IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2015.
Invited presentation M1OrA-01 given at CEC-ICMC 2015, Tucson, USA, June 28 – July 2, 2015.

Record J_e of 246 A/mm^2 at 17 T in CORC cables made by Advanced Conductor Technologies

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www.advancedconductor.com

CEC-ICMC 2015, Tucson, AZ, June 29th, 2015

Outline

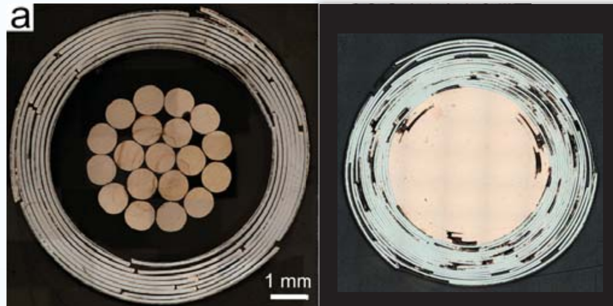
- **Introduction to CORC cables**
- **Early results on CORC cables for high-field magnet applications**
- **Quality improvements of CORC cables and their terminations**
- **Current status of CORC cable development for high-field magnet applications**
- **Future improvements in CORC cables as a result of conductor development**
- **Summary**

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).

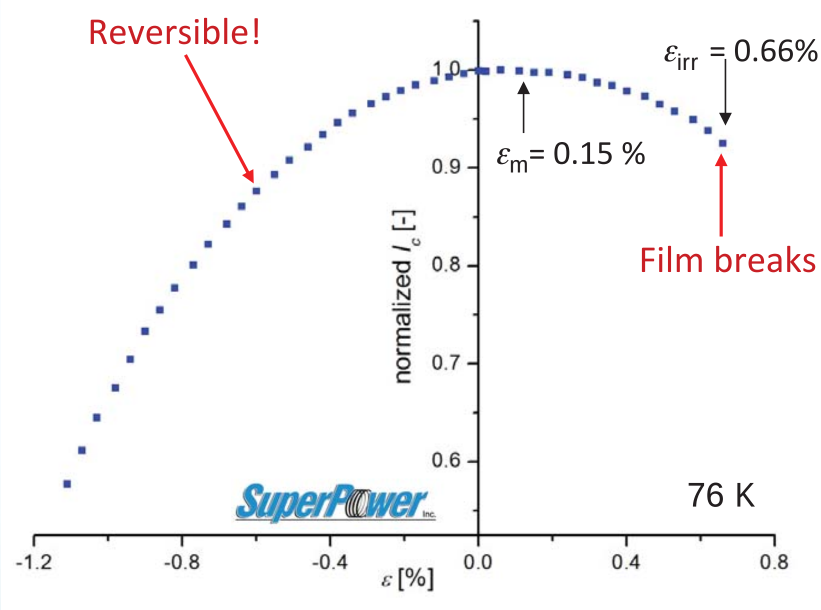


Benefits

- The most flexible HTS cable available
- Very high currents and current densities
- Mechanically very strong
- Current sharing between tapes
- Partially transposed

Science behind CORC cables: strain management

Reversible effect of axial strain on I_c of REBCO coated conductors



Large margin in compressive axial strain.

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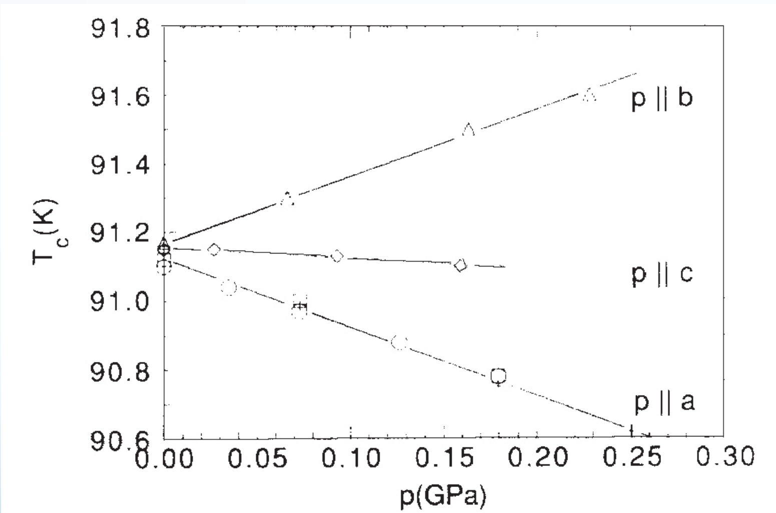
Relation between $T_c(\varepsilon)$ and $J_c(\varepsilon)$ in YBCO

NIST

$YBa_2Cu_3O_{7-\delta}$:
Anisotropic effect of pressure on T_c

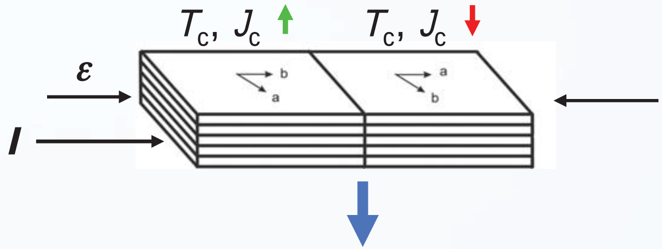
Effect of pressure on T_c is opposite for pressure applied along *a*-axis compared to *b*-axis



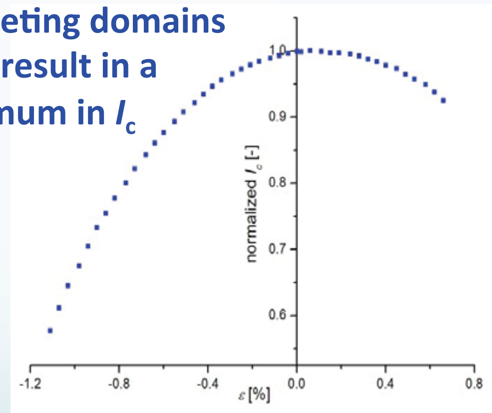
From:
U. Welp, *et al.*, Phys. Rev. Lett. 69, 2130-2133, 1992

Films in YBCO CC are twinned:

In case $T_c(\varepsilon)$ defines $J_c(\varepsilon)$:



Competing domains likely result in a maximum in I_c



Local competing changes in $T_c(\varepsilon)$ may result in a $I_c(\varepsilon)$ dependence seen in YBCO.

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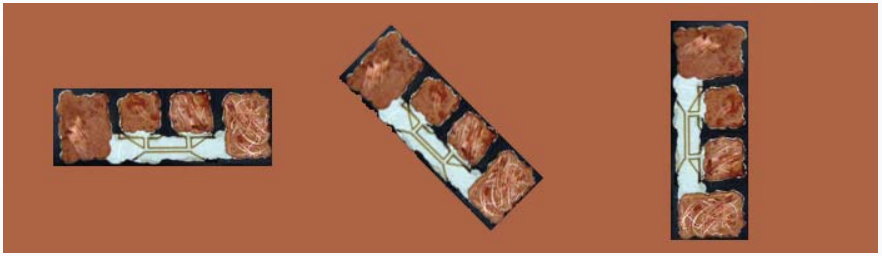
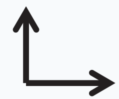
Anisotropic in-plane reversible strain effect in CC

MOCVD-IBAD: *a* - and *b* -axes aligned with conductor axis!

SuperPower

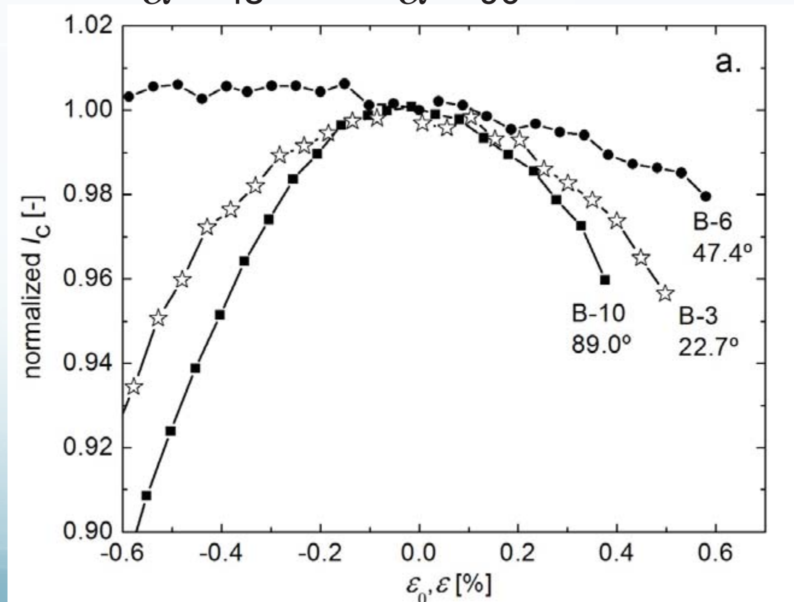




α = 0° α = 45° α = 90°

Cutting bridges at various angles from CC allows us to change the in-plane orientation of the strain.

Reversible strain effect disappears when strain is aligned 45° with the tape axis!



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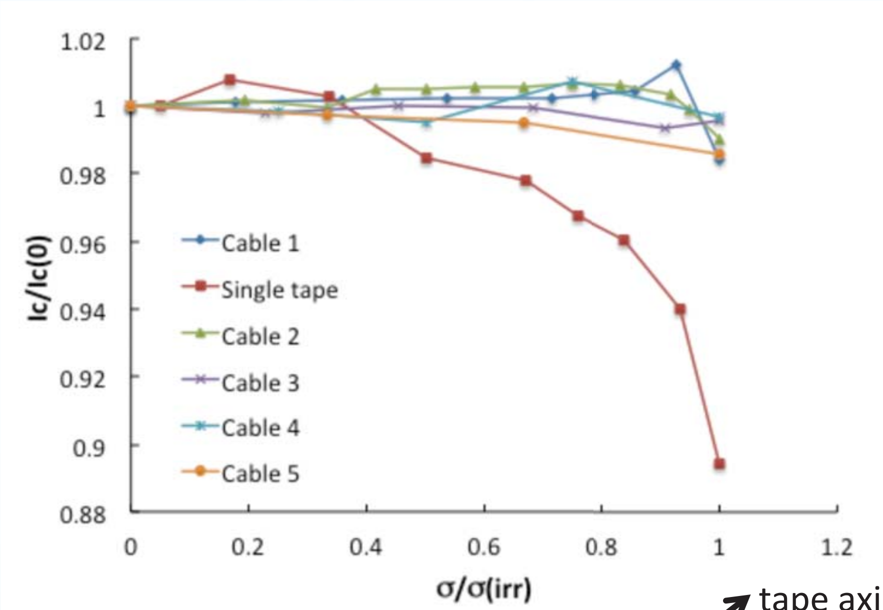
NIST

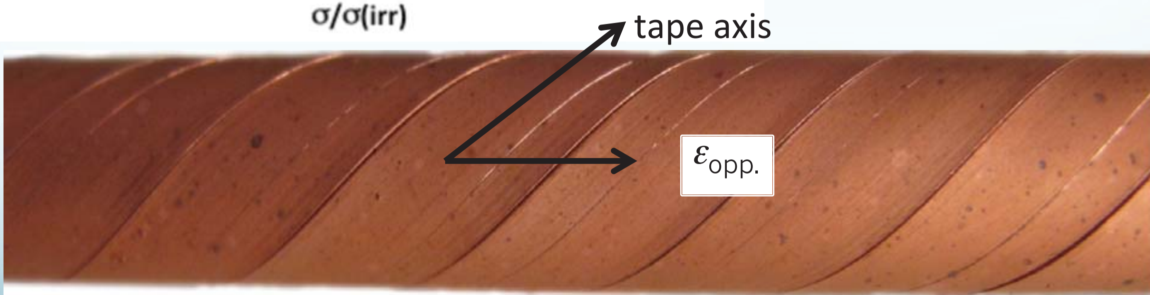
Strain effect on I_c of CORC cables



Tape: I_c (σ_{irr}) = 0.90 I_c(0)

CORC cable: I_c (σ_{irr}) > 0.98 I_c(0)

The strain effect in CORC cables is highly reduced when tapes are wound close to 45°!



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CORC cable development for accelerator magnets

Main program goals

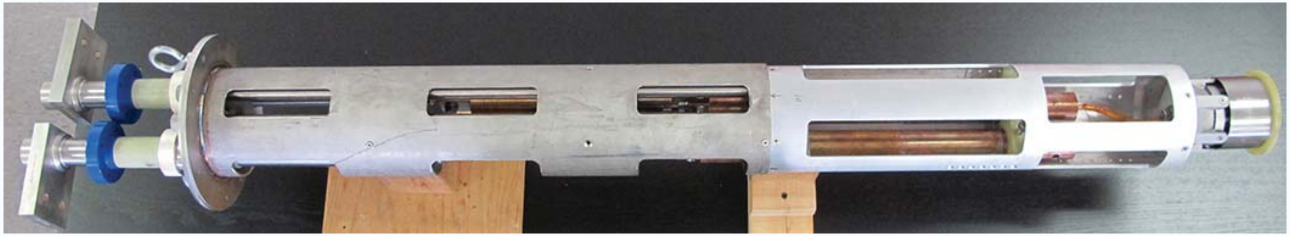
- Develop CORC cables with an engineering current density J_e > 300 A/mm^2 at 4.2 K and 20 T
- Improve the cable flexibility to allow bending to diameters of 60 mm or less

CORC cable development for accelerators is supported by the Department of Energy, Office of High Energy Physics

- At the University of Colorado: award number DE-SC0007891
- Phase II SBIR at Advanced Conductor Technologies: award number DE-SC0009545
- Support from NIST in the form of lab space and equipment

Testing of CORC cables at high fields

High-current insert with sample holder at bottom:



Sample holder for 10 cm diameter cables:

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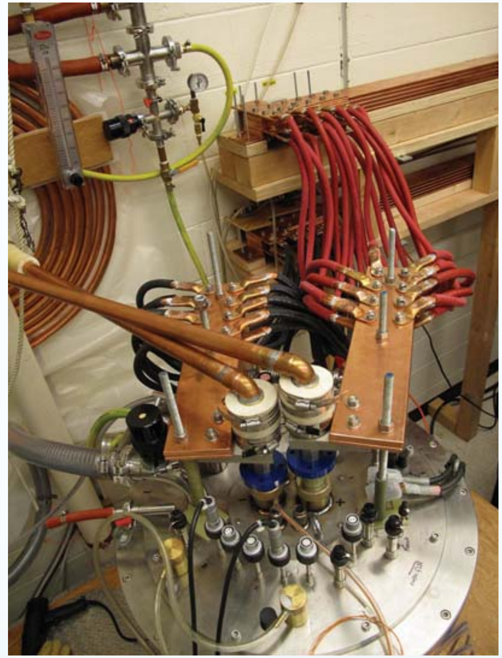
NIST

CORC cable test facilities in the U.S.

NIST/Univ. of Colorado:

- 8.75 T superconducting solenoid magnet.
- 12,800 A sample current.



NHMFL:

- 17 T resistive solenoid user magnet.
- 12,100 A sample current (switchers), 20,000 A in-house.

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University of Colorado program sponsored by:
DOE - Office of High Energy Physics, award DE-SC0007891

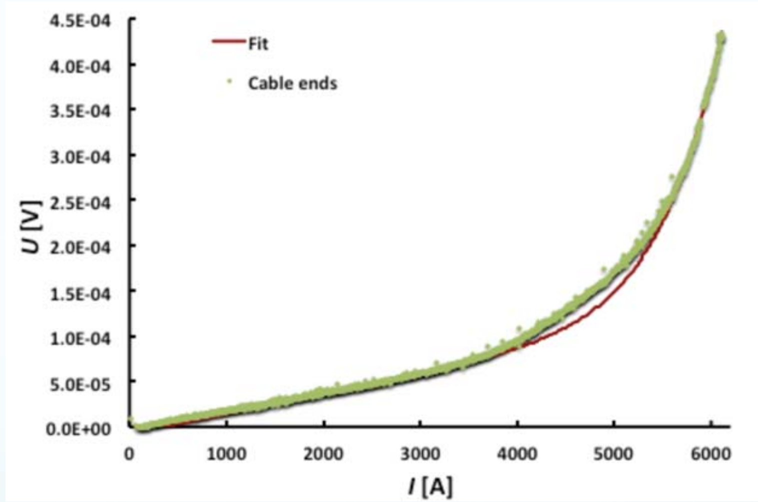
Early CORC accelerator cable development

CORC cables wound by hand until 2014

- 52 YBCO coated conductors
- 17 layers
- cable O.D. 7.5 mm

52 tape CORC cable tested at the NHMFL

- 4.2 K
- 19 T



I_c = 5,021 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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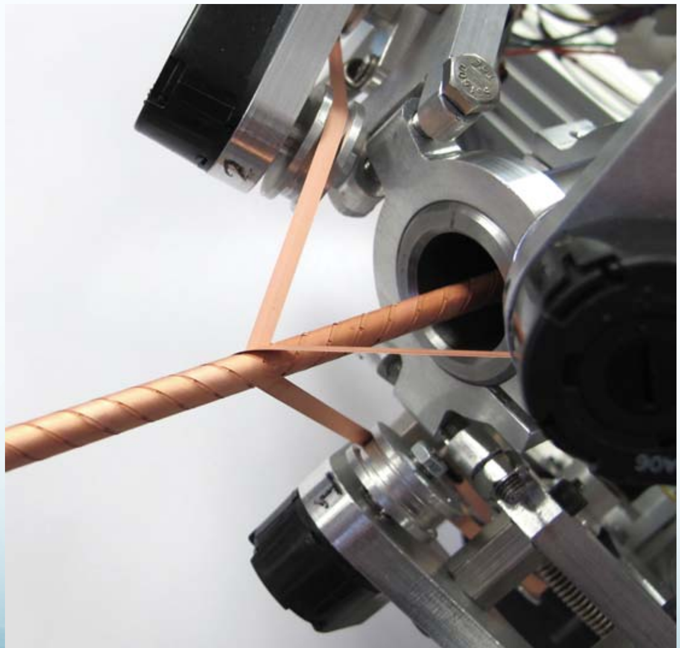
DOE - Office of Fusion Energy Sciences, award DE-SC0007660

CORC cable machine

Winding of long CORC cables with custom cable machine:

- Accurate control of cable layout
- Long cable lengths possible (>100 meters)



Commercial order from CERN:

- 12 meter CORC magnet cable
- Delivered August 2014

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University of Colorado program sponsored by:
DOE - Office of High Energy Physics, award DE-SC0007891

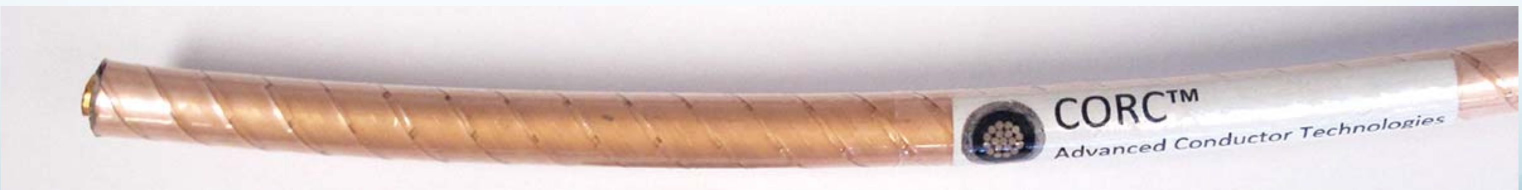
Improvement in CORC cable quality

CORC cables wound by hand

- 80 % density results in deformation during bending
- Variable gap spacing allows tapes to kink

CORC cables wound by machine

- >95 % density
- Even gap spacing allows for better cable flexibility

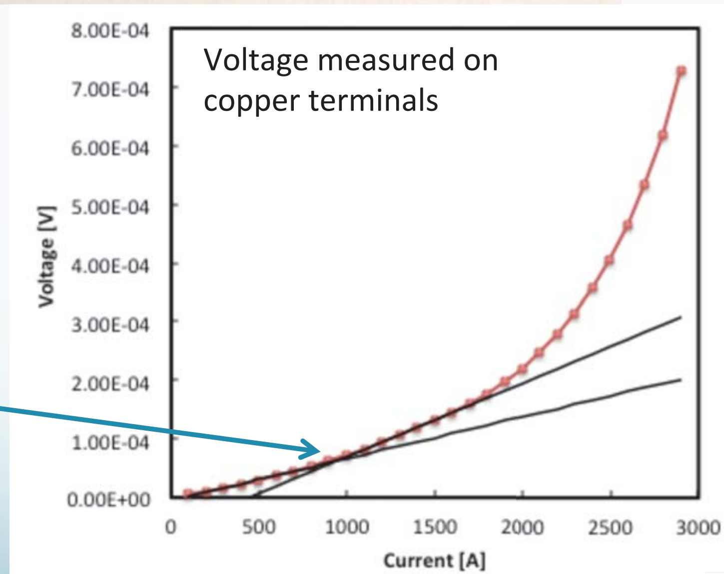


Early CORC cable terminations

Tapes each soldered to copper terminal

- long and difficult process
- large in size
- significant change of damage
- inhomogeneous contact resistance

Kink indicates inhomogeneous current distribution in cable



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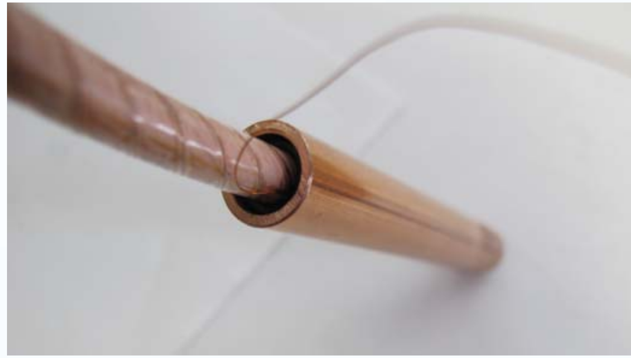
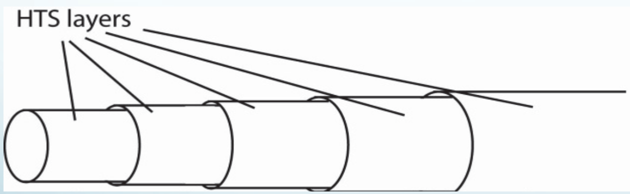
PSFC

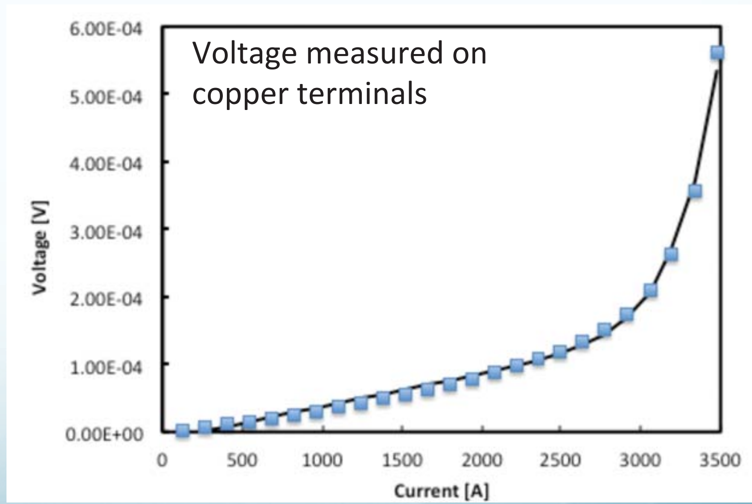
New CORC cable terminations

Cable end inserted in solder-filled copper tube

- less chance of damaging tapes
- much more practical
- smaller
- tapering the superconducting layers ensures each tape is in direct contact with copper tube
- more homogeneous current distribution in cable







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DOE - Fusion, awards DE-SC0007660 and DE-SC0009485

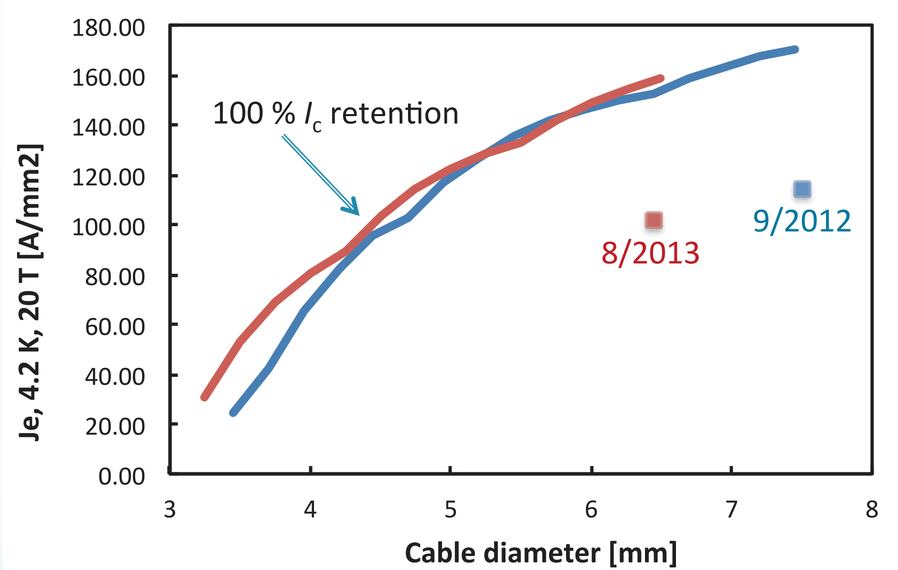
Current densities in early CORC cables

CORC cables made from "standard" SuperPower tapes

50 μm thick substrate, I_c = 100 – 120 A @ 77 K, I_c = 100 – 140 A @ 4.2 K, 20 T

Each added layer increases J_e, but also the cable size.

Adding tapes becomes less effective at some point.



"Standard" tapes limit J_e(20 T) to about 200 A/mm²

Accelerators need "advanced" tapes:
- thinner substrates
- better pinning
- higher I_c through thicker films

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Thinner tape 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

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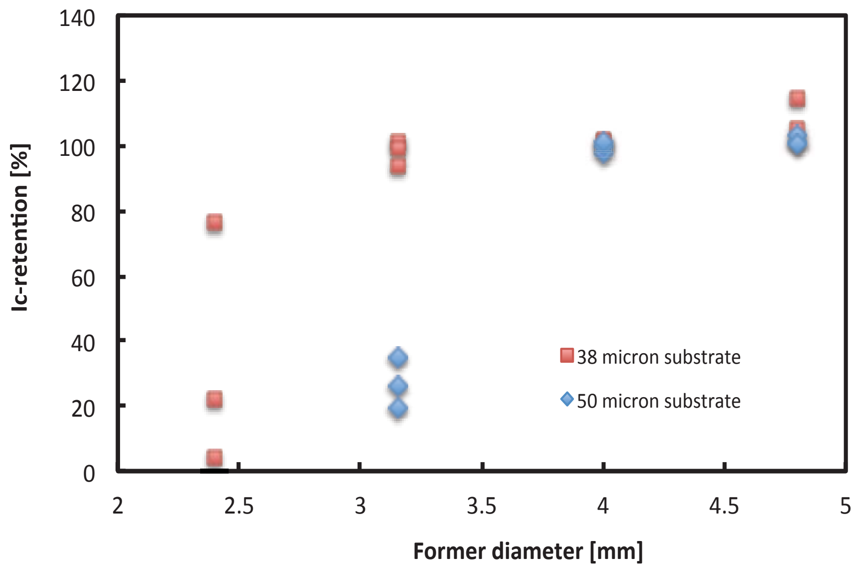
Effect of substrate thickness on minimum former size

I_c retention test

- tapes with 38 and 50 μm sub.
- ensuring a winding angle of 45°
- copper tape to ensure constant gap spacing
- 3 samples per diameter

Minimum former diameter

- 4 mm for 50 μm substrate
- 3.2 mm for 38 μm substrate
- 2-2.4 mm is expected for 30 μm substrate



Former diameter [mm]	Gap [mm]	α [°]	ε [%] (38 μm)	ε [%] (50 μm)
2.4	1.5	46.84	-1.58	
3.2	3	44.13	-1.19	-1.56
4	5	45.74	-0.95	-1.25
4.8	7	46.84	-0.79	-1.04

Degradation starts between -1.2 and -1.5 % strain

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CORC cable wound from tapes with 38 μm substrate

CORC cable

- 50 tapes with 38 μm substrate
- tapes are 4 mm wide.
- standard 7.5 % Zr doping
- Ic (77 K) = 116 – 129 A
- former diameter 3.45 mm
- cable outer diameter 5.9 mm
- cable wound with machine
- overall tape length 1.41 m/m cable
- tube terminations

SuperPower Inc.

Layer	# tapes	ID [mm]	Gap [mm]	Pitch [mm]	α [°]	Efficiency [-]
1	2	3.45	0.4	15.1	54.3	1.24
2	2	3.55	0.5	15.2	53.7	1.25
3	2	3.66	0.5	14.5	51.6	1.28
4	2	3.76	0.7	15.5	52.7	1.26
5	2	3.87	0.7	14.8	50.7	1.30
6	2	3.97	0.7	14.3	48.9	1.33
7	2	4.07	0.7	13.9	47.3	1.37
8	2	4.18	0.7	13.5	45.7	1.40
9	2	4.28	0.7	13.1	44.3	1.44
10	2	4.39	0.7	12.9	43.0	1.48
11	2	4.49	0.7	12.6	41.8	1.51
12	2	4.59	0.7	12.4	40.6	1.55
13	2	4.70	0.7	12.2	39.6	1.58
14	2	4.80	0.7	12.0	38.5	1.62
15	2	4.91	0.7	11.9	37.6	1.65
16	2	5.01	0.7	11.7	36.7	1.69
17	2	5.11	0.8	12.0	36.7	1.68
18	2	5.22	0.8	11.8	35.8	1.72
19	2	5.32	0.8	11.7	35.0	1.75
20	3	5.43	0.7	25.1	55.8	1.21
21	3	5.53	0.7	24.1	54.3	1.24
22	3	5.63	0.7	23.3	52.8	1.26
23	3	5.74	0.7	22.6	51.5	1.28

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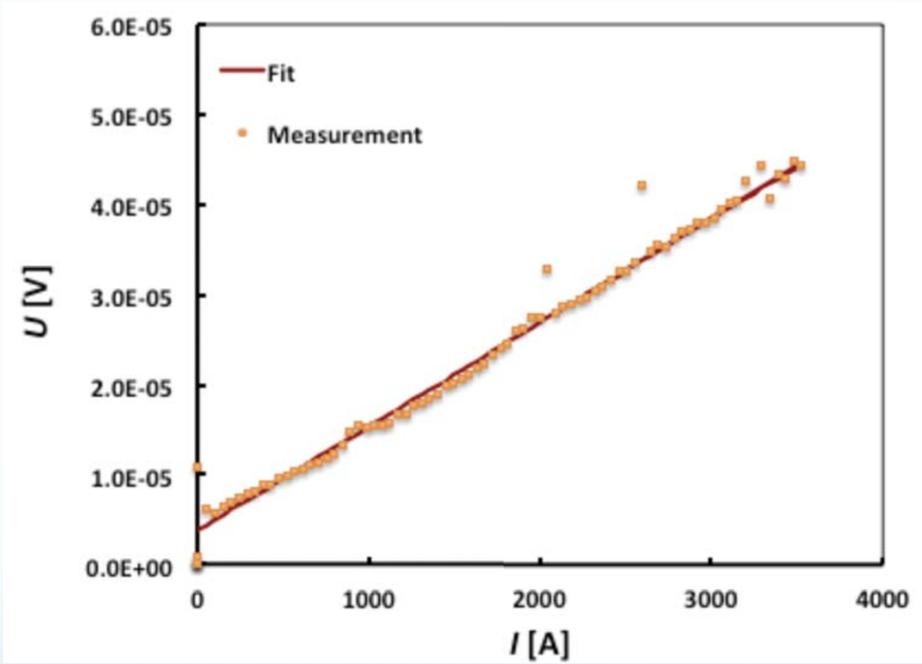
Contact resistance at 4.2 K and 17 T

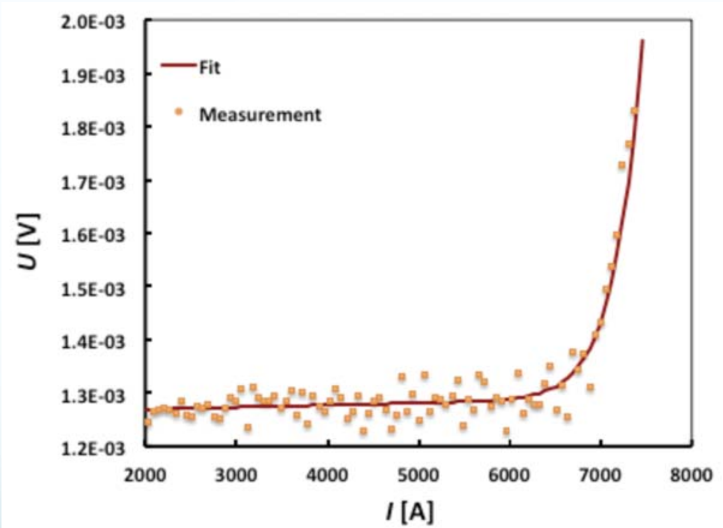


- Fit of voltage over terminals shows a **contact resistance of 5.8 nΩ per terminal.**
- Voltage contacts broke at 3,500 A due to incorrect sample current direction.

Performance at 4.2 K and 17 T

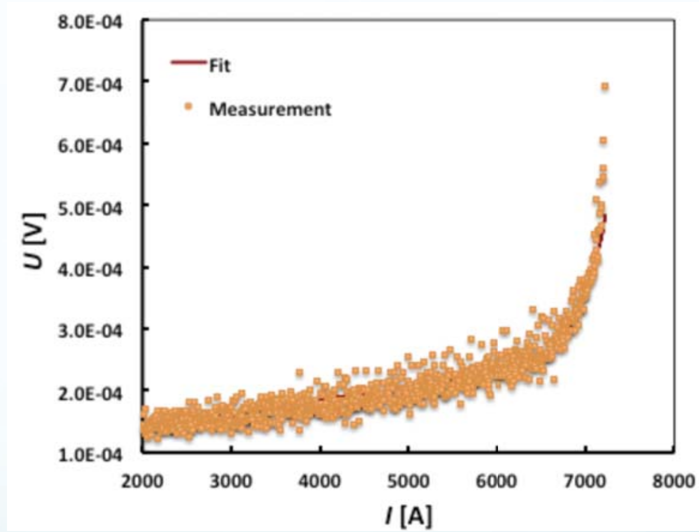
New voltage contacts no longer co-wound with cable, resulting in significant noise:

Current ramp rate 600 A/s:



I_c (4.2 K, 17 T) = 6,898 A

Current ramp rate 60 A/s:

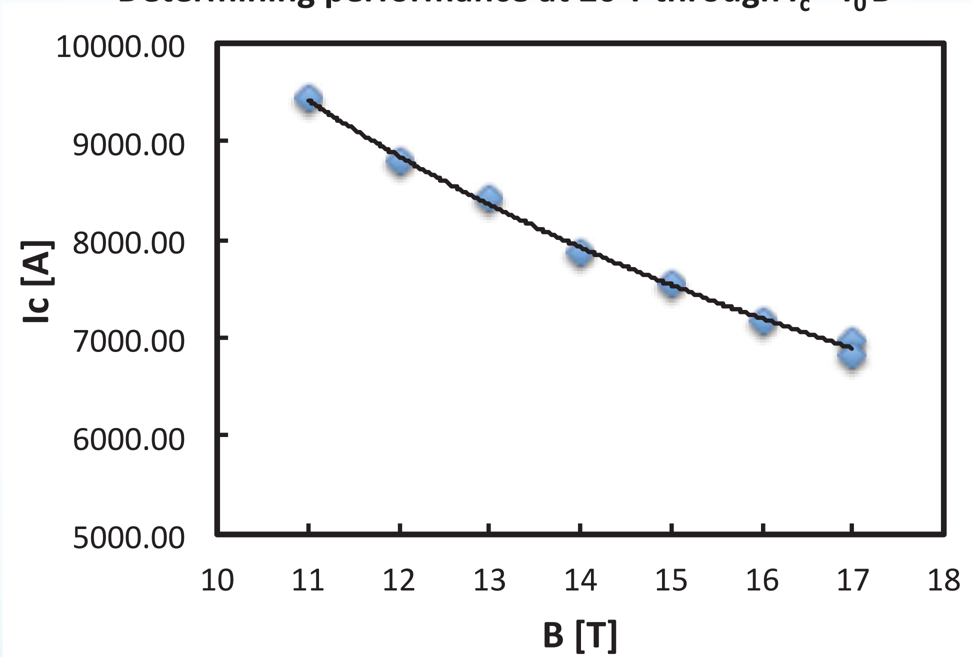


I_c (4.2 K, 17 T) = 6,966 A

J_e (4.2 K, 17 T) = 246 A/mm^2

Projected J_e 4.2 K and 20 T

Determining performance at 20 T through $I_c = I_0 B^{-0.72}$

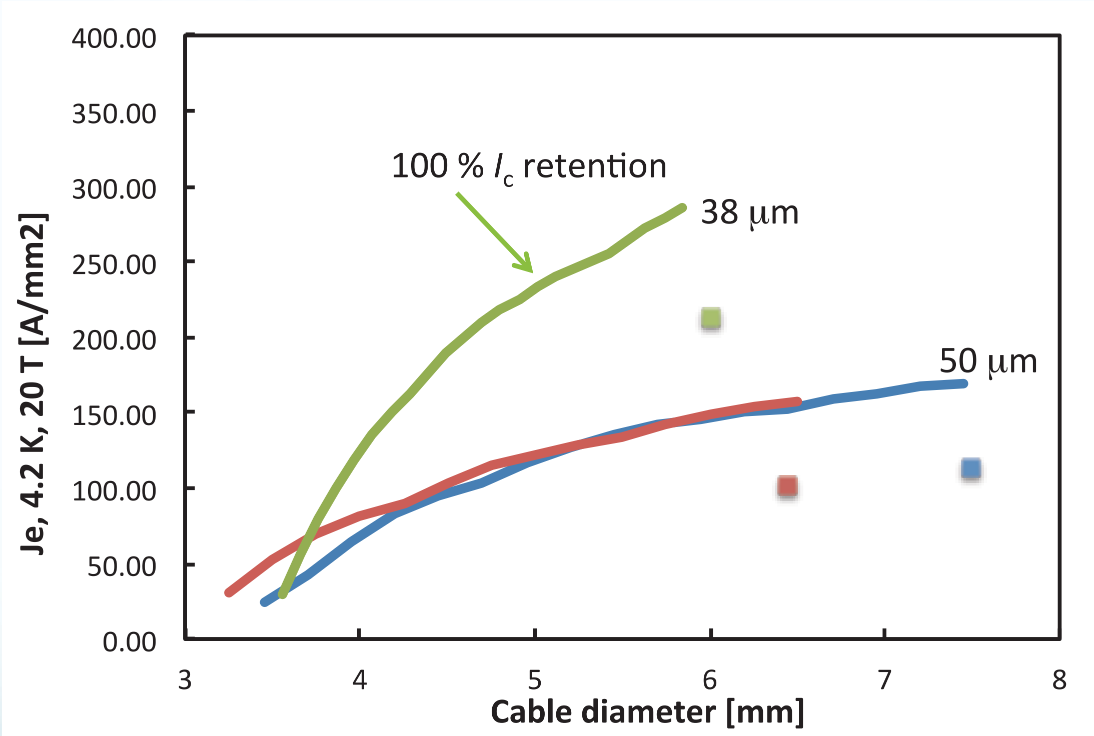


Projected I_c (4.2 K, 20 T) = 6,023 A

Projected J_e (4.2 K, 20 T) = 213 A/mm^2

Phase II SBIR DOE-High Energy Physics Award DE-SC0009545

Current status



CORC cable wound by machine has 75 % I_c retention at 20 T

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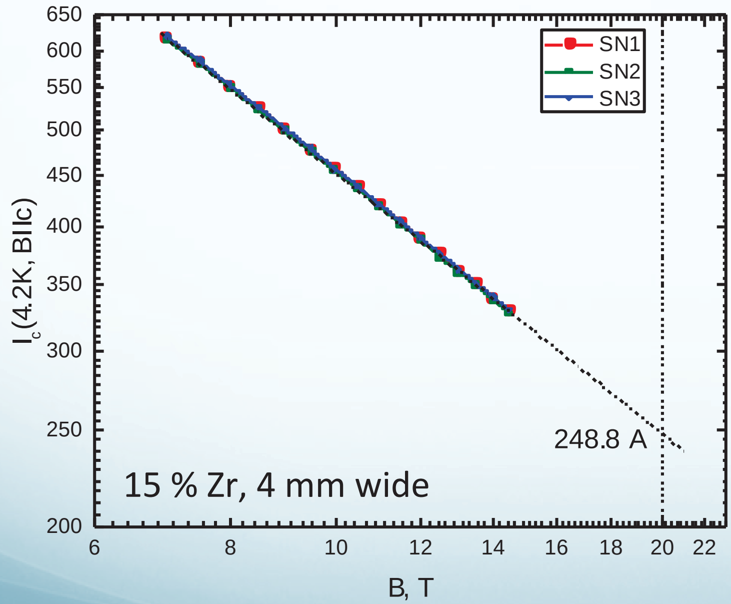
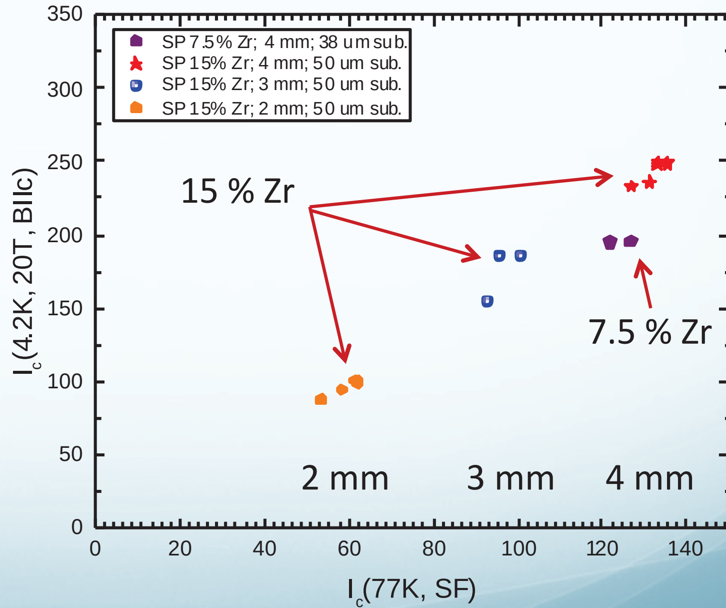
Phase II SBIR DOE-High Energy Physics Award DE-SC0009545

Tapes with enhanced pinning are becoming available

Tapes with enhanced pinning

- 15 % Zr doping, instead of 7.5 % Zr
- currently only on 50 μm substrate
- initial 600 meters received
- I_c(4.2 K, 20 T)/I_c(77 K, s.f.)= 1.9 (instead of 1.4)





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Tapes with thicker films are becoming available

Tape batch on 38 μm substrate received last week

SuperPower Inc.

Physica[l] ... of SCS3038-A[P]
ACT - 2015061[8]

Spool I.D.	Length (m)	Width (mm)	Thickness (mm)	Ic (A) Average	STDEV (%)	Ic (A) Minimum
20150618-1d	27		.051		0.31	119
20150618-1e	63		.051		0.56	119
20150618-1f	10		.052		0.22	105

Width (mm): 3.03, 3.02, 3.02, 3.02

Ic (A) Average: 128, 127, 119, 120, 105

**Thicker REBCO film of 1.7 μm results in increase in I_c of 30 %
and seem to become available soon!**

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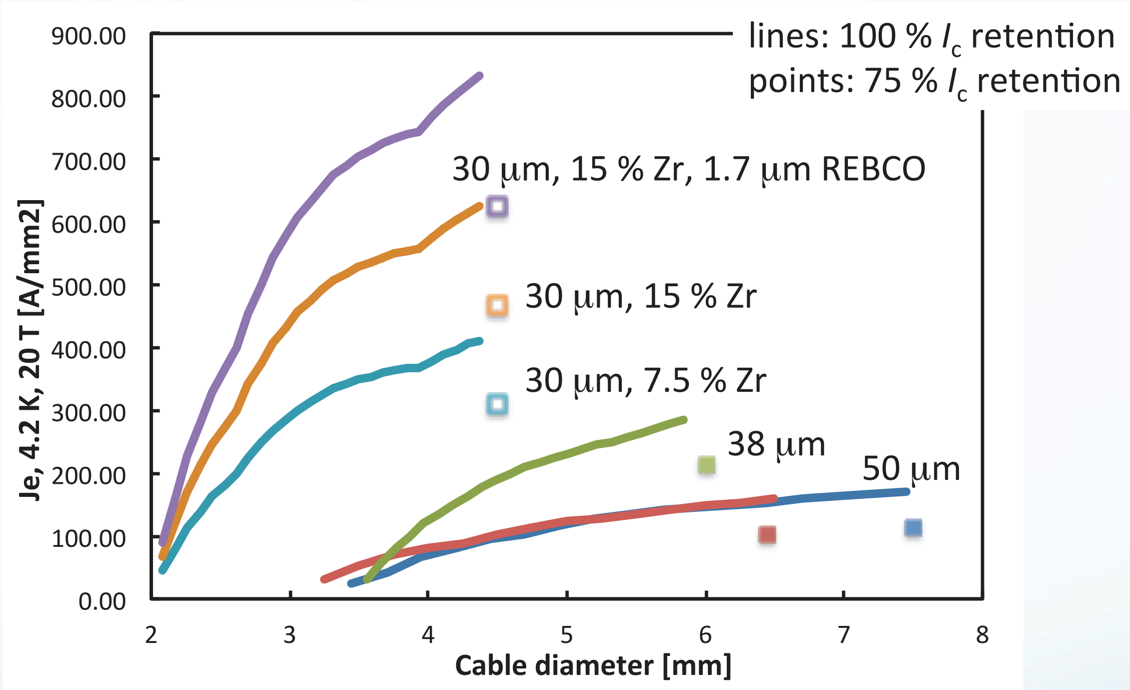
CORC cable performance projections



30 μm substrate: delivery **July 2015**: expected J_e (20 T) > 300 A/mm^2

30 μm + 15 % Zr: delivery **August 2015**: expected J_e (20 T) > 450 A/mm^2

30 μm + 15 % Zr + 1.7 μm REBCO: expected J_e (20 T) > 600 A/mm^2

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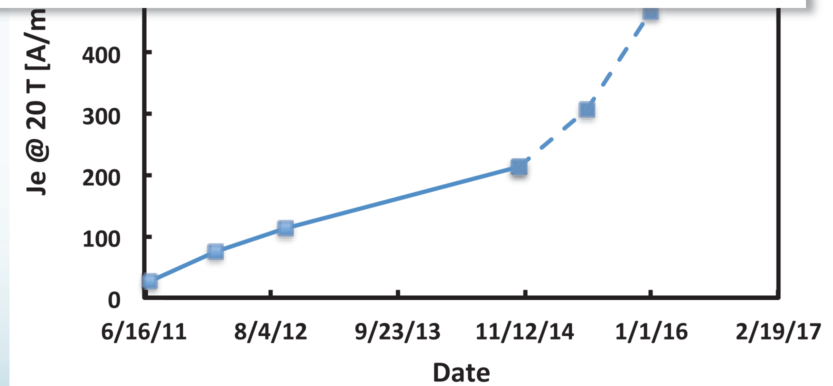
Summary

CORC cables are available in long lengths, right now

- I_c up to 6 kA at 20 T
- J_e of over 200 A/mm^2 at 20 T
- Cable outer diameter of less than 6.0 mm.

Many thanks to SuperPower for making incredible steps toward better conductor performance!

- > 300 A/mm^2 Sept. 2015
- > 450 A/mm^2 Dec. 2015
- > 600 A/mm^2 2016/2017



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