Ultra High Field Magnet Applications of Coated Conductors

Dr. Mark D. Bird
Chief Technology Officer
National High Magnetic Field Laboratory
Florida State University, Tallahassee, Florida, USA

Disclaimer: There has been a tremendous amount of development in recent years, I cannot mention everything. I apologize to those I’ve left out.
The Development of Superconducting Solenoids

Ultra-High Field (UHF) solenoids means >23.5 T

Many UHF test coils have been built but only a few magnets are in service.

The first Ultra-High Field High-$T_c$ user magnet.

Existing User Magnets > 23.5 T Worldwide

<table>
<thead>
<tr>
<th>Field</th>
<th>Conductors</th>
<th>Maker</th>
<th>Location</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 T</td>
<td>Bi-2223 + LTS</td>
<td>Toshiba</td>
<td>Sendai</td>
<td>2017</td>
</tr>
<tr>
<td>25.8 T (1.1 GHz)</td>
<td>REBCO + LTS</td>
<td>Bruker</td>
<td>Nashville</td>
<td>2019</td>
</tr>
<tr>
<td>28.2 T (1.2 GHz)</td>
<td>REBCO + LTS</td>
<td>Bruker</td>
<td>Florence (+6)</td>
<td>2020</td>
</tr>
<tr>
<td>32.1 T</td>
<td>REBCO + LTS</td>
<td>MagLab</td>
<td>Tallahassee</td>
<td>2017</td>
</tr>
</tbody>
</table>

Several Other Projects Underway at labs Worldwide!
Some UHF REBCO Magnet Concepts
There is significant variation in $I_c$ at 4 K between tapes. It cannot be predicted from a 77 K measurement. (Present variation seems to be less than in the past.)
Unpredictability of REBCO $I_c$ Dropouts

YateStar measurement of critical current at 77K of SuperPower tape M4-352-5 0912

77 K measurements with TapeStar & YateStar indicate there can be spots along a conductor with low critical current.

Similar measurements at 4K have not been made.

Variation at 4K is unknown.
Screening Currents: Tape Conductors

\[ J_t = \text{transport current in } \theta \text{ direction.} \]

- During charging of the magnet, \( B_r \) creates screening currents, \( J_s \), in the tape.
- \( J_s \) reacts with \( B_z \) to give radial forces \( F_r \), in addition to those created by the transport current.
- This gives rise to a Diamagnetic Torque and Twist and strain that is not uniform across the width of the tape.
- **Tape removed from test coils can display plastic deformation!**


Y. Yan, P. Song, C. Xin, M. Guan, Y. Li, H. Liu, and T. Qu, *SuST*. 34 (2021) 085012 (13pp)

Photo credit: Paul Hu
Insulated vs No-Insulation REBCO

Insulated REBCO
- MagLab 32 T, 2017
- Bruker 28.2 T (1.2 GHz), 2019
- RIKEN 30.5 T (1.3 GHz)
- Sendai 33 T

No-Insulation REBCO
- Resistive (Metal) Insulation
- Partial Insulation
- MIT 30.5 T NMR
- Grenoble/CEA 30 T
- IEE-Beijing: 30 T CMP + 27 T CM NMR

Current Bypasses Quench reducing hotspot temperature. Less Cu is Required → Smaller Coils [3, 4].
Less Reinforcement Required → Smaller Coils.
- Coil quench at $I_{op} = 412$ A ($1580 \text{ A/mm}^2$).
- No coil damage in 20-s “over-current” operation.

## Quench

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>Energy Margin</strong></td>
<td>Small (mJ)</td>
</tr>
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</table>
| **Small coils** | Self protect  
Quench propagates quickly  
Energy distributed uniformly |
| **Large Coils** | Require protection system  
1. Diodes allow current to bypass quench  
2. Heaters can accelerate quench  
3. External dump resistor extracts energy |

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Quench Wave (Tsunami) propagates through magnet.

Coil 7 experiences excessive current (over-stressed, redesigned).

Quench starts in Coil 1.  
Diode breaks down.  
Coil current Decays.

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Andy Gavrilin
## Quench

<table>
<thead>
<tr>
<th></th>
<th>LTS</th>
<th>HTS (REBCO, high field, operating at 4 K)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Margin</strong></td>
<td>Small (mJ)</td>
<td>Large (kJ)</td>
</tr>
<tr>
<td><strong>Small coils</strong></td>
<td>Self protect</td>
<td>Frequently burn</td>
</tr>
<tr>
<td></td>
<td>Quench propagates quickly</td>
<td>Quench propagates slowly</td>
</tr>
<tr>
<td></td>
<td>Energy distributed uniformly</td>
<td>Energy concentrated in a small volume</td>
</tr>
<tr>
<td><strong>Large Coils</strong></td>
<td>Require protection system</td>
<td>NI-REBCO magnets allow current to bypass quench.</td>
</tr>
<tr>
<td>1.</td>
<td>Diodes allow current to bypass quench</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Heaters can accelerate quench</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>External dump resistor extracts energy</td>
<td></td>
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NI-REBCO shows similar current spikes to those of diode-protection.
Many more degrees of freedom.
## Quench

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<tr>
<th>Energy Margin</th>
<th>LTS (Small (mJ))</th>
<th>HTS (REBCO, high field, operating at 4 K) (Large (kJ))</th>
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<td>Large Coils</td>
<td>Require protection system</td>
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</tr>
<tr>
<td></td>
<td>1. Diodes allow current to bypass quench (with potentially high induced currents and strains).</td>
<td>1. NI might require controlled inter-turn resistance to control quench dynamics (Metal Insulation, Resistive Insulation, Partial Insulation) [1, 2].</td>
</tr>
<tr>
<td></td>
<td>2. Heaters can accelerate quench</td>
<td>2. Heaters can accelerate quench</td>
</tr>
<tr>
<td></td>
<td>3. External dump resistor extracts energy</td>
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Operational UHF REBCO Magnets
**REBCO Unpredictability**

$I_c$ of all tapes was measured at 4K, 18° from $ab$-plane, 14 T. Magnet operates between 20% and 30% of $I_c$.

**Screening Currents**

Not fully appreciated at the time.

**Quench**

Heaters between REBCO double-pancakes (~100 kJ).

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**Commercial Supply:**
- 15 T, 250 mm bore LTS coils
- Cryostat (Oxford Instruments)
- REBCO tape (SuperPower)

**In-House development:**
- 17 T, 34 mm bore YBCO coils

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Liz Green, a Research Faculty member at the MagLab, leads the 1st User Experiment in the 32 T magnet performing NMR measurements of a frustrated magnet system.
Nuclear Magnetic Resonance is the largest steady market for SC magnets with fields > 3 T.

It requires field uniformity & stability <10 ppb.

Standard magnets are superconducting with compensation, shielding, persistence, and shimming.

To go beyond 1.0 GHz, HTS coil(s) replace inner Nb$_3$Sn coil(s) and stronger shim coils are needed.

The First 1.2 GHz (28.2 T) NMR Magnet Reached Full Field in 2019
1.1 and 1.2 GHz NMR systems using ReBCO coated conductors ordered and delivered worldwide (Q4 2022)

<table>
<thead>
<tr>
<th></th>
<th>Delivered</th>
<th>Ordered</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 GHz</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1.2 GHz</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

REBCO Unpredictability: all tape is characterized at 4 K

Layer-Wound

Slide courtesy of Patrick Wikus
UHF REBCO Magnets
Underway
REBCO Insert for MIT 1.3-GHz NMR Magnet

- **H835**: 19.7-T REBCO insert into a 10.93 T LTS NMR coil (L500)
- Towards an NMR quality 30.5T magnet – the MIT 1.3G
- **H835** Design Features
  - No-insulation (NI) double-pancake (DP) winding
  - High mechanical strength/stiffness
    - 304 stainless steel co-winding for DPs in strongest axial fields
    - 316 stainless steel overband for all DPs
- Learned from **H800** Quench
  - Single solenoid to avoid magnetic coupling between nested coils
  - Metallic insulation to accelerate relaxation of bypass current
- Screening-Current Effect Considered in the Design
  - Associated field reduction and stress/strain modification analyzed

**REBCO Unpredictability**
- MI-REBCO
  - $<70\% I_c$

**Screening Currents**
- Narrower tape than earlier version.
  - Strain $<0.7\%$ including SCS.

**Quench**
- MI-REBCO self-protection.
  - Dump resistor.
  - Heaters.

**Precedent H800**
- 3-Nested-Coils Design
- NI-REBCO
- Quenched & Damaged in standalone test (March 2018)

12 of 40 Double-Pancakes have been wound.
Due 2024

**New H835**
- Single Solenoidal Design
- MI-REBCO

Test of the 14 T NOUGAT HTS insert (made of 9 “Metal Insulated” Double Pancakes)

- March 2019
  - System reached 30.1 T (12.1 T HTS + 18 T Resistive).
  - System reached 29 T (10 T HTS + 19 T Resistive) when resistive magnet tripped off, inducing large current in HTS coil.
  - HTS coil worked well despite discharge of resistive background magnet.
  - HTS coils re-energized in self-field successfully.
  - System reached 32.5 T (14.5 T HTS + 18 T resistive) when Quench occurred.
  - Significant damage seen in HTS coil.
  - All 9 double-pancakes were repaired.
- Install HTS coil in LTS outsert @ Dresden to provide 30 T SC user magnet.

**Perspectives H2020 study call** for the design of an All Superconducting Magnet (40 T), Studies for future hybrids
Progress of SC Magnets at IEECAS

- **30T/Φ35mm user magnet at the IEE CAS for SECUF Project**: quantum oscillation

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total field</td>
<td>30 T</td>
</tr>
<tr>
<td>Insert coils</td>
<td>10.05 T (inner coil)</td>
</tr>
<tr>
<td>Background coil</td>
<td>15 T</td>
</tr>
<tr>
<td>Cold inner bore</td>
<td>35 mm</td>
</tr>
<tr>
<td>Operating current</td>
<td>140.1 A</td>
</tr>
<tr>
<td>Superconducting tape</td>
<td>YBCO</td>
</tr>
<tr>
<td>Co-wound tape</td>
<td>stainless steel tape</td>
</tr>
<tr>
<td>Coil structure</td>
<td>Double pancake</td>
</tr>
<tr>
<td>HTS conductor length</td>
<td>9290 m</td>
</tr>
<tr>
<td>Homogeneity</td>
<td>8 ppm @30 mm</td>
</tr>
</tbody>
</table>

- Preliminary test to 26 T was achieved for SECUF, at Huairou, Beijing, on Jul. 8, 2022

- NMR magnet reached 25T, with a homogeneity of 13ppm@10mm DSV, and a field drift of ~0.83ppm/hour (62 hours later);

- **REBCO Unpredictability**
  - **MI-REBCO Quench**
**REBCO Unpredictability**

Measure $I_c$ of each pancake at 77 K.
Wind 2 conductors in parallel.
50% $I_c$.

**Screening Currents**

Epoxy bonds turn to G10 spacers to eliminate strain due to screening currents.

**Quench**

Assume HTS will not quench.
If LTS quenches, use external resistor to prevent current increase in HTS coil.

Recent test coil w/ 20 pancakes generated 11 T HTS + 14 T LTS = 25 T total.
Development of a 1.3 GHz (30.5 T) NMR magnet in the JST-Mirai Program

30.5 T series-connected LTS/HTS coils in the persistent-mode with superconducting joints for HTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature (K)</td>
<td>4.2 (LHe)</td>
</tr>
<tr>
<td>Operating current (A)</td>
<td>231</td>
</tr>
<tr>
<td>Self-inductance (H)</td>
<td>988</td>
</tr>
<tr>
<td>Stored energy (MJ)</td>
<td>26.4</td>
</tr>
<tr>
<td>Weight of superconductors (ton)</td>
<td>3.9</td>
</tr>
<tr>
<td>Radial distance of 5G line (m)</td>
<td>9.9</td>
</tr>
<tr>
<td>Main coils</td>
<td>HTS+LTS series</td>
</tr>
<tr>
<td>HTS inner coils</td>
<td>Layer-winding</td>
</tr>
<tr>
<td>Layer-winding</td>
<td>REBCO / Bi-2223</td>
</tr>
<tr>
<td>HTS (REBCO+Bi-2223)</td>
<td>15.7 (8.7 + 7.0)</td>
</tr>
<tr>
<td>LTS</td>
<td>15.1</td>
</tr>
<tr>
<td>Conductor length for winding (km)</td>
<td>REBCO / Bi-2223/ LTS</td>
</tr>
<tr>
<td>Number of joints</td>
<td>RR / BB / RL / BL</td>
</tr>
</tbody>
</table>

Screening Currents
Stress < 550 MPa (~0.33%) including SCS.

Quench
1-REBCO, single power supply, resistance of LTS coils extracts energy from HTS coils.
The 40 T SC Magnet at MagLab

- Developed software to compute screening currents, strains, and field distributions that is being adopted by other labs worldwide.
- Developed quench modelling software for both MTI and RI coils.
- Introduced critical-current graded coils.
- Demonstrated coils survive
  - 50,000 cycles with 125 MPa axial pressure
  - >23,000 cycles at 0.4% strain; >200 cycles at 0.5% strain.
- Increase in copper current density, \( J_{cu} \), compared with 32 T.
- Introduced Reinforcement grading.
- Demonstrated numerous improvements to quench protection
- Tested 19 different REBCO coils.

REBCO Unpredictability

\[ \frac{I_{op}}{I_c} \sim 0.6. \]

I-REBCO = 2-in-hand
RI-REBCO

Screening Currents
Strain <0.45% including SCS.

Quench
I-REBCO version uses heaters between modules.
NI-REBCO version has controlled inter-turn resistance and fast quench heaters.

Two recent REBCO test coils from the 40 T magnet project.
REBCO Unpredictability
65% of $I_c$ at end of coil.

Screening Currents
Strain 0.68% max including SCS w/o coupling.

Quench
NI-REBCO for inner coil
MI-REBCO for 2nd coil

35 T All-SC Test Coil
20 T HTS coils quenched 5 times in stand-alone testing.

Each quench caused damage to Coil 1 DP 3.

HTS coils repaired & charged again to 23.2 T with no background field

Liangjun Shao, Xintao Zhang, Zhirong Yang, Yubin Yue, Yufan Yan, Peng Song, Yi Li, Huajun Liu, & Timing Qu, ASC 2022.
Summary

There are now > 7 organizations worldwide developing HTS coils for service at Ultra-High Fields.

- All SC magnets >25 T use REBCO.
- SC magnets are presently available at 28 – 32 T for condensed matter physics.
- NMR magnets are operating at 28.2 T (1.2 GHz).
- >4 groups are pursuing 30 – 35 T SC.
- 2 groups are pursuing 30.5 T (1.3 GHz) NMR.
- ~4 labs are pursuing 40 T SC.
- Variability of properties, effects of screening currents, and quench protection remain important challenges.

HTS materials are finally enabling a revolution in high field magnets and science!
Thank You!