LARP IR Cryogenics: Parametric Studies of Heat Transfer in IR Quadrupole Magnets – Beam Pipe to Internal Heat Exchanger

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Introduction

A design temperature profile for an upgraded LHC interaction region (IR) has been documented [1]. This design temperature profile and subsequent analyses [2, 3] have focused on the use of an external magnet heat exchanger. This document provides results of investigations into the use of a heat exchanger internal to the cold mass.

The heat transfer path discussed here has four segments: beam pipe annulus to collar pole tip, collar pole tip to yoke inner diameter, yoke inner diameter to yoke cooling holes, and heat exchanger pipe pressurized side to heat exchanger pipe saturated side. The original design temperature profile specified a temperature drop of 324 mK from the beam pipe to the saturated liquid surface. This design temperature drop is used in this analysis.

Analysis

The heat deposition data presented in [2] will not be repeated here. The non-IP end of the Q1 cold mass is again the focus of the analysis with a heat load of about 330 W.

Figure 1 is a schematic representation of the 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.

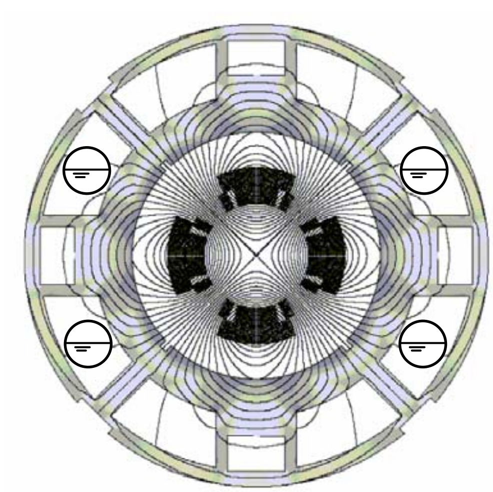
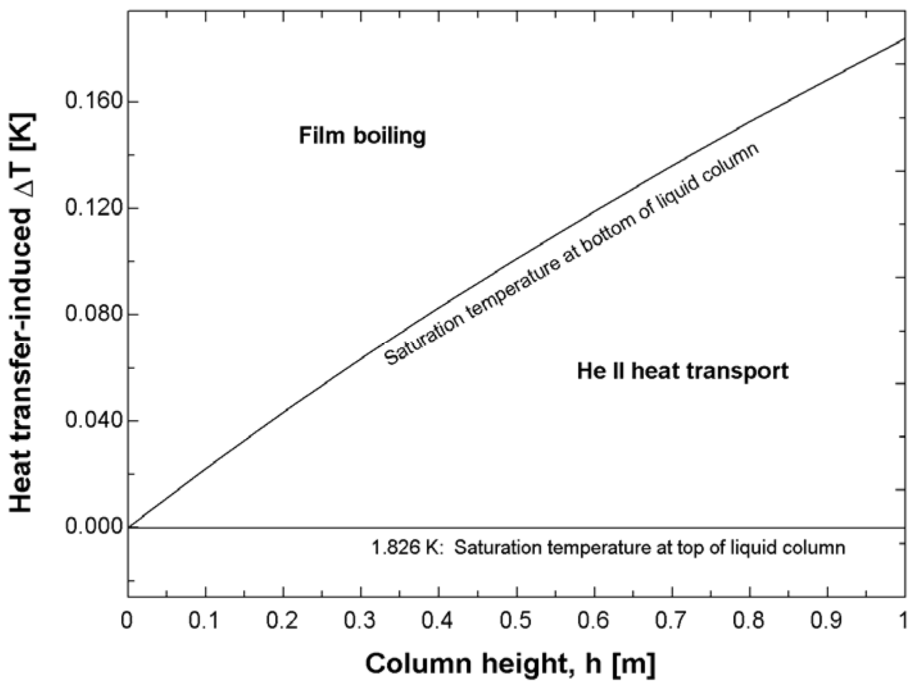


Figure 1 Cold mass cross-section with four internal heat exchanger pipes.

The heat exchanger arrangement shown in Figure 1 presents some special challenges. The four heat exchanger tubes are shown at two elevations, but liquid level must be maintained in the four tubes. Completely filling the bottom two heat exchanger tubes would change the heat transfer characteristics. One effect is that additional He II conduction is required to transfer heat to the liquid-vapor interface where vapor is generated. 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 2 with regions of desirable He II heat transport and undesirable film boiling noted.



<u>Figure 2</u> Heat transfer-induced ΔT vs. column height for film boiling and He II heat transport.

In the two-tiered system shown in Figure 1, the lower tubes must be connected to the upper tubes at the interconnects if liquid level is maintained in the upper tubes only and the lower tubes are filled completely. The vertical separation between heat exchanger tubes is about 0.2 m, and the heat load per heat exchanger tube is over 80 W. The resulting temperature drop through this vertical connection is calculated to be over 2 K. The lower tubes will not remain in superfluid if any sizeable heat load is present.

Figure 2 indicates that for a 0.2 m high column, the maximum allowed temperature drop is 40 mK in order to maintain He II heat transport. This limits the heat transfer rate per lower heat exchanger tube to 20 W.

These calculations support the need to control liquid level in all four heat exchanger tubes if internal heat exchanger tubes are used to remove the heat deposited in the cold masses.

The other cold mass parameter values established in [2] remain the same for the purposes of this analysis. These parameters and their values are repeated in Table 1.

Table 1 Cold mass parameters and values.

Design parameter	Value
Beam pipe He II annular gap	1 mm
Collar radial cooling channels	7% open (effective)
Yoke radial cooling channels	5 mm wide

The temperature profile of the cold mass cross-section was then calculated using these cold mass parameters and the heat load distribution used in previous analyses. One input to the model is the Kapitza conductance at the He II-heat exchanger pipe interface. The Kapitza conductance coefficient as defined in [4] 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. A second input is the wetted fraction of the heat exchanger pipe internal surface area. The minimum required fraction is 0.40, at which point the temperature in the beam pipe annulus reaches 2.12 K. This is just below the lambda point. The calculated cold mass temperature profile is shown in Figure 3. The temperature drop across the heat exchanger wall dominates with a value of 150-180 mK.

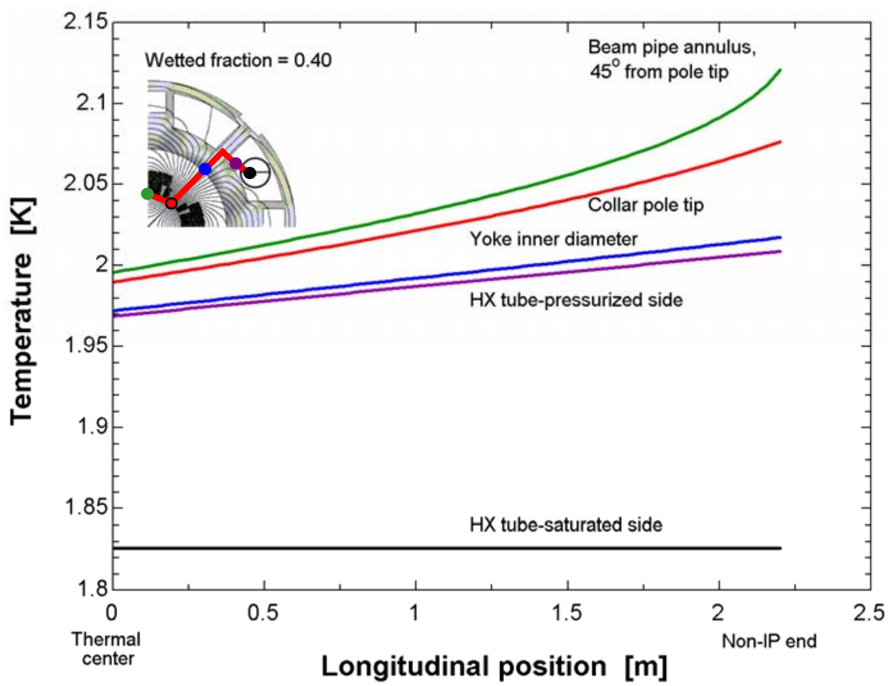
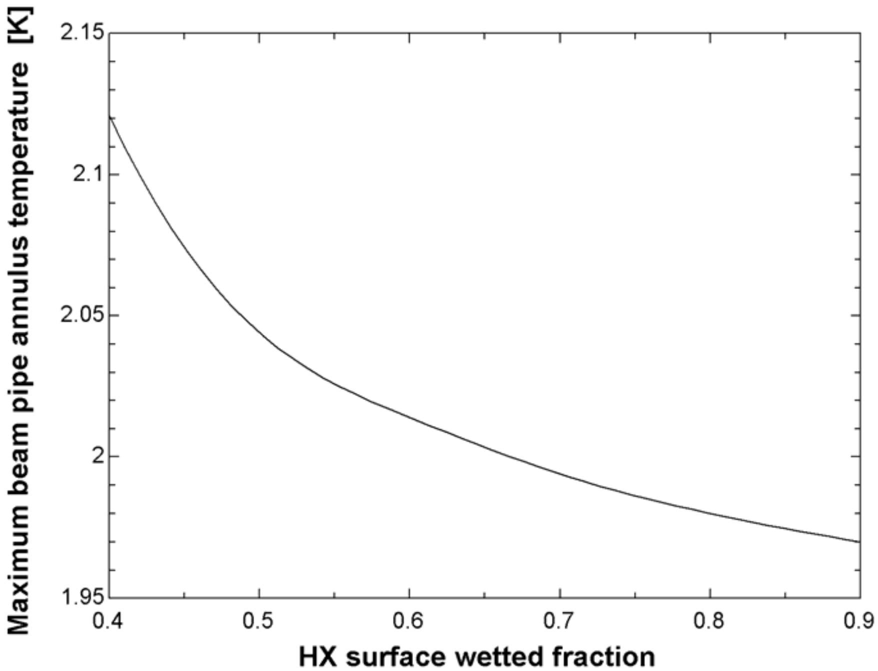


Figure 3 Cold mass cross-sectional temperature profile with four internal heat exchanger pipes, each with a 40% wetted surface.

The beam pipe annulus temperature as a function of heat exchanger pipe wetted fraction is given in Figure 4.



<u>Figure 4</u> Maximum beam pipe annulus temperature vs. heat exchanger wetted surface fraction.

Conclusions

Four internal heat exchanger tubes can be used to remove the heat deposited in the inner triplet cold masses as a result of the LHC luminosity upgrade. Calculated cold mass temperatures fall within the design temperature profile.

If this scheme is chosen, liquid level must be maintained in all four heat exchanger tubes. This has implications on interconnect piping, the number of control valves required by the inner triplet, and the feedbox design.

References

[1] R. Rabehl, "LARP IR Cryogenics: Design Temperature Profile," LARP Document 100, December 2005.

[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] R. Rabehl, "LARP IR Cryogenics: Investigation of the Limitations of an External Bayonet Heat Exchanger for the LHC Luminosity Upgrade," LARP Document 329, June 2006.

[4] Ch. Darve, et al., "He II Heat transfer through a Corrugate Tube – Test Report," Fermilab Technical Division Note TD-99-064, November 1999.