Calorimetric Measurements of YBCO Superconductor and Metallic Cables at High dB/dt in a Cryogenic Stator Machine Environment

Michael D. Sumption, Ph.D.  
Ohio State University  
Timothy J. Haugan, Ph.D.  
Aerospace Systems Directorate  
Air Force Research Laboratory
CO-AUTHORS, ACKNOWLEDGEMENTS

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Overview

- The U.S. Air Force Research Laboratory (AFRL) facility for the measurement of AC loss in superconductors at high $B^*dB/dt$
- The test device has a spinning rotor consisting of permanent magnets arranged in a Halbach array; which exposes samples in a stator position with a peak radial field of 0.57 T, and with high rotation speeds up to 3600 rpm achieves a radial $dB/dt$ is 543 T/s and tangential $dB/dt$ is 249 T/s.
- Loss is measured by calorimetry at 77.2K using nitrogen boil-off from a double wall calorimeter feeding a gas flow meter, and the system was calibrated using power from a known resistor.
- This work describes the use of this test facility to measure and compare AC losses of a variety of YBCO coated conductors and cable styles.
- Conductors of YBCO are provided by several manufacturers with different architectures including filamented, varying width, and stabilizers.
AC Loss Critical for Components of Interest to the AF

Power Transmission

Generators/Motors

Fault Current Limiters

(SMES) Energy Storage

Transformers

http://www.conectus.org

Cryocooler Efficiencies

- 294K Upper Stage (Heat Rejection)
- ~ 100-500x Reduction of Cryocooler Power (4 → 65 K)
- 4-6x Reduction of Cryocooler Power (15 → 65 K)

Cryocooler Inefficiency $(\frac{\text{Power}_{\text{in}}}{\text{Power}_{\text{cool@temp}}})$

Temperature (K)

Commercial Off-The-Shelf Cryocoolers

Turbo-Brayton Cryocooler
Need for high $B$ and $dB/dt$ Testing

- Windings in a motor/generator see high $dB/dt$ like no other superconducting machine (e.g., 400 Hz and 0.5-1 T)
- Extrapolate to high $dB/dt$ in principle, need actual tests to make predictions reliable
- Easy to imagine a magnet which can reach these values of $B$ and $dB/dt$, but
  - Such a magnet would need to be SC to reach the needed fields without Fe
  - The losses would require a SC of the kind we wish to develop
  - Would require high voltage (10s of kV).

Alternative: Move sample and field relative to each other
Effectively - a motor simulator- “mock” motor/generator!
Reduced loss expression plotted against reduced magnetic field for frequency of 171 Hz for (a) … (b) 40-filament sample. Dashed lines are approximate copies of weak field measurements published by Levin et al, and solid lines calculated from strong field results given here. From Carr et al, Supercond. Sci Technol. 20, 168 (2007).
Phase 2-External Magnetic Field
Stator Environment

8 Pole Permanent Magnet Rotor
Provides 0.62 Tesla
0 Hz to 400 Hz
Spin-around-magnet (SAM) AC Loss Test Device - Time-Varying Magnetic Field in a Stator Environment

8 Pole Permanent Magnet Rotor Provides 0.62 Tesla
0 Hz to 400 Hz

World-unique AC Loss Test Device
- 8-pole Hallbach Array of NdFeB Magnets
- B-field = 0.62 T
- **Frequency = 0 to 400 HZ (required for AF)**
- **Sweep Rate B*f = 240 T/s**
  (~ 15x higher than standard world-wide)
- Calorimetry Measurement – very precise
- **77K with liquid N\textsubscript{2}**
- **4.2 K with liquid He !**
- **20 K with liquid Hydrogen (?)**
- Tapes, Cables, Coils – small or large
- AC loss in real stator environment, complex
  \( B \) and \( I \) varying in time and space

Machine Cross Sections

Backiron

Magnets

Calorimeter/
Sample Holder
Sample Holder/Calorimeter

Sealed Sample holder
LN$_2$ Filled via remote operated valve on top
Sample inserted through bottom port which is sealed with a plug
Contains resistors for heating
All fiberglass except valve and resistance heater

Sample orientation:
Horizontal is parallel to the magnet motion
Vertical is perpendicular to the magnet motion

Direction of Magnetic Field Motion Relative to Sample Holder
SAM Machine (dB/dt) Calibration and Properties

- In the 0.35 Tesla plane (~ 10 mm from rotor)
- At 900 RPM (60Hz) sweep rate is 12.25 T/Sec
- At 6000 RPM (400Hz) sweep rate is 140 T/Sec

(dB/dt) at one location

Vertical Magnetic Field Profile

Pick up coil vertical position (cm) relative to center of rotor

Distance from Magnet Rotor
Finite Element calculations show both radial and tangential moving fields
Actual mapped fields correspond with the calculations
Radial Fields in SMC

- Radial $B$ at three different radial distances within the gap
- The peak radial field (0.566 T) drops slightly with increasing $R$
- Shown at right are the fft
- The signal is very similar to a pure sine wave, with small harmonics at 3 and 5 times the fundamental
Tangential Fields in SMC

- Tangential $B$ at three different radial distances within the gap
- The peak tangential field (0.242 T) drops with increasing $R$
- Shown at right are the FFT
- The signal is still primarily a sine wave, but with greater deviations than for the radial case
Calibration with Heater and Cu sample

Calibration of calorimeter. \( P(W) = -0.0096 + 2.7581*GF + 1.0575*GF^2 - 0.2346*GF^3 \)

Power loss \( (P) \) vs \( dB/dt \) for the Cu strip Sample. Fit assumes RR = 7.37
AC loss of 10 cm length YBCO tape, hysteretic and eddy current

- Power Loss ($P$) vs $dB/dt$ for YBCO tape samples 2 and 3
- Black line is fit for Brandt equation with $I_c = 38$ A, and red line includes eddy current contribution for RR (77 K) = 4.0

- Power Loss ($P$) vs $dB/dt$ for sample YBCO tape 2
- Black line is fit for Brandt equation with $I_c = 38$ A, and red line includes eddy current contribution for RR (77 K) = 4.0
Loss measured of *single tape* in SMC compared to standard Inductance Measurement

- Power loss (per unit length) normalized by $B_f f$ vs $B_f f$ for SMC (shown in red) (YBCO-2) and solenoidal susceptibility rig (shown in black, for YBCO-1)

- Solenoidal susceptibility rig measurements compared with Brandt theory (pink open triangles) ($I_c = 128$ A).

- In higher fields (> 0.05 T) the experimental data deviate from the theory (which uses $I_c$ independent of magnetic field) apparently due to $I_c(B)$ dependence
Two new Measurement Series—CORC and Carpet stacks

**Carpet Stack cables**

- 5 Layers
- 3 Layers
- 1 Tape Layer

- 4 mm wide Superpower YBCO coated conductor
- 5 layers
- 3 layers
- 1 layer
- Secured with narrow strips of Kapton tape

**Conductor on Round Core (CORC) cable sample from Danko**

- 3.13 mm OD SS304 former
- 4.76 mm overall cable OD
- 4 mm wide Sunpower YBCO coated conductor
- 2 layers with 3 tapes each, outer layer is twisted opposite of the inner layer
- 34 mm pitch with 1 mm spacing

Influence of stacking on loss?

Carpet Stack cables with Un-Filamented tapes

- 5 Layers
- 3 Layers
- 1 Tape Layer

4 mm wide Sunpower YBCO coated conductor
5 layers
3 layers
1 layer

Secured with narrow strips of Kapton tape

- Samples were unstriated
- L = 10 cm, untwisted
- Ic = 127 A 77 K, SF
- Loss is shown as power per meter of tape
- Here higher loss is seen for single stack, possible influence of demagnetization on loss
Loss in striated and Cu EP Tapes

Carpet Stack cables with Filamented tapes

4 mm wide YBCO coated conductors
Filamented and provided by Sunpower

- Samples were striated
- $L = 10\,\text{cm}$, untwisted
- Loss is shown as power per meter of tape
- Here no modification of loss with stacking of tapes is seen
CORC AC Loss Measurements

- Two layer CORC sample
- SS304 (3.13 mm OD) former
- Cable OD of 4.76
- Superpower Coated conductor
- 4 mm wide and 0.09 mm thick.
- Two layers, each with three tapes, with a 1 mm gap between the tapes.
- Twist pitch = 34 mm, outer layer twisted in an opposite sense to the inner layer.
- Measured Vertically and Horizontally

\[
H_A = \tilde{x}H_{x,max} \cos(\omega t) + \tilde{y}H_{y,max} \sin(\omega t)
\]
CORC compared to Tape it was wound with

- CORC cable loss per unit meter of tape multiplied by the factor $\pi/2$, as compared to tape loss per unit meter of tape. CORC cable was oriented horizontally.

- Simplistic integration of the field perpendicular to the tape appears to describe the loss for the tapes in the CORC!
Samples
Roebel Cable, IRL, NZ

TABLE I
PARAMETERS OF THE ROEBEL CABLE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable width (mm)</td>
<td>13</td>
</tr>
<tr>
<td>Cable thickness (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Cable twist pitch (cm)</td>
<td>30</td>
</tr>
<tr>
<td>Cable length (cm)</td>
<td>30</td>
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<tr>
<td>Number of tapes in the cable</td>
<td>15</td>
</tr>
<tr>
<td>Tape width (mm)</td>
<td>5</td>
</tr>
<tr>
<td>Cable $I_c$ (77.3K, self-field) (A)</td>
<td>1537.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tapes</th>
<th>$I_c$ (A)</th>
<th>ID (mm)</th>
<th>OD (mm)</th>
<th>Length (cm)</th>
<th>Striations</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>$2 \times 3 = 6$</td>
<td>608</td>
<td>4.96</td>
<td>6.17</td>
<td>11.7</td>
<td>none</td>
</tr>
<tr>
<td>S1</td>
<td>$2 \times 3 = 6$</td>
<td>349</td>
<td>4.95</td>
<td>6.07</td>
<td>12.2</td>
<td>5</td>
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<tr>
<td>R2</td>
<td>$3 \times 3 = 9$</td>
<td>904</td>
<td>4.93</td>
<td>6.37</td>
<td>11.7</td>
<td>none</td>
</tr>
<tr>
<td>S2</td>
<td>$3 \times 3 = 9$</td>
<td>535</td>
<td>4.94</td>
<td>6.38</td>
<td>11.8</td>
<td>5</td>
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<tr>
<td>R3</td>
<td>$4 \times 3 = 12$</td>
<td>1228</td>
<td>5.02</td>
<td>6.85</td>
<td>11.7</td>
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<tr>
<td>S3</td>
<td>$4 \times 3 = 12$</td>
<td>750</td>
<td>4.97</td>
<td>6.78</td>
<td>11.9</td>
<td>5</td>
</tr>
</tbody>
</table>
CORC Loss per meter of Cable

• 4 mm wide tape
• Cable: 2 layers, 3 tapes per layer, 1 mm gap
• $L_p = 34$ mm, outer layer twisted in an opposite sense to the inner layer.
• Each meter of cable has 6.552 m of strand

![Graph showing dB/dt vs Power for CORC-1 and CORC-2.](image)
Loss in Roebel Cable

The cable was from IRL

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Losses per meter Cable
At 77 K, $I_c$ per tape = 100 A, SF
• New CORC Wire is available which promises lower loss and higher flexibility for making very high amperage cable

• We measured this wire; OD 3.65 mm, 29 strands
Loss Measurements of 4 filament Al Hyperconductor wire

\[ P_{\text{tot}} = \begin{cases} 
P_{\text{matrix}}(d_s, \rho_m) + P_{\text{fill}}(d_f, \rho_{\text{fill}}) + P_{\text{coup}}(L_p, \rho_m) & \text{if } L < L_c \\
\frac{1}{2\rho_m} [fL_pB_m]^2 & \text{if } L > L_c 
\end{cases} \]

Where

\[ L_c = \pi d \sqrt{(\rho_m/\rho_{\text{fill}})} \]

We can generate a frequency limit expression for hyperconductors

\[ f = \sqrt{2} \frac{J_{\text{cc}} \rho_m}{L_p B} = \sqrt{2} \frac{J_{\text{cu,RT}} \rho_m}{L_p B} \sqrt{\frac{\rho_{\text{cu,RT}}}{\rho_{\text{fill}}}} \]
Recent Results on BNL Samples (exfoliated filament Cables)
Conclusions

• A new, High field, High ramp rate AC loss device operational which can reach 480 T/s!
• AC loss calibrations performed using (i) Standard resistor, (ii) Cu strip of known RR
• Explore high dB/dt characteristics of cables made of YBCO coated conductors
• Samples: striated tapes, CORC cables, Roebel cables, CORC Wires, Al Hyperconductors, Exfoliated filament samples, …. 
• Comparison to theory and analysis