This work was in part supported by the US Department of Energy under agreement numbers DE-SC0009545, DE-SC0014009, and DE-SC0020710

Successful demonstration of the first CORC® cable insert solenoid in 14 T background magnetic field operating at currents exceeding 4 kA, current densities of over 250 A/mm^2, and 275 MPa source (JBR) stress

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Applied Superconductivity Conference 2020

Wk2LOr2A-01 [Invited] - HTS Magnets - II

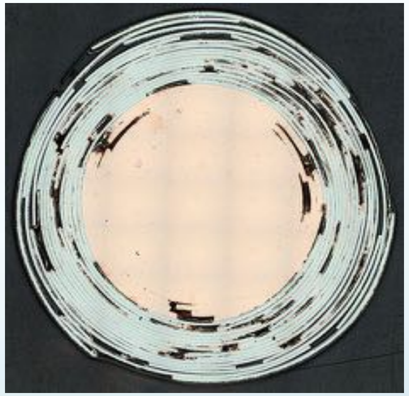
Conductor on Round Core (CORC®) cables

CORC® cable principle based on strain management
Winding many high-temperature superconducting REBCO coated conductors from SuperPower in a helical fashion with the REBCO under compression around a small former to obtain high cable currents

Single tape wound into a CORC® cable

Benefits of CORC® cables include

- Round and isotropic
- Very high currents and current densities
- Highly flexible in any direction
- High level of conductor transposition
- Current sharing between tapes

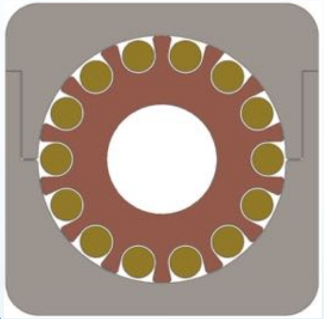


CORC® magnet cables and wires

CORC® wires (2.5 – 4.5 mm diameter)
- Wound from 2 – 3 mm wide tapes
- Tapes have 25 – 30 μm thick substrates
- Typically no more than 30 tapes
- Highly flexible: bending down to 50 mm diameter

CORC® cable (5 – 8 mm diameter)
- Wound from 3 – 4 mm wide tapes
- Tapes have 30 – 50 μm thick substrates
- Typically no more than 50 tapes
- Flexible: bending down to > 100 mm diameter

CORC®-Cable In Conduit Conductor (CICC)
- Performance as high as 100,000 A (4.2 K, 20 T)
- Combination of multiple CORC® cables or wires
- Bending diameter down to about 1 meter



UNIVERSITY OF TWENTE. CERN

CORC® conductor development for magnet applications

CORC® conductors for accelerator magnets (Main sponsor DOE – High Energy Physics)

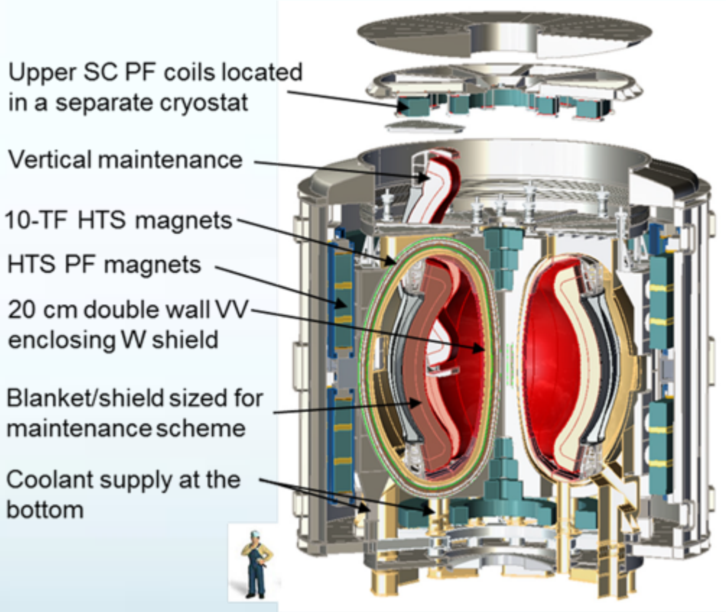
- Engineering current density J_e(20 T) > 600 A/mm^2
- Operating currents 10 – 20 kA
- Small cable bending diameters 20 − 50 mm

Large Hadron Collider at CERN

CORC® conductors for HTS fusion magnets (Main sponsor DOE – Fusion Energy Sciences)

- Operating current 10 – 100 kA
- Operating temperature 4.2 – 40 K
- Develop low-resistance CORC® cable joints for use in demountable fusion magnets

Fusion National Science Facility



Device configuration designed for vertical maintenance

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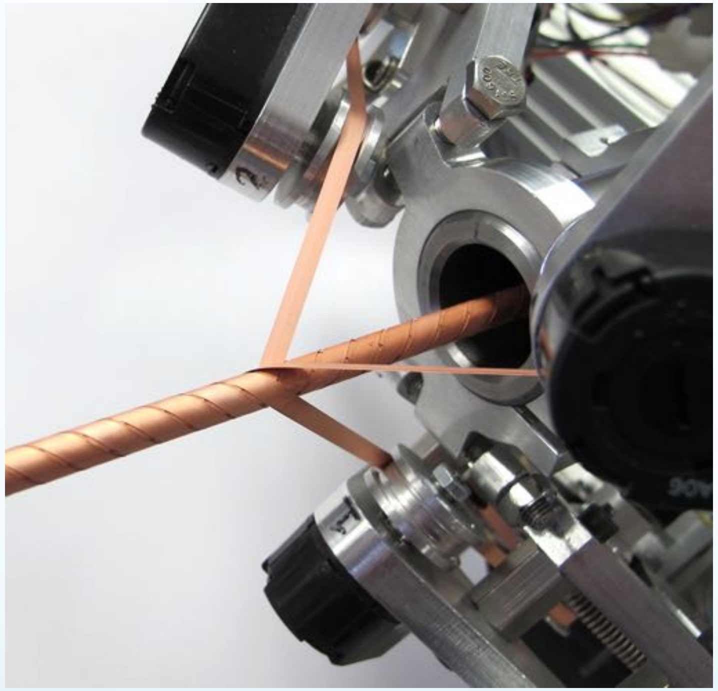
CORC® cable production

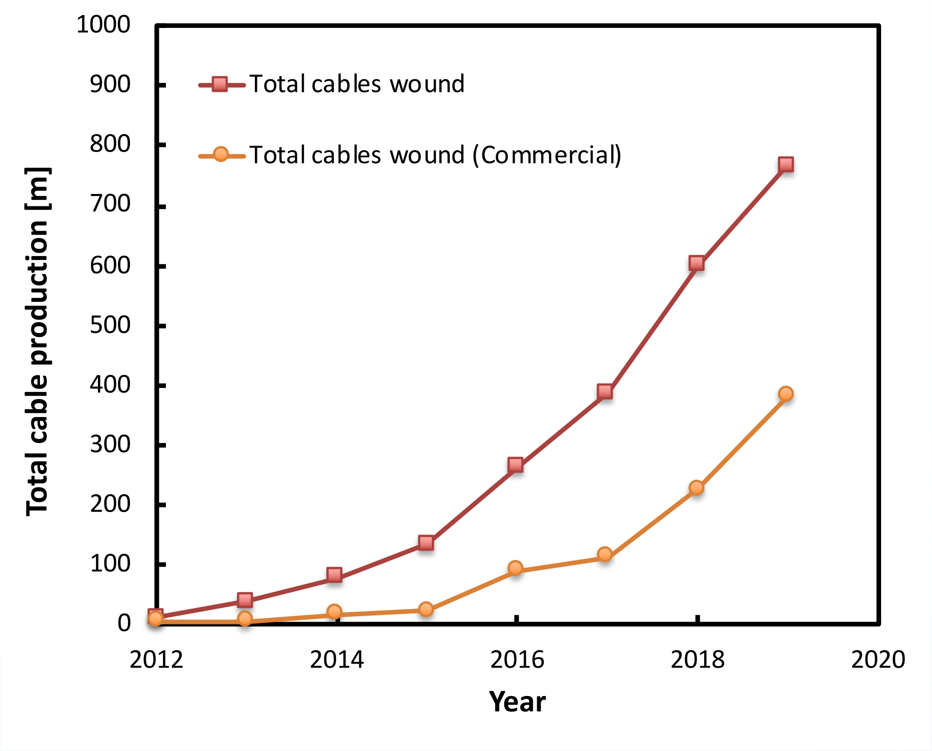
Winding of long CORC® cables with custom cable machine

- Accurate control of cable layout
- Long cable lengths possible (> 100 meters)
- I_c retention after winding 95-100 %



Cumulative CORC® production

- about 800 meters since 2012
- includes 430 meters for commercial orders (including about 140 meters for open orders)



CORC® magnet development

Demonstrating a functional magnet that operates at high current, current density, and stress

High-field insert solenoid wound from CORC® cables

Phase II SBIR in collaboration with ASC-NHMFL

Address 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**
- High current density: J_e **> 200 A/mm²**
- Significant **JBr source stress >250 MPa**

CORC® cable layout

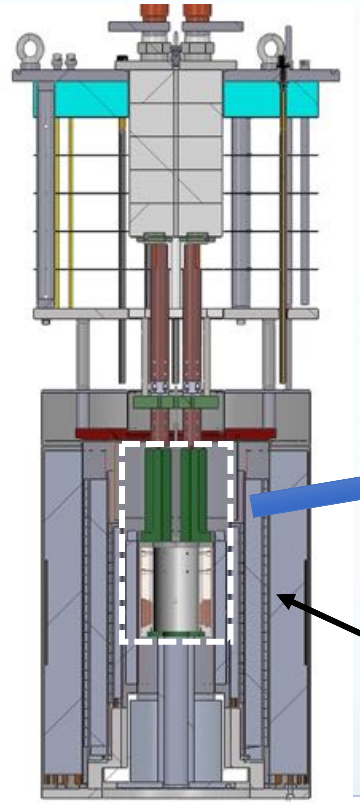
- 28 REBCO tapes of 3 mm width containing 30 μm substrates
- 4.56 mm CORC® cable outer diameter

CORC® insert layout

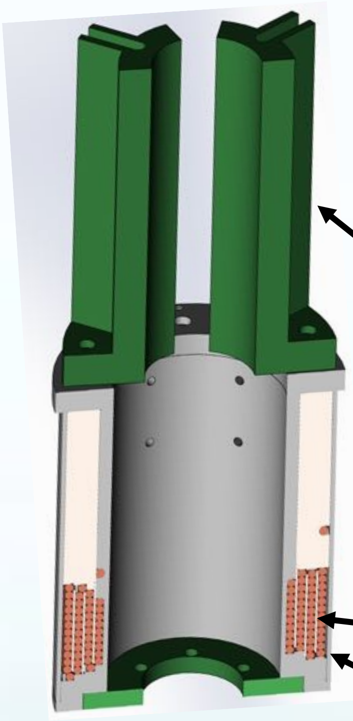
- 100 mm inner diameter, 143 mm OD
- 4 layers, 45 turns
- 18.5 m of CORC® cable
- Wet-wound with Stycast 2850 Epoxy
- Stainless steel overbanding between layers

CORC® insert magnet design features

CORC® insert had to be mechanically bolted to LTS magnet, so the coil was mechanically de-coupled from the header



14 T LTS
w/ 161
mm bore

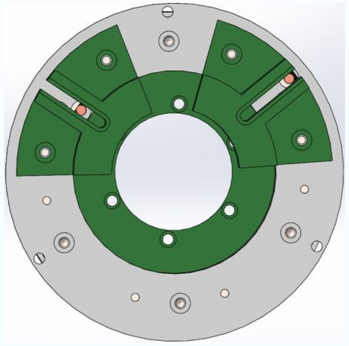


CORC® S-Bend through G10 slots utilizes CORC® flexibility to allow vertical travel of insert due to CTE mismatch between probe/coil-insert and LTS magnet

SS overbanding

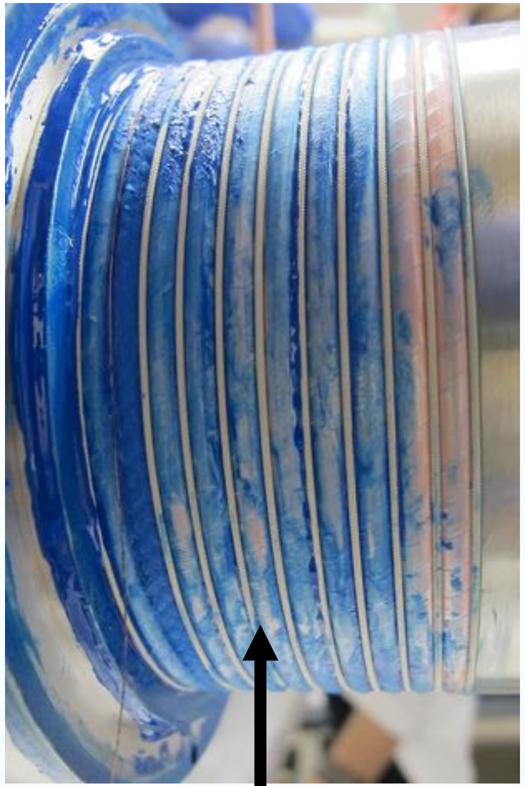
2.0 T CORC® coil
w/ 100 mm bore

Top view

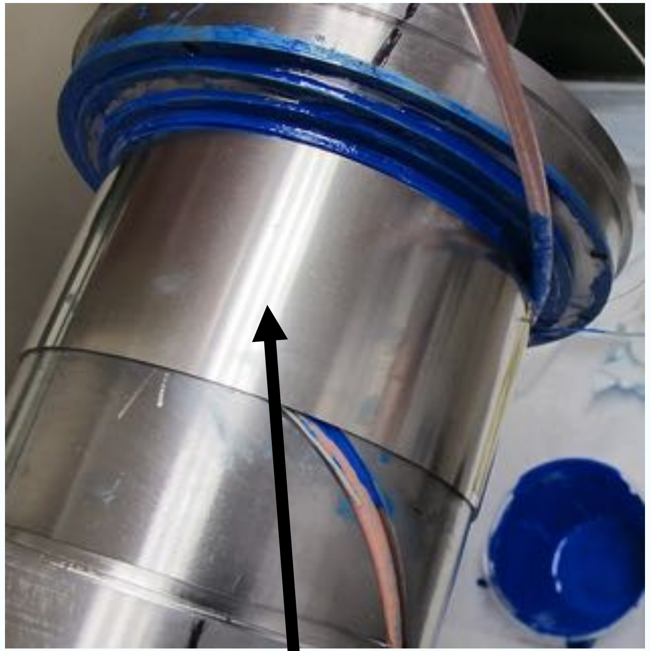


CORC® magnet winding

Wet-winding with Stycast



Co-wound voltage contacts and glass rope



Interlayer stainless steel overbanding

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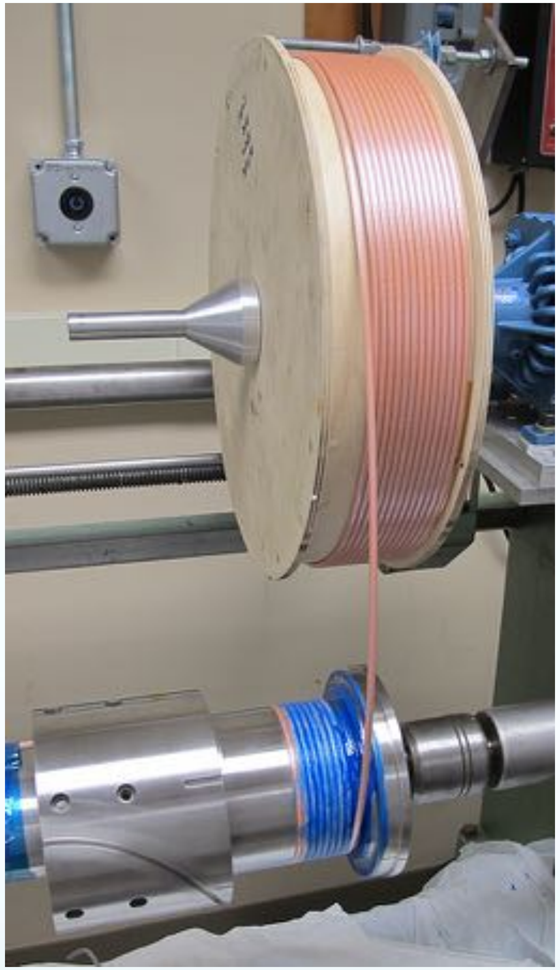
CORC® magnet winding (Cont.)



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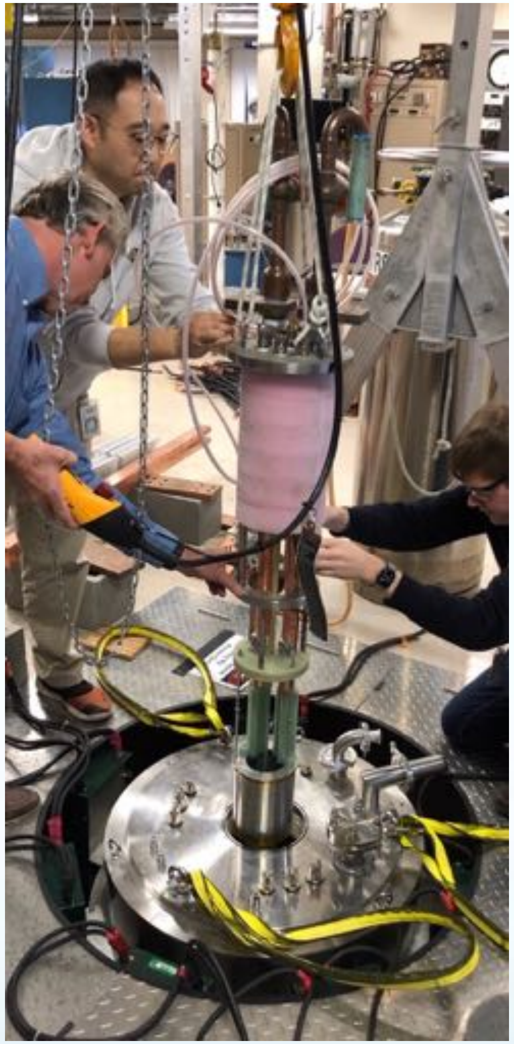
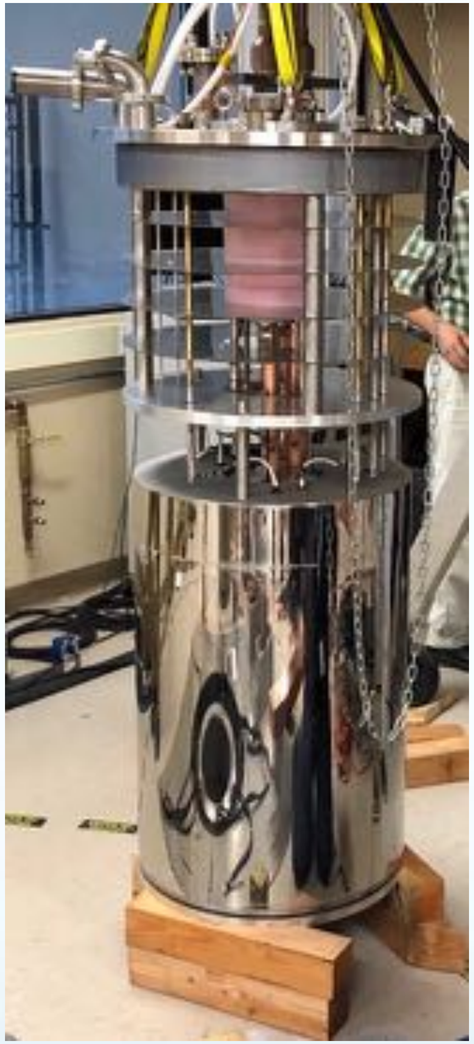
CORC® magnet installation

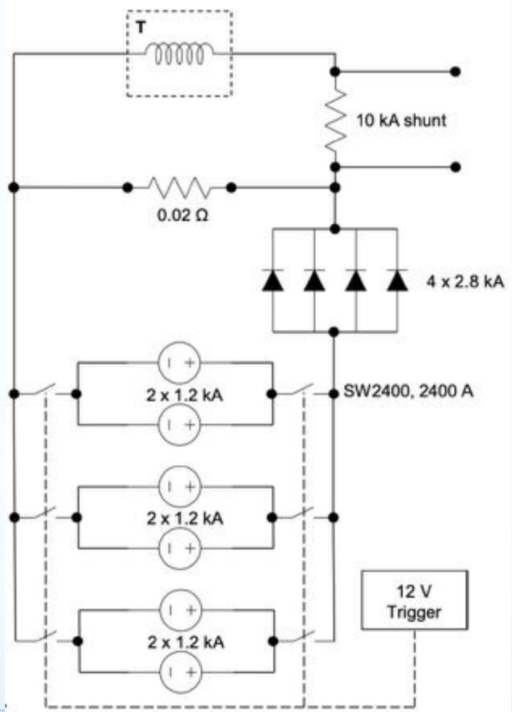


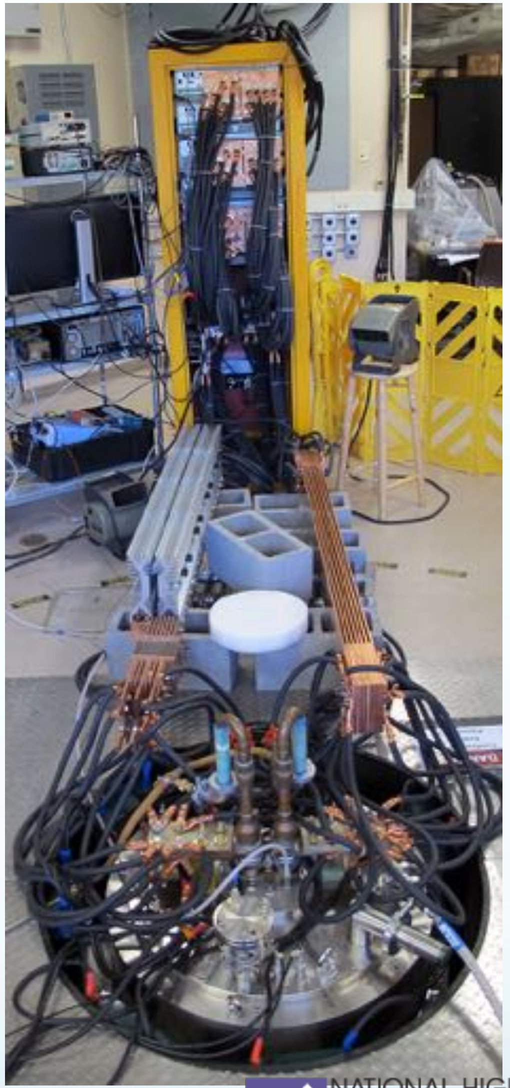


CORC® magnet test preparation

Magnet test details

- 14 T LTS outsert with 161 mm cold bore
- Insert current up to 7.2 kA with 6 Sorenson 1.2 kA supplies in parallel
- Insert magnet protection includes dump resistor, high-current diodes and contactors to disconnect the power supplies

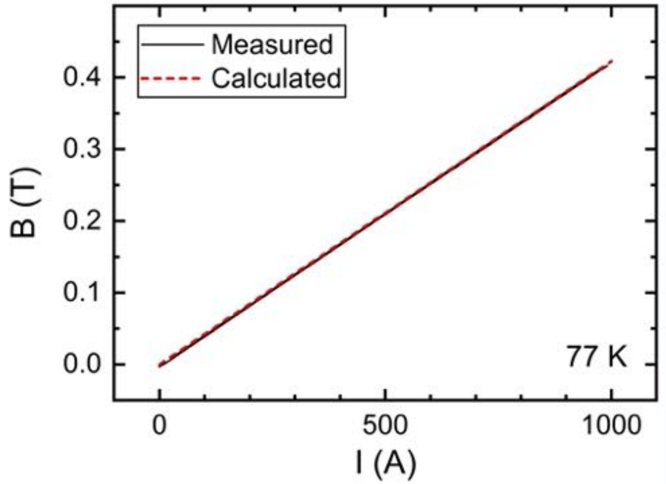


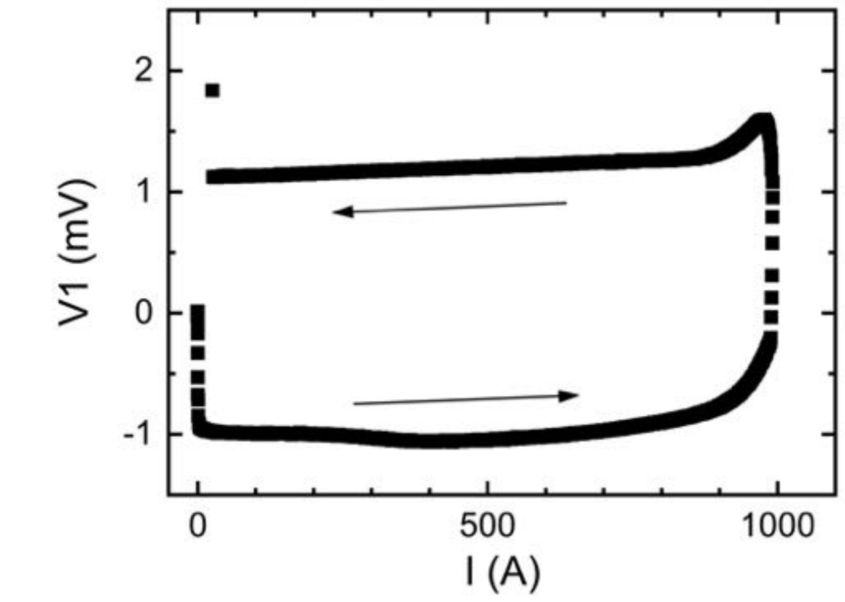


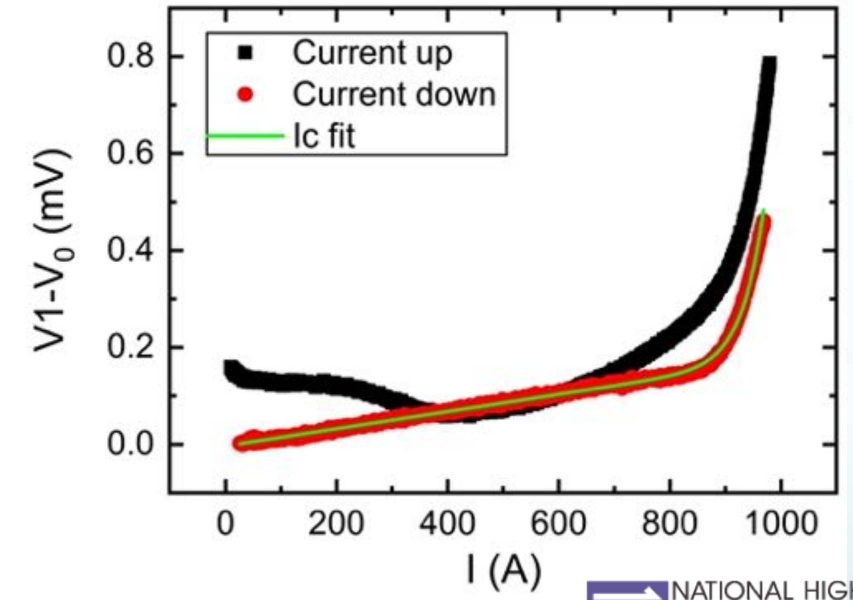
CORC® magnet test: 77 K, stand-alone

Results 77 K, stand-alone

- 0.63 T on conductor (at I_c)
- Hall probe: 0.42 T central field (at I_c)
- Voltage measured with co-wound wires
- I_c = 1,043 A @ 1 μV/cm (18.5 m contact length)
- *n*-value = 24.2
- Contact resistance 178 nΩ







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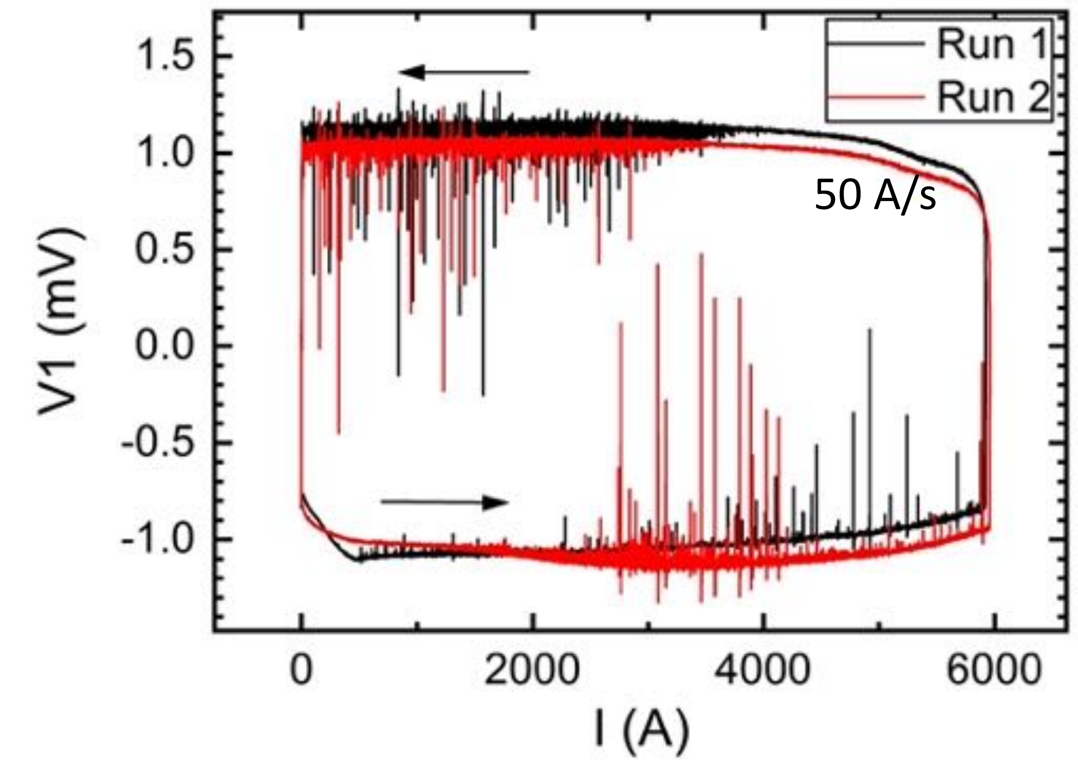
CORC® magnet test: 8 T background field



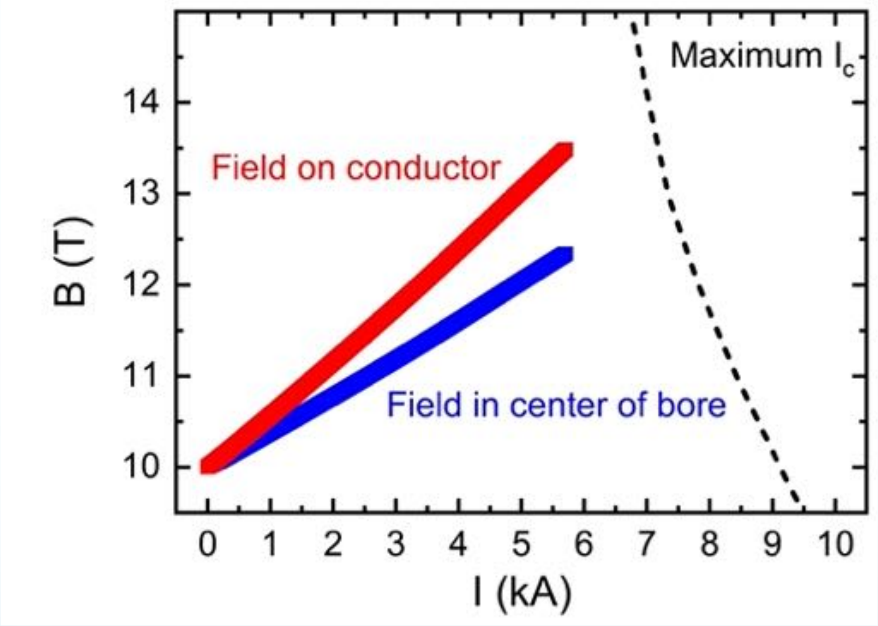
Results 8 T background field at 4.2 K

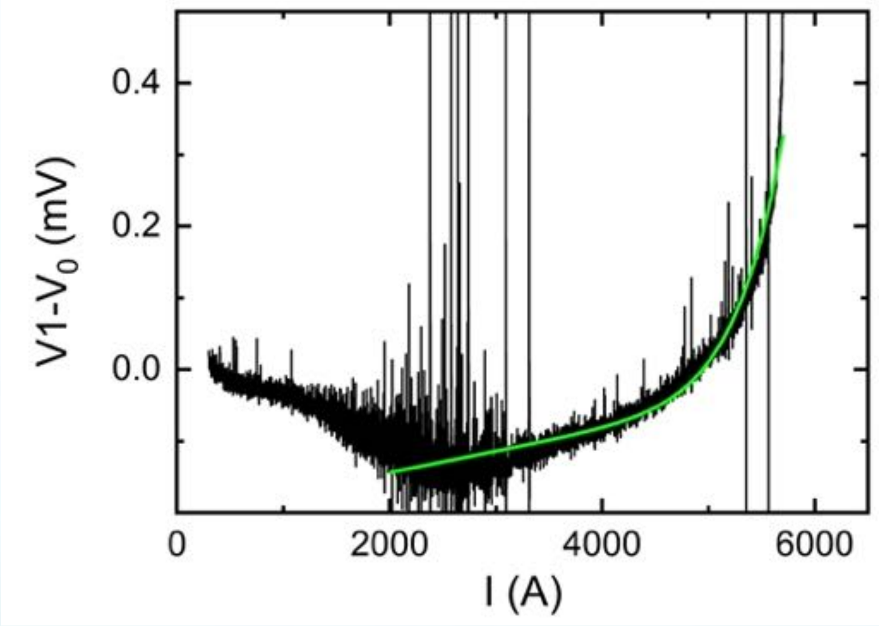
- Current ramped to 6 kA and back at 50 A/s
- No superconducting transition measured
- Inductive voltage shows many spikes from possible conductor movement

CORC® magnet test: 10 T background field

Results 10 T background field

- Peak current 5,500 A; central field 12.68 T, field on conductor 13.8 T
- I_c = 6,485 @ 1 μV/cm
- I_c = 5,410 @ 0.1 μV/cm
- Voltage spike tripped quench detector at 3 mV
- Dump of insert energy triggered partial LTS quench





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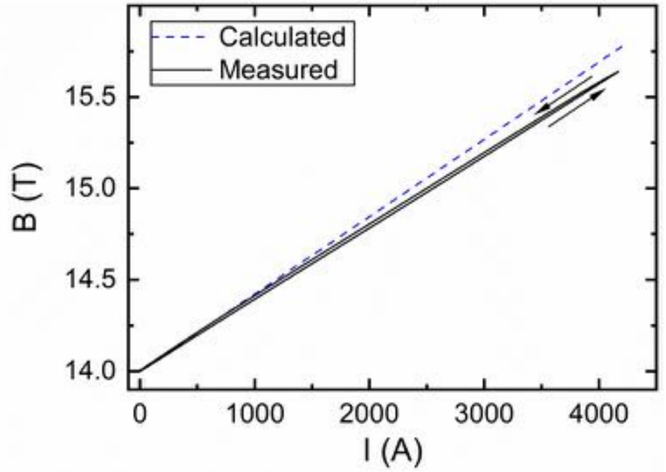
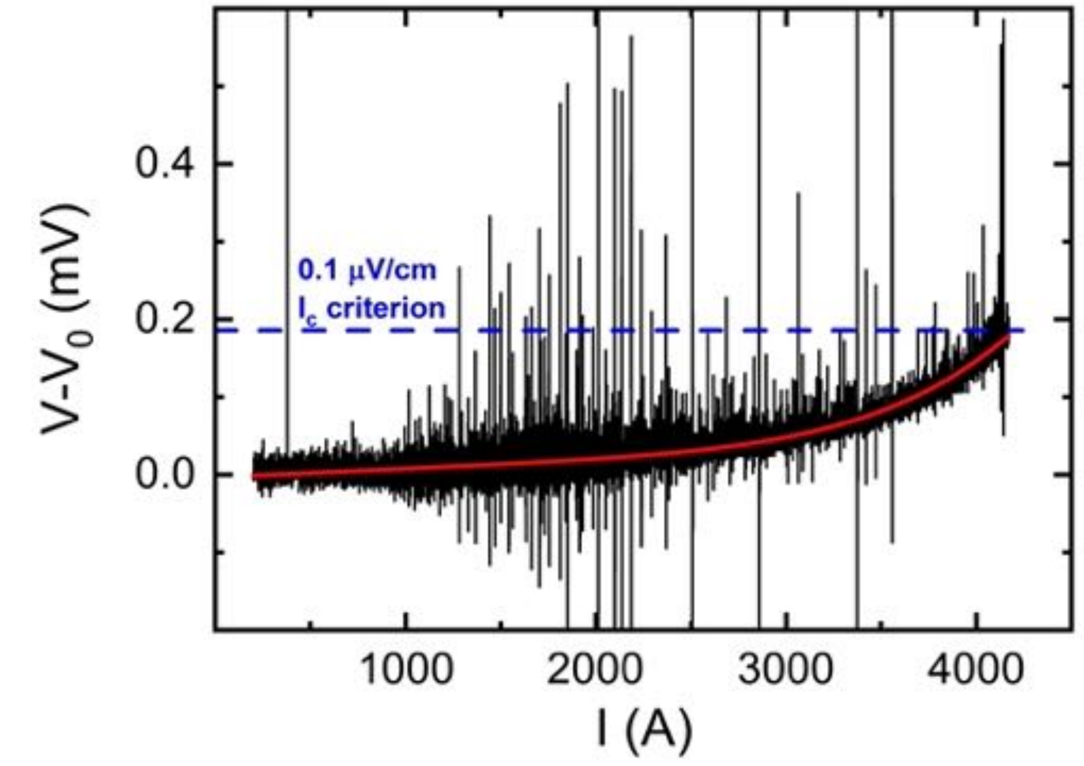
CORC® magnet test: 14 T background field

Results 14 T background field

- Maximum current 4,200 A to avoid quench trigger
- I_c = 4,404 @ 0.1 μV/cm
- Contact resistance 11.1 nΩ
- 15.86 T central field
- 16.77 T on conductor
- JBr source stress 275 MPa





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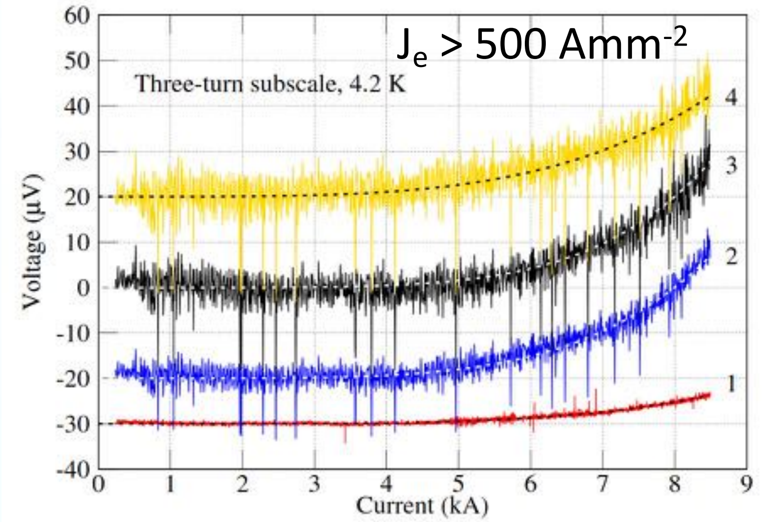
Current sharing between REBCO tapes in CORC® cables: an important feature for magnet protection

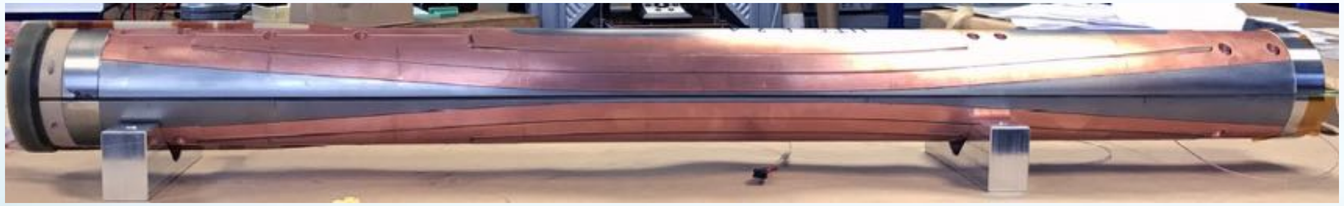
Voltage rise in each layer observed without thermal runaway

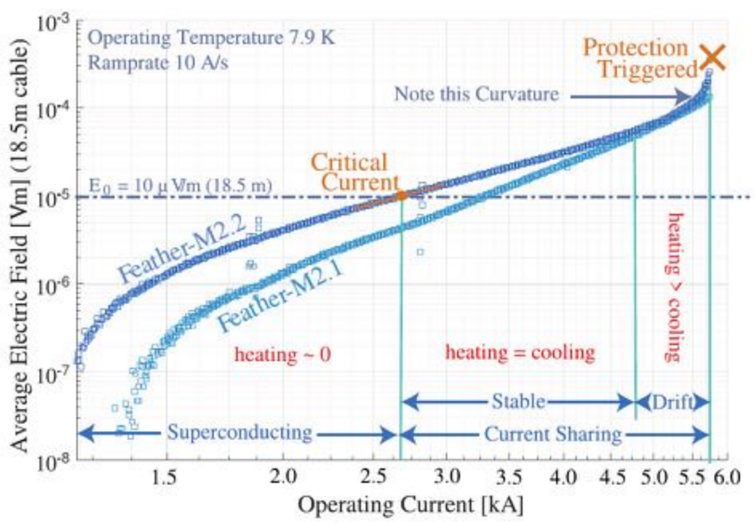
4-layer 2.9 T CCT dipole magnet (90 m of CORC® wire)



Xiaorong Wang: See talk Wk1LOr4B-02 - Development of Canted-CosΘ dipole magnets using CORC® wires

Feather M2 HTS dipole magnet demonstrator (18.5 m Roebel cable)





Nugteren et al. SUST 2018
https://doi.org/10.1088/1361-6668/aab887

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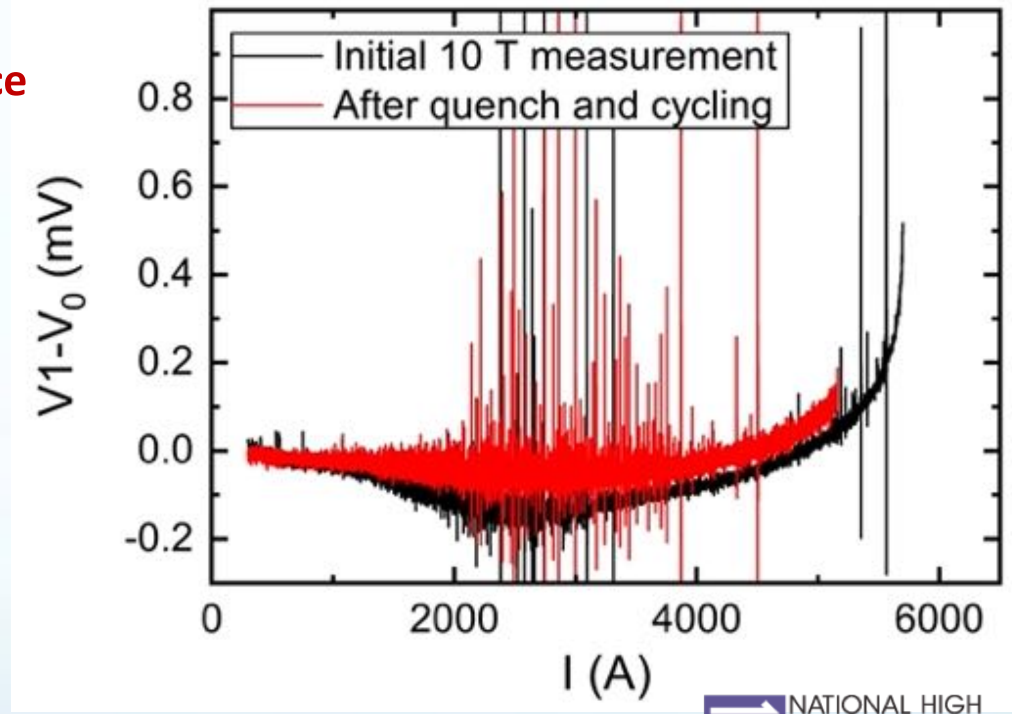
CORC® magnet test: final test at 10 T

Performance after measurement campaign

- Black curve: first measurement at 10 T followed by quench protection trigger
- Red curve: final measurement at 10 T after 10, 12 and 14 T tests, and 10 stress cycles at 10 T to 5 kA (220 MPa hoop stress)
- First 10 T test: I_c = 5,410 @ 0.1 μV/cm
- Final 10 T test: I_c = 5,315 @ 0.1 μV/cm (16th run)

No degradation in CORC® performance after full measurement campaign



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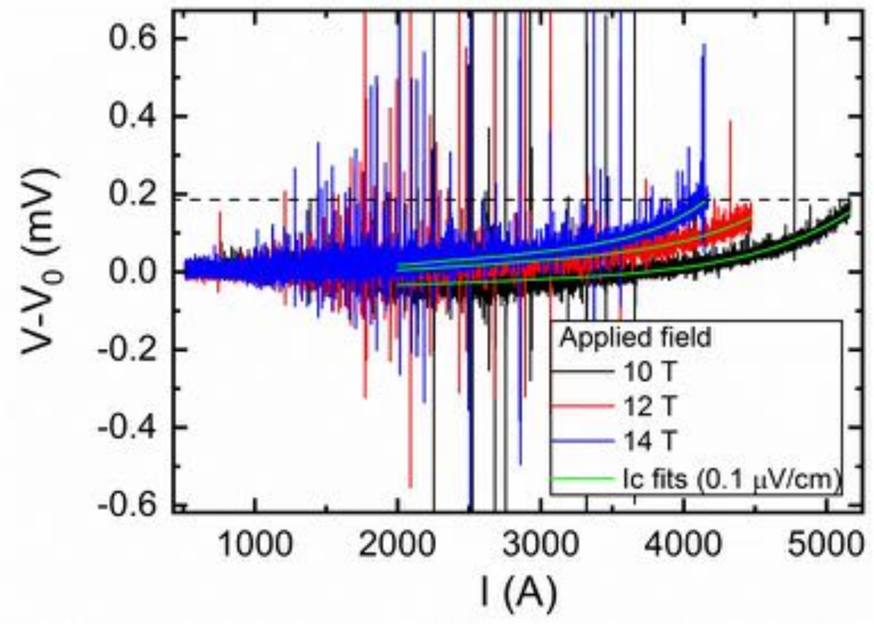
CORC® insert solenoid test: summary

CORC® insert impact

- **First HTS insert magnet tested at high current (>1 kA) in a background field**
- Highly stable operation into flux flow regime
- Stable operation likely due to current sharing between tapes in the CORC® cable
- Combination of high *I*, J_w and JBr demonstrated at 16.8 T peak field

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



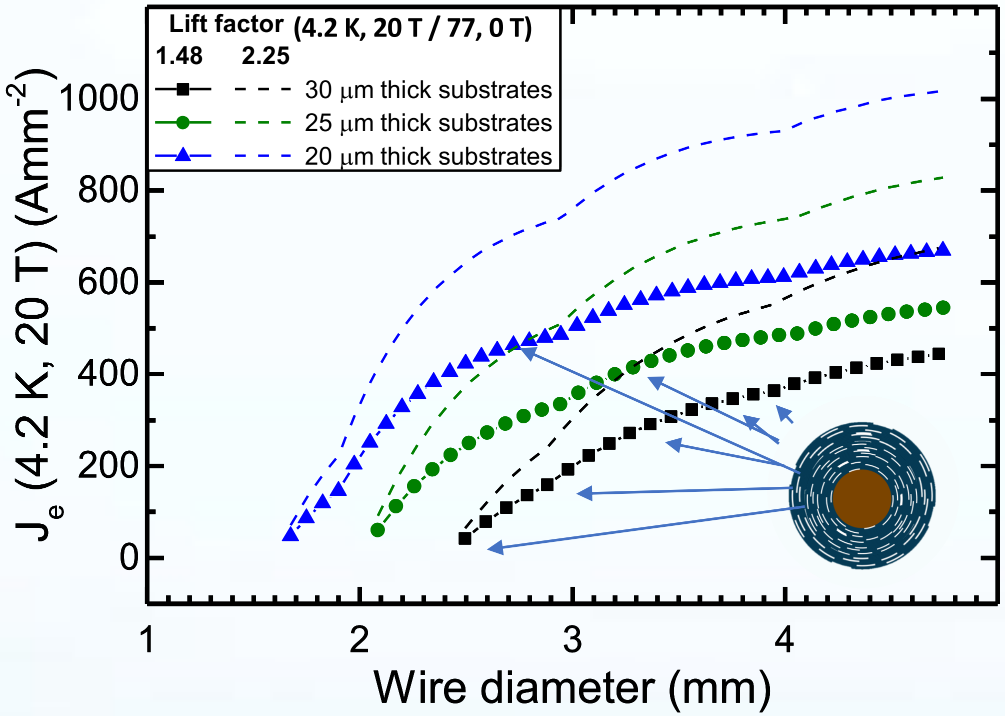
D. C. van der Laan, et al.,
Supercond. Sci. Technol. (2020)
https://doi.org/10.1088/1361-6668/ab7fbe

Future CORC® wire development

Increasing current density, strength, and functionality further

Thinner tapes with better pinning lead to much higher J_e in CORC® wires

Projected J_e vs wire diameter of CORC® wires using received tapes with subpar and best pinning



As you add more layers to the CORC® wire, its J_e increases towards the tape J_e

Assumptions for calculation:
-Realistic winding parameters
-Tape I_c (77K, SF) = 35 A/mm width

Substrate thickness is decreasing

- 30 μm now available
- 25 μm tape has been produced
- 20 μm would enable J_e of 600 Amm^{-2} at 20 T in a 2.4 mm diameter wire

Pinning force is increasing

- More control over artificial pinning centers
- Evidenced by higher lift factors

Tape lengths are increasing

- Delivered tape lengths exceeding 100-300 m are now a regular occurrence

Tape widths are decreasing

- 1 mm and 1.5 mm slitting

Nod to SuperPower for the rigorous R&D effort!

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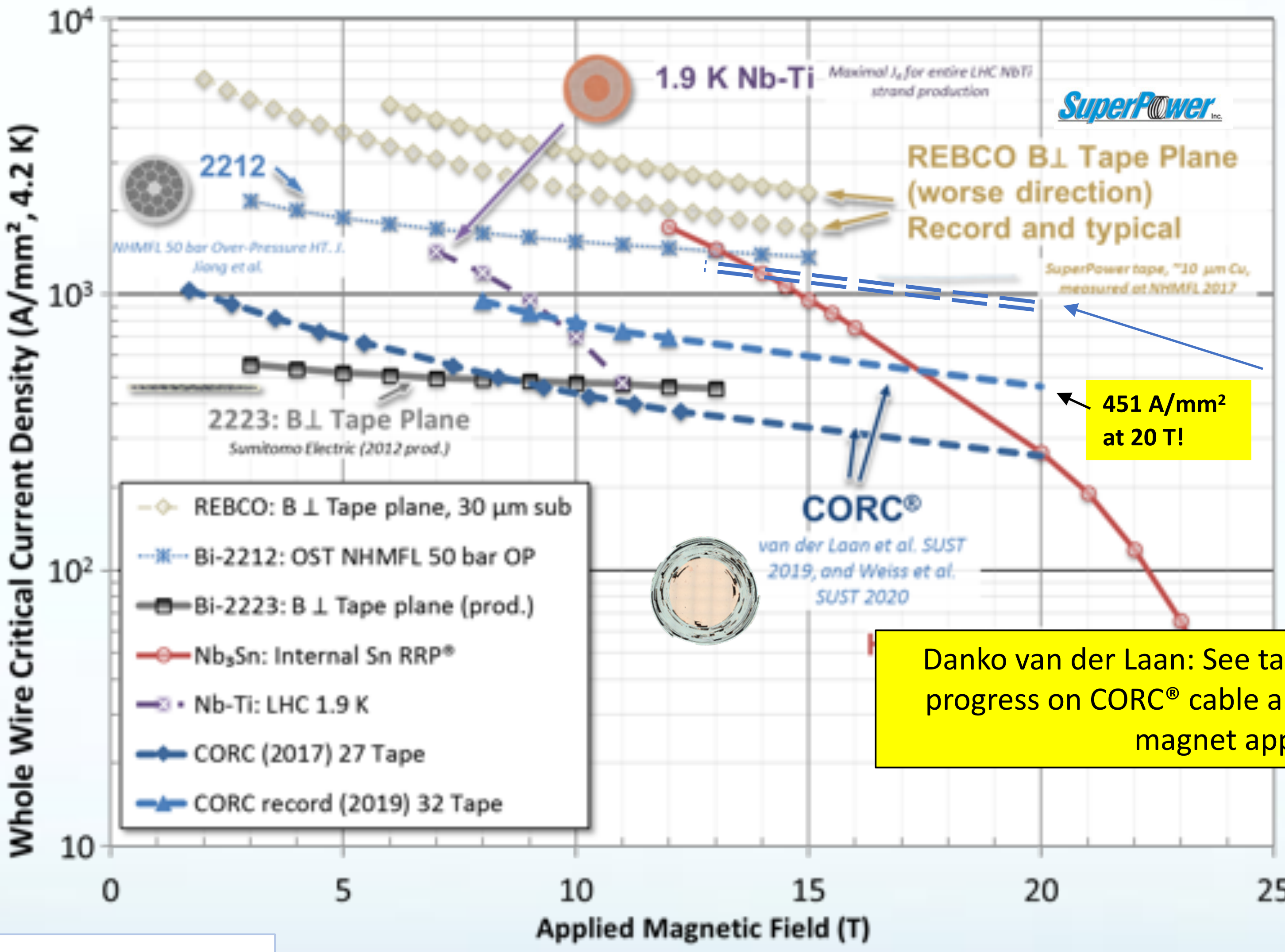
CORC® J_e comparison to high-field magnet wires



CORC®
Potential using tapes with 20 μm substrates best pinning received

Danko van der Laan: See talk Wk2LOr5C-03 - Recent progress on CORC® cable and wire development for magnet applications

Data from https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

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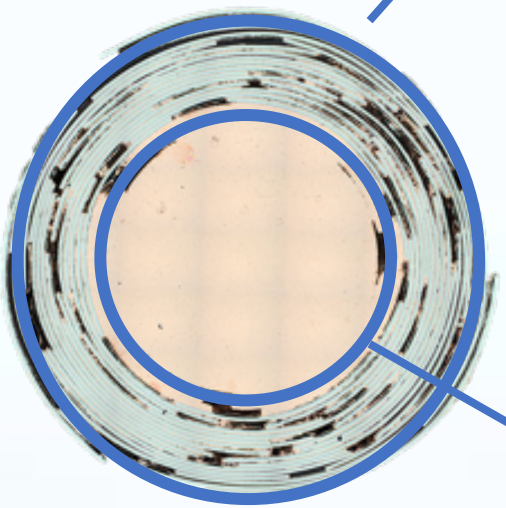
Anatomy of a high J_e CORC® wire



2 mm wide 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 OFHC copper
- Can be functional
  - Integrated diagnostics
- Can be stronger

Transverse cross section

See talk Wk1LOr2B-06 - Special Session: Recent Cable Achievements for Fusion Magnets

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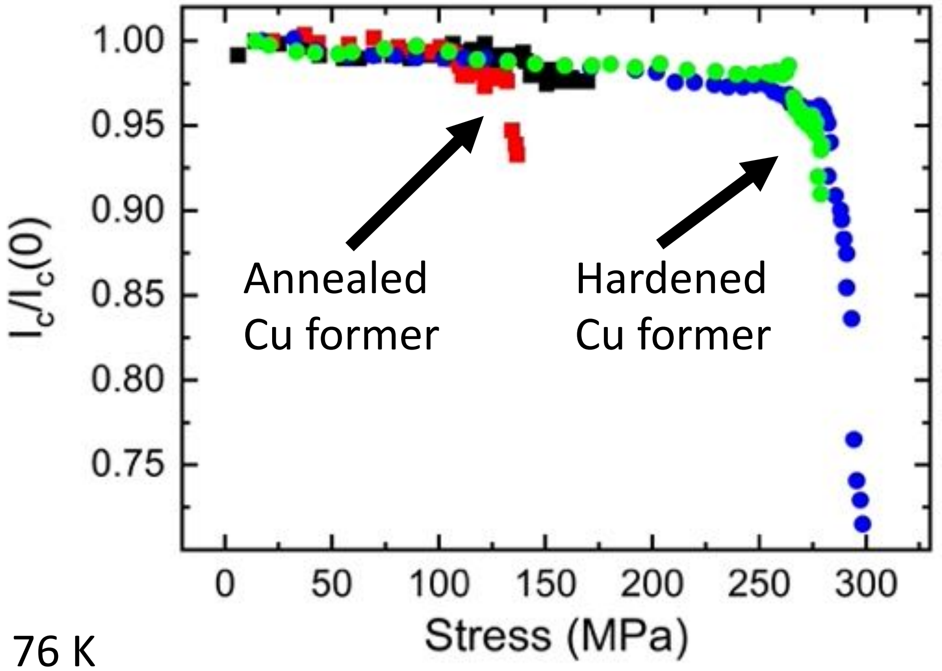
CORC® wires using high-strength formers being developed

High-current tensile tests performed in liquid nitrogen

Samples loaded by pulling on their terminations

Critical stress significantly increased by using stronger former material



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Summary

Successful test of a high-current, high-field, HTS insert solenoid (first of its kind)

- 19 m of CORC® wire successfully wound into a 45-turn magnet
- CORC® flexibility utilized in current-leads between magnet and CORC® termination
- High current operation demonstrated in a 14 T background field: > 4,000 A (4.2 K, 16.8 T)
- 16 high-current tests in background fields ranging from 10-14 T
- CORC® magnet operated into flux-flow regime, allowing current to be safely turned around as superconducting-to-normal transition was gradual
- High current densities > 650 A/mm^2 (4.2 K, 12 T) demonstrated in next generation CORC® wire
- High-strength CORC® capable of withstanding stresses in excess of 250 MPa being developed

Recent CORC® Publications

Topical review on 10 years of CORC® progress (2009-2019)

- Covers everything from conductor development to joints and magnets
- **https://doi.org/10.1088/2F1361-6668/2Faafc82**

Recent publications (2019-2020)

- CORC® CICC with integrated Hall sensors, Weiss et al **SUST** https://doi.org/10.1088/1361-6668/abaec2
- CORC® terminals with integrated Hall sensors, Teyber et al **SUST** https://doi.org/10.1088/1361-6668/ab9ef3
- CORC® solenoid magnet tested in 14 T LTS outsert, van der Laan et al **SUST** https://doi.org/10.1088/1361-6668/ab7fbe
- AC loss and contact resistance studies, Yagotintsev et al **SUST** https://doi.org/10.1088/1361-6668/ab97ff
- CORC® wires with integrated Fibers and V-taps, van der Laan et al **SUST** https://doi.org/10.1088/1361-6668/ab9ad1
- CORC® wires made with 25um Sub tapes, Weiss et al **SUST** https://doi.org/10.1088/1361-6668/ab72c6
- Progress on CORC® CICC development, Mulder et al **IEEE** https://doi.org/10.1109/TASC.2020.2968251
- Development of CORC® for FCL applications, Weiss et al **SUST** https://doi.org/10.1088/1361-6668/aafaa7
- 1.2 T CCT magnet demonstrator, Wang et al **SUST** https://doi.org/10.1088/1361-6668/ab0eba
- Axial tension and fatigue testing, van der Laan et al **SUST** https://doi.org/10.1088/1361-6668/ab06a3

Papers and presentations from conferences and workshops available online

- https://www.advancedconductor.com/technicalinformation/

Not possible without the support of DOE, the US Navy, and various collaborators. Thank you!

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