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Development of High-strength and High Strain Tolerant CORC® Conductors for High-Field Magnets

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CORC® magnet cables and wires

**CORC® wires (2.5 – 4.5 mm diameter)**
- Wound from 2 – 3 mm wide tapes with 25 and 30 µm substrate
- Typically no more than about 30 tapes
- Flexible with bending down to < 50 mm diameter

**CORC® cable (5 – 8 mm diameter)**
- Wound from 3 – 4 mm wide tapes with 30 – 50 µm substrate
- Typically no more than about 50 tapes
- Flexible with bending down to > 100 mm diameter

**CORC® Cable In Conduit Conductor (CI CC)**
- Performance as high as 100,000 A (4.2 K, 20 T)
- Combination of multiple CORC® cables or wires
- Bending diameter about 1 meter
High-field insert solenoid wound from CORC® cables

Addresses main challenges of low-inductance HTS magnets
• Operate CORC® insert solenoid in **14 T background field**
• CORC® insert should have meaningful bore: 100 mm diameter
• High operating current: **4,000 – 5,000 A**
• \(J_c > 200 \text{ A/mm}^2\)
• Operate at \(J_B\) source stress >250 MPa

**CORC® cable layout**
• 28 REBCO tapes of 3 mm width containing 30 μm substrates
• 4.56 mm CORC® cable outer diameter

**CORC® insert layout**
• 100 mm inner diameter, 143 mm OD
• 4 layers, 45 turns
• 18.5 m of CORC® cable
• Wet-wound with Stycast 2850
• Stainless steel overbanding between layers

14 T LTS (161 mm bore)
CORC® magnet winding

Interlayer stainless steel overbanding
Results 14 T background field

- Maximum current 4,200 A to avoid quench trigger
- $I_c = 4,404$ @ $0.1 \mu V/cm$
- Contact resistance 11.1 nΩ
- 15.86 T central field
- 16.77 T on conductor
- $J_B$ source stress 275 MPa
CORC® insert solenoid test: summary

**CORC® insert impact**
- First HTS insert magnet tested at high current (>1 kA) in a background field
- Stable operation likely due to current sharing between tapes in the CORC® cable
- Combination of high $I_c$, $J_w$, and $J_Br$ demonstrated at 16.8 T peak field

<table>
<thead>
<tr>
<th>Applied field [T]</th>
<th>Central field at $I_c$ [T]</th>
<th>Peak field at $I_c$ [T]</th>
<th>$I_c$ (0.1 µV/cm) [A]</th>
<th>$n$-value</th>
<th>$J_w$ [A/mm²]</th>
<th>$J_e$ [A/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>12.25</td>
<td>13.35</td>
<td>5,315</td>
<td>7.9</td>
<td>203.9</td>
<td>340.3</td>
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<td>12</td>
<td>14.08</td>
<td>15.09</td>
<td>4,908</td>
<td>9.1</td>
<td>188.3</td>
<td>314.2</td>
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<tr>
<td>14</td>
<td>15.86</td>
<td>16.77</td>
<td>4,404</td>
<td>10.5</td>
<td>168.9</td>
<td>281.9</td>
</tr>
</tbody>
</table>

https://doi.org/10.1088/1361-6668/ab7fbe

**Conductor challenges when going to higher field and larger coil diameters**
- A Central Solenoid in a future compact fusion reactor may have a $J_Br$ of 200 A/mm² x 20 T x 0.2 m = 800 MPa (source stress)
- How to further optimize the CORC® conductor to allow higher hoop stress, but also a higher irreversible strain limit?
Why is Nb-Ti the workhorse of superconducting magnets?

Nb-Ti is a superconducting magnet workhorse because

• It’s a round
• It’s fully isotropic (mechanically and electro-magnetically)
• Doesn’t require reaction after magnet winding
• It’s a transposed, multifilament wire
• It’s highly flexible, allowing very tight bends

How about CORO® wires?

✔ ✔ ✔ ✔

(At least partly)

(Not too tight please!)

We know this, so what’s new? To find out, let’s consider this 44 year old plot:

Irreversible strain limit under axial tension ($\epsilon_{irr}$) exceeds 2 % driven by reduction in Nb-Ti cross-section with strain

$\epsilon_{irr}$ defined at $I_c(0)/I_c(0) < 97-98$

Irreversible strain limit of practical superconductors

Irreversible strain limit (applied strain)

• Nb$_3$Sn: 0.65 % [1]
• Bi-2212 wires: 0.3 % [2]
• Bi-2223 tapes: 0.4 % [3]
• REBCO CC: 0.6 % [4]

How about CORC® wires?

The effect of axial tensile strain on $I_c$ of CORC® wires

Simplified description of CORC® wire structure

- REBCO tapes wound in a helical fashion on solid core
- Tapes behave as springs; extending axially and contracting radially under tensile load
- The core acts a central support, but also confines the radial contraction of the springs

Testing CORC® wires under axial tension

- Test performed in LN$_2$ at 77 K
- Maximum load of 13 kN applied to terminations
- Sample strain measured with pair of clamp-on extensometers
Performance of a standard 30-tape CORC® wire

**Standard CORC® wire**
- 30 REBCO tapes of 2 mm width
- Annealed copper former (2.55 mm diameter)
- Wire diameter 3.6 mm

- Critical strain is already twice that of a straight REBCO tape
- Critical stress of 150 MPa is competitive with magnet conductors such as Nb₃Sn
Effect of tape winding angle on $\varepsilon_{irr}$

Tape winding angle drives the irreversible strain limit in CORC® wires
Verification of tape $I_c$ retention after strain

**Procedure**

- Strain CORC® wire to $0.85 \times \varepsilon_{\text{rr}}$
- Extract tapes from CORC® wire
- Measure $I_c$ from extracted tapes

**Results**

- CORC® wire retention 98%
- Extracted tape $I_c$ retention 98%

*High $\varepsilon_{\text{rr}}$ of 3.3% is real!*
Analytical verification of strain results

Analytical approach

- Calculate the tape axial strain from change in geometry
- Ignore the torsion component

\[ \varepsilon_{\text{tape}} = \frac{\Delta S}{S} = \frac{l + \Delta l}{\sin \alpha} - \frac{l}{\sin \alpha} \approx \frac{\Delta l}{l} \left( \sin^2 \alpha - \nu \cos^2 \alpha \right) \]

![Diagram showing irreversible strain limit vs winding angle](image)
**FEM verification of results**

**FEM approach**
- Calculate REBCO value exceeding $\varepsilon_{rr}$
- Assumes $I_c$ correlates to remaining superconducting volume

![Graph showing FEM verification of results with applied tensile strain](image_url)

- **CORC® with low winding angles**
- **CORC® with high winding angles**
- **Single REBCO tape**
- **FEM-Calculated values**
Extending ε_{irr} of high tape count CORC® wires

**Optimized 28-tape CORC® wire layout**

- 28 tapes of 2 mm width (30 µm substrate)
- 14 layers wound on 2.55 mm copper former
- tape winding angle 25 – 35°, depending on layer

![Graph showing Ic(ε)/Ic(0) vs Strain, % for different samples]

**Optimized 28-tape CORC® wire : ε_{irr} = 6 – 7 %!!**

Advanced Conductor Technologies
www.advancedconductor.com

UNIVERSITY OF TWENTE.

NATIONAL HIGH MAGNETIC FIELD LABORATORY
Verification of tape $I_c$ retention after high strain

**Optimized 28-tape **CORC®**wire**
- **CORC®**wire $I_c$ retention 98 % at 7 % strain
- Extracted tape $I_c$ retention 99 %
- Only tapes in the inner layer are damaged

Irreversible strain limit in **CORC®**wires can be increased significantly by minimizing the tape winding angle
Axial strain practical superconductors Master Plot

CORC® wires can now be engineered to have $\xi_{\text{tr}}$:
- twice as high as Nb-Ti
- 10 times as high as REBCO coated conductors
- 20 times as high as Nb$_3$Sn, Bi-2212 and Bi-2223

Accepted for publication: van der Laan et al. “High-temperature superconducting CORC® wires with record-breaking axial tensile strain tolerance present a breakthrough for high-field magnets” DOI https://doi.org/10.1088/1361-6668/ac1aae
CORC® wires with improved mechanical tensile strength

Critical stress limit under tension (12-tape CORC® wire)

- Critical stress limit with soft annealed copper former: 134 MPa
- Critical stress limit with half hard copper former: 280 MPa
- Critical stress limit with CuBe former: 613 MPa

Irreversible tensile stress limit of CORC® wires can be engineered to exceed 600 MPa at 77 K
Summary

First high-current CORC® insert solenoid successfully tested
• Operation at over 4.4 kA in 14 T background field, generating a peak field of 16.77 T
• Operated at 282 A/mm² and 275 MPa JBr source stress at 14 T background field

The helical winding of REBCO tapes is CORC® wires allows
• To mechanically decouple the ceramic REBCO film from the CORC® wires
• Reduce the strain transfer from the CORC® wire to the REBCO film
• Allow the irreversible strain limit under axial tension in CORC® wires to far exceed that of the REBCO tape
• This allows extremely high irreversible strain limits in CORC® wires of 7 %

Optimized CORC® wires have an irreversible strain limit under tension
• More than 10x that of REBCO tapes
• More than 20x that of other HTS and Nb₃Sn
• Double that of NbTi

Mechanically decoupling of the REBCO layer allows
• The CORC® wire strength under axial tension to be determined almost entirely on that of the former
• CORC® wires with very high critical stress exceeding 600 MPa at 77 K have been demonstrated