CORC®: Results and Perspectives

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Outline

1. CORC® cables current and projected performance
2. CORC® cables applied in Common Coil accelerator magnets
3. CORC® wire development for accelerator magnets
4. CORC® wires wound into solenoids and Canted-Cosine-Theta magnets
5. CORC® magnet feeder cables

CORC® magnet cables and wires

CORC® wires (2.5-4.5 mm diameter)

- Wound from 2-3 mm wide tapes with 30 μm substrate
- Typically no more than 30 tapes
- Highly flexible with bending down to <50 mm diameter

CORC® cable (5-8 mm diameter)

- Wound from 3-4 mm wide tapes with 30 or 50 μm substrate
- Typically no more than 50 tapes
- Flexible with bending down to >100 mm diameter

CORC®-CICC

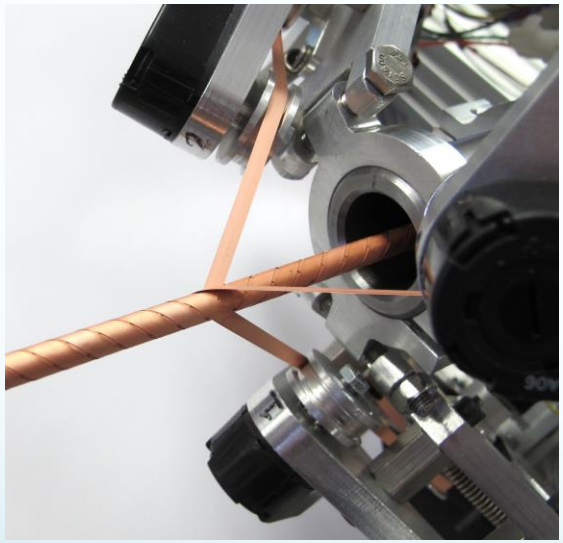
- Performance up to 100,000 A (4.2 K, 20 T)
- Combination of multiple CORC® cables or wires
- Bending diameter about 1 meter

Courtesy Tim Mulder (CERN/Univ. Twente)

Current CORC® cable performance

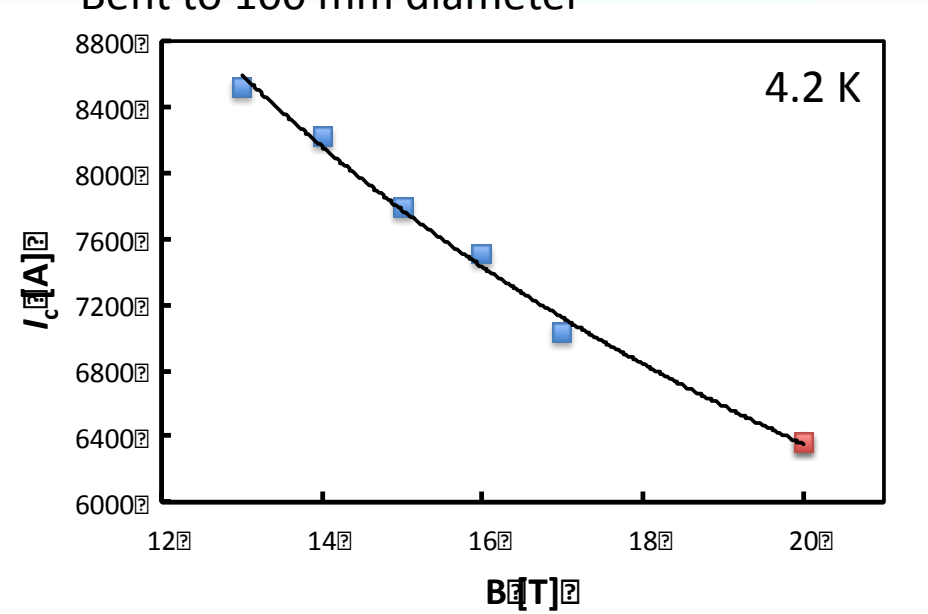
Winding CORC® cables

- Accurate control of cable layout
- Long cable lengths possible
- I_c retention after winding 95-100 %
- 120 meters wound in 2016, of which 70 meter for commercial orders



CORC® cable

- 50 tapes with 30 μm substrate
- 3 mm wide tape I_c (77 K) = 108 A
- Lift factor I_c(4.2K, 20T)/I_c(77K, s.f.) = 1.72
- Bent to 100 mm diameter



Extrapolated I_c (4.2 K, 20 T) = 6,354 A

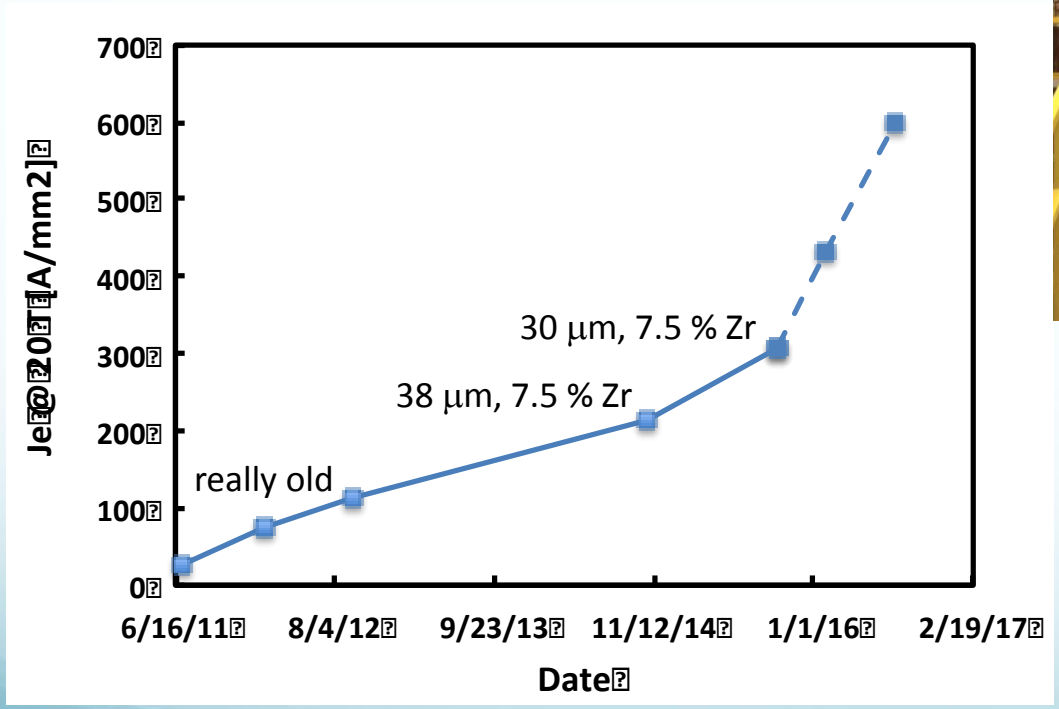
Extrapolated J_e (4.2 K, 20 T) = 309 A/mm^2

Oct. 2015

J_e in CORC® accelerator cables: current and future

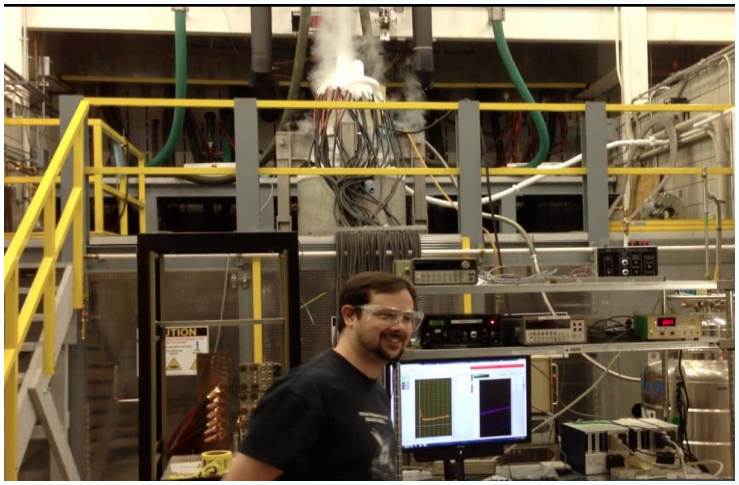
CORC® cable J_e on track to 600 A/mm² at 20 T

- J_e of 309 A/mm² at 20 T achieved in Oct. 2015
- Projected J_e 450 A/mm² mid 2016
- Projected J_e 600 A/mm² early 2017



In-field CORC® cable testing @ 100 mm

- Large bore magnet at NHMFL (17 T)
- Large bore magnet at CU (8.75 T)



Problems!

- NHMFL magnet decommissioned
- Cable I_c at 8.75 T >> 10 kA
- **No new tests after Oct. 2015!**
- **New 14 T large bore magnet expected at NHMFL in 2017**

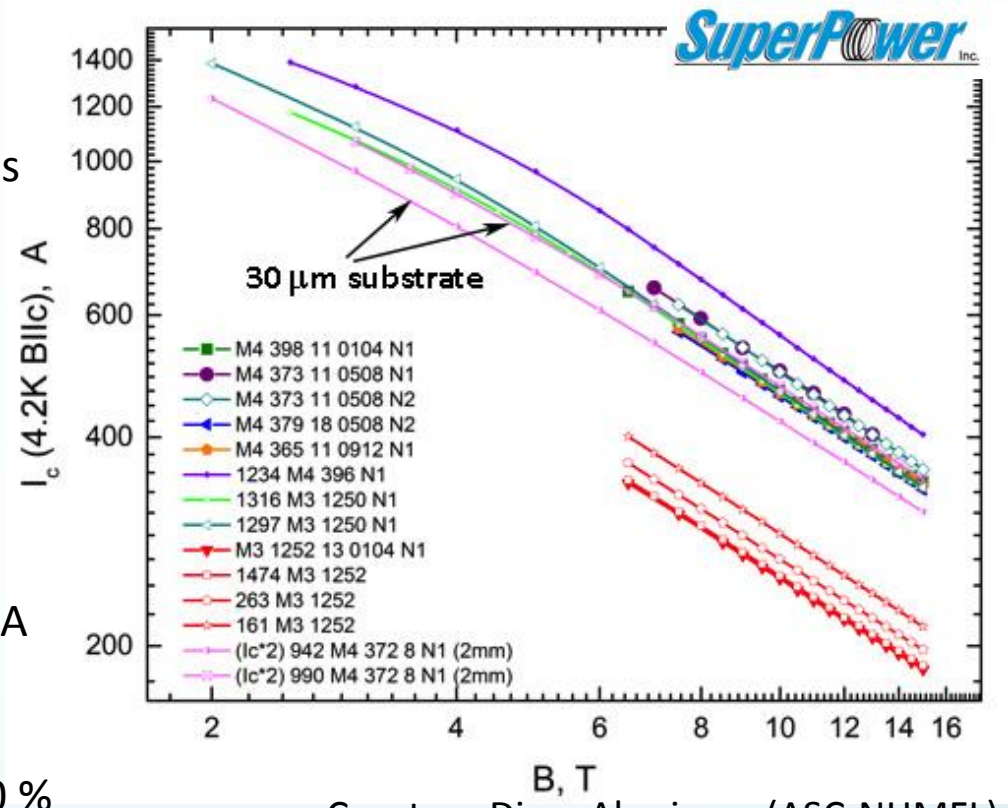
Current CORC® cable performance (untested!)

Performance of commercial tapes

- Purchased 8,300 meters from SuperPower in 2016
- Tapes with 30 and 50 μm substrates

Record 2016 samples

- M4-396: lift factor I_c(4.2K, 20T)/I_c(77K, s.f.) = **2.65**
- Typical lift factor (20 T) = 1.9
- I_c (77 K) = 167 A (4 mm, 50 μm)
- I_c (77 K) = 82 A (2 mm, 30 μm)
- Typical I_c (4 mm) 150 A, (2 mm) 68 A



Courtesy Dima Abraimov (ASC-NHMFL)

CORC® cable Oct. 2015 J_e(20 T)

- All estimates with I_c retention of 70 %
- Typical I_c and lift factor: J_e(20 T) = 375 A/mm^2
- Highest I_c and lift factor: J_e(20 T) = 560 A/mm^2
- At 90 % I_c retention: J_e(20 T) = 480-720 A/mm^2

- **On track to J_e(20 T) > 600 A/mm^2**
- **Need magnet to demonstrate!**

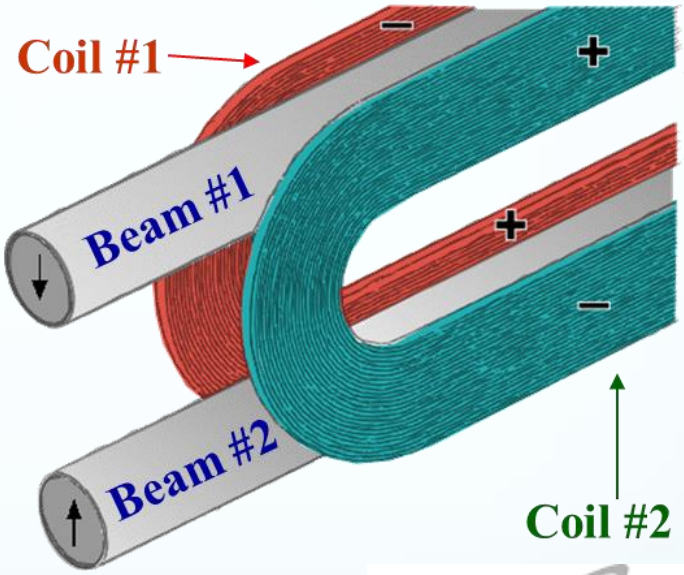
CORC® cables for Common Coil accelerator magnets

CORC® cables are ready for the next step

- R&D for their application into magnets
- Cable bending diameter > 100 mm
- Cable J_e(20 T) > 400 A/mm^2
- Operating current > 10,000 A (20 T)

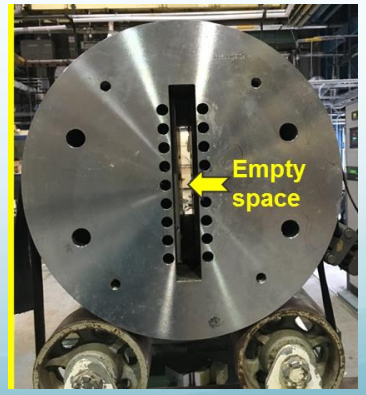
Common Coil magnet ideal for CORC® cables

- Conductor friendly design
- Performance determined by coil separation, not cable bending diameter
- Allows for large bending diameters > 250 mm



Proposed program to Department of Energy

- Teaming with Ramesh Gupta (BNL)
- 10 T LTS Common Coil outsert magnet
- Phase I SBIR funding requested to develop 5 T CORC® insert magnet



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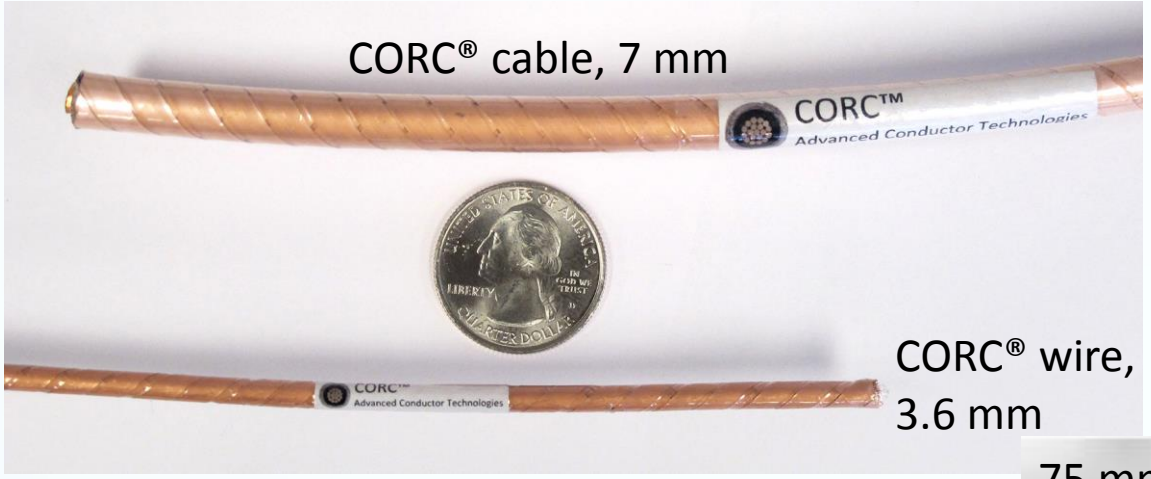
Introduction of flexible CORC® magnet wires



CORC® cables

- Cable diameter 5 – 8 mm
- Bendable to >100 mm diameter
- Typically 50 tapes or less (3 mm or 4 mm wide)
- Easier to reach high J_e (20 T)

CORC® wires

- Tapes with 30 µm substrate
- Wire diameter 2.5 – 4.5 mm
- Bendable to < 50 mm diameter
- Typically 30 tapes or less (2 mm and 3 mm)
- Size and flexibility requirements make it harder to reach high J_e(20 T)

First round, isotropic YBCO wire!

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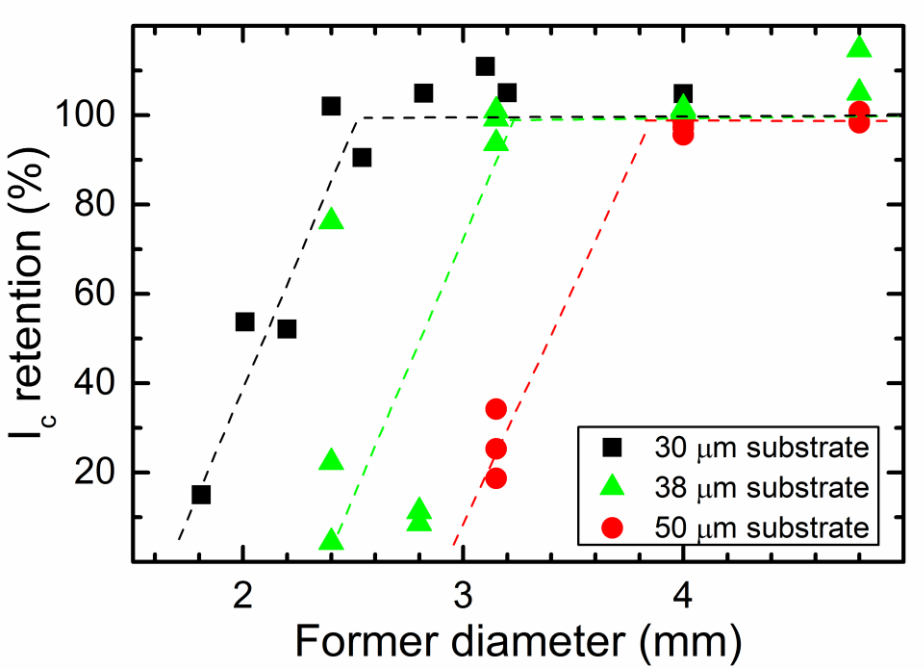
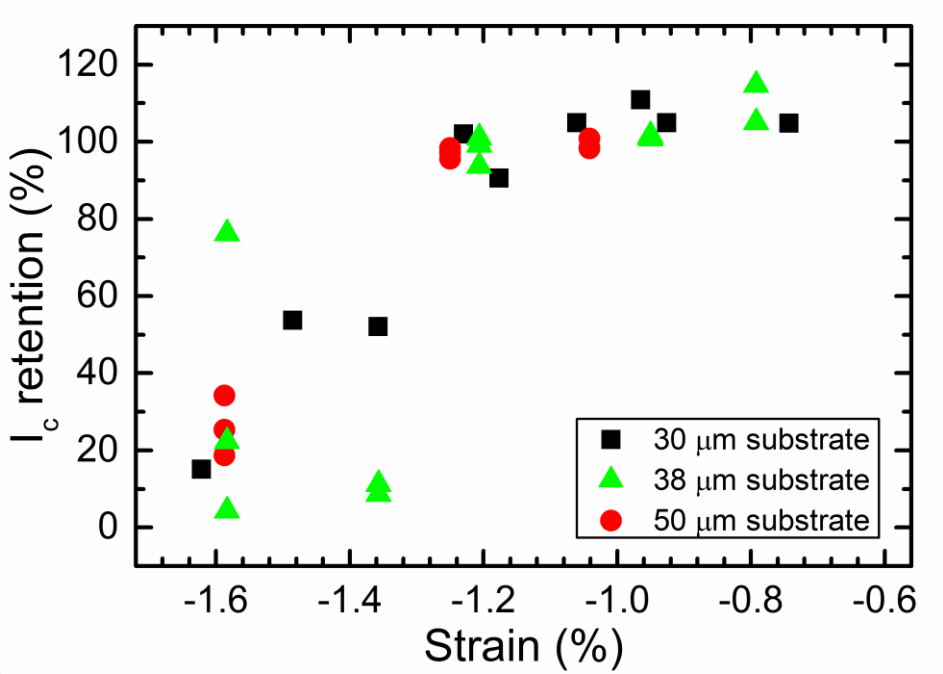
Thinner substrates enable CORC® wires

I_c retention test

- tapes with 30, 38 and 50 µm sub.
- ensuring a winding angle of 45°





Degradation starts at compressive strain exceeding -1.2 %

Minimum former diameter

- 4 mm for 50 µm substrate
- 3.2 mm for 38 µm substrate
- **2.4 mm for 30 µm substrate**

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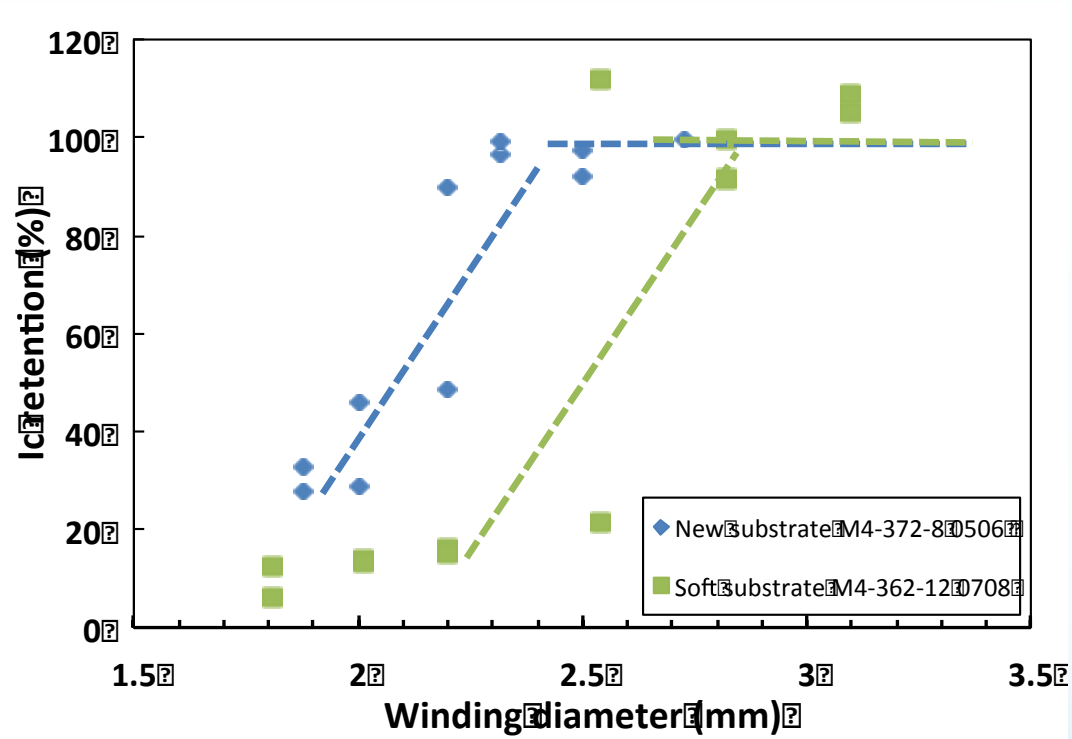
Strain tolerance depends on substrate quality

Tapes on 30 μm substrate from two Hastelloy batches

- Earlier batch of softer substrate material
- Latest batch with harder substrate material



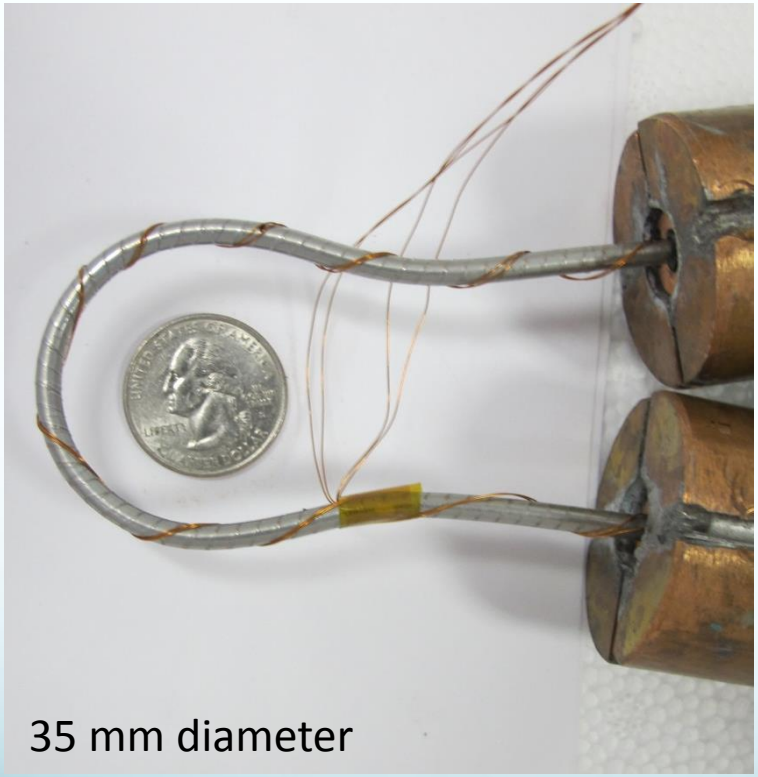
Substrate hardness or overall quality likely to affect minimum former size

Testing of CORC® wire flexibility

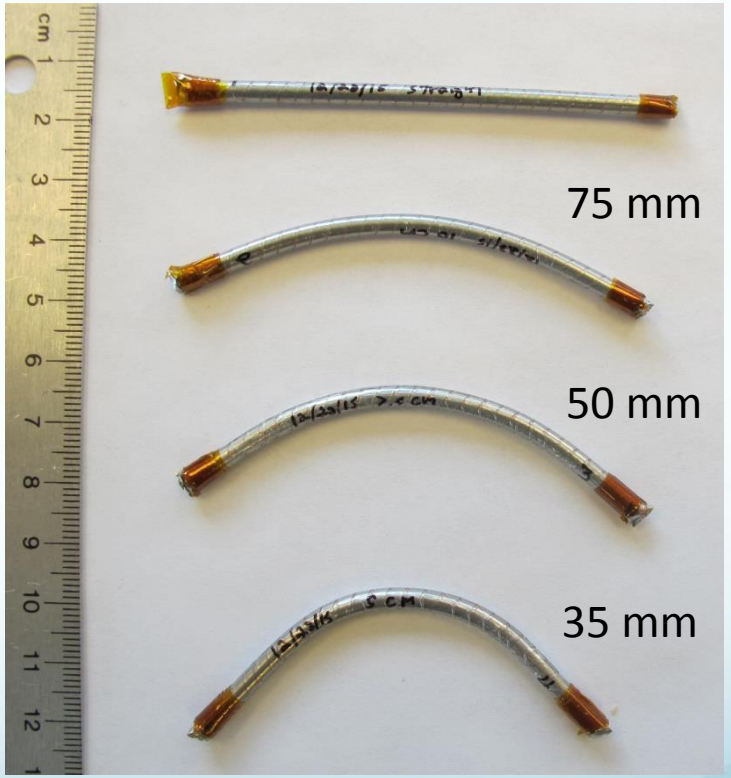
CORC® wire layout

12 tapes of 2 mm width (3.3 mm O.D.)

Bending wire followed by I_c measurement

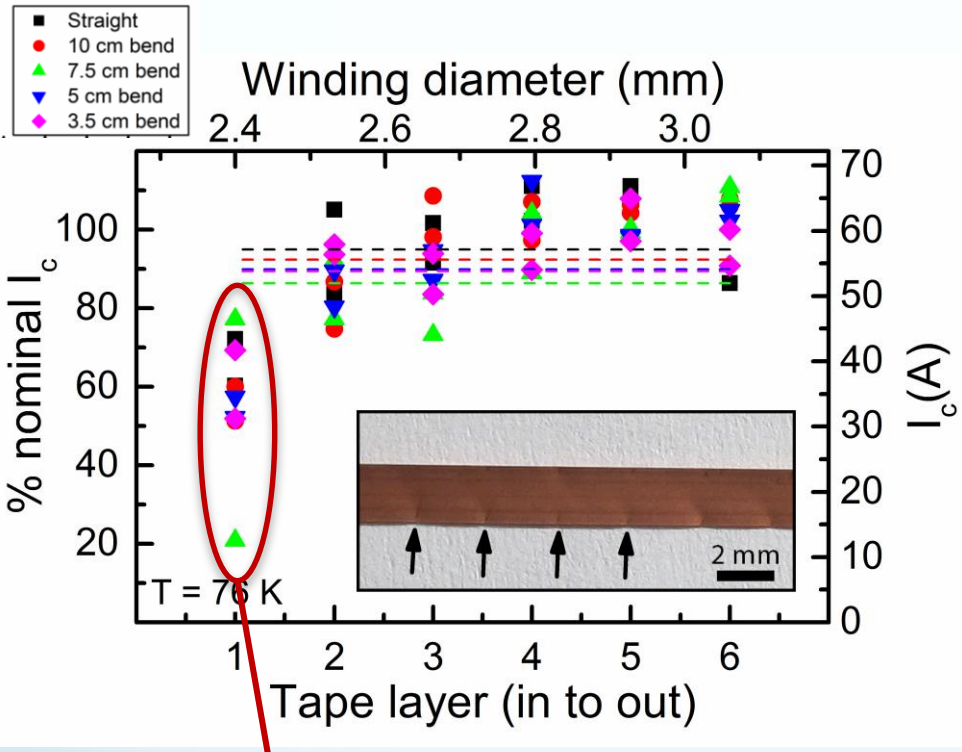


Bending wire sections followed by extracted tape I_c measurements



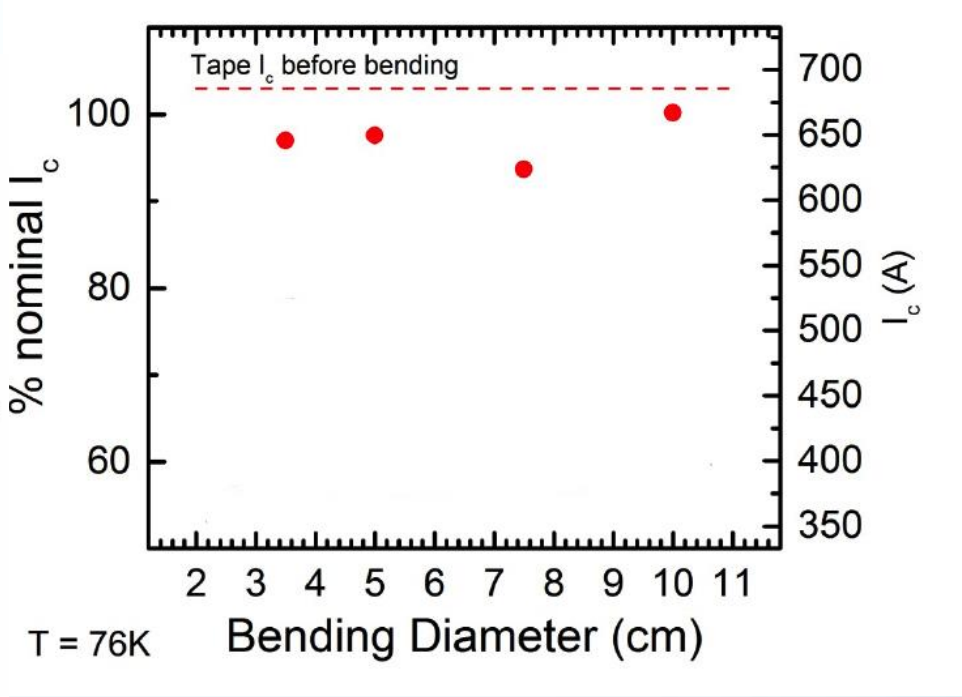
12-tape CORC® wire bending results

Bending wire sections followed by 2 mm wide tape I_c measurements



Degradation in inner layer due to surface roughness

CORC® wire I_c measurements after wire bending



> 93 % I_c retention even at 35 mm bending diameter

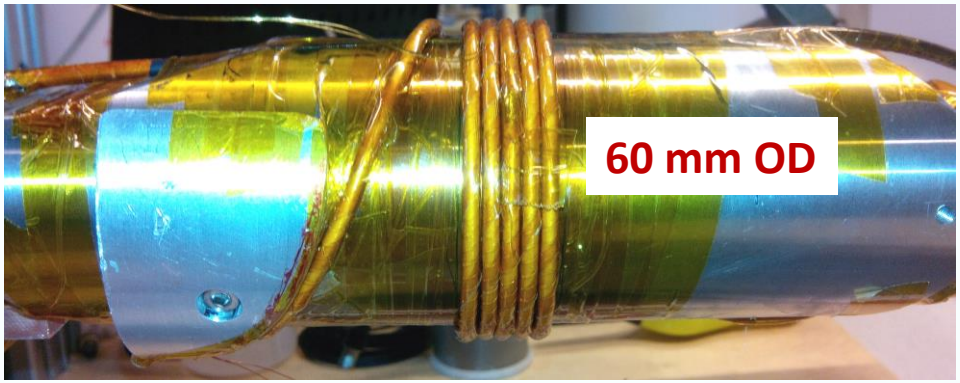
In-field performance of 16-tape CORC® wire

CORC® wire layout

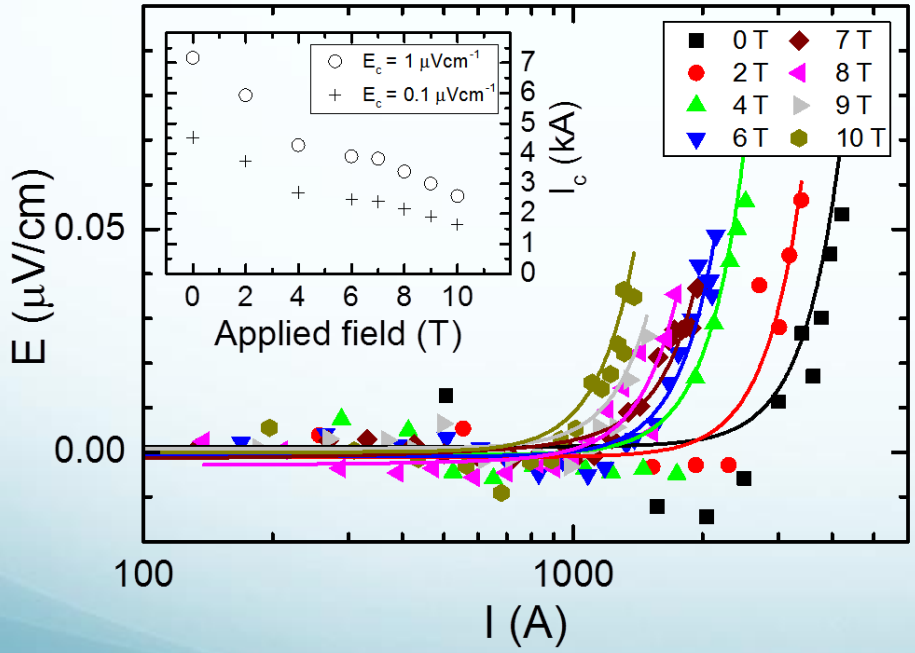
- 16 tapes of 2 mm width
- 3 mm diameter
- Expected I_c(10 T) = 2,900 A

Test layout

- 5 turns at 60 mm diameter
- Stycast reinforcement



Courtesy Tim Mulder (Univ. Twente/CERN)



Results

- I_c 1,695 A (4.2 K, 10 T, 0.1 μV/cm)
- I_c 2,560 A (4.2 K, 10 T, 1 μV/cm)
- Projected J_e(20 T) 145-210 A/mm^2

80 % I_c retention after extracted tape measurements agrees with CORC® wire measurement

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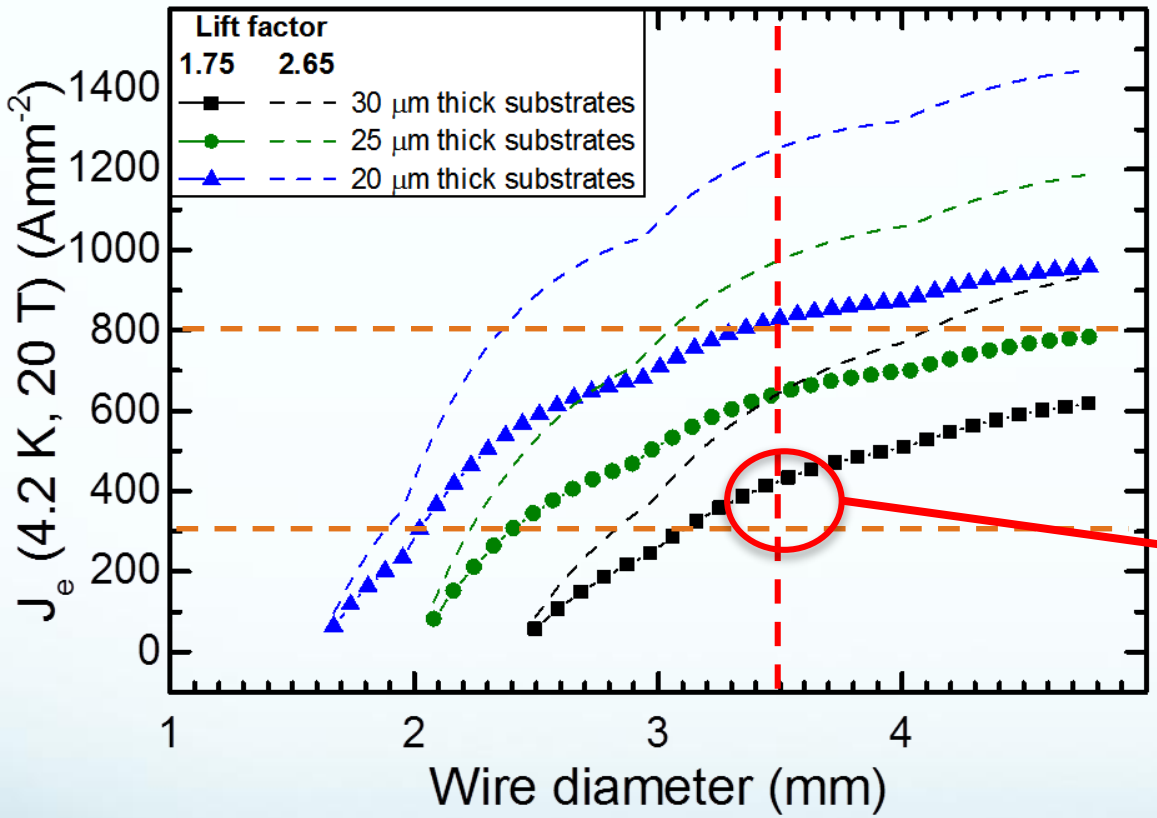
Projected J_e of CORC® wires

Advanced Conductor Technologies is working with SuperPower to further decrease the substrate thickness to 20-25 μm



29-Tape CORC® wire with J_e(20 T) > 300 A/mm² to be tested next week

J_e(20 T) of a 3.5 mm CORC® wire likely to increase from 300 A/mm² to 1,000 A/mm² when combining lift factor of 2.65 with 20 μm thick substrates

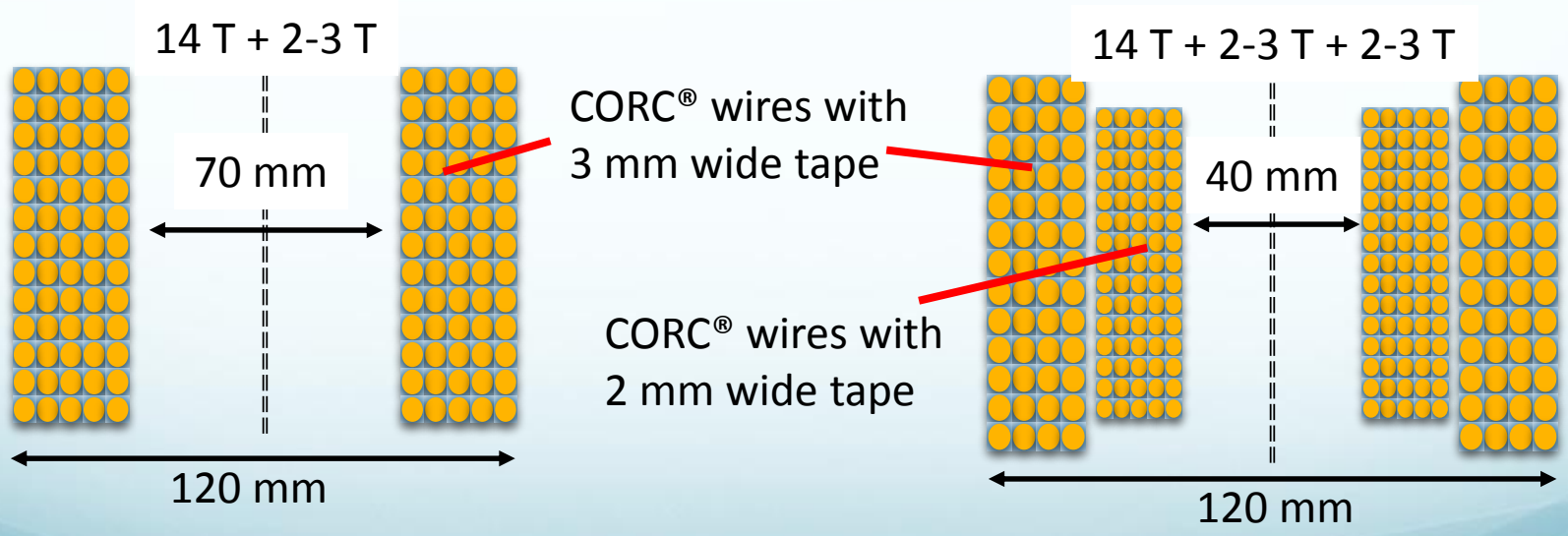
CORC® wires in high-field insert solenoid

Final deliverable Phase II SBIR with ASC-NHMFL

- Develop high-field insert solenoid wound from CORC® wires
- Test insert magnet at 14 T background field at ASC-NHMFL
- Aim for added field of at least 2-3 T, maybe 5 T depending on tape performance

CORC® wire solenoid details

- CORC® wires wound from 3 mm wide tape with 30 μm substrate
- 1,500 meter tape ordered, 1/3 already delivered
- CORC® wire length 20-30 meters depending on tape performance
- Potential for second insert using CORC® wires with 2 mm wide tape



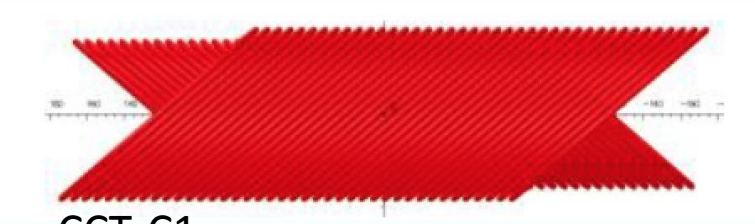
CORC® wires in Canted-Cosine-Theta magnets

Teaming up with Lawrence Berkeley National Laboratory

- Develop 5 T Canted-Cosine-Theta insert
- Insert wound from CORC® wires
- More details Xiaorong Wang talk tomorrow

Several steps

1. 2-layer insert C1
2. 4-layer insert C2
3. …



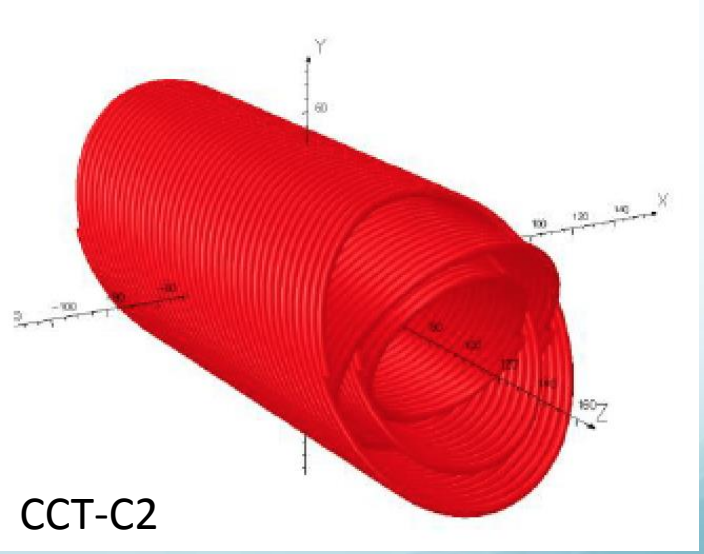
CCT-C1

CCT insert C1

- 2-layers, 40 turns per layer
- Determine feasibility and field quality
- 16-tape CORC® wire
- 50 meter CORC® wire delivered Aug. 2016

CCT insert C2

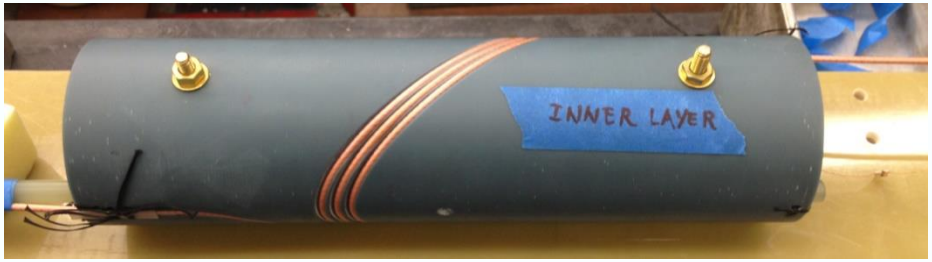
- 4-layers, 40 turns per layer
- Push for field: 2-3 T in 10 T external field
- 29-tape CORC® wire, expected J_e(20 T) 300 A/mm^2
- 100 meter CORC® wire order expected 2017



CCT-C2

C0: CORC® wire test for CCT-C1

Layer A



Layer B

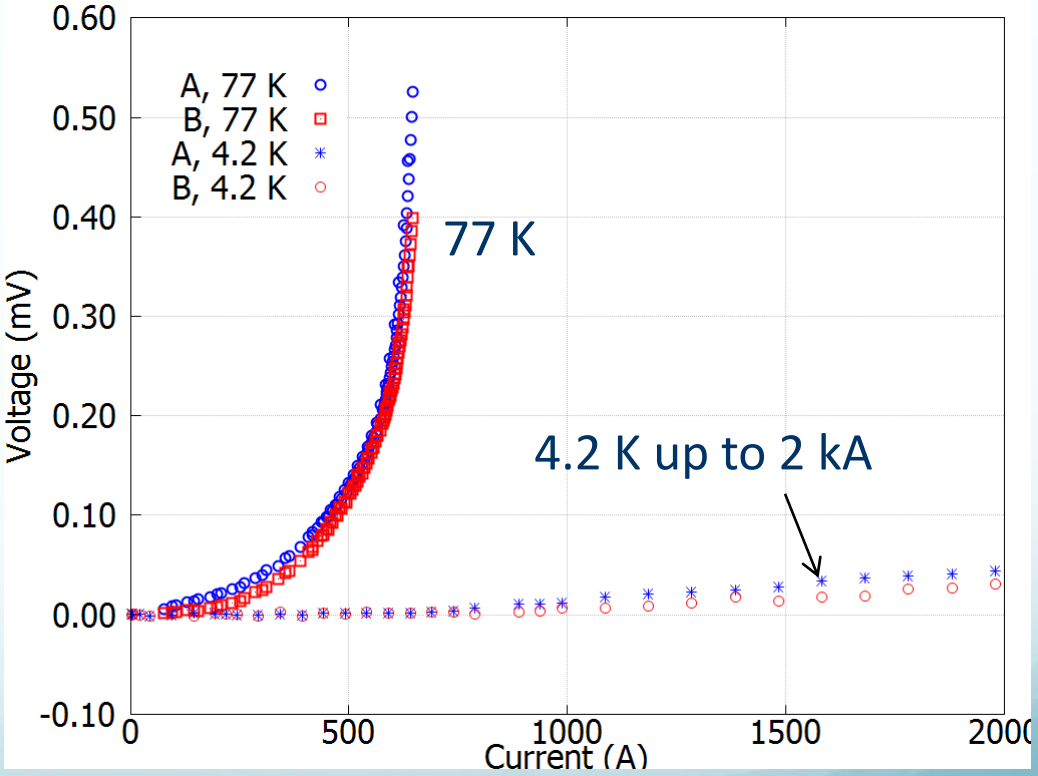
CCT C1

- Inner layer I.D. 70 mm
- Minimum bending diameter 50 mm

16-tape CORC® wire

- I_c (77 K) before winding = 718 A
- I_c (77 K) after winding = 662 A
- Only 8 % lower after winding

- **Feasibility of using CORC® wires in CCT magnets has been demonstrated**
- **4.2 K measurement needs better power supply (end of February)**



CORC® magnet feeder cables

CORC® magnet feeders

- Bi-2212 insert of the 23.5 T Platypus NMR magnet (I_{opp} = 400 A) (Ulf Trociewitz)
- REBCO insert coils of the 32 T magnet (I_{opp} = 200 A) (Huub Weijers)

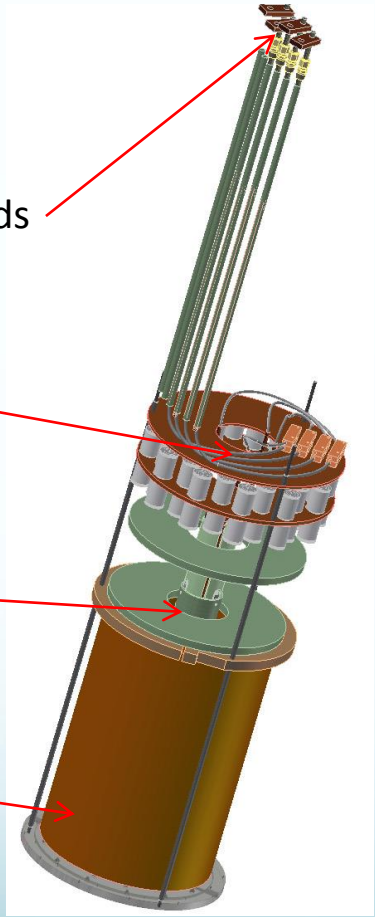
Platypus

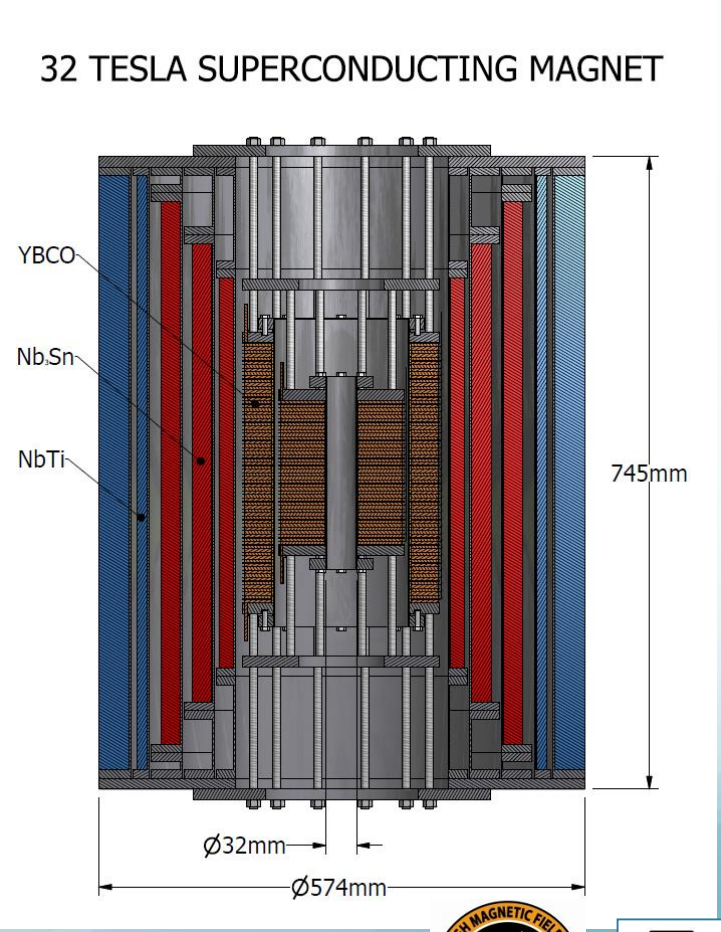
500 A vapor cooled leads

CORC® feeders

7.1 T Bi-2212 Magnet System

16.4 T magnet

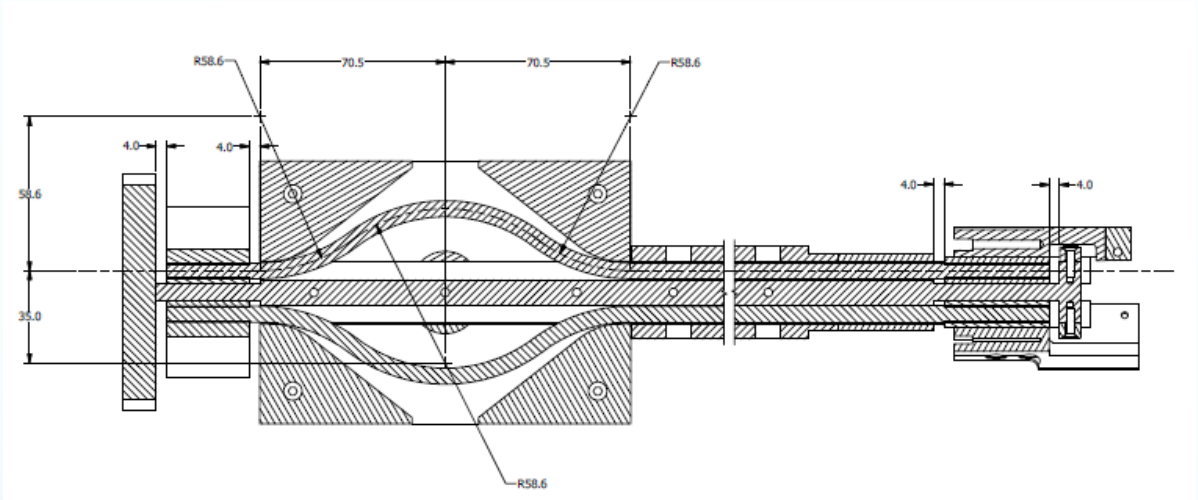


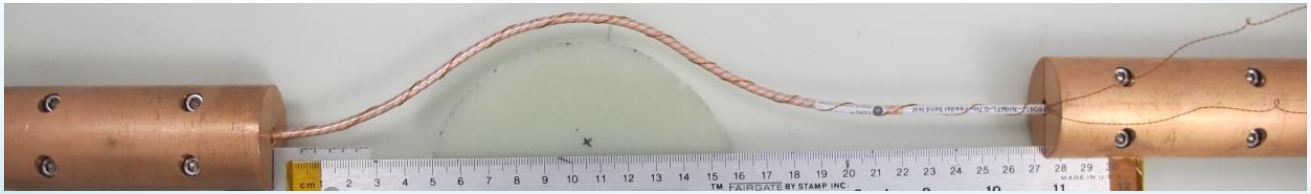


CORC® feeder cables: 32 T magnet

CORC® feeders for 32 T magnet

- I_{opp} = 200 A
- Background field 23 T
- Vertical motion of 4-8 mm during cool down and field ramping





Feeders delivered in 2016 and are installed into the 32 T magnet

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Summary

CORC® cables with bending diameter > 100 mm

- Demonstrated J_e(20 T) = 309 A/mm^2
- On track to reach J_e(20 T) > 600 A/mm^2
- No new CORC® cables measured at high field after Oct. 2015 due to decommissioning of large-bore magnet at NHMFL
- CORC® cables are ready for conductor friendly accelerator magnets such as Common Coil magnets

CORC® wires with bending diameter < 50 mm

- Demonstrated J_e(20 T) = 145-210 A/mm^2
- On track to reach J_e(20 T) > 300 A/mm^2 (Twente test next week)
- CORC® wires with thinner substrates and J_e(20 T) > 1,000 A/mm^2 on the horizon
- CORC® wires now wound into high-field solenoid and CCT insert magnets

CORC® magnet feeder cables now available

- CORC® feeder cables incorporated in 32 T REBCO magnets at NHMFL

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