TESTS OF COPPER AND HTS CURRENT LEADS WITH A TWO-STAGE PULSE TUBE DROP-IN COOLER

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ABSTRACT

LBNL has observed that the heat leak is often excessive in magnets cooled using small coolers. One of the sources of excessive heat has been the leads that carry current into the magnet. By running a cooler test that combines the copper and HTS leads with a cooler, we are able to better understand the copper lead performance and its effect on the cooler performance. When a single PT-415 cooler was tested with a pair of the leads that was actually used in an LBNL magnet, the heat flow at design current was much larger than expected. The heat leak with no current in the leads was less than expected. The IL/A of the copper leads used in the magnet was too high. Leads with a much lower IL/A were tested with improved results. The cooler and lead tests also showed the importance of reducing the total temperature drop between the top of the HTS leads and the cooler first stage. The test also measured the voltage drop across the copper leads, the HTS leads and the LTS lead splices used in the test. As a result, the design of leads future magnets that are cooled using small coolers is improved.

KEYWORDS: Pulse Tube Coolers, HTS Leads, and Cu Leads from Room Temperature

INTRODUCTION

With the advent of reliable two-stage coolers, it is possible to keep superconducting magnets cold using small coolers. While most of these magnets operate in the persistent mode with leads that are retracted, there are magnets that have the leads continuously connected to a power supply. These magnets have leads that are conductively cooled by the first-stages of one or more small coolers.

LBNL has been building superconducting magnets that are continuously powered since the late 1990's [1] to [3]. The first magnets were superconducting dipole magnets used on ALS light source. These magnets are cooled using a single 1.5 W (at 4.2 K) two-stage cooler that keeps the magnet at temperatures from 4.2 to 4.6 K. The first-stage and provides cooling for the shield and intercepted the heat coming down a pair of 300 A copper leads. The actual heat load into these magnets was higher than the design value.

LBNL built its first superconducting magnet system with multiple two-stage coolers in 2003 [4]. This magnet had a couple of coils that require two pairs of 300 A leads to power them. Since the leads require a significant portion of the available refrigeration from the cooler first-stages, the magnet was initially cooled using a pair of 1.5 W two-stage GM coolers. The magnets for the Muon Ionization Cooling Experiment (MICE) [5] are cooled with 1.5 W (at 4.2 K) two-stage coolers [6]. Because most of the MICE magnets produce magnetic fields above 0.05 T at the coolers, the decision was made to use more than one 1.5 W (at 4.2 K) two-stage pulse tube coolers on each of the MICE magnet modules [7].

Theoretically, the copper current leads generate more than half of the heat that is taken up by the first-stages of the coolers used to cool a magnet that is powered. Optimizing the copper current leads from room temperature is necessary, so that the heat flow to the first stages of the coolers is minimized.

OPTIMIZATION OF THE LEADS FROM ROOM TEMPERATURE

A conduction-cooled lead or a gas cooled lead is optimized so that the net heat flow at the top of the lead (at say 293 K) is zero. At optimum current, all of the heat leaving the lead at the bottom is from resistive heating. The heat leak down a lead to the cooler first-stage (without gas cooling) can be calculated using the following expression [8], [9];

$$Q_l = [L_o(T_R^2 - T_1^2)]^{0.5} I_0 \tag{1}$$

where Q_I is the heat leak down an optimum lead carrying a current I_o with an upper end temperature T_R (T_R is room temperature.) and a lower end temperature T_1 (T_1 is the cooler first-stage temperature. L_o is the Lorenz number; (Nominally $L_o = 2.45 \times 10^{-8}$ W Ω K^{-2}.) When $T_R = 293$ K and $T_1 = 60$ K, $Q/I_o = 0.045$ W A^{-1} per lead. Since all of the heating in an optimum lead is due to I^2R heating, the voltage drop for an optimum $V_{opt} = Q_1/I_o$. One can measure the voltage across a lead to determine whether the IL/A of the lead is near the optimum value.

The other lead design issue is the IL/A function that relates the lead design current I_o to the lead length L_L and cross-section area A_c. One can estimate the IL/A for a current lead with a design current I_o (whether it is gas-cooled or not) by using the following approximate expression [16];

$$\left[\frac{I_0 L_L}{A_c}\right]_{opt} = \frac{1}{\sqrt{L_O}} \int_{T_1}^{T_R} \frac{k(T)dT}{\sqrt{(T_R^2 - T^2)}} \tag{2}$$

where L_L is the lead length; A_c is the lead cross-section area; and k(T) is the thermal conductivity as a function of temperature. The solution for IL/A given by equation (2) requires numerical integration. It is clear that leads made from high RRR material (pure metals) will have a higher thermal conductivity, and as a result, the leads will be longer. Equation (2) applies for leads made from other metals as well. A lead can be divided into sub-sections. The lead IL/A is the sum of the IL/A's of the sub-sections. The L/A of each subsection is a physical parameter. For the lead to be optimum, the sum of the sub-section IL/A's must be equal to the value of the optimum IL/A given by equation (2).

When the lead current is less than the optimum current, there is heat flow into the lead at the room temperature end of the lead. The heat conducted into the cooler first-stage is a combination of the heat flow into the lead plus the I^2R heating. A lead that is operating at a current less than its optimum current will have a voltage drop that is too low, because the lead is colder than an optimum lead. When the lead current is greater than the optimum design current for the lead, the room temperature end of the lead will become warmer than room temperature. Part of the I^2R heating will be rejected at room temperature. The rest of I^2R heating goes into the cooler first stage. A lead that is operating at a current above its optimum current will have a voltage drop that is too high. A lead made from a high RRR material may runaway when it operates substantially above its design current [8].

The leads for the SuperBend magnets [3], the Venus ion source magnet [4], and the MICE spectrometer solenoids [10] were all built using same conduction cooled copper leads. These leads have a calculated IL/A of 5.2x 10^6 A m^{-1} at 275 A [11]. The engineers at the Harbin Institute of Technology calculated IL/A of the MICE coupling magnet leads using Equation 2. The IL/A value for RRR = 10 leads was 3.1x10^6 A m^{-1} at 210 A [12]. What is the correct value of IL/A? Given the cooling difficulties on all of the LBNL cooler cooled magnets, we decided that we had to measure the lead performance directly with the leads connected to a cooler. We measured the heat going into the cooler first-stage from the leads with no current and with 275 A in the leads, we measured the voltage drop in the leads, and we calculated the I^2R heating in the leads. This was done for the standard LBNL leads used since 1999 and a pair of leads with an IL/A close to the Chinese design.

THE APPARATUS FOR MEASURING THE COPPER LEAD PERFORMANCE

FIGURE 1 shows the physical apparatus for measuring the copper lead performance with a Cryomech PT415 two-stage drop-in cooler [13]. The heat from the copper leads is taken up by the first-stage of the cooler. Heating due to the resistive heating within the HTS leads, the LTS leads and the splices between superconductors is taken to the helium tank where liquid helium is vaporized to be re-condensed by the second-stage of the cooler.

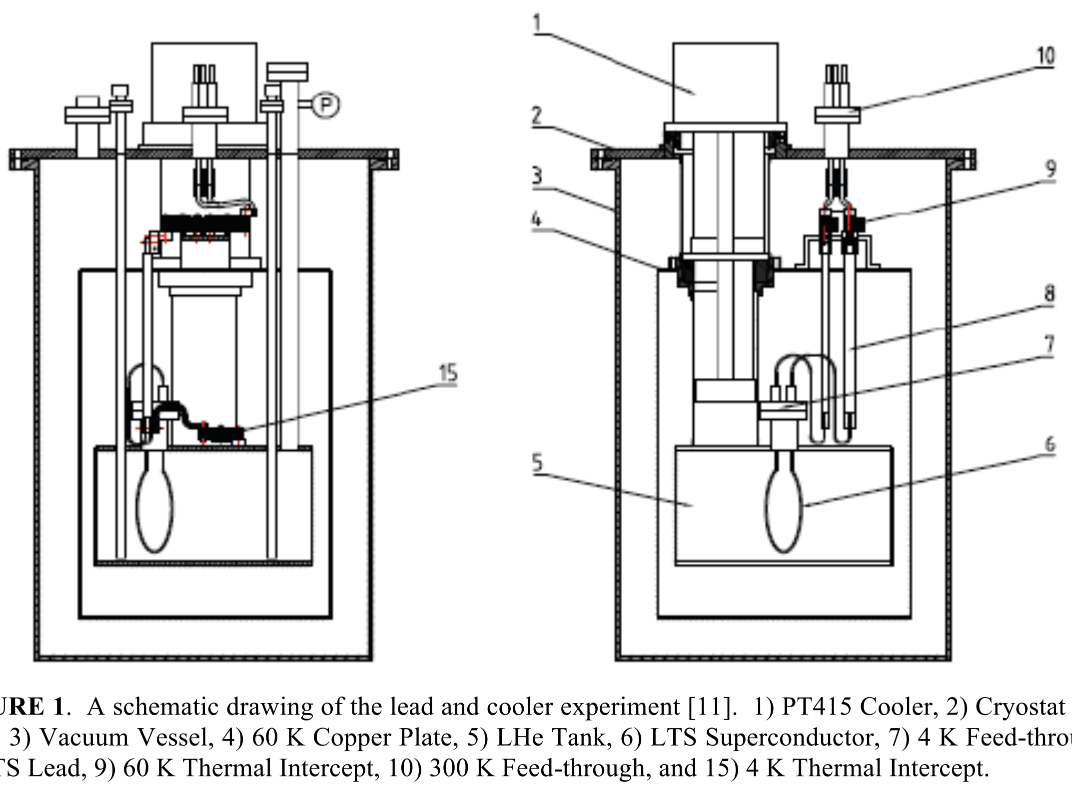

FIGURE 1. A schematic drawing of the lead and cooler experiment [11]. 1) PT415 Cooler, 2) Cryostat Top Plate, 3) Vacuum Vessel, 4) 60 K Copper Plate, 5) LHe Tank, 6) LTS Superconductor, 7) 4 K Feed-through, 8) HTS Lead, 9) 60 K Thermal Intercept, 10) 300 K Feed-through, and 15) 4 K Thermal Intercept.

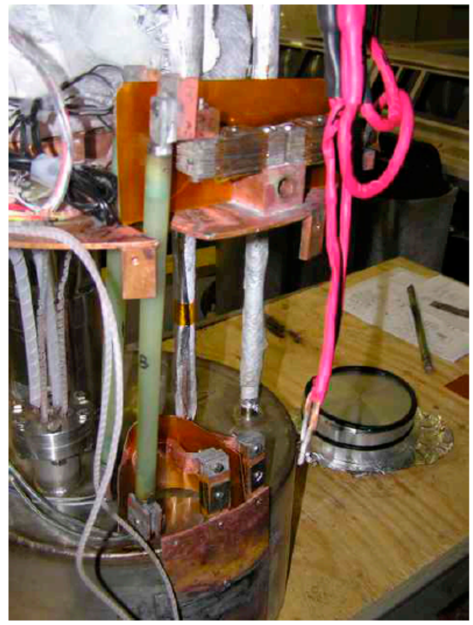

FIGURE 2. Two photos views of the lead-cooler experiment between the 60 K copper plate and the liquid helium tank. In the photo to the left, one can see the tube that contains the lower part of the PT415 cooler. The HTS leads are to the right in the photo on the left side of the figure. The thermal intercepts at 60 K (attached to the copper plate) and 4 K (attached to the helium tank) are shown in the right hand photo.

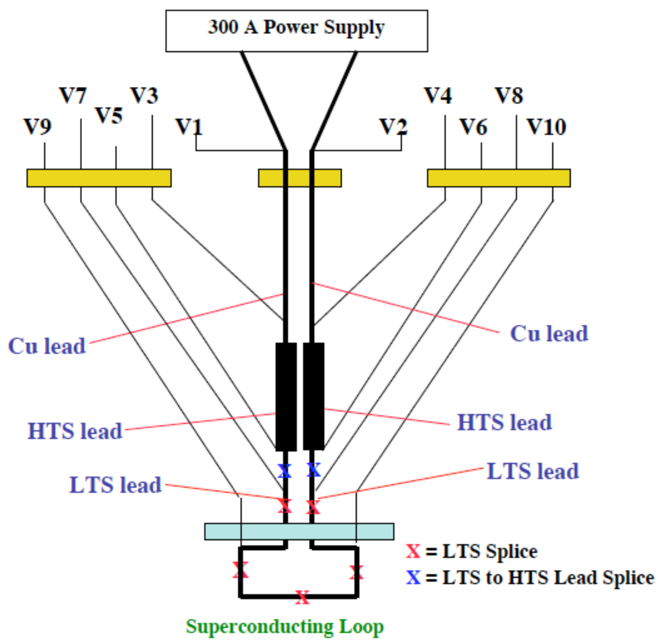

FIGURE 3. An electrical Schematic of the current carrying circuit (copper leads, HTS leads and, the LTS leads) and the voltage tap that are used to measure the voltage drops in the lead-cooler experiment [11].

FIGURE 2 shows photos of the lead-cooler experiment between the 60 K copper plate and the 4 K liquid helium tank. FIGURE 3 shows an electrical schematic of the lead cooler experiment. Current flows from the power supply through the copper leads, the HTS leads and the LTS superconducting loop. The voltage taps permit one to measure the voltage drops across the leads and the splices between the superconductors.

The temperature sensors mounted on the experiment include the following: T5 is a sensor mounted directly on the cooler first-stage. T2 is a sensor mounted directly on the cooler second-stage. T1 is a sensor located on the helium tank. T7 is a sensor located near the drop-in cooler joint. T6 is a sensor located on the copper plate near the leads. T8 and T9 sensors are located on the tops of the HTS leads. Sensors T1 and T2 are silicon diodes. Sensors T5 through T9 are platinum resistor sensors that are well calibrated. Sensors T1 and T2 (Si diodes) were calibrated using the vapor pressure of the helium in the tank.

FIGURE 4 shows the thermal network for the lead cooler experiment and the location of the temperature sensors. In addition to the sensors there are a heaters located on the copper plate connected to the cooler first-stage (near T7) and the bottom of helium tank. A thermal siphon transfers heat Q2 from the helium in the tank to the 2nd-stage cold head. Q1 is transferred to the cooler 1st-stage through the drop-in cooler joint.

FIGURE 5 shows a set of copper leads used in one of the LBNL magnets. The lead assembly consists of the copper lugs in the feed through, and the copper cable (either #2 or #4 insulated copper cable depending on the lead IL/A) connecting the feed-through to the connector at the top of the HTS lead.

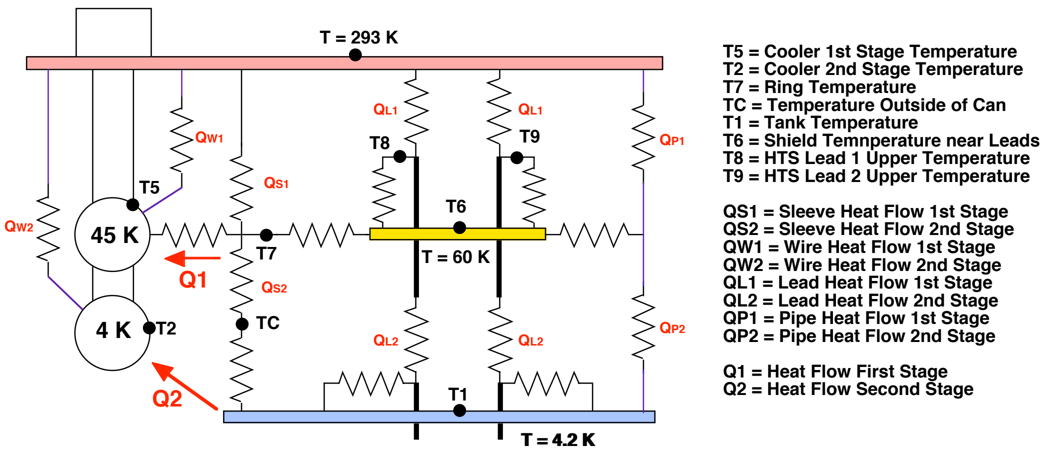

FIGURE 4. The thermal network diagram for the lead and cooler experiment shown in FIGURES 1 and 2.

FIGURE 5 The lead assembly that is typically used for an LBNL superconducting magnet that is cooled using small coolers. The flexible leads are commercial insulated copper cables that connect the feed-through to the connector that connects to the HTS lead. Most of the lead IL/A is in the copper cable.

Two different copper lead assemblies were tested using the feed though assembly shown in FIGURE 5. Lead assembly 1a was used on several LBNL Magnets. The upper section of lead 1a had an IL/A of 1.43x10^{6} A m^{-1} at 275 A. The cable section of lead 1a, made from number 2 cable, has an IL/A of 3.77x10^{6} A m^{-1} at 275 A. The total IL/A for lead 1a is 5.20x10^{6} A m^{-1}. The second lead assembly tested (1b) has an upper section IL/A of 1.29x10^{6} A m^{-1} at 275 A. The flexible section of lead 1b, made from number 4 cable, has an IL/A of 2.00x10^{6} A m^{-1} at 275 A. The total IL/A for lead 1b is 3.29x10^{6} A m^{-1}.

THE RESULTS OF TESTING OF TWO DIFFERENT COPPER LEAD DESIGNS

FIGURE 6 is the operating diagram for a Cryomech PT415 cooler over a range of first and second stage temperatures [14]. Lines of equal first-and second-stage refrigeration (Q1 and Q2) are plotted on a diagram that has the first-stage temperature T1 on the horizontal axis and the second-stage temperature T2 on the vertical axis. This diagram shows the relationship between the first and second-stages of refrigeration. From this diagram, one sees that one needs ~40 W of Q1 in order to get the lowest value of T2 when Q2 = 1.5 W. The operating points for leads 1a and 1b are plotted on FIGURE 6 [11]. The operating points plotted for lead 1a are I = 0, I = 275 A, and I = 275 A plus Q_A = 20 W of added heat load to the copper plate. The operating points plotted for the 1b leads at I = 0, I = 275 A, and I = 275 A plus a Q_A = 30 W added heat load to the copper plate.

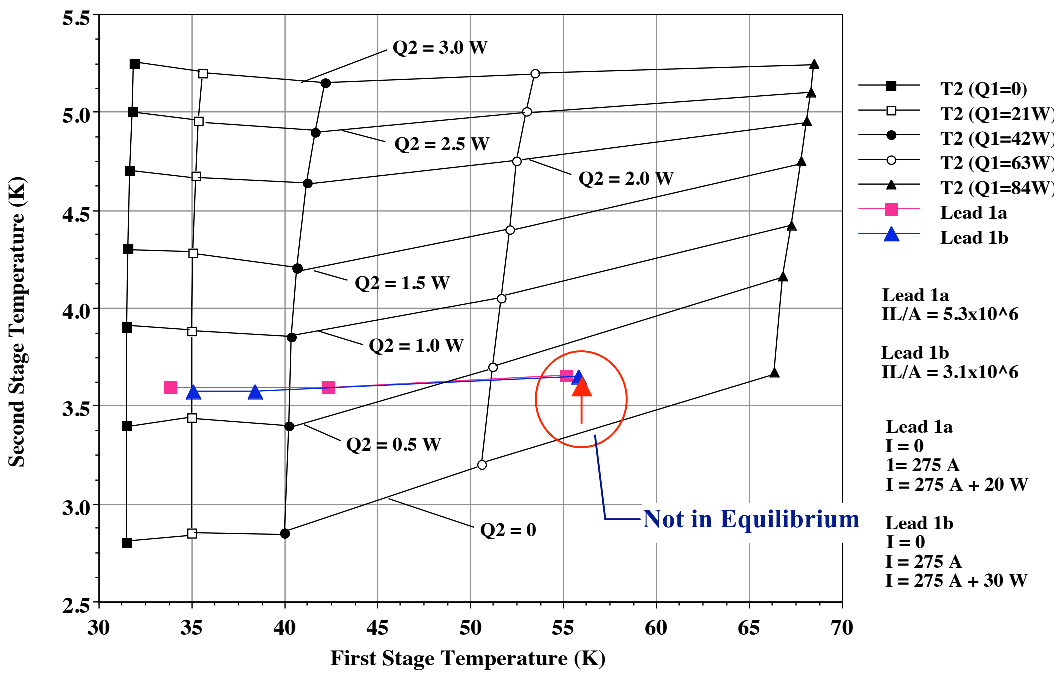

FIGURE 6. The operating diagram for the 1st-stage temperature T1 and the 2nd-stage temperature T2 of a PT415 pulse tube cooler as a function of the 1st-stage heat load Q1 and the 2nd-stage heat load Q2 [14]. The operating points for leads 1a and 1b are superimposed on the typical PT415 cooler operating diagram.

In FIGURE 6 the baseline 4 K heat leak is ~0.6 W. Half the heat comes down the cooler sheath tube; the other half is from other sources. Two points in FIGURE 6 don't appear to be in equilibrium. The equilibrium time constant for mass connected to the first-stage is ~1000 s. The second-stage time constant is controlled by the C_V of 17 L of liquid helium. This time constant is ~11000 s. The time to come to equilibrium is about five time constants. For the first-stage, this is ~1.4 hr. For the second stage, this is ~ 15 hr.

TABLE 1 shows the temperatures measured by the temperature sensors during a test of leads 1b. The temperature measured by the platinum resistor sensors T5, T6, T8, and T9 are probably accurate to about ±0.03 K. TABLE 2 shows the calculated resistive heating in various parts of the circuit as a function of current in leads 1b. The measured voltage drop changes with time, the measurements shown in TABLE 2 are taken as the current is removed from the circuit shown in FIGURE 3. TABLE 3 compares the lead heat flow to the cooler first-stage from leads 1a and 1b at no current and at 275 A. TABLE 3 also compares the resistive heating for leads 1a and 1b at 275 A.

TABLE 1. Measured Temperature as a Function of Added Heat Load and Current in the Copper leads. (T1 is the He tank temperature and T2 is the 2nd-stage Temperature. T5 is the 1st stage temperature; T6 is the copper plate temperature and, temperature T8, and T9 are the HTS lead temperatures.)

Time	3:30 PM	5:00 PM	5:30 PM	5:45 PM	6:00 PM	6:45 PM
I (A)	275	275	275	275	275	0
Q_A (W)	0	30	30	0	0	0
T1	3.67	3.69	3.71	3.71	3.70	3.66
T2	~3.6	~3.6	~3.6	~3.6	~3.6	~3.6
T5	38.4	55.1	55.9	49.5	46.7	38.1
T6	52.2	72.3	73.4	68.4	63.7	48.9
T8	51.6	72.8	73.8	68.9	64.2	48.1
T9	52.7	73.8	75.1	69.4	65.2	48.9

TABLE 2. The calculated resistive heating across various taps as a function of lead current for leads 1b. Note: voltage taps V5-6 includes all of the voltage taps between V5 and V6. This allows one to calculate the voltage drop across the five low temperature superconductor splices between V5 and V6.

	Resistive Heating between Taps (mW)							**Lead Type**
I (A)	**275**	**250**	**200**	**150**	**100**	**50**	**10**	
V1-3	11234.7	10052.1	7402.0	5286.9	3269.0	1506.8	281.5	**Cu 2**
V4-2	10948.1	9617.6	7300.5	5038.2	3140.3	1465.4	278.1	**Cu 1**
V3-5	56.3	49.9	36.5	26.5	17.0	8.3	1.9	**HTS 2**
V6-4	44.6	37.2	27.6	18.2	10.7	4.5	0.6	**HTS 1**
V5-6	7.65	4.00	1.78	0.51	0.09	0.05	0.01	**LTS splices**
All	22291.4	19760.8	14772.9	10370.3	6437.1	2985.1	562.1	**Total**

TABLE 3. The estimated heat flow down a pair of copper leads 1a and 1b from 293 K into the first-stage of a single PT415 two-stage cooler with and without current. The total resistive heating developed in the lead circuit (see FIGURE 3) for leads 1a and 1b is also shown in the table.

Lead	**IL/A ($A\ m^{-1}$)**	**Lead Pair Heat Leak (W)**		**Lead Pair I^2R Heating (W)**
		I = 0 A	**I = 275 A**	
1a	5.2×10^6	~8	~42	57.4
1b	3.3×10^6	~16	~31	23.4

In TABLE 1, the temperatures T1 and T2 have not come to equilibrium in any of the cases. By 3:30 PM, the leads had been at 275 A for 1.5 hr. As a result, temperatures T5, T6, T8 and T9 were equilibrium at 3:30 PM. The heater generating Q_A = 30 W was turned on at 3:32 PM. As a result, temperatures T5, T6, T8 and T9 had come to equilibrium by 5:30 PM. The heater was shut off at 5:32 PM. Temperatures measured between 5:32 PM and 6:45 PM were not at equilibrium. The bulk of the temperature difference between T8 or T9 and T5 is within the copper plate. The temperature drop from T7 to T5 is <2.5 K.

The voltage drops measured in TABLE 2 were measured as the experiment current was decreased from 275 A to zero in about 45 minutes. The copper plate wasn't at equilibrium, but the leads, were probably at equilibrium. The apparent HTS lead heating in TABLE 2 is not real. The heating is in the copper attached to the leads. This heat goes to the cooler 1st stage. There are five LTS splices and two HTS to LTS splices between V5 and V6. Voltage measurement errors come into play at the level of 50 micro-volts. The expected heating in the five 75 mm long LTS splices is ~3 mW [15]. The LTS to HTS splice resistance on the HTS lead ends can account for some of the extra heating observed.

In TABLE 3, it is interesting to observe that for lead 1a, the resistive heating is 15 W more that the heat-load into the first-stage. This 15 W is expelled at the room temperature.

The IL/A of lead 1a is too large. In lead 1b, the resistive heating is less that the heat leak to the cooler first-stage. The heat coming in from room temperature indicates that the lead IL/A is too low. The RRR in the flexible lead cable is likely to be greater than 10. An optimum lead with the cable used in leads 1b should have an IL/A of ~3.6×10^6 A m^{-1}. It is clear that the performance of lead 1b is much better than the performance of lead 1a.

CONCLUDING COMMENTS

The lead cooler experiment measured the performance of the copper and HTS leads, when they were cooled using a two-stage PT-415 pulse tube cooler. The experiment showed that near optimum conduction cooled copper lead performance could be achieved. The experiment demonstrates the importance of keeping the cooler first-stage temperature less than 45 K. The design of the heat transfer path between the tops of the HTS leads and the cooler first-stage is also very important. The experiment showed that the resistive heating in the LTS splices and the splices between LTS and HTS conductors can be low.

As a result of this experiment, the leads of all of the 300 A leads in LBNL magnets cooled with coolers will be changed to a design with an IL/A that is close 3.6×10^6 A m^{-1}. This paper shows that it may be important to test the copper leads before their installation.

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