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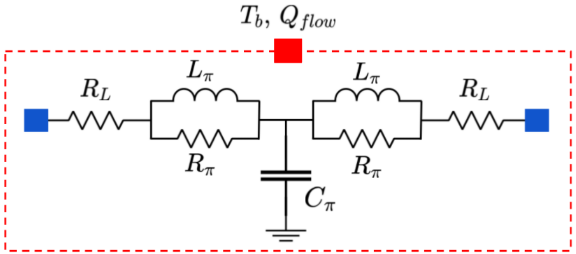

Electro-Thermal Modeling of HTS Power Lines for Cryogenically-Cooled Electric Aircraft Design

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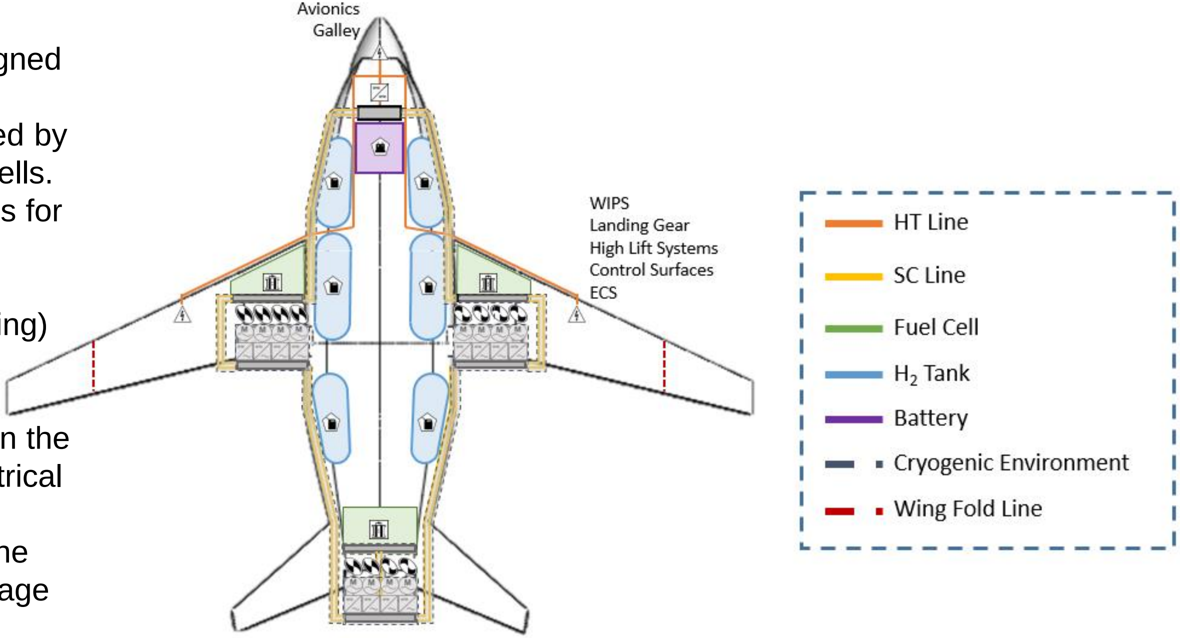
Outline

- **Introduction**
- **CHEETA Electrical System Architecture**
- **Multi-Domain Modeling for High Temperature Superconducting Power lines**
- **Validation Results**
- **Conclusions and Next Steps**
  - Modeling of bus bars, current leads, and integration with the rest of the system

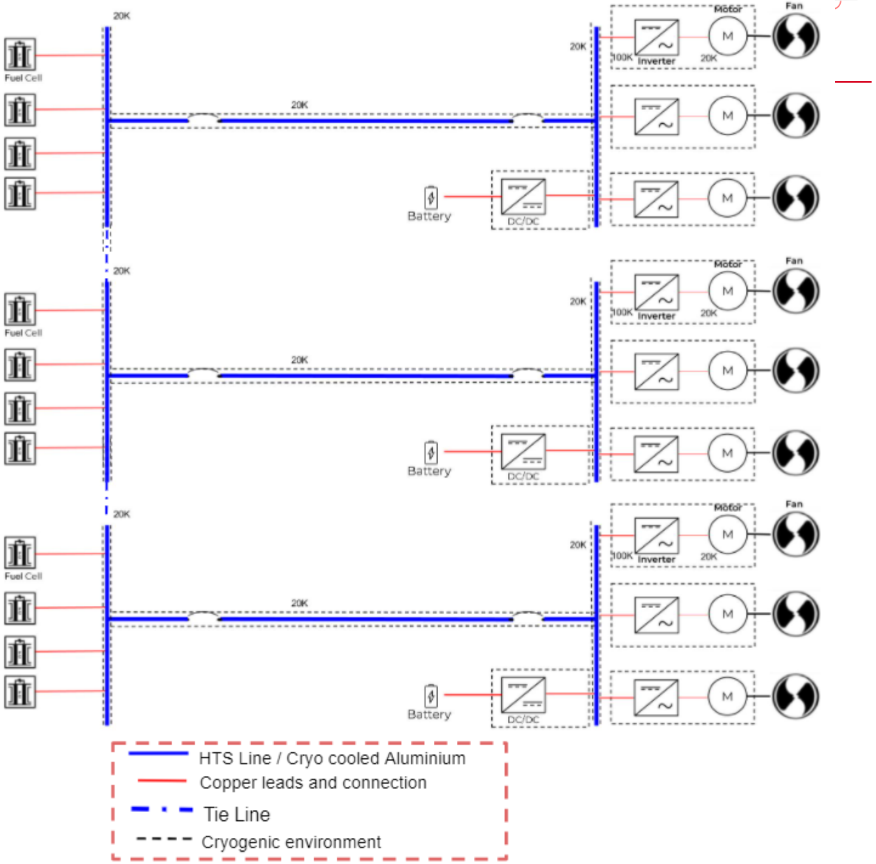
CHEETA Aircraft Overview and Layout

- CHEETA explores future technologies in electrified aircraft.
    - Aircraft components are designed to be cryogenically cooled.
    - Hybrid electric aircraft powered by batteries and hydrogen fuel cells.
- Aircraft consists of multiple domains for modeling:
    - Electrical
    - Thermal (liquid and gas cooling)
    - Mechanical/aerodynamics
    - Control signals
- This presentation mostly focuses on the modeling of the **HT line** in the electrical and thermal domains
    - The model was made using the Modelica programming language



Electrical System Architecture

- Hybrid centralized and distributed electrical architecture
  - Three different areas for propulsion: two on the wings and one on the body
- Added reliability from having the batteries connected at the motor bus
- More balanced aircraft weight with the batteries located in the wings
- Tie line between the fuel cells adds reliability to balance power between generation



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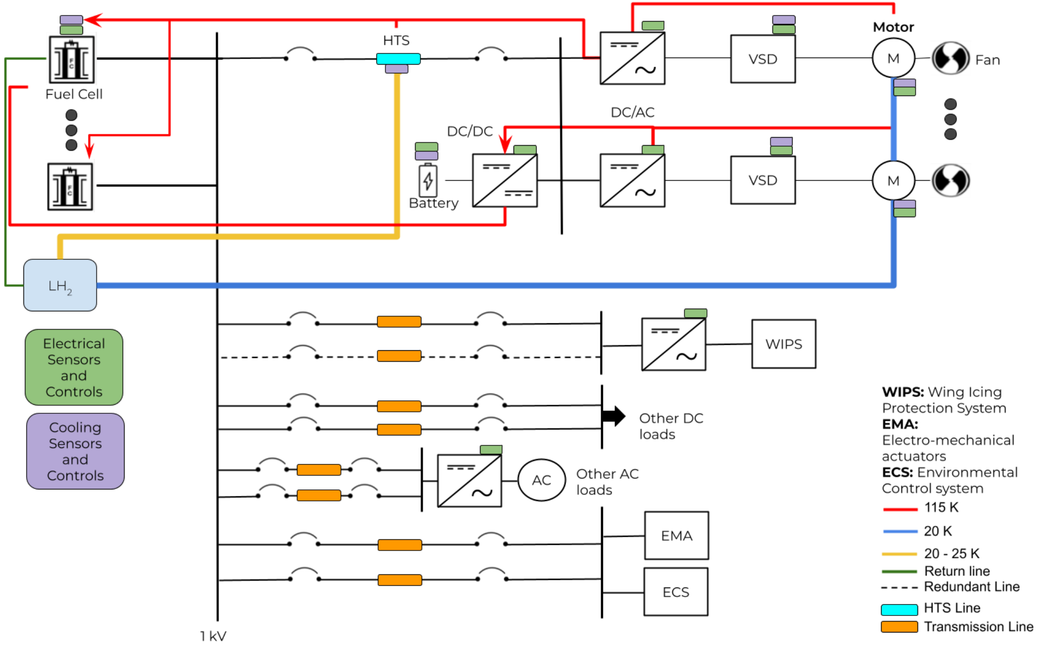
Electrical System Architecture: Cooling System

- HTS lines and bus bars are cooled separately from the drivetrains and fuel cells
  - Ensures a stable, constant temperature applied to components
  - Protects system to ensure maximum capability to remove heat during fault
  - Motors, power electronics, and current leads contribute to most of the heat generation



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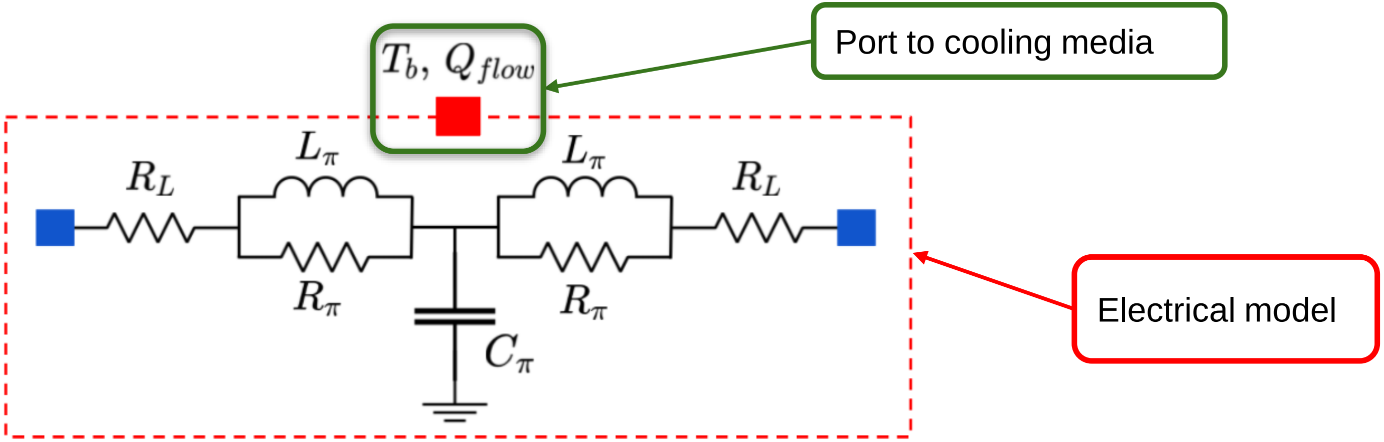
Multi-Domain Modeling of HTS Power Lines

- Multi-domain transmission line represented as co-axial model with a thermal model to dictate the surface temperature of the line
  - The resistances of the line are dependent on the surface temperature of the line and cooling bath temperature
  - Temperature of line is held constant by a fixed boundary condition that specifies ideal temperature of cooling system



Multi-Domain Modeling of HTS Power Lines

I = Current flowing through the cable (A)
I_C = Critical current (A)
I_{C0} = Critical current at 20K (A)
T_C = Critical temperature of the superconductor (K)
T_l = Temperature of the surface of the line (K)
ρ = Resistivity of HTS cable ($\Omega \cdot \mathrm{m}$)
E = Electric field (V/m)
E_0 = Reference electric field for the critical current (V/m)
A_{cu} = Cross-sectional area of copper portion of line (m^2)

$$I_C = I_{C0}\left(1 - \frac{T_l}{T_C}\right)$$

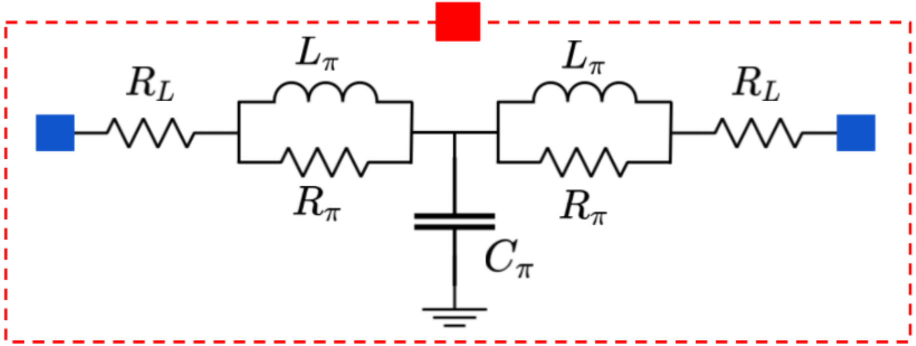
$$\rho = \frac{E * A_{cu}}{I_C}$$

$$E = E_0\left(\frac{I}{I_C}\right)^n$$

Line is modeled using equations for cold-end cooling

- First need to determine the maximum current rating of the line, resistivity, and electric field

T_b, Q_{flow}



Multi-Domain Modeling of HTS Power Lines

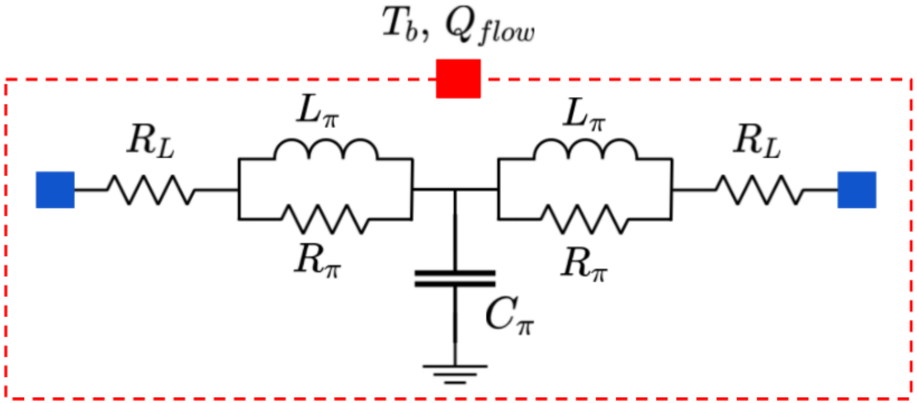
I = Current flowing through the cable (A)
I_C = Critical current (A)
ρ = Resistivity of HTS cable ($\Omega \cdot \mathrm{m}$)
E = Electric field (V/m)
a = Inner radius of the HTS annular electrical cable (m)
b = Outer radius of the HTS electrical conductor (m)
n = Index value of superconductor (unitless)
ϵ = Permittivity of tape material (unitless)
μ = Permeability of tape material (unitless)
R_π = Permeability of tape material (Ω)
C_π = Capacitance of pi-line capacitor (C)
L_π = Inductance of the pi-line inductor (H)
R_L = Current lead resistance (Ω)

$$R_\pi = E_0 * \frac{\left(\frac{I}{I_C}\right)^n}{I}$$

$$L_\pi = \frac{\mu}{2\pi}\log\left(\frac{b}{a}\right)$$

$$C_\pi = \frac{2\pi\epsilon}{\log\left(\frac{b}{a}\right)}$$

Pi-line resistance, inductance, and capacitance all vary depending on the line’s temperature and carrying current



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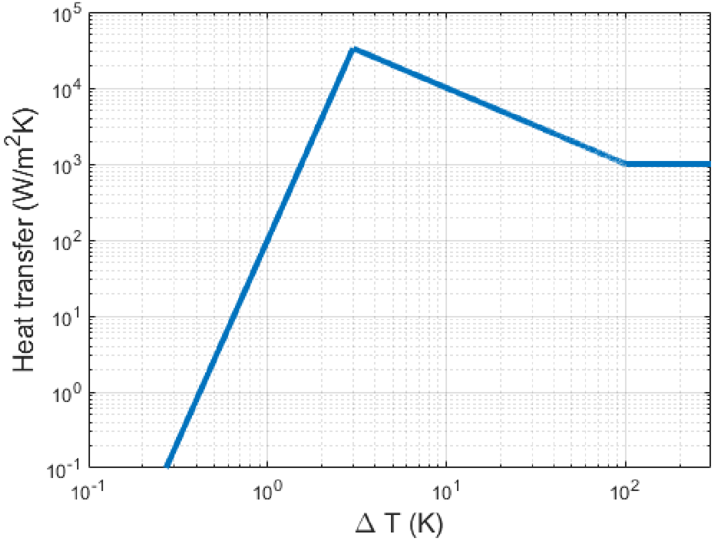
Liquid hydrogen heat transfer model

Heat transfer coefficient of the line is a function of the nucleate boiling curve for liquid hydrogen

- Determines the heat generated by the line (h = Q/ΔT_ρ)
- This helps determine if the line will remain in the cryogenic cooling region

$$h = \begin{cases} 100(\Delta T_\rho)^{5.3} & \Delta T_\rho < 3 \\ \frac{10^5}{\Delta T_\rho} & 3 \le \Delta T_\rho < 100 \\ 1000 & \Delta T_\rho \ge 100 \end{cases}$$

h = Heat transfer coefficient (W/m^{2}K)
ΔT_ρ = Difference in temperature between cable and cooling media (K)
Q_{flow} = Heat flow generated by the cable (W)



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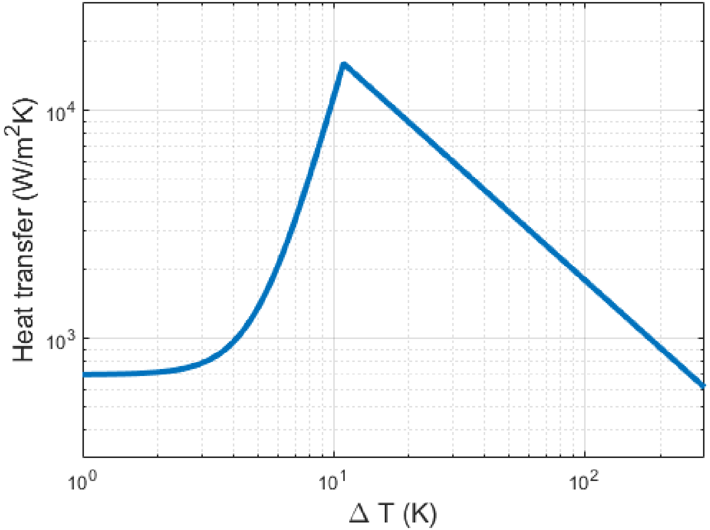
Liquid nitrogen heat transfer model

Heat transfer coefficient of the line is a function of the nucleate boiling curve for liquid nitrogen

- Determines the heat generated by the line (h = Q/ΔT_ρ)
- This helps determine if the line will remain in the cryogenic cooling region

$$h = \begin{cases} 1000\left(0.6953 + 0.001079\Delta T_\rho^4\right) & \Delta T_\rho < 11 \\ 1000\left(\frac{-5.787-0.155\Delta T_\rho}{1-0.546\Delta T_\rho}\right) & \Delta T_\rho \geq 11 \end{cases}$$

h = Heat transfer coefficient (W/m^{2}K)
ΔT_ρ = Difference in temperature between cable and cooling media (K)
Q_{flow} = Heat flow generated by the cable (W)



HTS model thermal functions - liquid cooling

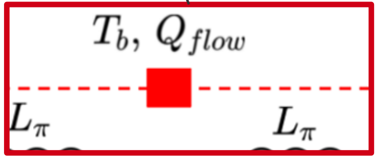
The cooling functions for the rest of the cable is shown accordingly, which relate to the interfacing between the thermal junction to the cooling media.

h = Heat transfer coefficient $(\mathrm{W/m^2K})$
ΔT_ρ = Difference in temperature between cable and cooling media (K)
Q_{flow} = Heat flow generated by the cable (W)
Q_{ce} = Cold end cooling of cable
G_d = Heat due to a potential additional fault (W)
I_C = Critical current (A)
ρ = Resistivity of HTS cable $(\Omega \cdot \mathrm{m})$
κ = Average, effective, radial thermal conductivity of electrical cable (W/mK)
T_b = Temperature of cooling media bath (K)
P = Perimeter of cable (m)
A_{cu} = Cross-sectional area of copper portion of line $(\mathrm{m^2})$

$$\Delta T_\rho = \frac{\left(\frac{\rho I_C^2}{P A_{cu}} + G_d\right)}{h}$$

$$Q_{flow} = h \Delta T_\rho + Q_{ce}$$

$$Q_{ce} = T_b \sqrt{2 \kappa A_{cu} P h}$$



HTS model thermal functions - gas cooling

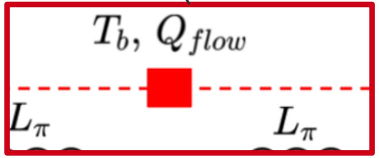
The cooling functions for the rest of the cable is shown accordingly, which relate to the interfacing between the thermal junction to the cooling media.

C_{pv} = Heat capacity of gas coolant (J/K)
h = Heat transfer coefficient (W/m^{2}K)
Q_{ce} = Cold end cooling of cable
Q_{flow} = Heat flow generated by the cable (W)
R_C = Inner radius of cable (m)
R_0 = Outer radius of cable (m)
T_{inlet} = Temperature of cooling media bath (K)
v = Velocity of gas coolant (m/s)
z = Distance from gas coolant inlet (m)
ΔT_ρ = Difference in temperature between cable and cooling media (K)
ΔT_z = Difference in temperature between cable and cooling media from gas inlet (K)
ΔT_{total} = Total temperature jump at interface between cryogen and HTS surface in gas cooling (K)

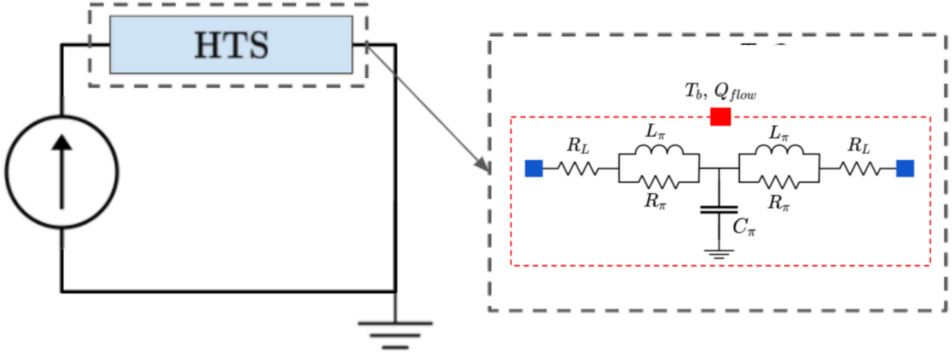
$$< T(z) > \; = T_{inlet} + \frac{Q_{flow} * z}{v * C_{pv} * 2\pi (R_C - R_0)^2}$$

$$\Delta T_z = \; < T(z) > \; - T_{inlet}$$

$$\Delta T_{total} = \Delta T_z + \Delta T_\rho$$



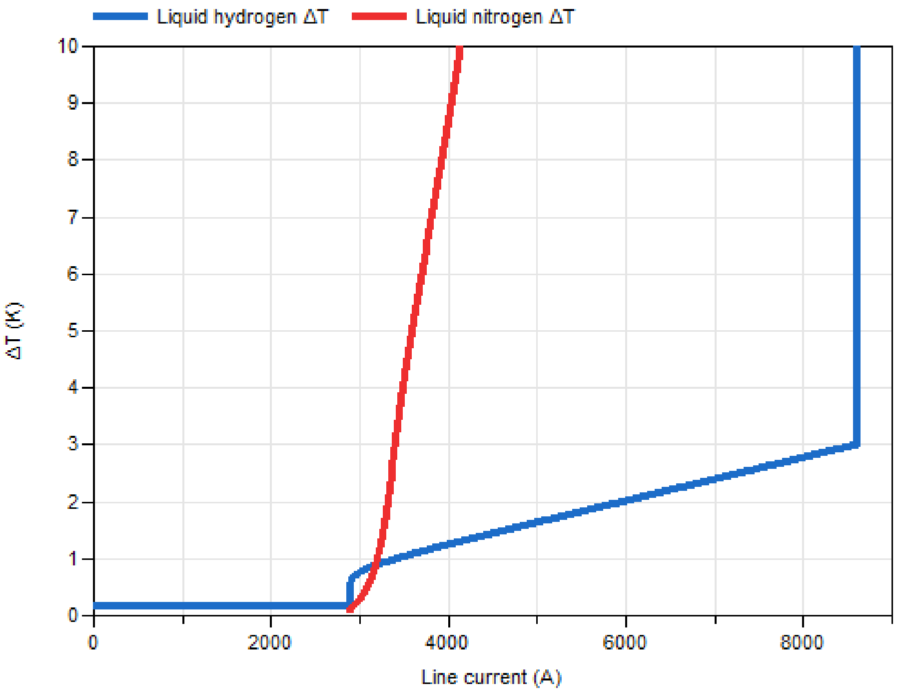
Validation Results



A circuit was set up to match the experiments run on previous HTS tapes to validate the model's behavior

- Apply a current source to the HTS line, where the current ramps from 0 to twice the value of Ic (critical current)
- Tested line for liquid hydrogen, liquid nitrogen, and gas hydrogen

Validation Results



Applied a current that ramped from 0 to 2*Ic to determine where thermal failure would occur for each cooling media

- The lines have a critical current of 3.7kA
- The liquid hydrogen cooled line remained in cryogenic cooling region until nearly twice the value of Ic
- The liquid nitrogen cooled line enters film boiling when the current in the line is at 3.7kA

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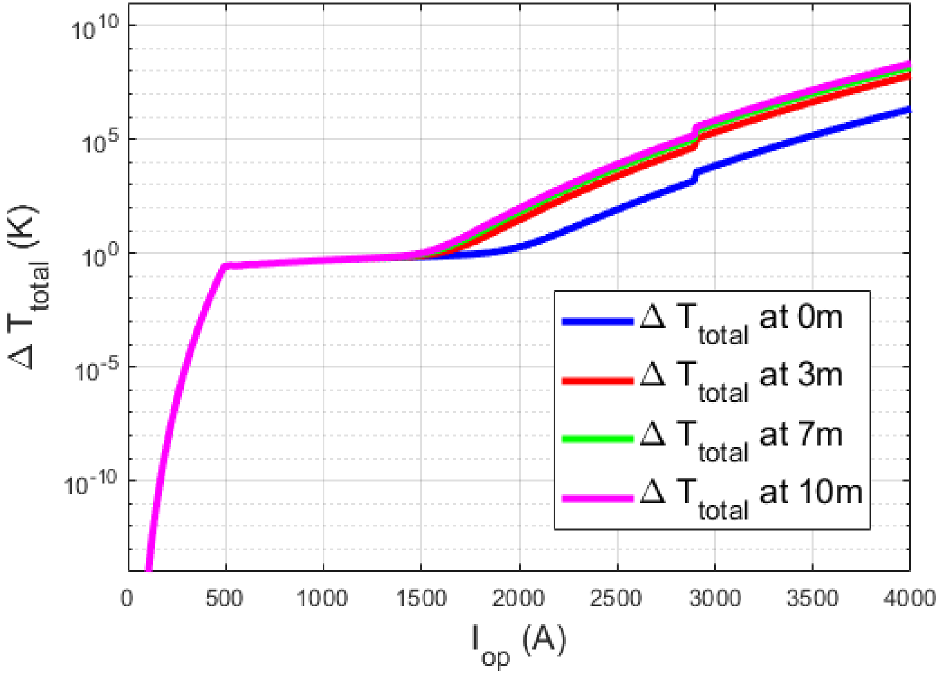
Validation Results



Applied a current that ramped from 0 to 2*Ic to determine where thermal failure would occur for each cooling media

- The lines have a critical current of 3.7kA
- Based on the rapid heating of the gas cooled line prior to Ic, we cannot use the media for an aircraft application

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Conclusions and Next Steps

HTS component modeling:

- Given an electrical architecture focused on cryogenic cooling, we have defined mathematical models for HTS components that can be coupled to other multi-domain models for other portions of the aircraft
- Enables integration of thermal management/cooling system (thermo-fluidic network).
- Allows for design driven by mission profiles.

Next Steps and Lessons Learned:

- Early integrated system models can be helpful at early stages of the development of new propulsion concepts:
    - Allows to identify domain boundaries and delineation of responsibilities for different components/subsystems
    - Help to identify original concept gaps and technology needs and aid in communication between experts in different disciplines, and enables early discussion on concept principles
- Next goal is to develop the models for the bus bars
    - Bus bars will be made of cryogenic metal to minimize size and weight
    - Integrate the bus bar and transmission line models to the rest of the power system
- Need to couple the HTS transmission line model with dynamic fluid media model
    - Instead of assuming a constant temperature applied to the cooling media bath, we will couple the model to a dynamic fluid model

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