C2PoN-03

Solid-cryogen-stabilized, cable-in-conduit superconductor cables

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Motivation

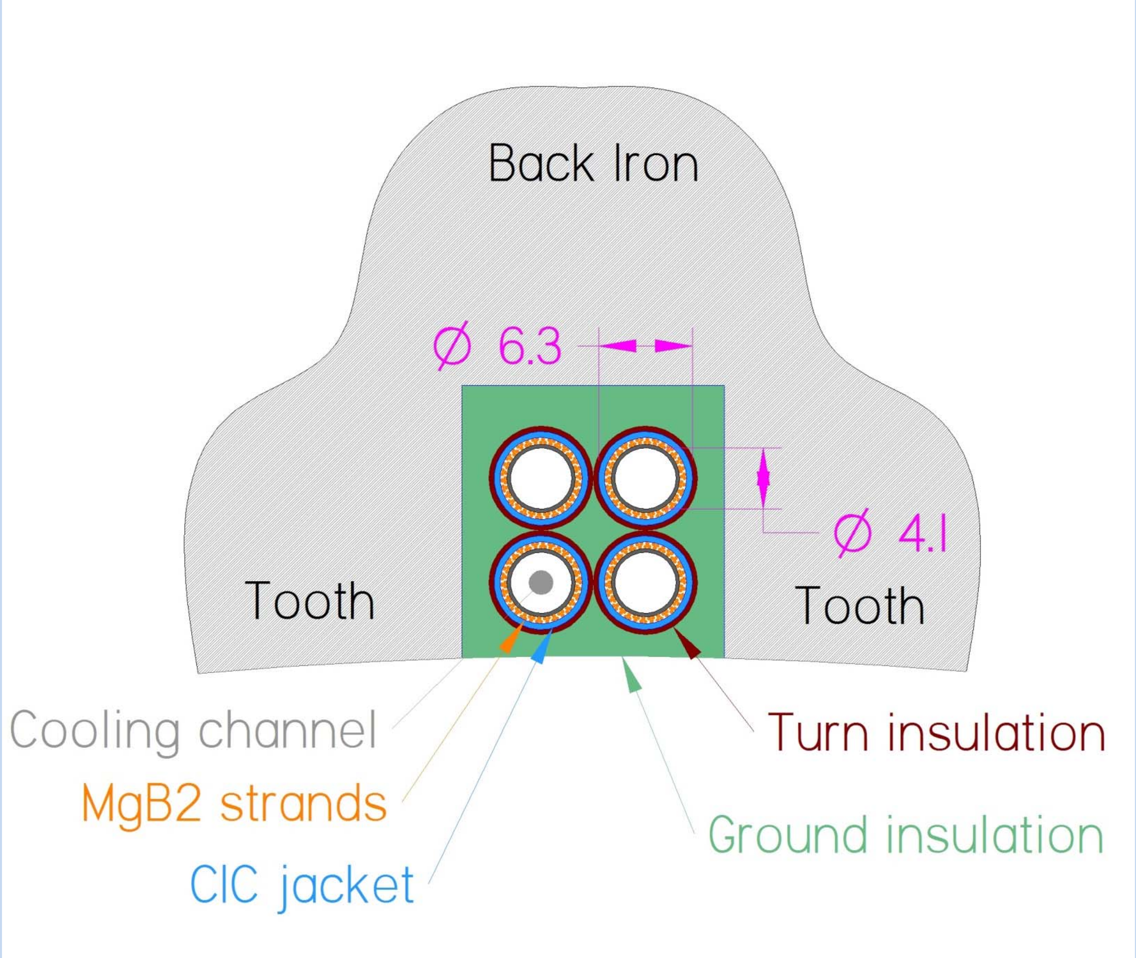
- MgB_2 strand has been proposed for many applications, including ac rotating electric machinery
  - Isotropic, filamentary conductor with high matrix resistivity and moderate ac loss
  - Operation at temperatures significantly above 4 K can ease cryoplant requirements
- Cooling with 20 K helium gas is challenging
  - Especially in high-frequency applications like an AC stator for a motor or generator
    - Need for enhanced cooling capacity
    - Need to ensure adequate stability / quench protection

Objectives

- Examine feasibility of MgB_2 miniature cable-in-conduit conductor for ac applications
- Investigate use of solid cryogens for improved heat transfer and thermal stability

Proposed conductor configuration

- Consider stator conductor for 2-pole, 7000 rpm machine (117 Hz)
  - Target 10~15 MW operation at 2 kA peak phase current
  - Use optimized strand parameters
    - e.g.1st generation Hyper Tech strand 36-CM, with
    - 10 μm filament diameter
    - 10 mm twist pitch
    - 10^{-6} Ohm-m matrix resistivity
    - Operating at 60% of critical at peak current
  - Field amplitude on conductor typically in 0.5~1.0 T range
  - Scale strand diameter as needed to pack neatly into a two-channel cable-in-conduit configuration
  - Minimum cooling path length ~15m / winding
- AC losses from hysteresis, transport current and coupling
  - 30~60 W AC loss / conductor length
- 20 atm, 20 K He gas cooling at conductor inlet
  - ½ atm pressure drop
  - 3 K temperature rise

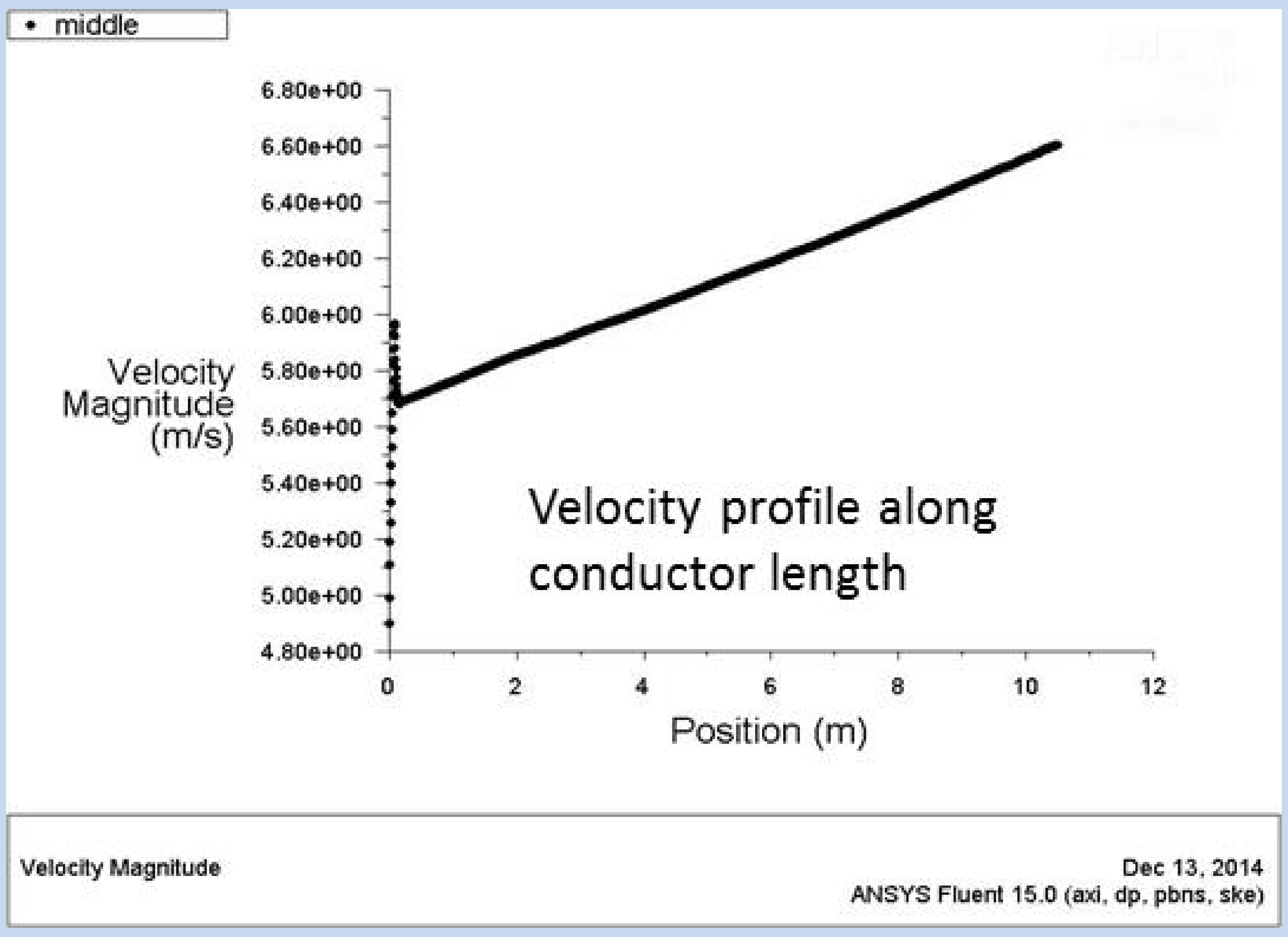


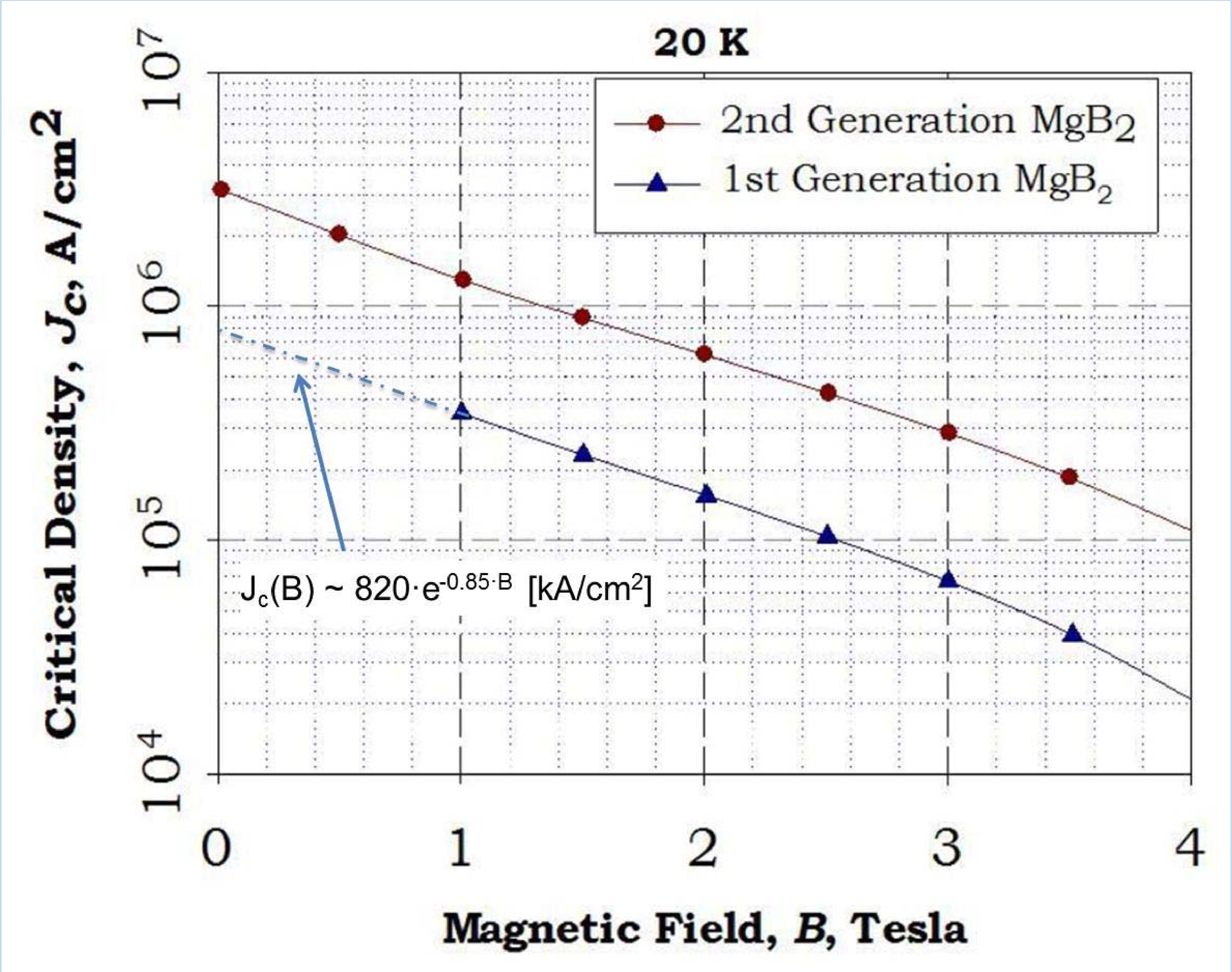
$$p(t) = \frac{2}{3\pi} d_f J_c^{ov} \left[1 + \left(\frac{I}{I_c}\right)^2\right] \left|\frac{dB}{dt}\right| + \frac{1}{2\beta}\left(\frac{l_p}{2\pi}\right)^2 \frac{1}{\rho_t}\left(\frac{dB}{dt}\right)^2 \quad (W\ m^{-3})$$

Instantaneous loss power from Tixador, *Handbook of Applied Superconductivity*

Product #	# filaments	fill factor (%)	copper component (%)	Cross section
36-CM	36	15	15	

From Hyper Tech product data sheet

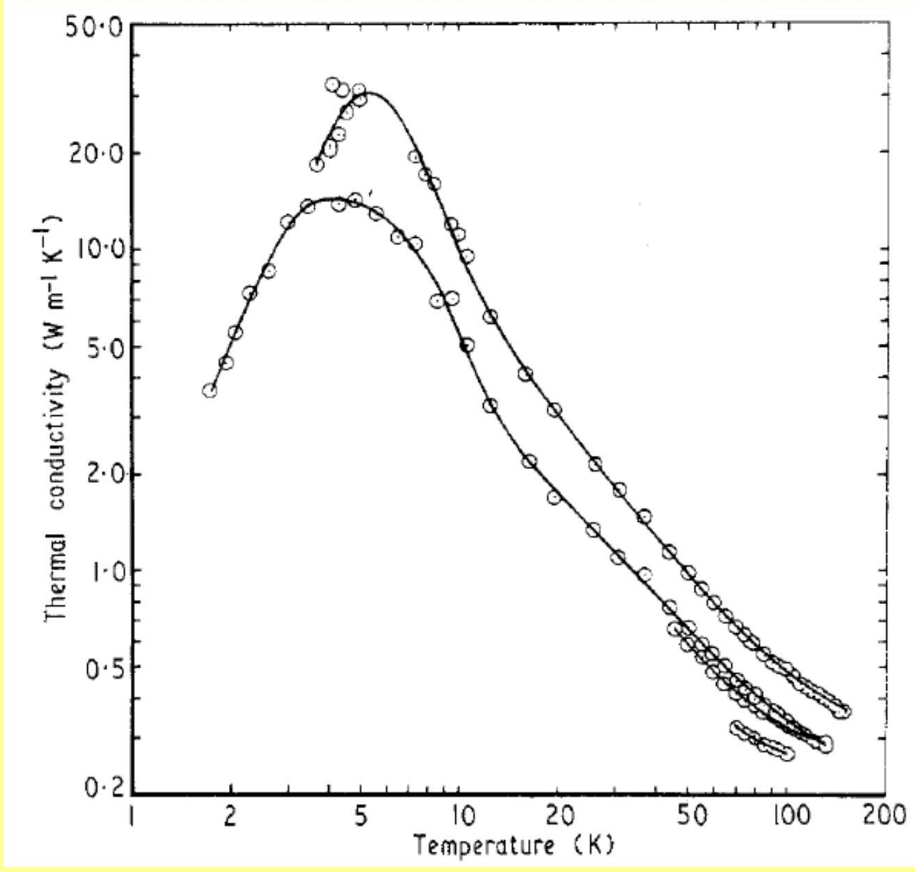




Presented at EUCAS 2013

Solid cryogen selection

- Choice of liquid or gas at room temperature
  - Volumetric expansion
  - Conductor pressure rating
- Two-channel cable-in-conduit configuration
  - Inner cooling channel diameter accommodates conductor ac losses (hysteresis, coupling, transport current)
  - Outer channel filled with solid cryogen during 20 K operation



Thermal conductivity vs. temperature for solid argon of different densities. Data from Clayton and Batchelder, 1973 *J. Phys. C: Solid State Phys.* **6** 1213.

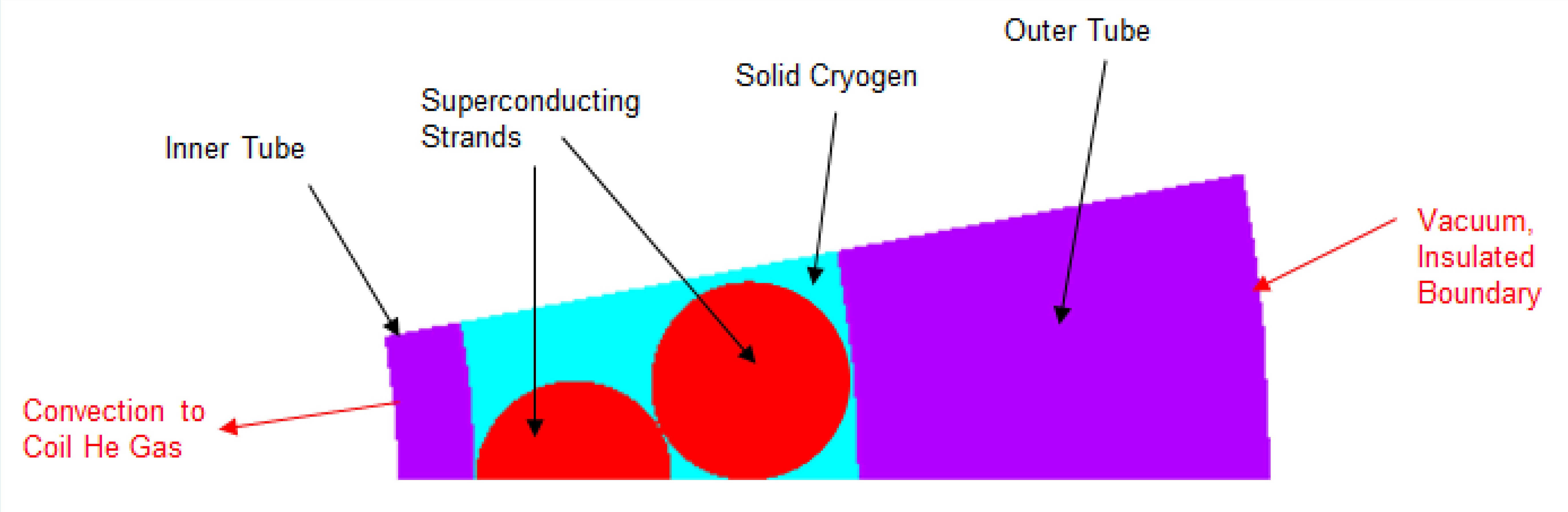
Data for Select Cryogens

Cryogen	Molar Mass [g/mole]	Density @ 20 K [g/cc]	Thermal conductivity @ 20 K [W/m-K]	Melting point @ 1 atm [K]	Heat of Fusion [J/cc]	Boiling point @ 1 atm [K]	Density @ 298 K [g/cc]	Porosity @ 20 K [%]
Argon (Ar)	39.9	1.71 (solid)	1.8~3[a] (- slope)	83.8	41	87.2	0.17 (gas @ 100 atm)	90
Helium gas (He)	4.0	0.047 (@ 20 atm)	0.032[b] (+ slope)	n.a.	n.a.	4.2	0.015 (gas @ 100 atm)	n.a.
Nitrogen (N_2)	28.0	1.02 (solid)	0.4[c] (- slope)	63.1	20	77.4	0.11 (gas @ 100 atm)	89
Methanol (CH_3OH)	32.0	1.03 (solid)	0.12[d] (+ slope)	151	10	337	0.79 (liquid @ 1 atm)	23
Propane (C_3H_8))	44.1	0.73 (solid)	1~1.5[e] (- slope)	84.5	39	231	0.49 (liquid @ 10 atm)	30

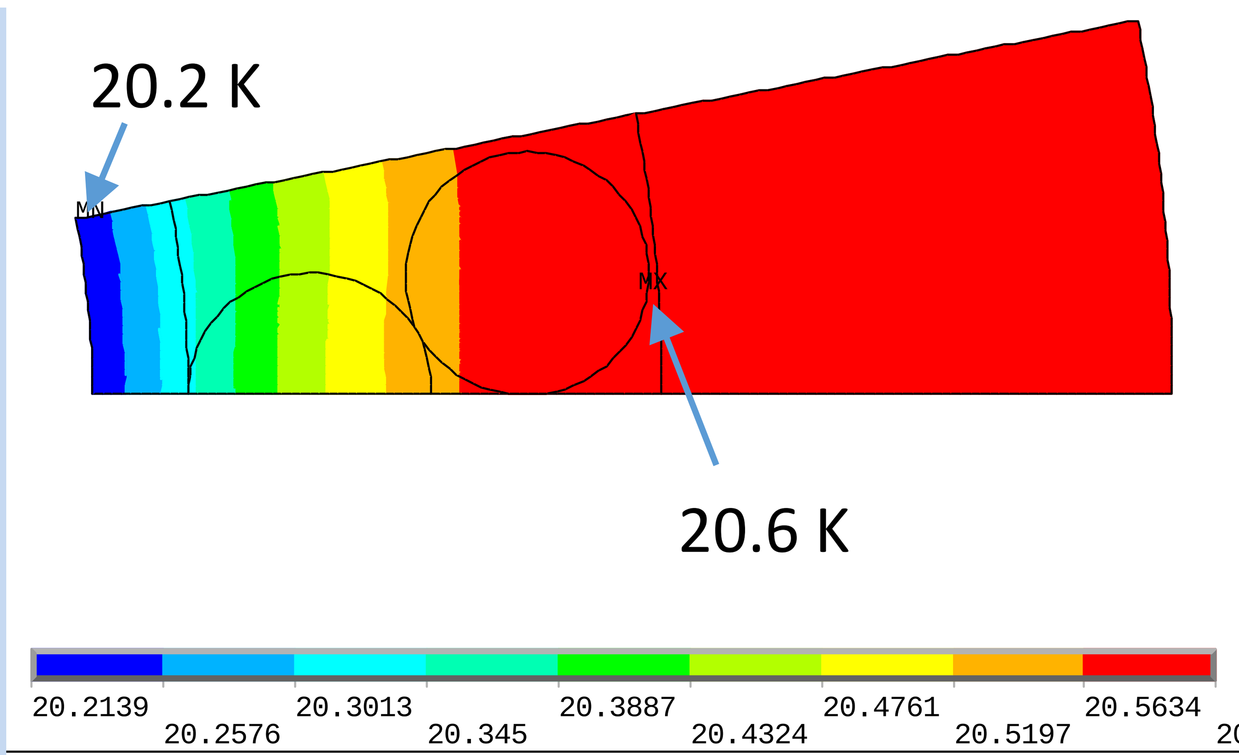
[a]Clayton F and Batchelder 1973 *J. Phys. C: Solid State Phys.* **6** 1213, [b]REFPROP, [c]Stachowiak P *et al* 1994 *Phys. Rev. B* **50** 543, [d]Krivchikov *et al* 2011 *J. Non-Crystalline Solids* **357** 483, and [e]Konstantinov *et al* 2009 *Low Temp. Phys.* **35** 577.

Steady-state heat transfer

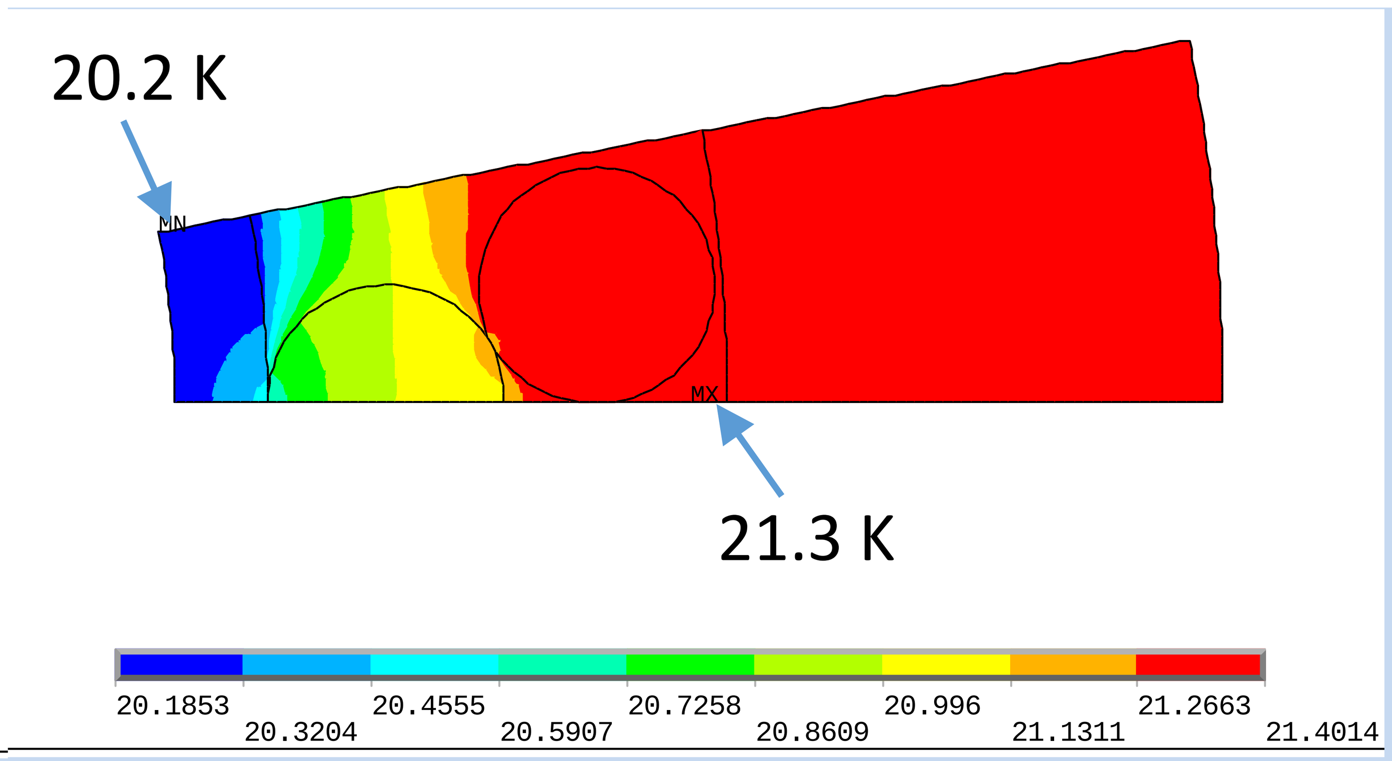
- Model
  - Thermal model takes into symmetry and 17 triplet geometry.
  - AC loss heating of 55 W distributed uniformly over all 51 strands.
- Helium gas cooling
  - Internal gas flow results in a heat transfer coefficient of ~3000 W/m^2-K.
  - Flow in cable space is essentially stagnant due to low density, small hydraulic diameter.
- Temperature gradients
  - Cable space temperature gradient maintained at ~0.4 K by conduction through solid cryogen, which has a thermal conductivity ~1 W/m-K.
  - Stagnant helium gas (~0.025 W/m-K) results in a gradient of ~1.1 K.



Solid Cryogen (ΔT ~ 0.4K)

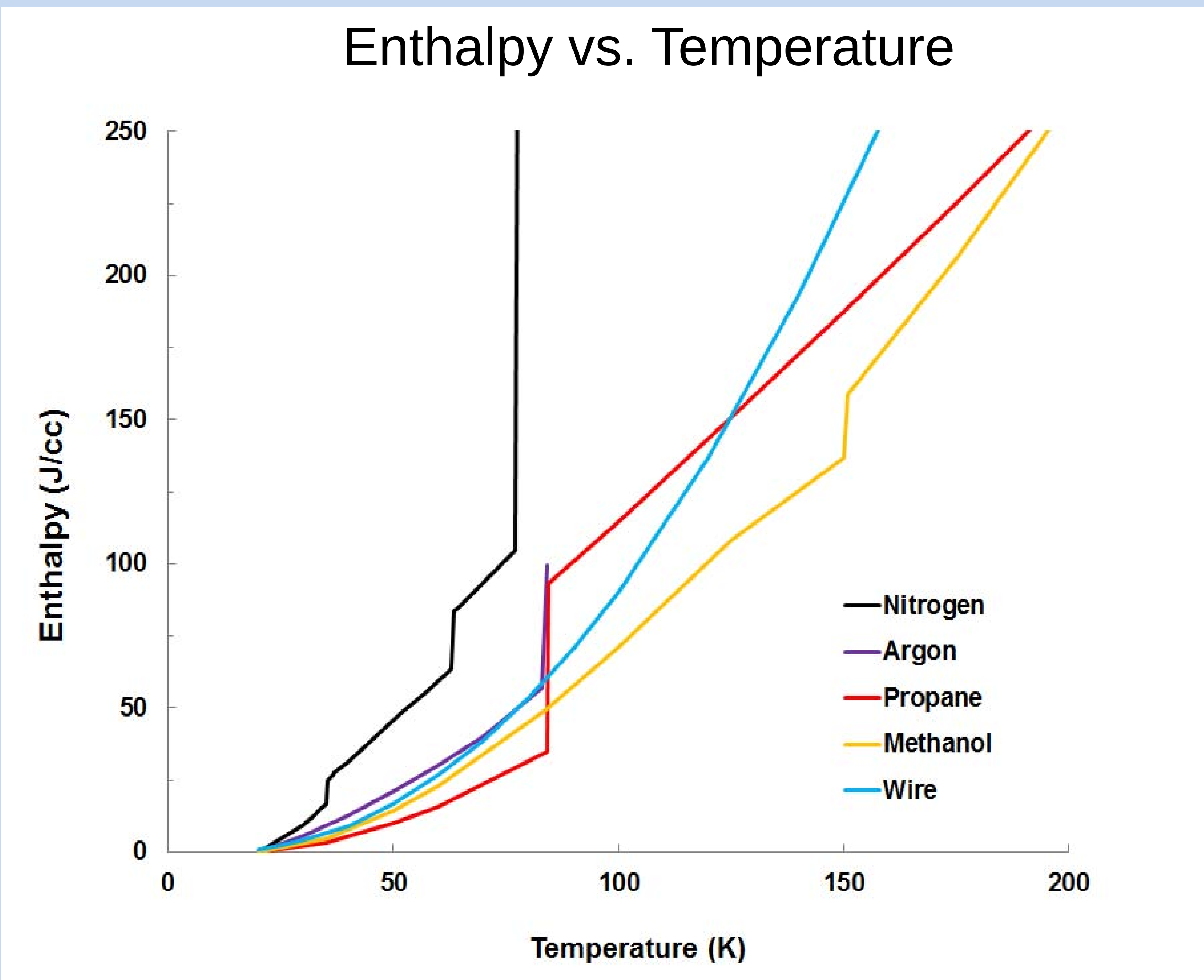


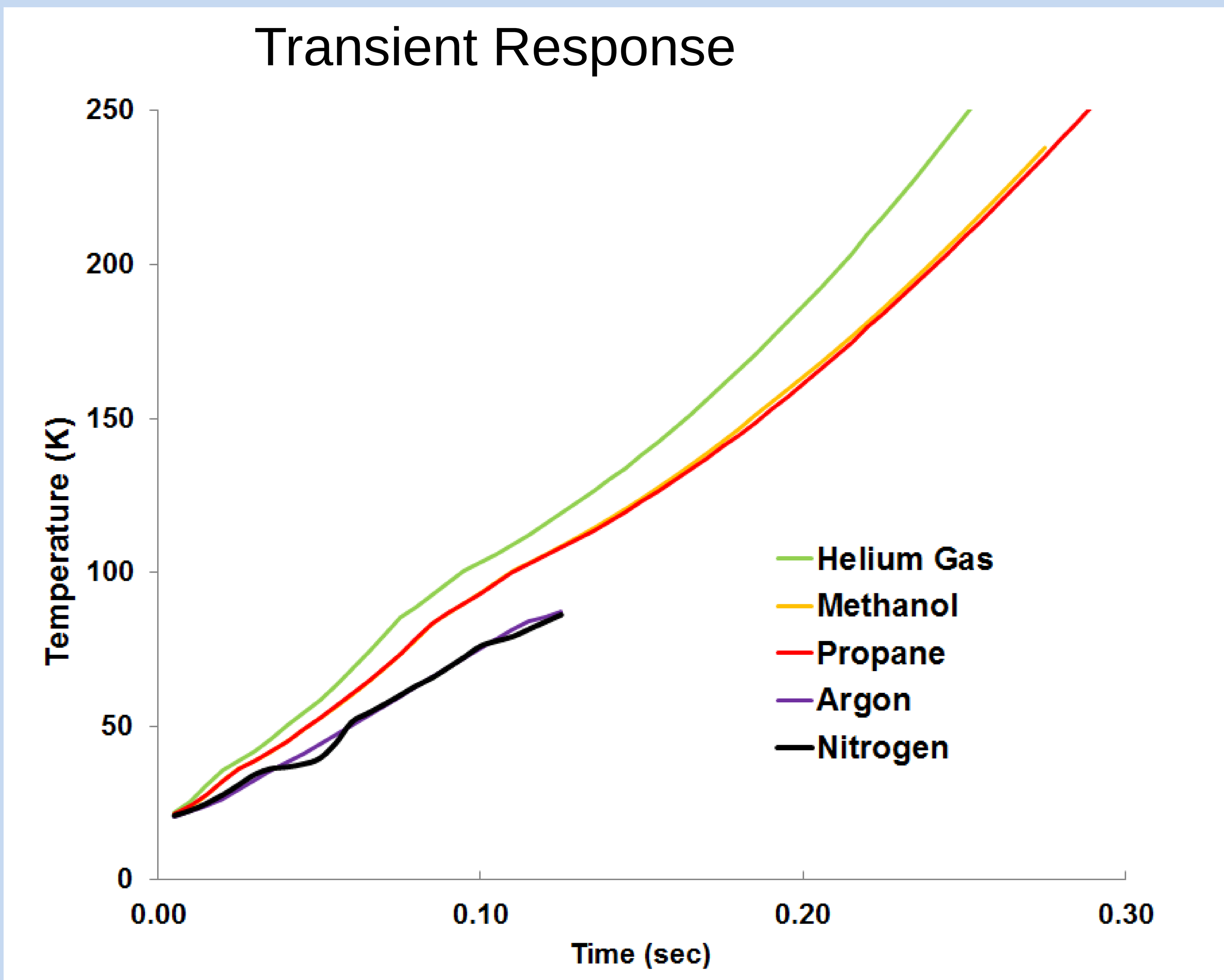
Stagnant Helium Gas (ΔT ~ 1.1 K)



Transient behavior

- Model
  - Enthalpies of selected cryogens, tubes and strands considered in model.
  - Assumes copper-superconductor ratio of 10:1.
  - Accounts for increasing copper stabilizer resistance with temperature and Joule heating.
- Assumptions
  - All strands quench simultaneously, which is a conservative assumption.
  - Pressure rise due to vaporization is undesirable; therefore, only study up to that point.
- Results
  - Response dominated by the MgB2 wire enthalpy.
  - Minor effect due to the enthalpy of specific cryogens.
  - Lower boiling temperatures of nitrogen and argon limit thermal response time.
  - Propane and methanol enable response times over 250 msec.





Summary

- The use of solid cryogen to stabilize, both mechanically and thermally, an MgB2-based CIC was cable investigated.
- Steady-State Thermal Anaysis
  - Analysis performed by uniformly distributed estimated 1000 W AC loss heat load.
  - Increased thermal conductivity of the solid cryogen, as compared to stagnant helium gas, limits the internal temperature difference to an acceptable level (~0.4 K, as opposed to ~1.1 K).
- Transient Thermal Analysis
  - Effect of various enthalpies considered during a quench event.
  - Response dominated by enthalpy of the MgB2 wire.
- Cryogen Selection
  - Low boiling points of argon and nitrogen limit time before undesirable vaporization occurs.
  - Propane and methanol can be filled as a liquid at room temperature, minimizing porosity upon cooldown, as compared to high porosity in either nitrogen or argon.

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