# Fault Current Limiting CORC® Distribution Cables

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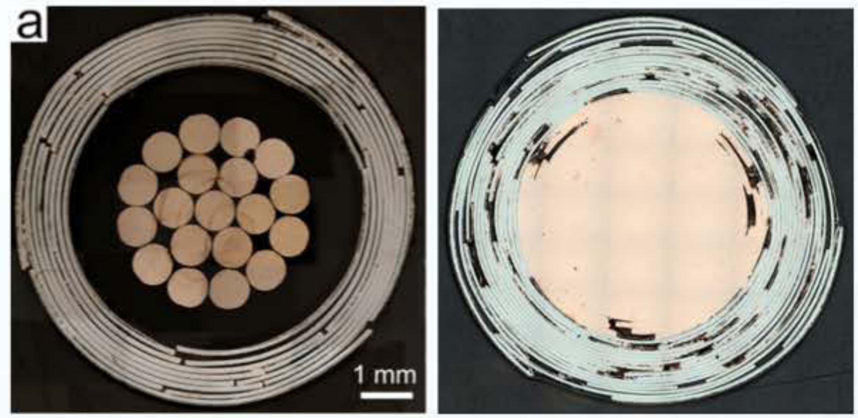
# Conductor on Round Core (CORC®) technology

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

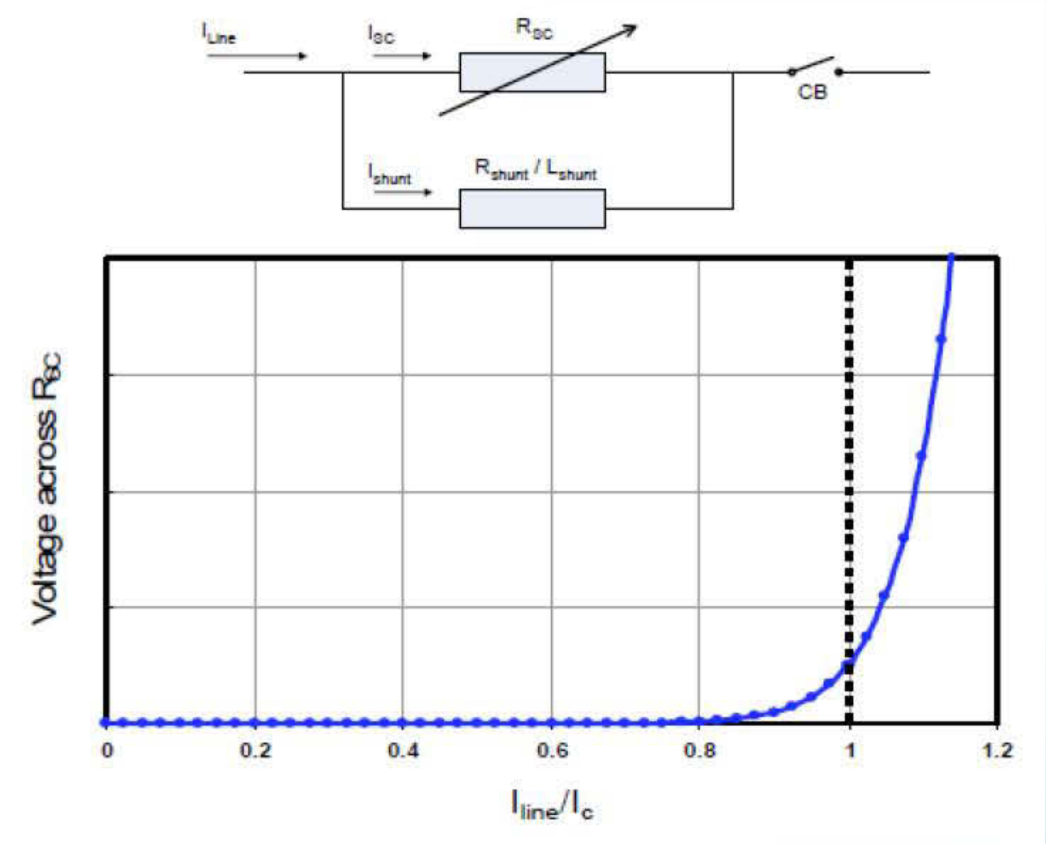




**Benefits**

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

# 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.



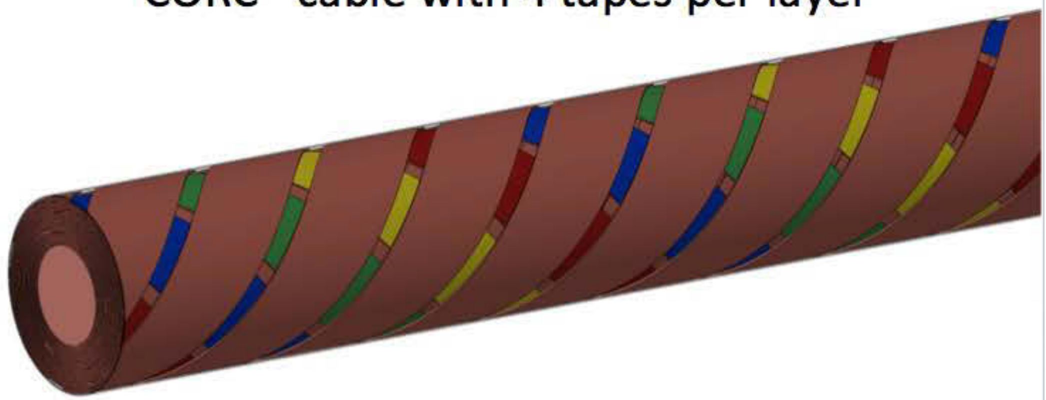

EPRI, 2009

# 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

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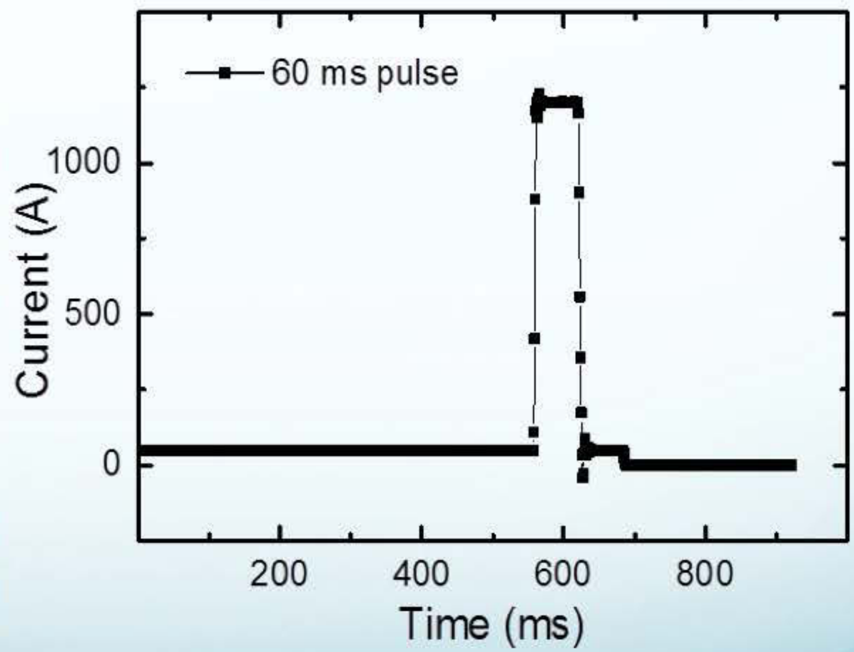
# ACT's FCL Overcurrent Test Facility

**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® cable designs

## SuperPower tape chosen for CORC® FCL wires

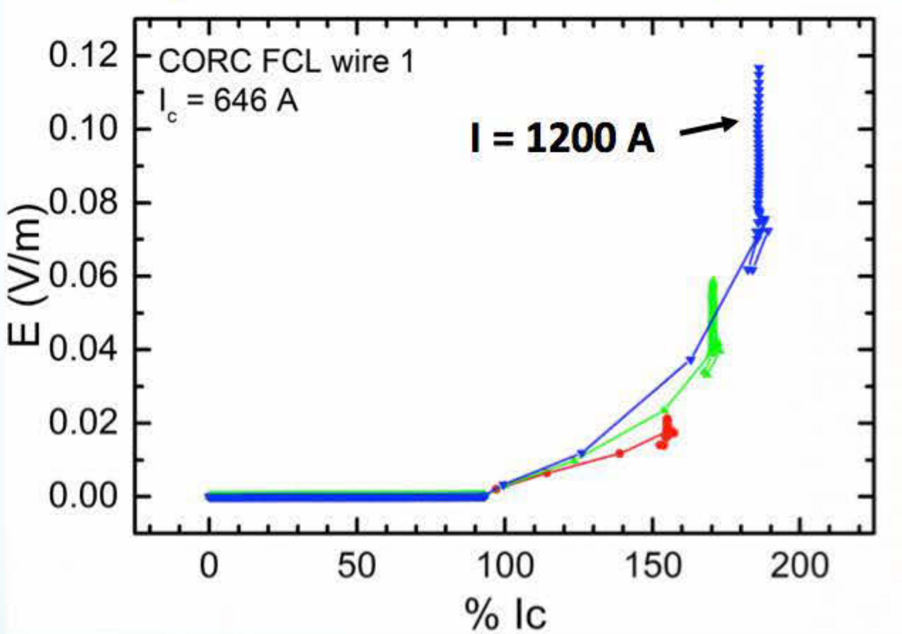
| Sample name | $I_c$ at 76 K (A) | $J_c$ at 76 K (A/ $mm^2$) | Total wire diameter (mm) |
|---|---|---|---|
| CORC FCL wire 1 | 646 | 80 | 3.2 |
| CORC FCL wire 2 | 1124 | 99 | 3.8 |

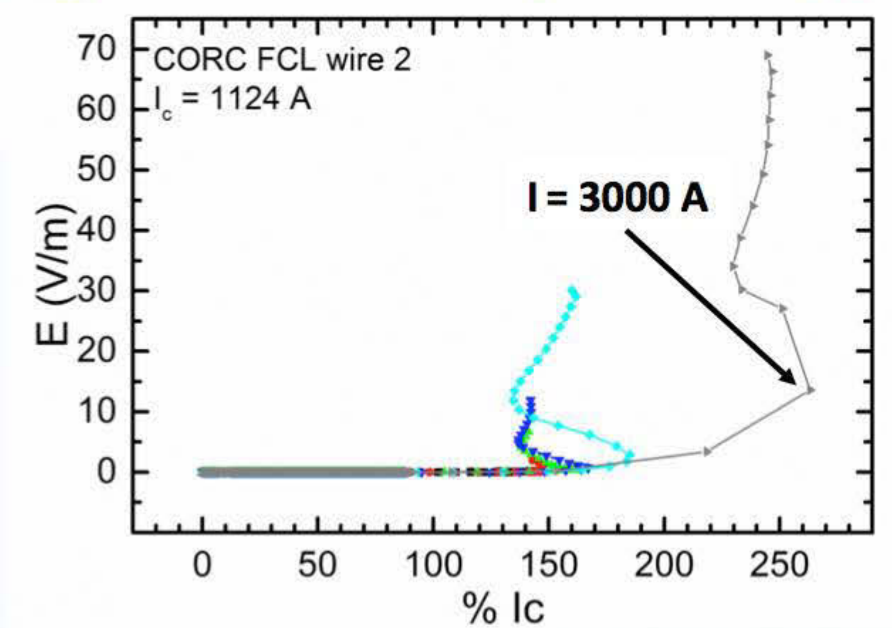
## Key features

- 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 “Franken-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.**

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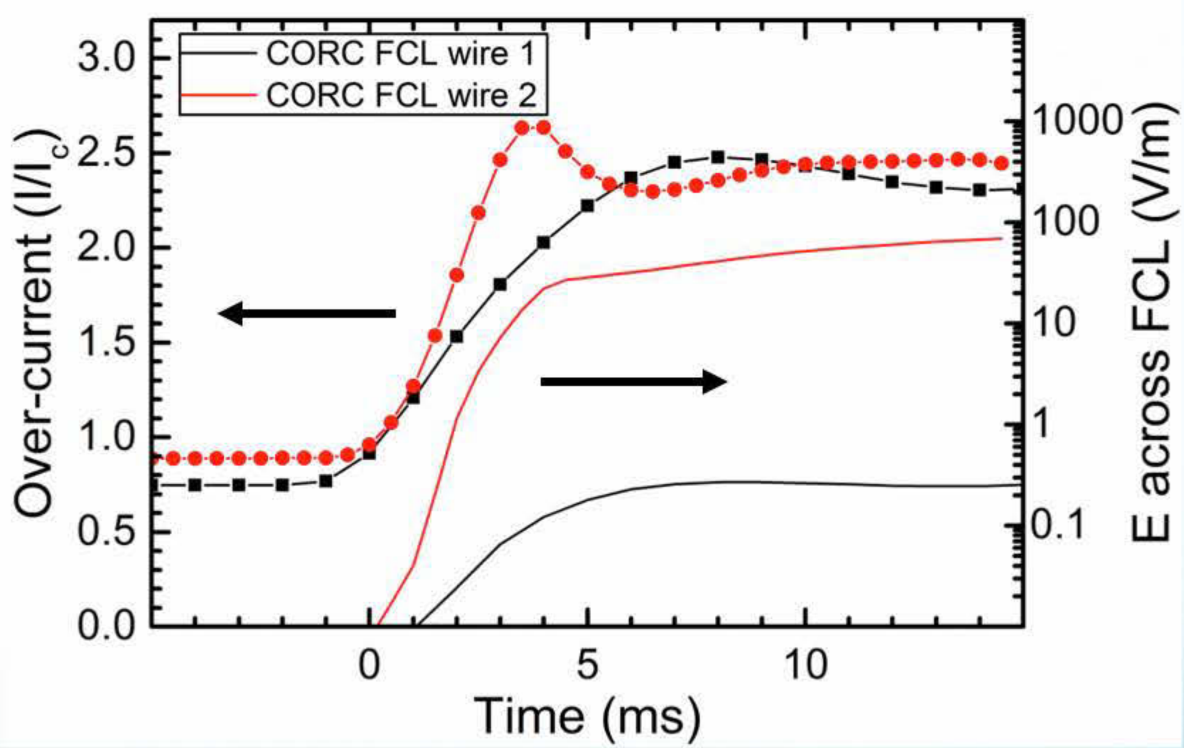
# Overcurrent testing of CORC® FCL wires in nitrogen

**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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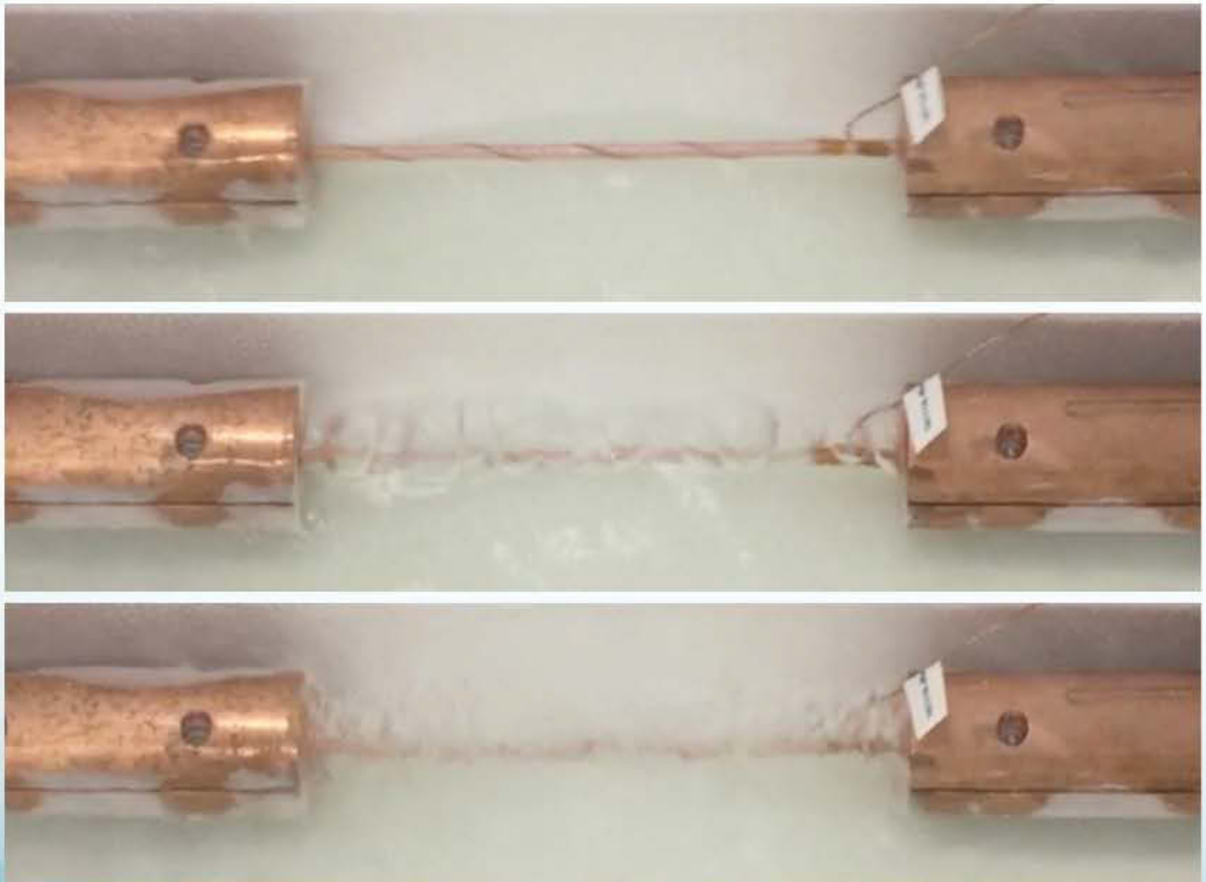
# Overcurrent testing of CORC® FCL wires in nitrogen

**Rapid boiling across entire wire section is observed during overcurrent tests**



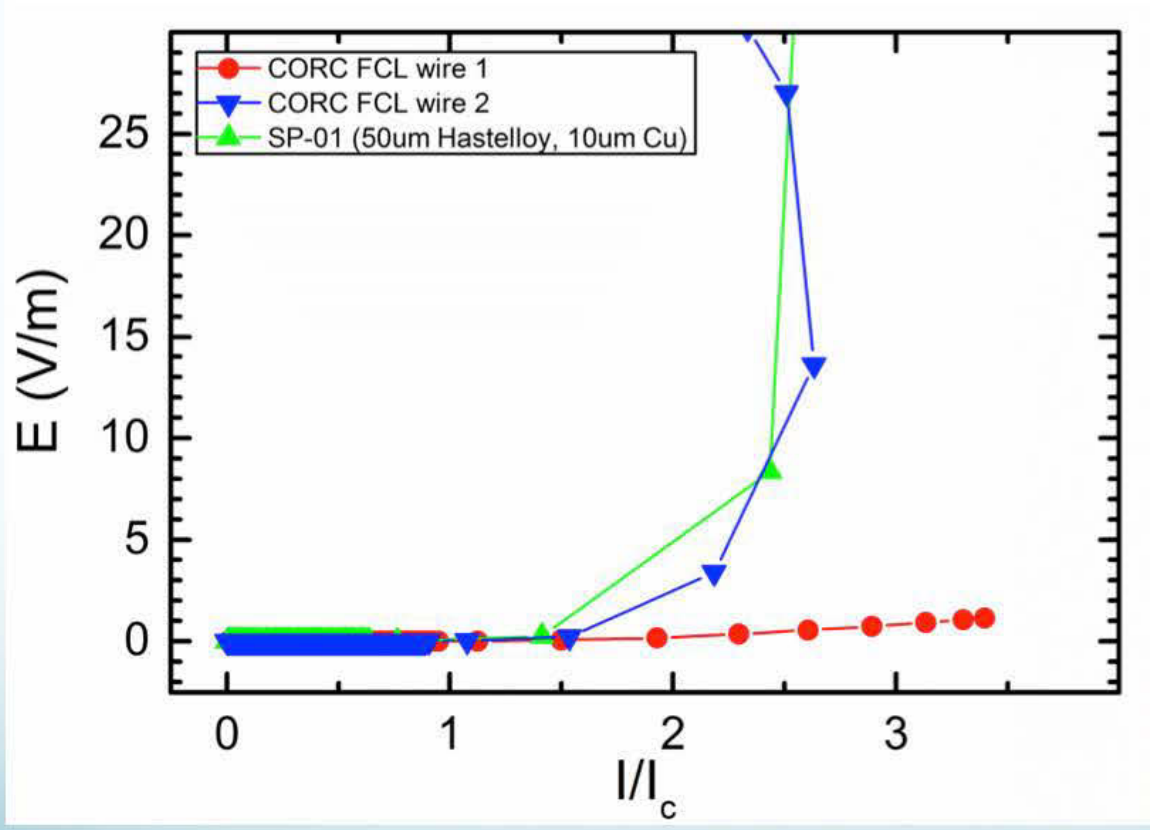
**High speed movie captures the quench that occurs uniformly across the wire**

**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**

# 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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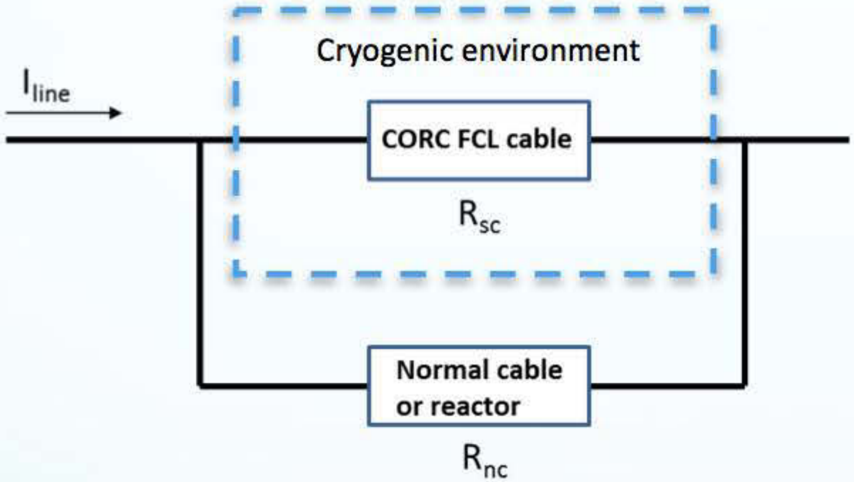
# Overcurrent testing of a hybrid CORC® FCL system

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

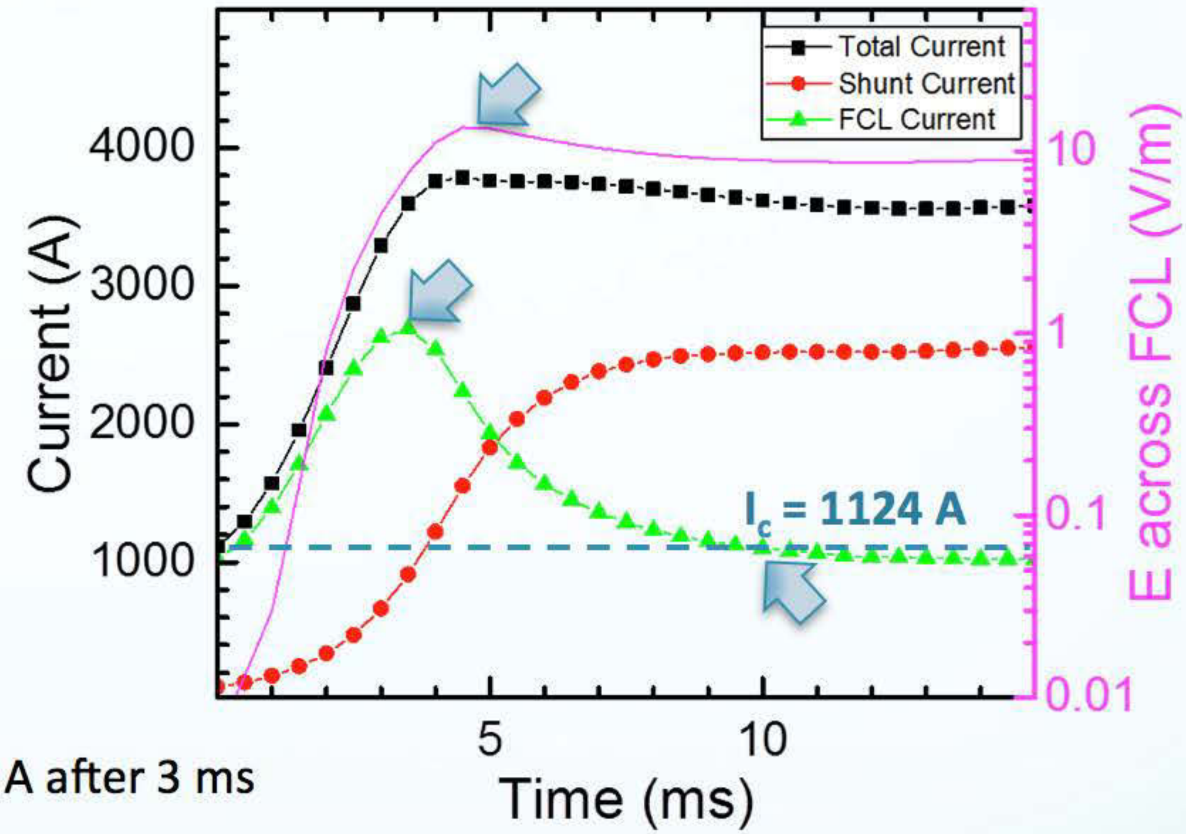
## Schematic of experimental setup




## 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

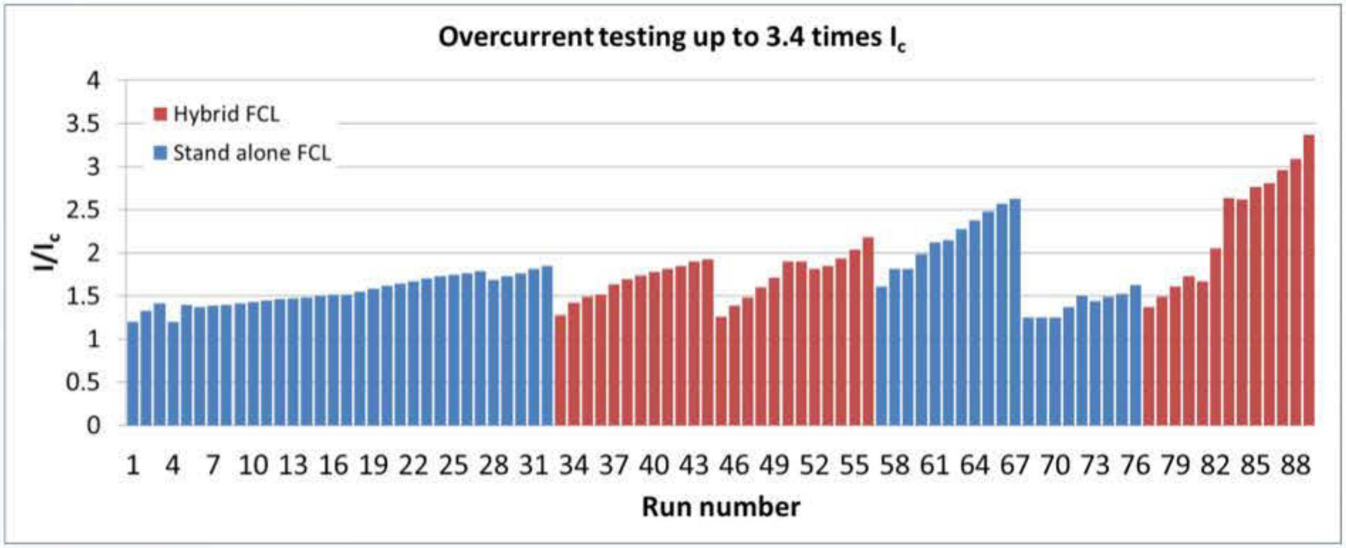



**Fault overcurrent of 320% $I_c$**

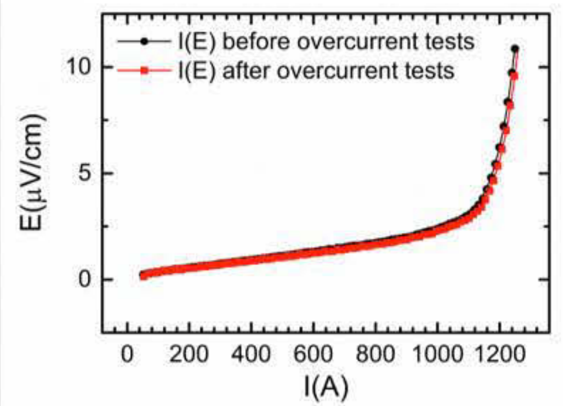
- Peak current in FCL wire 2,700 A after 3 ms
- FCL voltage 10 V/m after 5 ms
- Current in FCL wire back below $I_c$ after 10 ms, while maintaining ~10 V/m over hybrid cable system
- Constant voltage suggests CORC® wire remains at constant temperature, although dissipation at ~10 kW/m
- Rapid cool down 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 "Franken-wire"
  - Critical currents that varied between 56 and 81 A because they were from 5 different batches and slit from various locations
- Franken-wire is still alive!

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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**

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