The Heat Load of an 80 K Liner for the SSC

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Abstract

The Superconducting Super Collider (SSC) will be the first proton machine in which synchrotron radiation significantly affects the cryogenic system and the beam tube vacuum. Synchrotron radiation represents the single largest heat load on the 4 K single-phase helium. It also provides a mechanism by which hydrogen can be desorbed from the beam tube wall, gradually worsening the vacuum. Insertion of a perforated and heated liner into the cold beam tube, together with a strip of cryosorber, effectively creates a distributed cryopump. Such an arrangement is an attractive solution to possible vacuum problems, provided it does not increase the heat load on the single-phase helium. In this paper, the primary mechanisms of heat transfer from an 80 K liner are considered, and the results of measurements on heat conduction through prototypical mechanical supports are presented.

I. INTRODUCTION

Synchrotron radiation desorbs hydrogen from the beam tube of the super collider, reducing the vacuum and adversely affecting the luminosity lifetime [1]. One solution to this problem is to place a distributed cryopump within the beam tube which will trap desorbed gasses.

A distributed 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 load can then be removed to 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.

II. HEAT LOADS

The SSC is the first proton machine in which the synchrotron radiation heat load is significant. At baseline operation the synchrotron load is 10.85 W per half-cell. (A half-cell, which is the basic unit of the collider, is 90 m long and consists of five dipoles, one quadrupole, and one spool piece). The syhchrotron radiation 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 a fixed heat load associated with the liner, while the intercepted synchrotron load is transferred to the LN2 system. This fixed or static liner heat load is independent of the collider beam current.

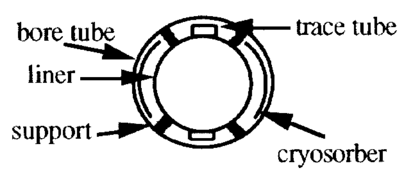

Figure 1. Cross-section of magnet bore tube with liner.

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 5 W per half-celi, which is less than half the nominal baseline synchrotron radiation heat load. Details are shown in Table 1. 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 (BPM).

Table 2
Static Liner Heat Load (W per component)

	Dipole	Quad	Spool	Half-cell
Support	0.50	0.50	0.30	3.30
IR radiation	0.20	0.06	0.04	1.10
Interconnect	0.05	0.05	0.05	0.35
BPM			0.26	0.26
Total	0.75	0.61	0.65	5.01

One BPM is located at the lead end of each spool piece. and represents a major portion of the heat load attributed to the spool. However, since there is only one per half-cell, its contribution to the total is small . The case is similar for interconnect contributions, in that they are discrete not dependent on length. There are seven interconnects per half-cell, one associated with each component. Trace tube penetrations of the 4 K bore tube have been carefully designed to keep the heat load associated with each one small. Thus the

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sum of the interconnect heat loads is only 7% of the total heatload per half-cell. BPM and interconnect designs are generally considered to be within budget.

Blackbody radiation from the 80 K liner to the 4 K bore tube and conduction through mechanical supports combine to generate the largest portion of the heat load, with conduction through the supports being the greater of the two. Radiation is difficult to reduce to budgeted levels when the cryosorber, which is likely to have an emissivity near 1, is taken into account. Conduction through the supports, however, is the most difficult heat load to reduce, since long path lengths are difficult to achieve given the limited radial space available. Both radiation and support conduction are discussed in the following sections.

III. BLACKBODY RADIATION LOAD

Radiant heat exchange between the liner and bore tube is given by,

$$Q = \sigma E(T_H^4 - T_C^4), \quad (1)$$

where,

$$E = \{(1/A_L\varepsilon_L) + (1/A_B)(1/\varepsilon_B - 1)\}^{-1}. \quad (2)$$

The subscripts refer to the liner (L) and bore tube (B), ε is the emissivity (in this case both surfaces are stainless steel) and A the surface area.

In general the emissivity of a material is a function of temperature and surface preparation. The heat transferred by radiation between a stainless steel surface at 77 K and one at 4.2 K has been measured by Obert et.al. [2]. The results for a variety of surface preparations are reported in terms of emissivities, and reproduced in Table 2.

Table 2
Emissivity of Stainless Steel [2]

Surface preparation	Emissivity from 77 K to 4.2 K
As found	0.120 ± 5%
Mechanically polished	0.074 ± 5%
Electro-polished	0.065 ± 5%
Silver plated	0.013 ± 5%

To determine the radiation heat load of an 80 K liner, it is necessary to include the effect of holes in the liner tube and cryosorber on the bore tube. To account for these effects, average emissivities for the liner (ε_L) and bore tube (ε_B) are defined. Each is taken to be the weighted average of the appropriate stainless steel emissivity (ε_{ss}) and the hole (e_h) or cryosorber (ε_c) emissivity. The liner holes are assumed to have an emissivity of 1, and the cryosorber an emissivity between 0.8 and 1, depending on the particular cryosorber.

The resulting average emissivity of each tube is a linear function of the fraction of surface coverage (f_h) or (f_c).

$$\varepsilon_L = (1 - \varepsilon_{ss})f_h + \varepsilon_{ss}, \quad (3)$$

$$\varepsilon_B = (\varepsilon_c - \varepsilon_{ss})f_c + \varepsilon_{ss}. \quad (4)$$

While this is a rather simplistic model, more detailed numerical calculations indicate that it gives an accurate estimate of the total heat transfered by radiation.

To evaluate eq. (1) it is necessary to know the bore tube and liner tube diameters, the surface preparation of the stainless steel, the number and size of holes in the liner and the surface area of cryosorber. The last two numbers are not well known. The fraction of holes may vary up to 0.05, while the fraction of cryosorber coverage may be as high as 0.15. If (f_h) and (f_c) turn out to be near the maximum of their respective ranges, they will dominate the radiated heat leak. This is especially true in the case of the cryosorber.

As an example, assume a 33 mm liner with $f_h = 0.05$, and a 42 mm bore tube with $f_c = 0.15$. This arrangement will radiate 0.6 W/dipole with as found stainless, and 0.4 W/dipole with electro-polished stainless. For the same geometry, with $f_h = 0.03$ and $f_c = 0.10$ the heat leaks are reduced to 0.5 W/dipole and 0.3 W/dipole respectively. This last number is probably achievable, but is still 50% greater than the budgeted amount. Still, since radiation is only budgeted at 20% of the total load to begin with, this is considered acceptable.

IV. SUPPORT CONDUCTION LOAD

A prototype support, shown in Figure 2, consists of four stainless steel legs, bent in the middle, with a rectangular cross-section of 6 mm x 1.2 mm thick. To provide the necessary rigidity, support legs are less than 17.2 cm long, have both ends welded to the liner, and are spaced at 2 m intervals.

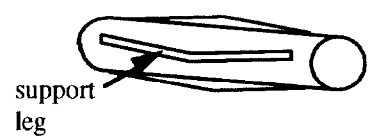

Figure 2. Mechanical support

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, the heat leak through a single leg is

$$Q = (2A/L) \int kdT \quad (5)$$

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. Evaluation of the integral from 4 K to 80 K predicts a heat load of 0.06 W per leg. If all four legs are in contact with the bore tube, this results in a heat load of 1.9 W per dipole. This is less than the baseline synchrotron radiation load but nearly four times the static heat load budget.

The material and geometry of the support are more or less fixed by mechanical stability considerations and radiation resistance, so that contact resistance becomes the primary design parameter with which to reduce the heat load. Contact resistance can be expressed as

$$R_{contact} = f(\Delta T, k, F, G), \quad (6)$$

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 [3]

The total heat leak as a function of liner temperature for a number of cases is shown in Figure 3.

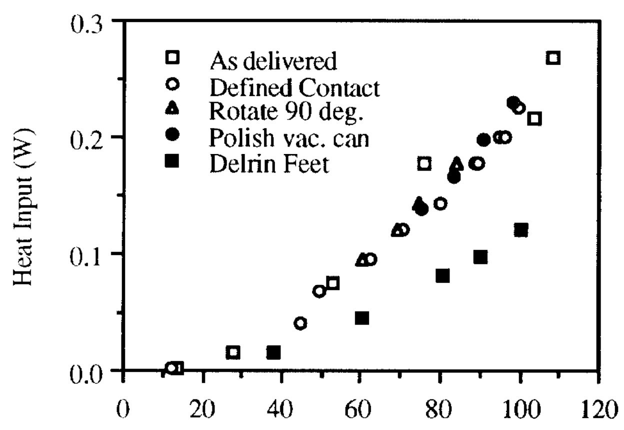

Figure 3. Results of heat leak test on mechanical support

Contact conductance generally obeys a power law dependence on temperature of the form

$$h_c = \alpha T^n, \quad (7)$$

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

$$Q_i = A_c \int h_c \, dT, \quad (8)$$

with A_c the nominal contact area. Substituting eq. (7) into eq. (8) and integrating gives,

$$T_{contact} = [(n+1)Q_i / \alpha A_c + T_{bath}^{n+1}]^{1/(n+1)} \quad (9)$$

T_{bath}^{n+1} is much less than the leading term and can be neglected, so that average values of α and n can be extracted from a log-log plot of $T_{contact}$ versus Q_i. The value of n measured in this way is 1.5 and 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. Its measured value of 0.75 is about two orders of magnitude lower than published data [4] for smooth stainless-to-stainless contacts under similar applied load, and indicates the potential sensitivity of the heat load to surface roughness.

In a 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 plastic buttons to the supports should an acceptable material be identified.

V. DISCUSSION

Blackbody radiation and conduction through the support system are the primary sources of 4 K liner heat load. In the case of radiation, hole and cryosorber coverages would have to be reduced to zero and electro-polished stainless used in order to meet the budget. However, the radiated heat load is a relatively small fraction of the total heat load. Thus, it is concluded that expensive surface treatment of the liner for the purpose of reducing the radiated power is unnecessary.

The heat load due to conduction through the supports is a strong function of the force applied at the contact. 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, and no preloading is required. Thus, 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 0.7 W per dipole.

Finally, it appears that the contact resistance can also be increased by the addition of insulating buttons, though more work is required to identify an acceptable material and confirm that such is the case.

VI. REFERENCES

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