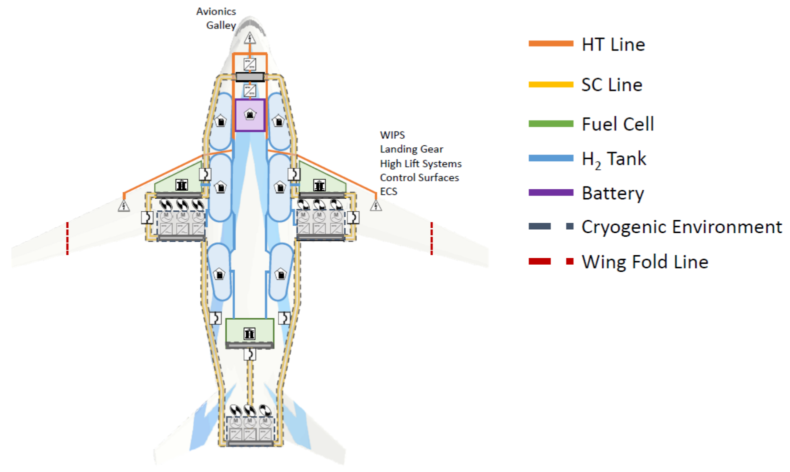
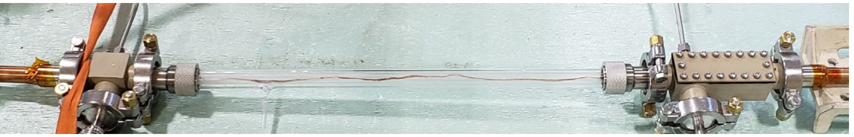
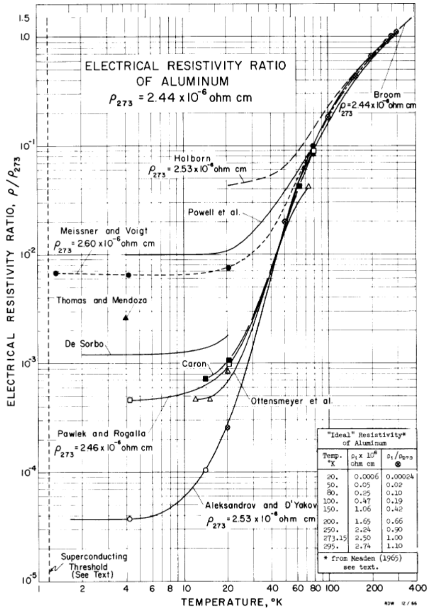


Cryoresistive and Superconductive Aerospace Main Power Transmission Cables





Chris Kovacs[1,2], Matt Rindfleisch[1], Tom Bullard[3], Timothy Haugan[3], Michael Sumption[4], Mike Tomsic[1], Kiruba Haran[5]

[1]Hyper Tech Research Inc., [2]Scintillating Solutions LLC, [3] Air Force Research Laboratory, [4]The Ohio State University, [5]University of Illinois Urbana-Champaign

ICMC 2023

July 11, 2023

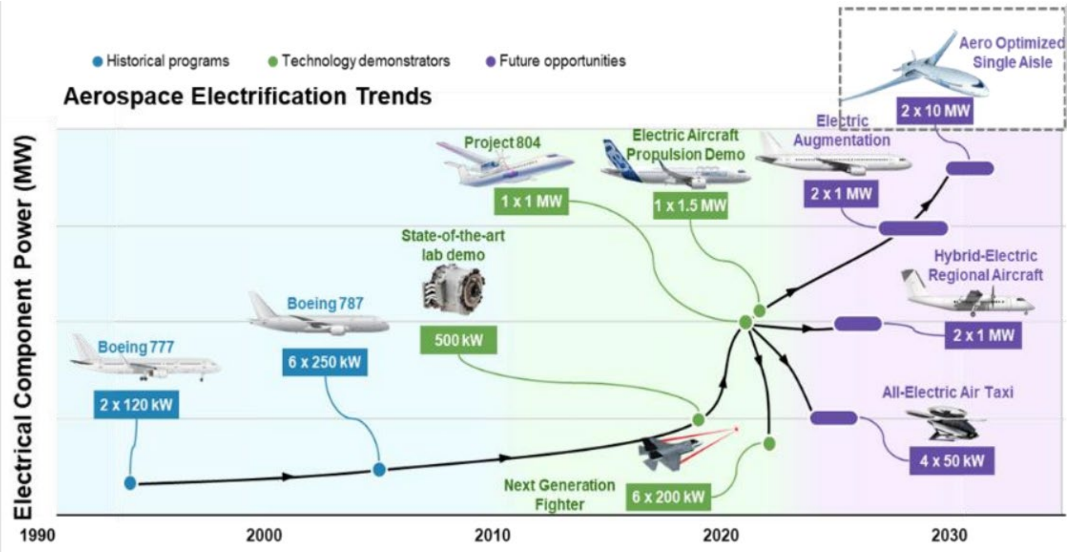
CHEETA
Center for High-Efficiency Electrical Technologies for Aircraft

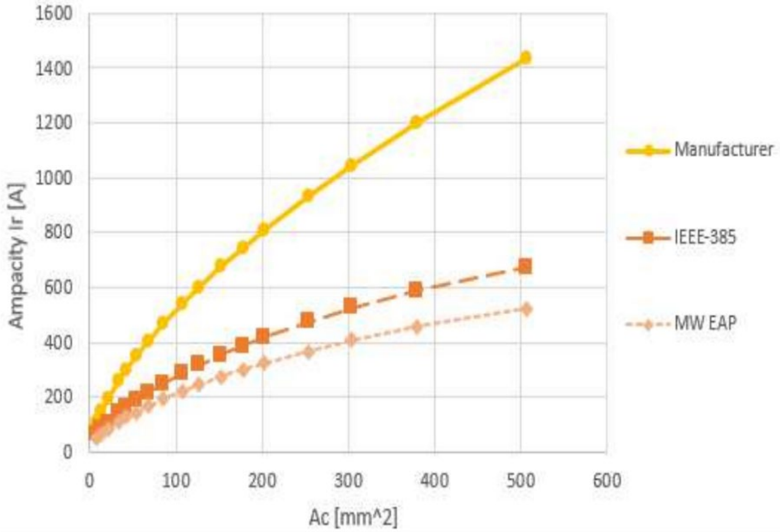
Summary

- Motivation for DC aerospace cryo-cables
  - ARPA-E CABLES and NASA-ULI
- Current State of the Art (Non-Cryo)
- Cryoresistive cables
  - A proposed layout
  - Thermal management
  - Ampacity demonstrators
  - Terminations
  - Electric fields and insulation testing
- Superconducting cables
  - Thermal management
- Future Work

ARPA-E CABLES and NASA ULI

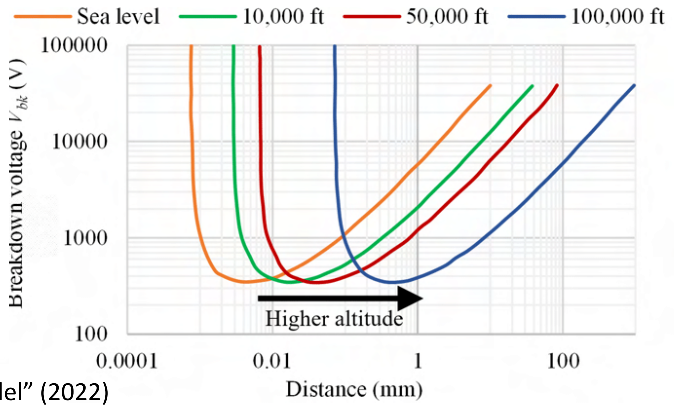
- Both NASA and ARPA-E are in the process of developing lower mass aerospace electrical wiring and interconnection systems (EWIS)
- Innovations in electrical insulation and current carrying capacity
- Very high voltages (10 kVDC) makes ambient temperature cables more competitive versus cryogenic options
    - Cryogenic system masses
    - Cryoresistive substantially lighter for higher currents which do not require advances in insulation and other components (±270 VDC)
- The mass of the EWIS is a show-stopper for MEA if not lightweighted from COTS
    - System Redundancy for MEA





THERMAL ENVIRONMENTS

Configuration	Ambient Temp (°C)	Max Conductor Temp (°C)
IEEE-835	25	90
MW EAP	130	180



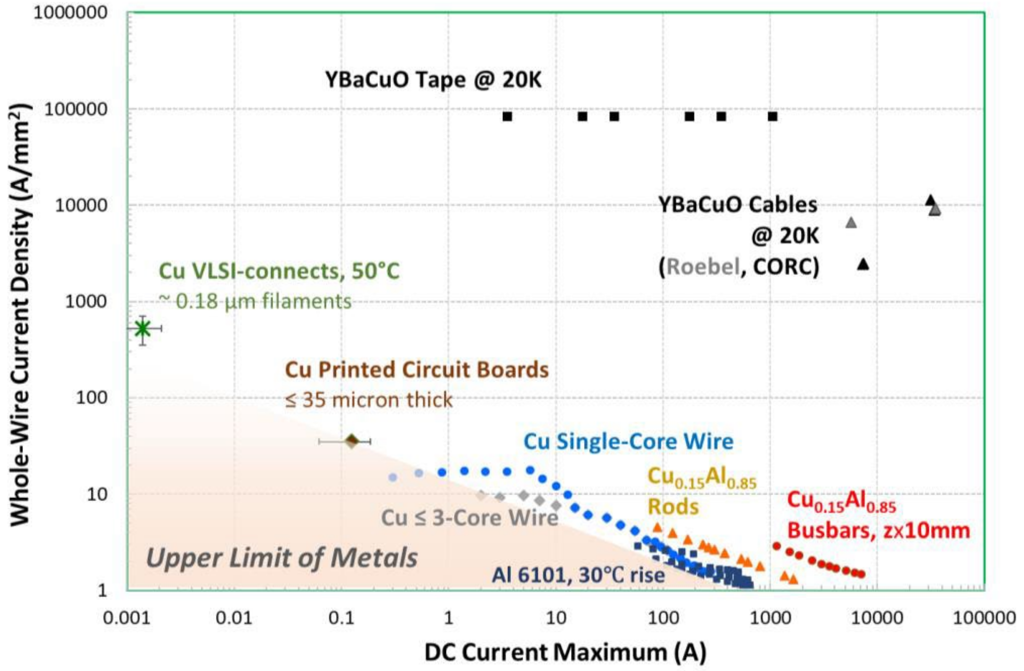
Dever "Cable Key Performance Parameters for Megawatt Electrified Aircraft Propulsion Conceptual Aircraft Model" (2022)
Kshirsagar "Anatomy of a 20 MW Electrified Aircraft: Metrics and Technology Drivers" (2020)

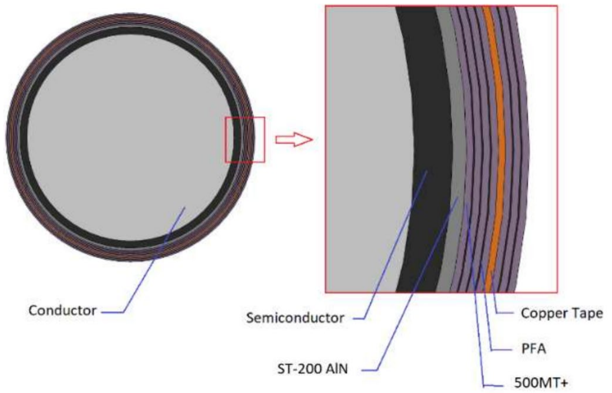
Current State of the Art (Non-Cryo)

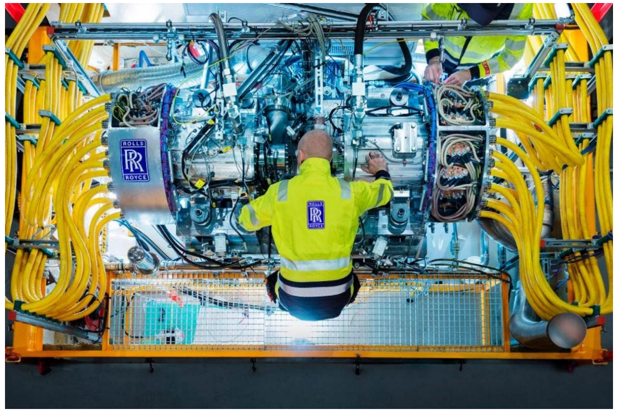
- Increasing voltage to drop current and mass of heavy conductor
- For fixed ampacity (a few A/mm^2) and current, cable metal fraction determined
- Smaller cable = thicker insulation for same voltage and material (E-field)

$$Insulation\ Thickness\ (m) = r \times \left(e^{SF\times V / r\times BDS} - 1\right)$$

- Increased risk of PD and degradation overtime with MVDC
- Cuponal (Cu-Al composite) or Al best conductor option



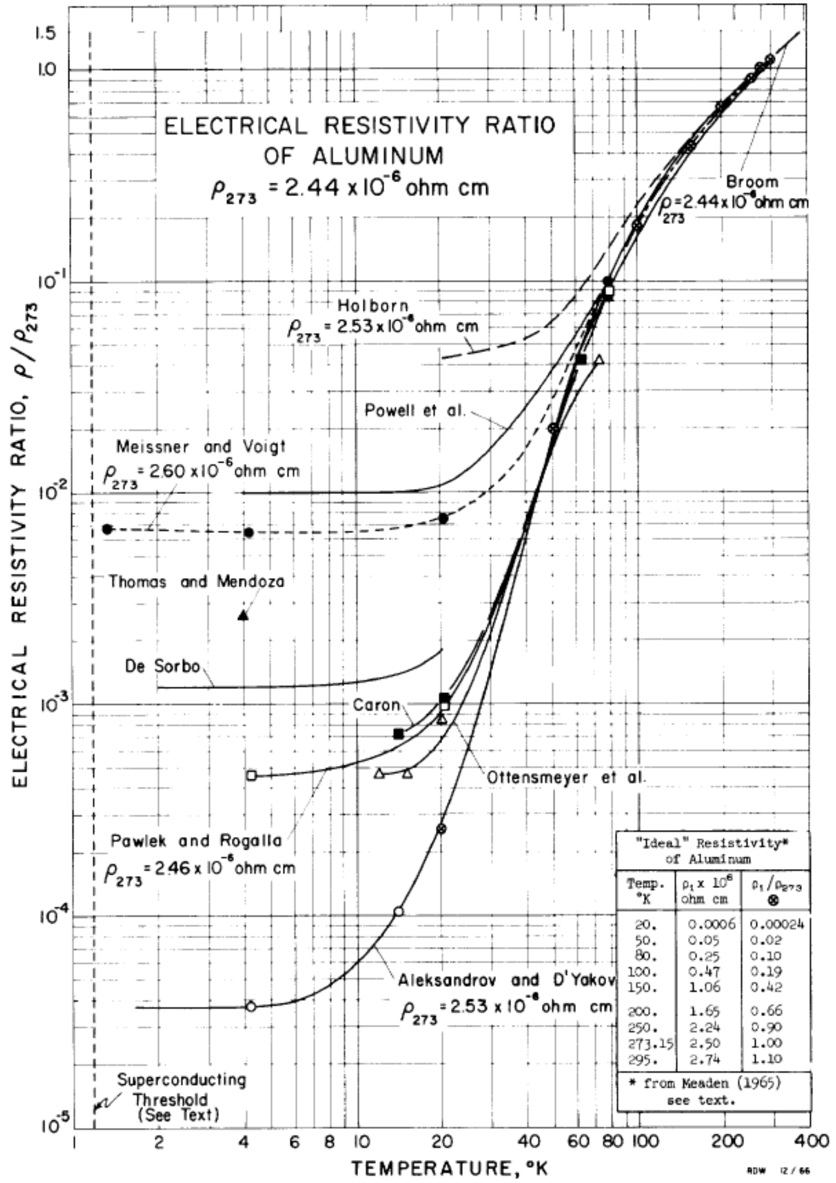




Sebastian "Design and Scaling Laws of a 40-MW-class Electric Power Distribution System for Liquid-H2 Fuel-Cell Propulsion" (2021)
https://newatlas.com/aircraft/rolls-royce-delivers-2-5-megawatt-generator-hybrid-air-propulsion/
Azizi "Design of a Cable System for a High-Power Density MVDC Aircraft Electric Power System" (2022)

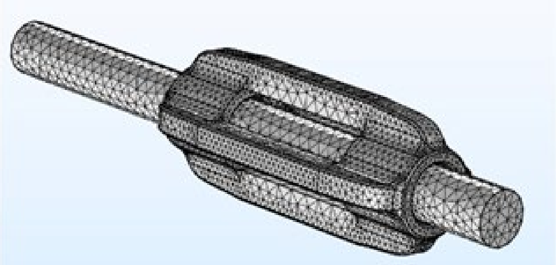
Cryoresistive Cables

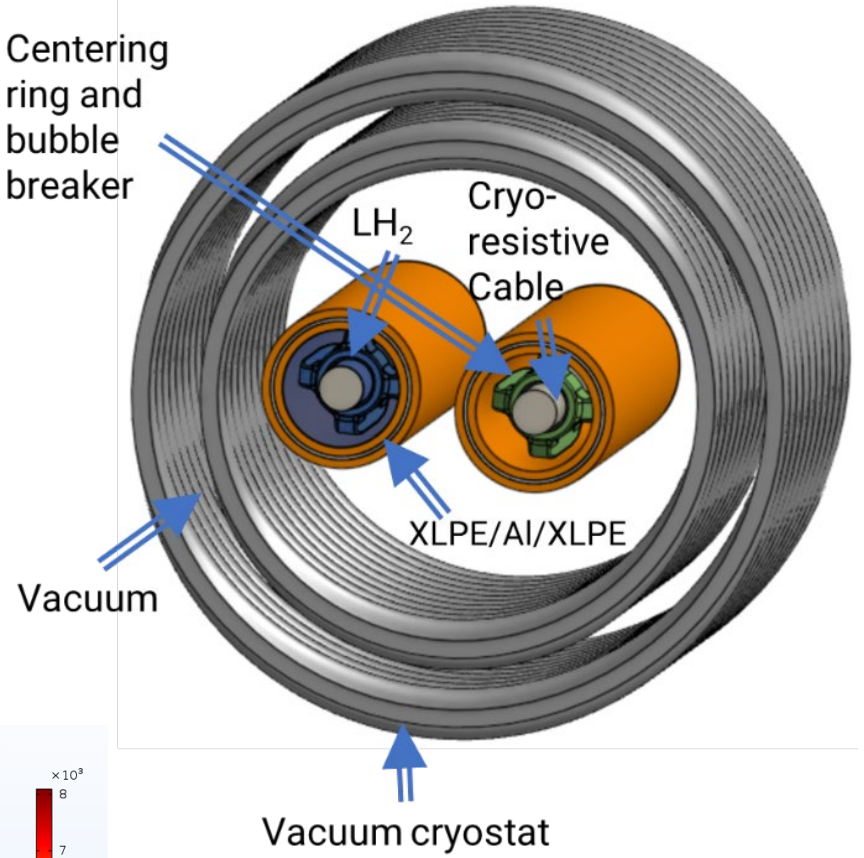
- LH$_2$ or LNG, cold sink fuel onboard to utilize
  - Requires vaporization for consumption
- Direct force-flow cryogen fluid cooling, cryoresistive cables can carry large ampacities
  - Lower voltages for fixed power
- Cryogenic fluid circulation system
- Replenishing dielectric fluid can reduce PD
  - Do not fully rely on it (bubbles)
- LH$_2$ cable lower mass than LNG cable

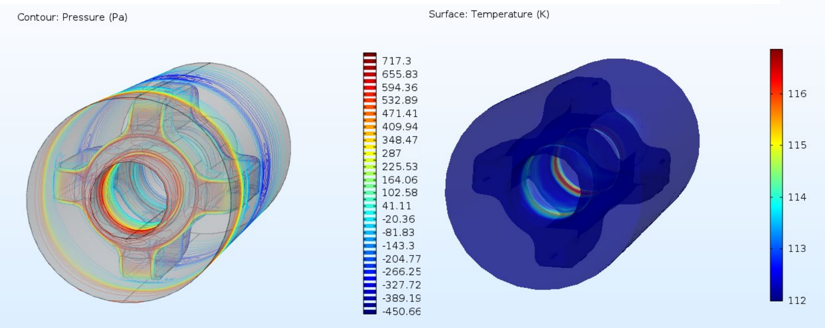


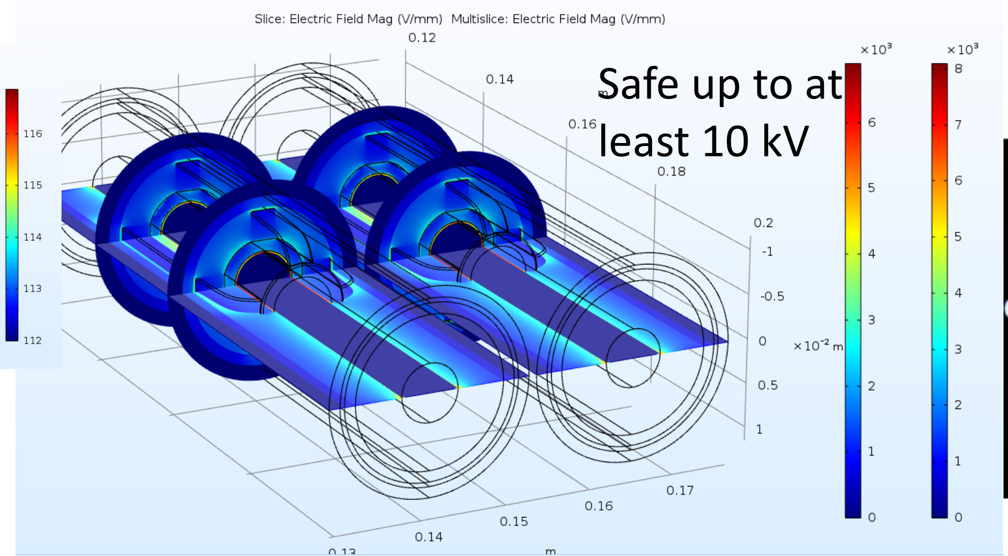
Cryoresistive Cable Proposed Layout

- Multifilamentary uninsulated cable, direct fluid cooled
- Centered in XLPE-Al-XLPE conduit
  - Al-layer ground shield
  - Centering ring geometry and permittivity matter
- XLPE is a good insulator at cryogenic temperatures up to high voltages

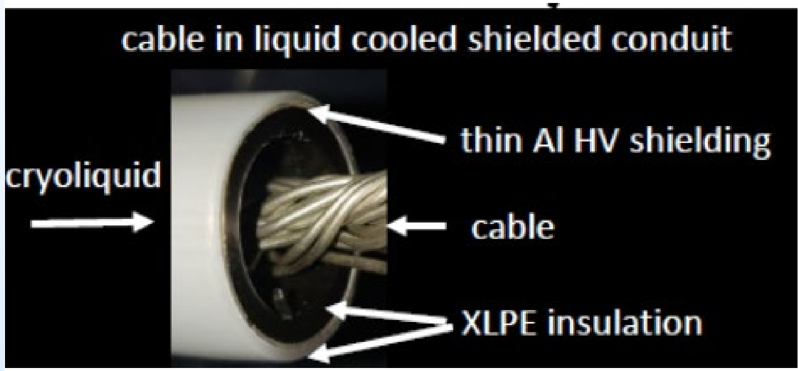






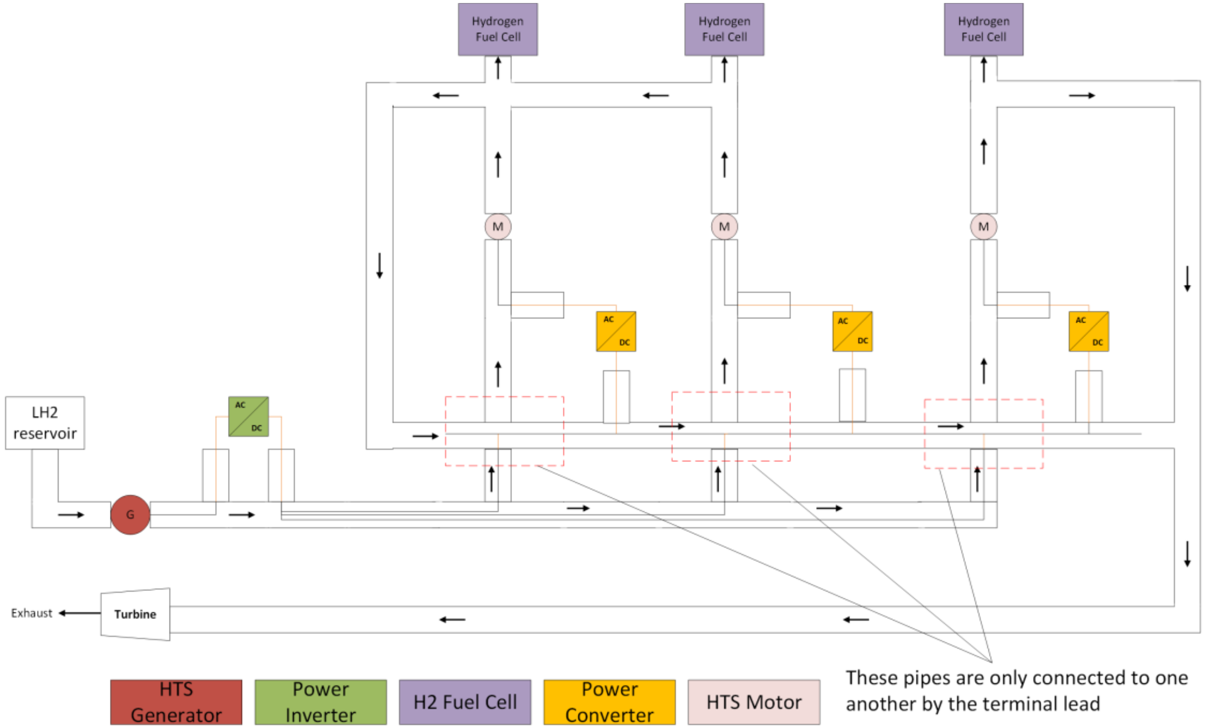


Safe up to at least 10 kV

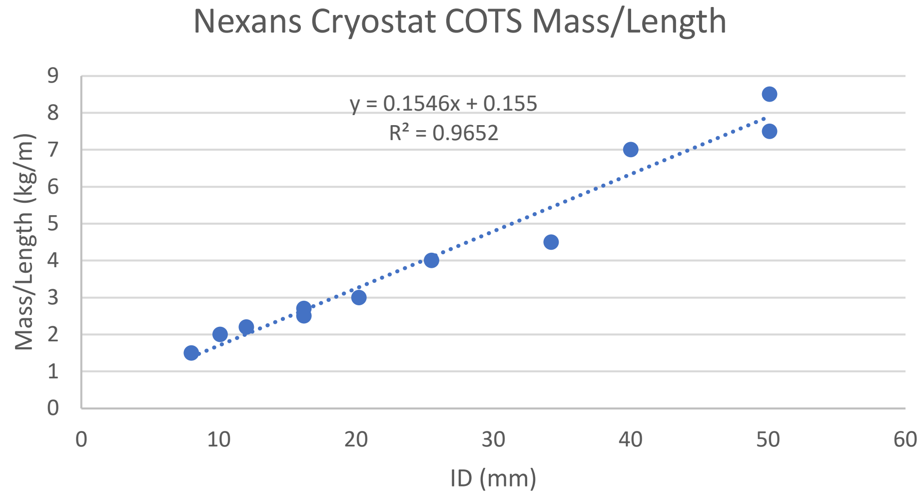


Cryoresistive Cable Thermal Management

- High surface area cable
- Flowing cryogen pressure drop with small channels over long cable lengths
- Circulation/fuel pumps (fluid/fluid heat exchangers are low mass)
- Smaller conduit → smaller cryostat → lower cable mass
- Smaller conduit → larger pressure drop → larger pump mass (or pressure limit of conduit)
- Subcooled pressurized fluid (low thermal budget)
  - 2-phase flow and latent heat of vaporization
- Fuel primary or secondary coolant
- Many (AC and DC) EWIS architectures possible

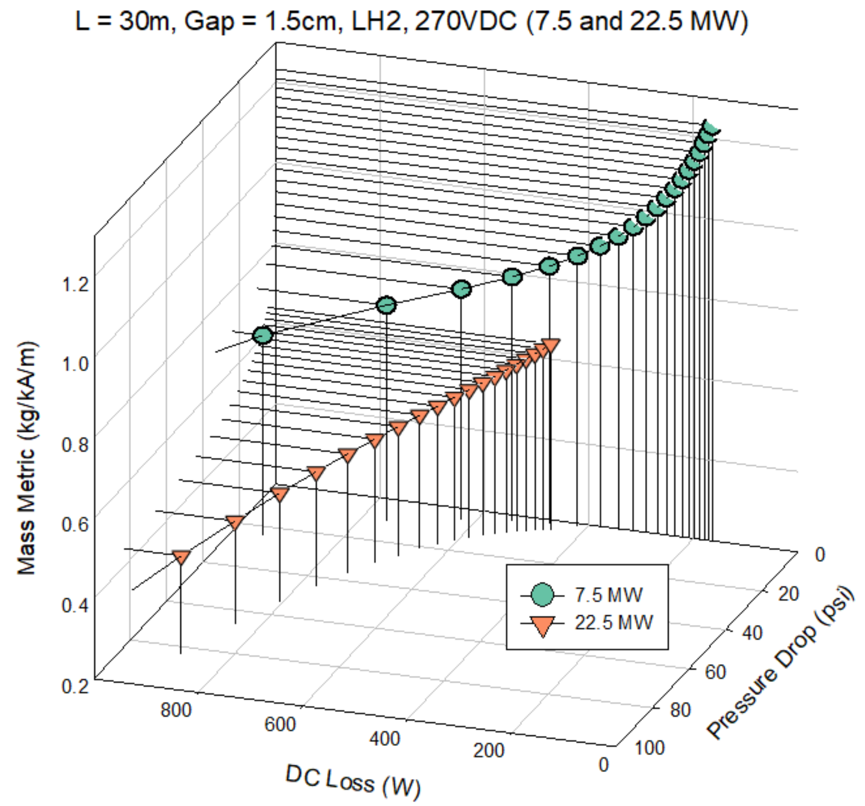


Telikapalli "Electric Aircraft Fueled by Liquid Hydrogen and Liquified Natural Gas" (2022)



Armored stainless steel cryostat = 7.0 kg/m
Unarmored stainless steel cryostat = 3.5 kg/m
Unarmored aluminum cryostat = 1.2 kg/m

Cryoresistive Cable Optimization



- 2-phase flow along length, Lockhart-Martinelli
  - Model (currently) assumes constant vapor quality
- Pressure limit: conduits, pump, weakest link
- Vapor volume quality = thermal limit (0.3)
  - Vapor density dependent on system pressure
  - Avoiding slug-plug flow
- Change gap to conduit after finding suitable cable size

$$\chi_{LH2} = 0.3 = \frac{I^2 \frac{\rho(T)\times L}{A_{x-cable}} + Q_{cryostat}\times L}{v_{flow}\left(L_v\left[{}^{J}/_{kg}\right]\times \rho_{gas}\right)}$$

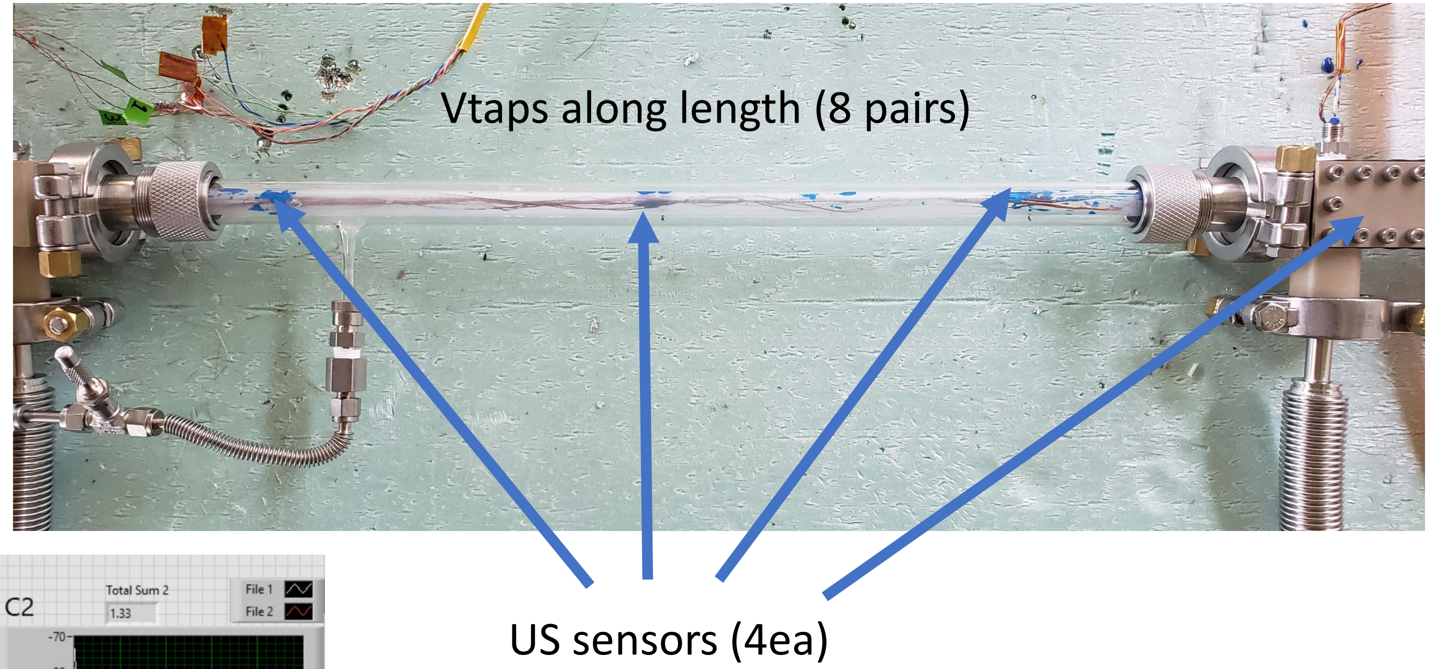
Cable Length 30 m	30% vapor safe cable radius (mm)	Gap to conduit for < 200 Psi (mm)	ID cryostat needed (mm)	Mass Cryostat, Nexans (kg/m)	Mass Cable (kg/m)	Cryocable Total Mass (kg)	COTS (kg)	Cryo versus COTS Ratio (#)	Je (A/mm2), high h
27777 A, 0.1 kg/s	41.20	1.45	182.60	28.38	28.80	1715.44	9475.16	0.18	5.21
27777 A, 1 kg/s	13.03	18.29	137.28	21.38	2.88	727.76	9475.16	0.08	52.08
83333 A, 0.1 kg/s	123.60	0.49	508.36	78.75	259.17	10137.45	68763.69	0.15	1.74
83333 A, 1 kg/s	39.04	9.28	205.28	31.89	25.86	1732.42	68763.69	0.03	17.40

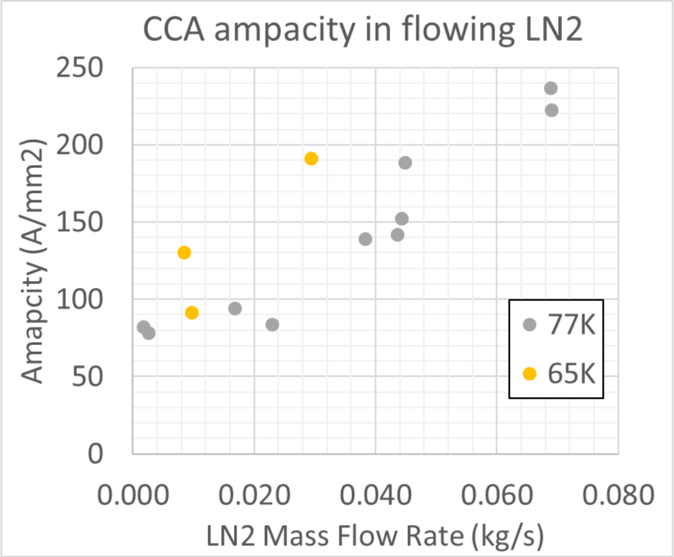
Cable Length 20 m	30% vapor safe cable radius (mm)	Gap to conduit for < 200 Psi (mm)	ID cryostat needed (mm)	Mass Cryostat, Nexans (kg/m)	Mass Cable (kg/m)	Cryocable Total Mass (kg)	COTS (kg)	Cryo versus COTS Ratio (#)	Je (A/mm2), high h
27777 A, 0.1 kg/s	33.66	1.57	152.92	23.80	19.22	860.34	9475.16	0.09	7.80
27777 A, 1 kg/s	10.64	18.23	127.48	19.86	1.92	435.68	9475.16	0.05	78.10
83333 A, 0.1 kg/s	100.77	0.53	417.20	64.65	172.27	4738.45	68763.69	0.07	2.61
83333 A, 1 kg/s	31.90	9.78	178.72	27.79	17.26	900.97	68763.69	0.01	26.07

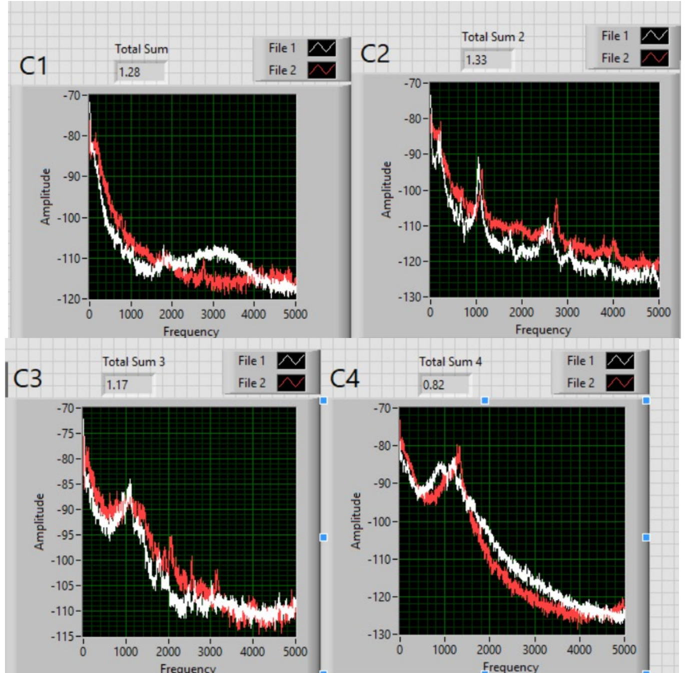
Cable Length 10 m	30% vapor safe cable radius (mm)	Gap to conduit for < 200 Psi (mm)	ID cryostat needed (mm)	Mass Cryostat, Nexans (kg/m)	Mass Cable (kg/m)	Cryocable Total Mass (kg)	COTS (kg)	Cryo versus COTS Ratio (#)	Je (A/mm2), high h
27777 A, 0.1 kg/s	23.79	1.79	114.32	17.83	9.60	548.60	9475.16	0.06	15.62
27777 A, 1 kg/s	7.52	17.85	113.48	17.70	0.96	373.17	9475.16	0.04	156.35
83333 A, 0.1 kg/s	71.25	0.62	299.48	46.45	86.12	2651.53	68763.69	0.04	5.23
83333 A, 1 kg/s	22.57	10.55	144.48	22.49	8.64	622.67	68763.69	0.01	52.07

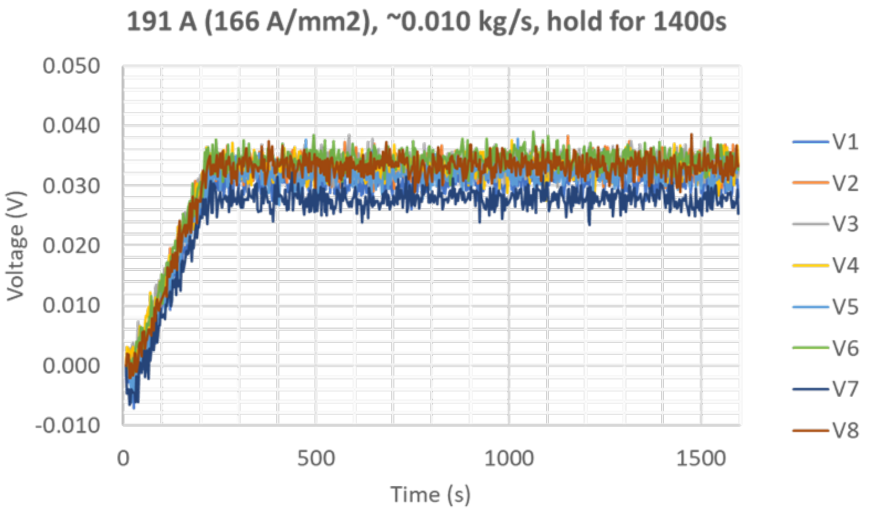
Transparent Vacuum Jacketed Cryostat

- Attempt to quantify ampacity and vapor fraction
- Ultrasonic transducers, precursors
- So far, just a proof of ampacity
  - Pressure drop (L=1 m) too small



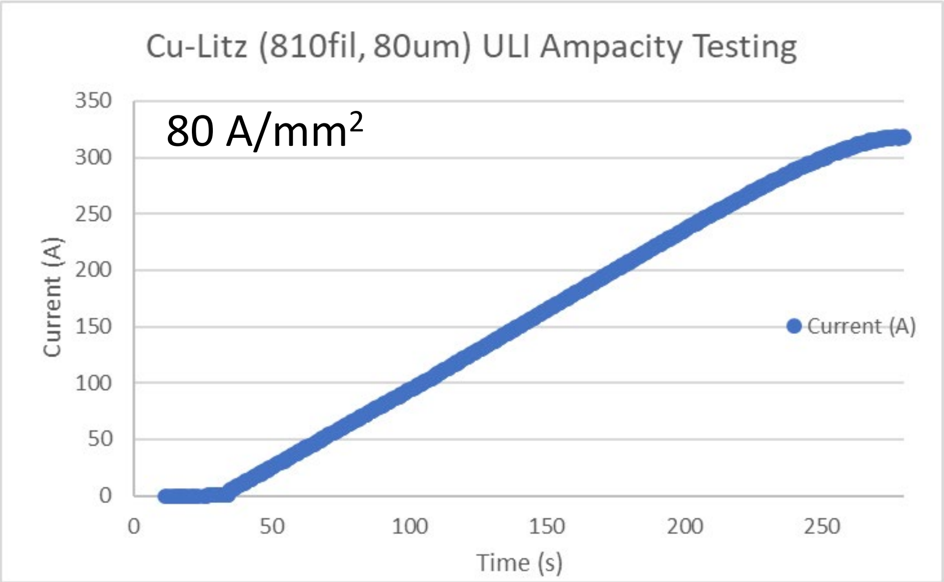


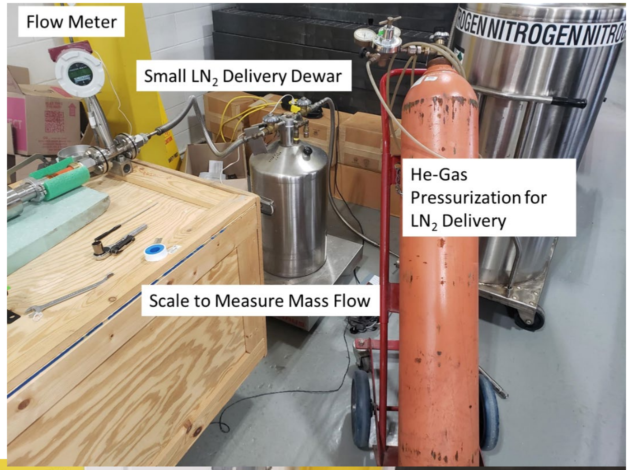


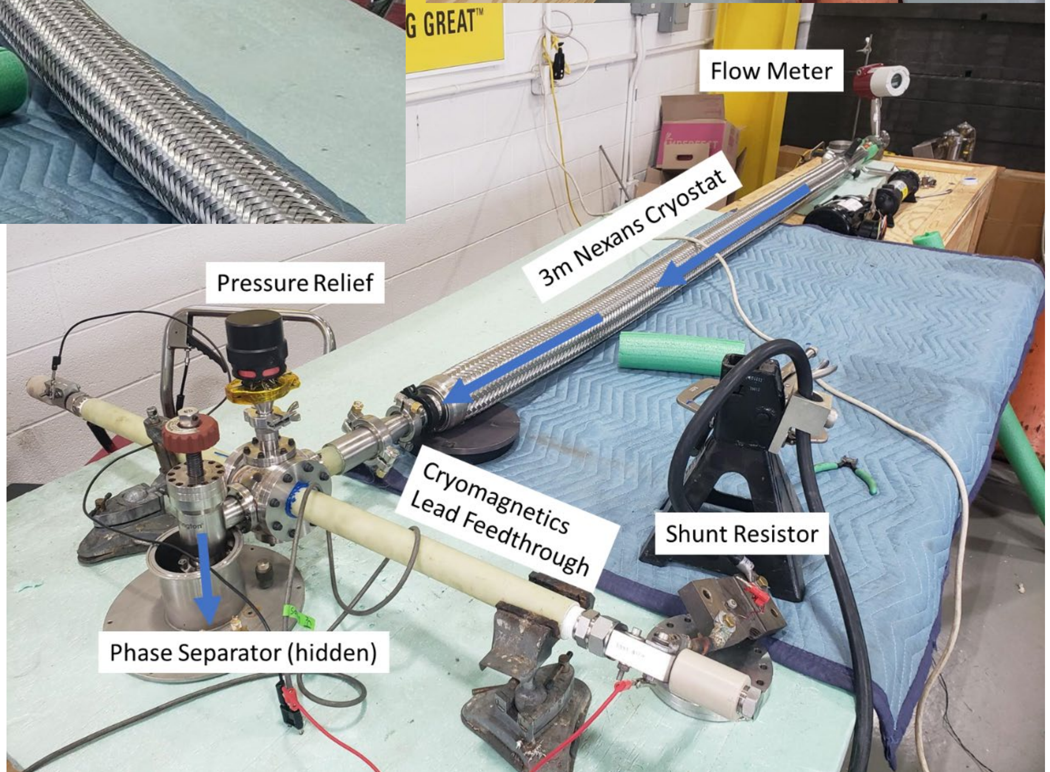


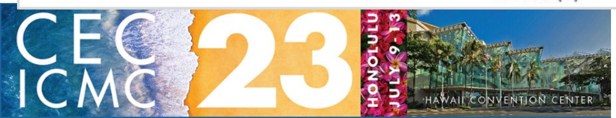
3-m Flexible Armored Nexans Cryostat

- Proof of conduits, sealing techniques, and ampacity over longer length
- Cu-Litz in flowing LN_2
- Weak bonds from XLPE-epoxy-XLPE in manifolds/junctions



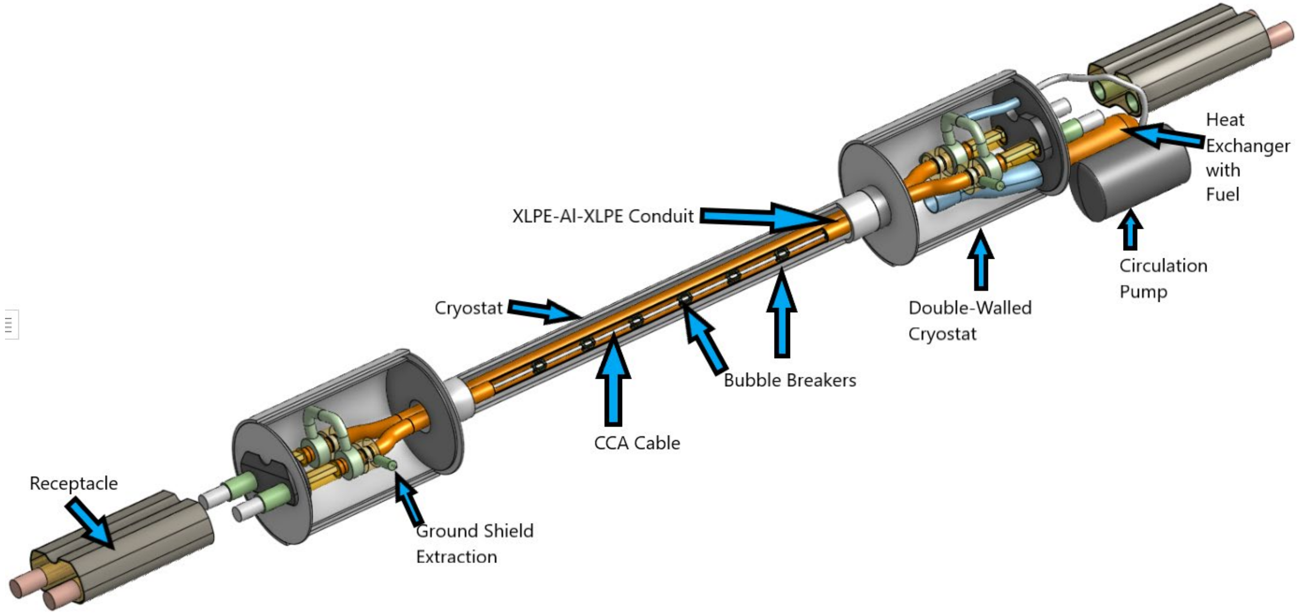


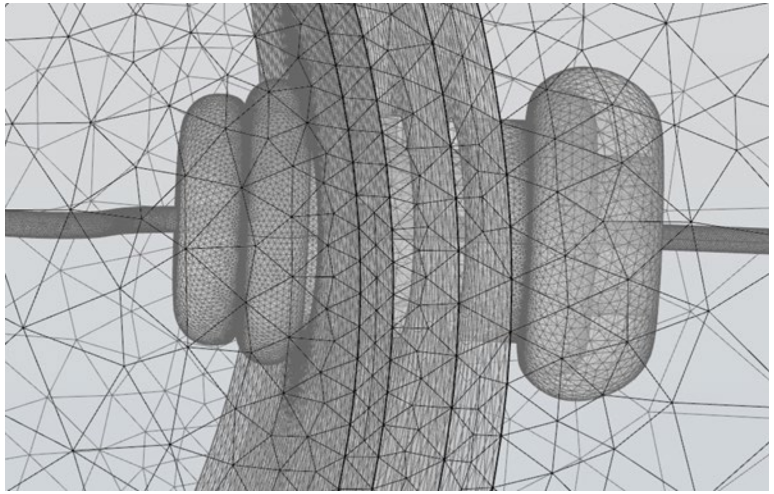


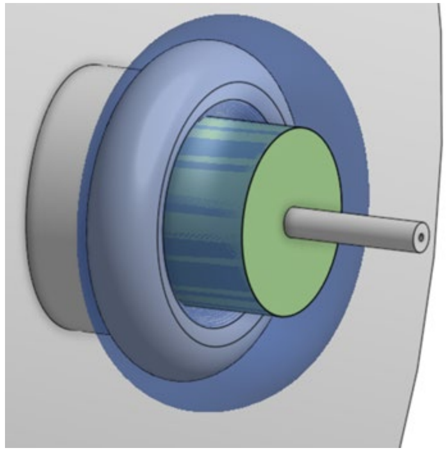


Cryoresistive Terminations

- Plug-receptacle style, up to 10 kVDC 2-pole 10 MW cable
  - Voltage rating much higher
- Closed-loop, fuel as secondary coolant
- Fluid flow is parallel in the conduits, anti-parallel on the return outside of the conduits
  - Turn around within termination
  - Takes advantage of space left by non-coaxial design
  - Requires an internal manifold system
- Compact MVDC ground shield extraction
  - Paschen curve

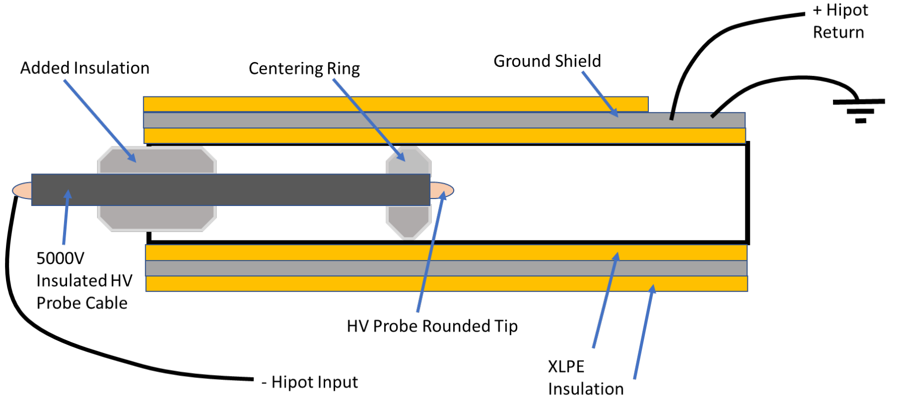


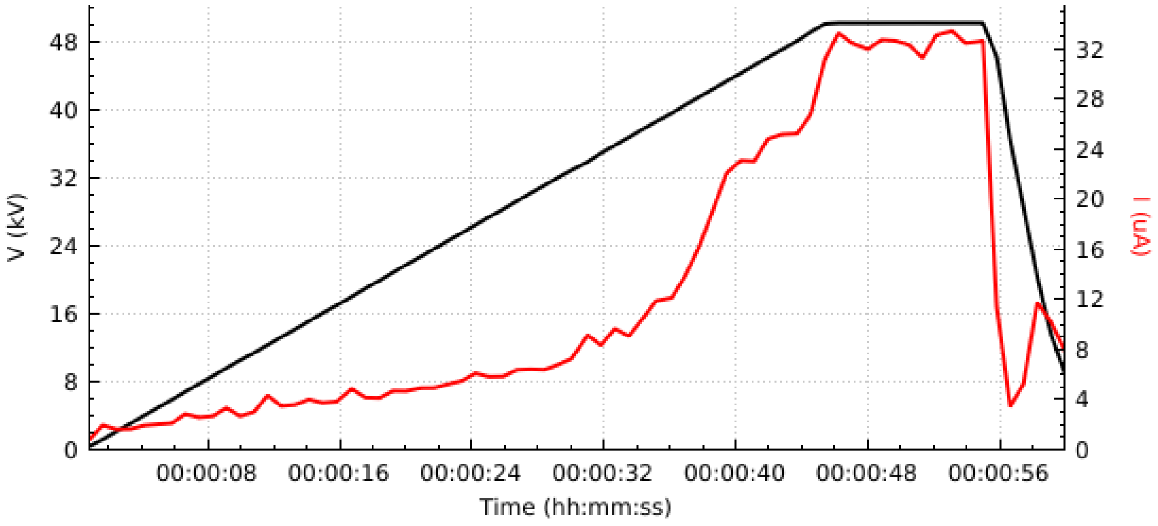


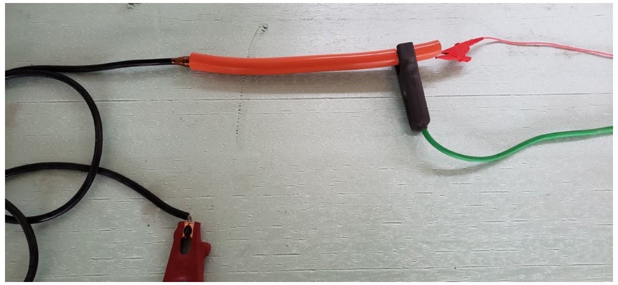


Cryoresistive Cable Electric Fields and Insulation

- XLPE is a known reliable cryogenic insulation
- Hipot tested across inner XLPE layer at room temperature, good to 50 kV

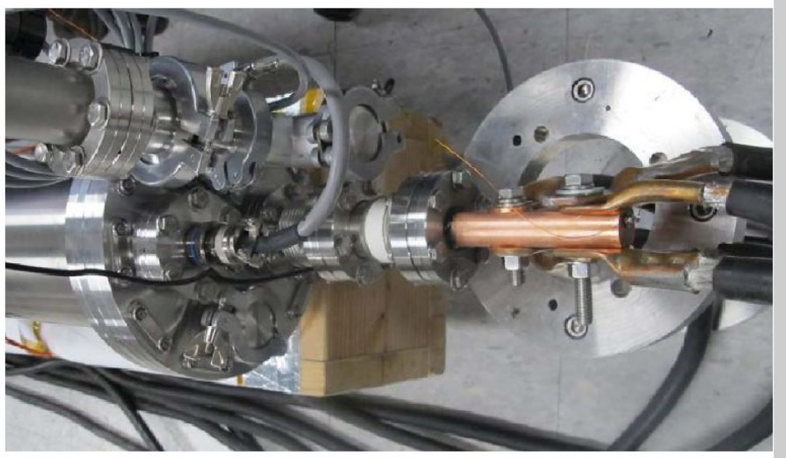


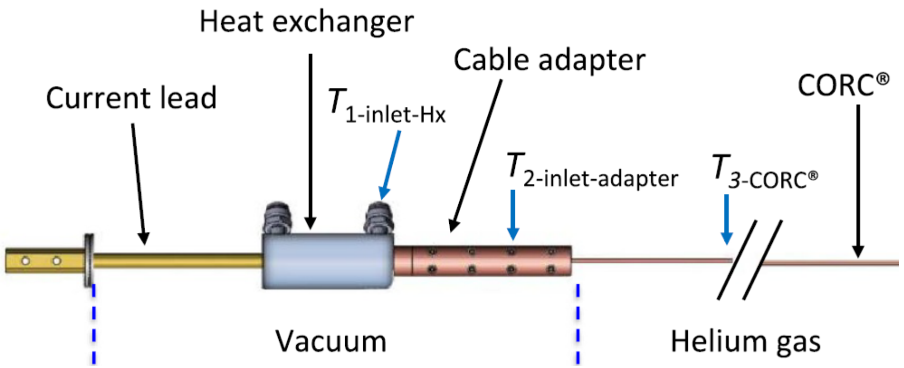




Superconducting Cable (Future Work)

- As part of NASA ULI, CORC cable in cryostat from Advanced Conductor Technologies (Boulder, CO)
- Look for avenues for lightweighting and advanced thermal management particularly at terminations
- He-gas cooled
- Less than single digit psi (10s of mbar)
- Eventually NASA will ask for mass of demonstration system
- ±270 VDC





van der Laan “A turnkey gaseous helium-cooled superconducting CORC® dc power cable with integrated current leads” (2022)

Future Work

- Pushing forward with cryoresistive cable terminations demonstrations
- Further cable testing to validate sealing mechanisms at polymer/polymer interfaces
- Advance lightweighting strategies in demonstration systems
- He-gas cooled CORC demonstration

Thank You CEC-ICMC 2023!

"Hawaii is one of those places that keeps topping itself. Just when you think you'll never see another sunset as beautiful, there comes a sunrise that only Gauguin could imagine."

-Thomas Sullivan Magnum IV (1982)