Transposed high current cables made with strong Bi2212 superconductor wire

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President and CEO

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## Acknowledgements & Collaborators

### Development network

- Plasma Science & Fusion Laboratory at MIT (Cabling line)
- Profs Yuki Iwaza and John Voccio (Ic testing)
- Francis Bitter Magnet Laboratory at MIT (Ic testing)
- Applied Superconductivity Center at Florida State University (Wire dev’t, testing)

### Funding

- DOE Phase 1 SBIR DE-SC0017709 (Just started)
- DOE Phase 2 SBIR DE-SC0011334 (Just finished)
- Solid Material Solutions, LLC
Objectives

- **Strong round & rectangular HTS wires**
  - Like proven LTS – Nb3Sn wires, but with superior $J_e(B, T)$ and still affordable
  - Built on unique Bi2212 properties, with our strengthening, dev’t expertise
    - Reaction to achieve high $J_e$ does not require tape shape
  - As low-cost / m as 1G tape, but with lower $$/kAm$ price due to higher $J_e(4.2K)$

- **Transposed cables for robust, low loss coils with these wires**
  - Like proven LTS – Nb3Sn cable designs
  - But with superior $J_e(B,T)$ while meeting all other requirements
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- **HEP design targeted**
  - The LTS Rutherford round wire cable type below (CERN)
  - Compression, tension tolerant as needed
# Applications

<table>
<thead>
<tr>
<th><strong>Particle Accelerator</strong></th>
<th><strong>Fusion Development</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics – quadrupole, saddle / racetrack</td>
<td>Tokomak central solenoid → Ramped field, large coil</td>
</tr>
<tr>
<td>Proton therapy – large solenoid</td>
<td></td>
</tr>
<tr>
<td>(SMES / Transformer)</td>
<td>(Generator / Motor)</td>
</tr>
</tbody>
</table>
Strong Wire? Attach Reinforcement

- **Why? Silver cannot be modified** to attain required stress tolerance
  - Modulus too low, $\sim 80$ GPa versus $>150$ GPa needed
  - Annealed by reaction so even weaker than just from low modulus

- **Why rectangular initially? Easier to produce, prove approach basics**
  - Plus better cabling density is likely without much deformation
  - And, lower contact pressures, with much fewer internal damage issues

- **Round development? Now ongoing with cabling starting soon**
Strong Bi2212 Wire Designs

Rectangular (ReSRW)
- Surface bonded strips on Opposite sides
- Reinforcement strips
- Silver alloy sheath
- Multifilament region
- O2 paths in reaction
- Reaction Barriers / Electrical Insulation

Round (RoSRW)
- Surface bonded strips, spiral wound
- Reinforcement strips
- Silver alloy sheath
- Multifilament region
- O2 paths in reaction

This approach enables:
- High Je Bi2212 to form by oxygen exchange between the 2212/Ag core and atmosphere during reaction
- Needed strength and prevention of contact damage
- Many design variations
- Straightforward, scalable, low cost production

Reinforcement strips bonded to some surfaces
- Rectangular: square to ~ 2:1
- Round: 0.8 mm – 1.6 mm diameter
Strip dimensions: as needed, 10% - 50% by area
Stress tolerance: 250 to ~600 MPa
Use modes: Wind & React, React & Wind

ReSRW with core wider than strips
Long ReSRW on cabling reel
1st Process: Rectangular Wire → Cable → Coil

- 2212/Ag round wire, strong strips
- Form square or rectangular shape
- Assemble components
- Bond by heat treatment
- Wind coil
- Heat treat to form high Jc 2212
- Add fixture, leads
- Wind coil, add fixtures, leads
Tests indicate:
- Sufficient ductility
- Adhesion for retained integrity
- Good $J_e$ even with 1 atm reaction
- No leakage or other defect

$\rightarrow$ Great news for cabling!
Analysis of $J_e$ for wires needed, dimensions

Number of wires

Key points

- $J_e$ scaling well behaved with field and $J_c$
- Analysis completed for 10 kA cable dimensions, # of wires

For ideal build like this

Je Present Status (2212/Ag)

<table>
<thead>
<tr>
<th>Wire State</th>
<th>Reaction</th>
<th>$J_e$(4K, 5T) (A/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawn round</td>
<td>1 atm</td>
<td>~350</td>
</tr>
<tr>
<td>SMS roll densified</td>
<td>1 atm</td>
<td>700-800</td>
</tr>
<tr>
<td>Drawn or densified</td>
<td>50 atm</td>
<td>1200</td>
</tr>
</tbody>
</table>

$J_e$ increased by mechanical densification
$J_e$ increased even more by gas pressure

$J_e$ (4.2K) of BSCCO HTS with added reinforcement
(Estimated from strength and $J_e(B)$ data)

$J_e (A/sq \, mm, 4.2K)$

Magnetic Field (T)

A little algebra ...

$I_c(B_c) = A(2212/Ag) \times (-270 \ln(B_c) + 270 \ln(B_t) + J_e(B_t))$

With required wires = $(I_{op}/F)/I_c(B_c)$
Cable design analysis: baseline result

**Result**

**For 25 T, 10 kA**

- Dimensions like Nb3Sn 10 kA cables
  - 1.9 mm x 25 mm for 1 atm reacted  30 wires
  - 1.9 mm x 16 mm for 50 atm reacted  20 wires
Cabling mode: without wire rotation, wrapping

**Side view: illustration of planetary cabling**

- Cabling guide / die
- Rolls may be used but with minimal deformation

**Front view: plate & payoff reels**

- Wire and cable surfaces ~ parallel

**Plate** rotates opposite to and at same rate as each reel

- Payoffs, each with a wire guide
- Cabling guide / die
- Cable pull speed $V_c$

**Pitch ~ $V_c / \omega$**

**Plate** rotates opposite to and at same rate as each reel

- Payoffs, each with a wire guide

- Each of six payoffs
- To wire guide and cable

**Wires**

**Cable**

- Denser pack with less deformation
- No wire to wire sintering
- Large contact areas with hard coating avoids local indent damage

(used for some round wire Nb3Sn cables to minimize local strains)
Cabling Set up and Procedure Development

Cabling line
- At the Plasma Science & Fusion Center (PSFC) of MIT

Set up
- Designed and applied our guides and tooling
- Added our cable pull mechanism and take up

Procedures and process
- Developed procedures with rectangular copper wire
- Produced, tested copper cables with different designs

Cross section of copper analog cable
- Packing factor here is ~ 85% within the cable
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Photo of cabling line

Typical local deformation from consolidation rolling with round wire
Bi2212 Wire Transposed Cabling Feasibility

Cable exiting assembly die
→ stable in < 2 pitch lengths

ReSRW Wire Used

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>1.02 mm x 0.78 mm</th>
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<tbody>
<tr>
<td>Strips</td>
<td>0.9 mm x 0.1 mm</td>
</tr>
<tr>
<td>Strip content</td>
<td>24 % (~300 MPa)</td>
</tr>
</tbody>
</table>

Cabling

<table>
<thead>
<tr>
<th># wires</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch setting</td>
<td>4.5 cm</td>
</tr>
<tr>
<td>Wire tensions</td>
<td>14 N</td>
</tr>
</tbody>
</table>
Result: Uniform Bi2212 Cables, No Damage

Cable Inspection

- **Pitch**: ~ 4.7 cm measured, and uniform
- **Layup**: Wires retained ~ parallel orientation to cable surface planes
- **Condition**: No sign of damage, cables very stiff
- **Width**: 3.1 mm
- **Thickness**: 2.3 mm
- **Packing fraction**: ~67%
- **Cable bend tests**: To 4.5 cm
- **Bend Limit**: At ~ 5 cm

Approach qualified and works

→ Wire handles process
Fabricated first mini cabled coils w/o damage

Coil production and tests
Coiling: Wound 3 mini coils
Wind method: By hand, ends free, some rebound
Diameters: 5.5 cm
Control samples: Wire pieces cut from cable ends
Cable condition: Wrapped with strip for reaction
Reaction: At standard 1 atm
Inspection: No sign of damage, reacted coils very stiff

Coil winding & reaction responses good
Ic tests so far: for wires (4K), coils (64K-70K)

**Wire Ic’s (4K, self field)**
- average Ic, cable 2
- Ic std dev, cable 2

End pieces tested
- 940 A
- 2 %

**Projected cable Ic(4K, 5T)**
- 2 kA by scaling wire Ic’s

**Tested cable Ic(64K-70K)**
- 170 A at 64K ~full length

**Cable Ic tests at 4K in-field**
- Pending

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Cable 1 Ic Versus Temperature in 64 K to 70 K Range

**Test Details**
- Criterion: 1 micro-volt / cm
- Portion Tested: ~ Full Length
- Voltage Taps: Soldered onto 4 wires
- Tc ~ 74.5 K

Ic data so far promising

But, additional data required

Looking to complete in-field 4.2K Ic tests
Now About RoSRW Cable Development

- Built and qualified equipment
- Developing design, process
- Testing $I_c/J_e$, properties for cabling

2212/Ag round wire
Strip payoffs
Assembly tooling
Assembled wire, >80% coverage

$9 \text{ mm } \phi$ then reacted

Je of 2212/Ag in RoSRW
Versus Bent Wire Diameter

Reacted wire
Cross-section
Coiled piece

Wire properties seem suitable for cabling
Next Steps

• Complete Ic (4K) testing of first cables
• Produce and test cables with more wires, longer lengths
• Build strong round wire cables and test – first one by Dec. 2017
• Achieve 10 kA (~15 T) design like CERN cable – first one Q1 2018
• Complete dev’t & testing: LBNL, CERN, PSFC, NHMFL, others
• Integrate cable development with coil program(s)
Messages...

We demonstrated feasibility of making transposed cables with strong Bi2212 rectangular wire

Adapted and qualified cabling equipment and procedures
6-wire pay off (for now)  Planetary layup  Capable of long lengths

Produced first cables with 1 mm wide wires in pre-reacted condition
Okay packing (~67%)  4.7 cm pitch  Wire integrity retained

Tested bending, then wound & reacted 5.5 cm diameter mini coils
Coil-able to 5 cm dia.  Cable integrity retained  No defects observed

Ic tests underway
Cabled wire Ic’s(4K) ~940 A/mm²  Projected cable Ic(4.2K, 15T) ~ 1.5 kA

Preparing strong round & rectangular wire cables for dev’t & testing

➡️ Very promising first results
For achieving strong, LTS-like 10 kA transposed HTS cable
THANK YOU

Alexander Otto (PhD)
Linda Saraco

Solid Material Solutions, LLC