Magnet Current Leads

Tom Peterson, SLAC

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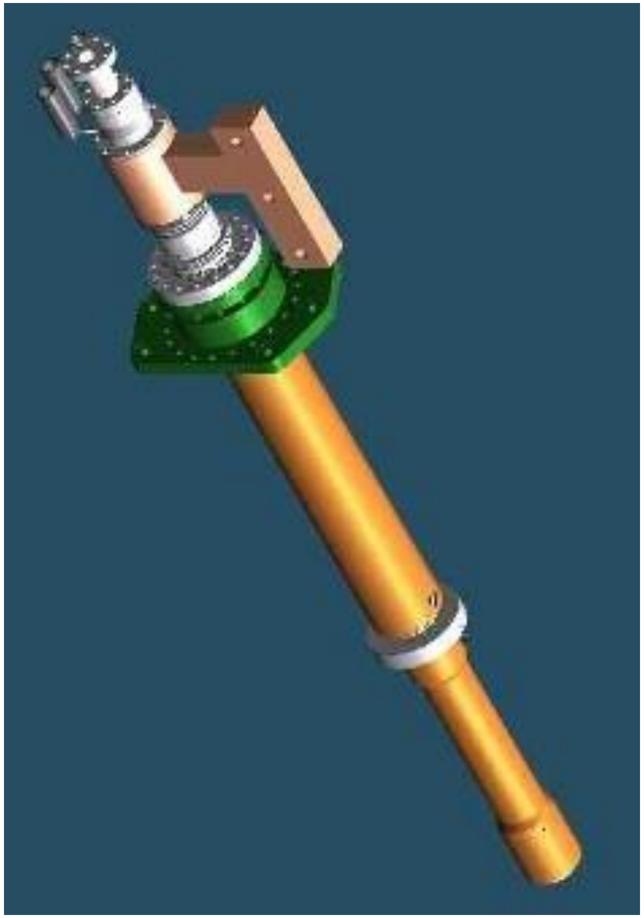
USPAS

Current lead introduction

- Problem: carry electric current, often 100's or 1000's of amps, to superconductor at LHe temperature with minimal heat conduction down the current lead
  - In theory a nice one-dimensional optimization
  - Many papers describing mathematical solutions and analyses. I have collected a few favorites over the years which I'll cite here.
  - Date back to the 1960's with the development of SC magnets, for example for bubble chambers
- Sometimes referred to as "counterflow current leads" since often cooled with helium vapor flowing up the lead
- Also may be called "power leads" since carrying electrical power into the superconductor

Current leads

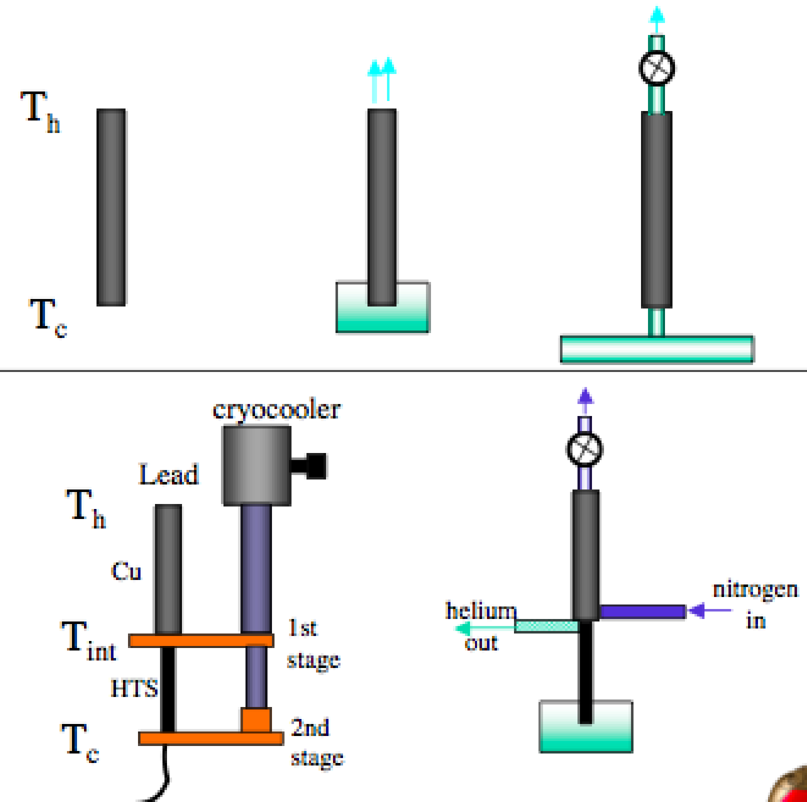


- Well-developed technology
- Much information in the cryogenics literature
- HTS materials work very well in current leads up to 80 K

From John Pfotenhauer, University of Wisconsin, Madison

Configurations

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



University of Wisconsin - Madison

Current lead design issues, material and dimensions

- Material selection
  - One seeks a balance of heat conducted down the lead (it must be an electrical conductor, hence thermal conduction is significant) with heat generated within the lead
  - The optimum is generally a low RRR copper
  - Conductor properties vary over the large temperature range up the lead
- Optimize dimensions (length, cross section)
  - Many authors present optimized length x current / area (LI/A) for various material parameters and cooling temperatures

Current lead design issues, thermal and fluid dynamic

- Heat transfer for convective cooling
  - Huge range of fluid temperatures up the lead, hence large changes in fluid density, velocity, convection coefficients
- Cooling conditions – saturated vapor
  - Many papers and designs consider current leads for operation in a dewar
  - "Self-cooling" in generating saturated vapor from boiling liquid based on heat transfer to bottom of lead
  - Very low pressure drop up the lead is required
- Cooling conditions – pressurized helium (subcooled, supercritical, or gas at the lead base)
  - Flow control is independent of heat input
  - Heat may be convected into the flow stream passing the lead

Current lead mathematical model

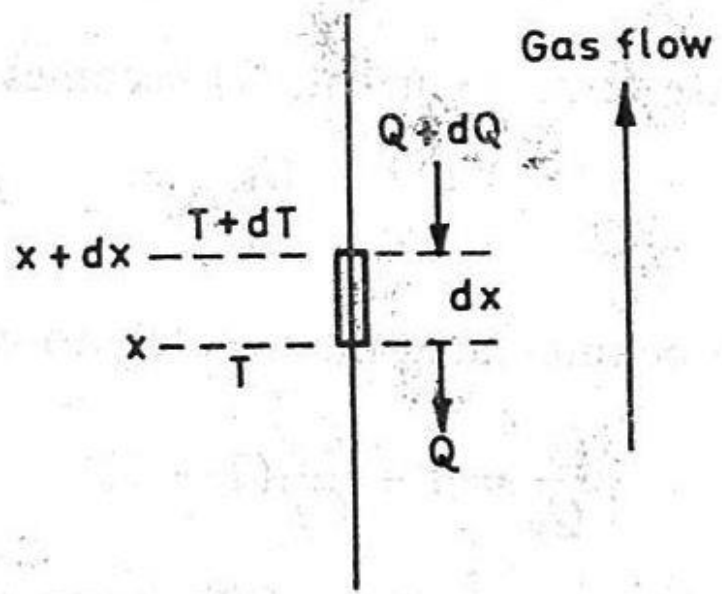
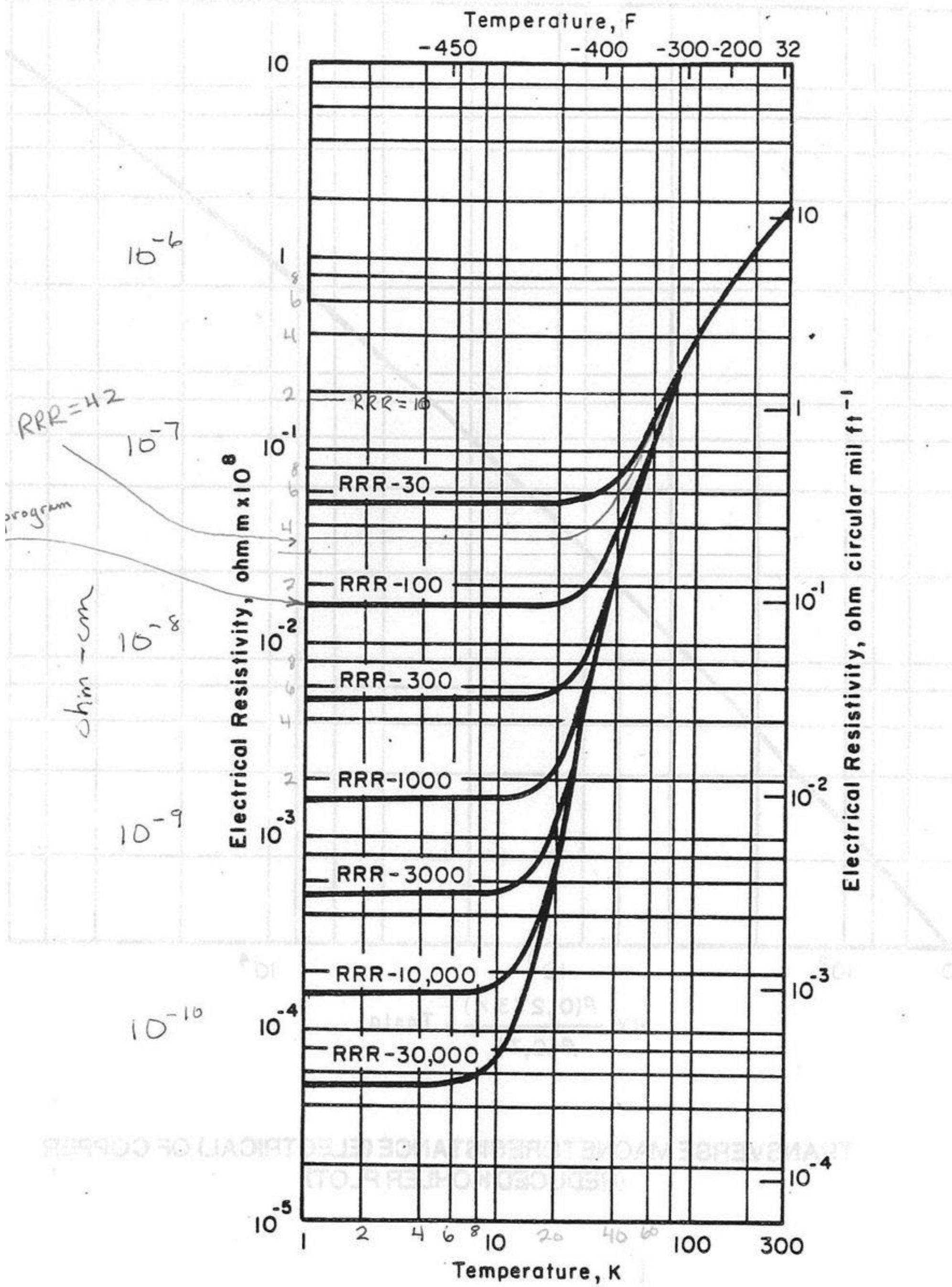


Figure 1. Thermal equilibrium in a current carrying conductor

From Lock (ref 1)

Resistivity of copper vs temperature



ELECTRICAL RESISTIVITY VERSUS TEMPERATURE FOR COPPER

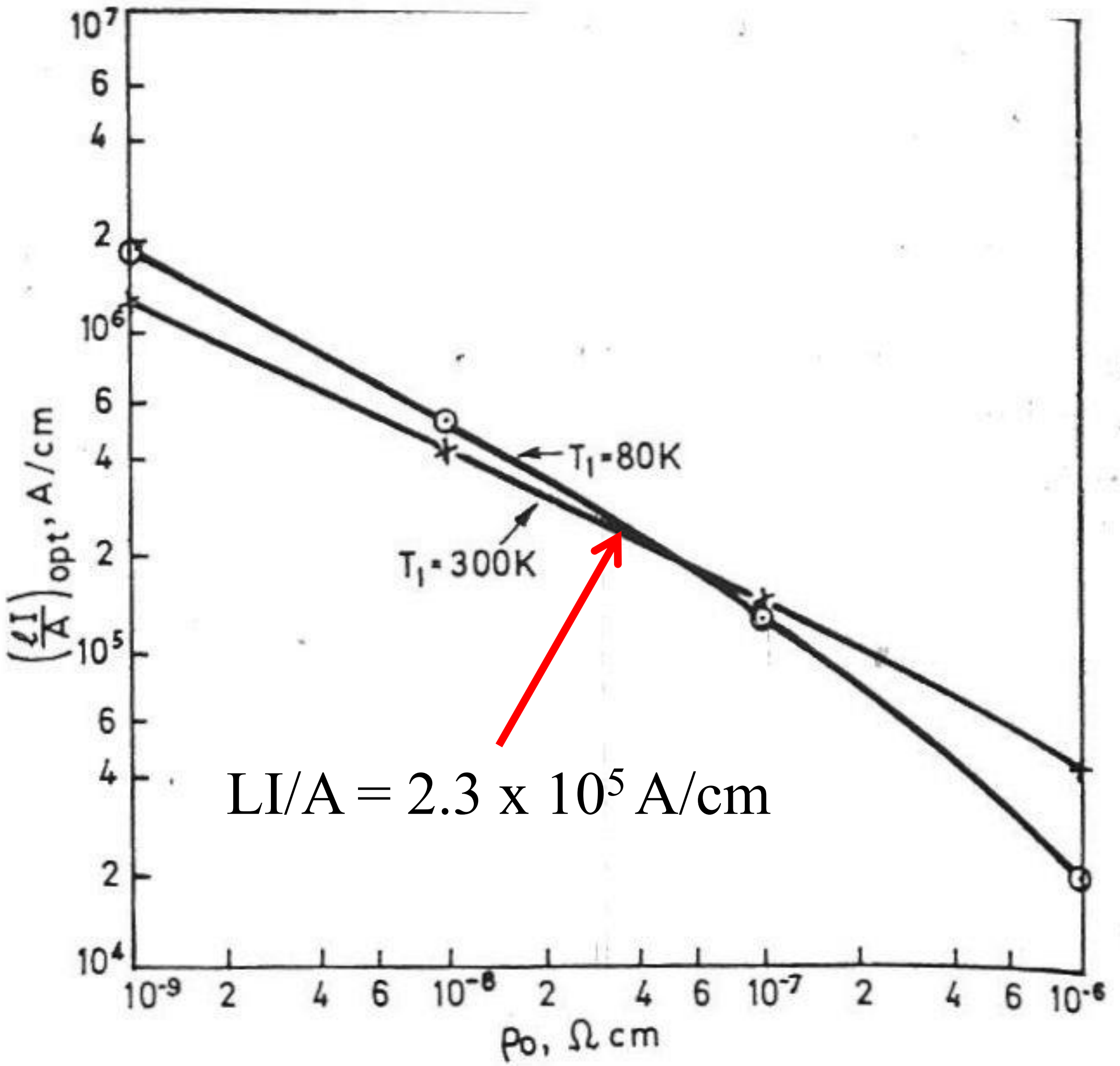


Figure 8. Optimized values of *lI*/*A* as a function of $\rho(0)$

Optimum LI/A from Lock (ref 1)

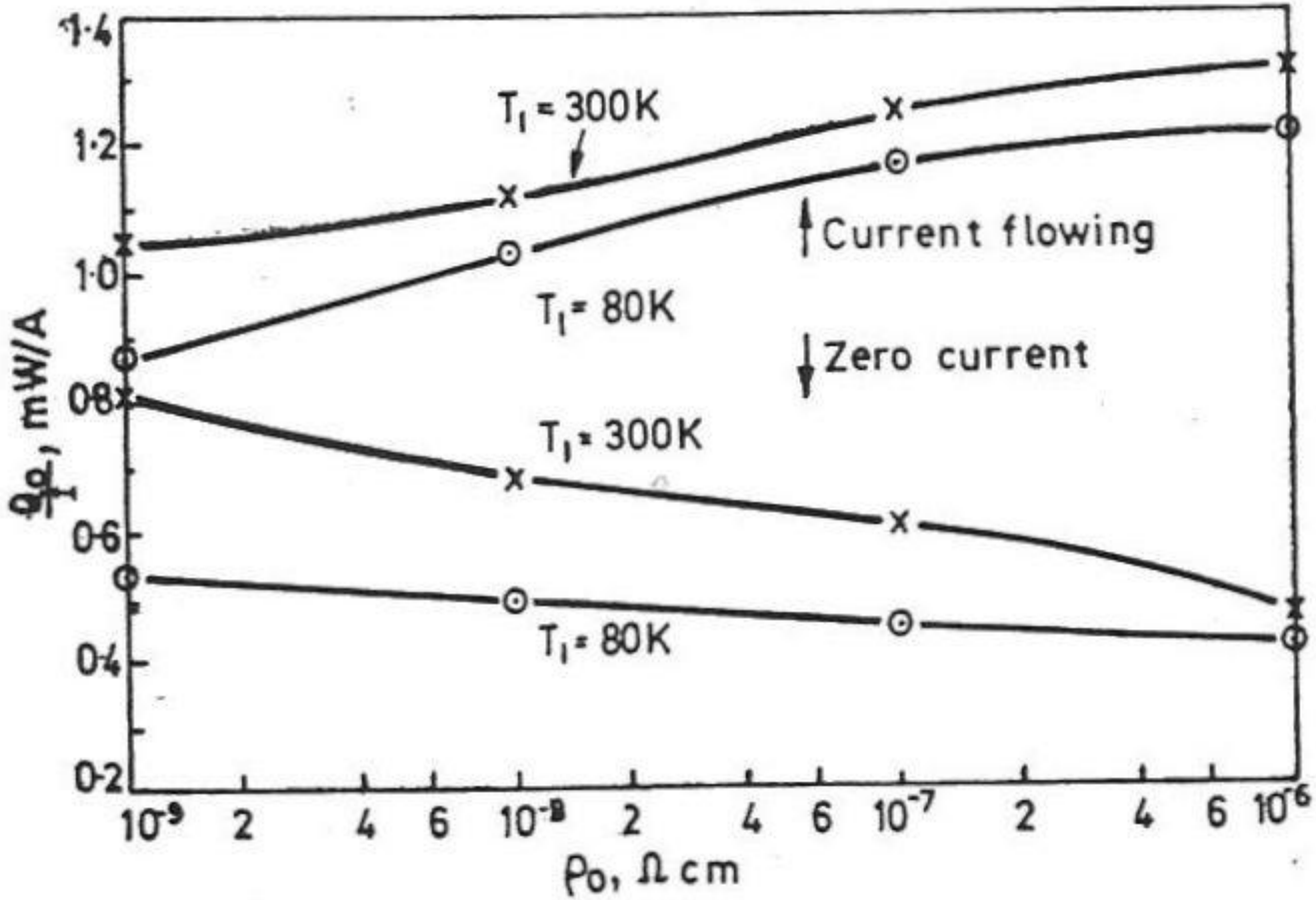
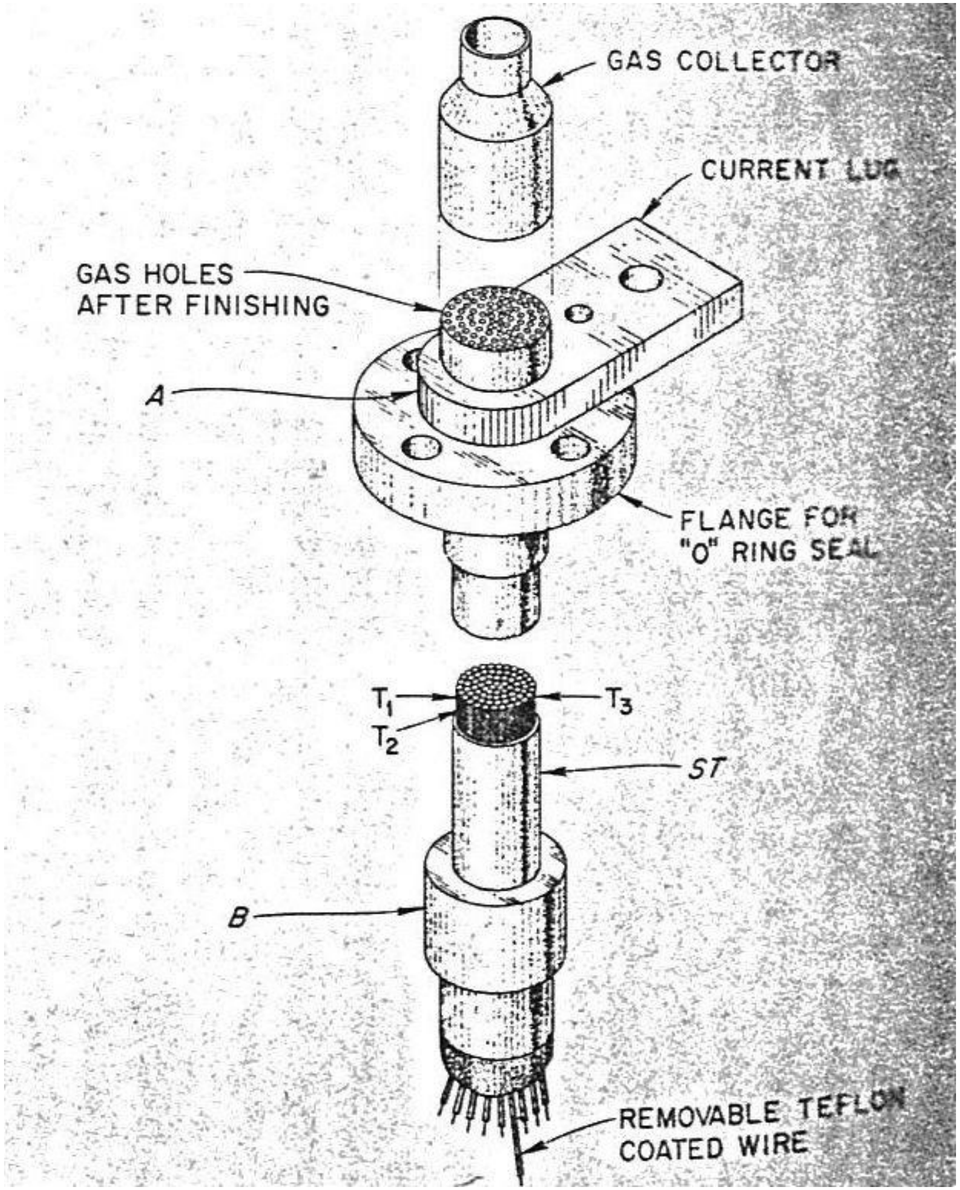


Figure 7. Optimized heat dissipation as a function of $\rho(0)$ with and without current

Optimum residual resistivity, from Lock (ref 1)



American Magnetics, Inc. (AMI) current lead design by K. R. Efferson (ref 2)

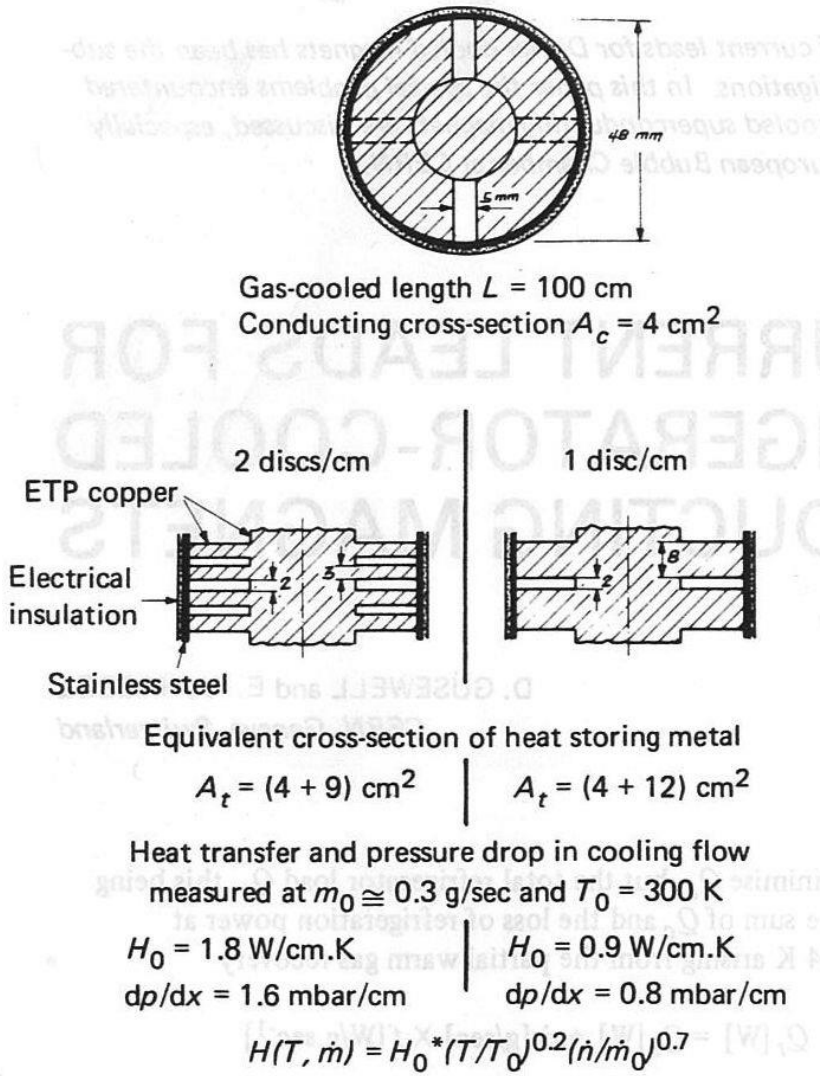
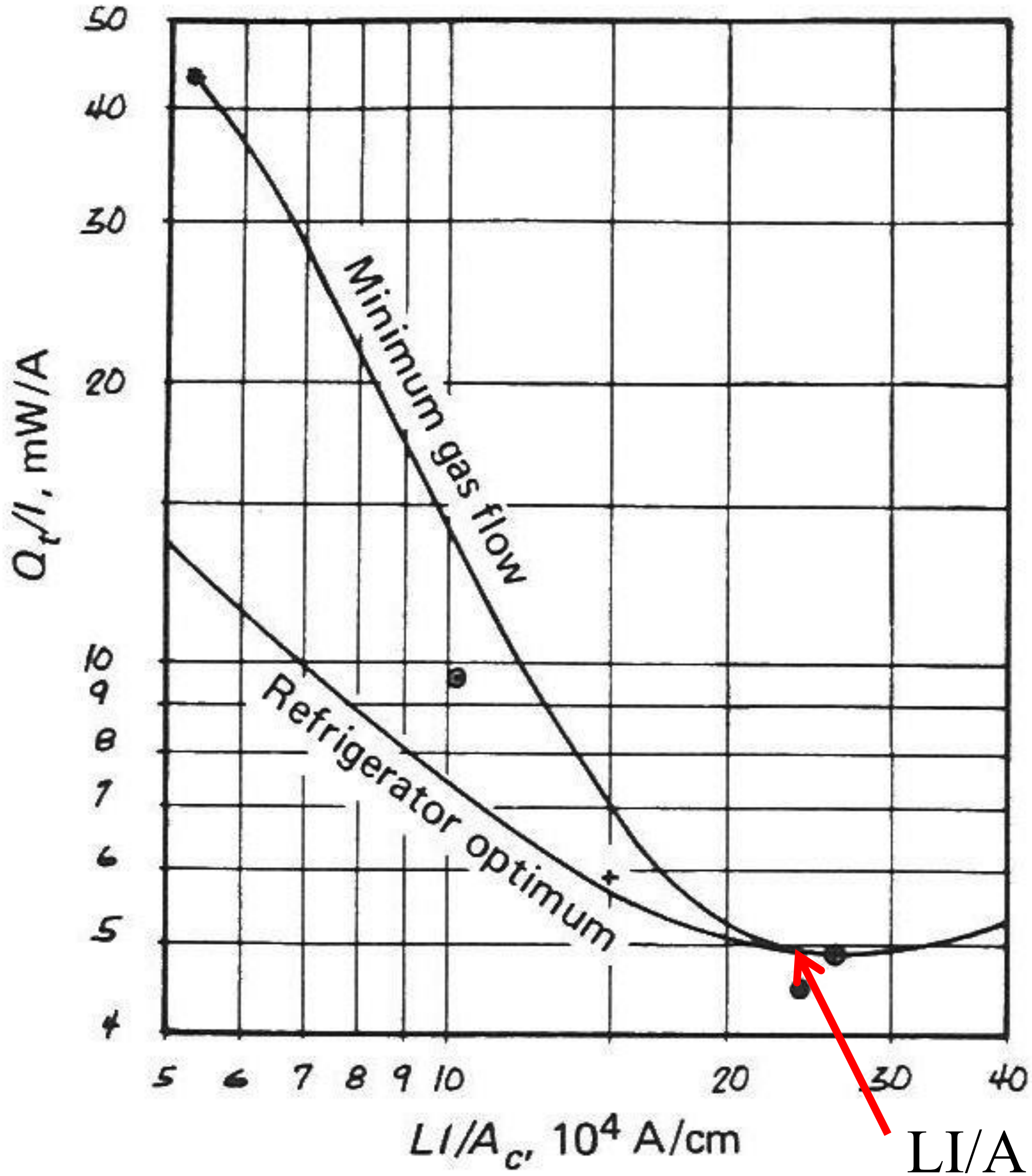


Figure 1. The 6,000 A gas-cooled current lead of the supercondcut-ing BEBC magnet, working between 4.4 and 300 K •

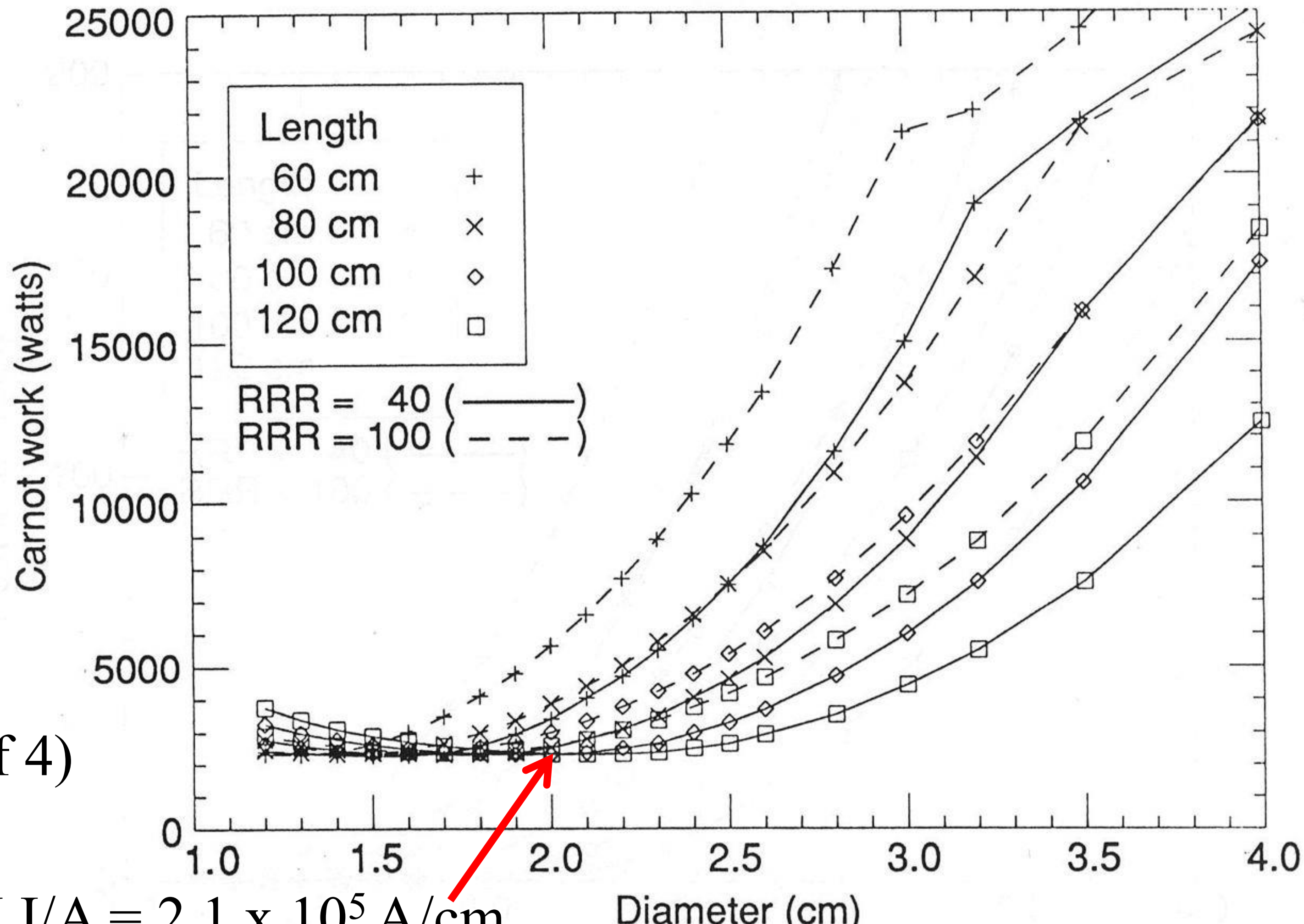
Big European Bubble Chamber (BEBC, CERN) current lead design for heat exchange with the helium gas (ref 3)



CERN BEBC current lead optimum considering refrigeration as well as current lead flow (ref 3)

LI/A = 2.3 x 10^5 A/cm

Parameter study for SSC lead



(ref 4)

$LI/A = 2.1 \times 10^5$ A/cm

Typical temperature distribution

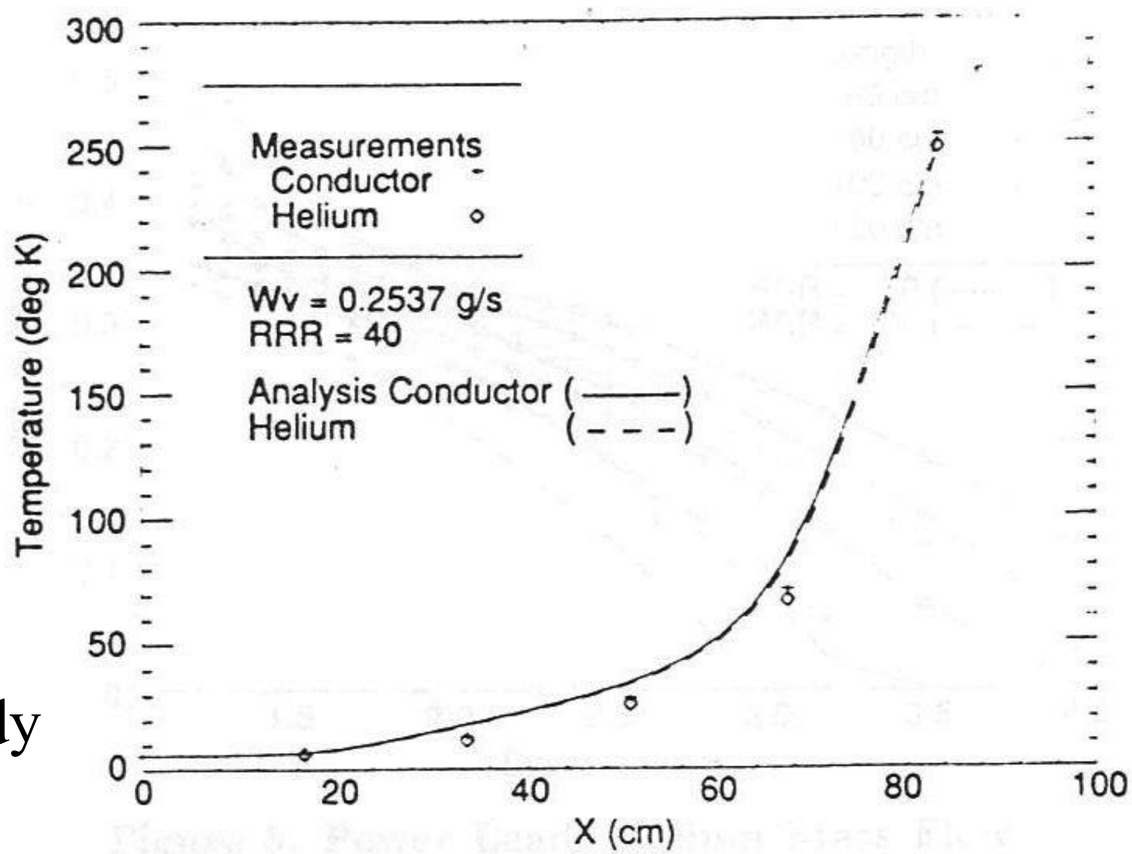


Figure 2. Test Lead Temperature Distributions.

SSC study (ref 4)

Voltages in the lead

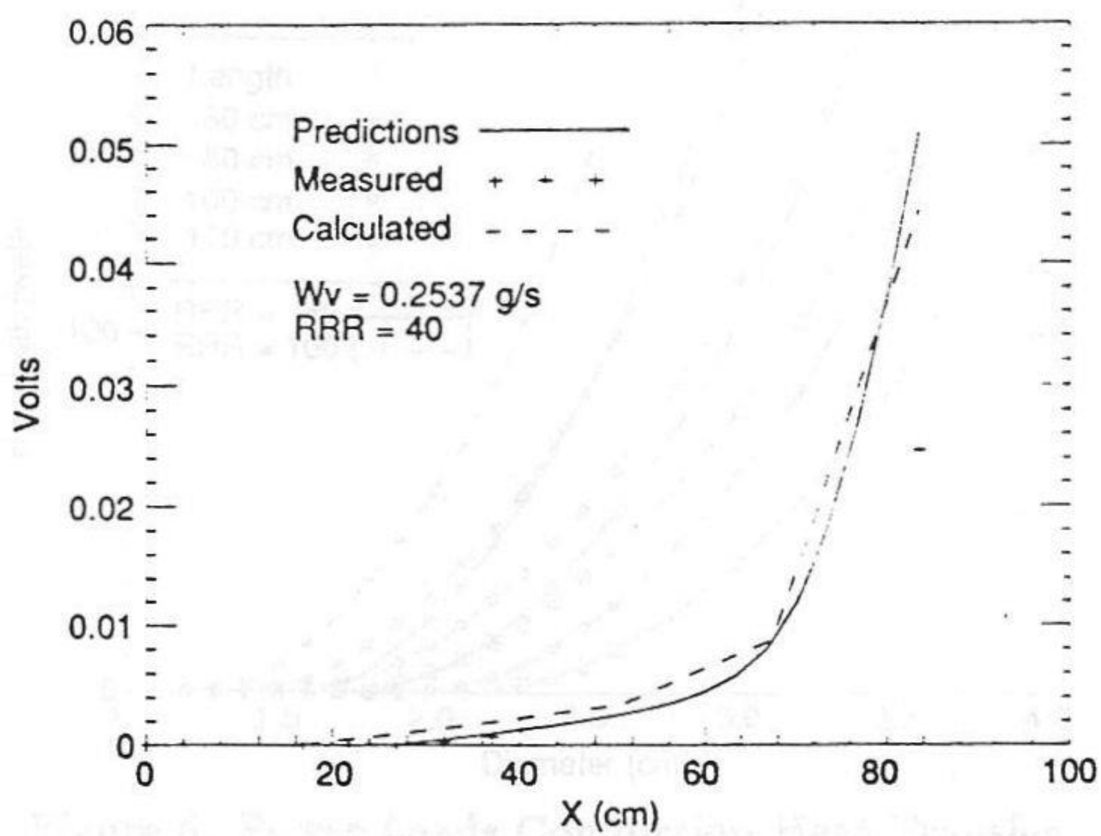
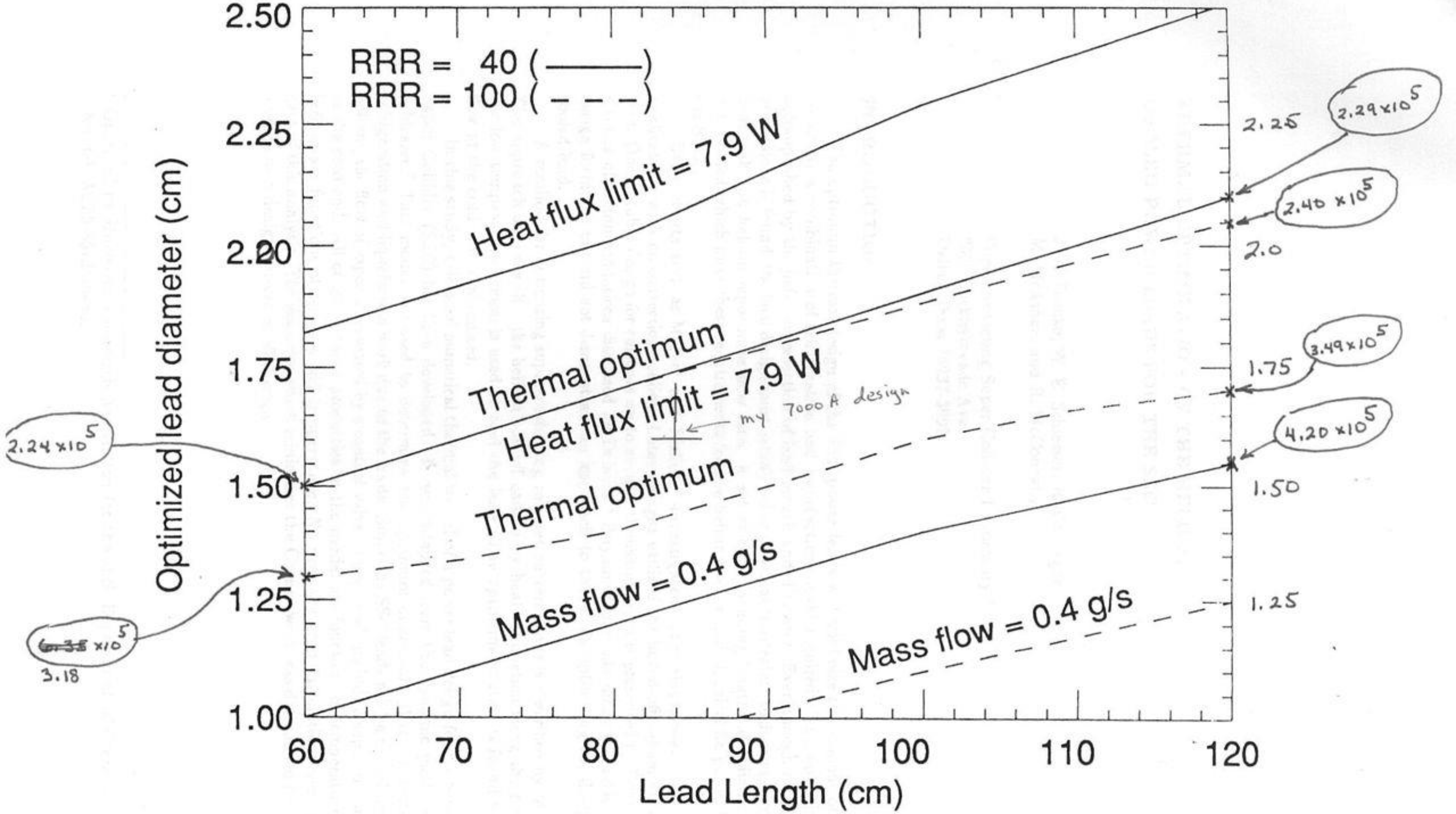


Figure 3. Test Lead Voltage Distributions.

(ref 4)

Lead voltage

- The overall voltage in a current lead provides an integrated resistance measurement, so indirectly an integrated temperature measurement
- Lead voltages for forced-flow cooled current leads at Fermilab were all typically in the 40 to 100 mV range, above 100 mV indicating a cooling problem



A = 6600 Amps $\frac{LI}{A}$

Note: Lock's optimum $\frac{\ell I}{A} = 3.5 \times 10^5$ for RRR = 100

" " $\frac{\ell I}{A} = 2.5 \times 10^5$ for RRR = 40

A page from the SSC paper (ref 4) with my notes

Average system-wide current lead flows for the Tevatron at 4 kA (data taken by Tom P., 6 May 1987)

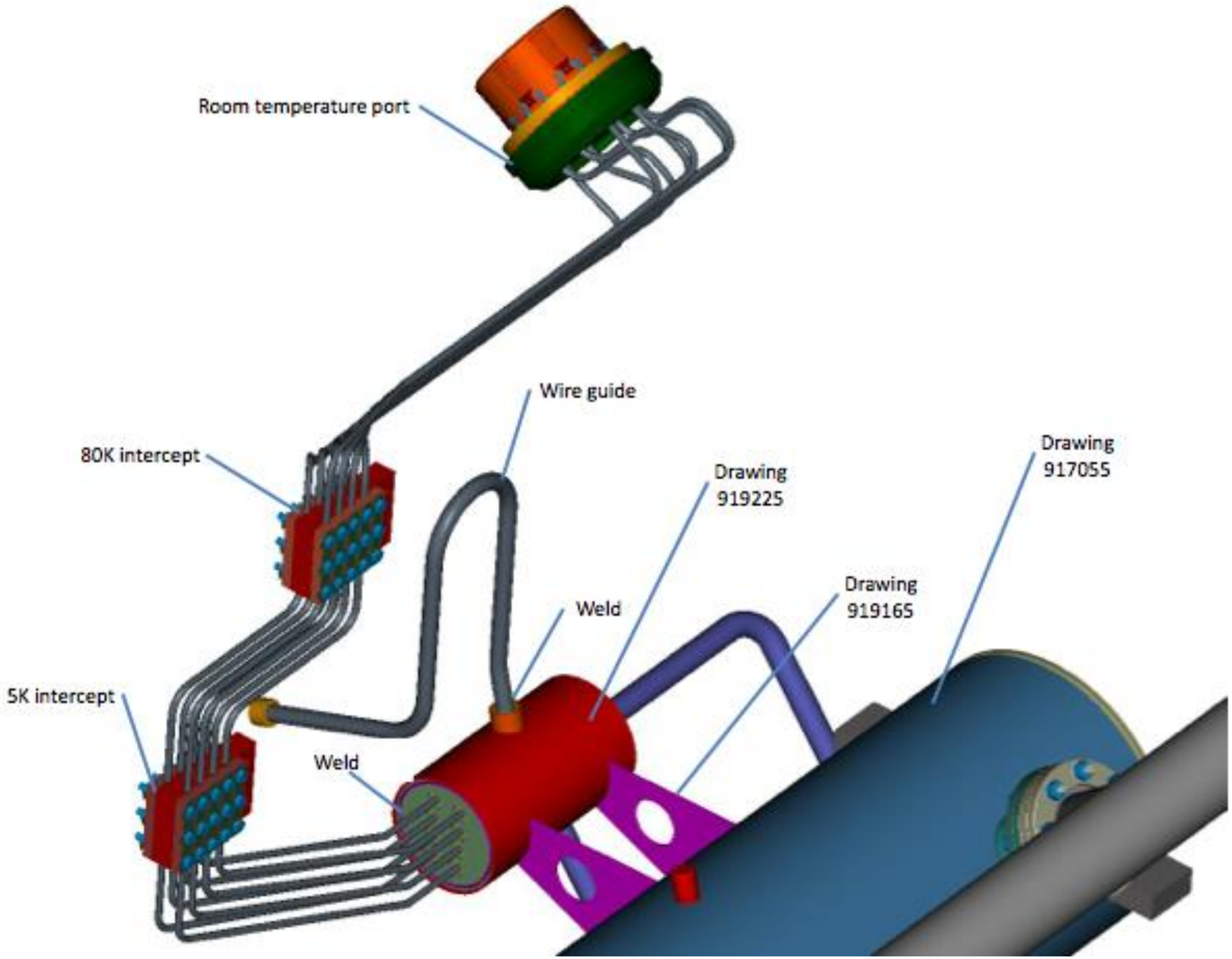
Notes: feedcan and power spool had very different configurations, with better convective cooling at the lead base in the feedcan.
Average is about 0.4 grams/sec for 4 kA.
0.1 grams/sec helium cooling per kA was typical also at MTF.

FIUL/DL (feedcan)	92.3 (.32 g/s)	100+ (many)	65 (several)
FIUL/DL (pwr spool)	122.0 (.42 g/s)	140 at A4	65 (at D1; maybe the modification works!)
FIUM/DM	32.8	44 (F2 FIDM)	20 (A3 FIUM)
Total avg sat liq load (g/s)	0.97		
Low-beta lead flow	130 (.45 g/s)		

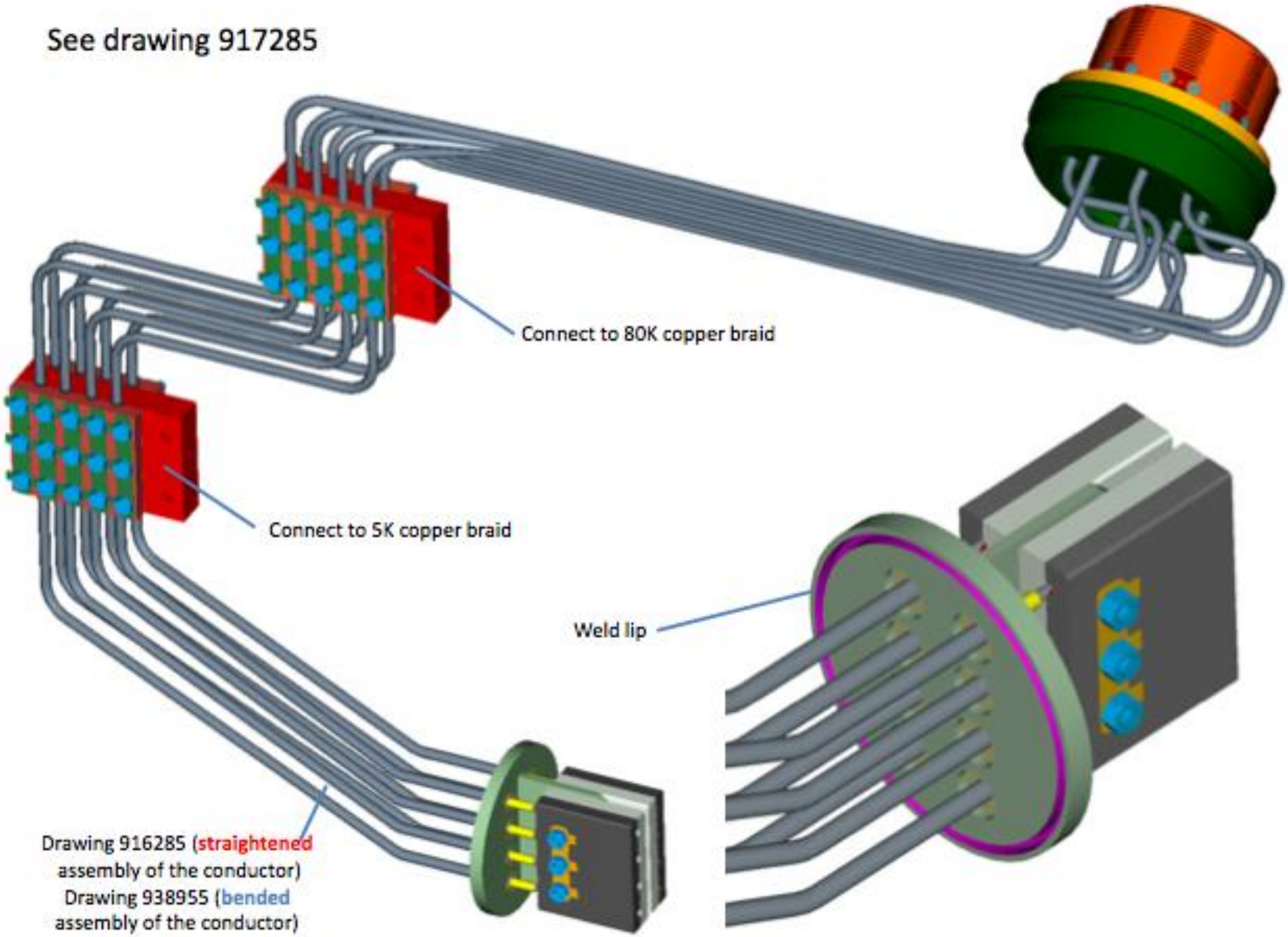
Conductively cooled leads

- No counter-current gas flow
- OK for lower current (<100 A)
- Heat load penalty offset by simplification
- Subatmospheric 2 Kelvin space cannot drive lead flow, need another cooling source or conductive cooling
- CERN corrector leads, XFEL magnet leads, others for magnets in 2 K SRF systems

Conductively cooled lead package



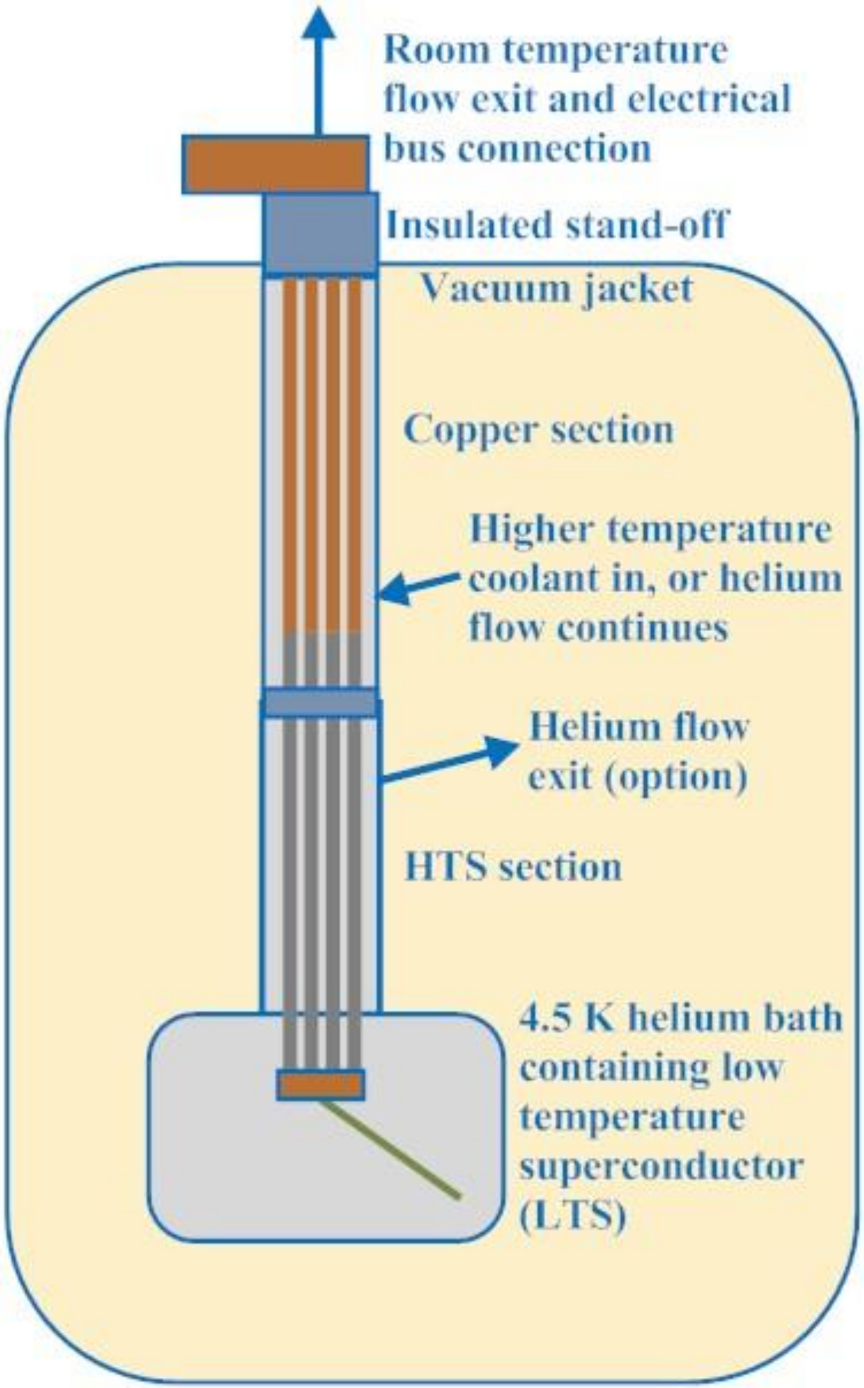
Conductively cooled lead package



High Temperature Superconductors

- 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 5 and 6 for more information

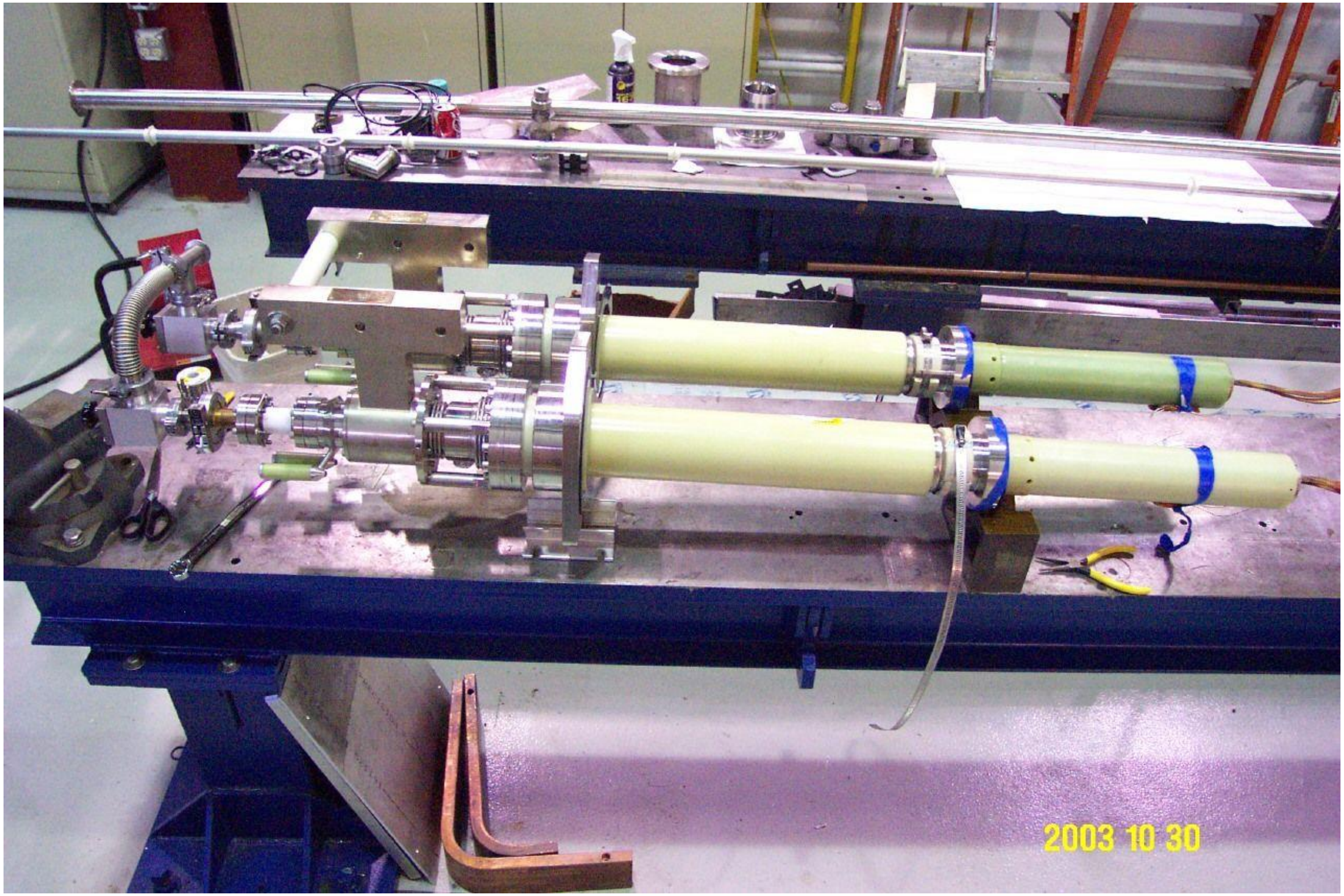
HTS lead arrangement

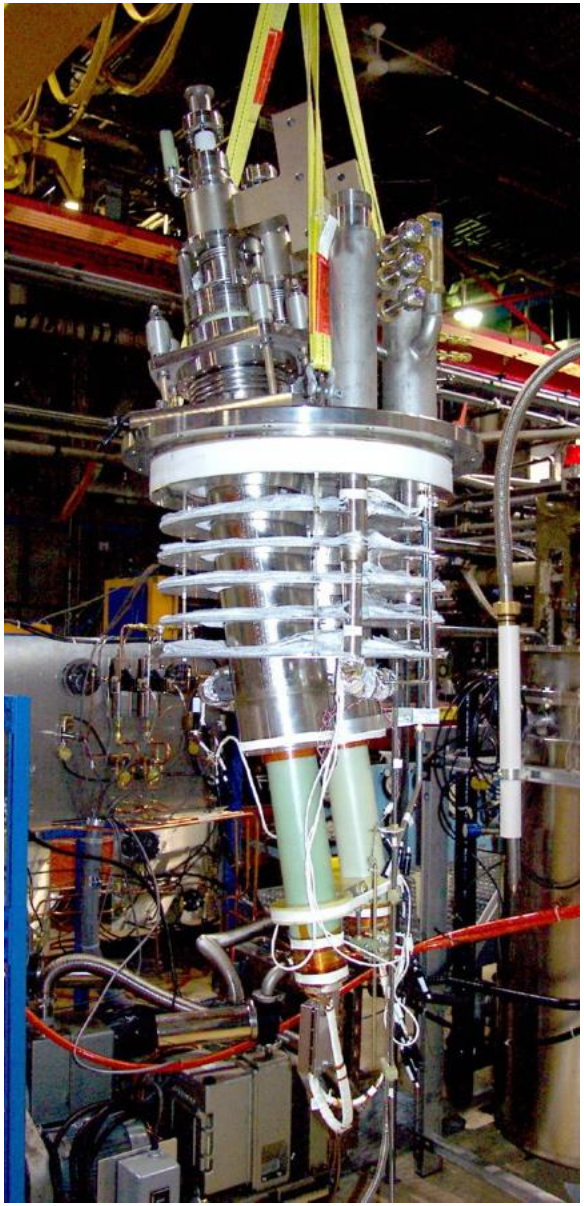


High Temperature Superconductors

- 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 7 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

7.5 kA HTS leads for DFBX




DFBX HTS leads

Current lead installation

- Most problems today arise with current lead integration into the supply box
  - Temperature at top plate
    - Leakage of cold seals
  - Vacuum or "chimney" enclosure
    - Heat transfer around or into lead
  - Temperature at joint to superconductor
    - Quench avoidance forces higher than optimal current lead flow

Current leads conclusion

- Looks like a nice, one-dimensional problem
- Much good analysis in the literature
- The difficulties arise in implementation
  - Integration with the cryostat
  - Superconductor-to-copper splice joints or HTS to LTS joints
  - Flow balance and control: heat load at cold end versus frost at warm end, heat exchange not as good as anticipated
  - Hi pot problems, electrical stand-off issues
- My advice is to search the literature and access experience regarding leads which you need, but also assume they will require some engineering attention

Current lead references

1. J.M. Lock, "Optimization of Current Leads into a Cryostat," *Cryogenics*, Dec 1969.
2. K.R. Efferson, "Helium Vapor Cooled Current Leads," *The Review of Scientific Instruments*, Vol 38, No. 12, Dec 1967.
3. D. Guesewell and E. –U. Haebel, "Current Leads for Refrigerator-Cooled Large Superconducting Magnets," 3rd International Conference on High-energy Physics and Nuclear Structure, New York, NY, USA, 8 - 12 Sep 1969.
4. J.A. Demko, et al, "Thermal Optimization of the Helium Cooled Power Leads for the SSC," Proceedings of the Supercollider 4 Conference, New Orleans, 1992.
5. 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.

Current lead references

5. J. Brandt, S. Feher, T.J. Peterson, W.M. Soyars, "HTS Leads in the Tevatron," Advances in Cryogenic Engineering, Vol. 47A, pg. 567.
6. A. Ballarino, S. Mathot, and D. Milani, "13000 A HTS Current Leads for the LHC Accelerator: from Conceptual Design to Prototype Validation," LHC Project Report 696, Presented at the 6th European Conference on Applied Superconductivity (EUCAS 2003) 14-18 September 2003.
7. T.P. Andersen, V. Benda, B. Vullierme, "600 A Current Leads with Dry and Compact Warm Terminals," LHC Project Report 605
8. A. Ballarino, "Conduction-Cooled 60 A Resistive Current Leads for LHC Dipole Correctors," LHC Project Report 691