Recent progress on CORC® cable and wire development for magnet applications

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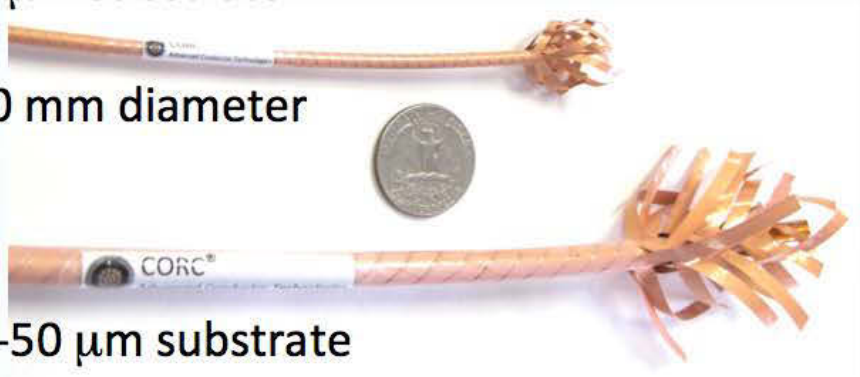
CORC® magnet cables and wires

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

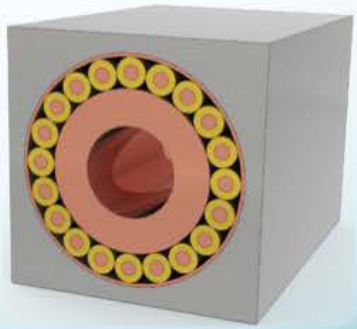


CORC® cable (5-8 mm diameter)

- Wound from 3-4 mm wide tapes with 30-50 μm substrate
- Typically no more than 50 tapes
- Flexible with 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 about 1 meter



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CORC® wire composition: almost perfect?

		CORC® cables		CORC® wires			
		1	2	1	2	3	4
Former size	[mm]	5.25	5.3	2.4	2.55	2.55	2.55
Tape number	-	24	42	16	27	29	50
Tape width	[mm]	4	4	2	2	2	2+3
Number of layers	-	9	14	8	11	12	21
Outer diameter	[mm]	7.1	7.24	3.2	3.65	3.63	4.5
Cross-sectional area	[mm^2]	39.6	41.2	8.0	10.5	10.3	15.9
Hastelloy C-276 fraction	-	0.18	0.31	0.18	0.23	0.25	0.35
Copper fraction	-	0.69	0.60	0.62	0.57	0.58	0.44
I_c (76 K, s.f.)	[A]	3360	5880	1120	1890	2030	4410
I_c (4.2 K, 20 T), LF = 1.48	[A]	4973	8702	1658	2797	3004	6527
J_e (4.2 K, 20 T), LF = 1.48	[A/mm^2]	126	211	206	267	290	410
I_c (4.2 K, 20 T), LF = 2.25	[A]	7560	13230	2520	4253	4568	9923
J_e (4.2 K, 20 T), LF = 2.25	[A/mm^2]	191	321	313	406	441	624

Copper and Hastelloy fraction

- Hastelloy fraction between 20 – 35 %
- Copper fraction 45 – 65 %

Near-ideal copper fraction for magnet conductors due to former!

Projected I_c and J_e at 20 T

- Based on typical lift factor of 1.48
- Based on typical I_c(76 K) of 35 A/mm
- Assuming 100 % I_c retention

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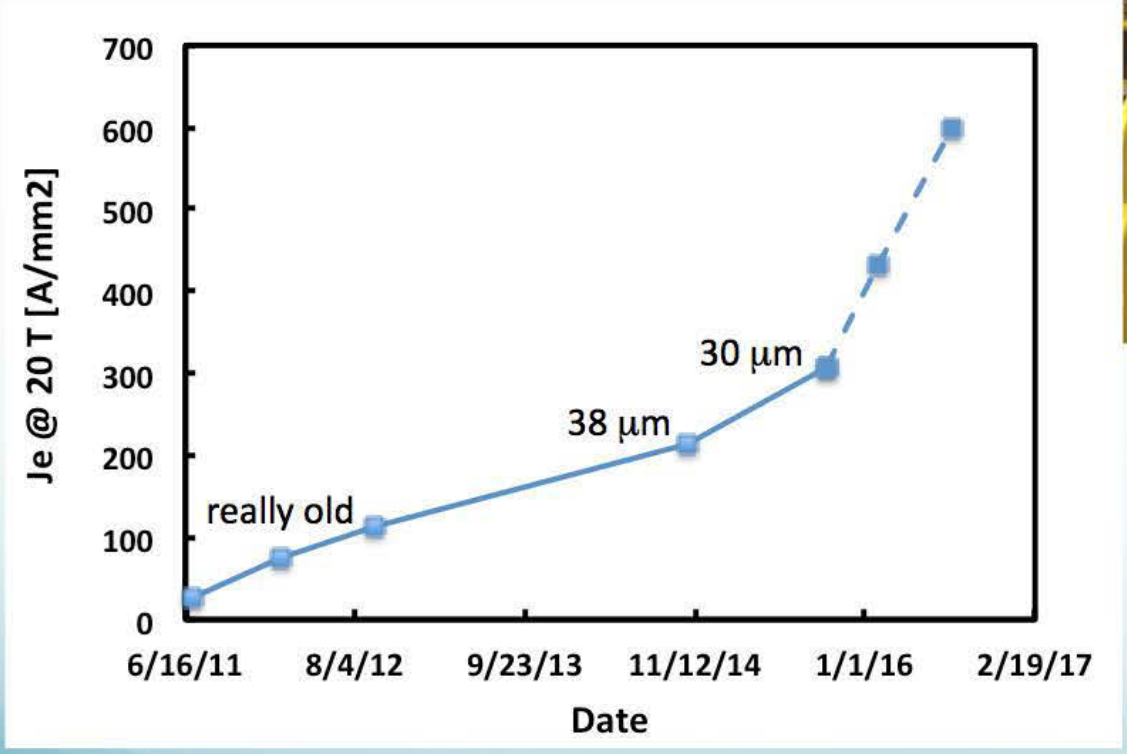
Increasing J_e in CORC® cables to 600 A/mm^2 (20 T)

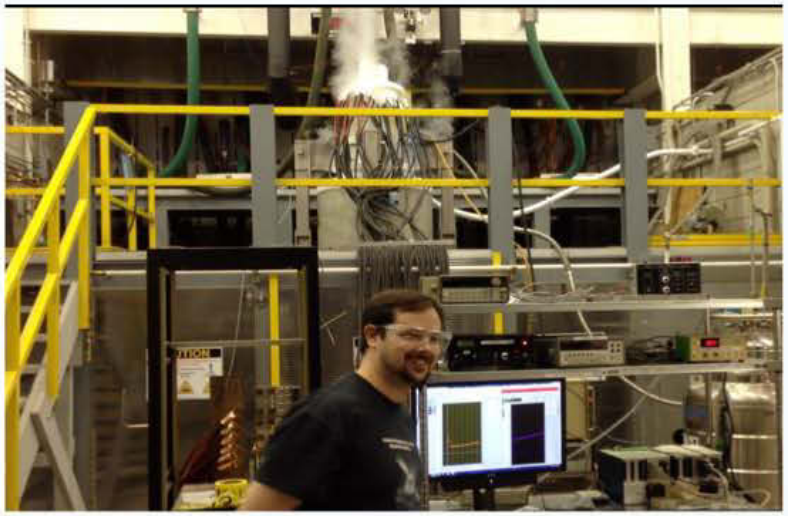
CORC® cable J_e on track to 600 A/mm^2 at 20 T

- .....
- J_e of 309 A/mm^2 at 20 T achieved in Oct. 2015



In-field CORC® cable testing @ 100 mm

- Large bore magnet at NHMFL (17 T)



Problems!

- NHMFL magnet decommissioned

Tests now need to be performed in-house!

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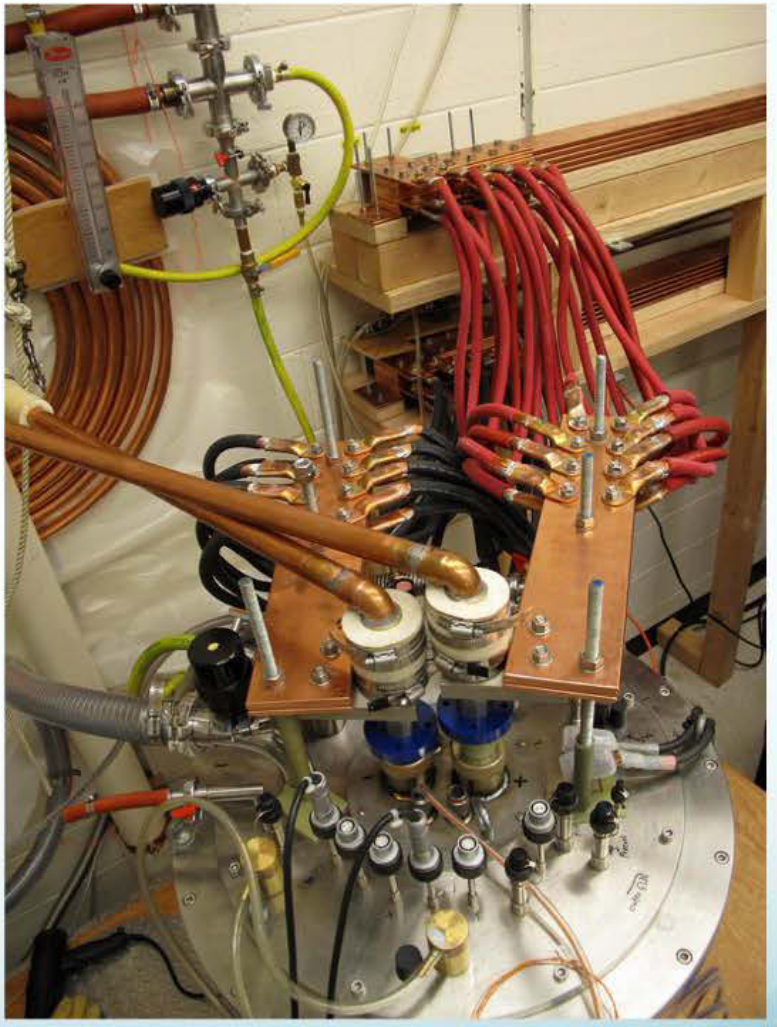
In-house CORC® test facility

Advanced Cond. Tech./Univ. of Colorado

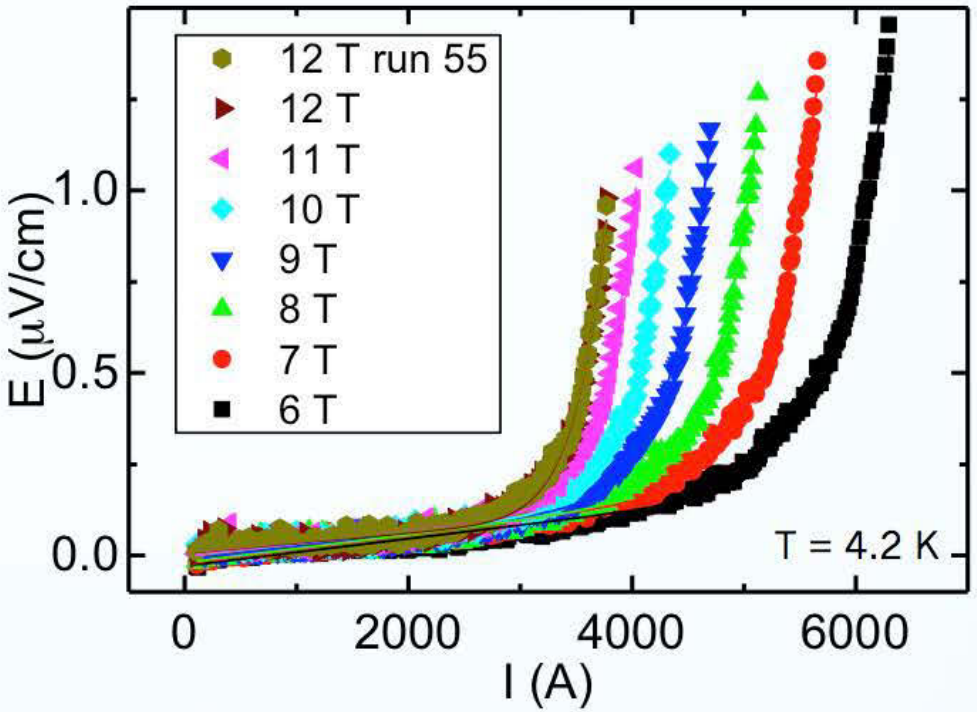
- 12 T superconducting solenoid magnet
- 80 mm bore
- 16,500 A sample current



Highly flexible CORC® magnet wires

CORC® wires based on 2 mm wide tapes

- 27 tapes, 2 mm wide, 30 μm substrate
- 3.65 mm CORC® wire thickness
- 5 turns on 60 mm diameter mandrel



B [T]	B + s.f. (T)	I_{quench} [A]	I_c [A]	*n*-value [-]
1	1.68		10525	3.8
2	2.61	9700	9394	6.2
3	3.54	8543	8350	8.1
4	4.49	7730	7492	11.8
5	5.44	7005	6802	14
6	6.4	6365	6216	12.8
7	7.36	5723	5619	12.9
8	8.33	5193	5119	13.4
9	9.31	4736	4708	13.2
10	10.28	4390	4363	12.9
11	11.26	4091	4076	12.9
12	12.25	3835	3831	13.2

Reliable high-field performance of CORC® wires

- **Projected J_e(20 T) 259 A/mm²**
- **No degradation after 55 stress cycles at 12 T**

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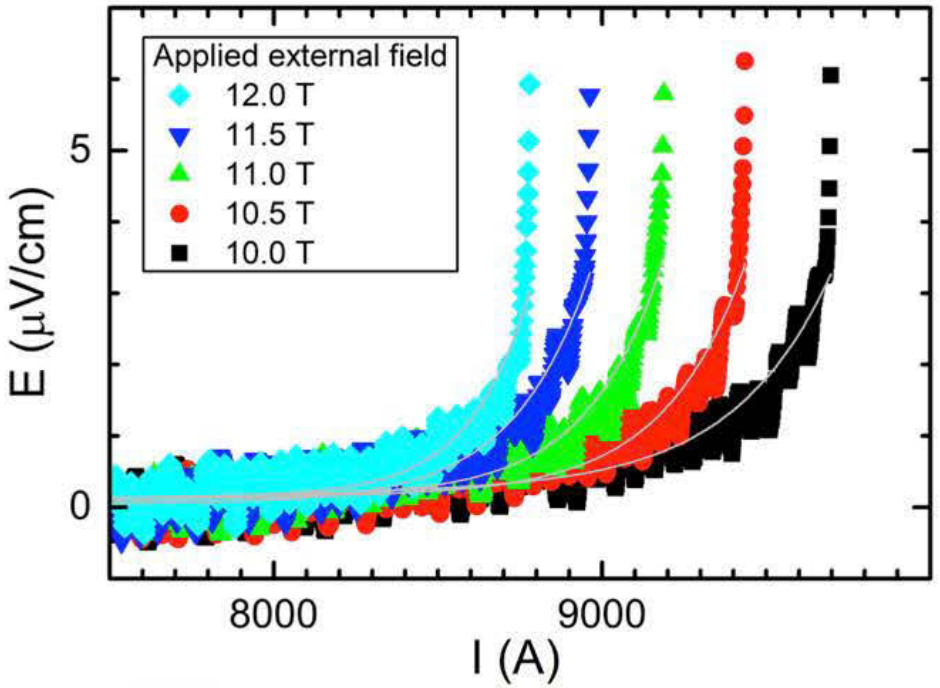
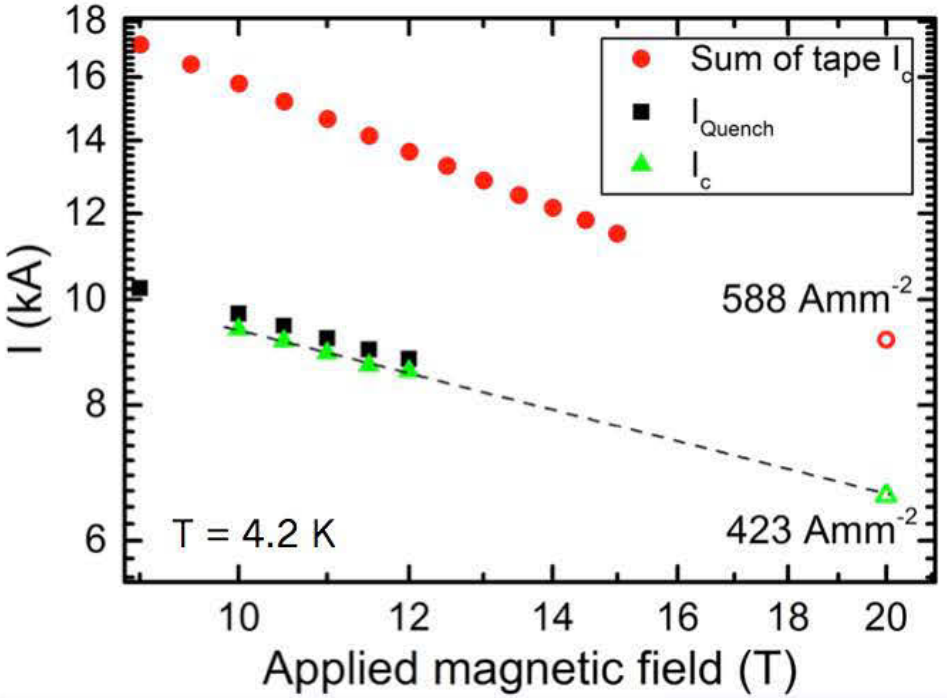
Record CORC® magnet wire performance

High-J_e CORC® wire layout

- 50 tapes, 2-3 mm wide, 30 μm substrate
- 4.46 mm CORC® wire thickness





B [T]	I_{quench} [A]	I_c [A]	*n*-value [-]
9	10239		
10	9710	9390	33.3
10.5	9461	9157	38.5
11	9206	8924	40.6
11.5	8995	8694	38.3
12	8813	8591	48.1
20		6601	

New record J_e in CORC® wires!

- **Projected J_e(20 T) 423 A/mm²**
- Projected I_c(20 T) = 6,600 A

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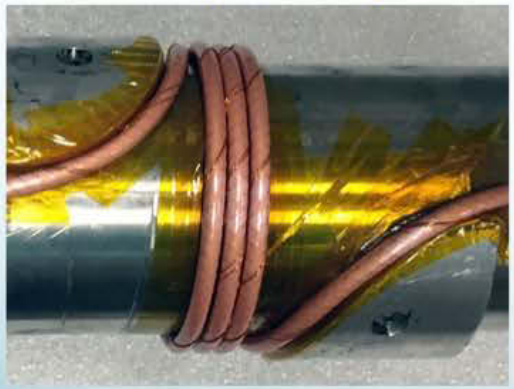
CORC® cable and wire performance recap

CORC® cable tested at 100 mm diameter (2011 – 2015)

CORC® wire tested at 60 mm diameter (2016 –)



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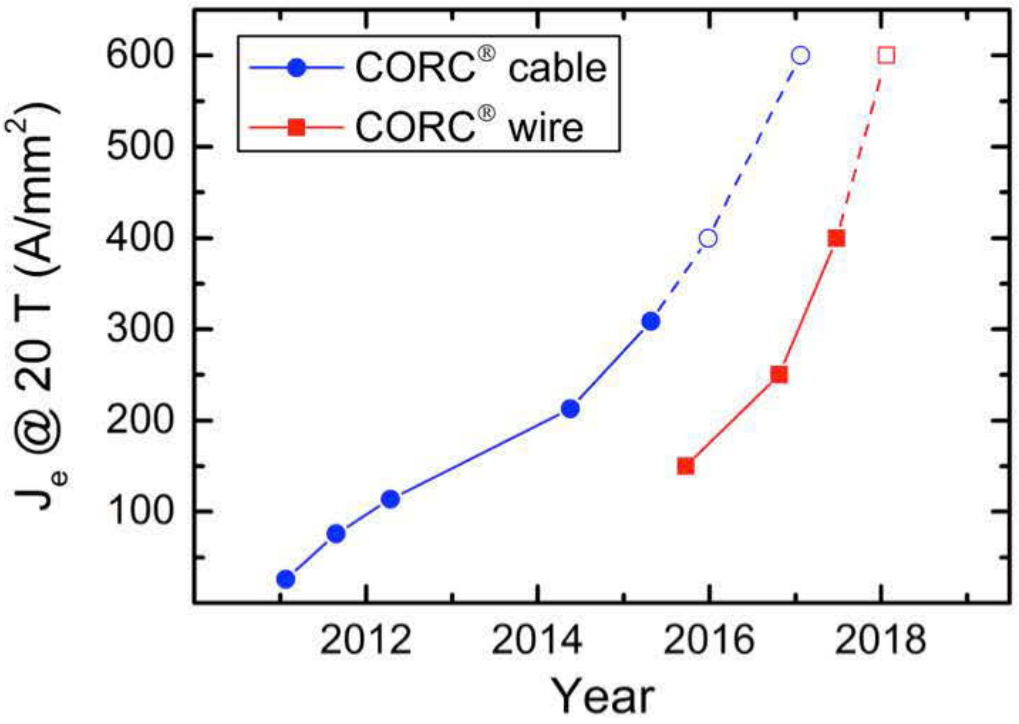


Closing in on J_e > 600 A/mm^2 goal

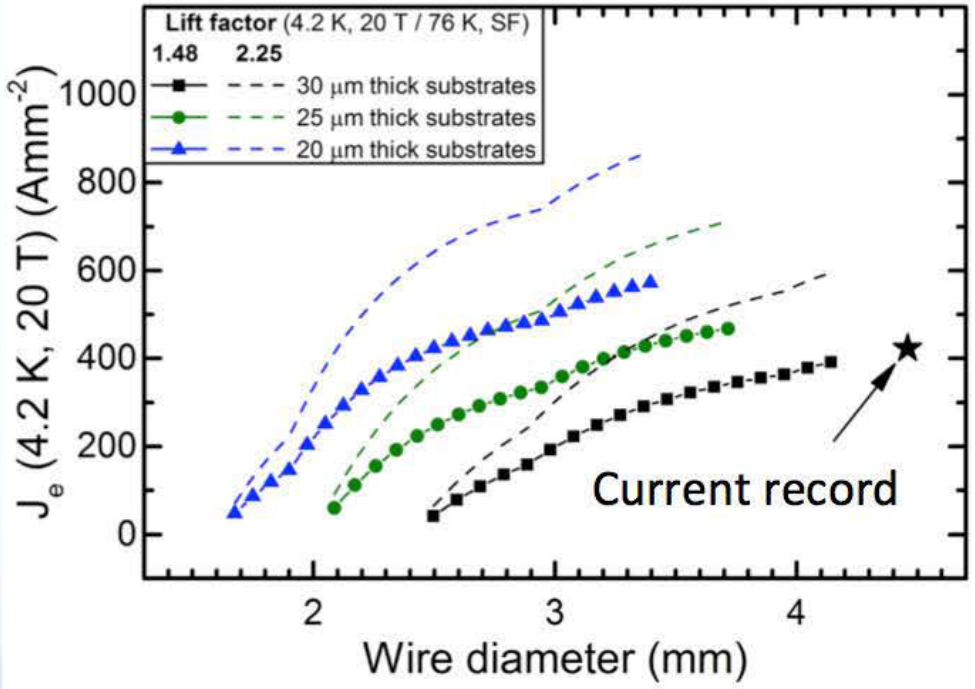
- J_e (20 T) now exceeded 400 A/mm^2 in CORC® wire
- Combined with I_{opp}(20 T) > 6,500 A
- Next step is thinner substrates 20 – 25 μm

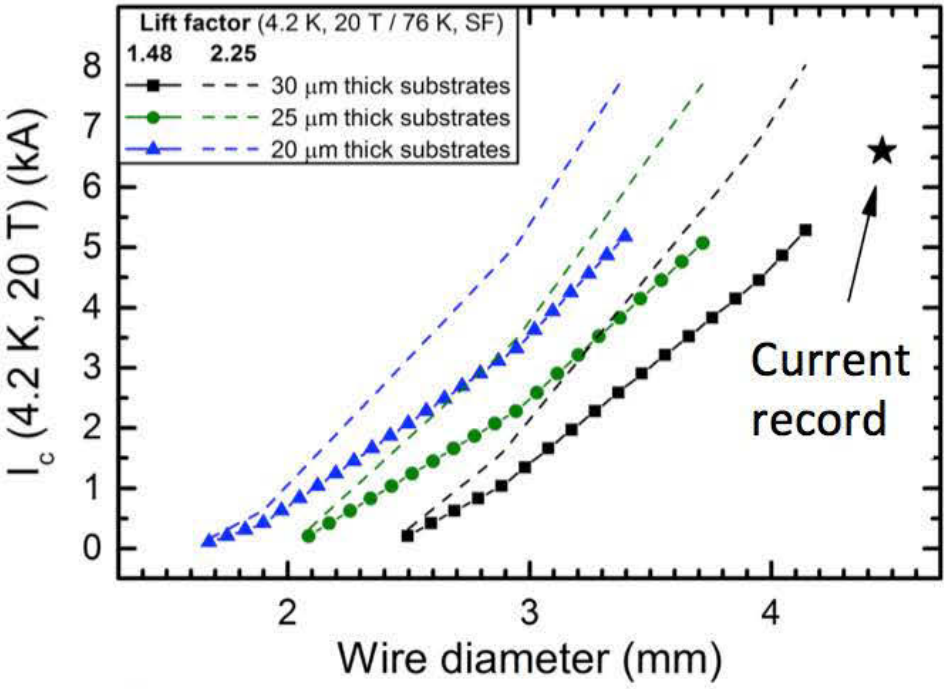
Highest demonstrated J_e values in any multi-kA HTS cable!

Future CORC® magnet wire performance

Thinner CORC® wires are coming (collaboration with SuperPower)

- Tapes with 25 μm substrates are in R&D stage
- First CORC® wires with 25 μm substrates before end of 2018
- Tapes with 20 μm substrates expected to move in R&D stage early 2019





Thinner, more flexible CORC® wires expected end 2018

- J_e (20 T) > 500 A/mm^{2}and I_c (20 T) >5,000 A early 2019
- J_e (20 T) > 600 A/mm^{2}and I_c (20 T) >6,000 A middle 2019

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The road to 21 T in CORC®-CCT magnets

Magnet program with Lawrence Berkeley Nat. Lab. (Xiaorong Wang)

- Develop a canted cosine-theta CORC® insert magnet
- Generate 5 T in a 16 T background field

Step 1: 2-Layer, 40-turns CCT magnet (C1)

- Generate **1 T in self-field**
- CORC® wire J_e(20 T) = 150-200 A/mm^2
- Learn to wind and protect CORC®-CCT magnets

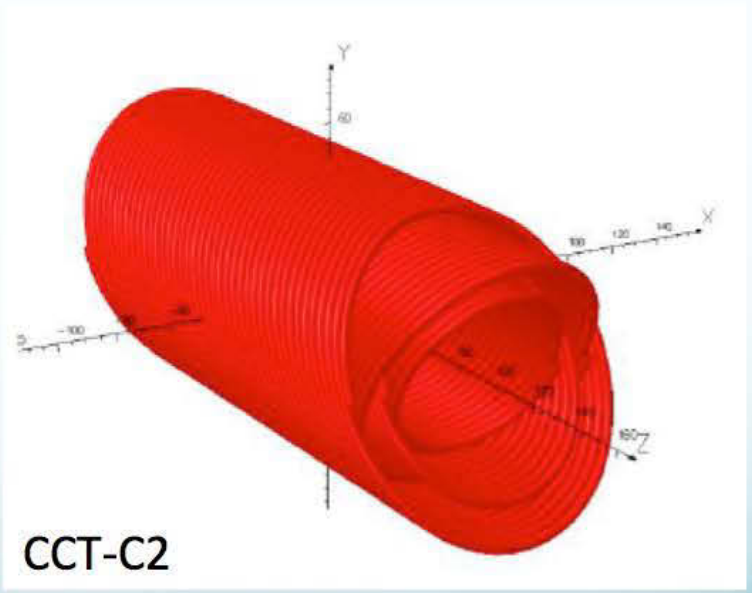
CCT-C1

Step 2: 4-Layer, 40-turns magnet (C2)

- Generate **3 T in self-field**
- CORC® wire J_e(20 T) = 200-300 A/mm^2
- CORC® wire bendable to 60 mm diameter

Step 3: 6-Layer, 40-turns CCT magnet (C3)

- Generate **5 T in self-field**
- CORC® wire J_e(20 T) = 300-400 A/mm^2
- CORC® wire bendable to 30 mm diameter



CCT-C2

Step 4 – : CORC®-CCT inserts in 10 T background field

Baby coil C0a: CORC® wire test for CCT-C1

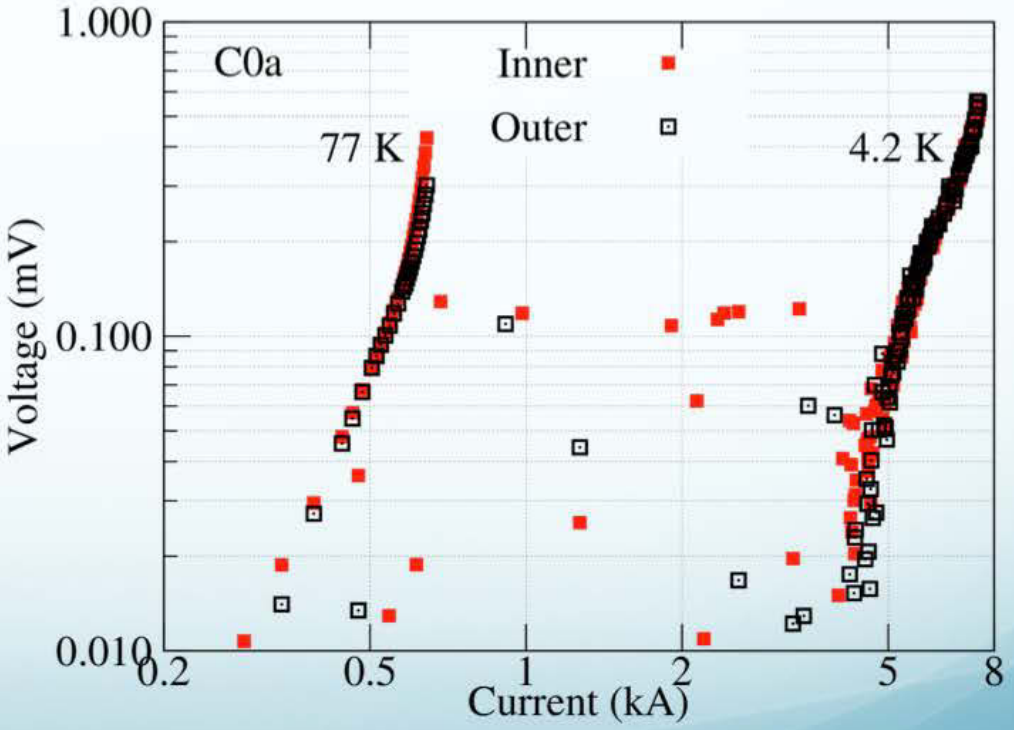
CCT C0a: CORC® wire with 16 tapes

- 2 Layers
- 3 Turns per layer
- Inner layer I.D. 70 mm
- Minimum bending diameter 50 mm

CCT C0a performance

- I_c (77 K) = 646 A (layer A) and 675 A (layer B)
- I_c (4.2 K) = 6,700 A (both layers)

Successful performance test resulted in green light for magnet CCT-C1



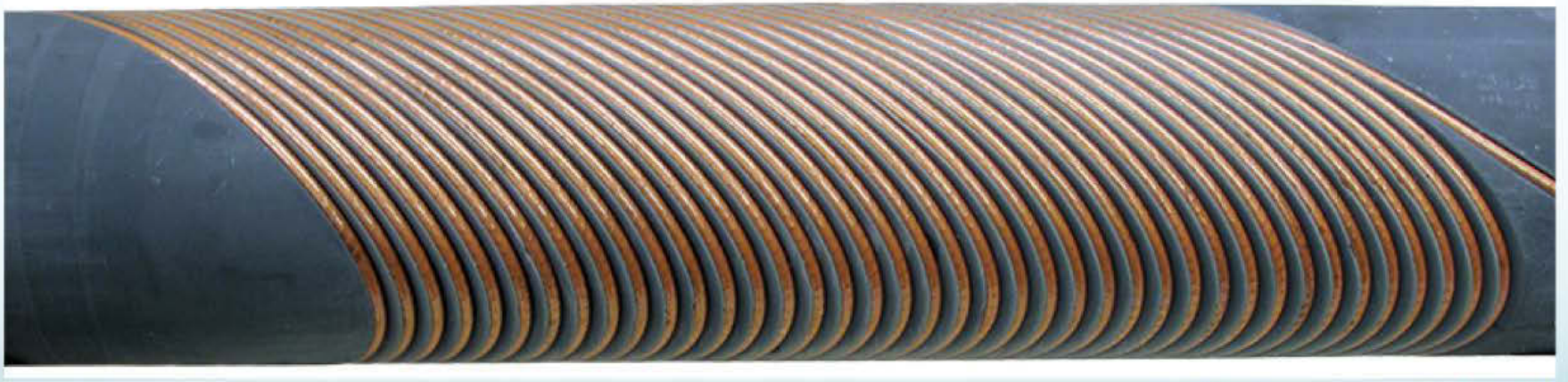
CORC® CCT-C1 construction

CORC® wire for CCT-C1 Magnet

- 2 Layers, 40 turns per layer, 70 mm aperture
- LBNL ordered 50 m of CORC® wire in 2016
- CORC® wire contains 16 tapes, J_e (20 T) = ~150 A/mm^2
- Magnet layers wound dry, no impregnation applied

CORC® wire for CCT-C1 was delivered to LBNL in Q2 2017

Magnet CCT-C1 was wound at LBNL in Q3 2017

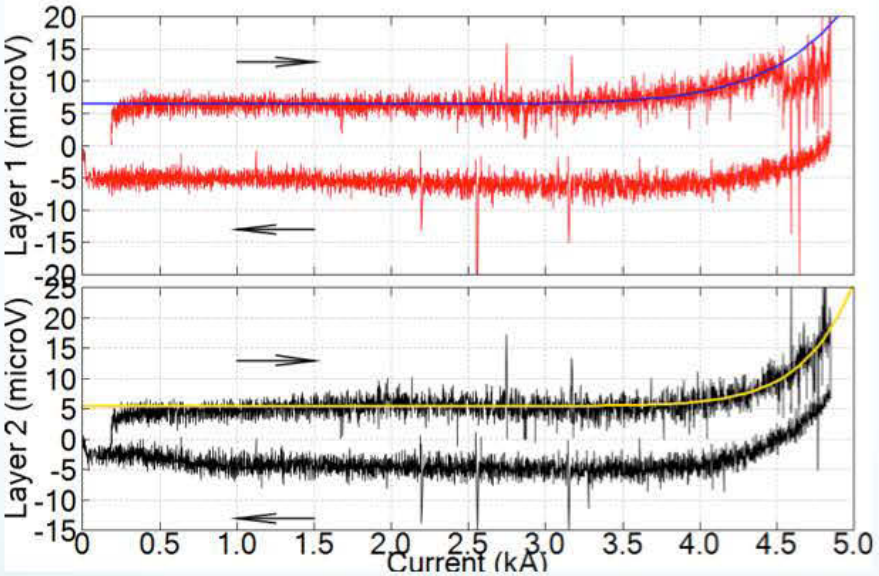


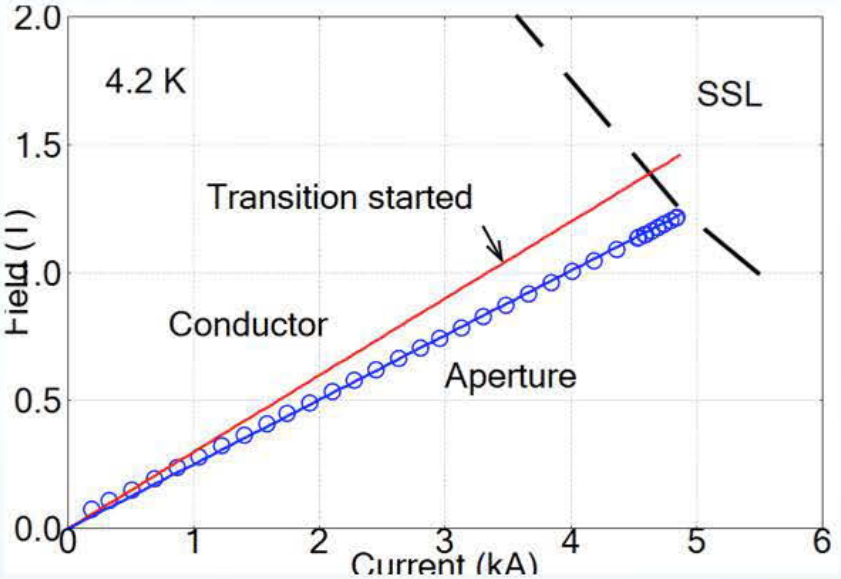
Outer layer of CCT-C1

CORC® CCT-C1 test results

Magnet CCT-C1 tested at 4.2 K

- Slow current ramp to 4,800 A
- Initial transition started at ~ 3,500 A
- Current ramped to 15 μV (= 0.001 μV/cm)





Magnet CCT-C1 generated 1.2 T at 4,800 A (104 % of expected performance)

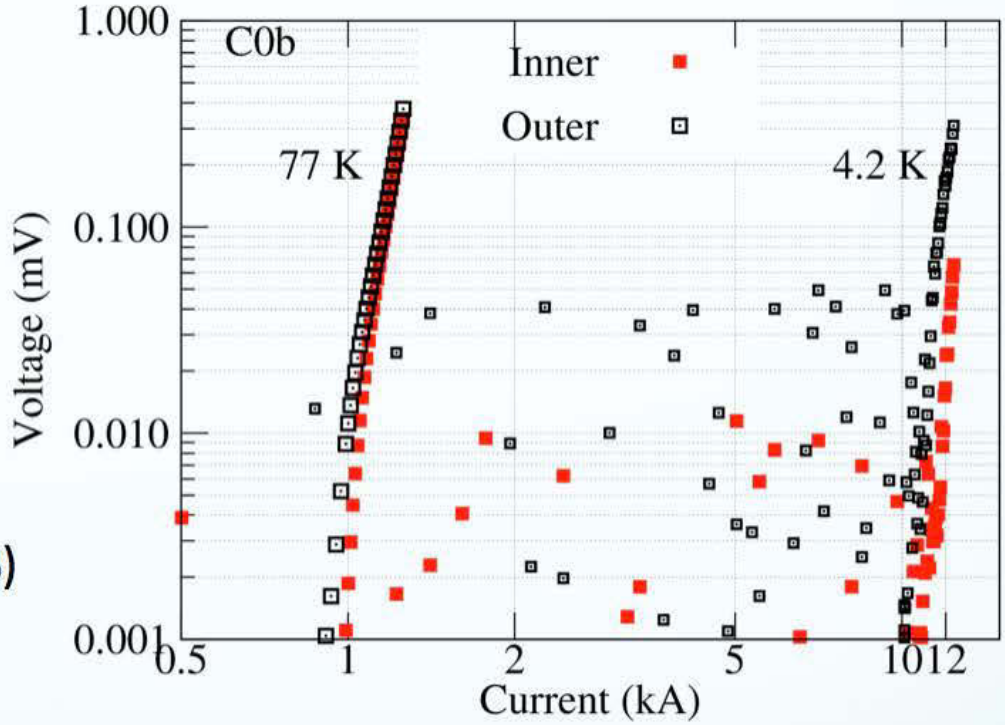
Baby coil C0b: CORC® wire test for CCT-C2

CCT C0b: CORC® wire with 29 tapes

- 3-turn per layer
- Inner layer I.D. 85 mm
- CORC® wire J_e (20 T) = ~300 A/mm²

CCT C0b performance

- I_c (77 K) = 1.092, 1,067 A (layer A, B)
- I_c (4.2 K) = 12,141, 11,078 A (layer A,B)
- Dipole field 0.68 T (4.2 K)
- Peak J_e(4.2 K) = 1,198 A/mm²



Successful performance test resulted in green light for magnet CCT-C2

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CORC® CCT-C2 wire delivery

CCT-C2 Magnet

- 4 Layers, 40 turns per layer, 70 mm aperture
- LBNL ordered 80 m of CORC® wire in 2017

Final CORC® wire section was delivered to LBNL on September 10, 2018

Magnet C2 winding and performance test expected before end of the year

28 meter CORC® wire

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Summary

CORC® wires and cables have matured into magnet conductors

- High currents have been demonstrated > 8,000 A (4.2 K, 12 T)
- High current densities have been reached > 400 A/mm^2 (4.2 K, 20 T)
- CORC® cables and wires have always shown the latest record J_e (20 T) performance of any HTS cable
- CORC® wire layout with copper former results in a close to optimum conductor layout for magnets with around 50 % copper fraction

First CCT accelerator magnets wound from CORC® wires

- The first CORC®-CCT magnet was successfully tested at 1.2 T in 2017
- 80 Meters of CORC® wire has been delivered to LBNL to wind the next CORC®-CCT magnet, designed to generate 3 T at 4.2 K
- The third CORC®-CCT magnet with 5 T dipole field is expected in 2019