This work was in part supported by the US Navy under agreements N00024-14-C-4065, N00024-16-P-4071, and N68335-18-C-0151

Development of CORC® power transmission and fault current limiting cable systems

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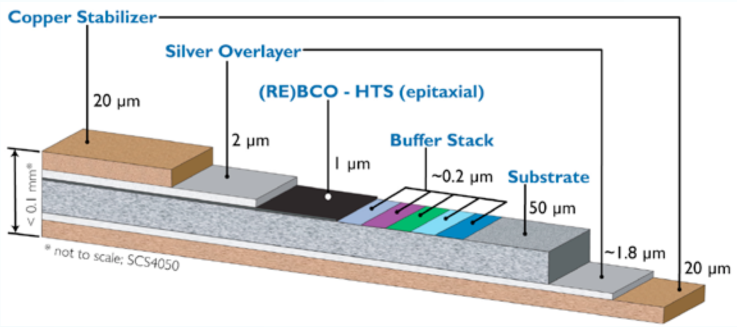
CEC ICMC. July 24th, 2019.
Hartford, Connecticut. M3Or3A-03

Georgia Tech

Conductor on Round Core (CORC®)

CORC® cable principle based on strain management
Winding many high-temperature superconducting REBCO coated conductors in a helical fashion with the REBCO under compression around a small former to obtain high conductor currents



RE-$Ba_2Cu_3O_{7-\delta}$ coated conductor made by SuperPower Inc.

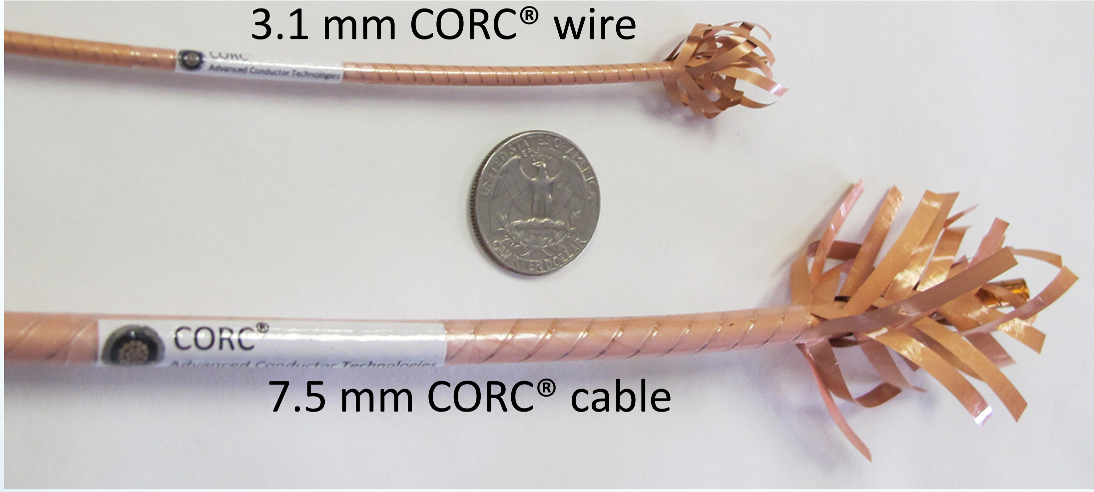
Single tape wound into a CORC® cable

Benefits of CORC® cables and wires
- Very high currents and current densities
- Mechanically very strong
- Very flexible
- High level of conductor transposition

CORC® power transmission cables and wires

We are developing high-current power transmission systems for operation in helium gas at 50 K

- Currents up to 10 kA/phase at 50 K
- Voltage rating of 1-12 kV



Typical CORC® wire

- 3.6 mm diameter with 29 tapes
- I_c (77 K) = 2,000 A
    - J_e (77 K) = 200 A/mm^2
- I_c (50 K) = 8,000 A
    - J_e (50 K) = 800 A/mm^2

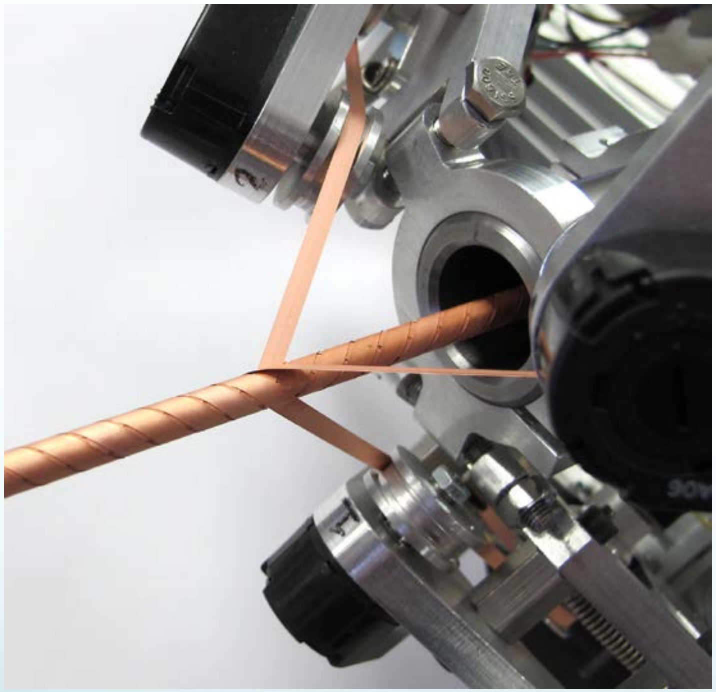
Typical CORC® cable

- 7.5 mm diameter with 42 tapes
- I_c (77 K) = 4,500 A,
    - J_e (77 K) = 100 A/mm^2
- I_c (50 K) = 18,000 A,
    - J_e (50 K) = 400 A/mm^2

CORC® cable production at ACT

Winding of long CORC® cables with custom cable machine

- Accurate control of cable layout
- Long cable lengths possible (> 100 meters)
- I_c retention after winding 95-100 %



First commercial sale (CERN)

- 12 meter CORC® cable (38 tapes)
- Cable for detector magnets
- Delivered August 2014

Many commercial orders followed

Over 400 meters of CORC® cable and wire sold thus far to various customers

Programs at Advanced Conductor Technologies

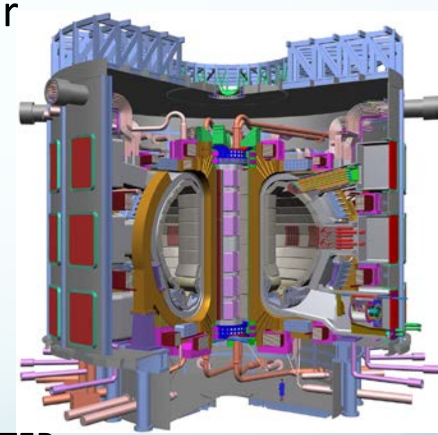
1. Department of Energy – Office of High Energy Physics (DOE-HEP)

CORC® wires and cables for accelerator magnets including Canted Cosine Theta magnets and Common Coil magnets

LHC at CERN

2. Department of Energy – Office of Fusion Energy Sciences (DOE-OFES)

CORC® cable for fusion magnets, cable joints, and terminations for fusion magnets



ITER

3. Navy

CORC® power transmission, fault current limiting cables, and Dielectrics for CORC® power transmission

NAVSEA WARFARE CENTERS Philadelphia

CORC® power transmission cables for the US Navy

CORC® power cables in collaboration with Center for Advanced Power Systems

- Operation in helium gas at 50 K
- DC and AC cables
- 3-10 kA per phase
- 1-20 kV operation
- Fault current limiting capabilities

LCS 4 USS Coronado

Potential applications for 1 – 100 MW power transmission

- Navy ships
- Electric aircraft
- Data centers

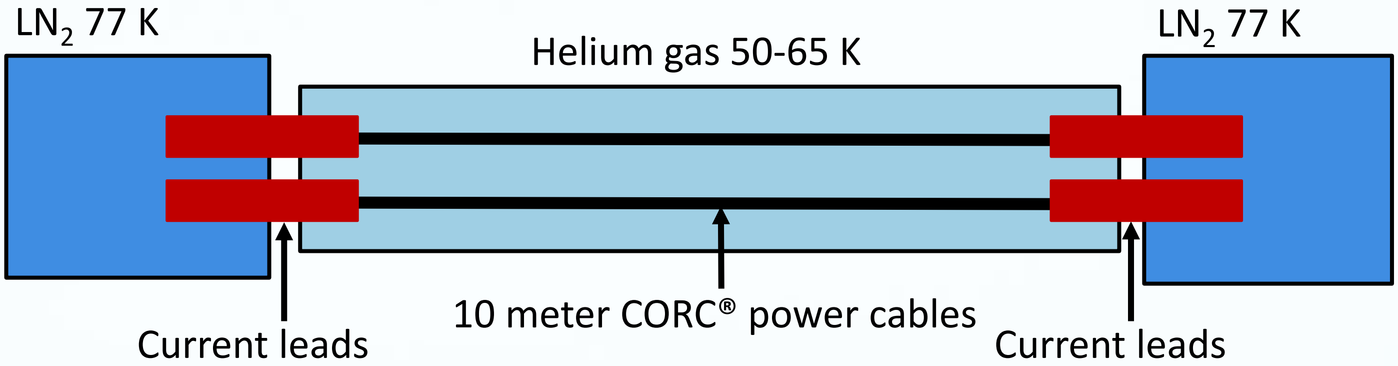
NAVSEA
WARFARE CENTERS
Philadelphia

Challenges of power transmission in confined spaces

- Operating voltage is relatively low: 270 V (Air Force) – 12,000 V (Navy)
- High operating currents are required to reach high power rating
- Tight bends require flexible cables
- Asphyxiation hazards may prevent use of liquid cryogens in some cases

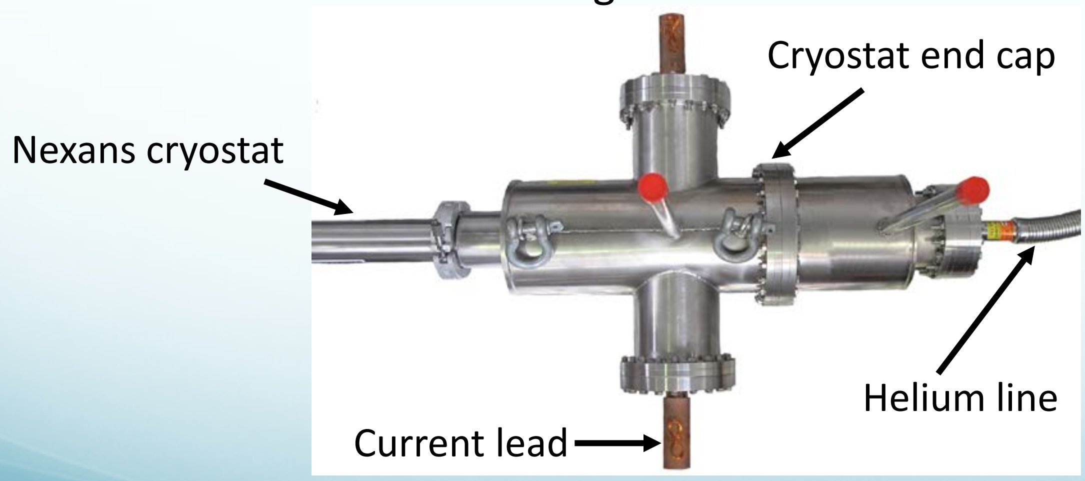
Development of a demonstrator 10-meter 2-pole DC CORC® power transmission system

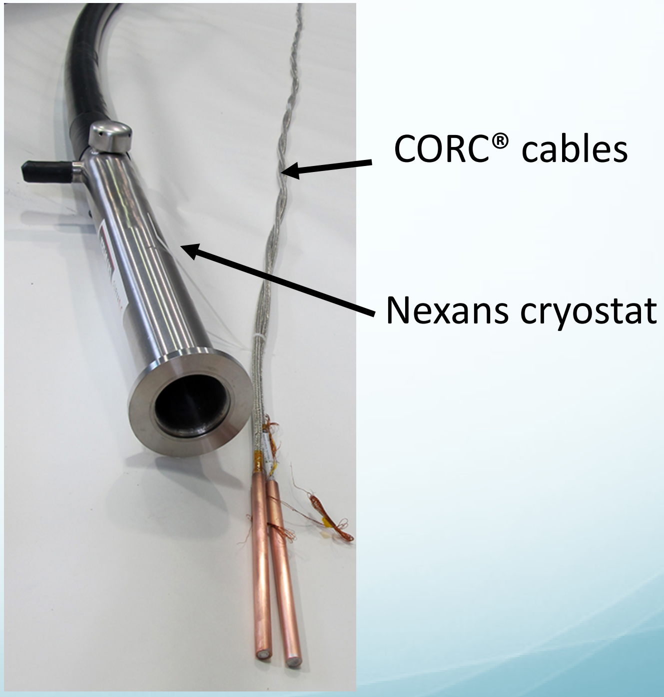
10-meter 2-pole CORC® DC power system



Goal

- 2-Pole DC CORC® power transmission cable
- 10 meter long twisted pair cable layout
- Operating current 4,000 A (50 K)
- Cooled with 2 MPa helium gas

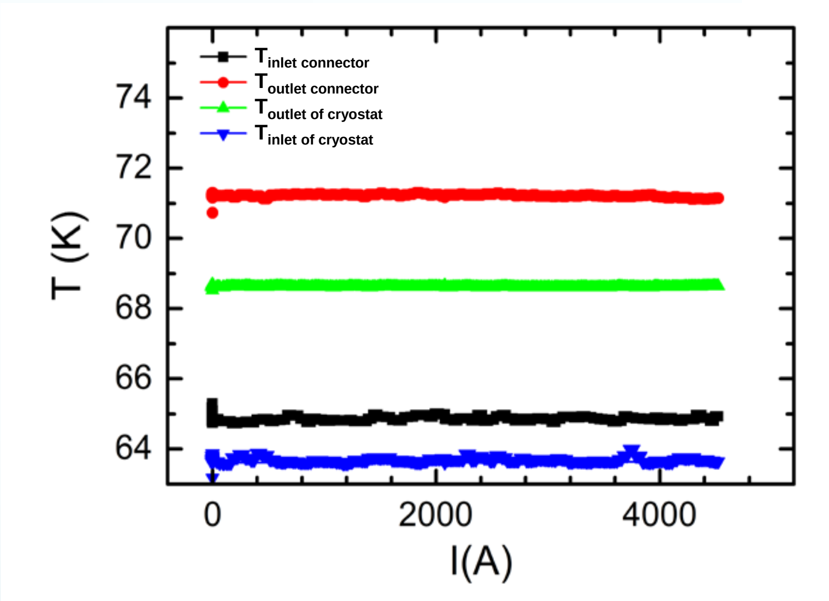


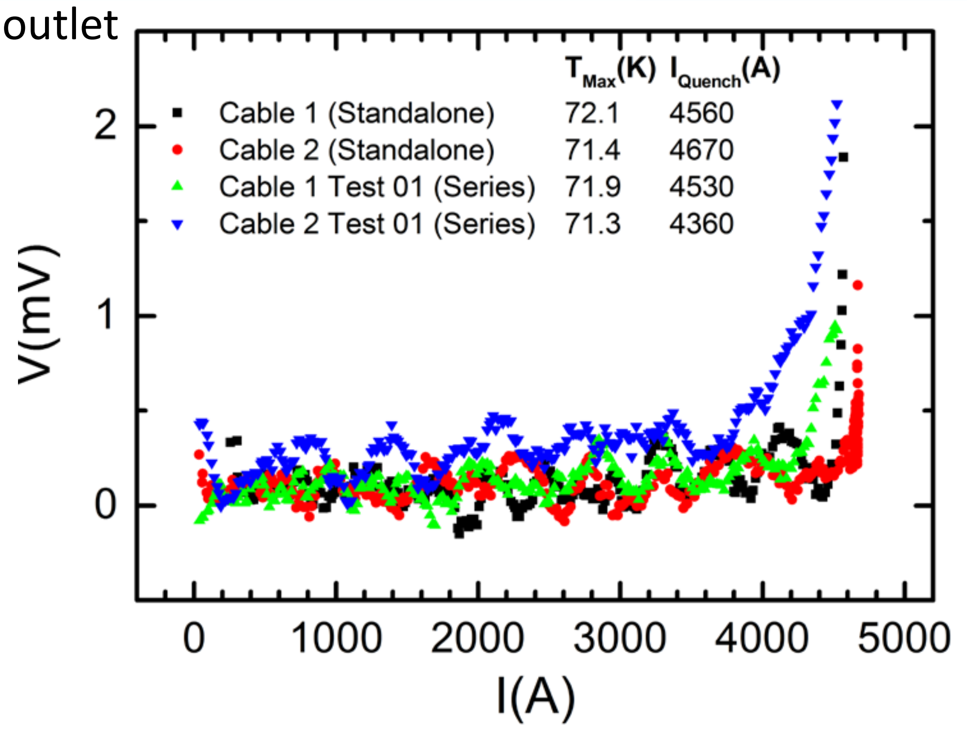


10-meter 2-pole CORC® system test

Test procedure

- Cool-down to 64 K inlet, and 72 K outlet
- Test each phase individually
- Test phases connected in series





- **Individual cable tests I_{quench} (Phase 1) = 4,560 A, I_{quench} (Phase 2) = 4,670 A**
- **Series connected cable tests I_{quench} (Phase 1) = 4,530 A, I_{quench} (Phase 2) = 4,360 A**
- **Results suggest that I_{quench} at 50 K would be > 10,000 A**

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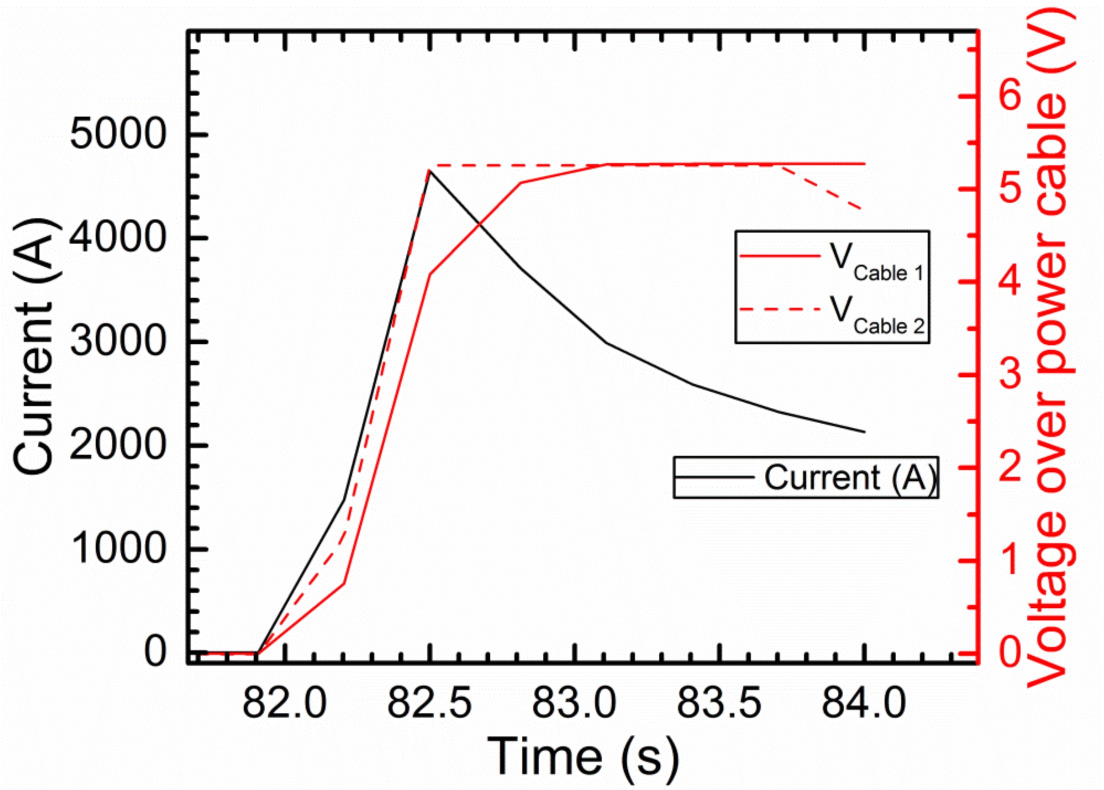
CORC® power cable overcurrent test

Fault Current Limiting Test

- Current to 6,000 A
- 10 V supply voltage

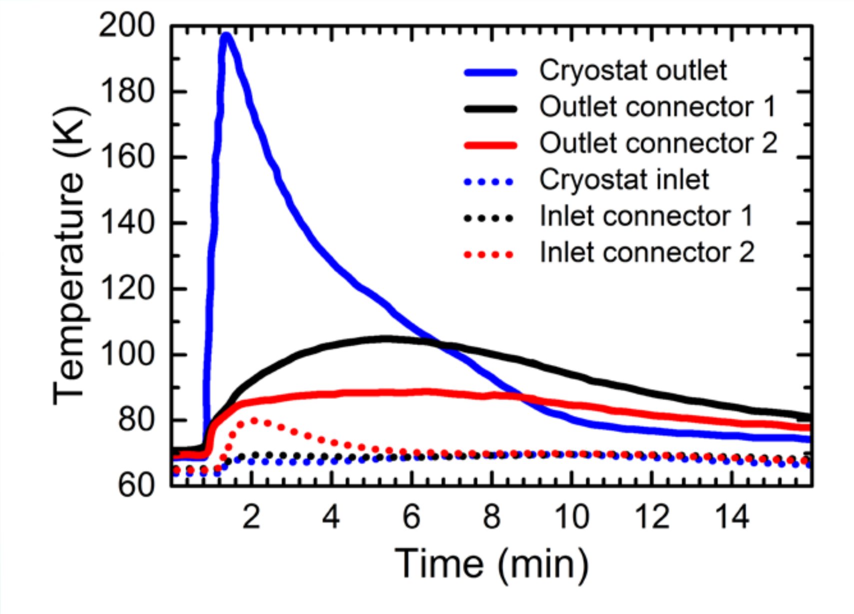


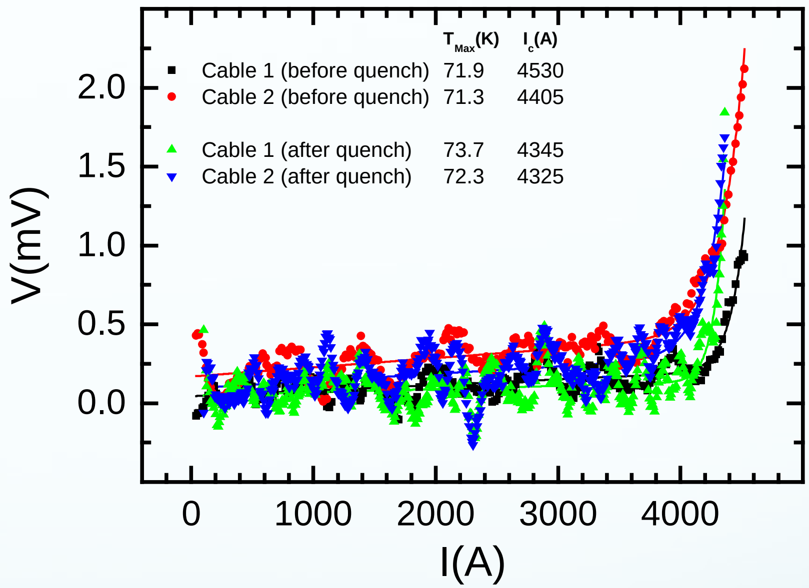
- **Current was limited to 2,000 A after 2 seconds**
- **Voltage over each pole was 5 V**
- **Maximum power dissipation: 43.4 kW**
- **Total energy dissipated: 53.7 kJ**

CORC® power cable performance verification

Recovery and performance verification

- Maximum helium temperature 200 K
- Recovery time > 20 minutes





- **CORC® power cable performance unchanged after FCL test**
- **Dissipation within helium gas needs to be limited during FCL event**
  => use of hybrid FCL cable with fast acting switch as solution

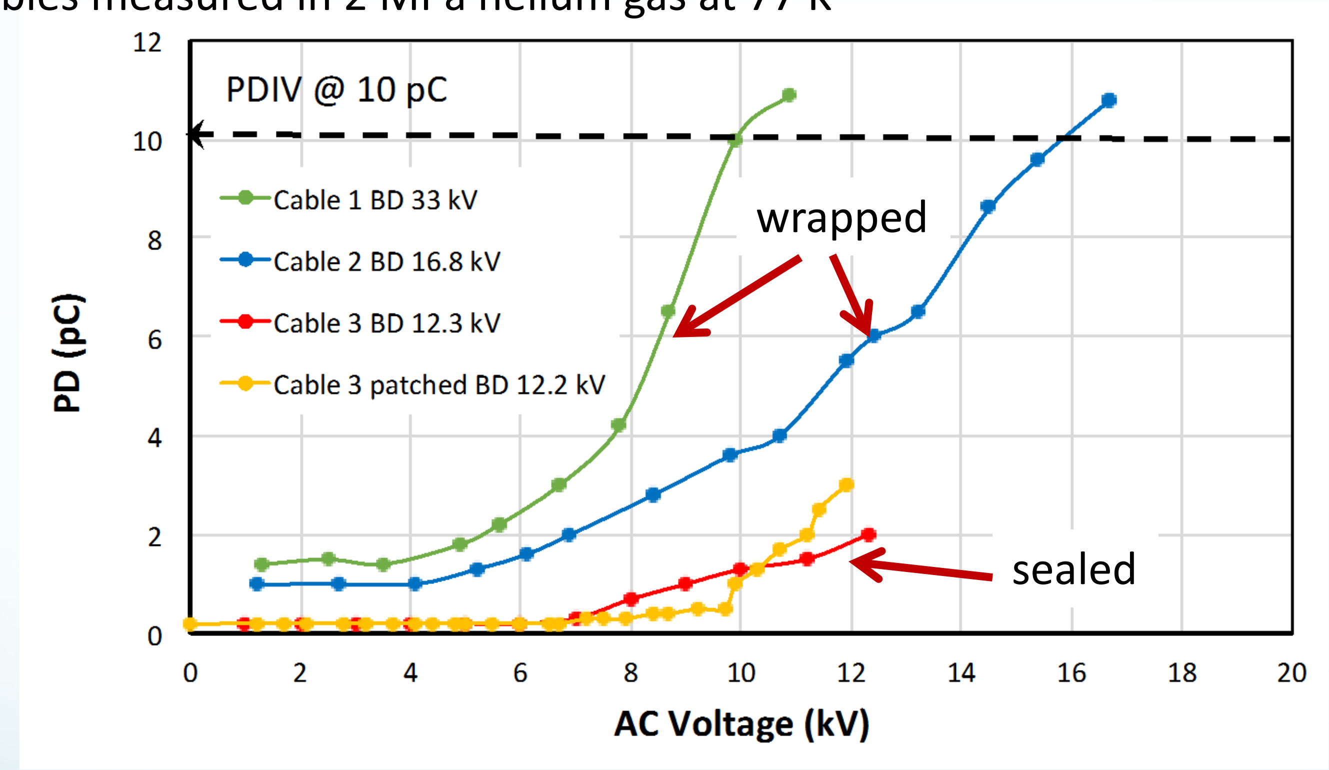
CORC® power transmission system shipped to Navy

CORC® power transmission cables: Additional progress

Increasing the voltage rating on CORC® cables

Investigating wrapped (unsealed) dielectrics and sealed dielectrics

- Partial Discharge (PD) and Break Down (BD) measurements
- Cables measured in 2 MPa helium gas at 77 K



- Partial discharge for sealed dielectric is much lower than for wrapped dielectric
- **Preventing helium gas penetration significantly reduces the partial discharge**
- **Breakdown voltage depends on cable insulation thickness**

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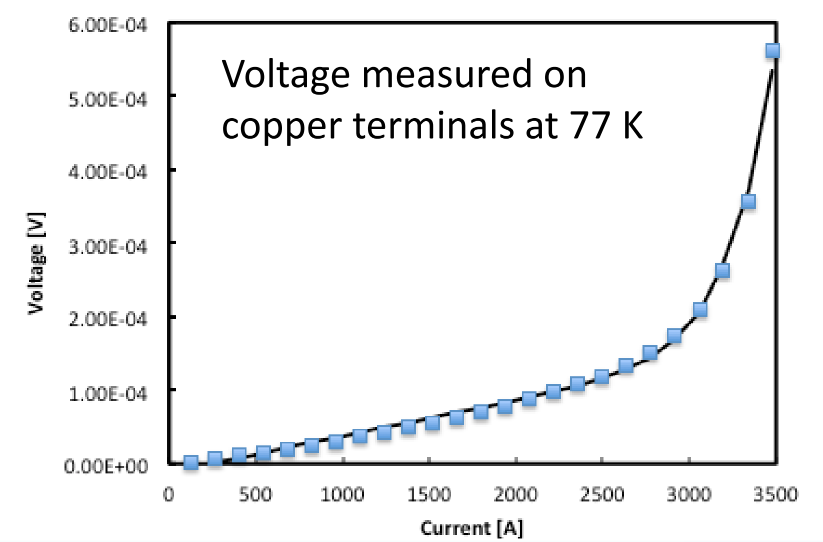
CORC® cable terminations and joints

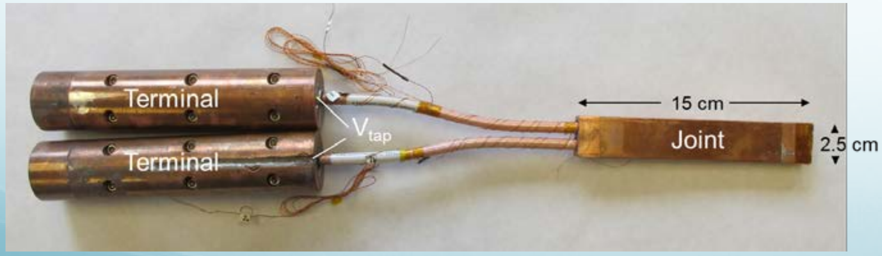
CORC® cable terminations

- Very compact
- Capable of injecting large currents
- R (77K) = 5 to 50 nΩ



CORC® cable Joints

15 cm long simple double terminal joint
R (77 K) ~100 nΩ



20 cm long praying hands demountable joint
R (77 K) < 200 nΩ

Courtesy of
Xiaorong Wang

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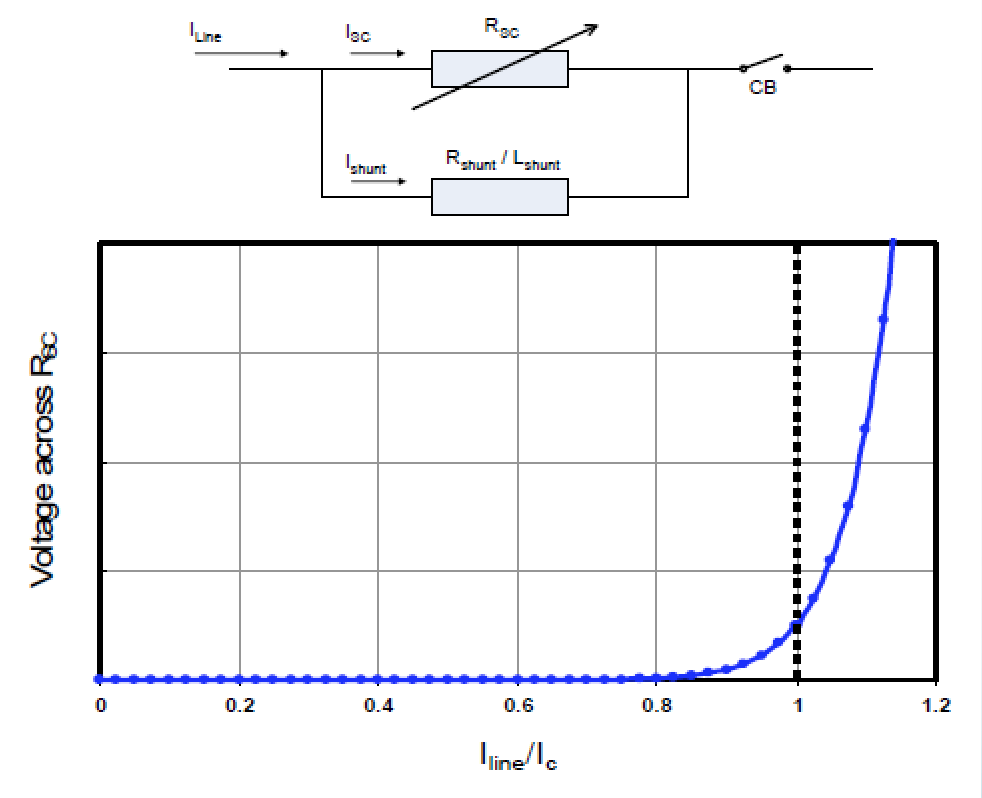
CORC® for fault current limiting (FCL) applications

Background: resistive fault current limiting

- When a fault develops, the superconductor quenches, it's resistance rises and current is diverted to a parallel circuit with the desired higher impedance.
- When in the resistive state, the cryogenic cooling system must be capable of removing the heat generated to restore the cable to its superconducting state in a suitable timeframe (recovery time)
- A switching component may need to be incorporated to isolate the superconducting/cryogenic component from the resistive shunt.



EPRI, 2009

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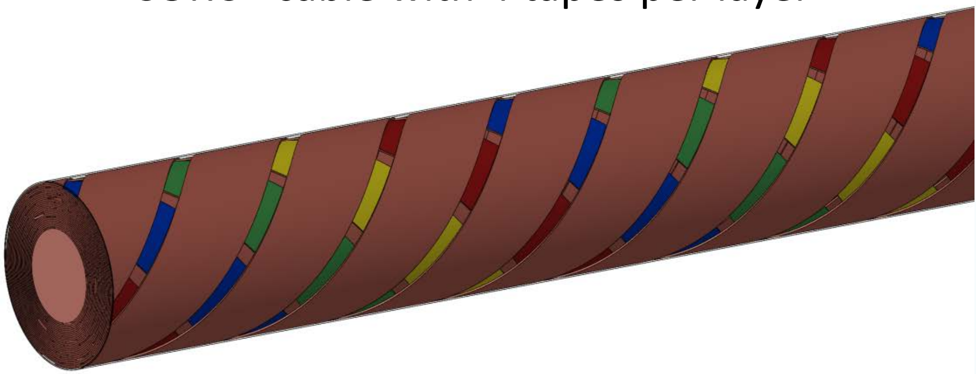
Advantages of CORC® topology for FCL application

Versatile architecture allows for tunable properties

- Can incorporate any number of normal and superconducting tapes to tailor operating current, normal state resistivity, and thermal management
- Extremely compact package delivering 1-20 kA in a 4-8 mm outer diameter

CORC® cable with 4 tapes per layer



HTS tapes are layered and transversed

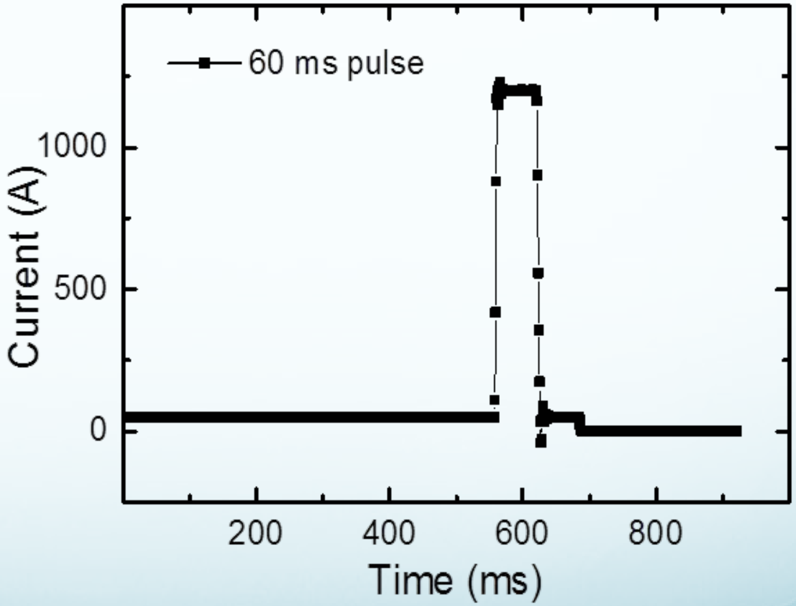
- Direct contact between each tape and up to 8 other tapes
  - ✧ More paths for current sharing adds electrical stability
  - ✧ More thermal contacts allows proficient cooling
- Such high level of current sharing is not available in conventional HTS FCL cables that typically require laminates

ACT's FCL Overcurrent Test Facility

Key features of our V(I) test setup:

- **13.5 kA worth of current supplies**
- **Ramp rates up to 1 MA/s**
- **Highspeed data acquisition (50 kS/s)**

Example of a 60 ms current pulse



Two CORC® wire designs tested

SuperPower tape was chosen for the CORC® FCL wires

Sample name	I_c at 76 K (A)	J_e at 76 K (A/mm^2)	Total wire diameter (mm)
CORC® wire 1	646	80	3.2
CORC® FCL wire 2	1124	99	3.8

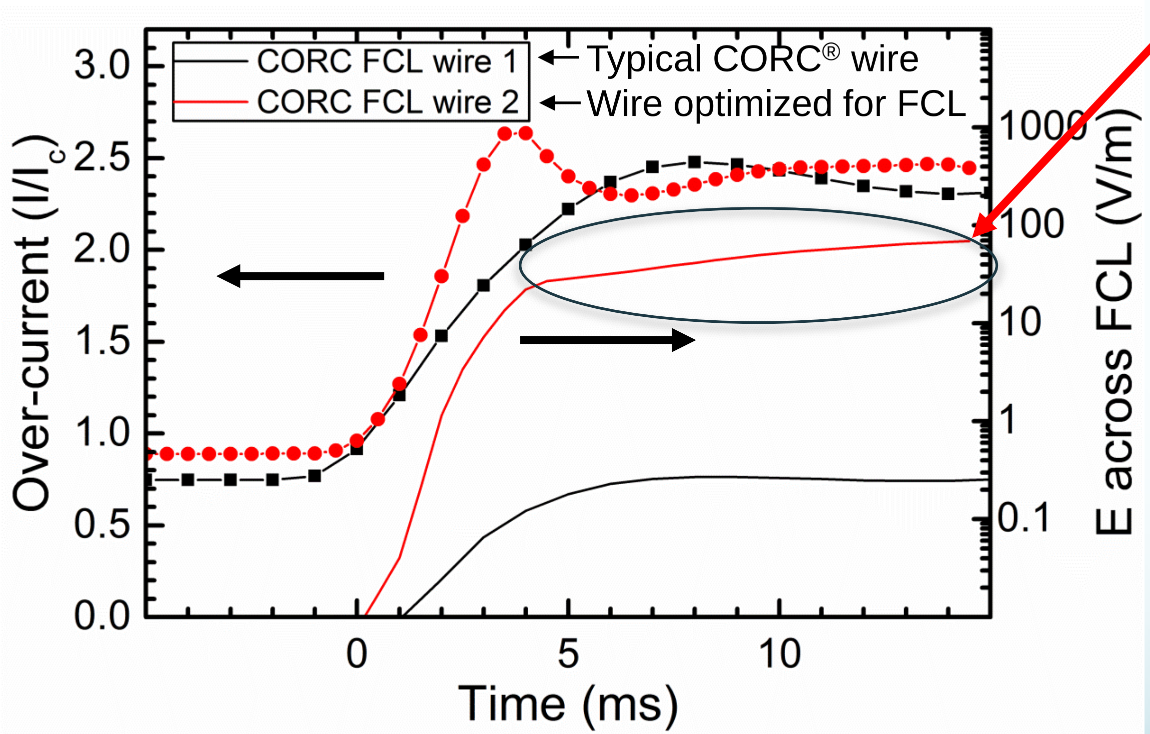
Key features

- Wire length between terminals = 20 cm
- CORC® wire 1 was not optimized for FCL operation
- CORC® FCL wire 2 was optimized for FCL operation
- Wires also contain several tapes of varying quality “Frankenstein’s wire”
  - Average I_c = 72.9 A (STDEV ~8.7)

Overcurrent response of CORC® FCL wires

CORC® FCL wires

- Fast response to overcurrent
- Voltage develops concurrent with the current-pulse rise time



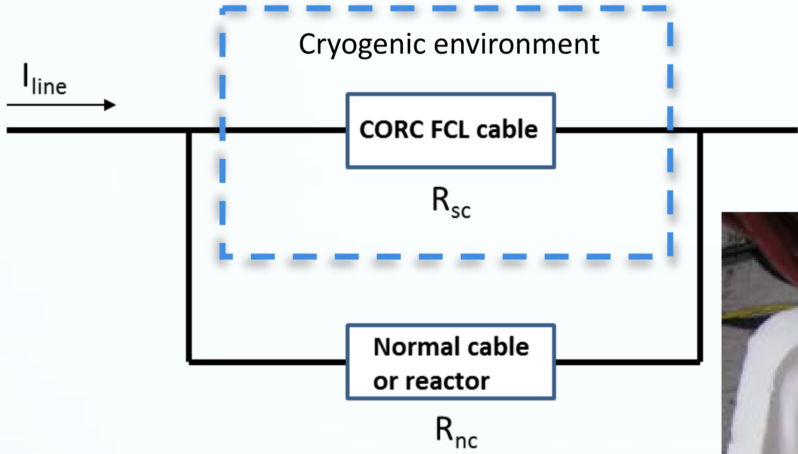
Electric field over CORC® wire 20 V/m with the current pulse, and 50 V/m after 5 ms!

Applied overcurrent I/I_c=2.5

- CORC® FCL wire 1: 1,600 A
- CORC® FCL wire 2: 2,800 A

Overview of a hybrid CORC® FCL system

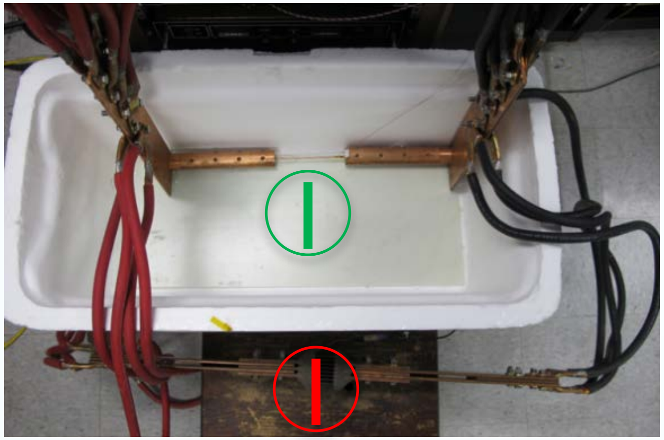
CORC® FCL wire in parallel with room temperature nonsuperconduting cable

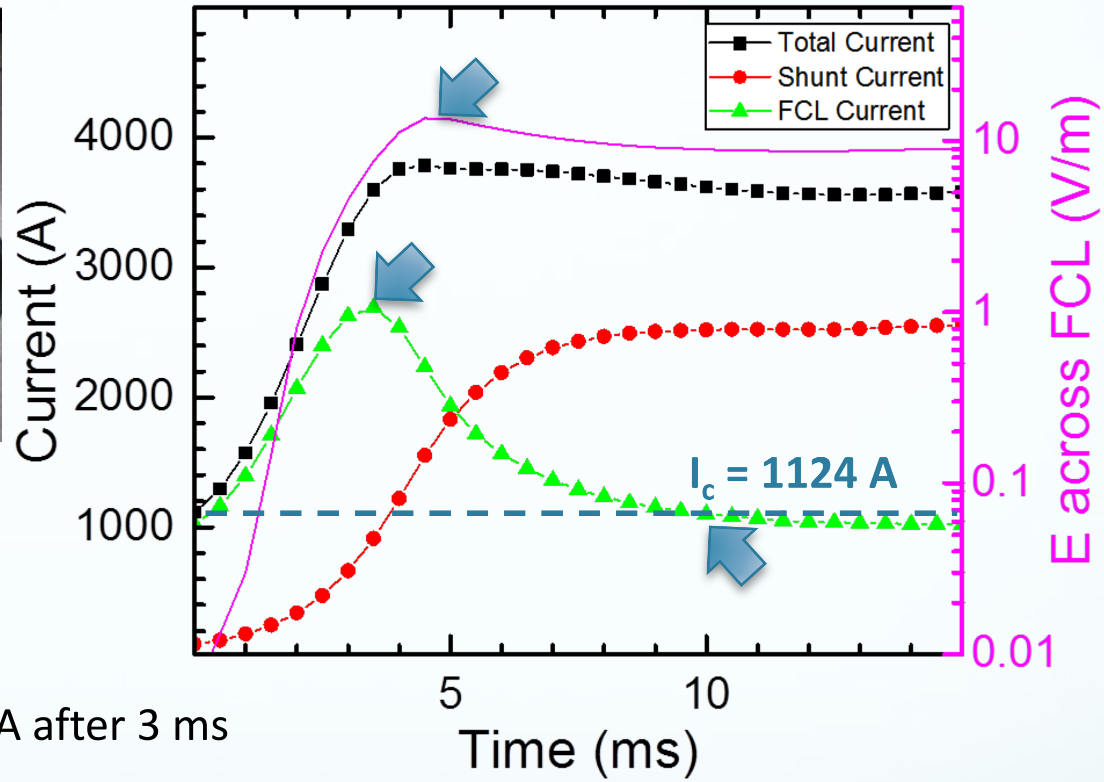


Configuration allows current to bypass superconducting part of circuit to protect sensitive equipment and/or lesson switching requirements.

Cable can be isolated after fault, enabling faster recovery cool-down to cryogenic temperature

Overcurrent testing of a hybrid CORC® FCL system

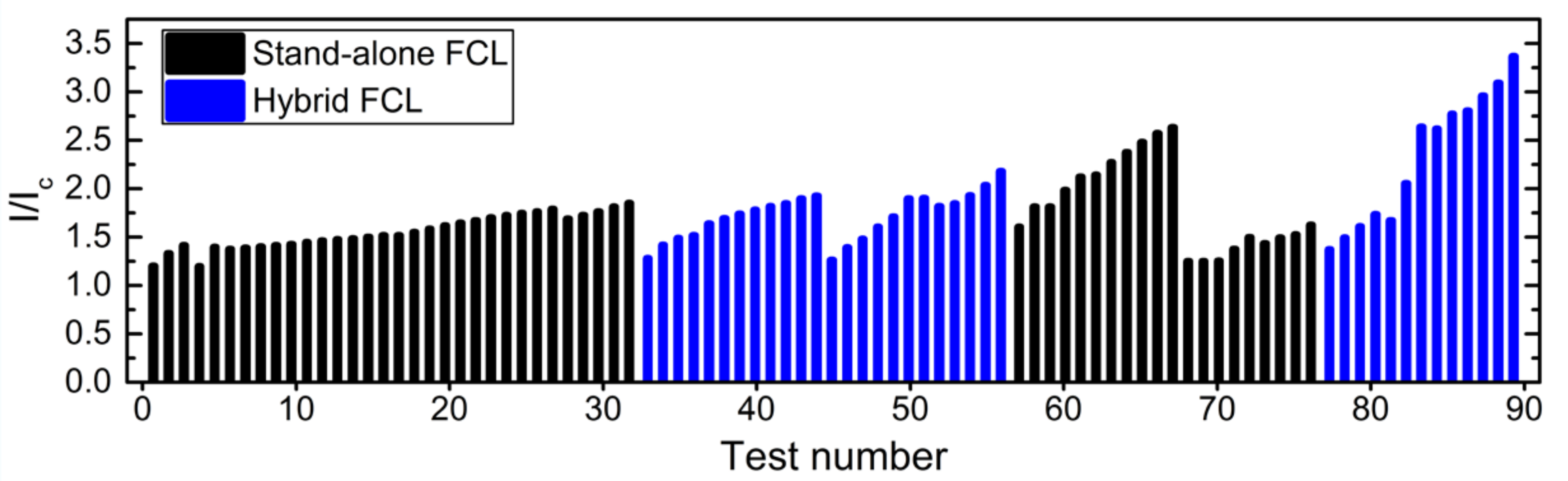




Fault overcurrent of 320% I_c

- Peak current in FCL wire 2,700 A after 3 ms
- FCL voltage 10 V/m after 5 ms
- Current in FCL wire back below I_c after 10 ms, while maintaining ~10 V/m over hybrid cable system
- Constant voltage suggests CORC® wire remains at constant temperature, although dissipation at ~10 kW/m
- Rapid cool down requires switch to isolate the CORC® wire

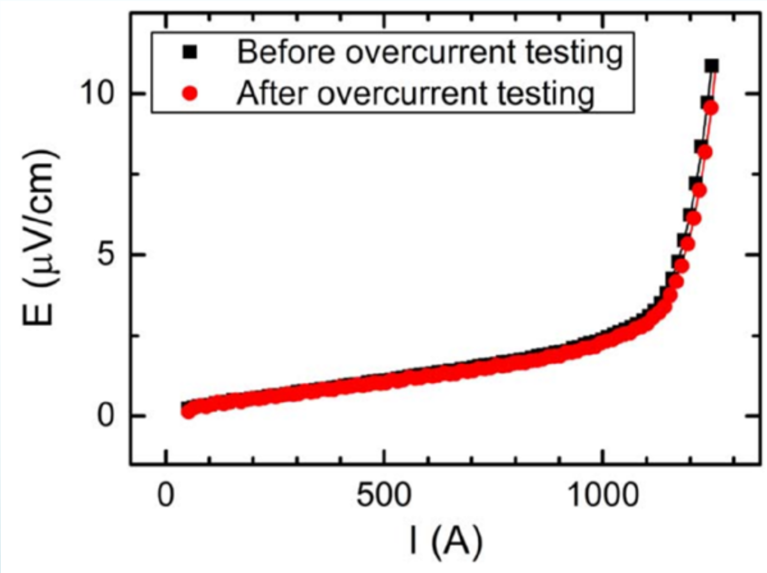
Extensive cycling did not degrade CORC® FCL conductor



Includes

- several non-controlled cool-down cycles (thrown into LN_2 bath)
- full warm-up cycles to room temperature (during 10-20 ms fault)

No degradation after more than 90 faults and several rapid thermal cycles



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Summary

CORC® cables and wires enable high-current density power transmission

- Helium gas-cooled 2-pole CORC® dc power cable system demonstrated
- Current rating of 10 kA at 50 K easily realized with plenty of margin

CORC® cables and wires can be operated as Fault Current Limiters

- Current sharing between tapes in CORC® cables/wires allows us to produce CORC® FCL conductors without the need for laminates
- low thermal capacity and high normal resistance allow for very fast response to fault currents
- Response time is nearly instantaneous, with voltage rise following the current ramp which takes 3-4 ms to reach $I/I_c = 2.5$
- Fast acting CORC® FCL wire demonstrated with 50 V/m after 5 ms of overcurrent in LN_2
- No degradation in CORC® wire performance after more than 90 faults

Recent publications

IOP Publishing — Superconductor Science and Technology
Supercond. Sci. Technol. 31 (2018) 085011 (10pp) — https://doi.org/10.1088/1361-6668/aacf6b

Development of CORC® cables for helium gas cooled power transmission and fault current limiting applications

D C van der Laan[1,2,6], J D Weiss[1,2], C H Kim[3], L Graber[4] and S Pamidi[3,5]

CORC® power transmission cable development and test

IOP Publishing — Superconductor Science and Technology
Supercond. Sci. Technol. 32 (2019) 034005 (8pp) — https://doi.org/10.1088/1361-6668/aafaa7

Hybrid superconducting fault current limiting CORC® wires with millisecond response time

Jeremy D Weiss[1,2], Chul Kim[3], Sastry Pamidi[3,4] and Danko C van der Laan[1,2]

CORC® hybrid FCL wire development and test

IOP Publishing — Superconductor Science and Technology
Supercond. Sci. Technol. 32 (2019) 033001 (33pp) — https://doi.org/10.1088/1361-6668/aafc82

Topical Review

Status of CORC® cables and wires for use in high-field magnets and power systems a decade after their introduction

D C van der Laan[1,2,3], J D Weiss[1,2] and D M McRae[1,2]

Topical review of CORC® conductor and applications