Development of REBCO dipole magnets using CORC® wires – results from the C2 magnet


Lawrence Berkeley National Laboratory

D.C. van der Laan and J.D. Weiss

Advanced Conductor Technologies & University of Colorado
REBCO can enable 20+ T accelerator magnets: a new paradigm for magnet technology

- The community has achieved significant progress
  - Record $J_e$ of 5000 A/mm² at 4.2 K, 15 T, Univ. Houston
  - 40 T total dc field with non-insulation insert, ASC/NHMFL

- EuCARD2 successfully demonstrated accelerator-quality REBCO dipole magnets using Roebel cable withstanding 350 MPa transverse stress. ARIES will double the conductor performance and reduce cost

- The USMDP also set a near-term goal to reach 5 T in HTS dipole magnets
We are developing CORC® CCT dipole magnet technology to address key driving questions

- How to make dipole magnets using REBCO conductors?
- What is the magnet performance and required conductor performance?
- What issues limit the magnet performance? How to address them?
- What are the implications for the HEP community?

- CORC® wire is a promising HEP cable option
  - Isotropic for magnetics and mechanics
  - High current (~10 kA) at small bending radius (30 mm)

- CCT design is ideal for insert [D. Arbelaez, Thur-Af-0r24-05]
  - Low conductor stress
  - Excellent geometric field quality
Together with industry partners, the USMDP chooses a systematic and phased approach towards 5 T and beyond

- Develop dipole magnets with increasing fields and complexities
  - C1, 1.2 T at 2017. Demonstrated initial concept
  - C2, 2.9 T at 2019. Demonstrated metal mandrel
  - C3, target 5 T at 2020. Demonstrate magnet technology towards higher fields
  - We are formulating roadmaps beyond 5 T

- Strongly coupled magnet/conductor work provides effective feedback to conductor development based on magnet performance
- Collaboration within MDP and the community through MDP
The success of the 2-layer C1 laid a solid foundation for C2

- Successfully wound 30 m long CORC® wire
- Developed praying-hand joints with 10 – 100 nΩ joint resistance
- Detected voltage rise and showed high thermal stability at $J_e$ of 620 A/mm²
- Generated 1.2 T dipole field at 4.2 K with printed plastic mandrels
C2 aims to generate 3 T with longer conductors, metal mandrels and Stycast to constrain the conductors.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilt angle, L1/2</td>
<td>50°</td>
</tr>
<tr>
<td>Tilt angle, L3/4</td>
<td>35°</td>
</tr>
<tr>
<td>Min. bending radius</td>
<td>30 mm</td>
</tr>
<tr>
<td>Transfer function</td>
<td>0.47 T/kA</td>
</tr>
<tr>
<td>Target dipole field</td>
<td>3 T</td>
</tr>
</tbody>
</table>
C2 used the state-of-art 30-tape CORC® wire to boost the magnet current

- SuperPower tapes: 2 mm wide, 30 µm substrate, 5 µm surrounded Cu stabilizer
- Layer 4 wire contains high- and low-pinning tapes – conductor grading
- Measurements at ASC/FSU detected deviation from expected tape performance, allowing the quick feedback to SuperPower and wire design at ACT

<table>
<thead>
<tr>
<th>Wire ID</th>
<th>Length (m)</th>
<th>Wire OD (mm)</th>
<th>Average tape Ic (A) 77 K, SF</th>
<th>Peak field on wire (T)</th>
<th>Min bend radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2-L1</td>
<td>18</td>
<td>3.80</td>
<td>70</td>
<td>3.6</td>
<td>30</td>
</tr>
<tr>
<td>C2-L2</td>
<td>20</td>
<td>3.80</td>
<td>70</td>
<td>3.6</td>
<td>35</td>
</tr>
<tr>
<td>C2-L3</td>
<td>24</td>
<td>3.77</td>
<td>69</td>
<td>3.2</td>
<td>30</td>
</tr>
<tr>
<td>C2-L4</td>
<td>28</td>
<td>3.67</td>
<td>57</td>
<td>2.8</td>
<td>35</td>
</tr>
</tbody>
</table>
We expect C2 to reach 3 T at 4.2 K based on the in-field performance data of a Layer 1 sample

- V(I) transition of a Layer 1 sample measured by ACT at different background fields
- Bending radius close to C2

Jeremy Weiss and Danko van der Laan
Mechanical analyses confirm that C2 and beyond needs a metal mandrel

- Mandrel stresses of 150-200 MPa is too high for 3D printed Bluestone that was used for C1 mandrel

- C2 mandrel used Aluminum Bronze to leverage the experience of the CCT program at LBNL [D. Arbelaez, Thur-Af-Or24-05]

Lucas Brouwer
We reduced groove depth on mandrels as an interim solution to continue the magnet development.

- Full-depth radial groove: Straightforward to machine but challenge to wind with tension
- We will continue investigating this

Meanwhile, we used half-depth groove to help with winding.

Laura Garcia Fajardo
Bill Ghiorso, Hugh Higley
We used a systematic and progressive approach to develop and understand the fabrication technology for C2.

### 3-turn

1. Test at 77 K → Wind
2. Test at 77 K → Assembly
3. Test at 77 K → Apply Stycast
4. Test at 77 K

### 40-turn

1. Layer 1 → Wind
2. Test at 77 K → Apply Stycast
3. Test at 77 K
4. Layers 2 – 4 → Wind
5. Test at 77 K → Apply Stycast
6. Test at 77 K

Assembly → Test at 77 K → Test at 4.2 K
We learned several important things by developing 3-turn models and addressed issues not foreseen

- Used 30-tape prototype wire, 3.81 mm diameter
- Developed fabrication techniques (winding, joints, assembly, applying Stycast, ...)
- Modified exit lead design to reduce conductor handling
- Co-wound voltage tape wires covering all turns
... and also gained further confidence to develop C2

- Systematic tests on six coils showed negligible impact of Stycast (< 3% $I_c$ reduction)

Data wrt $I_c$ before winding. 10 µV, 77 K, self-field

<table>
<thead>
<tr>
<th>Layer</th>
<th>After winding</th>
<th>After styecast</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS-Layer 1</td>
<td>n/a</td>
<td>-29%</td>
<td></td>
</tr>
<tr>
<td>BS-Layer 2</td>
<td>-30%</td>
<td>-33%</td>
<td>-3%</td>
</tr>
<tr>
<td>BS-Layer 3</td>
<td>-28%</td>
<td>-31%</td>
<td>-3%</td>
</tr>
<tr>
<td>BS-Layer 4</td>
<td>-30%</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>AB-Layer 1</td>
<td>-12%</td>
<td>-14%</td>
<td>-2%</td>
</tr>
<tr>
<td>AB-Layer 3</td>
<td>-23%</td>
<td>-24%</td>
<td>-1%</td>
</tr>
</tbody>
</table>
So we started

Winding with Hugh’s winding table

Mandrel designed by Bill Ghiorso and machined by Maxwell Maruszewski
Co-wound voltage-tap wires with the conductor to reduce the inductive pickup during tests
Painted Stycast 2850MT after winding to constrain the conductors

- Wrapped fiber cloth on top of conductor
- Wrapped and heated heat shrink tapes around coil before Stycast cured

Hugh Higley
We measured the transport performance of each layer at 77 K before making the next layer.

Hugh Higley and Timothy Bogdanof
Few months layer, four layers of C2 oriented for a dipole configuration.
Prof. D. Larbalestier at ASC/NHMFL loaned the cryostat
R. Hafalia, R. Lee, T. Lipton, and L. Wang developed the adaptor
Layer 4 showed lower performance than the other three layers at 77 K but get closer to Layer 1 after assembly.

Before assembly

After assembly

- ~30% $I_c$ reduction due to higher fields
- Potential to perform at 4.2 K
Layers became superconducting in sequence, indicating cooling from outer to inner layers.
A controlled increase in the maximum current allowed us to probe the true performance of C2.

- Increasing the threshold for quench detection
A controlled increase in the maximum current allowed us to probe the true performance of C2

- Increasing the threshold for quench detection
A controlled increase in the maximum current allowed us to probe the true performance of C2.

- Increasing the threshold for quench detection
A controlled increase in the maximum current allowed us to probe the true performance of C2

- Increasing the threshold for quench detection
- Reproducible V(I) transition between ramps
  - $n = 13.1$ for Layer 4
  - $n = 6.8$ for Layer 1, consistent with the behavior of short sample measured at ACT
- Wire $J_e = 595$ A/mm$^2$ at 6.3 kA
Inter-layer joint resistance ranges from 8 to 24 nΩ at 4.2 K - room for improvement

Joint voltage is measured across the voltage taps in each layer

Layer 1
1VT5 1VT4 1VT3

Layer 2
2VT5 2VT4 2VT3

Layer 3/4
Layer 1/2

Join voltage (microV)

Current (kA)
We measured the field quality of C2 and observed strong persistent-current effects at the magnet center.

- Measurement with a 100 mm long rotating coil developed by J. DiMarco at FNAL.
Stronger effects at 4.2 K – 30 tapes with large $J_c$

- Cory Myers from OSU will present detailed field quality study, Thu-Mo-Po4.07-05
Can we use the persistent-current effects to identify the normal zones and transition locations?

Ramp 19, measurement at the magnet center

- Temperature can erase persistent currents
- Local thermal history due to transitions may leave a signature in magnetization → PC effects at the center may indicate the normal zones are outside the center
- Will test the idea at 77 K
We close the chapter on C2 with a good result

“A good result and more questions. That’s what we need.” – S. Gourlay

- C2 reached 2.9 T, 98% of the expected value
- Layer 1 started transitioning at 4.8 kA, 73% of the short-sample prediction. Why?
- What caused the low performance of Layer 4?
- Where is the heat/voltage generated?
- How can we improve for the next magnet?
We start the chapter on C3 to address the challenges to reach 5 T and beyond.

- **USMDP is progressing consistently with a phased approach towards 5 T for REBCO**
  - C1, 1.2 T, demonstrated initial concept
  - C2, 2.9 T, demonstrated metal mandrel and supporting conductor with Stycast
  - C3 to demonstrate 5 T magnet technology and higher Lorentz force

- **Magnets continue desiring wires with smaller bending radius and higher performance**
  - 20 μm thick substrate as the next target
  - Narrower tapes and higher pinning at 4.2 K

- **More magnet results are critical and coming – ASC/NHMFL, BNL, CERN, FNAL**
  - Great opportunity to collaborate and push together
A great team effort

- Team at LBNL – H. Higley, T. Bogdanof, B. Ghiorso, M. Maruszewski, S. Prestemon

- Advanced Conductor Technologies LLC and DOE HEP SBIR programs – Danko van der Laan and Jeremy Weiss

- ASC/FSU for testing the samples for ACT with quick turn-around – D. Abraimov
- ASC for loaning a cryostat to test C2 – D. Larbalestier

- SuperPower Inc. – Drew Hazelton

- U.S. Magnet Development Program/Collaboration supported by DOE Office of Science, Office of High Energy Physics, Office of Fusion Energy Sciences
  - L. Cooley at ASC/FSU
  - J. DiMarco at FNAL
  - C. Myers and M. Sumption at OSU