Themes and Goals of the 2016 Coated Conductor Workshop for Applications

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Thanks especially to my REBCO colleagues at the MagLab: Dima Abraimov, Seungyong Hahn, Xinbo (Paul) Hu, Jan Jaroszynski, Tak Kametani, and Huub Weijers and to collaborations with colleagues at SuperPower who have provided the majority of the coated conductors used by us for magnets – and to SeungHyun Moon of SuNAM who are beginning to deliver wonderful conductors too.
Know the competition

How do we make a potential superconductor “real”?

“Real” implies applications that can deliver orders and keep a conductor manufacturer in business.............

• LTS – Nb-47Ti, Nb₃Sn
• HTS – REBCO, Bi-2223, Bi-2212
• MTS – MgB₂
• Anything else?
  – The MTS K-122 (K,Ba/Sr)Fe₂As₂
  – H – solid H₃S or H-charged Pd
  – The elusive Room Temperature Superconductor

Where should the CC community concentrate going forward?

LTS – low temperature superconductor: $T_c < 20\, \text{K}$
MTS – medium temperature superconductor: $20\, \text{K} < T_c < 77\, \text{K}$
HTS – high temperature superconductor: $T_c > 77\, \text{K}$
“Push” applications have been the principal driver of HTS – 2223 then, CC now

This 1996 WTEC commission was very successful in raising the DOE program from about $25M to $40M/yr – but lack of utility interest in HTS led to cancellation in 2010

1.1. Superconductivity in the electric power system of the future, with widespread use of superconducting generators and motors, fault-current limiters, underground transmission cables, and superconducting magnetic energy storage (Blaugher 1995).
Key questions for CC today - I

Strengths

• Has enabled technical success for most of the applications of 1996 WTEC report
  – In multiple continents
• The highest magnetic fields generated by superconductors have been done with REBCO CC
  – Now broken the 40 T barrier
• Multiple (5-10?) companies world-wide supplying CC
Key questions for CC today - II

Weaknesses

• It is far from being a mature product yet
• It is a single filament conductor
• The big markets are still “push” markets, rather than pull markets
• Profitability is elusive
Opportunities

• The complex materials engineering behind CC is being mastered – no obvious technical barrier to "perfection" – the Nb-Ti case is interesting – single 400 kg piece lengths usual

• A liquid nitrogen Nb-Ti equivalent would be game-changing
Key questions for CC today - IV

**Threats**

- Costs are huge— for cable use, $/kA.m may be a good metric – for magnet use, $/liter and usable conductor current density may be much more useful
  - Nb-Ti ~$5K/l, Nb$_3$Sn ~$15K/l, 2212 ~$100K/l, REBCO $100-200K/l
- Can CC manufacture ever be profitable?
- What is yield?
- The seductiveness of the elegant nanoscience and vortex pinning sucks up too many of the resources needed to turn this into the real Nb-Ti competitor
- Too much effort is put into the conductor rather than into end-use devices
National Academy provides a “Pull” project list

**MagSci recommendations: MagLab renewal plans**

- Design and build a 40 T all-superconducting magnet,
- **Design and build a 60 T DC hybrid magnet** that will capitalize on the success of the current 45 T hybrid magnet in Tallahassee
- **Design and build** a 150 T pulsed magnet
- Establish at least 3 US 1.2 GHz NMR instruments (thought to be commercial) and **plan for ~1.5 GHz class system development**
- Establish high field (~30 T) facilities at neutron and photon scattering facilities
- Consider regional 32 T superconducting magnets at 3-4 locations optimized for easy user access.
- Construct a 20 T MRI instrument (for R&D with Na, P etc)
Danger: Quench Must be Addressed!

- Undetected normal zones can provoke magnet burn up (several significant HTS magnets have burned following spontaneous quenches).
  - HTS has high stability but very undesirable slow normal zone propagation velocity.
    - Few m/s for Nb-Ti and Nb$_3$Sn.
    - <10 cm/s for 2223 and YBCO.
    - 40-100 cm/s for 2212 at 20-30 T (like Nb$_3$Sn at 15 T)*
  - Quench is being addressed with:
    - NI REBCO – but pancakes only
    - Quench heaters protect 32 T REBCO – much easier in pancakes than layer windings
    - New idea CLIQ (Coupling-Loss Induced Quench) now introduced in US at LBL (Emanuele Ravaioli -Toohig Fellow LBNL)

*Shen et al., LBNL-NHMFL collaboration

4 K operation requires large heating to drive YBCO to the normal state – lower $H_{irr}(T)$ makes protection easier

32 T quench heater: 1. G10, 2. Kapton, 3 the SS heaters
Single Filament, Insulated REBCO Tapes are Vulnerable to Manufacturing Defects and MUST be actively protected as 32 T is

- 32 T used about 10 km of far from perfect 4 mm wide tape
- A unique MagLab, continuous, in field measurement tool (YateStar) allows understanding positional variation of Ic with 2 cm resolution

During accelerated 32 T prototype coil fatigue testing in Fall15 at unusually high current and ramp rates, one pancake was damaged – due to low Ic spot??

Magneto-optical images of the damage zones in layers 10-17 show extremely localized damage – an illustration of very low quench velocities
Very compact, high $J_E$ cables (CORC) enabled by 30 $\mu$m substrates are now being made

Danko van der Laan advocated the CORC (Conductor on Round Core) as the route to a round, multifilament, twisted REBCO conductor, working closely with SuperPower, the MagLab and others

Multilayer Barber pole wrap built up in many layers leading to cables capable of kiloamps

$J_e$ (4.2 K, 20 T) = 310 A/mm²
Achieved at end of 2015
- Enabled by advanced pinning (AP – 15Zr vs. 7.5Zr) tapes
- Enabled by thinner conductor substrates (30 $\mu$m vs. 50 $\mu$m today))

Latest NHMFL test results

$I_c$ (4.2 K, 17 T) = 7,030 A

$J_e$ (4.2 K, 17 T) = 344 A/mm²
The route to a liquid nitrogen conductor

Key points:
- Eu-123 seeds fewer a-axis grains and allows better epitaxial growth
- Avoidance of nanorods means more isotropic pinning
- Demonstration on the 100 m scale
- SuperPower is now delivering 30 mm substrates which enabled MagLab 40 T magnet – very close to Nb-Ti if all combined

Current Transport Property of BaHfO$_3$ Doped EuBCO Coated Conductor over a wide range of Temperature and Magnetic Field up to 25T

Kyushu University

AIST
A. Ib, T. Izumi

<table>
<thead>
<tr>
<th>Superconducting layer</th>
<th>BHO</th>
<th>thickness</th>
<th>$J_C@77K, s.f$</th>
<th>$I_C@77K, s.f$</th>
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<tbody>
<tr>
<td>EuBa$_2$Cu$<em>3$O$</em>{7-δ}$+BaHfO$_3$</td>
<td>3.5 mol%</td>
<td>3.3 μm</td>
<td>2.3 MA/cm$^2$</td>
<td>760 A/cm-w</td>
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<tr>
<td>GdBa$_2$Cu$<em>3$O$</em>{7-δ}$+BaHfO$_3$</td>
<td>3.5 mol%</td>
<td>3.2 μm</td>
<td>2.1 MA/cm$^2$</td>
<td>670 A/cm-w</td>
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<tr>
<td>GdBa$_2$Cu$<em>3$O$</em>{7-δ}$</td>
<td>—</td>
<td>2.5 μm</td>
<td>2.3 MA/cm$^2$</td>
<td>580 A/cm-w</td>
</tr>
</tbody>
</table>

Potential of thinner Hastelloy subst.
100μm -> 50μm

Superconducting process using BHO doped EuBCO target

$J_C$ vs $B$ and $\theta$ for NbTi and EuBCO.
Some additional metrics for CC?

- $/liter
- $e$ at 1 and 3 T, 65 and 77 K at all angles
- Routine, no-premium length delivery capability

Underlying principle – $J_c$ and $J_e$ are both quite high enough at 4 K
REBCO Coated Conductor Reflections

- Today’s REBCO CC is an amazing conductor for high field magnets
  - 40 T today, 3 all superconducting 26-27 T magnets demonstrated in K, J and USA, 32 T expected soon
  - No Insulation (NI) is allowing (small) magnets to operate at the 1000 A/mm² level safely
- 4 K magnets deliver “Pull” – but can they deliver profitability?
- 65-77K magnet use for 1-10 T magnets should be the aim
  - Thicker REBCO (3-5 µm), probably liquid-driven routes, thin substrates
- Electric Utility customers vital to major markets, especially for power cables
- Affordable, profitable, multi-filament, isotropic, safe conductors should become the goal

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