SuperCIC: enhanced winding current density for high-field windings of tokamaks

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Fusion is a staggering application for superconducting magnetics

Figure 3. (left) First TF winding pack ready for insertion into the case; (right) first TF case ready for winding pack insertion.

Figure 4. (left) Fabrication proceeding on the first CS module; (right) PF6 sixth double pancake resin impregnated.
Today there are three *privately funded (>100M each)* projects to use REBCO windings for fusion

CFS tokamak; TE tokamak, LMA mirror

Each would require complex windings of high-current cables with cable current \(\sim 20 \text{ kA} - 40 \text{ kA}\)
ACT has developed such a REBCO cable that has the potential to meet their requirements

- See ten Kate’s talk this morning...

**CORC® wire to increase $J_e(20 \, T)$**
- 32 tapes (2 mm (25 μm) and 3 mm (30 μm) width)
- Outer diameter 3.42 mm
- Average pinning
- 81 % $I_c$ retention

New record $J_e (12 \, T)$ 678 A/mm$^2$
Extrapolated $J_e (20 \, T)$ 451 A/mm$^2$
$I_c(B)$ closely follows that of the tapes

Danko, ICMC 2019
There’s just one problem... REBCO is ruinously expensive!

This has motivated us to develop a cable-in-conduit technology that

- Preserves the full wire current density in a ~30 A cable under the conditions of background field and Lorentz stress in a >16 T winding;
- Can be fabricated using NbTi, Nb$_3$Sn, and Bi-2212 wires;
- Sub-windings of all three superconductors can be wound and heat-treated separately to yield optimum performance;
- Sub-windings can be assembled and preloaded into as hybrid windings in toroid and solenoid geometries while preserving wire performance;
- Windings can be spliced to NbTi interconnect cables with ~nΩ resistance, and splices can be de-mounted and remounted.
- High-modulus armor can be co-wound with the CIC to support large radial and hoop stress in >16 T windings.

Accelerator Technology Corp. and Texas A&M are developing a SuperCIC technology that can accomplish all of those goals.
Menard evaluated the importance of the current density $J_{WP}$ in the winding package and the toroid aspect ratio $A$ as performance parameters for the particular case of tokamak configurations.

The current density $J_{WP}$ in the conventional CIC used in fusion magnet magnets arises from damage to the wires.

$J_{WP} = 20$ for ITER CIC
Super-CIC:
Support all wires within the cable and protect them from all exterior stress, so that they maintain the full wire performance in the cable and in the winding.
Fabrication of SuperCIC:

1. Draw sheath tube onto cable.
2. Pull straight 150 m cable through sheath tube with loose fit.
3. Apply foil over-wrap.
4. Cable superconducting wires onto center tube.
5. Perforated center tube.

ATC now manufactures 2-layer SuperCIC in lengths up to 150 m as a manufactured product.
Draw sheath onto cable to immobilize wires; spring-load them against center tube; stress management at cable level.

Form small-radius bends using robotic bender. No damage to filaments in wires, Preserve wire performance in CIC.
Co-wound armor to provide robust high-modulus support for radial and hoop stress.

Two half-shells of armor are co-wound with SuperCIC configuration for coil-winding co-wound armored SuperCIC for a solenoid winding.
Hybrid windings using SuperCIC for a spherical tokamak

The division of sub-windings follows naturally the decreasing field-at-conductor. Hybrid windings can be used to minimize the expensive superconductor in the windings.
Payoff: 16 T hybrid-coil toroid with $J_{WP} = 140$ A/m²
Spherical tokamak with $A = 2.0$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
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</thead>
<tbody>
<tr>
<td>$R_0$</td>
<td>1.2</td>
<td>M</td>
</tr>
<tr>
<td>$B @R_0$</td>
<td>6.7</td>
<td>T</td>
</tr>
<tr>
<td>$B @coil$</td>
<td>17.4</td>
<td>T</td>
</tr>
<tr>
<td>$A$</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>CIC</td>
<td># strands, wire dia.</td>
<td></td>
</tr>
<tr>
<td>Bi-2212</td>
<td>42 strands, 0.97 mm</td>
<td></td>
</tr>
<tr>
<td>Nb₃Sn</td>
<td>42 strands, 0.97 mm</td>
<td></td>
</tr>
<tr>
<td>NbTi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$J_{WP}$</td>
<td>140</td>
<td>MA/m²</td>
</tr>
<tr>
<td>$I_{op}$</td>
<td>28.7</td>
<td>kA</td>
</tr>
<tr>
<td>$I_{op}/I_c @4.2K$</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td># layers</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>SC (Layers)</td>
<td>Bi-2212 = 5 layers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nb₃Sn = 6 layers</td>
<td></td>
</tr>
<tr>
<td>Quantity of SC</td>
<td>Bi-2212 = 2.25 Ton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nb₃Sn = 1.9 Ton</td>
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<tr>
<td>Cost of SC</td>
<td>Bi-2212 = $31M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nb₃Sn = $3.3M</td>
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<tr>
<td></td>
<td>$34M</td>
<td></td>
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</tbody>
</table>
Magnetic field in the windings:

Stress management in windings:

Winding package;
Stress in armor < 250 MPa
Stress in SuperCIC < 120 MPa

Structural support:
Stress < 600 MPa
Conclusions

SuperCIC windings brings several innovations to high-field magnetics for fusion systems:

• The SuperCIC manages stress at the cable level, so the huge accumulated Lorentz forces within windings cannot degrade fragile filaments of high-field superconductors. Round-profile SuperCIC makes it possible to integrate the cylindrical sheath and high-strength support elements as separate ingredients.

• The SuperCIC windings can be formed with small radius of curvature without harm to the wire or cable. It therefore provides a basis for high-field, small-radius solenoids, flexibility in reducing the aspect ratio of toroid windings, and challenging configurations for poloidal windings.

• SuperCIC supports hybrid coil strategies, in which sub-windings of different high-field conductors can be separately fabricated and heat-treated and then assembled as a winding.

• SuperCIC with Bi-2212 can be fabricated with provisions for sheath tube and over-wrap metals for which the sheath tube can serve as the pressure retort for over-pressure processing (no high-pressure retort).

• SuperCIC can be co-wound with a 2-piece armor shell that provides robust management of radial and hoop stress.

• Cryogen flow within SuperCIC distributes cooling throughout the volume of the winding, so that the variation in winding temperature from non-uniform heat loads is suppressed.

TAMU and ATC are collaborating with PPPL to develop conceptual designs utilizing SuperCIC for the solenoid and toroid windings of their spherical tokamak.