High-temperature superconducting Conductor on Round Core magnet cables operated at high current ramp rates in background fields of up to 19 T

Danko van der Laan & Xifeng Lu
Advanced Conductor Technologies & University of Colorado, USA

Anne de Jager
University of Colorado, USA

Leslie Bromberg & Joe Minervini
Massachusetts Institute of Technology, USA

Patrick Noyes, George Miller & Huub Weijers
National High Magnetic Field Laboratory, USA

Advanced Conductor Technologies LLC
www.advancedconductor.com

MT23 2013, Boston, MA, July 16th, 2013

Outline

1. Programs supporting CORC cable development.
2. Mechanical testing of CORC cables.
3. CORC cables for power transmission.
4. CORC magnet cables for fusion.
5. CORC magnet cables for accelerators.
6. Projected performance improvements.
7. Summary.

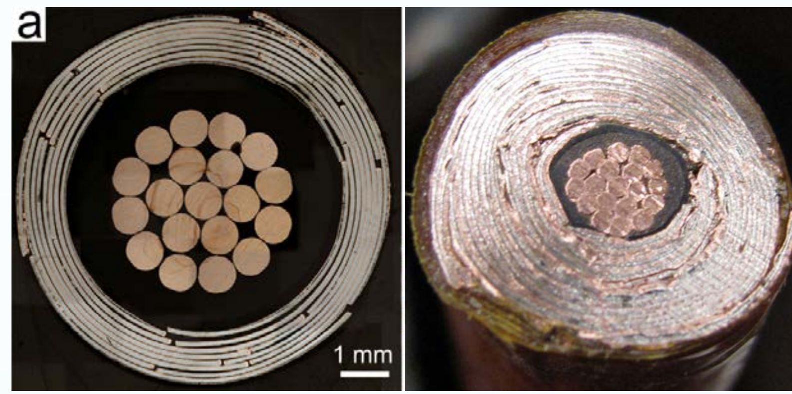
Advanced Conductor Technologies LLC
www.advancedconductor.com

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:

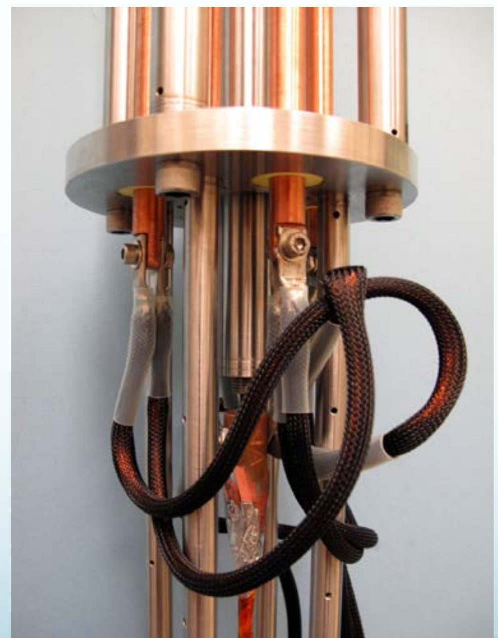
- Very flexible, capable of bending diameters less than 10 cm.
- Very high currents (> 7 kA) and current densities (> 100 A/mm2)
- Mechanically very strong
- Minimum degradation from cabling (< 10 %)

Advanced Conductor Technologies LLC
www.advancedconductor.com

Mechanical testing of CORC cables

Test facility at NIST for determining the effect of axial stress on the cable I_c:

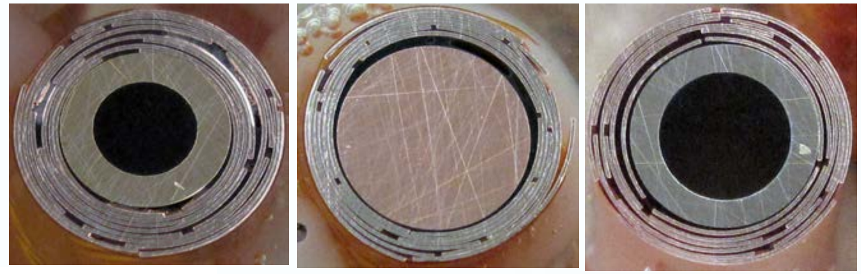
- Cable installed with flexible current leads.
- Current lead capacity > 1.5 kA at 77 K.
- Mechanical load up to 3,000 lbs.
- I_c measurement while at load.

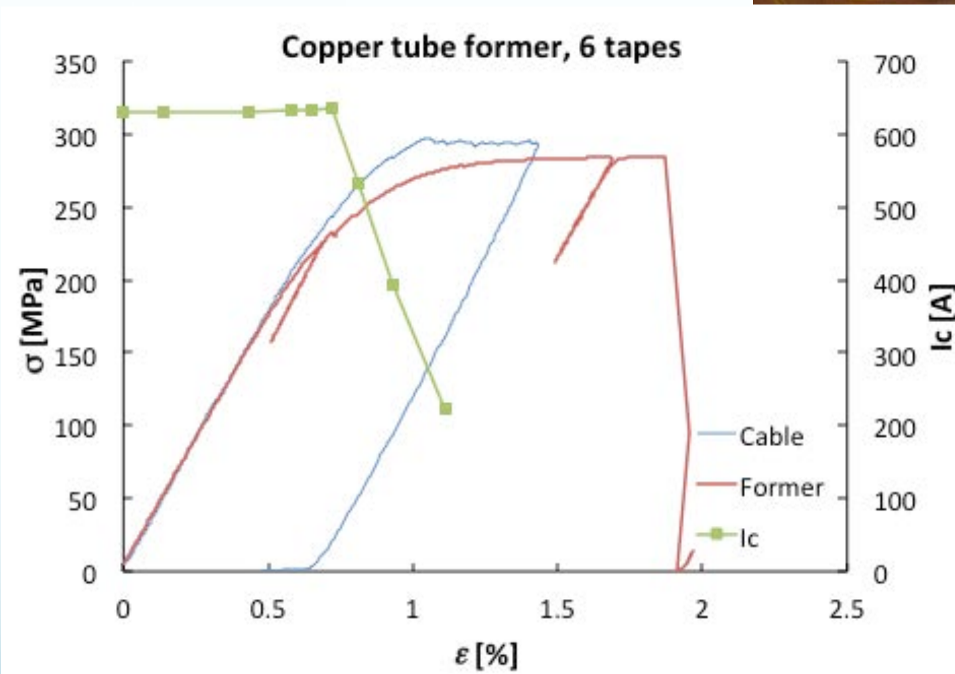


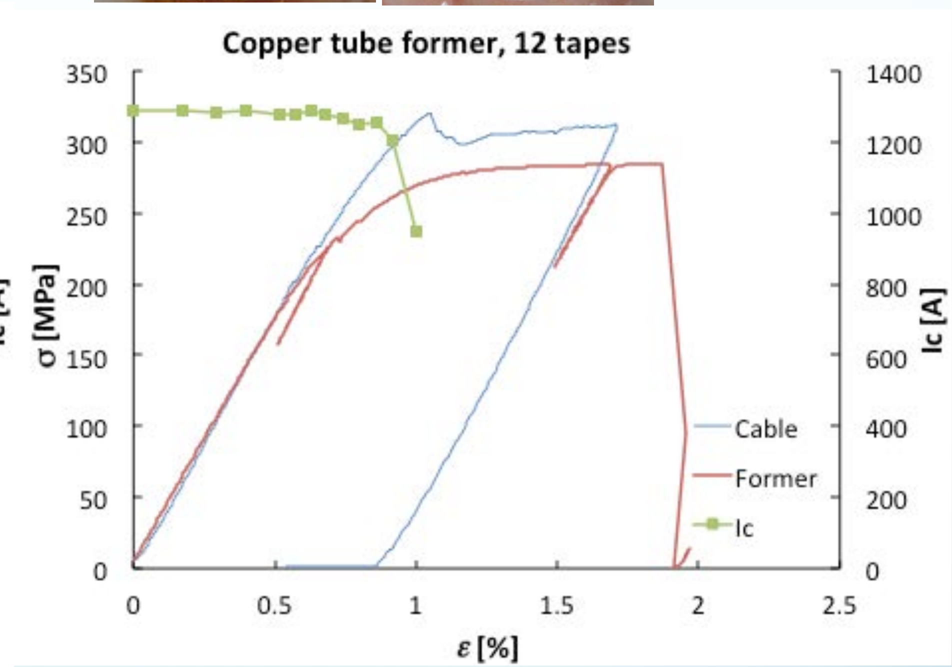
Current leads can handle >1500 A at 76 K.

Mechanical strength of CORC cables

Various options are explored regarding the formers and cable layout:







3/16” O.D. Cu former, with 0.032” wall thickness:

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

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

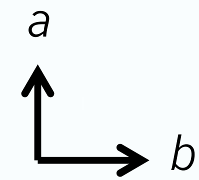
Advanced Conductor Technologies LLC
www.advancedconductor.com

No reversible strain effect on I_c before sharp irreversible drop-off!

Anisotropic in-plane reversible strain effect in CC

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

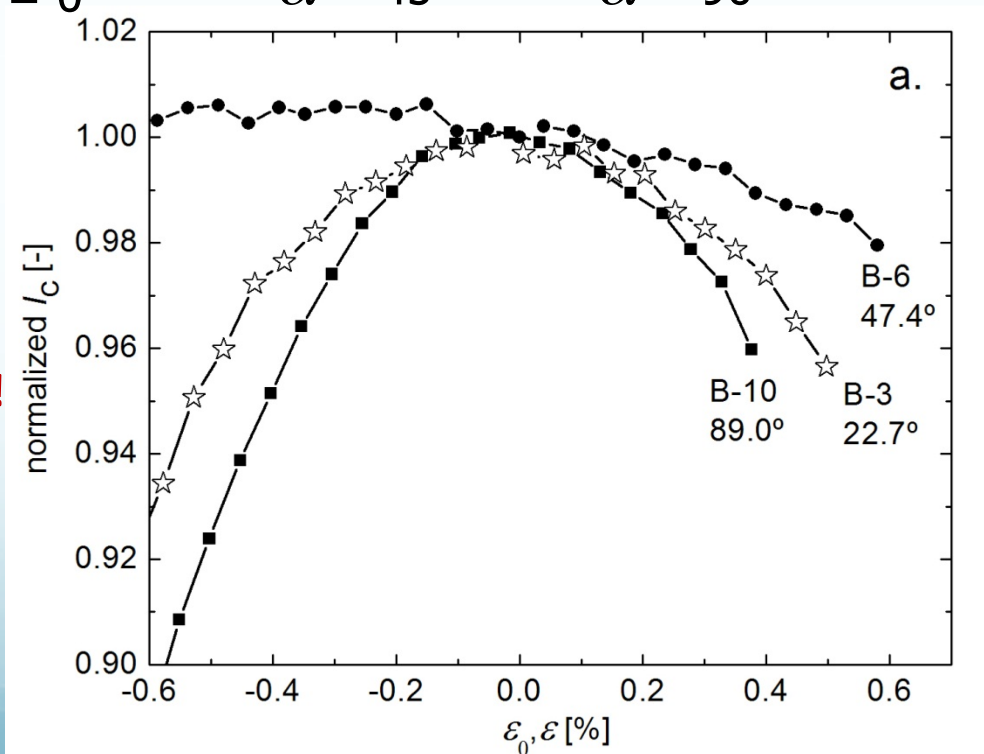
Bridges cut from CC allow us to apply strain at different in-plane angles:



SuperPower

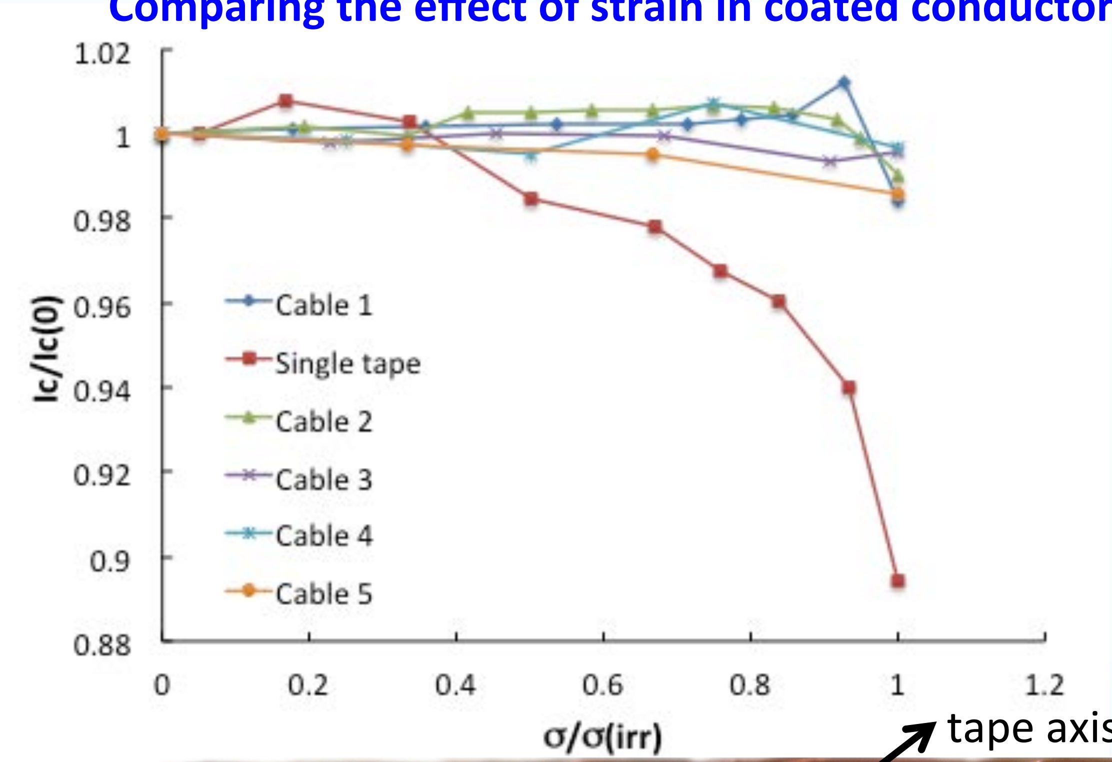
$\alpha = 0°$ $\alpha = 45°$ $\alpha = 90°$

Reversible strain effect on I_c depends on the in-plane orientation of the applied strain!



Strain effect on I_c in CORC cables

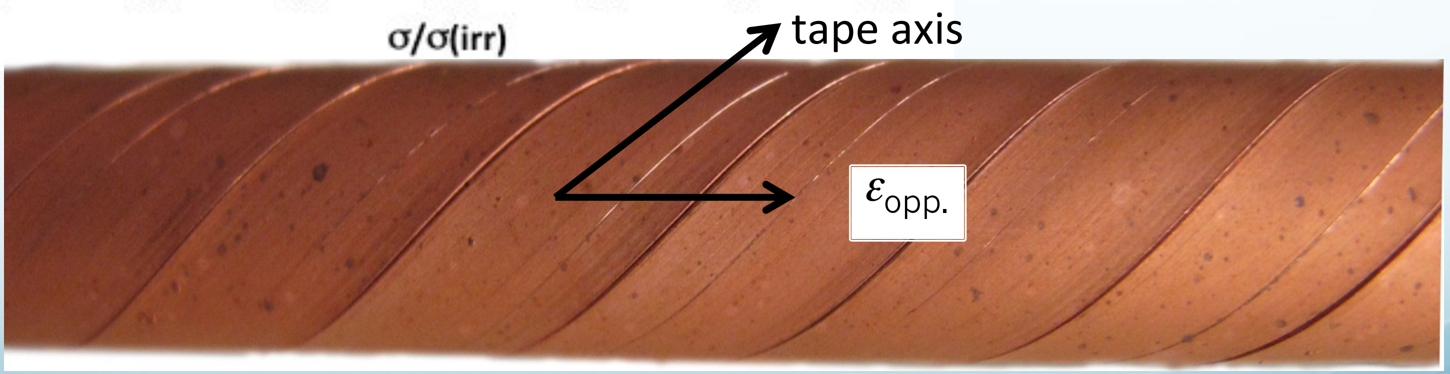
Comparing the effect of strain in coated conductors and CORC cables:



Tape: $I_c\ (\sigma_{irr}) = 0.90\ I_c(0)$

Cable: $I_c\ (\sigma_{irr}) > 0.98\ I_c(0)$

The strain effect in CORC cables is highly reduced because strain is applied at about 45 degrees!



Advanced Conductor Technologies LLC
www.advancedconductor.com

CORC cables compared to others

"Conventional" low power density HTS power transmission cables:

Low current and very inflexible.

High power density HTS cables:

Twisted Stack-Tape Cable (MIT)

Roebel Cable (KIT)

High current density, but inflexible.

CORC cable

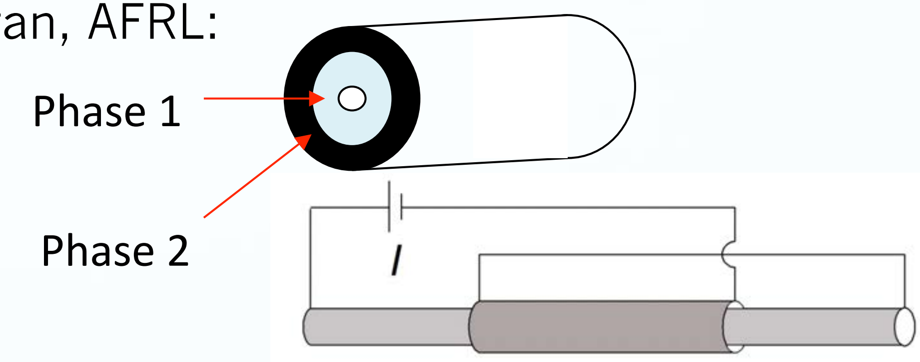
High power density and very flexible.

CORC cables for dc-power transmission

Development of a 2-phase CORC power transmission cable:

Collaboration with Tim Haugan, AFRL:

- 79 tapes in 17 layers
- 2-phase configuration
- **cable O.D. 10 mm**



76 K (liquid nitrogen): I_c (Phase 1)=3745 A; I_c (Phase 2)=3816 A

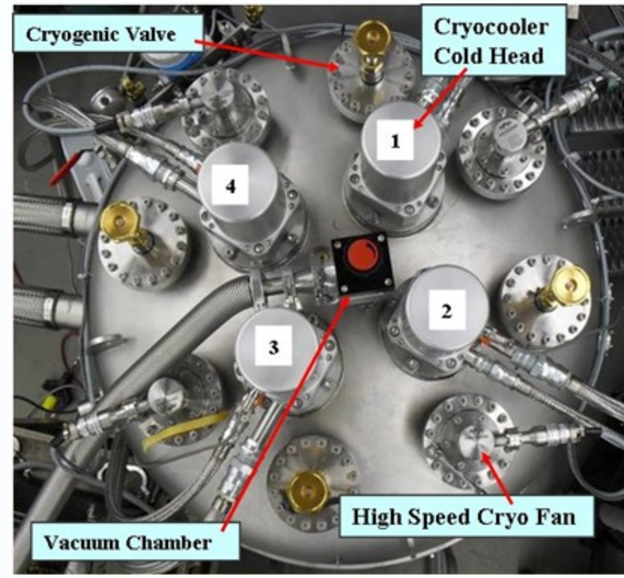
When phases operated in series:
I_c (total)= 7561 A

Advanced Conductor Technologies LLC
www.advancedconductor.com

Helium gas test facility at CAPS

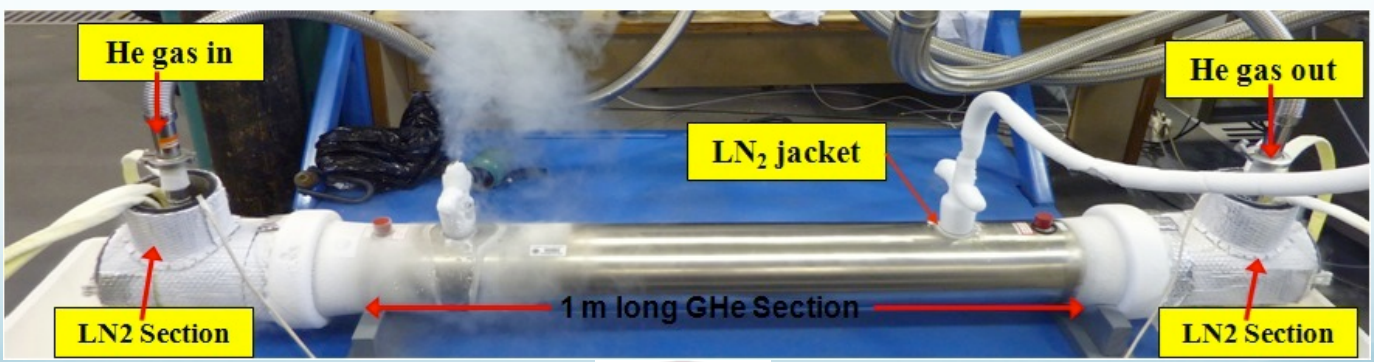
Collaborators at Center for Advanced Power Systems:
Chul Kim and Sastry Pamidi

Purpose of GHe system:
To test HTS cables in helium gas for Navy and Air Force applications.



Cryogenic helium gas setup at CAPS:

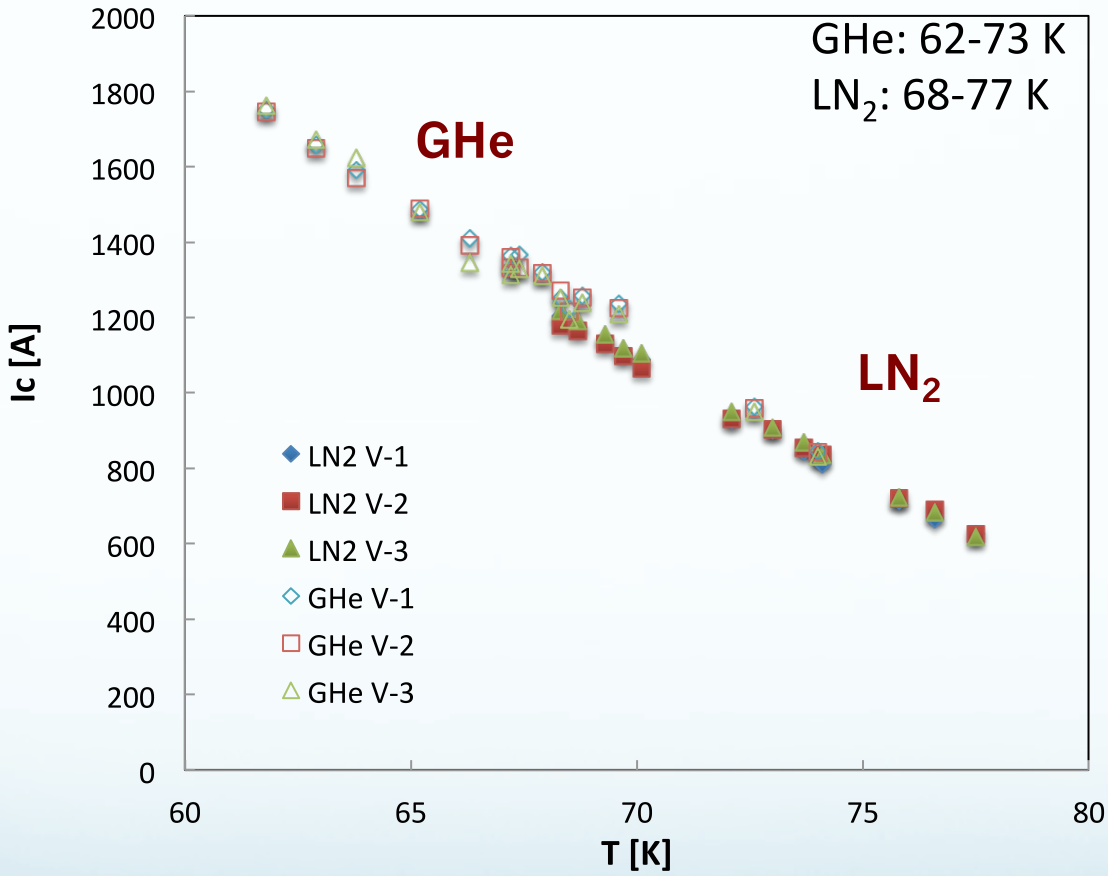
- 4 cryocoolers: He gas at T > 50 K.
- High-speed cryo fans allow for 20 bar pressure.
- Short sample cryostat with 1 meter GHe section
- Cable ends located in LN_2 baths at cryostat ends.



Advanced Conductor Technologies LLC
www.advancedconductor.com

CORC cable tested in LN_2 and helium gas

$I_c(T)$ in pumped LN_2 and GHe of 9-tape (3 layers) CORC cable:



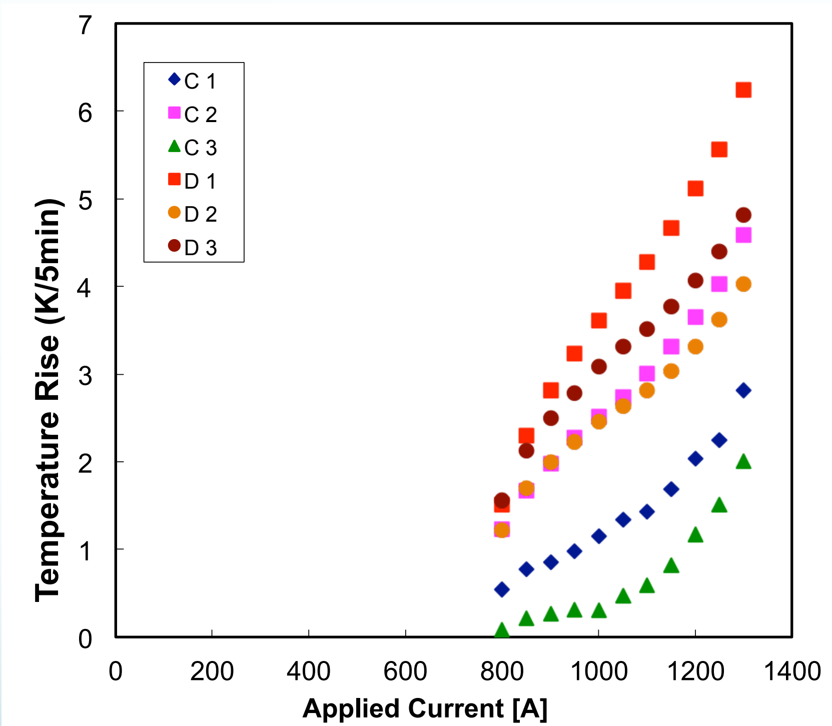
Measurements in GHe and LN_2 coincide: near-linear *T*-dependence of I_c.

Advanced Conductor Technologies LLC
www.advancedconductor.com

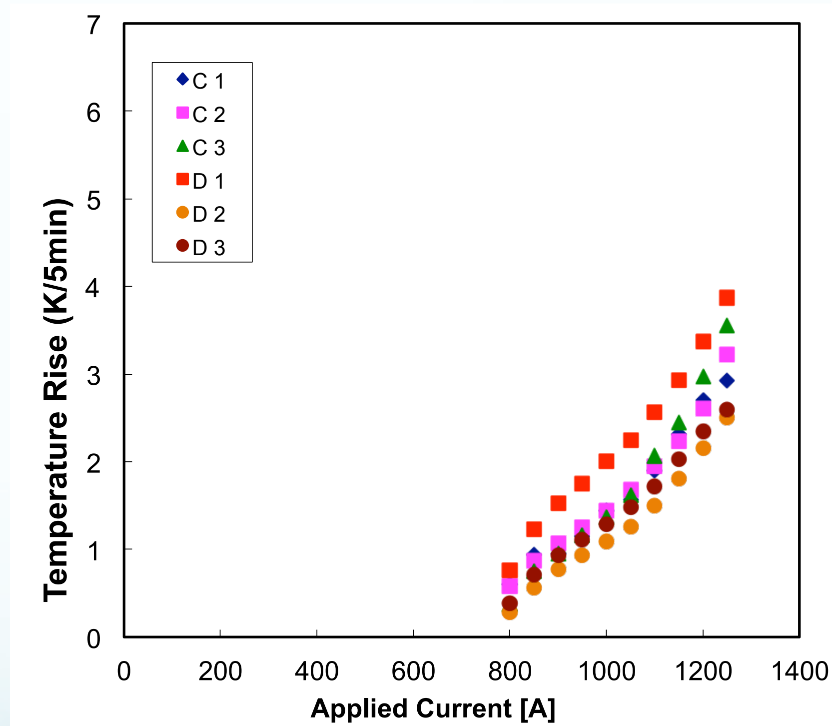
Temperature rise during operation in GHe

T-rise (K/5 min.) in GHe as a function of current ($0.5I_c < I < I_c$=1300 A):

flow rate: 2.1 g/s



flow rate: 3.6 g/s



Temperature rise may be caused by resistive heating of the copper leads.

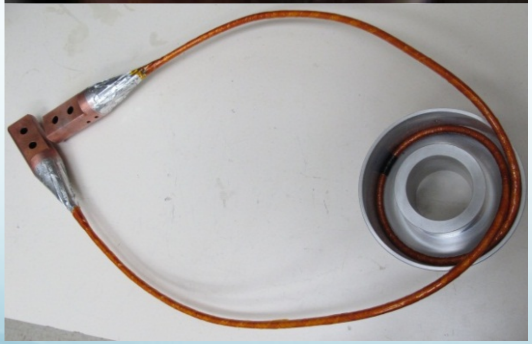
Advanced Conductor Technologies LLC
www.advancedconductor.com

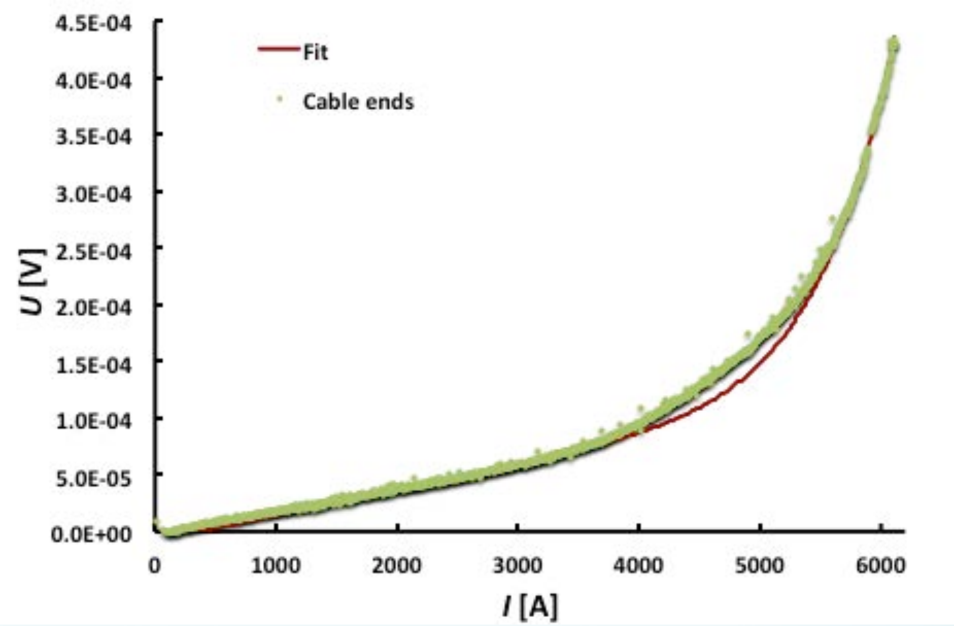
CORC cables for fusion magnets

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/mm² @ 4.2 K, 19.0 T

Advanced Conductor Technologies LLC
www.advancedconductor.com

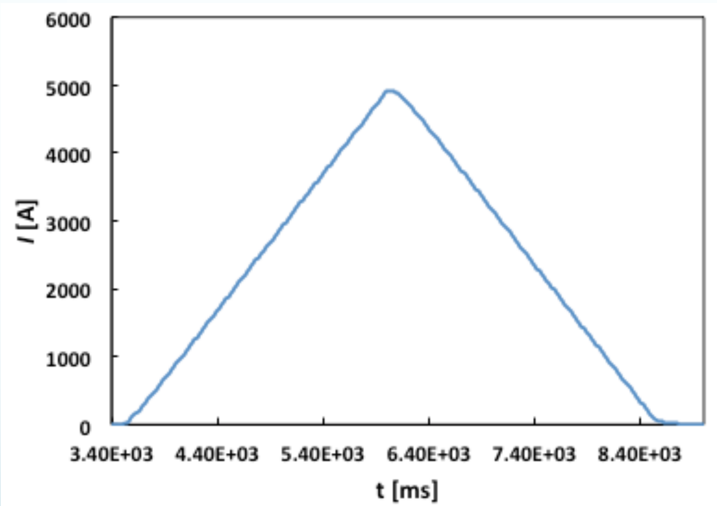
ACT: Phase II STTR DOE-Fusion Energy Sciences Award DE-SC0007660,
NHMFL: DOE, NSF, agreement DMR-0654118, and the State of Florida

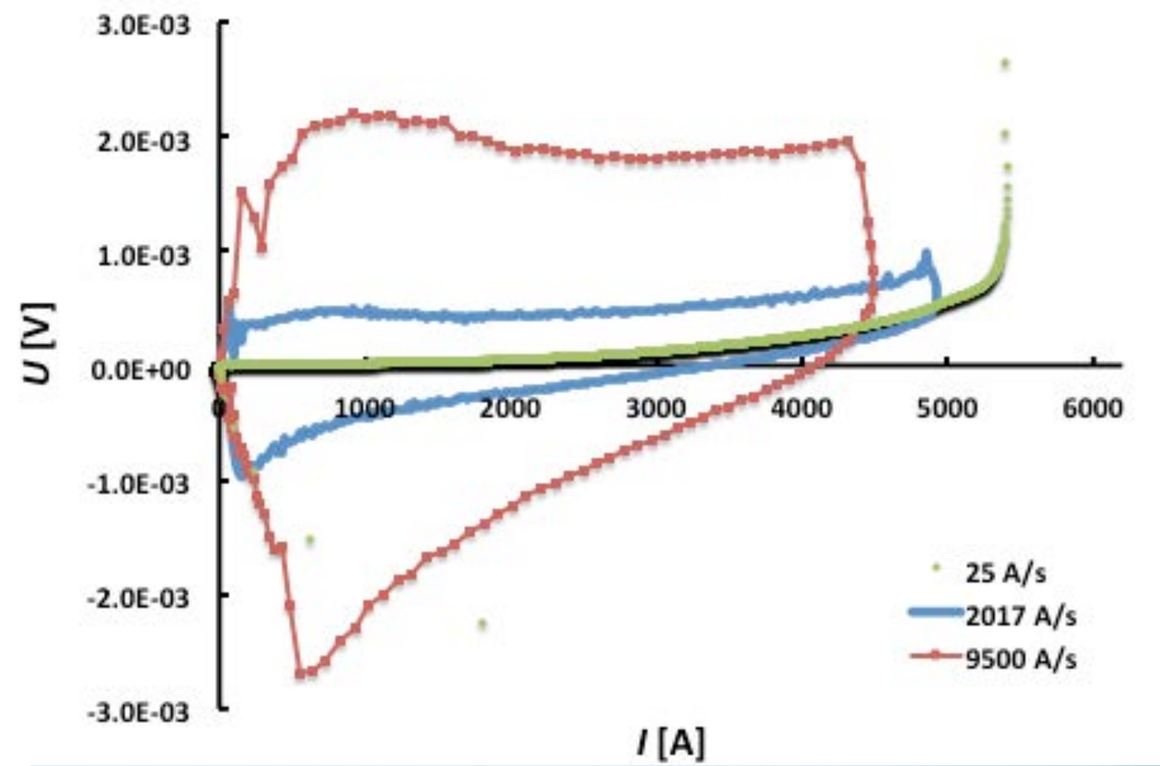
High-current ramp rates at 19 T

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_{quenc}
- 2017 A/s
- 9500 A/s





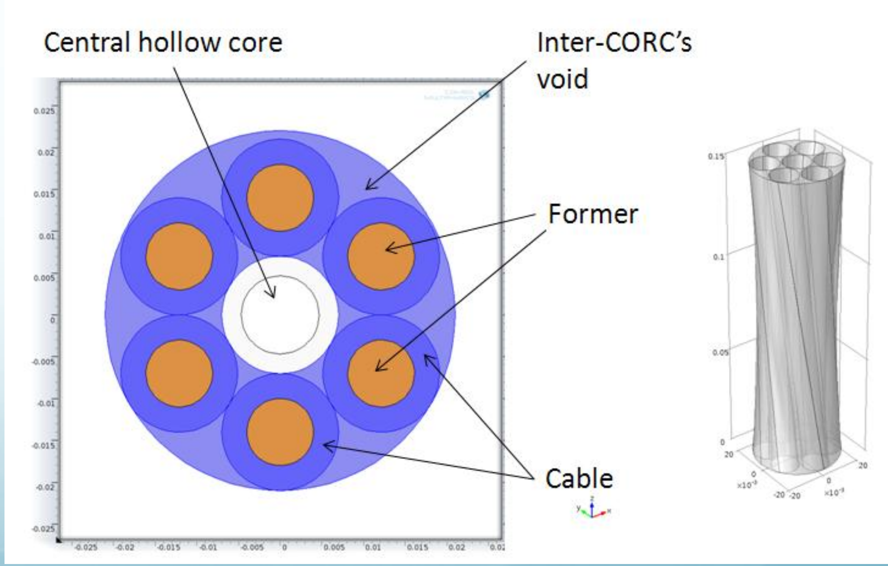
No effect of high current ramp rates!

Phase II STTR DOE-Fusion Energy Sciences Award DE-SC0007660

CORC cable for fusion magnets – Phase II

CORC triplet rated at potentially 3 x 5 kA = 15 kA at 4.2 K, 19 T.

CORC 6-around-1 rated at potentially 6 x 5 kA = 30 kA at 4.2 K, 19 T.



Phase II STTR DOE-Fusion Energy Sciences Award DE-SC0007660

Room for improvement

I_c = 5021 A @ 4.2 K, 19 T

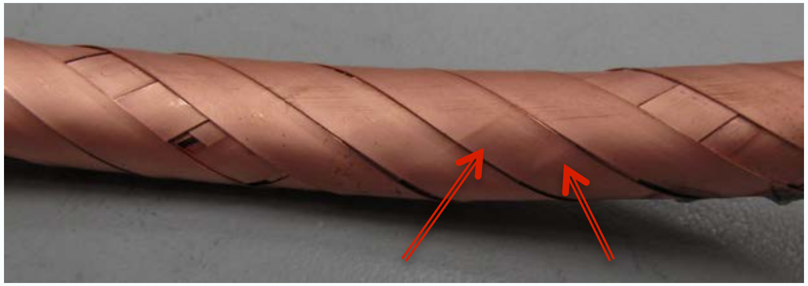
During cable inspection after test at 19T:

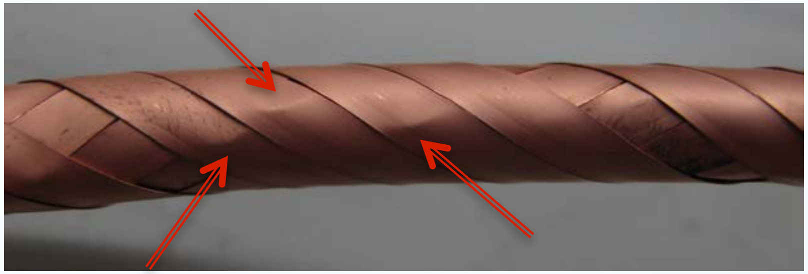
Many damaged tapes in outer layers due to cable bending!

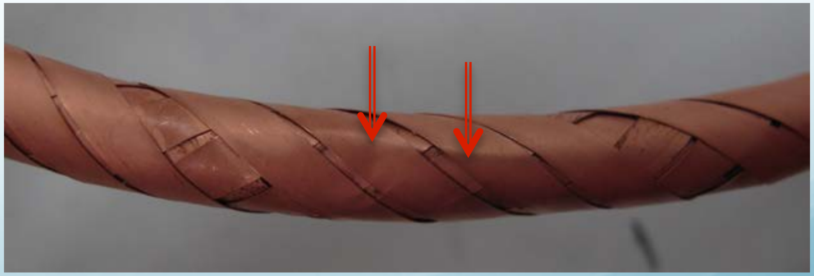
Caused by loose winding pack.

Winding pack needs to be controlled:

=> Cabling machine is needed.







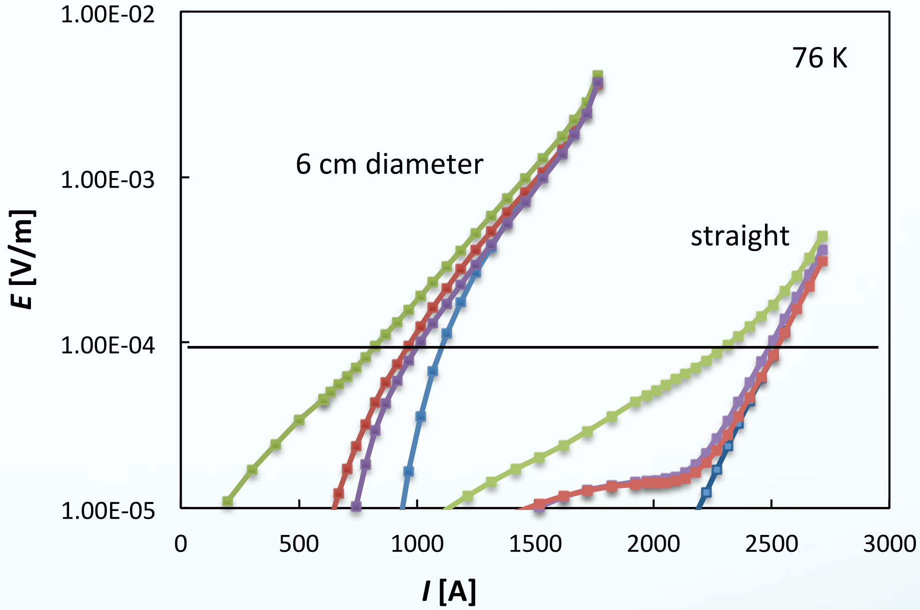
DOE - Office of High Energy Physics grant DE-FG02-12ER41801

Early CORC performance at 6 cm diameter

Improving the flexibility of CORC cables for application in accelerators:

Earlier cable (2012):
26 YBCO CC, 11 layers, cable O.D. 6.0 mm

Straight: **I_c = 2425 A @ 76 K**



6 cm diameter:

I_c = 1057 A @ 76 K

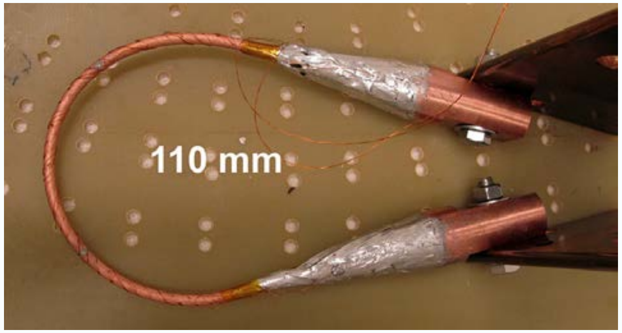
I_c = 1264 A @ 4.2 K, 19 T
J_e= 29 A/mm^2

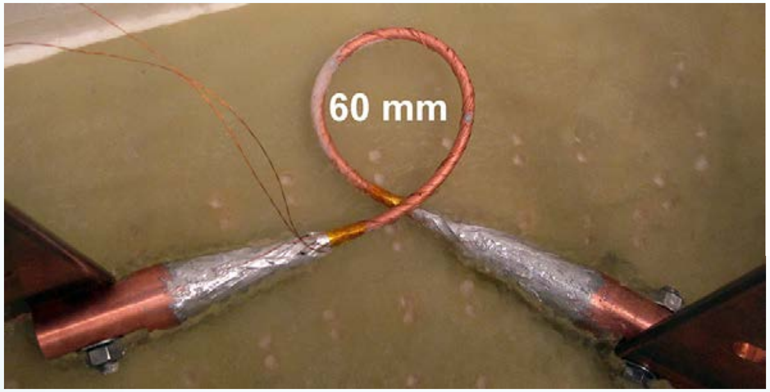
Large degradation of 56 % due to bending!

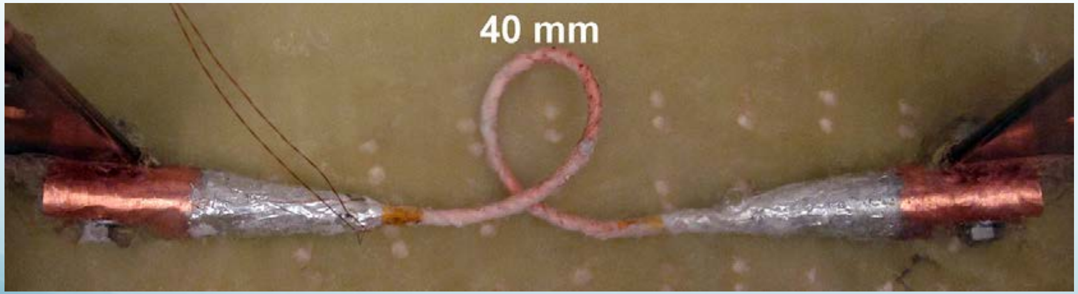
Advanced Conductor Technologies LLC
www.advancedconductor.com

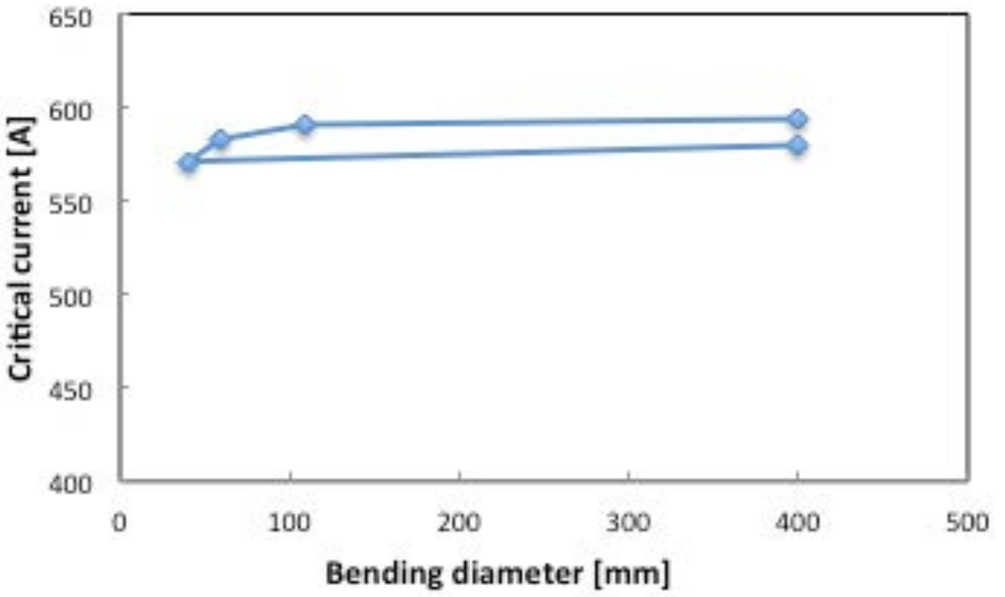
CORC cables for accelerator magnets – Phase I

Improved CORC cable (2013):







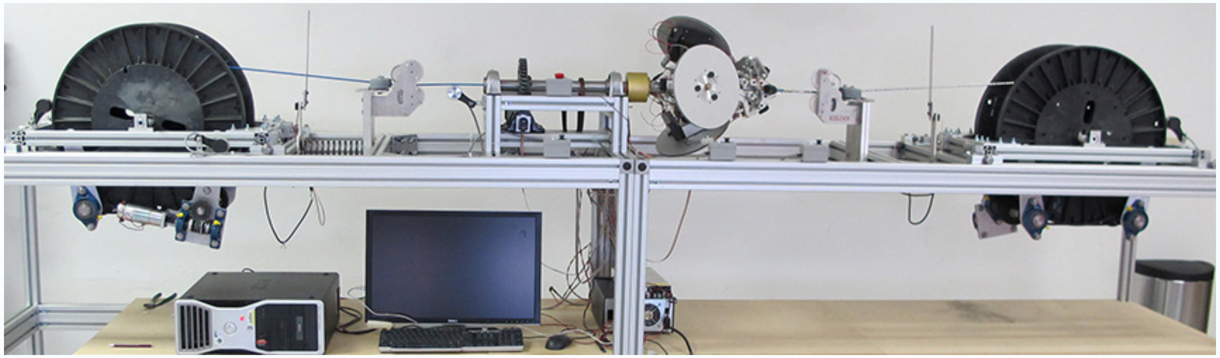


Irreversible degradation of only 2.5 % due to bending to 40 mm diameter!

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

CORC cable winder

Winding of long CORC cables with a machine:



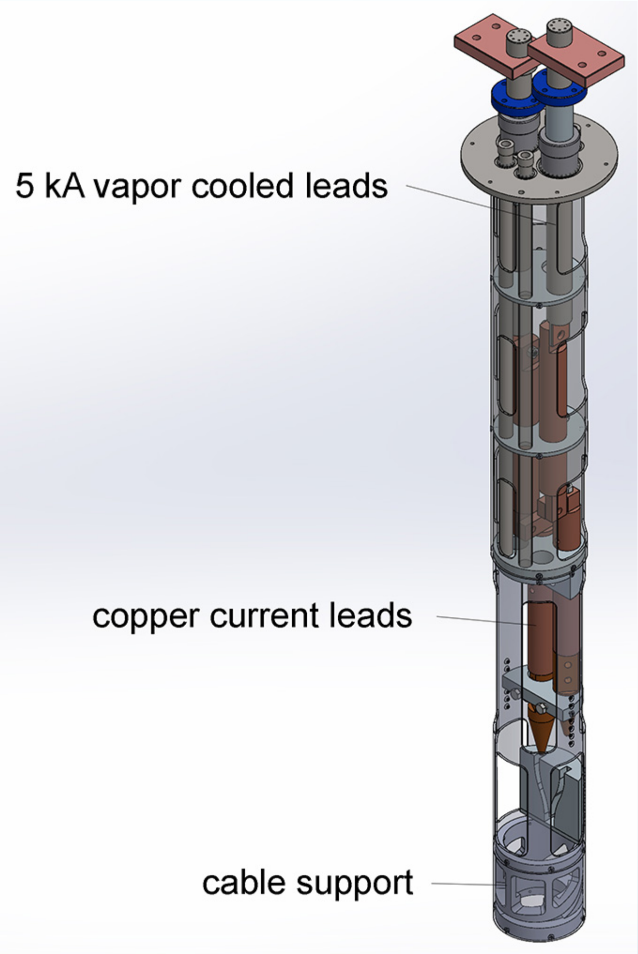
Dummy CORC cable:
12 meter long 28 layers

Advanced Conductor Technologies LLC
www.advancedconductor.com

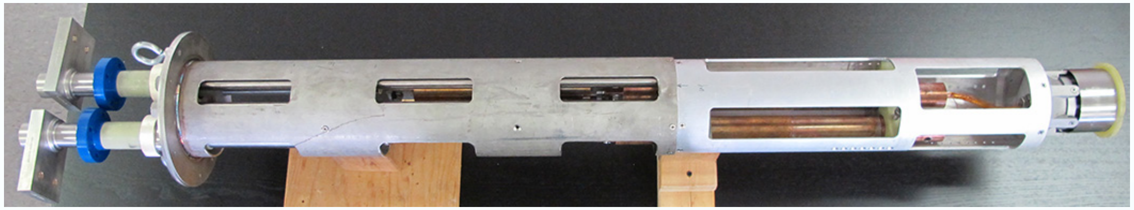
Sponsored by the Department of Energy
Office of High Energy Physics grant DE-FG02-12ER41801

In-field testing of CORC cables at CU/NIST

Magnet insert for 8.75 T solenoid magnet for CORC cable testing at NIST:

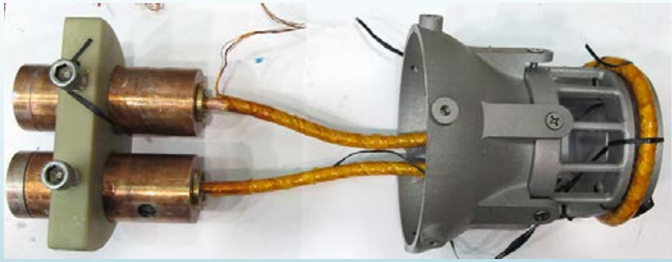


Actual probe:



Sample holder for 10 cm diameter cables:

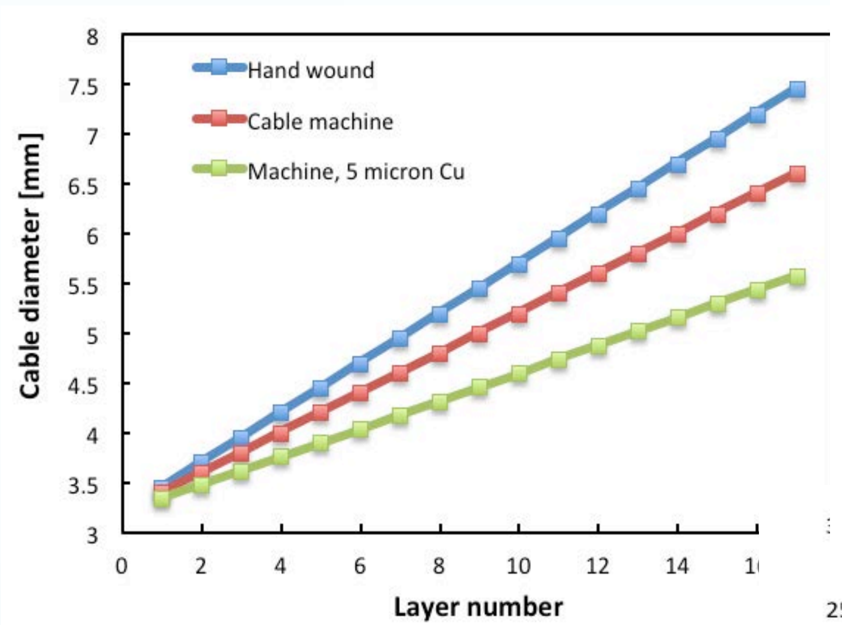
Sample holder for 6 cm diameter cables:

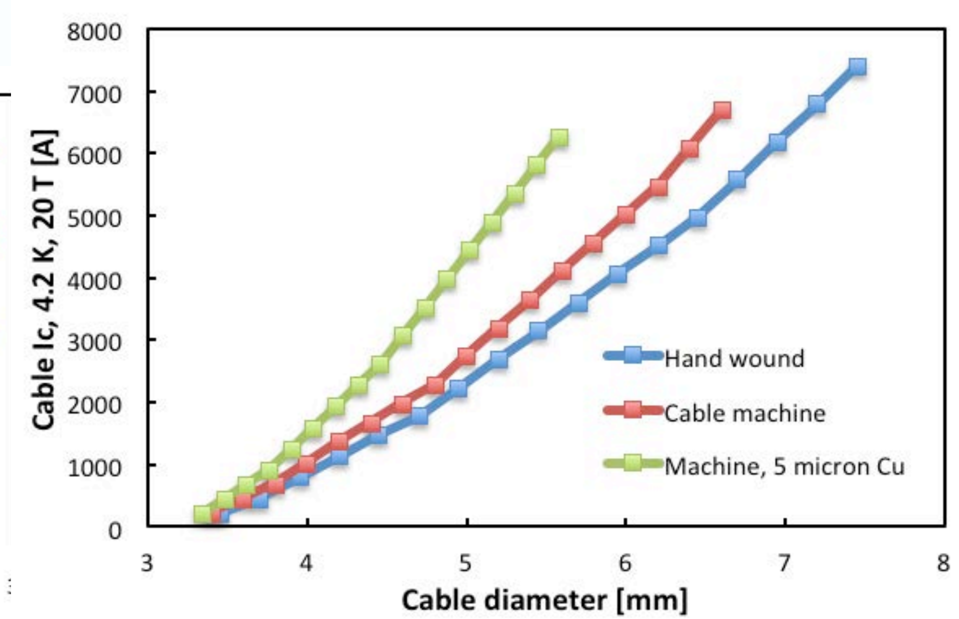


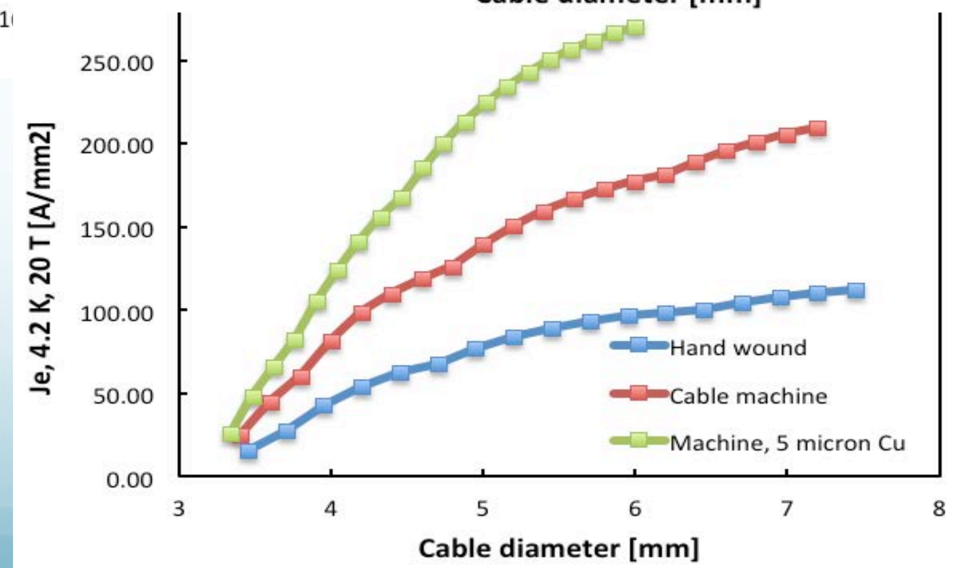
Sponsored by the Department of Energy
Office of High Energy Physics grant DE-FG02-12ER41801

CORC cable performance projections

Improved performance due to winding machine and reduced copper thickness:



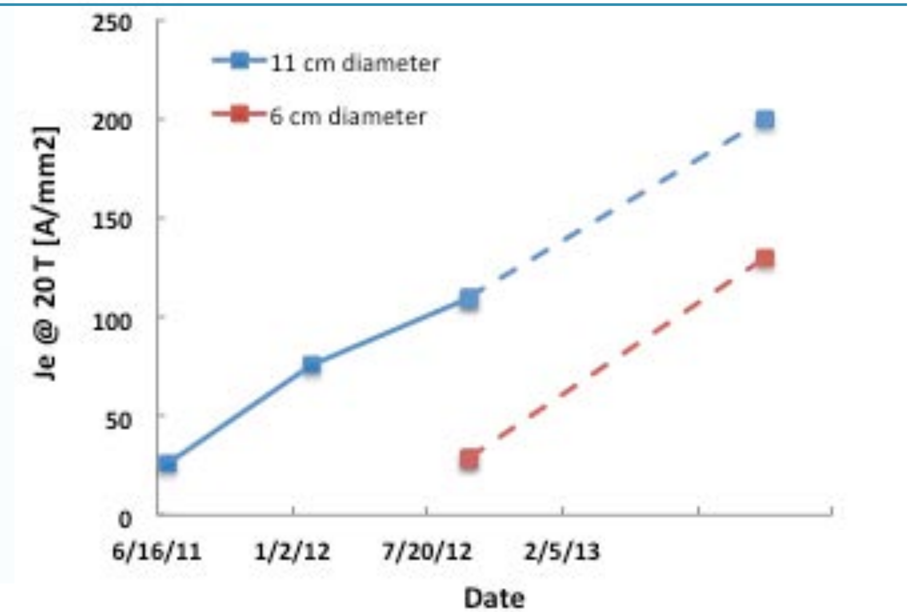




CORC cable performance projections (Cont.)

Cable optimization:

Raise J_e(4.2 K, 20 T) to above 200 A/mm^2 and reduce degradation at low cable bending radius.



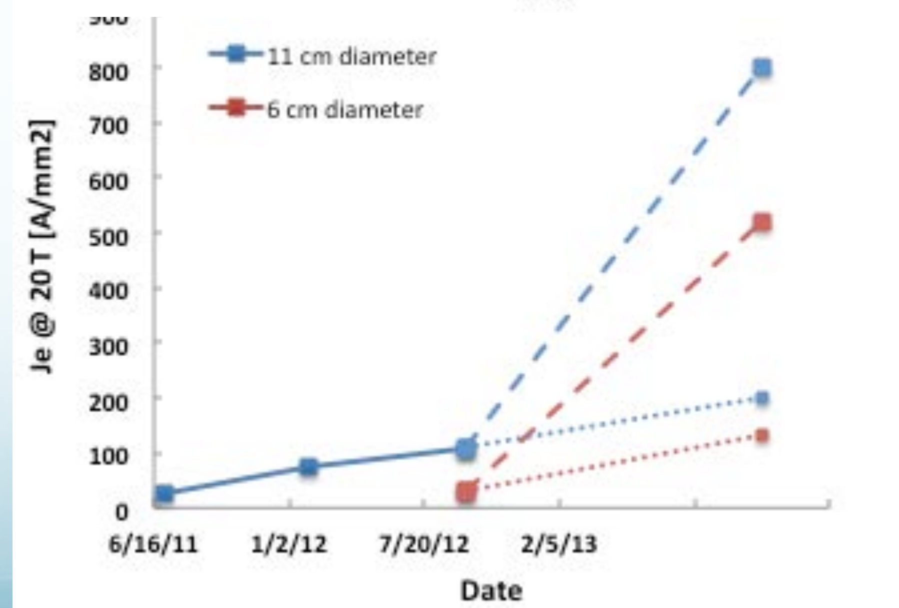
Raising J_e further by:

- Pinning: 2x in I_c at 4.2 K, 20 T?
- Thicker YBCO or thinnner substrates: 2x in I_c?

This would bring current J_e(4.2 K, 20 T) to 2 x 2 x 110 A/mm^2 = 440 A/mm^2!

Or two methods combined:

J_e(4.2 K, 20 T) = 4 x 200 A/mm^2 = 800 A/mm^2!



Advanced Conductor Technologies LLC
www.advancedconductor.com

Summary

- CORC cables are currently the only high-current, **flexible** HTS cables.
- Proven performance of CORC cables:
  - 7500 A in liquid nitrogen at cable O.D. of 10 mm.
  - 5000 A in liquid helium at 19 T.
- CORC cables experience no strain effect on I_c.
- No effect of current ramp rates up to 68 kA/s on the in-field performance.
- CORC cable machine fully operational.
- Large improvements of CORC I_c expected due to cable machine and CC layout.

Advanced Conductor Technologies LLC
www.advancedconductor.com