The NHMFL HTS Coil and Conductor Development Program - Presentation to Muon Accelerator Program May 10, 2013

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34T (in 31T) – Bi-2212

35T (in 31T) – REBCO coated conductor
Presentation outline

The global drivers of the MagLab program

MagLab team
- Science and engineering, R&D and project foci

MagLab goals
- HTS magnets for users
- Collaboration with others interested in advancing HTS technologies

A Coupled conductor-coil focus
- REBCO
- Bi-2212

Outlook
- Major new accomplishments not possible with LTS are now in prospect
- Possible perils can be avoided by good collaborations
The Global Context is provided by COHMAG- Opportunities in High Magnetic Field Science – 2004

Grand magnet challenges:
- 30T NMR (All SC)
- 60T Hybrid (R + SC)
- 100T Long Pulse (R)

Means:
- ....the involved communities [users and magnet builders] should cooperate to establish a consortium whose objective would be to address the fundamental materials science and engineering problems that will have to be solved…….. COHMAG report 2004

All require materials in conductor forms that were not available in 2004

They now are!

And in 2013 by a new NRC study MagSci – High Magnetic Field Science and technology – under review now
..and locally by user demands, the power bill, and the NSF budget....

- Provides the world’s highest magnetic fields
  - 45T DC in hybrid, 32 mm warm bore
  - Purely resistive magnets: 35T in 32 mm warm bore, 31 T in 50 mm bore and 19T in 195 mm warm bore

- 20 MW resistive magnet ~$1500/hr at full power (7.5c/kWhr)
MagLab team formed in 2007-2010

- Cross-divisional effort in ASC and MS&T
  - Applied Superconductivity Center (left Wisconsin in 2006) and Magnet Science and Technology

- 32 T all superconducting magnet is in construction
  - Project leader Huub Weijers, designer Denis Markiewicz, conductor characterization lead Dmytro Abraimov

- HTS R&D effort
  - REBCO characterization (leader Jan Jaroszynski)
  - 2212 conductor (leaders DCL, Eric Hellstrom, Jianyi Jiang and Fumitake Kametani in strong collaboration with BSCCo – Bismuth Strand and Cable Collaboration – BNL (Ghosh) – FNAL (Shen and Cooley) – LBNL (Godeke) – NHMFL and CDP (Dietderich))
  - High homogeneity REBCO and 2212 coil construction – leader Ulf Trociewitz

Funding:

32 T is supported by a Major Research Instrumentation award of NSF and by the NSF core grant to the NHMFL

Bi-2212 conductor work is supported by DOE-HEP through a university grant

HTS coil work (REBCO and 2212) is supported on the NSF core grant
REBCO Test Coils: 2007-2009

SuperPower I.
B\(_{\text{max}}\) = 26.8 T
\(\Delta B\) = 7.8 T

SuperPower II.
B\(_{\text{max}}\) = 27 T
\(\Delta B\) = 7 T

NHMFL I.
B\(_{\text{max}}\) = 33.8 T
\(\Delta B\) = 2.8 T

NHMFL II.
B\(_{\text{max}}\) = 20.4 T
\(\Delta B\) = 0.4 T

These coils made with cooperation of SuperPower (Drew Hazelton and V. Selvamanickam) showed that REBCO tapes were excellent for small high field coils. They allowed us to propose a 32 T user magnet to NSF in 2010.
HTS insert coil trends – ’09 update

<table>
<thead>
<tr>
<th>year</th>
<th>year</th>
<th>$B_A + B_{HTS} = B_{total}$ [T]</th>
<th>$J_{ave}$ [A/mm²]</th>
<th>Stress [MPa]</th>
<th>Stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td></td>
<td>20+5=25 $T_{(tape)}$</td>
<td>89</td>
<td>125</td>
<td>175</td>
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<tr>
<td>2008</td>
<td></td>
<td>20+2=22 $T_{(wire)}$</td>
<td>92</td>
<td>69</td>
<td>109</td>
</tr>
<tr>
<td>2008</td>
<td></td>
<td>31+1=31 $T_{(wire)}$</td>
<td>80</td>
<td>47</td>
<td>89</td>
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<tr>
<td>2007</td>
<td></td>
<td>19+7.8=26.8 $T$</td>
<td>259</td>
<td>215</td>
<td>382</td>
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<tr>
<td>2008</td>
<td></td>
<td>31+2.8=33.8 $T$</td>
<td>460</td>
<td>245</td>
<td>324</td>
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<tr>
<td>2009</td>
<td></td>
<td>20+7.2=27.2</td>
<td>211</td>
<td>185</td>
<td>314</td>
</tr>
<tr>
<td>2009</td>
<td></td>
<td>20+0.1= 20.1</td>
<td>241</td>
<td>392</td>
<td>~611</td>
</tr>
</tbody>
</table>

open symbols: BSCCO
solid symbols: ReBCO

Bi-2212
$\phi$ 38 mm
$\phi$ 39 mm
$\phi$ 163 mm
YBCO SP 2007 $\phi$ 87 mm

Summary by Weijers
REBCO Layer Wound High Field Coil

Conductor insulation facility

- Wet layer-wound, epoxy filled
- no splices
- thin walled polyester heat-shrink tube insulated conductor
- Coil instrumented with array of voltage taps every 5 – 10 layers

<table>
<thead>
<tr>
<th>Conductor &amp; Coil</th>
<th>EM Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cond. Width [mm]: 4.02</td>
<td>Operating Current [A]: 200</td>
</tr>
<tr>
<td>Cond. Thickness [mm]: 0.096</td>
<td>Je (Engineering) [A/mm^2]: 518.24</td>
</tr>
<tr>
<td>Inner Radius [mm]: 7.16</td>
<td>Jw (Winding) [A/mm^2]: 308.93</td>
</tr>
<tr>
<td>Outer Radius [mm]: 18.92</td>
<td>B(0,0) [mT]: 4221.01</td>
</tr>
<tr>
<td>Height [mm]: 64.52</td>
<td>Coil Constant (0,0) [mT/A]: 21.11</td>
</tr>
<tr>
<td>Layers [-]: 80</td>
<td>L [mH]: 8.90</td>
</tr>
<tr>
<td>turns/Layer [-]: 14.65</td>
<td>Total Field Energy [J]: 187.92</td>
</tr>
<tr>
<td>turns total [-]: 1172</td>
<td></td>
</tr>
<tr>
<td>Cond. Length [m]: 96.03</td>
<td></td>
</tr>
</tbody>
</table>

“Twist-bend” coil termination

64.5 mm

Trociewitz, Dalban-Canassy et al. APL 2011
Field Generation and Coil Load Line

- World record field – 35.4 T
- Some signs of limiting a low Ic point in conductor – stimulated us to pursue length-dependent Ic
- Fully insulated and robust

4.2 T Field increment achieved in 31.2 T background field

Coil did not degrade even under repeated fast thermo-cycling

Showed that stress levels >340 MPa and conductor current density $J_e \approx 500$ A/mm² are possible

Introducing layer decoupling during coil manufacturing, bypasses transverse stress weakness

Trociewitz, Dalban-Canassy et al. APL 2011
32 T Overview

**Commercial Supply:**
- 15 T, 250 mm bore Nb$_3$Sn/NbTi “outsert”
- cryostat

**In-House development:**
- 17 T, 32 mm cold bore YBCO coils
- YBCO tape characterization & quality check
- Insulation technology
- Coil winding technology
- Joint technology
- Quench analysis & protection

**Choices so far**
- Pancakes, not layer-winding
- Dry, i.e. no epoxy
- 4 mm wide tape, 50 µm Cu plating
- Insulation on co-wound steel strip
- Quench heaters for protection

Weijers and Markiewicz: LTSW 2012 talk
Status of 32 T now

- Design is stable,
  - $I_{\text{op}} \leq 0.7 \cdot I_c$, $\sigma_{\text{hoop}} \leq 400$ MPa, $J_{\text{ave}}=188$ A/mm$^2$, $J_{\text{Cu}} = 420$ A/mm$^2$
- Coil winding, joint, cross-over, termination procedures well developed (updating and formal documentation ongoing)
- Insulation development complete
  - Commercial sol-gel Silica with added Alumina on co-wound stainless steel reinforcement tape (2-3 µm layer)
- Conductor characterization transitioning into Quality Assurance:
  - (4 K $I_c$ specifications, 14 parameters total)
- Repeated tests on sc. test coils in 20 T background
  - >100 dumps after quench initiation and quenches
- AC (ramp-) loss and Quench codes in use (underway)
- Outsert + cryostat is on order (21-30 months for delivery)
- Working on first of two prototype coils
  - (full-featured, radially full size, limited height)

Weijers: LTSW 2012 talk

More extended tests of a 6 module 20/70 coil in March 2013 were successful – outer 82/116 now in design
Critical aspects of 32 T design

Most restrictive condition: $B = 16$ T, angle $\phi = 18^\circ$ 

$-B_z \frac{dB_z}{dz_{max}} = \sim 5000$ T$^2$/m: windings may be *poorly cooled* in area where $-B_z \frac{dB_z}{dz_{max}}$ exceeds 2100 T$^2$/m (gas bubbles get trapped)

10 km of 4 x 0.15 mm REBCO tape

Translation of these aspects to conductor specification has been complex
LTS outsert magnet is an expensive challenge

15 T in 250 mm is at limit of previous 4 K systems
HTS Quench management

- **Active quench protection heaters** *(NZP is slow but not zero, $\kappa_{\text{axial}}$ a factor)*
- **Voltage based quench detection**
  - 10 mV normal zones recover
- **Refinement ongoing**

Example of quench code run

Model for assembly practice
Why insulation for 32 T?

- 32 T users may ramp often or even non-stop
- $5 \times 10^{-4}$ homogeneity and stability in magnetic field are the specifications
- Non-insulated conductor/co-wind would lead to high ramping losses and reduced field quality
  - Quench seems manageable at $J_{\text{ave}} = 200 \, \text{A/mm}^2$ with turn-to-turn insulation
  - At 6 $\mu$m thickness per turn it represents only 3% of winding volume
Conductor specification issues

- Geometrical properties
- Mechanical properties
- Electrical properties
  - Normal state properties
  - Superconducting properties
- Magnetic properties
- Environmental
- Traceability and records
  - Materials and production procedures
- Quality Control, Quality Assurance
  - Measurement techniques, procedures, standards
- Handling Non-conformity

+ tolerances (uniformity)

Two examples mentioned here

Routine for LTS, breaking new ground for HTS conductors
Geometrical uncertainties

Dimensions and tolerances

Surface conditions

- Cleanliness for
  - reliable soldering of joints
  - Application of insulation
- No pinholes
- No “deep” scratches (scratches may cause deformation reaching SC layer)

- Trapped He gas leads to poor He cooling
  - maximize thermal conductivity of windings
  - Need good radial contact between turns
  - Need good axial contact between pancakes

- Specify “flatness” of conductor
- Consistent width (over 10 km) important for
  - Axial thermal conductivity
  - Transfer of axial loads in windings
  - Packing factor
- Minimum Cu area for stability
- Minimum Substrate area for strength

Pancakes need to be firm, flat and consistent in width
Is the critical current predictable and reproducible? Not yet!

Dominant flux pin size and pin morphology differs between 77 K self-field and 4 K, 15+ T

>> somewhat weak correlation

77 K Self-field data is a weak indicator of 4 K, high-field performance

>> 4 K $I_c$ specification

QA: no reel-reel capability >> sampling only,

$I_c$ [A] at 77 K, self-field

$I_c$ [A] at 4.2 K, 14 T

B//c-axis
Superconducting $I_c$ anisotropy plays a strong role in magnet design

Specify $I_c$ at most demanding angle in design to counter potential anisotropy variability.
Superconducting length (non) uniformity

Data courtesy of SuperPower

M3-854-2 MS (762-882m)

Tapestar

I\textsubscript{c}Amps

NValue

Not detected with LANL device ("Yatestar")

Used in section of coil where quenches originate

**Tapestar:**
- Magnetization-\(I\textsubscript{c}\) corresponds well to transport \(I\textsubscript{c}\) over 5 meters at 77 K
- High through-put
- Spikes may or may not correlate to physical realities

"Yatestar"
- Transport \(I\textsubscript{c}\) per 2 cm
- \(T = 75\ \text{K (LN}_2\text{)}\ B = 0.5\ \text{T,} \)
  .....variable angle
- Low throughput

\(B \parallel c\)
\(B \parallel ab\)
\(\theta = 72\ \text{deg}\)

We have many elements of what is needed to accurately measure long lengths in transport at 77K and to correlate magnetization at 77 and 4 K

Proto-system built at LANL by Yates Coulter and engineered for 200m lengths at NHMFL by Jan Jaroszynski and John Sinclair, now with Hall probes operating at both 77 and 4 K (Alex Stangl)
Concentrate effort on:

- 32 T construction – early 2015 assembly
- Extensive characterization of REBCO tapes from SuperPower
- Layer wound quasi-NMR quality coil – late 2013
  - REBCO is first attempt
  - 2212 will be 2nd attempt when OP furnace is proven
- Development of round wire Bi-2212 into a full-fledged coil technology (within BSCCo team with DOE-HEP support)
How can 2212 and 2223 be so different as conductors when they are so similar as structures?

**Round wire vs. tape BSCCO Technology**

**RW - 2212**

**Versus**

**tape 2223**
Multifilamentary 2212 has been made for years without much interest

Why was 2212 round wire ignored?
Because, being untextured, it was obvious (!) that high angle GBs were producing a connectivity-compromised current path of low $J_c$…….

ARRA support for a multi-lab collaboration (VHFSMC – DOE-HEP support) in 2010-2012 enabled a much fuller understanding

Principal current limitation is by agglomerated void space in the filaments (bubbles of residual gas) not HAGBs!

Overall conductor $J_c$ of Bi-2212 now exceeds that of any coated conductor when 100 bar overpressure is used to eliminate bubbles
Isotropic, multifilament 2212 has higher conductor $J_c$ than REBCO coated conductor!

- Requires $\sim 100$ bar 890°C processing
- High $J_c$, high $J_e$ and high $J_w$ has been demonstrated in a coil already (2.4T in 31T)
- Much less field distortion from 2212 than from coated conductors – better for high homogeneity coils
- 7 times increase in long length $J_e$ by removing bubbles

Larbalestier et al. submitted arXiv 1305.1269
OP furnaces are needed to allow short samples to be translated into coils – NHMFL capabilities

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Length</th>
<th>Max pressure</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mm</td>
<td>15 cm</td>
<td>100-200 bar</td>
<td>Today’s workhorse</td>
</tr>
<tr>
<td>48 mm</td>
<td>15 cm</td>
<td>25 bar</td>
<td>Commissioning now</td>
</tr>
<tr>
<td>45 mm</td>
<td>25 cm</td>
<td>75-120 bar</td>
<td>On order, June delivery</td>
</tr>
<tr>
<td>170 mm</td>
<td>50 cm</td>
<td>100 bar</td>
<td>On order, July delivery</td>
</tr>
</tbody>
</table>

• Capabilities are available to all in BSCCo and many samples have been shared with LBNL and FNAL
• FNAL is designing a 100 bar capability for straight Rutherford Cables suitable for reacting 2212 cable designed for test in FRESCA at CERN
2212 Filaments contain many HAGBs – and (without bubbles) have high Jc

Polished sections of filaments in their surrounding Ag

Exposed filaments show their plate-like nature and frequent strong misalignments.

EBSD images show some local texture and significant 2nd phase content within filaments

The filaments cannot be fully connected – yet do have high Jc

Kametani and Jiang unpublished
Outlook is very positive

More than 35 T (in 31T) with REBCO has been safely and reproducibly generated

- All superconducting 32 T magnet is under construction and should be ready for NHMFL users in 2015 (highest field LTS magnet is 23.5T)

Although HTS conductors are MUCH more complex than Nb-Ti or Nb$_3$Sn, we are getting a handle on their properties

Very strong collaboration is in place with wire vendors (SuperPower and OST) and planned users in Accelerator labs

- BSCCo unites Fermilab, LBNL, BNL and NHMFL on 2212
- CERN is linked to BSCCo through EUCARD2 task 10 20 T magnet aspect of LHC energy upgrade
The case for a long term R&D effort

**Magnet-pull focus**
- NMR HTS coil
- 40 T small HTS coil (31 T background)
- Accelerator demands (MAP, LHC)
- Finding the limits (stress, energy density, quench….)

**Conductor-pull focus**
- YBCO coated conductors are evolving rapidly driven by 40-77K, 0-3 T use – what about 4 K, 20-40 T properties?
- Bi-2212 is round wire and multifilament – but has intrinsically poor vortex pinning due to large electronic anisotropy

2212 and YBCO have 3 times the critical fields of Nb₃Sn but their conductor technology is still primitive….

What we really want are the vortex pinning properties of YBCO and the grain boundary properties of 2212

Why not…………..?
Some recent relevant papers

**Planar GBs in YBCO**

**Non-planar GBs in YBCO**

**Bi-2212 wires without macroscopic texture**
- D. C. Larbalestier¹, J. Jiang¹, U. P. Trociewitz¹, F. Kametani¹, C. Scheuerlein², M. Dalban-Canassy¹, M. Matras¹, P. Chen¹, N. C. Craig¹, P. J. Lee¹ and E. E. Hellstrom¹, submitted to Nature Materials, arXiv 1305.1269*

**High Field coils**