Development of round flexible HTS CORC® wires for fault current limiting applications

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EUCAS, 2017 Geneva

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Funded by Navy SBIR contract number N00024-16-P-4071

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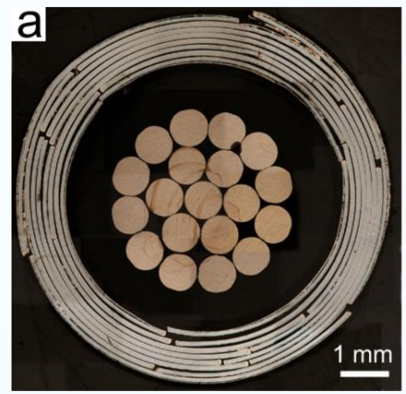
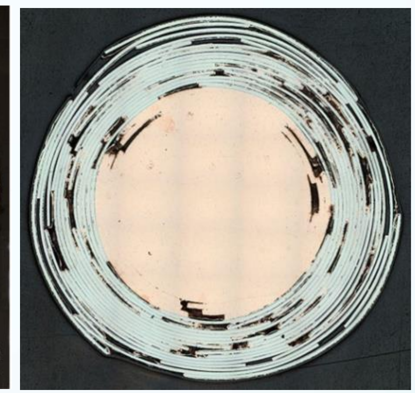
Conductor on Round Core (CORC®) technology

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





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

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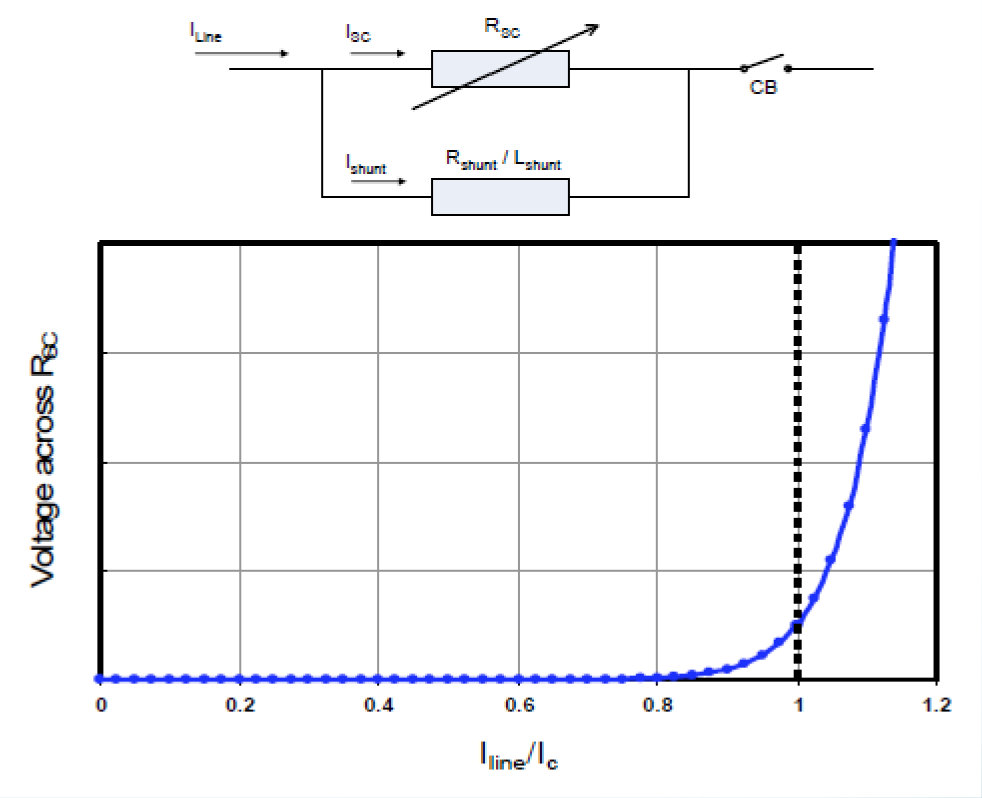
Background: Resistive fault current limiting

- 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.



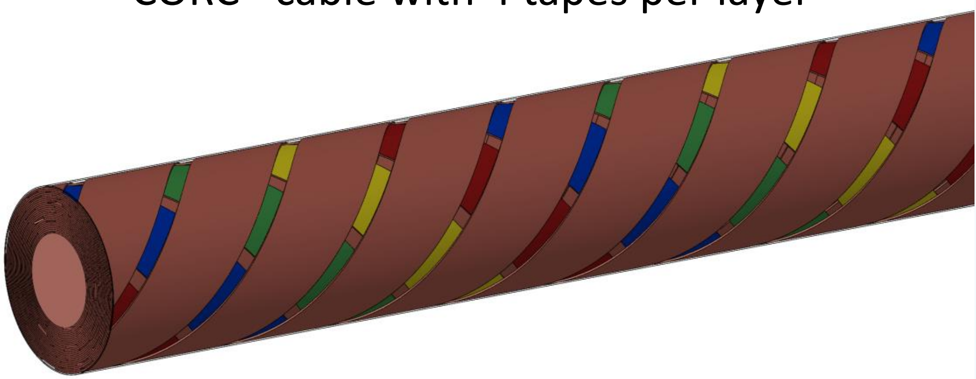
EPRI, 2009

Advantages of CORC® topology

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

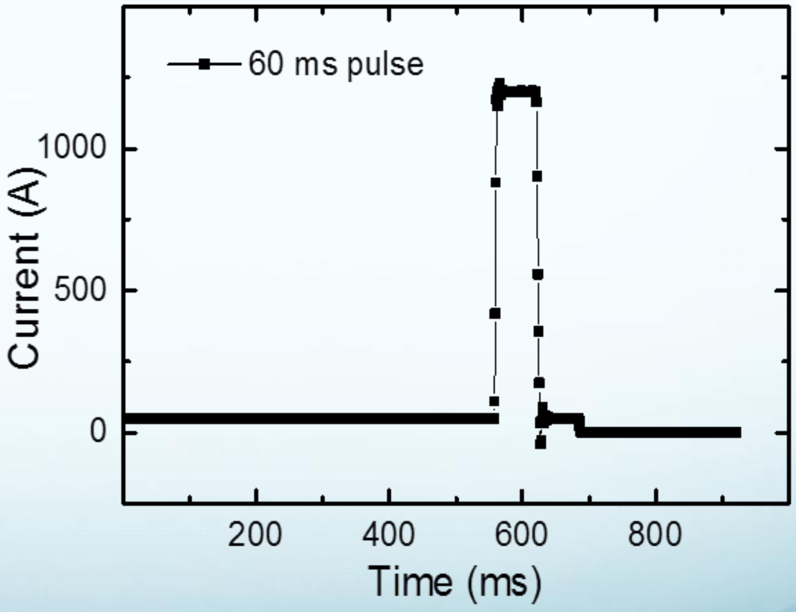
- Direct contact between each tape and up to 8 other tapes
  - ✧ More paths for current sharing adds electrical stability
  - ✧ More thermal contacts allows proficient cooling
- Such high level of current sharing is not available in conventional HTS FCL cables that typically require laminates

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



Short FCL CORC® wire designs

SuperPower tape was chosen for the CORC® FCL wires

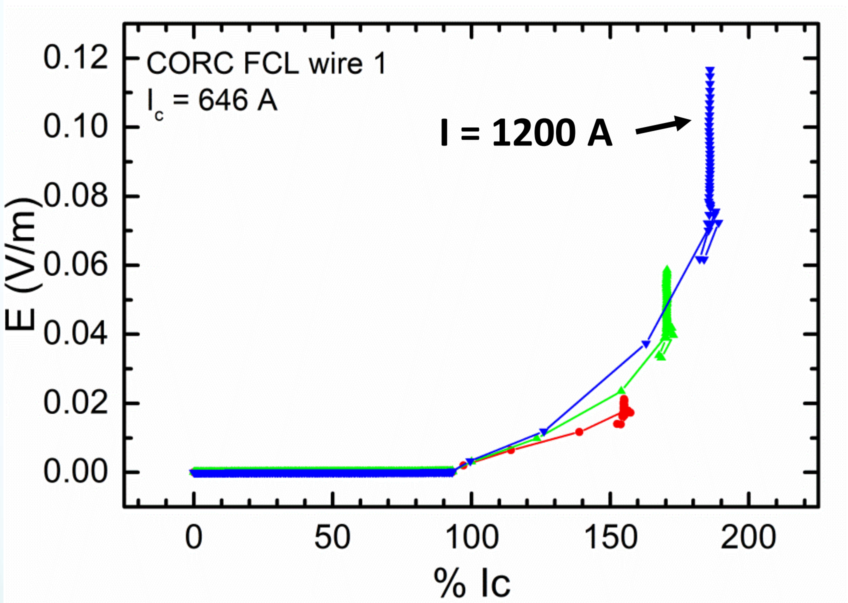
Sample name	I_c at 76 K (A)	J_e at 76 K (A/mm^2)	Total wire diameter (mm)
CORC FCL wire 1	646	80	3.2
CORC FCL wire 2	1124	99	3.8

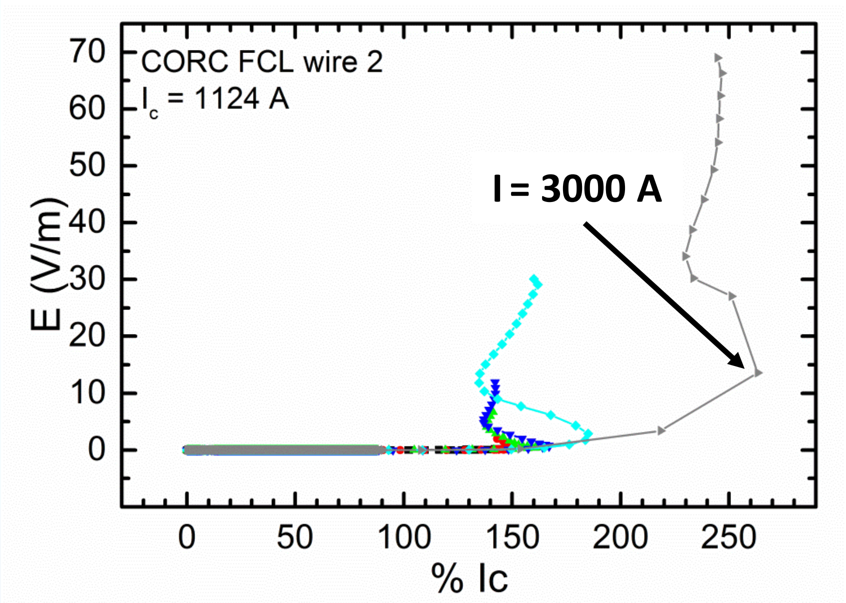
Key features

- Wire length between terminals = 20 cm
- CORC® FCL 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 testing of CORC® FCL wires in nitrogen

E(% I_c) of CORC® wires pulsed to various overcurrents
Optimized wire 2 develops orders of magnetude more voltage at same I/I_c





The oscillations of applied current observed is an experimental artifact due to the use of switching power supplies used to drive current

Data points shown at 1 ms time intervals.

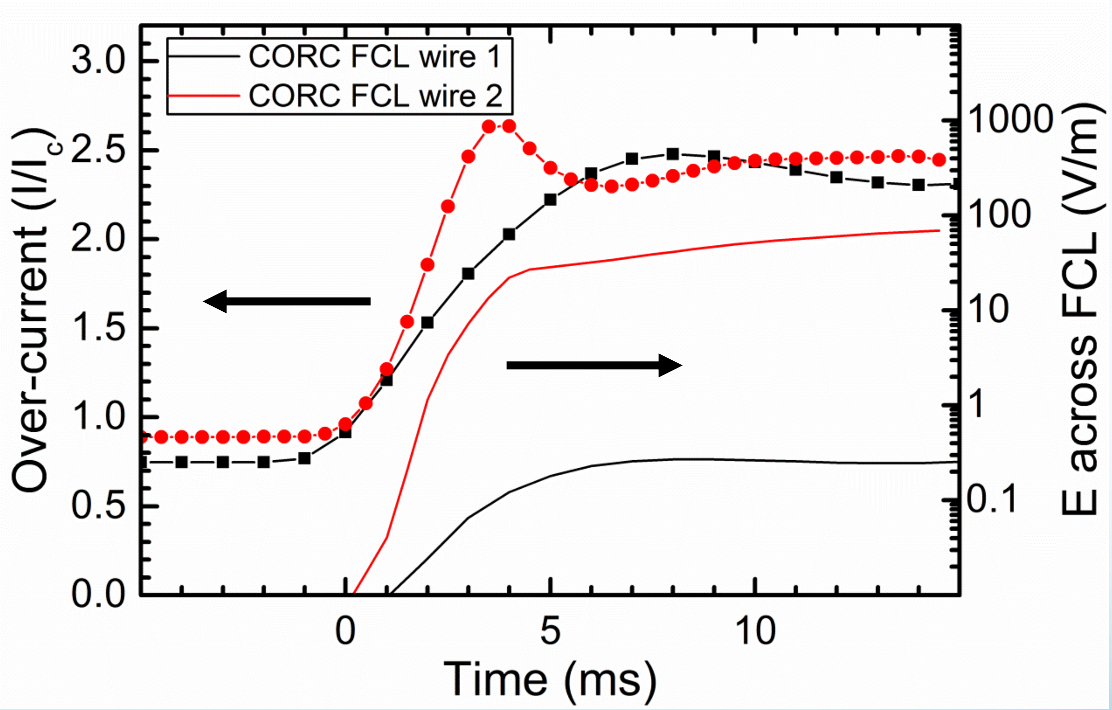
Overcurrent testing of CORC® FCL wires in nitrogen

Applied overcurrent I/I_c=2.5

- CORC® FCL cable 1: maximum current is 1,600 A
- CORC® FCL cable 2: maximum current is 2,800 A

Voltage developed over CORC® wire

- **Wire 1: 0.3 V/m**
- **Wire 2: 70 V/m**



Test shows that the optimized cable design maximizes E vs time and overcurrent

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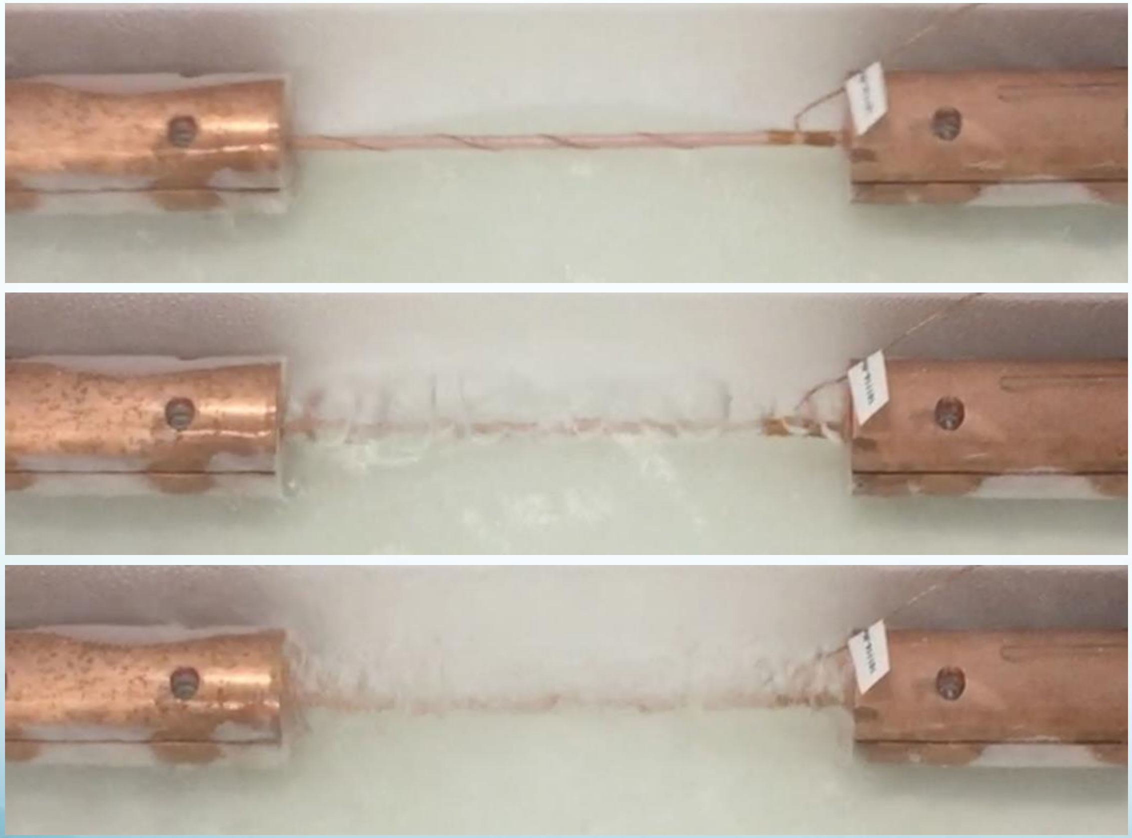
Overcurrent testing of CORC® FCL wires in nitrogen

Rapid boiling across entire wire section is observed during overcurrent tests



High speed movie captures the quench that occurs uniformly across the wire

Wires were tested several times from 110 % to 350 % I_c for wire 1 and up to 270 % for wire 2

No I_c degradation was observed for either wire following the overcurrent tests. Similar tests on individual tapes resulted in burnouts due to hot spots

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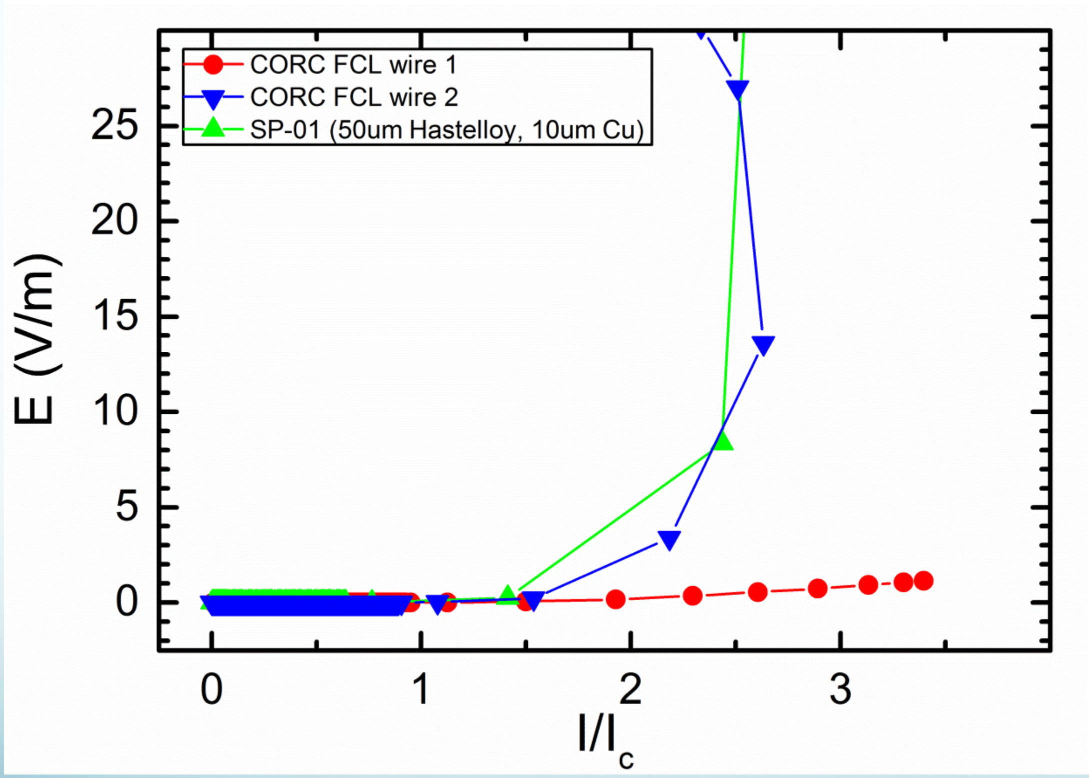
Overcurrent testing of CORC® FCL wires in nitrogen

$E(I/I_c)$ for wire 2 develops similarly to SP-01 tape with similar level of applied overcurrent



Data points shown at 1 ms time intervals.

While individual tapes can burn out due to localized dissipation at defects (hot-spots), current sharing in the CORC® wires provides more stability as voltage develops.

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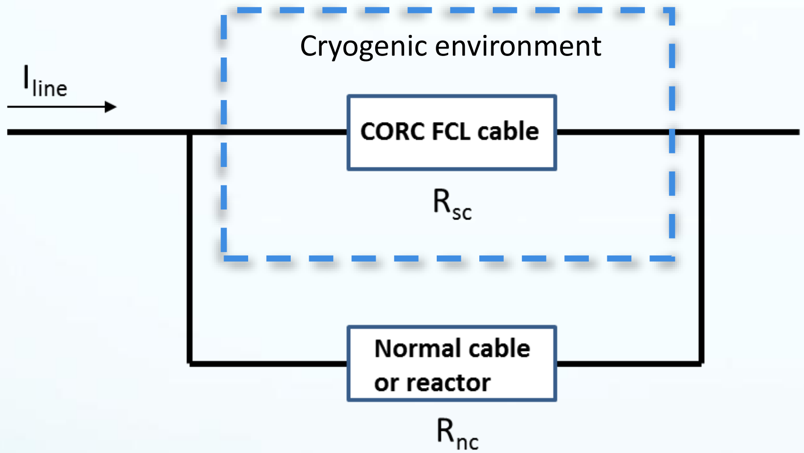
Overcurrent testing of a hybrid CORC® FCL system

CORC® FCL wire in parallel with normal conducting shunt located outside of cryostat

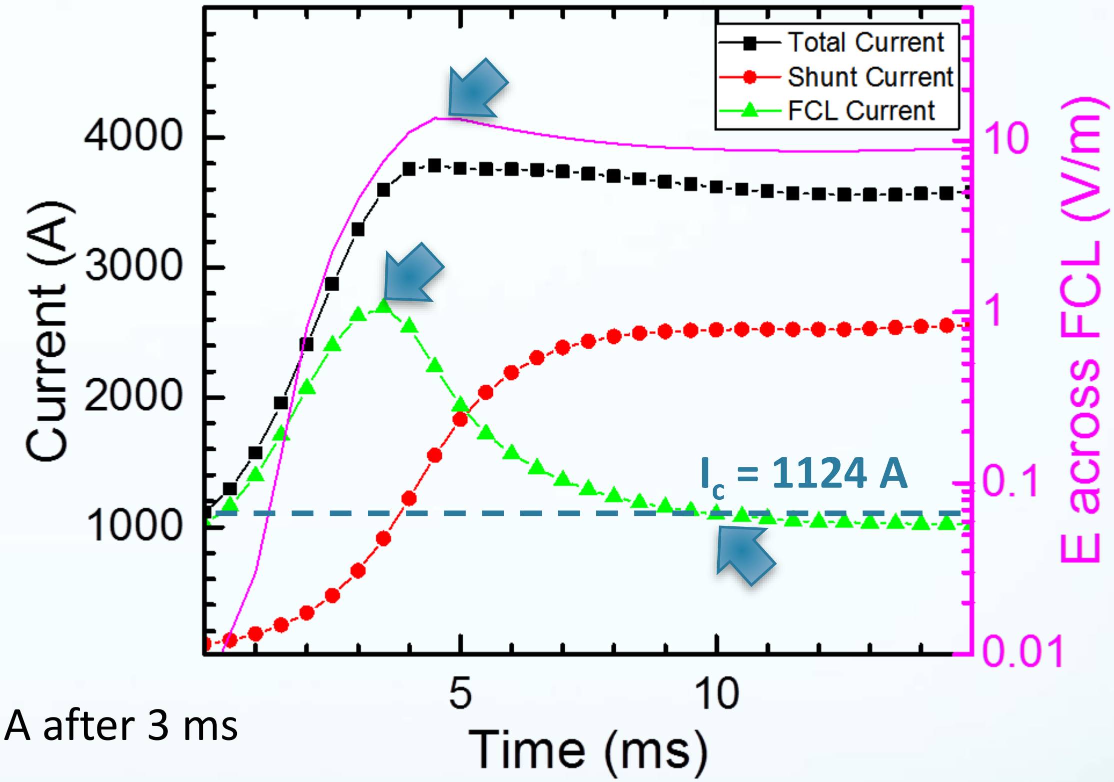
Schematic of experimental setup



Picture of experimental setup

Experimental setup does not include fast acting switch that could be used to isolate the superconducting wire for recovery

Overcurrent testing of a hybrid CORC® FCL system

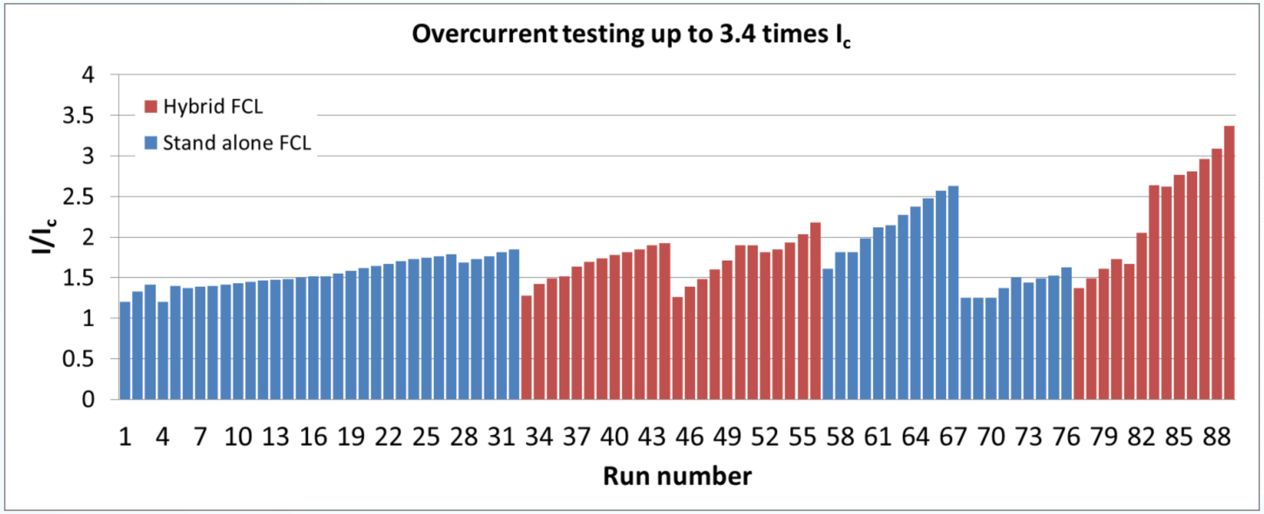


Fault overcurrent of 320% I_c

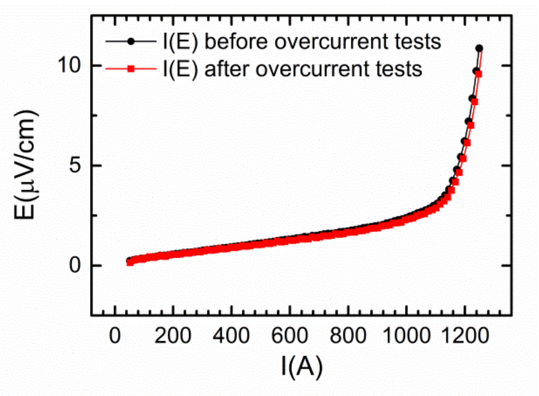
- Peak current in FCL wire 2,700 A after 3 ms
- FCL voltage 10 V/m after 5 ms
- Current in FCL wire back below I_c after 10 ms, while maintaining ~10 V/m over hybrid cable system
- Constant voltage suggests CORC® wire remains at constant temperature, although dissipation at ~10 kW/m
- Rapid cool down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

Extensive cycling did not degrade CORC® FCL conductor

Includes several non-controlled cooldowns (placed into LN_2 bath) and full warmups to room temperature



E(I) curve is same after 90 Faults!



To reiterate:

- CORC® wire 2 "Frankenstein's wire"
  - Critical currents that varied between 56 and 81 A because they were from 5 different batches and slit from various locations
- Frankenstein's wire is still alive!

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Development of High-Temperature Superconducting CORC® Power Transmission Cable Systems

Funded by Navy SBIR contract number N00024-14-C-4065

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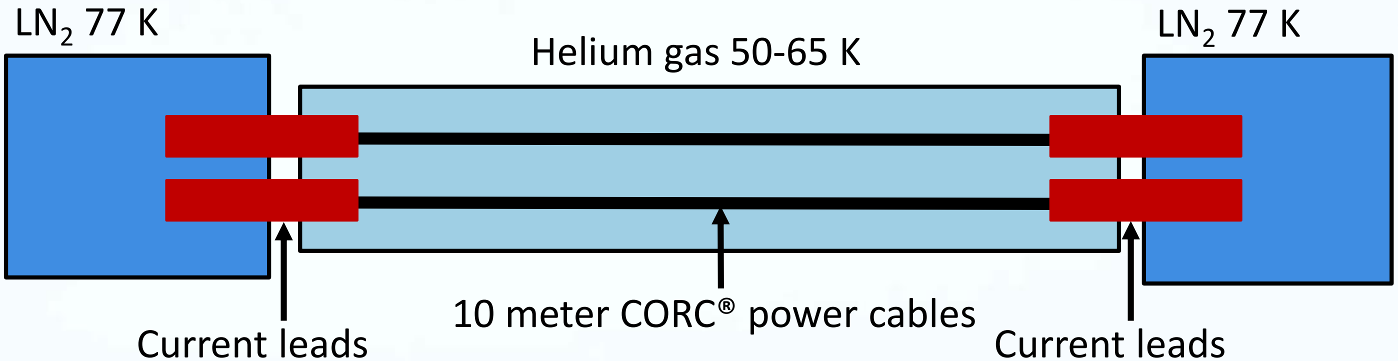
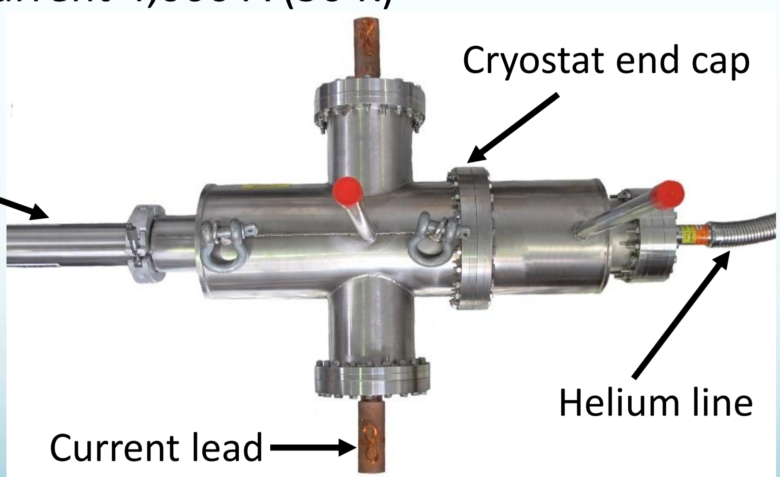
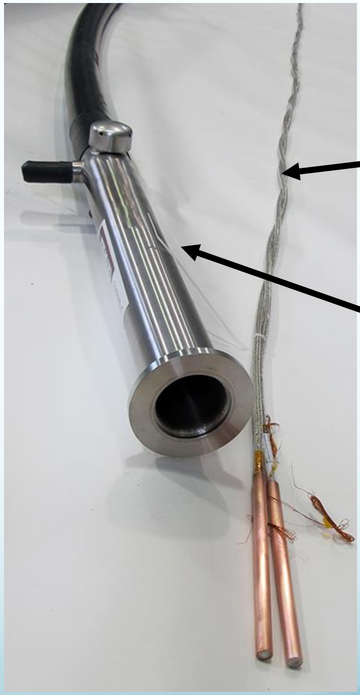
10-Meter 2-Pole CORC® Power System



Goal

- 2-Pole dc CORC® power transmission cable
- Including all cryogenic hardware
- 10 meter long twisted pair cable layout
- Operating current 4,000 A (50 K)





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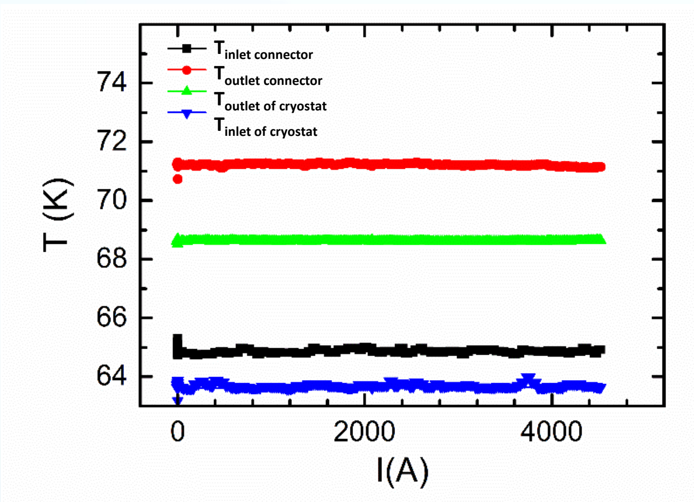
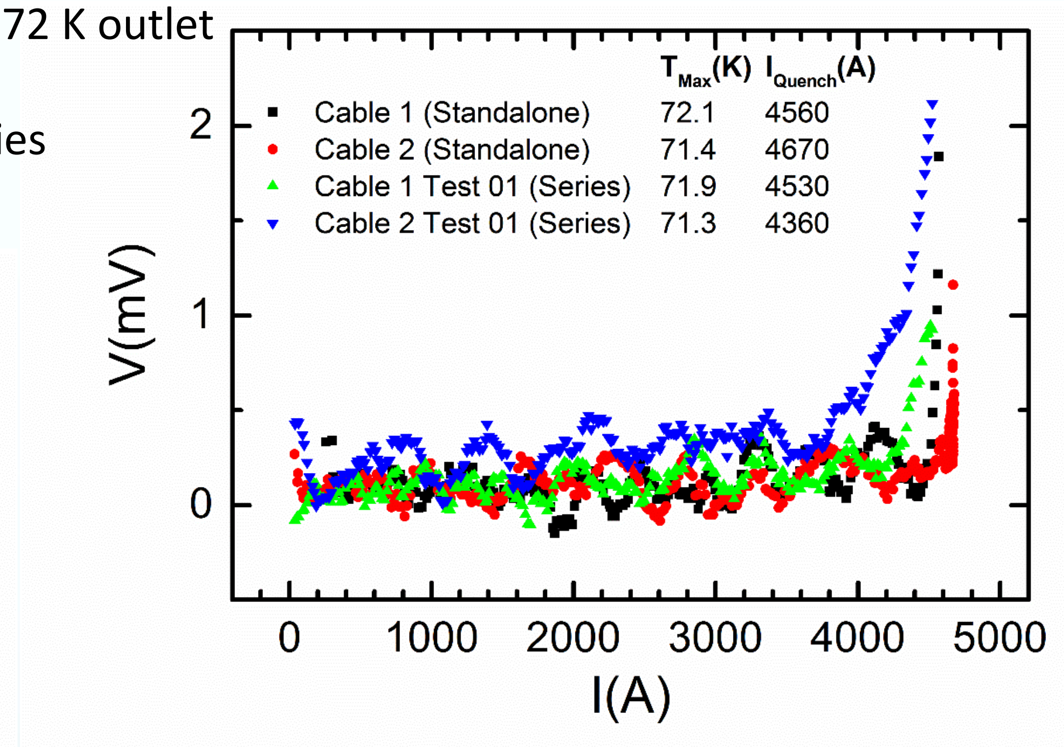
10-Meter 2-Pole CORC® System Test

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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Conclusions

- **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**
- **Successfully demonstrated a hybrid CORC® FCL system with 10 V/m after 5 ms**
- **ACT is also equipped to develop robust power transmission systems**