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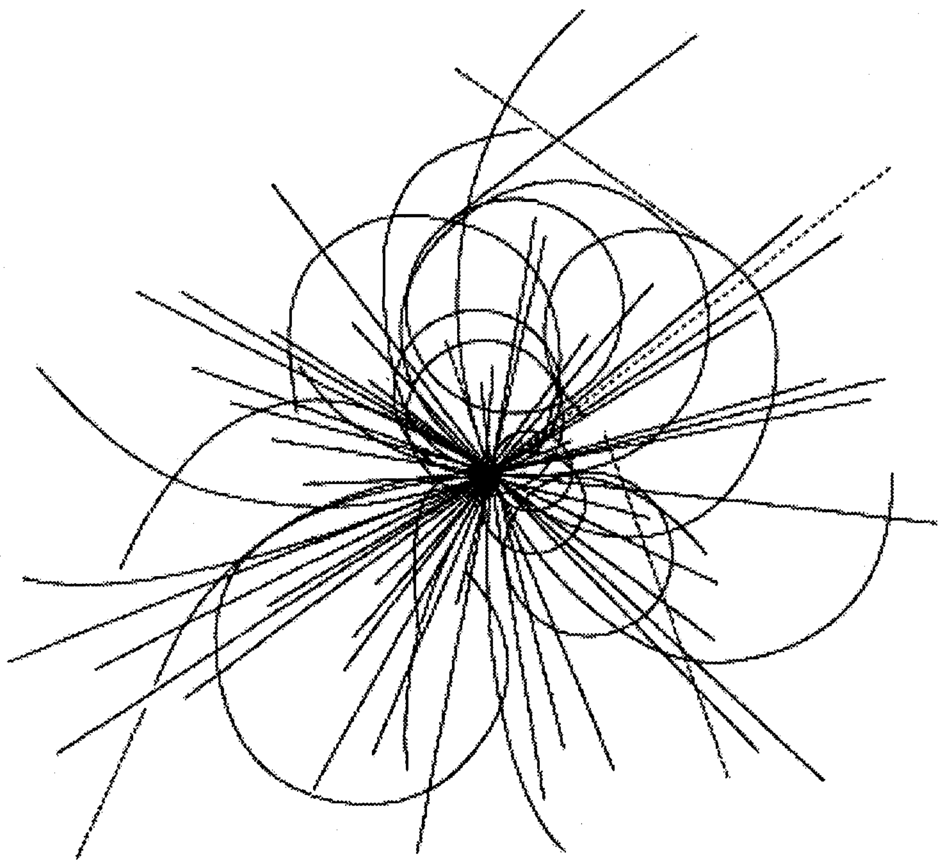

Superconducting Super Collider Laboratory

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HEAT LEAK MEASUREMENTS AND THERMAL MODELING OF A MECHANICAL SUPPORT FOR A SSC BEAM TUBE LINER

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INTRODUCTION

Hydrogen desorbed from the beam tube of the super collider by synchrotron radiation may adversely affect the luminosity lifetime of the proton beam.[1] One solution to this problem[2] is to place a distributed cryopump within the beam tube which will trap desorbed gasses.

Such a cryopump can be effected by attaching cryosorber to the cold (4 K) magnet bore tube. A concentric tube, or liner, centered within the magnet bore tube shields the cryosorber from the synchrotron radiation, and becomes the beam tube. By perforating a fraction of the liner surface with small (on the order of 1-3 mm) holes, the liner/cryosorber assembly becomes a distributed pump. The liner temperature may be allowed to equilibrate at a temperature close to that of the 4 K bore tube. However, actively stationing the liner at 80 K is of interest because the synchrotron radiation heat can then be deposited in the liquid nitrogen system. This, at least partially, decouples the allowable beam current from the helium cryogenic system. Active control is accomplished by means of 80 K helium flowing through a trace tube attached to the outside of the liner. A cross section of the magnet bore tube with an 80 K liner is shown in Figure 1.

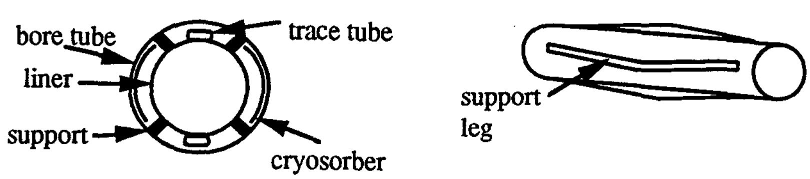

Figure 1 Cross section of magnet bore tube with liner, and schematic of support leg attached to liner.

DESCRIPTION OF HEAT LOADS

The SSC is the first proton machine in which the heat load of the synchrotron radiation will be significant. At baseline operation the synchrotron load is 0.14 W/m, all of which is deposited in the single phase 4 K helium. This represents about 40% of the total 4 K heat load. With an 80 K liner, however, the 4 K synchrotron radiation load is replaced by the static heat load of the liner, while the intercepted synchrotron load is transferred to the LN2 system.

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For an 80 K liner to be practical, it must not impose a heat load on the single phase helium that is greater than the baseline dynamic heat load of the synchrotron radiation. A conservative budget for the static heat load has been set at 0.07 W/m. Non-negligible contributions to the static heat load arise from conduction through mechanical supports, blackbody radiation, end conduction through interconnect pieces where the trace tube penetrates the 4 K bore tube, and conduction through the beam position monitor. By far the largest heat load arises from the support system, so that half of the static heat load budget (0.035 W/m) is allocated to it.

Mechanical supports must be optimized to provide accurate centering of the liner within the bore tube while having minimal cross-section for heat transport. Because the supports are located in the beam tube they must also be radiation resistant. This requirement precludes the use of insulating composites like G-10. Other material candidates, such as polyimides, have been shunned because relatively little is known of their low temperature radiation resistance, thermal conductivity, or mechanical properties. Thus a prototype support consists of four stainless steel legs, each with a rectangular cross-section, approximately 6 mm x 1.2 mm thick. The legs are bent slightly in the middle, as shown in Figure 1, in order to position the liner concentric to the bore tube. To provide the necessary rigidity, support legs must be less than 17.2 cm long, have both ends welded to the liner, and be spaced at 2 m intervals.

The resistance to heat flow of each leg is the sum of the stainless steel resistance and the contact resistance between the support and bore tube. Neglecting contact resistance for the moment , the heat leak through a single leg is given by

$$Q = 2A/l \int k dT \qquad (1)$$

where A is the cross sectional area of a support leg, l is half the leg length and k is the thermal conductivity of stainless steel. The integral is evaluated from 4 K to 80 K, and predicts a heat load of 0.06 W per leg. Assuming that all four legs are in contact with the bore tube, this results in a heat load of 0.12 W/m, which is less than the baseline synchrotron radiation load but more than the static heat load budget.

Since the material and geometry of the support are more or less fixed by other considerations, the contact resistance is the only remaining design parameter with which to reduce the heat load. Contact resistance can be expressed as,

$$R_{contact} = f(\Delta T, k, F, G) \qquad (2)$$

where ΔT is the temperature difference across the contact, k is the mean thermal conductivity of the materials in contact, F is the force with which the contacts are pressed together, and G is a geometric factor related to surface roughness. In general, $R_{contact}$ is not well known. For this reason, tests were conducted to measure both the heat leak of a prototypic support and the average resistance of a stainless to stainless contact.

DESCRIPTION OF EXPERIMENT

Apparatus

For reference, a schematic of the test apparatus is included in Figure 2. The support used is an early, prototype, which has been machined from a piece of Nitronic 40 stainless steel tubing. As indicated in Figure 2, it has two end rings which hold the four legs together in a single unit. The end rings fit tightly over a short piece of liner tubing and are thermally bonded to it with copper impregnated grease. The liner tube (no holes) is plated with 50 μm of copper on the inner surface. Four 2.2 kΩ metal film resistors serve as a heater. They are varnished into brass sleeves that are soldered to the Cu surface of the liner tube, and wired in series. Thermometers are located on the inside surface of each leg directly behind each contact point. In addition, one thermometer is located on the liner tube and another is located on one end ring near a support leg. Three thermometers are carbon ceramic resistors,[3] and three are standard silicon diodes.

The whole assembly is placed in a stainless steel vacuum container and immersed in a saturated helium bath at 4.2 K. Upon insertion of the support assembly into the vacuum container, the contact points of each leg are deflected by 0.75 mm. An independent measurement of the spring constant indicates that this deflection corresponds to an applied force per contact of approximately 12 to 14 N, about the same as that expected to arise from the weight of a liner.

Procedure

The insulating vacuum is pumped to approximately 1×10^{-5} Torr at room temperature using a diffusion pump. During the transfer of liquid, a helium leak detector remains open to the vacuum space. Once the apparatus is immersed in LHe and no leaks have been observed, the detector is valved off.

When the heater is turned on, temperatures slowly rise to steady state values. The time constant for steady state is on the order of a few hours for liner temperatures above 20 K. As a matter of practice, then, the heater is turned up to full capacity and the liner temperature monitored until it is close to the desired value. The heat is then slowly reduced until a steady temperature is achieved. This process takes approximately one half hour. Accuracy of the method was verified on several occasions by allowing the perceived steady state to remain for a few hours. In all cases, the temperatures changed by less than a few percent.

The heater is powered with a dc voltage supply. A precision resistor in series with the heater provides a means of measuring the current, which together with the applied voltage provides a measure of the heat input. When the steady state is achieved, the heat input as well as the temperatures are recorded. In this way, the heat leak of the support is measured for liner temperatures ranging from 10 K to 100 K.

Heat leak measurements are repeated, over the entire temperature range, for a series of contact surface preparations. The first data were obtained with the support and inner vacuum container wall in "as delivered" condition. This means simply that the contact surfaces were oxidized and the contact area undefined. Later, the inner wall of the vacuum container was polished to remove the oxide layer, and the contact area defined. The definition was accomplished by welding beads of stainless steel rod to the contact points, filing them to a specified 2 mm x 3 mm area with a jeweler's file, and lapping them slightly to seat well against the wall of the vacuum can. Since highly polished surfaces (submicron roughness) present the least resistance to heat flow, our treatment was intended to produce a uniformly rough surface.

DATA ANALYSIS

The total heat leak as a function of liner temperature for a number of cases is shown in Figure 3. Scatter in the data indicates the contact resistance is reproducible to approximately ± 15%. In addition, oxide on the "as delivered" contact surfaces seems to have little effect on the heat leak, as expected for rough surfaces. For a liner temperature of 80 K, the measured heat leak is 0.04 W per leg, a reduction of 30% from the estimate obtained by neglecting contact resistance.

As a check of the total heat leak measurement, the heat leak through each leg is computed from ΔT across the leg and the thermal conductivity of stainless steel. The sum over all four legs agrees reasonably well with the total heat leak measured at all temperatures. This indicates that there are no significant parallel heat paths, as for instance through gas conduction, radiation, or instrumentation leads.

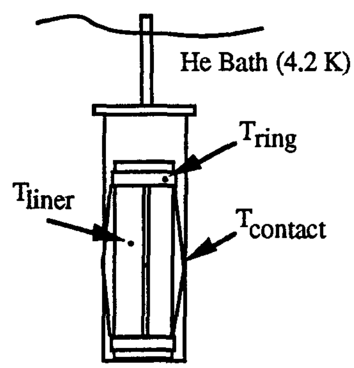

Figure 2 Schematic of apparatus

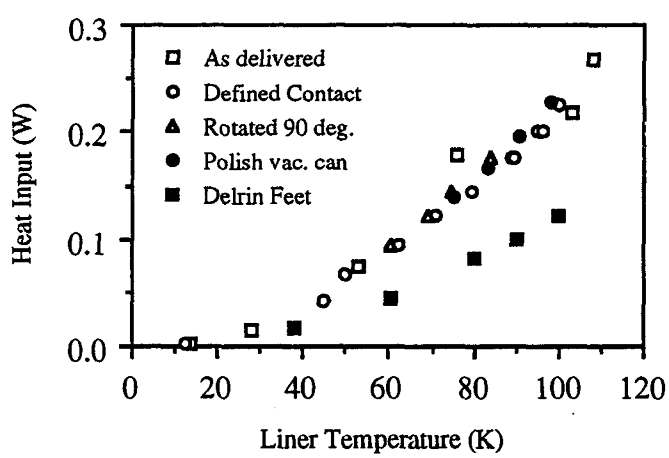

Figure 3 Measured heat leak of a dipole liner support.

The same method can be used to determine an average value of contact conductance (h_c), measured in units of W/m^2K. Assume the heat leak through each leg (Q_i) is one fourth of the measured total. Then Q_i is given by equation (1), with the integral evaluated from $T_{contact}$ to T_{liner}.

In general, contact conductance is found to observe a power law dependence on temperature of the form

$$h_c = \alpha T^n, \tag{3}$$

where α is a function of applied force and surface roughness. In addition,

$$Q_i = A_c \int h_c \, dT, \tag{4}$$

with A_c the nominal contact area. Substituting eq. (3) into eq. (4) and integrating, results in a expression for $T_{contact}$.

$$T_{contact} = [(n+1)Q_i /\alpha A_c + T_{bath}{}^{n+1}]^{1/(n+1)} \qquad (5)$$

Practically speaking, $T_{bath}{}^{n+1}$ is much less than the leading term and can be neglected. Average values of α and n are extracted from a log-log plot of $T_{contact}$ versus Q_i. The result indicates n = 1.5 and α= 0.75. The value of n compares favorably with stainless to stainless conductances published in the literature.[4] The value of α was determined from the largest values of Q_i so the data could be used to predict an upper bound for the heat leak. The measured value of 0.75 is about two orders of magnitude lower than published data[4] for smooth stainless to stainless surfaces under similar applied load. This indicates the potential sensitivity of the heat load to surface roughness.

In one final run, each contact point of a second support was fitted with a Delrin button. The buttons were attached by press fitting into holes drilled at the points of contact. Only the total heat leak and liner temperature were measured, so that no conductance can be extracted from the data. The data are included in Figure 3. Although Delrin is an unacceptable material for use in the bore tube, the data give an indication of the effect of attaching some sort of plastic buttons to the supports should an acceptable material be identified.

DISCUSSION

The applied contact force in the collider will be determined by three factors: preloading by compression of the supports at the time of insertion in the bore tube, further loading or unloading of support legs due to differential contraction during cooling, and compression of the lower legs and unloading of the upper legs due to the weight of the liner. A simple model of the differential contraction predicts a net reduction in the applied contact force after cooling to 4 K. Thus, if no preloading is required only the lower two support legs will be in contact with the bore tube when the collider is in operation. Under these circumstances, the support heat leak will only be a few percent over budget.

If preloading of the supports turns out to be necessary, the heat leak will be more than double that measured here, depending on the amount of preloading. It appears, however, that the contact resistance can also be increased by the addition of insulating buttons. More work is required, though, to identify an acceptable material and confirm that such is the case.

ACKNOWLEDGEMENTS

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