Develop high-field accelerator magnet technology using REBCO CORC® conductors

Coated Conductors for Applications
Virtual Workshop 2021

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Acknowledgment

- **U.S. Magnet Development Program**
  - ASC: D. Abramov, L. Cooley, A. Francis, X. Hu, D. C. Larbalestier
  - BNL: A. Ben Yahia, R. Gupta
  - FNAL: J. DiMarco, V. Kashikhin, V. Lombardo

- **Advanced Conductor Technologies**
  - D. van der Laan and J. Weiss

- **SuperPower**
  - D. Hazleton, Y. Zhang

To study the origin of the Universe, circular colliders need stronger magnetic fields to collide particles at higher energy.

\[ E \propto B \cdot R \]

Beam energy [TeV]  
Dipole field [T]  
Radius of beam trajectory [km]

Superconducting magnets are the only choice

- Rossi and Bottura, Superconducting Magnets for Particle Accelerators, \textit{Rev. Accelerator Sci. and Tech.}, 2012

Images courtesy of CERN
We need HTS to generate dipole fields beyond 16 T

Barletta et al., *NIMA, 2014*
Gourlay, *NIMA, 2018*
Various programs successfully developed accelerator magnets using REBCO tapes – examples from Japan, Korea and Russia

- Kyoto Univ., KEK, NIRS, Tohoku Univ., and Toshiba: saddle-shaped coil for medical applications
- KEK, NIMS and Fujikura: a REBCO sextupole magnet for superKEKB
- IBS, KERI, Changwon National Univ.: a REBCO quadrupole magnet used in a heavy-ion accelerator
- IHEP and SuperOx: a dipole magnet

The EuCARD and EuCARD2 collaborations, led by CERN, significantly advanced the high-field REBCO accelerator magnet technology based on multi-tape REBCO cable conductor

- EuCARD demonstrated a REBCO dipole field of 5.4 T at 4.2 K with a double-tape conductor

- EuCARD2 demonstrated accelerator-quality REBCO dipole magnets using Roebel cable, reached 4+ T dipole field at 4.2 K

The U.S. Magnet Development Program, supported by DOE Office of High-Energy Physics, is addressing the technology needs for future high-field accelerator magnets, including REBCO.

### A long-range R&D program

<table>
<thead>
<tr>
<th>Year</th>
<th>Nb3Sn &amp; HTS Magnets</th>
<th>Technology &amp; Conductor Development</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>Stress-managed Nb3Sn - effect on training &amp; degradation</td>
<td>Dev. of materials, components, diagnostics, protection</td>
</tr>
<tr>
<td>2021</td>
<td>Explore field &amp; aperture limits of stress-managed magnets</td>
<td>Continued developments in diagnostics; integrated systems</td>
</tr>
<tr>
<td>2022</td>
<td>HTS coil design &amp; technologies developments</td>
<td>Development &amp; study of high-performance Nb3Sn</td>
</tr>
<tr>
<td>2023</td>
<td>Demonstration of 20+T HTS/LTS &amp; performance optimization</td>
<td>HTS wires/tapes development &amp; understanding; cable developments</td>
</tr>
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</table>

CCA 2021, Develop high-field REBCO accelerator magnets using CORC® wires
The MDP is collaborating with industry and university partners to make REBCO magnets with increasing dipole fields in the coming years to address several driving questions:

- How to make REBCO dipole magnets and what kind of multi-tape cables works best?
- What is the magnet performance and required conductor performance? What issues limit the magnet performance? How to address them?
- What is the maximum dipole field a REBCO magnet can generate?
- What are the impacts on magnet community and user community?

Overarching goal: REBCO dipole magnets to enable 20 T dipole field at LHe temperature
We started using the round CORC® wires as a magnet conductor

• CORC® wire is a promising conductor configuration
  o Multi-tape cable. High current, O(10 kA), 4.2 K
  o Isotropic for magnetics and mechanics

• Enabling characteristics of commercial tapes from SuperPower
  o Thin substrate, 30 µm currently
  o Narrow tape, 2 mm currently
  o High $I_c$ at 4.2 K, background fields
We are investigating three different dipole magnet concepts featuring stress management for high-field applications.

- **Common coil**
  - van der Laan and Gupta, *EUCAS19*, supported by a DOE STTR program

- **Conductor On Molded Barrel (COMB)**
  - Kashikhin *et al.*, *IPAC19*

- **Canted cosθ (CCT)**
  - Wang *et al.*, *SuST, 2018*
Together with industry partners, we develop CORC® CCT magnets as a technology vehicle towards 5 T and beyond

- Develop dipole magnets with increasing fields and complexities
  - C1, 1.2 T, 2017. Demonstrated initial concept
  - C2, 2.9 T, 2019. Used metal mandrel with Stycast impregnation
  - C3, target 5 T at 2022. Develop magnet technology towards higher fields
  - We also have a road map beyond 5 T

Strongly coupled magnet/conductor work provides effective feedback to conductor development based on magnet performance

CCA 2021, Develop high-field REBCO accelerator magnets using CORC® wires
C1: first attempt to make a magnet with 15 m long CORC® wires

- 2016 – 2017
- 70 mm ID, 94 mm OD, 0.5 m long
- 1 T designed dipole field at 4.2 K at 4 kA
- 3D printed plastic Bluestone® mandrels
- No impregnation
- Magnet used 30 m long 16-tape CORC® wire
  - 16-tape architecture; prioritized low technical risk over high transport performance
  - 25 mm minimum bending radius
  - 1.3 km of 2 mm wide SuperPower tapes with 30 µm substrates

Ref: SuST, 2019
Careful winding and handling two magnet layers

Test winding with Cu dummy wire

A short video on the winding process

C1 magnet on testing header
C1 generated 1.2 T dipole field at 4.2 K, a first successful step for CCT magnet using REBCO conductor

- Inner layer transitioned at 81% of prediction
- No obvious or significant defect over 30 m long CORC® wires
C2: generate 3 T with longer conductors, metal mandrels and Stycast to constrain the conductors

- 2018 – 2019
- 65 mm ID, 127 mm OD, 0.6 m long
- 3 T designed dipole field at 4.2 K at 6.4 kA
- Aluminum bronze machined mandrels
- Painted Stycast after winding
- Magnet used 100 m long 30-tape CORC® wire
  - 5 km of 2 mm wide SuperPower tapes with 30 µm substrates
  - 30 mm minimum bending radius

Ref: SuST 2021
C2 used another record length of CORC® wire: issues were encountered and addressed

- The transport measurement at ASC/FSU showed some tapes with lower than expected performance
- ACT increased tape count in CORC® wires to boost the wire performance

<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><strong>C2-L4</strong></td>
<td><strong>28</strong></td>
<td><strong>3.67</strong></td>
<td><strong>57</strong></td>
<td><strong>2.8</strong></td>
<td><strong>35</strong></td>
</tr>
</tbody>
</table>

- Layer 4 wire has the lowest field, opportunity for grading
Layer 4 shows the lowest performance at 77 K – an interesting mystery

Each layer tested individually

- Layer 4 wire contains high- and low-pinning tapes
- Local current sharing between the tapes or not?

After assembling all layers together

- ~ 30% $I_c$ reduction due to higher fields
- Potential to perform at 4.2 K

CCA 2021, Develop high-field REBCO accelerator magnets using CORC® wires
Reproducible transition behavior allowed a controlled increase in the maximum current to probe the true performance of C2 ramp 4.

- Increasing the threshold for quench detection
- Conductor $J_e = 460$ A/mm$^2$
Reproducible transition behavior allowed a controlled increase in the maximum current to probe the true performance of C2

- Increasing the threshold for quench detection
- Conductor $J_e = 520$ A/mm²
Reproducible transition behavior allowed a controlled increase in the maximum current to probe the true performance of C2

- Increasing the threshold for quench detection
- Conductor $J_e = 530$ A/mm$^2$
Reproducible transition behavior allowed a controlled increase in the maximum current to probe the true performance of C2

- Reached 2.9 T dipole field at 6.3 kA
- Conductor \( J_e = 550 \text{ A/mm}^2 \)
- Also paid a price by pushing for higher current ...
Layer 1 conductor degraded during the thermal runaway at a $J_e$ of 550 A/mm$^2$ at 4.2 K

Ramp 14 showed an $I_c$ degradation by 5% after the thermal runaway in Ramp 13

The 77 K test following the 4.2 K test also confirmed the $I_c$ degradation in Layer 1
Joule heating during thermal runaway possibly degraded the conductor: try to avoid thermal runaway.

V(t) traces for Ramps 12 and 13

What could be the peak wire temperature?

15 cm or shorter of heated section is possible due to the slow propagation of normal zones.
In addition to a 2.9 T field, C2 also generated several open questions. We will address them with next magnets.

- Why did Layer 1 started transitioning at 4.8 kA, 73% of the short-sample prediction?
  - Expected or conductor degradation?
- What caused the low performance of Layer 4?
  - Mix of tapes of different $I_c$ values?
- Where is the heat/voltage generated?
  - Distributed sensing?
- How can we improve for the next magnet?
C3: generate 5 T, push for higher conductor performance, and start probing the impact of electromagnetic stresses on conductors

- 2020 – 2023
- 65 mm ID, 160 mm OD, 0.9 m long
- 5 T designed dipole field at 4.2 K at 7 kA
- Aluminum bronze machined mandrels
- Use Stycast to mechanically couple all layers
- Magnet will use 181 m long 30-tape CORC® wire
  - 10 km of 2 mm wide tapes with 30 µm thick substrate
  - 30 mm minimum bending radius
Ongoing conductor procurement becomes one of the growing pains

• We ordered commercial REBCO tapes with a specification on the minimum $I_c$: 350 A at 4.2 K, 6 T

• Non-trivial to meet the specification, even though earlier commercial tapes demonstrated the specified performance

• An excellent opportunity for us to step up to the challenges and grow

• Highlights the strong impact of conductor vendors in REBCO magnet technology development. How can we better help each other?
The US MDP is developing REBCO magnet technology to enable 20+ T dipole magnetic fields

- Critical component of a long-range R&D program supported by DOE Office of Science

We started working with CORC® wires with a constant need of higher current, 10 – 20 kA, at a smaller bending radius, 10 – 15 mm, at 4.2 K

- Higher tape $I_c$
- Thinner and narrower tapes: substrate thickness of 20 – 25 µm

Making magnets with incrementally higher fields is critical to the technology development, and eventually market cultivation

- Most effective for magnet builders and conductor manufacturers to work together
More flexible high-current REBCO wires are critical to demonstrate higher dipole fields

- Thinner tapes are the key
  - They allow smaller CORC® bending radii and tilt angles → higher dipole fields
  - 30 µm substrate → 25 µm corresponds to 25% increase in $J_e$

- Increase pinning performance at 4.2 K

- The resulting tapes will have strong technology and market impact
  - Need to develop them now

CO reference
# Questions & Answers for Application Speakers

<table>
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<tr>
<th>Question</th>
<th>Answer</th>
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<tbody>
<tr>
<td>What are the biggest benefits of using super-conducting technology in your application? <em>(e.g. Efficiency, Weight, Size)</em></td>
<td>We develop high-field magnets for accelerator and fusion applications. The benefit is higher fields in compact magnets without significant resistive heating or energy consumption.</td>
</tr>
<tr>
<td>What are the factors that prevent your application from moving to the commercial phase? <em>(e.g. Cost, Reliability, Productivity, Performance, Related Laws, Standardization, Infrastructure)</em></td>
<td>We are still learning how to make magnets and magnet conductors. The magnet performance is yet to be demonstrated and understood.</td>
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</tbody>
</table>
| What do you require from the coated conductors in your application? *(e.g. Low Cost, High Ic@T & B, Low AC loss, Long Piece Length, Reliability, Applicability for Coiling, Mass Production Ability)* | **1st** Engaged conductor partner as part of the magnet development that can quickly respond magnet needs, assuming an equally responsive counterpart on the magnet side  
**2nd** Keep pushing the conductor geometry and performance: robust thinner and narrower tapes with higher $I_{c}$ @ T and B  
**3rd** Consistent and reproducible geometry and performance of raw tapes and resulting magnet conductors/cables |
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</table>
| What do you require from the other fundamental technologies in your application? (e.g. Superconducting Joint, Persistent Current Switch, Light Weight Cooling System with High Efficiency) | • Flexible multi-tape cables; cable of cables  
• Low-resistance joint  
• Impregnation technique without degrading conductors and then with high radiation tolerance  
• Distributed sensing of temperature and perhaps strain and magnetic field  
• Characterize performance of 10 – 100 m long multi-tape cables: geometry, transport current, local weak spots in tapes  
• Technology enabling the conduction-cooled operation of magnets with an operating current of the order of 10 kA, e.g., cryocoolers, current leads |