Development of high-temperature superconducting CORC® power transmission cable systems

Danko van der Laan and Jeremy Weiss
Advanced Conductor Technologies & University of Colorado,
Boulder, Colorado, USA

Chul Kim and Sastry Pamidi
Center for Advanced Power Systems, Florida State University,
Tallahassee, USA

Lukas Graber
Georgia Institute of Technology,
Georgia, USA

Advanced Conductor Technologies LLC
www.advancedconductor.com

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Outline

- Introduction to CORC® cables and wires
- CORC® power transmission systems cooled with helium gas
- Demonstration of 6 kA CORC® cable at 60 K
- Development of 10 kA/Phase stranded CORC® cables
- Increasing the voltage rating of CORC® cables for use in helium gas
- Summary

CORC® Cables and Wires

CORC® wires (2.5 - 4.5 mm diameter)

- Wound from 2-3 mm wide tapes with 30 μm substrate
- Typically no more than 30 tapes
- Highly flexible with bending down to <50 mm diameter

CORC® cable (5 - 8 mm diameter)

- Wound from 3-4 mm wide tapes with 30 or 50 μm substrate
- Typically no more than 50 tapes
- Flexible with bending down to >100 mm diameter

CORC®-CICC

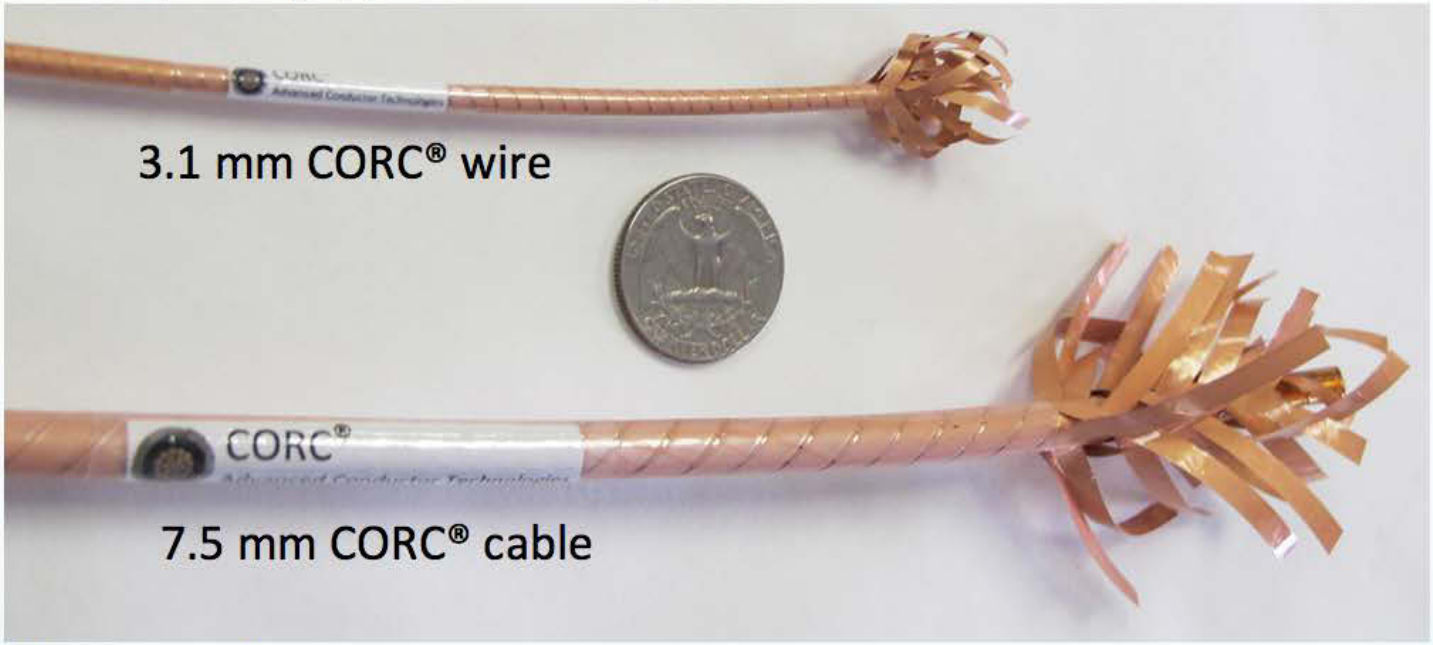
- Performance up to 100,000 A (4.2 K, 20 T)
- Combination of multiple CORC® cables or wires
- Bending diameter about 1 meter

Courtesy Tim Mulder (CERN/Univ. Twente)

CORC® Cable and Wire Performance

CORC® cable example

- 7.5 mm diameter cable 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® wire example

- 3.6 mm diameter cable 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

Power Transmission in Confined Spaces

Applications that need power transmission of 1 – 100 MW

- Navy ships
- Data centers
- Electric aircraft

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

Gaseous helium-cooled CORC® cables and wires

1. **Operating current of 4,000 A and voltage of 0.5 - 1 kV: 2 – 4 MW**
    - **A. 1.5 meter long 1-pole DC power system**
    - **B. 10 meter long 2-pole DC power system**
2. Operating current of 10,000 A and 0.5 – 1 kV: 5 – 10 MW
3. Increase voltage rating to 12 kV to reach 120 MW power rating

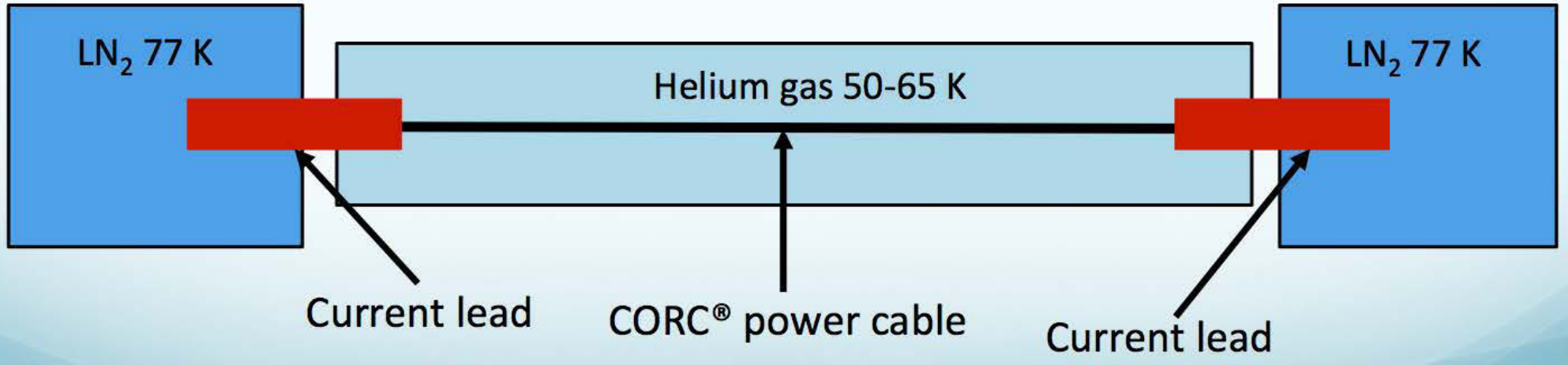
CORC® Power Transmission Cable Systems

System specifications

- 2-Pole dc CORC® power transmission cables rated 4 kA/phase
- Operating temperature 50-60 K in helium gas
- Voltage rating 12 kV

Components

- 2-Pole dc CORC® power transmission cable
- Current leads to bridge 77 K to 50 K
- 10 meter long cryostat and interface with current leads
- Dielectrics for all helium gas facing components



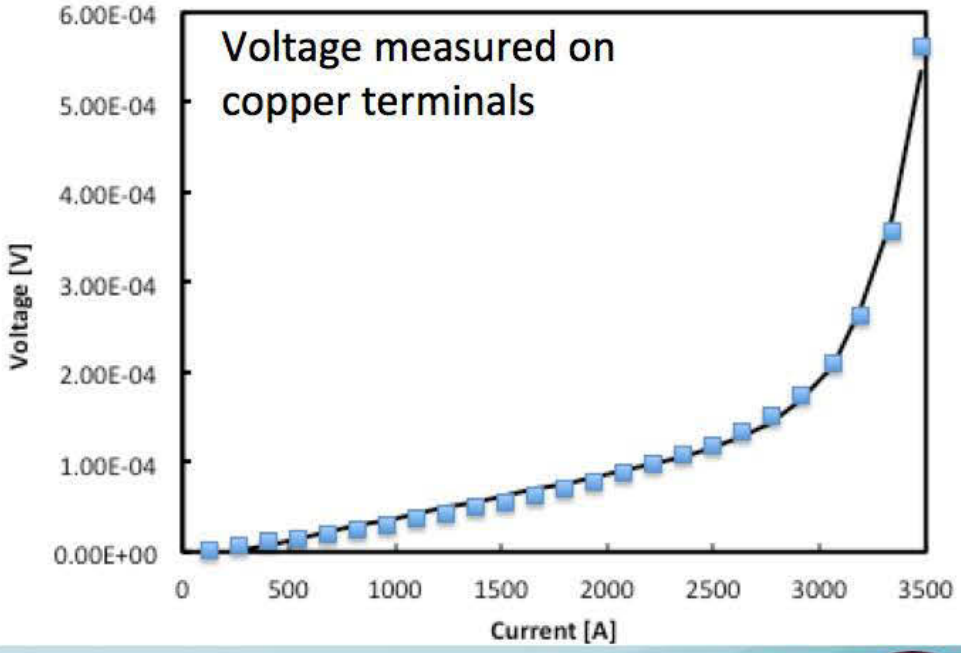
CORC® Power transmission Cable and Terminations

CORC® cables wound by machine

- Designed with I_c to exceed 2,400 A at 77 K
- Expected I_c at 50 K > 10,000 A

CORC® cable terminations

- Capable of injecting large currents
- Low contact resistance < 25 nΩ



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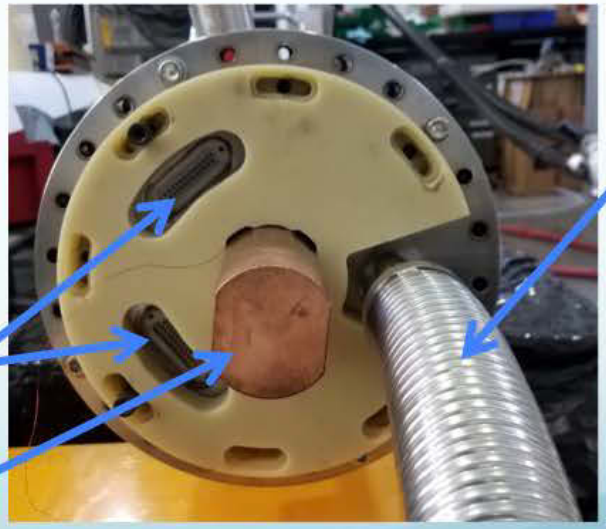
CORC® Power Transmission Cable Test at 60 K

Short cable testing at CAPS

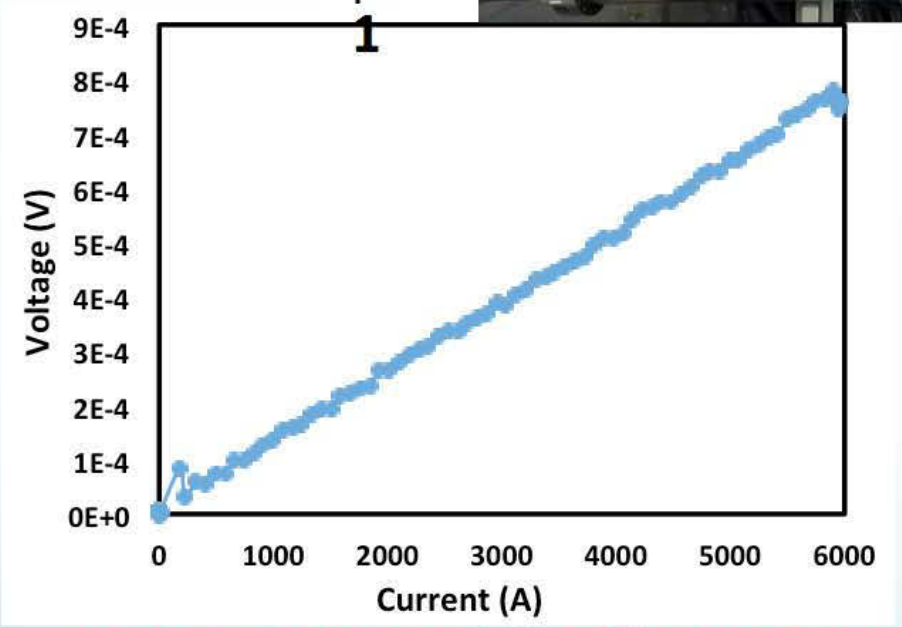
- 1.5 meter rigid cryostat
- 20 bar maximum helium gas pressure
- Maximum flow rate 8-10 g/s

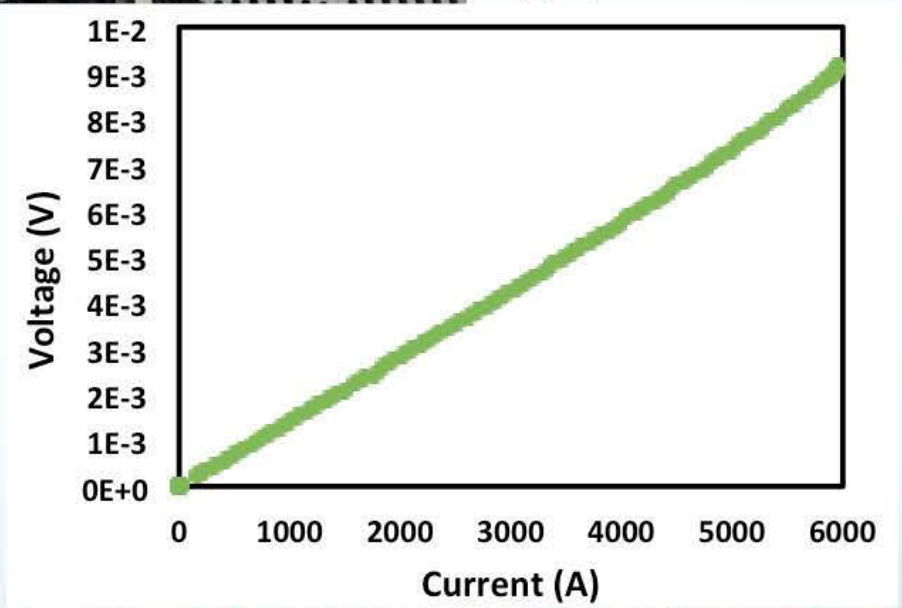
Cable with current leads installed in cryostat

- Each feeder is equipped with 2 temperature sensors and 17 voltage taps
- Indium inserted between power cable and current lead



CORC® Cable System Contact Resistances 60 K





- **Contact resistance inlet side: 0.125 µΩ**
- **Dissipation at 6,000 A: 4.5 W**

- **Contact resistance outlet side: 1.46 µΩ**
- **Dissipation at 6,000 A: 52.5 W**
- **Due to connection between power cable and current lead**

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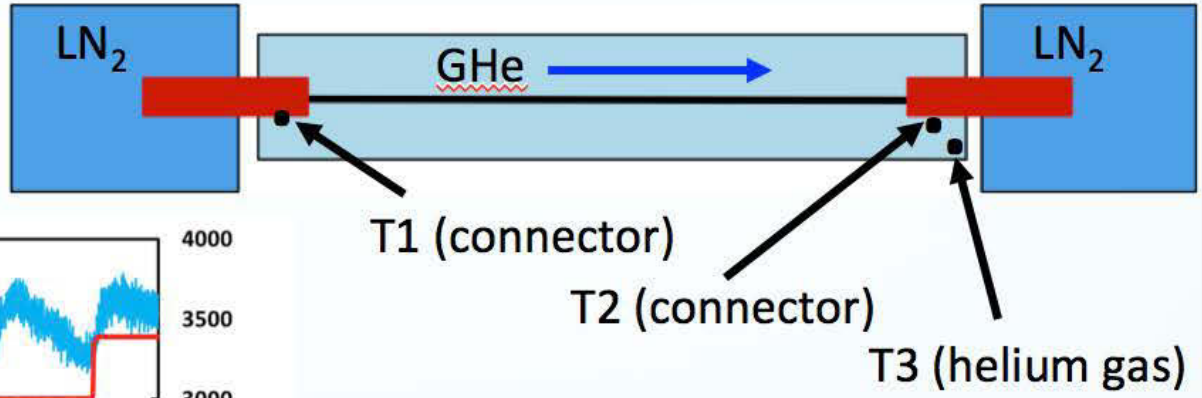
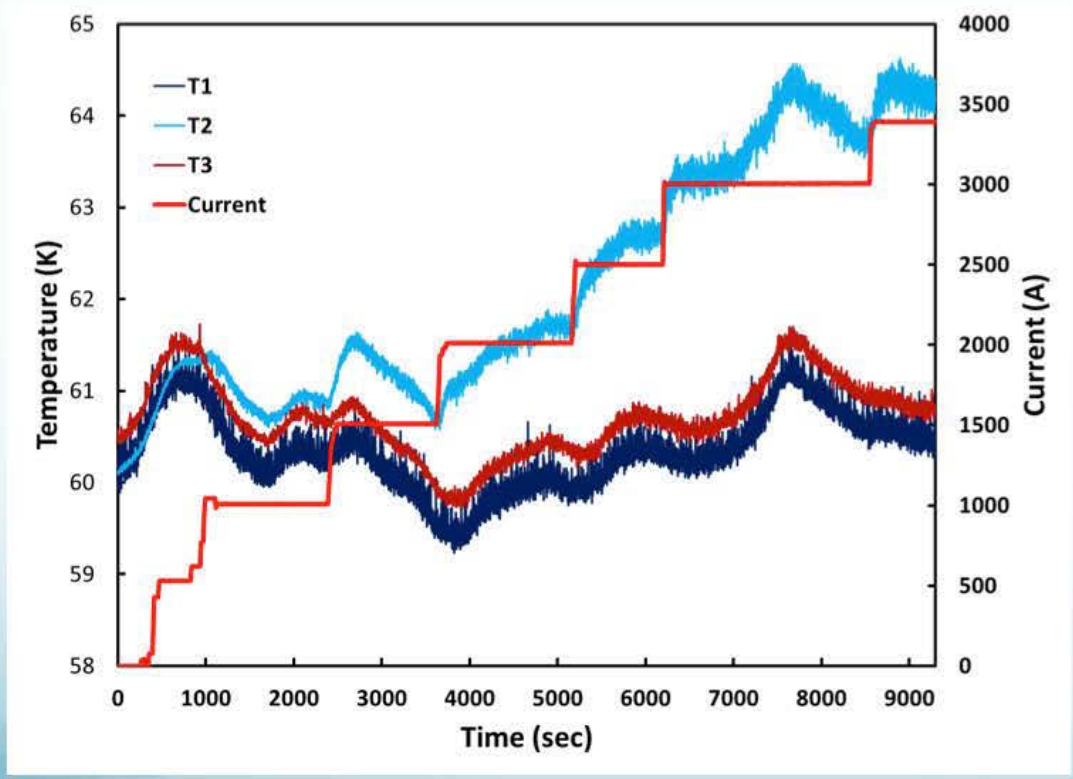
CORC® System Temperature to 3,300 A

Helium gas inlet temperature 60 K

- Current ramped stepwise with 500 A every 20 minutes
- Maximum current of 3,300 A
- Total time at current 2.5 hours
- Helium flow is 5 g/s at 60 K





- **Temperature stable within 0.5 K**
- **Connector at outlet heats up at currents exceeding 1,000 A**
- **Connector will be closed better in final cryostat**
- **Current limited to 3,300 A due to copper cables to power supply**

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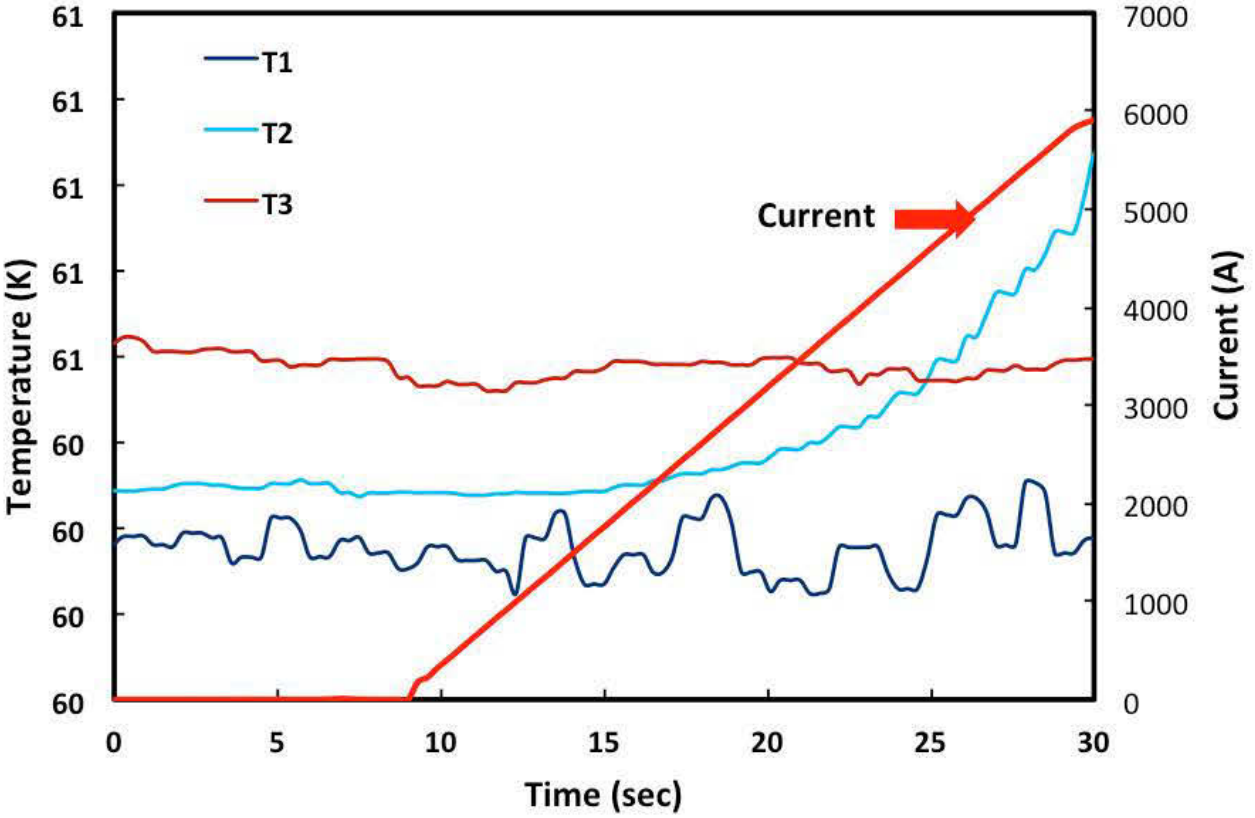
CORC® System Temperature to 6,000 A

Continuous current ramp rate at 60 K inlet temperature

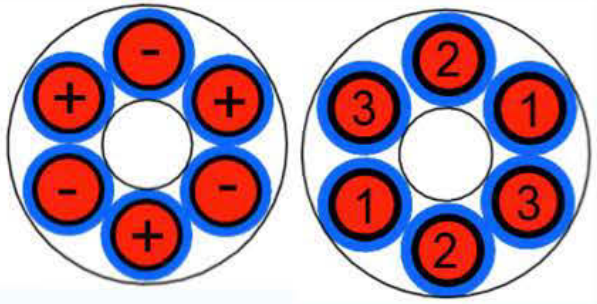
- Current ramped at 300 A/s to 6,000 A
- Temperature of all components (except connector 2) within 60-61 K
- Temperature at connector 2 increased once current exceeded 1,500 A



Increasing the Current rating of CORC® Power Systems

Multi-strand CORC® power transmission cable

- Bundle of 6 CORC® wires into 2-pole dc, or 3-phase ac cable
- **Goal is a current rating of 10 kA/phase (50 K)**



- 4 mm diameter strands
- 12 mm diameter cable

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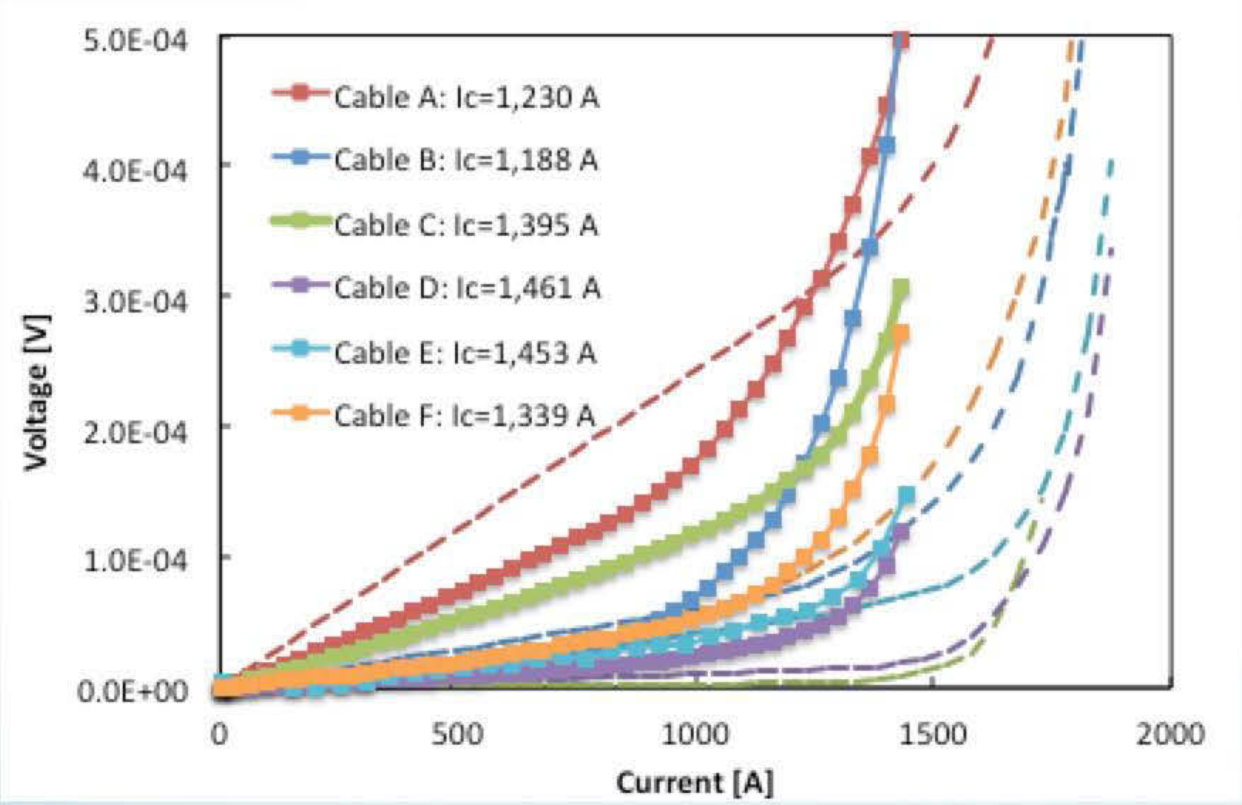
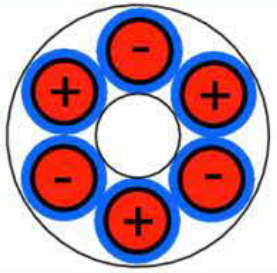
10 kA/Ph. CORC® 2-Pole DC Cable Test

Strands connected as a 2-phase cable

- 10 kA/Ph. operating current at 50 K => I_c(50 K) > 15 kA
- I_c(77 K) > I_c(50 K)/4.4 = 3,400 A





	Ic
A	1230.38
B	1187.58
C	1394.83
D	1460.70
E	1452.95
F	1339.48

I_c(Phase 1) = 4,078 A, I_c(Phase 2) = 3,988 A => I_c(50 K) = 16 kA/Ph.

Self-field of 0.25 T at 3,800 A between strands reduces I_c by 25 % at 76 K

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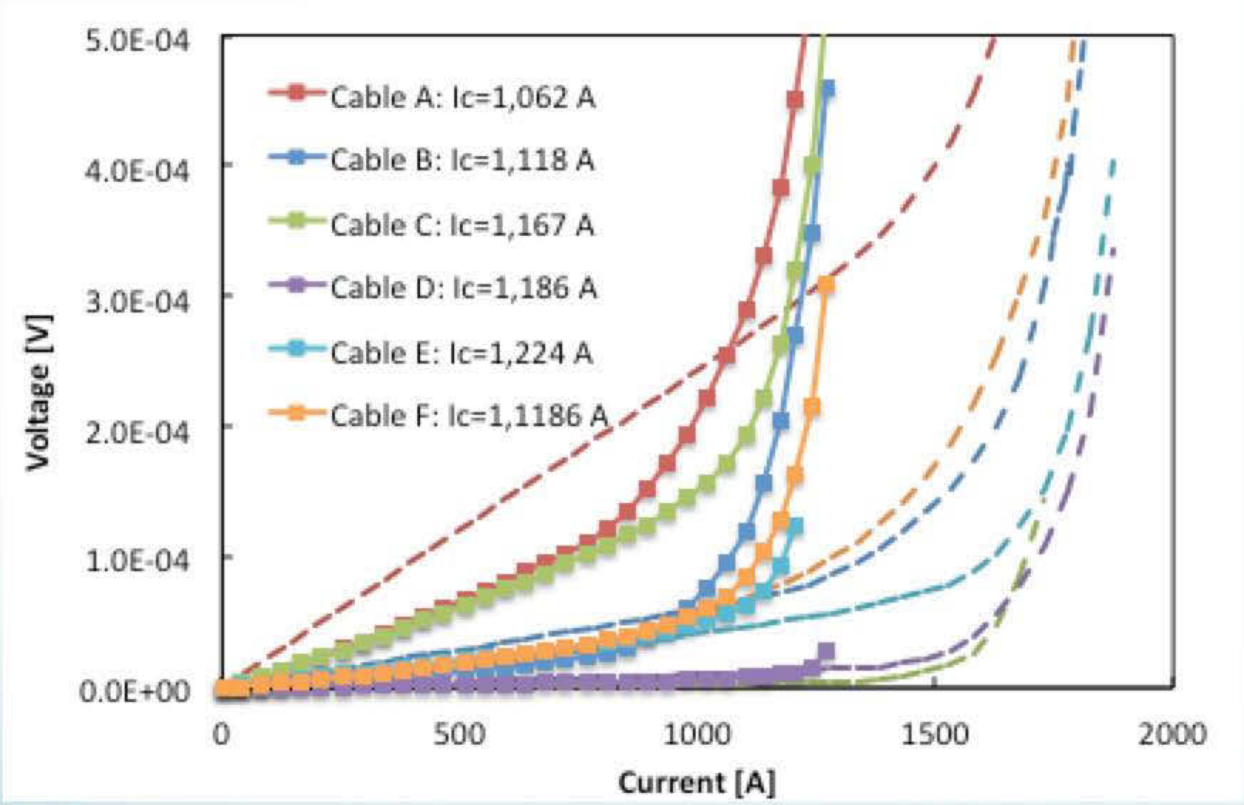
20 kA Single-phase CORC® Cable Test

All strands are connected parallel

- 20 kA single-phase operating current at 50 K => I_c(50 K) > 30 kA
- I_c(77 K) > 6,800 A



	Ic
A	1061.83
B	1118.24
C	1166.79
D	1368.89
E	1223.69
F	1186.05

I_c(76 K) = 7,125 A => I_c(50 K) = 30 kA

Self-field of 0.25 T at 7,800 A reduces I_c by 30 % at 76 K

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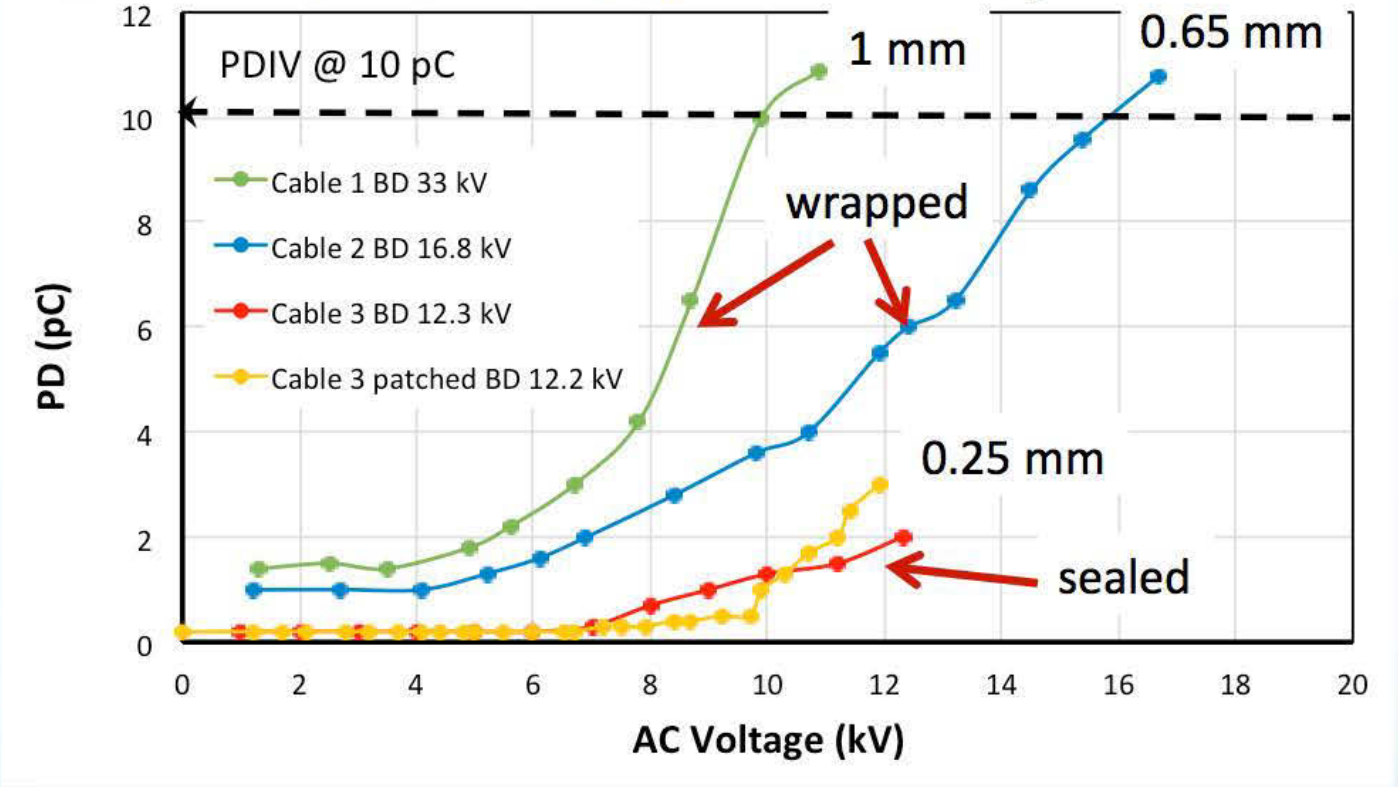
Breakdown Behavior Sealed vs. Wrapped Dielectrics

Partial Discharge (PD) and Break Down (BD)

- measured in 2 MPa helium gas at 77 K
- Investigating wrapped (unsealed) typically used in LN_2 cables and sealed dielectrics



- 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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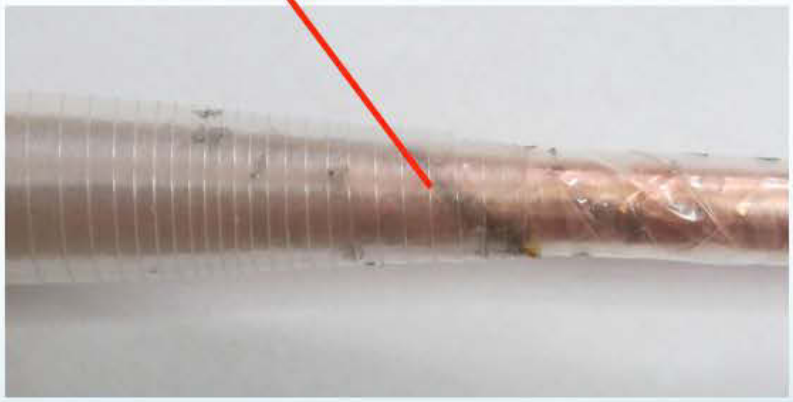
Breakdown of Wrapped Dielectric

Overall results show

- Partial breakdown likely follows paths of helium gas penetration
- High-voltage breakdown depends on insulation thickness

Multiple traces within the stress cones



Focus on sealed dielectrics to increase CORC® cable voltage rating to 12 kV in GHe

Summary

Current rating of CORC® power transmission cables for operation in helium gas

- Demonstrated feasibility of operating CORC® cable system at 4 kA at 60 K in helium gas
- Current leads and connection to cable results in only 0.125 μΩ per side
- Total dissipation at 6 kA of only 9 W in helium gas cryostat possible
- Current rating of 10 kA/phase at 50 K demonstrated in stranded CORC® cables

Voltage rating of CORC® power transmission cables for operation in helium gas

- Voltage rating of 0.5 - 1 kV at 77 K in 2 MPa helium pressure not a problem
- Increasing the voltage rating to 12 kV in the coming years using dielectrics sealed against helium gas penetration

Power rating of CORC® power transmission cables for operation in helium gas

- Current status in 1.5 meter cable system of 4 kA/Phase and 1 kV: 4 MW
- Demonstration of 10 meter long 2-pole dc power transmission system July 2017
- Rating of 10 MW with 10 kA stranded cable possible for 2-pole dc and 3-phase ac cables
- Power rating of 120 MW in coming years when combining 10 kA and 12 kV ratings