Development of high-temperature superconducting CORC® power cables for electrified aviation and naval applications

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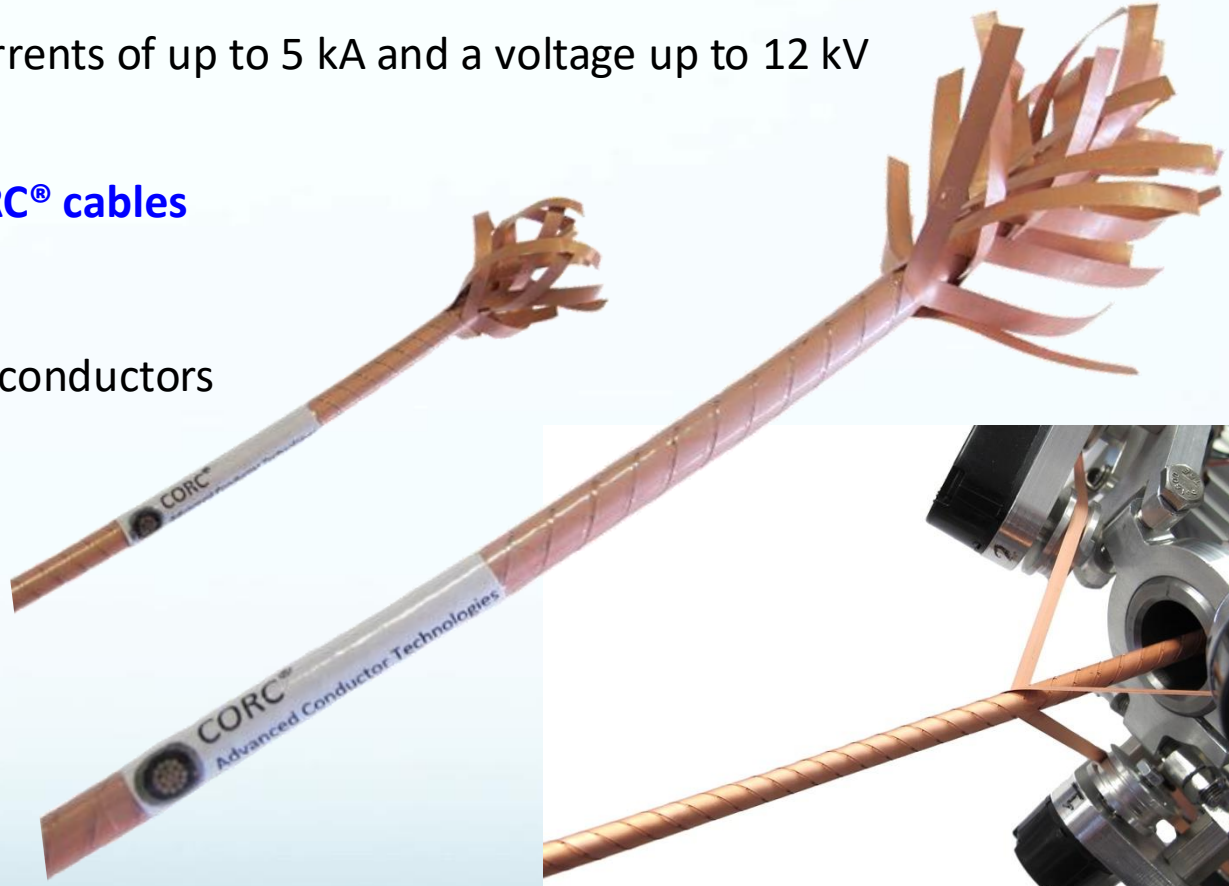
CORC® cables and wires pioneered by Advanced Conductor Technologies

Power cables for Navy ships and electric aircraft

- Require 25 – 50 MW DC power rating requiring currents of up to 5 kA and a voltage up to 12 kV
- Cooled with cryogenic helium gas to 30 – 50 K

Advanced Conductor Technologies is developing CORC® cables and wires for power applications

- Based on REBCO coated conductors
- Offering highly-flexible and isotropically bendable conductors
- High currents at high current densities
- Allowing low-resistance cable joints
- coaxial configurations for AC and DC applications



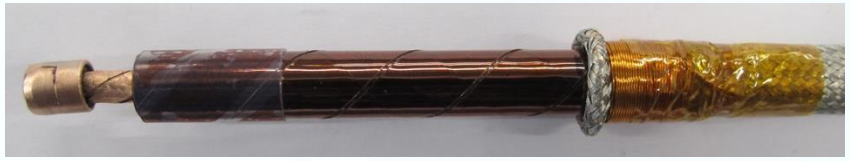
CORC® performance

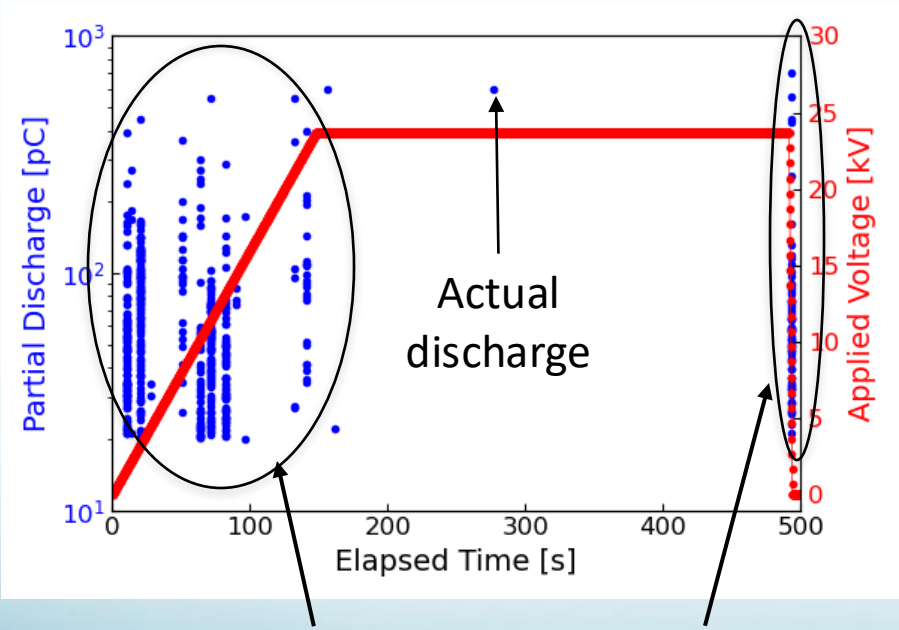
- 3 – 7.5 mm cable diameter (without insulation)
- Bending diameter < 40 – 100 mm
- I_c (77 K) > 4,500 A, I_c (50 K) > 18,000 A
- Voltage rating up to 12 kV DC

Wrapped dielectrics for cryogenic applications in DC-fields

DC electric field performance

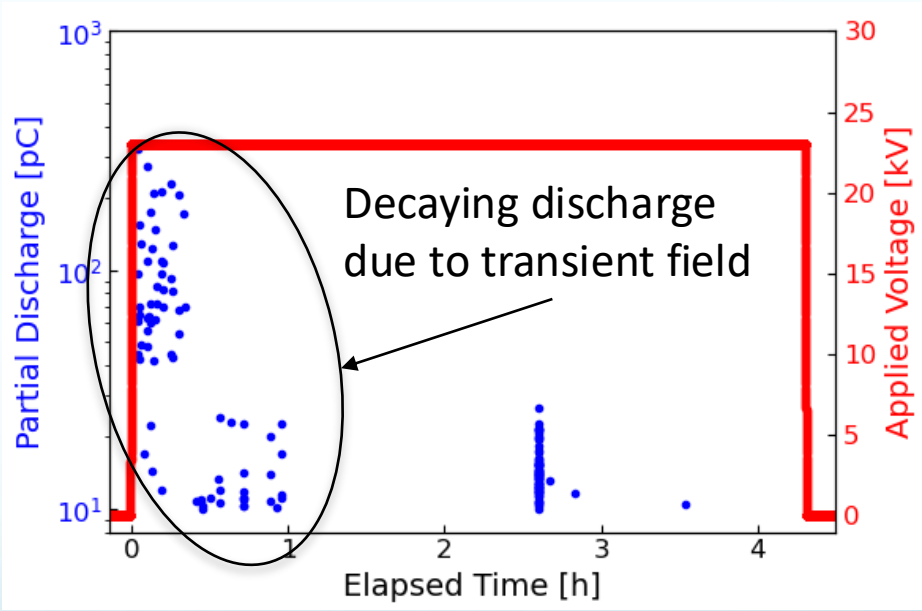
- PDIV and voltage breakdown 2x higher under DC voltages than AC voltages
- Transient voltage decay component observable in PD measurements





77 K, DC PD in vacuum

77 K, DC PD in 2 MPa GHe

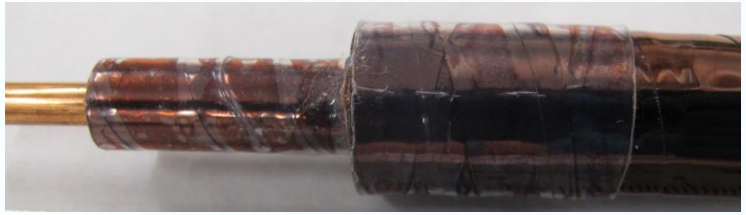


Transient field component time constant ~1-2h

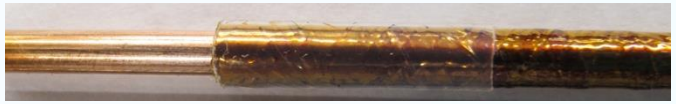
Low voltage wrapped dielectric for cryogenic applications

Lower voltage advantages

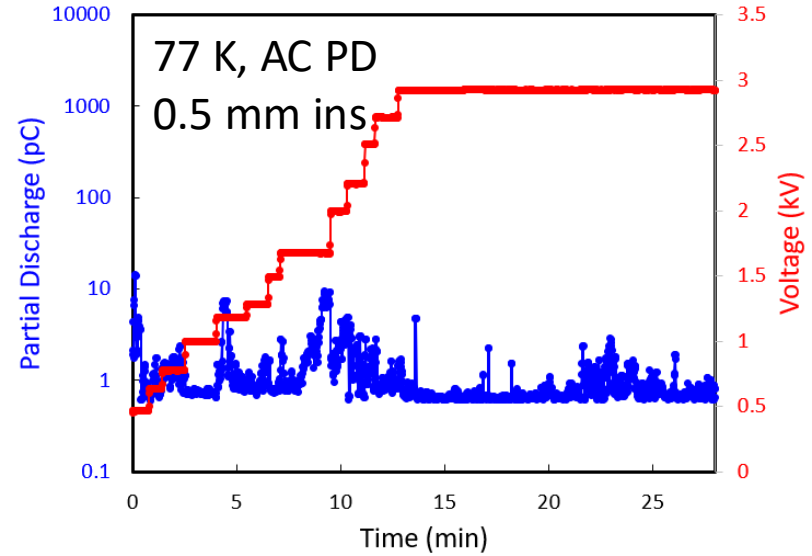
- Electric aircraft much more likely to be operated at lower voltage of 1 kV or below
- Reduced complexity to achieve electric performance
- Reduced size and increased cable flexibility

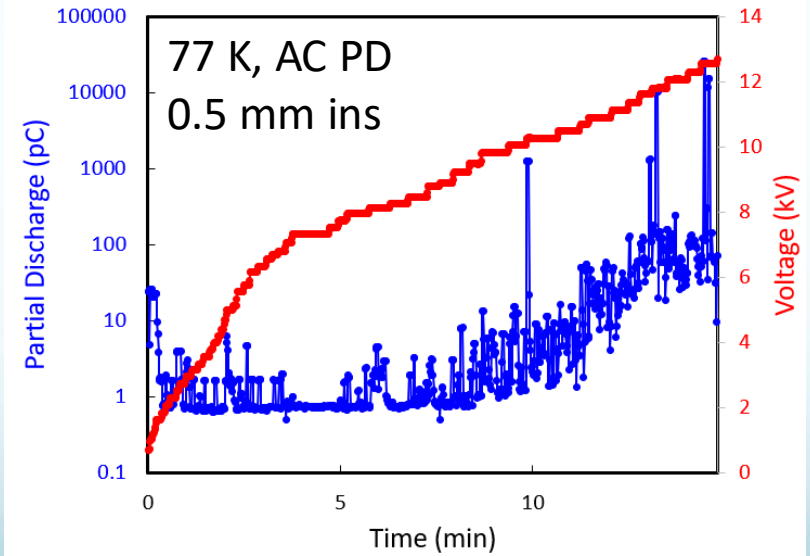


10 kV cable



2-3 kV cable

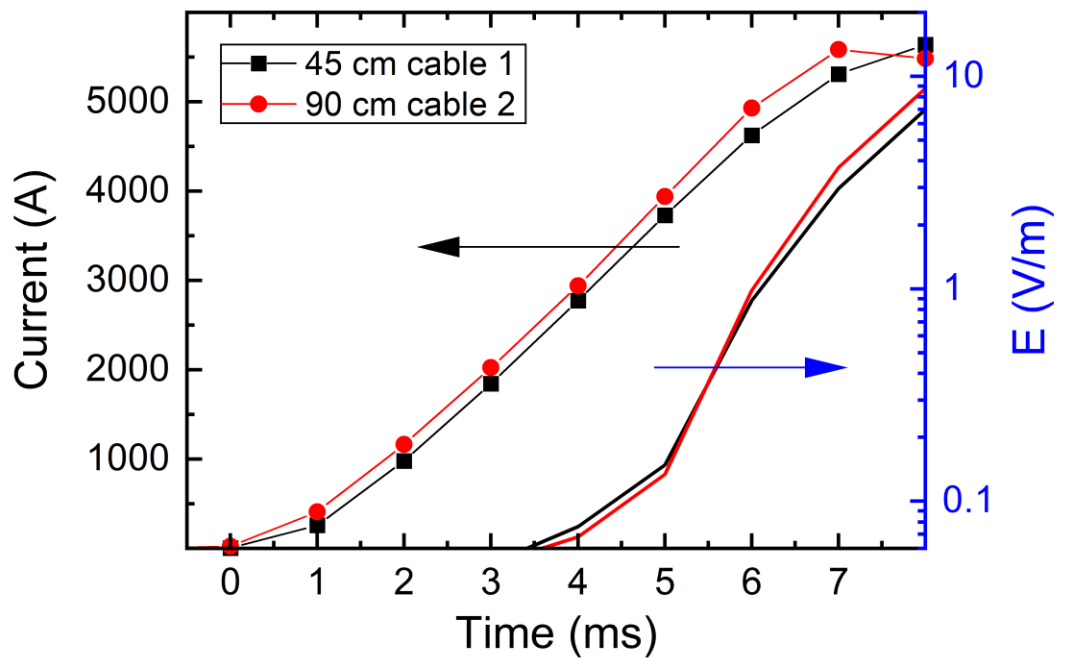




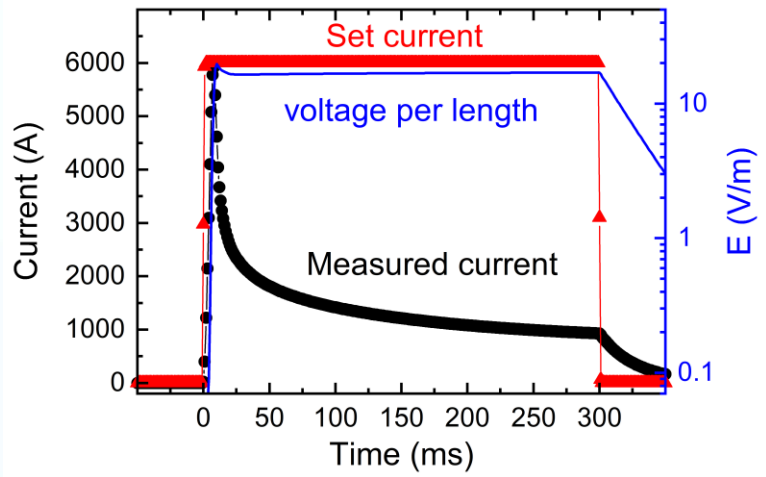
CORC® cable with fault current limiting functionality

Short sample CORC® FCL cable tests at ACT

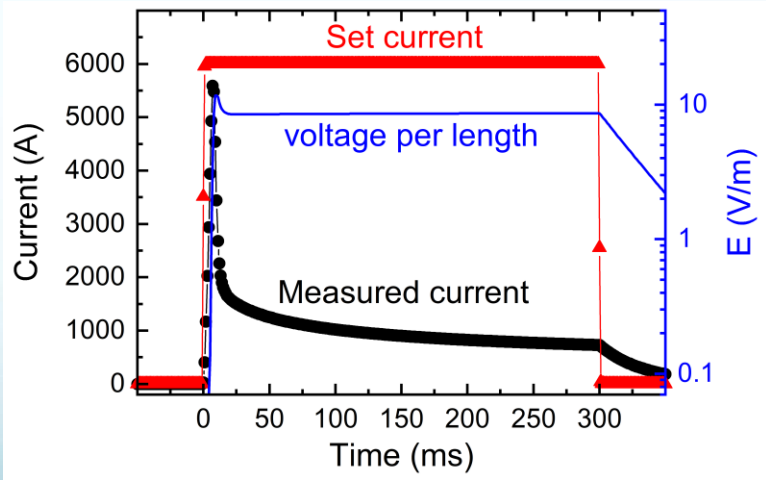
- Single-pole CORC® cable critical current 2.8 kA at 76 K
- Electric field > 7.5 V/m within 5 ms after 6 kA fault starts
- Current limited to less than 2 kA within 7 ms
- No damage to cable even after 300 ms of fault current



0.45 meter CORC® cable



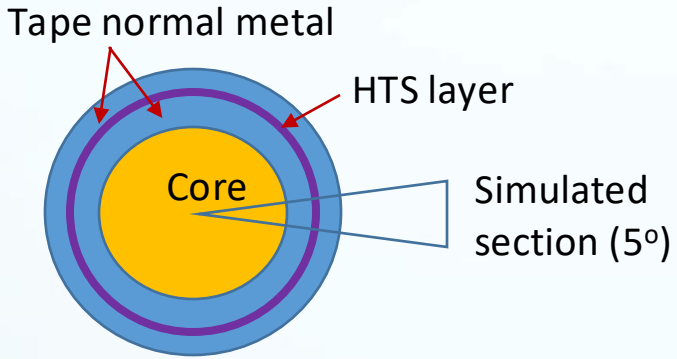
0.9 meter CORC® cable

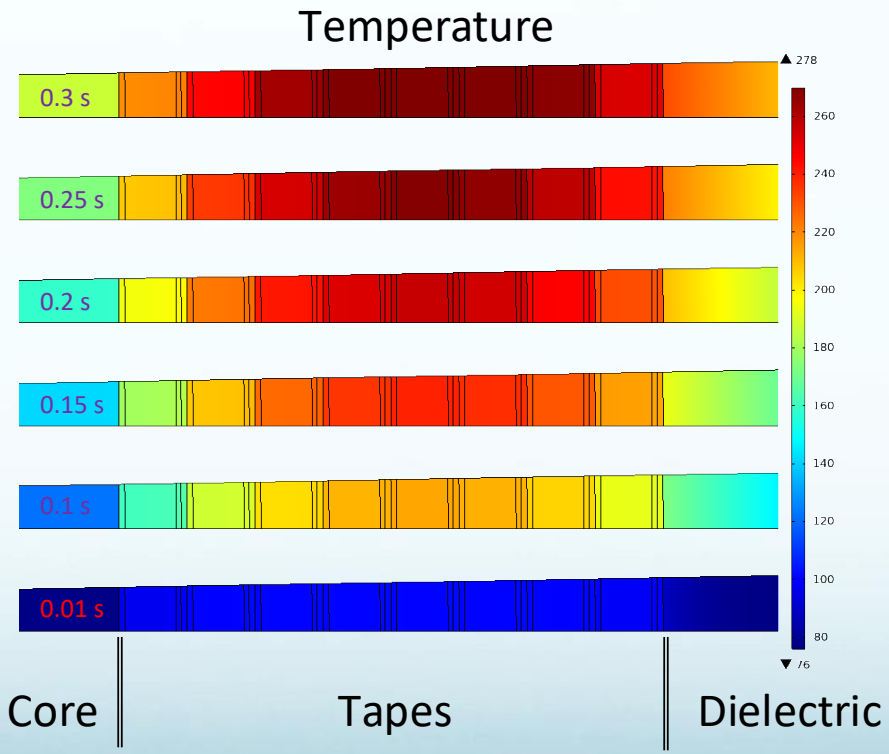


CORC® FCL cable modeling

Modeling details

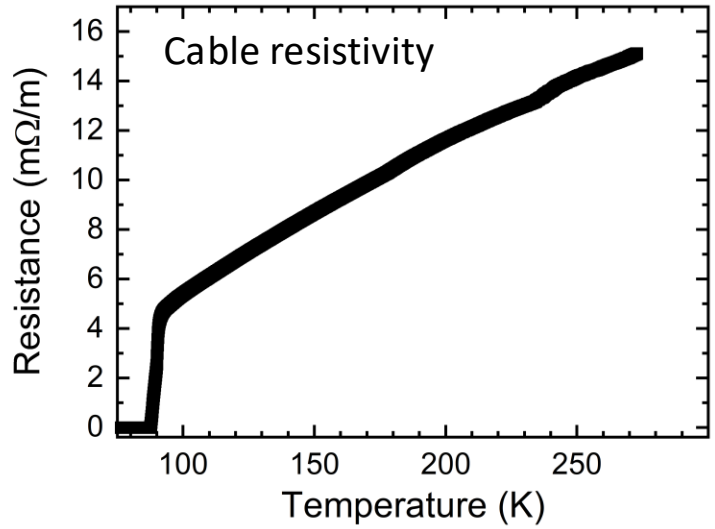
- Simulation is limited to 5° section due to symmetry
- Includes cooling to liquid nitrogen
- Case of a 0.45-meter CORC® FCL cable at 6 kA fault

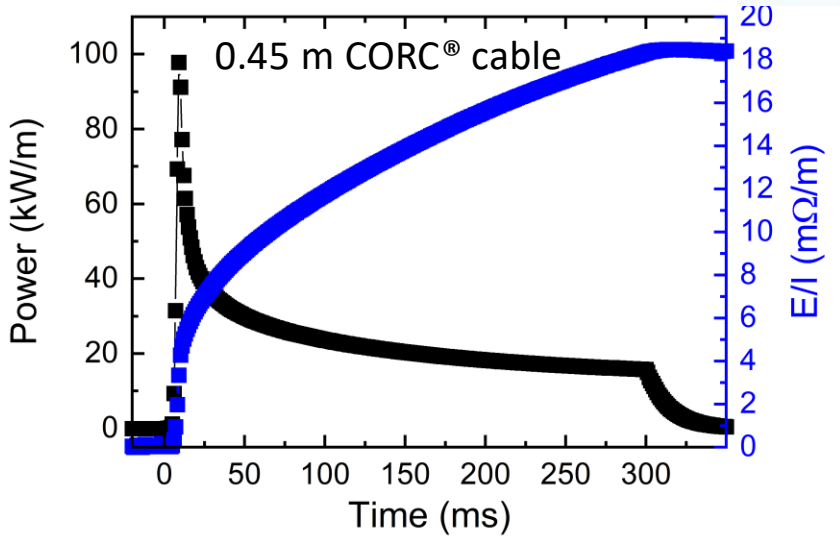




Model results

- Peak temperature of 278 K after 300 ms
- Confirmed by cable resistance measurements





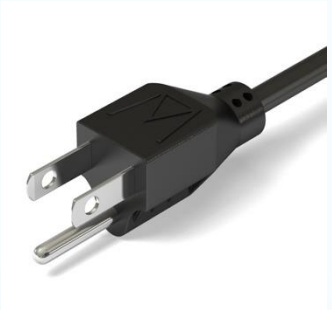
Where cables end

Cables

- Current capacity up to more than 5 kA
- Dielectric insulation rated up to 12 kV

→ 50 MW power rating

- FCL capabilities
- Coaxial configuration
- Central cooling tube



Connectors/ Interfaces

- Current needs to interface to same or different temperature
- Insulation needs to be interrupted without compromising voltage rating
- Instrumentation needs to be interfaced to ambient condition
- Coolant needs to be injected/ extracted

→ **Application specific complex challenges without standard solution**

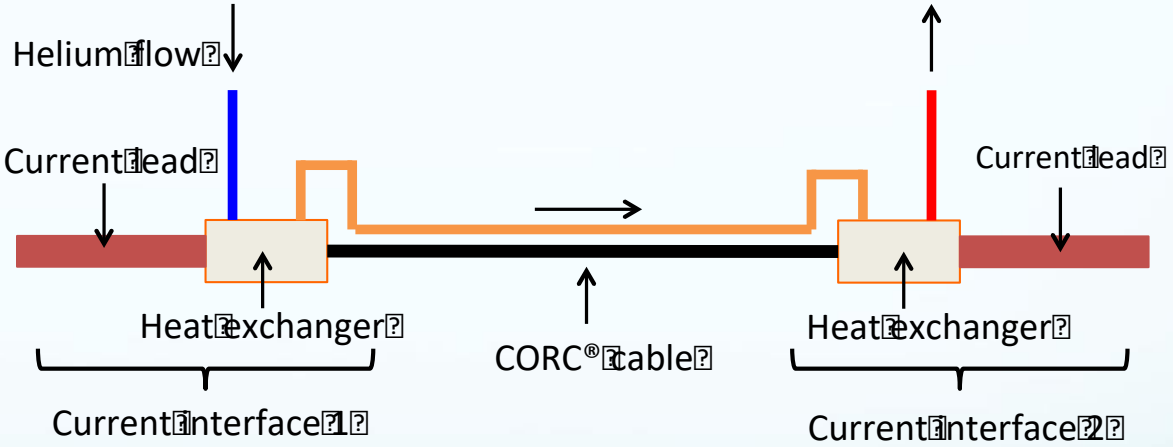
Development of compact CORC® cable terminations with 300 K interface

Development of compact cable terminations

- Develop a compact cable interface between 50 K and ambient temperature
- Current leads with helium gas heat exchangers, removing all needs for LN_2 use
- Allow turn-key, continuous operation of the CORC® power cable system using pressurized helium gas cooling
- Initial design and demonstration using mainly off-the-shelf components

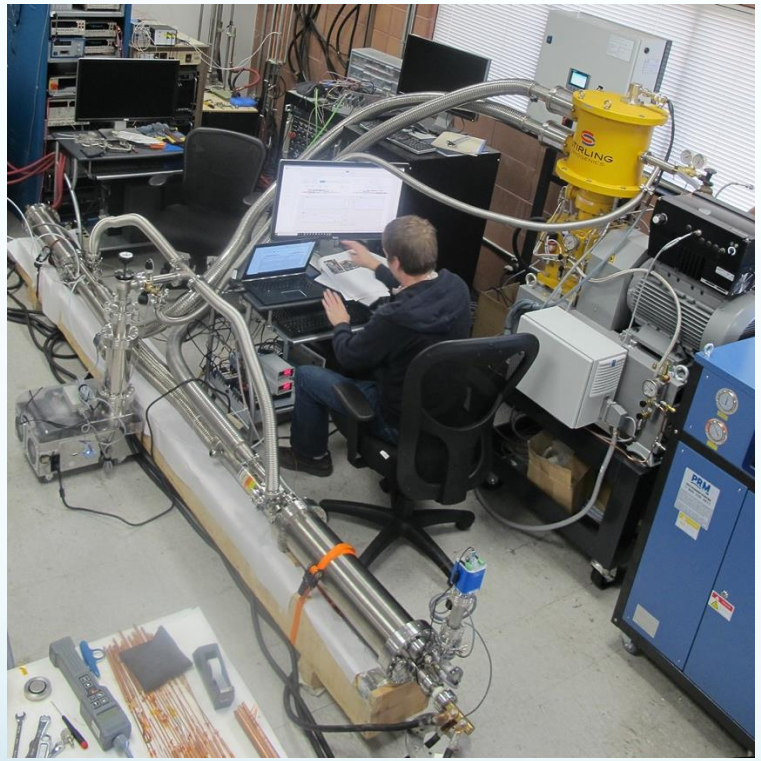
Initial system configuration

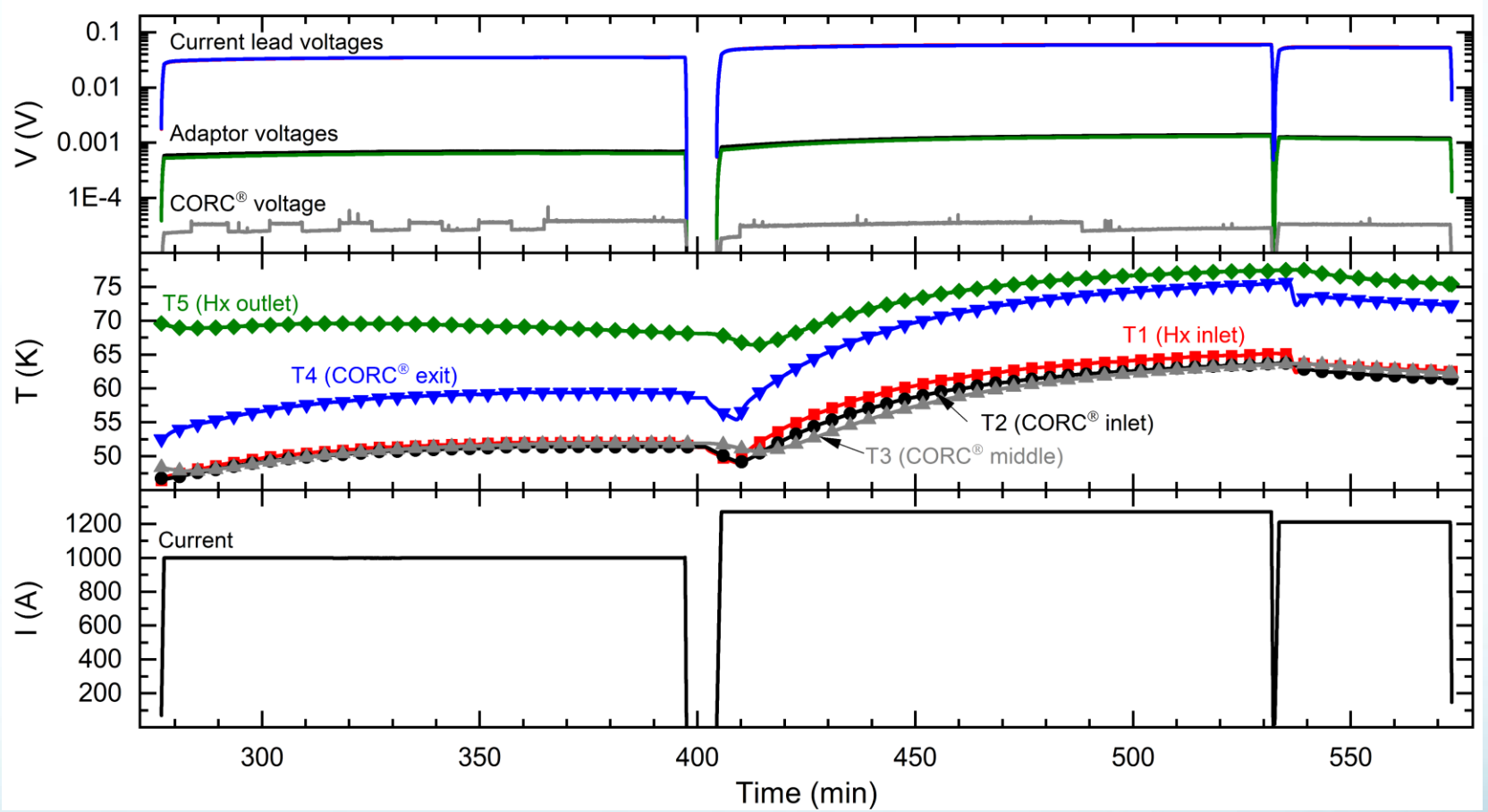
- Single-pole CORC® cable
- Flexible cryostat (2 m)
- Conduction-cooled leads, optimized for 1,200 A



Operation of a turnkey, gaseous helium cooled CORC® dc power cable with integrated current leads,
D.C. van der Laan, C.H. Kim, S. Pamidi, and J.D. Weiss, *Supercond. Sci. Technol.* **35**, 065002 (2022)

Results of GHe cooled CORC® cable with interface to room temperature



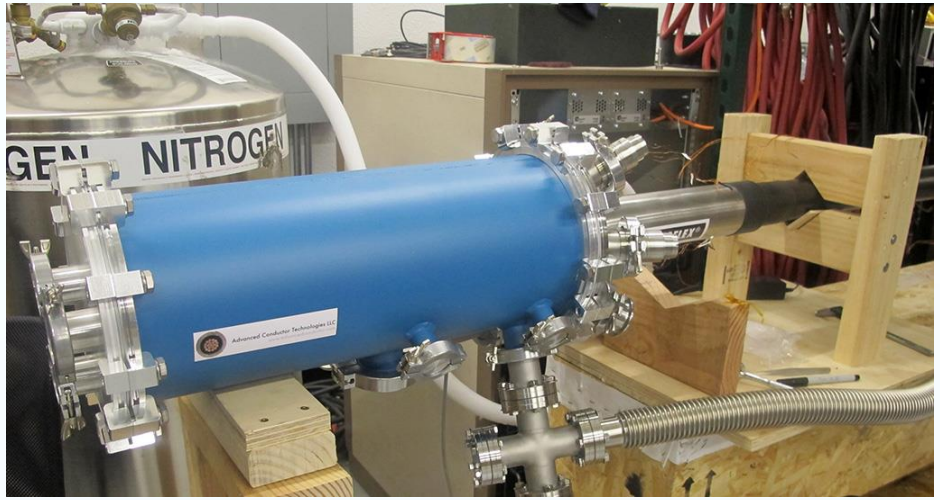


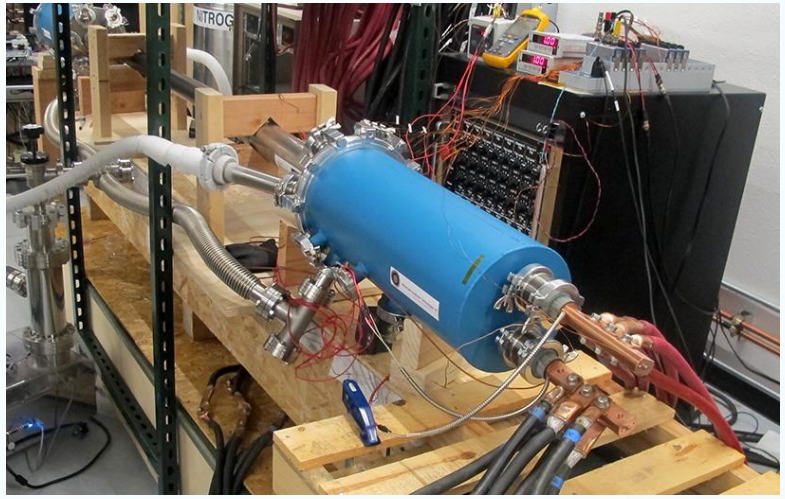
- Cool down from room temperature to operating temperature within 5 hours
- Continuous operation at the rated current of 1,200 A demonstrated

Airbus ASCEND: CORC® DC bus qualification at ACT

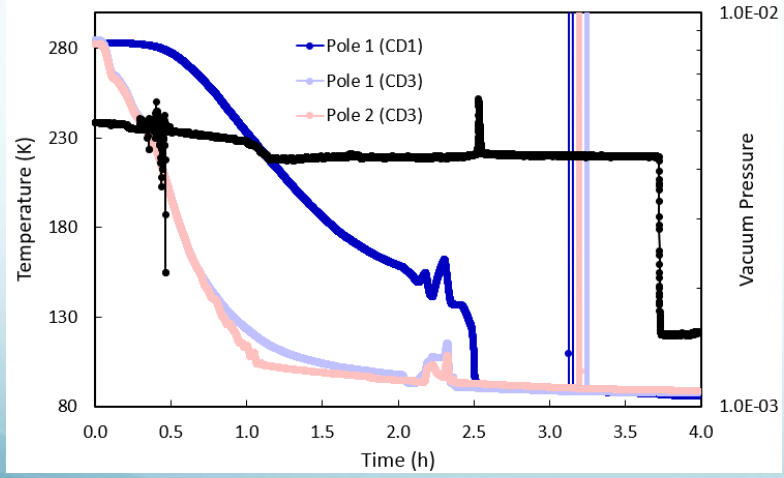
DC bus qualification

- Cooled with LN2 from pressurized dewar (80 K)
- Cooldown in 3 hours
- DC CORC® power cables energized to 1,700 A
- Contact and current lead resistances characterized

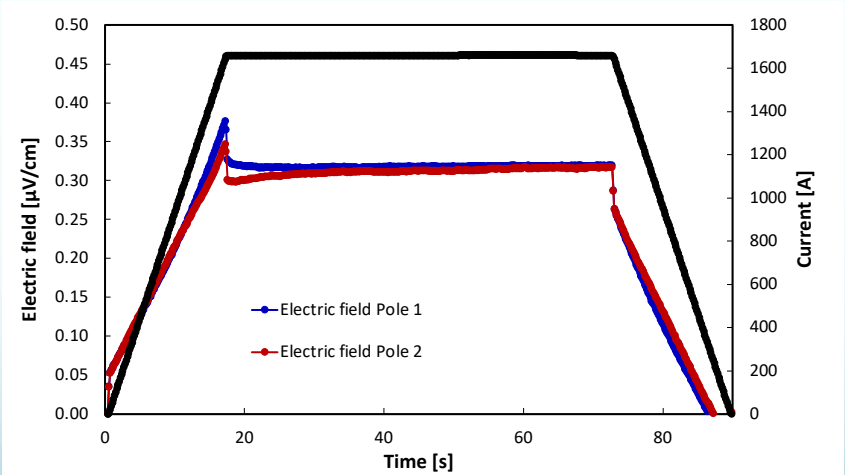




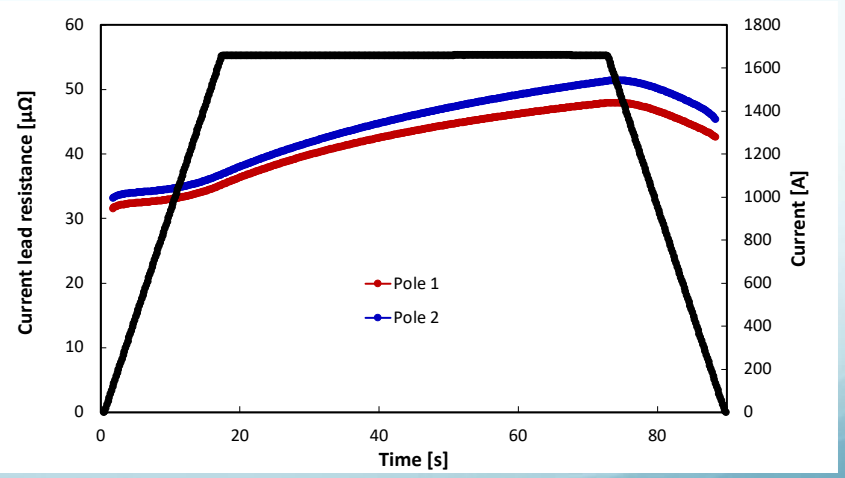
Temperature of connecting devices



CORC® cable voltage



Current lead resistance

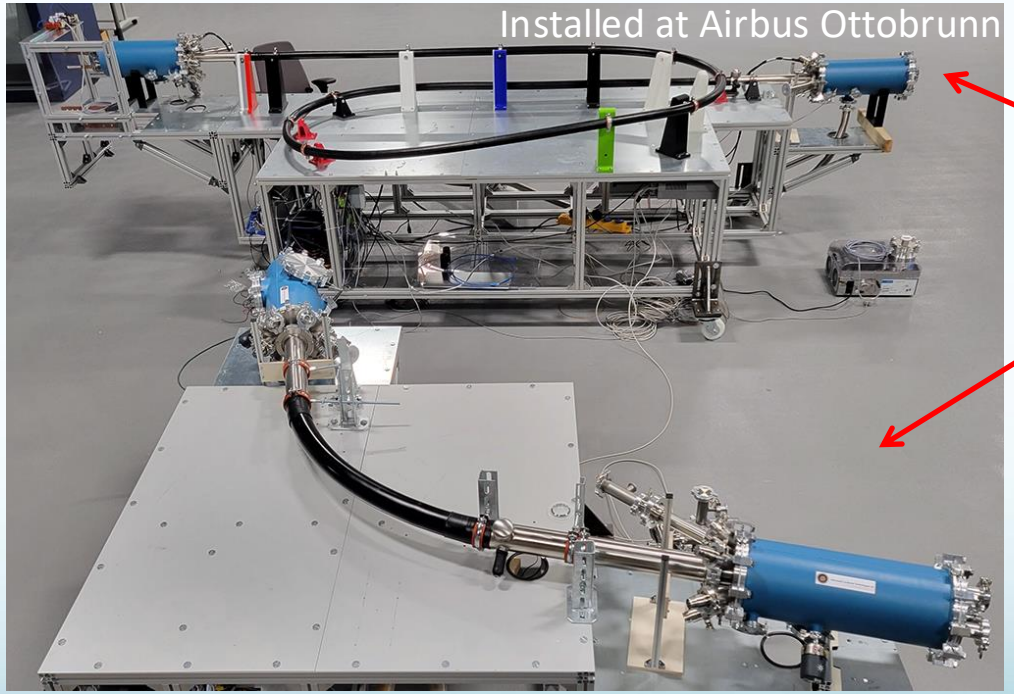


Airbus ASCEND: CORC® AC and DC bus development

CORC® AC and DC bus status

- Assembly and commissioning of CORC® AC and DC bus for ASCEND in April/May 2023
- Successful test of the ASCEND demonstrator in November 2023
- First time CORC® cable interfaces with voltage rating were developed

Two 10-meter long CORC® cables for the dc bus



High Power Cables for Naval Applications

DC power cables for naval applications

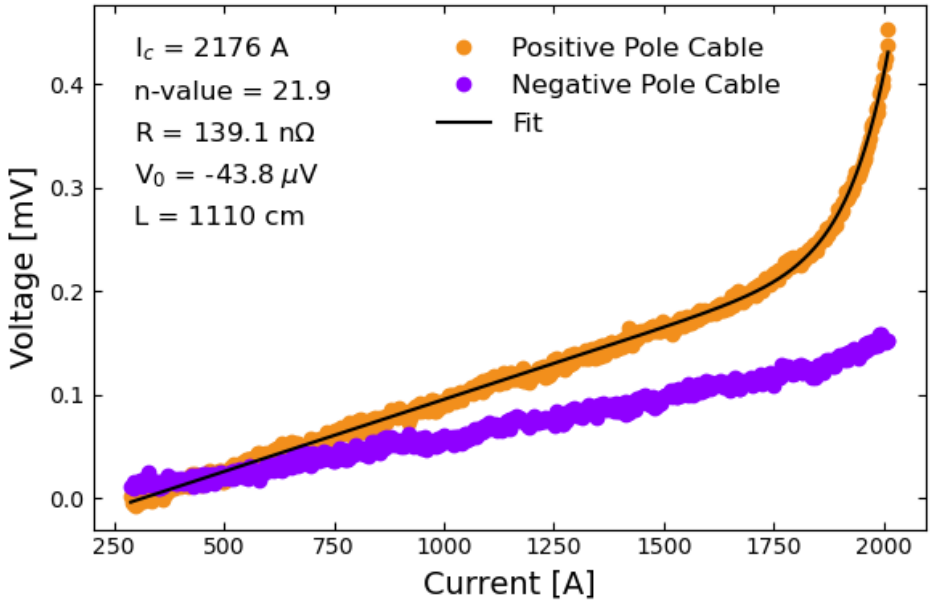
- Colinear two-pole cable
- 4 kA current rating
- 12 kV voltage rating
- 48 MW power rating
- GHe cooled operation at 30-50 K
- Prototype demonstrator assembled and tested @ CAPS in Tallahassee

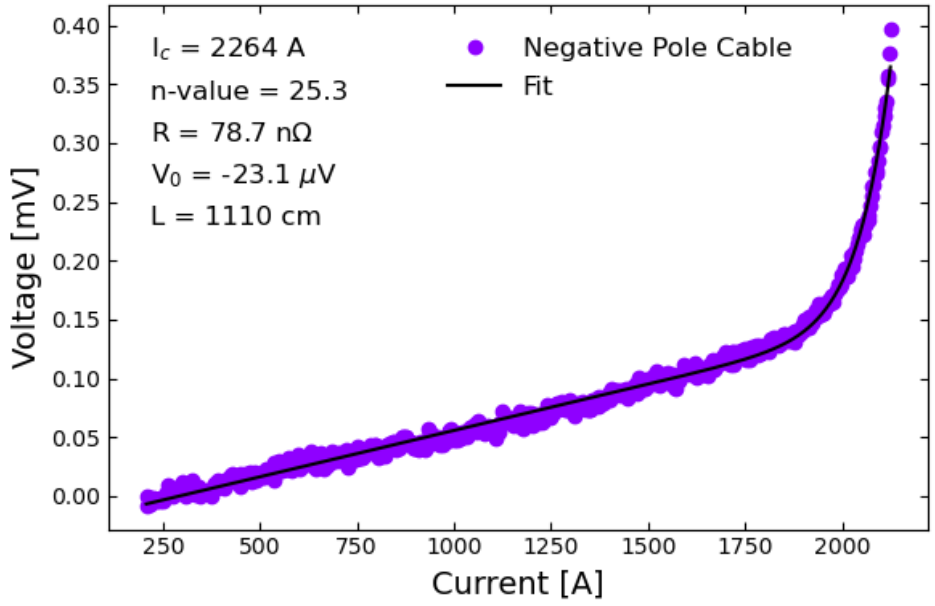
High Power Cable for Naval Applications: Current Testing

Current Testing

- Temperature of 46 – 64 K measured at different locations in the interfaces (highest temperature measured at helium return line)
- The CORC® cables could be operated to about 1.8 – 2 kA before transitioning
- Cable performance limited by elevated temperature, indirect cooling to part of the cable, and potentially some cable damage due to torquing of the cable during assembly
- Small helium leak in one interface limited vacuum quality

Location	Temp [K]
T_Tee	42.9
T_In+ Short	46.2
T_In– Short	47.1
T_HX+ Short	53.2
T_HX– Short	53.0
T_Out+ Short	52.6
T_Out– Short	56.0
T_In+ PS	54.5
T_In– PS	52.8
T_HX+ PS	60.0
T_HX– PS	60.7
T_Out+ PS	64.4
T_Out– PS	58.0



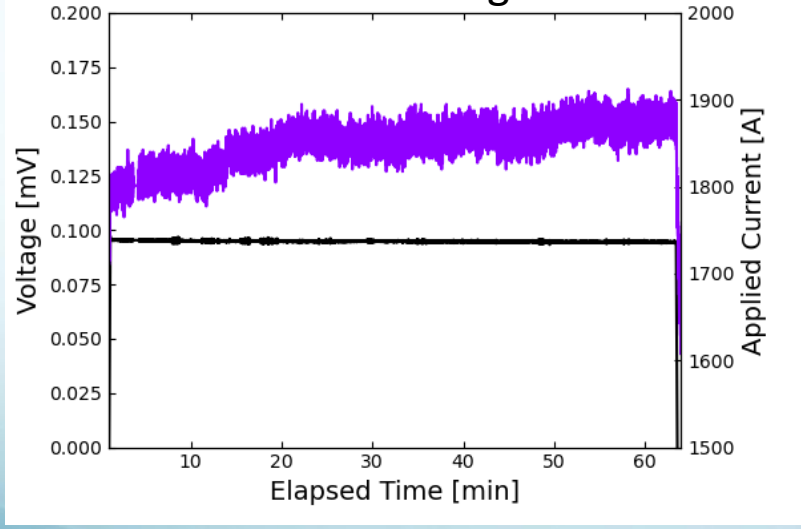


High Power Cable for Naval Applications: Continuous Operation

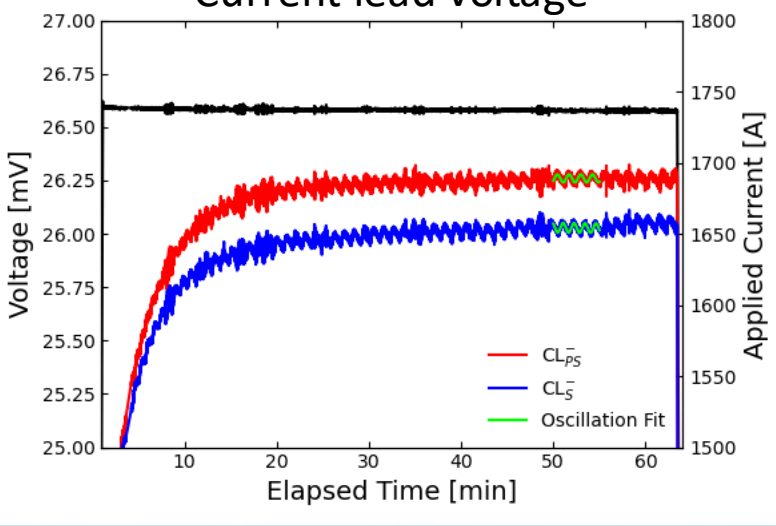
Negative pole operated continuously at 1,740 A

- Temperatures and voltages stabilize within 30 minutes
- Heat exchanger voltages show an oscillation caused by the current lead heaters (to prevent icing) with 30 % duty cycle at 125 W
- Heater input of 37.5 W indicates effective current lead optimization at about 3,200 A (80 % of design current rating)

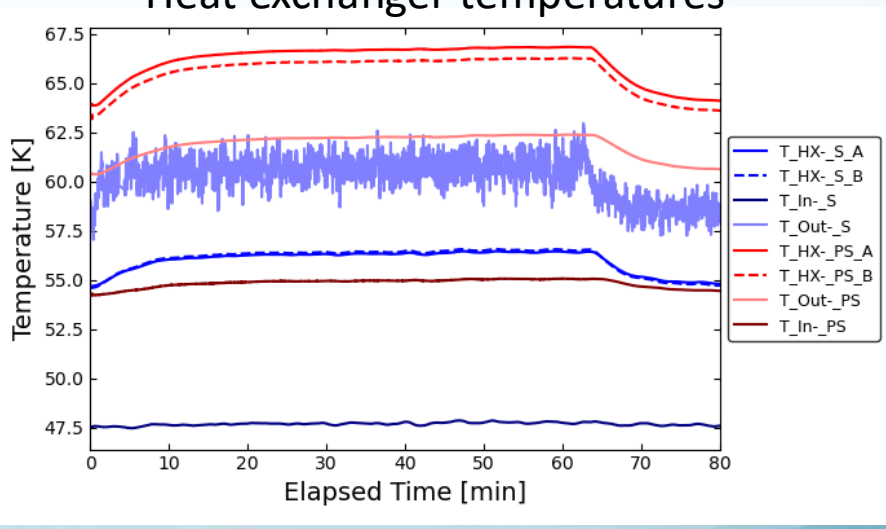
Cable voltage



Current lead voltage



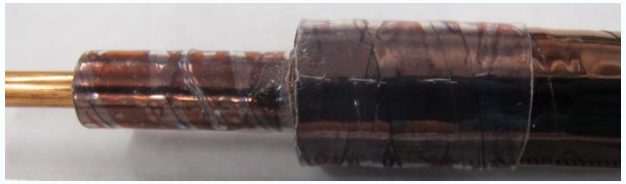
Heat exchanger temperatures



Summary

High Voltage dielectrics for CORC® power cables now available for operation up to 12 kV

- Voltage rating for AC and DC applications up to 12 kV tested and confirmed
- Insulation rating customizable between 1 kV and 12 kV
- With current ratings of up to 5kA, power rating in excess of 50 MW possible



Additional features makes CORC® power cables even more versatile

- FCL capabilities limiting 3x overcurrent current to I_c within 10 ms and without burnout after 300 ms
- Coaxial cable configurations with power ratings up to 50 MW
- Core integrated cooling tube decreases overall cross-section

Connecting interfaces for CORC® power cables custom designed for any application

- Interfaces to other cryogenic equipment or ambient conditions possible
- Custom solutions for any available coolant
- Standard thermal insulation with heat losses to the environment < 5 W