Conductor on Round Core (CORC) cable development for accelerator magnets

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Advanced Conductor Technologies LLC
www.advancedconductor.com

WAMHTS-1, Hamburg, Germany, May 22, 2014

Outline

1. Introduction to ACT and CORC cables.
2. CORC cables for fusion magnets.
3. Mechanical properties of CORC cables.
4. CORC cables for high-energy physics magnets.
5. Production of long, high-quality CORC cables.
6. CORC cable performance projections.

Advanced Conductor Technologies LLC (ACT)

Founded in June 2011 as a spin-off from the University of Colorado and the National Institute of Standards and Technology (NIST)

Advanced Conductor Technologies focuses on the commercialization of high-temperature superconducting Conductor on Round Core (CORC) cables for high-density power transmission and high-field magnets.

Personnel at ACT:

1. Danko van der Laan, Ph.D.
2. Annemiek Kamphuis, M.Sc.
3. Fraser Douglas Ph.D.

New location:

3082 Sterling Circle Unit B, Boulder, CO 80301 (2851 SF)

Programs supporting CORC cable development

Advanced Conductor Technologies:

1. Department of Energy – Office of Fusion Energy Sciences

- CORC cable for fusion magnets
- Phase II STTR (2 years – April 2013 to April 2015)
- Subcontractor is MIT (Joe Minervini, Phil Michael and Leslie Bromberg)

2. Department of Energy – Office of High Energy Physics

- CORC cables for accelerator magnets
- Phase II SBIR (2 years – April 2014 to April 2016)
- Subcontractor: NHMFL (David Larbalestier and Ulf Trociewitz)

3. Navy

- He-gas cooled CORC power transmission cables
- Phase II STTR (2 years – February 2014 to January 2016)
- Subcontractor is CAPS (Sastry Pamidi and Chul Kim)

University of Colorado:

1. Department of Energy – Office of High Energy Physics

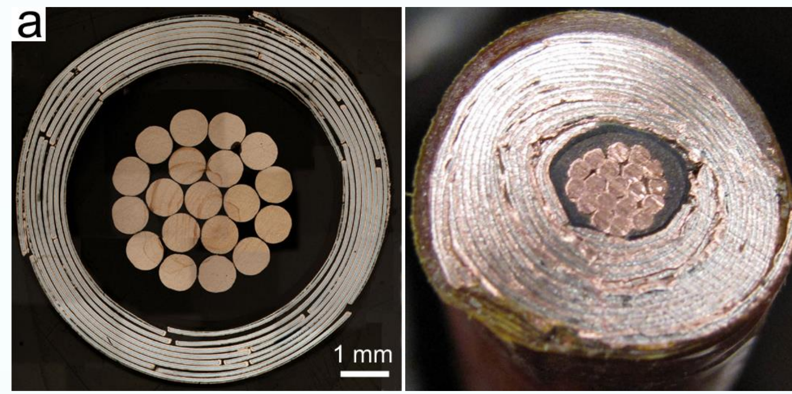
- support for high-J_e CORC cable development
- Base program (3 years – April 2012 to March 2015)

Conductor on Round Core cables

CORC cable principle:
Winding many high-temperature superconducting YBCO coated conductors from SuperPower in a helical fashion with the YBCO under compression around a small former.

SuperPower Inc.

D.C. van der Laan, *SUST* 22, 065013 (2009).



Benefits:

- Very flexible
- Very high currents and current densities
- Mechanically very strong
- Minimum degradation from cabling (< 10 %)
- Current sharing between tapes possible

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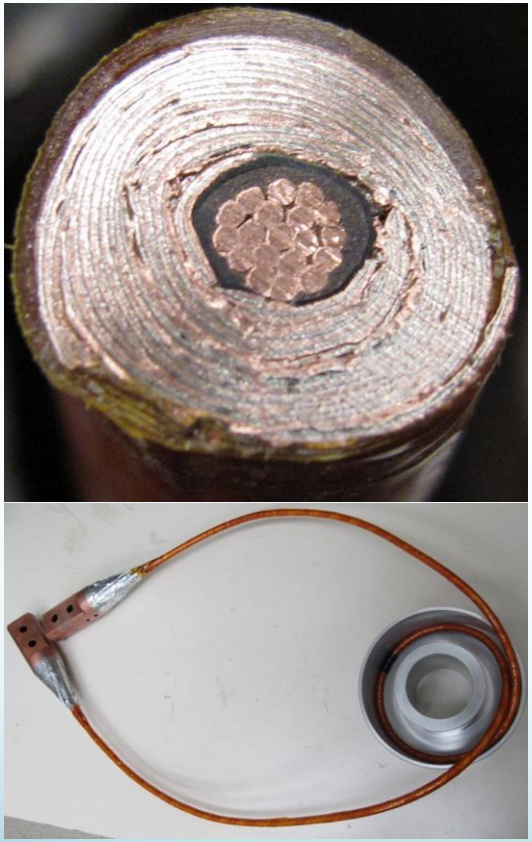
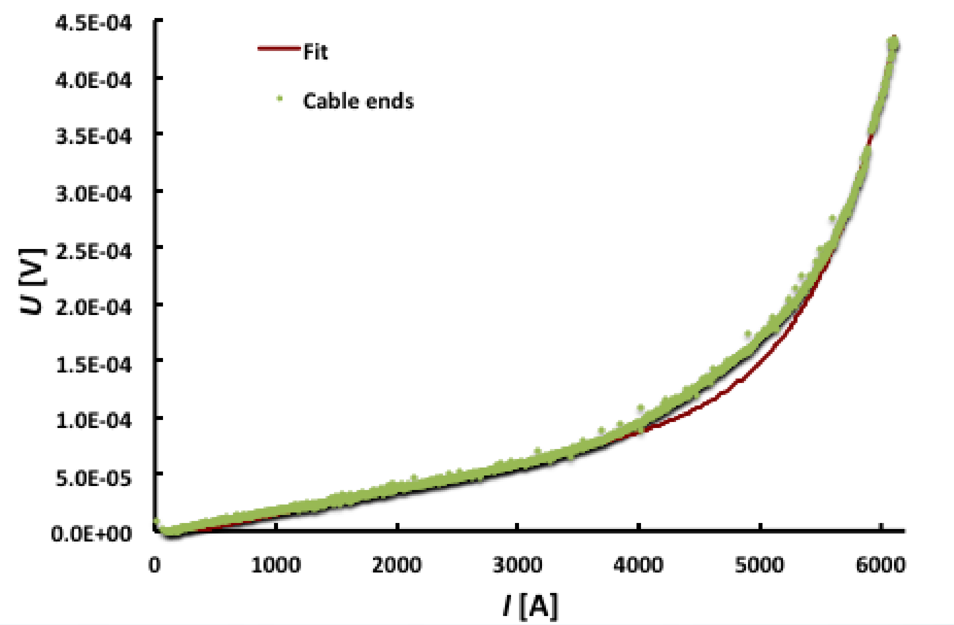
CORC cables for fusion magnets

Goal is to reach a cable current >30 kA at 4.2 K and B > 12 T.

Cables tested at the NHMFL in 19.8 T background field:

52 YBCO coated conductors, 17 layers, **cable O.D. 7.5 mm**:





I_{quench} = 6000 A @ 4.2 K, 19 T

I_c = 5021 A @ 4.2 K, 19 T, 1 μV/cm

J_e = 114 A/mm^2 @ 4.2 K, 19.0 T

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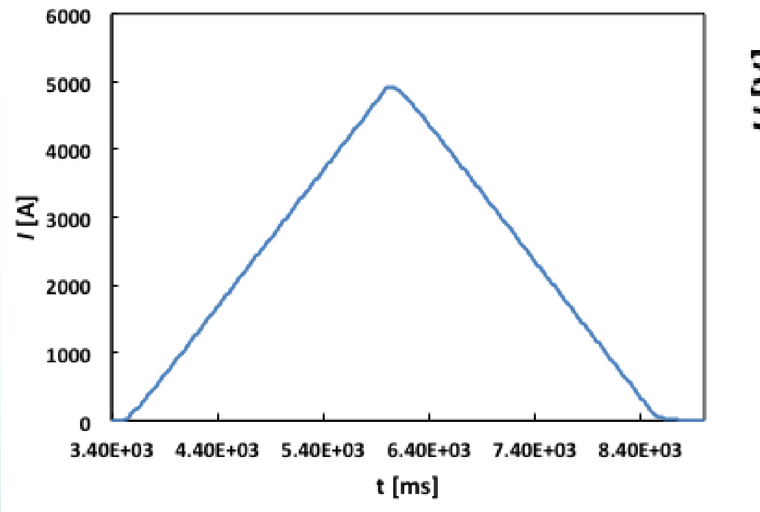
ACT: DOE – Office of Fusion Energy Sciences Award DE-SC0007660,
NHMFL: DOE, NSF, agreement DMR-0654118, and the State of Florida

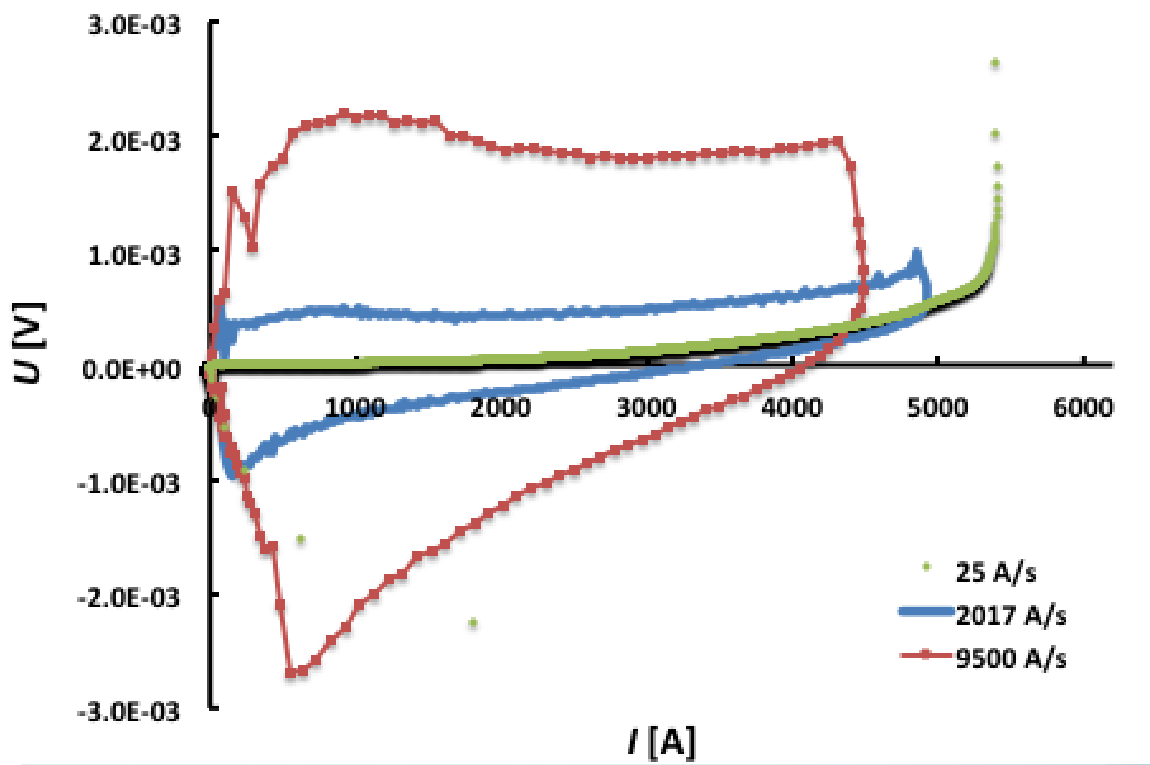
High-current ramp rates at 19 T

Will current distribution become inhomogeneous in cables with many layers at high current ramp rates?

Cable: 52 CC in 17 layers.

Current ramp rates at 4.2 K, 19 T to 90 % of I_{quench}:
- 2017 A/s
- 9500 A/s





No effect of high current ramp rates!

Ramp rates of 68,000 A/s at 19 T

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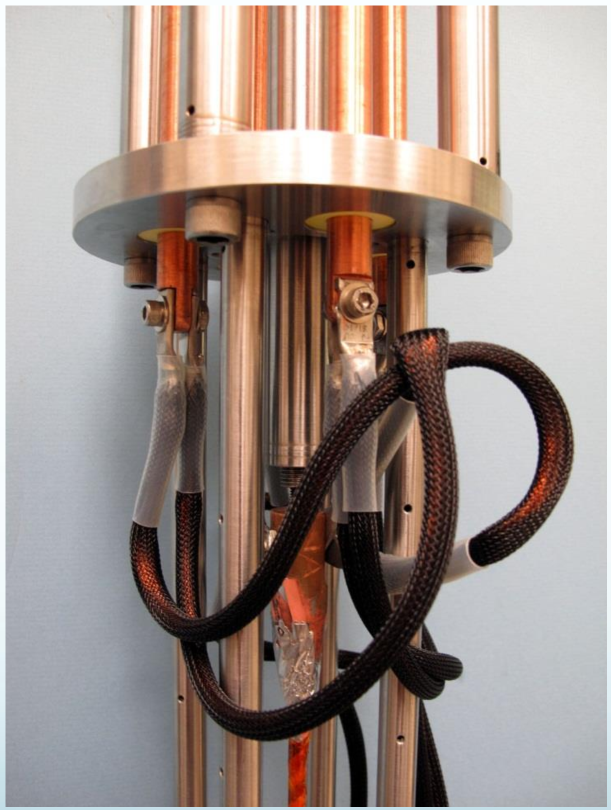
ACT: DOE – Office of Fusion Energy Sciences Award DE-SC0007660,
NHMFL: DOE, NSF, agreement DMR-0654118, and the State of Florida

Testing of CORC cables under axial stress

σ

Cable installed with flexible current leads:



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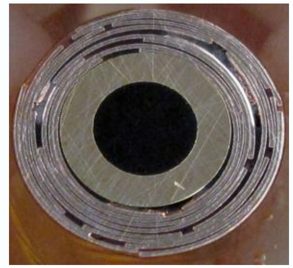
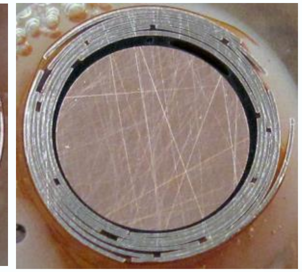
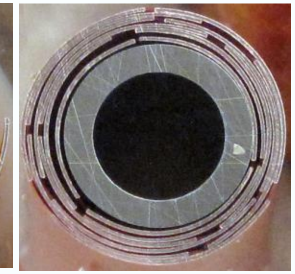
Current leads can handle >1500 A at 76 K.

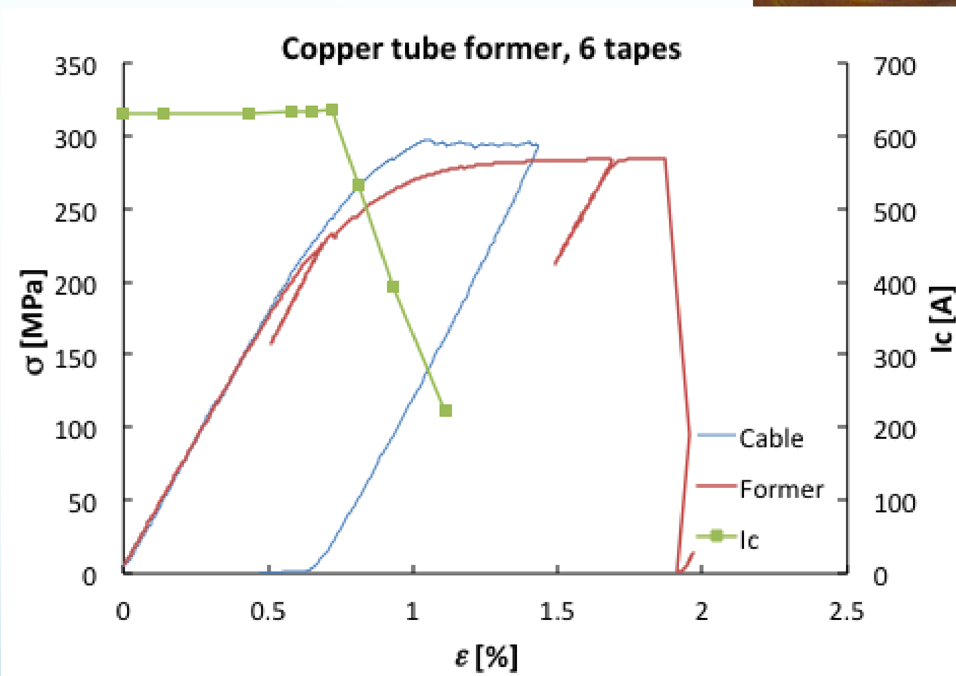
Testing of CORC cables under axial stress

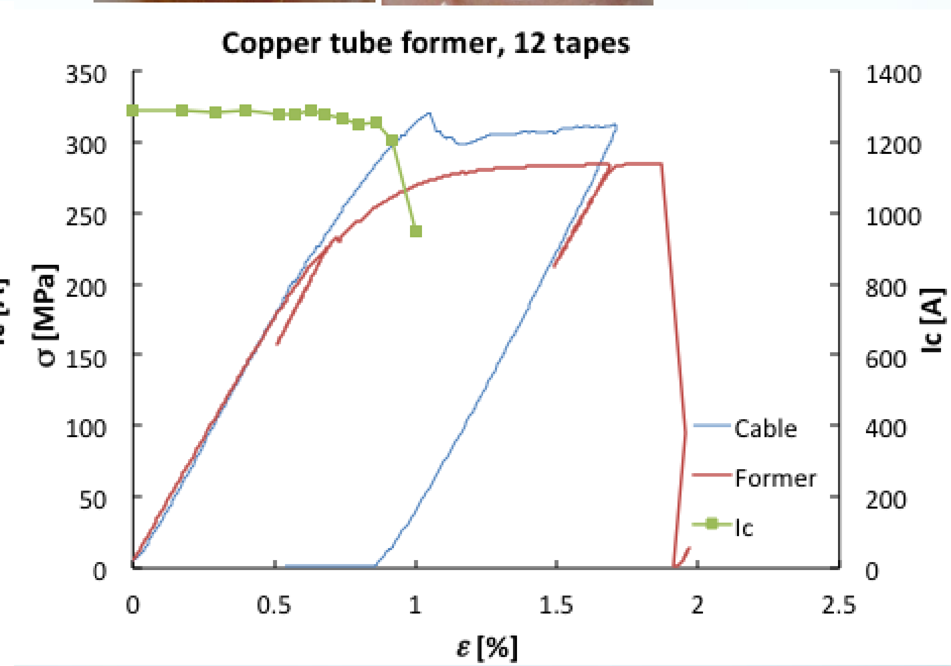
Various options:











3/16” O.D. Cu former, 0.032” wall:

6 tapes in 2 layers: σ_{irr} = 228 MPa

12 tapes in 4 layers: σ_{irr} = 277 MPa

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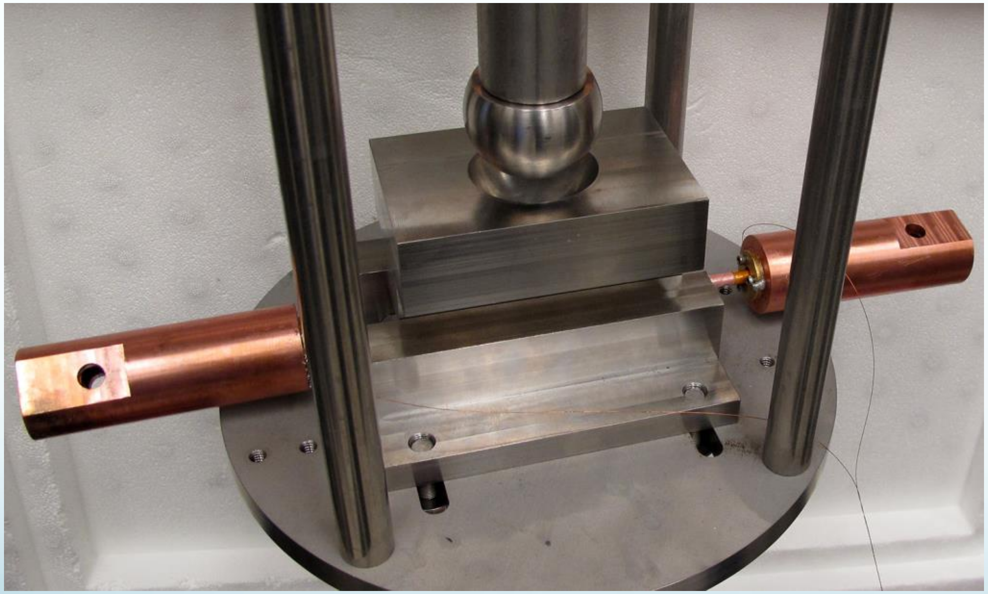
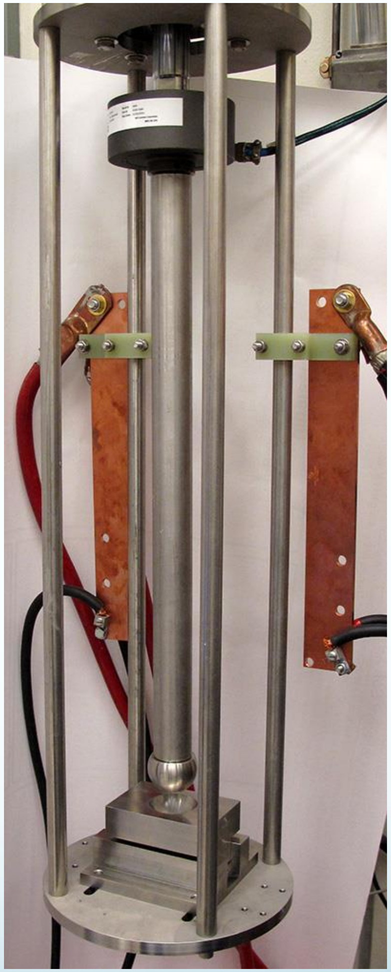
Testing CORC cables under transverse compression

Compressive stress test facility:

- maximum load 10,000 lbs, or 44.5 kN.
- anvil lengths 50 mm or 100 mm.
- testing at room temperature and 76 K.
- sample current exceeding 2 kA.





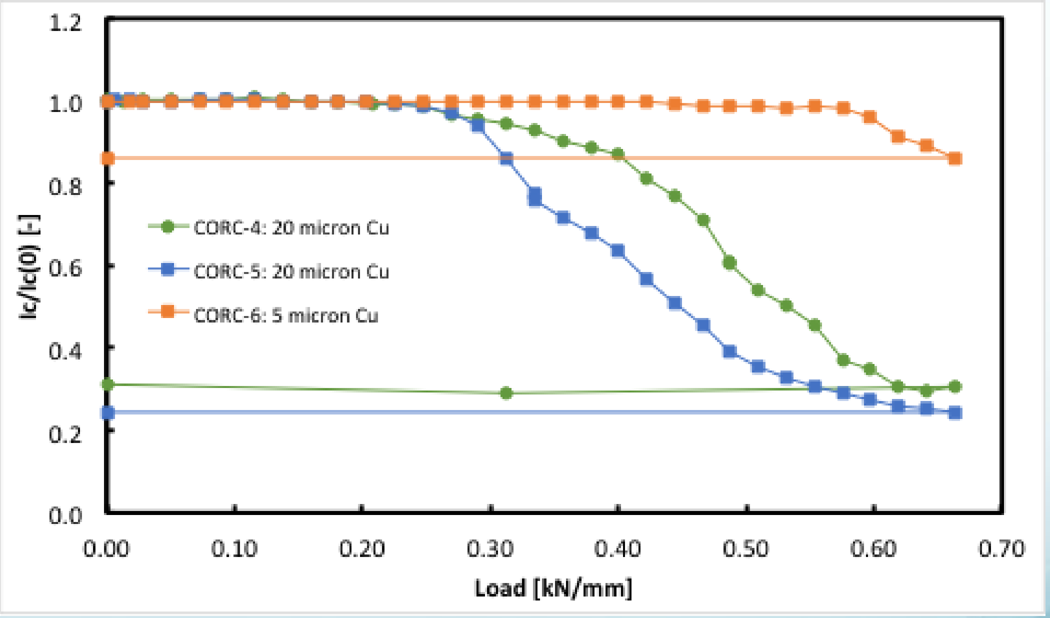
Transverse compression test results (Cont.)

CORC cables:

- solid stainless steel former
- former O.D. 4.8 mm
- 3 layers

Anvil length: 5 cm.

CORC-4:
9 tapes, 0 mm gap, **20 μm Cu**
CORC-5:
9 tapes, 0.5 mm gap, **20 μm Cu**
CORC-6:
9 tapes, 0 mm gap, **5 μm Cu**

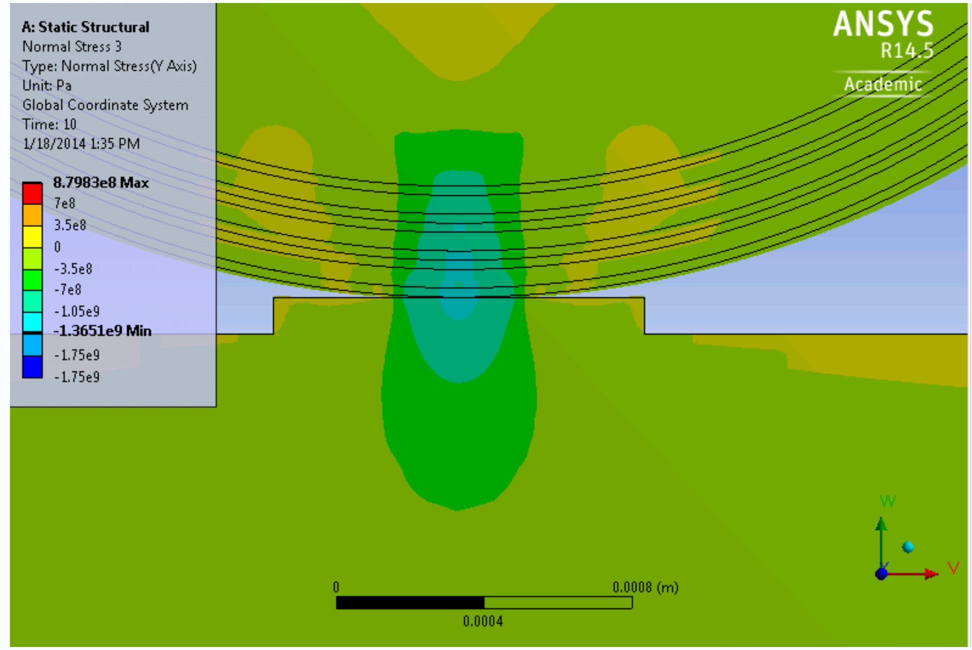


Decrease in I_c depends on gap size and copper thickness.

Modeling of transverse compressive stress

PSFC

Maximum compressive stress at 7,500 lbs with 5 cm anvil: 1340 MPa



0.5 mm-wide imprint in 5 cm long brass anvil after 7,500 lbs load suggests a stress of 1.3 GPa!

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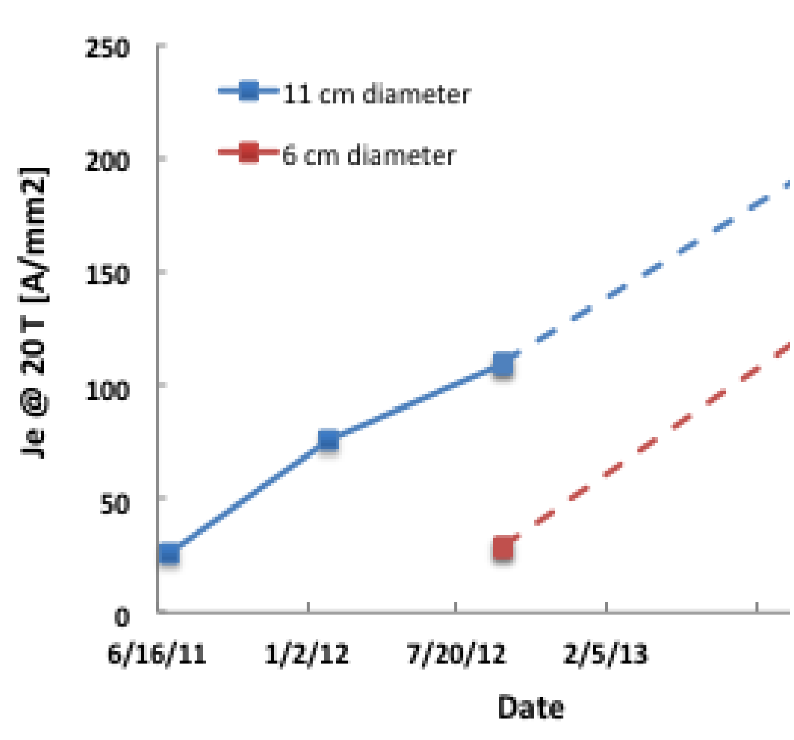
CORC cables for accelerator magnets

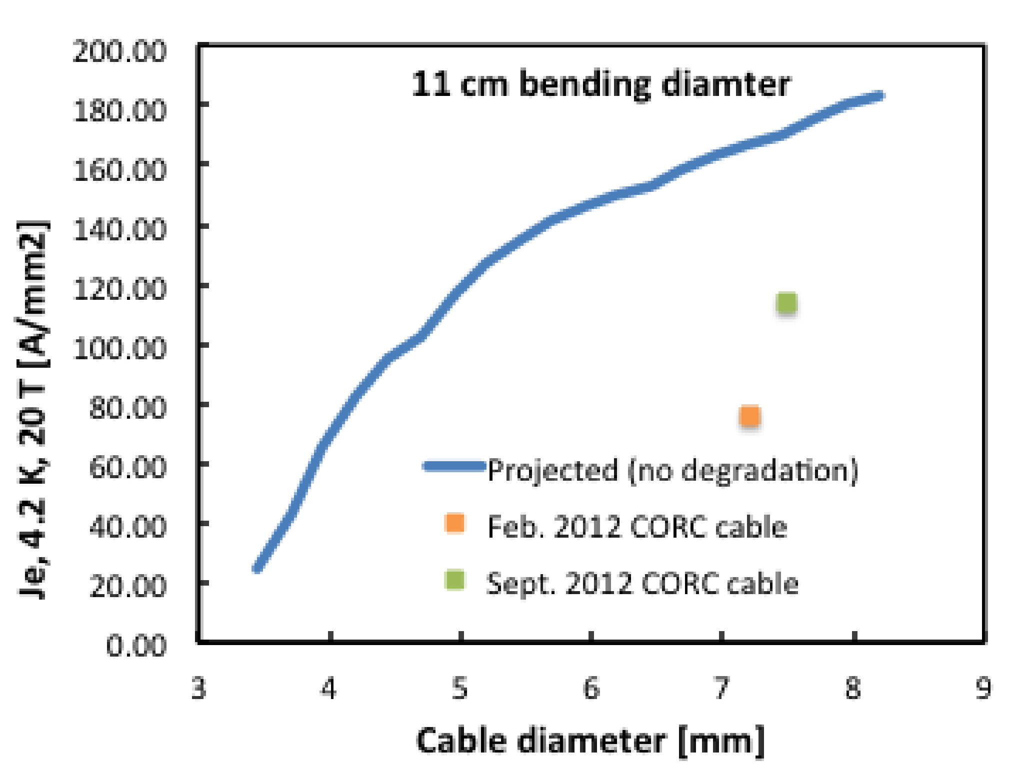
Collaborators: David Larbalestier and Ulf Trociewitz (NHMFL)

Goal 1: J_e of > 300 A/mm^2 at 20 T at 11 cm bending diameter using basic tape.

Goal 2: improve CORC flexibility : J_e > 200 A/mm^2 at 20 T and at 6 cm bending diameter.

Status at beginning of program (2013):





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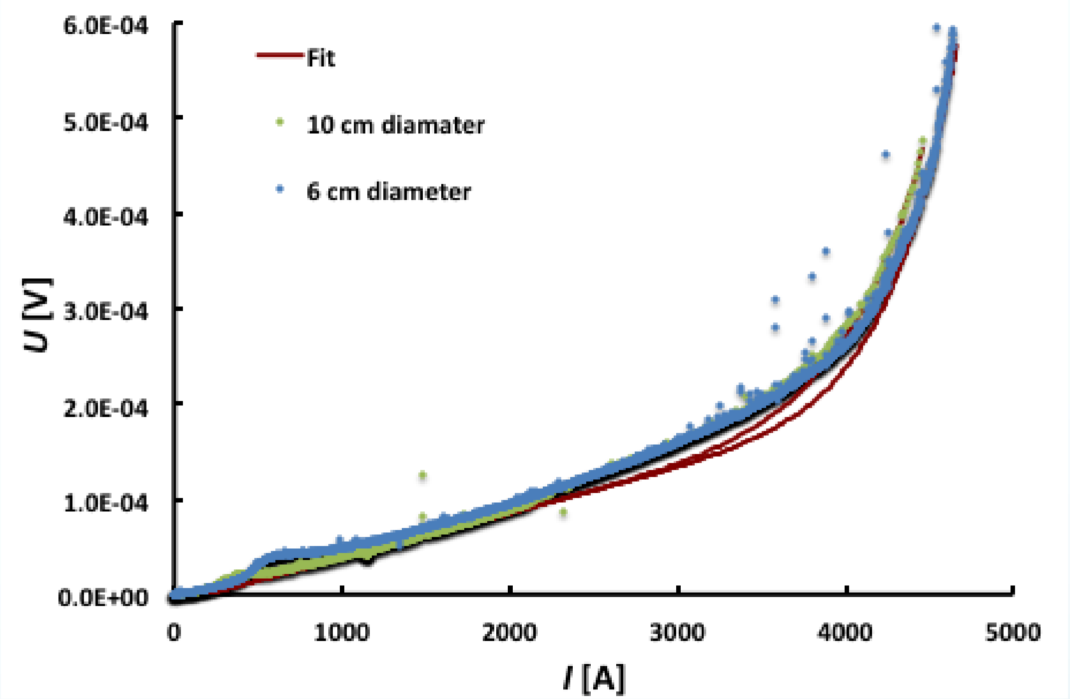
DOE-High Energy Physics Award DE-SC0009545

CORC J_e>100 A/mm² at 20 T and 6 cm diameter

Cable:
- 37 YBCO CC, 14 layers
- cable O.D. 6.4 mm



I_c = 3989 A (10 cm) 3967 A (6 cm)@ 4.2 K, 15 T (J_e=122 A/mm²)
Expected J_e = 103 A/mm² @ 4.2 K, 20 T

No degradation when bending from 10 cm to 6 cm: J_e(20T) = 103 A/mm²!

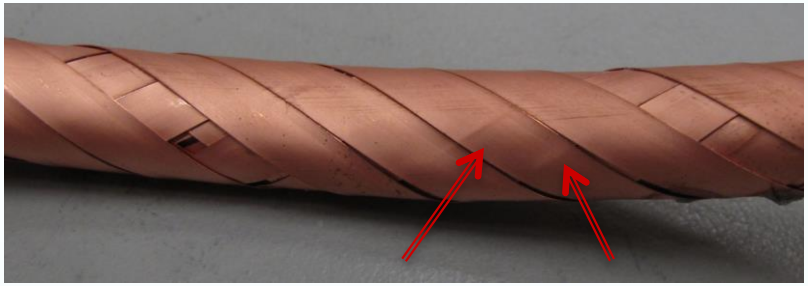
DOE - High Energy Physics Award DE-SC0009545

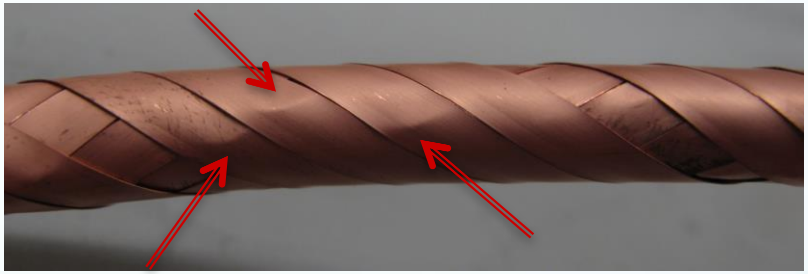
Room for improvement

I_c = 5021 A @ 4.2 K, 19 T

During cable inspection after test at 19T:

Many damaged tapes in outer layers due to cable bending!

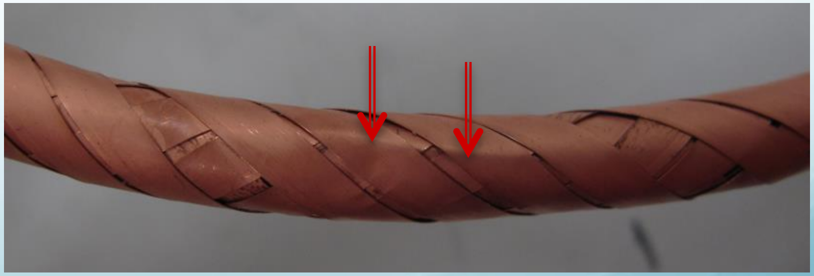




Caused by loose winding pack.

Winding pack needs to be controlled:

=> Cabling machine is needed.

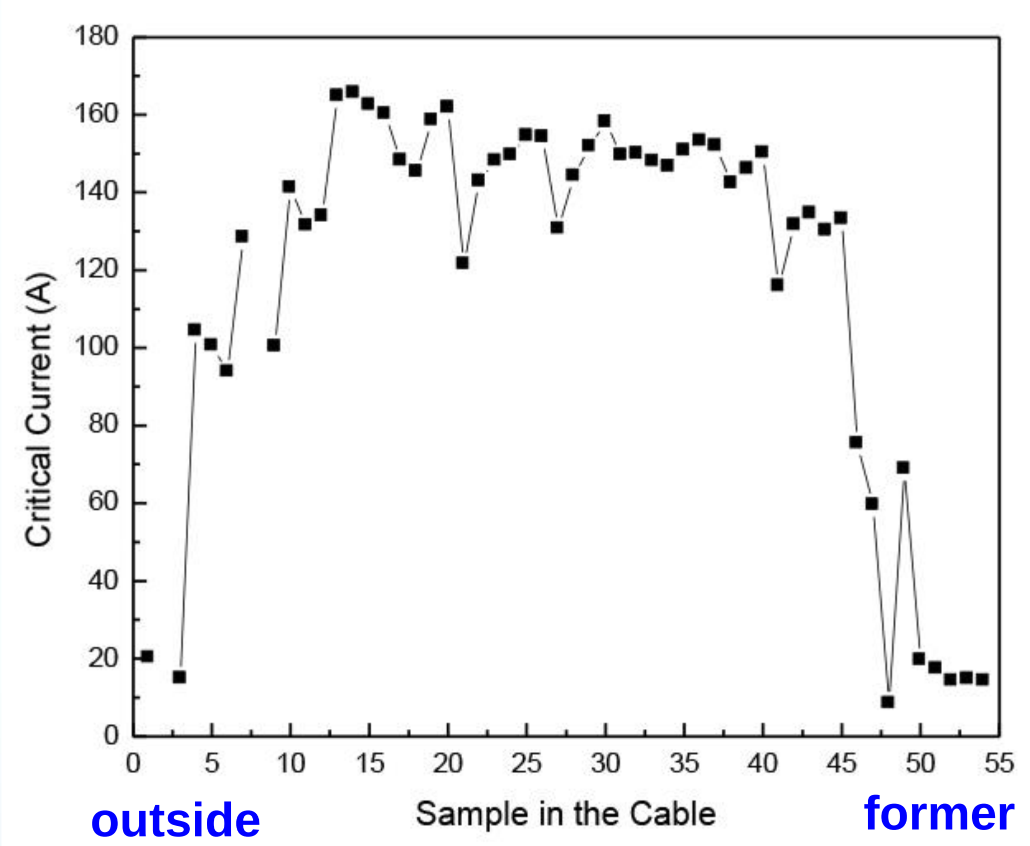


DOE - Office of High Energy Physics grant DE-FG02-12ER41801

Performance of tapes extracted from CORC cables

52 tape CORC cable:

- 3 mm former
- wound into 11 cm diameter
- tested at 19 T: I_c was 50 % of projected value.
- I_c(76 K) after test 3300 A



Extracting all tapes from cable and measure I_c at 76 K:

Outer layers show degradation due to tape kinking.

Inner 4 layers show large degradation due to small former.

About 80 % of the tapes near 100 %

Sum of tape I_cs 6,100 A!

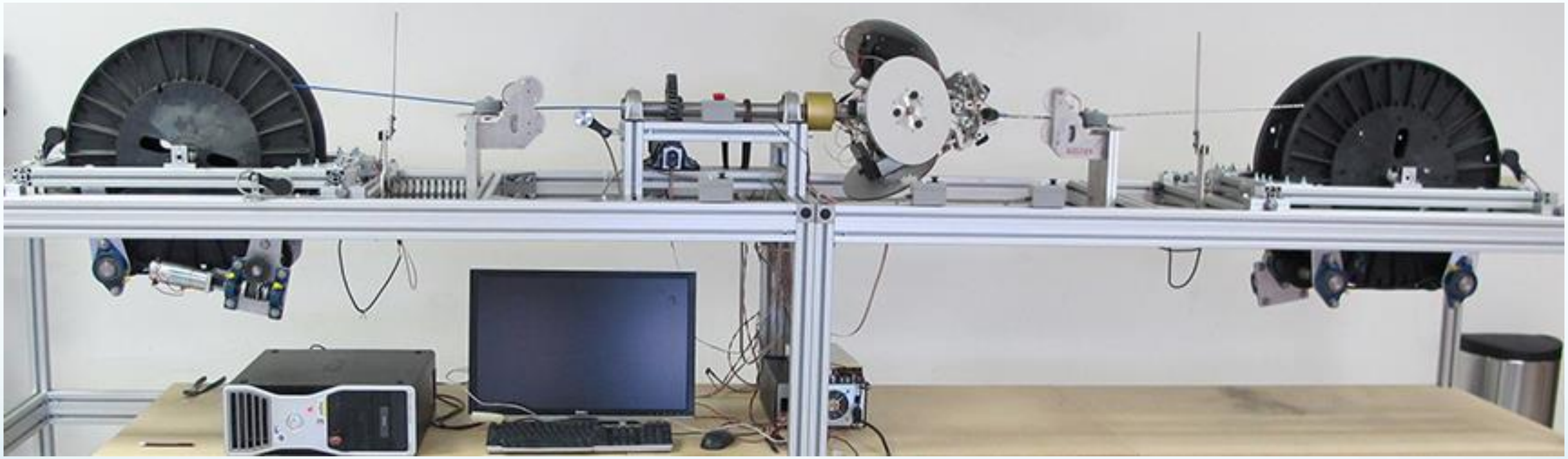
Low cable performance mainly due to terminations.

DOE - Office of High Energy Physics grant DE-FG02-12ER41801

CORC cable machine

Winding of long CORC cables:

- winding CORC cables layer-by-layer
- accurate control of: 1. tape tension
  2. winding angle
  3. spacing between tapes



Long, high-quality CORC cables are now available!!!

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University of Colorado program sponsored by:
DOE - Office of High Energy Physics grant DE-FG02-12ER41801

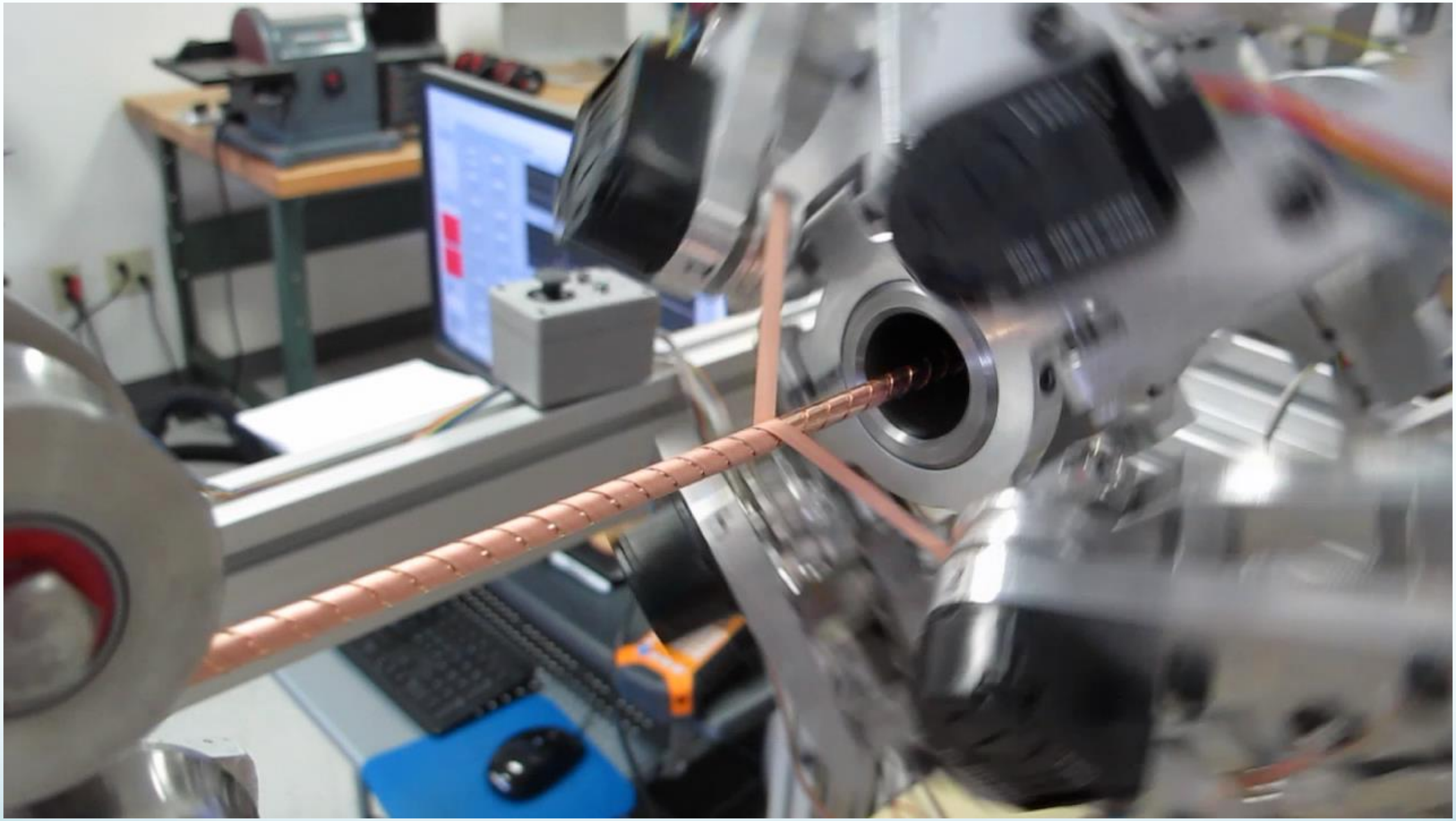
CORC cable for CERN order

Cable specification:

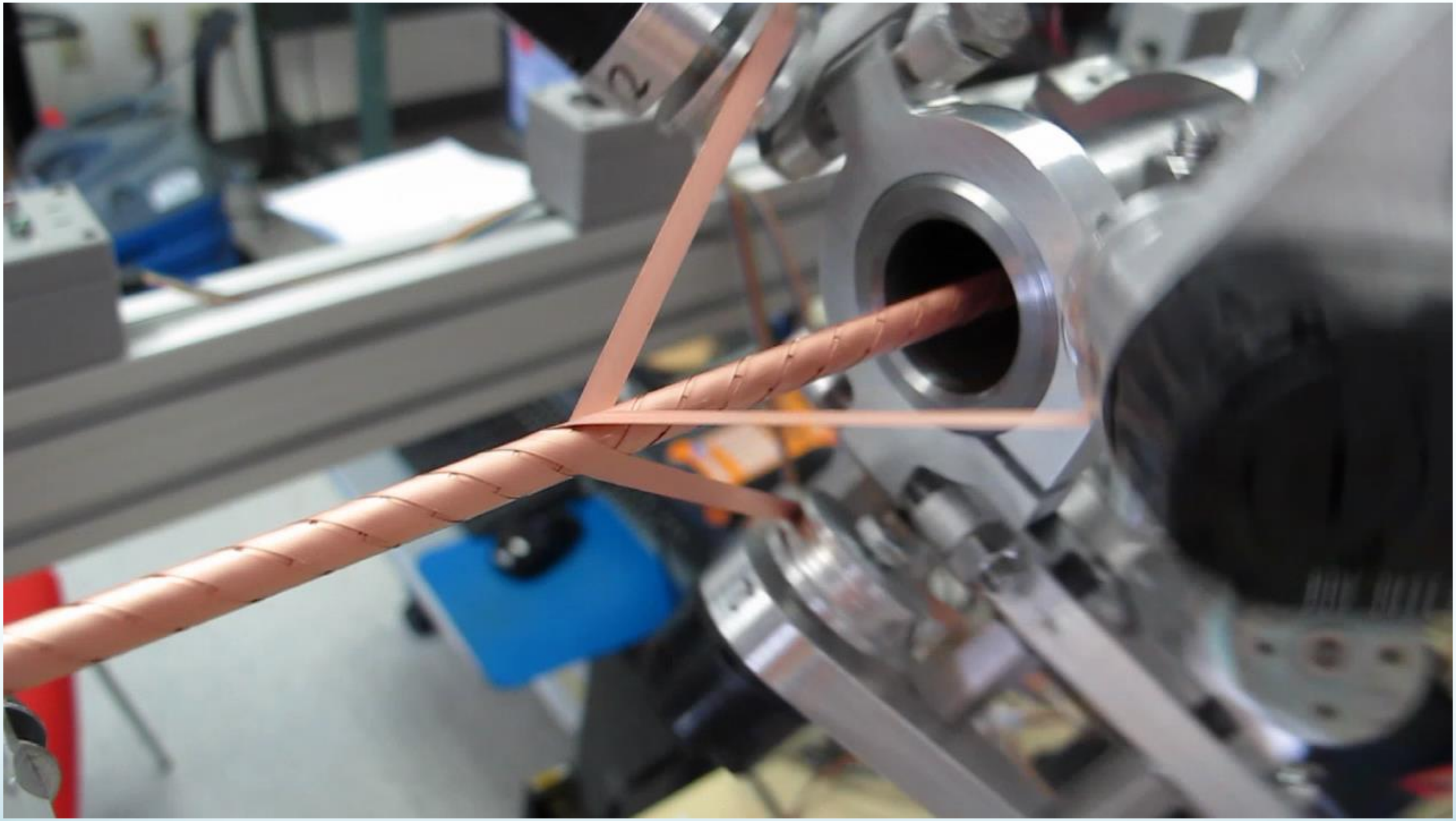
- 12 meter long
- 38 tapes (4 mm wide, 20 microns of copper)
- 5 mm diameter former (Al + Cu)

Cable finished Saturday May 17th.
Liquid nitrogen test scheduled first week of June.

Winding the CERN CORC cable

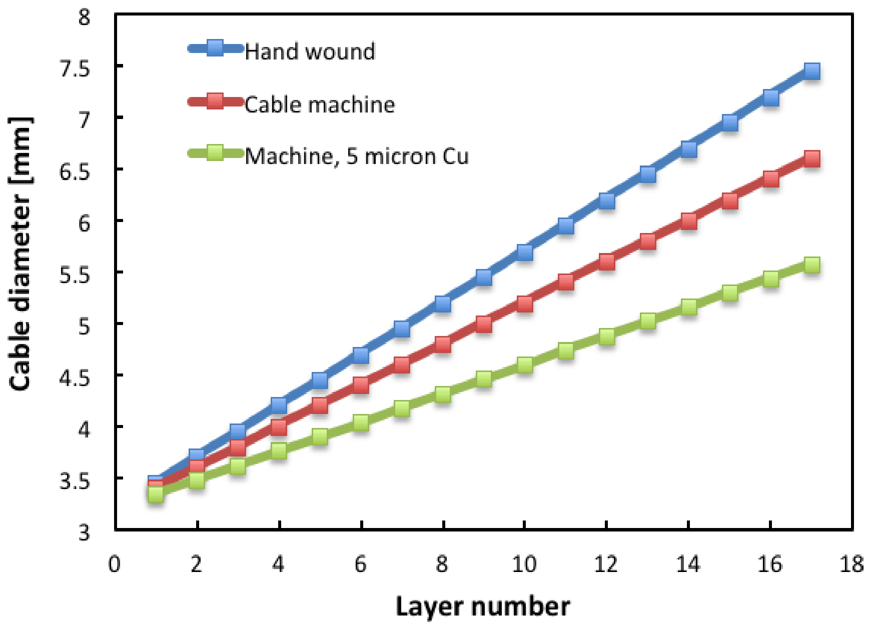


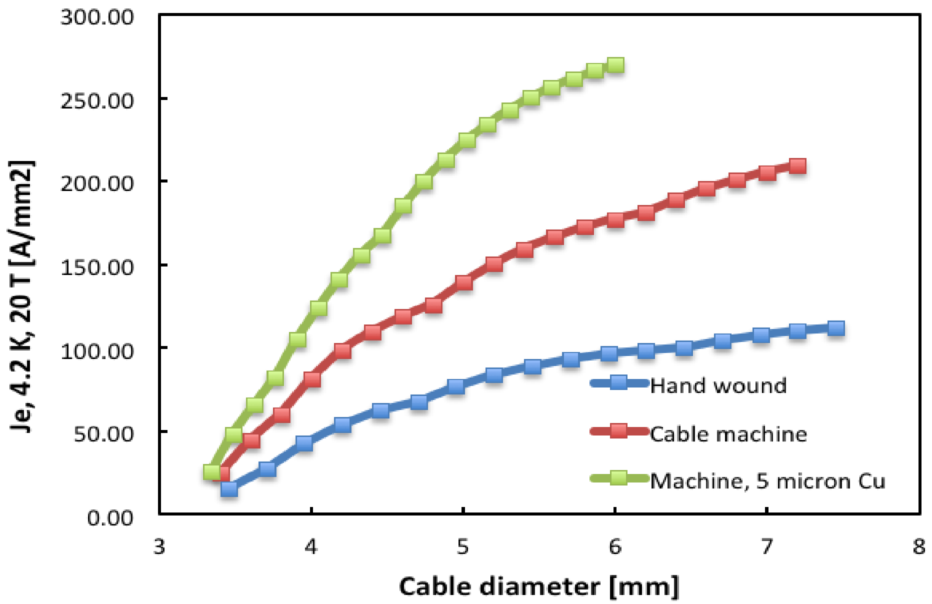
Winding the CERN CORC cable (Cont.)



CORC cable performance projections

Improved J_e at 20 T due to winding machine and reduced copper thickness:



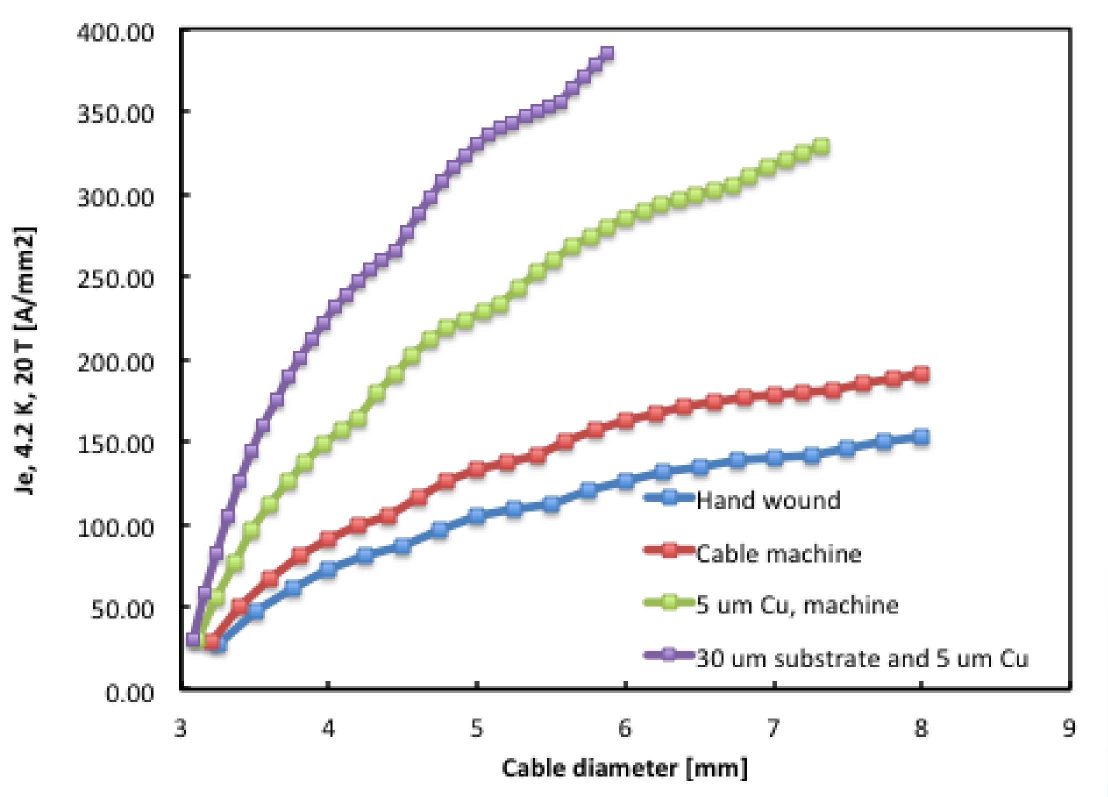


Roughly 30 % reduction in cable diameter when using 5 microns of copper and a cable machine.

Roughly 3x improvement of J_e at a cable diameter of 6 mm.

CORC cable performance projections (Cont.)

Improved J_e at 20 T due to reduced substrate thickness:



Roughly 50 % improvement of J_e when using 30 microns substrate.
CORC cable with 300 A/mm^2 is less than 5 mm in diameter!

Thinner substrates are coming!

SuperPower Inc.
A Furukawa Company

superior performance.
powerful technology.

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SUPERPOWER ADDS THINNER SUBSTRATE OPTIONS TO SUPERCONDUCTING WIRE OFFERINGS

SuperPower adds thinner substrate options to superconducting wire offerings

- *SuperPower adds a 30 micron substrate geometry to further increase product flexibility and increase current densityem>*

"Advanced Conductor Technologies has been eagerly awaiting this new, thinner profile conductor for incorporation into our high current density Conductor on Round Core (CORC) cable," said Dr. Danko van der Laan, founder and chief executive officer of the start-up company located in Boulder, Colorado…"

"Advanced Conductor Technologies has been eagerly awaiting this new, thinner profile conductor for incorporporation into our high current density Conductor on Round Core (CORC) cable," said Dr. Danko van der Laan, founder and chief executive officer of the start-up company located in Boulder, Colorado. "The 33% reduction in conductor profile in combination with much better mechanical properties, will contribute to an increase of as high as 50% to our extremely current dense, flexible cable that is being eagerly awaited for incorporation into devices such as the next generation of accelerators and high-field scientific magnets."

http://superpower-inc.com/content/superpower-adds-thinner-substrate-options-superconducting-wire-offerings

CORC cable performance exceeding 600 A/mm² (20 T)

Based on tapes available within 6 months:

30 μm substrate, I_c(77 K, 4 mm) = 150 A, lift factor =2 (I_c(4.2 K,20 T)/I_c(77 K, s.f)

	O.D.	Tape width	Gap	# tapes	Layer-Ic	Ic (77 K)	Ic (4.2 K, 20 T)	Je (4.2 K, 20 T)
Layer #	[mm]	[mm]	[mm]		[A]	[A]	[A]	[A/mm2]
1	3.08	3	0.5	2	225	225	432	58
2	3.16	3	0.5	2	225	450	864	110
3	3.24	3	0.5	2	225	675	1296	157
4	3.32	3	0.5	2	225	900	1728	200
5	3.4	3	0.5	3	338	1238	2376	262
6	3.48	3	0.5	2	225	1463	2808	295
7	3.56	3	0.5	2	225	1688	3240	326
8	3.64	3	0.5	2	225	1913	3672	353
9	3.72	3	0.5	2	225	2138	4104	378
13	4.04	3	0.5	2	225	3038	5832	455
14	4.12	3	0.5	2	225	3263	6264	470
15	4.2	3	0.5	2	225	3488	6696	483
16	4.28	3	0.5	3	338	3825	7344	510
17	4.36	3	0.5	3	338	4163	7992	535
18	4.44	3	0.5	3	338	4500	8640	558
19	4.52	3	0.5	3	338	4838	9288	579
20	4.6	3	0.5	3	338	5175	9936	598

J_e (4.2 K, 20 T) > 600 A/mm² possible in 4.5 mm diameter CORC cable!
Cable bending diameter of 10x cable diameter => 4-5 cm!

CORC cable performance exceeding 1300 A/mm^2 (20 T)

Based on tapes available within 1-3 years:

15 μm substrate, I_c(77 K, 4 mm) = 200 A, lift factor =3 (I_c(4.2 K,20 T)/I_c(77 K, s.f)

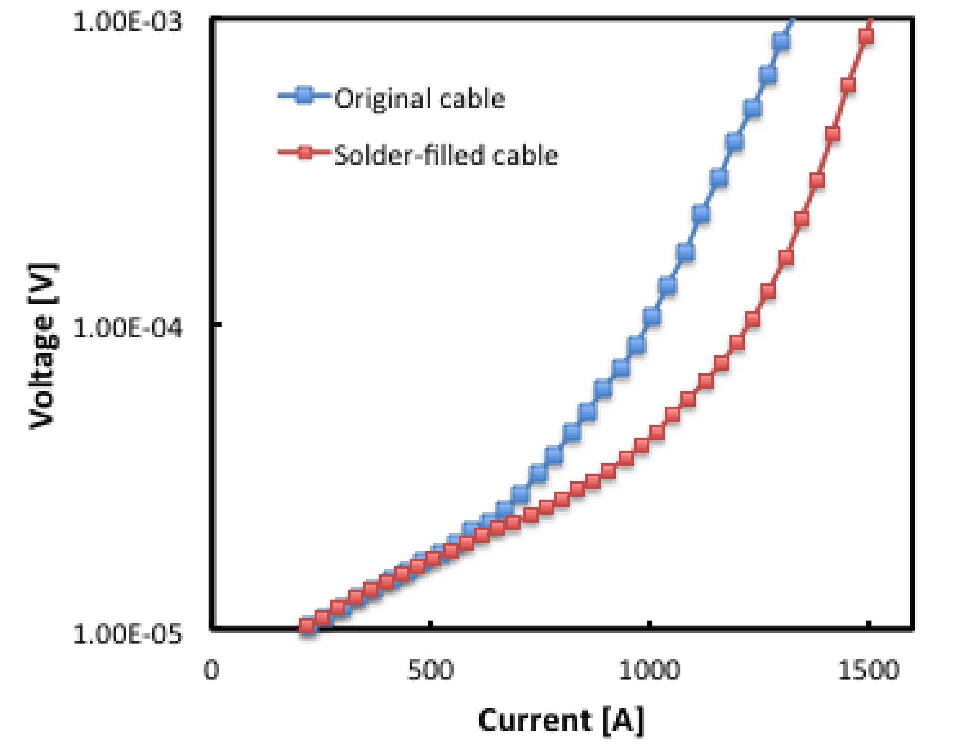
Layer #	O.D. [mm]	Tape width [mm]	Gap [mm]	# tapes	Layer-Ic [A]	Ic (77 K) [A]	Ic (4.2 K, 20 T) [A]	Je (4.2 K, 20 T) [A/mm2]
1	3.05	3	0.5	2	300	300	864	118
2	3.1	3	0.5	2	300	600	1728	229
3	3.15	3	0.5	2	300	900	2592	333
4	3.2	3	0.5	2	300	1200	3456	430
5	3.25	3	0.5	2	300	1500	4320	521
6	3.3	3	0.5	2	300	1800	5184	606
7	3.35	3	0.5	2	300	2100	6048	686
8	3.4	3	0.5	2	300	2400	6912	761
9	3.45	3	0.5	2	300	2700	7776	832
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12	3.6	3	0.5	2	300	3600	10368	1019
13	3.65	3	0.5	2	300	3900	11232	1073
14	3.7	3	0.5	2	300	4200	12096	1125
15	3.75	3	0.5	2	300	4500	12960	1173
16	3.8	3	0.5	2	300	4800	13824	1219
17	3.85	3	0.5	2	300	5100	14688	1262
18	3.9	3	0.5	2	300	5400	15552	1302
19	3.95	3	0.5	2	300	5700	16416	1340
20	4	3	0.5	2	300	6000	17280	1375

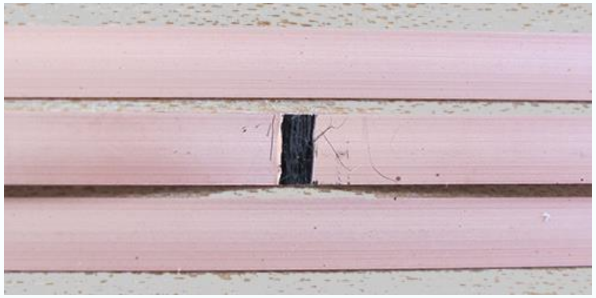
J_e (4.2 K, 20 T) > 1300 A/mm^2 possible in 4.0 mm diameter CORC cable!

Effect of tape inhomogeneity on CORC cable performance

CORC cable with 12 tapes in 4 layers:

- two tapes with a 2 mm long interruption.





Cable with defects:

I_c = 991 A

n-value = 10.8

Solder-filled cable:

I_c = 1244 A

n-value = 16.8

Current sharing in CORC cables lowers conductor homogeneity and piece length requirements!

CORC cable performance is largely independent of tape production quality!

DOE - High Energy Physics Award DE-SC0009545

Summary

CORC cables are being developed for three different markets:

1. High-current magnet cables for fusion and scientific magnets.
2. Power transmission cables and magnet feeders and busbars.
3. High-current density cables for HEP magnets:

Cable concept	Achieved		Potential		M	$\sigma_{transverse}$	$\varepsilon_{longitudinal}$
	I_{op}	J_{cable}	I_{op}	J_{cable}			
	(kA)	(A/mm^2)	(kA)	(A/mm^2)	(mT)	(MPa)	(%)
CORC	5	114 (19 T)	>10	>1300 (20 T)	?	1000	0.6

CORC cable performance improvements:

- J_e > 300 A/mm^2 possible with standard conductor ($I_{c,tape}$(20 T) = 150 A
- J_e > 600 A/mm^2 using 30 μm substrate and improved pinning ($I_{c,tape}$(20 T) = 300 A
- J_e > 1300 A/mm^2 using 15 μm substrate and improved pinning ($I_{c,tape}$(20 T) = 600 A

High-quality CORC cables can now be delivered in long lengths!

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