Current leads for cryogenic systems

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Goals of this lecture

• Learn about the applications of current leads in cryogenic systems
• Gain familiarity with different types of current leads
• Look at techniques for designing optimal current leads for cryogenic systems
Introduction

• Powering a superconducting device involves transfer of current into a cryogenic environment from an outside source. Current leads perform this function.
• The current can be DC or RF, and can greatly vary in magnitude depending on the application
  • μA – mA DC current for cryogenic sensors
  • 100s of A DC current for superconducting magnets
  • 100s of kW of RF (AC) power for SRF cavities
• In this lecture, we will focus on
  • DC leads for magnets carrying current from room temperature into a LHe environment at ~4.2 K
  • RF power for SRF cavities in covered in a separate USPAS class on RF power couplers
Configurations – conventional ‘resistive’ leads

- Conventional “resistive”
  - Usually made of low RRR copper
  - Low material and fabrication cost; lots of design references available
  - Heat sinking can be tricky; improper design can result in thermal runaway

- Conduction cooled
  - Vacuum
  - $T_h$
  - $T_c$

- Vapor cooled
  - Self cooled
  - Forced flow
  - $T_h$
  - $T_c$
  - $T_1$
  - $T_2$
Configurations – conventional ‘resistive’ leads

Resistive current leads for orbital corrector magnet of the LHC
Configurations – conventional ‘resistive’ leads

Resistive current lead package (Courtesy: Tom Peterson, SLAC)
Resistive: low RRR copper; HTS: Bi-2223 tapes matrixed in Ag-Au alloy

Very low heat leak to 4 K at even at very high amperage

HTS leads must be designed to accommodate a magnet quench or the leads turning resistive; need low resistance contacts at $T_1$ and $T_c$. 
Configurations – hybrid ‘resistive + SC’ leads

Helium cooled, 7.5 kA hybrid leads for LHC inner triplet magnet power distribution boxes (courtesy: Tom Peterson/SLAC)
Design of resistive current leads

Heat flow definitions

$Q_h$ = heat flow entering or leaving the lead from the ambient ($T_{amb}$)

$q(l)$ = heat flow at location $x$

$Q_c$ = cryogenic load

Design goal: minimize $Q_c$ for a given operating current, $I$

Parameter space:

Lead dimensions – length, $L$ and cross section, $A_{CS}$

Lead material – thermal conductivity, $k(T)$ and electrical conductivity, $\sigma(T)$
R. McFee (1959) set up a simple 1D model for optimization of resistive leads operating in vacuum.

Heat conduction:

\[dT = -\frac{dl}{kA}Q,\]

Joule dissipation:

\[d\dot{Q} = I^2 \frac{dl}{\sigma A},\]

Solution (assuming constant properties):

\[\dot{Q} = I \left[ \frac{2k}{\sigma} (c - T) \right]^3,\]

\[c = \text{constant of integration}\]
Design of resistive current leads

Conditions for minimum $Q_c$:

- The warmest point in the current lead is $x = 0$ at $T = T_H$
- No heat enters the lead at $x = 0$ (i.e., $T_H = T_{amb}$)

$$[Q_L]_{\text{min}} = I \left[ \frac{k}{2\sigma} (T_H - T_L) \right]^{\frac{1}{2}}.$$  

Lead dimensions for minimum $Q_c$:

$$L = \frac{\sigma A}{I^2} [Q_L]_{\text{min}} = \frac{A}{I} \left[ 2\sigma k (T_H - T_L) \right]^{\frac{1}{2}}.$$  

- For materials that obey Wiedeman-Franz law ($k/\sigma = L_0 T$), $Q_{L,\text{min}}$ is independent of the material!
- However, the $L/A$ for $Q_{L,\text{min}}$ depends on the material.
Design of resistive current leads

Solution technique for temperature dependent $k$ and $\sigma$:

\[ \dot{Q}_n = I \left[ 2 \left( \frac{k}{\sigma} \right) \left( T_H - T_L \right) \right]^{\frac{1}{2}}, \quad \left( \frac{k}{\sigma} \right)_{\text{av}} = \frac{1}{n} \left[ \frac{k_1}{\sigma_1} + \cdots + \frac{k_n}{\sigma_n} \right] \]

\[ L_n = \frac{1}{A} \sum \Delta l_p = \frac{1}{I^2} \left[ (\sigma_1 - \sigma_2) \dot{Q}_1 + (\sigma_2 - \sigma_3) \dot{Q}_2 + \cdots + (\sigma_{n-1} - \sigma_n) \dot{Q}_{n-1} + \sigma_n \dot{Q}_n \right] \]

$n \sim 10$ gives reasonably accurate solutions
Design of resistive current leads

Deviation from the design current $I_D$

- $I = I_D$
  - $Q_c$ is minimum

- $I > I_D$
  - $Q_c$ increases due to an increase in Joule dissipation

- $I < I_D$
  - $Q_c$ increases due to an increase in thermal conduction (steeper temperature gradient)

Resistive current lead in vacuum – temperature profile along the lead (From R. McFee (1959))
Design of gas cooled resistive current leads


Energy balance for the lead
\[ \frac{d}{dx} \left( k(T) A \frac{dT}{dx} \right) = -\frac{\rho(T)I^2}{A} + P \mathcal{H}(T)(T - \mathcal{G}) \]

Energy balance for coolant gas
\[ mc_p(\mathcal{G}) \frac{d\mathcal{G}}{dx} = P \mathcal{H}(T)(T - \mathcal{G}) \]

Coolant boiloff rate
\[ m = \frac{kA}{C_L} \frac{dT}{dx} \]

Assuming perfect heat exchange (large h)
\[ \frac{d}{dx} \left( k(T) A \frac{dT}{dx} \right) + \frac{\rho(T)I^2}{A} - mC_p(T) \frac{dT}{dx} = 0 \]
Design of gas cooled resistive current leads

- Gas cooled leads also need $Q_H = 0$ to minimize $Q_c$ (like conduction cooled leads)
- $Q_{c,\text{min}}$ independent of material
- $L/A$ for $Q_{c,\text{min}}$ depends on material

[Graph showing $Q_{4.2K}$ vs. $(IL/A)/10^4$ (A/m) with Over cooling, Sub cooling, and GC, SS, GC, Cu ETP labels]
Resistive leads: minimum heat leak

Table 1: Minimum heat inleak (W kA\(^{-1}\)) of conventional current leads

<table>
<thead>
<tr>
<th>Type of lead</th>
<th>(Q_{C,min} (4.2\text{ K}))</th>
<th>(Q_{C,min} (77\text{ K}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conduction-cooled</td>
<td>47</td>
<td>45</td>
</tr>
<tr>
<td>Gas-cooled</td>
<td>1.1(^a)</td>
<td>23(^b)</td>
</tr>
</tbody>
</table>

\(^a\)Helium gas cooling; \(^b\)nitrogen gas cooling

Design of hybrid current leads

The optimization of a hybrid current lead is done in two parts:

- **Resistive part**
  - Procedures described earlier
- **HTS part considerations**
  - Choice of HTS and matrix material and their size (L/A) to minimize conduction heat leak
  - Parallel shunt for current discharge during quench
  - Use configurations less sensitive to self-fields (e.g., Bi2223 tapes are wound cylindrically to make the self-field parallel to the plane of the tapes)
Practical design considerations

• The analytical models presented earlier are a good starting point
• However, final optimization a current lead designed for transferring high currents must include 2D and possibly 3D finite element calculations for the detailed definition of the geometry
• Consider the modelling of
  • thermal performance – temperature dependent thermal conductivity, heat transfer coefficient
  • electrical performance – temperature dependent electrical resistivity, shunt for HTS leads
  • fluid dynamic performance – pressure drop for gas cooled leads
  • Magnetization of HTS leads in self field
• Current leads design is a mature topic with lot of literature – take benefit of this for your design!
Examples of HTS leads

• Fermilab tested and operated some HTS current leads at 4.5 kA to 6 kA for the Tevatron, and a few of them ran for many years in the Tevatron
  – LN2 cooled copper section
  – Small helium vapor flow up HTS section
  – Very stable and reliable
  – Design issues involved solder joints to various conductors (LTS – HTS – copper) and isolation of N2 from helium channels
  – See references 3 and 4 for more information
Examples of HTS leads

• CERN’s LHC current leads for currents above a few 100 amps are HTS leads, helium gas cooled from nominally 20 K gas
  – See reference 5 for more information
• The Fermilab/Berkeley collaboration incorporated 7.5 kA HTS current leads into the DFBX feed boxes for the LHC inner triplet magnets, also helium cooled
References and further reading