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AMO EERE: DE-EE0007872

Recent Progress in Conductor-On-Round-Core (CORC®) conductor and magnet development

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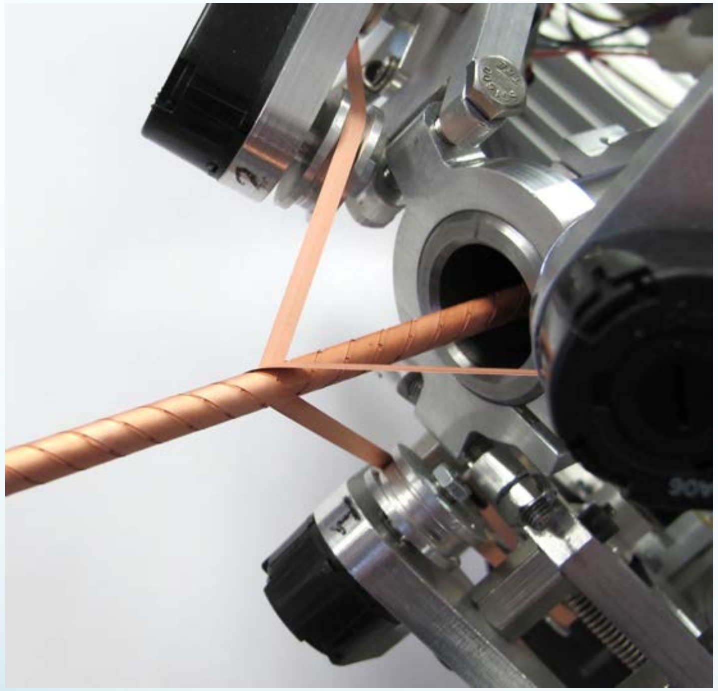
LTSW 2023

CORC® production

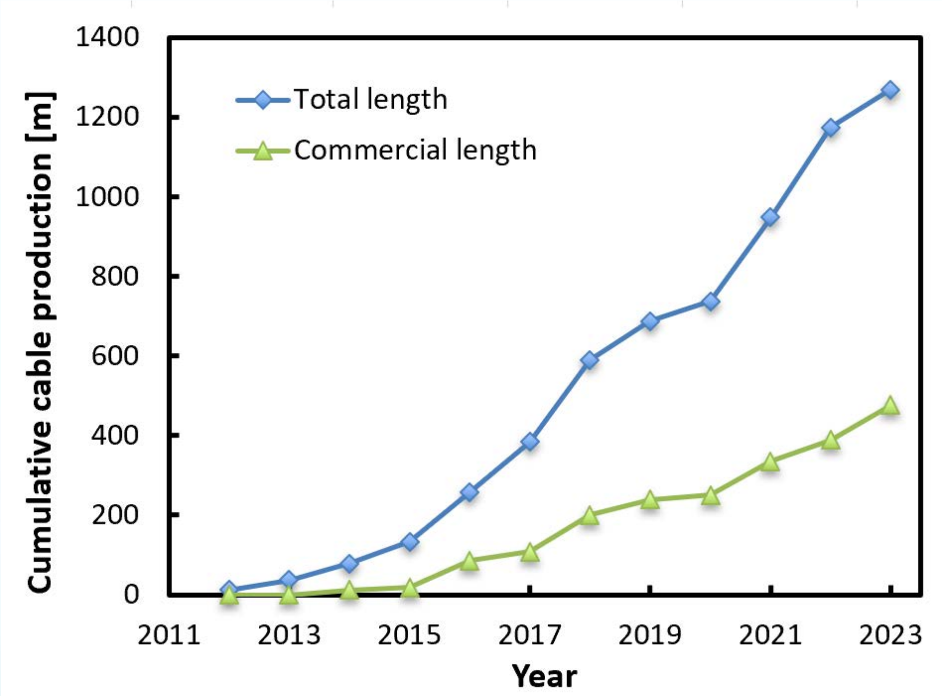
Winding of long CORC® cables and wires with custom machine

- Accurate control of cable layout
- Long lengths possible (> 100 meters)
- **Longest continuous CORC® cable: 42 meters (30 tapes)**
- I_c retention after winding 95-105 %



Cumulative CORC® production

- Over 1,300 meters since 2012
- Over 400 m for commercial orders



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Recent advances in CORC® wires and cables

Where are the limits and how do we push them?

High resilience of CORC® cables against operating stress

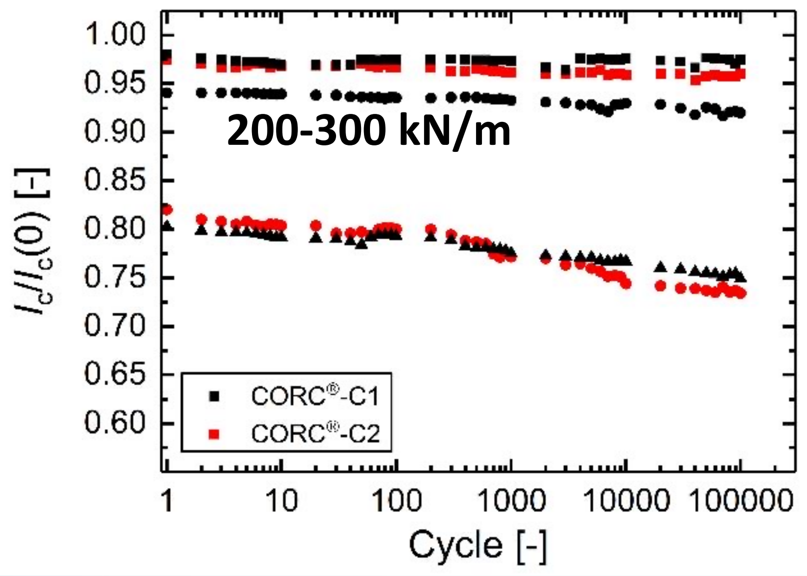
CORC® cable under transverse compressive load

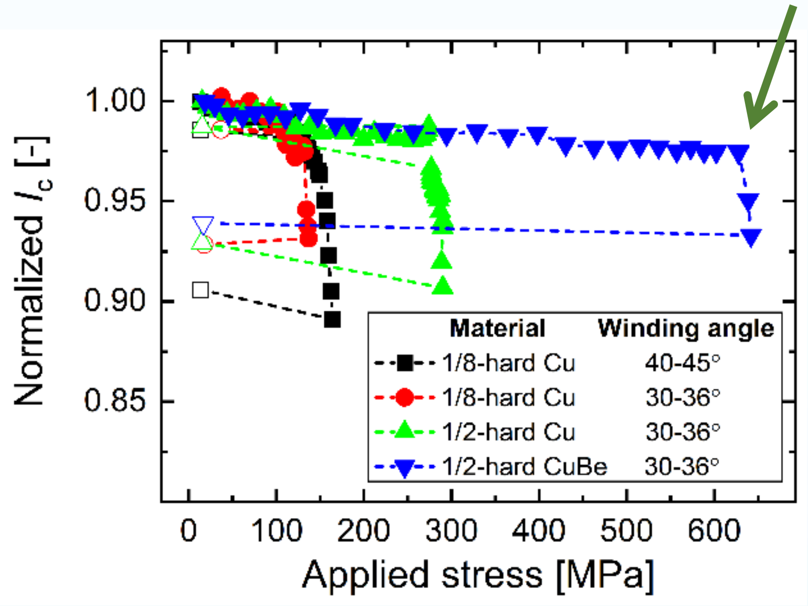
- Is independent of orientation
- Has shown high resilience against cyclic loading

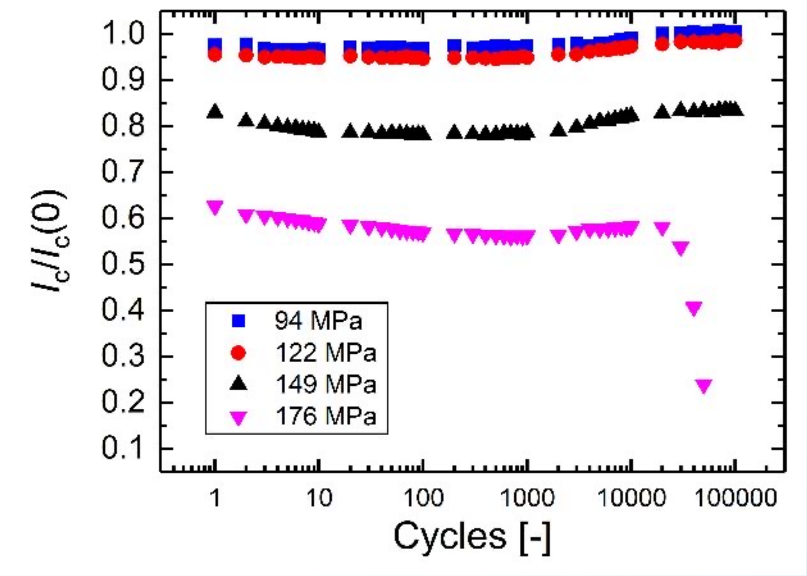
CORC® cable under axial tensile strain

- Axial strength is driven by core material
- Has shown high resilience against cyclic loading

1,036 lbs!







van der Laan, D.C. et al, *Superconduct. Sci. Technol.* **32** 015002 (2019)
van der Laan, D.C. et al, *Superconduct. Sci. Technol.* **32** 054004 (2019)

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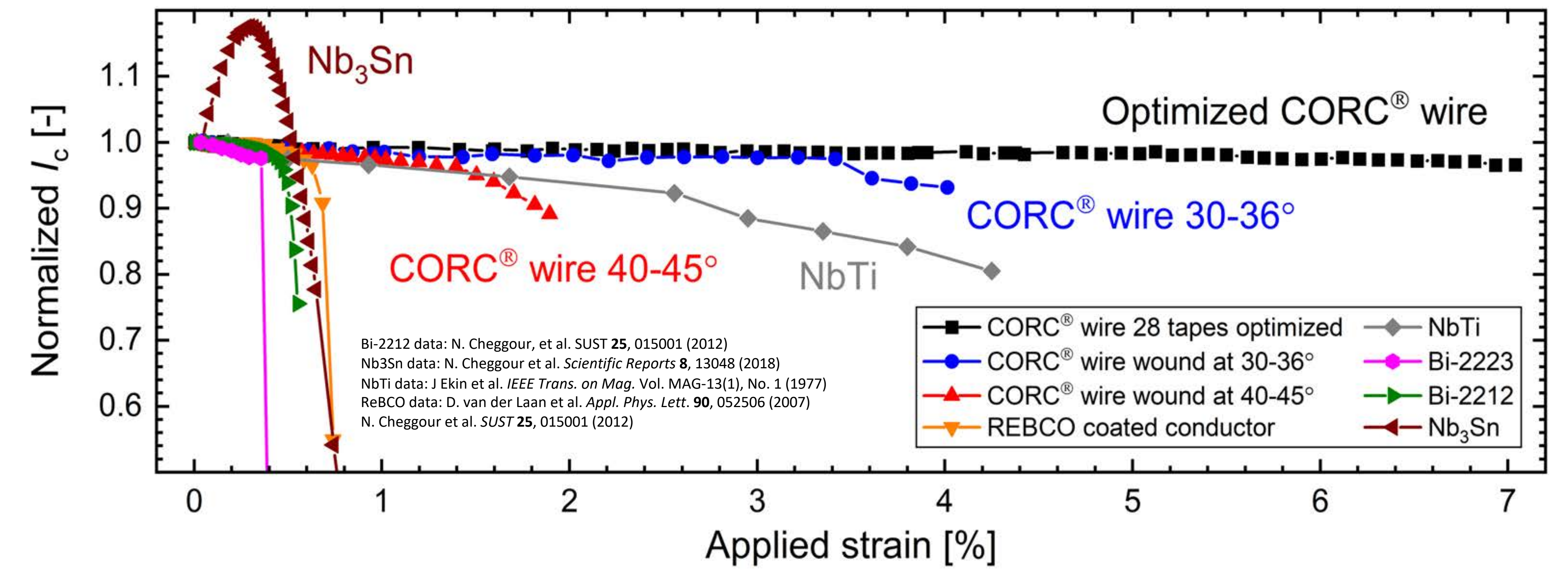
High irreversible tensile strain limits beyond 7 % achieved in CORC®

- Comes from uncoupling REBCO layer from the former that makes up the core of the CORC®
- **Tapes wound into a helical fashion extend as springs, allowing large elongations before degradation**
- **Irreversible strain limit of CORC® depends mainly on tape winding angle**



Laan at all. High-temperature superconducting CORC® wires with record-breaking axial tensile strain tolerance present a breakthrough for high-field magnets," *SUST 2021*
doi: 10.1088/1361-6668/ac1aae.

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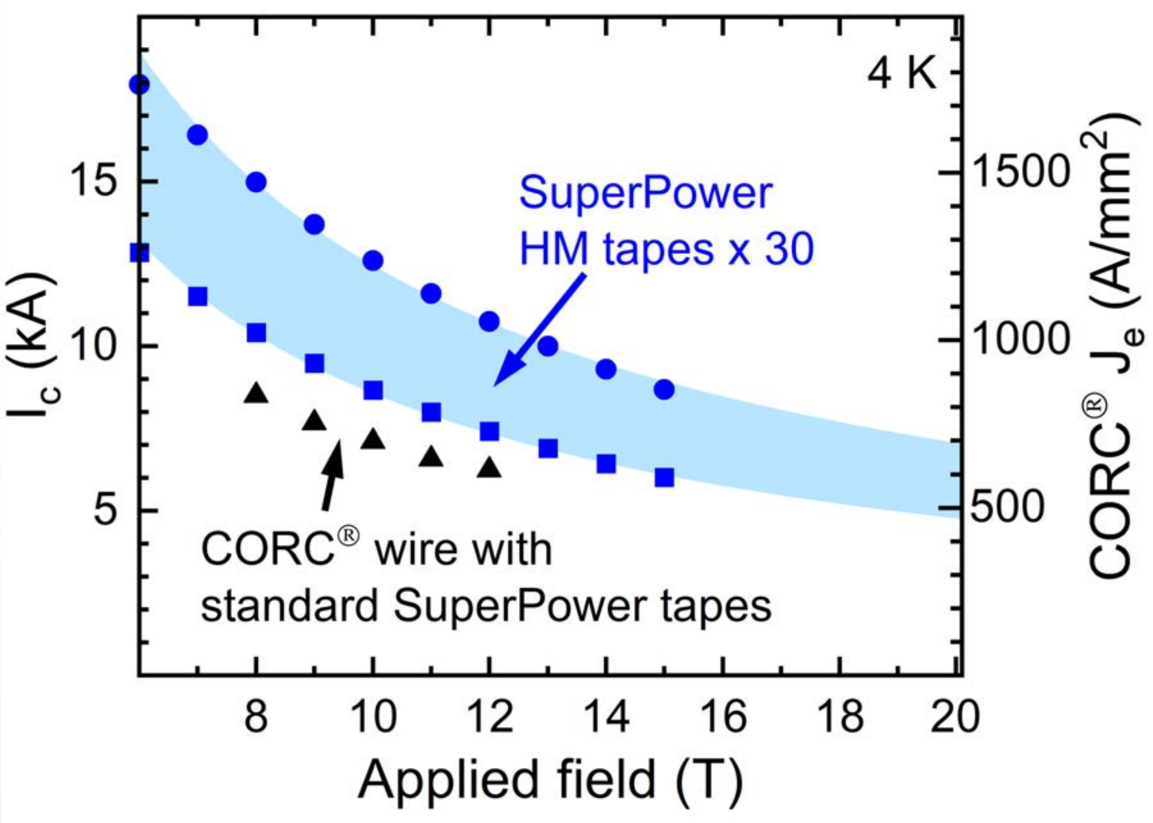
High-Mag (HM) tapes developed in 2020-2022

Performance of 3.6 mm OD 30-tape CORC® wire based on tapes with 30 μm substrate



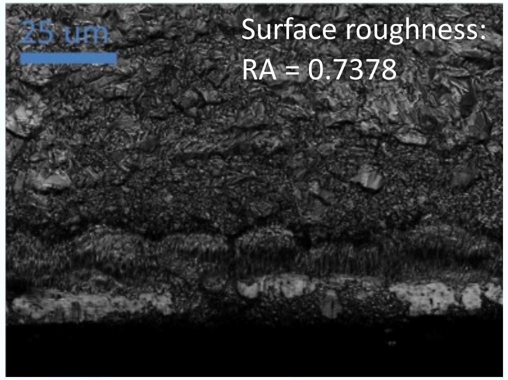
New high-pinning 2 mm wide tapes offer 20-40 % performance increase

Currents at 20 T in the range of 5-7 kA at 500-700 A/mm² for a 3.6 mm OD CORC® wire

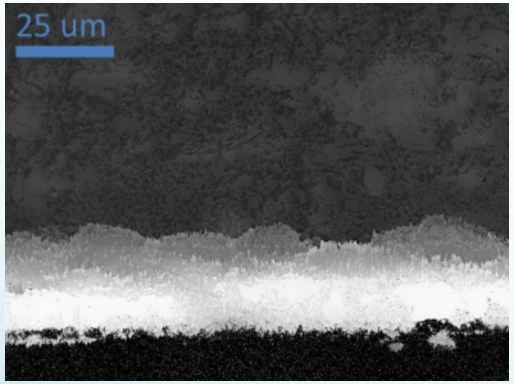
Increased performance also opens the door for CORC® cables to reach even higher currents > 20 kA at 20 T

Extensive effort to evaluate recent REBCO tapes

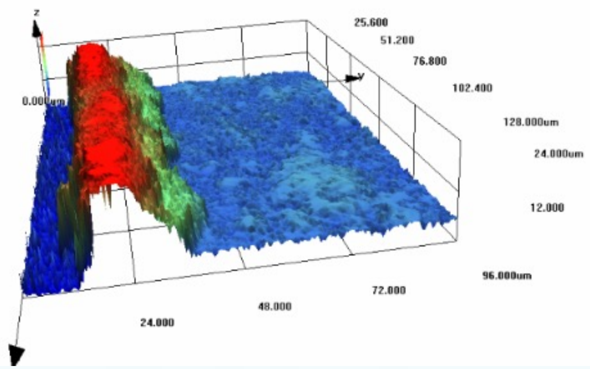
- Bending performance of CORC® wires has varied significantly
- For some CORC® wires, bending to 60 mm diameter resulted in 35 – 40 % degradation, which is unacceptable for HEP applications
- Cause seems to be varied surface roughness and presence of slitting burr that can affect bending performance



2021 – 2022 SCS-2030-HM tape



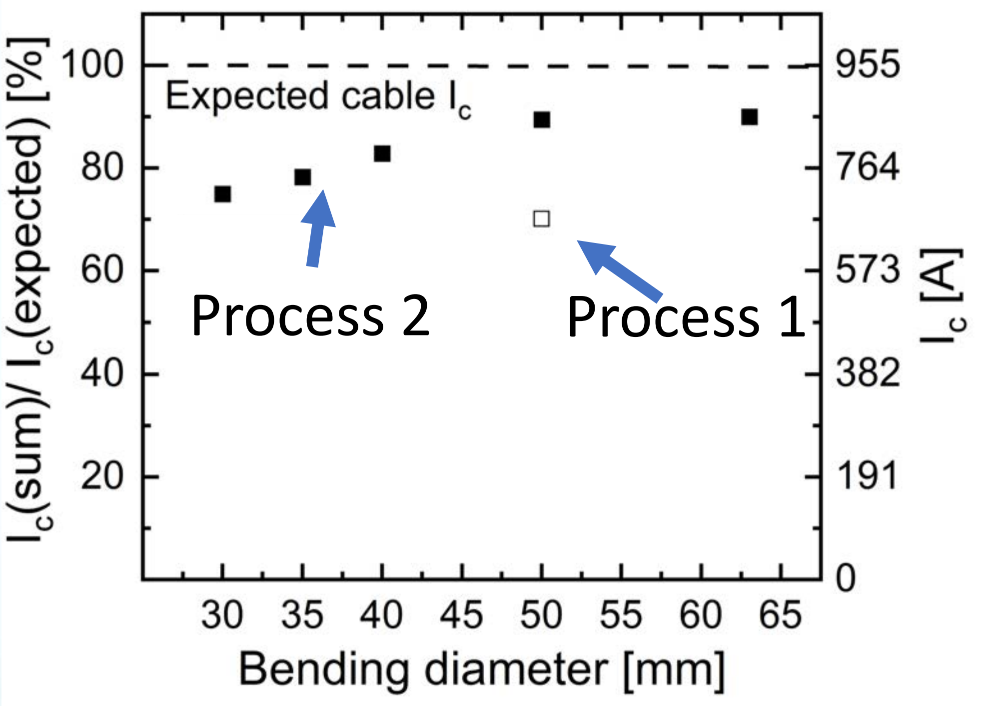
10-20 μm thick,
Intermittent burr



Height map

New cabling process had to be developed to retain CORC® flexibility

I_c as a function of bending a hairpin sample

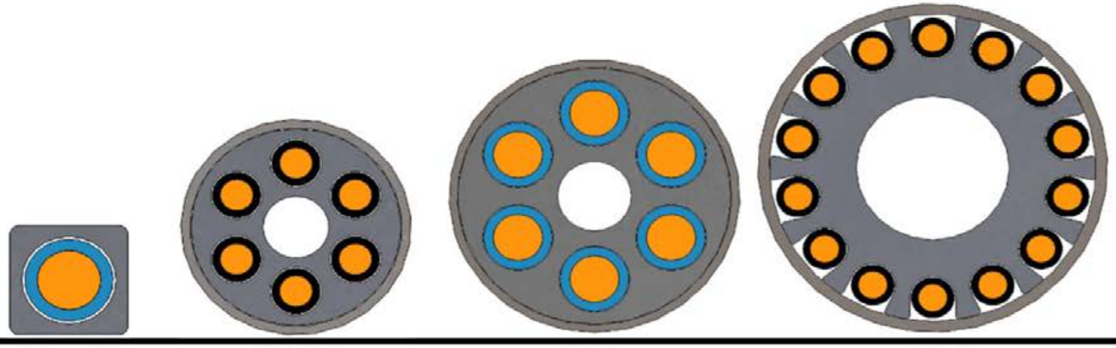


Recent advances in CORC® CICC

How do we build and test reliable high-current CICC for Fusion applications?

CORC® CICC development

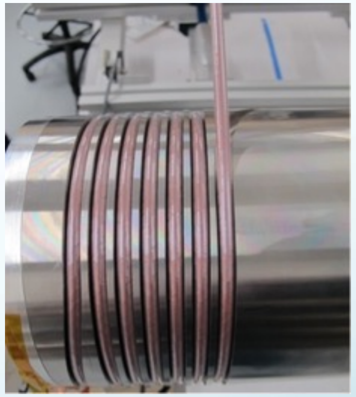
Different layouts being developed for magnet systems: Central solenoid, Toroidal, etc



CORC®-CICC size	[mm]	10 x 10	22.23	31.75	38.1
CORC® conductors	[-]	1 cable	6 wires	6 cables	14 wires
Tapes per conductor	[-]	42	30	42	30
Tape width	[m]	4	3	4	3
I_c (4.2 K, 20 T)	[kA]	13.4	43.0	80.3	100.4
J_e (4.2 K, 20 T)	[A/mm^2]	133.8	110.8	101.4	88.0
I_c (20 K, 20 T)	[A]	6.7	21.5	40.1	50.2
J_e (20 K, 20 T)	[A/mm^2]	66.9	55.4	50.7	44.0

HTS Cable Conductor for Compact Fusion Tokamak Solenoids, Zhai et al.
IEEE doi: 10.1109/TASC.2022.3167343

Tests of straight samples in background field at SULTAN test facility planned as well as subscale CS coil tests



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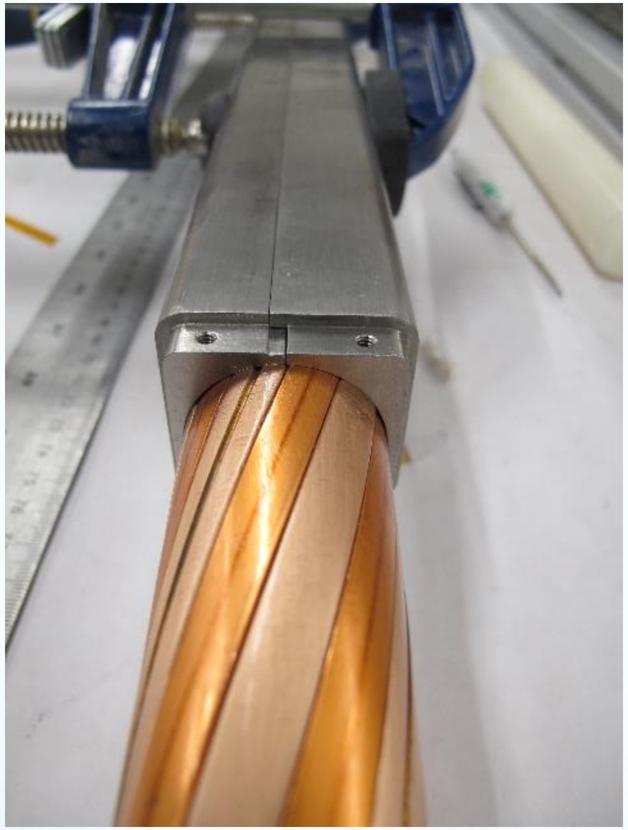
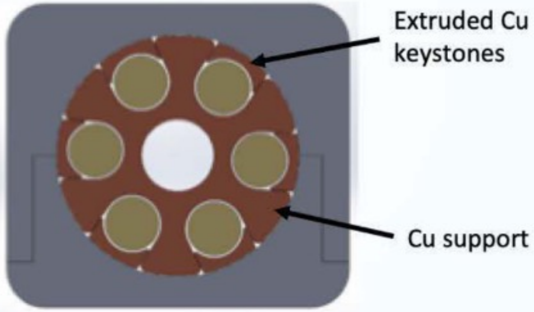
80 kA CORC® CICC to be tested in Sultan



Preparation of 6x1 with distributed conductor support

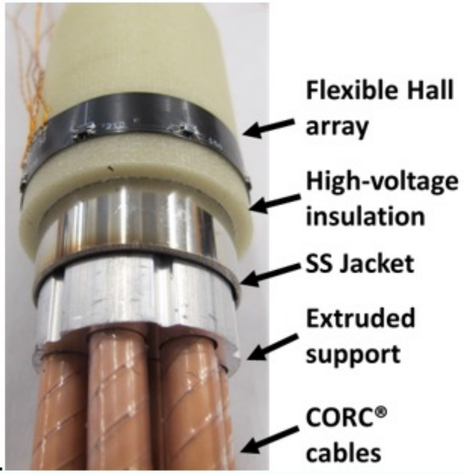
- Six 36-tape CORC® cables
- Estimated testing by July 2023
- Results by MT/EUCAS conferences

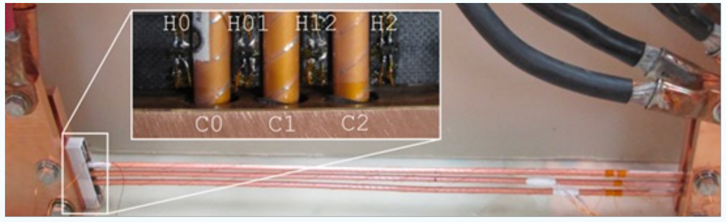
Sample #4



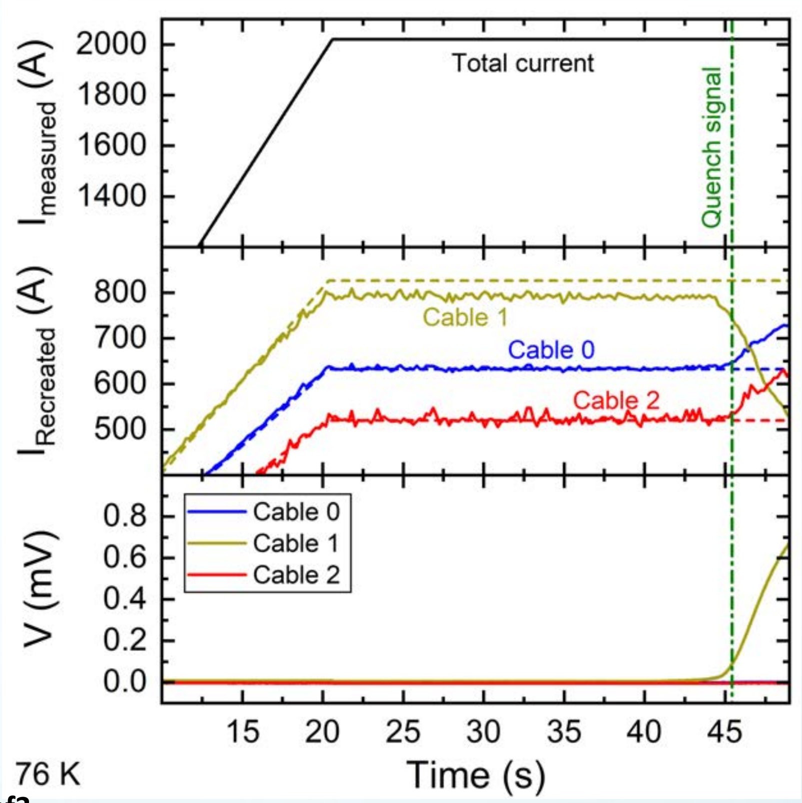
Hall array based quench detection for CICC

Designing Hall arrays for various cable and CICC geometries to monitor current distribution





Real-time inverse Biot Savart current recreation using Hall array data for a CORC® CICC triplet



J. D. Weiss, et al Quench detection using Hall sensors in CICC for fusion applications doi: 10.1088/1361-6668/abaec2.
R. Teyber, et al CORC® cable terminations with integrated hall arrays for quench detection doi: 10.1088/1361-6668/ab9ef3.
R. Teyber, et al Current distribution monitoring in fusion magnets doi: 10.1038/s41598-022-26592-2.

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Recent advances in CORC® magnet development

How do we develop HTS magnet technology that is innovative and useful?

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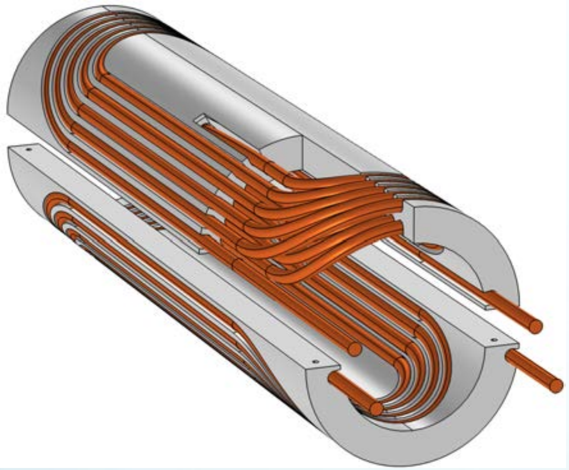
HTS Accelerator magnets: towards 20 T and beyond

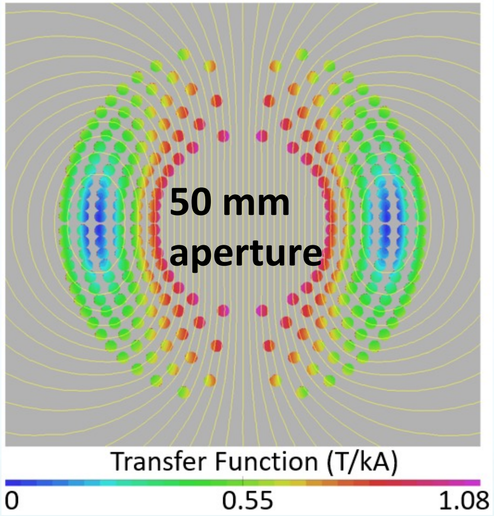
Canted Cosine Theta magnets in collaboration with LBNL

C2 magnet: 4-layer 2.9 T dipole demonstrated
C3 magnet: 6-layer 5 T dipole under development

COMB magnet being develop by FermiLab



120 mm OD Cos-Theta insert



Both concepts want more flexible CORC® wires, with bending radius below 30 mm desired

- Tests and FEM modeling show flexibility in CORC® is a function of substrate thickness, tape width, winding angle, and friction between tapes
- **A major effort to increase the bending flexibility of current production CORC® wires is under way at ACT**
- Insert magnets with conductor friendly bends are being proposed for high-field testing in the near term

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U.S. MAGNET DEVELOPMENT PROGRAM
Fermilab
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CORC® Common Coil insert magnets

CORC® Common coil insert magnets with large (>100 mm) bending radius

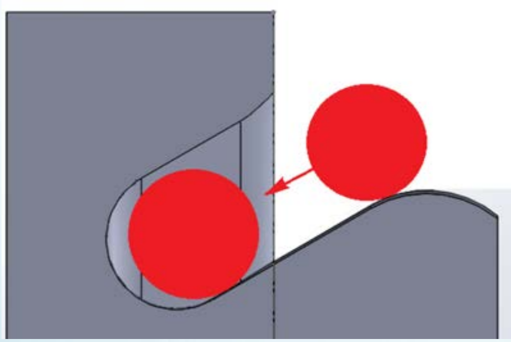
- Based on opposing racetrack coils wound from a high current CORC® cable
- Operated within the BNL 10 T LTS Common Coil outsert
- Powered: 1) separately at 5 – 6 kA (MDP coil), or 2) in series at 10 kA (STTR coil)

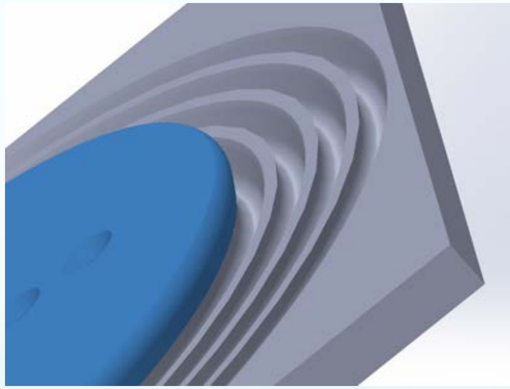
Winding technology for CORC® Common Coil inserts developed at CU/ACT

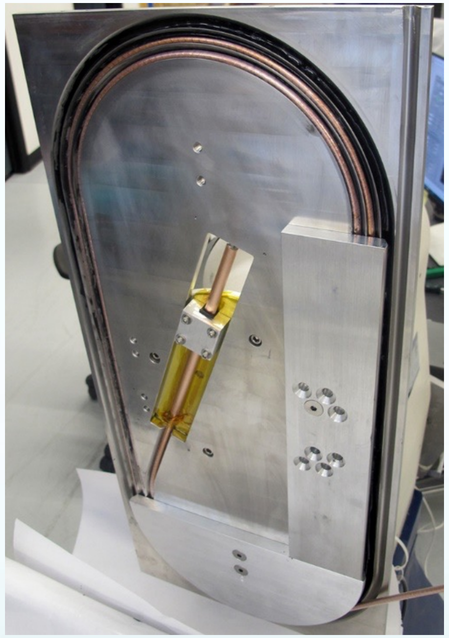
- Based on slated groove machined in pancake support plates
- Allows winding under tension while providing sufficient support

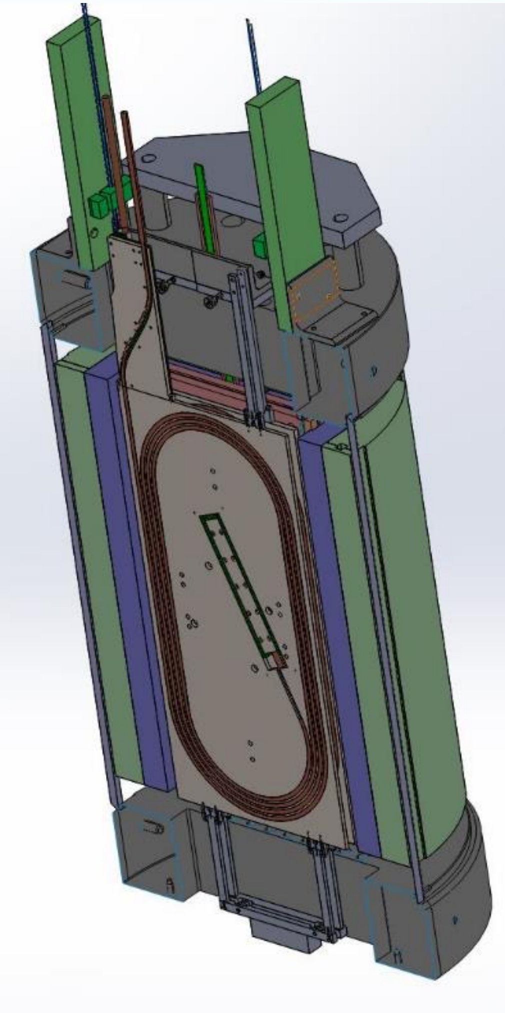
CORC® Common Coil manufacturing at CU/ACT

- MDP coil (2 single pancakes - 4 turns) – Wound and testing underway
- STTR coil (2 double pancakes - 14 turns)





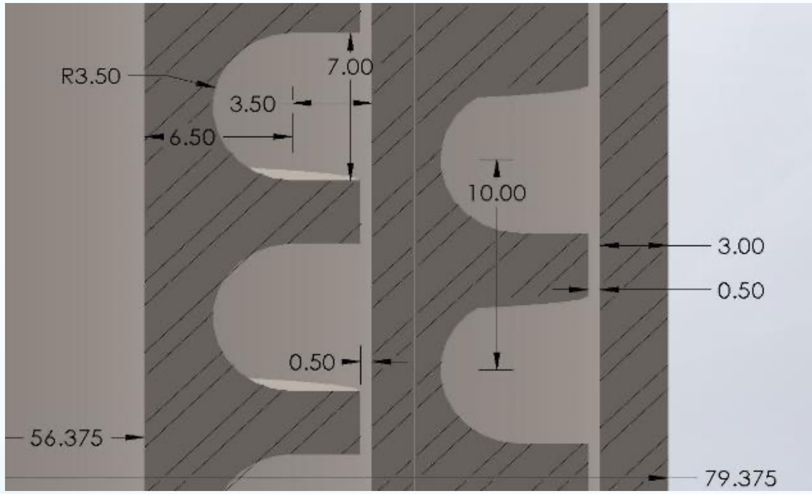


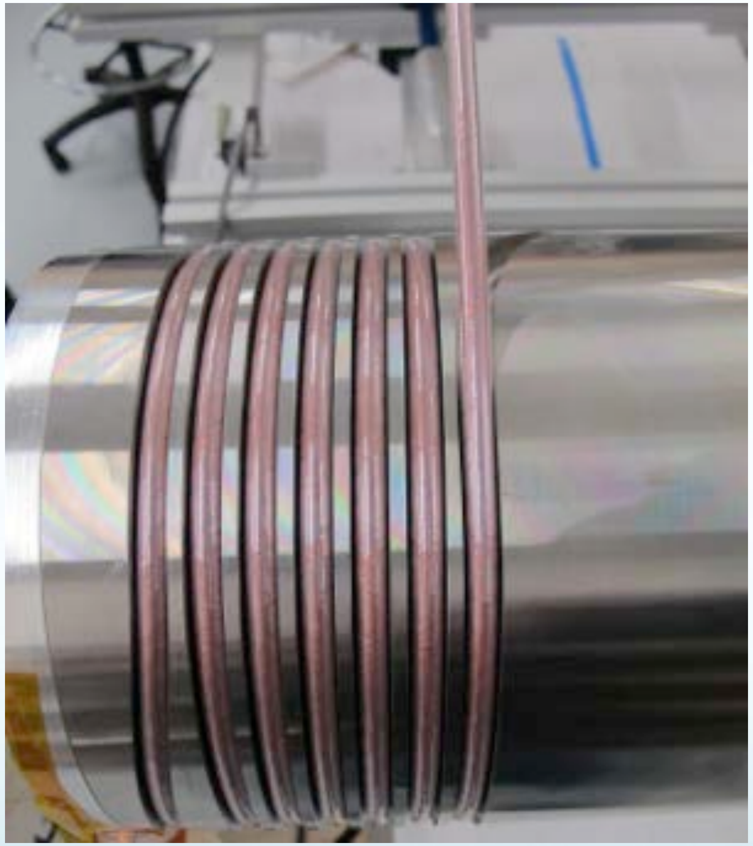


Development of prototype Ohmic Heating coil

First Ohmic Heating coil prototype based on CORC®

- Medium cable performance (I_c (16 T) 3.5 kA, J_e(16 T) = 150 A/mm^2
- 2-layers, 6 turns per layer, ID 119 mm, OD 159 mm, 60 mm height
- 6 mm thick cable in 7 mm groove
- Clearance of 1 mm results in about 1 % conductor strain





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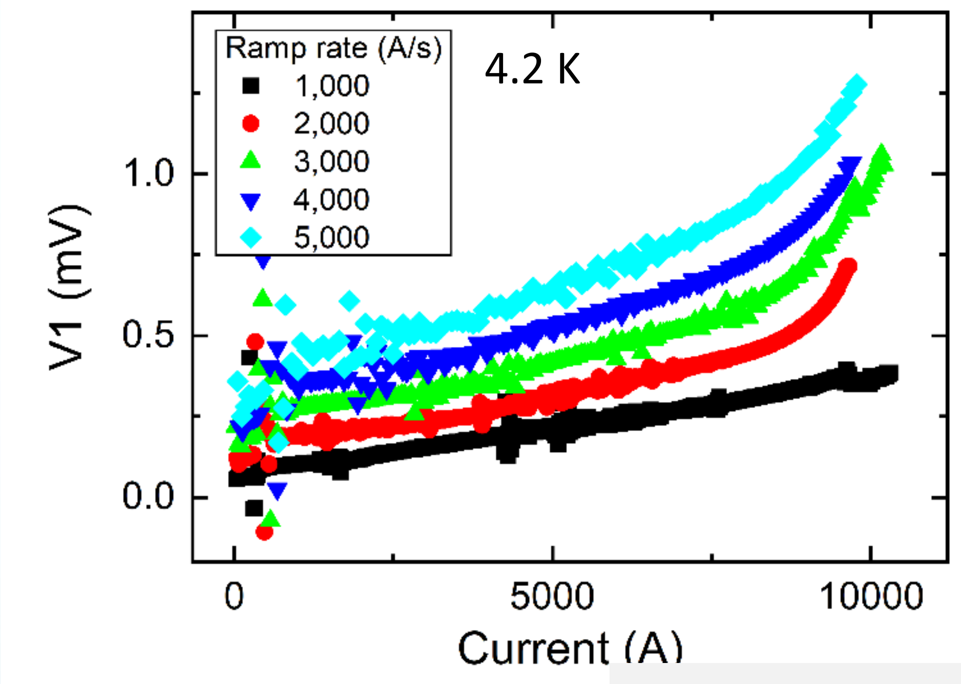
Testing of Ohmic Heating coil

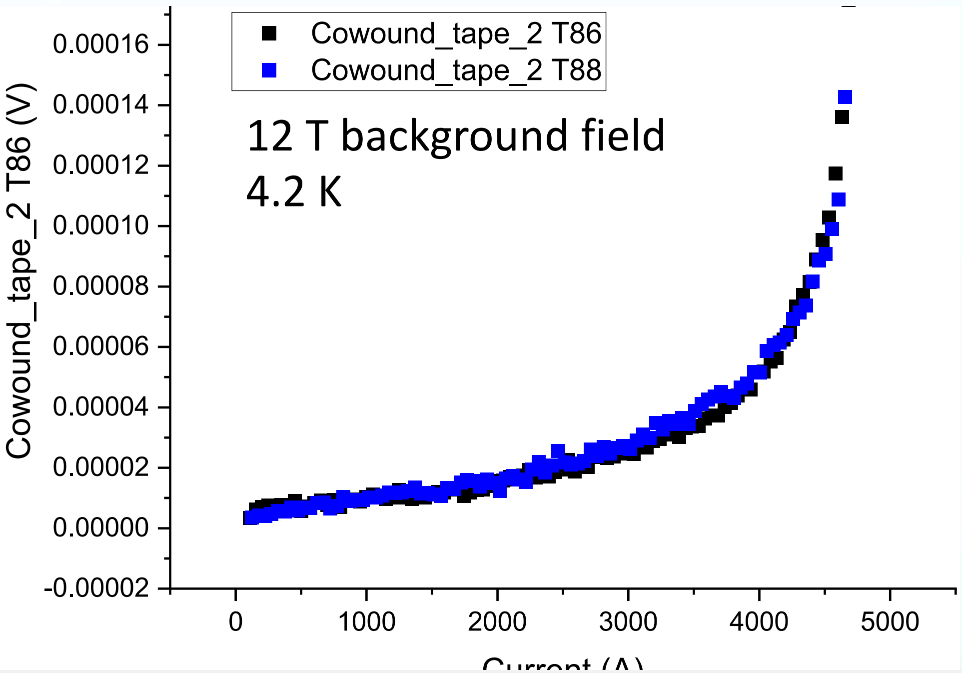
Testing done at ACT to high ramp-rates

- Current ramp rates up to 5 kA/s to 10 kA at 4 K
- Current distribution remained mostly homogeneous



Testing done at ASC-NHMFL: 14 T 160 mm outsert

- Repeated current ramping at 12 T into transition
- J_e 200 A/mm^2, JBr hoop stress 185 MPa
- No degradation after 68 stress cycles



Supported by DOE contracts DE-SC0014009, DE-SC0013723 and DE-SC0018125

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Next steps

- Prepare set of CORC® OH coils with higher current and current density to allow higher JBr stresses of 200 to 500 MPa
- Test higher elongation of cable: (1 – 2 % axial strain)

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Current sharing in CORC® cables

Can HTS cables with electrically coupled strands tolerate local strand-level dropouts, particularly when operated at elevated temperatures (20-77 K)?

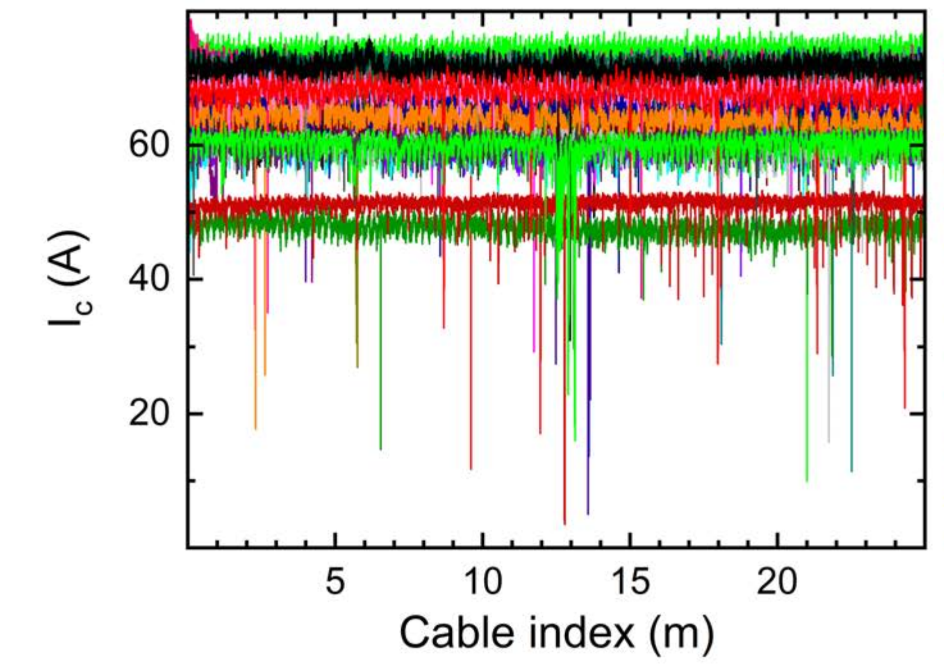
See **Virgina Phiffer's** thesis:
"EXPERIMENTAL INVESTIGATIONS OF TAPE-TO-TAPE CONTACT RESISTANCE AND ITS IMPACT ON CURRENT DISTRIBUTION AROUND LOCAL IC DEGRADATIONS IN CORC® CABLES" FSU 2023

Making use of REBCO tapes with variable I_c (VIC tapes)

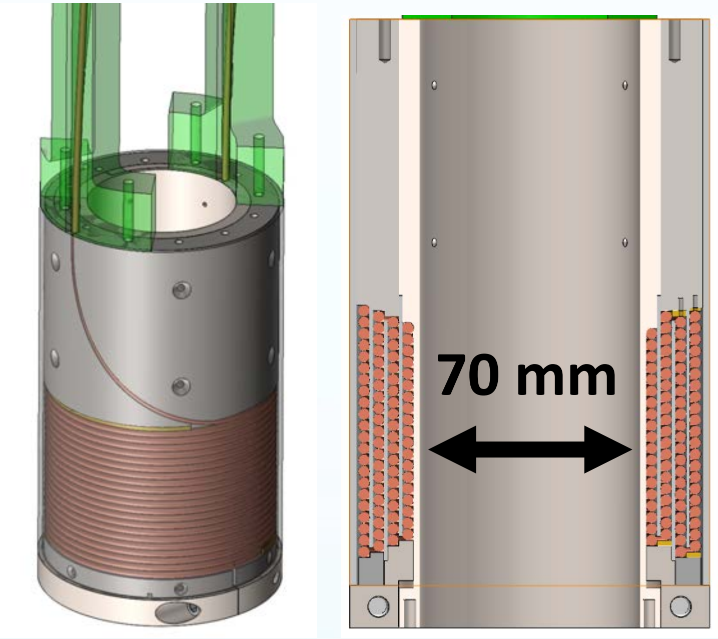
AMO funded project:

Cost-effective Conductor, Cable, and Coils for High Field Rotating Electric Machines

I_c vs location in CORC® wire with 27 tapes (2 mm wide)



82 turn Coil design



Coil winding at ACT

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ACT facility for high-current testing at 20 – 60 K

Facility details

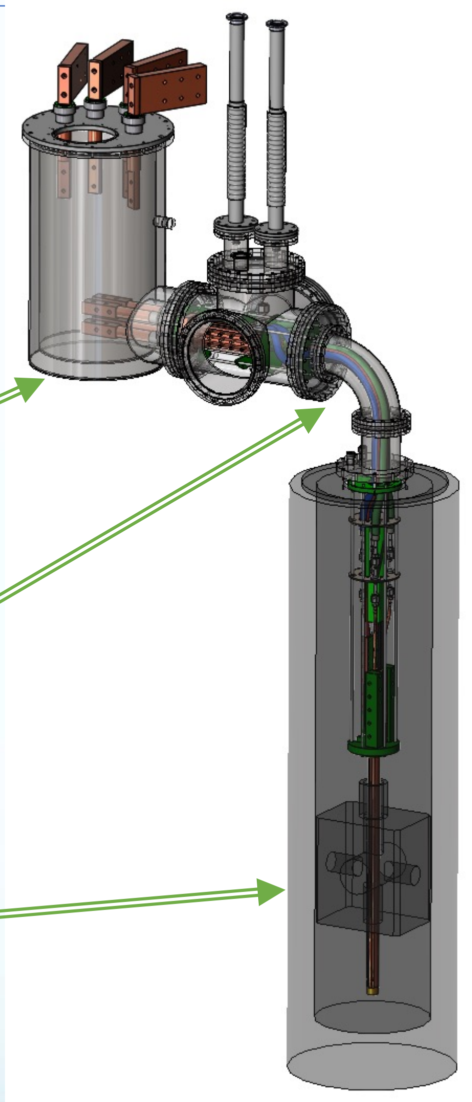
- Samples cooled with pressurized helium gas
- Liquid nitrogen pre-cooling of feeder cables
- Current capacity of 5 kA (continuous)
- Future expansion: 10 kA and 8 T magnetic field

Stirling GHe circulation system

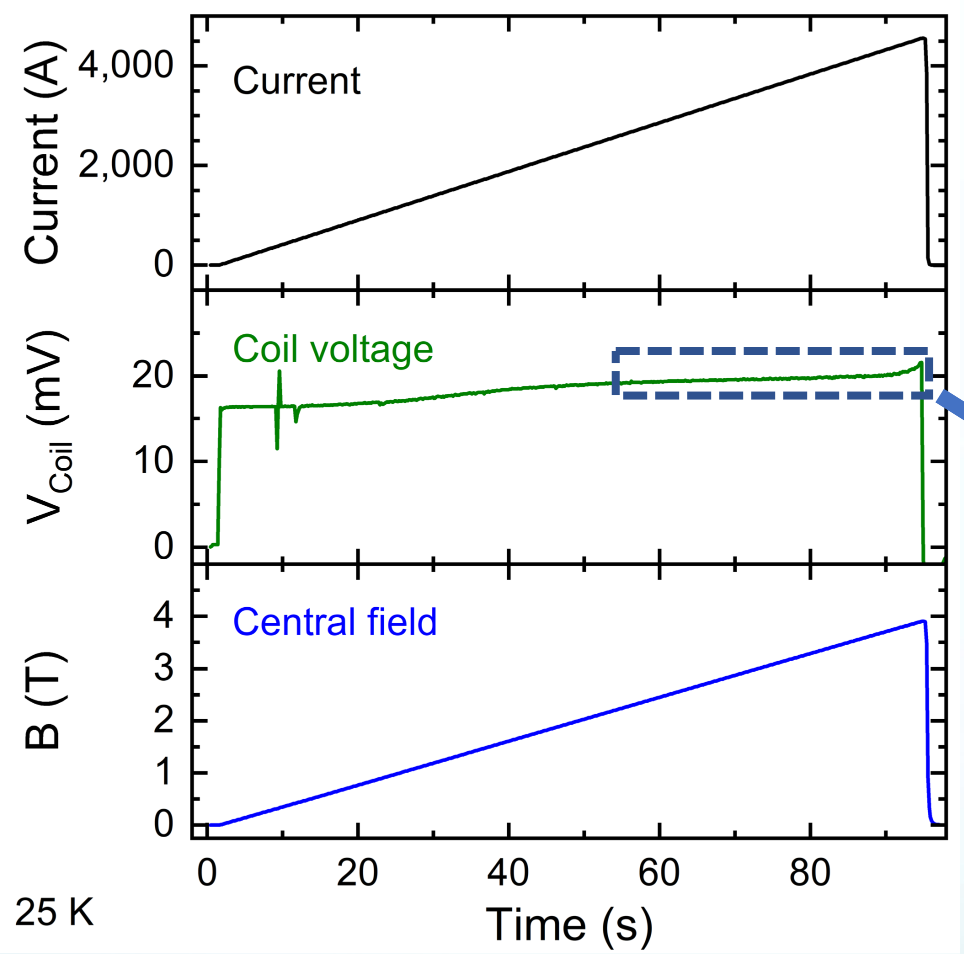
Liquid nitrogen pre-cooling

Superconducting CORC® feeder cables

Low-temperature sample space

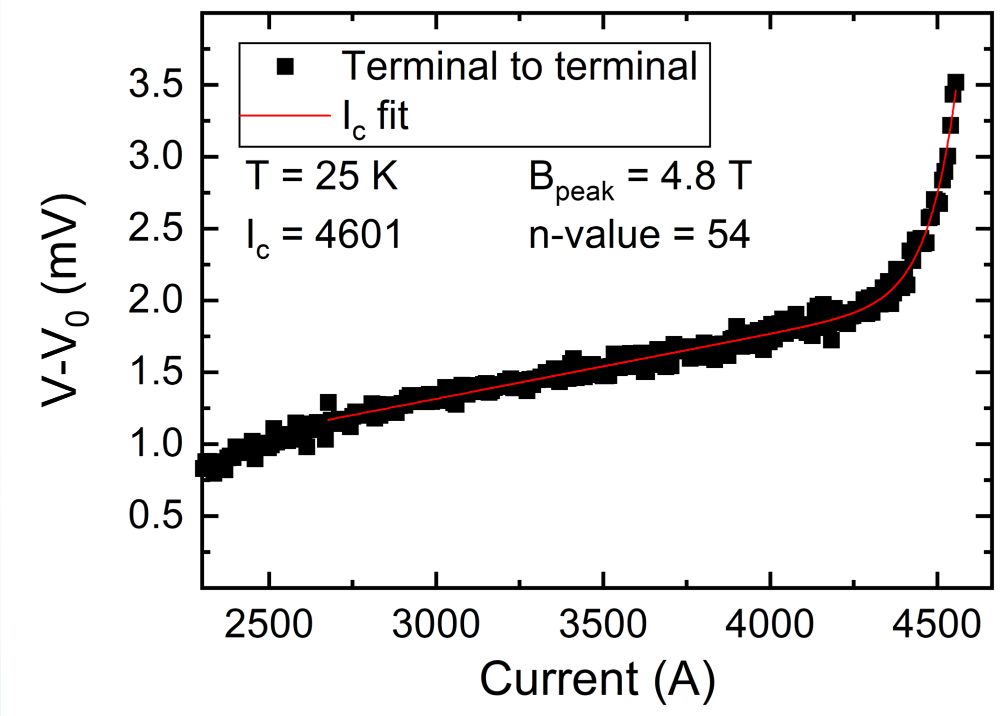


VIC coil performance limit determined at 25 K



- Coil was ramped into normal state at 50 A/s
- Peak field: 4.8 T on the conductor

superconducting to normal transition



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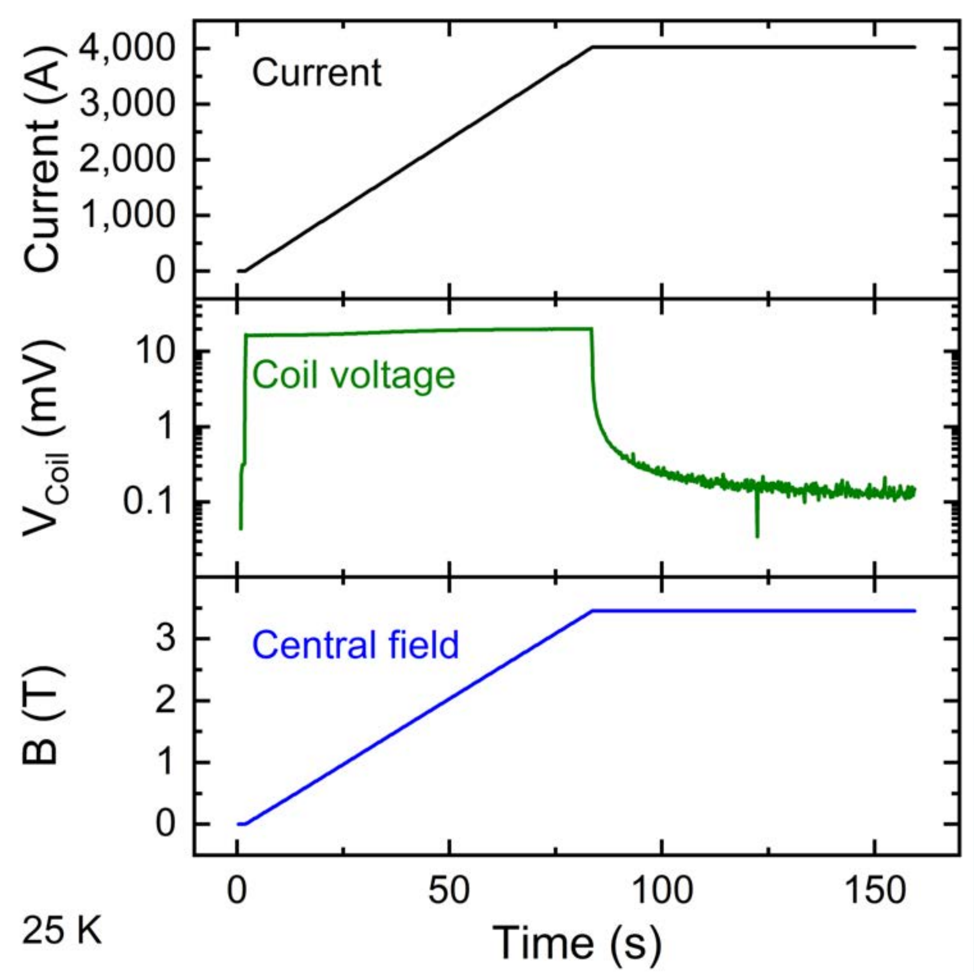
Steady state operation at 25 K close to I_c



- Coil was ramped to 4021 A (87% I_c) and current was held constant
  - This is a current density of 395 A/mm² (J_w = 243 A/mm²)
- Voltage over coil after inductive decay was 0.11 mV at held current of 4021 A
  - Power dissipation is 0.44 W as measured over the terminations

Next steps

- What if instead of dropouts associated with intrinsic defects, we incorporated tape-to-tape joints?
  - Would we get away from tape length limitations?

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Collaborative needs for CORC® development

Tape development

- Consistency still needs to be increased. **ACT is working actively with tape manufacturers to qualify tapes and identify where improvements are needed**
- Narrower widths (1 mm, 1.5 mm) could increase the flexibility of CORC® wires
- 20-25 μm thick substrates would hit the sweet spot in terms of size and J_e
    - Demonstrated value, but R&D effort of tape from commercial venders is stalled
        - Many challenges remain with tape handling of long lengths

CORC® development

- How do we work within the limitations of the REBCO that's currently commercially available?
- What variations in REBCO tape properties create challenges and how do we overcome them?
    - Pinning: Tapes are getting better, but batch-to-batch I_c variations are still on the order of 50 % or more
    - Geometry: Thickness variations across width and surface roughness can affect bending properties of CORC®
    - Mechanical properties: Some tapes **allow bending onto smaller formers**, allowing more compact CORC® to be wound. Why?

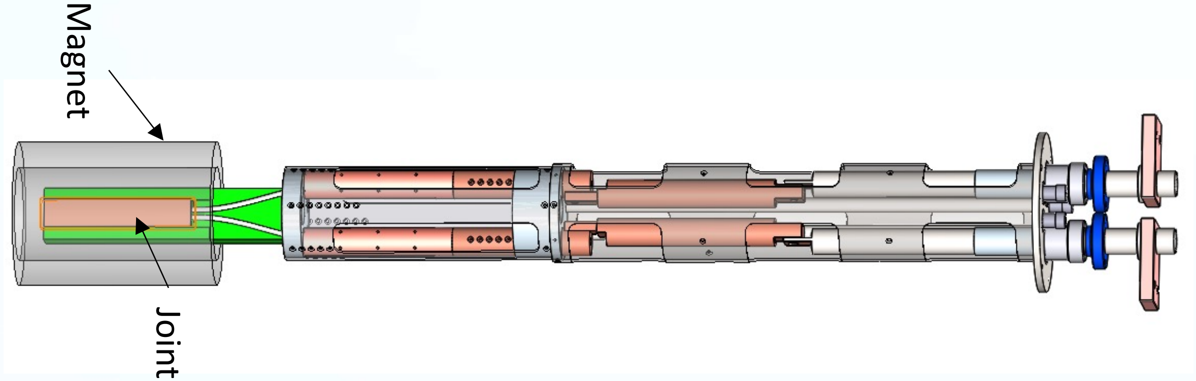
Magnet development

- We need to develop the technology as soon as possible
    - More testing to understand how the conductor ticks
    - **Model coils, demonstrators**

Thank you for your attention!

Extra slide: CORC® joint development

Soldered Joint between two CORC® cables

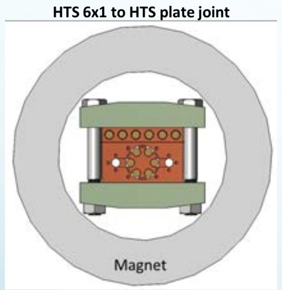


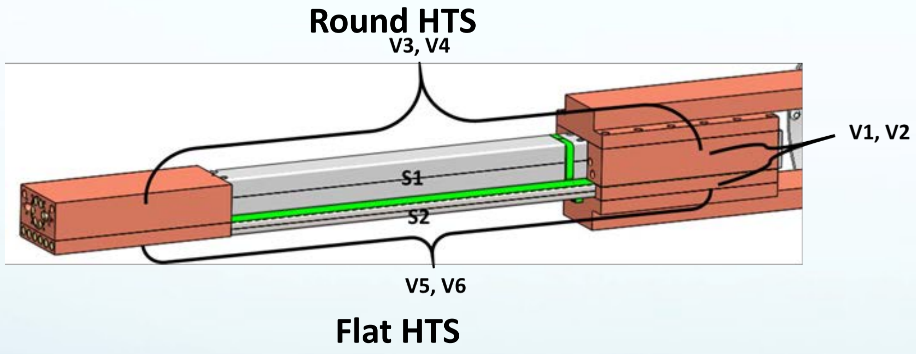
		CORC® cable joint
Joint dimensions [TxWxL]	mm	16 x 38 x 200
77 K Terminal resistance	nΩ	14.7
77 K Joint resistance	nΩ	51.4
4 K, 0 T Terminal resistance*	nΩ	0.3
4 K, 0 T Joint resistance*	nΩ	1.9
4 K, 8 T Joint resistance**	nΩ	8.3

*Determined at 200 A/s ramp rate

**Determined at 1000 A/s ramp rate

Dry copper Joint between two CORC® CICC





4 K

Applied Field [T]	Average Resistance [nΩ]		
	Total	Round HTS	Flat HTS
0	4.1	2.8	0.8
4	5.2	3.0	1.3
6	6.1	3.4	1.5
8	6.9	3.6	1.9

*Calculated using average voltages as measured on either side of sample

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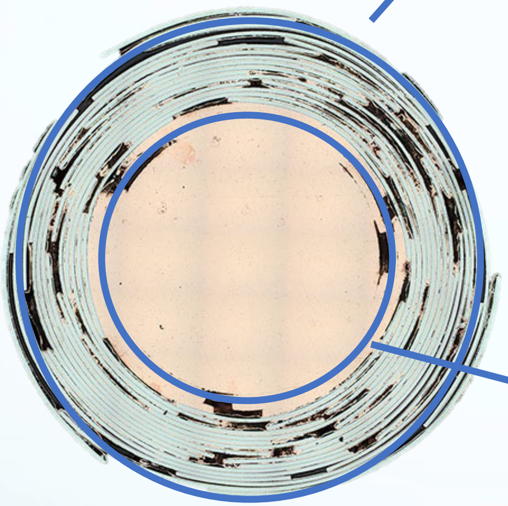
UK Atomic Energy Authority

Extra slide: the anatomy of a CORC® conductor



Transverse cross section

REBCO Tapes
(60-40% area)

- Hastelloy (51%)
- Copper (17%)
- Void/lubricant (17%)
- CORC® insulation (8%)
- Silver (4%)
- ReBCO (2-3%)

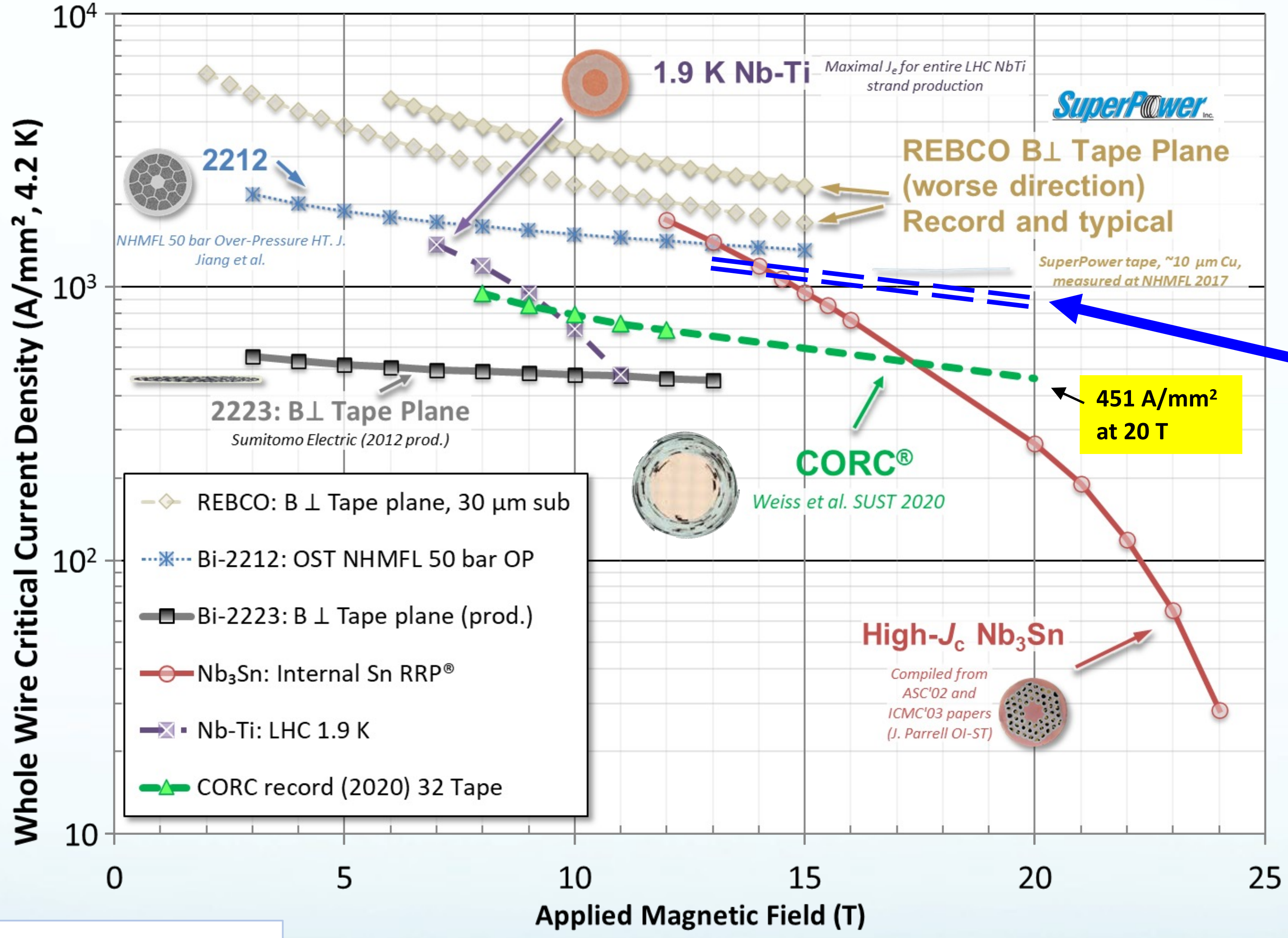
Core / former
(40-60% area)

- Typically soft OFHC copper
- Electrical Stabilizer in-case of conductor quench

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
- <u>Strength of the conductor then depends largely on the strength of the former…</u>

Extra slide: CORC® high-field performance compared to other superconducting wires



CORC®

Potential using tapes with 20 μm substrates and best pinning received

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Data from:
https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots
Weiss et al **SUST** (2020) https://doi.org/10.1088/1361-6668/ab72c6