Advanced second generation high temperature superconductor wire for fusion
Credits

A. Molodyk, A. Markelov, A. Mankevich, V. Scherbakov, S. Samoilenkov, A. Vavilov

SuperOx Japan

V. Petrykin, S. Lee

B. Sorbom
Outline

- The SuperOx group
- High temperature superconductors (HTS) enable compact fusion
- Challenges to HTS for fusion---being resolved
  1. High $J_e$ in magnetic field
  2. Consistent quality
  3. Production capacity and cost
  4. Cable technology
The SuperOx group

S Innovations (Moscow) and SuperOx Japan (Tokyo)

- 2G HTS wire production and development
  - Supply wire to SuperOx projects
  - Supply wire to customers worldwide

SuperOx (Moscow)

- HTS Applications development and commercialisation
  - Fault Current Limiters: 220 kV FCL in Moscow city grid in 2019
  - Coils: 0.5 MW motor for aircraft
  - AC/DC cables: 12 MW AC cable system for aircraft
Commonwealth Fusion Systems’ high-field path to fusion
The CFS plan to get to clean fusion energy will use a lot of HTS

**Completed:**
- Proven science
- Alcator C-Mod

**In Progress for Summer 2021**
- Demonstrate groundbreaking HTS magnets

**Construction Planning Underway for 2025 Launch**
- Achieve net energy from fusion
- SPARC, Q>2

**Early 2030s**
- Fusion power on the grid
- ARC, Q>10, \( P_{\text{electric}} \sim 200 \text{MW} \)

- **Demonstrate magnet technology**
- **Value inflection from showing net energy**
- **Carbon-free fusion energy**
  - Requires \( \sim 10,000 \text{ km of HTS} \)
  - Requires \( \sim 20,000 \text{ km of HTS per fusion device} \)
  - **500 km ordered, delivered, characterized, and put into a magnet**
**SuperOx 2G HTS wire: Technology**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate thickness</td>
<td>40 or 60 or 100 μm</td>
</tr>
<tr>
<td>Critical bend diameter</td>
<td>&lt; 10 mm (40 μm)/15 (60)/25 (100)</td>
</tr>
<tr>
<td>Tensile strength (95% ( I_c ) retention)</td>
<td>&gt; 500 MPa / 0.4% deformation</td>
</tr>
</tbody>
</table>

**For LN2**

- **Wire width**
  - 4 mm
  - 12 mm

- **Average critical current @ 77 K, s.f.**
  - 100-200 A
  - 300-700 A

- **Critical current uniformity**
  - \( I_c \) standard deviation 1-3%

**In-field**

- **Wire width**
  - 4 mm
  - 12 mm

- **Average critical current @ 20 K, 20 T**
  - 150-250 A
  - 450-750 A

- **Average critical current @ 4.2 K, 20 T**
  - 340-560 A
  - 1000-1700 A

- **Critical current uniformity**
  - \( I_c \) standard deviation 2-5%

\( J_e \) > 500 A/mm\(^2\) at 77 K, s.f.
\( J_e \) > 1000 A/mm\(^2\) at 20 K, 20 T
\( J_e \) > 2000 A/mm\(^2\) at 4.2 K, 20 T
SuperOx wire for in-field use: Simple and amenable to industrial production

Conventional approach to pinning in HTS wire: c-axis correlated extrinsic defects (e.g. BaZrO₃)

SuperOx 2G HTS wire for in-field use: Uniformly distributed intrinsic Y₂O₃ nanoparticles in YBCO

- Complex composition and nano-structure
- Difficult to control
- Issues with reproducible manufacturing

✓ Simple composition and nano-structure
✓ Easy to control
✓ Good reproducibility in manufacturing


Challenge 1: High performance SuperOx wire for in-field use
Best commercial wire for magnets today

- I_c 30% higher than competition
Challenge 2: Consistent quality
SuperOx wire for in-field use: 2G HTS wire is becoming industrial
300+ km of 4 mm wire delivered to customers in 9 months
300+ km more in another 6 months; 3,000 km in 2022

- Reasonable statistical spread of in-field properties. StD \sim 15\%
- Wires fabricated at different sites are identical
# SuperOx 2G HTS wire: Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate thickness</td>
<td>30 or 40 or 60 or 100 μm</td>
</tr>
<tr>
<td>Critical bend diameter</td>
<td>&lt; 10 mm (30 &amp; 40 μm)/15 (60)/25 (100)</td>
</tr>
<tr>
<td>Tensile strength (95% $I_c$ retention)</td>
<td>&gt; 500 MPa / 0.4% deformation</td>
</tr>
<tr>
<td>For LN2</td>
<td></td>
</tr>
<tr>
<td>Wire width</td>
<td>4 mm</td>
</tr>
<tr>
<td>Wire width</td>
<td>12 mm</td>
</tr>
<tr>
<td>Average critical current @ 77 K, s.f.</td>
<td>100-200 A</td>
</tr>
<tr>
<td>Average critical current @ 20 K, 20 T</td>
<td>150-250 A</td>
</tr>
<tr>
<td>Average critical current @ 4.2 K, 20 T</td>
<td>340-560 A</td>
</tr>
<tr>
<td>Average critical current @ 77 K, s.f.</td>
<td>300-700 A</td>
</tr>
<tr>
<td>In-field</td>
<td></td>
</tr>
<tr>
<td>Wire width</td>
<td>4 mm</td>
</tr>
<tr>
<td>Wire width</td>
<td>12 mm</td>
</tr>
<tr>
<td>Average critical current @ 20 K, 20 T</td>
<td>150-250 A</td>
</tr>
<tr>
<td>Average critical current @ 4.2 K, 20 T</td>
<td>340-560 A</td>
</tr>
<tr>
<td>$I_c$ uniformity along wire</td>
<td>$I_c$ standard deviation 1-3%</td>
</tr>
<tr>
<td>$I_c$ uniformity along wire</td>
<td>$I_c$ standard deviation 2-5%</td>
</tr>
</tbody>
</table>

**Customisation:**
- Variable copper thickness
- Insulation: 10-20 μm thin polyimide varnish
- Solder plating
- Lamination
- Low resistance splices
- … just ask
Challenge 3: Production capacity and cost

- Demand drives capacity scale-up
- Economies of scale bring the price down
Challenge 4: HTS cables for fusion
Paul Scherrer Institute: 60 kA @ 4.2 K, 12 T

D. Uglietti et. al, 2015 Supercond. Sci. Technol. 28 124005
Challenge 4: HTS cables for fusion
MIT / CFS: VIPER design

Zachary S Hartwig et al 2020 Supercond. Sci. Technol. 33 11LT01
Challenge 4: HTS cables for fusion
SuperOx: Canted Stack in the Channel Conductor (CSCC)

50 HTS tapes 4 mm
Cu shell
Cu tapes
Solder

200 HTS tapes 4 X 0.06 mm
Cu: 245 mm²
SS: 260 mm²

70 kA; 4.2 K
35 kA; 20 K

20 T

100 kA; 4.2 K
50 kA; 20 K

Bending diameter, mm

Solder filling:
- full
- partial

I_c / I_{c0}

0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

50 100 150 200 250 300 350 400 450 500
Summary

• The SuperOx group:
  o Produce and sell 2G HTS wire
  o Commercialise HTS applications

• HTS will turn the fusion dream into reality
  o High magnetic field: path to compact commercial reactors

• Challenges to HTS for fusion---being resolved
  1. High $J_e$ in magnetic field: 1,000+ A/mm² (20 K, 20 T), 2,000+ A/mm² (4.2 K, 20 T)
  2. Consistent quality: through simple superconductor
  3. Production capacity and cost: tonne-scale projects two-digit $$/kAm
  4. Cable technology: choice among designs that work
Thank you for your attention