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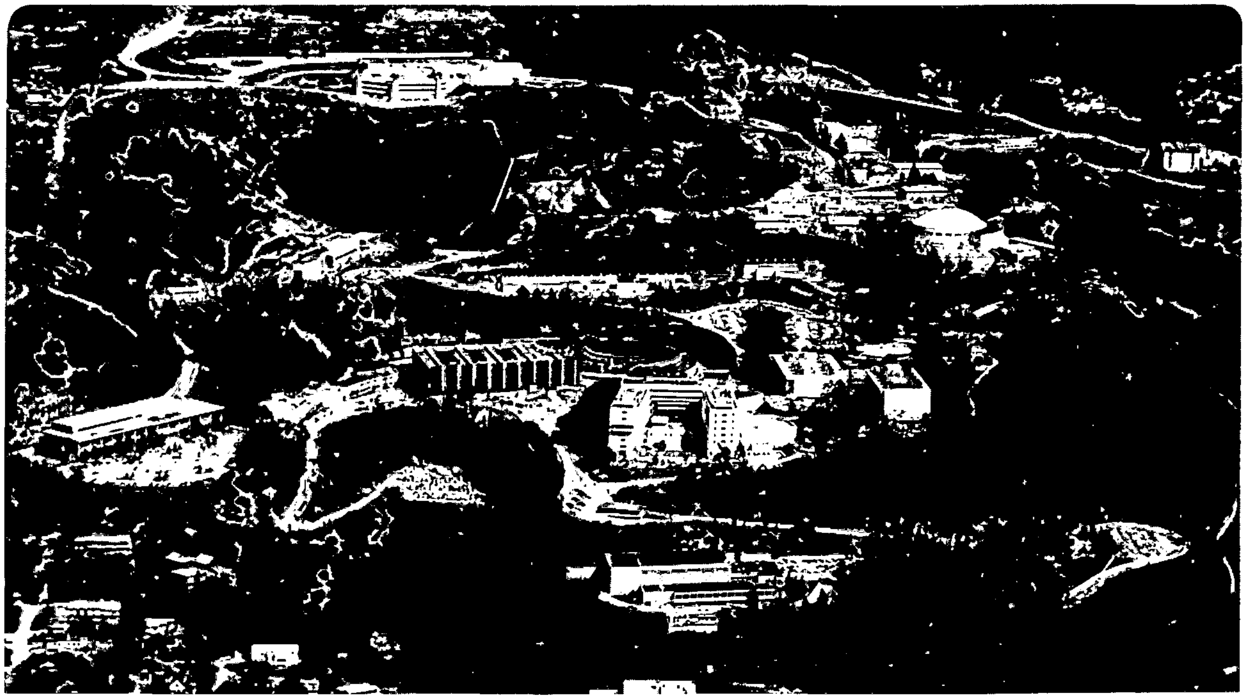

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RETRACTABLE GAS COOLED LEADS FOR ASTROMAG

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ABSTRACT

This paper discusses retractable gas cooled leads for the ASTROMAG experiment superconducting solenoid which will operate on the space station. The ASTROMAG magnet will be cooled by superfluid helium pumped from a storage tank by a fountain effect pump. Since it is desirable to keep the helium consumption low, retractable gas cooled leads are proposed for the ASTROMAG magnet. These leads, which will be in the cryostat vacuum space, will connect directly with the helium flow circuitry which cools the magnet. The leads will operate in a flow circuit separated from the shields.

INTRODUCTION

The ASTROMAG experiment consists of a superconducting magnet facility and at least two experiments[1,2]. The superconducting magnet generates the magnetic field which permits the charged particles in cosmic rays to be identified and analyzed. The ASTROMAG magnet central facility consists of two coils which carry current in opposite polarity. The two coils are two meters apart with a superfluid helium tank between them. The magnet cryostat shown in Figure 1 is 2.57 meters long and 2.12 meters in diameter. The superconducting coils are located outside of the helium storage tank so that they can be located as close to the experiments as possible (100 mm from the nearest experiment detector). At its design stored energy of 11 MJ, the ASTROMAG magnet current is about 810 A.

The ASTROMAG cryogenic system shown in Figure 2 consists of a 3500 liter superfluid helium storage tank, three shields, four cold mass support intercepts and a vacuum shell. The total mass of the two superconducting coils, persistent switch, helium tank, helium, shields and insulation, plumbing and the vacuum vessel will be less than 2000 kg. The projected cryogen lifetime for the cryogenic system is approximately four years. Phase separation of the gas and superfluid helium is achieved using a porous plug. The magnet coils and persistent switch are cooled using a fountain effect superfluid helium pump.

The magnet electrical leads are an important part of the ASTROMAG cryogenic system. In order to achieve a cryostat lifetime of four years, the helium consumption has to be limited to about 3.6 mgs^{-1} (about 0.09 liter of helium at 1.8 K per hour). The operation of OFHC copper gas cooled electrical leads which carry 810 A requires 70 mgs^{-1} when the two leads carry full current and about 50 mgs^{-1} when the leads carry no current. Clearly, the gas cooled leads should be disconnected electrically and thermally when the magnet is not being charged or discharged. When the leads are disconnected, the magnet operates in the persistent mode. The stored energy loss, in the persistent mode, is estimated to be less than one percent per year.

FIGURE 1

BASELINE ASTROMAG MAGNET AND CRYOSTAT

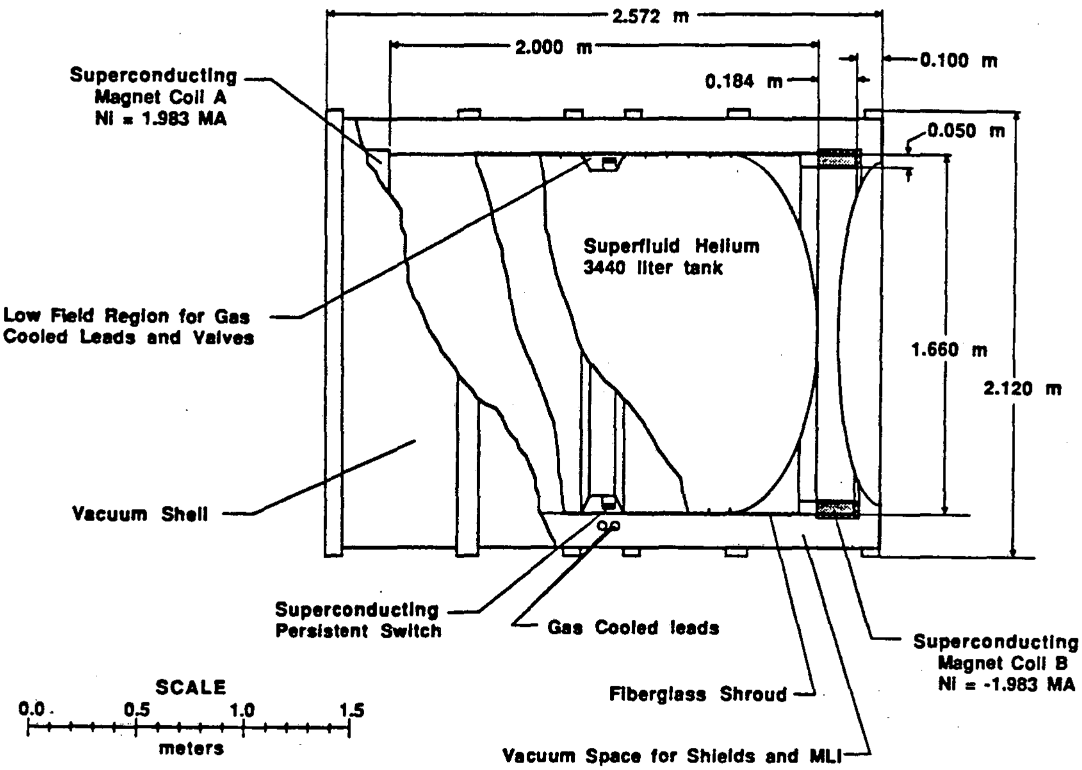
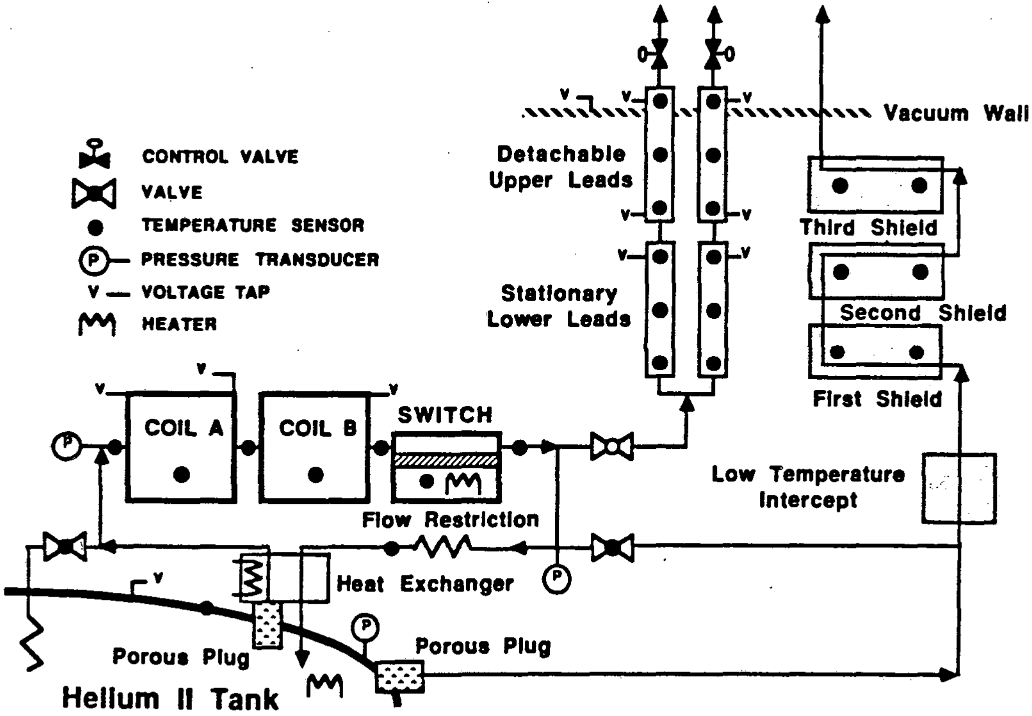


Figure 2

THE HELIUM FLOW DIAGRAM FOR THE ASTROMAG MAGNET



LEAD INTEGRATION INTO THE CRYOSTAT VENT SYSTEM

Preliminary studies of the ASTROMAG cryogenic system called for the gas cooled leads to be operated in series with the gas cooled shields[3]. This was re-examined in view of the overall performance of the magnet cryogenic system.

The shield gas comes from the helium storage tank when the gas cooled leads are not in operation. The pressure drop in the shield circuit must be low in order that the tank pressure be kept low enough to ensure that the helium in the tank is well below the lambda transition temperature (2.17 K). For 1.8 K operation, the tank pressure should be below 1660 Pa (12.3 Torr). This pressure should be maintained even when the magnet is being charged and discharged. When the mass flow is 3.6 mgs^{-1} a low pressure drop can be maintained across the leads and shields. When the mass flow increases to 70 mgs^{-1} or more, low pressure drop operation becomes much more difficult. The desire to maintain a low tank pressure suggests that the gas cooled leads not be operated from the porous plug phase separator on the tank. The gas cooled shields, however, must be operated from the tank porous plug phase separator. A clear case can be made for operating the gas cooled leads off of the pumped helium circuit which circulates helium through the coils and persistent switch. The superfluid helium pump is capable of delivering up to 3 gs^{-1} over pressure drops as high as 5×10^4 Pa (380 Torr).

Once we make a case for separating the lead gas source from the shield gas source, we should go one step further and separate the leads from the shields entirely. The temperature distribution in the shields when the magnet is operating with the leads retracted is not compatible with efficient gas cooled lead operation. The mass of the shields and surrounding insulation (about 180 kg) ensures that the shields and insulation will not respond to changes in temperature profile required to ensure proper operation of the leads.

One can make a case for two approaches to the way helium gas is supplied to the gas cooled leads when they are connected for charging. The first approach shown in Figure 2 is to bleed helium off of the pumped helium circuit to cool the leads. In this case, the mass flow through the magnet coils and persistent switch would be 1.0 to 1.5 gs^{-1}. The peak temperature at the persistent switch would be 3.0 to 3.6 K, depending on the flow rate. Helium entering the leads would enter at that temperature. The pressure in the tank would rise during the charge or discharge. (When the tank is filled with 450 kg of helium, the pressure rises 0.11 Torr during a magnet charge. Even when the tank is two percent full, the pressure rise is only 5.3 Torr.) The second approach calls for not returning any helium circulated through the coils and switch to the superfluid tank during magnet charge or discharge. In this case, the gas mass flow through the leads is determined by the temperature one wants at the exit of the persistent switch (where about 2.5 W is deposited during a charge or discharge) as well as the flow required for adequate cooling of the leads. The tank pressure during a charge or discharge does not rise in this case.

Unlike conventional retractable gas cooled leads, which are located in the neck of a magnet dewar, the ASTROMAG magnet's gas cooled leads are located within the vacuum space between the outer vacuum shell and the superfluid helium tank. Leads of this type were used on the TPC magnet[4]. Orientation of the TPC leads with respect to gravity had little effect on lead performance. The performance of the ASTROMAG gas cooled leads is expected to be unaffected by either the location of the leads or a weightless environment. Leads which are within the magnet cryostat should be vacuum tight and capable of withstanding short-term internal pressures of up to 30 atmospheres during a magnet quench.

DESIGN PARAMETERS FOR THE LEADS

Several design parameters have been considered in the gas cooled lead conceptualizations. These include: the selection of lead material, the superconductor attached to the leads, the geometric configuration of the lead, options for contacts, contact relative location and operating media, and options for a lead connect/disconnect drive system.

It is well known that low residual resistance ratio (RRR) copper alloys provide more stable operation for currents above the design current. Ordinary phosphor-deoxidized copper ($2 \leq RRR \leq 10$) is a good selection for most leads. The low RRR leads have a slightly higher cold end heat leak at the design current and require more gas for stable operation (about 79 mgs^{-1} versus 70 mgs^{-1} for OFHC at 810 A). Low RRR leads also have an inherently lower zero current heat leak[5], however we have not investigated what advantage this may be in the case of disconnected retractable leads. Besides the gain in stability with low RRR leads, one gets a shorter lead which operates at a low enough current density so that the leads can carry current for many minutes with no gas flow. The extra margin is an important safety consideration.

Superconductor attached to the lead improves thermal performance, particularly when the lead operates with excess gas flow. (The cold end heat leak goes down under conditions of excess gas flow.) The superconductors of choice are Nb-Ti (good to a temperature of 9.0 K at low field), Nb_3Sn (good to a temperature of 15 K) or Nb_3Ge (good to 21 K). There is little to be gained from the use of high T_c superconductor in this application.

Four geometric types of leads have been studied for use on ASTROMAG. They are: (1) round tube leads, (2) metal foam or cable leads, (3) annular leads, and (4) flat plate leads. For a given pressure drop, the highest heat transfer coefficients can be achieved with annular and flat plate leads. For a given flow passage thickness and flow passage cross section, the flat plate leads will have better heat transfer. (The annular and flat plate leads have similar characteristics if both walls are used to carry current). In an annular lead, the pressure drop along the lead for a given mass flow and lead diameter is inversely proportional to the cube of the flow channel thickness. In most applications, where the lead is operated continuously, the flow channel thickness (distance between plates in a flat plate lead) should be no more than about 0.5 to 0.6 mm in order to eliminate thermal oscillations. In the ASTROMAG leads, which are used intermittently, these oscillations may be less important. When the lead gas flow is separated from the venting of the tank and the shields, lead pressure drop is also less important. Ruggedness, simplicity of construction and reliability are more important. A cross-section of the flat plate type used in the lead performance calculations is shown in Figure 3a.

The gas cooled lead detachment point will be in the cryostat's vacuum region. Depending upon configuration details to be described later, the contacts might operate either in about 0.1 atmosphere helium gas or in cryostat vacuum at about 10^{-6} Torr . Two factors are important for the leads: the lead contact resistance (voltage drop) should be low and the contacts must not weld together. The contact resistance will also be influenced by it's relative position along the lead--the closer it is to the cold end, the lower the contact resistance[6], but not necessarily the lower the cold end heat leak. Commercial multiple finger type, sliding contacts should provide sufficiently low voltage drop for this application, and ASTROMAG operating conditions should preclude welding. This type of contact does not require large compressive forces across the joint, and provides a useful make/break contact wiping action.

The range of motion required for disconnect (to achieve a low radiation "view factor" when retracted) is about 2-3 lead "diameters", or roughly 50 to 100 mm for the ASTROMAG leads. This kind of motion can be provided using a motor driven linear actuator which drives the retractable lead sections together.

MODELING THE PERFORMANCE OF RETRACTABLE GAS COOLED LEADS

The thermal and hydraulic performance of flat plate detachable gas cooled leads was modeled for the charge/discharge mode using the LBL program NWLEAD. The flat plate leads in the computer simulation assumed phosphor-deoxidized copper with RRR = 2.17. The simulated lead's generic cross-section is defined in Figure 3a.

We used the properties of copper[7] and helium[8] from NBS. The exact laminar flow Nusselt number and friction factor as defined by Shah and London[9] are calculated in the program for each location along the lead (the lead is separated into discrete elements along its length by the program). Because of the additional local disconnect power dissipation, the resulting increase in cold-end heat leak and pressure drop depend upon the current, the joint's

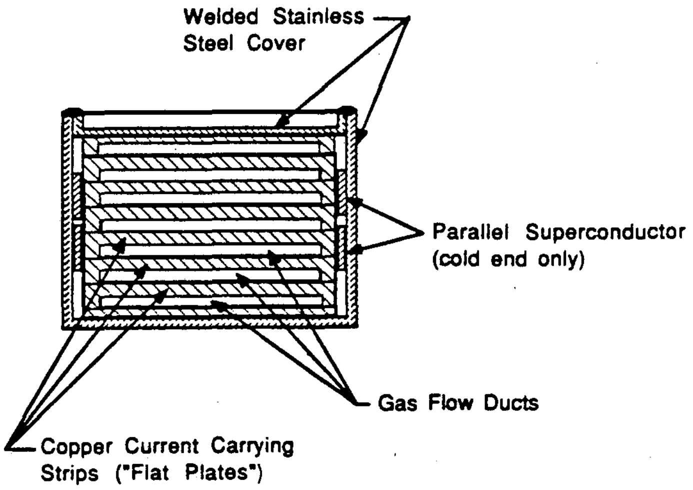


FIGURE 3a PICTORIAL SKETCH OF PARALLEL PLATE CROSS-SECTION (NO SCALE–DISTORTED FOR CLARITY)

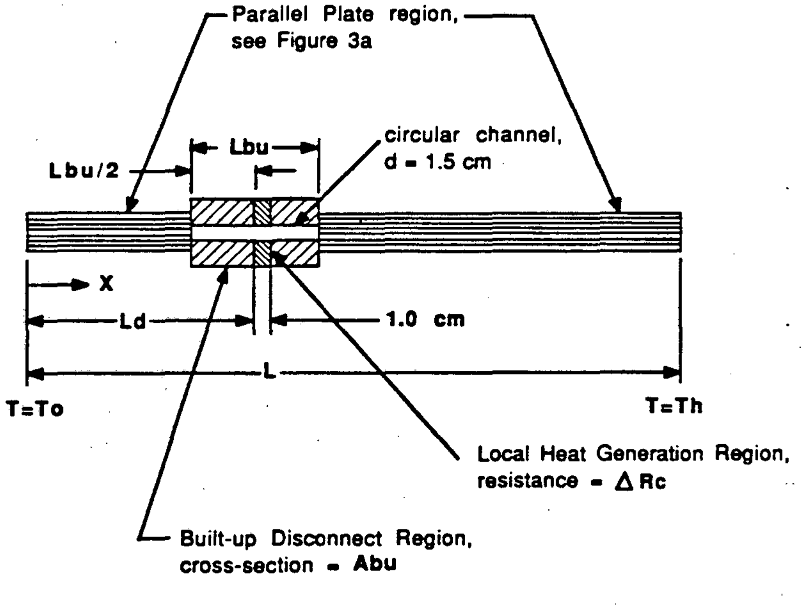


FIGURE 3b DEFINITION OF TERMS FOR THE DISCONNECTABLE CURRENT LEAD IN THE "CLOSED POSITION"

effective axial conductance, the contact's heat generation per unit volume, and how far the joint is located from the cold end. The design current for ASTROMAG is 810 A and the cooled length of the simulated leads is about 65 cm.

To provide potentially useful design information with regard to lead heat leak and pressure drop, we did a series of approximate calculations[10] at various assumed values of contact heat generation per unit volume at 2 contact locations; L_D= 10 cm and 20 cm--See Figure 3b. All calculations assumed the contact was located in an axi-symmetric built-up lead region of area A_{BU}. The built-up region length, L_{BU}, was 4.0 cm long, and the concentric circular gas flow duct through the built-up region of the disconnect was 1.5 cm in diameter. Each of these selections were quite arbitrary.

Figure 4a shows a pictorial sketch of a physical lead configuration compatible with the conceptualization of Figure 3b. In this case, the contact is located in the lead's gas coolant space which is isolated from cryostat vacuum by the hermetic, low thermal conductivity tube. Figure 4b is another possible lead configuration for ASTROMAG where the contact is located within the cryostat's vacuum. Here the contact's heat generation is locally transmitted by conduction in the built-up copper region to the gas coolant channel in close proximity. Contact "welding" is not expected to be a problem in this case, because; a) the joint operates at low temperatures (less than about 150 K), and b) is "connected" for relatively short periods (about 4 hrs).

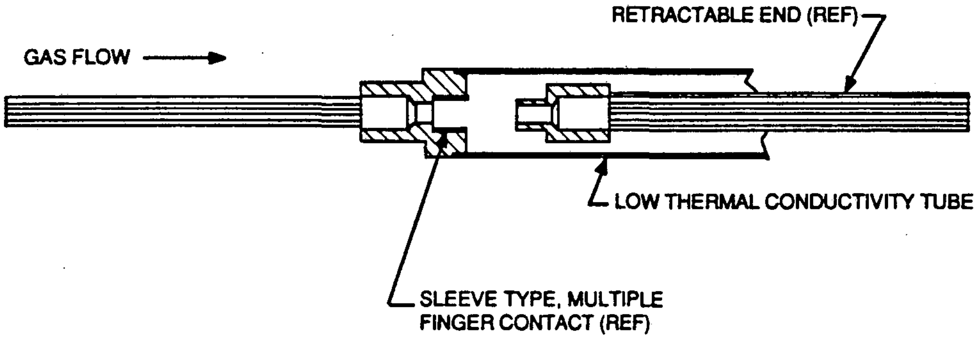


FIGURE 4a SKETCH OF CONCEPTUAL LEAD WITH CONTACTS IN LEAD GAS SPACE

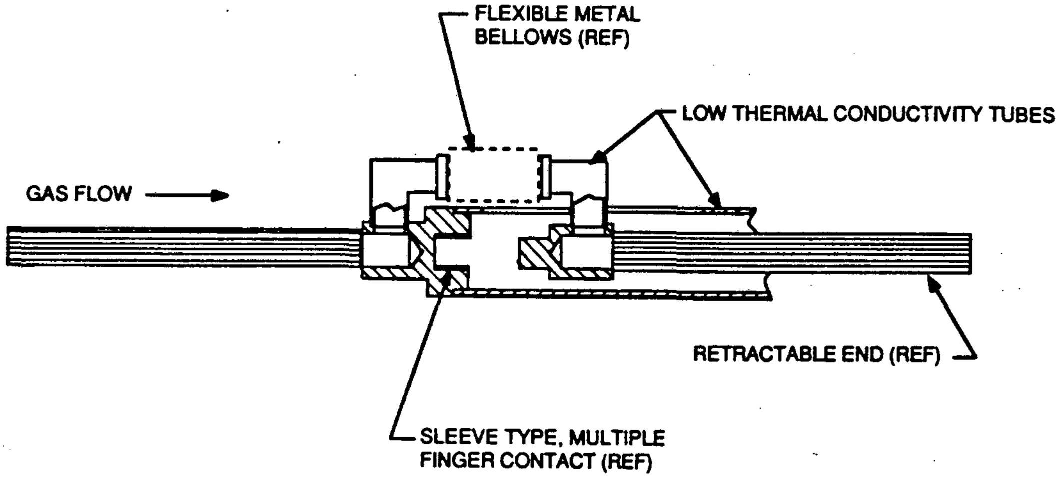


Figure 4b SKETCH OF CONCEPTUAL LEAD WITH CONTACTS IN CRYOSTAT VACUUM

LEAD CALCULATED RESULTS

All calculations were done for "optimum" leads, defined herein as leads with a warm end temperature gradient of zero in the self-sufficient mode. The calculations assumed a 9.0 K superconductor attached in parallel at the cold end of the lead, a flow channel thickness of 0.51 mm, and a warm end temperature of 300 K. The assumed pressure at the entrance of the lead was 1.013×10^4 Pa (76 Torr).

Figure 5 presents the dimensionless cold end heat leak -- DMLS $Q_o/I = [(q_o/I)_{Rc} - (q_o/I)_{Rc=0}]/(q_o/I)_{Rc}$ -- as a function of the contact resistance over built up area function, R_c/A_{BU}, and the distance of the contact resistance from the cold end, L_D. The dimensionless cold end heat leak (and the amount of gas needed to cool the lead) is seen to be a relatively weak function of the lead contact resistance, but increases (for a given R_c/A_{BU}) with a reduction in L_D from 20 cm to 10 cm. In general, the higher the contact resistance the larger the built up region has to be (lower heat generation per unit volume) for a given cold end heat leak. The calculated cold end heat leak, q_o/I, for the point labeled "Ref." in Figure 5 is 1.13 mW/A per lead.

Figure 6 shows the gas cooled lead's dimensionless pressure drop -- DMLS $dp/L = [(dp/L)_{Rc} - (dp/L)_{Rc=0}]/(dp/L)_{Rc}$ -- as a function of R_c/A_{BU} and L_D. The contact resistance increases the lead pressure drop because the helium viscosity (temperature) is increased. The further the contact is from the cold end, the larger the pressure drop becomes, but as seen here, the pressure drop "penalty", at a given R_c/A_{BU}, is about the same for either L_D = 10 or 20 cm. The calculated pressure drop for the point labeled "Ref." in Figure 6 is about 40.5 Torr.

FIGURE 5 DIMENSIONLESS COLD END HEAT LEAK

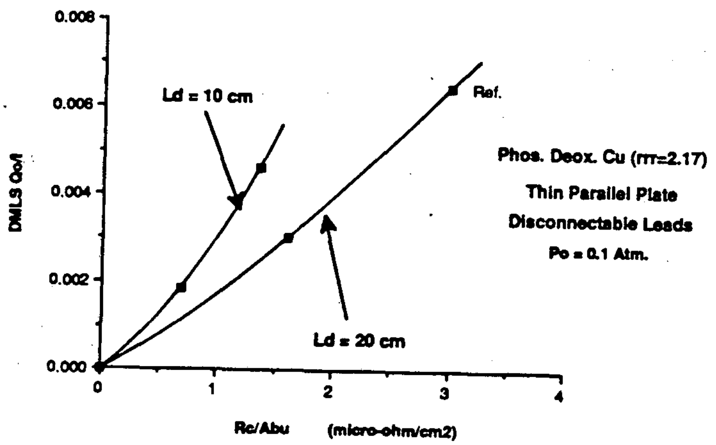
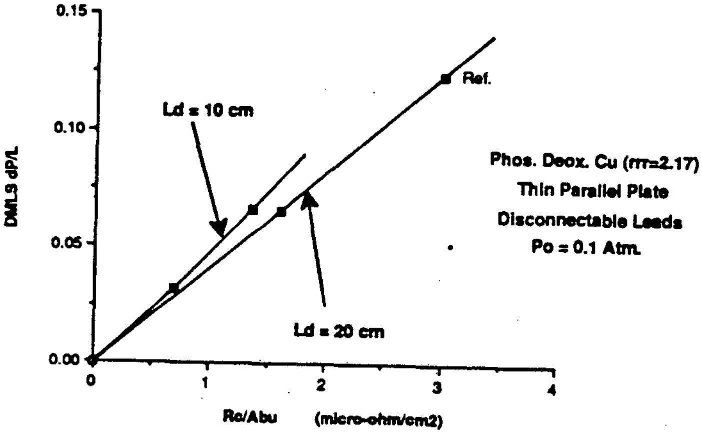


FIGURE 6 DIMENSIONLESS PRESSURE DROP



CONCLUSIONS

Operation of retractable gas cooled leads on the ASTROMAG experiment does not appear to pose any insurmountable problems provided the gas cooled lead flow circuit is separated from the shield gas flow circuit. The lead gas flow should come from the pumped helium flow circuit which circulates helium from the tank through the coils and back to the tank. The retractable lead contact will operate either in vacuum or a low pressure helium atmosphere depending on the properties of the contacts and local contact cooling details. With appropriate selection of flow passage dimensions, thermal oscillations can be avoided. Contact welding is unlikely for the described ASTROMAG operating conditions.

At a design current of 810 A, the leads would be expected to have an overall length of 65 to 70 cm if they are fabricated from phosphor-deoxidized copper with an RRR of about 2. The minimum gas flow through the gas cooled leads at their design current would be about 80 mgs^{-1}. For four three-hour charges and discharges of the ASTROMAG magnet per year, one can expect to consume about 7 kg of superfluid helium per year from the storage tank. We find that neither the position of the disconnect nor its resistance (if the contact voltage drop is less than about 30 mV per lead) have much effect on cold end heat leak or the minimum gas flow needed to operate the leads. The location of the lead disconnect and its contact resistance, however, do have a moderate influence on the pressure drop needed to drive gas through the lead. By choosing to operate the gas cooled leads off of the helium flow circuit through the coils and the switch, sufficient pressure head can be provided to ensure reliable operation. Lead flow can be controlled by using either the temperature near the warm end of the lead or by using the voltage drop across each lead.

ACKNOWLEDGEMENTS

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