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

Roger Rabehl
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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]. For the Q1, Q2, and Q3 magnets, this bayonet heat exchanger is external to the cold mass. For the D1 dipole, this bayonet heat exchanger is internal to the cold mass. Use of a similar heat exchanger, internal to the cold masses, has been investigated for the expected dynamic heat loads of the LHC luminosity upgrade.

Analysis

The largest heat load in the upgraded triplet occurs at the non-IP end of the Q1 cold mass. The heat load from energy deposition in the non-IP end of the cold mass is 250 W [2].

Figure 1 is a schematic representation of an internal heat exchanger cooling scheme. Multiple heat exchanger tubes are required to distribute the heat flow within the cold mass and keep the cold mass cooling channel sizes reasonable. The four heat exchanger tubes shown have an approximate diameter of 45 mm.

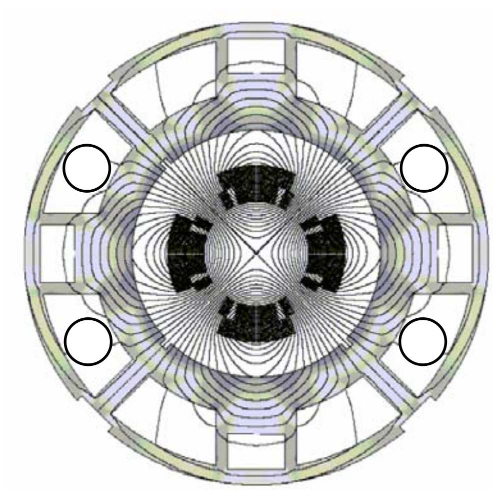

Figure 1 Cold mass cross-section with four internal heat exchanger pipes.

One possible way to operate with multiple heat exchanger tubes is to completely fill all the heat exchanger tubes with He II, filling just up into the pumping line. This is shown in Figure 2.

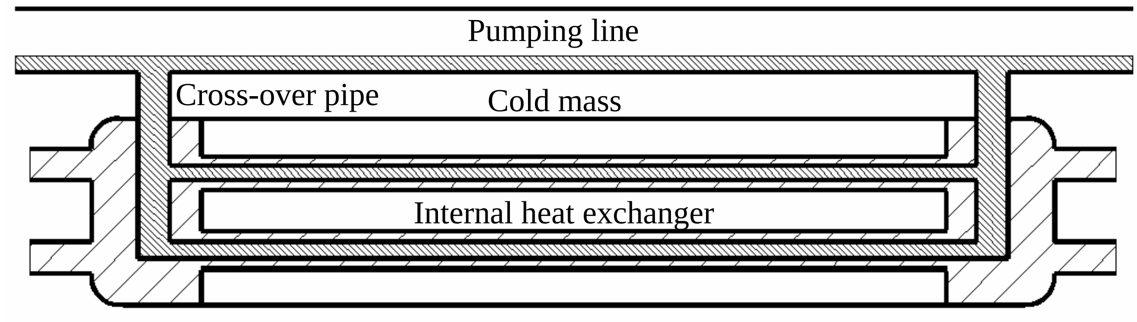

Figure 2 Schematic showing cooling of a cold mass with multiple internal heat exchanger tubes completely filled with He II.

In this configuration, longitudinal He II conduction must be considered. Figure 3 plots the calculated temperature drop between the Q1 thermal center and the non-IP end as a function of the He II cross-sectional area in the heat exchanger tubes. For comparison, the four heat exchanger tubes shown in Figure 1 have a total He II cross-sectional area of about 64 cm^2. At least 2.5 times more He II cross-sectional area is needed to maintain a reasonable longitudinal temperature drop.

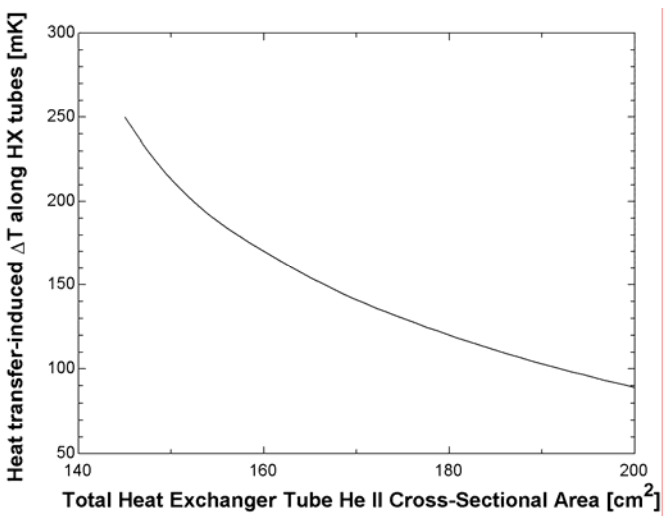

Figure 3 Longitudinal temperature drop vs. He II cross-sectional area in the four heat exchanger tubes for the non-IP end of the Q1 cold mass.

Figure 4 presents similar data in another manner, plotting longitudinal temperature drop as a function of heat exchanger tube He II cross-sectional area for various Q1 non-IP end heat loads.

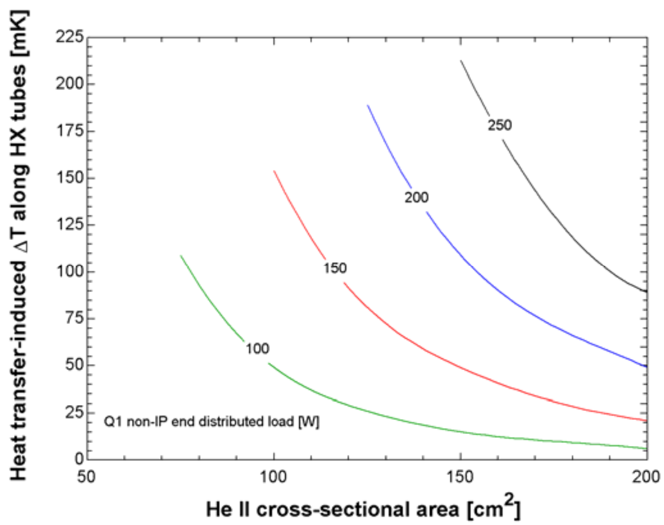

Figure 4 Longitudinal temperature drop vs. heat exchanger tube He II cross-sectional area for a range of heat distributed heat loads.

In addition to cross-sectional area for longitudinal He II conduction, the Kapitza resistance at the He II-heat exchanger surface must also be considered. The need for a large cross-sectional area for He II conduction in addition to a large surface area to minimize Kapitza resistance temperature drop suggests the use of tube bundles inserted through the cold mass cooling holes as shown in Figure 5.

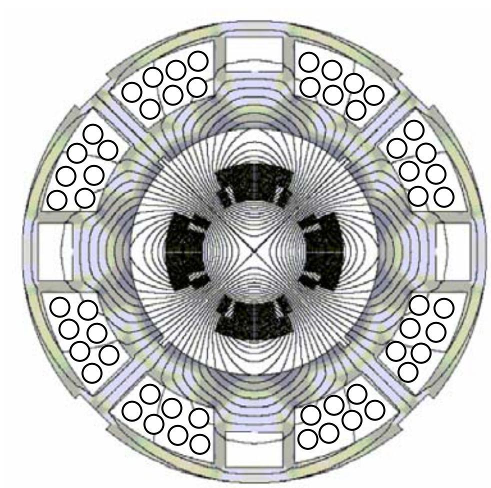

Figure 5 Cold mass cross-section with multiple tube bundle heat exchangers.

Figure 5 shows a cold mass with eight tube bundles, seven ¾ inch tubes per bundle. An optimization has determined that ¾ tube is an approximately optimum size. For tubes larger than ¾ inch, the He II conduction cross-sectional area decreases quickly as fewer large tubes can be placed in each cooling hole. For tubes smaller than ¾ inch, the He II conduction cross-sectional area is also decreased. There are more tubes, but each has a smaller He II cross-section. Figures 6-9 show the calculated temperature distribution at the non-IP end of Q1 for various sizes of tubes and number of tubes per bundle. The Kapitza conductance coefficient as defined in [3] was taken as 892.8 W/m^2-K^4, the value measured for the existing external heat exchanger pipe in the LHC inner triplet. As more, smaller tubes are used, the temperature difference between the outside of the tube (pressurized) and the inside of the tube (saturated) is decreased as the increased surface area reduces the total Kapitza resistance.

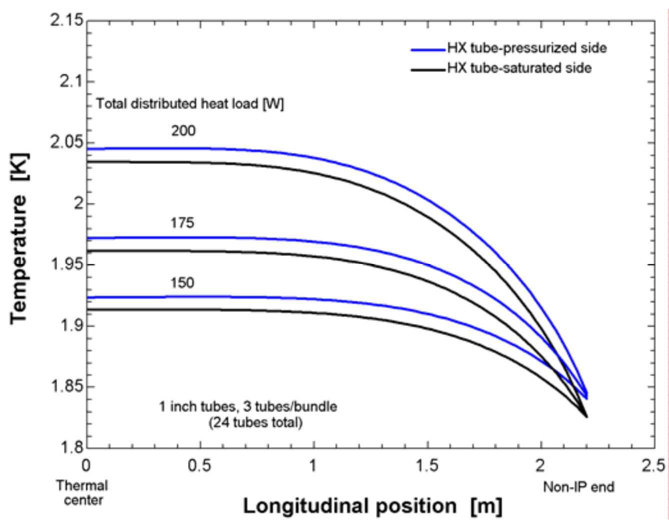

Figure 6 Temperature vs. longitudinal position for 24 1-inch heat exchanger tubes.

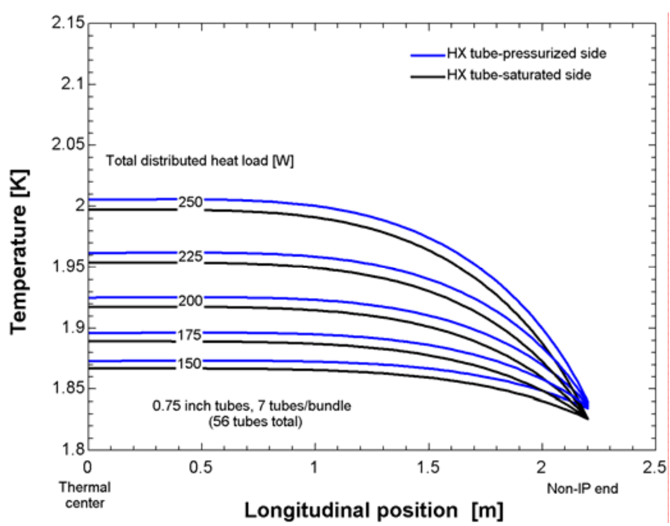

Figure 7 Temperature vs. longitudinal position for 56 0.75-inch tubes.

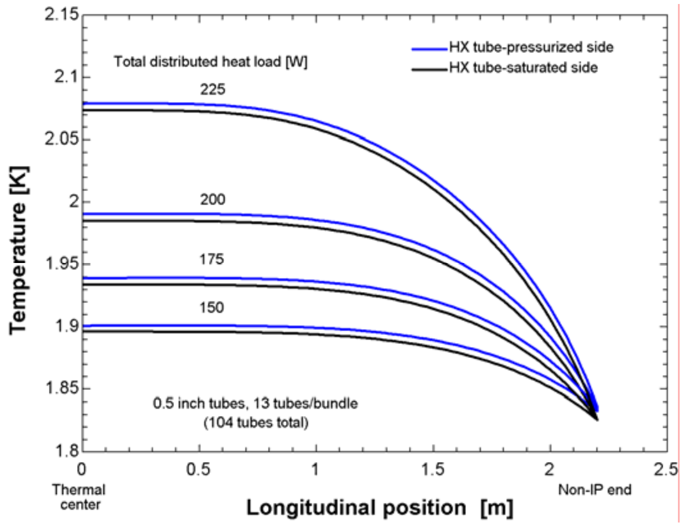

Figure 8 Temperature vs. longitudinal position for 104 0.5-inch tubes.

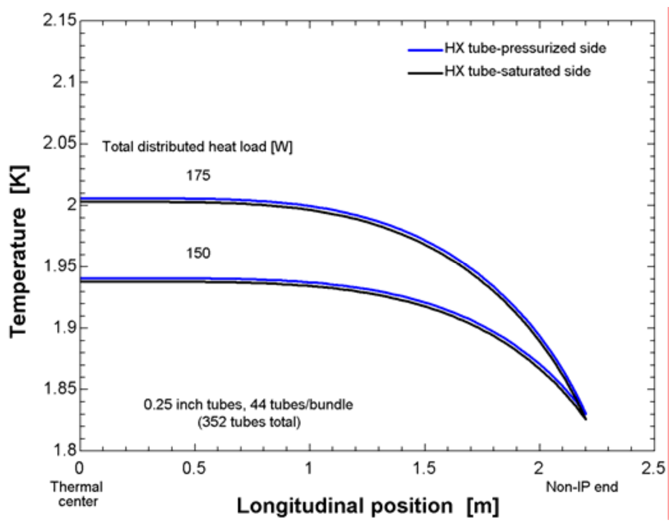

Figure 9 Temperature vs. longitudinal position for 352 0.25-inch tubes.

A second effect that must be considered is the relationship between the height of the liquid column and the heat transfer-induced temperature drop. For a given liquid column height, if the heat transfer-induced temperature drop is too high then the local saturation temperature will be exceeded and localized film boiling will occur, drastically changing the system heat transfer characteristics. This dependence on the liquid column height is illustrated in Figure 10 with regions of desirable He II heat transport and undesirable film boiling noted.

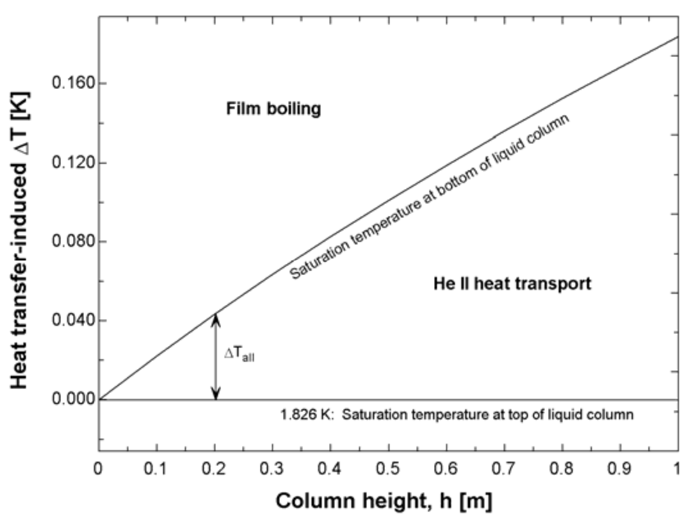

Figure 10 Heat transfer-induced ΔT vs. column height for film boiling and He II heat transport.

This relationship can then be used to calculate required cross-over pipe sizes. Approximating a linear relationship between the liquid column height h (i.e., cross-over pipe length) and the allowable temperature drop ΔT_{all}, Equation 1 shows that the maximum allowable heat flux q''_{all} is a constant. The minimum cross-over pipe size then depends only on the heat transfer rate, as shown in Figure 11. The required cross-over pipe heat transfer rate at the Q1 non-IP end is estimated to be 330 W (250 W from the Q1 cold mass, 80 W from the MCBX-1 corrector), and the temperature at the liquid surface in the pumping line is assumed to be 1.825 K.

$$\left(q''_{all}\right)^3 = f^{-1}(T)\frac{\Delta T_{all}}{h} = f^{-1}(T)\frac{C\,h}{h} = \text{Const.} \qquad (1)$$

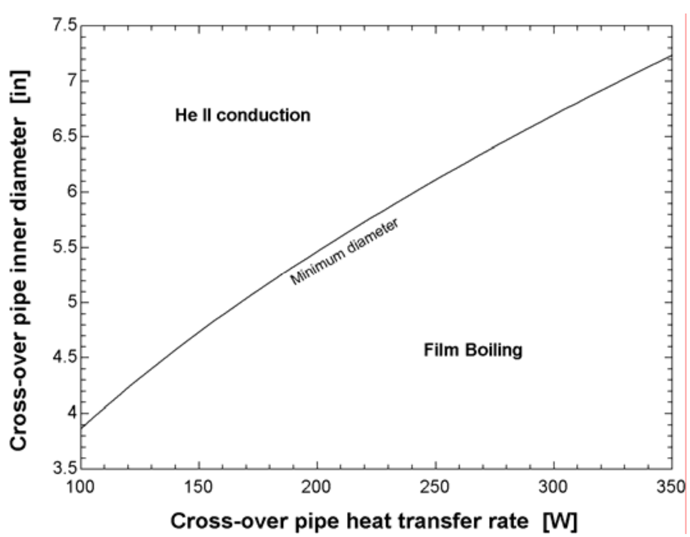

Figure 11 Cross-over pipe diameter vs. cross-over pipe heat transfer rate.

It is critical to note that the temperature drop restriction of Figure 10 applies to not only the cross-over pipe but the entire saturated He II volume. The longitudinal temperature drops along the heat exchanger tubes must be included and compared to the allowable temperature drop ΔT_{all}. The green area in Figure 12 approximates the range of column heights for the Figure 5 cold mass, from the uppermost cooling holes to the lowermost cooling holes.

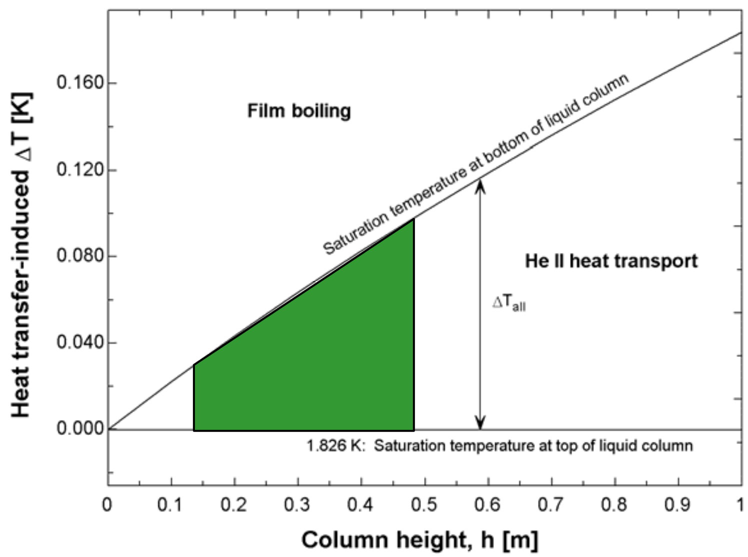

Figure 12 Heat transfer-induced ΔT vs. column height for film boiling and He II heat transport with the estimated range of liquid column heights within the magnet indicated.

For the uppermost cooling holes, a 30 mK temperature drop from the cold mass thermal center to the He II liquid surface is allowed. For the lowermost cooling holes, a 100 mK temperature drop from the cold mass thermal center to the He II liquid surface is allowed.

Figures 6-9 show that even if only 150 W of the Q1 non-IP end heat load is taken at the 1.9 K temperature level, the longitudinal temperature drop will be at least 50 mK. This does not include the additional temperature drop that would occur in the cross-over pipe. The result would be film boiling in the upper cooling holes, possibly in the lower cooling holes as well. For this reason, filling the heat exchanger tubes into the pumping line is not a thermally feasible cooling scheme.

A second internal heat exchanger cooling scheme that has been analyzed elsewhere [4] is shown in Figures 13 and 14. This scheme also uses multiple heat exchanger tubes, but they are only partially filled with liquid. Liquid column height considerations that have been extensively discussed here are eliminated, but regulation of multiple liquid levels is required.

From a thermal standpoint, this scheme is feasible within the design temperature profile even though the relatively small heat transfer area results in a large temperature drop across the heat exchanger tube walls due to Kapitza resistance.

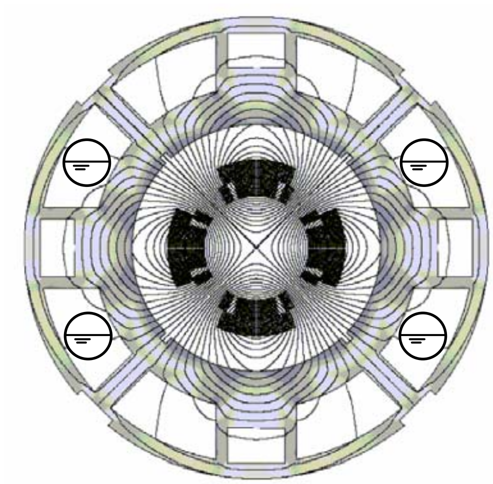

Figure 13 Cold mass cross-section with four internal heat exchanger pipes partially filled with liquid.

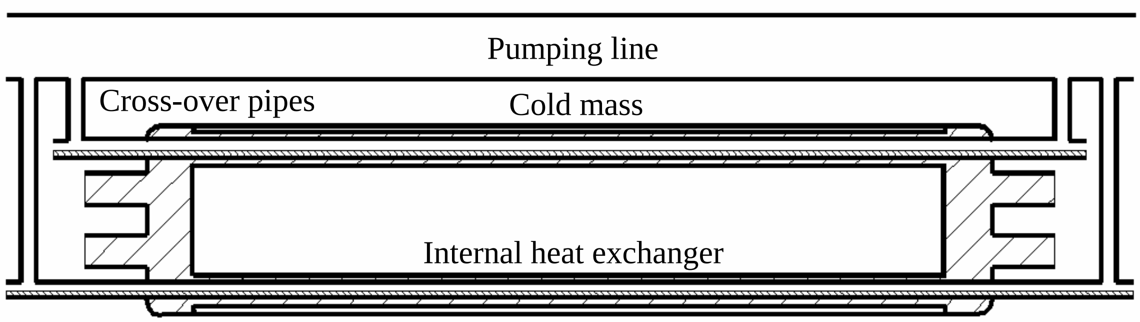

Figure 14 Schematic showing cooling of a cold mass with multiple internal heat exchanger tubes partially filled with He II.

Conclusions

Two internal heat exchanger cooling schemes have been studied.

One scheme uses multiple heat exchanger tubes completely filled with He II. This scheme is not thermally feasible. The required heat transfer through the saturated He II would exceed the allowable temperature drop, resulting in film boiling and insufficient cooling within the cold mass.

The second scheme uses multiple heat exchanger tubes partially filled with He II. This scheme is thermally feasible. Regulation of multiple liquid levels is required, which has implications on interconnect piping, the number of control valves required by the inner triplet, and the feedbox design.

References

[1] Ph. Lebrun, et al., “Cooling Strings of Superconducting Devices Below 2 K: The Helium II Bayonet Heat Exchanger” in Advances in Cryogenic Engineering 43A, edited by P. Kittel, Plenum Press, New York, 1998, pp. 419-426.
[2] R. Rabehl, “LARP IR Cryogenics: Parametric Studies of Heat Transfer in IR Quadrupole Magnets – Beam Pipe to External Heat Exchanger,” LARP Document 279, May 2006.
[3] Ch. Darve, et al., “He II Heat transfer through a Corrugated Tube – Test Report,” Fermilab Technical Division Note TD-99-064, November 1999.
[4] R. Rabehl, “LARP IR Cryogenics: Parametric Studies of Heat Transfer in IR Quadrupole Magnets – Beam Pipe to Internal Heat Exchanger,” LARP Document 341, July 2006.