Enhanced flexibility of round high-temperature superconducting CORC® Wires for high-field magnet applications

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Introduction

Three major conductor challenges for >20 T HTS accelerator magnets

1. High engineering current density J_e (20 T) > 600 A/mm^2
2. Small cable bending diameters 30 – 50 mm
3. Practical and low-risk means of making the magnets

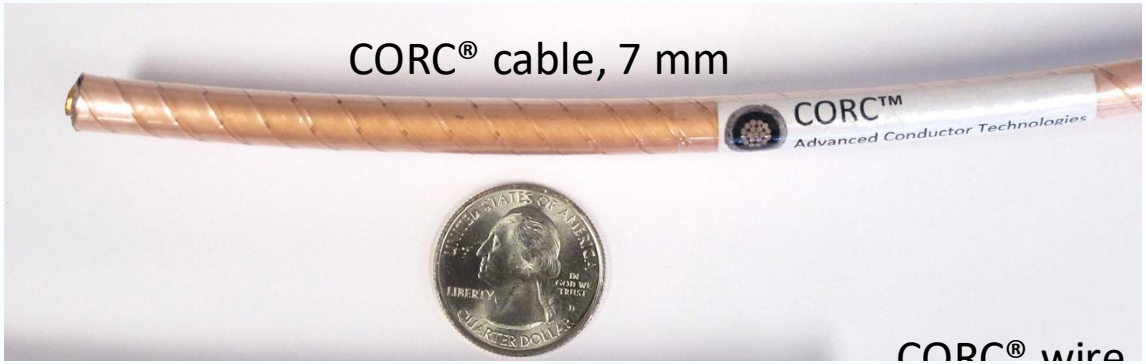
CORC® cable principle

Winding many HTS YBCO coated conductors in a helical fashion with the YBCO under compression around a small former.

Initial CORC® cable development 2012-2015

- Up to 50 tapes wound in 20 layers with I_c from anywhere up to 10 kA+
- Tapes with 50 μm substrate and 10 μm copper plating
- Cable outer diameter 6-8 mm

Development of CORC® magnet wires



CORC® cables

- tapes with 50 μm substrate
- tapes of 3 mm and 4 mm width
- O.D.: 5 – 10 mm

CORC® wires

- tapes with 30 μm substrate
- tapes of 2 mm and 3 mm width
- O.D.: 2.5 – 5 mm

Going from cables to wires increases conductor flexibility

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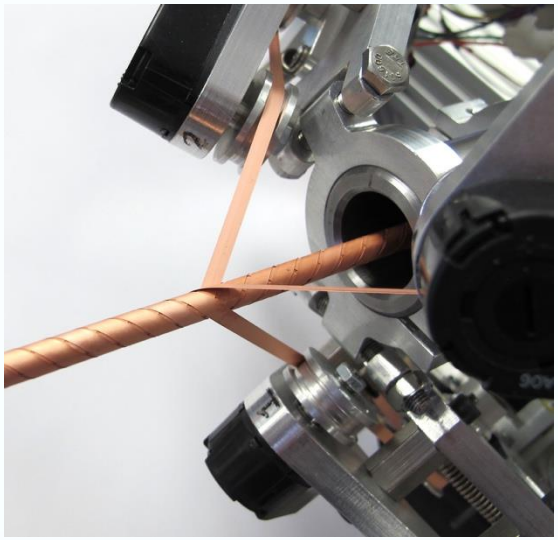
Two wires were constructed for bending tests



Cabling machine winding 3 tapes into a single layer

Wire 1: "2 mm wide tapes"

- Wound using 2 mm wide tapes
- 6 layers of tape with 2 tapes/layer
- Nominal tape I_c: 55.5 A (76 K)
- Nominal wire I_c: 665.8 A (76 K)
- Wire diameter: 3 mm

Wire 2: "3 mm wide tapes"

- Wound using 3 mm wide tapes
- 12 layers of tape with 2 or 3 tapes/layer
- Nominal tape I_c: 73-83 A (76 K)
- Nominal wire I_c: 2217 A (76 K)
- Wire diameter: 4.7 mm

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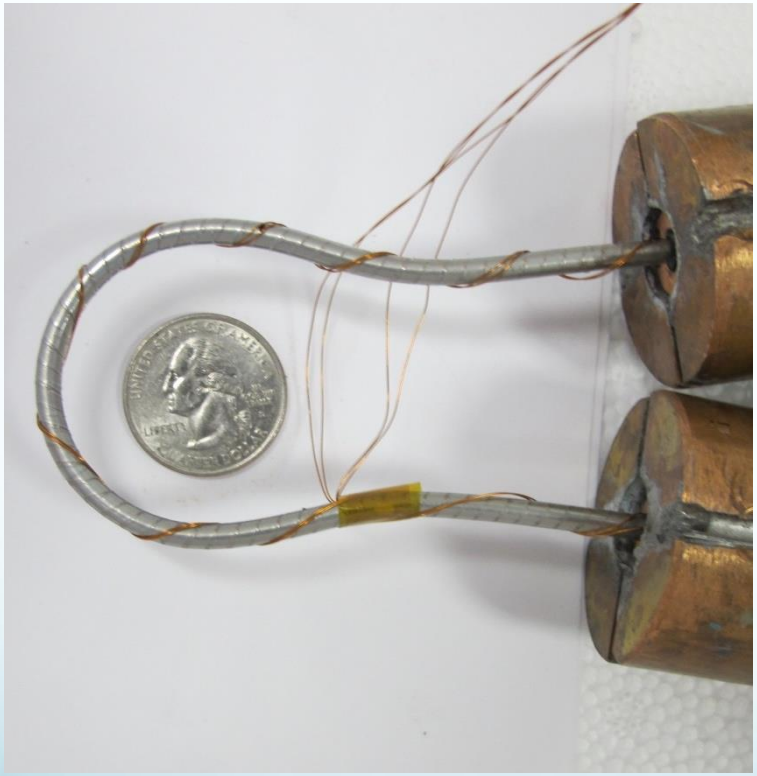
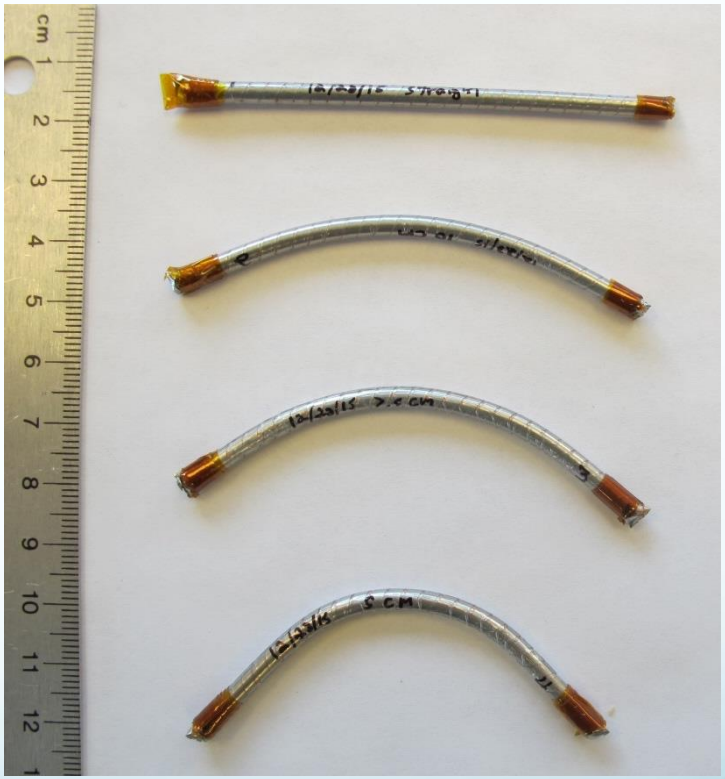
Testing the CORC® wire flexibility

Bending wire followed by I_c measurement



Bending wire sections followed by extracted tape I_c measurements



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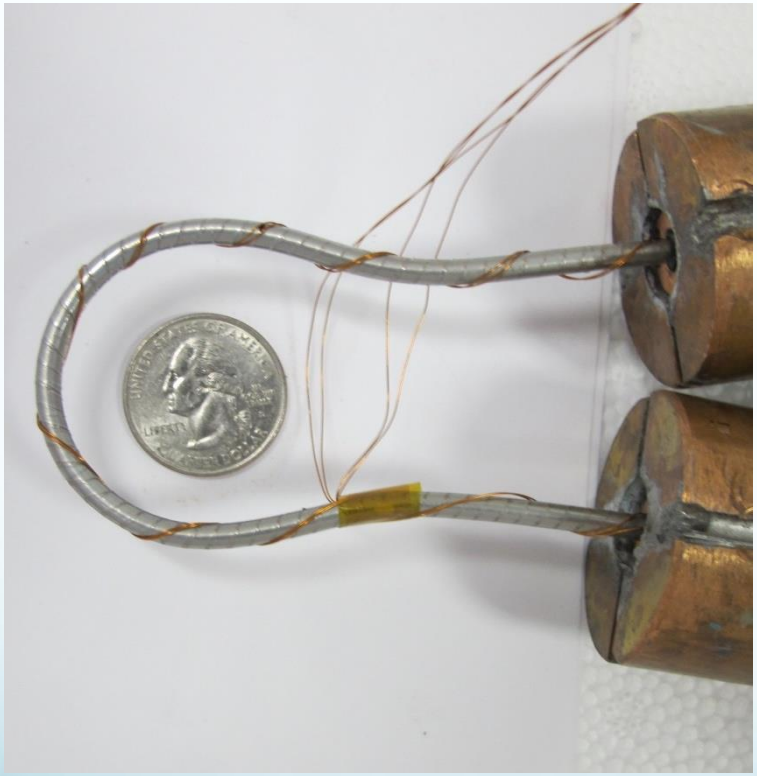
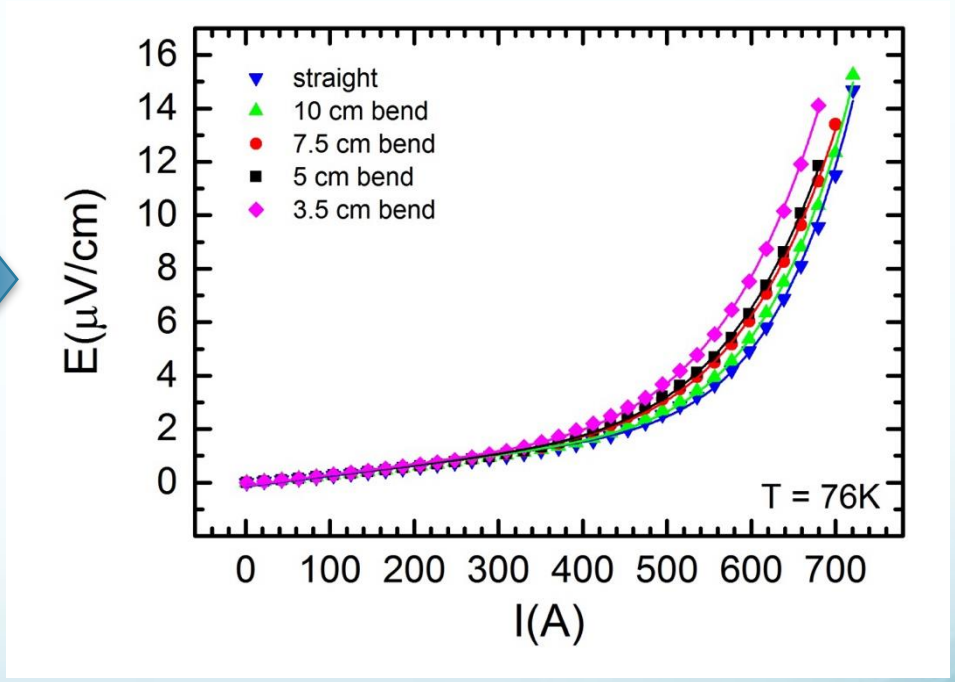
CORC® Wire 1 (2 mm wide tapes) bending results

Bending wire followed by I_c measurement



After bending to 3.5 cm the cable retains 85% I_c compared to before bending.

Strain and/or self-field could contribute to trend



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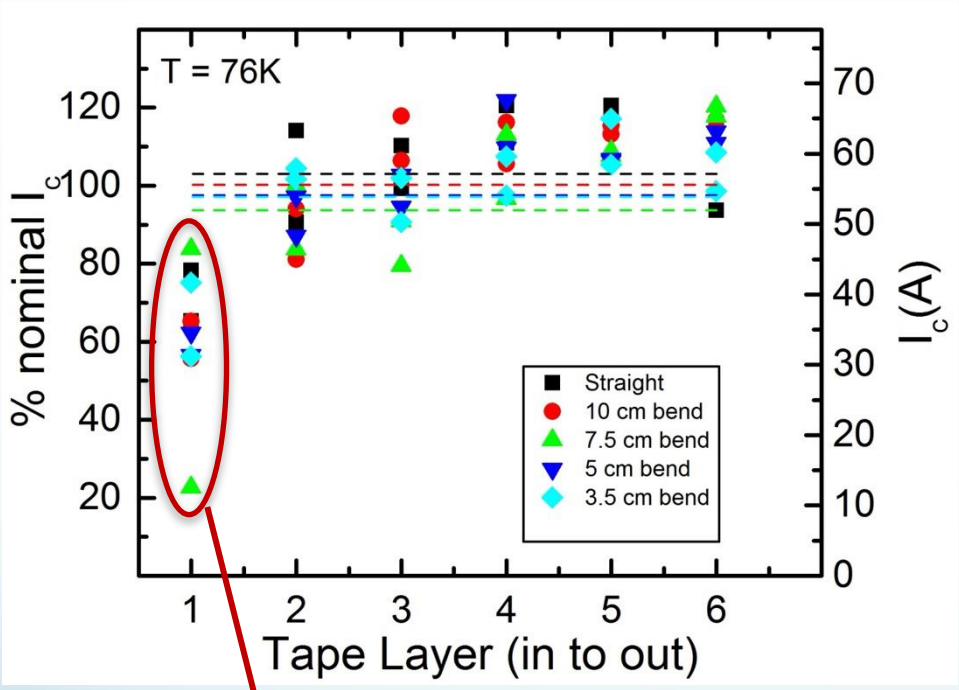
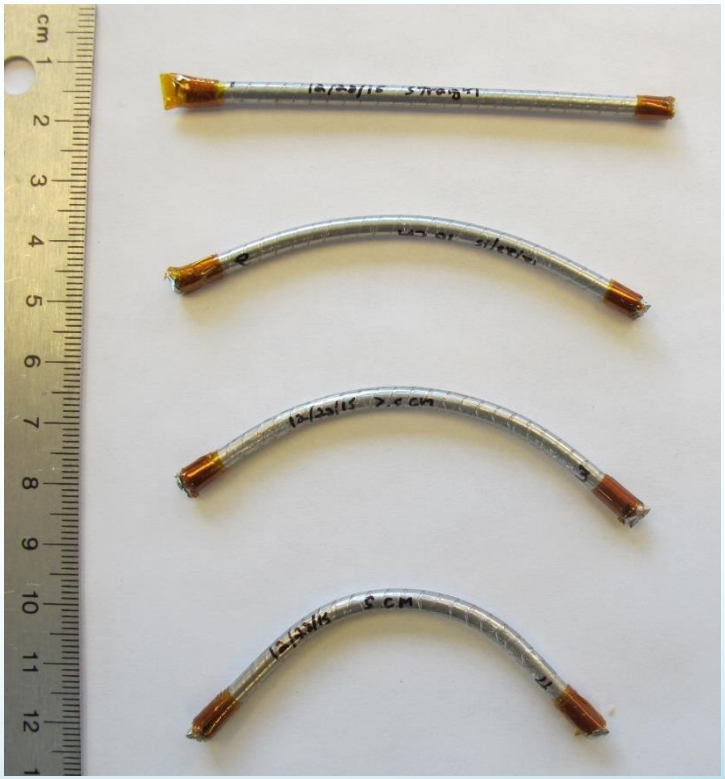
CORC® Wire 1 (2 mm wide tapes) bending results

> 94 % I_c retention even at 35 mm bending diameter



Degradation in inner layer due to surface roughness

Bending wire sections followed by extracted tape I_c measurements



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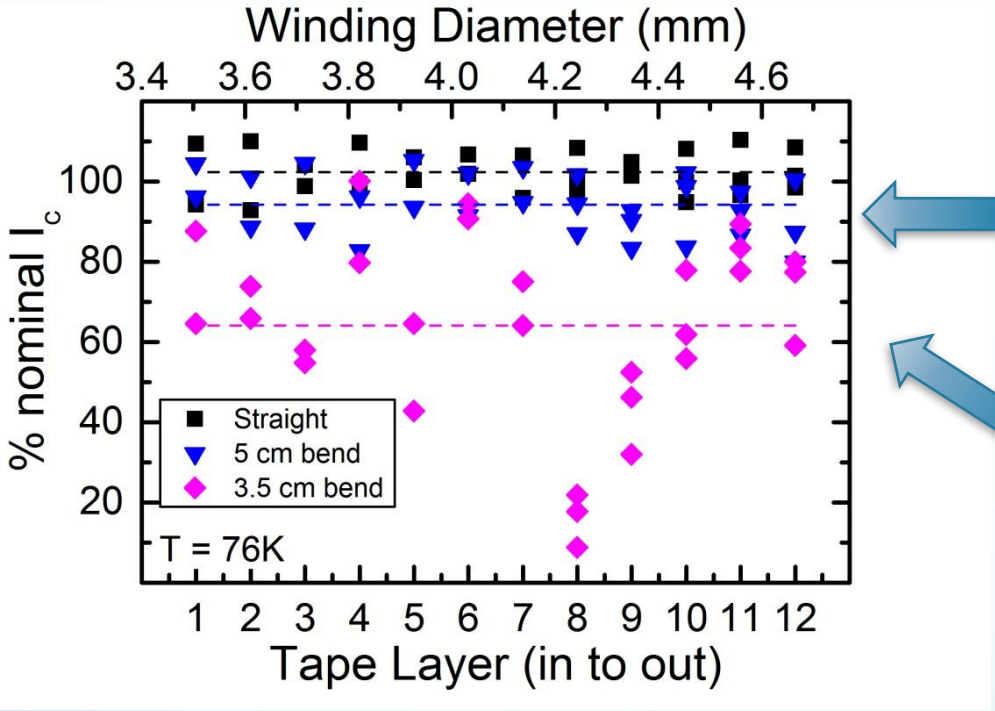
CORC® Wire 2 (3 mm wide tapes) bending results

> 90 % I_c retention at 50 mm bending diameter



Bending wire sections followed by extracted tape I_c measurements

Degradation at 35 mm diameter due to closing of gaps between tapes

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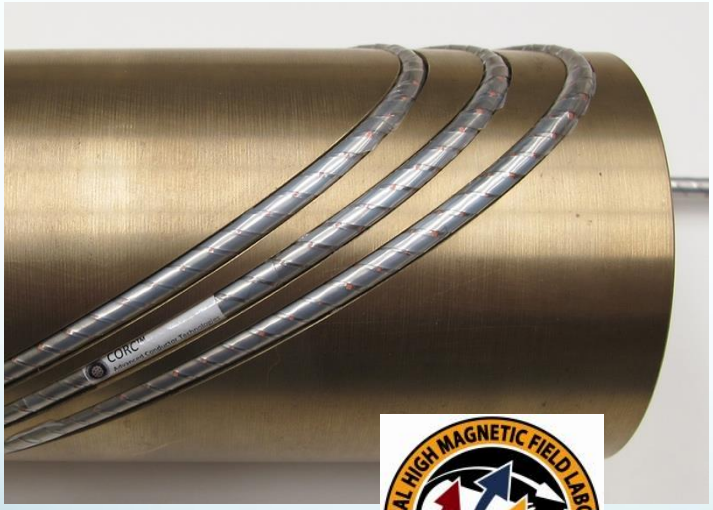
CORC®-based Canted-Cosine Theta (CCT) magnet

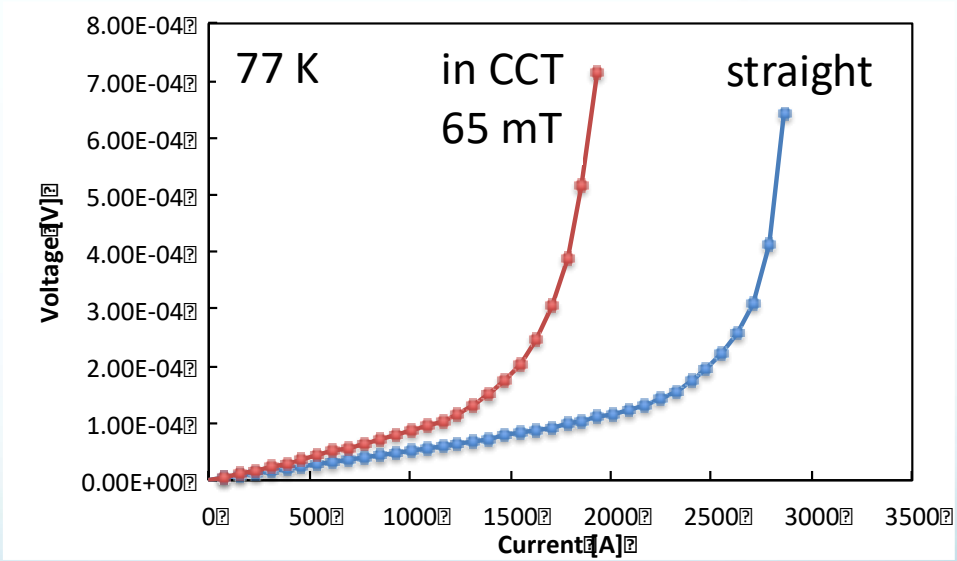
CORC® wire layout

- 26 tapes of 3 mm width
- 4.5 mm diameter

CCT magnet layout

- 80 mm O.D.
- 60 degree angle
- 46 mm diameter bend





I_c (76 K) = 2,800 A (straight)

I_c (76 K) = 1,774 A (in CCT, 65 mT on wire)

J_e (20 T) expected at 280 A/mm^2

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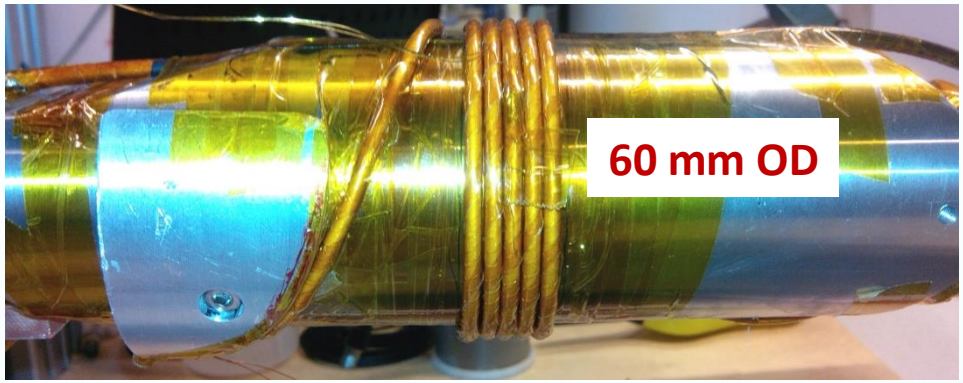
First in-field performance of CORC® wires

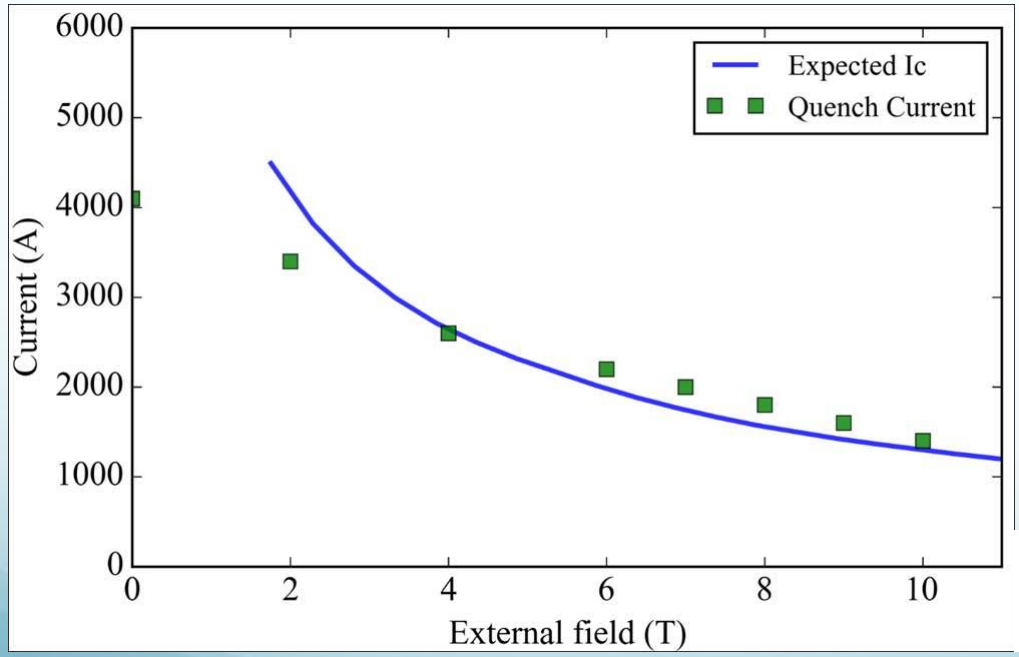
CORC® wire layout

- 16 tapes of 2 mm width
- 3 mm diameter

Test layout

- 5 turns at 60 mm diameter
- Stycast reinforcement





Results

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

No significant degradation observed

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Advanced Conductor Technologies LLC
www.advancedconductor.com

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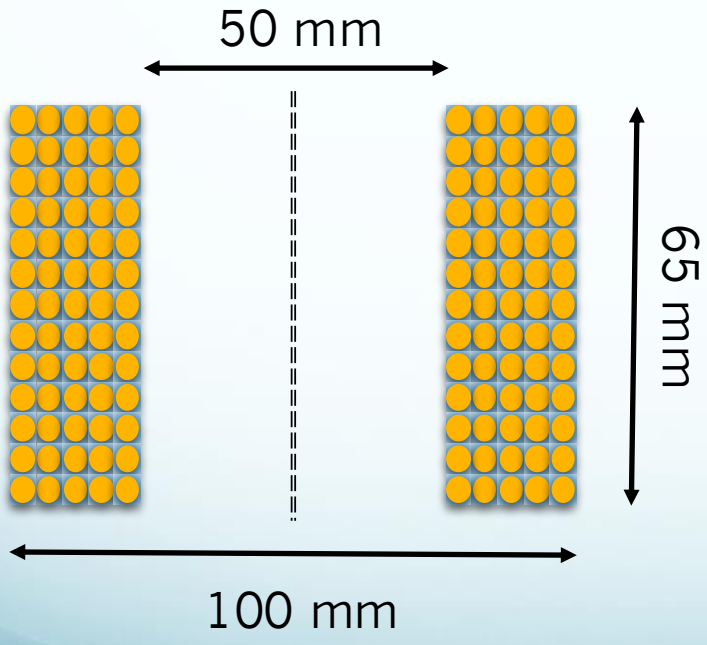
Thinking about a 5 T insert for 15 T magnet

CORC® wire made up of both 2 and 3 mm wide tapes to bring J_e up to 480 A/mm^2 at 4.2 K and 20 T

- Simple approximation using 5x5 mm squares for 4.55 mm diameter cable
- Calculation is fairly conservative (80% I_c retention, 1.9 m extra length for current leads, lift factor 1.6, non-optimized geometry)

Magnet cross section



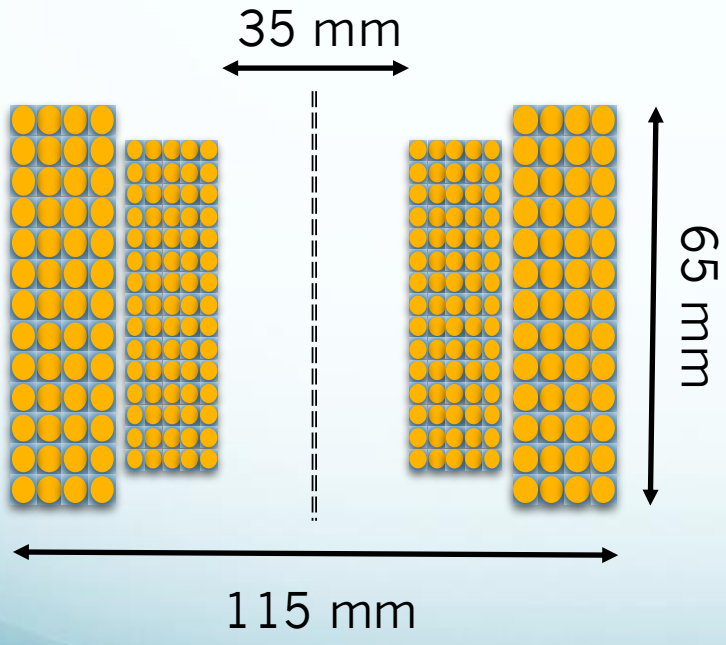
Wire length	17	m
Wire Diameter (including insulation)	4.55	mm
Total length of 2 mm wide tape	~800	m
Total length of 3 mm wide tape	~660	m
Maximum piece lengths needed	< 30	m
Number of tapes in cable	62	
Average I_c per tape (77 K)	78.8	A
Wire J_e (77 K, SF)	300.4	A/mm^2
Lift factor (I_c (4.2 K, 20 T) / I_c (77 K, SF))	1.6	
Wire J_e (4.2 K, 20 T)	480.6	A/mm^2
Number of turns	65	
J_{ave} (4.2 K, 20 T) (assuming 80% I_c retention)	248	A/mm^2
$B_z(0,0)$	5.16	T

Making the 5 T insert in two parts

Using CORC® wires similar to those that were tested for flexibility made from 2 mm wide tapes on the inner coil and 3 mm wide tapes on the outer coil

- Calculation uses 90% I_c retention, since we know how the wires will behave.
- Less risky, since we can make one coil at a time to test before assembly.

Magnet cross section



	Inner Coil	Outer Coil	
Wire length	15	16.7	m
Wire Diameter (including insulation)	3.2	4.7	mm
Total length of tape	~550	~880	m
Maximum piece lengths needed	< 22	< 32	m
Number of tapes in cable	24	31	
Average I_c per tape (77 K)	60	100	A
Wire J_e (77 K, SF)	183.4	165.1	A/mm^2
Wire J_e (4.2K, 20T)	293.4	264.2	A/mm^2
Number of turns	75	52	
J_{ave} (assuming 90% I_c retention)	169.3	178.6	A/mm^2
$B_z(0,0)$	2.64	2.55	T

DOE-HEP (DE-SC0009545)

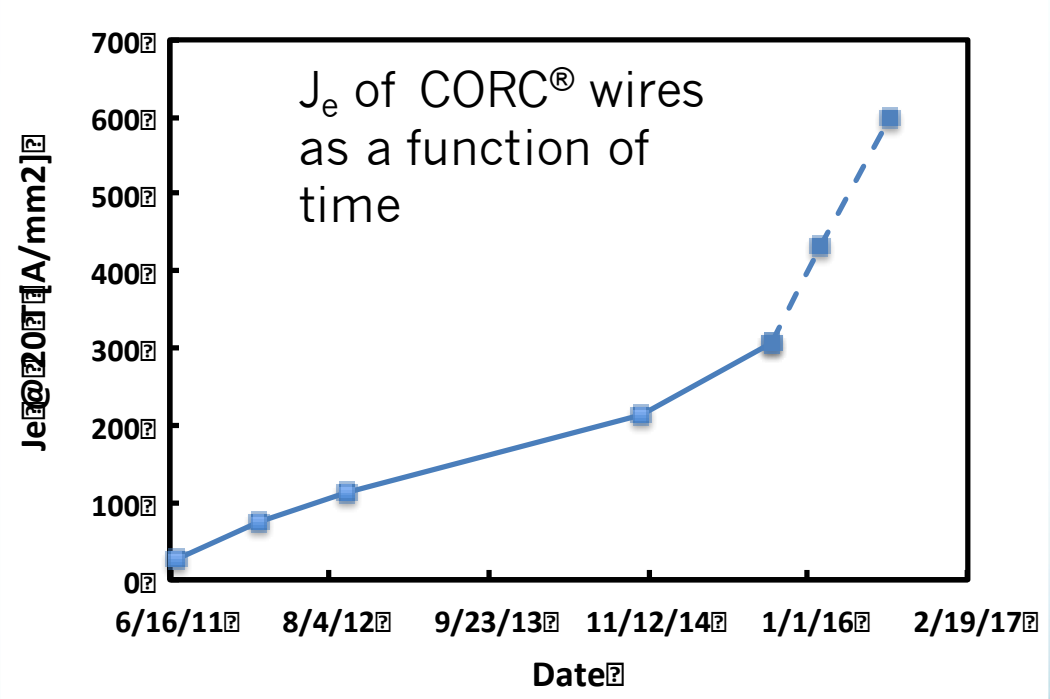
Summary

CORC® wires developed with enhanced flexibility

- > 90% I_c retention after bending to 35 mm for wires made with 2 mm wide tapes or 50 mm for wires made with 3 mm wide tapes

CORC® wires are now suitable for use in high field magnets

- In field test of 5 turn solenoid with 60 mm bending diameter showed expected I_c (B) performance
- Bending diameter down to 35 mm with projected J_e as high as 600 A/mm^2 makes CCT and other accelerator magnet configurations feasible
- Design of 5 T insert for 15 T magnet requires only short tape lengths (< 30 m) and can be accomplished with less than 1.5 km of tape



Many thanks to SuperPower for making the transition to 30 μm substrates!