Development of high-temperature superconducting CORC® power cables for use on Navy ships and electric aircraft

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EUCAS, September 9th, 2021

The Need for High Power Dense Superconducting Cables

Many future applications require compact, lightweight superconducting cables capable of delivering 10 – 50 MW of power in confined spaces.

Electric ship applications

- The U.S. Navy is developing HTS dc power cables for shipboard applications
- Size and weight are an important consideration, while liquid cryogens should be avoided

Image courtesy of General Atomics

Electric aircraft

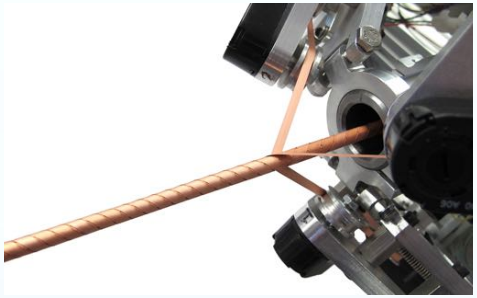
- Efforts to develop electric aircraft are ramping up
- Size, weight and reliability are important, while future use of liquid hydrogen as a fuel may ease cooling requirements

Image courtesy of Airbus

CORC® Power Cables and Wires

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

- Based on REBCO coated conductors
- Offering highly-flexible conductors
- Carrying high currents at high current densities
- Allowing low-resistance cable joints
- Having Fault Current Limiting abilities



Typical CORC® cable

- 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

Typical CORC® wire

- 3.6 mm diameter wire with 30 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

Technical Challenges to Overcome

To achieve reliable delivery of high electric power in dc CORC® cables requires

- Operation with pressurized helium gas cooling
- High current operation at 2,000 – 10,000 A
- Operating voltage of up to 12 kV
- Efficient current injection from room temperature
- High level of serviceability

Advanced Conductor Technologies has several programs in place to solve these technical challenges

U.S. Navy

Several Small Business Innovative Research (SBIR) grants awarded since 2013:

- N00024-14-C-4065 (He gas cooled cables)
- N00024-16-P-4071 (CORC® FCL cables)
- N68335-18-C-0151 (CORC® cable dielectrics)
- N68335-20-C-0648 (Cable interface to 300 K)

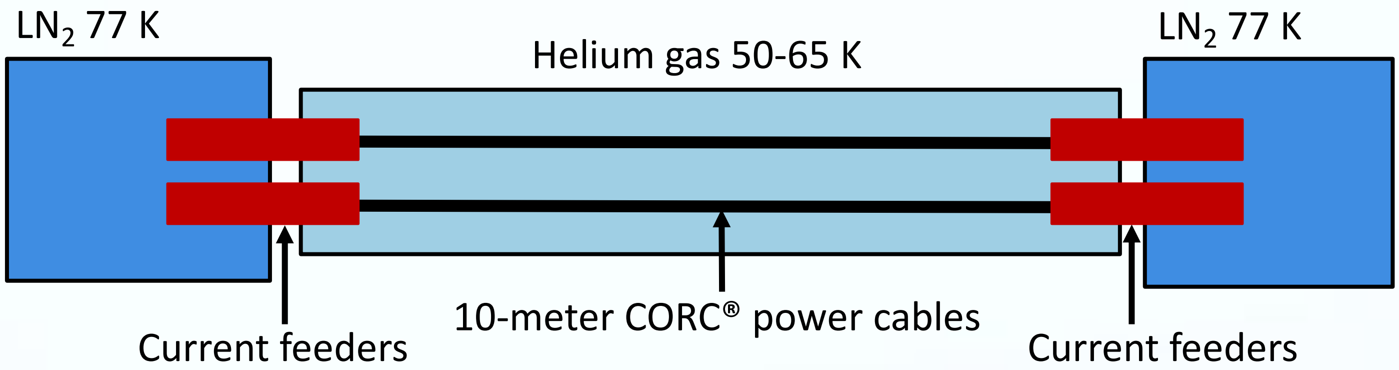
DOE, ARPA-E

A three-year program was selected for award to develop power cables for twin-aisle electric aircraft

- Coaxial CORC® dc FCL power cables and connectors
- Operation at 5 kA, 10 kV (50 MW)

Development of High-Current CORC® Power Cables

The goal is to develop and demonstrate high-current operation in a 10-meter long 2-pole CORC® power cable cooled with pressurized flowing helium gas.



Not part of the initial program (N00024-14-C-4065)

- Cable dielectric (no voltage rating)
- Helium gas cooled current leads (still requires LN_2 pre-cooling)

Components

- 10-meter long, 2-pole dc CORC® power cable
- All cryogenic hardware
- Current feeders between LN_2 and GHe environment
- Connectors between feeder and power cables

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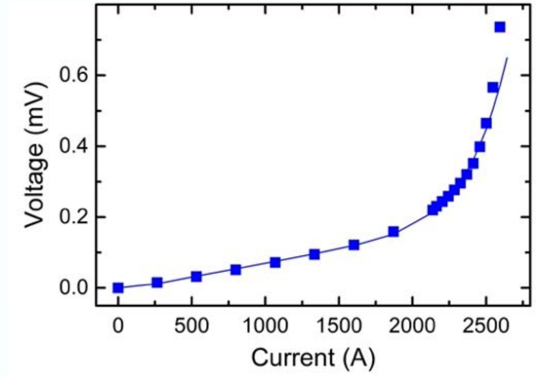
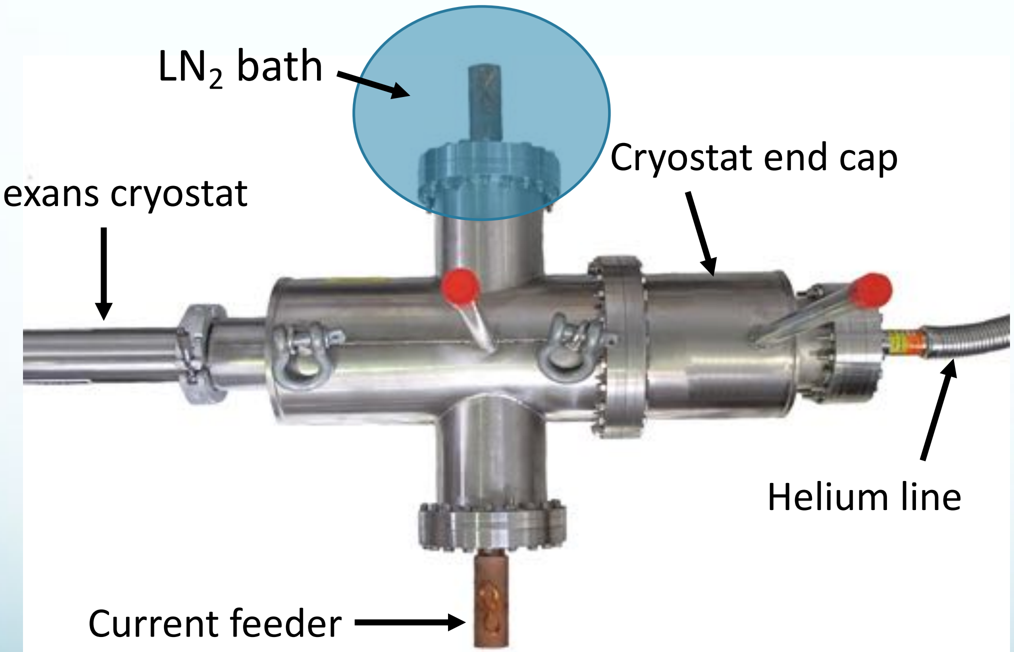
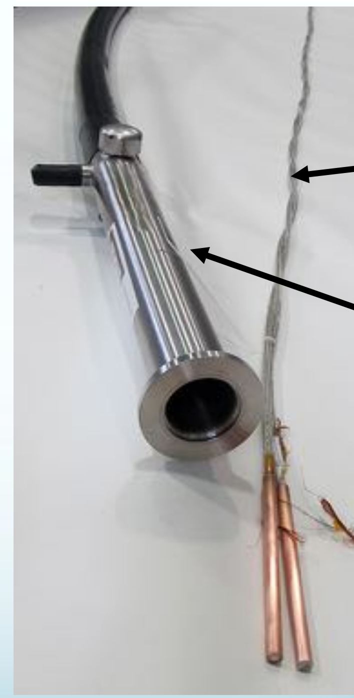
10-Meter 2-Pole CORC® DC Power Cable

CORC® cable

- 24 tapes of 4 mm width
- wound on an aluminum former
- I_c (76 K) = 2,287 A
- Projected I_c (50 K) = 12 – 14 kA



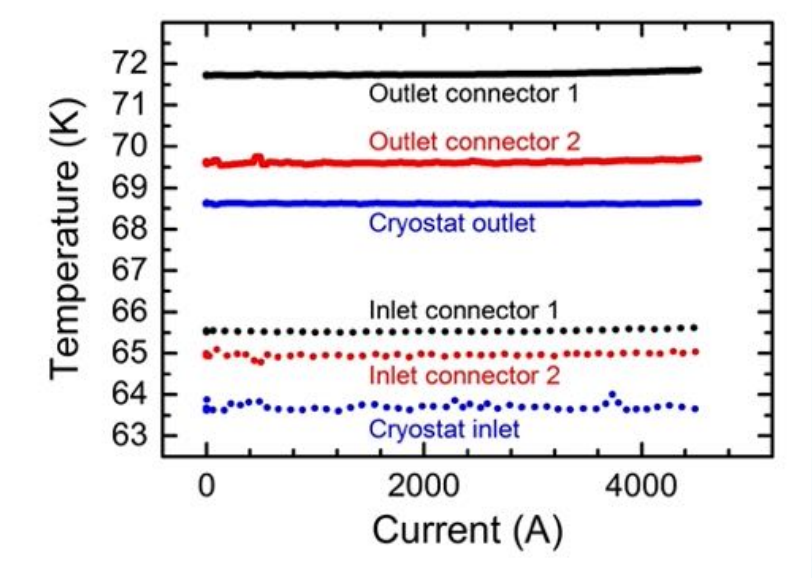


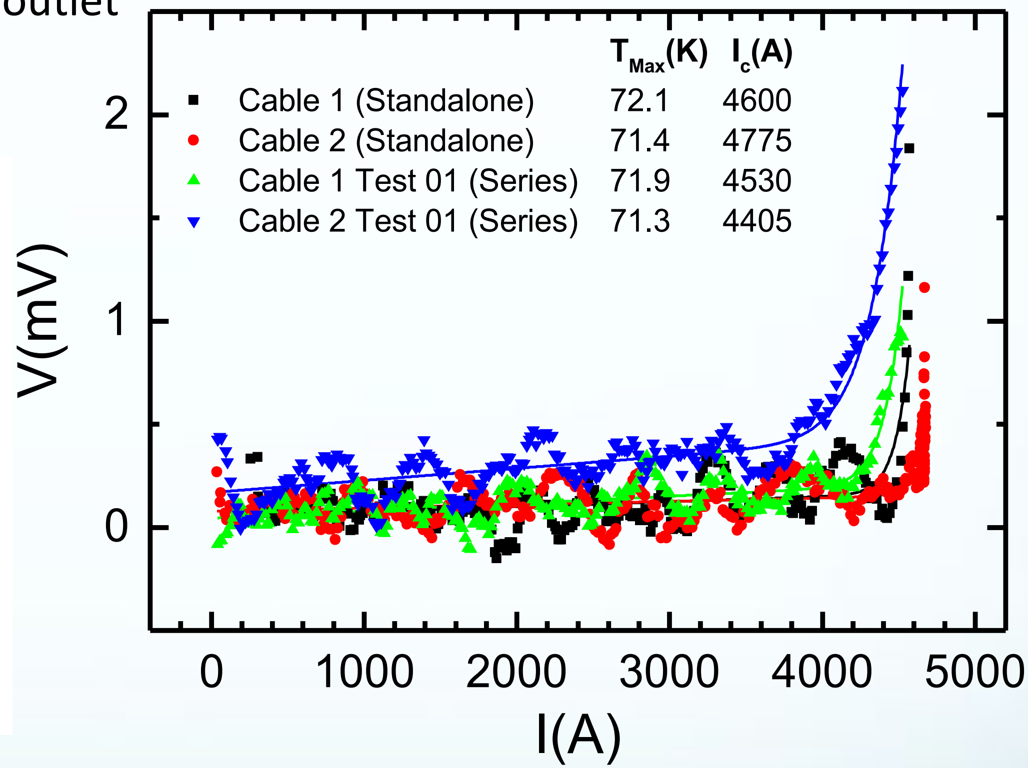


10-Meter 2-Pole CORC® Power Cable Test

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_c (Cable 1) = 4,600 A, I_c (Cable 2) = 4,775 A**
- **Series connected cable tests I_c (Cable 1) = 4,530 A, I_c (Cable 2) = 4,405 A**
- **Results suggest that I_c at 50 K > 10,000 A**

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High-Voltage HTS Cable Dielectrics

"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

NEXANS Best Path cable
http://www.bestpaths-project.eu/en/demonstration/demo-5

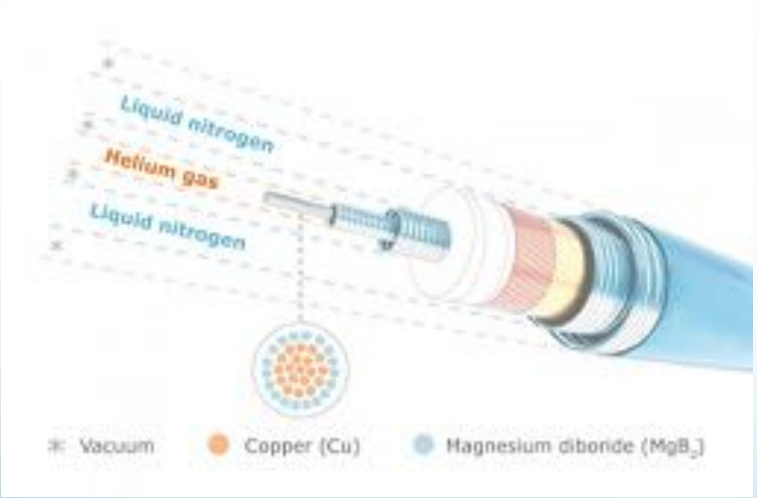

Image courtesy of SuperPower Inc.

Land-based power cables that require GHe cooling

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

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The Need for CORC® Cables With LN_2-Free Dielectrics

Overall goals

- Shipboard applications (Navy): 12 kV dc in helium gas cooled twisted-pair CORC® cables, while not allowing liquid cryogens
- Electric aircraft applications (ARPA-E): 10 kV in coaxial dc CORC® cables, independent of cooling method

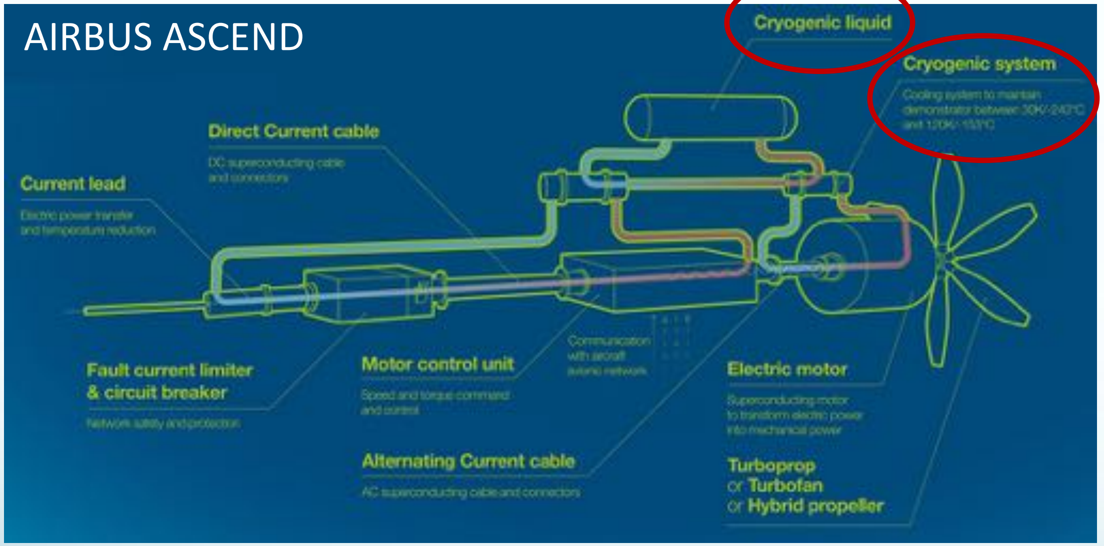


Image courtesy of Airbus

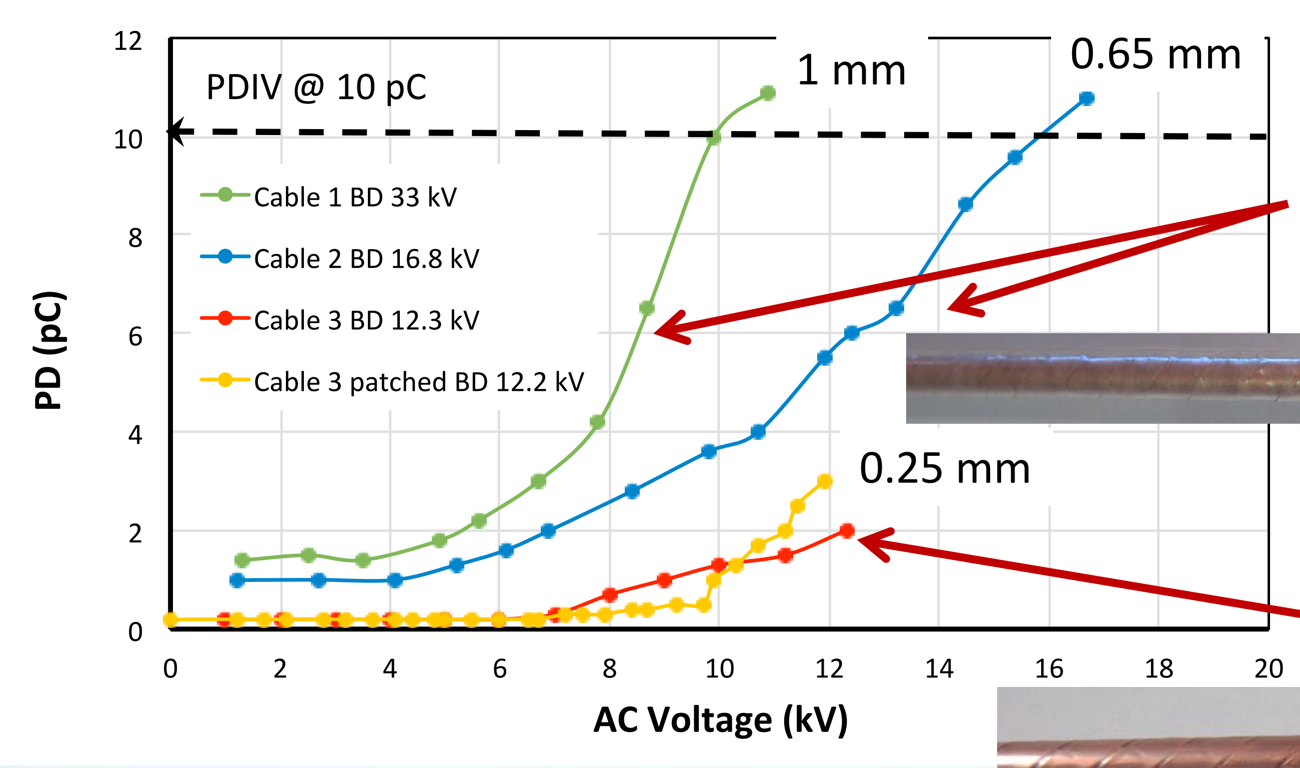
Perfect example: AIRBUS ASCEND

- Liquid hydrogen onboard as fuel and cold buffer
- Cooling of the superconducting components to 30 – 120 K likely through helium gas
- Operating voltage of ASCEND below 500 V, but future systems require much higher operating voltage to achieve 25 – 50 MW for take-off (5 kA x 5 – 10 kV)

Electric aircraft will face similar dielectric challenges as naval applications!

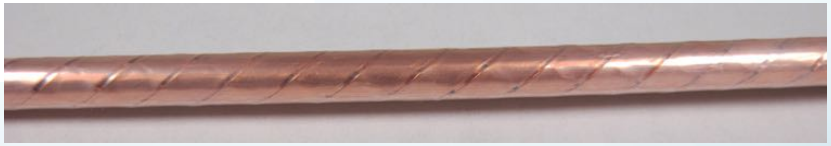
Dielectrics for Helium Gas Cooled CORC® Cables

Partial Discharge (PD) measurements at 77 K



Wrapped dielectric:
Southwire's Cryoflex

Continuous dielectric:
Polyester heat shrink tube



Preventing helium gas penetration significantly reduces the partial discharge

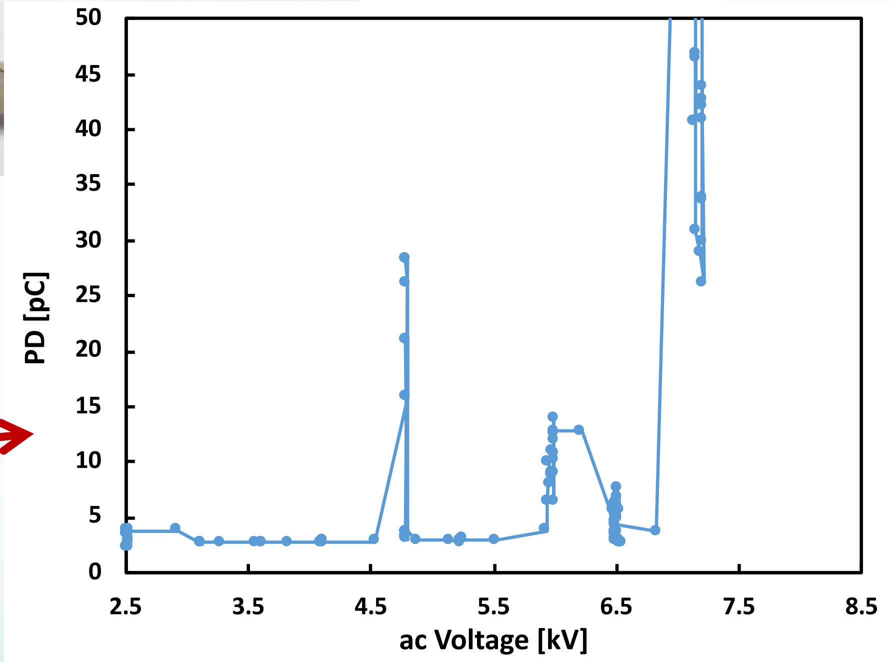
Exploring Various Continuous Dielectrics

Considerations to be taken into account

- How to increase the dielectric thickness without getting in trouble during cool down to cryogenic temperatures due to large CTE mismatch with the CORC® cable?
- How can the dielectric be applied without degrading the superconducting cable?

Extruded polyester cracked upon cool down

Extruded PEEK on copper cable to better match CTE



Partial discharge becoming a problem above 6.5 kV for 1 mm thick PEEK

Alternative Approaches to Develop Sealed Dielectrics

Why it's better to not go the extrusion route

- Extruding of PEEK onto the superconducting cable would likely harm it (extrusion temperature of PEEK is around 350 °C)
- Higher voltage rating would require thicker PEEK layers, making the cable very stiff

Dielectric separated from the helium gas as in the NEXANS Best Path case, and replacing it with:

- Nothing (air)
- A dielectric liquid

What would happen at 50 K?

- Most particles in air would freeze
- The dielectric liquid would solidify

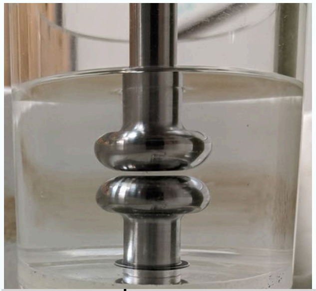
Alternative Approaches to Develop Sealed Dielectrics

Wrapped NOMEX 410 dielectric in air

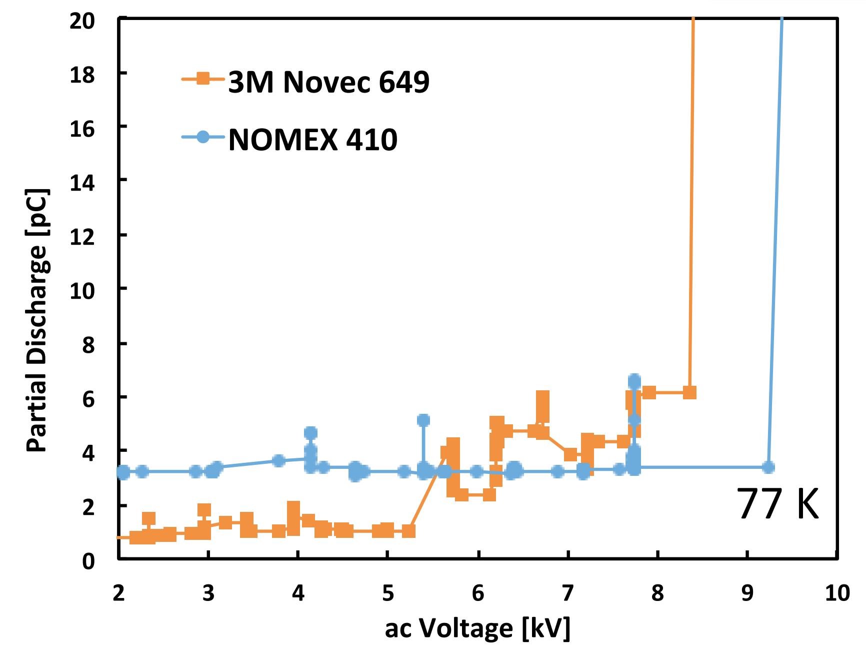
- 20 layers resulting in a 2.3 mm thick layer
- Sample was a 8 mm diameter copper rod

3M Novec 649 engineering liquid

- Liquid forms a continuous solid when frozen
- Using ABS, GPO or FTPE spacers



Run #	RT BD (kV)	Run #	77 K BD (kV)
1	17.7	1	57.9
2	17.4	2	41.9
3	20.6	3	43.5
4	26.1	4	38.9
5	27.7	5	8



Initial results of alternative approaches with low PD up to 9.5 kV are encouraging!

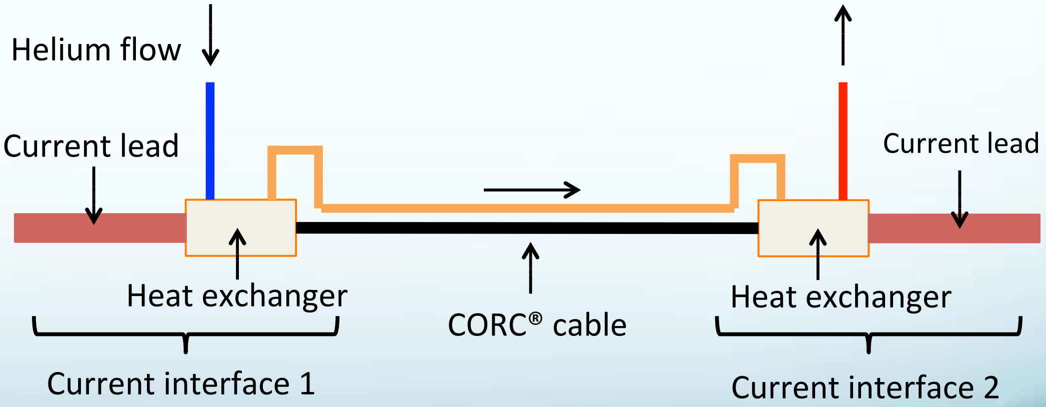
Development of Efficient CORC® Cable Interface

Overall goal

- Develop a compact cable interface between 50 K and room 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

System configuration

- Single-pole CORC® cable
- Flexible cryostat (2 m)
- Conduction-cooled leads, optimized for 1,200 A
- Mainly off-the-shelf vacuum hardware



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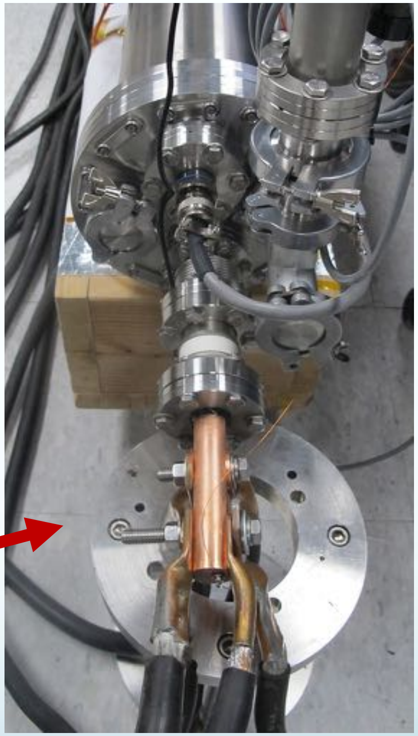
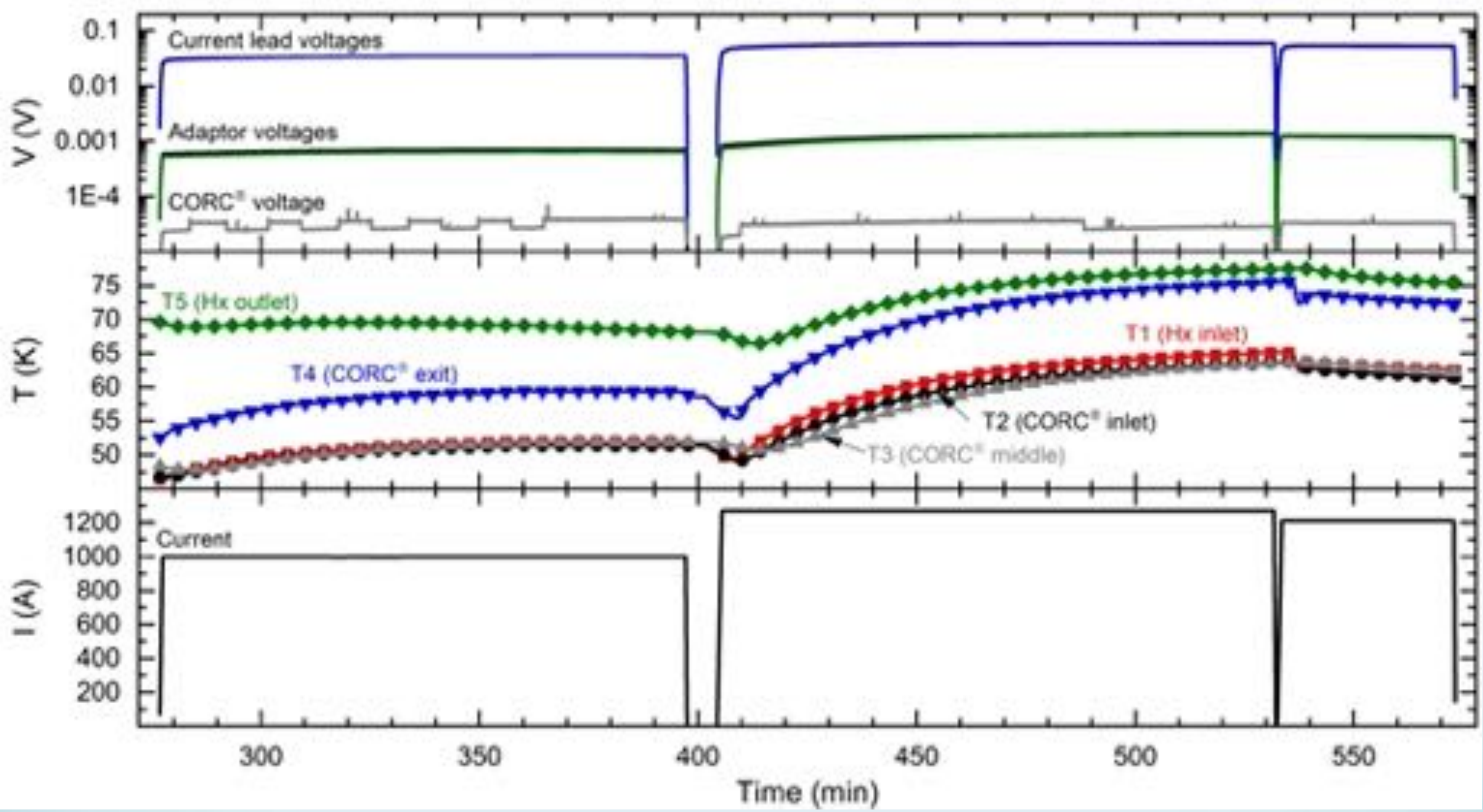
CORC® Cable and Current Lead Test Setup

Stirling Cryogenics cryogenerator with closed-loop helium gas flow loop at Advanced Conductor Technologies



Continuous Operation at 1,200 A of the CORC® Cable



- **Cool down from room temperature to operating temperature within 5 hours**
- **Temperature increasing at 1,230 A and dropping at 1,200 A**

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Summary

Successful initial demonstration of a helium gas cooled CORC® cable

- 2-pole dc cable operation demonstrated at over 4,000 per pole
- Cable was cooled with pressurized helium gas
- Current leads were cooled with liquid nitrogen

Development of dielectrics for helium gas cooled CORC® cables underway

- Several approaches to seal the dielectric from helium gas penetration explored
- Dielectrics now allow operation at about 6 kV, halfway to our goal of 12 kV

CORC® cable terminations with helium gas cooled current leads developed

- Removes the requirement of liquid nitrogen pre-cooling and only requires helium gas
- Turnkey, continuous operation at 1,200 A demonstrated