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Recent progress on CORC®-based high-field magnet development

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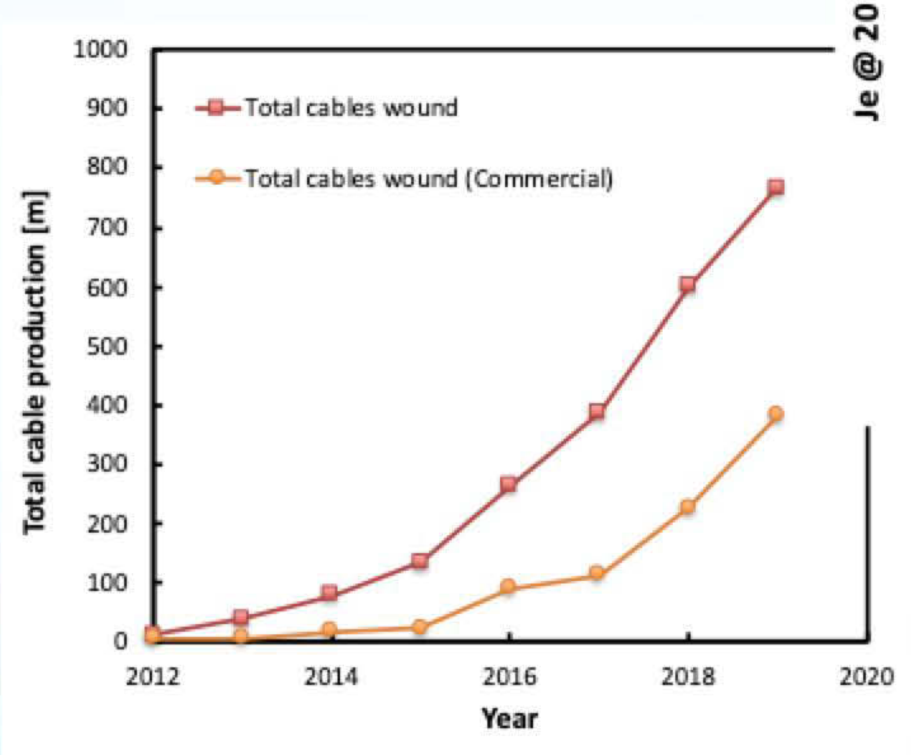
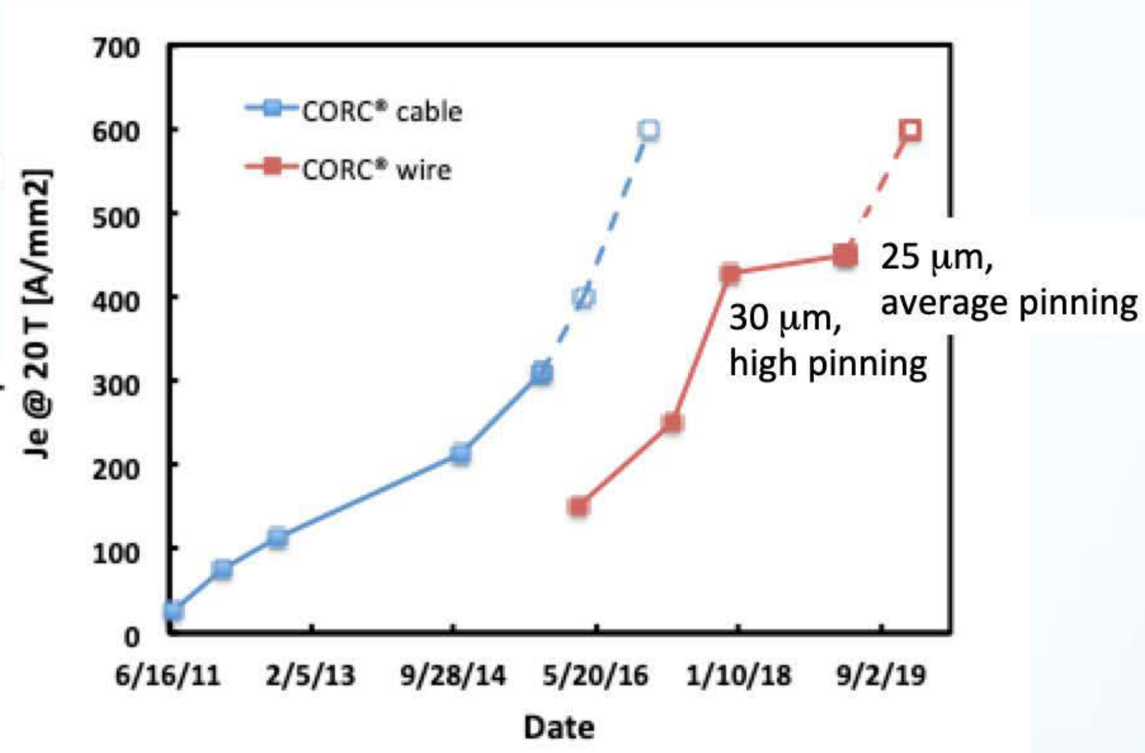
LTSW 2020, Berkeley, CA, February 28, 2020

CORC® conductors a viable magnet conductor

Cumulative CORC® production

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





CORC® conductors

- J_e (20 T) > 450 A/mm^2
- I_{opp}(20 T) > 6,500 A

More than enough performance and lengths to make magnets!

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Several programs to develop CORC® magnets

Stand-alone CORC®-based accelerator magnets

- Develop the magnet technology needed to wind and support CORC® conductors
- Demonstrate the ability to wind long, high-quality CORC® wires
- Develop CORC® long wires with higher in-field performance
- Demonstrate magnet operation at 1, 3, 5 and eventually 8 T before developing 20 T LTS-HTS hybrid magnets

Canted-cosine-theta magnets developed at Lawrence Berkeley National Laboratory

Individually-powered hybrid LTS/HTS CORC® magnets

- Demonstrate operation at high field, high current, high J_e and high hoop stress
- Develop the initial technology that would allow 25 – 30 T hybrid solenoids and eventually 40 – 60 T

CORC® solenoids tested at ASC-NHMFL and CERN/Univ. of Twente

Series-connected hybrid LTS/HTS CORC® magnets

- Demonstrate series-connected hybrid magnet operation at 10 kA
- Learn about quench protection

Common Coil at Brookhaven National Laboratory

CORC®-based Canted-Cosine-Theta accelerator magnets

Collaboration with Berkeley National Laboratory (Xiaorong Wang)

- Demonstrate 1 T (CCT-C1), 3 T (CCT-C2) and 5 T (CCT-C3) magnets
- When LTS CCT outserts become available, develop 5 – 7 T CORC®-CCT inserts that operate in 13 – 15 T outserts to deliver 20 T field

Stand-alone CORC® CCT-C1 magnet

- Use “**low performance**” CORC® wire (16 tapes)
- Learn how to wind CCT magnets from CORC® wires
- Demonstrate 1 T

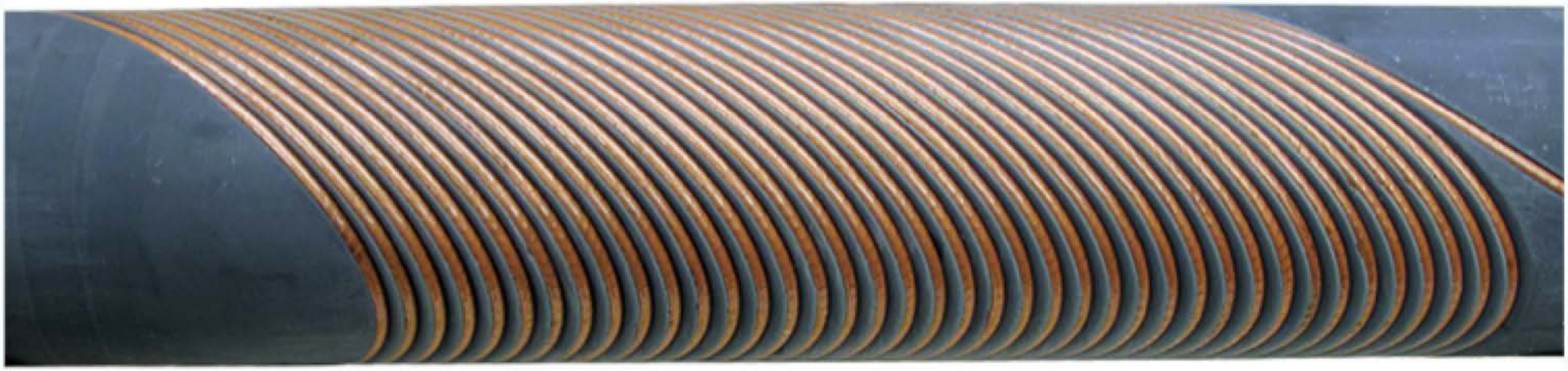
Stand-alone CORC® CCT-C2 magnet

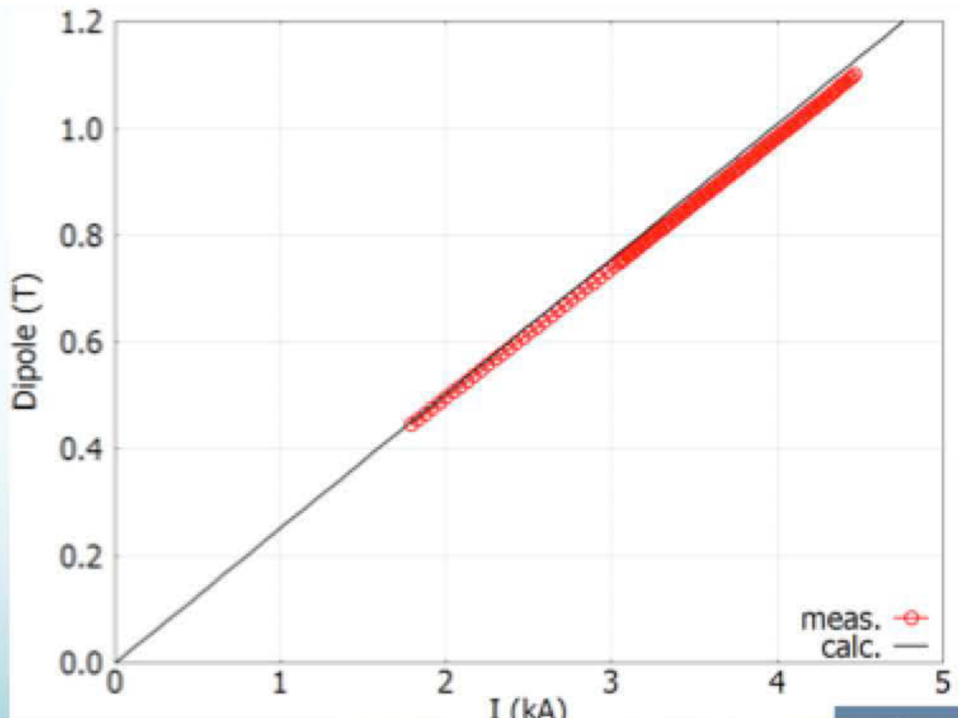
- Use “**best average performance**” CORC® wire (27 – 30 tapes)
- Wind long CORC® wires (20 – 30 meter lengths, 80 meters total)
- Demonstrate 3 T

Stand-alone CORC® CCT-C3 magnet

- Use “**high-performance**” CORC® wire (27 – 30 tapes), minimum I_c (4.2 K, 6 T)
- Wind long CORC® wires (20 – 40 meter lengths, 140 meters total)
- Demonstrate 5 T

CORC®-based Canted-Cosine-Theta magnet CCT-C1





CCT-C1 magnet

- 2 layers, 40 turns/layer
- 3D printed Bluestone mandrels
- 20 meters of CORC® wire
- about 500 m of 2 mm wide tape with 30 μm substrate

1.1 T reached at 4,500 A

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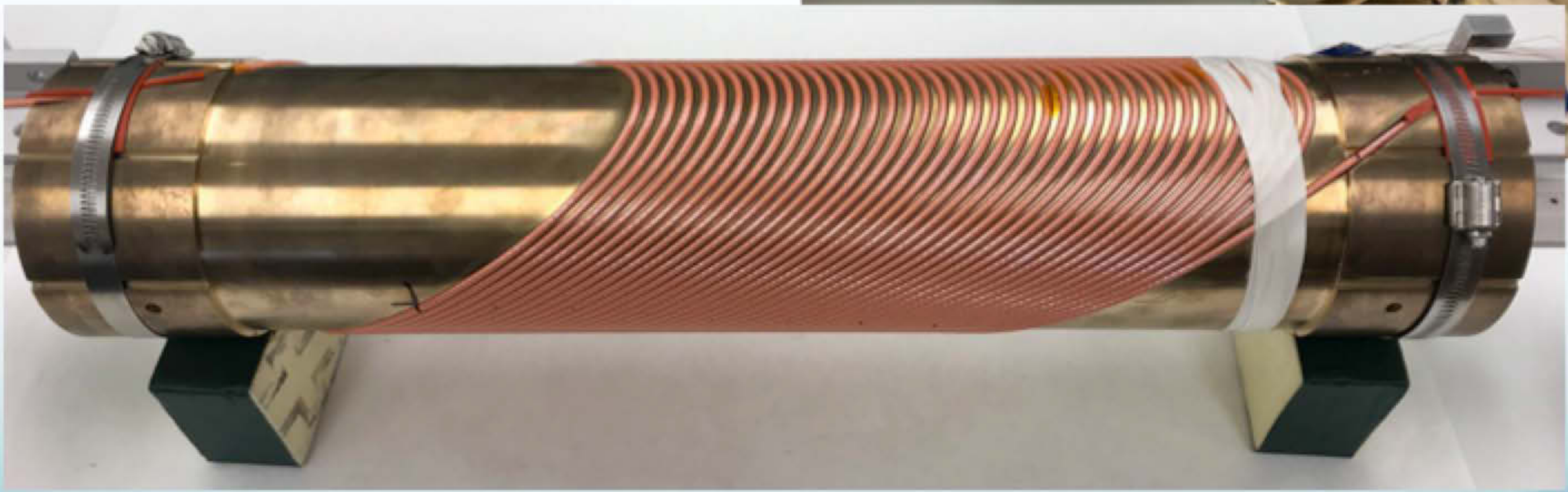
Development of magnet CCT-C2

Major steps in technical development

- 4 layers, 40 turns/layer
- 80 m of CORC® wire, about 4 km of tape
- Metal mandrels and Stycast impregnation



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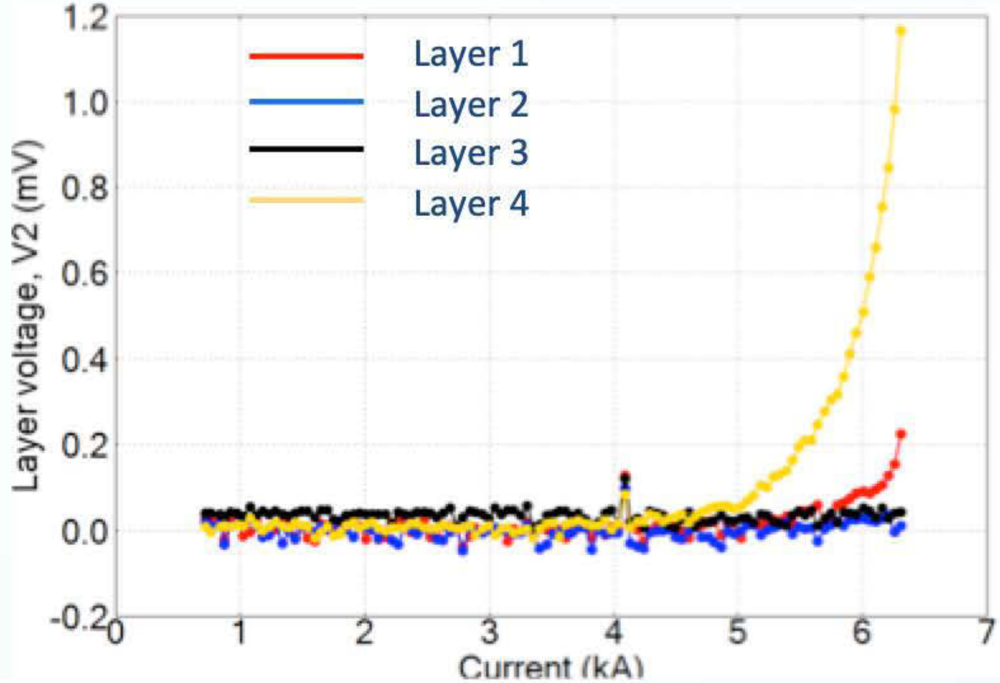
CCT-C2 Test at 4.2 K

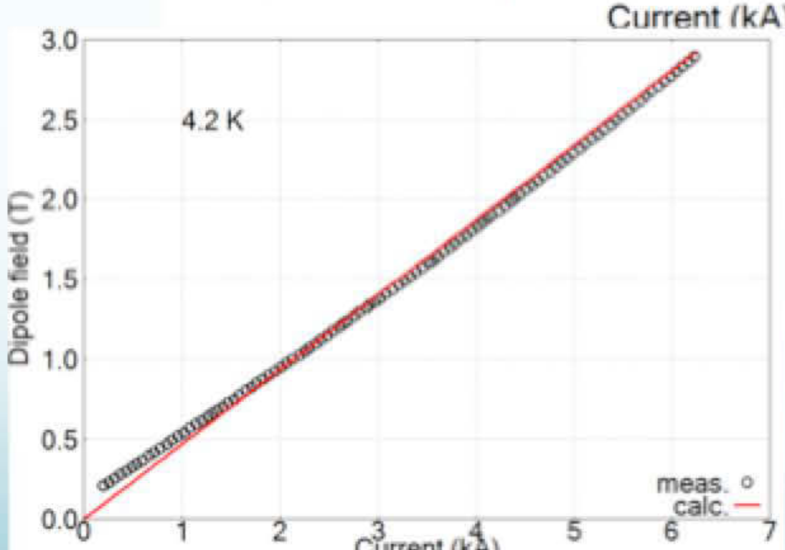
Test results at 4.2 K

- Peak dipole field 2.9 T (98 % of goal)
- Layer 4 started transitioning at 4.8 kA
- Likely caused by too large of tape I_c variation in the wire of layer 4

Below average tape pinning is the main reason for slightly lower performance

High-field magnets ask for minimum tape I_c at operating field





CORC®-CCT magnet development: CCT-C3

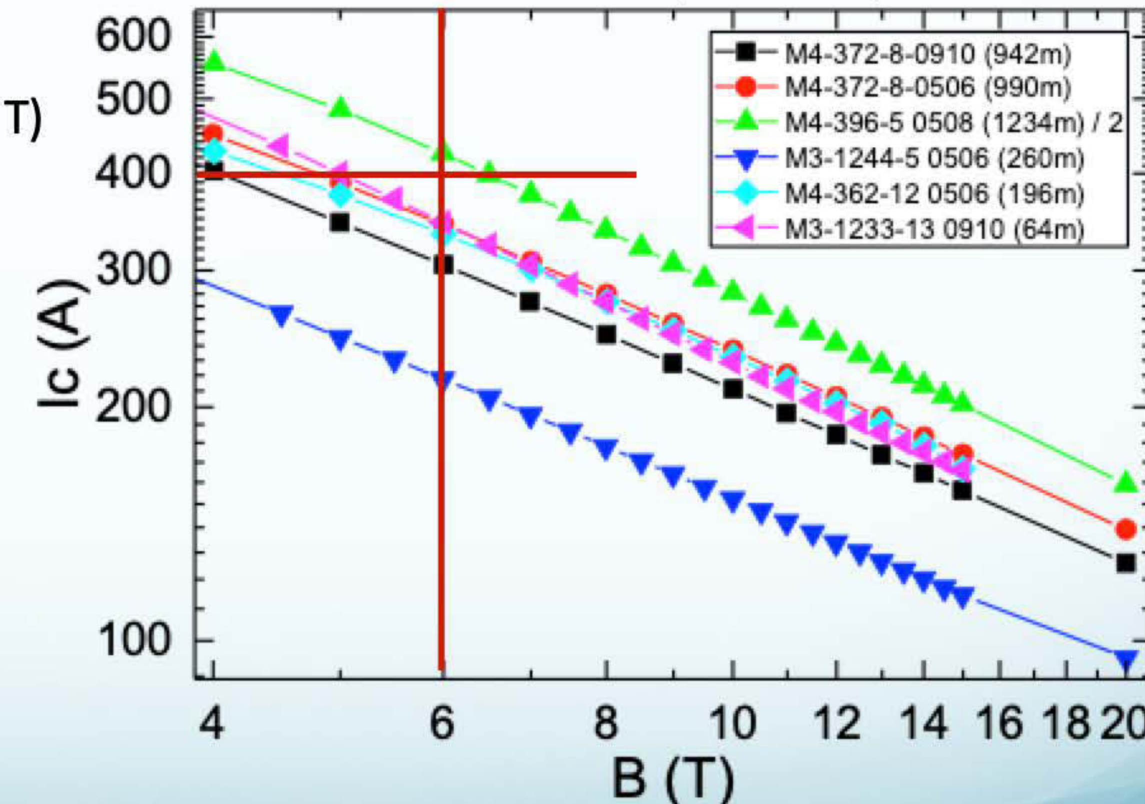
Magnet specifications CCT-C3
- Should deliver 5 T at 4.2 K
- 6-layer, 40-turns/layer
- 70 mm aperture, 60 mm min. bend

CORC® wire specifications CCT-C3
- 30-tape CORC® wire (30 μm)
- Total length about 140 meters

REBCO tape requirements
- Minimum average I_c (4.2 K, 6 T) = 400 A for 2 mm wide tape

About 9 km of 2 mm wide tape expected in April/May 2020

Performance of 2 mm wide tape over the years



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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**
- J_e **> 200 A/mm²**
- Operate at **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
- Stainless steel overbanding between layers

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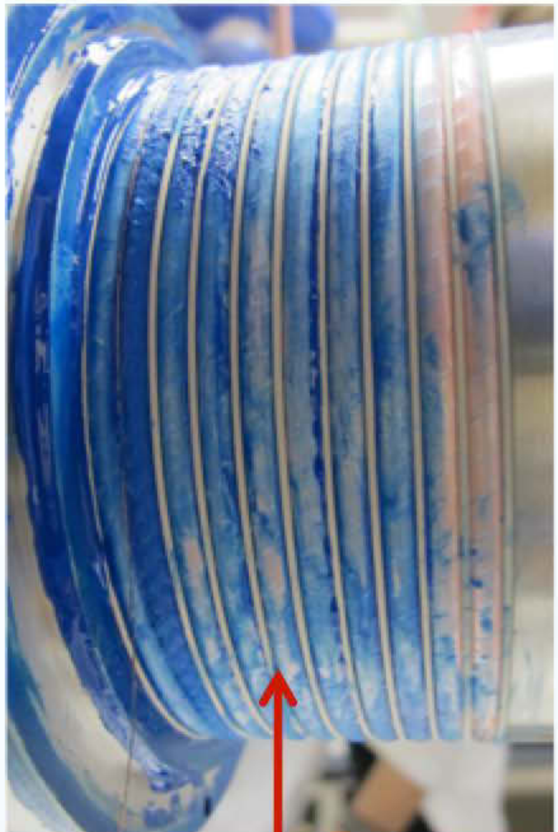
CORC® magnet winding

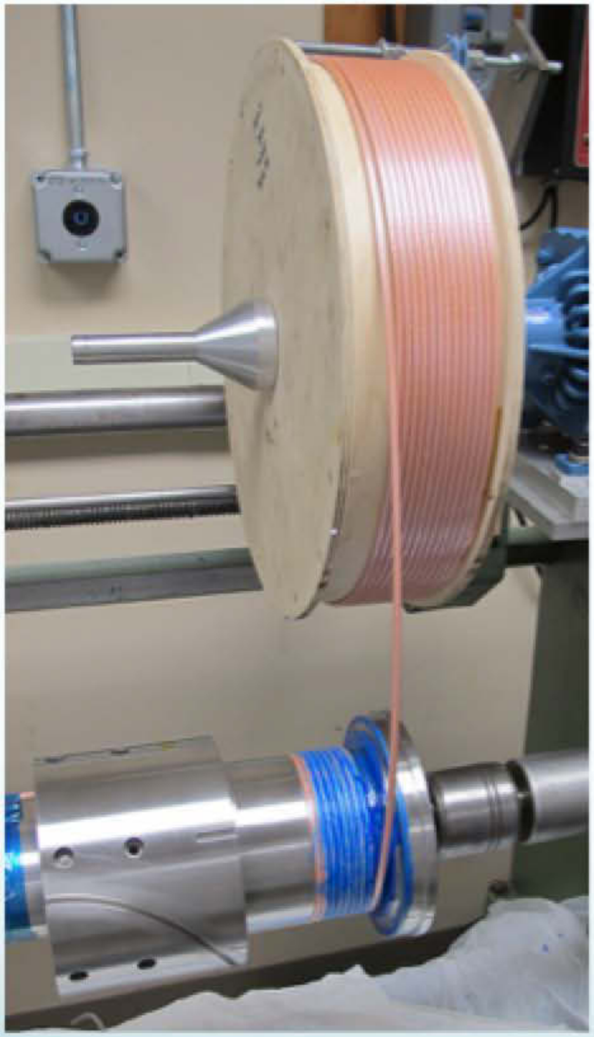
Wet-winding with Stycast

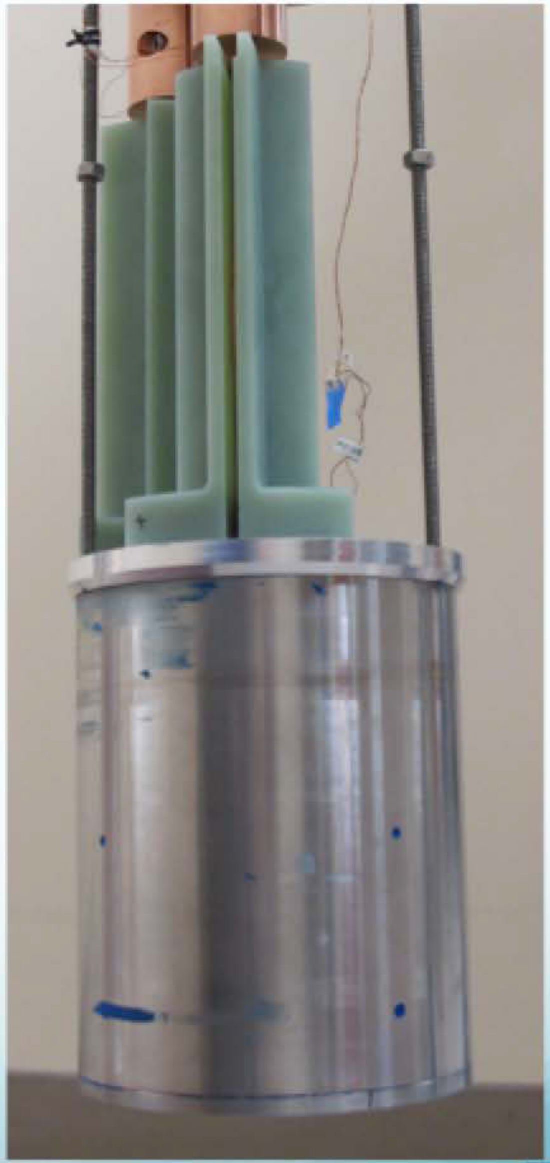


Co-wound voltage contacts and glass rope

Interlayer stainless steel overbanding

CORC® magnet winding (Cont.)





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CORC® magnet installation

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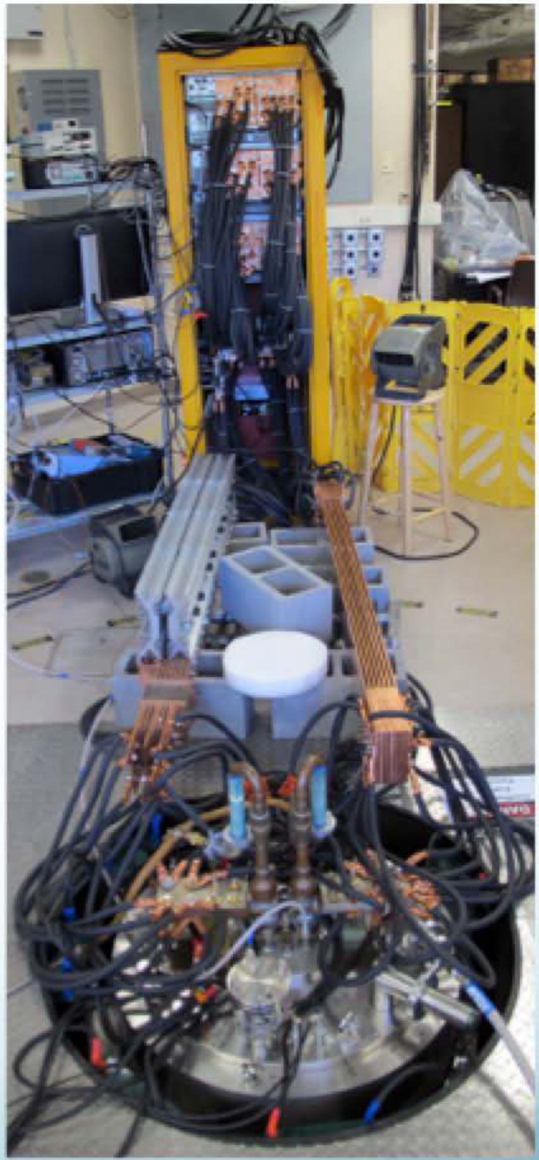
CORC® magnet test preparation

Magnet test details

- 14 T LTS outsert with 160 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



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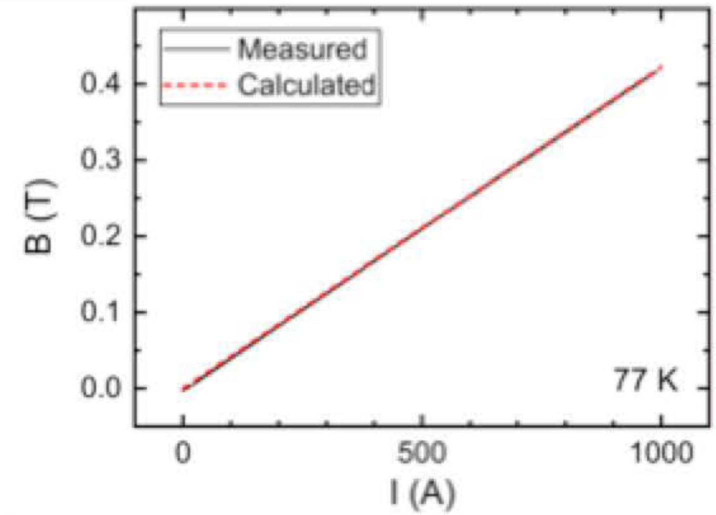
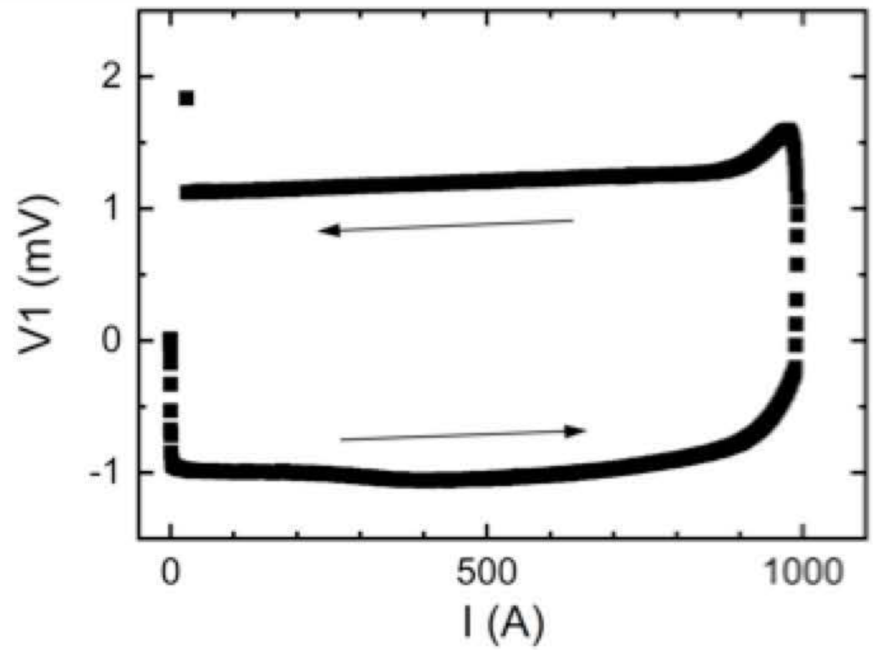
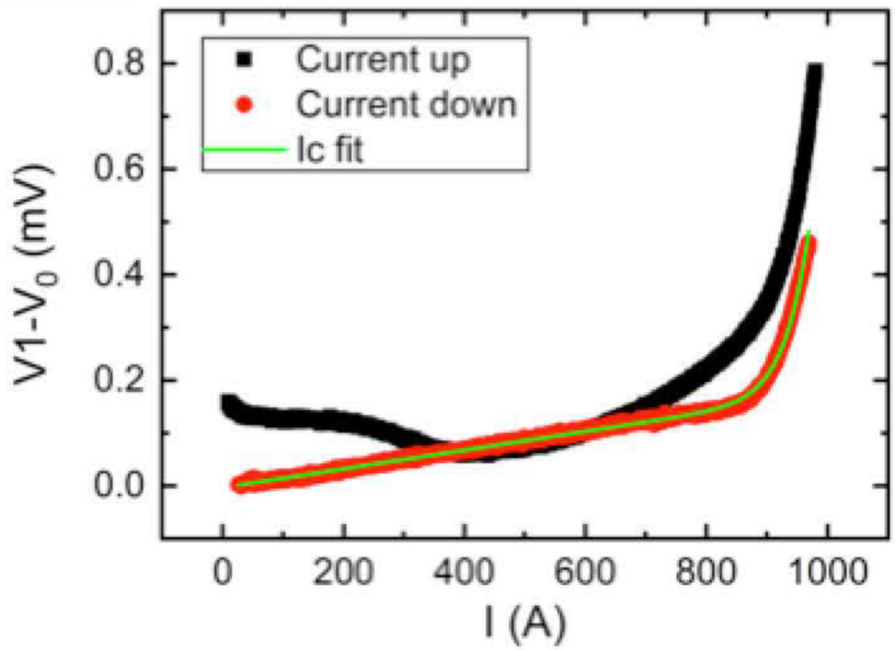
CORC® magnet test: 77 K, stand-alone

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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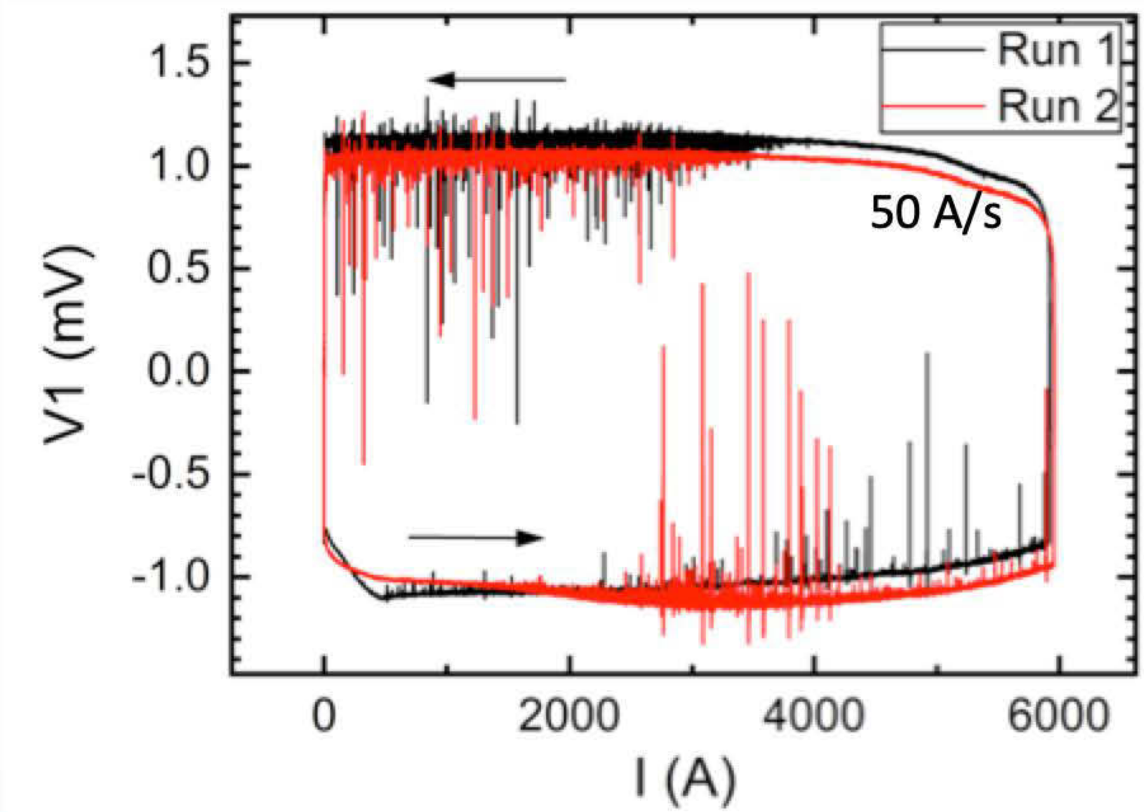
CORC® magnet test: 8 T background field



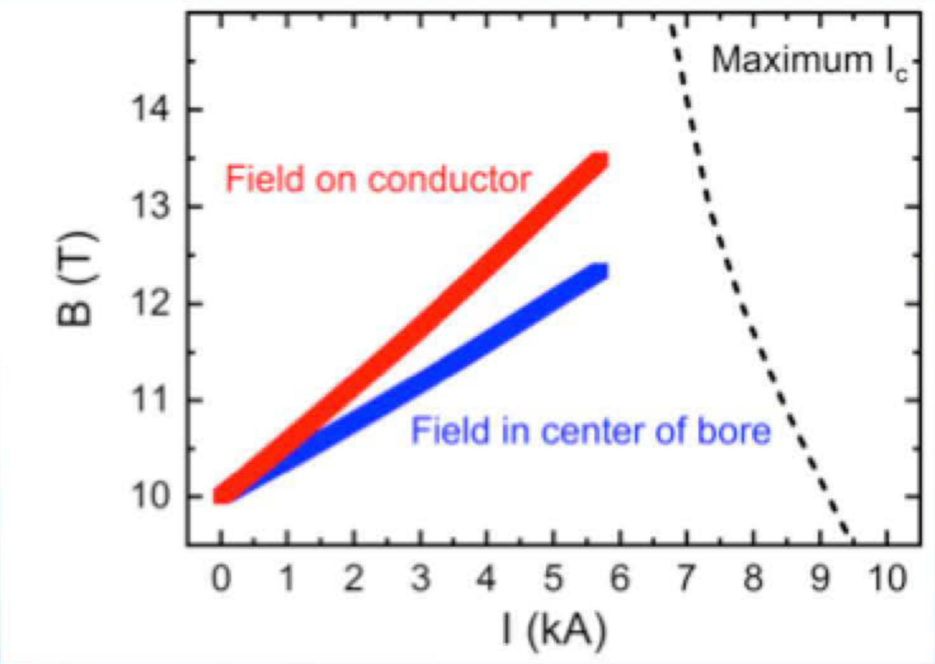
Results 8 T background field at 4.2 K

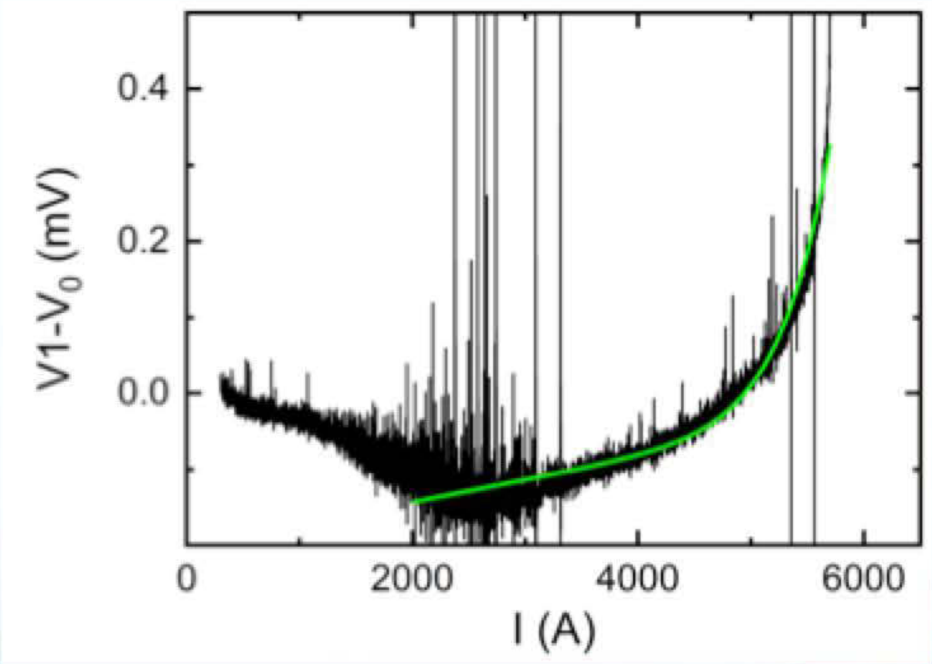
- Current ramped to 6 kA and back at 50 A/s
- No superconducting transition measured
- Inductive voltage shows many spikes from possible conductor movement

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

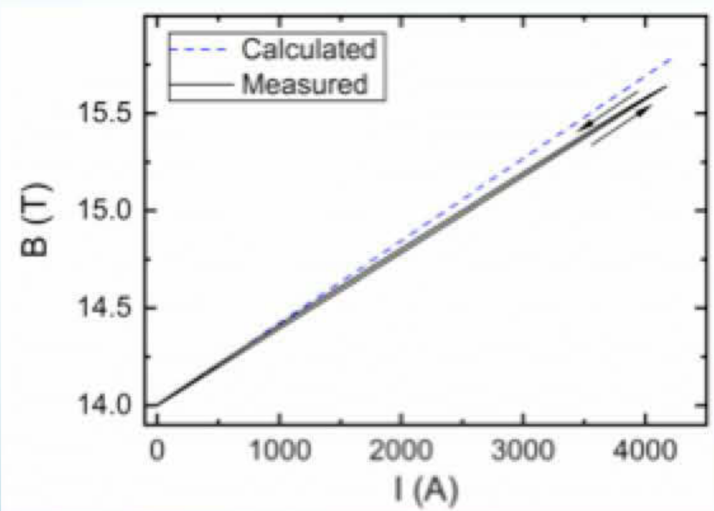


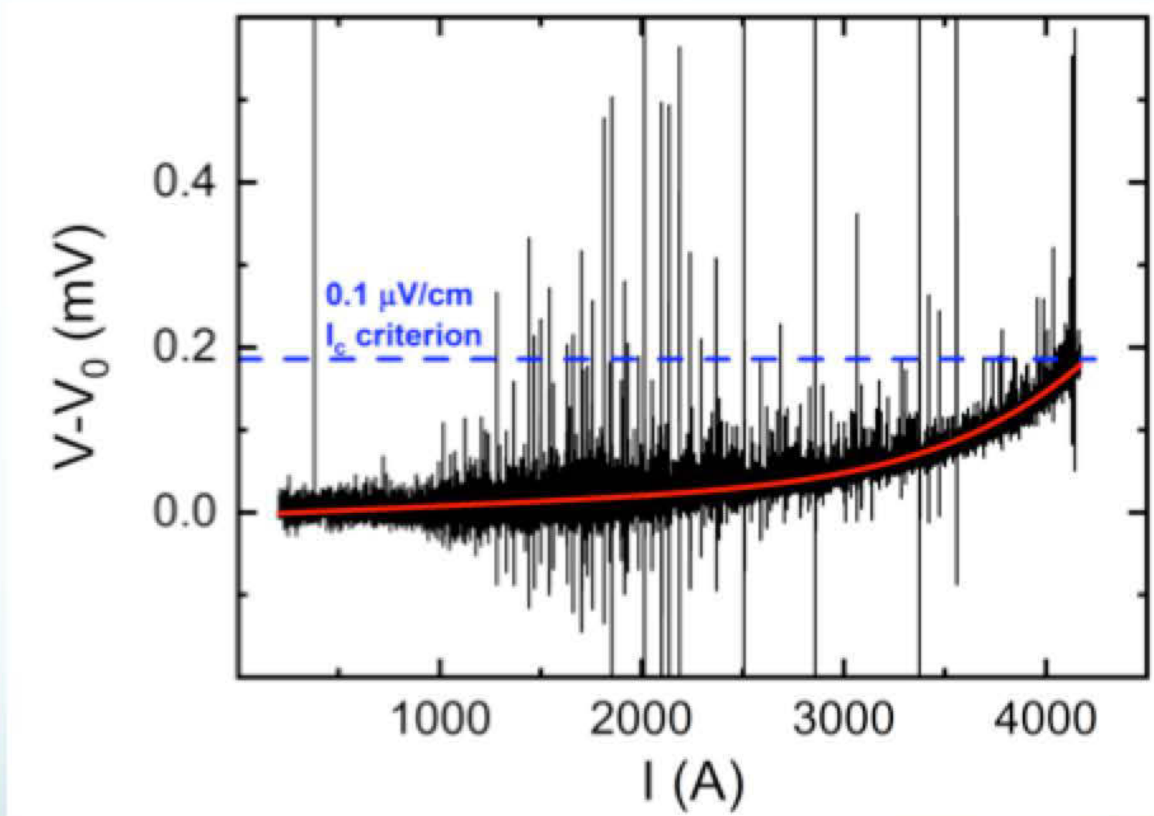


CORC® magnet test: 14 T background field

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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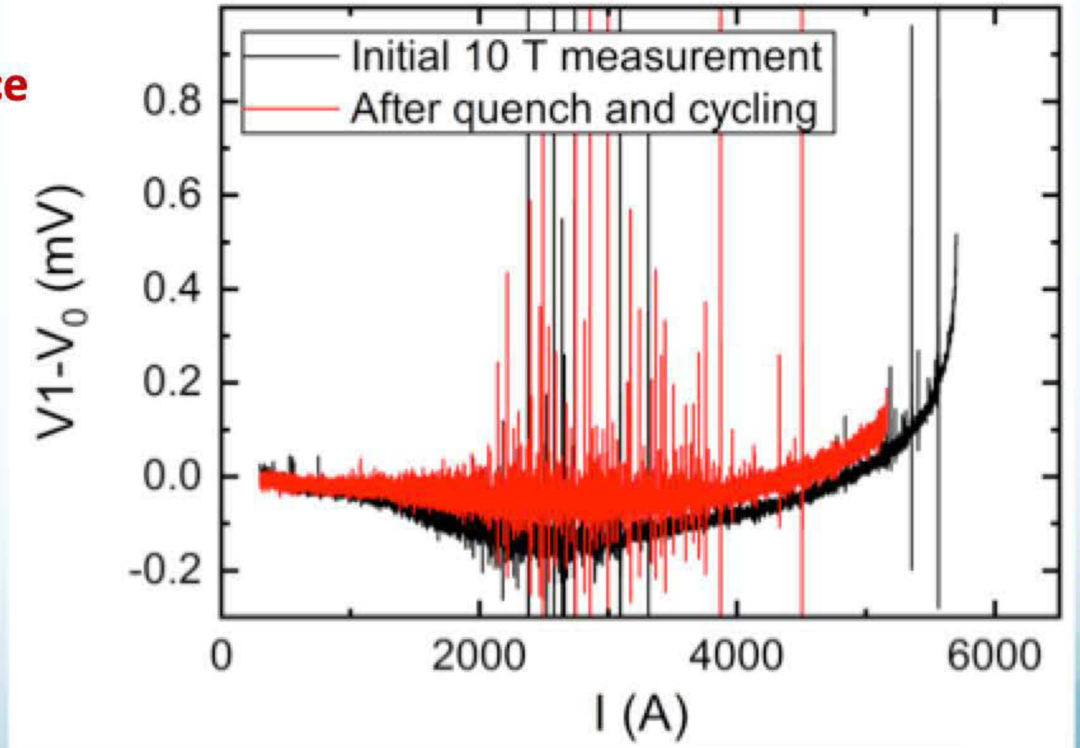
CORC® magnet test: final test at 10 T

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



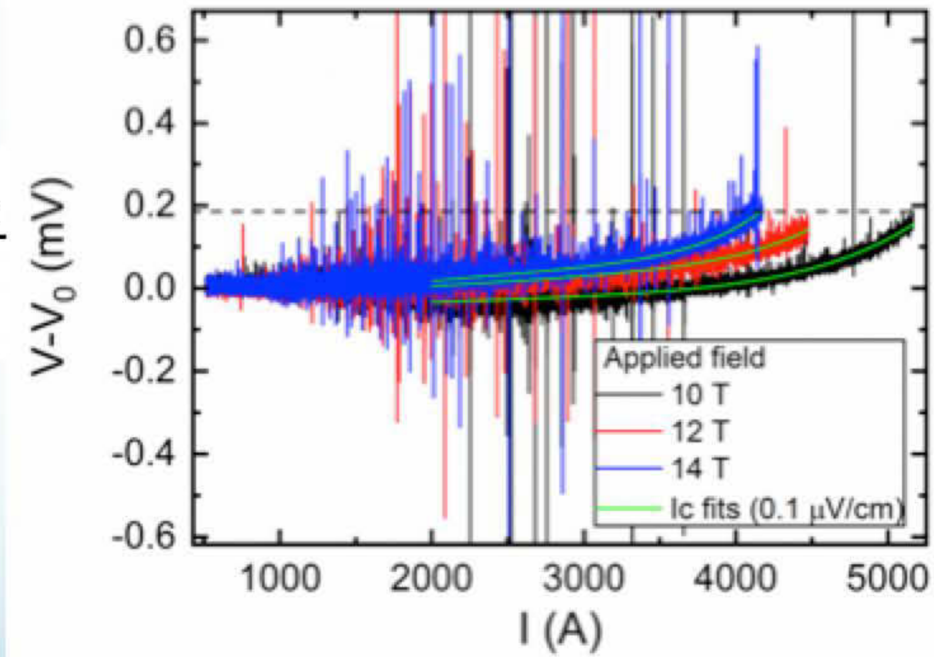
CORC® insert solenoid test: summary

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., under review at Supercond. Sci. Technol. (2020)



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CORC® wire insert solenoid

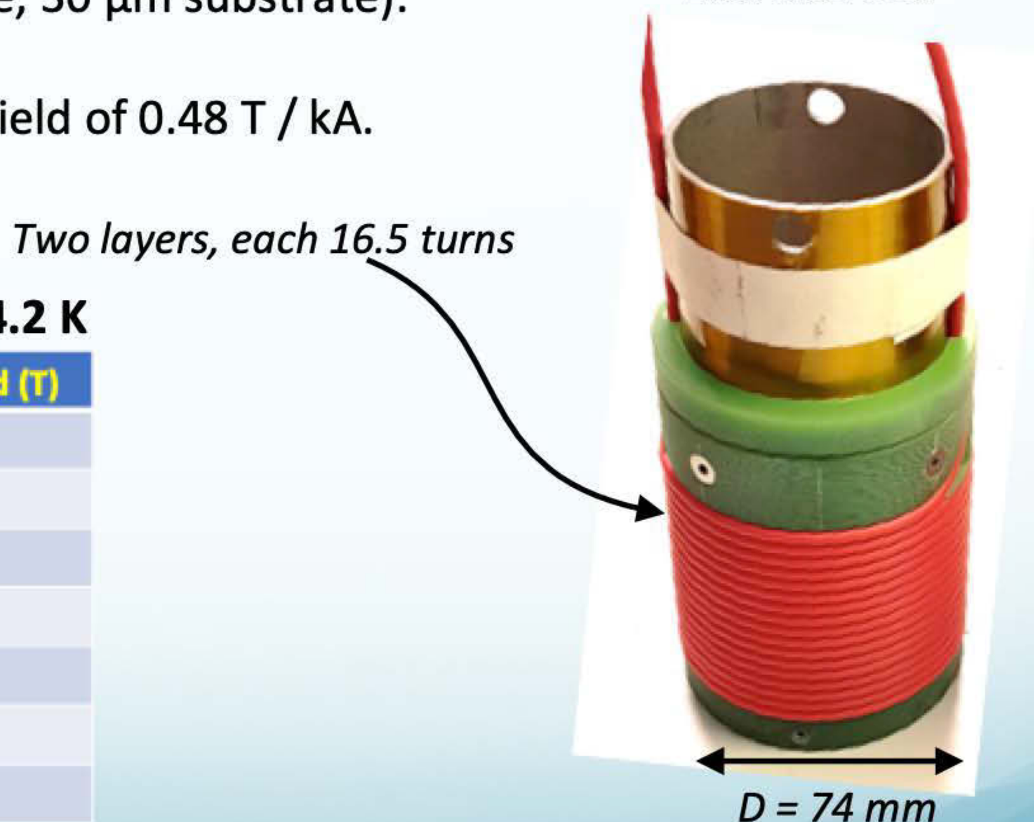
CORC® wire insert magnet (Tim Mulder & Herman ten Kate)

- A series of compact 2-layer CORC® solenoids developed at CERN to demonstrate practical handling, materials choices, conductor robustness, and high performance of CORC® wires for magnets.
- CORC® wire: 27 tapes (2 mm wide, 30 µm substrate).
- Coil ID 60 mm
- Peak field of 0.58 T / kA, central field of 0.48 T / kA.

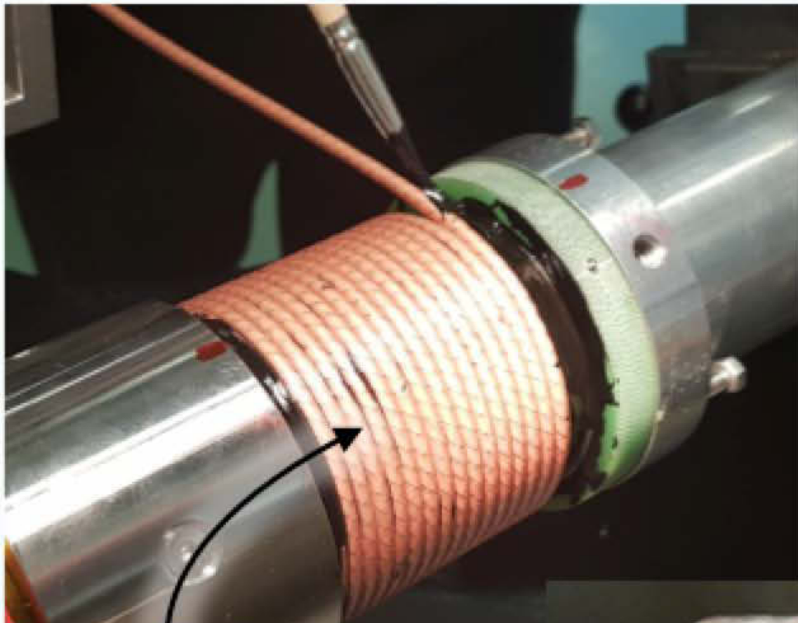
Calculated in-field performance at 4.2 K

BG (T)	Ic (kA)	Peak field (T)	Central field (T)
0	9.76	5.73	4.69
2	8.56	7.02	6.12
4	7.39	8.34	7.55
6	6.50	9.81	9.13
8	5.83	11.4	10.8
10	5.20	13.0	12.5
12	4.74	14.5	14.3

Exercise Coil

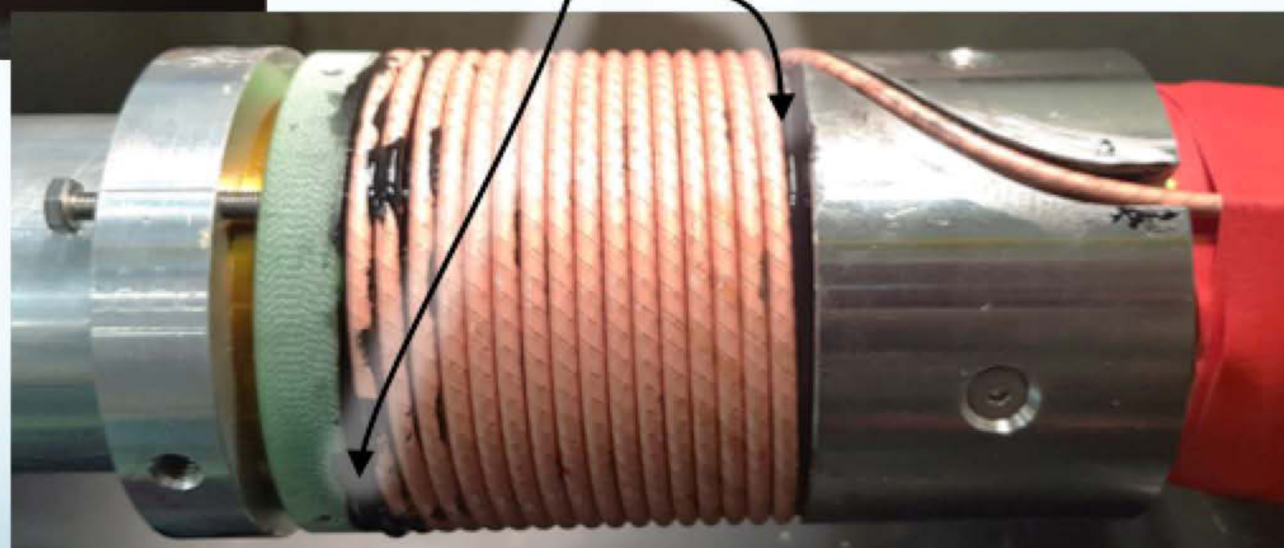


CORC® wire insert solenoid winding

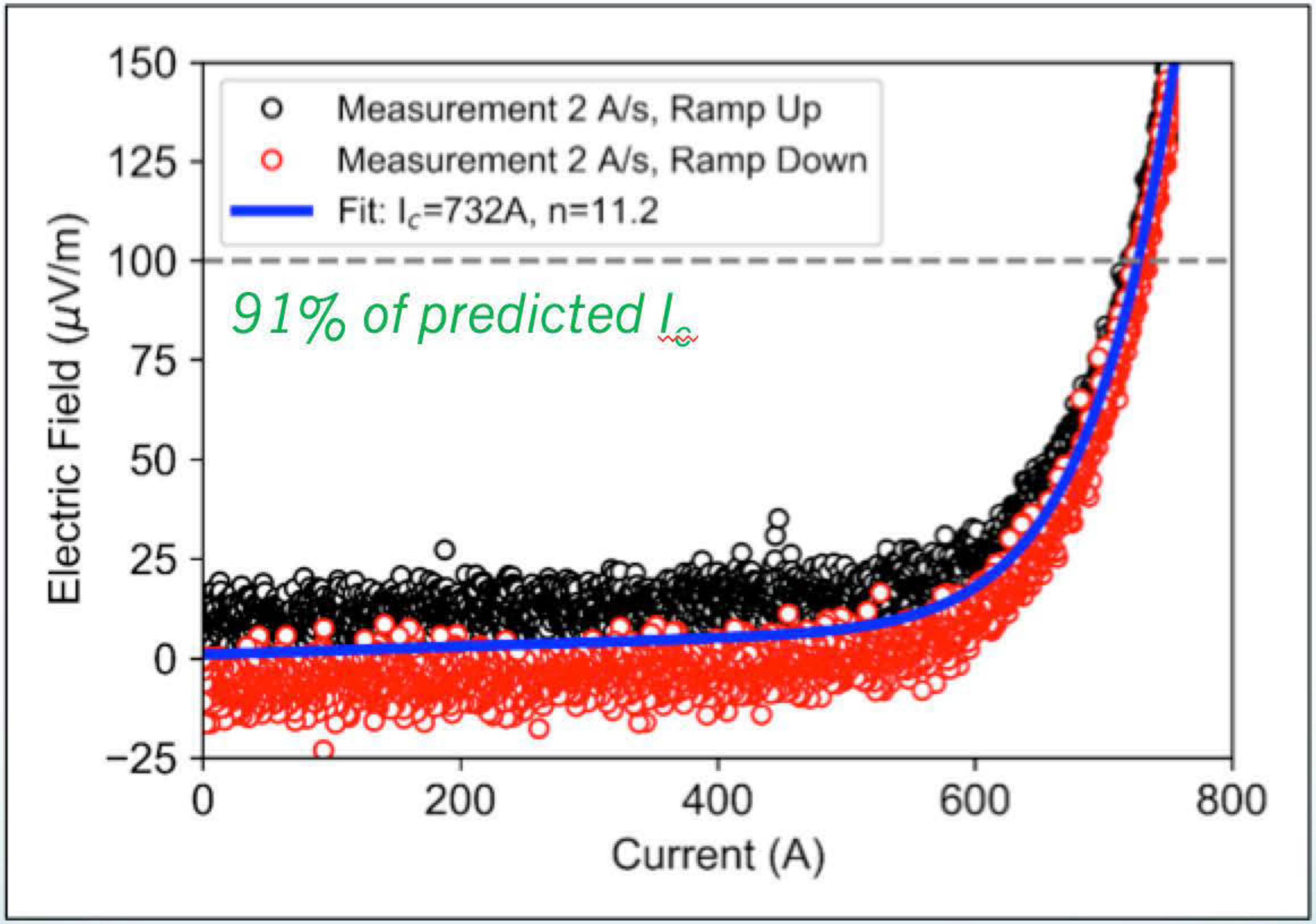


Winding of layer 1

G10 spacers



CORC® wire insert solenoid test at 77 K



Next: in-field test at 4.2 K at the University of Twente

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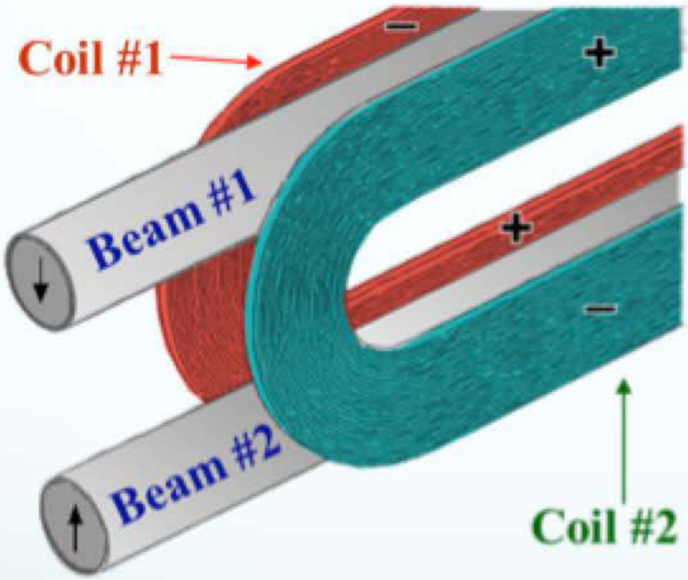
UNIVERSITY OF TWENTE.

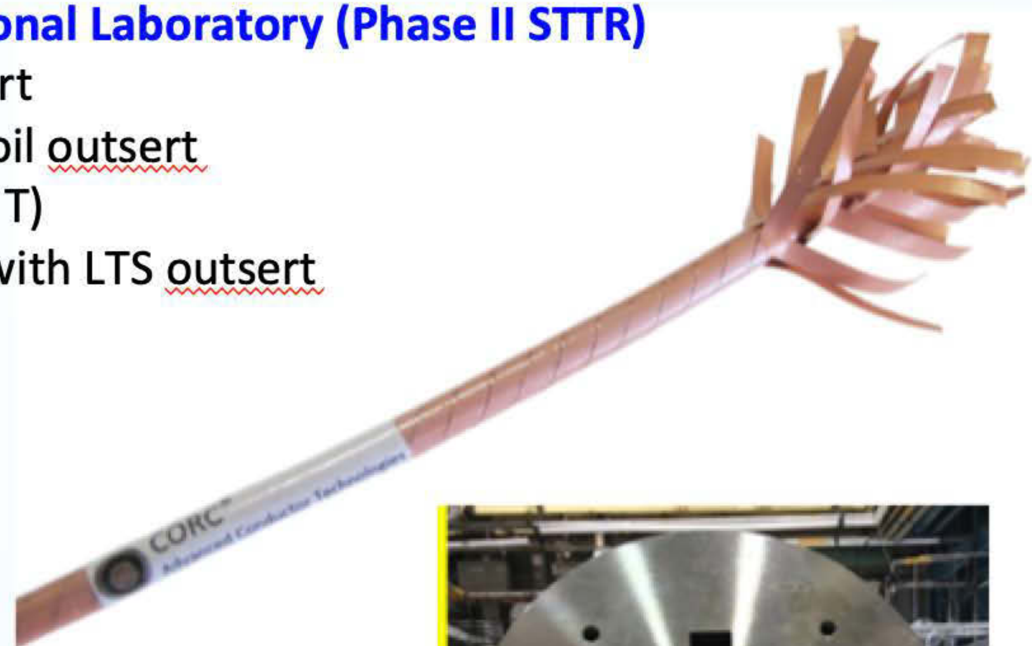
CERN

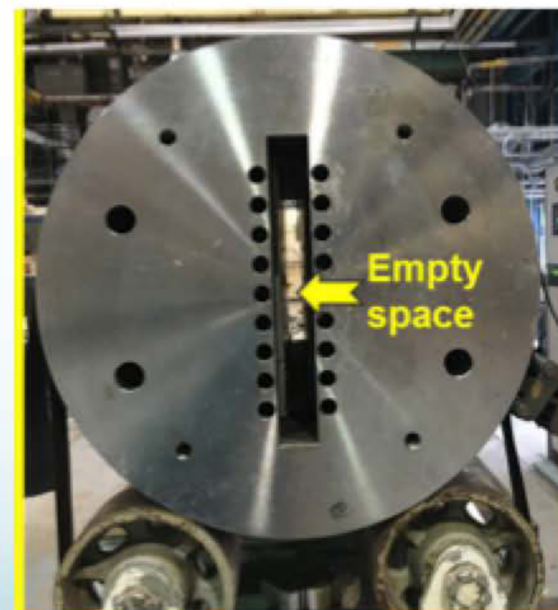
Series-connected Common Coil CORC® magnet

Collaboration with Brookhaven National Laboratory (Phase II STTR)

- 3 T CORC® cable common coil insert
- Combine with 10 T LTS common coil outsert
- Operating J_e 400 – 500 A/mm^2 (20 T)
- Operating current 10 kA in series with LTS outsert







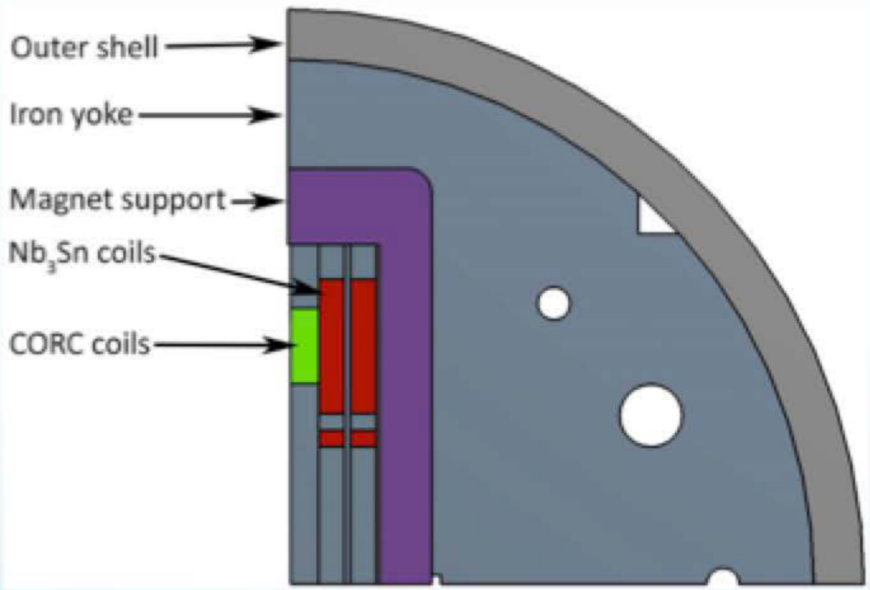
Common coil benefits

- Only large bending diameters required
- Allowing CORC® cables to be used
- Allowing use of highest J_e cables

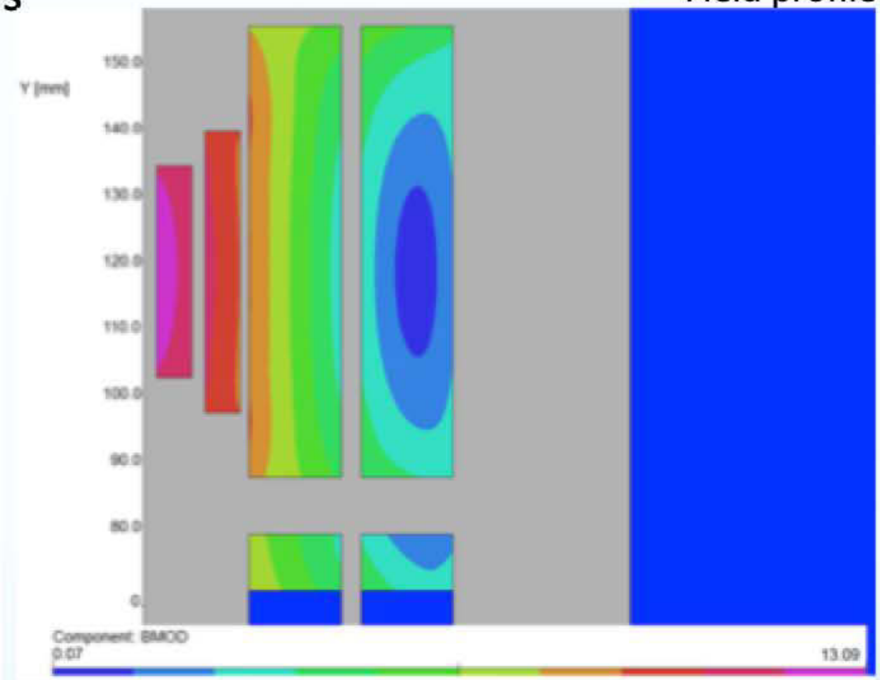
Common Coil magnet design and construction

Common Coil insert design to reach 13 T

- Based on a pair of double CORC® pancakes
- Overall CORC® cable length about 40 meters
- Conductor layout depends on tape I_c
- About 50 % of tapes have been received



Field profile



Timeline

- MDP-funded CORC® coil quench test Q3 2020
- SBIR-funded 13 T series-connected CORC® coil (10 kA) test Q1-2 2021

Summary