Bi-2212 Coil Technology at the NHMFL

Ulf P. Trociewitz


RAI – Amsterdam, The Netherlands
August 27 - September 1, 2017

This work is supported by the National Science Foundation under DMR-1157490, by a grant from the National Institute of Health under 1 R21 GM111302-01, by the state of Florida, and amplified by the Magnet Development Program (MDP).
• Why 2212?
• Ongoing 2212 coil R&D
• Platypus, NMR demo magnet approaching 1 GHz
• Summary of OPHT runs in our OP-furnace
• Final notes
Why is Bi-2212 Conductor a Good Candidate High Field Magnets?

Significant development over past years

~10 years ago:
• 2212: transition from single stack 19 fil. tape to much more versatile multi-filament round-wire conductor
• Wire with internal porosity after heat treatment
• One foreign powder manufacturer

Now:
• Wide range of architectures with 1500 – 2200 fil. with piece lengths of ~1 mile (1400 m at 1.0 mm dia., twisted) available
• Single wire and cable (e.g. Rutherford) possible
• Over pressure heat treatment process (OPHT) available to achieve consistent and high transport properties
• Semi-persistent joints appear possible
• Reinforced coils are possible
• R&D on aspected and reinforced Bi-2212 wire ongoing
• Two US-based powder manufacturers for Bi-2212

Our concern is **not if** Bi-2212 can be used in high field magnets **but how** we can build them most efficiently!
2212 Coils for Properties Tests and Field Generation

- We build Coils of various sizes from small bobbins to fully instrumented larger coils for in-field testing applying analysis lead design
- Confidence builder for larger high-field coils like Platypus and beyond (testing concepts, models, manufacturing procedures)

About 1 km of conductor!
Coil Tests: Goals and Results

Goal: Understand performance limits of our 2212 coils

Recent coils:

- Riky-3:
  - No electric short after OPHT
  - Was optimally processed based on analysis of OPHT run
  - Small hysteresis (about ± 1 mT), rapid response to \( I_{op} \) change
  - Clearly showed that the FEA modeling works to predict coil performance, 348 A predicted for onset of damage, and Riky-3 tripped at 350 A
  - In no-reinforced condition the outer layer would have experienced a stress of ~300 MPa: reinforcement works
  - Showed saturation of \( I_c \) retention on subsequent quenches
  - Below onset of thermal runaway the coil could be load-cycled many times

- Pup-4:
  - No electric short after OPHT
  - Small hysteresis (about ± 5 mT), rapid response to \( I_{op} \) change
  - Coil reached 25% field of PYP-II at 170 A (at 16% coil height)
  - Below \( I_c \) the coil was load-cycled many times

Coil performance predictions

Riky-1, 2 & 3

(Thu-Mo-Or33: Ernesto Bosque)

After test:

Riky-3

No cracks in the epoxy

Pup-4
“Platypus”: A Bi-2212 NMR Demo-Magnet

Goals:
- **MagSci: 30 T NMR magnet using HTS**
- NMR demo magnet of ~ 900 MHz (21 T) targeting ppm field homogeneity and stability
- LTS/HTS coil with all conductors twisted, round and multifilament (16 T Nb-Ti/Nb3Sn + 5 T Bi2212)

Specs:
- 240 mm high
- 92 mm OD, 44 mm ID
- 179 turns
- 18 layers
- 0.7 km of 1.0 mm dia. wire

Status:
- Several test coils and Platypus dummy made and successfully characterized
- Platypus tests towards end of this year
Arriving at a Layout for Platypus

Task: Find high-field, high-homogeneity design with single piece length supplied by B-OST

- HTS section with one compensation coil pair to control the Z2 component
- Optimization applies Monte-Carlo method, uses field profile modeling of all magnets involved

\[ B_{\text{tot}} = 21.3 \, \text{T at } I_{\text{op}} = 310 \, \text{A} \]
\[ B_{\text{LTS}} = 16.0 \, \text{T} \]
\[ I_{\text{cond}} \approx 700 \, \text{m plus 100 m for comp coils} \]
Platypus EM and Mechanical Models

Design criteria

- HTS + LTS at ~900 MHz
- HTS model on conductor level properties
- Still has margin for higher field before approaching 0.41% design strain (strain limit in short samples is 0.55% (D. Davis, M. Brown))

Calc. field profile with Z2 compensation

Z2 compensation (for now)

- The compensation coils reduce the only dominate term (Z2) to less than ppm levels of the ideal design

Azimuthal % Strain Map:
LTS: 134 A, 16 T
Inserts (in series): 310 A, 21.35 T total ~900 MHz

Without Z2 compensation
\[ h \text{ [ppm]} = 0.30 \text{ (10 mm DSV)} \]

With Z2 compensation
\[ h \text{ [ppm]} = 73 \text{ (10 mm DSV)} \]
Need Insulation for Bi-2212 Conductor

- $I(t) \Rightarrow B(t)$, don’t want redistributing currents particularly not in high homogeneity magnets
- Need insulation to withstand $890^\circ C$ reaction T, homogeneous thick coating, abrasion resistant
- Dip coating process with TiO$_2$ particles dispersed in a polymer
- Polymer burns off leaving strong ceramic layer

- >1 km lengths now being coated reliably
- Recently added alumino-silicate braid to improve stand-off and winding pack integrity

NHMFL Insulation line, Jun Lu, J. Levitan
A Step Towards Platypus: Dummy Coil

- Dummy coil with three 18 layer, 3 turn test sections to verify calibration and OPHT procedure
- Stack of metal rings to simulated thermal mass of coil
- Thermocouples to monitor temperature at various places on dummy
- Coil support structure

- All Platypus coil components are now ready, awaiting winding and processing some time after MT.
Dummy Coil, OPHT Results

- No leaks and proper electrical resistance of windings after OPHT

- Coils performed consistently throughout the dummy stack
- There was a slight increase in $I_c$ towards the ID of the windings
Platypus-1 conductor had TiO₂ insulation only
Had substantial electrical shorts after OPHT
Showed large charging delay and produced strong field screening
However, during winding and no electric shorts were observed in the coils
After burnout of polymer content in insulation coating, coil resistances remained the same
Substantial resistance drop was observed only after the OPHT
Droplets of Ag can breech the insulation and form conductive bridges

...but there are also solutions:

Insulation issue solved since by combining TiO₂ coating and braid around conductor
Coil Section at very bottom of Furnace had turns with no $I_c$:
- Layer 1 and terminal region just started to melt
- All layers after layer 4 melted
- All other coil sections had $I_c \sim 720$ A at 5 T, 4.2 K ($J_e = 1020$ A/mm$^2$)

- $I_c$ tests on extracted samples showed that almost all coil sections worked as expected and well
- Thermal conduction from coil into the colder coil support structure prevented a few turns from reacting properly
### Coils OPHT’ed in Deltech, for Maglab and Collaborations

<table>
<thead>
<tr>
<th>Coil</th>
<th>Outcome</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platylong</td>
<td>Success</td>
<td>Verified conductor densification concern (was ‘shop floor wire’ -- not tested)</td>
</tr>
<tr>
<td>Platypup-1</td>
<td>Success</td>
<td>Experimental performance in self-field and in Cell14 external field consistent with expected strain limitations to coil</td>
</tr>
<tr>
<td>Platypup-2</td>
<td>Success</td>
<td>Coil was superconducting out of furnace. Experimental performance was limited by material incompatibility of overbanding.</td>
</tr>
<tr>
<td>Platypup-3</td>
<td>Success</td>
<td>Experimental performance validated efficacy of strain management system. Coil was still strain limited, but much higher field and current than Pup-1</td>
</tr>
<tr>
<td>PreDensified / Compression Coil</td>
<td>Success</td>
<td>Adequate melting of pre-densified coil, i.e. successful OPHT. Compression coil was wound of shop-floor to test insulation resilience -- overall OPHT was successful</td>
</tr>
<tr>
<td>Platypus</td>
<td>Insulation (solved 2016)</td>
<td>Coil Debilitating Shorting Issue: Diagnosed as wires shorting through very thin TiO2 insulation</td>
</tr>
<tr>
<td>Riky-1</td>
<td>Success</td>
<td>Coil performed very well: strain limited coil which matched FEA Modeling predictions</td>
</tr>
<tr>
<td>Riky-2</td>
<td>Success</td>
<td>Performed exceptionally well: outperformed testing rig -- well beyond the strain of Riky-1 (also predicted by FEA Modeling)</td>
</tr>
<tr>
<td>Riky-3</td>
<td>Success</td>
<td></td>
</tr>
<tr>
<td>LBNL Race-Track Coil-1</td>
<td>Success</td>
<td>RECORD HIGH Performance of Rutherford Cable in RaceTrack coil</td>
</tr>
<tr>
<td>LBNL RaceTrack Coil-2</td>
<td>Success</td>
<td>OPHT Expected to be Successful: Test still pending at LBNL</td>
</tr>
<tr>
<td>RIKEN</td>
<td>Heat distribution</td>
<td>Issues at coil ends: diagnosed as thermal mass and heat sinking issue; coil former extensions acted as fins extending beyond the working hot zone within the Deltech furnace</td>
</tr>
<tr>
<td>CERN/Twente Rutherford Cable</td>
<td>Success</td>
<td>Short witness samples look great. Main cable sent to Twente for further testing. CERN collaborators quite pleased</td>
</tr>
<tr>
<td>OI Coil</td>
<td>Success</td>
<td>Short witness sample microstructure looks great, ic measurements pending. Main coil and barrels still being prepped to ship back to London</td>
</tr>
<tr>
<td>Platypup-4</td>
<td>Success</td>
<td></td>
</tr>
<tr>
<td>LBNL Race Track Coil-3</td>
<td>Success</td>
<td>More Race Track Coils on the way</td>
</tr>
</tbody>
</table>

- ... and many, many other OPHT runs on short samples, furnace balancing, and tuning
- In general we feel good about the OPHT process.
Bi-2212 Coils – Final Notes

Overpressure heat treatment required for optimum properties

- Requires large equipment
- Management of high thermal masses (large coils) requires diligent heat treatment setup

Ag has low $E$ (~70 GPa) and conductors have low filament fracture stress (~150 MPa)

- Requires diligent approach on distribution of mechanical reinforcement on conductor and coil level to control strain

Bi-2212 can have a bright future. Let’s build it!
Thank You!
(2212: OST NHMFL 50 bar overpressure HT. Sample pmm170123, 0.78 mm Diam. (after HT), OST 55x18 composite using nGimat powder. J. Jiang et al. (NHMFL), August 2017 unpublished.)