LBL-35890
UC-414

Presented at the Cryogenic Engineering Conference (CEC-ICMC 95)
Columbus, OH, July 17–21, 1995, and to be published in the Proceedings

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December 1994

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

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* This work was performed at the Lawrence Berkeley Laboratory and at Brookhaven National Laboratory with the support of the Director of the Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, United States Department of Energy under BNL contract number DE-AC02-76CH00016 and LBL contract number DE-AC03-76SF00098.

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ABSTRACT

This report presents a method for designing 5300 A gas cooled electrical leads for the g-2 solenoids and 2850 A leads for the g-2 self shielded inflector dipole magnet. Empirical design equations for annular tube gas cooled leads are presented. The leads are bundled tube leads which are cooled by helium flowing in annular cooling passages between tubes. Each tube in the bundle consists of nested circular copper tubes that can be cooled on both sides. Multiple current carrying tubes will increase the lead current capacity and cooling the tubes on both sides will increase lead efficiency for a given helium flow pressure drop. The design method presented here can applied to leads made from a variety of materials.

INTRODUCTION

The g-2 storage ring magnet system consists of four large superconducting solenoids that are up to 15.1 m in diameter[1]. The four solenoids will be hooked in series and they will be powered through a single pair of 5300 A gas cooled electrical leads. In addition there is an actively shielded inflector dipole that is separately powered through a pair of 2850 A gas cooled leads. Both sets of leads will be cooled using cold helium drawn directly from the forced two-phase helium cooling system used to cool the four solenoids and the inflector.

Tubular gas-cooled electrical leads have been used at various laboratories since the mid 1960s to power superconducting magnets. An insert was used to improve the heat transfer in tube leads in the late 1960s, allowing one to increase the lead current by as much as a factor of three. The use of annular flow leads was described in the literature by Smits in 1981[2]. The concept of bundling tube leads to increase their current was applied to curved gas cooled leads for the PEP-4 solenoid.

THEORY

Gas cooled leads can be described by a set of two coupled non-linear differential equations. These one-dimensional differential equations take the following form:

$$\frac{d}{dx}\left[k(T)\,A\,\frac{dT}{dx}\right] + \frac{\rho(T)\,I^2}{A} = h\,P\,(T - \theta) \qquad (1a)$$

$$\dot{M}\,c_p(\theta)\,\frac{d\theta}{dx} = h\,P\,(T - \theta) \qquad (1b)$$

where x is the distance along the lead length; T is the temperature of the lead metal; θ is the temperature of the gas stream in the lead; A is the lead cross-sectional area; I is the current carried by the lead; h is the heat transfer coefficient between the metal in the lead and the cooling fluid; P is the wetted perimeter per unit length of the lead; k(T) is the temperature dependent thermal conductivity of the metal in the lead; $\rho(T)$ is the temperature dependent electrical resistivity of the metal in the lead; and $c_p(\theta)$ is the temperature dependent specific heat at constant pressure for the gas flowing up the lead. Different boundary conditions can be applied to T, dT/dx, at the two ends at $x = 0$ and $x = L$.

The helium flow through optimum tubular gas cooled electrical leads is always laminar ($Re < 1500$)[3]. The Nusselt number for well developed laminar flow in tubes is around four[4]. (Some authors claim the Nusselt number is eight, but this comes from their definition of hydraulic diameter. Regardless of the definition that is used, the heat transfer coefficient is the same.) Since the Nusselt number is around four regardless of the tube geometry, a tube with an insert that has an annular flow passage has a higher heat transfer coefficient at the tube wall (by as much as a factor of 60) than does the same size round tube without the insert to form an annular flow passage.

When one tries to solve the lead equations, one finds that an optimum lead (with minimum heat leak to 4.5 K and a minimum gas flow needed to cool the lead) will have a particular value of the current density length function IL/A. Once one knows the IL/A function for the lead and one can estimate the heat transfer coefficient between the tube wall and the helium, one can calculate an approximate value for the average temperature difference between the lead wall and the helium in the flow passage T*.

The Optimum IL/A function for an Efficient Lead

The IL/A function for gas cooled leads comes directly from the lead equations[5]. For a gas cooled lead IL/A is a function of a number of factors that include material properties and the lead heat transfer efficiency[6]. For perfect leads, the optimum IL/A function G_0 can be estimated using the following approximate empirical expression:

$$G_0 = \frac{IL}{A} = 286\,[\rho_{4.2}]^{-0.5} \qquad (2)$$

where $\rho_{4.2}$ is the resistivity of the lead material at 4.2 K. Equation 2 can be applied to a wide variety of materials from OFHC copper to 304 Stainless Steel. Contrary to popular opinion, leads do not have to be made from good copper. A range of materials can be used for gas cooled leads as long the IL/A function is correctly selected and the product of the heat transfer coefficient times the heat transfer area is large enough to insure good heat transfer and a small temperature difference between the current carrying wall and the helium flowing through the lead. The advantages of using high low-temperature resistivity materials, such as phosphorous deoxidized copper[7] or 6061 aluminum[8], are 1) mistakes in selecting IL/A are not costly in terms of lead overall performance (unlike OFHC copper) and 2) the leads can be designed to operate at their root mean squared current rather than at their peak current. Table 1 presents the optimum IL/A for different materials.

Table 1 Low Temperature Resistivity and the Optimum Lead IL/A Function for Various Materials

Material	4.2 K resistivity (ohm m)	IL/A Value (A per m)
OFHC Copper (RRR = 180)	8.7×10^{-11}	2.7×10^{7}
Copper (RRR = 30)	5.3×10^{-10}	1.1×10^{7}
1100-O Aluminum (RRR = 25)	1.0×10^{-9}	9.0×10^{6}
Type M Copper Pipe (RRR = 6.5)	3.1×10^{-9}	5.6×10^{6}
Phos. Deox. Copper (RRR = 3)	6.7×10^{-9}	3.5×10^{6}
6061-T6 Aluminum (RRR = 2)	1.4×10^{-8}	2.4×10^{6}
70 Cu 30 Zn Brass (RRR = 2)	2.8×10^{-8}	1.7×10^{6}
5456 Aluminum (RRR = 1.4)	3.3×10^{-8}	1.6×10^{6}
304 Stainless Steel (RRR 1.1)	3.7×10^{-7}	4.7×10^{5}

The Average Temperature Difference between the Tube Wall and the Gas

The average temperature difference between the tube wall and the helium gas in a lead T* (for a lead without superconductor) for an annular tube lead can be estimated using the following expression:

$$T^* = \frac{J_o^2 A E}{G_o} \frac{t}{2\pi N_s . N_t D_A k(T)} \qquad (3)$$

where J_o is the current density in the tube; G_o is the design IL/A for the lead; A is the cross-section area of the current carrying material in the lead; t is average thickness of the annuli between the tubes in the lead; k(T) is the average thermal conductivity of the helium in the tube (T=120 K for low RRR copper leads; for high RRR copper leads T<70 K); N_t is the number of current carrying tubes in the lead N_s is ratio the number of tube surfaces cooled by the gas to the number of tubes (N_s is between 1 and 2); and D_A is the average diameter of the tubes in the lead. E is the optimum voltage drop along the lead when it carries its design current. (Use 80 mV as design value for E[7].) The value of T* calculated by Equation 3 is approximate and should be regarded as a performance function for comparison purposes. A good rule of thumb is that the value of T* should be less than 5 K for a well designed annular tube leads. Lower values of T* are better.

Design Current Density for the Lead

From the IL/A constant, one finds that the length of an optimum gas cooled lead is proportional to its current carrying cross-section. The current carrying cross-sectional area is some function of the desired time for the lead to operate safely without gas flow. The most conservative approach is to assume the lead is adiabatic at its upper end. Using this approach and assuming a temperature change of 200 K at the upper end of the leads, the design current density for copper leads can be estimated using the following expression;

$$J_o = 1.78 \times 10^8 [t_o]^{-0.5} \qquad (4a)$$

where t_o is the design time for the leads to operate without gas flow. The expression in Equation 4a is suitable for times t_o less than 100 seconds. Using this experimental data for phosphorus deoxidized copper leads with the upper end held at 300 K, the design current density for copper leads can be estimated using the following expression when t_o is greater than 100 seconds[2,3];

$$J_o = 4.48 \times 10^7 [t_o]^{-0.2} \qquad (4b)$$

When leads are made of 1100 or 6061 aluminum, the values of J_o calculated using Equations 4a and 4b should be multiplied by 0.62. For 5465 aluminum multiply the copper J_o by a factor of 0.54; for leads made from brass multiply the copper J_o by a factor of 0.63; and for 304 Stainless steel leads multiply the copper J_o by a factor of 0.22.

The current density calculated using Equations 4a or 4b is the maximum allowable value of J_o. A second criterion is the allowable value of T* calculated using Equation 3. If having a value of T* less than a certain value (say < 5 K) is a design criteria, one should insert the value of J_o calculated using Equations 4a or 4b into Equation 3. If necessary, J_o can be adjusted downward so that the desired value of T* is reached.

Helium Mass Flow through the Gas Cooled Leads

One can estimate the design helium flow through the leads by using the assumption that a well designed lead, operating at its design current, will have no heat flow into or out of the room temperature ends of the leads. An estimate of the design mass flow M (in kilograms per second) through a lead can be estimated using following expression:

$$M = 6.5\times10^{-7} E\, i_o \qquad (5)$$

where i_o is the design current for the lead, and E is the optimum lead voltage drop. (Wilson suggests $E = 80$ mV[7].) When one applies the value of M from Equation 5 into the equation for the Reynolds number, one finds that the flow Reynolds number is always below 1500[3]. Leads that operate off their design current (in either direction) will require more gas flow per unit current than is suggested by Equation 5.

SELECTION CRITERIA FOR THE g-2 LEADS

Tube Material Selection

Standard phosphorous deoxidized copper pipe was selected as the current carrying material for the g-2 magnet gas cooled leads. The reasons for selecting standard copper pipe are as follows: 1) Copper pipe is generally available in the marketplace in a series of sizes that are compatible with nested tube lead construction. 2) The copper pipe has a low residual resistance ratio (the measured RRR for samples of the pipe to be used in the g-2 leads is about 6.5), which means that the design IL/A is a factor of five lower than for good copper. (The IL/A of the selected pipe material is about 5.6×10^6 A m^{-1}.) For a given lead current density, the leads will be more compact. Short leads are an advantage provided the heat transfer coefficient to the helium is high enough so that T* is small. 3) Leads made from low RRR material can be designed based on the root mean square current rather than the maximum current because they are stable when operated at currents well above the design current of the lead. If one has a stable lead, one can operate that lead safely above its design current by increasing the helium mass flow per unit current above the minimum design value. Leads made with phosphorous deoxidized copper will operate safely at a current 2.5 times the design current for the lead. (The gas flow per unit current is increased about forty percent.) 4) The gas usage at zero current is less for a phosphorous deoxidized copper lead than it is for a good (high RRR) copper lead.

Number of Tube Bundles and the Number of Nested Tubes per Outer Tube

The number of tube bundles was set at five for each 5300 A g-2 solenoid gas cooled lead. A design current of 1060 A per tube in the bundle was used to determine the design of the nested tube set. For each 2850 A g-2 inflector lead, the number of tube bundles can be set as low as two. Since the inflector has a low stored energy (about 9 kJ), the inflector lead current density can be set above 10 A per square millimeter. The design current per tube in the bundle is 1425 A when two tube bundles are used. Table 1 shows the parameters for single standard Type L and Type M copper tubes that can be used to fabricate leads[3,9].

Table 2 Lead Parameters for Copper Tube Annular Leads (Inside Cooling Only)
($IL/A = 5.6\text{x}10^6$ A m^{-1}, $k(T) = 0.086$ W m^{-1} K^{-1} at 120K, $J_o = 10^7$ A m^{-2}, $N_s = 1$, $N_t = 1$)

Copper Tube Type	OD (mm)	Wall thick (mm)	D_A (mm)	t (mm)	i_o (A)	T* (K)
0.375 inch Type L	12.70	0.89	10.92	0.70	330	5.6
0.500 inch Type L	15.88	1.02	13.84	0.57	476	5.2
0.625 inch Type L	19.05	1.07	16.91	0.52	604	4.9
0.750 inch Type L	22.23	1.14	19.95	0.44	755	4.4
0.500 inch Type M	15.88	0.71	14.46	0.88	339	5.5
0.625 inch Type M	19.05	0.76	17.53	0.83	438	5.5
0.750 inch Type M	22.23	0.81	20.61	0.77	545	5.4
1.000 inch Type M	28.58	0.89	26.80	0.70	774	5.3
1.250 inch Type M	34.93	1.07	32.79	0.52	1138	4.8

Three nested tube lead options are apparent from Table 2: 1) A single 1.25 inch Type M tube with a stainless steel insert ($N_s = 1.00$ while $N_t = 1$) can be used for each tube in the bundle. For the g- 2 solenoid leads, L = 0.60 m; $J_o = 9.31$ A per square mm; and T* = 4.1 K. 2) A single 0.625 inch Type L tube inside of a single 0.75 inch Type L tube can be used for each tube in the bundle. The inner tube can have a stainless steel insert such that $N_s = 1.5$ while $N_t = 2$. For the g- 2 solenoid leads, L = 0.72 m; $J_o = 7.80$ A per square mm; and T* = 1.9 K. 3) Three nested Type M tubes with a 0.5 inch tube inside of a 0.625 inch tube, which is in turn inside of a 0.75 inch tube. A stainless steel insert can be installed inside the inner tube so that $N_s = 1.67$ while $N_t = 3$. For the g-2 solenoid leads, L = 0.70 m; $J_o = 8.02$ A per square mm and T* = 2.1 K.

Option 1 was eliminated on the basis of physical size (each lead would be 105 mm wide and 68 mm thick not including electrical insulation) and lower heat transfer efficiency. Options 2 and 3 are smaller (67 mm wide by 43 mm thick not including electrical insulation.) and they are more efficient. Option 3 was selected because there is enough space between the tubes to attach superconductor to all three of the current carrying tubes. Using option 3 on two tube bundle inflector magnet leads, L = 0.52 m; $J_o = 10.8$ A per square mm; and T* = 3.8 K.

CONCLUSION

Short gas cooled electrical leads for the g-2 solenoids and the inflector can be built using bundled tube leads where each of the tubes in the bundle consists of nested standard Type L or Type M copper tubes. Nested leads allow more current to be carried in a smaller physical space. Cooling of both sides of the copper tube increases the average efficiency of the gas cooled electrical leads. Both of the 5300 A solenoid leads will fit in a cylinder that is 110 mm in diameter by 750 mm long (see the cross-section of the solenoid leads in Figure 1). Both of the two tube bundle 2850 A inflector leads will fit within a cylinder that is 75 mm in diameter by 550 mm long. Superconductor will be attached to the tubes of both the solenoid and inflector leads in order to reduce the heat leak into the 4.5 K two-phase helium cooling circuit. The superconductor will reduce the amount helium needed to cool the leads by a few percent. It is estimated that 0.55 grams per second of helium is needed to cool the pair of 5300 A leads for the g-2 solenoid. The 2850 A inflector leads will require about 0.30 grams per seconds of helium to cool them.

ACKNOWLEDGMENTS

This work was performed at the Lawrence Berkeley Laboratory and at Brookhaven National Laboratory with the support of the Director of the Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, United States Department of Energy under BNL contract number DE-AC02-76CH00016 and LBL contract number DE-AC03-76SF00098.

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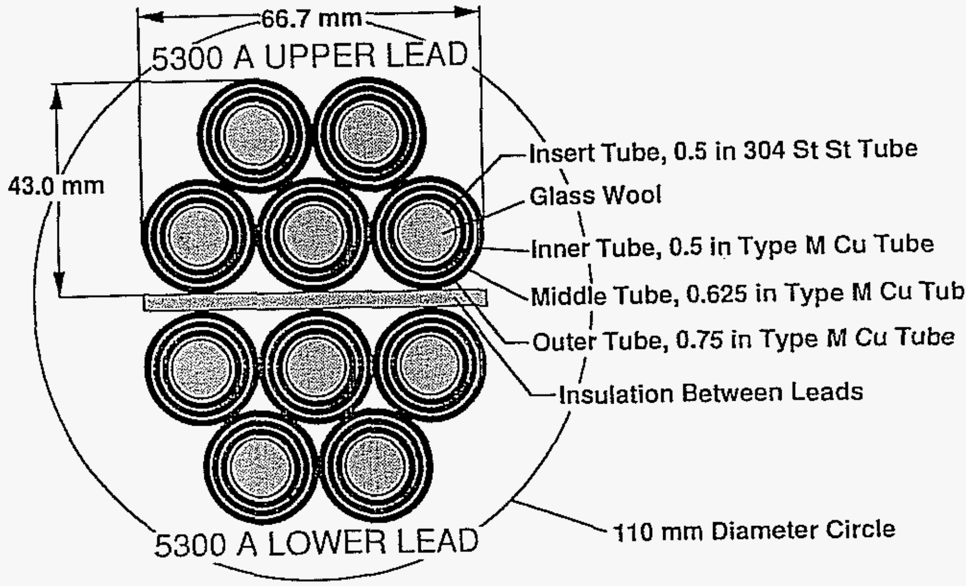

Figure 1 A Cross-section of the 5300 Ampere Gass Cooled Leads for the g-2 Solenoids