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The 100 kA Current Leads for a Superconducting Transmission Line Magnet

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***Abstract*—A pair of current leads to power a transmission line magnet cooled at liquid helium temperature has been designed and developed at Fermilab. The leads designed to carry 100 kA dc current. Each lead consists of a warm end, heat exchange section and a cold end. The warm end is a half moon plate and cylinder brazed together. The heat exchange section is made of 202 copper rods arranged in a staggered pattern. Each rod is 6.35 mm in diameter and 1650 mm in length. The rods were soft-soldered into 12.7 mm deep holes at both warm and cold ends. The helium gas flow, guided by anodized aluminum baffles along the lead length, allows for a relatively high heat transfer coefficient between the current carrying rods and cooling helium gas. As a result the current leads were successfully tested with a ramping current of up to 104 kA. The current lead design, assembly work and the test results are presented.**

***Index Terms*—Transmission line magnet, current leads, power supply, and low field magnet.**

I. Introduction

THE current leads are used to carry the current from the power supply at room temperature to the superconducting test magnet at helium temperature. Commercially available current leads are usually arranged vertically and the nominal operating current is below 50 kA. The hybrid current leads cooled by forced flow supercritical helium developed at Karlsruhe, Germany was in the range of 20 to 80 kA [1]. For Fermilab's transmission line magnet test program, a pair of current leads carrying up to 100 kA to the transmission line magnet cooled in liquid helium at 4.4 K is needed. The transmission line superconductor consists of 9 NbTi cables and each cable has 18 wires. The details of the transmission line magnet testing system are given in [2]. The power supply providing a dc current up to 104 kA was developed for this program and the detailed information can be found in [3]. Contrary to the conventional current leads arrangement, our current leads were arranged horizontally for easier access to the power supply system. Each lead has three parts~~,~~: warm end, heat exchange section and cold end. The warm end has two parts~~,~~: a 76.2 mm thick half moon copper plate and a cylindrical copper block. The half moon plate is connected to the power supply by 10 buss bars, each with a cross-section of 25.4 mm by 101.6 mm. The lead heat exchanger section consists of 202 copper rods arranged in the staggered pattern by anodized aluminum baffles. The rods are 6.35 mm in diameter and 1650 mm in length. The total cross-sectional area of 202 rods is about 6400 mm^2. The copper rods were cooled by forced flow helium gas which was guided by the anodized aluminum baffles and G-10 baffle spacers to repeatedly flow across the rod stack, enhancing the heat transfer between the rods and the helium gas ~~to~~ and avoiding temperature stratification within the cooling helium gas. The resistance of the copper rods was measured at both room temperature and liquid helium temperature.

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II. The Current Leads Thermal Design

A. Energy Balance Equations

The transient energy equations of the current lead and the cooling helium gas are as follows:

$$\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}\right)+\frac{\rho I^2}{A}-hP\left(T-\theta\right)=\gamma CA\frac{\partial T}{\partial t} \quad (1)$$

$$hP\left(T-\theta\right)=\dot{m}\,C_p\frac{d\theta}{dx} \quad (2)$$

where k and ρ are the lead thermal conductivity and electrical resistivity, I is the operating current, A is the lead cross sectional area, T is the helium vapor temperature, h is the heat transfer coefficient between the rods and helium gas, P is the cooling perimeter, θ is the helium gas temperature, γ is the rod material density, C is the rod specific heat, t is the time, m is the helium mass flow rate, and C_p id the specific heat of helium gas.

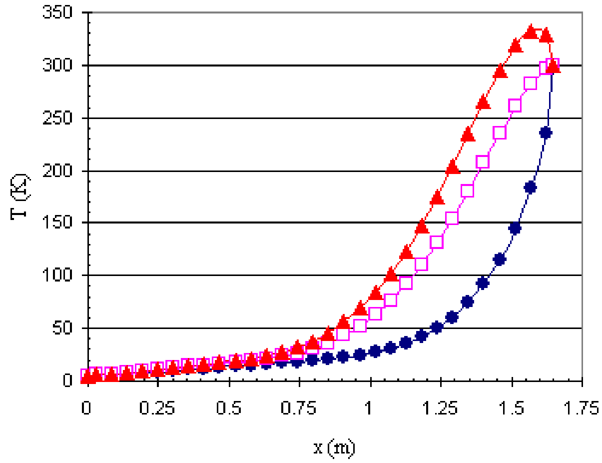

Fig. 1. Computer simulation calculated the lead temperature profiles at various operating current with heat transfer coefficient value of 200 W/ m^2K. Solid dot represents the temperature profile at zero current, open square is for operating current of 90 kA and temperature profiles are stable, the solid triangle is the temperature profile for operating current of 100 kA and lasted for only 15 minutes and the resulting helium mass flow is 5.6 g/s.

A 1-D computer simulation program has been developed at Fermilab to help the lead design work. The lead temperature profiles can be obtained for various parameters such as length, cross-sectional area etc. The lead cooling modes could be either self-cooling mode, in which the helium mass flow rate is generated by the heat load at the low temperature end or forced flow mode, in which the helium mass flow rate is constant no matter how much the heat load at cold end is and controlled by the pressure of supply dewar. The required inputs are lead length, cross-sectional area, warm end temperature, RRR value, lead cooling perimeter, and the heat transfer coefficient between leads and cooling helium gas. Fig. 1 shows the lead temperature profiles for operating currents of 100 kA, 90 kA, and zero in the self-cooling mode. It is worth noting that the optimum operating current of this lead is 90

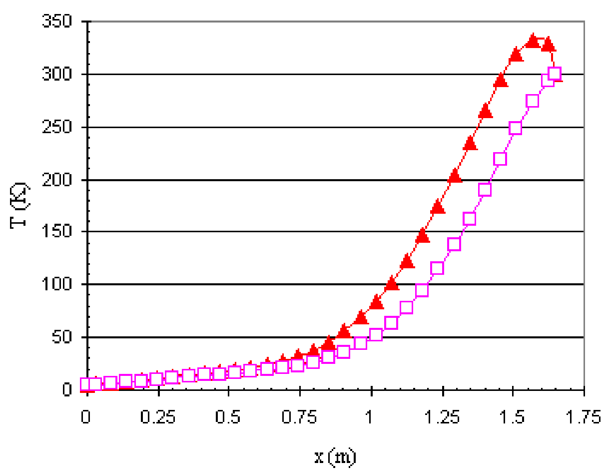

Fig. 2. Computer simulation calculated lead temperature profiles for the operating current of 100 kA and heat transfer coefficient of 200 W/ m^2K with different helium mass flow rate. The open square is for operating current of 100 kA with the helium mass flow rate at 6.1 g/s in forced flow cooling mode, the solid triangle is the temperature profile for lead operated at 100 kA for 15 minutes and helium mass flow is 5.643 g/s, self cooling mode.

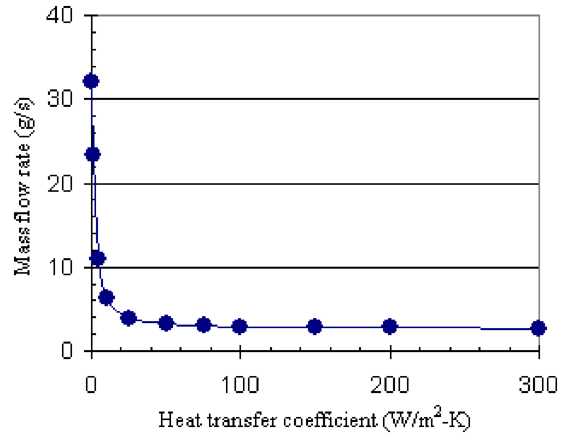

Fig. 3. The helium vapor mass flow rate in self-cooling mode as a function of heat transfer coefficient between lead and cooling helium gas. The lead length is 1.65 m and its cross sectional area is 6397 mm2. There is no current in this case.

kA. However, if additional helium gas flow is available, then the lead can be safely operated at 100 kA as shown in Fig. 2.

Fig. 3 shows the heat transfer coefficient effect on the heat load at the cold end causing the helium gas flow rate in self-cooling mode. If the heat transfer coefficient is below 100 W/m^2K the helium mass flow rate will increase dramatically. The lead length effect on the heat leak at the cold end with the same lead cross sectional area is shown in Fig. 4. It is obvious that the determination of the heat transfer coefficient value is the key for the success of the current leads design and safe operation. The detailed current lead parameters are decided based on the computer simulation results as shown in Figs 3 and 4 and are listed in TABLE I.

B. Heat Transfer Coefficient and Friction Factor

The lead heat exchange section is cooled by helium gas and the heat transfer coefficient between the copper rods and the cooling helium gas is calculated in the correlation [4].

$$St \cdot \Pr^{2/3} = C_h \cdot \mathrm{Re}^{-0.4} \tag{3}$$

where *St*, Pr, and Re are dimensionless parameters and called Stanton number, Prandtl number and Reynolds number respectively. The value C_h is determined based on the longitudinal-rod pitch ratio and transverse-rod pitch ratio of the staggered circular rods. In our case, the value C_h is 0.23. The heat transfer coefficient is then obtained from (3) as a function of helium gas temperature. The average calculated heat transfer coefficient along the lead length is 200 W/m^2K.

The friction factor of helium gas flow across the rods arranged in a staggered pattern was calculated in the following correlation [4]

$$f = C_f \cdot \mathrm{Re}^{-0.18} \tag{4}$$

The value C_f is determined to be 0.16 based on the longitudinal-rod pitch ratio and transverse-rod pitch ratio of

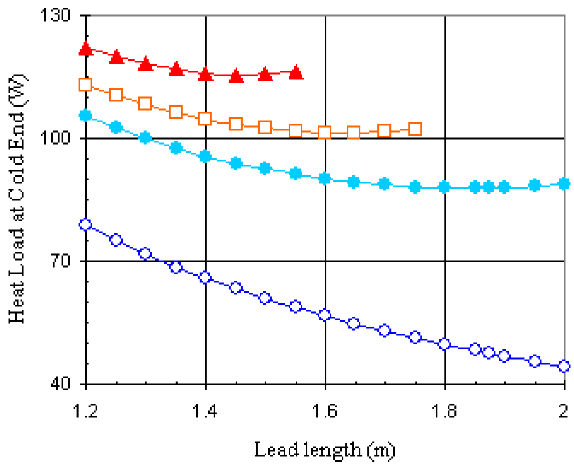

Fig. 4. Heat leak at lead cold end as a function of lead length at various operating current. Solid triangle represents 100 kA operating current, open square is for 90 kA, solid circle is for 80 kA and open circle represents the zero current case. The heat transfer coefficient between the lead rods and helium gas is 200 W/m^{2}K for all cases.

the staggered circular rods. The total pressure drop of helium gas flow across the heat exchange section of the current lead can be calculated as

$$\Delta P = fn\gamma_h \frac{u^2}{2} \qquad (5)$$

where n is the number of rod rows in the flow direction, γ_h is the helium gas density and u is the helium gas average velocity through area between rods, the f is the friction factor obtained from (4). The calculated total pressure drop in the lead heat exchange section alone is around 1000 Pa, a small and manageable value.

C. Lead Runaway Time

The current lead thermal runaway time can be calculated in the case when cooling helium flow is suddenly stopped. Assuming the adiabatic approximation and ignoring the conduction term so that both conduction and convection terms in (1) can be eliminated, then the expression is obtained,

$$t = \frac{\gamma A^2}{I^2} \int_{T_i}^{T_f} \frac{C_l dT}{\rho} \qquad (6)$$

where C_l is the current lead specific heat, A is the power lead cross sectional area, γ is lead density, and ρ is lead electrical resistivity. Inserting lead physical properties and operating current and integrating (6) from initial temperature T_i to final temperature T_f the time required to reach the final temperature can be estimated. For example, if the lead local initial temperature is at 280 K when cooling helium flow is stopped then the local lead temperature will reach 600 K in 175 seconds. The computer simulation model can also calculate the temperature profile at any moment when the lead is operated at a current level when cooling helium gas is suddenly stopped. Fig. 5 shows the lead temperature profile as time progresses. Since the computer model simulation does not include the conduction term, the time required to reach the same final temperature is longer than that calculated by (6).

III. Power Leads Assembly

The lead warm end consists of two parts: a half-moon shaped copper plate and a copper cylinder. The half-moon is brazed to the cylinder shaped block and the contact area is 203.2 mm by 226.8 mm. The half-moon is connected to the power supply by ten copper buss bars and each buss bar has a cross-sectional area of 25.4 mm by 101.6 mm. The buss bar itself is cooled with low conductivity water to remove the heat generated within the buss bar. The function of the cylindrical shaped copper is to carry the current to the 202 copper rods and electrically insulate-them from the vacuum vessel.

The power lead heat exchange section consists of 202 copper rods. The rods are arranged by the anodized aluminum baffle staggered pattern holes and aluminum baffle then slid into the slot on the G-10 baffle spacers after the leads were soldered at both warm and cold ends.

The rods are soldered to the warm end and the cold end in the oven simultaneously. The G-10 baffle spacers were then installed on both sides to form the helium cooing channel. Fig. 8 shows the final assembled power lead before being inserted into the stainless steel helium vessel.

IV. Experiment Setup And Test Results

The transmission line magnet testing system consists of 100 kA power supply, a pair of current leads, a 1.5 m long superconducting transmission line magnet, magnetic measurement system and vacuum system. The leads are connected to 9 superconducting NbTi cables at cold end and power supply at room temperature. One 500 l helium portable dewar is used to cool both current leads through a cold valve box and another 500 l dewar is used to cool the 15 m long superconducting transmission line magnet system. Thermometers are mounted at lead warm ends, cold ends and 1.3 m away from the lead cold end to monitor the lead performance. Voltage taps are also mounted to measure the voltage drop during the test. A simplified flow schematic can be found in [2].

The system total electrical resistance at room temperature was measured to be 1720 μΩ, in which each lead resistance is about 4 μΩ. Once the system is cooled to liquid helium temperature and stabilized, the total resistance of the system is measured. Each lead resistance is about 0.5 μΩ and the superconducting transmission line is in superconducting state.

The system was tested three times in 2004. Helium consumption for each lead was 3 g/s for the standby mode and 6.0 g/s for ramping current up to 104 kA until system was quenched. The current leads performed quite well and reached the design requirements.

V. Conclusions

The 100 kA current leads have been tested successfully to power the transmission line magnet system up to 104 kA and maintained a flat top for a while until superconductor quenched. The voltage tap signal on both leads showed that the lead resistance was stable when quench started.

References

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TABLE I
100 kA Lead Key Parameters

Parameters	Units	Descriptions
Designed operating current	[kA]	100
Lead material	[-]	Copper
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Lead length	[m]	1.65
Number of rods	[-]	202
Copper rod diameter	[mm]	6.35
Total cross sectional area	[mm^2]	6397
Maximum current density	[A/mm^2]	15.63
RRR	[-]	80
Helium mass flow rate	[g/s]	6.1 at 100 kA
Heat transfer coefficient	[W/m2K]	200
Calculated pressure drop	[Pa]	1000
Highest operation current	[kA]	104

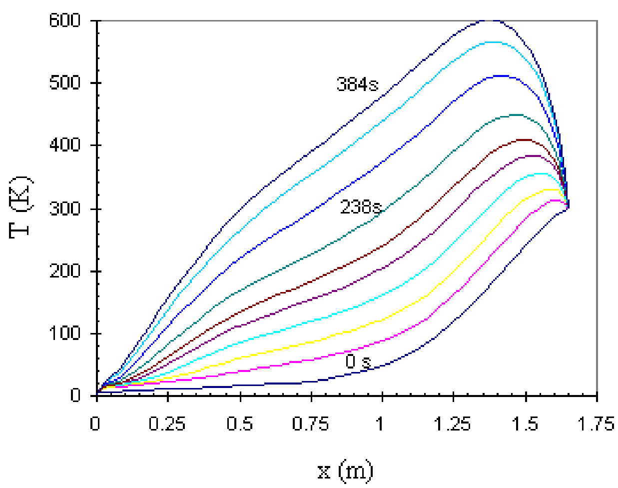

Fig. 5. Lead temperature profiles calculated by the computer simulation as a function of time when cooling gas is suddenly stopped.

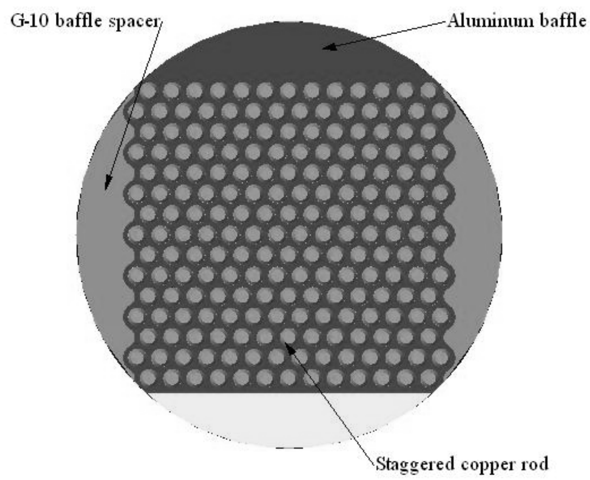

Fig. 6. Cross section view of current lead showing staggered arranged copper rods, aluminum baffles and G-10 baffle spacers. The cooling helium vapor was guided by the aluminum baffle and G-10 baffle spacer to flow cross the rods which enhance the heat transfer between the rods and helium vapor.

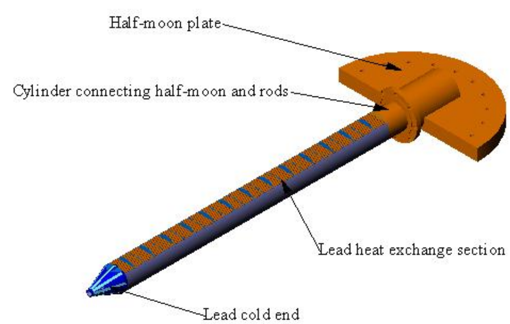

Fig. 7. Assembled power lead without G-10 insulation sheet wrapped before inserted into the helium vessel.