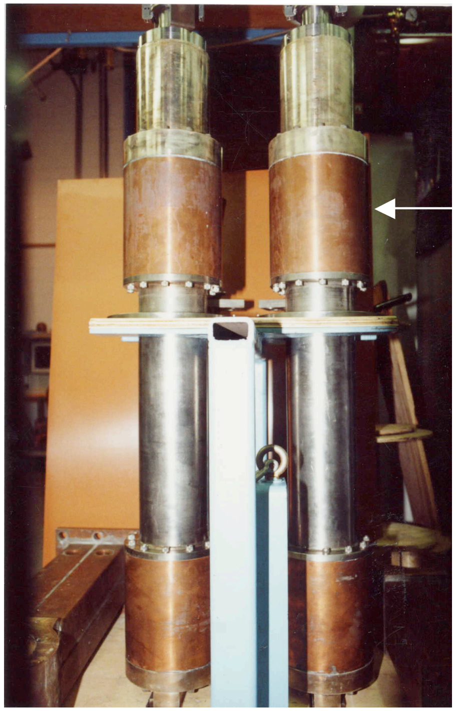
Current Lead Design

US Particle Accelerator School
June 21-25, 2004

Current Lead Design

- What is a current lead and what are the design challenges?
- Design goal - minimize cryogenic impact
- Configurations
- What do you expect?
- Designing conventional leads
  - Conduction cooled
  - Vapor cooled
  - Forced flow cooled
- Designing HTS (hybrid) leads
  - Cooling options
  - Additional factors to consider

Purpose, Design Challenge



AMI 75 kA Conventional, helium vapor-cooled leads

75 kA leads at zero current

- <u>Purpose:</u> Communicate electric power from room temperature to cryogenic coils, magnets, transmission lines, or devices.
- <u>Design challenge:</u>
  - Cryogenic heat load due to:
    - Heat conduction
    - Heat generation (I^2R)
  - Reducing conduction (reduce area, increase length, reduce k) increases heat generation
  - Reducing heat generation (increase area, decrease length, reduce) increases conduction
  - Optimization required

Goal: Minimize Impact on Cryogenic System

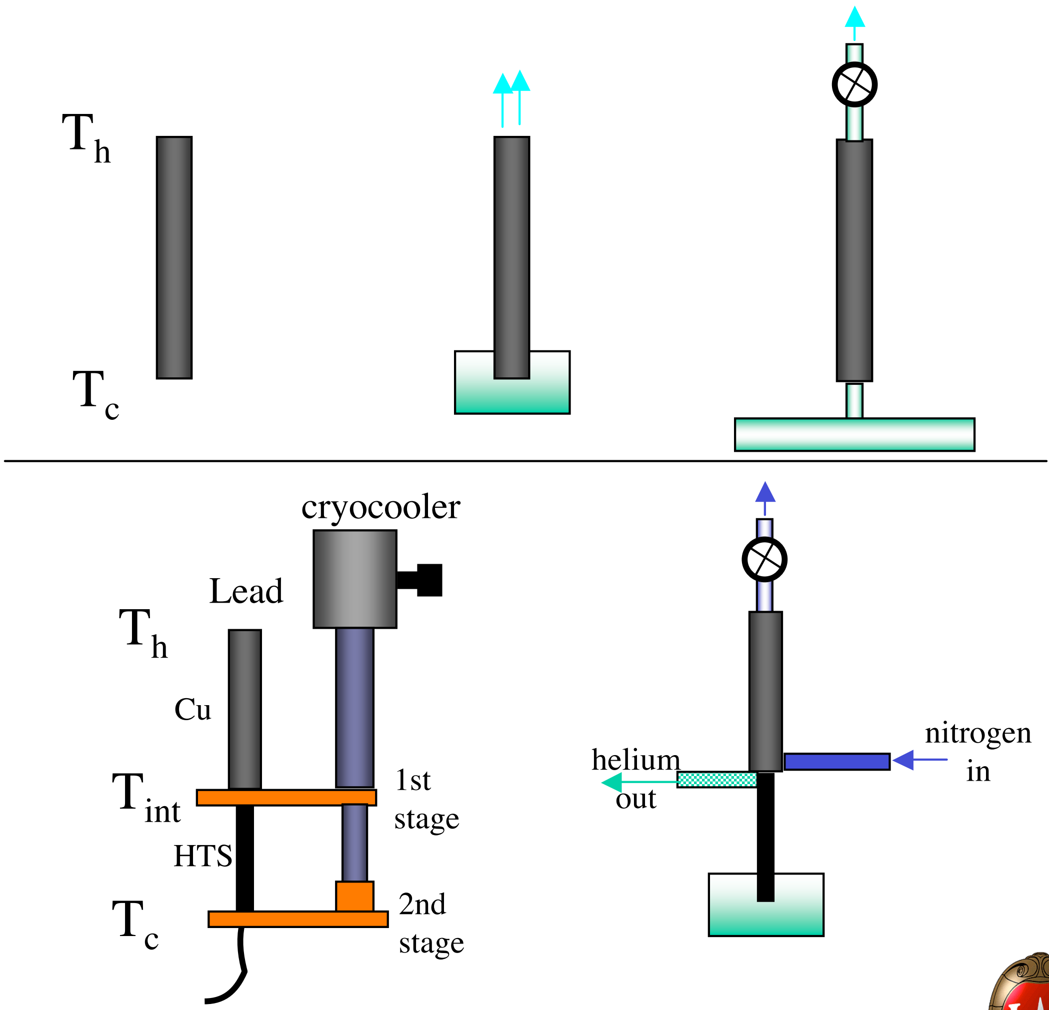
- Open systems: reduce cryogen boil-off
    - Benchmark: 1.1 W/kA-lead = 3 liter/hr-kA-pair

      for conventional helium vapor cooled leads
- Closed cycle refrigerator: improve performance
    - Reduce the required electrical power to refrigerate vapor exiting warm end of leads:

      ≈ 7 kW electrical power for pair of 1 kA conventional leads
    - Improve reliability by using a cryocooler to re-condense vapor at 4.2 K
    - Replacing conventional 5 kA leads with HTS versions provides Fermilab Tevatron excess refrigeration to reduce magnet temperature from 4.2 K to 3.5 K.

Configurations

- Conventional
  - Conduction cooled
  - Vapor cooled
  - Forced-flow cooled
- HTS - hybrid
  - Conduction cooled
  - Vapor cooled
  - Forced-flow cooled

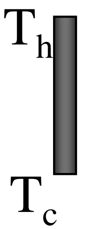


What Do You Expect?

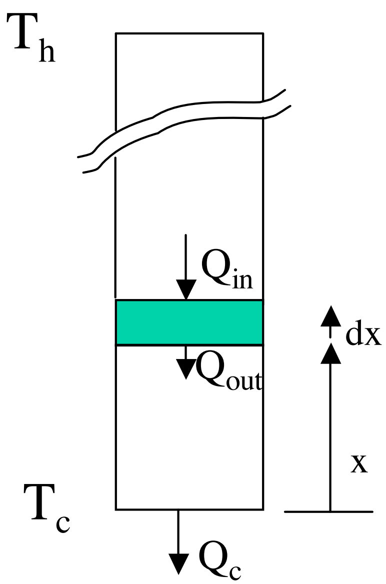
- The functional dependence of Q on I_{max}:
  - For an optimized conduction cooled lead _______________
  - For an optimized vapor cooled lead _______________
- The functional dependence of the aspect ratio L/A on I_{max}:
  - For an optimized conduction cooled lead ______________
  - For an optimized vapor cooled lead _______________
- Compare the cold-end heat leak for a 1 kA vapor cooled lead:

  Q (helium vapor cooled) _______ Q(nitrogen vapor cooled)
- Compare the aspect ratio for a 1 kA vapor cooled lead:

  L/A (neon vapor cooled) _______ L/A (nitrogen vapor cooled)



Conduction Cooled Lead: Derivations



- Energy balance on control volume:

$$Q_{in} - Q_{out} + Q_{gen} = 0$$

$$kA\frac{dT}{dx}\bigg|_{x+dx} \quad kA\frac{dT}{dx}\bigg|_{x} + \frac{I^2}{A}dx = 0$$

note that if $dT/dx > 0$, $Q_{in} > 0$

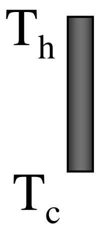
$$\frac{d}{dx} \quad k\frac{dT}{dx} \quad + \quad J^2 = 0$$

- Change variables: let $s = k\dfrac{dT}{dx}$

$$\frac{ds}{dx} + \quad J^2 = 0; \qquad \frac{ds}{dT}\frac{dT}{dx} + \quad J^2 = 0$$

$$\frac{s}{k}\frac{ds}{dT} + \quad J^2 = 0; \qquad sds = \quad k \quad J^2 dT$$

$$s = \frac{Q}{A}; \quad ds = \frac{dQ}{A}; \quad {}_c^h QdQ = \frac{1}{2}Q^2\Big|_c^h = \quad I^2 \; {}_{T_c}^{T_h} k \quad dT$$



Conduction Cooled Lead: Derivation (cont.)

$$Q_h^2 \quad Q_c^2 = \; 2I^2 \; {}_{T_c}^{T_h} k \;\; dT \qquad Q_c^2 = Q_h^2 + 2I^2 \; {}_{T_c}^{T_h} k \;\; dT$$

- Q_c is minimized when $Q_h = 0$.

$$Q_{c,\ min} = I \;\; 2 \; {}_{T_c}^{T_h} k \;\; dT \quad {}^{1/2}$$

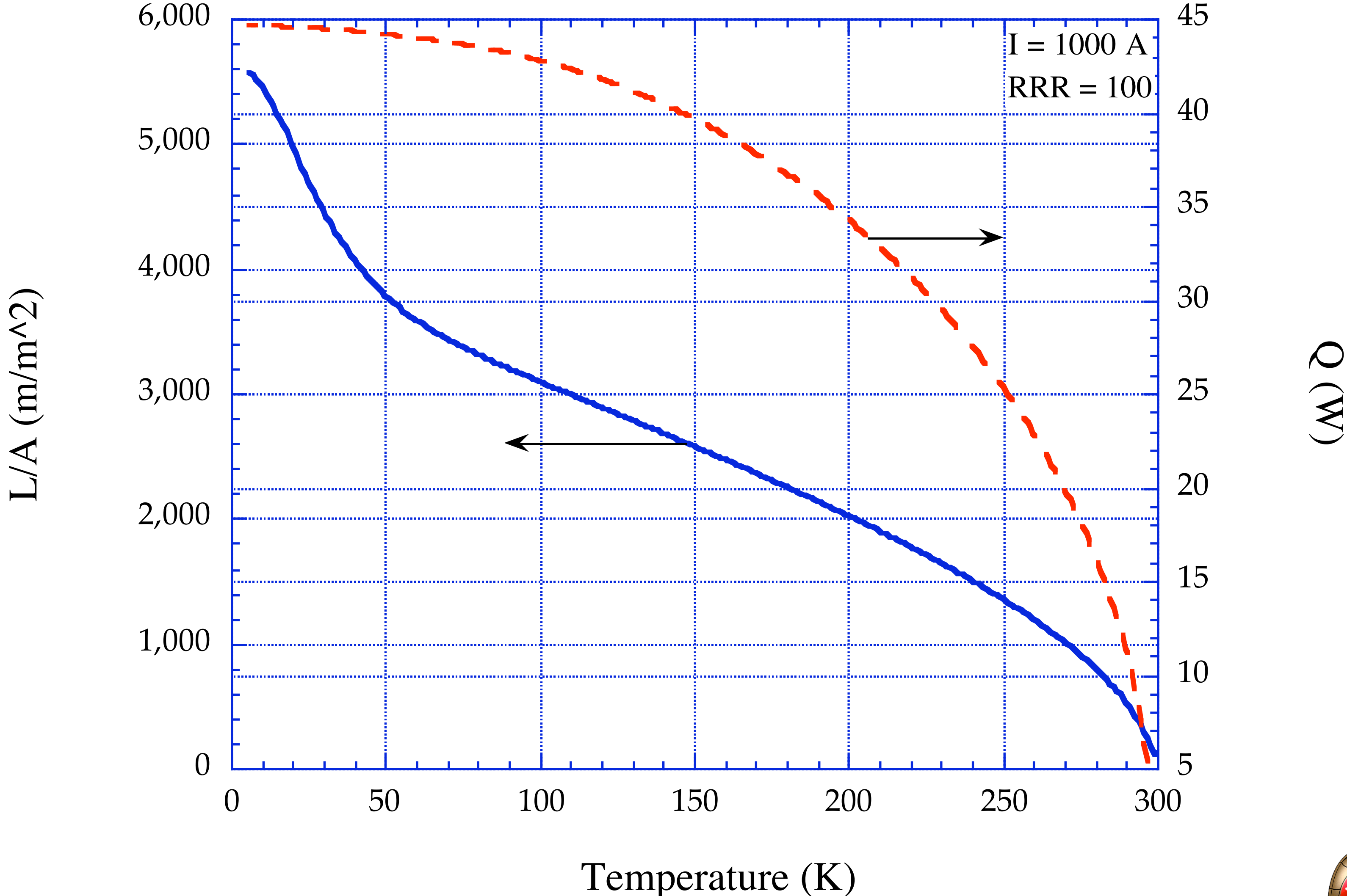
$$kA \frac{dT}{dx} {}_{c}^{2} = 2I^2 \; {}_{T_c}^{T_h} k \;\; dT \qquad dx = \frac{kA\, dT}{\sqrt{2} I \left({}_{T}^{T_h} k \;\; dT \right)^{1/2}}$$

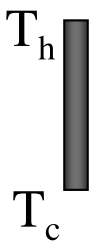
As T is lowered, this equation defines the additional length required to produce Q_{min} at T_c

- Finally:

$$\frac{L}{A} = \frac{1}{I\sqrt{2}} \; {}_{T_c}^{T_h} \frac{k\, dT^*}{\left({}_{T^*}^{T_h} k \;\; dT \right)^{1/2}} \quad \text{OR} \quad JL = \frac{1}{\sqrt{2}} \; {}_{T_c}^{T_h} \frac{k\, dT^*}{\left({}_{T^*}^{T_h} k \;\; dT \right)^{1/2}}$$

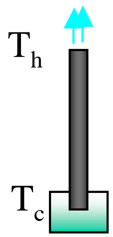
Conduction Cooled Lead: Sample Results





Conduction Cooled Lead: Conclusions

- An 'optimized' lead is optimized for a single (maximum) current
- $Q_{c,\ min} \sim I$
- $Q_{c,\ min}$ is a function of T_h, T_c, I, and (weakly) on material choice
- JL = constant dependent only on T_h, T_c, and mtl. choice
- $L/A \sim 1 / I$



Vapor Cooled Lead

- Energy balance at steady state is given by:

$$\frac{I^2}{A} + \frac{d}{dx} \quad Ak\frac{dT}{dx} \quad \dot{m}C_p\frac{dT}{dx} = 0$$

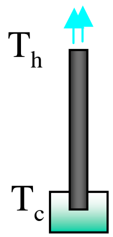
- Goal is to minimize $\dot{m}$ with $\dot{m} = \frac{1}{C_L} kA \frac{dT}{dx}\Big|_{x=0}$

- Variety of solution methods: J.E.C. Williams (1963), Deines (1965), Lock (1969), Dresner (1995) - similarity solution: (special units)

$$\ln \frac{T_h}{T_c} = \ln \frac{s_c^2}{T_c^2} \quad \frac{s_c^2}{T_c} + 1 \quad ^{1/2} + s_c\left(4 \quad s_c^2\right)^{1/2} \arctan \frac{\left(s_c\left(4 \quad s_c^2\right)^{1/2} +\right)}{2T_c \quad s_c^2 \quad -}$$

- Q_{min}/I (ordinary units) = $s_c L_o^{1/2} \frac{C_L}{C_p}$

- Examples:
  - Helium: T_h= 300 K, T_c= 4 K, s_c= 1.79, Q/I = 1.12 W/kA
  - Neon: T_h= 300 K, T_c= 27 K, s_c= 1.23, Q/I = 16.1 W/kA
  - Nitrogen: T_h= 300 K, T_c= 77 K, s_c= 0.855, Q/I = 25.4 W/kA



Vapor Cooled Lead (cont.)

- Optimum aspect ratio (similarity solution - special units)

$$\frac{L}{k} = 2\left(4 \quad s_c^2\right)^{1/2} \arctan \frac{s_c\left(4 \quad s_c^2\right)^{1/2}}{2T_c \quad s_c^2} \quad ; \qquad JL = \frac{L}{k}_{\text{special units}} \quad \frac{k}{L_o^{1/2}}$$

using an integrated average value of k over the temperature range, and the Lorentz constant $L_o = 2.45 \times 10^{-8}$ ($W\Omega/K^2$) gives (for a 1 kA lead)

- Helium VCL (300 K - 4.2 K)

$$\frac{L}{k}_{s.u.} = 4.87 \qquad LJ = \frac{LI}{A} = 1.62\text{x}10^7 \text{ A / m} \qquad \frac{L}{A} = 162 \text{ cm / cm}^2$$

- Neon VCL (300 K - 27 K)

$$\frac{L}{k}_{s.u.} = 1.985 \qquad LJ = \frac{LI}{A} = 6.28\text{x}10^6 \text{ A / m} \qquad \frac{L}{A} = 62.8 \text{ cm / cm}^2$$

- Nitrogen VCL (300 K - 77 K)

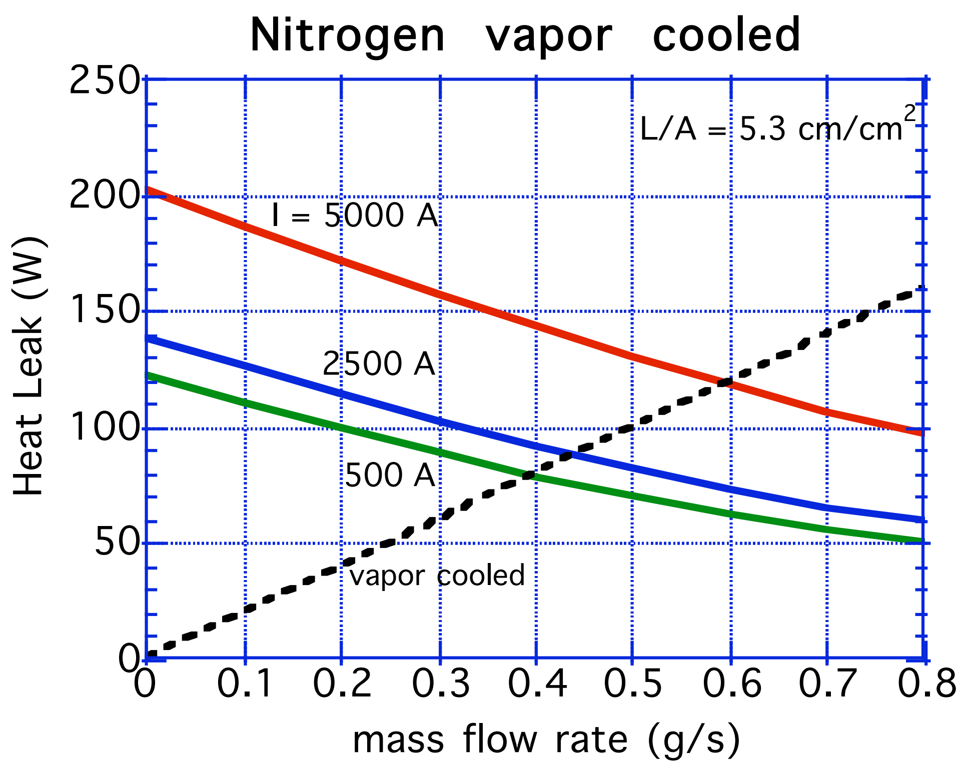
$$\frac{L}{k}_{s.u.} = 1.675 \qquad LJ = \frac{LI}{A} = 4.93\text{x}10^6 \text{ A / m} \qquad \frac{L}{A} = 49.3 \text{ cm / cm}^2$$

Vapor Cooled Lead - Conclusions

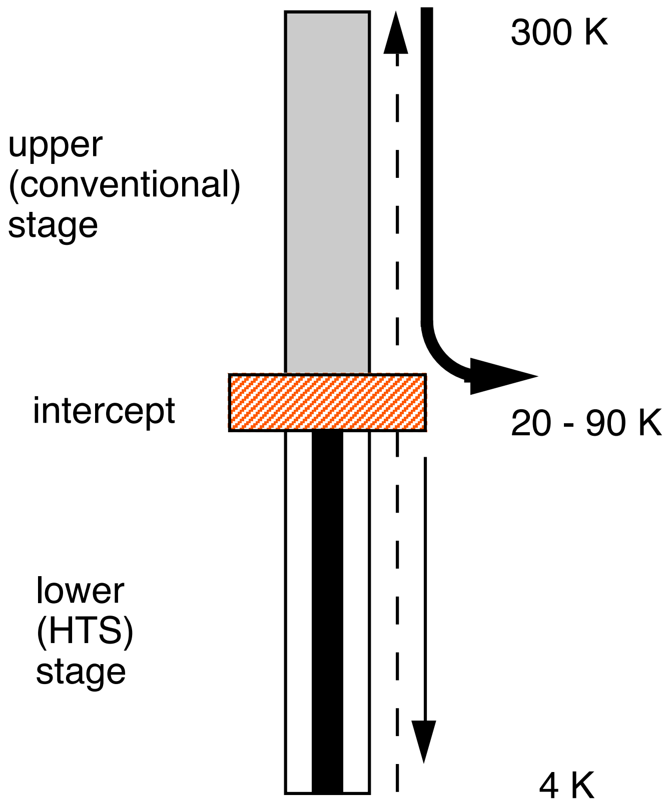
- Minimum heat leak:
  - As with conduction cooled leads, $Q_{min} \sim I$
  - Dependence of Q_{min} on coolant is dominated by (C_L / C_p)
- Optimized aspect ratio:
  - $L/A_{opt} \sim 1/I$ smaller current larger aspect ratio
  - L/A_{opt} dependence on coolant: colder range larger aspect ratio

Forced Flow Cooled

- Behavior governed by same energy balance equation as vapor cooled
- E. Barzi, (Fermi-lab, 1998): numerical solution, with variable mass flow rate, for lead designed for a maximum current of 5 kA



HTS Current Leads



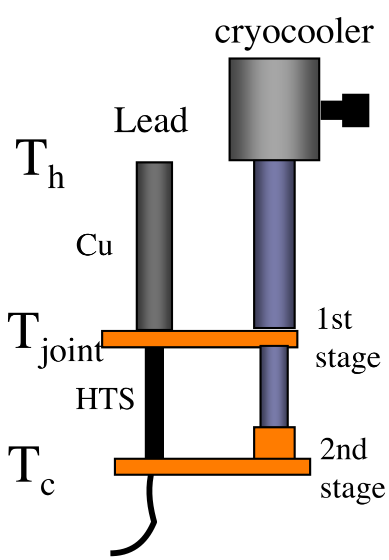
- Reduced cryogenic impact
  - Heat generation significantly reduced (eliminated) in HTS segment.
  - Heat conduction reduced
  - Cold end heat load reduced by factor of 3 - 10.
- Wide variety of cooling options
- Additional design issues to consider

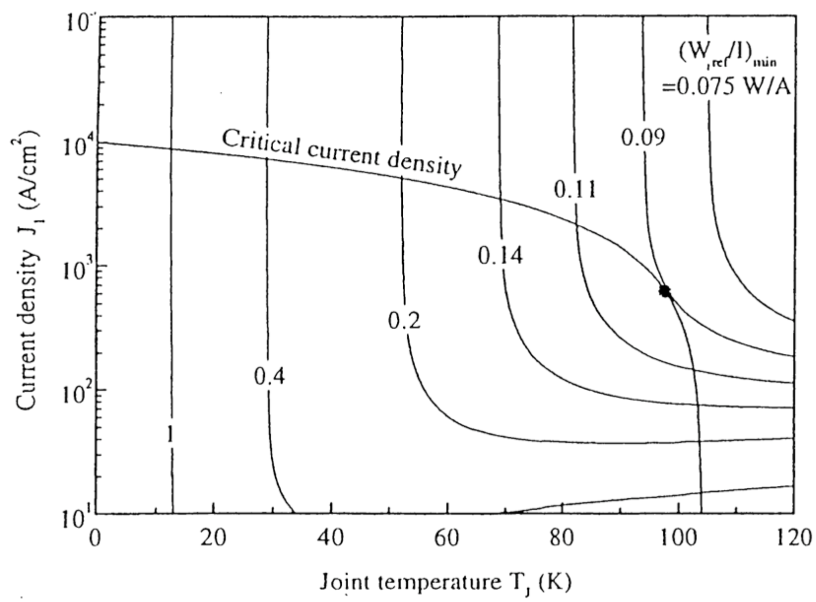
Cooling Options for HTS Leads

- Conduction cooled via cryocooler - Chang & Van Sciver
  - Minimize combined 1st and 2nd stage cooling power

$$\frac{W_{ref}}{I} = \frac{1}{FOM_L}\left(\frac{T_H}{T_L} - 1\right)\frac{1}{JL_{hts}}\int_{T_L}^{T_J} k_{hts}\, dT + \frac{1}{FOM_J}\left(\frac{T_H}{T_J} - 1\right)\left(\sqrt{2\int_{T_J}^{T_H} k_{cu}\, dT} - \frac{1}{JL_{hts}}\int_{T_L}^{T_J} k_{hts}\, dT\right)$$

  - Optimized joint temperature ~ 90 K for Bi2223

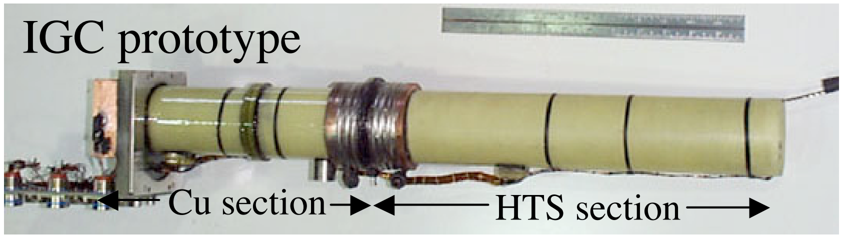


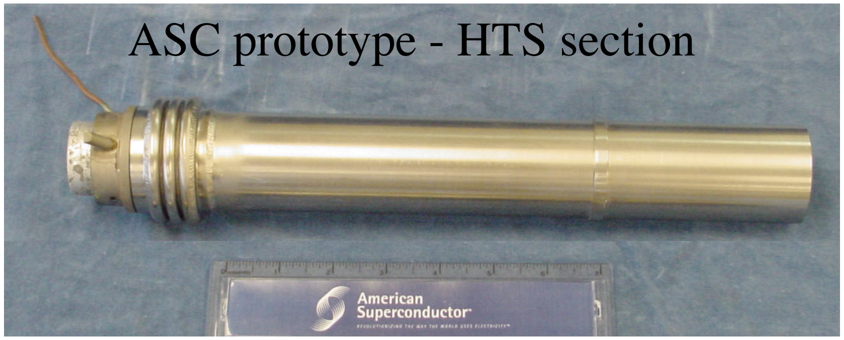


Cooling Options for HTS Leads

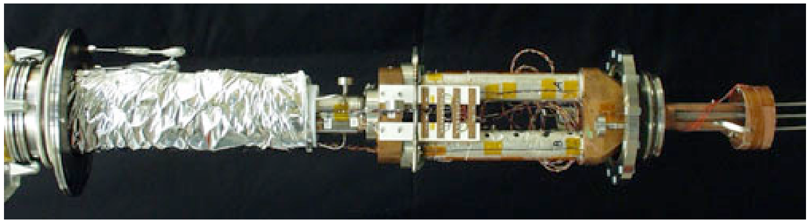
- Forced flow cooling - Fermilab, CERN, ITER

- Fermilab: 5 kA lead retrofit for Tevatron
  - helium vapor cooled HTS section
  - nitrogen gas cooled upper section
  - prototypes from ASC and IGC
  - heat loads: 101 W @ 80 K, 0.7 W @ 4 K





- CERN: 13 kA, 6 kA, 0.6 kA for LHC
- ITER Toroidal Field Coils: 10kA, 20kA
  - conduction cooled HTS
  - helium gas cooled 50 K - 300 K
  - multiple vendors
  - < 1 g/s helium flow @ 20 K inlet

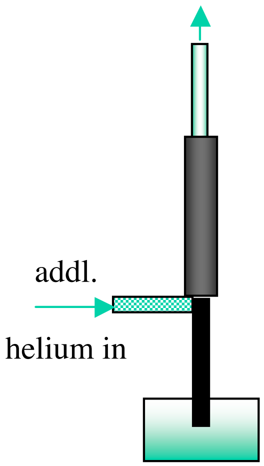


10 kA prototype for ITER-FEAT
FZK, CRPP-TF, Aventis/Nexans

13kA prototype for CERN
Eurus/NHMFL

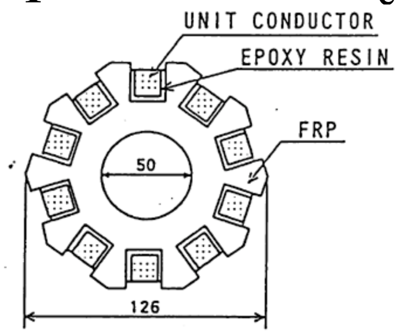
Cooling Options for HTS Leads

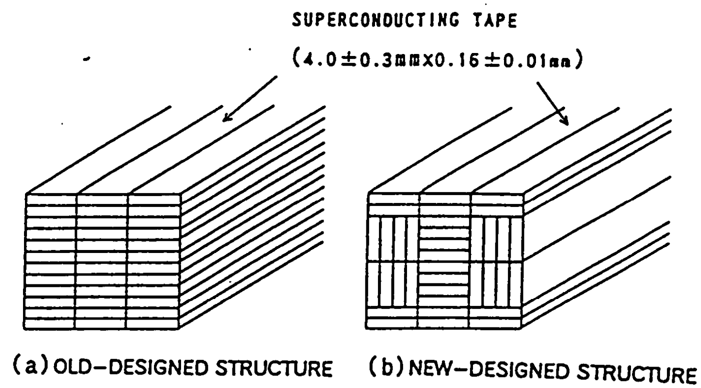
- Vapor cooling - AMI / MIT
  - Hybrid lead designed so that HTS section operates above I_c
    - 6 kA
    - Stacked tapes (240 vs 480) of Bi-2223/Ag-4%Au
    - Short (~ 0.4 cm / 28 cm) portion of HTS produces joule heating
    - Additional joule heat removed by effluent helium vapor
  - Improved characteristics as compared to fully superconducting version
    - Optimized versions: Q_c = 0.36 W vs. 0.71 W
    - Quantity of Ag & Au reduced by a factor of ~2.



Additional Considerations for HTS Leads

- Field dependence of J_c





- Fabrication process / materials

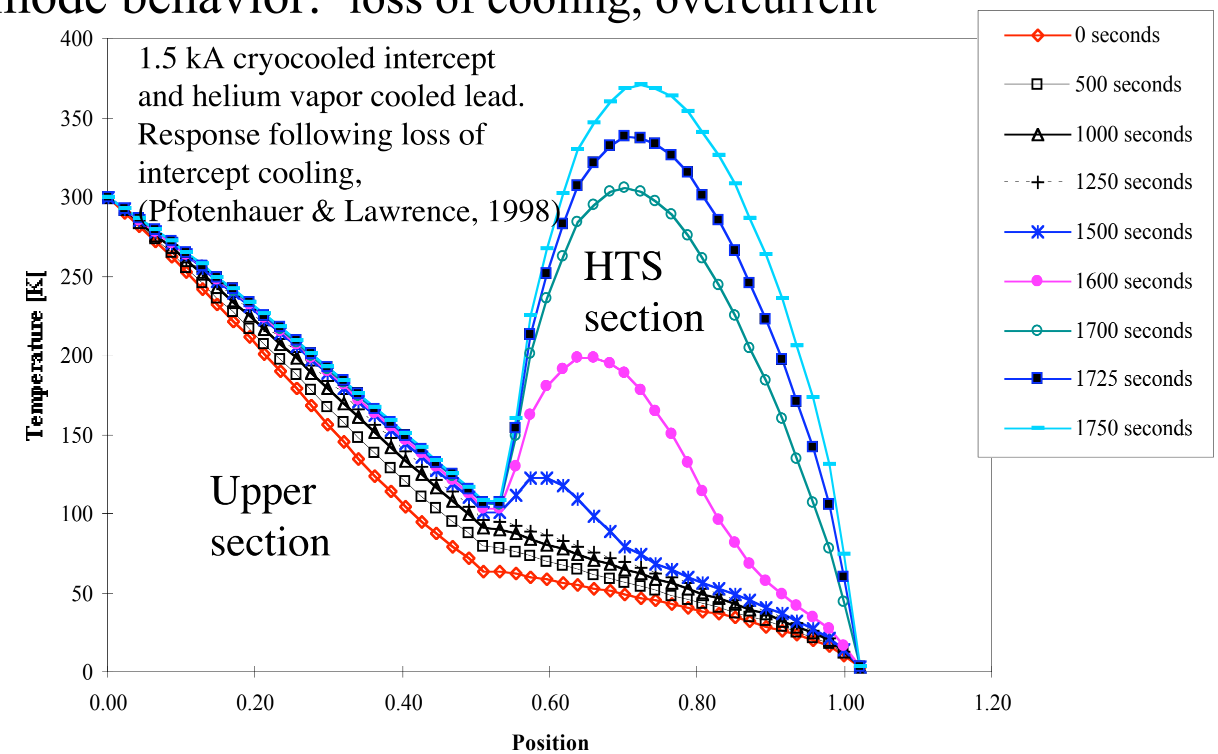
Stacked tapes of Bi2223 / Ag+4%Au
American Superconductor Corporation

Melt Textured YBCO
ATZ GmbH

MCP Bi2212
ACCEL/ART GmbH

Additional Considerations for HTS Leads

- Joint resistance ~ 0.1 μΩ
- Protection
  - Localized hot spots, cracking
  - Fault mode behavior: loss of cooling, overcurrent



References

- S. Deiness, "The Production and Optimization of High Current Leads," *Cryogenics,* vol. 5, pp. 269-271, October 1965
- J.E.C. Williams, "Counterflow Current Leads for Cryogenic Applications," *Cryogenics,* vol. 3, pp. 234-238, December 1963.
- Yu.L. Buyanov, "Current Leads for use in Cryogenic Devices. Principle of Design and Formulae for Design Calculations," *Cryogenics,* vol. 25, pp. 94-110, February 1985.
- J.R. Hull, "High Temperature Superconducting Current Leads," *IEEE Trans. on Applied Superconductivity,* vol. 3 (1), pp. 869 - 875, 1992.
- L. Dresner, *Stability of Superconductors,* Plenum, 1995, pp. 190-197.
- R. Wesche and A.M. Fuchs, "Design of Superconducting Current Leads," *Cryogenics,* vol. 34, pp. 145-154, February 1994.
- E. Barzi, "Gas/Vapour-Cooled Binary Current Leads: Copper Part," Fermilab internal report number TD-98-026, March 1998.
- H.M. Chang and S.W. Van Sciver, "Thermodynamic Optimization of Conduction Cooled HTS Current Leads," *Cryogenics*, vol. 38 (7), pp. 729-736, July 1998.
- T.M. Taylor, "HTS Current Leads for the LHC," *IEEE Trans. on Applied Superconductivity,* vol. 9 (2), pp. 412 - 415, June 1999.
- J.M. Pfotenhauer and J.W. Lawrence, "Characterizing Thermal Runaway in HTS Current Leads," *IEEE Trans. on Applied Superconductivity,* vol. 9 (2), pp. 424 - 427, June 1999.
- A. Hobl *et.al.*, "HTc Current Leads in Commercial Magnet Systems Applying Bi 2212 MCP BSCCO Material," *IEEE Trans. on Appl. Superconductivity,* vol. 9 (2), pp. 495-498, June 1999.
- R. Heller *et.al.*, "Status of the Development Program of a 60 kA HTSC Current Lead for the ITER Toroidal Field Coils," *IEEE Trans. on Applied Superconductivity,* vol. 9 (2), pp. 507 - 510, June 1999.
- 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. 45, pp. 1549 - 1564 2000.
- Y. Iwasa and H. Lee, "High Temperature Superconducting Current Lead Incorporating Operation in the Current-sharing Mode," *Cryogenics* vol. 40 pp. 209-219, 2000.