65K, 2T (GbBCO 100m, 19-turn, 20-layer)

- **a2_65K_2T_40A**
  - $\tau_1$: 10.352
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- **a2_65K_2T_80A**
  - $\tau_1$: 10.084
  - Slope: $2.8663 \times 10^{-7}$
\[ B_{\text{center}} = B_0 + B_1 \left(1 - e^{-\frac{I}{\tau_1}}\right) + B_2 \]

\( \tau_1 \) and \( B_2 \) do not depend on \( B \) and increase with \( I \) for \( I < I_{\text{th}}(B) \).

\( \tau_1 \) and \( B_2 \) start to decrease for \( I > I_{\text{th}}(B) \). \( I_{\text{th}}(B) \) is proportional to \( I_c(B) \).
$B_{\text{center}} = B_0 + B_1 \left( 1 - e^{-\frac{t}{\tau_1}} \right) + B_2 t$

$\tau = \frac{L}{R}$

$R = \frac{V}{I} = \frac{V_c}{I_c} \left( \frac{I}{I_c} \right)^{n-1}$

Equivalent resistance becomes larger with current and then decay time constant becomes small.
65K, 1T (Scribed EuBCO 30m, 19-turn, 6-layer)

\[ B(t) \]

- **$f_{65K\_1T\_80A}$**
  - $\tau_1 = 8.7215$
  - slope: $1.5064 \times 10^{-7}$

- **$f_{65K\_1T\_160A}$**
  - $\tau_1 = 9.5096$
  - slope: $2.3012 \times 10^{-7}$

- **$f_{65K\_1T\_180A}$**
  - $\tau_1 = 10.296$
  - slope: $1.1875 \times 10^{-7}$

- **$f_{65K\_1T\_195A}$**
  - $\tau_1 = 8.958$
  - slope: $3.6295 \times 10^{-8}$
$T_1$ and do not depend on $B$.

$B_2$ increase with $I$ and $B$ for $I < I_{th}(B)$.

$T_1$ and $B_2$ start to decrease for $I > I_{th}(B)$.

$I_{th}(B)$ is proportional to $I_c(B)$. 
Comparison of $\tau_1$

Little difference

Non-scribed tape

Scribed tape into 4-filament structure
Comparison

Normalized by Ic

Gradient was much reduced by scribing.

Scribing brings about benefit for DC use.
Operating pattern of MRI magnets to enhance the decay of shielding current

- Cooling pattern
- $I_c$ variation
- $I_{op}/I_c$: small
- Large temperature margin
- Decay of shielding current
3. Summary

(1) Magnetization and ac loss of REBCO SC tapes can be reduced by scribing & special winding.

(2) It brings about benefits for both of ac and dc uses.

(3) Improvement in superconducting property of REBCO tapes will realize operation in subcooled LN₂ at 65 to 77K.

(4) It brings about very good cooling condition and high stability.