LARP IR Cryogenics: Investigation of the Limitations of an External Bayonet Heat Exchanger for the LHC Luminosity Upgrade

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Introduction

The LHC inner triplet is cooled to 1.9 K using a bayonet heat exchanger, which has been described elsewhere [1]. Use of a similar heat exchanger, external to the cold masses, has been investigated for the expected dynamic heat loads of the LHC luminosity upgrade.

Analysis

The current triplet uses an external, bayonet heat exchanger. The inner copper corrugated pipe containing the saturated He II has an OD of 98 mm and a wall thickness of 0.7 mm. The outer annular pipe has an OD of 168 mm and a wall thickness of 2.77 mm. The annular space containing pressurized He II is therefore approximately 13400 mm^2. These dimensions are illustrated in Figure 1.

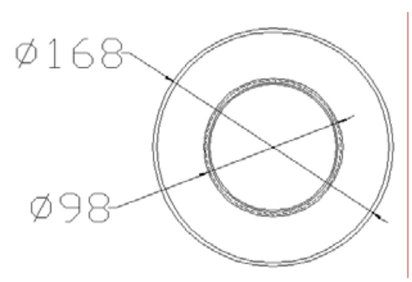

Figure 1 Cross-sectional dimensions of the bayonet heat exchanger.

The Kapitza conductance of the corrugated line-He II interface and the thermal conductivity of the corrugated line have been measured to be $h_K = 892.8\ T^3$ W/m2-K and k = 88 W/m-K, respectively [2]. It is estimated that approximately 22% of the corrugated pipe inner surface is wetted by liquid He II.

Previous work [3] has estimated heat loads to be handled by the upgraded cryogenic cooling system. This work assumes more connections to the heat exchanger than the current triplet, namely seven connections: two in the Q1 cryostat, three in the Q2a&b cryostat, and two in the Q3 cryostat. The connection with the highest heat load is at the non-IP end of Q1 with a heat load of 329 W.

Analysis has been completed here to look at how much heat could be removed by a bayonet-style heat exchanger with a larger fraction of its surface wetted. The effect of possible heat transfer enhancements (e.g., extended surfaces) to reduce the heat transfer resistance is also included.

A finite difference model for a 3 m length of bayonet heat exchanger was constructed. Based on the design temperature profile for the upgraded interaction region [4], the temperature of the pressurized He II at the outlet of the crossover pipe is specified as 1.95 K. The temperature of the saturated He II in the corrugated pipe is specified as 1.825 K. The final boundary condition was a thermal gradient dT/dx = 0 in the pressurized He II due to symmetry. These parameters are illustrated in Figure 2.

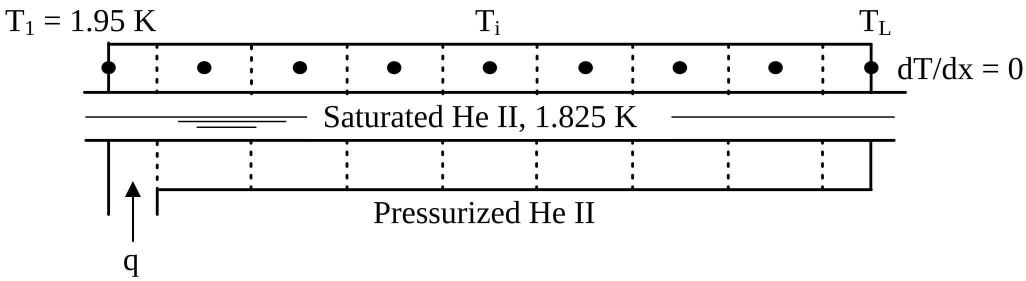

Figure 2 Finite difference model for calculating bayonet heat exchanger performance.

Figures 3 shows the calculated longitudinal temperature profile in the pressurized He II as a function of radial conductance enhancement. Figure 4 shows the calculated longitudinal distribution of radial heat transfer per unit length as a function of radial conductance enhancement, where 1 signifies no enhancement, 2 is a two-fold increase in heat transfer conductance, etc.. These figures illustrate an important limitation of He II systems in general: longitudinal conduction. The resulting large longitudinal temperature gradients mean that a large fraction of the heat transfer occurs at the near end of the cold mass. The effect of heat transfer conductance enhancement is also illustrated: reducing the temperature difference between the pressurized He II and the saturated He II, and significantly improving the heat transfer at the near end of the cold mass.

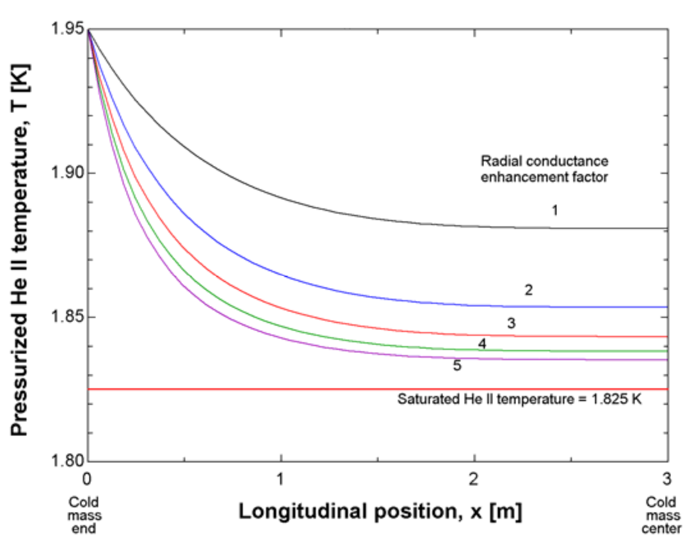

Figure 3 Calculated pressurized He II temperature vs. longitudinal position for the specified boundary conditions of $T_{press,i=1}$ = 1.95 K, $\left.\frac{dT}{dx}\right|_{x=L} = 0$, and T_{sat} = 1.825 K.

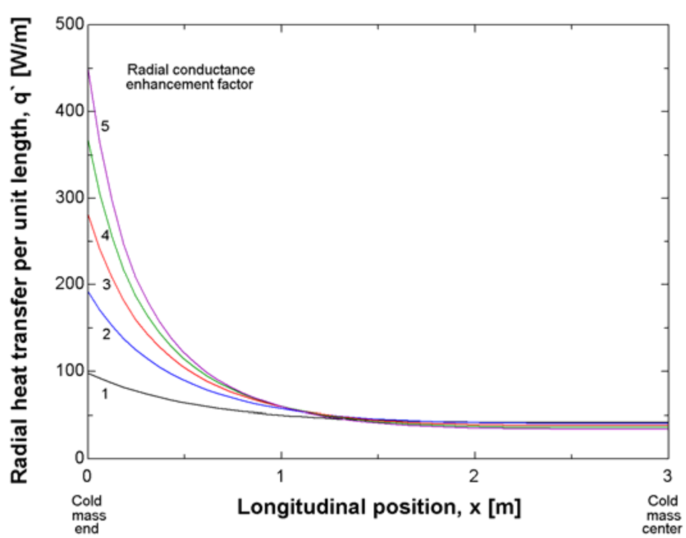

Figure 4 Calculated radial heat transfer per unit length vs. longitudinal position for the specified boundary conditions of $T_{press,i=1}$ = 1.95 K, $\left.\frac{dT}{dx}\right|_{x=L} = 0$, and T_{sat} = 1.825 K.

The total heat that could be removed based on this geometry and these temperature boundary conditions was then calculated. Figure 5 shows the resulting heat transfer rates as a function of the radial conductance enhancement factor for various fractions of wetted surface area.

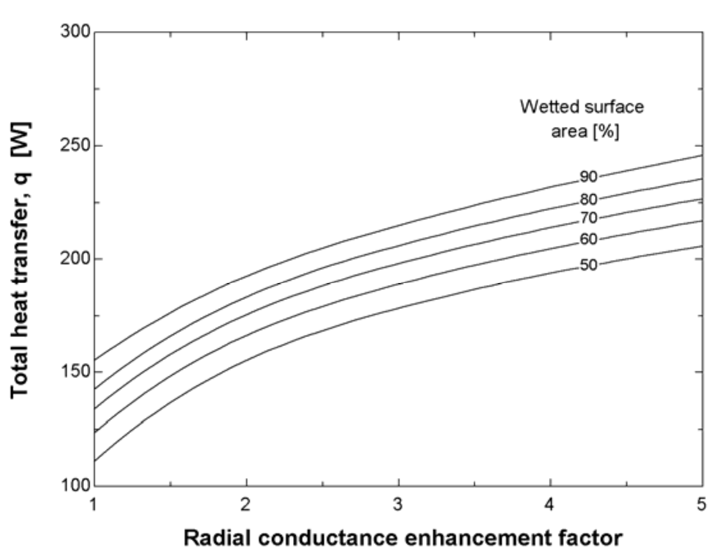

Figure 5 Calculated total heat transfer vs. radial conductance enhancement factor

With no enhancements, a little more than 150 W can be transferred. Increasing the conductance by a factor of five increases the heat transfer rate to 250 W. The heat transfer conductance of a bare Cu heat exchanger pipe is limited by the Kapitza resistance at the pressurized He II-Cu interface and the Kapitza resistance at the Cu-saturated He II interface. The use of extended surfaces (i.e., fins) on both the inside and outside surfaces of the Cu heat exchanger pipe could achieve this five-fold conductance enhancement. Figure 6 illustrates the number of 0.030 m fins that are required to reduce the pressurized He II-Cu Kapitza resistance by a factor of five as a function of fin thickness. Fewer fins are needed as the fin thickness increases due to reduced conduction resistance along the fin, but at least 200 fins would be required on the outside of the heat exchanger tube. A similar number of fins would also be required on the inside of the heat exchanger tube. This would make manufacturing and handling of the long heat exchanger tubes extremely difficult.

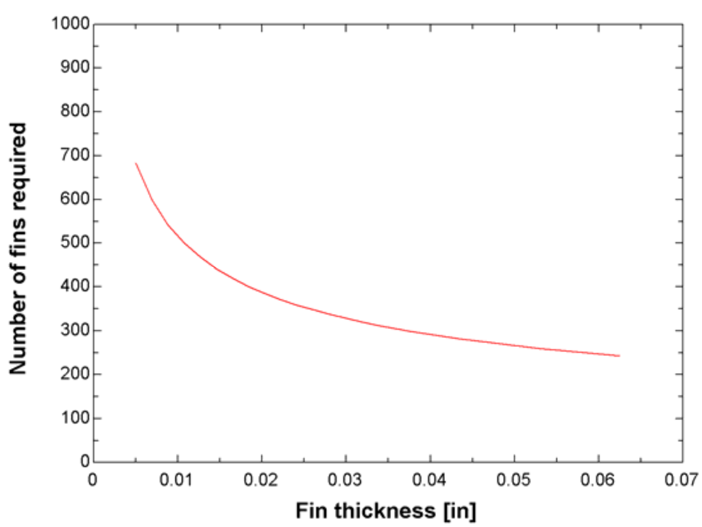

Figure 6 Number of fins required vs. fin thickness to decrease the pressurized He II-Cu Kapitza resistance by a factor of five.

Conclusions

These calculations indicate that a simple, external bayonet heat exchanger is not sufficient to remove the expected heat load of the LHC luminosity upgrade. The existing design could remove up to 150 W with sufficient wetted surface area.

The number of fins required to sufficiently enhance the performance of a single bayonet heat exchanger makes this possibility unattractive. There is the possibility that the thoroughly-studied bayonet heat exchanger design could be used in conjunction with another heat exchanger in some portions of the triplet, or even two external bayonet heat exchangers could be used.

References

[1] Ph. Lebrun, et al., “Cooling Strings of Superconducting Devices Below 2 K: The Helium II Bayonet Heat Exchanger,” Adv. In Cryogenic Engineering, Vol. 43A, pp. 419-426.
[2] Ch. Darve, et al., “He II Heat transfer through a Corrugated Tube – Test Report,” Fermilab Technical Division Note TD-99-064.
[3] R. Rabehl, “LARP IR Cryogenics: Parametric Studies of Heat Transfer in IR Quadrupole Magnets – Beam Pipe to External Heat Exchanger,” LARP-doc-279.
[4] R. Rabehl, “LARP IR Cryogenics: Design Temperature Profile for an LHC Upgraded IR,” LARP-doc-100.