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

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Applications with need for high power density cables

Electrification of modern life requires compact, lightweight power distribution of up to 50 MW

Electric ship applications

- The U.S. Navy is investigating HTS DC power cables for shipboard applications
- Size and weight are important considerations
- Liquid cryogens need to be avoided

Image courtesy of General Atomics

Electric aircraft applications

- Increasing efforts for electrification of twin aisle passenger aircraft
- Size, weight and reliability are critical to design
- Many busses needed to power distributed electric propulsion

Image courtesy of Airbus

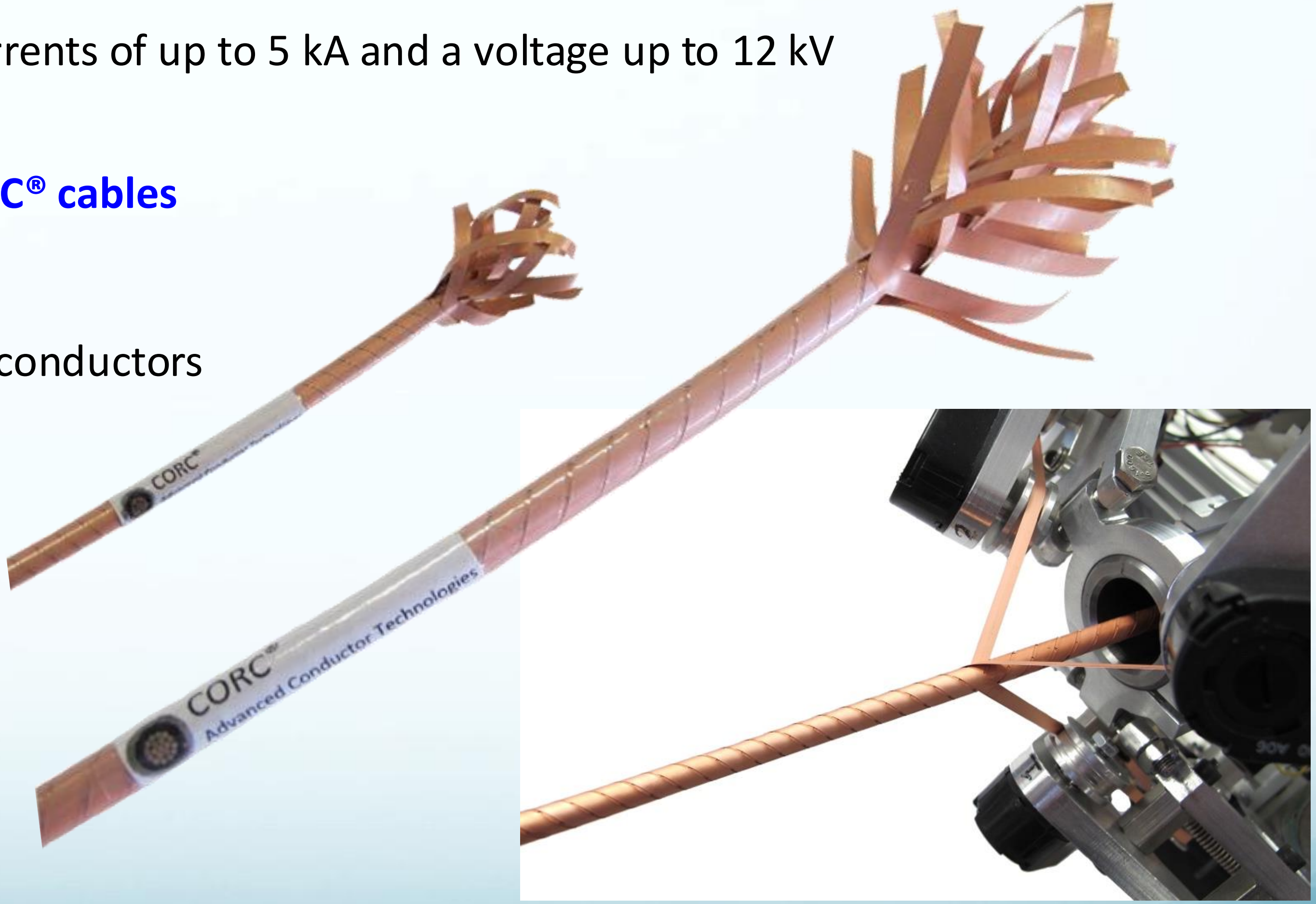
CORC® cables and wires pioneered by Advanced Conductor Technologies

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
- Having fault current limiting abilities
- 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

Outline

High voltage dielectrics for superconducting CORC® power cables

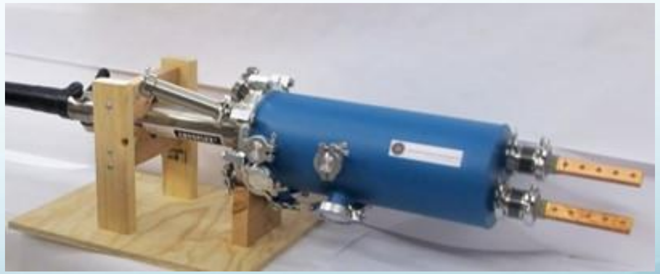
- Dielectric choice and application
- Performance under AC conditions
- Performance under DC conditions

Features of CORC® power cables

- Fault current limiting capabilities of CORC® cables
- Coaxial CORC® power cables

Connecting interfaces for CORC® power cables

- Interfaces for CORC® cables to ambient condition
- Coolant independent CORC® power interfaces
- Optimizing performance of CORC® power interfaces



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High temperature superconducting power transmission cables

"Conventional" HTS power cables

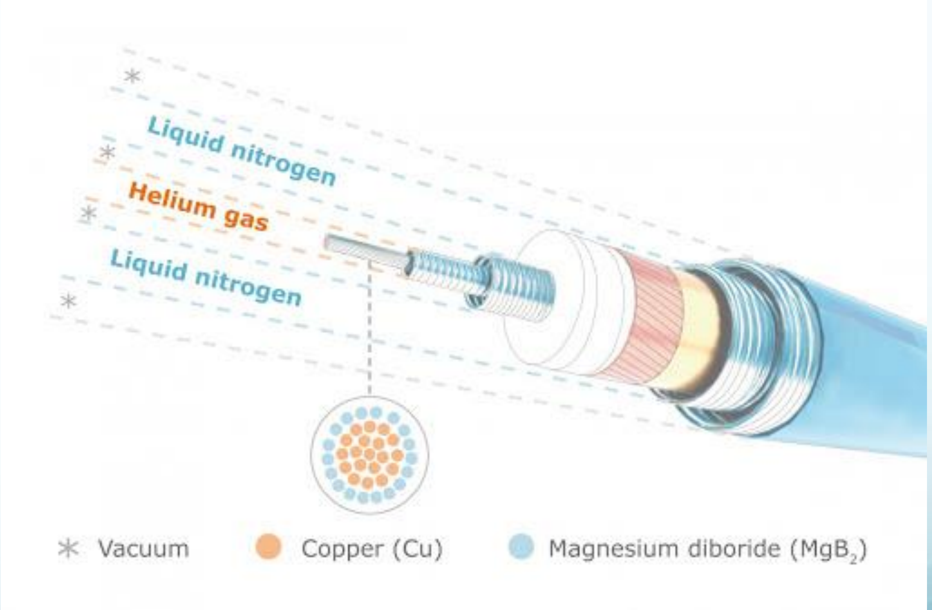
- Are cooled with sub-cooled LN_2, which is a good dielectric
- Contain a wrapped dielectric that's penetrated with LN_2

High operating voltage exceeding 100 kV "easy" to achieve in LN_2

Image courtesy of SuperPower Inc.

Example of land-based power cables that require GHe cooling

- NEXANS Best Paths cable project based on MgB_2
- Superconducting cable cooled with helium gas
- Wrapped dielectric remains cooled with LN_2 to achieve 320 kV rating



NEXANS Best Paths cable

Our approach to reach 10 - 12 kV voltage rating

- Separate the CORC® cable from the coolant (helium gas)
- Prevent penetration of coolant into the cable dielectric
- Use vacuum as cable medium

Dielectrics for cryogenic applications

Liquid dielectrics
- Used successfully in ambient temperature applications
- Void/ crack formation during freezing compromises dielectric properties
- Heavy

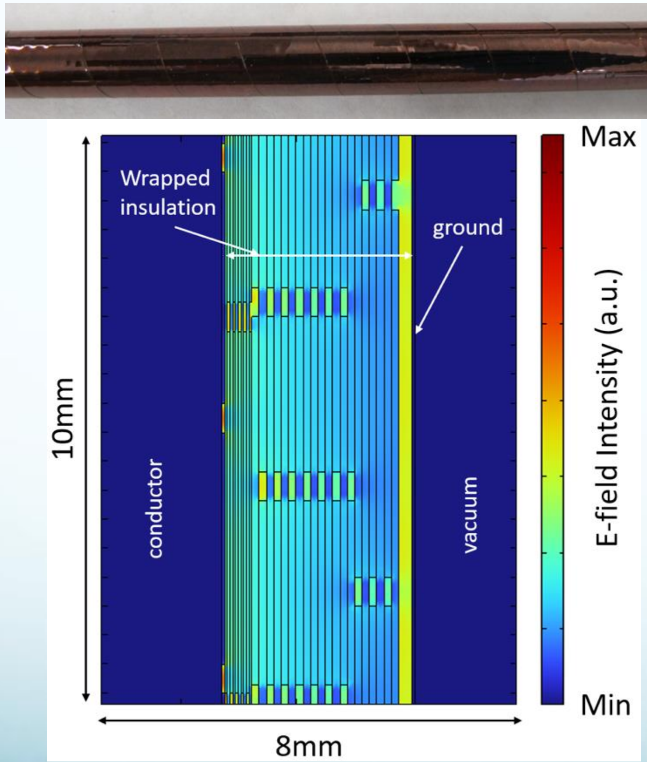
Extruded dielectrics
- Well researched (for ambient temperature applications)
- Difficult to apply to superconducting cables
- CTE mismatch can cause failure, especially for thicker dielectric

Wrapped dielectrics
- Simple to apply to superconducting cables
- Flexible for customization, especially for lab/ research scale production
- Void formation in the dielectric unavoidable

Wrapped dielectrics for cryogenic applications

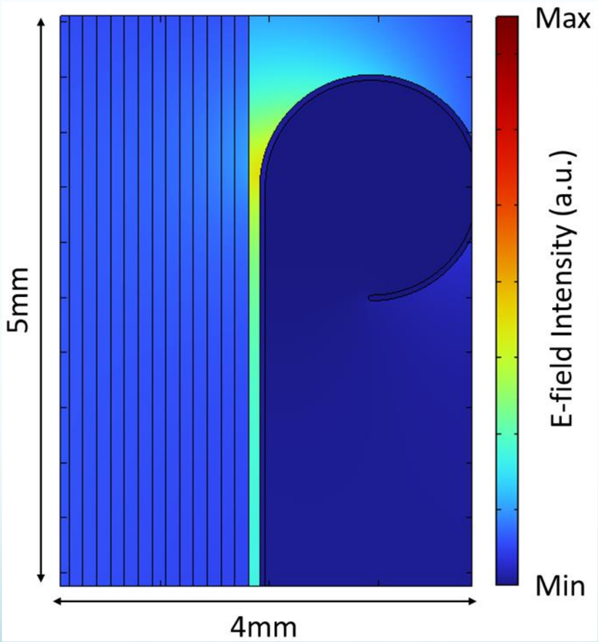
Comsol Modelling for AC voltage application

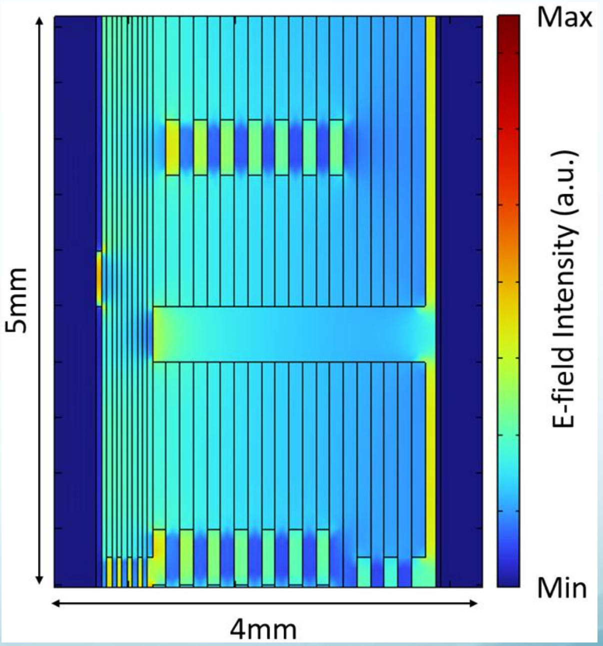
- Electric field concentration highest in voids
- Especial care necessary where voids intersect/ overlap



Special cases

- Triple point at termination of cable
- Overlapping voids forming pin hole through insulation





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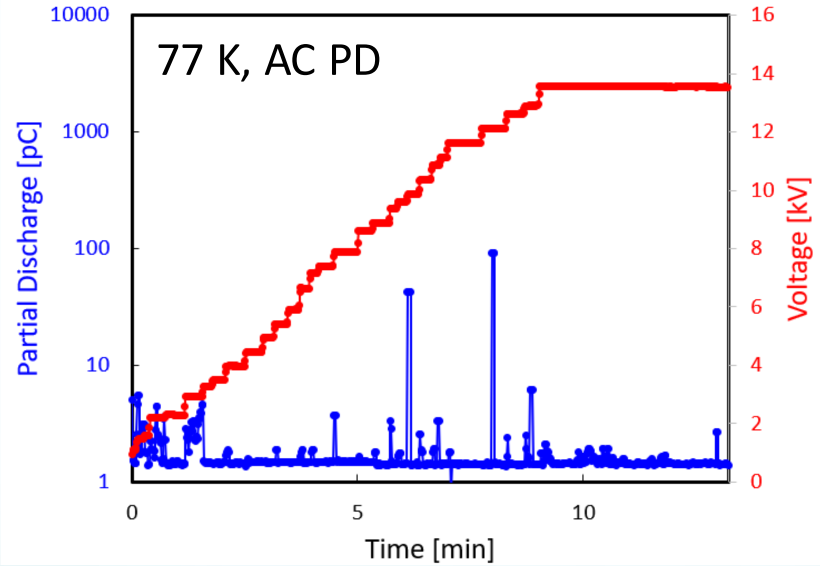
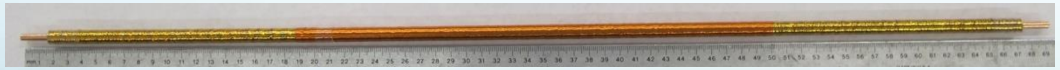
Wrapped dielectrics for cryogenic applications

High quality hand-wound dielectric

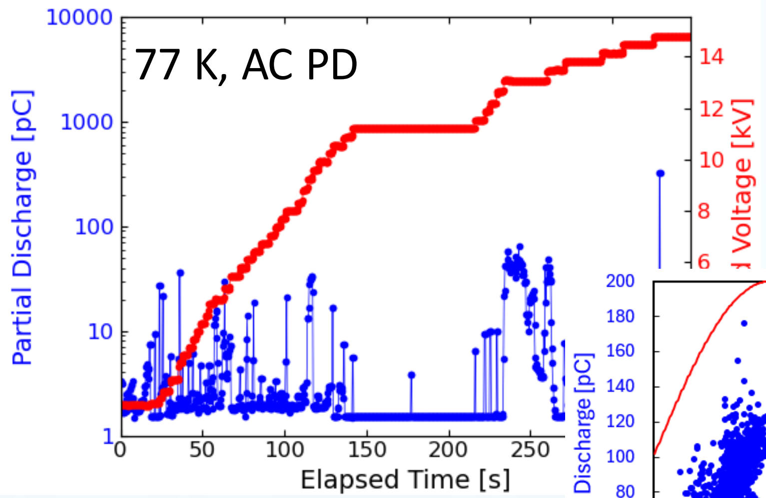
- Wound with overlapping tapes
- Void formation minimal (only at overlap fold between two tapes)

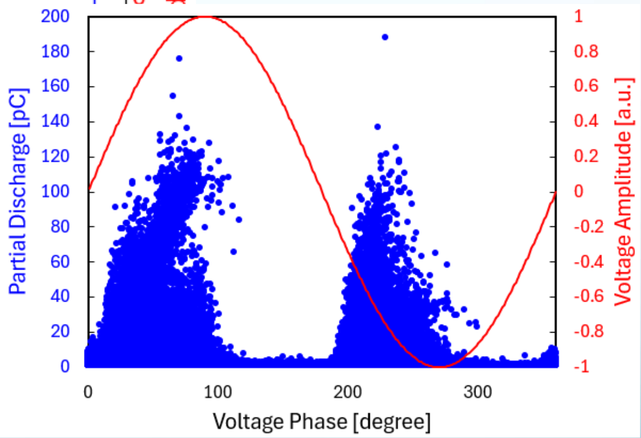




Machine wound dielectric

- Wound with overlapping (inside) and butt-gapped tapes
- Larger voids at butt gaps between tapes
- Bending and straightening cycles during winding





PD characteristics indicate surface discharge inside voids

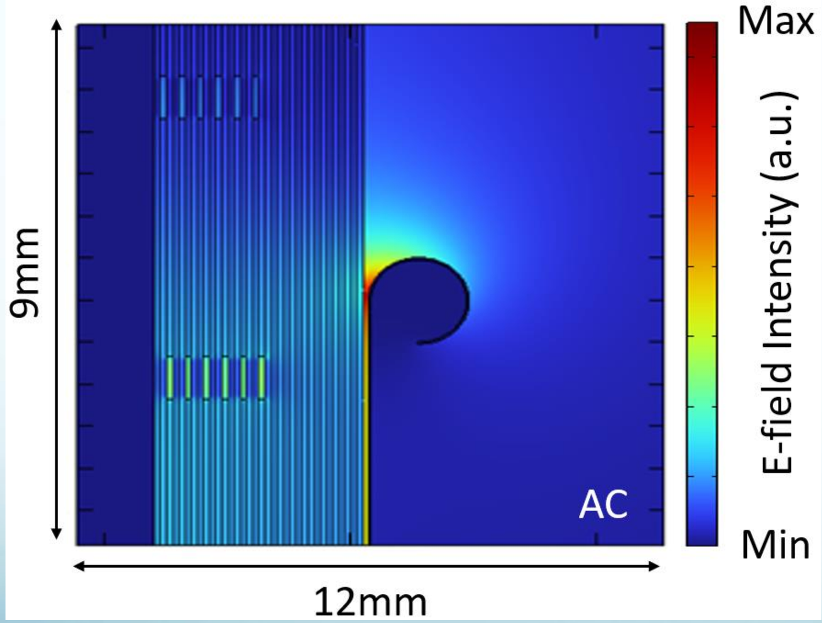
Dielectric stresses in DC vs AC applications

Presence of different dielectric stresses

- DC-field electric stresses not present in AC applications
- AC-field electric stresses only transiently present during voltage ramps

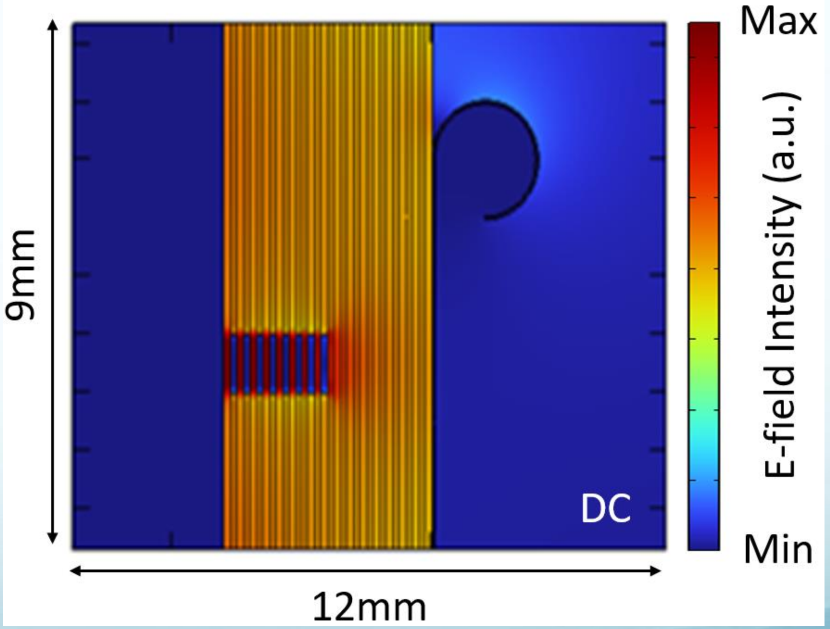
Dielectric Stress for AC electric fields

- Maximum field enhancement at triple point at ground/insulation/vacuum interface



Dielectric Stress for DC electric fields

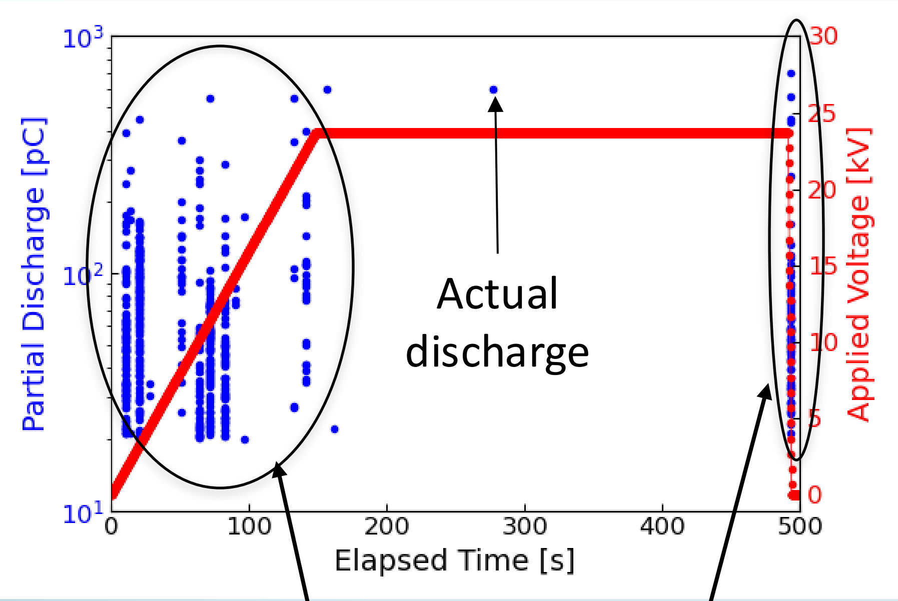
- Maximum field enhancement at dielectric interfaces within the insulation



Wrapped dielectrics for cryogenic applications in DC-fields

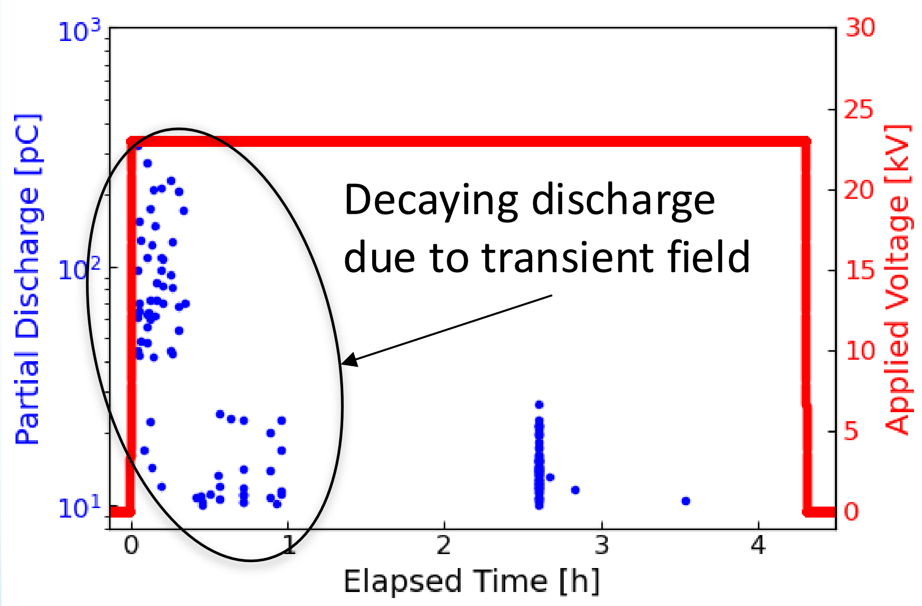
DC electric field performance

- 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

Power supply operation switching noise



77 K, DC PD in 2 MPa GHe

Transient field component time constant ~1-2h

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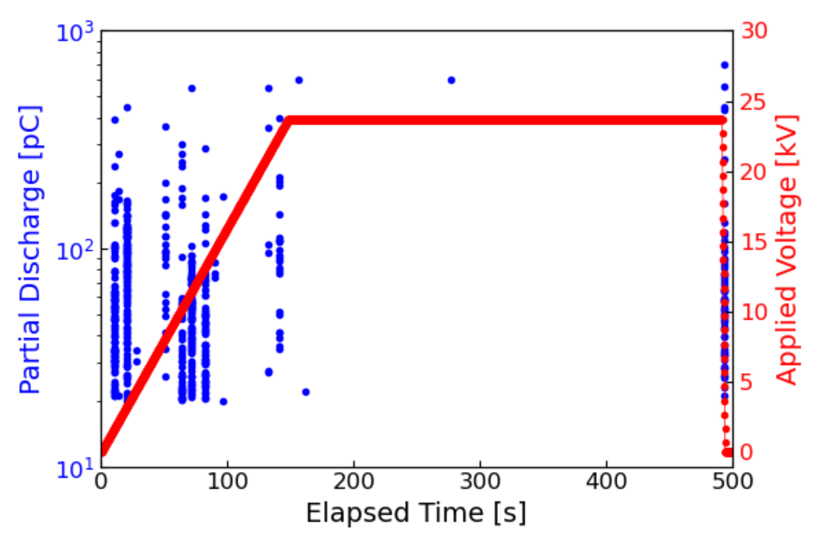
Environment for cryogenic dielectrics

Vacuum

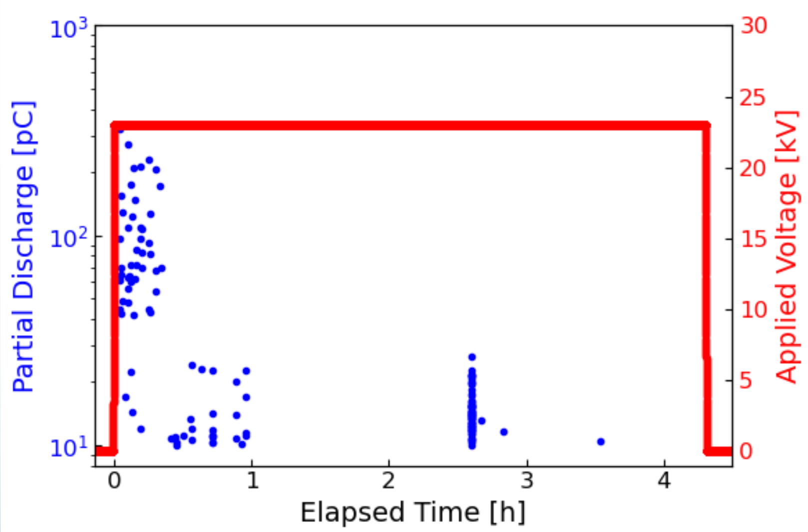
- Better dielectric performance
- Can functionally be used as thermal insulation
- Quality difficult to control, especially in situations with many local voids
- Difficult to maintain, establish in long length cables
- Random impurities catastrophic to performance



77 K, DC PD in vacuum

High pressure gaseous helium

- Poorer dielectric performance
- Generally used as coolant
- Purity critical for good cooling performance ensures homogenous environment
- Length independent maintenance
- Random impurities minor against high pressure background

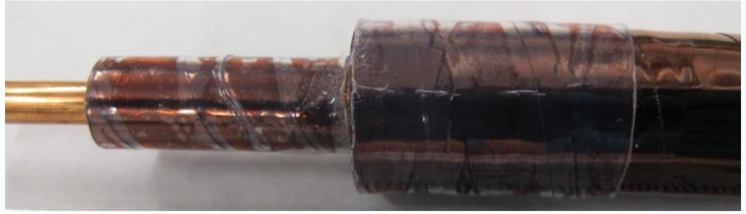


77 K, DC PD in 2 MPa GHe

Low voltage wrapped dielectric for cryogenic applications

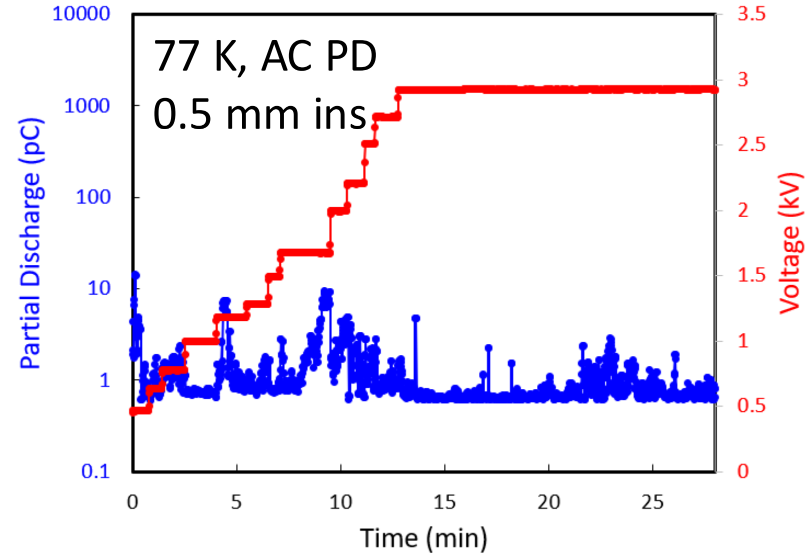
Lower voltage advantages

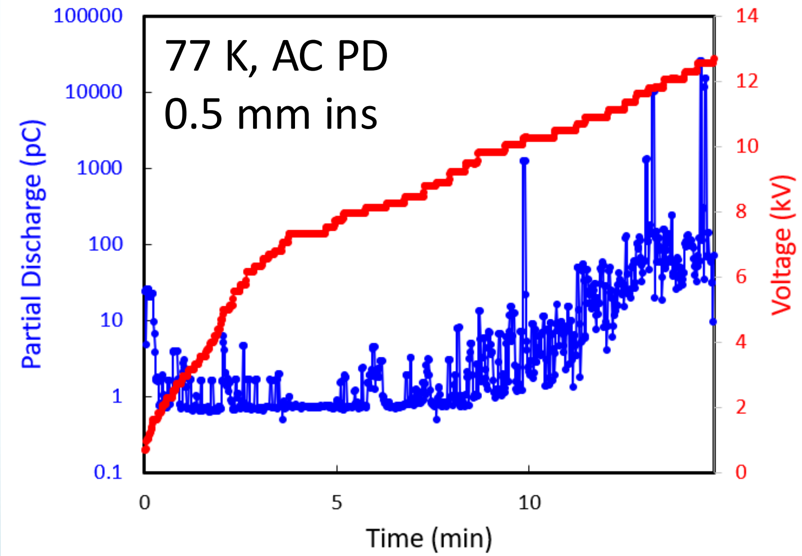
- Electric aircraft much more likely to be operated at lower voltage of 1 kV or below
- Reduced complexity to achieve electric performance
- Reduced size and increased cable flexibility



10 kV cable

2-3 kV cable





Features of CORC® power cables

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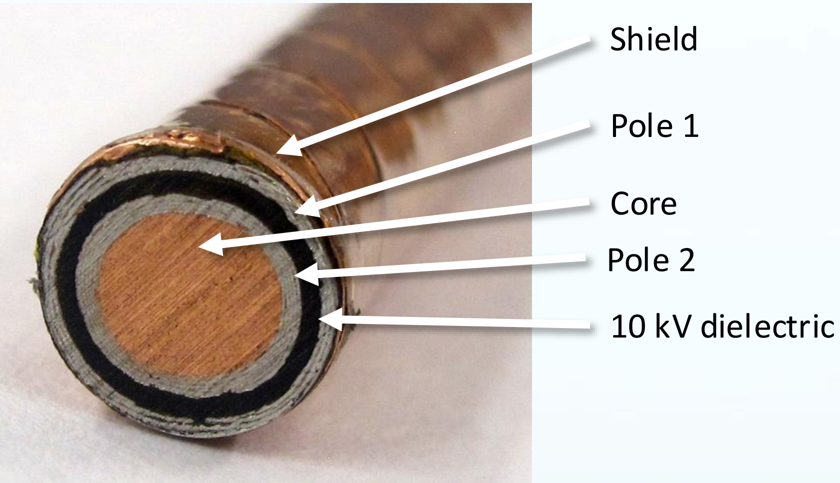
Development of coaxial CORC® cables for power applications

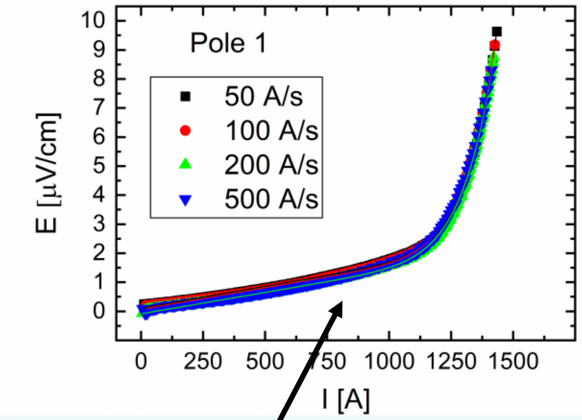
Coaxial CORC® power cables

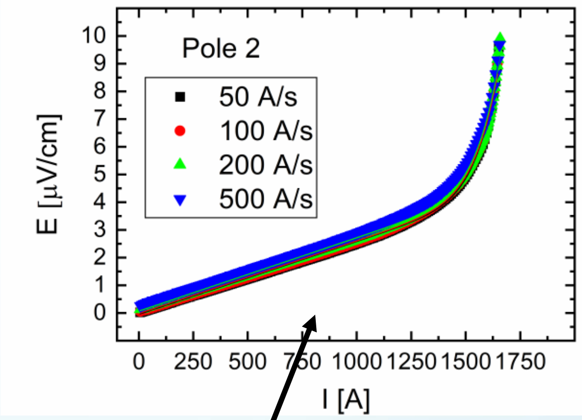
- Increased power density
- Relevant for AC power distribution



Coaxial dc CORC® cable performance

- I_c(76 K) = 1,203 A – 1,499 A
- Expected I_c (30 K) > 7 – 9 kA
- 10 kV rating between poles
- **50 MW power rating**
- **Power density 1 MW/mm²**

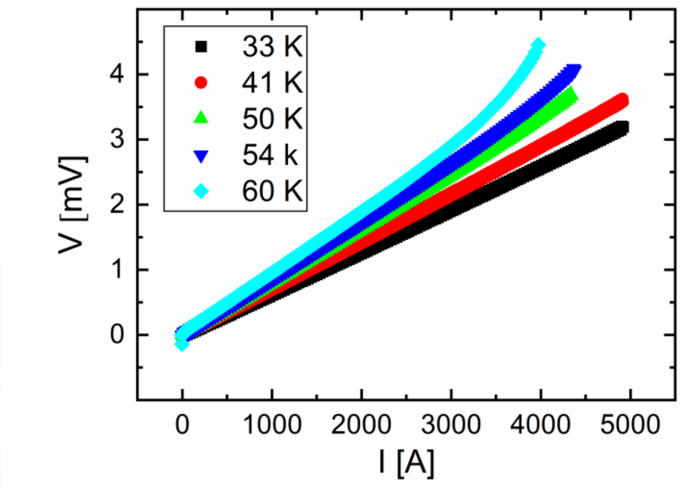


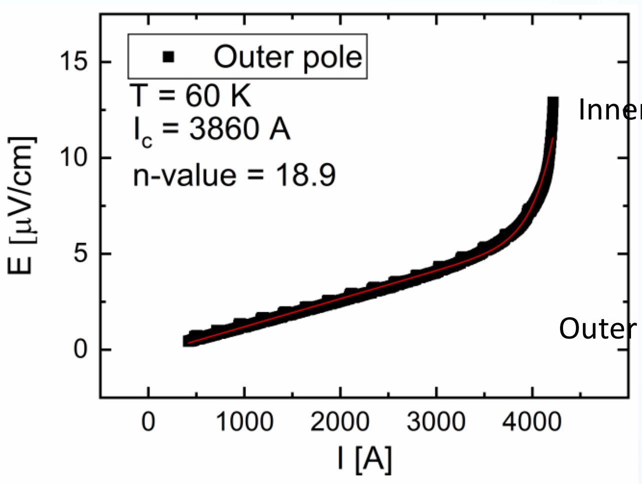


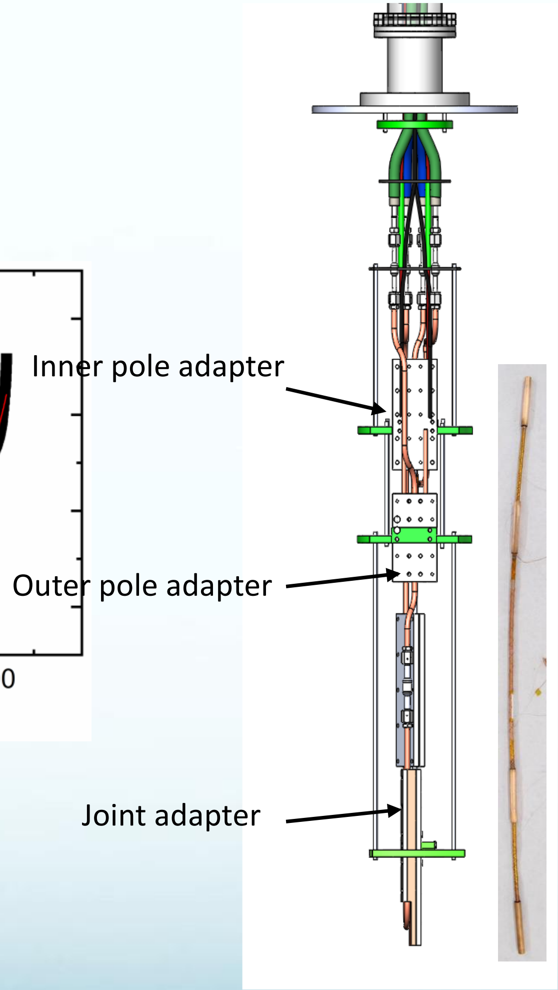
2-Pole coaxal CORC® power cable test at 30 – 60 K

Closed-loop helium test facility at ACT

- Stirling cryocooler with custom cryostat
- LN_2 precooling allows for continuous currents at 5 kA
- Sample temperature 20 – 70 K







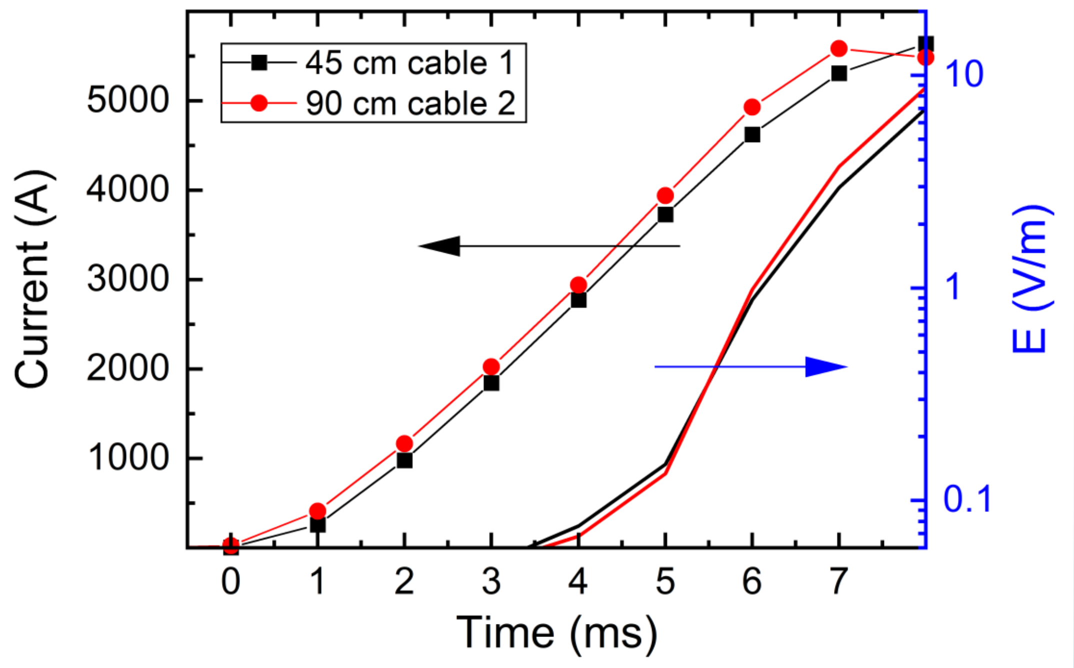
2-Pole coaxial CORC® cable

- 10 kV dielectric
- Rated current > 7 – 9 kA (30 K)
- I_c (60 K) is 3,860 A (outer pole)

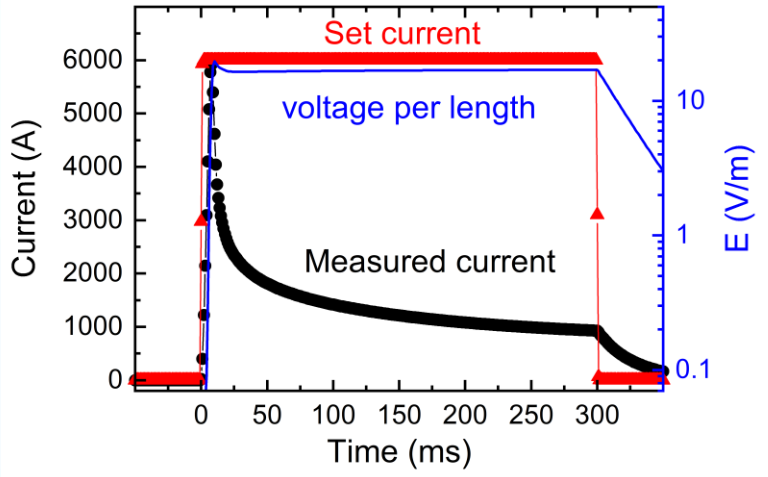
CORC® cable with fault current limiting functionality

Short sample CORC® FCL cable tests at ACT

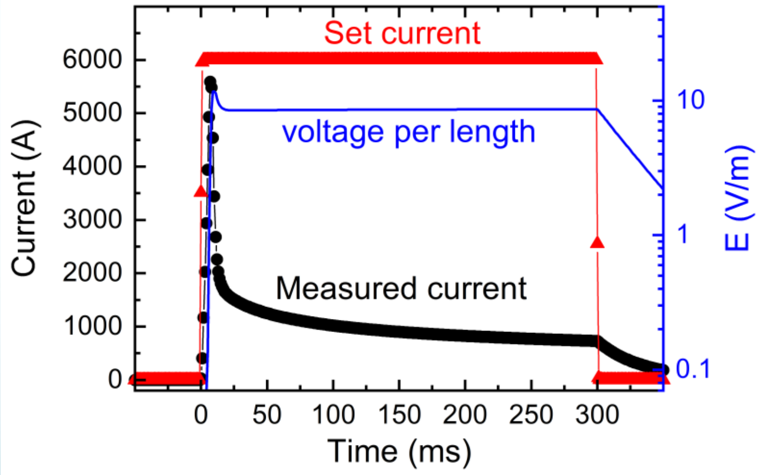
- Single-pole CORC® cable critical current 2.8 kA at 76 K
- Electric field > 7.5 V/m within 5 ms after 6 kA fault starts
- Current limited to less than 2 kA within 7 ms
- No damage to cable even after 300 ms of fault current



0.45 meter CORC® cable



0.9 meter CORC® cable



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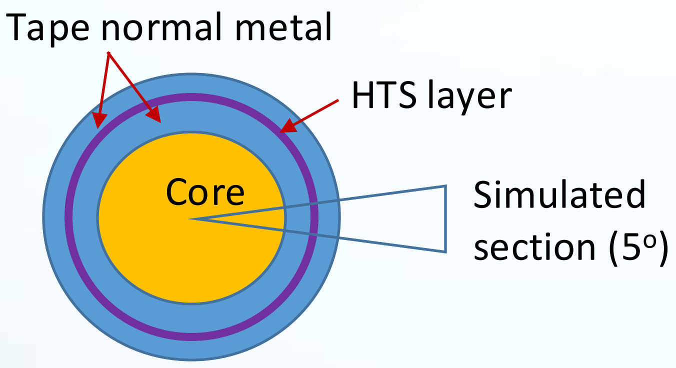
CORC® FCL cable modeling

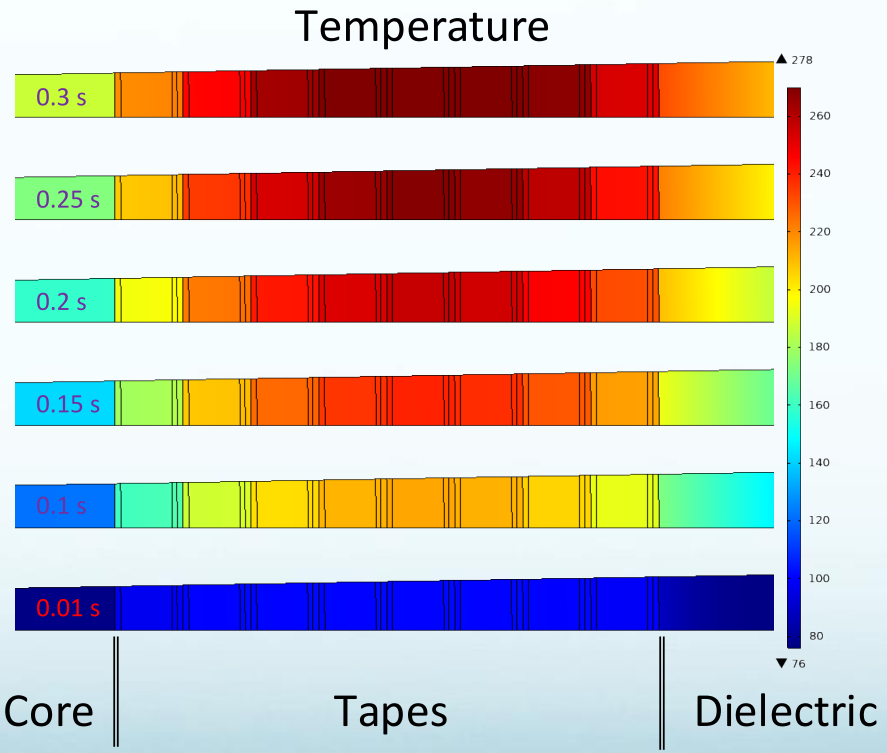
Modeling details

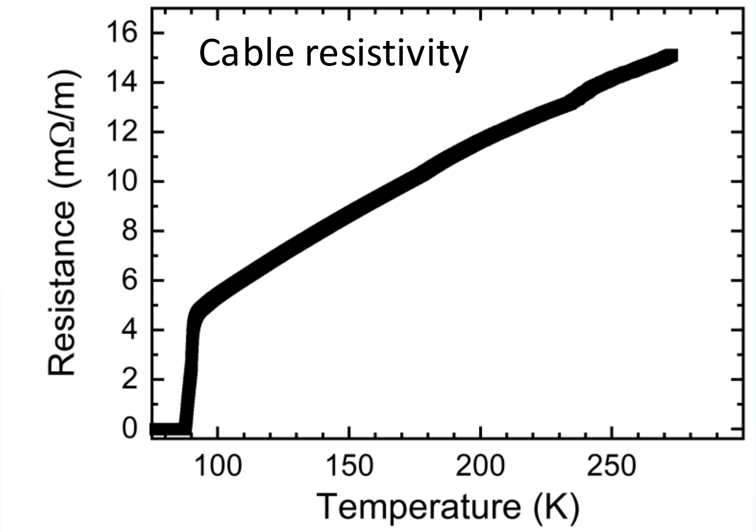
- Simulation is limited to 5° section due to symmetry
- Includes cooling to liquid nitrogen
- Case of a 0.45-meter CORC® FCL cable at 6 kA fault

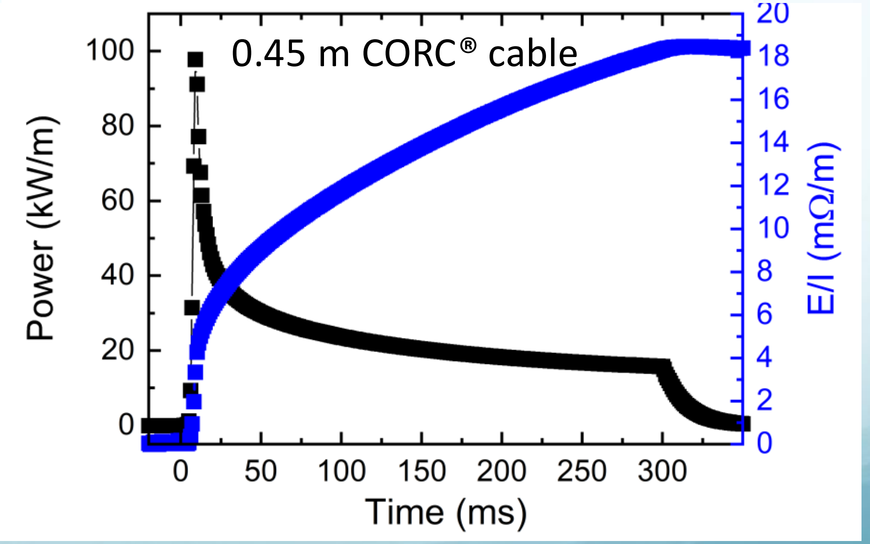


Model results

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







Connecting Interfaces for CORC® power cables

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- Performance under AC conditions
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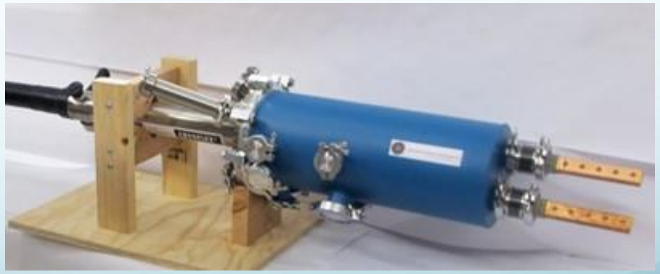
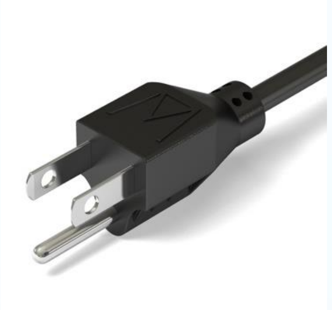


Where cables end

Cables

- Current capacity up to more than 5 kA
- Dielectric insulation rated up to 12 kV
- FCL capabilities
- Coaxial configuration
- Central cooling tube

→ 50 MW power rating



Connectors/ Interfaces

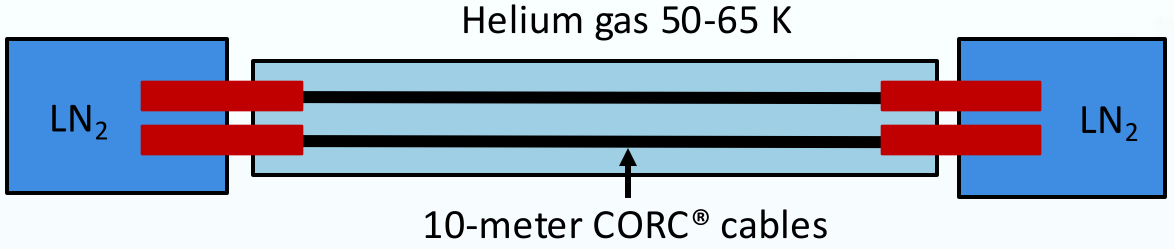
- Current needs to interface to same or different temperature
- Insulation needs to be interrupted without compromising voltage rating
- Instrumentation needs to be interfaced to ambient condition
- Coolant needs to be injected/ extracted

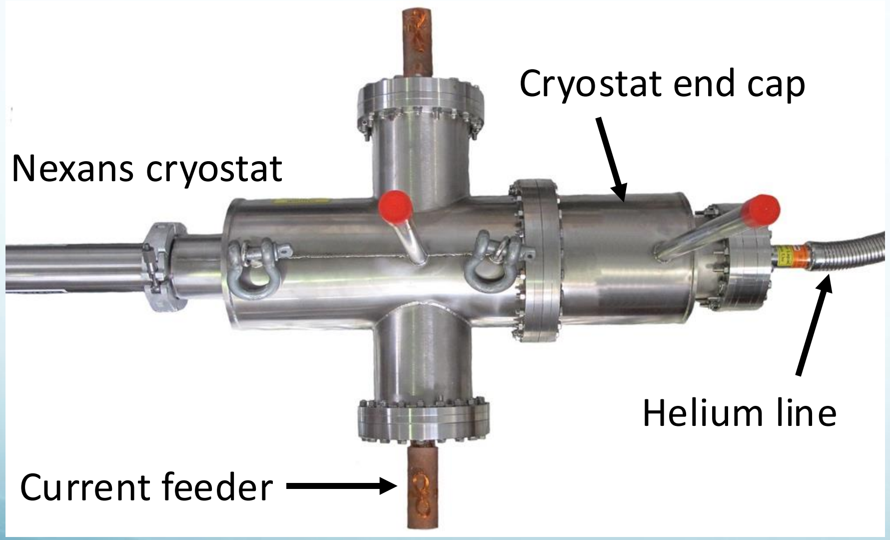
Application specific complex challenges without standard solution

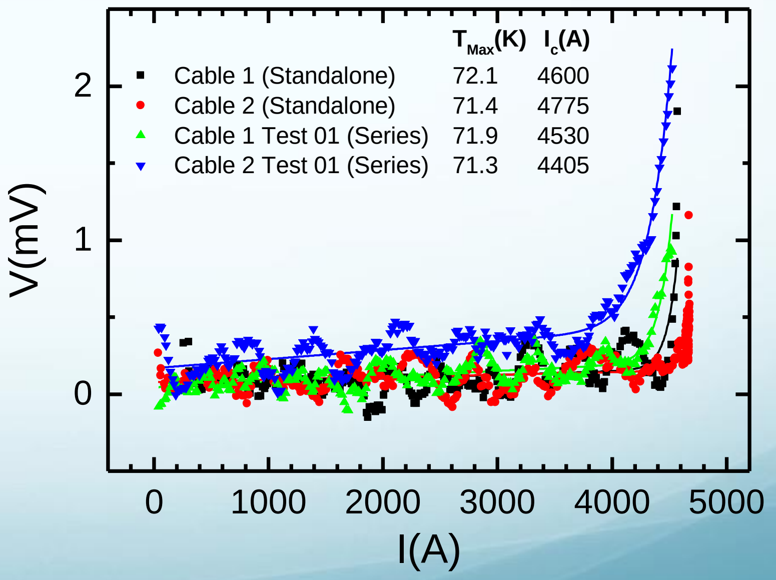
Helium gas cooled CORC® cable with LN_2 cooled interface

Challenges of operating a 2-pole cable at 4 kA/pole using helium gas cooling

- Expecting to cool about 200 W per current lead: 800 W total
- Pre-cooling current leads with liquid nitrogen highlighted disadvantages of this method







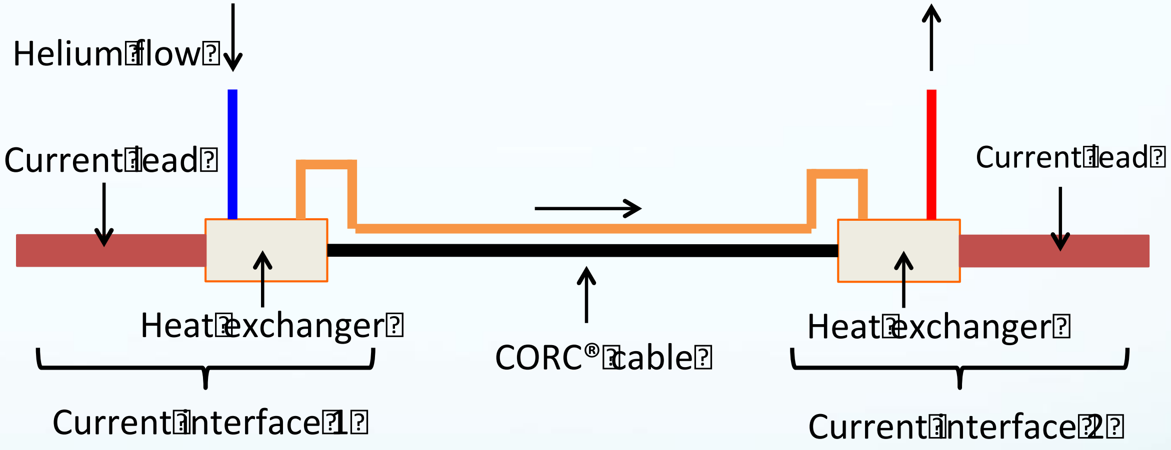
Development of compact CORC® cable terminations with 300 K interface

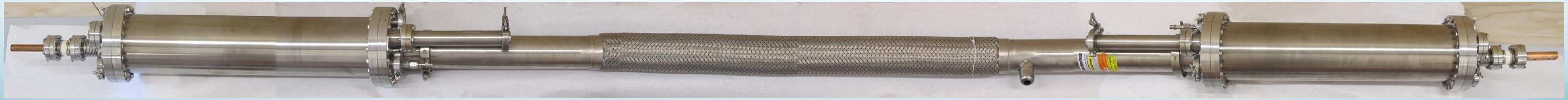
Development of compact cable terminations

- 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

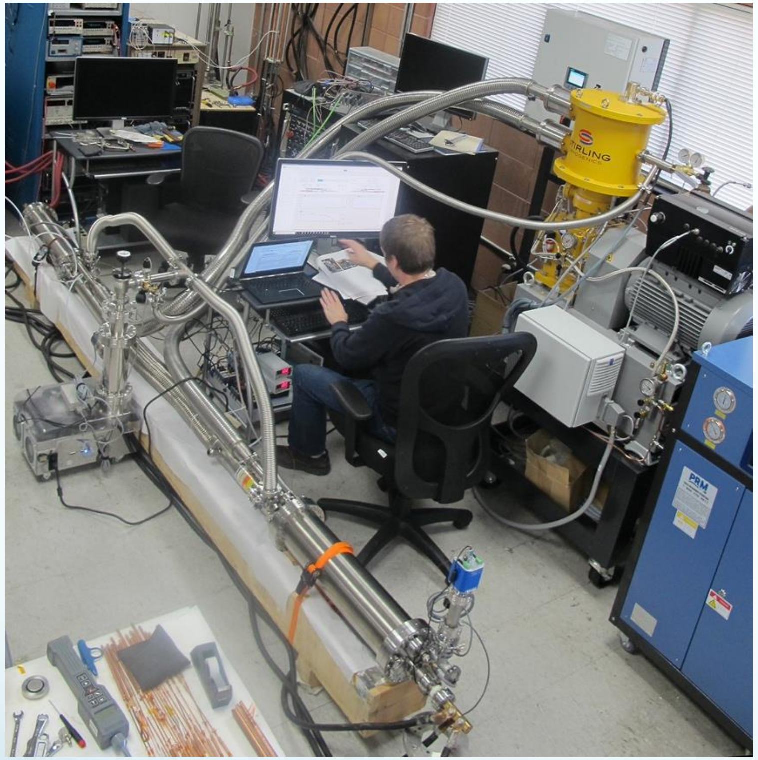
- Single-pole CORC® cable
- Flexible cryostat (2 m)
- Conduction-cooled leads, optimized for 1,200 A

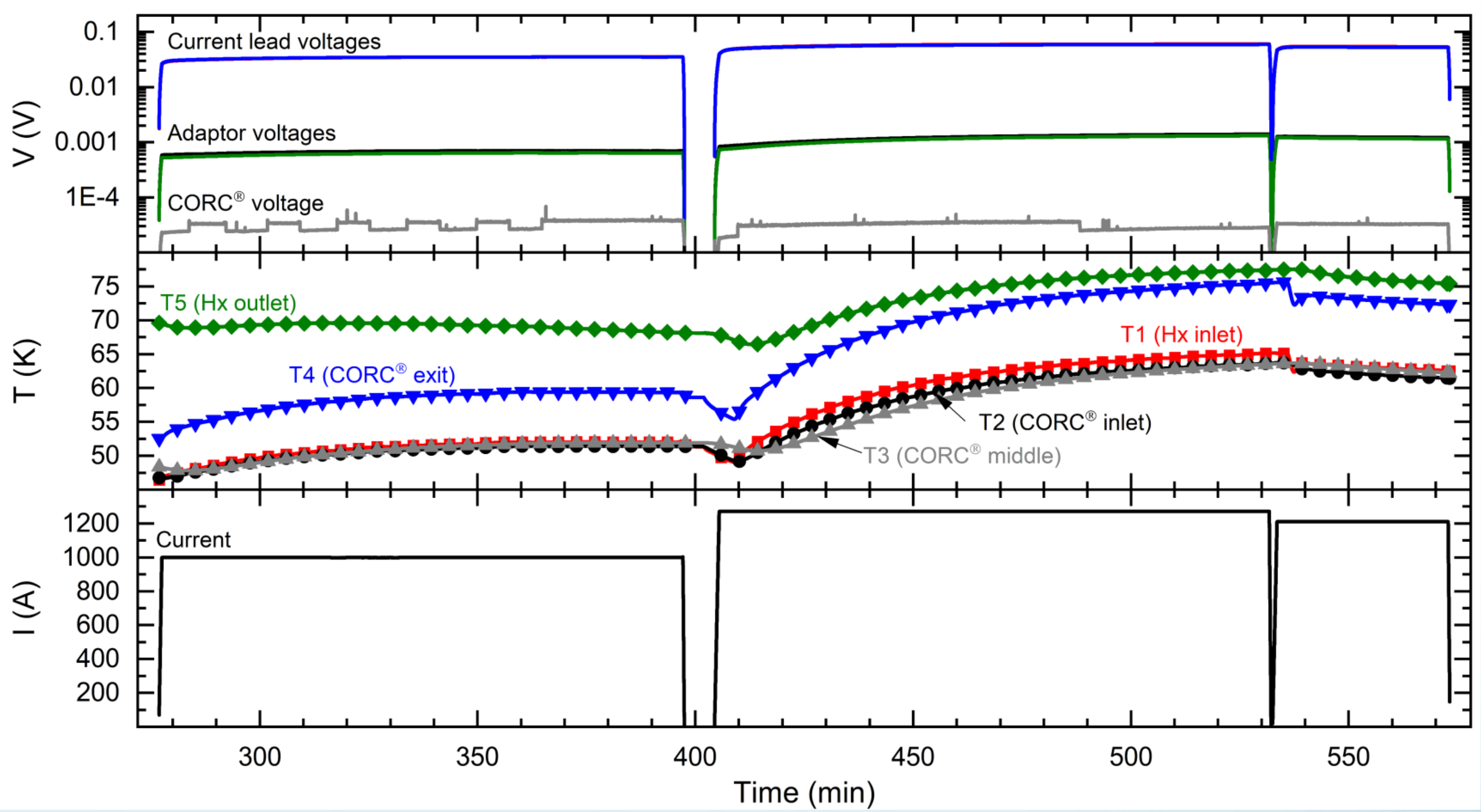




Operation of a turnkey, gaseous helium cooled CORC® dc power cable with integrated current leads, D.C. van der Laan, C.H. Kim, S. Pamidi, and J.D. Weiss, *Supercond. Sci. Technol.* **35**, 065002 (2022)

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

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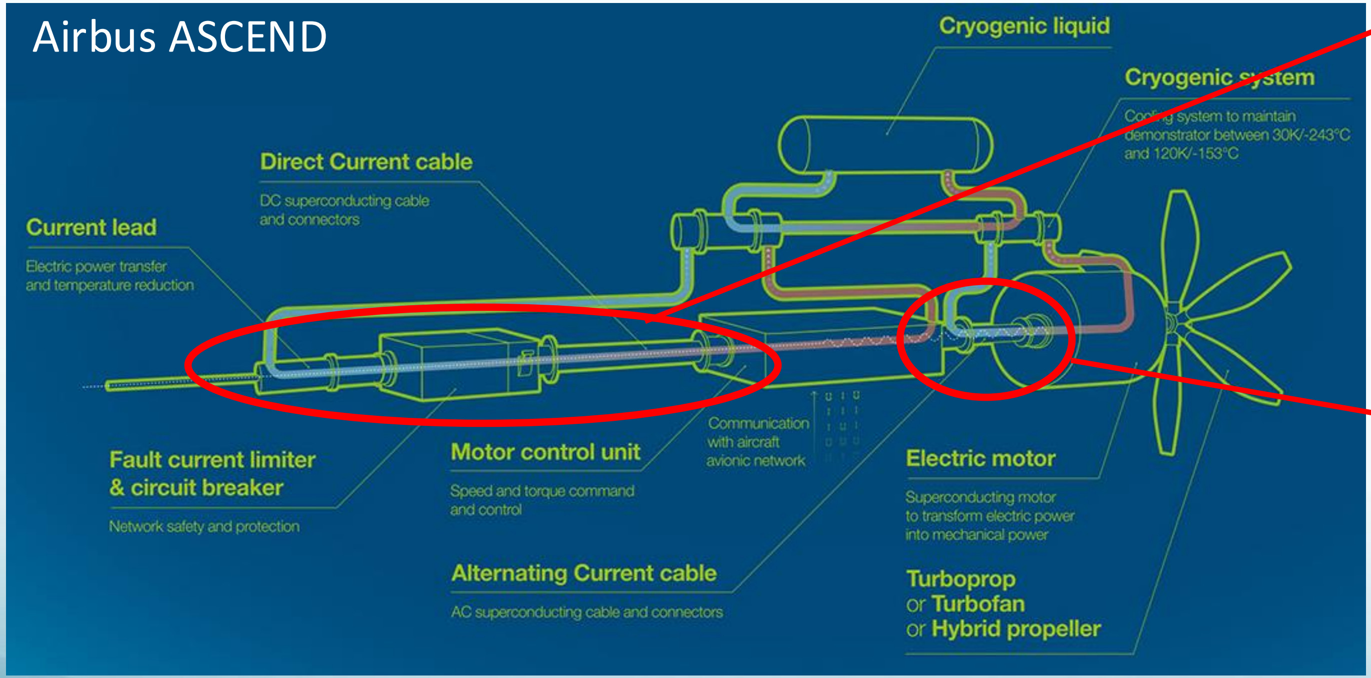
Airbus ASCEND: first demonstration of CORC® cables for electric aircraft

Airbus ASCEND (Advanced Superconducting & Cryogenic Experimental powertrain Demonstrator)

- Ground based powertrain demonstrator of the various cold technologies needed for future electric aircraft
- Identify showstoppers: technological, but also economical (size, weight) and visual (elegance)
- Rated at 0.5 MW, cooling with sub-cooled liquid nitrogen
- **Advanced Conductor Technologies delivered the DC and AC busses for ASCEND**



DC bus ASCEND

- 2-Pole twisted pair, 10 meter in length
- Operating current 1.7 kA
- Operating voltage 300 V (2 kV fault)
- Fault Current Limiting abilities
- Current leads to room temperature
- Interface to motor control unit (~100 K)

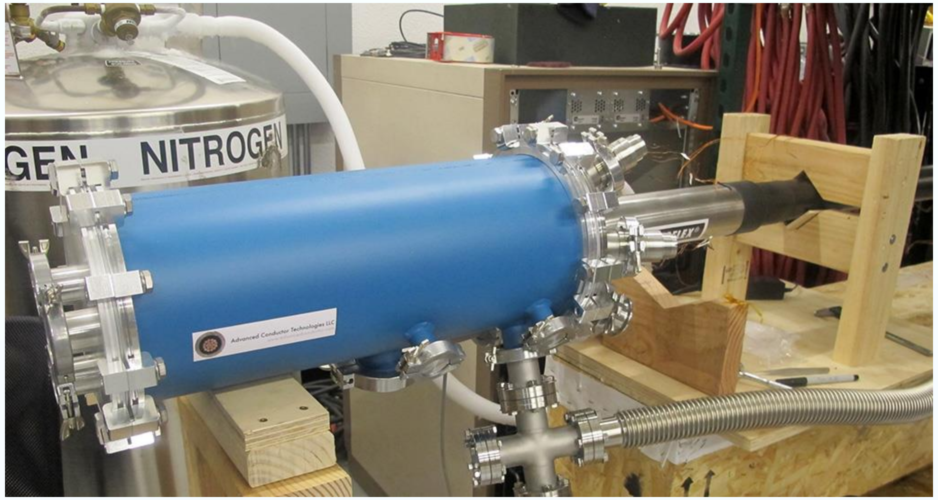
AC bus ASCEND

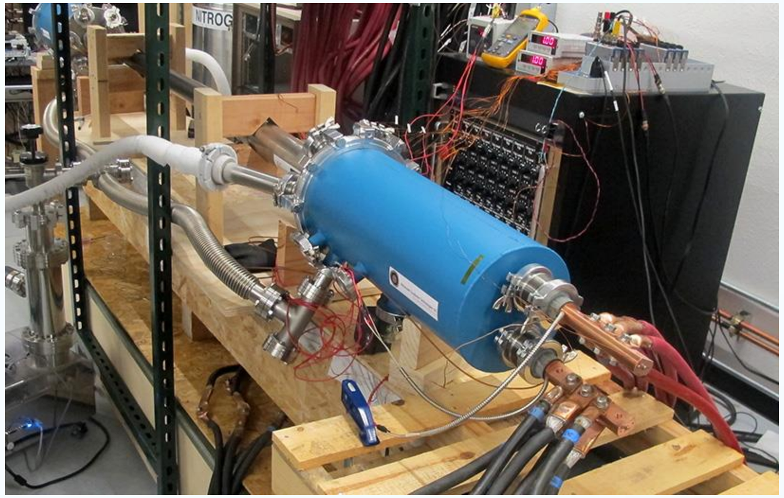
- 3-Phase (3 monopoles), 2 meter in length
- Operating current 1.66 kA rms
- Operating voltage 300 V
- 500 Hz
- Interface to MCU and motor (30 K)

Airbus ASCEND: CORC® DC bus qualification at ACT

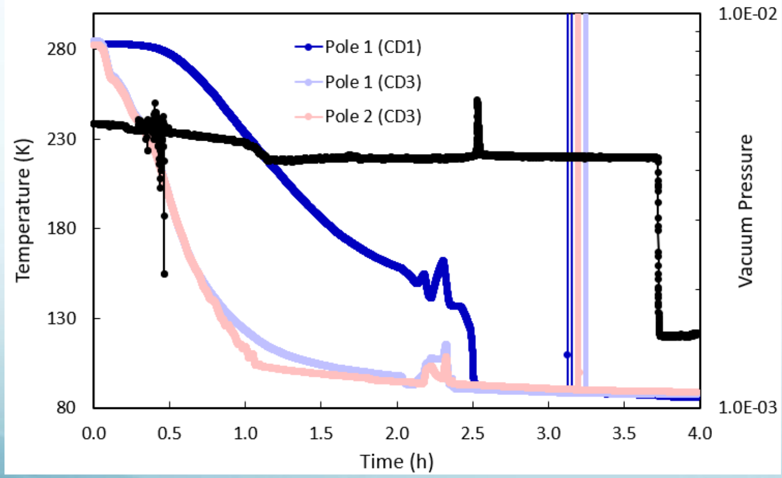
DC bus qualification

- 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

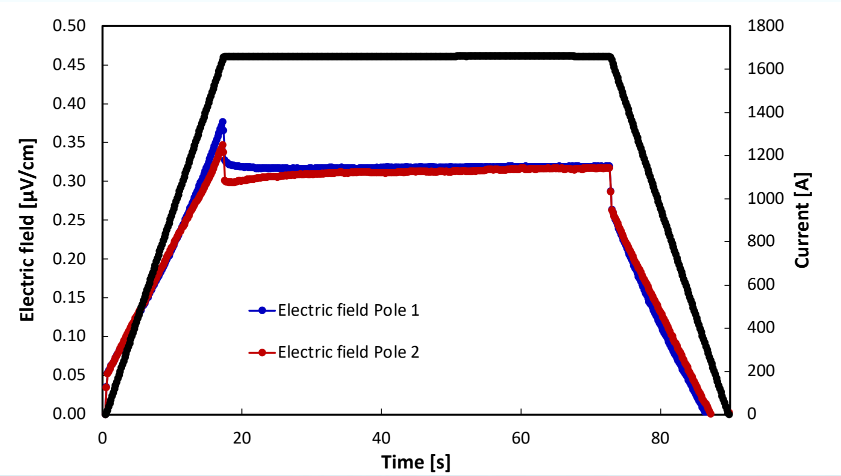




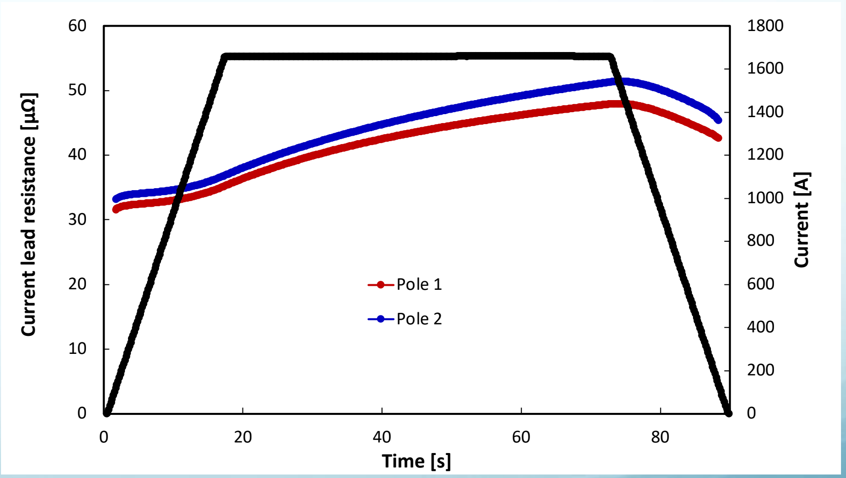
Temperature of connecting devices



CORC® cable voltage



Current lead resistance



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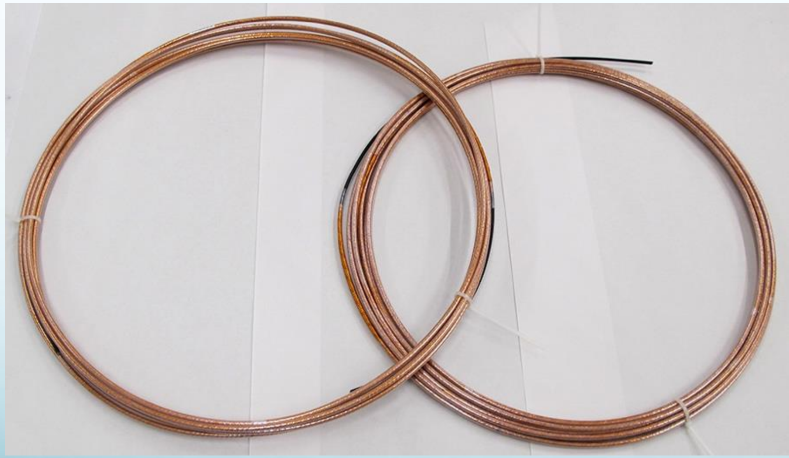
Los Alamos NATIONAL LABORATORY

Airbus ASCEND: CORC® AC and DC bus development

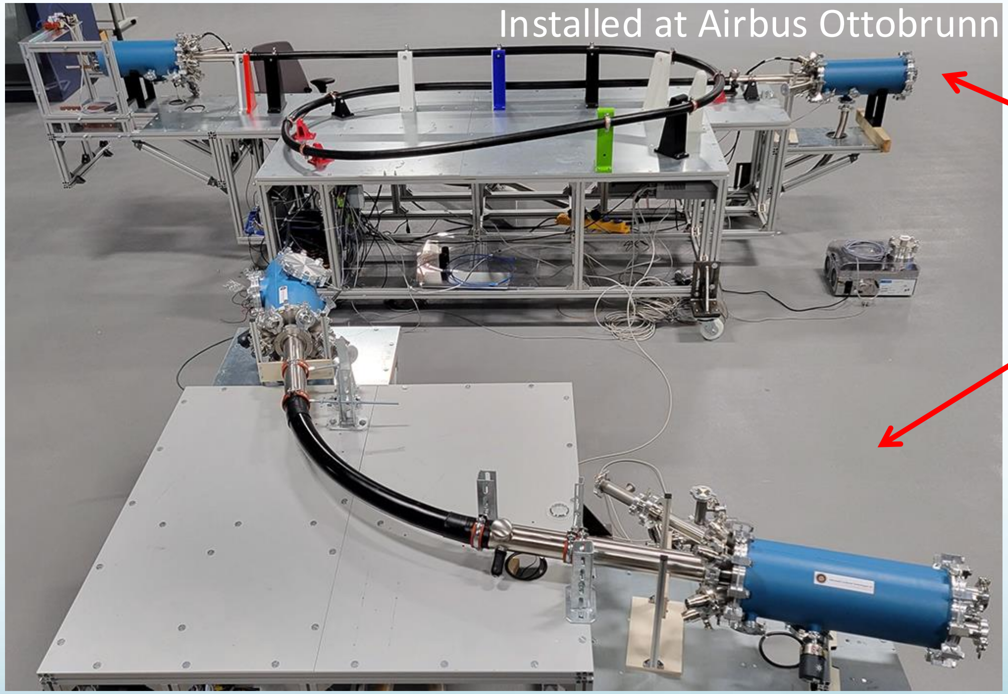
CORC® AC and DC bus status

- 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



ASCEND CORC® DC bus ready for testing at ACT



Installed at Airbus Ottobrunn

CORC® DC bus

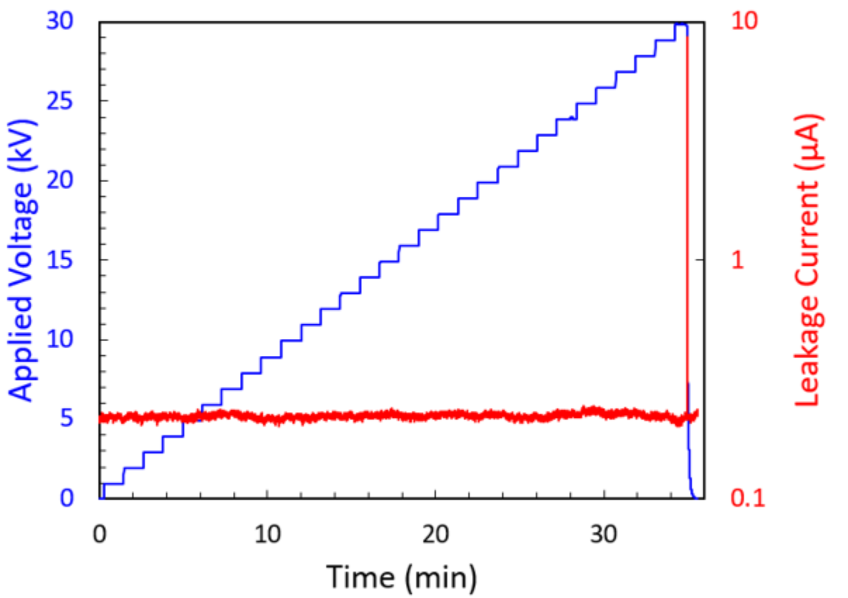
CORC® DC bus

High voltage compatibility of connecting interfaces

Challenges for cryogenic high voltage interfaces

- Next to current carrying components, cooling lines and instrumentation also need to be isolated
- High quality vacuum environment necessary for thermal and electrical insulation

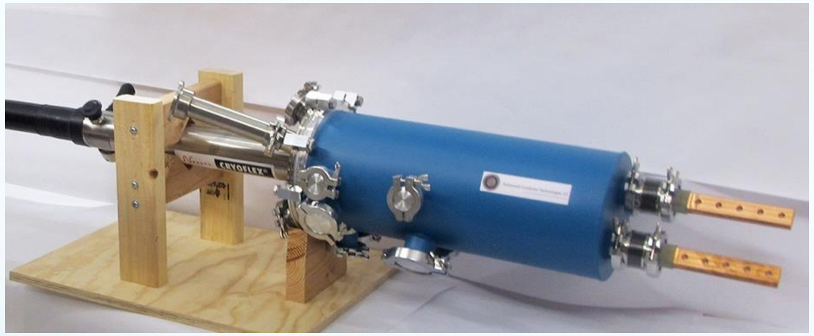
In prototype connecting interface configuration high voltage breakdown observed at 30 kV

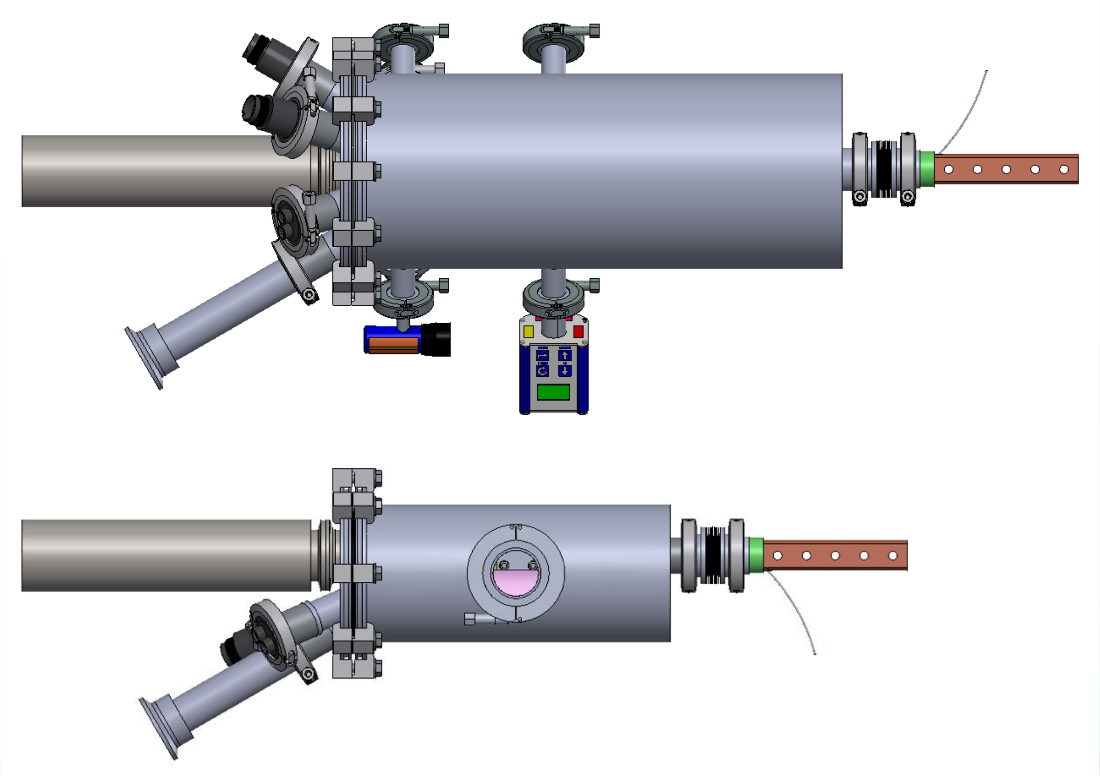


Connecting interface optimization

Current state of the art connecting interface

- Hardware for Airbus ASCEND demonstrator largely designed to for low risk and low repair cost in case of failure
- Previous connecting interfaces for Navy projects based on commercially available components with little customization



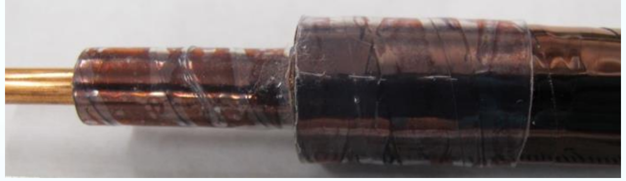


Upgraded design with similar performance points to Airbus ASCEND hardware designed with 3x volume reduction and 2-3 x weight reduction

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 with out 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