IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2019.
Invited presentation given at CCA 2018, September 10-13, 2018, Vienna (Austria).

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

Danko van der Laan, Jeremy Weiss and Dustin McRae
Advanced Conductor Technologies & University of Colorado, Boulder, Colorado, USA

X. Wang, H. Higley and S. O. Prestemon
Lawrence Berkeley National Laboratory, Berkeley, California, USA

Advanced Conductor Technologies LLC
www.advancedconductor.com

CCA 2018, September 11th, 2018, Vienna, Austria

BERKELEY LAB

CORC® magnet cables and wires

Different CORC® cable and wire configurations optimized for different magnet requirements

CORC® wires (2.5-4.5 mm diameter)

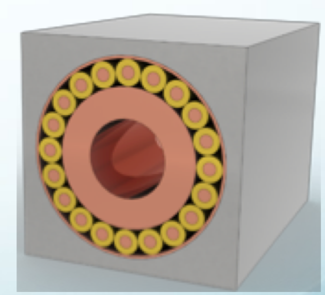
- Wound from 2-3 mm wide tapes with 30 ∝m substrate
- Typically no more than 30 tapes
- Highly flexible with bending down to < 50 mm diameter

CORC® cable (5-8 mm diameter)

- Wound from 3-4 mm wide tapes with 30-50 ∝m 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



UNIVERSITY OF TWENTE. CERN

Advanced Conductor Technologies LLC
www.advancedconductor.com

BERKELEY LAB

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2019. Invited presentation given at CCA 2018, September 10-13, 2018, Vienna (Austria).

CORC® wire composition: almost perfect?

		CORC® cables		CORC® wir es			
		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

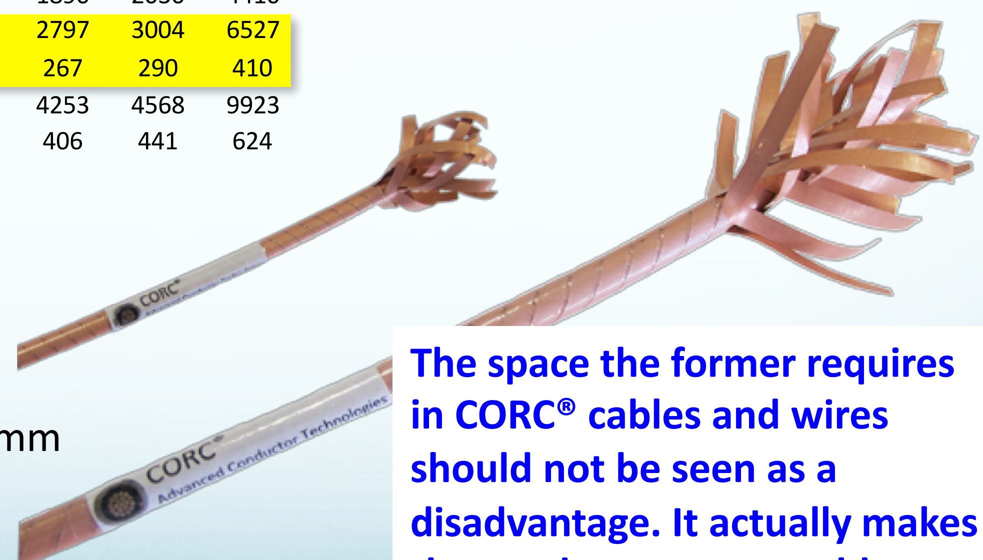
Copper and Hastelloy fraction

- 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 20T

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



The space the former requires in CORC® cables and wires should not be seen as a disadvantage. It actually makes the conductor more stable.

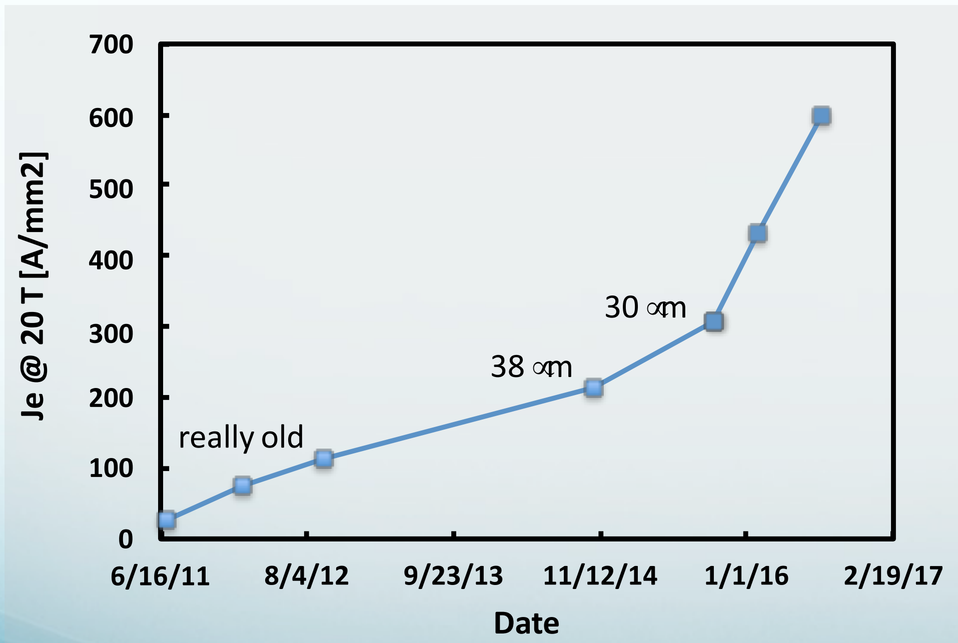
Advanced Conductor Technologies LLC
www.advancedconductor.com

BERKELEY LAB

Increasing J_e in CORC® cables to 600 A/mm² (20 T)

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



In-field CORC® cable testing @ 100 mm

- Large bore magnet at NHMFL (17 T)

After 2015, in-field CORC® cable testing was halted due to the decommissioning of the magnet at the NHMFL and development of thinner CORC® wires was needed for further in-field testing in smaller magnets.

Problems!

- NHMFL magnet decommissioned

Tests now need to be performed in-house!

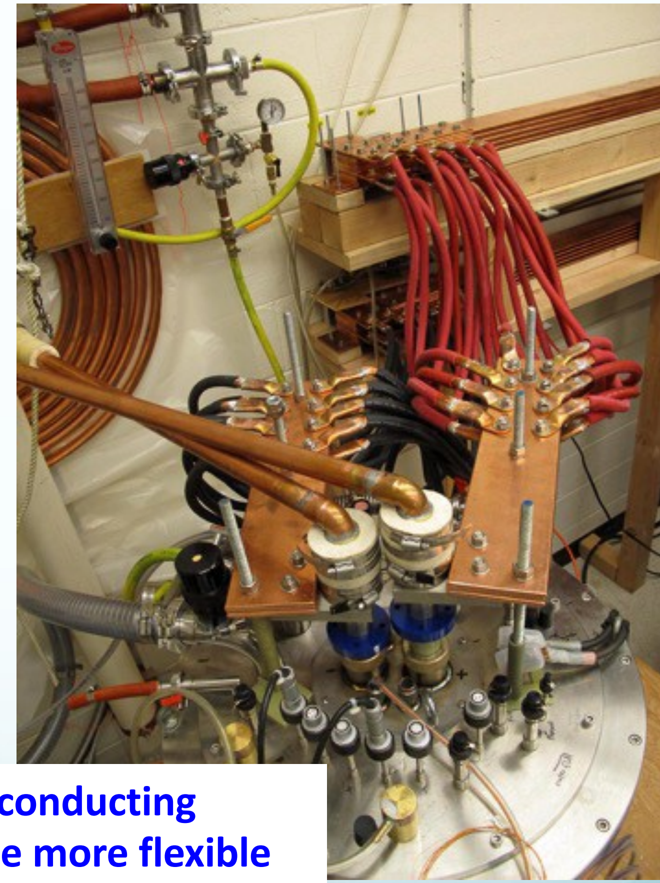
Advanced Conductor Technologies LLC
www.advancedconductor.com

BERKELEY LAB

In-house CORC® test facility

Advanced Cond. Tech./Univ. of Colorado

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



The in-house superconducting magnet in which the more flexible CORC® wires are now tested at a bending diameter of 60 mm

Advanced Conductor Technologies LLC
www.advancedconductor.com

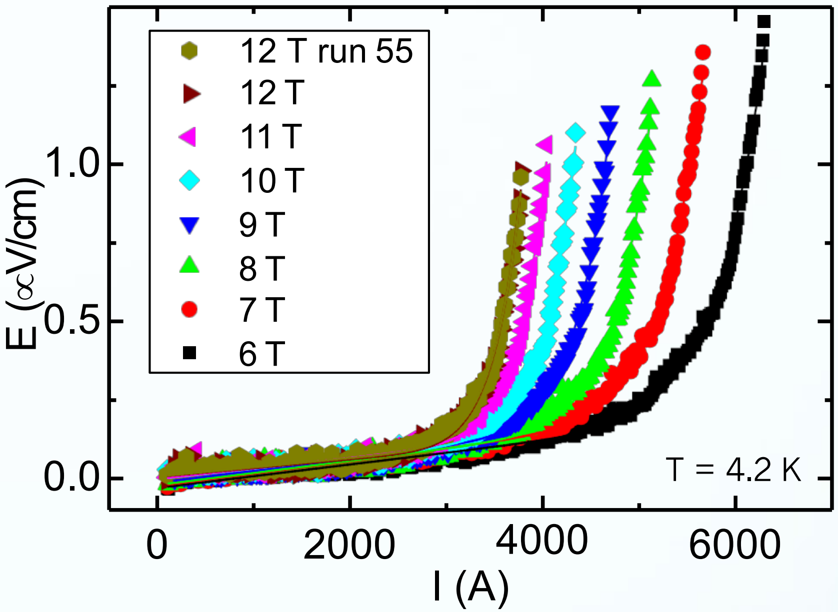
BERKELEY LAB

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2019. Invited presentation given at CCA 2018, September 10-13, 2018, Vienna (Austria).

Highly flexible CORC® magnet wires

CORC® wires based on 2 mm wide tapes

- 27 tapes, 2 mm wide, 30 ∝m 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**

These are the in-field performance results of a typical high-current CORC® wire

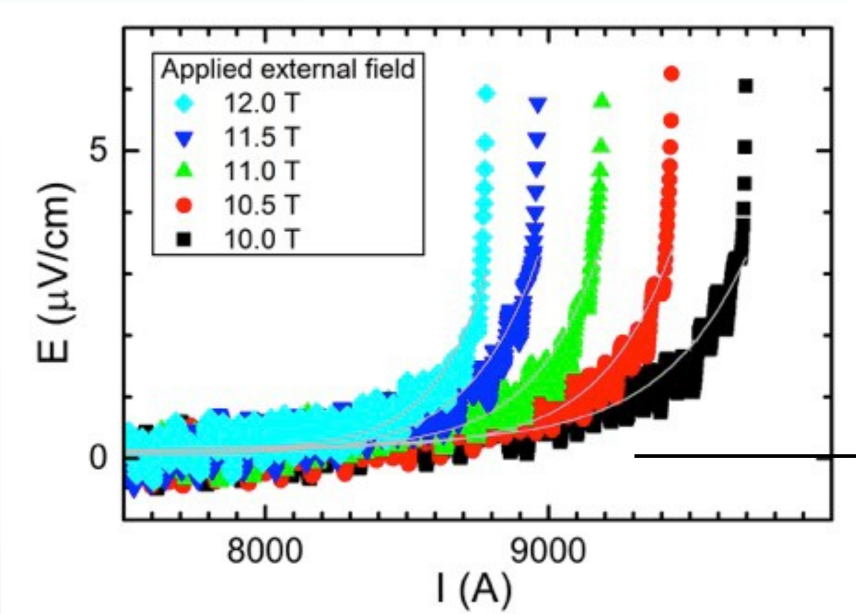
Advanced Conductor Technologies LLC
www.advancedconductor.com

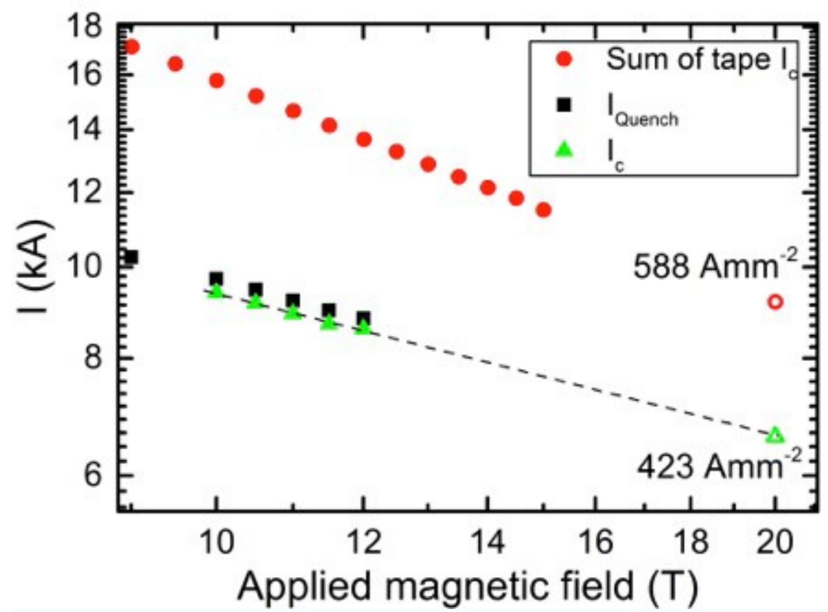
BERKELEY LAB

Record CORC® magnet wire performance

High-J_e CORC® wire layout

- 50 tapes, 2-3 mm wide, 30 ∝m 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/m m^2**
- Projected I_c(20 T) = 6,600 A

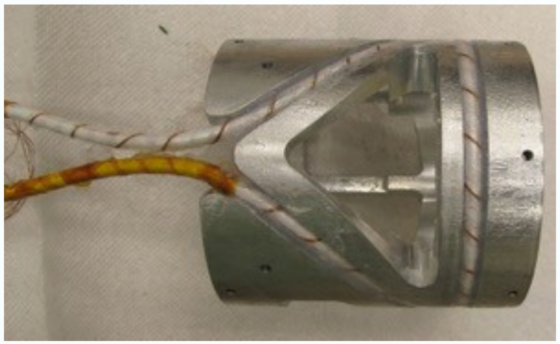
A new record J_e CORC® wire, although the 60 mm diameter bending caused some damage. Future development should result in even high J_e and less degradation.

Advanced Conductor Technologies LLC
www.advancedconductor.com

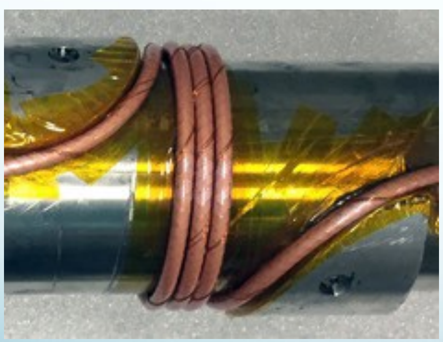
BERKELEY LAB

CORC® cable and wire performance recap

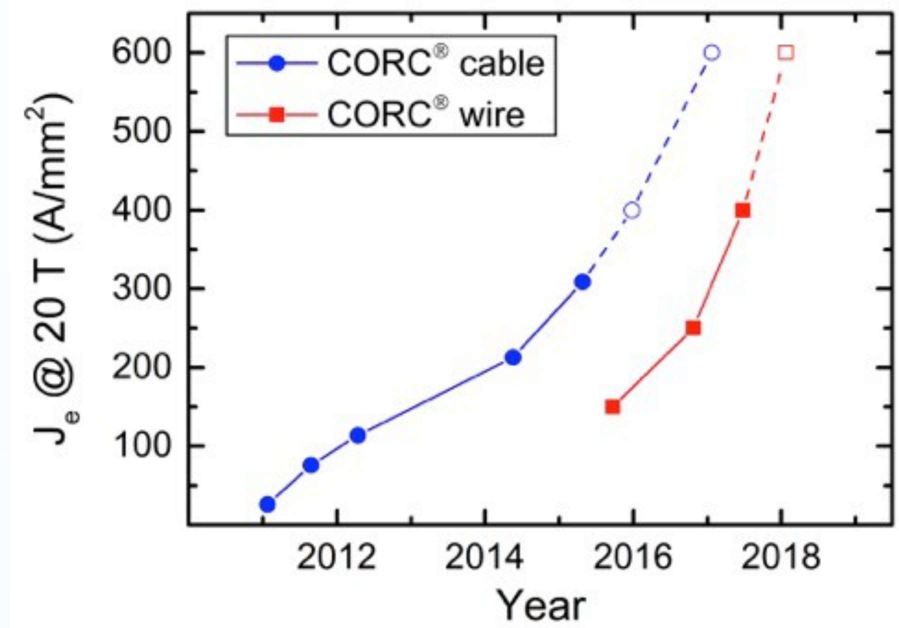
CORC® cable tested at 100 mm diameter (2011 – 2015)



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



UNIVERSITY OF TWENTE.



Closing in on J_e > 600 A/mm² goal

- J_e (20 T) now exceeded 400 A/mm² in CORC® wire
- Combined with I_{opp}(20 T) > 6,500 A
- Next step is thinner substrates 20 – 25 ∝m

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

Advanced Conductor Technologies LLC
www.advancedconductor.com

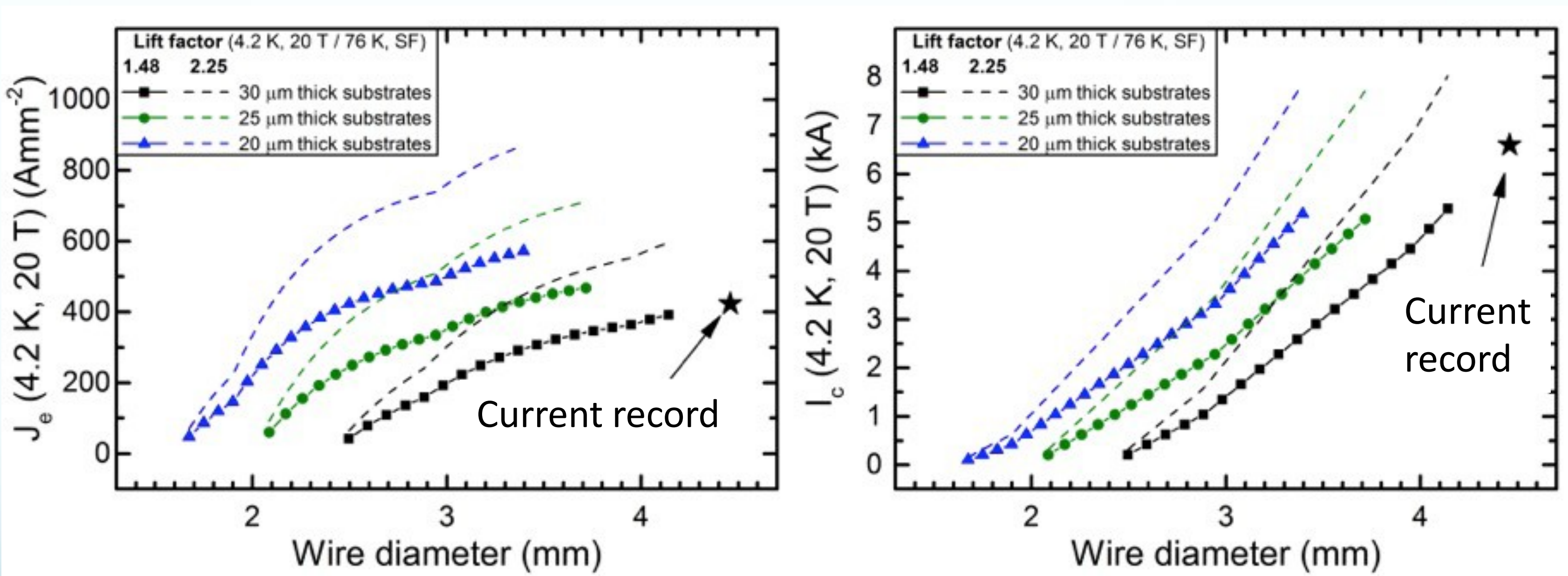
The in-field performance of CORC® wires has now exceeded that of CORC® cables, but only because cables haven't been tested

BERKELEY LAB

Future CORC® magnet wire performance

Thinner CORC® wires are coming (collaboration with SuperPower)

- Tapes with 25 ∝m substrates are in R&D stage
- First CORC® wires with 25 ∝m substrates before end of 2018
- Tapes with 20 ∝m 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

Advanced Conductor Technologies LLC
www.advancedconductor.com

BERKELEY LAB

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

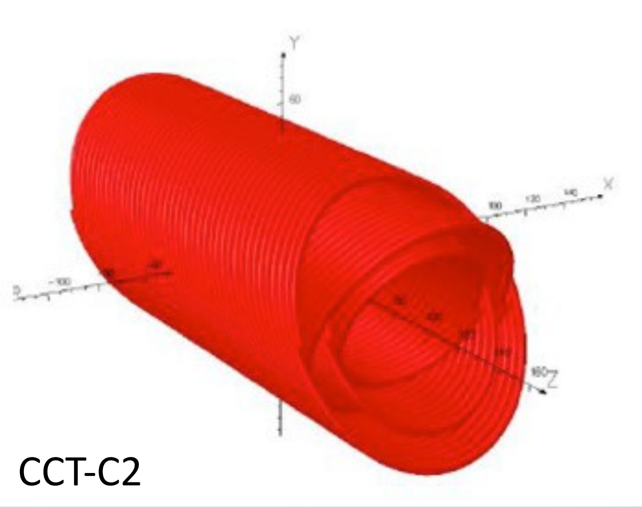
Step 1: 2-Layer, 40-turns CCT magnet (C1)

- 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



CCT-C2

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

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

Advanced Conductor Technologies LLC
www.advancedconductor.com

BERKELEY LAB

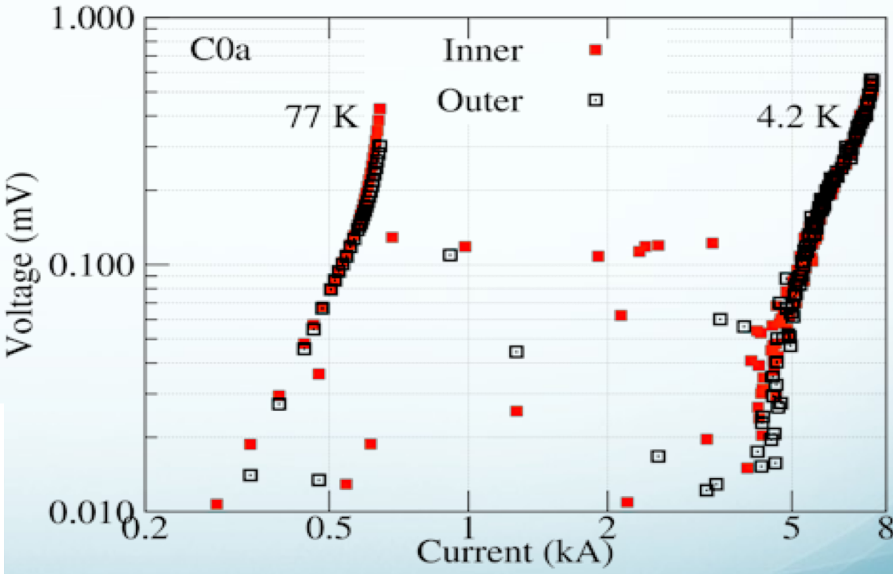
Baby coil C0a: CORC® wire test for CCT-C1

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

The test is performed with a low-J_e CORC® wire to learn the relevant steps to wind CORC®-CCT magnets.

Advanced Conductor Technologies LLC
www.advancedconductor.com

BERKELEY LAB

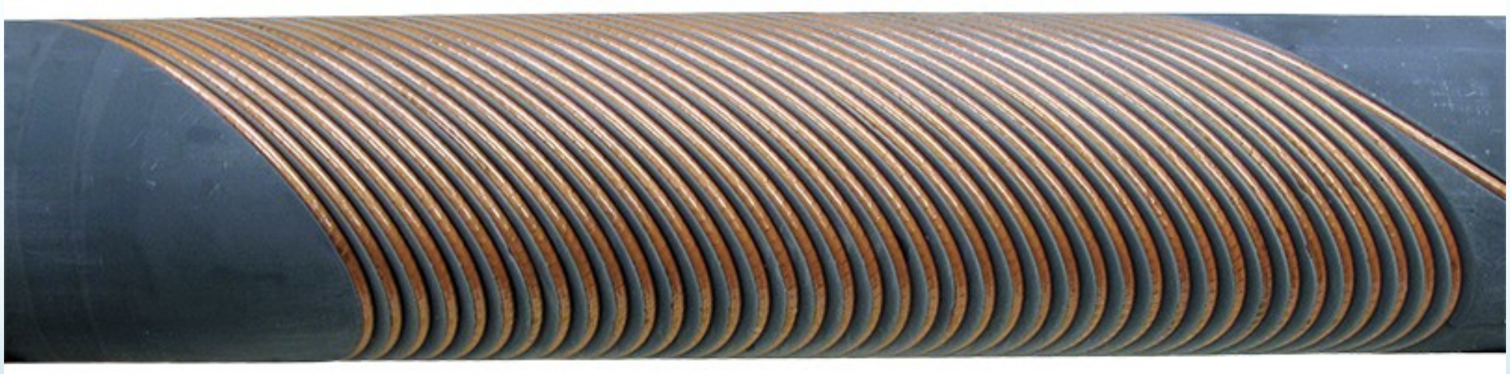
CORC® CCT-C1 construction

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/mm²
- 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

Winding a CCT magnet from CORC® wires is almost as simple as winding with copper strand!

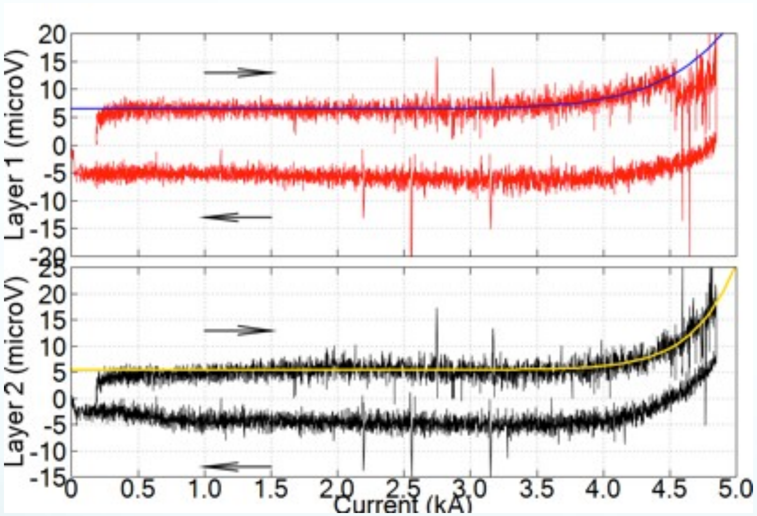
Advanced Conductor Technologies LLC
www.advancedconductor.com

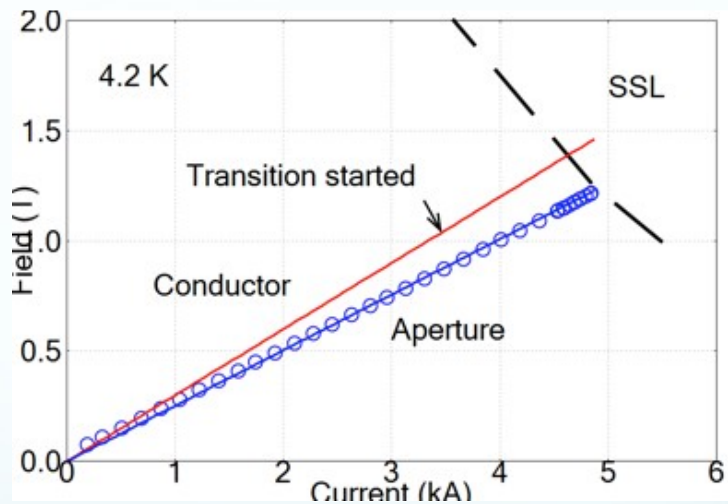
BERKELEY LAB

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 ∝V (= 0.001 ∝V/cm)





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

The successful test has shown that the CORC®-CCT magnet technology is viable and could now continue with higher performance CORC® wires.

Advanced Conductor Technologies LLC
www.advancedconductor.com

BERKELEY LAB

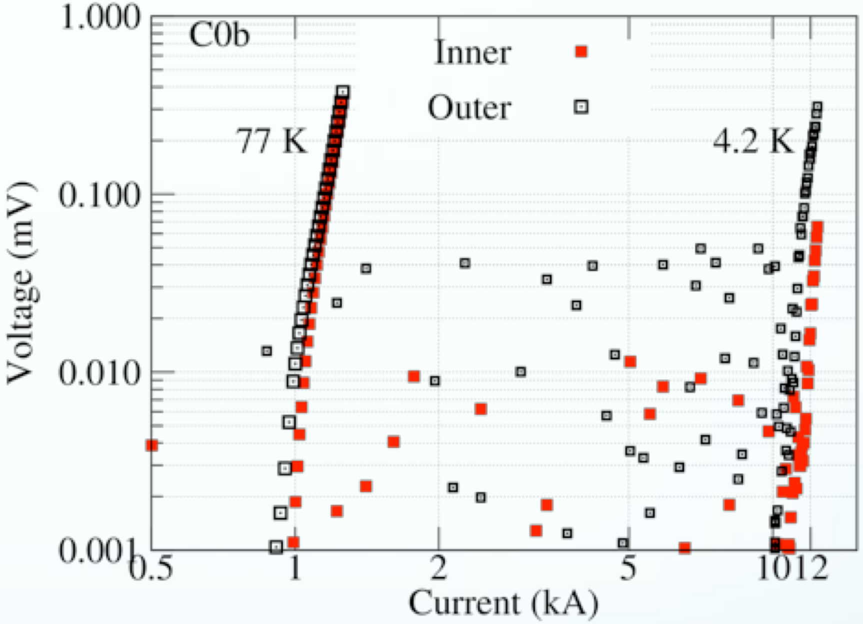
Baby coil C0b: CORC® wire test for CCT-C2

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

The CORC® wire layout was selected to allow for a high-J_e, while making sure the CORC® wire remains flexible enough to wind into a CCT magnet with relatively high transfer function (generated dipole field per kA).

Advanced Conductor Technologies LLC
www.advancedconductor.com

BERKELEY LAB

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

Advanced Conductor Technologies LLC
www.advancedconductor.com

BERKELEY LAB

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

Advanced Conductor Technologies LLC
www.advancedconductor.com

BERKELEY LAB