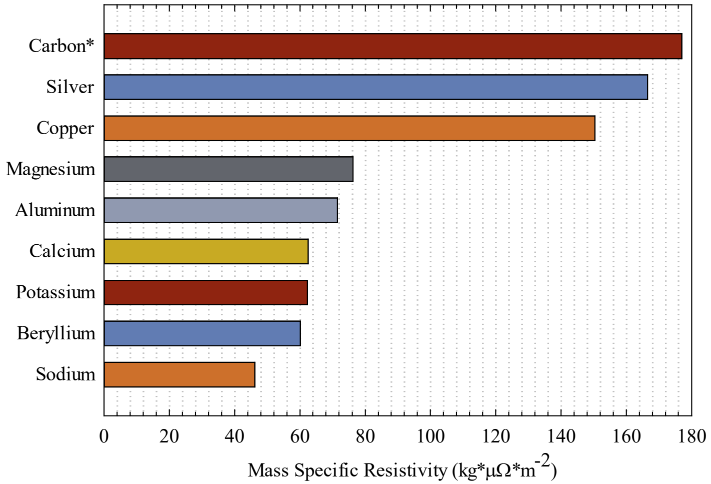

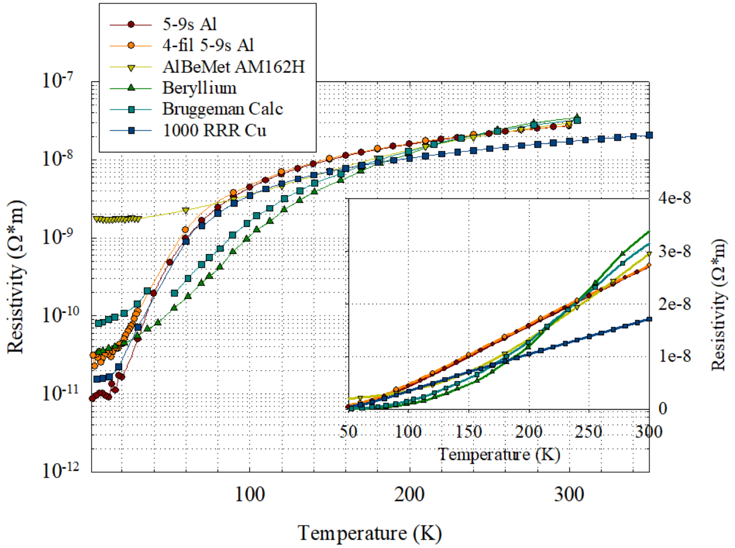

Cryoresistive Aluminum-Beryllium Nanocomposites for Aerospace Electrical Conductors

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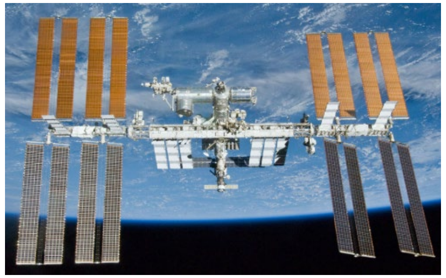
Summary

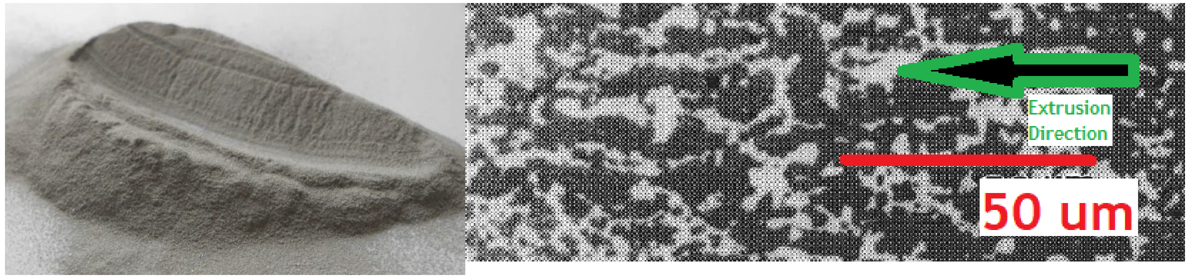
- AlBeMet AM162H
- Mass specific resistivity comparison and resistivity of AlBeMet AM162H versus state-of-the-art cryoresistive materials
- Magnetoresistance of AlBeMet AM162H
- DC current carrying capacity of AlBeMet AM162H versus state-of-the-art cryoresistive materials and REBCO coated conductor
- AlBeMet AM162H current leads
- AlBeMet AM162H for low AC loss conductors
- Future Work

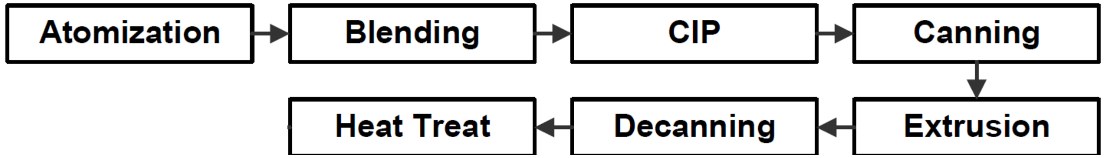
AlBeMet AM162H, an Al-Be Nanocomposite

- Beryllium is an amazing material, but hard to process (machining, bonding, etc.)
- AlBeMet AM162H 38%wt Al matrix, 62%wt Be reinforced composite (not an alloy, nanocomposite)
- AlBeMet AM162H is machinable, bondable, and processable as other Al aerospace grade alloys
- AlBeMet AM162H:
  - High κ (RT=250 W/mK)
  - High E (RT=200 GPa)
  - Low ρ (2.1 g/cm^3)
  - High σ_y (RT>300 MPa)

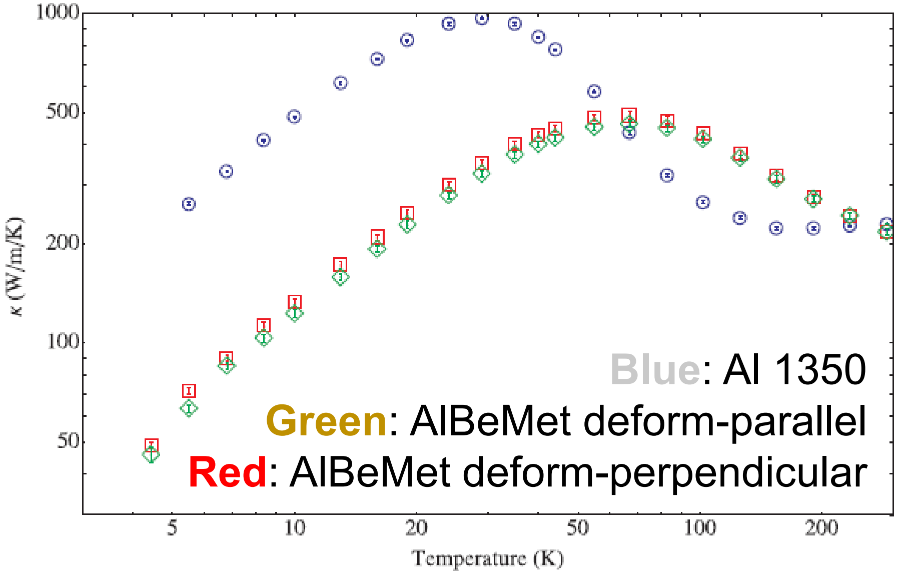


- What about cryogenic electrical resistivity and magnetoresistance?





Atomization → Blending → CIP → Canning → Extrusion → Decanning → Heat Treat

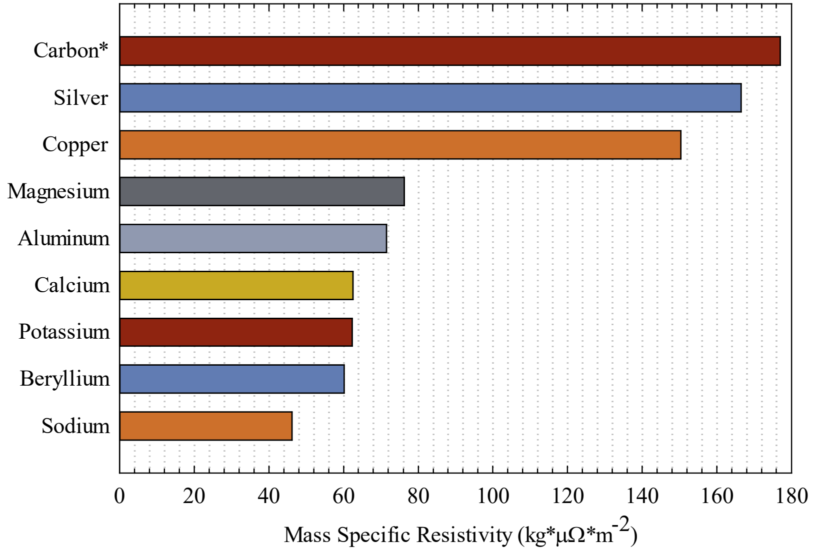


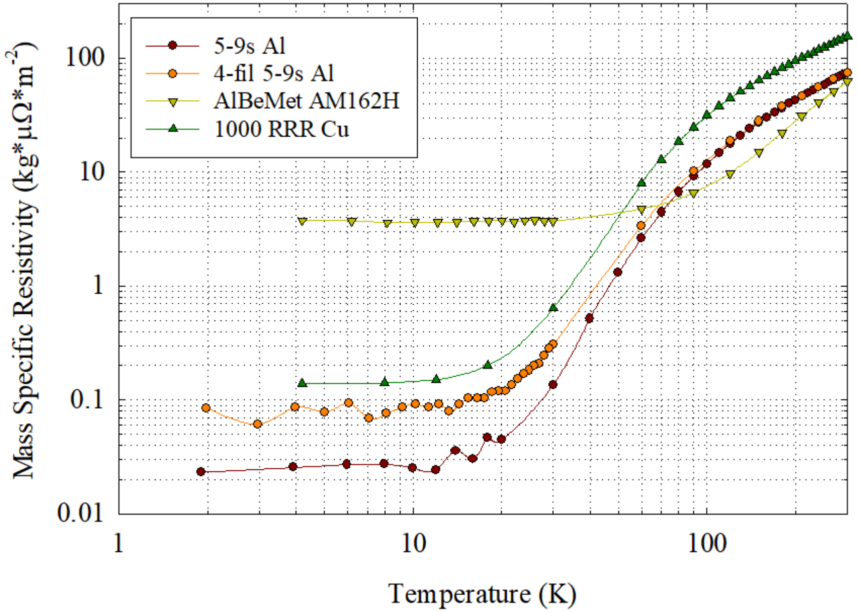
https://materion.com/-/media/files/beryllium/albemet-materials/maab-009mechanicalandthermalpropertiesofaluminumberylliumalloyam162.pdf
Tuttle "Cryogenic thermal conductivity measurements on candidate materials for space missions" (2017)

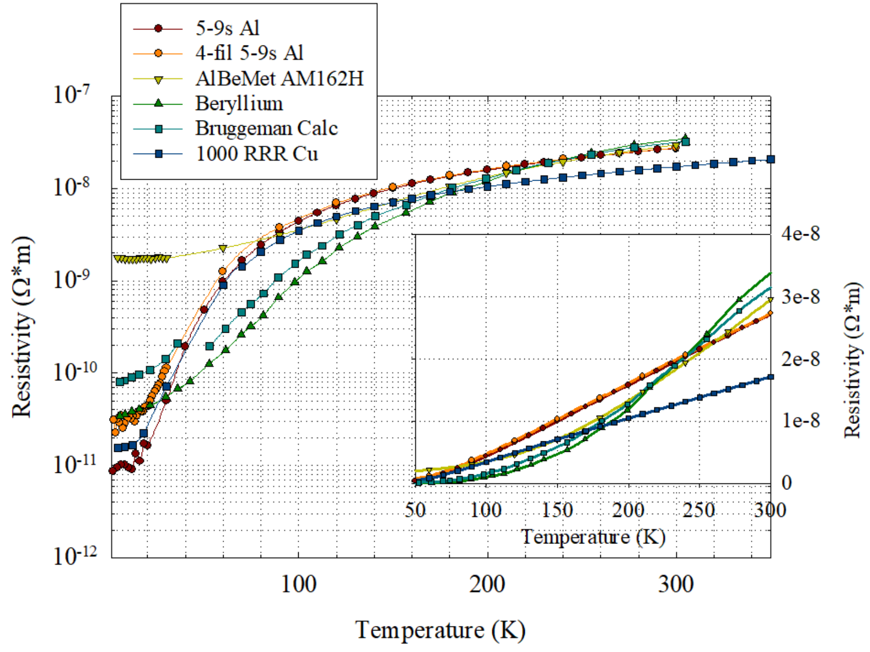
Mass Specific Resistivity

- Mass specific electrical resistivity (MSR) is an important material metric for aerospace
- Density multiplied by resistivity (small is good)
- Be has the lowest mass specific resistivity of any structural rated and chemically stable metal, next up is Al
- Be hard to shape and bond, AlBeMet AM162H is not
- Be ρ_{elec} < Cu starting from 180K
- AlBeMet AM162 (RRR=17) ρ_{elec} < Cu 105K to 150K

- AlBeMet AM162 (RRR=17) ρ_{elec} < Cu 105K to 150K
- AlBeMet AM162 MSR < Al greater than RT to 75 K





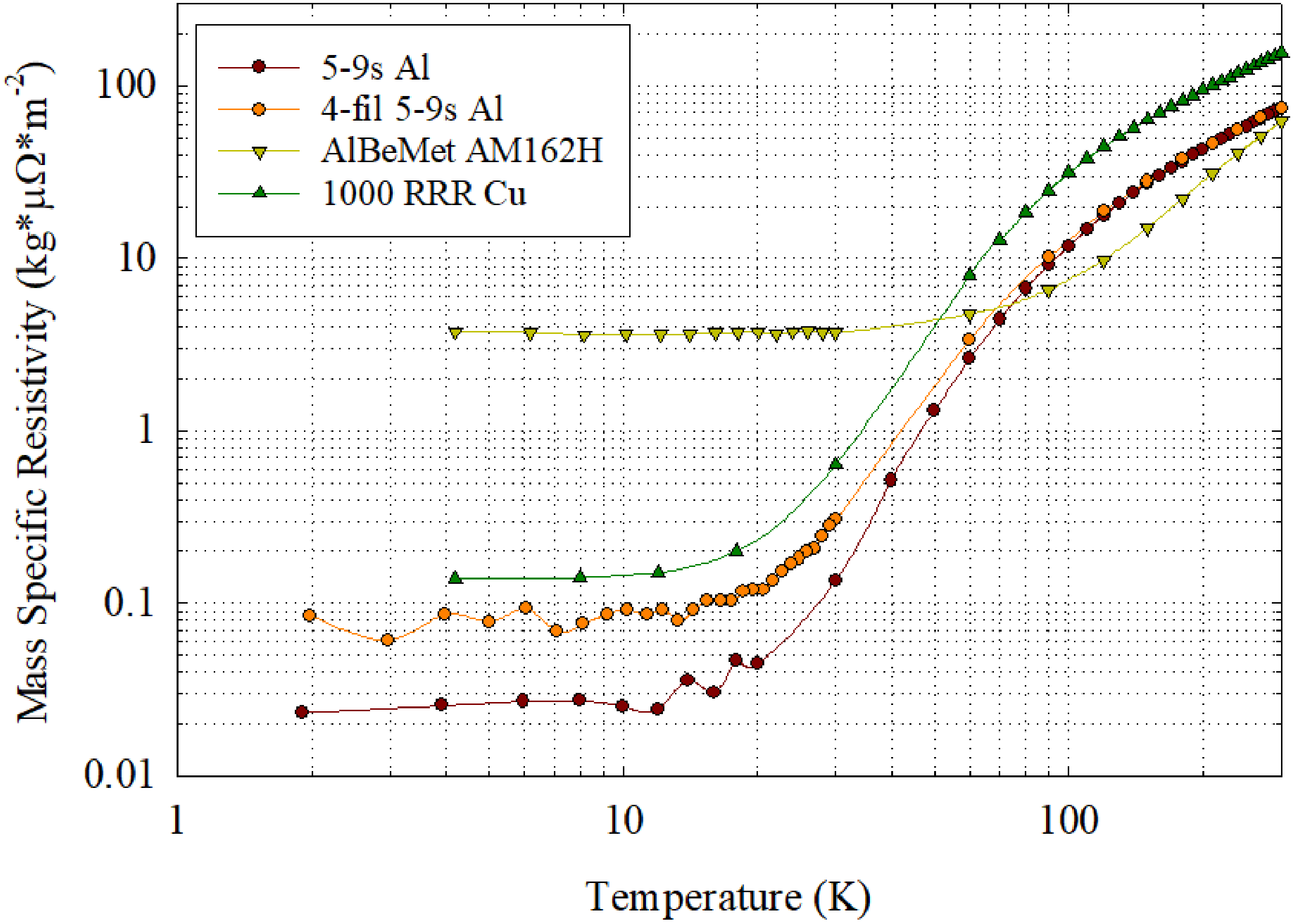


$$\rho_{eff} = \rho_m \times \frac{2\theta_i(\rho_i - \rho_m) + \rho_i + 2\rho_m}{2\rho_m + \rho_i - \theta_i(\rho_i - \rho_m)}$$

Bruggeman effective medium approximation
Composite resistivity “rule-of-mixtures”

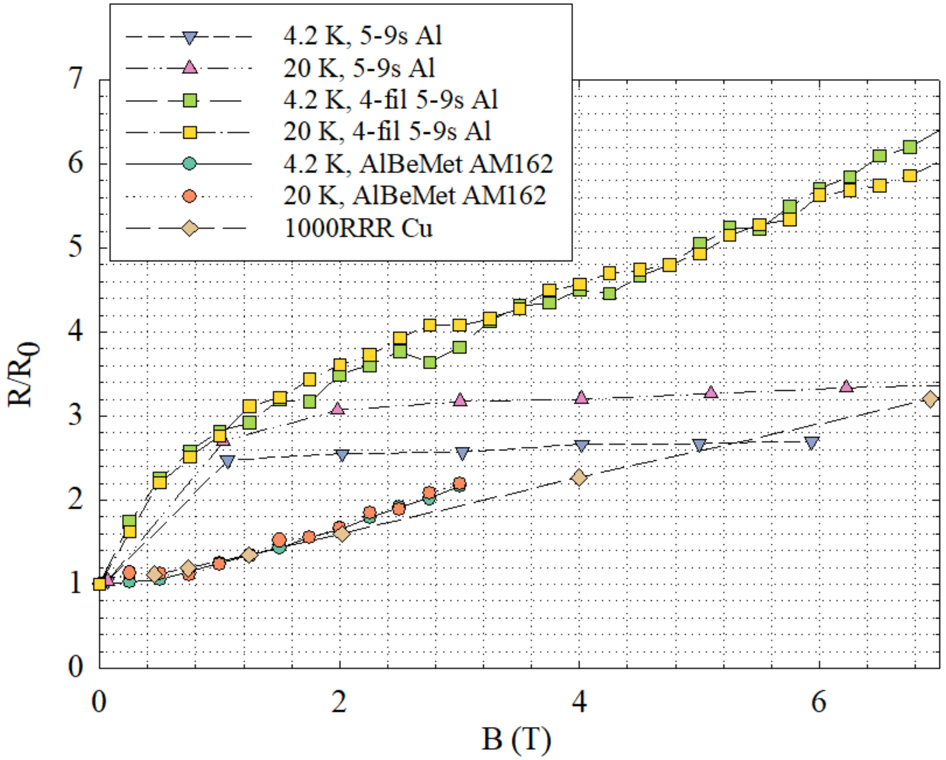
Note on AlBeMet Cryogenic MSR

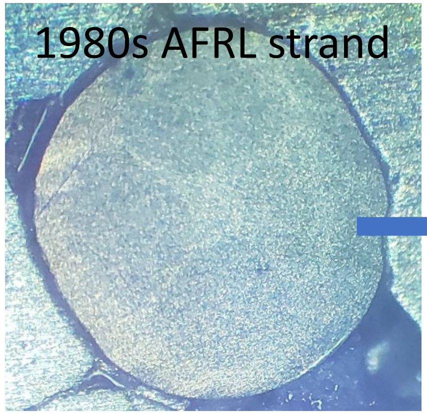
- AlBeMet AM162H metal powders are high purity Al 1100 and Be (grade B-26-D)
- Annealed (593C x 24hr) AlBeMet AM162H is RRR = 17 even though predicted much lower from Bloch-Gruneisen resistivity + Bruggeman effective medium approximation for composites.
- High electron scattering at composite interfaces, which becomes more relevant with increases of mean free path at cryogenic temperatures (l_{MFP} is proportional to $1/\rho_{elec}$)
- Tough to avoid oxygen contamination from high surface area metal powders



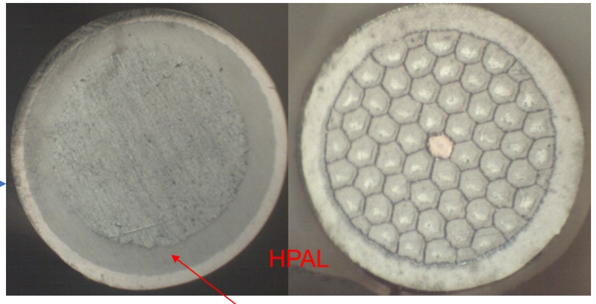
Magnetoresistance of AlBeMet vs. Other Cryoresistive Options

- Cu follows Kohler plot well, 5-9s Al not so well, [Fickett (1971)]
- “Anomalous magnetoresistance” in 5-9s multifilamentary wire is large
  - New composites reduce this (see OSU/HTR research M3Or4M-03)
- AlBeMet AM162H magnetoresistance is similar to Cu, and smaller than 5-9s Al up to 3 T.
- At 4.2 K and 20K AlBeMet AM162H is much higher resistivity than other state-of-the-art cryoconductors





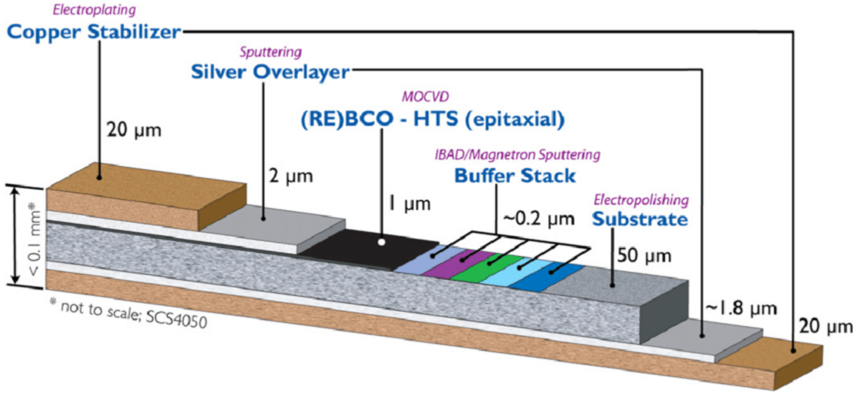
2020s HTR strand



Fickett “Aluminum 1. A Review of Resistive Mechanisms in Aluminum” (1971)
Eckels “Magnetoresistance in Composite Conductors” (1990)

DC “Ampacity” of Cryoresistive and Superconducting Options

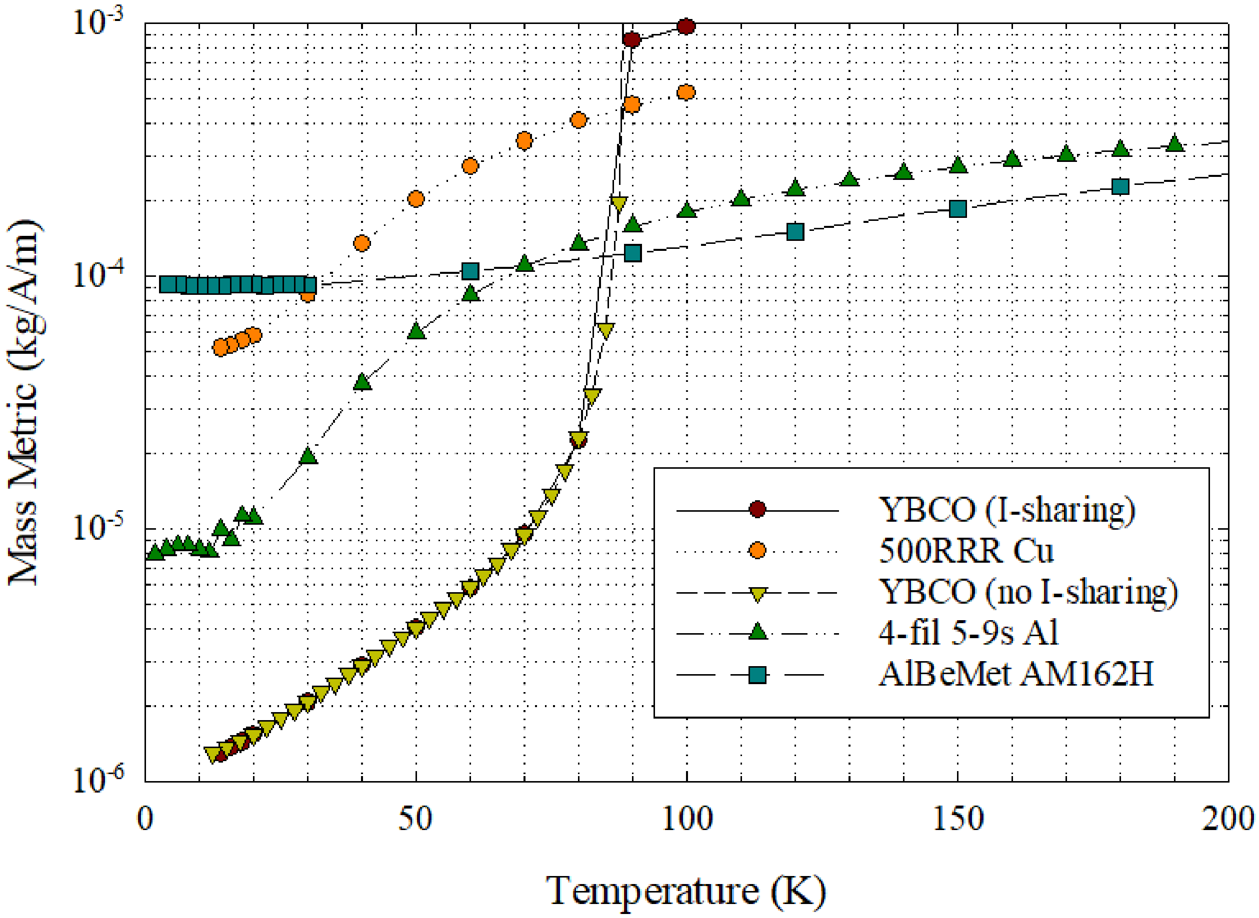
- “Current carrying capacity”, known as Ampacity, is a function of effective cooling rate and resistivity of the ohmic material
  - For unit cross section and unit length:
  - $J_{e-ampacity}[A/m^2] = \frac{Q[\frac{W}{m}]}{\rho_{elec} \times I}$ and
  - $J_{e-ampacity}[A/m^2] = \sqrt{\frac{Q[\frac{W}{m^3}]}{\rho_{elec}}}$
  - Where “Q” is a known cooling-rate and “I” is current
  - Knowing current, it is then possible to calculate the safe cross-sectional area of a wire/cable.
  - Can also calculate an important performance metric which is mass density divided by ampacity [kg/(A*m)] (smaller is better)



- Ampacity also exists in superconducting composites. Incorporating current sharing with the stabilizer increases ampacity to greater than J_c.
  - $J_{e-ampacity(SC\ composite)}[A/m^2] = \frac{J_{c-eng} \times A_{tot} + J_{e-ampacity(stabilizer)} \times A_{stabilizer}}{A_{tot}}$
  - Where “A_{tot} and $A_{stabilizer}$” is total cross-sectional area of the superconducting composite and stabilizer respectively and “J_{c-eng}” is the critical current density of the superconducting composite.

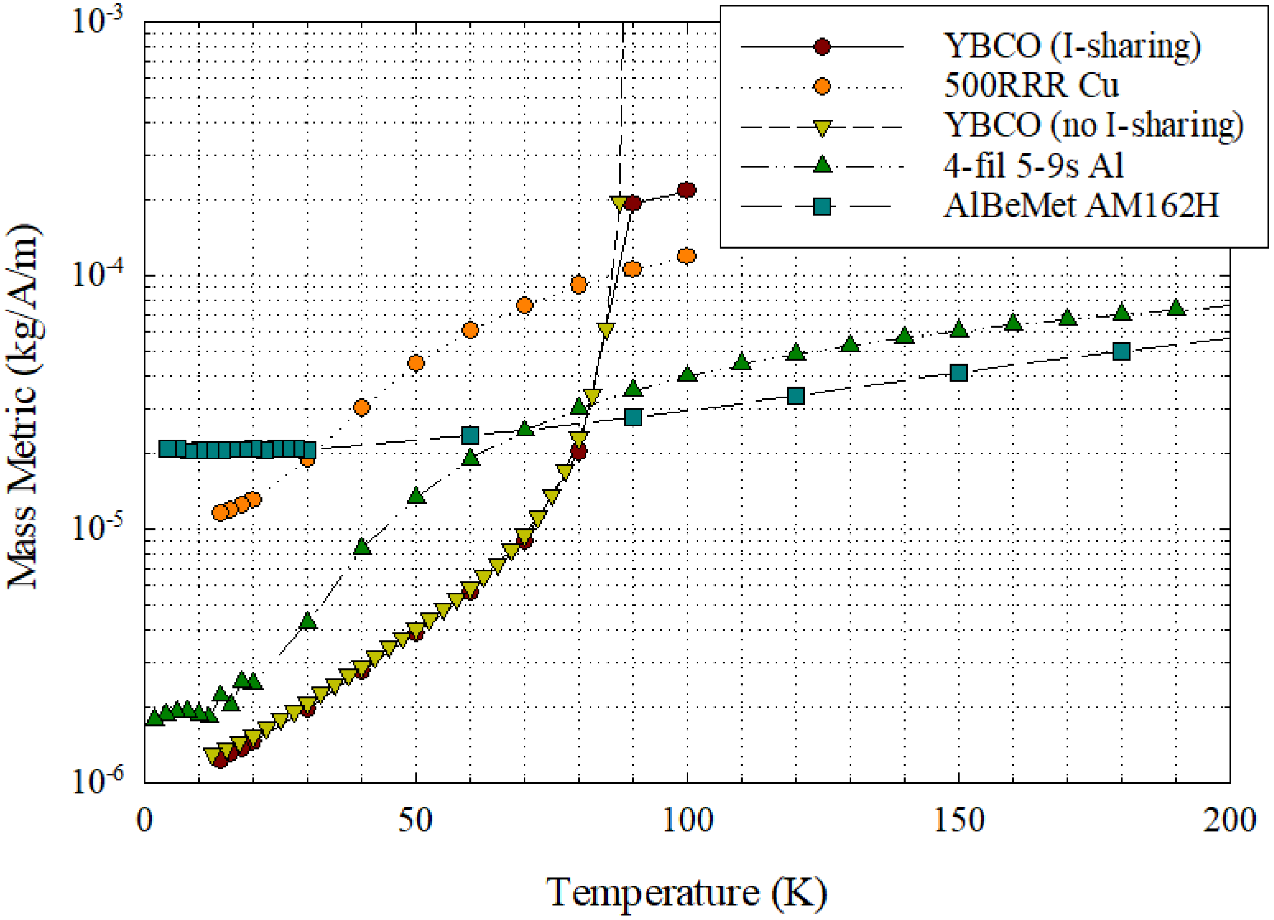
DC "Ampacity" of Cryoresistive and Superconducting Options

- Ampacity is a strong function of available cooling
- This comparison is for:
  - High performance YBCO (I_c data for AP Superpower tape [https://htsdb.wimbush.eu/]) customized with a 20 μm thick 500RRR Cu stabilizer and 30 μm substrate.
  - Q = 1 W/cm^3
  - 4-filament 5-9s Al wire, 5-9s 51% cross-section and matrix low RRR
  - And AlBeMet AM162H
- YBCO has best metric <87.1K, <T_c.
  - YBCO coated-conductor still has ampacity above T_c, but a positive offset versus pure stabilizer because the stabilizer is a fraction of the cross-section.
- Above 87.1K, AlBeMet AM162H has best metric
- 4-filament 5-9s Al wire is less competitive versus HTS at lower temperatures



DC “Ampacity” of Cryoresistive and Superconducting Options

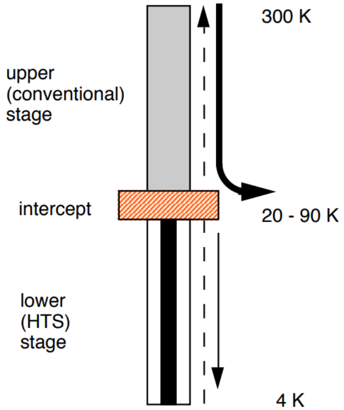
- Ampacity is a strong function available cooling
- This comparison is for:
  - High performance YBCO (I_c data for AP Superpower tape [https://htsdb.wimbush.eu/]) customized with a 20 µm thick 500RRR Cu stabilizer and 30 µm substrate.
  - Q = 20 W/cm^3
  - 4-filament 5-9s Al wire, 5-9s 51% cross-section and matrix low RRR
  - And AlBeMet AM162H
- YBCO has best metric <81.3K, <*$T_{c.}$*
  - YBCO coated-conductor still has ampacity above *T_c*, but a positive offset versus pure stabilizer because the stabilizer is a fraction of the cross-section.
- Above 81.3K, AlBeMet AM162H has best metric
- 4-filament 5-9s Al wire is more competitive versus HTS at lower temperatures

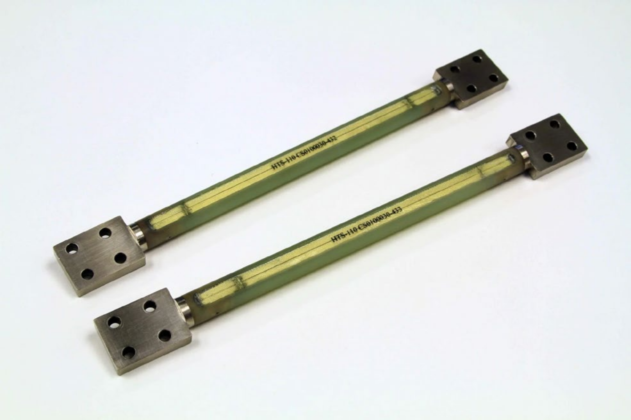


Cryoresistive DC Current Leads

- For high amperages, any current leads for cryo-power systems in the cryo → ambient (or higher T) transition will have substantial mass
- Standard techniques
  - Tapered leads, thin in cryo and thicker up top
  - Multi-cryoresistive material leads
  - HTS composite leads
- Minimize Joule Heating + Heat Leak
- First examining single material tapered leads

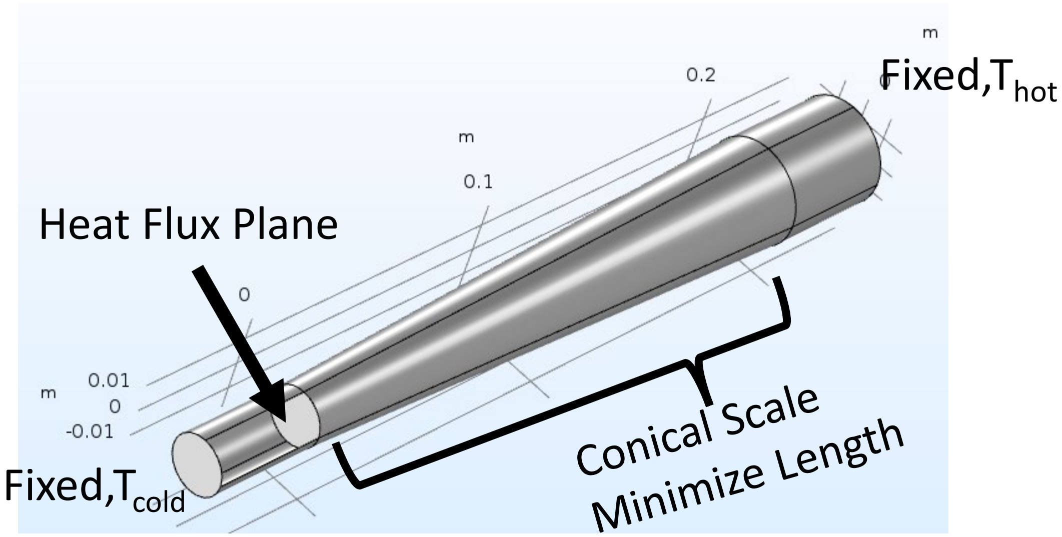
37 kA room temperature copper termination, 120 kg





Cryoresistive 3.3 kA DC Current Leads

- HPAL(RRR=9000) and AlBeMet AM162H examined as a tapered single material current lead, k(T) and ρ(T)
- Optimization to minimize incoming heat flux by changing length
- Parametric study of different conical scaling ratio, radii, and T_{cold} (20, 60, 77, and 112K)

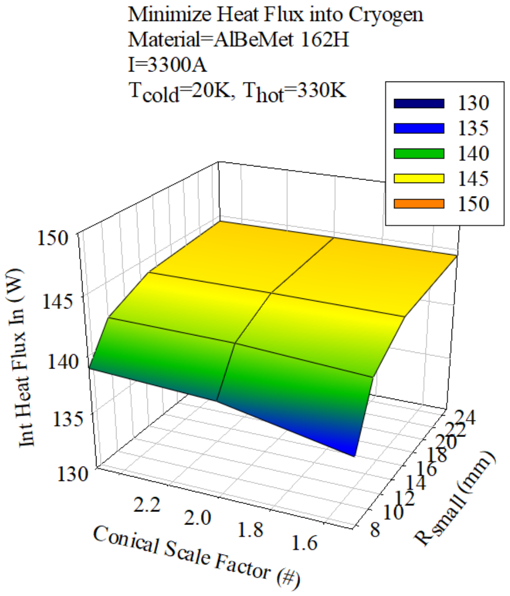


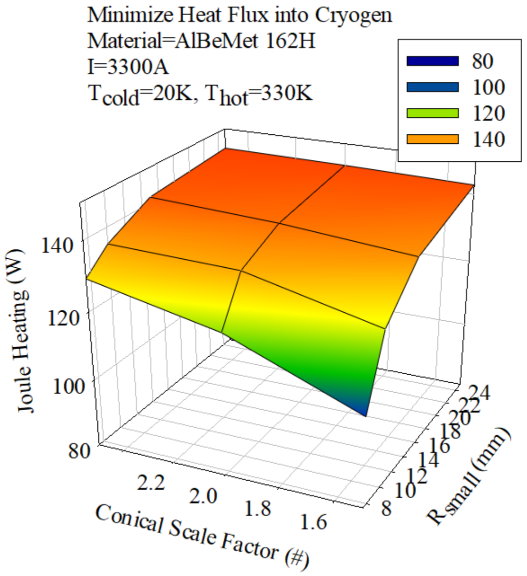
Fixed,T_{hot}

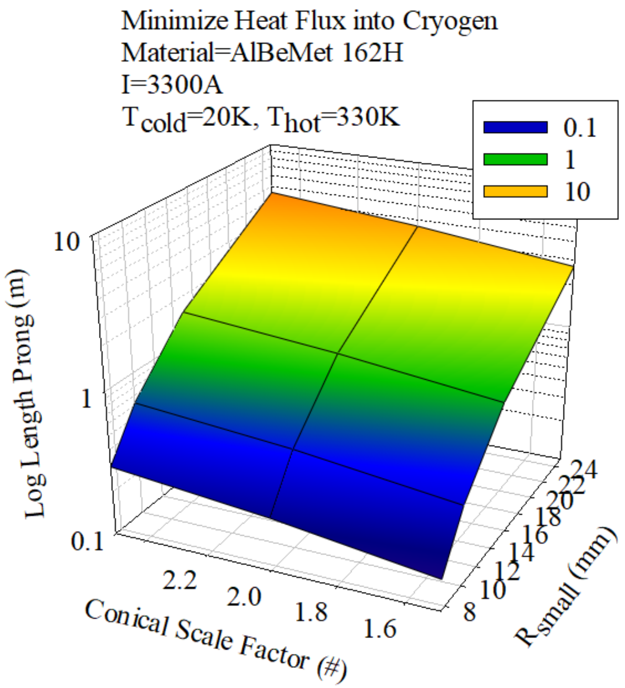
Heat Flux Plane

Fixed,T_{cold}

Conical Scale
Minimize Length


Minimize Heat Flux into Cryogen
Material=AlBeMet 162H
I=3300A
T_{cold}=20K, T_{hot}=330K


Minimize Heat Flux into Cryogen
Material=AlBeMet 162H
I=3300A
T_{cold}=20K, T_{hot}=330K


Minimize Heat Flux into Cryogen
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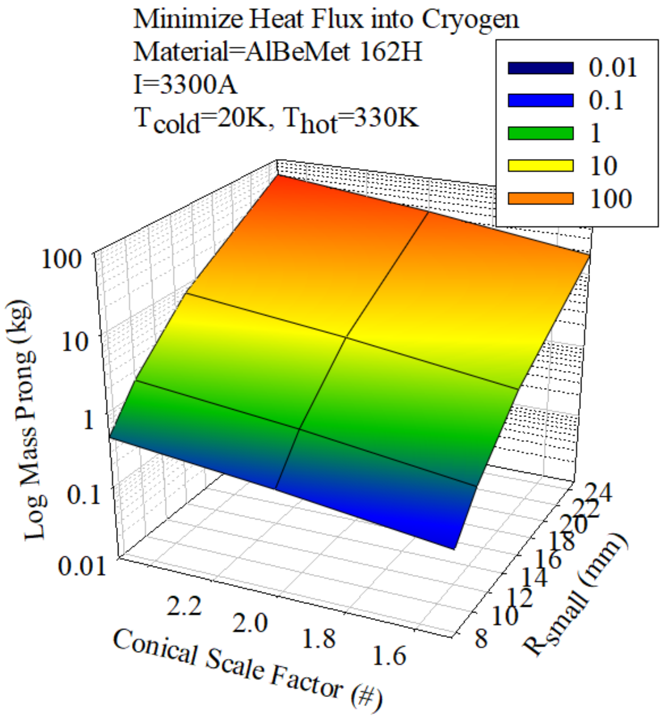
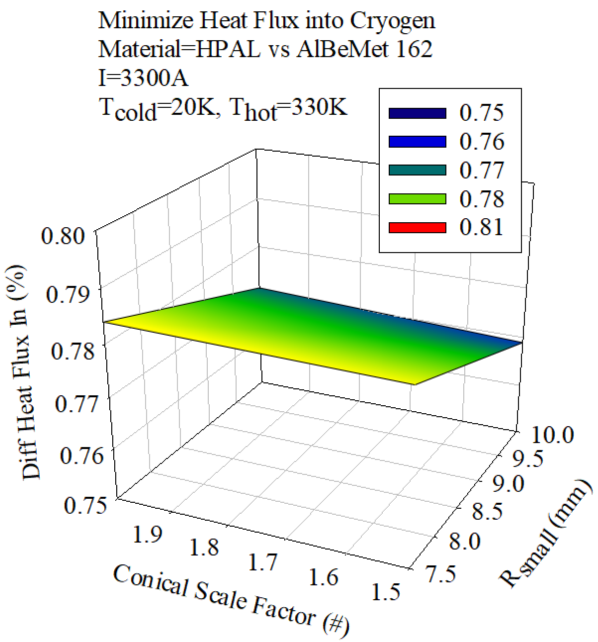
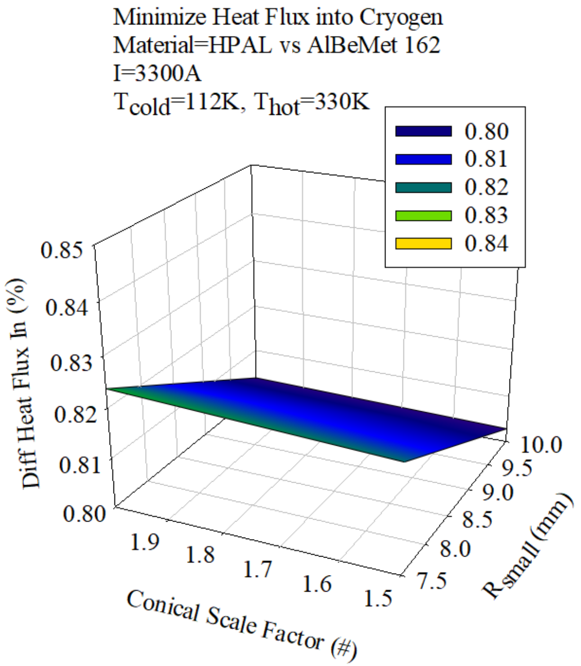
T_{cold}=20K, T_{hot}=330K

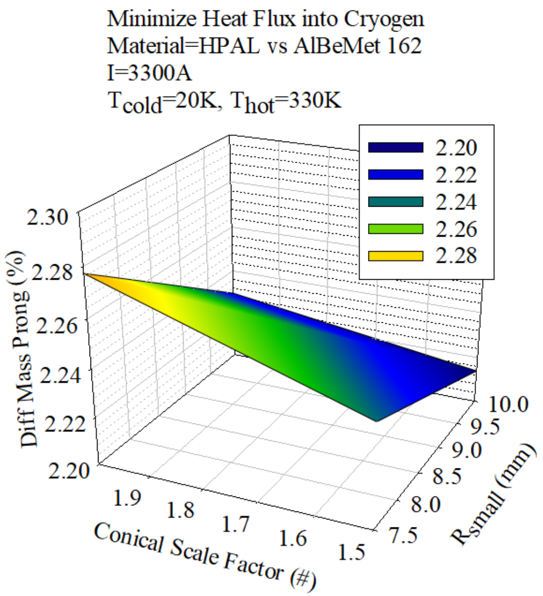

Minimize Heat Flux into Cryogen
Material=AlBeMet 162H
I=3300A
T_{cold}=20K, T_{hot}=330K

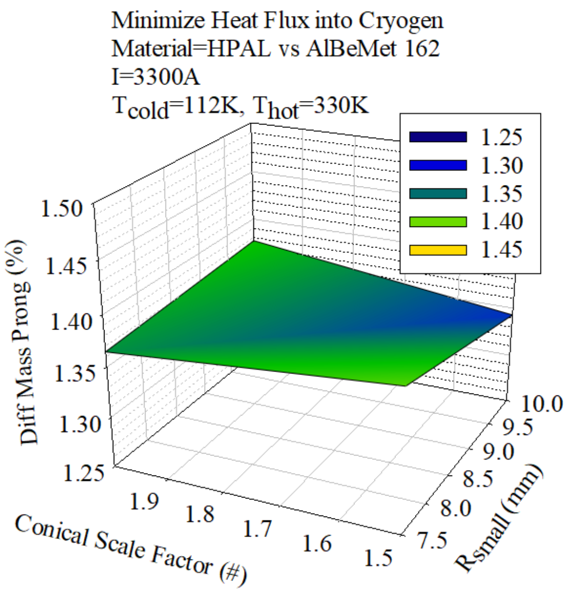
Cryoresistive 3.3kA DC Current Leads Comparison

- AlBeMet 162H is substantially lower mass for low temperatures, but slightly higher heat flux in
  - For radii and scale factor examined
  - Lower electrical and thermal conductivity reduces length slightly to reach min heat flux
  - Density 2.1 g/cm^3 vs 2.7 g/cm^3
- Need to examine different thermal gradients and consider incorporating into an HTS composite lead
- At 112K (LNG$_{StdP}$) AlBeMet 162H is still lower mass and higher heat flux in, but the difference is smaller
- AlBeMet 162H is substantially more expensive per kg than aluminum (~$700/kg)
  - Critical components such as low heat leak current leads for space and suborbital vehicles an analysis is necessary.







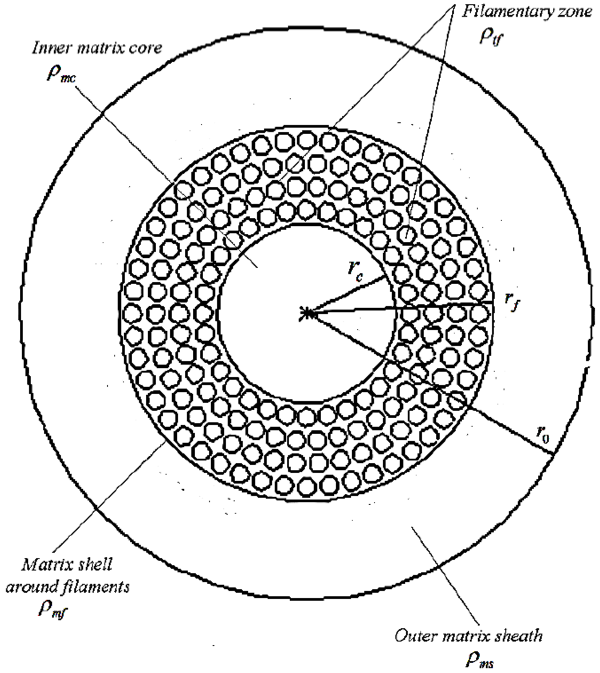


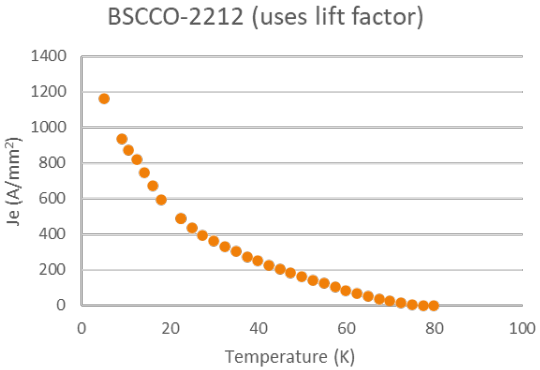
AlBeMet AM162H for Cryogenic Low AC-Loss Applications

- Litz cable of cryoresistive conductors (50 µm filament diameter)
- Comparison with low-loss BSCCO-2212 wire
- Q = 1, 5, 20 W/cm^3, Solve for safe sinusoidal frequency at different temperatures
- Higher frequency desired for many rotating machines
- Power loss for BSSCO-2212 composite

- $P_{Coupling+Eddy} = \left(\frac{r_f}{r_0}\right)^2 \left(\frac{\pi^2}{2} B_m f\right)^2 \left(\frac{L_p}{2\pi}\right)^2 \left(\frac{1}{\rho_{ms}} \frac{{r_0}^2 - {r_f}^2}{{r_0}^2 + {r_f}^2} + \frac{1}{\rho_{tf}} \frac{{r_f}^2 - {r_c}^2}{{r_f}^2} + \frac{1}{\rho_{mc}} \frac{{r_c}^2}{{r_f}^2}\right) + \frac{\left(\frac{\pi^2}{2} B_m f\right)^2}{4\rho_{ms}} \left(\frac{{r_0}^4 - {r_f}^4}{{r_0}^2}\right)$
- $P_{Hysteresis} = \left(\frac{8}{3\pi}\right) f \lambda B_m J_c d \left[1 + \frac{1}{3}\left(\frac{J_m}{J_c}\right)^2\right]$
  - Where “f”=AC frequency, “B_m”=AC field magnitude, “λ”=SC%, “d”=filament diameter, “J_m”=AC J magnitude, “r_{xxx}” = different radii within of composite, “ρ_{xxx}” = different resistivities within composite, and L_p = twist pitch of superconducting filaments

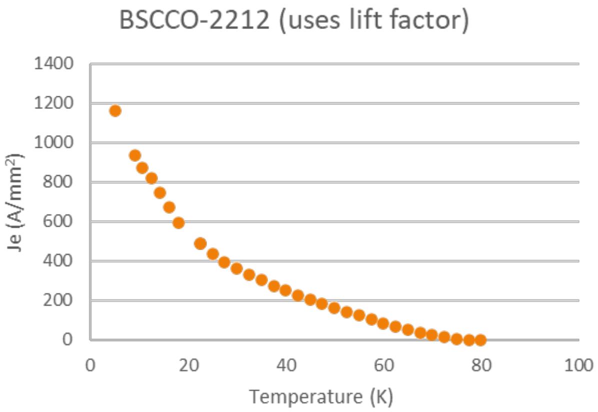
- Power loss calculated for Cryoconductor Litz
- $P_{Litz}[W/m^3] = {J_{eng\ BSCCO}}^2 \times \rho_{elec} + \frac{\pi^2}{4 * \rho_{elec}} (B_m f d_f)^2$



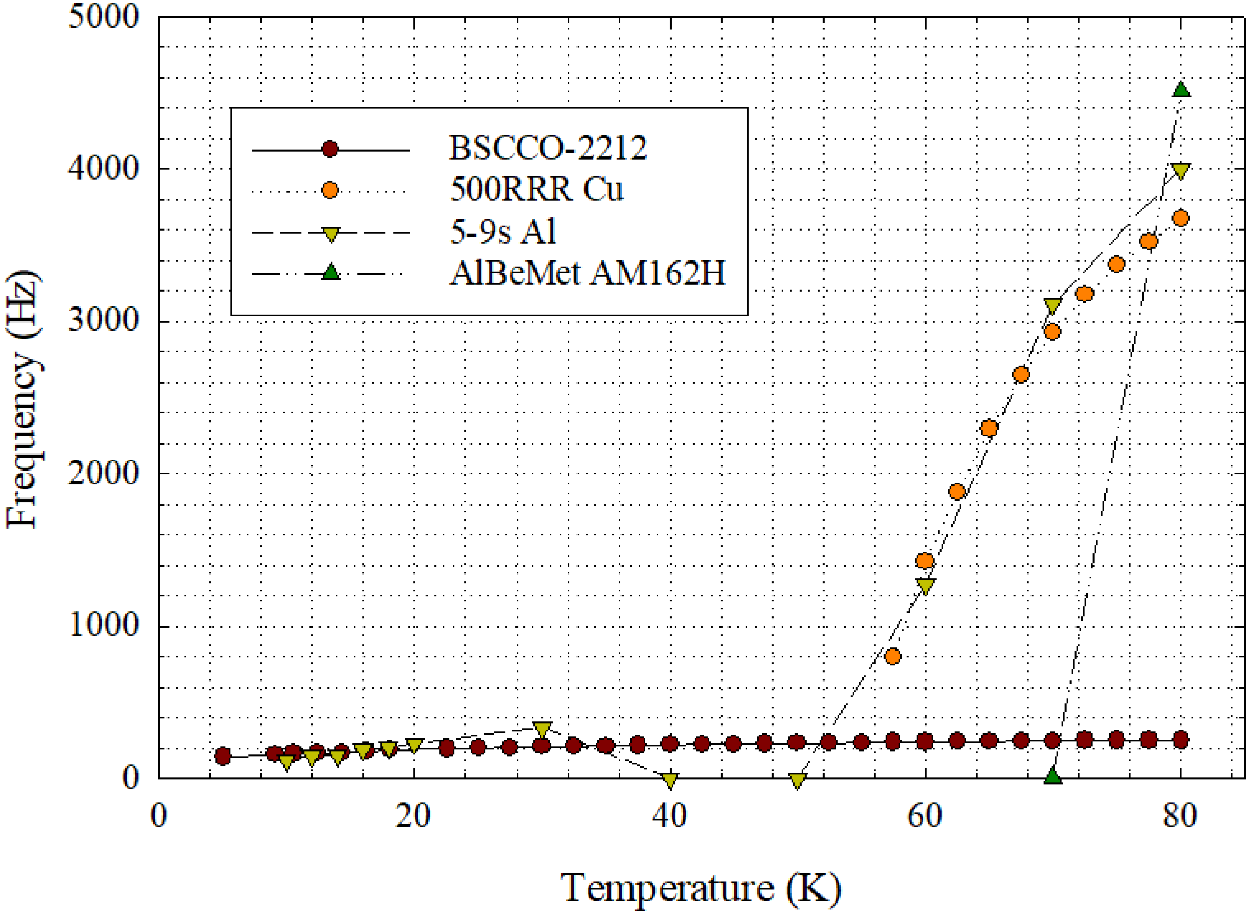


Low AC Loss Cryoresistive versus SOA Bi-2212

- Frequency = 0 Hz when Ohmic losses from comparable BSCCO-2212 Je are higher than Q
- AlBeMet AM162H can only compete versus BSCCO-2212 when J_e miniscule near T_c
- 5-9s Al and Cu are both better options than BSCCO-2212 above 55K
- 5-9s Al is reentrant versus below 40K and surpasses BSCCO-2212 again near 30K



- **Q = 10 W/cm3**



Future Work

- Design, fabrication, and testing of optimized AlBeMet AM162H tapered current leads
- Brazing and crimp studies with AlBeMet AM162H leads to HPAL cable or solderable lugs
- Environmental coating for AlBeMet AM162H study
- Reachout/collaboration with Materion, NASA, others for studies

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)