EFATS 22, Glasgow Scotland,
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Development of high-temperature superconducting CORC® power cables for use on electric aircraft

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AIRBUS Los Alamos NATIONAL LABORATORY Georgia Tech

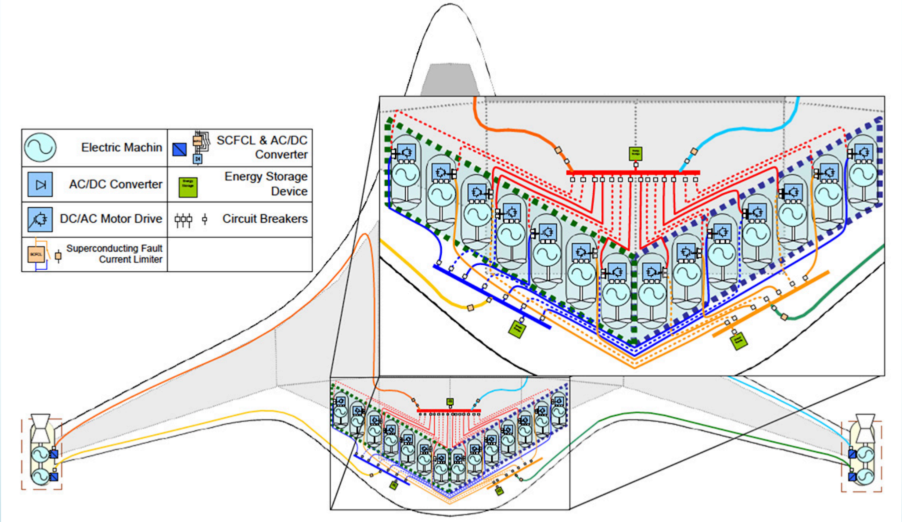
Considerations for the superconducting power bus in electric aircraft

Carbon-free passenger air travel

- May include transitioning to liquid hydrogen fuels and distributed electric propulsion
- But twin-aisle electric aircraft may require 25 MW during take-off

Conceptual design of a distributed propulsion electric grid by Rolls Royce for NASA

- Generators powered by jet engines
- Main busses between generators and distribution network that feed the motors



Armstrong M., et al., "*Architecture, Voltage, and Components for a Turboelectric Distributed Propulsion Electric Grid,*" NASA/CR—2015-218440

Superconducting electric powertrain by Airbus

- Liquid hydrogen fuel acts as cold source (20 K)
- Cooling of superconducting components by helium gas at 20 – 30 K

Image courtesy of Airbus

CORC® cables and wires pioneered by Advanced Conductor Technologies

Power cables for twin-aisle electric aircraft

- Require 25 MW dc power rating requiring currents of up to 5 kA and a voltage up 10 kV
- Won't allow any significant heating due to the high cost to remove heat from the aircraft
- **Only superconducting cables can meet these requirements**

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

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

CORC® performance

- 3 – 7.5 mm diameter
- Bending radius < 30 – 100 mm
- I_c (77 K) > 4,500 A, J_e (77 K) > 200 A/mm^2
- I_c (50 K) > 18,000 A, J_e (50 K) > 800 A/mm^2

Status of CORC® Cables and Wires for Use in High-Field Magnets and Power Systems a Decade After Their Introduction ,D.C. van der Laan, J.D. Weiss and D.M. McRae, Supercond. Sci. and Technol. **32**, 033001 (2019)

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: operating current 1.7 kA (dc bus) 1.66 A rms (ac bus), operating voltage 300 V
- Cooling with sub-cooled liquid nitrogen
- **Advanced Conductor Technologies was awarded the contract to deliver the dc and ac busses for ASCEND**
- Hardware delivery January 2023, demonstrator commissioning before June 2023

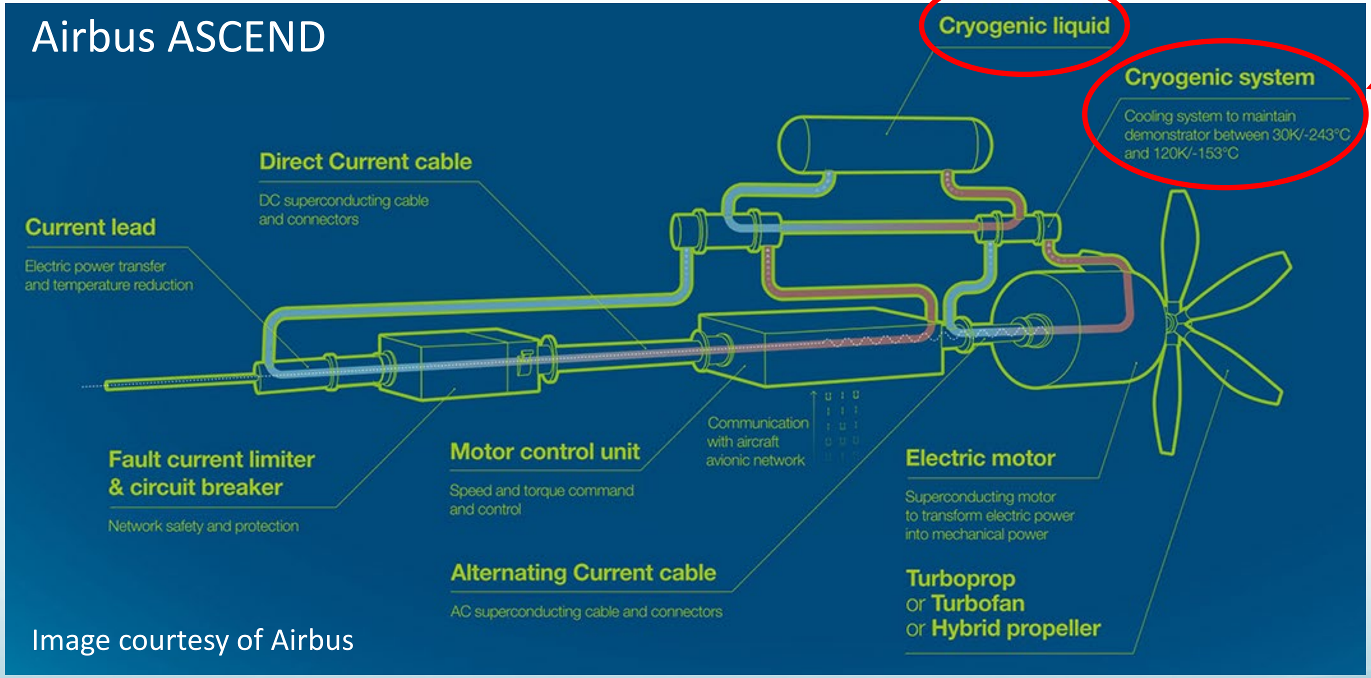


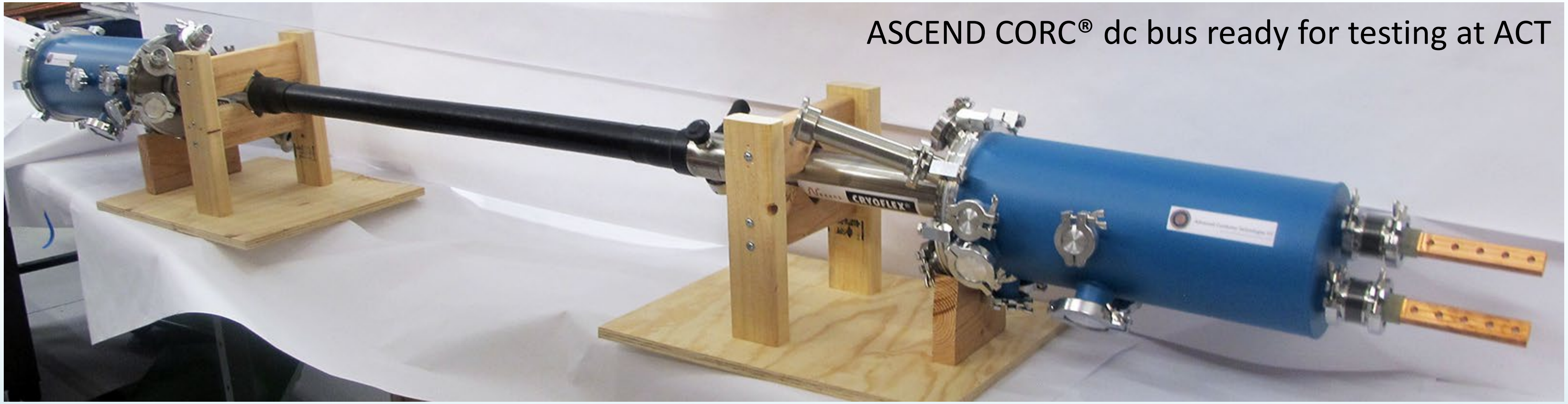
Image courtesy of Airbus

Although ASCEND uses LN_2, eventually gaseous helium (GHe) is required!

Airbus ASCEND: CORC® dc bus

Based on current CORC® technology

- Twisted-pair CORC® power cable, 10 meters in length
- Interfaces to room temperature (Connecting Device 1 "CD-1") and 100 – 120 K power electronics (CD-3)
- Sub-cooled liquid nitrogen for maximum cooling and low-risk dielectrics
- Operating current of 1.7 kA, but low voltage of 300 V (2 kV peak during fault)
- Fault Current Limiting (FCL) capability to limit 6.8 kA overcurrent fault for 10 ms



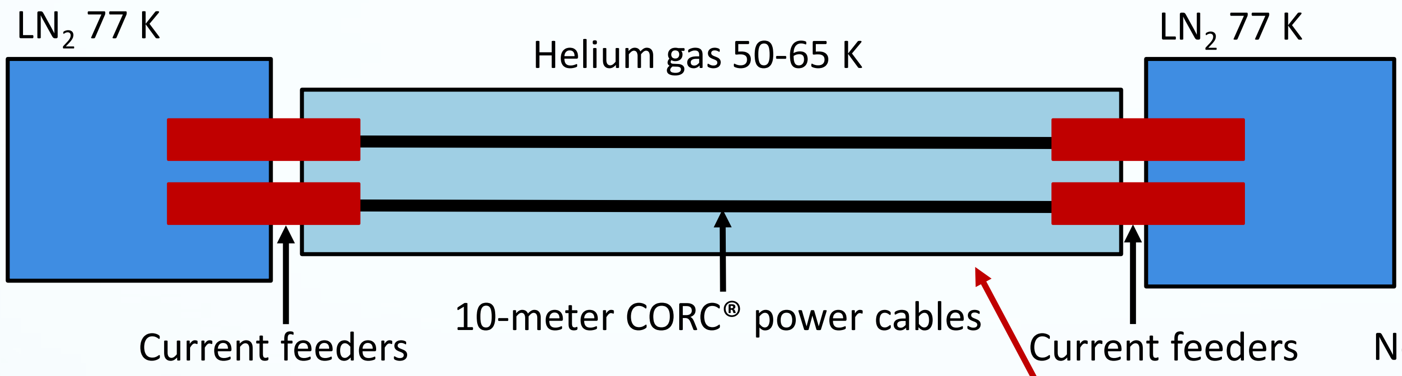
ASCEND CORC® dc bus ready for testing at ACT

See talk Emelie Nilsson (Airbus UpNext) at 18:00 today

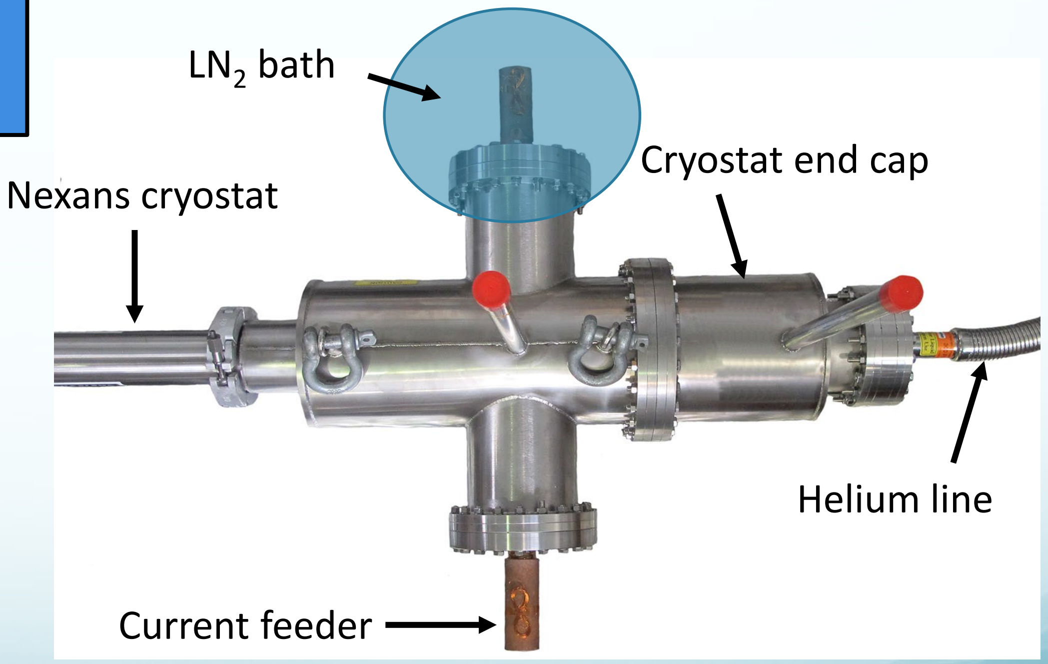
Development of helium gas cooled CORC® power cables

Why cool with helium gas?

- Liquid nitrogen is incompatible as coolant between the liquid hydrogen tank and superconducting powertrain
- Lower operating temperatures with helium gas allows higher currents needed to achieve 25 MW power rating



"Showstopper" termination



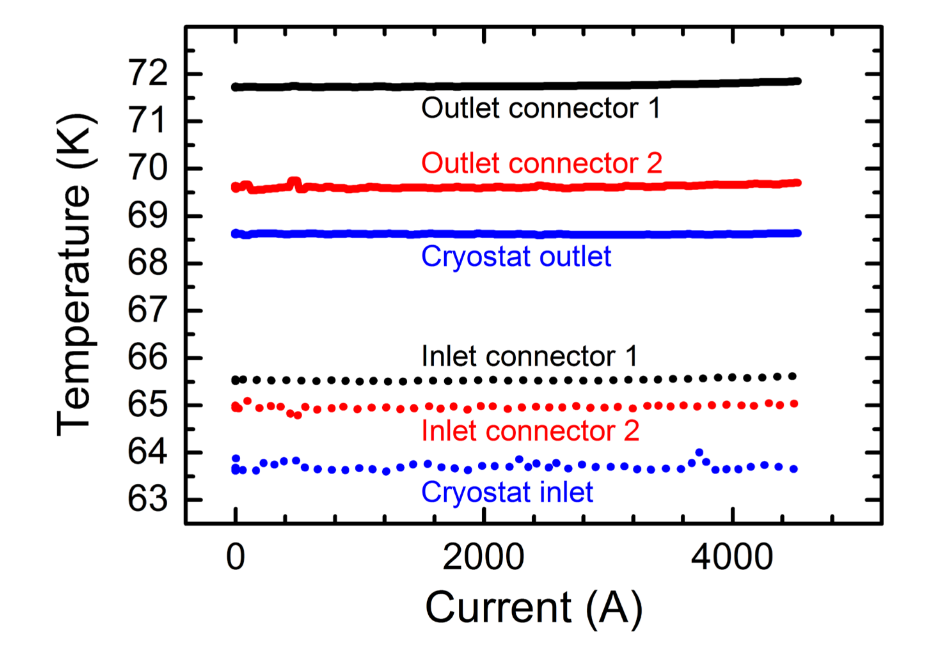
Initial CORC® power cable test in GHe

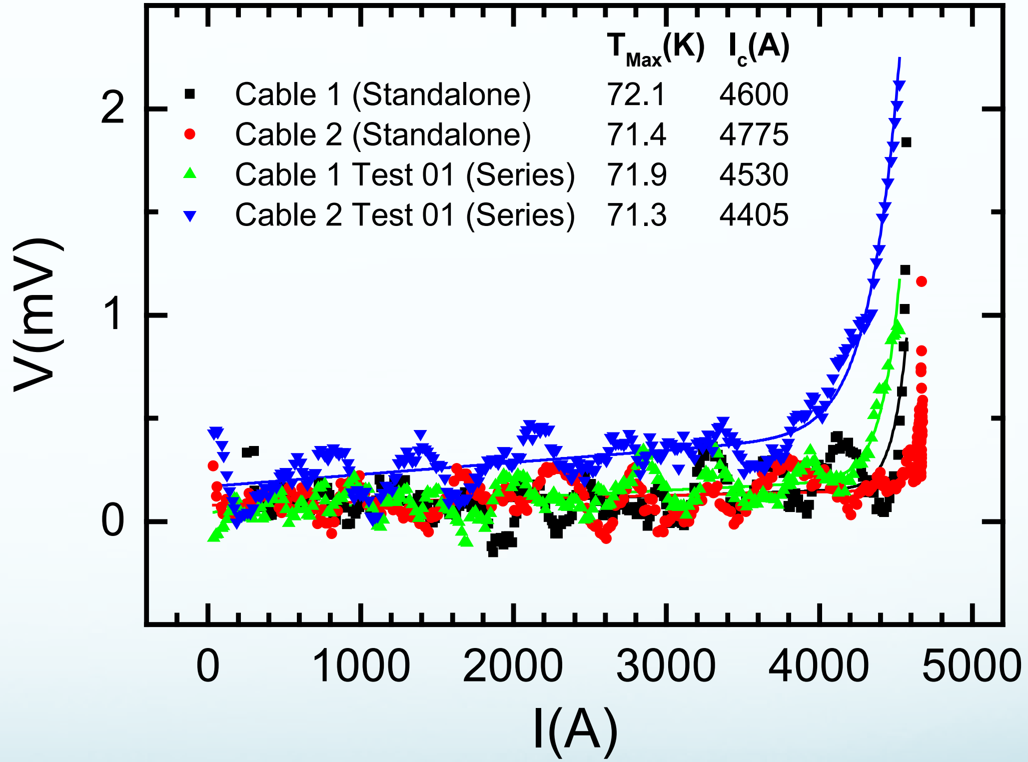
- Navy contract N00024-14-C-4065
- Operating current 4 kA per pole
- Dc CORC® cable cooled with He gas to 65 K
- Liquid nitrogen baths to cool the 4 current leads to room temperature

Operation of helium gas cooled CORC® power cables

CORC® power cable test in GHe results

- 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





Development of CORC® cables for helium gas cooled power transmission and fault current limiting applications, D.C. van der Laan, J.D. Weiss, C.H. Kim, L. Graber and S. Pamidi, *Supercond. Sci. and Technol.* **31**, 085011 (2018)

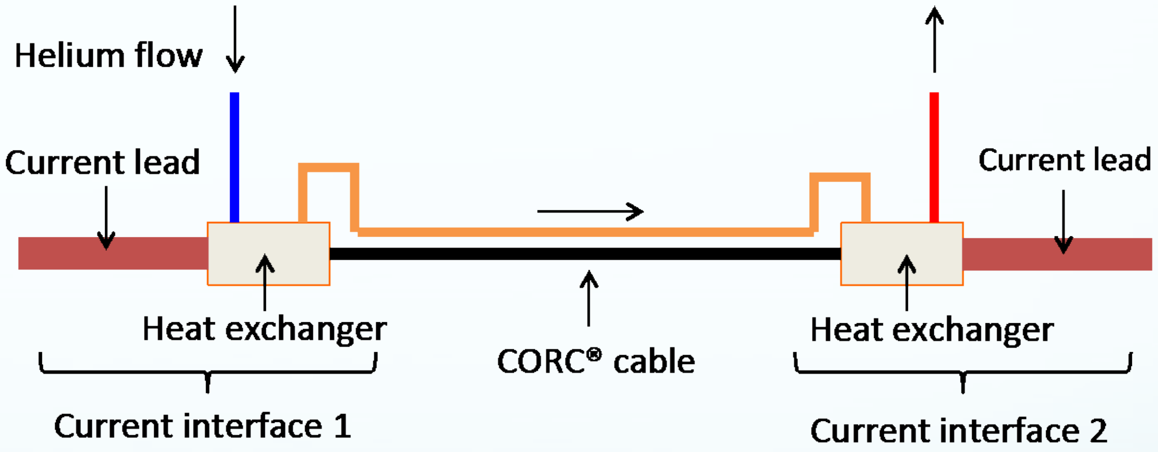
Development of compact CORC® cable terminations with 300 K interface

Development of compact cable terminations (Navy contract N68335-20-C-0648)

- 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
- 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

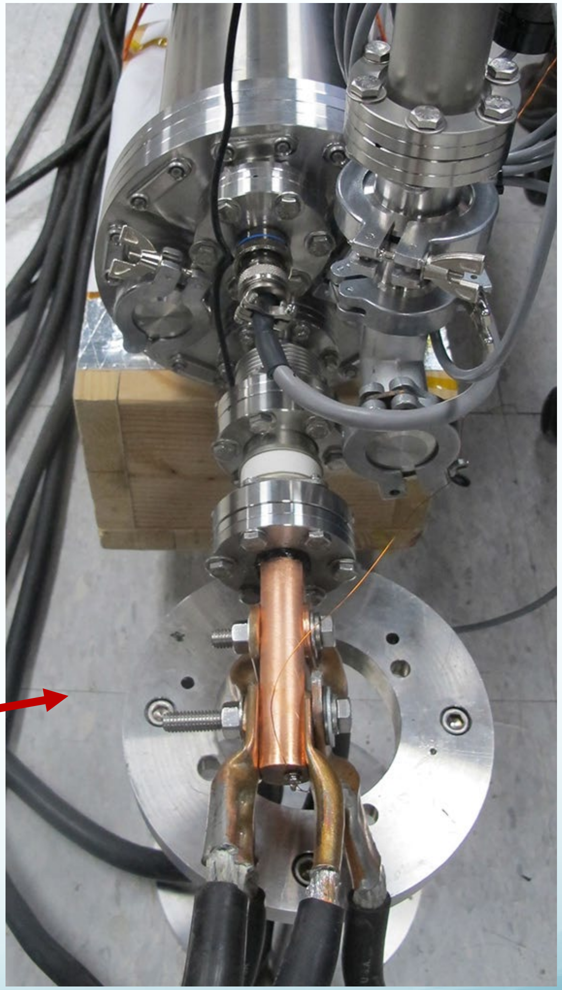


Operation of a turnkey, gaseous helium cooled CORC® dc power cable with integrated current leads,
D.C. van der Laan, C.H. Kim, S. Pamidi, and J.D. Weiss, *Supercond. Sci. Technol.* **35**, 065002 (2022)

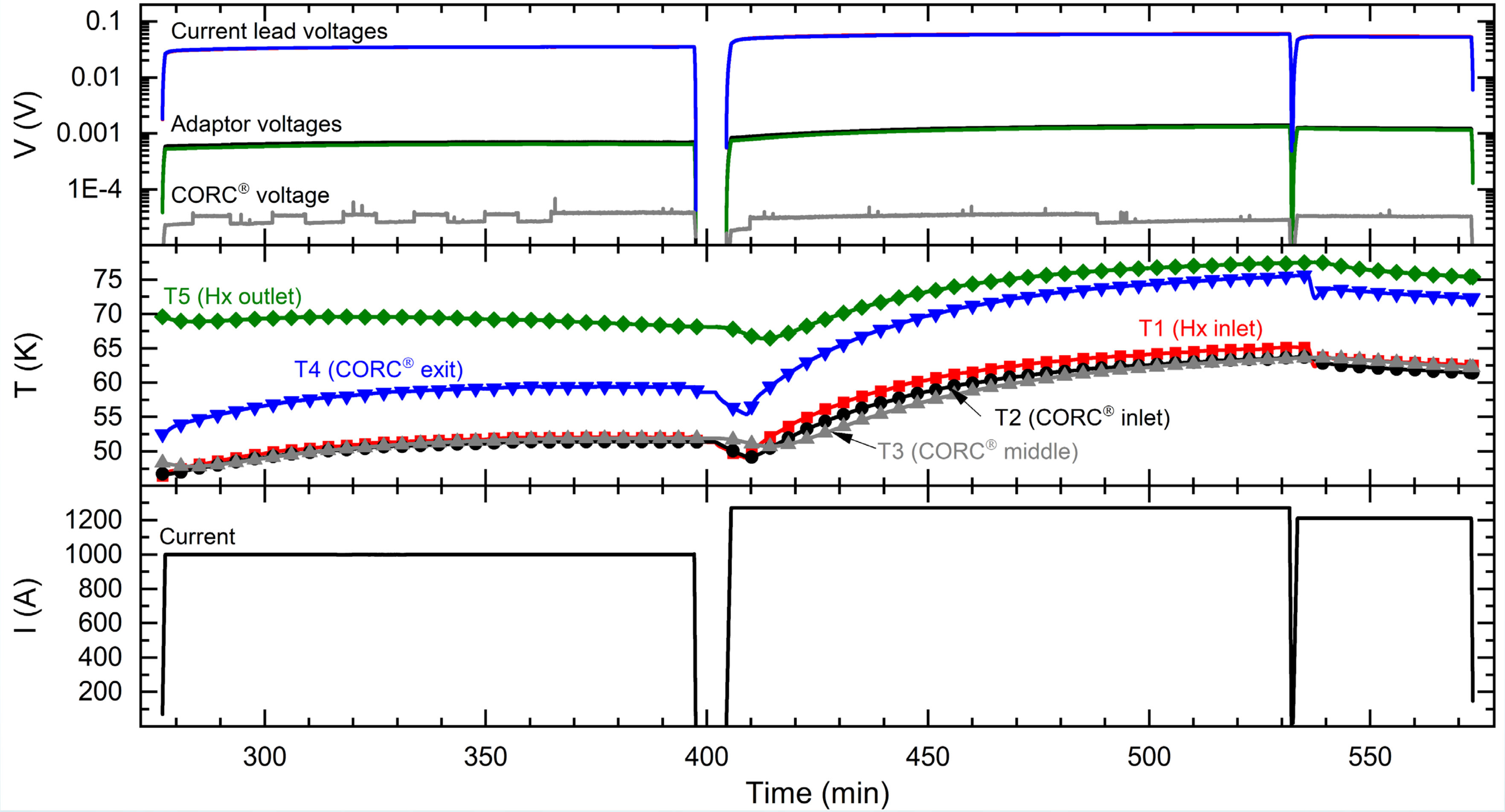
Operation of GHe cooled CORC® cable with interface to room temperature

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

Room temperature current lead connected to copper power cables



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**

Development of 12 kV dielectrics for GHe cooled CORC® 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
- This approach is currently being followed for the ASCEND demonstrator

High operating voltage exceeding 100 kV “easy” to achieve in LN_2

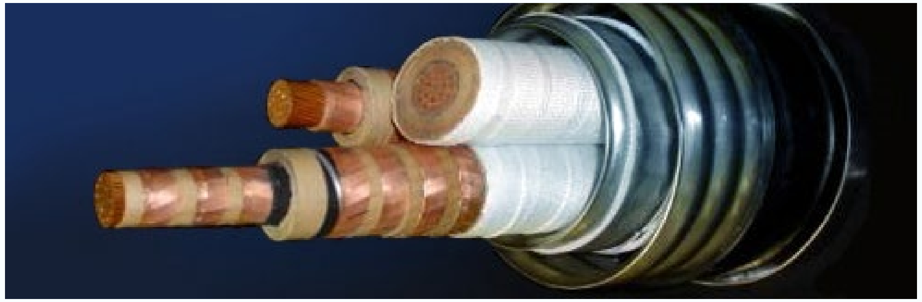


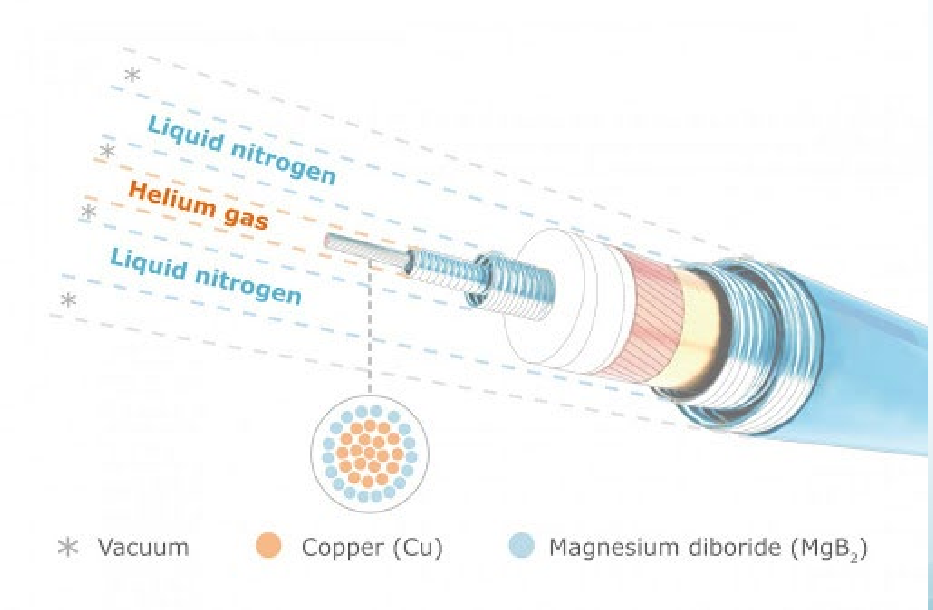
Image courtesy of SuperPower Inc.

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

Our approach to reach 12 kV rating (Navy contract N68335-18-C-0151)

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



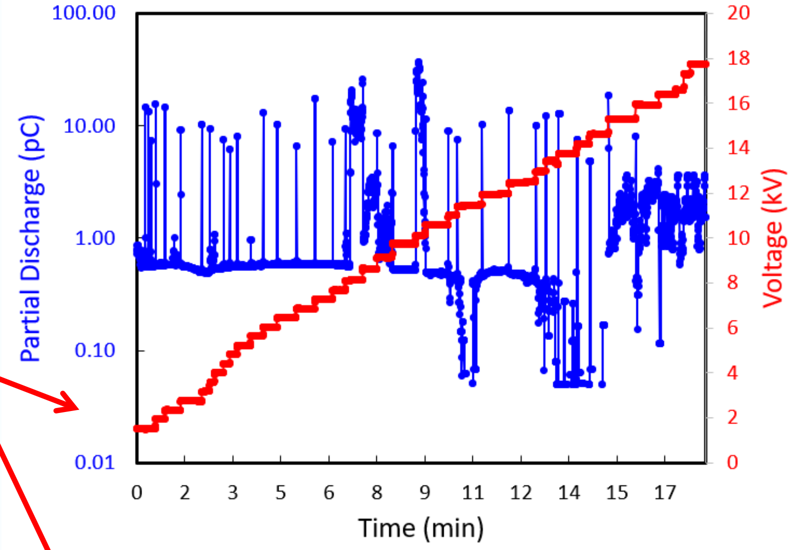
NEXANS Best Paths cable
http://www.bestpaths-project.eu/en/demonstration/demo-5

Development of coaxial CORC® cables rated 50 MW (5 kA and 10 kV)

Dielectric requirements

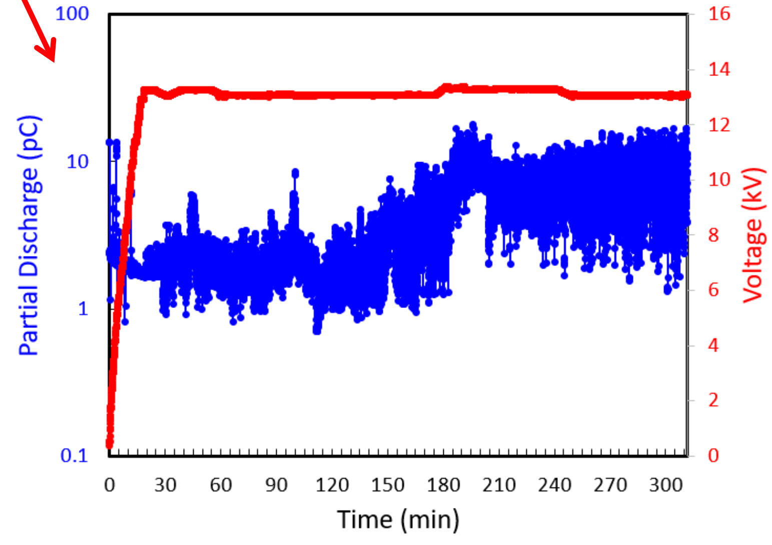
- Rating of 12 kV dc independent of cryogenic medium
- Partial Discharge Inception Voltage > 15 kV
- Breakdown voltage > 25 kV

NOMEX 410 dielectric



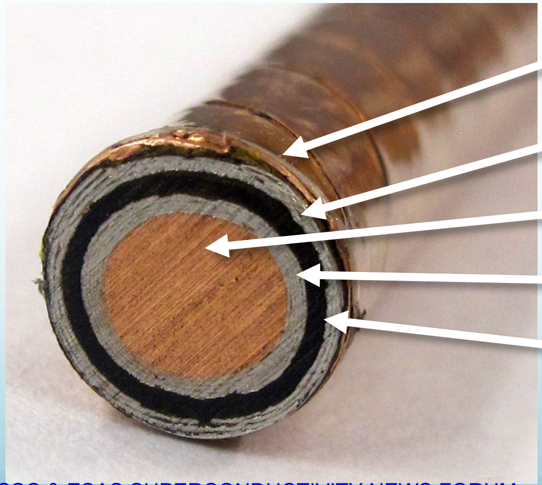
Example wrapped dielectric: 2.3 mm NOMEX 410

- Partial discharge free to 18 kV at 77 K
- Flashover at 25 kV (not shown)



2-Pole coaxial CORC® cable (ARPA-E contract DE-AR0001459)

- 5 kA per pole @ 30 K
- 10 kV between poles
- **50 MW power rating**
- 8 mm thickness
- **Power density 1 MW/mm²**



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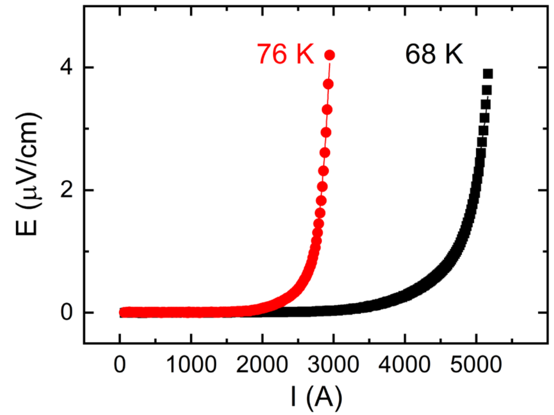
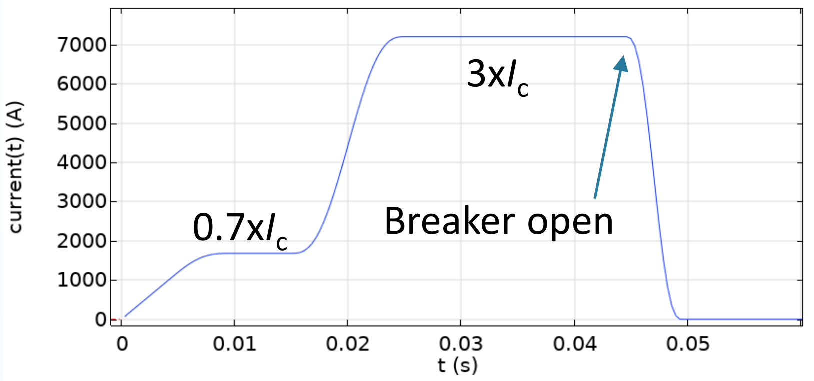
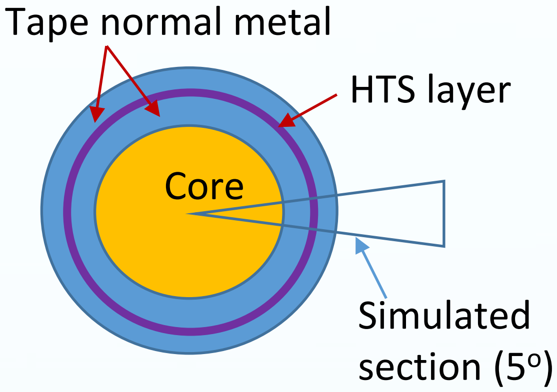
Development of CORC® Fault Current Limiting cables: modeling

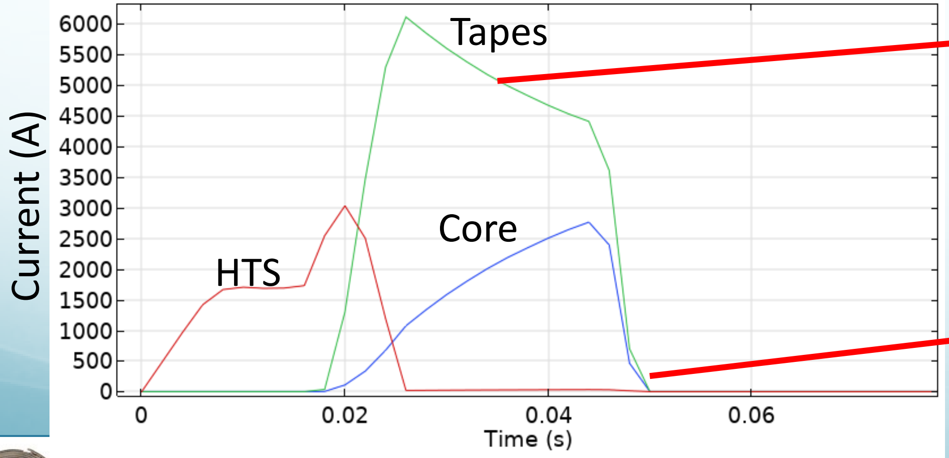
Principle of CORC® cable FCL operation

- No voltage below the critical current (I_c) of the cable
- Overcurrent drives the cable into a dissipative state
- Normal-state resistivity results in a large voltage, which limits the current



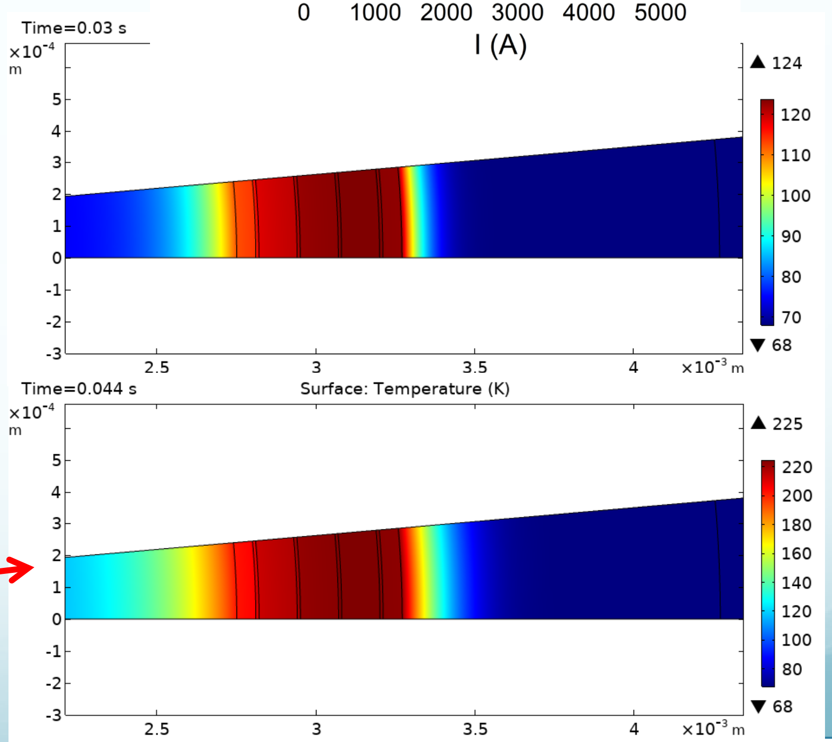






30 ms:
cable at 123 K

44 ms:
220 K, still confined within the cable

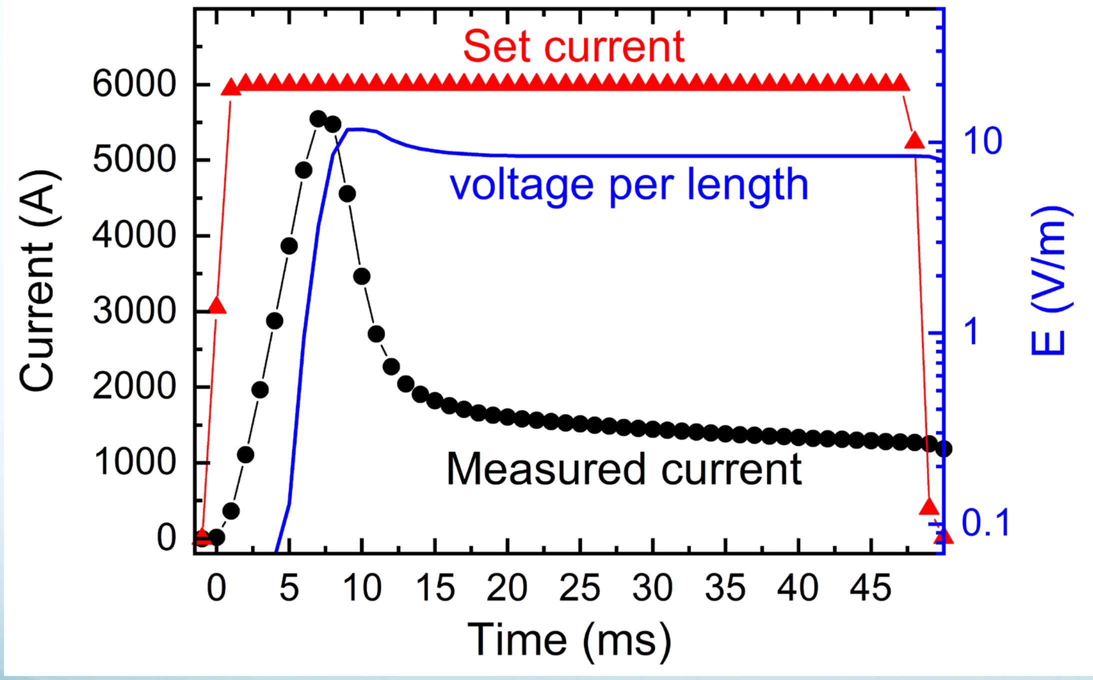


Development of CORC® FCL cables: Initial results

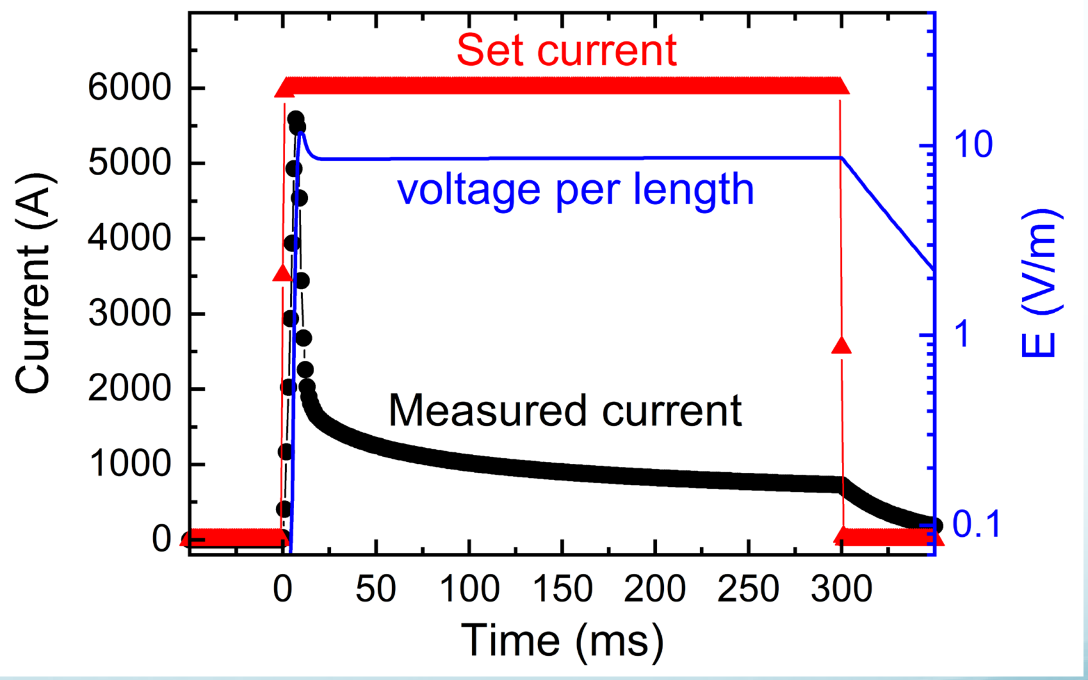
CORC® FCL cable test (0.9 meters in length)

- 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 1.5 kA within 10 ms
- No damage to cable even after 300 ms of fault current

Fault duration: 50 ms



Fault duration: 300 ms



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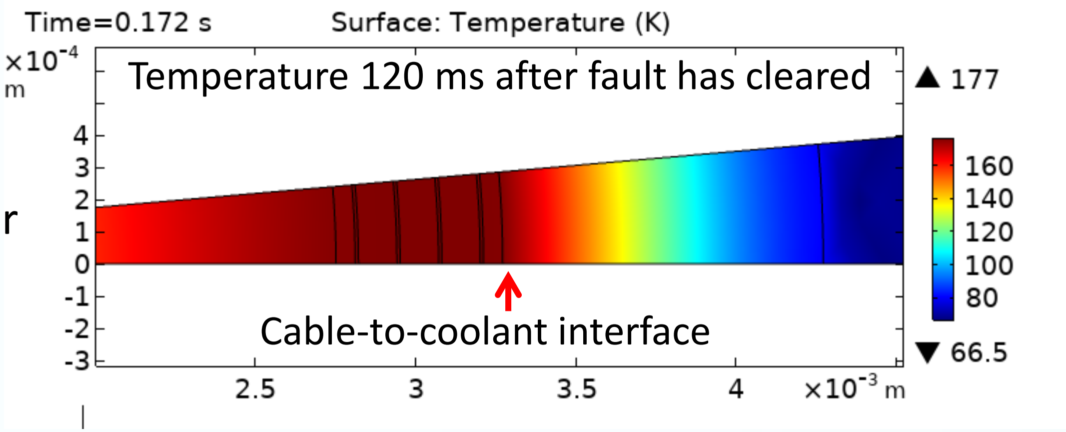
Considerations regarding CORC® FCL cables within electric aircraft

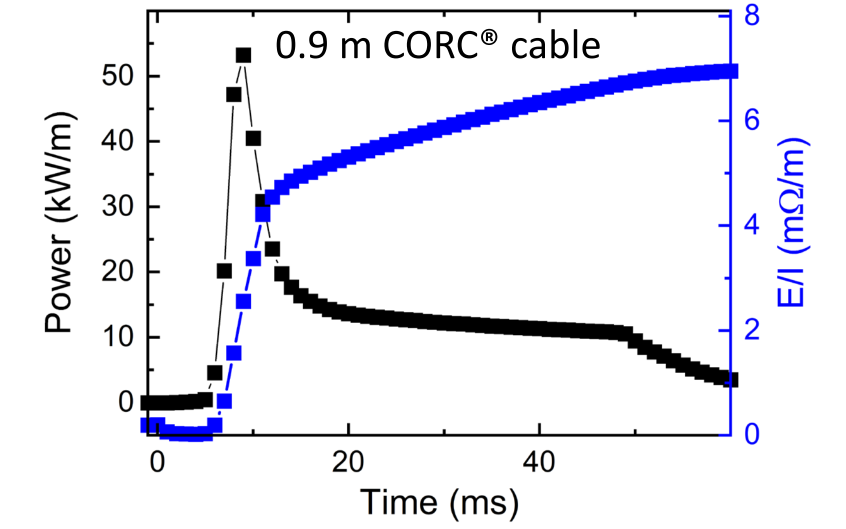
The energy dissipated within the CORC® FCL cable goes somewhere

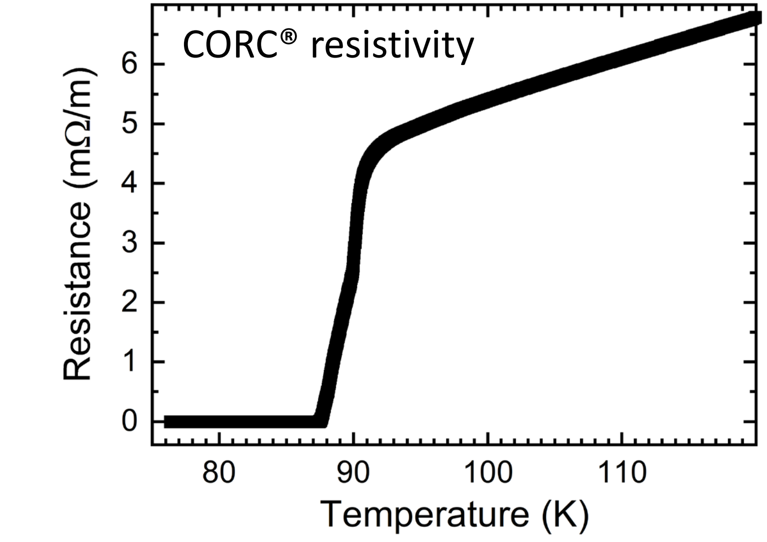
- Heating initially confined within the REBCO tapes
- Energy transferred to coolant after 50 – 100 ms depending on thermal barrier formed by dielectric
- Peak dissipation 50 kW/m (0.9 m cable) , peak temperature (sensor under cable dielectric) 95 K, cable resistivity suggests 125 K

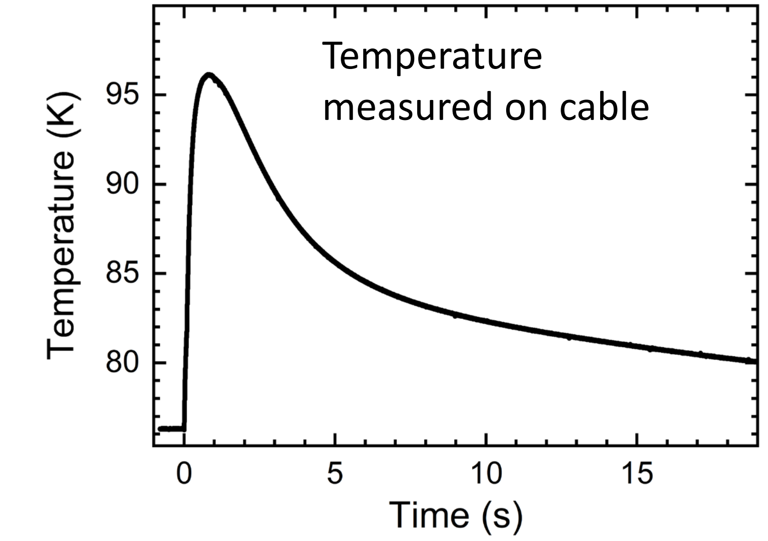


Heat transfer to cryogen

- Likely results in phase transition (boiling) of LN_2
- **Large increase in system pressure can be expected!**







Overcurrent in GHe-cooled CORC® non-FCL power cable

Overcurrent test 10 meter 2-pole CORC® cable in helium gas

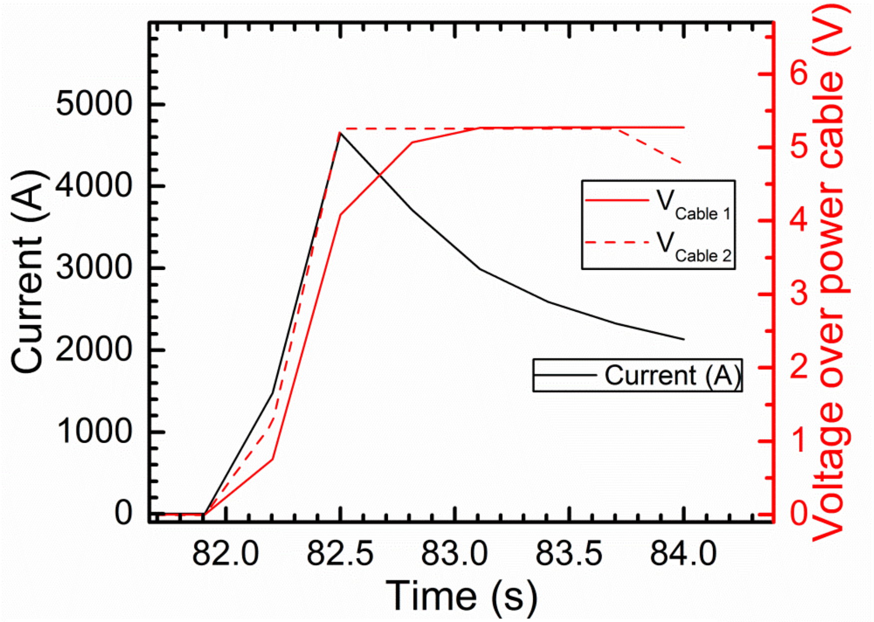
- Helium gas pressure 10 bars before fault
- Applied current of 6,000 A (136 % of I_c)
- 10 V supply voltage limit
- Overcurrent duration 2 seconds

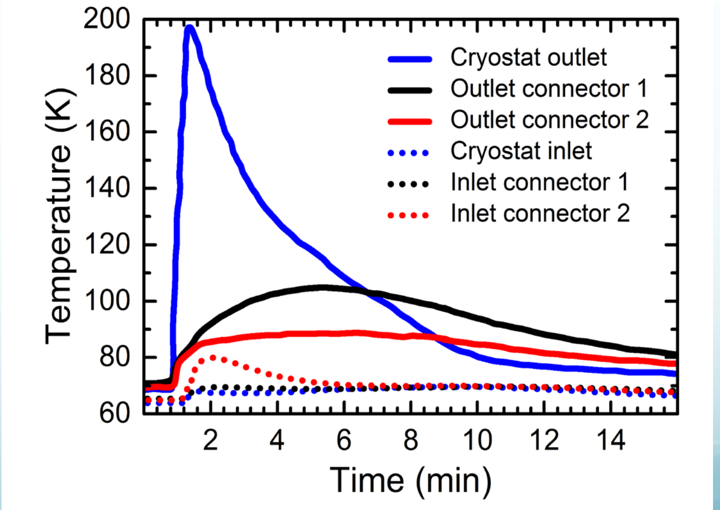
Effect of overcurrent

- Increased resistance limited current to 2,000 A within 2 seconds
- Maximum power dissipation: 43.4 kW
- Total energy dissipated: 53.7 kJ
- Maximum helium gas temperature 200 K
- Maximum helium gas pressure 30 bars

Helium gas cooled CORC® FCL cables

- Have the potential to limit the peak system pressure due to an overcurrent fault
- Pressure increases linearly with temperature in absence of a phase change
- Potential use of gas buffer tank to further reduce peak pressure





Summary

Superconductivity is an enabling technology for twin-aisle electric aircraft

- Required 25 MW of power during takeoff can't be achieved in a conventional distribution system due to its extremely high weight and excessive cable heating that needs to be removed
- Liquid hydrogen as a fuel makes superconducting power trains extremely attractive because there's no need for cryocoolers or liquid coolant storage
- Such a system would likely use helium gas as coolant of the superconducting system

CORC® cables offer a highly attractive solution for electric aircraft

- The 0.5 MW dc and ac busses of the Airbus ASCEND demonstrator will be based on CORC® cables, cooled with flowing sub-cooled liquid nitrogen
- CORC® cables have demonstrated their ability to operate at 4 kA in gaseous helium at 70 K, with a clear path to 5 – 10 kA at 30 K
- CORC® cable dielectrics have been developed to allow 12 kV dc operation, independent of cryogen
- A 50 MW 2-pole CORC® dc power cable has been developed

Superconducting cables have additional benefits for electric aircraft, but also require careful consideration

- CORC® power cables have demonstrated their ability to limit overcurrents as high as 3 times the operating current without burnout after 300 ms
- Potential pressure buildup in the cryogenic system during a fault has to be taken into account in a closed-loop cooling system

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