Current leads for cryogenic systems

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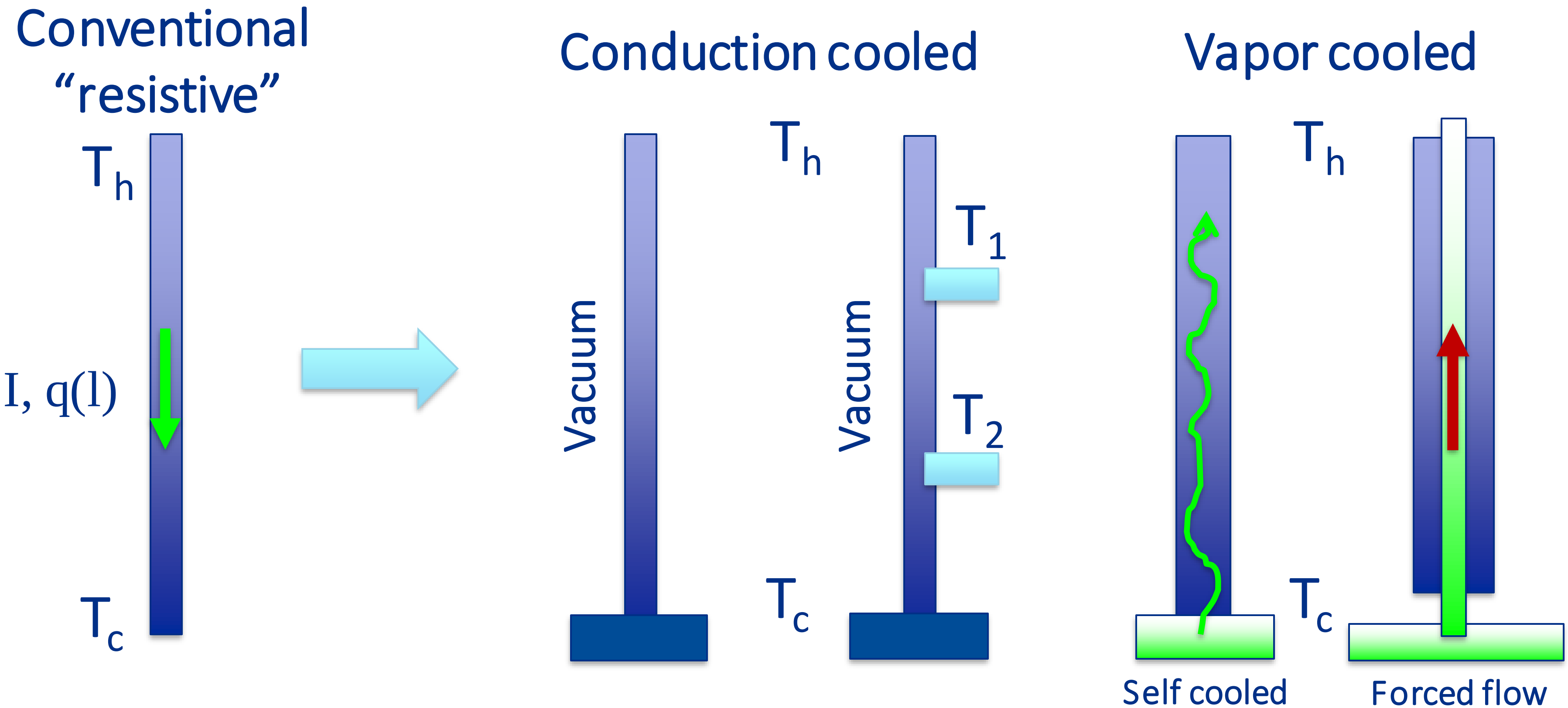
Goals of this lecture

- 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. <u>Current leads</u> 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

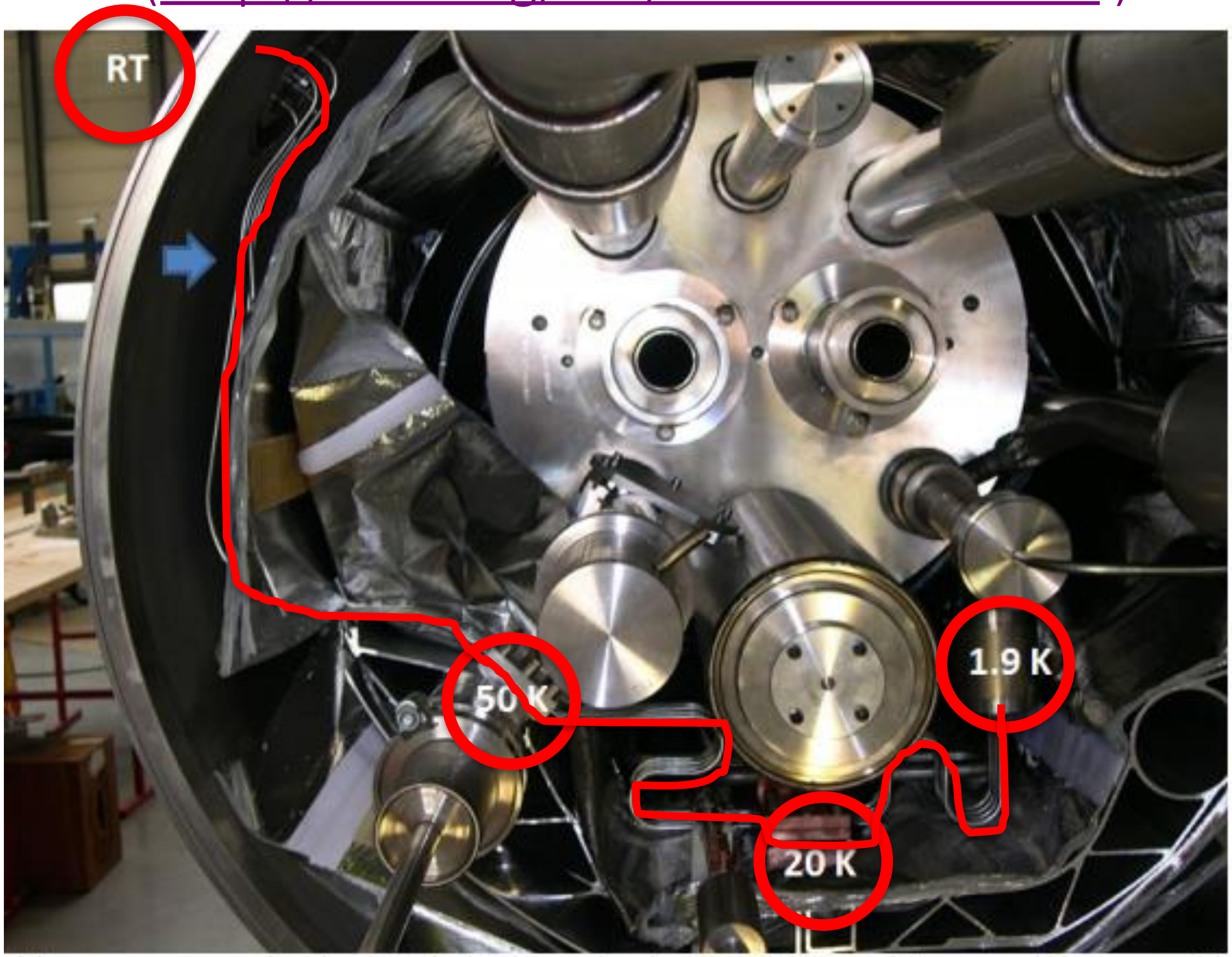
Configurations – conventional 'resistive' leads



- 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

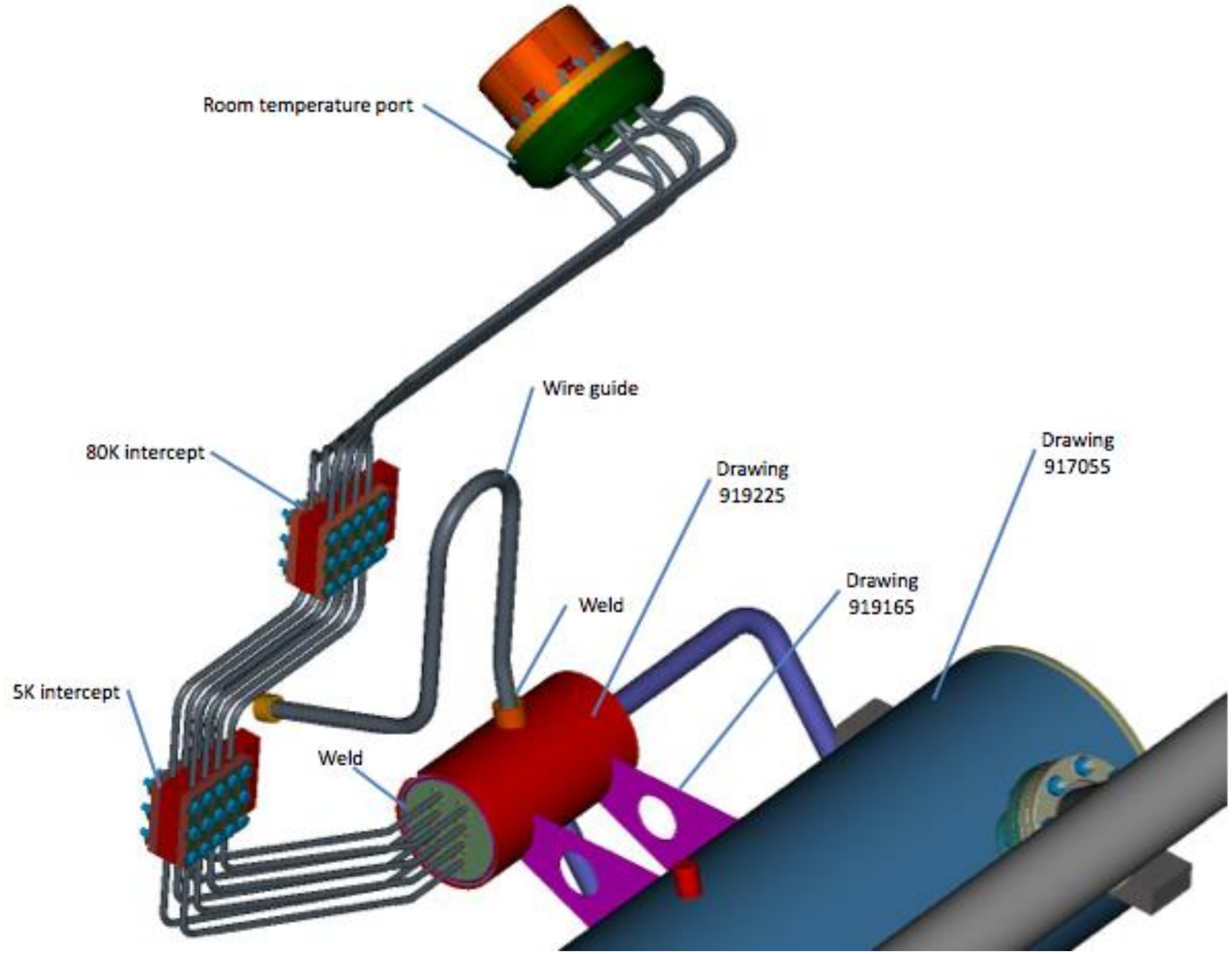
Configurations – conventional ‘resistive’ leads

Resistive current leads for orbital corrector magnet of the LHC
(http://arxiv.org/abs/arXiv:1501.07166)

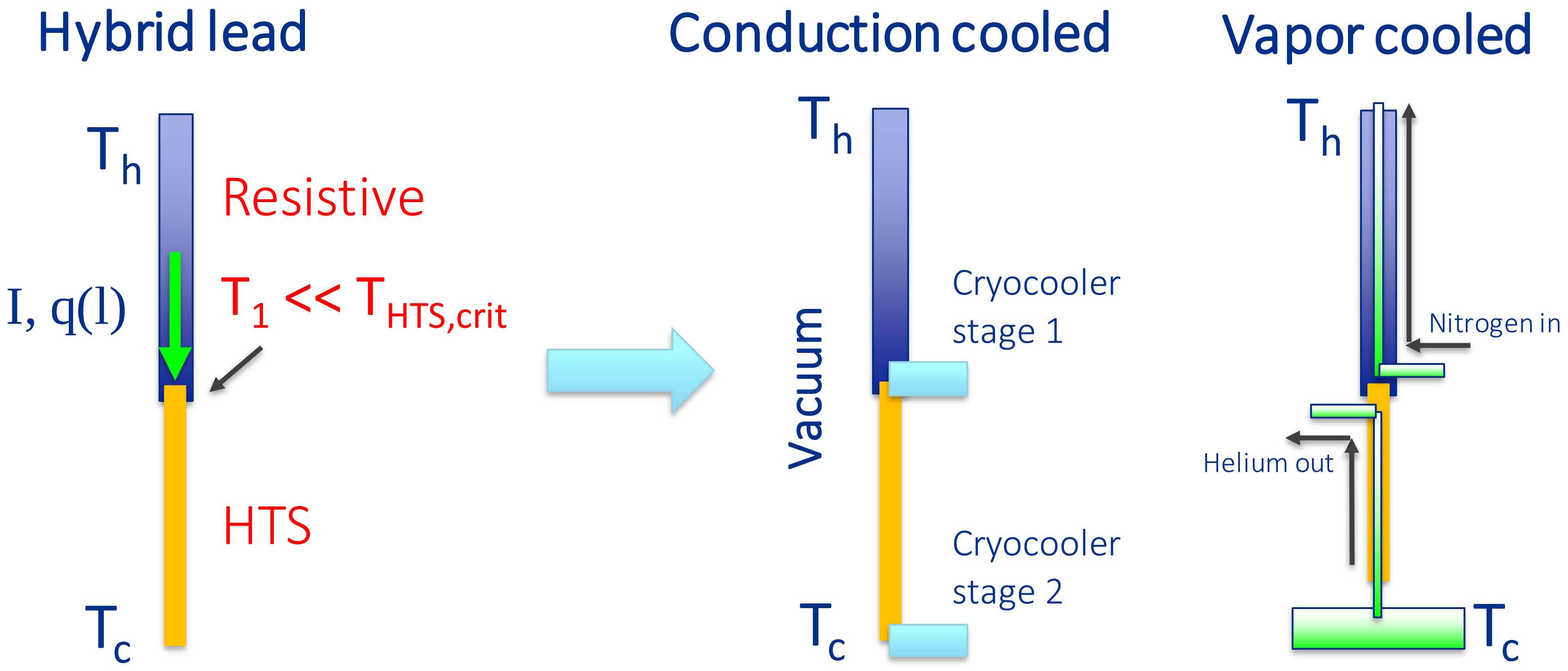


Configurations – conventional ‘resistive’ leads

Resistive current lead package (Courtesy: Tom Peterson, SLAC)



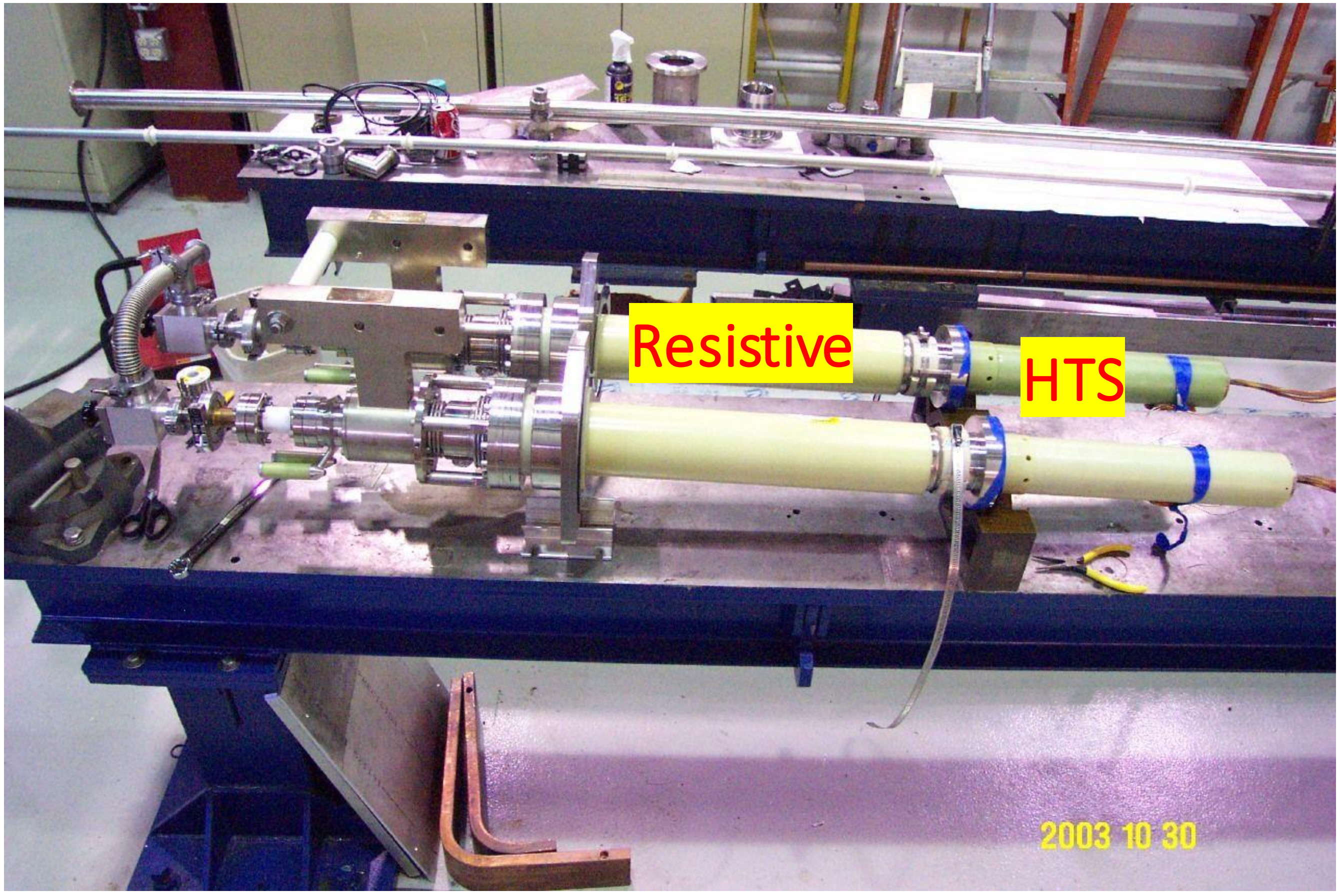
Configurations – hybrid 'resistive + SC' leads



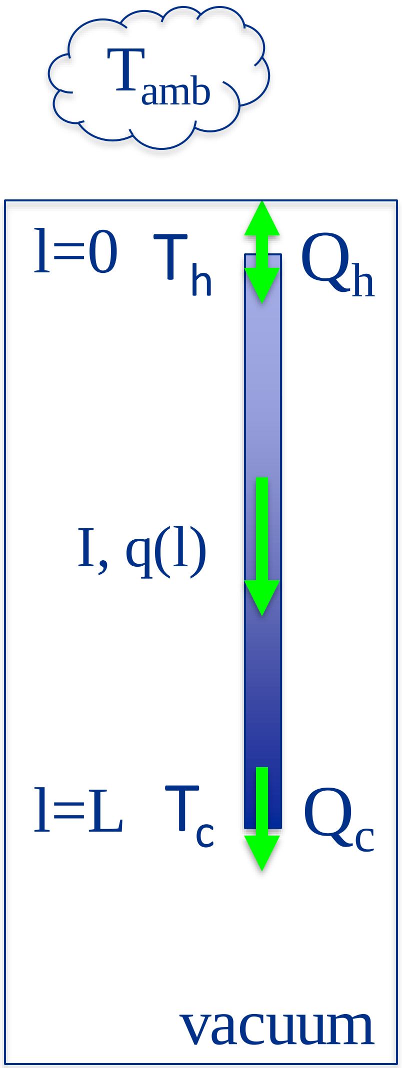
- Resistive: low RRR copper; HTS: Bi-2223 tapes matrixed in Ag-Au alloy
- Very low heat leak to 4 K at even at very high amperage
- HTS leads must be designed to accommodate a magnet quench or the leads turning resistive; need low resistance contacts at T_1 and T_c

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

= $q_{cond}(l) + q_{Joule}(l)$

Q_c = cryogenic load

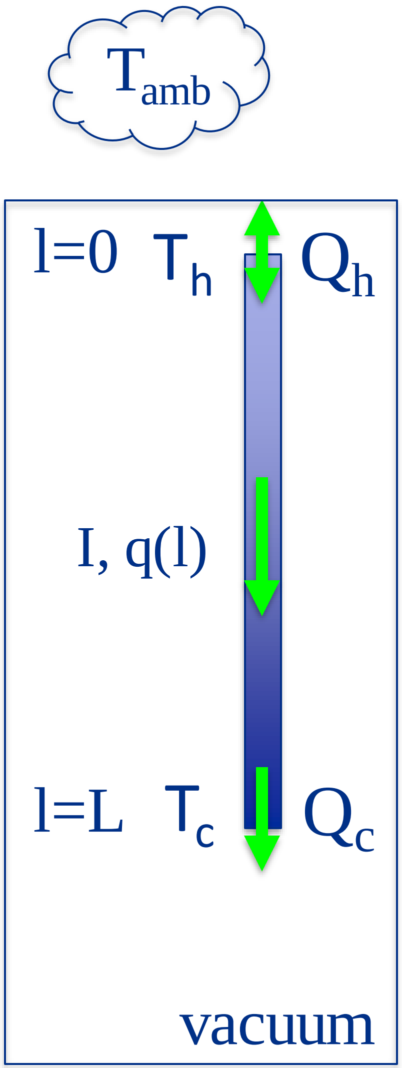
Design goal: minimize Q_c for a given operating current, I

Parameter space:

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

Lead material – thermal conductivity, k(T) and electrical conductivity, σ(T)

Design of resistive current leads



R. McFee (1959) set up a simple 1D model for optimization of resistive leads <u>operating in vacuum.</u>

Heat conduction: $$dT = -\frac{dl}{kA}\dot{Q},$$

Joule dissipation: $$d\dot{Q} = I^2\frac{dl}{\sigma A},$$

Solution (assuming constant properties): $$\dot{Q} = I\left[\frac{2k}{\sigma}(c-T)\right]^{\frac{1}{2}},$$

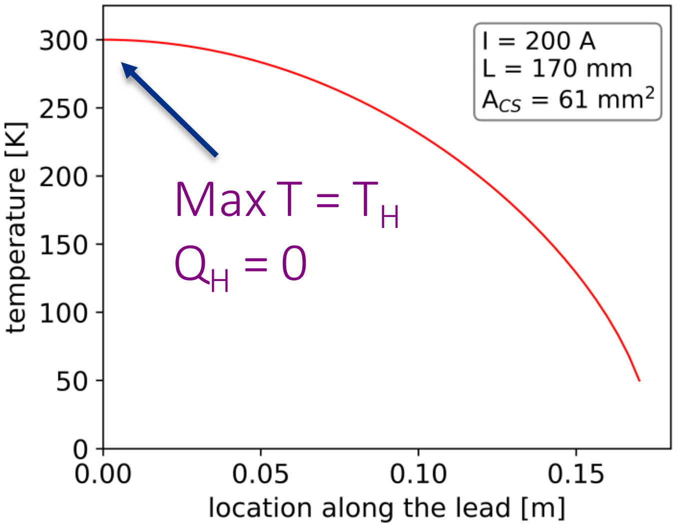
c = constant of integration

Design of resistive current leads

Conditions for minimum Qc:

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

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



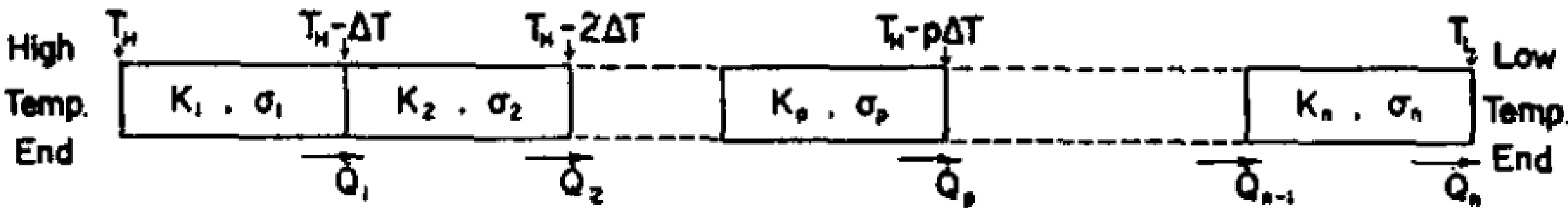
Lead dimensions for minimum Qc:

$$L = \frac{\sigma A}{I^2}[\dot{Q}_L]_{min} = \frac{A}{I}[2\sigma k(T_H - T_L)]^{\frac{1}{2}}.$$

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

Design of resistive current leads

Solution technique for temperature dependent k and σ:



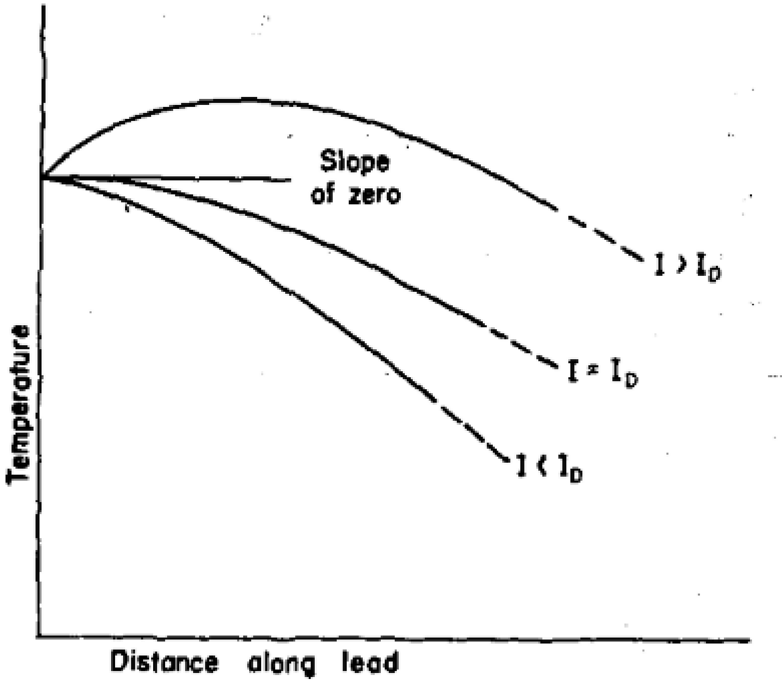
$Q_{L,min}$: $$\dot{Q}_n = I\left[2\left(\frac{k}{\sigma}\right)_{Av}(T_H - T_L)\right]^{\frac{1}{2}}, \quad \left(\frac{k}{\sigma}\right)_{Av} = \frac{1}{n}\left[\frac{k_1}{\sigma_1} + \cdots + \frac{k_n}{\sigma_n}\right]$$

L/A for $Q_{L,min}$: $$\frac{L_n}{A} = \frac{1}{A}\sum \Delta l_p = \frac{1}{I^2}\left[(\sigma_1 - \sigma_2)\dot{Q}_1 + (\sigma_2 - \sigma_3)\dot{Q}_2 + \cdots\right.$$
$$\left. + (\sigma_{n-1} - \sigma_n)\dot{Q}_{n-1} + \sigma_n \dot{Q}_n\right].$$

n ~ 10 gives reasonably accurate solutions

Design of resistive current leads

Deviation from the design current I_D



Resistive current lead in vacuum – temperature profile along the lead (From R. McFee (1959))

$I = I_D$

- Qc is minimum

$I > I_D$

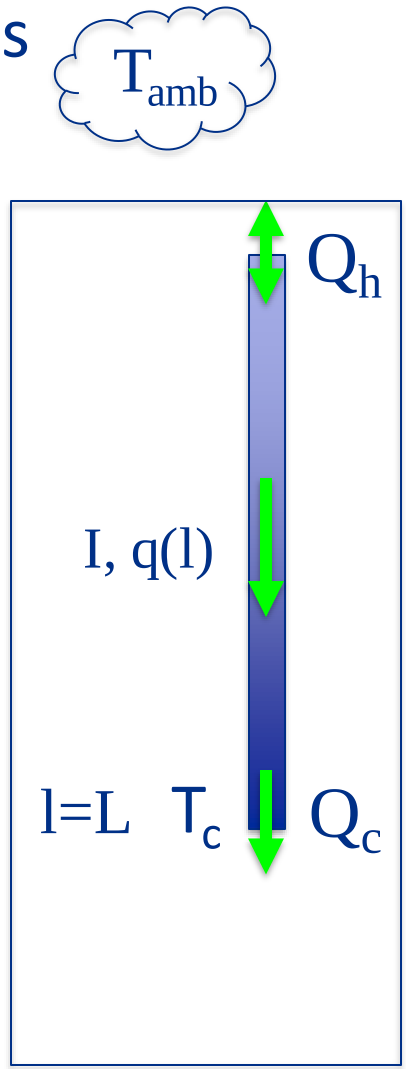
- Qc increases due to an increase in Joule dissipation

$I < I_D$

- Qc increases due to an increase in thermal conduction (steeper temperature gradient)

Design of gas cooled resistive current leads

1D model for self-cooled resistive current leads
(http://arxiv.org/abs/arXiv:1501.07166)



Energy balance for the lead

$$\frac{\mathrm{d}}{\mathrm{d}x}\left(k(T)A\frac{\mathrm{d}T}{\mathrm{d}x}\right) = -\frac{\rho(T)I^2}{A} + Ph(T)(T-\vartheta)$$

Energy balance for coolant gas

$$mc_{\mathrm{p}}(\vartheta)\frac{\mathrm{d}\vartheta}{\mathrm{d}x} = Ph(T)(T-\vartheta)$$

Coolant boiloff rate

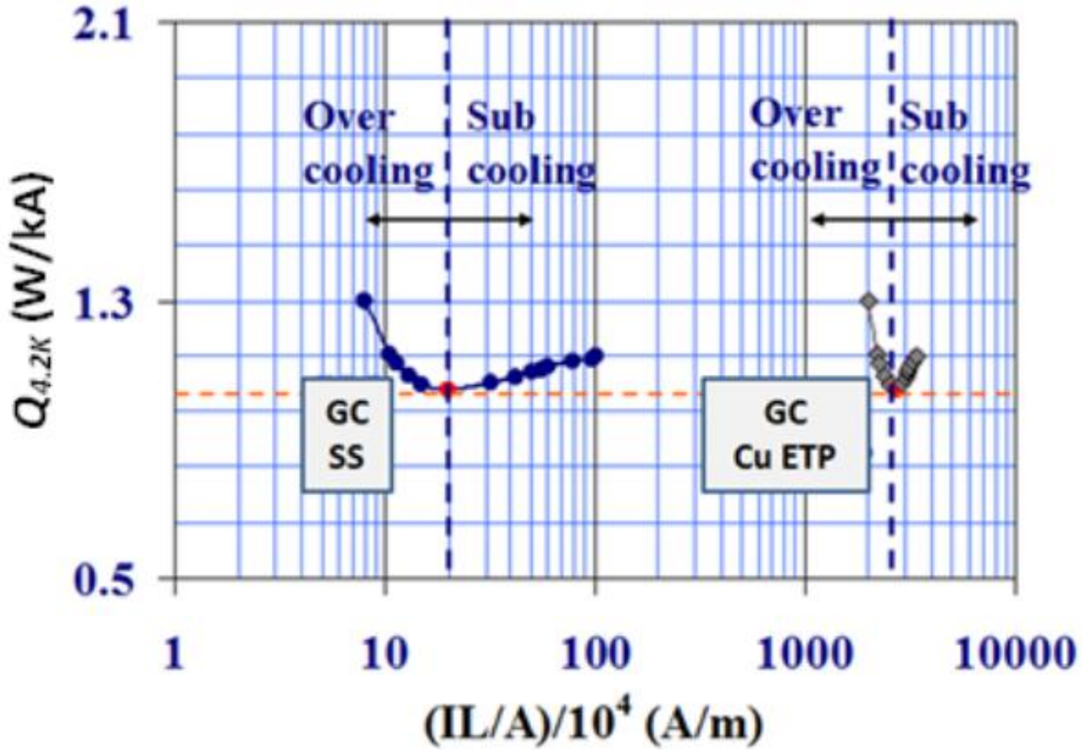
$$m = \frac{kA}{C_L}\frac{\mathrm{d}T}{\mathrm{d}x}$$

Assuming perfect heat exchange (large h)

$$\frac{\mathrm{d}}{\mathrm{d}x}\left(k(T)A\frac{\mathrm{d}T}{\mathrm{d}x}\right) + \frac{\rho(T)I^2}{A} - mC_{\mathrm{p}}(T)\frac{\mathrm{d}T}{\mathrm{d}x} = 0$$

Design of gas cooled resistive current leads

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



(http://arxiv.org/abs/arXiv:1501.07166)

Resistive leads: minimum heat leak

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

Type of lead	$Q_{C,\mathrm{min}}$ **(4.2 K)**	$Q_{C,\mathrm{min}}$ **(77 K)**
Conduction-cooled	47	45
Gas-cooled	1.1[a]	23[b]

[a]Helium gas cooling; [b]nitrogen gas cooling

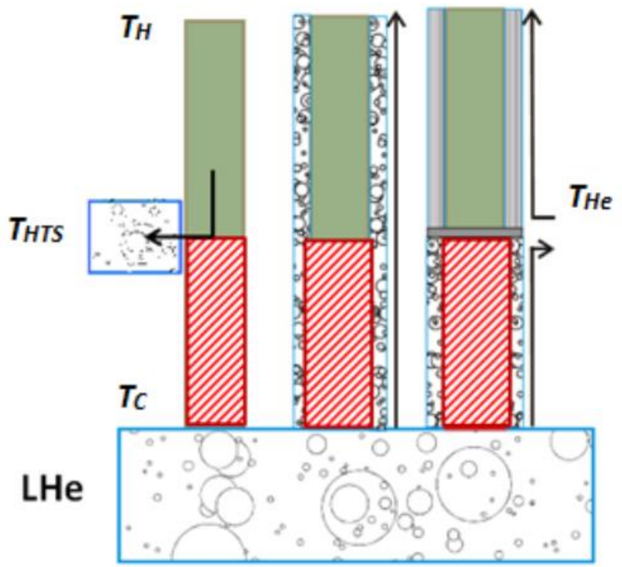
(http://arxiv.org/abs/arXiv:1501.07166)

Fermilab

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 (eg. 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
  - http://tdserver1.fnal.gov/peterson/tom/DFBXimages/HTSleads/index.html

References and further reading

1. R. McFee, "Optimum Input Leads for Cryogenic Apparatus," *Review of Scientific Instruments*, 1959.
2. A. Ballarino, "Current Leads, Links, and Buses," http://arxiv.org/abs/arXiv:1501.07166.
3. G. Citver, S. Feher, T.J. Peterson, C.D. Sylvester, " Thermal Tests of 6 kA HTS Current Leads for the Tevatron," Advances in Cryogenic Engineering, Vol. 45B, pg. 1549.
4. J. Brandt, S. Feher, T.J. Peterson, W.M. Soyars, "HTS Leads in the Tevatron," Advances in Cryogenic Engineering, Vol. 47A, pg. 567.
5. T.P. Andersen, V. Benda, B. Vullierme, "600 A Current Leads with Dry and Compact Warm Terminals," LHC Project Report 605.