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# Power Leads for Test Stands

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# Outline

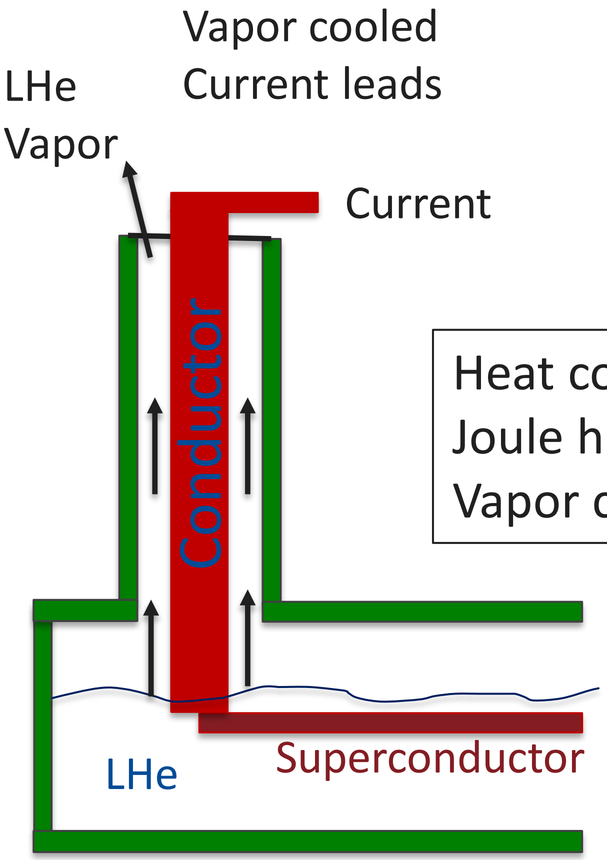
- Introduction
- Current leads design considerations
- Test stand requirements with respect to Power Leads
- What can go wrong?
- Summary

# Introduction

- With the discovery of Superconductors, the electric power to be transmitted from room temperature to low temperature environment was always necessary for testing or operating any test samples or devices at cryogenic temperatures. Using Current Leads (CL) was a necessity.
- From the very beginning the CL operation was an issue:
  - Steady operation with low heat losses.
- In 1950s the ever-lasting interest to optimize the current leads (power leads) for low power consumption to operate them has started.
  - Probably R. McFee (1959) was the first who pointed out how to optimize the CL only considering heat conduction in the process – he claimed that if the design value differ by a factor of 4 the losses will be 100 % higher than using his CL design optimization.
  - J.M. Lock (1969) was one of the first who discussed the advantages of using vapor cooled current leads – boil off He to be used to cool the lead.
  - In CLs was the very first useful application of the HTS material (discovered in 1986).

# CL Basics

- Function: Carry the current from 300 K down to cryogenic temperatures – for LTS magnets 4.3 K for HTS devices 4.3 - 80 K.



Heat conduction
Joule heating (current)
Vapor cooling

For the past 70 years countless experience fabricating and using current leads.

Modeling and reality many times were different:

- Efficiency was not as high.
- Stability was not as calculated.
- Lead integration issues.

Leads are strongly application dependent.

# Why was the CL Optimization an Exciting Subject?

In principle, modeling the leads is straight forward; partial differential equations can be solved numerically.

## Energy balance equations:

Conductor

$$\frac{\partial}{\partial t}(\rho_c e_c)dv = \frac{\partial}{\partial x}\left(kA\frac{\partial T_c}{\partial x}\right)dx - h_{conv}P(T_c - T_v)dx + \frac{\rho_{elec}I^2}{A}dx$$

Helium Vapor

$$\frac{\partial}{\partial t}(\rho_v e_v)dv = \dot{m}\frac{\partial h_v}{\partial x}ds - h_{conv}P(T_c - T_v)dx$$

| | |
|---|---|
| $e_c e_v$ | internal energy of the conductor and the helium vapor |
| $\rho_c \rho_v$ | density of the conductor and helium vapor |
| $k$ | thermal conductivity |
| $h_v$ | helium vapor enthalpy |
| $h_{conv}$ | convective heat transfer coefficient |
| $P$ | convective surface area per unit length of the conductor |
| $\dot{m}$ | helium mass flow rate |
| $T_c, T_v$ | conductor and helium temperatures |
| $dv$, $dx$, $ds$ | differential volume, distance along the conductor and gas path |
| $\rho_{elec}$ | electrical resistivity |
| $A$ | conductor cross section |
| $I$ | current |
| $t$ | time |

One dimensional equations – reality is 3D and the radiation term has been neglected.

$k$ and $\rho_{elec}$ temperature dependent.

Cooling options:

- Forced flow.
- Boil-off.

# Steady State

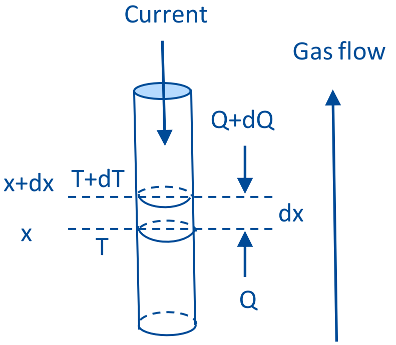
(J.M. Lock, Cryogenics, Dec. 1969)

Assuming perfect heat exchange and using:

$$Q = kA\frac{dT}{dx}, \qquad dh_v = C_p dT$$

Heat flow equation becomes manageable:

$$dQ + \frac{\rho_{elec} I^2}{A} dx = \dot{m} C_p dT$$



Introducing $Q_0 = \dot{m} C_L$ Heat flow into the LHe – He vapor is generated

Some normalization $Q = Iq,$ $Q_0 = I q_0$ and using the Lorentz number $\frac{k\rho_{elec}}{T} = L(T)$

Simplified diff eq. to be solved

$$\boxed{\frac{dq}{dT} = \frac{C_p}{C_L} q_0 - \frac{L(T)T}{q}}$$

Optimization: to find minimum value of $q_0$ at a given temperature range and current value.

With known $q(T)$ lead parameters can be calculated

$$\boxed{\frac{Il}{A} = \int_{T_0}^{T_1} \frac{kdT}{q}}$$

Lead form factor current lead conductor material dependent.

Gas cooled no current

$$\frac{Q_0 l}{A} = \int_{T_0}^{T_1} \frac{kdT}{1 + \left(C_p/C_L\right)(T - T_0)}$$

Guidance for HTS lead optimization: maximizing $l$ and minimizing $A$.

Conduction cooled lead

$$q_0 = \sqrt{L_0 I^2 (T_1^2 - T_0^2)} \qquad \left(\frac{l}{A}\right)_{opt} = \int_{T_0}^{T_1} \frac{kdT}{\sqrt{\left(Q_0^2 - L_0 I^2 (T^2 - T_0^2)\right)}}$$

$L_0$ is the Lorentz constant

# Some Conclusions

Design considerations:

- Due to the Wiedemann-Franz law $L(T)$ does not have a strong variation form one metal type to another → $q_0$ minimum is insensitive to the choice of metal.
- No gain by cooling down the hot end of the lead; but making an intercept by different way of cooling ($LN_2$ or other coolant if available) can help.
- The optimum solution at the hot end → temperature gradient is zero. There is a negative solution; heat is flowing toward the hot end of the lead.
- Stand by condition for conduction cooled leads favor selection of low RRR conductor; stability is also better.
- The lead is optimized for one current value; at test facility the current value will be different, picking the highest current value means the leads will not be used in optimum condition most of the time.

Practical number by Amalia Ballarino's study for minimum heat leak (W/kA):

| Type of lead | Q at 4.2 K | Q at 77 K |
|---|---|---|
| Conduction cooled | 47 | 45 |
| Gas-cooled | 1.1 (Helium vapor) | 23 (Nitrogen vapor) |

# Solving Transients or Stability Criteria for the CLs

- Once the lead has been optimized for minimum heat leak it needs to be checked for stability
  - Runaway condition – temperature never stabilizes; positive feed back between the temperature and electrical resistivity.
  - Max temperature of the lead is below a limit that will not damage the lead (solder joints).
  - Once the lead has been disturbed (lost of coolant) it will get into a stable condition.
- Energy balance equation for the conductor to be solved
  - Even for numerical solutions simplifications are introduced: transverse temperature gradients neglected, heat transfer perfect between helium and conductor, simplified resistivity model (constant conductivity-linear resistivity) etc.
  - Solutions will help to identify whether the leads can operate steadily.
- Many leads have been made and tested for stability
  - The calculations helped, but hardly given perfect agreement with experimental results.
  - The leads can operate at higher cooling rate – stability can be re-established.

$$\left(\frac{\pi}{L}\right)^2 + \left(\frac{\dot{m}_2 \cdot c_p}{2Ak}\right)^2 - \frac{J_2^2 a}{A^2 k} > 0$$

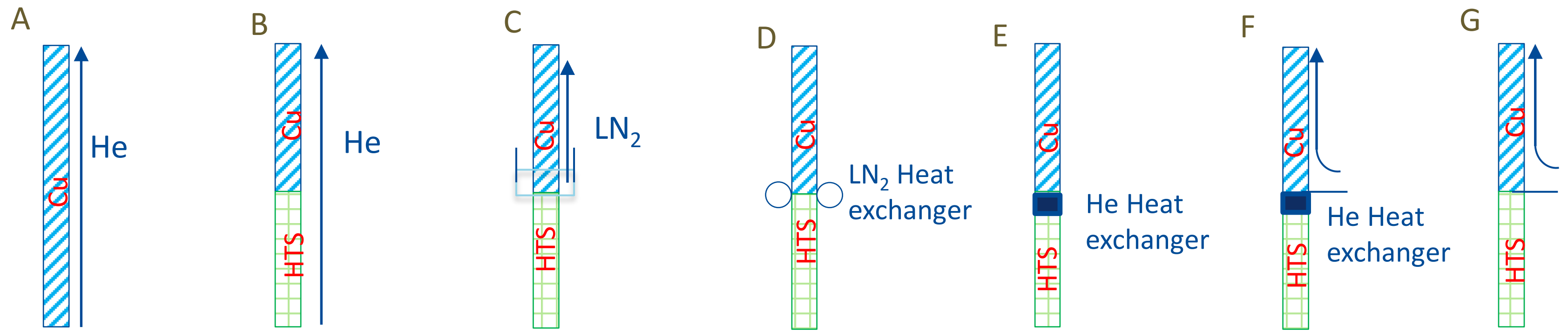
$L$ Lead Length

$$\rho(T) = aT + b, \text{ where } a > 0$$

Copper section of the 6 kA lead operating between 80 – 300 K

G. Citver et al., Steady State and Transient Current Lead Analysis IEEE Trans on Appl. Super., Vol 9, NO 2, June 1999

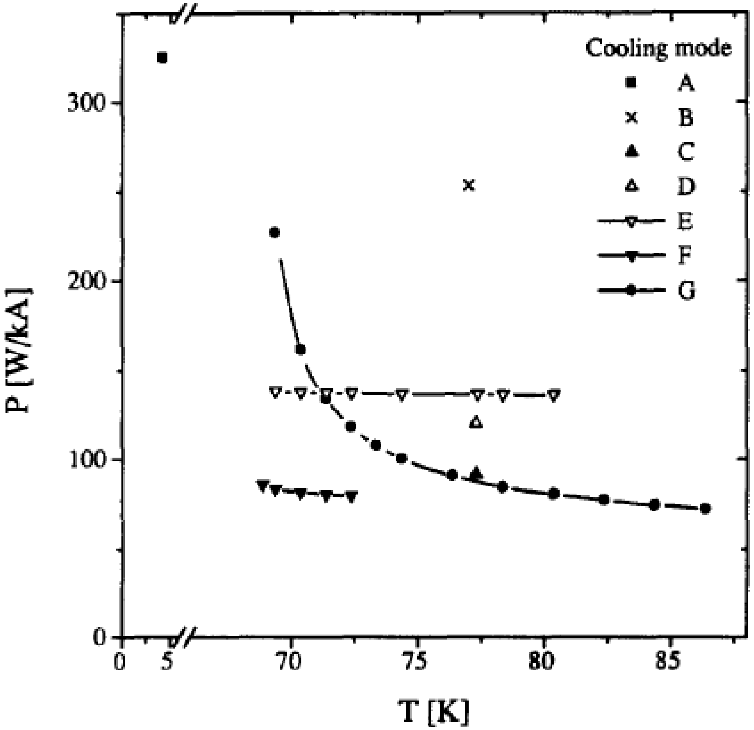
# Current Lead Cooling Schemes



Conventional Vapor cooled
$Q_0$ = 1W/kA;
*P* = 328 W/kA
300 K Refrigeration Power (RP)

Binary Vapor cooled Cu – HTS (silver sheeted)
$Q_0$ = 0.77 W/kA
no heat intercept

To cool the whole current lead
$P_{ideal} = P_{Cu} + P_{HTS}$
$P_{HTS}/P_{cu} = 0.2$



Binary-HTS leads advantages (in terms of RP)

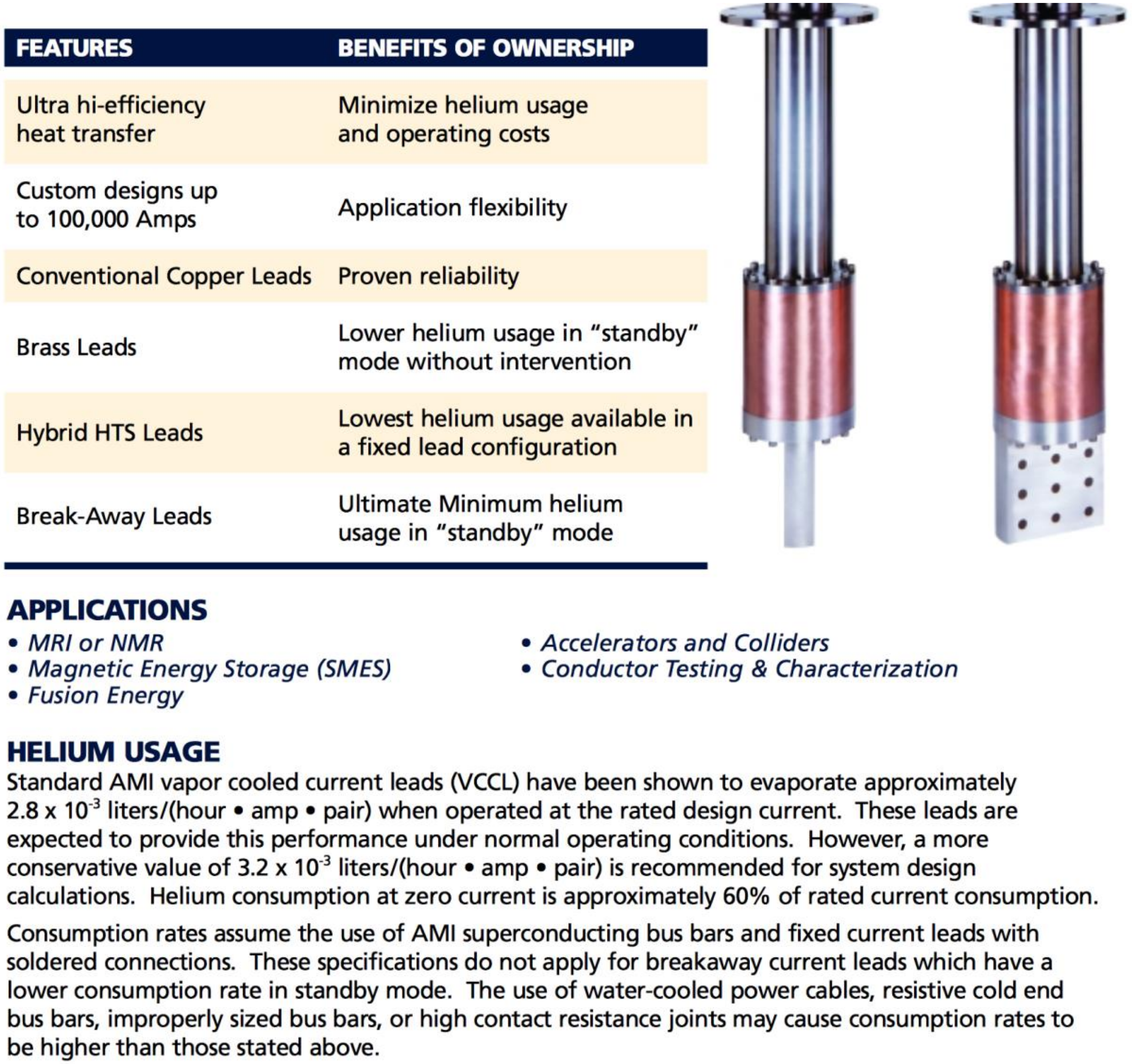
- Heat leak to LHe bath can be reduced by factor of 10.
- Copper section can be reduced by factor of 3.

R. Wesche, Design of superconducting current leads, Cryogenics 1994 Vo 34,No2

# Practical Solutions

- In copper section cooling, to obtain good heat transfer from the vapor, the conductor geometry is important; large area
  - Braided conductor; was not optimal for transferring the heat.
  - Mesh, better with larger surface area.
  - Rolled sheets with punched holes.
  - Forced flow through spiral channels.
- Anchoring the mid temperature – phase separator at the bottom of the lead was important for $LN_2$ boil off case.
- Insulation solution scheme of the current lead, especially if high pressure requirements needs to be met.
- Removable leads – not for test stands.
- Encapsulating the HTS material from He bubbles.

# Power Leads are Commercially Available



| FEATURES | BENEFITS OF OWNERSHIP |
|---|---|
| Ultra hi-efficiency heat transfer | Minimize helium usage and operating costs |
| Custom designs up to 100,000 Amps | Application flexibility |
| Conventional Copper Leads | Proven reliability |
| Brass Leads | Lower helium usage in "standby" mode without intervention |
| Hybrid HTS Leads | Lowest helium usage available in a fixed lead configuration |
| Break-Away Leads | Ultimate Minimum helium usage in "standby" mode |

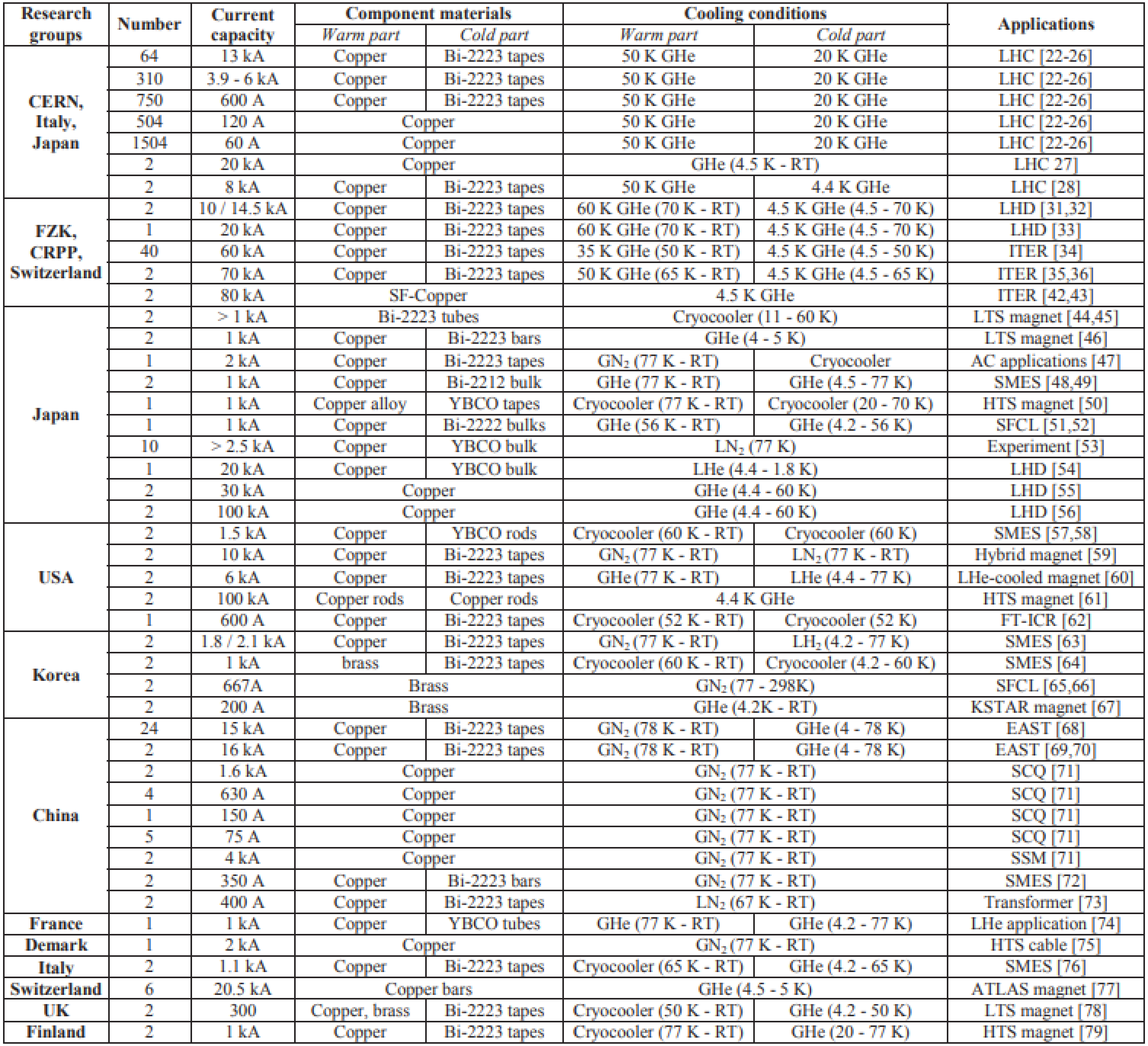
**APPLICATIONS**

- *MRI or NMR*
- *Magnetic Energy Storage (SMES)*
- *Fusion Energy*
- *Accelerators and Colliders*
- *Conductor Testing & Characterization*

**HELIUM USAGE**

Standard AMI vapor cooled current leads (VCCL) have been shown to evaporate approximately 2.8 x $10^{-3}$ liters/(hour • amp • pair) when operated at the rated design current. These leads are expected to provide this performance under normal operating conditions. However, a more conservative value of 3.2 x $10^{-3}$ liters/(hour • amp • pair) is recommended for system design calculations. Helium consumption at zero current is approximately 60% of rated current consumption.

Consumption rates assume the use of AMI superconducting bus bars and fixed current leads with soldered connections. These specifications do not apply for breakaway current leads which have a lower consumption rate in standby mode. The use of water-cooled power cables, resistive cold end bus bars, improperly sized bus bars, or high contact resistance joints may cause consumption rates to be higher than those stated above.



| Research groups | Number | Current capacity | Component materials | | Cooling conditions | | Applications |
|---|---|---|---|---|---|---|---|
| | | | *Warm part* | *Cold part* | *Warm part* | *Cold part* | |
| **CERN, Italy, Japan** | 64 | 13 kA | Copper | Bi-2223 tapes | 50 K GHe | 20 K GHe | LHC [22-26] |
| | 310 | 3.9 - 6 kA | Copper | Bi-2223 tapes | 50 K GHe | 20 K GHe | LHC [22-26] |
| | 750 | 600 A | Copper | Bi-2223 tapes | 50 K GHe | 20 K GHe | LHC [22-26] |
| | 504 | 120 A | Copper | | 50 K GHe | 20 K GHe | LHC [22-26] |
| | 1504 | 60 A | Copper | | 50 K GHe | 20 K GHe | LHC [22-26] |
| | 2 | 20 kA | Copper | | GHe (4.5 K - RT) | | LHC 27] |
| | 2 | 8 kA | Copper | Bi-2223 tapes | 50 K GHe | 4.4 K GHe | LHC [28] |
| **FZK, CRPP, Switzerland** | 2 | 10 / 14.5 kA | Copper | Bi-2223 tapes | 60 K GHe (70 K - RT) | 4.5 K GHe (4.5 - 70 K) | LHD [31,32] |
| | 1 | 20 kA | Copper | Bi-2223 tapes | 60 K GHe (70 K - RT) | 4.5 K GHe (4.5 - 70 K) | LHD [33] |
| | 40 | 60 kA | Copper | Bi-2223 tapes | 35 K GHe (50 K - RT) | 4.5 K GHe (4.5 - 50 K) | ITER [34] |
| | 2 | 70 kA | Copper | Bi-2223 tapes | 50 K GHe (65 K - RT) | 4.5 K GHe (4.5 - 65 K) | ITER [35,36] |
| | 2 | 80 kA | SF-Copper | | 4.5 K GHe | | ITER [42,43] |
| **Japan** | 2 | > 1 kA | Bi-2223 tubes | | Cryocooler (11 - 60 K) | | LTS magnet [44,45] |
| | 2 | 1 kA | Copper | Bi-2223 bars | GHe (4 - 5 K) | | LTS magnet [46] |
| | 1 | 2 kA | Copper | Bi-2223 tapes | $GN_2$ (77 K - RT) | Cryocooler | AC applications [47] |
| | 2 | 1 kA | Copper | Bi-2212 bulk | GHe (77 K - RT) | GHe (4.5 - 77 K) | SMES [48,49] |
| | 1 | 1 kA | Copper alloy | YBCO tapes | Cryocooler (77 K - RT) | Cryocooler (20 - 70 K) | HTS magnet [50] |
| | 1 | 1 kA | Copper | Bi-2222 bulks | GHe (56 K - RT) | GHe (4.2 - 56 K) | SFCL [51,52] |
| | 10 | > 2.5 kA | Copper | YBCO bulk | $LN_2$ (77 K) | | Experiment [53] |
| | 1 | 20 kA | Copper | YBCO bulk | LHe (4.4 - 1.8 K) | | LHD [54] |
| | 2 | 30 kA | Copper | | GHe (4.4 - 60 K) | | LHD [55] |
| | 2 | 100 kA | Copper | | GHe (4.4 - 60 K) | | LHD [56] |
| **USA** | 2 | 1.5 kA | Copper | YBCO rods | Cryocooler (60 K - RT) | Cryocooler (60 K) | SMES [57,58] |
| | 2 | 10 kA | Copper | Bi-2223 tapes | $GN_2$ (77 K - RT) | $LN_2$ (77 K - RT) | Hybrid magnet [59] |
| | 2 | 6 kA | Copper | Bi-2223 tapes | GHe (77 K - RT) | LHe (4.4 - 77 K) | LHe-cooled magnet [60] |
| | 2 | 100 kA | Copper rods | Copper rods | 4.4 K GHe | | HTS magnet [61] |
| | 1 | 600 A | Copper | Bi-2223 tapes | Cryocooler (52 K - RT) | Cryocooler (52 K) | FT-ICR [62] |
| **Korea** | 2 | 1.8 / 2.1 kA | Copper | Bi-2223 tapes | $GN_2$ (77 K - RT) | $LH_2$ (4.2 - 77 K) | SMES [63] |
| | 2 | 1 kA | brass | Bi-2223 tapes | Cryocooler (60 K - RT) | Cryocooler (4.2 - 60 K) | SMES [64] |
| | 2 | 667A | Brass | | $GN_2$ (77 - 298K) | | SFCL [65,66] |
| | 2 | 200 A | Brass | | GHe (4.2K - RT) | | KSTAR magnet [67] |
| **China** | 24 | 15 kA | Copper | Bi-2223 tapes | $GN_2$ (78 K - RT) | GHe (4 - 78 K) | EAST [68] |
| | 2 | 16 kA | Copper | Bi-2223 tapes | $GN_2$ (78 K - RT) | GHe (4 - 78 K) | EAST [69,70] |
| | 2 | 1.6 kA | Copper | | $GN_2$ (77 K - RT) | | SCQ [71] |
| | 4 | 630 A | Copper | | $GN_2$ (77 K - RT) | | SCQ [71] |
| | 1 | 150 A | Copper | | $GN_2$ (77 K - RT) | | SCQ [71] |
| | 5 | 75 A | Copper | | $GN_2$ (77 K - RT) | | SCQ [71] |
| | 2 | 4 kA | Copper | | $GN_2$ (77 K - RT) | | SSM [71] |
| | 2 | 350 A | Copper | Bi-2223 bars | $GN_2$ (77 K - RT) | | SMES [72] |
| | 2 | 400 A | Copper | Bi-2223 tapes | $LN_2$ (67 K - RT) | | Transformer [73] |
| **France** | 1 | 1 kA | Copper | YBCO tubes | GHe (77 K - RT) | GHe (4.2 - 77 K) | LHe application [74] |
| **Demark** | 1 | 2 kA | Copper | | $GN_2$ (77 K - RT) | | HTS cable [75] |
| **Italy** | 2 | 1.1 kA | Copper | Bi-2223 tapes | Cryocooler (65 K - RT) | GHe (4.2 - 65 K) | SMES [76] |
| **Switzerland** | 6 | 20.5 kA | Copper bars | | GHe (4.5 - 5 K) | | ATLAS magnet [77] |
| **UK** | 2 | 300 | Copper, brass | Bi-2223 tapes | Cryocooler (50 K - RT) | GHe (4.2 - 50 K) | LTS magnet [78] |
| **Finland** | 2 | 1 kA | Copper | Bi-2223 tapes | Cryocooler (77 K - RT) | GHe (20 - 77 K) | HTS magnet [79] |

Xiaoyuan Chen et. al.

Development and Techniques of High Current Leads for HTS Device Applications

Proceedings of 2009 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices Chengdu, China, September 25-27, 2009

# Magnet Test Stands Requirements – Power Leads

- Magnet test stands primary purpose is to validate magnet designs by testing R&D, Prototype and Production magnets.
- Test stands should be capable of simulating operational environments and requirements for multiple designs for similar, but different magnet types:
  - Dipole, Quadrupole, Multipoles.
  - Current and future accelerators (LHC, HL-LHC, FCC etc.).
  - Operational environment might be different (pressure, temperature range, magnetic field, voltage and electrical current rating, etc.).
- Power leads are part of the magnet test stand, so they need to follow the same approach with respect to operational environment and providing current to different magnet designs:
  - Current.
  - Voltage.
  - Pressure.
  - Cooling scheme - heat load at the cold end.
  - Protection.
- If we extend the application for cable/bus bar tests, then we might need extra magnet to generate the background magnetic field:
  - In this case a special targeted lead design can be used, since the requirements will be for one type of a magnet – of course most likely a superconducting one.

# Current Rating and Range

Test stands are designed to be able to test at least one magnet type, but in mind that the stand will be used for multiple purposes. Choosing the power leads for test stands are not obvious, since CLs are optimized for one operational current:

- Current rating can be up to 100 kA – Pipetron magnets
    - In general, low current considered up to 1-2 kA.
    - ”Regular” rating is up to 30 kA – low inductance, high current.
- Ramp rate up to 500 A/s – Eddy current issues are negligible, but still need to be designed to withstand high ramp rates.

# Voltage Rating

- HV test of the magnets also means that we are HV testing the leads:
  - Can be as high as 3 kV.
  - Leakage current threshold is as low as < 10 µA.
- Running the power leads at different current than the designed (optimum) current value leads overcooling the upper ends of the leads.
- Condensation at the insulating surface is probably the most problematic issue with the current leads.

# Pressure Rating

- It is usually not an issue, however, sometimes in special test cases, the power leads need to be robust:
  - Pressure rating can be up to 4-5 bars.
  - Insulation scheme must be appropriate with metal sealing surfaces.
  - If we include CIC magnet designs, then forced flow helium will be available and might be utilized in power lead design.
- Other extreme case is when the power leads need to operate in vacuum:
  - Conduction cooled leads – cryo-cooler can be used at the cold end.
  - Bi-functional HTS lead, upper section vapor cooled, lower HTS section is conduction cooled.
- Testing feed boxes – pressure rating is higher.
- Testing the power leads itself
  - Paschen test can be challenging – p*d has the minimum.

# Cooling Scheme - Heat Load at the Cold End

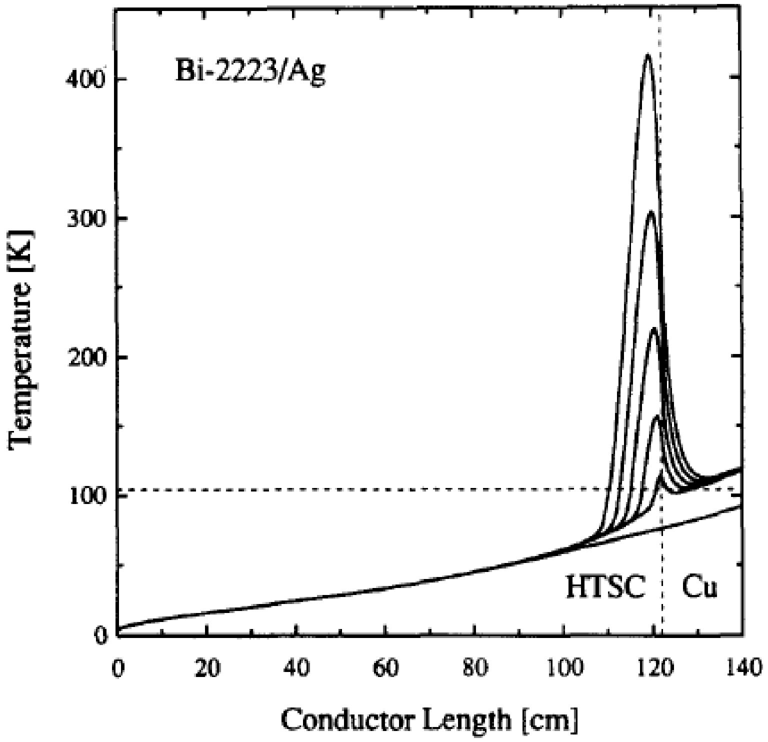
- Optimizing the cooling consumption of the leads are not the primary goal for test stands, since they are not operating all the time; saving money is not the driving force, but cooling capacity sometimes can be an issue
  - Heat load at the cold end to be minimized.
- Power leads utilize several different cooling solutions:
  - LHe vapor cooled leads – most common solution to minimize coolant consumption:
    - Lead stability can be obtained by overcooling the lead.
    - The excess boil off helium from other heat losses can be also used for cooling the current lead.
  - Conduction cooled leads – most useful for cryo-cooler solutions or small current applications:
    - Powering corrector magnets might be easier.
  - Bifunctional leads can use different cooling types – LHe vapor, $LN_2$ and $LN_2$ vapor.

# Regulation and Protection

- Vapor cooled leads cooling depends on the operating electrical current value, even if the leads are optimized to one current value:
  - Current dependent flow rate.
  - Usual solution is a standby current and operating current flow rate adjustment.
  - It is possible to use voltage drop as a feedback to regulate the flow rate.
- Optimized power leads are using optimized copper cross section and length:
  - Leads can be unstable if cooling is not sufficient – coolant loss case.
- Protection is based on voltage threshold:
  - Simple fixed threshold value – maximum allowable voltage drop value for the current lead.
  - Based on resistance change: voltage drop value is bucked against the current (traditionally used at FNAL).

# HTS Current Leads

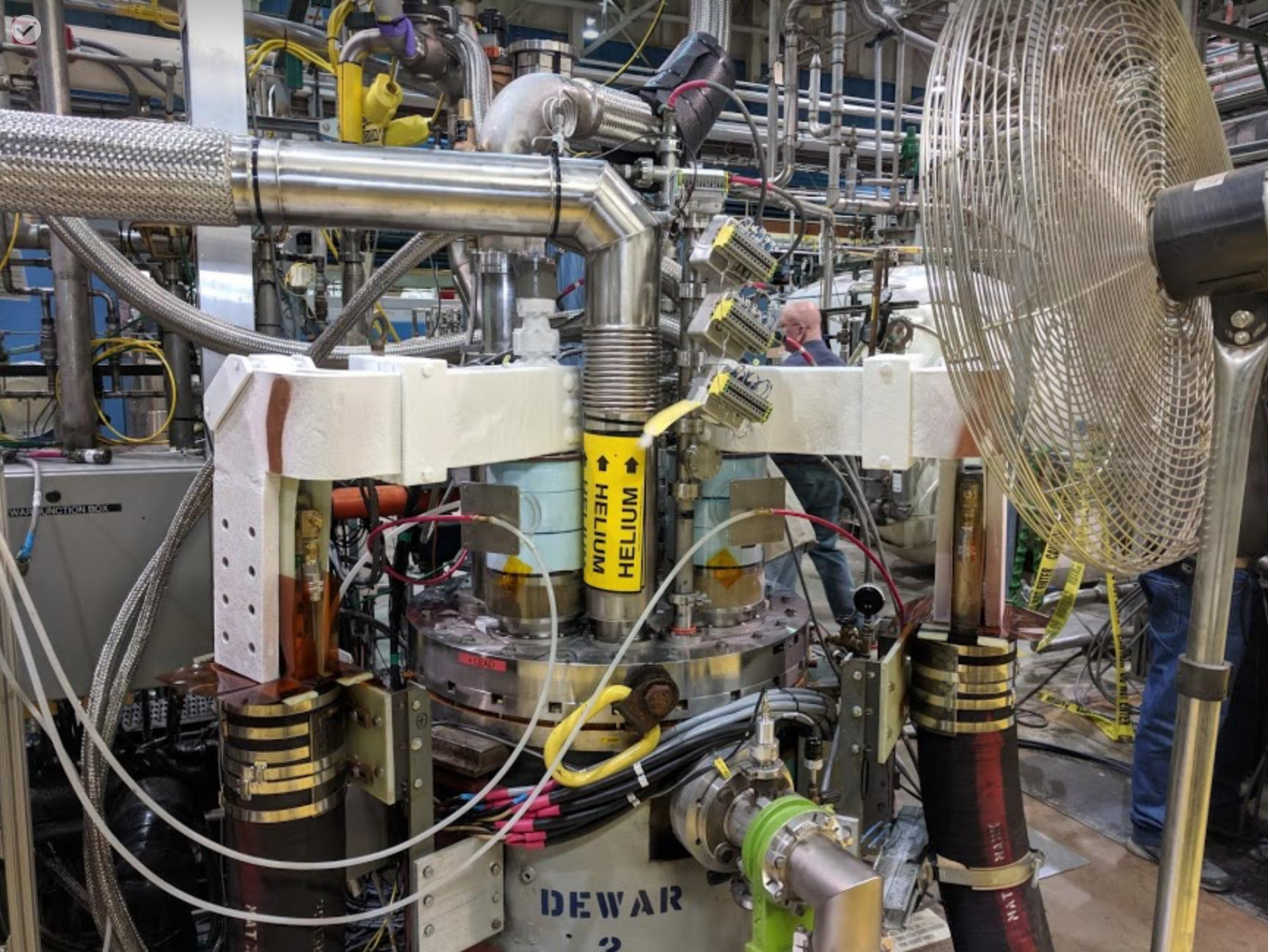
- In a case the cooling capacity is limited HTS leads are an excellent choice:
  - LHe vapor – re-utilized helium gas at higher temperature 20-50 K - CERN Leads by Amalia.
  - LN2 is used at 80 - 82 K – FNAL leads; LN2 is cheap.
- HTS needs special protection scheme:
  - 1 mV threshold value.



R. Wesche, Design of superconducting current leads, Cryogenics 1994 Vo 34,No2

# What Can Go Wrong?

- HV withstand test is compromised by power leads:
  - Overcooled uppers section – wet insulation, high leakage current.
  - Multiple solutions to prevent it:
    - Dry nitrogen cover.
    - Active temperature control.
    - Passive thermal insulation.
    - Special coating to prevent moisture to be absorbed into the current leads.
    - Special power lead design that is not sensitive to excessive cold gas trough the lead.
- Copper flag joint compromised and too much heat generated at the upper end.
- Lower joint is compromised and too much heat transferred to the liquid, or the cooling will not be sufficient, and it will warm up the LTS (HTS) and quench it.
- Improper protection and lead burn out:
  - HTS proper protection 1 mV threshold value.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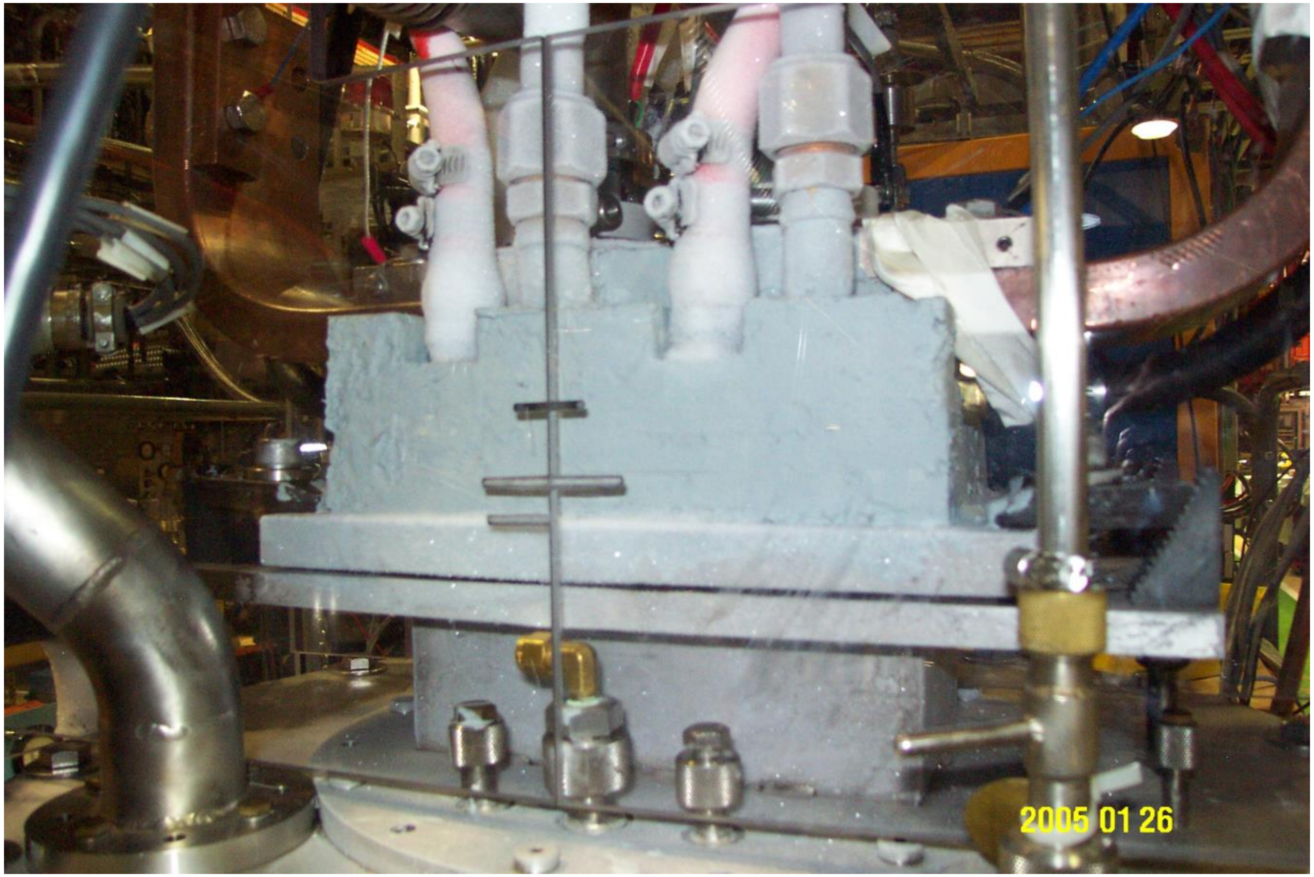
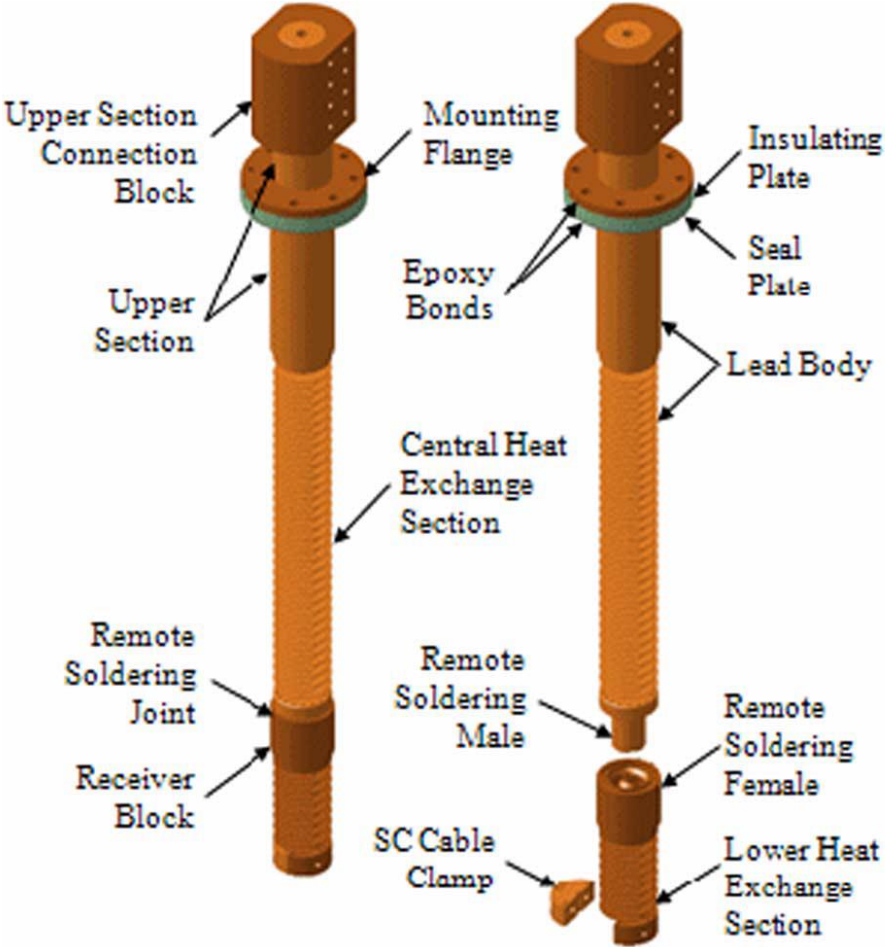
# Passive Cooling Solution

Fermilab Tevatron spool boxes were using ASC built bi-functional HTS leads. Special closed cell foam covered with silicon coating was utilized to prevent moisture on the insulation of the lead.



# Special Design of the Upper End of the Lead



Heat exchanger starts deeper inside the lead. This allows the upper end of the lead, even in case the cooling of the lead excessive at standby condition, to prevent frosting the insulating plate of the lead.

# Summary

- Power leads are test stand specific.
- Magnet or test subject specifications will influence choosing the lead design parameters.
- Vapor cooled leads are common, but conduction cooled leads are also used for test stands with low current < 2000 A.
- Bi-functional HTS leads are not common for test stands, but occasionally are used if cooling capacity is limited to save liquid or cryo-coolers are used.
- Optimizing CL designs for practical use is also important.
- CLs are commercially available.