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TESTS OF A GM CRYOCOOLER AND HIGH TC LEADS FOR USE ON THE ALS SUPERBEND MAGNETS

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ABSTRACT

A 1.5 W (at the second stage) Gifford McMahon (GM) cryocooler was selected for cooling the superconducting SuperBend dipoles for the Advanced Light Source (ALS) at Berkeley. A GM cryocooler is a reasonable choice if conduction cooled leads are used to provide current to the superconducting magnet. The expected parasitic heat leaks are expected to range from 0.1 to 0.5 W at 4.2 K depending on the temperature of the shield and the cold mass support intercepts. Heat flow to 4 K down the SuperBend 350 A high Tc superconducting leads is expected to vary from 0.11 to 0.35 W depending on the intercept temperature and the current in the leads. The high Tc leads are designed to carry 350 A without significant resistive heating when the upper end of the lead is at 80 K. The 1.5 W cryocooler is expected to provide 45 to 50 W of refrigeration at the first stage at 50 K. The parasitic heat load into the first stage of the cryocooler will be about 8 W. The heat flow from 300 K down the upper copper leads is expected to be around 30 W. The cryocooler and high Tc lead test will measure the performance of the cryocooler and the high Tc leads. The heat leak down the cryocooler, when it is not operating, is also of interest.

INTRODUCTION

The Advanced Light Source (ALS) at the Lawrence Berkeley National Laboratory (LBNL) is a national user facility that produces high brightness vacuum ultraviolet (energies from 6 eV to 6 keV) and soft x ray (energies >6 keV) synchrotron radiation. The 200 meter diameter, 1.9 GeV, ALS electron storage ring consists of twelve cells each cell having three combined function C shaped 1.3 T gradient bending magnets (with the return flux leg pointing to the inside of the ring) about one meter long. Each dipole generates photons with a critical energy of 3.1 keV when the storage ring electron beam energy is 1.9 GeV. These photons can be delivered to users through forty-eight ports to users outside of the synchrotron shielding. Some years ago, a study was commissioned on ways to increase the photon energy from the ALS bending magnets[1]. The selected approach is to increase the maximum photon energy from the ring, by increasing the bending field in some of the ring dipoles. (The critical energy of photons from the storage ring dipole is proportional to the dipole induction times the electron energy squared.) To maximize the utility of the ALS, three ring dipoles could be replaced with 5 T superconducting dipoles. This has minimum disturbance to the ring lattice and user experiment currently underway at the ALS.

A number of experimental SuperBend dipole coils were built and tested. The fourth set of SuperBend coils were successful in that they did not train and acceptable field quality. They could be charged to the their full design current in less than 100 seconds. Once a successful SuperBend test magnet with a suitable magnetic field was made, the SuperBend project could move forward[2,3]. The 5 T superconducting dipoles that will generate photon beams with a critical energy of about 12 keV.

A study of possible cooling systems[4] for the SuperBend dipoles yielded some interesting results. The least attractive cooling option appeared to be a central refrigerator or liquefier with transfer lines to the three SuperBend magnets. Cooling by using liquid helium and liquid nitrogen did not fare much better. Small pure Gifford McMahon (GM) cryocoolers, without J-T circuits, appear to be the most cost effective and reliable cooling system for the three SuperBend dipoles for the ALS. Pure GM cryocoolers can provide refrigeration at 50 K and 4 K simultaneously. The use of high Tc superconducting (HTS) current leads between 50 K and 4 K permits the SuperBend magnets to be powered continuously while operating on a pure GM cryocooler. It was found that the size of the GM cryocooler is dictated by the cooling requirements at 50 K, not the 4 K cooling requirements. In an emergency, the SuperBend magnets can be kept cold using stored liquid helium and liquid nitrogen. The HTS current leads must carry up to 350 A with their upper end at 80 K, since the cooling system is a GM cryocooler with back-up cooling, in an emergency, supplied by liquid helium and liquid nitrogen.

Reliability is a key issue for the ALS. In order to insure that we understand the operating characteristics of cryocoolers and HTS current leads, the Lawrence Berkeley National Laboratory (LBNL) had contracted with Wang NMR to build a test stand for a GM cryocooler and 350 A HTS current leads. This report describes the LBNL test stand and presents the results of the cryocooler and HTS current lead tests.

THE GM CRYOCOOLER AND THE HTS LEADS

After some study of the available options, LBNL selected the Sumitomo SRDK-415D pure GM cryocooler that develops up to 1.5 W at 4 K while developing up to 60 W of cooling at a temperature between 50 and 60 K. The cryocooler selection process was driven by the following factors: 1) The 4 K heat load for SuperBend is expected to be about 0.5 W while the projected heat load at 50 K is about 40 watts. The size of the cryocooler was driven by the heat load on the first stage. 2) LBNL selected a pure Gifford McMahon cryocooler. We felt that a pure GM cryocooler to be more reliable. 3) LBNL selected a cryocooler company that already had a large number of 4 K cryocoolers operating in the field. The pure GM cryocooler business is changing rapidly. We expect that there will several more pure GM and pulse tube cryocoolers on the market, in the near future.

A set of typical refrigeration capacity curves for the 1.5 W Sumitomo SRDK-415D pure GM cryocooler is shown in Figure 1[5]. Figure 1 shows that the temperature on first stage (50 K stage) is strongly dependent on the first stage heat load Q1. There is a weak first stage temperature dependence on the second stage (4K stage) heat load Q2. The refrigeration capacity curves show that the second stage temperature is dependent primarily on the second stage heat load Q2. Figure 1 suggests that the second stage temperature will go down as the heat load on the first stage Q1 is increased. The minimum second stage temperature is about 2.8 K, which means the superconducting magnet temperature margin could be larger during normal operation with the cryocooler.

LBNL specified that the HTS current leads should carry 350 A with a high end temperature of 82 K with a low end of heat leak of 0.3 W. The two types of HTS leads tested were: 1) The American Superconductor Corporation (ASC) HTS leads were made with BSCCO silver tape that appears to be encapsulated in a NEMA G-10 rod. 2) The Intermagnetics General Corporation (IGC) HTS leads were made from melt textured BSCCO inside a stainless steel tube. In both cases, the leads were sold to LBNL as commercially available leads . We do not know the details of the design of either of these HTS leads.

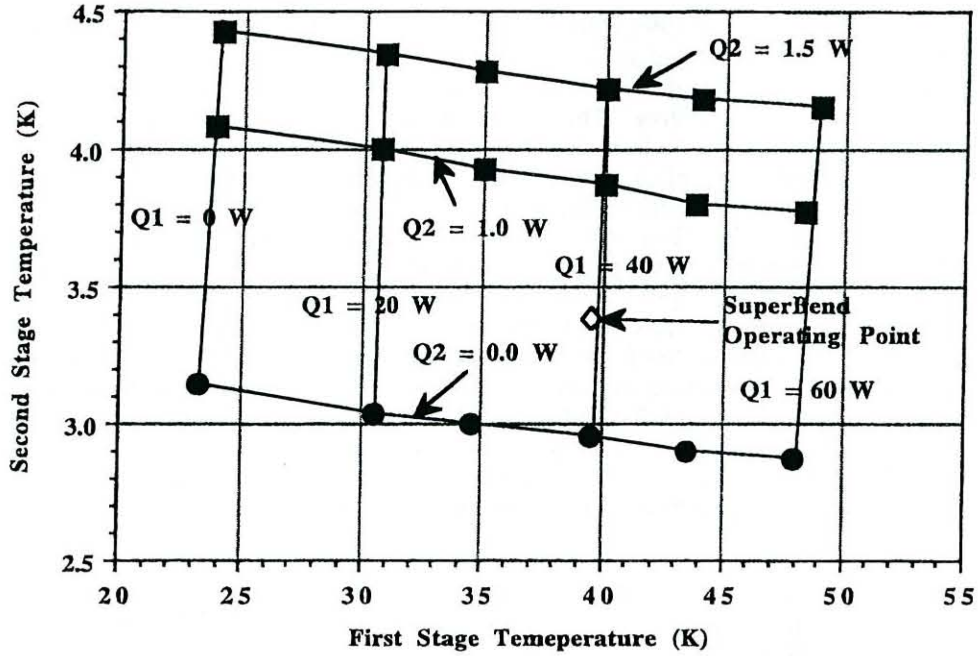

Fig. 1 Typical Refrigeration Capacity Curves for the 1.5 W Sumitomo SRDK-415D Cryocooler

Table 1 Estimated Heat Leaks into the Cryocooler Experiment and the Mass of Various Components in the Experiment

Parasitic Heat Leaks at 50 to 80 K	
Static Heat Leak MLI and Cold Mass Support	5.8 W
Heat Leak Down the Solid Copper Leads, Current = 0 A	19.0 W
Heat Leak Down the Solid Copper Leads, Current = 290 A	26.5 W
Heat Leak Down First Cryocooler Stage when Off (Est.)	>50. W
Estimated 50 K Heat Leak, Cooler On, Current = 0 A	23.8 W
Estimated 50 K Heat Leak, Cooler On, Current = 290 A	32.3 W
Estimated 80 K Heat Leak, Cooler Off, Current = 0 A	>73.8 W
Estimated 80 K Heat Leak, Cooler Off, Current = 290 A	>82.8 W
Parasitic Heat Leaks at 4 K	
Static Heat Leak through MLI and Cold Mass Support	0.22 W
Heat Leak Down Leads, Upper End = 50 K	0.17 W
Heat Leak Down Leads, Upper End = 80 K	0.30 W
ASC Lead Resistive Heating at 290 A, Upper End T = 50 K	0.11 W
ASC Lead Resistive Heating at 290 A, Upper End T = 80 K	0.22 W
Heat Leak Down Cryocooler Second Stage when Off (Meas.)	~1.96 W
Estimated 4 K Heat Load with No HTS Leads Installed	0.22 W
Estimated 4 K Heat Load with Cooler On, Current = 0 A	0.39 W
Estimated 4 K Heat Load with Cooler On, Current = 290 A	0.50 W
Estimated 4 K Heat Load with Cooler Off, Current = 0 A	~2.48 W
Estimated 4 K Heat Load with Cooler Off, Current = 290 A	~2.70 W
Experiment Component Masses	
Estimated Cryostat Mass at 50 to 80 K	20.0 kg
Estimated Stage 1 Cold Head Mass (50 to 80 K End)	~2.0 kg
Estimated Mass at 50 to 80 K	22 kg
Estimated Cryostat Mass at 4 K	25.0 kg
Estimated Stage 2 Cold Head Mass (4 K End)	~0.5 kg
Estimated Mass at 4 K	25.5 kg

THE CRYOCOOLER AND HTS CURRENT LEAD TEST STAND

During the first quarter of 1999, a test stand was built for testing the cryocooler and the HTS leads in a reasonable simulation of the SuperBend configuration. Table 1 on the previous page shows an estimate for the heat leaks at 50 to 80 K and at 4 K for the test apparatus shown in Figure 2 below. The test stand was 495 mm in diameter and 760 mm high. The HTS leads are located on the outside of the helium tank so that they can be changed when the vacuum vessel and super insulated shield have been removed. Connected to the test stand is a pair of twenty meter long flexible metal hoses that connect a helium compressor to the cryocooler. The hoses also serve as a surge volume for pressure pulses. Cables from a 600 A power supply were also connected to the test stand.

The test stand shown in Figure 2 below includes the 1.5 W Sumitomo SRDK-415D cryocooler, a 30 liter storage tank for liquid helium, a 14 liter storage tank for liquid nitrogen, conduction cooled copper leads from 300 K, HTS current leads that are accessible when the experiment is disassembled, a copper based Nb-Ti superconducting interconnect between the HTS leads, a 50 to 80 K shield, twelve silicon diode temperature sensors, eight voltage taps and four resistive heaters to provide additional heat to various parts of the test stand. Figure 3 at the top of the next page shows a schematic representation of the test stand that shows the location of the temperature sensors, voltage taps and the resistive heaters.

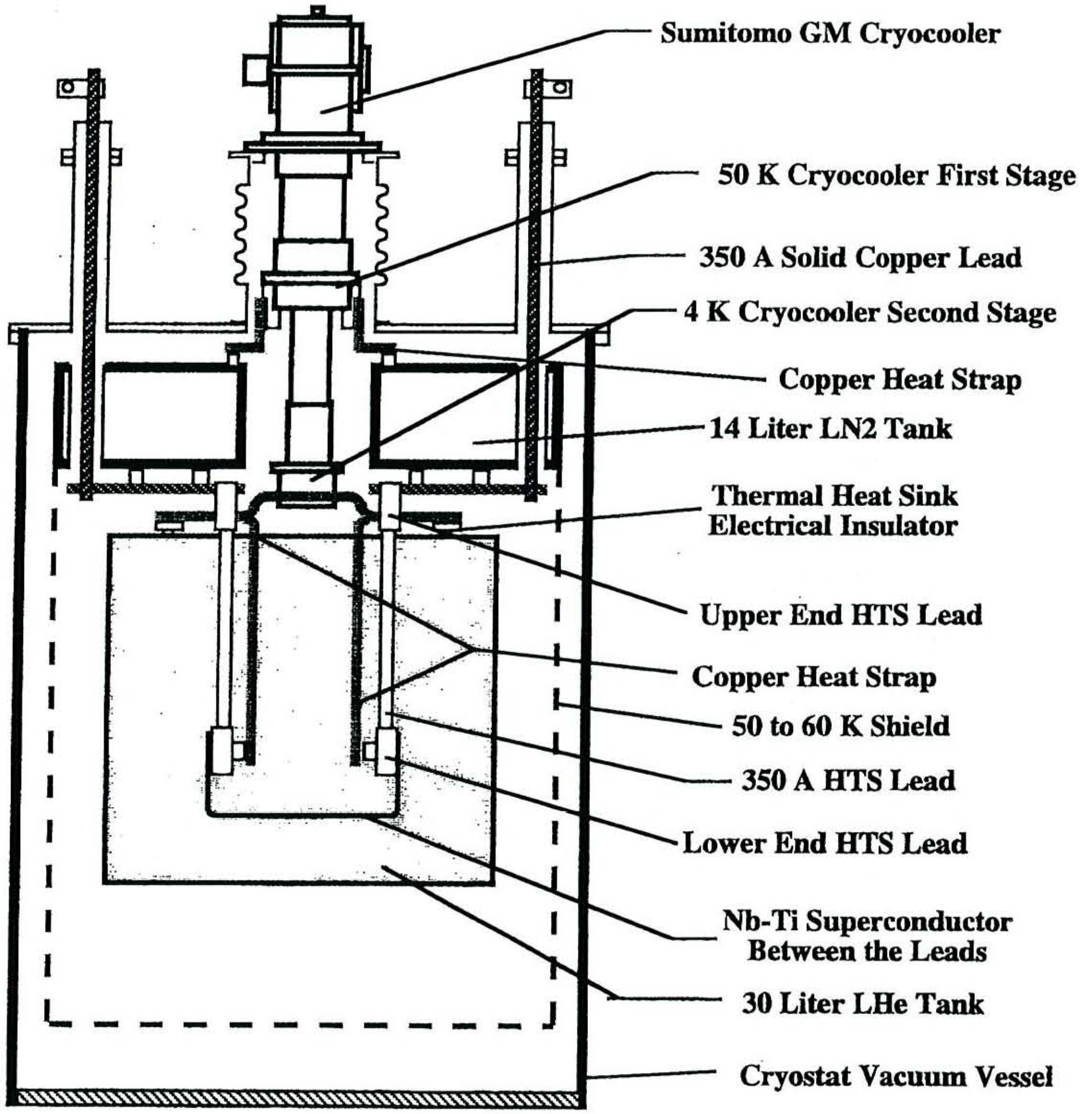

Fig. 2 Cross-Section View of the SuperBend Cryocooler and HTS Lead Test Stand

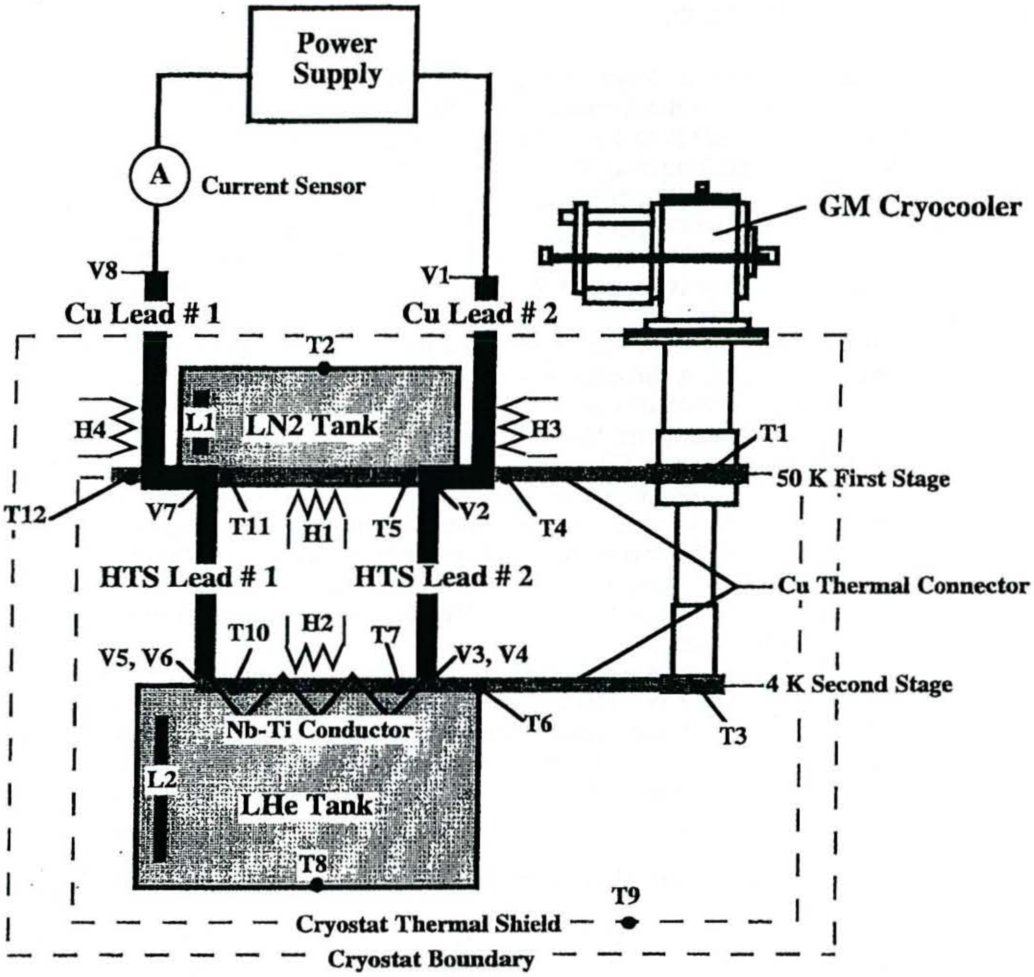

Fig. 3 A Schematic Representation of the SuperBend Cryogenic Test Stand
for the 1.5 W Sumitomo Cryocooler and HTS Leads

Figure 3 above shows the location of eight voltage taps labeled V1 through V8, twelve silicon diode temperature sensors labeled T1 through T12, and four resistive heaters labeled H1 through H4. Voltage drops can be measured across the HTS leads and the copper leads using the voltage taps. The temperature sensors are located as follows: T1 measures the temperature of the cryocooler first stage (the 50 K stage). T2 measures the temperature of the nitrogen tank. T3 measures the temperature of the cryocooler second stage (the 4 K stage). T4 and T12 measure the temperature at the cold end of the conduction cooled current leads. T5, and T11 measure the temperature of the upper ends of the HTS leads. T6 measures the temperature of the end of the copper strap connecting the second stage of the cryocooler with the helium tank. T7 and T10 measure temperature at the lower ends of the HTS leads. T8 measures the temperature of the helium tank. T9 measures the temperature of the shield. The diodes T3, T6, T7, T8, and T10 are accurate to about 0.1 K, with proper calibration. The diodes T1, T2, T4, T5, T9, T11 and T12 are accurate to about 0.3 K

L1 and L2 are liquid cryogen level sensors for nitrogen and helium. The heaters H1 through H4 serve the following functions: H1 heats the nitrogen tank. Heat from H1 must pass through the copper strap to the first stage of the cryocooler. H2 heats the helium tank. Heat from H2 must pass through the copper strap that carries heat to the second stage of the cryocooler. H3 and H4 heat the lower end of the copper current leads and the upper end of the HTS current leads. The current entering the experiment was measured and controlled using the current sensor shown in Figure 3. The apparatus shown in Figure 3 allows one to vary the heat load (and temperature) on both stages of the cryocooler. System control and data acquisition were performed using a Lab View based program written by LBNL and run on a PC. A quench detection circuit independent of the PC was built by LBNL to turn off the power supply, in the event of an HTS lead quench.

EXPERIMENTAL RESULTS

The test stand was cooled down using the cryocooler on a number of different occasions. The 25 kg of cooled mass connected to the second stage of the cryocooler took about 13 hours to cool from 300 K to 4 K. The 22 kg of mass connected to the first stage of the cryocooler took somewhat longer to cool down, about 15 hours. If the masses are scaled to the projected cold masses for SuperBend, the expected cool down time for the magnet would be from 550 to 850 hours depending on how the masses are counted in the scaling process. At 150 K, the cooling from the first stage is estimated to be about 80 W while the cooling rate for the second stage is about 45 W. It is clear that liquid cryogens must be used to cool down SuperBend rapidly.

Table 2 shows test results once the experiment has been cooled down to its normal operating temperatures. Cases A through N are cases where the upper copper leads were powered, but there were no HTS leads connecting the upper and lower temperature stages of the experiment. Cases O, P and Q are tests with the ASC HTS current leads between the upper and lower temperature stages. Cases R, S and T are tests with the IGC HTS current leads between the upper and lower temperature stages. The table shows cases where various amount of heat are put into the experiment using heaters H1 and H2. Q1 is our best estimate for the heat entering stage 1 of the cryocooler. Q2 is our best estimate for the heat entering stage 2 of the cryocooler. The temperature on sensors T1 and T3 were chosen so that the performance given in Table 2 can be compared directly with the typical Sumitomo cryocooler performance curves given in Figure 1.

Table 2 and Figure 4 show cases where the estimated heat entering the first stage of the cryocooler varies from 24 W to 62 W. The estimated heat entering stage 2 of the cryocooler varies from 0.22 W to 1.22 W in Table 2 and Figure 5. The range of first stage temperatures was from 29 K to 48.6 K. The second stage temperatures varied from 2.9 K to 4.1 K. Figures 4 and 5 compare our measured data with the standard refrigeration curves for the Sumitomo SRDK-415D Cryocooler.

Table 2 Temperatures versus Heat Loads for Various Refrigeration Cases

CASE	Current (A)	H1 (W)	Q1* (W)	H2 (W)	Q2* (W)	T1 (K)	T3 (K)
No HTS Leads are Installed; Test with Upper Copper Leads Only							
A	0	0.0	23.8	0.0	0.22	31.1	3.2
B	290	10.0	42.3	0.0	0.22	37.3	3.1
C	290	10.0	42.3	0.2	0.42	37.3	3.3
D	290	10.0	42.3	0.37	0.59	37.3	3.4
E	290	20.3	52.6	0.2	0.42	42.5	3.4
F	290	20.4	52.7	0.37	0.59	43.2	3.6
G	290	20.4	52.7	0.62	0.84	43.2	3.7
H	290	20.4	52.7	0.75	0.97	43.2	3.9
I	290	20.4	52.7	0.87	1.09	43.5	4.0
J	290	20.4	52.7	1.00	1.22	44.0	4.1
K	0	0.0	23.8	0.25	0.47	29.0	3.3
L	0	0.0	23.8	0.50	0.72	30.0	3.5
M	290	0.0	32.3	0.50	0.72	33.7	3.6
N	290	0.0	32.3	0.75	0.97	34.2	3.8
ASC Leads Installed and Tested, Upper Copper Leads							
O**	290	10.0	42.3	0.20	0.64	38.1	3.5
P**	290	10.0	42.3	0.74	1.18	38.2	3.9
Q**	290	30.0	62.3	0.75	1.19	45.9	4.0
IGC Leads Installed and Tested, Upper Copper Leads							
R	290	10.0	42.3	0.20	0.64	37.8	3.5
S**	290	20.0	52.3	0.37	0.81	37.3	3.4
T**	290	30.0	62.3	0.74	1.18	48.6	4.0

* Q1 is the estimated heat flow into Stage 1 of the cryocooler. Q2 is the estimated heat flow into stage 2 of the cryocooler.

** Liquid Helium and Solid Nitrogen are in the reservoirs.

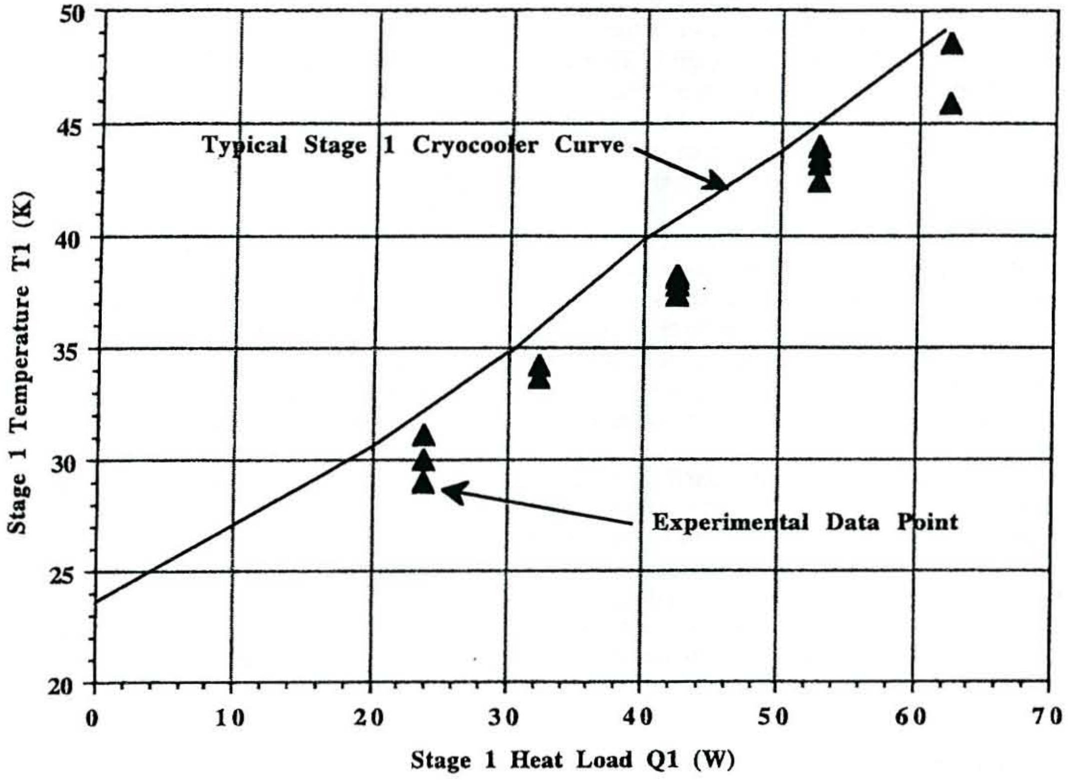

Fig. 4 First Stage Temperature T1 as a Function of First Stage Heat Load Q1
A comparison of Experimental Data with Sumotomo Data

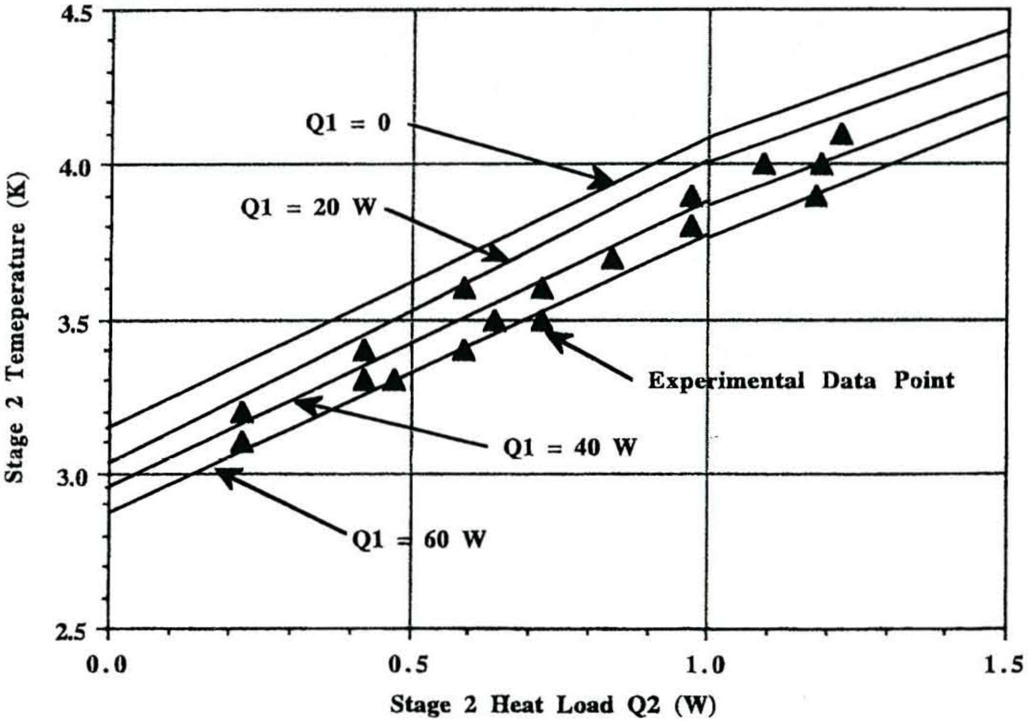

Fig 5 Second Stage Temperature as a Function of Second Stage Heat Load Q2 and Q1
A Comparison of Experimental Data with Sumitomo Data

The experimental data shown in Figure 4 suggests that value of Q1 was over estimated by a few watts. The data shown in Table 2 and Figure 5 do not show the stage 2 temperature going down with heat load on stage 1. There was little change in the stage 2 temperature seen by T3 as the heat load Q1 in stage 1 increased. One explanation for this is that there is an increased heat flow through the cold mass supports between the nitrogen tank and the helium tank as the temperature at T1 goes up. Data was taken from the other temperature sensors besides T1 and T3. At the beginning of the experiment, there was a difference between the temperature measured by sensors T6, T7, T8 and T10 from that measured by sensor T3. This temperature difference increased with the heat from H1. A change in the copper strap between the cryocooler second stage and the helium vessel eliminated this thermal drop.

Both the ASC and the IGC leads performed well on the test stand. There appears to be little difference in the heat leak to the low temperature end of the experiment between two brands of leads. The ASC leads were tested using heater H3 and H4 to put heat into the upper end of the leads. The ASC leads operated 333 A in a satisfactory way even when the temperature at the upper end was as high as 88K. The ASC leads, we tested, appeared to be slightly resistive. The resistance of the leads was dependent on the upper end temperature. One explanation for this is that LBNL measured the resistance of the joint between the copper and the superconductor at the top of the lead and not the resistance of the superconductor in the lead. The resistance experiment has not been repeated using the IGC leads.

The GM cryocooler was shut off and the experiment was operated at full current while the cryocooler was shut off. The cold end heat leak down the cryocooler was about 2 W while stage one of the cryocooler was kept at 80 K by the liquid nitrogen in the tank attached to stage one. The heat leak down stage one from 300 K with the cryocooler off was not measured because of a faulty level gauge in the liquid nitrogen tank.

CONCLUSIONS

The test of the 1.5 W Sumitomo cryocooler was successful. The cryocooler operated over a range of heat loads at both 40 K and 4 K simultaneously. The performance of the cryocooler was satisfactory over the range of operating conditions tested. Our experiments indicate that the thermal bond between the cryocooler heads and the rest of the cold mass is very important. The HTS leads from ASC and IGC appeared to perform in a satisfactory way under the conditions of the LBNL experiment. More experimental work is needed on both the ASC and the IGC leads. From the experimental data taken to date, it can be concluded that small GM cryocoolers are an attractive and cost effective way to cool the three superconducting SuperBend dipoles for the ALS.

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