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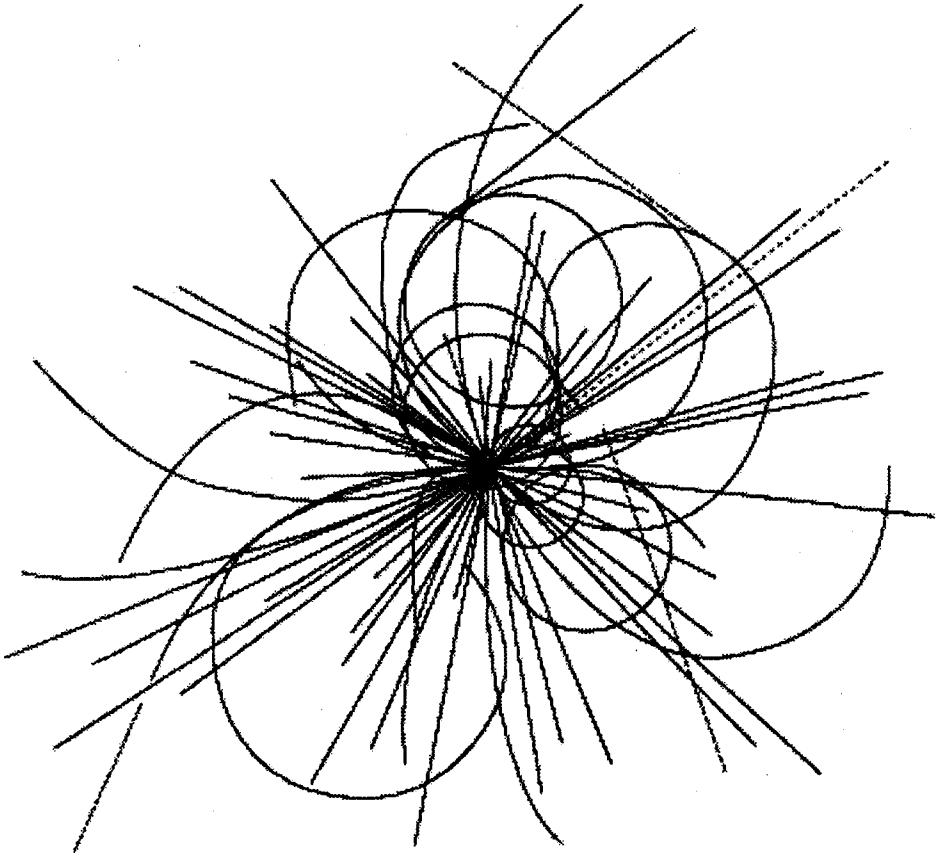

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CONCEPTUAL DESIGN STUDIES FOR HE II COOLED LOW BETA QUAD IR MAGNETS

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INTRODUCTION

This paper discusses the results of the Cryostat Design Group's effort on the Conceptual Studies of the Low Beta Quad Magnets (LBQ) cooled by superfluid Helium (He II). The conclusion of this study is that the "adapted CERN" He II cooling design does present a satisfactory system for cooling the LBQ magnet interaction region (IR) radiation heat loads; however, for the increased luminosity heat load some research on the cable insulator is required to achieve an effective thermal connection between the outer coil and the He II bath. The LBQ magnets are the final four magnets on either side of the IR detector. These four magnets are named Q1, Q2A, Q2B, and Q3, reaching outward from the interaction point (IP). All magnets have a 50-mm magnet bore and produce a gradient of 193 T/m. Magnetic lengths were all considered to be 15 meters for the purposes of this study.

Radiation from the proton-proton collisions results in a significant heat deposition on the LBQs which is most severe for Q1 and least severe for Q2 and Q3. This is reduced with a 25-mm aperature, 3 meter long steel collimator installed upstream of Q1. Total heat to be removed from Q1 is 47 watts at the baseline luminosity (10^{33} proton/cm2 –sec) which presents the most severe design challenge.1 Maximum local heat deposition is 0.25 mw/g. The average value for the inner coil compared to the worst 2.5-meter length is 1.01 w/m average compared to 2.24 w/m maximum. The thermal model results were generated for both the maximum heat loads and the average heat load. The design loads for the 10^{34} luminosity design can be obtained by multiplying the above values by ten. The assumption has been made that a cooling collimator is installed inside the beam tube along the entire length of the magnets to absorb one-half of the total heat load for the increased luminosity design.

"ADAPTED CERN" CONCEPT

The CERN superfluid cooled magnet design[2] was adapted to our requirements to come up with the "adapted CERN design" shown in Figure 1. Heat is removed from the cold mass

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by a 1 atm He II bath at approximately 1.9 K. The heat sink for the 1 atm bath is two-phase He II at 1.8 K flowing inside a heat exchanger(s) that runs the entire length of the cold mass. Cryogenics would supply 2.2 K liquid He II which is then expanded through a Joule-Thompson (JT) valve into two-phase flow at 1.8 K saturation conditions (1.8 K, 0.001638 MPa) and flows to a concentric tube heat exchanger. It was concluded from a mechanical design viewpoint that routing the liquid supply portion (or low quality two-phase flow) outside the cold mass (inside the 4.2-K shield) would be preferable to making concentric tube connections at the interconnects. The recirculating pump shown in Figure 1 is not required. By design the pressure drop in the system is very low and the required head pressure can be obtained from pressure downstream of the JT valve. The 1.8-K heat exchanger is pumped to keep constant saturation conditions. The intermediate shield is a 4.2-K cooled shield that plays a part in the cooldown and quench protection procedures. Magnet cooldown begins by diverting some of the 4.2-K supercritical He and circulating this fluid through the magnets. The safety relief valves (SRV) are open during this cooldown period. When the magnet has been cooled to 4.2 K, the SRV and the cooldown and fill valves are closed. The magnets are now filled and pressurized to 1 atm. The He II heat exchangers are now activated to bring the magnets down to their operating temperature of 1.9 K. During a quench the SRV opens at 20 atm and the He II bath is relieved into the 4-K cooling duct. All cryogenic resources are concentrated in the spool piece which is sufficiently far from the IR not to impose any significant maintenance problems. The advantages of the "adapted CERN" design are that it requires no re-invention of the wheel, the design makes efficient use of cryogenic resources, and has planned cooldown and quench recovery procedures. Also heat exchangers can be sized for either baseline luminosity or for increased luminosity levels.

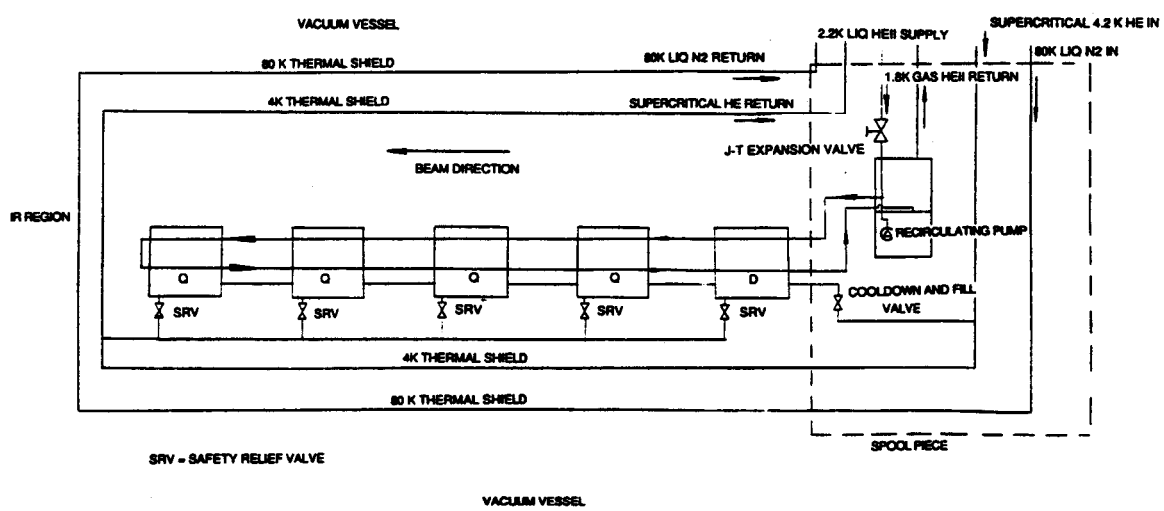

Figure 1. Cooling Flow Schematic for the "Adapted CERN" Concept.

He II Heat Exchanger Duct Size Calculations

The number of heat exchangers and their dimensions were determined by the need to limit pressure drop and the need to provide enough area to limit heat flux and the associated temperature drop. The design assumption was to limit pressure drop to 0.14 kPa. This was done to keep the two-phase He II as close as practical to 1.8-K saturated conditions and to minimize the "reverse" Joule-Thompson effect.[3] The total heat load was assumed to be applied uniformly over the heat exchanger length and all heat was absorbed by the latent heat of He II (20 J/g). The two-phase pressure drop was calculated by homogeneous model.[4] The assumption was made that initial quality was zero and the quality rose toward

0.95 at heat exchanger exit as it absorbed heat. The pressure drop predicted by the homogeneous model was close to a gas-only pressure drop.

Heat Transfer Design

The heat transfer analysis approach was to evaluate the heat flux that the LBQ cooling system is required to remove against the available driving delta temperature. It is a design ground rule that the maximum temperature of the superconducting material is 2.0 K. This was chosen in part to provide a 150 mK margin above the Lambda temperature at 1 atm. The ultimate sink temperature is saturated He II at 1.8 K. Consequently, in our design we have, without margin, a driving temperature of 200 mK to remove heat deposited by IR radiation and static heat leaks. The available driving temperature is the sum of five primary components: (1) ΔT_1 – Temperature difference required to remove the IR radiation energy deposited on the inner/outer coils (also collars/yoke) to the He II bath at 1 atm, (2) ΔT_2 – Temperature difference across the He II bath to carry heat to the outside of the heat exchanger duct, (3) ΔT_3 – Kaptiza Resistance at heat exchanger duct – He II interface, (4) ΔT_4 – Conduction resistance across heat exchanger wall, and (5) ΔT_5 – Kaptiza resistance at He II/inner wall interface. The first and last of these are discussed below. The assessment resulted in the conclusion that the 200 mK limit could be obtained.

ΔT_1. CERN conducted a test of the heat transfer of heated conductors in a superfluid bath (1.7 – 1.9K).[5] The test utilized stainless steel as a pseudoconductor and electrically heated a central turn and two of its neighbors and measured the temperature difference between the sample and the surrounding bath. The conductor was prepared similarly to the way that SSC fiberglass epoxy conductors are prepared. A 2-mm channel between rows of fiberglass tape was left for He II flow. CERN varied the heat input from 0 to 56 mW which corresponds to 0 to 8.78 mW/cm^3 using their cable dimensions. The 10^{33} luminosity maximum heat load value of 0.896 mw/cm^3 corresponds to CERN test data at 5.7 mw. The 10^{34} luminosity maximum heat load of 2.816 mw/cm^3 corresponds to CERN data at 17.98 mw. From CERN data with heat transfer at all four faces we would expect only a 14 mK delta temperature rise at the increased luminosity heat load. The CERN test investigated the effect of one of the small faces insulated from transferring heat to the bath by thermal grease. The increased luminosity delta temperature rises to to 25 mK and the overall heat transfer coefficient is backed out to be 0.0132 W/cm^2 –K. The power removed by a small face is shown in the CERN paper[5] and from this data a heat transfer coefficient can be calculated separately for the large face and the small face. The small face heat transfer coefficient is 0.140 W/cm^2 –K and the large face coefficient is 0.00462 W/cm^2 –K.The CERN data did not address the isolated outer layer of conductors which are effectively isolated from the bath by the inter-layer Kapton sheets and the Kapton sheets at the collar interface.

ΔT_5. The temperature difference between the inner wall and the He II depends on test data. Normal engineering boiling correlations are not applicable here because He II does not boil (nucleate bubble growth, etc.) like normal fluids. Because of the very high thermal conductivity, He II boiling takes place on the liquid surface and not the heat transfer surface. The most applicable test data is a heated two-phase flow test of He II conducted at CERN.[6] The CERN test heat exchanger tube was 25.6 mm, and the heated test section was 2 m (the actual flow length was 24 m). The heat flux input was 0–3.5 W/m (0.0044 W/m^2), the flow rate 0.83 g/sec, and the saturation temperature was 1.9 K. The input quality was 0.64 and exit quality ranged from 0.68 to 1.0. The test results indicate that the heat transfer coefficient (ΔT_{3-5}) was 0.059 W/cm^2 –K and was independent of quality up to dryout. The He II liquid covered 35% of the tube perimeter independent of local heat flux. The results for a heat flux of 0.00164 W/cm^2 is ΔT_{3-5} =27.8 mK. CERN test results are independent of quality and heat flux within the limits tested. Heat flux is linearly proportional to ΔT. The CERN heat transfer coefficient includes the effect of the inside/outside Kapitza resistance, conduction resistance across the heat exchanger duct, and the effect of 35% liquid coverage of the inner perimeter.

2D Thermal Model

A two-dimensional thermal model of the LBQ cross section was created[7] using SINDA[8] to investigate the effectiveness of the He II cooling and to conduct whatever trade studies (such as insulation thickness) might be required.The thermal model was generated on the following assumptions: He II bath radial temperature drop was neglected, He II/ inner coil heat transfer based on the convection coefficients backed out of the CERN experiment, outer coil heat transfer by conduction only, no He II heat transfer between laminations, and Kaptiza resistance at all He II/ solid boundary interfaces. Kaptiza resistance and gas conduction SINDA subroutines were created to include these effects. Model results for baseline luminosity show inner conductor maximum temperature of 1.808 K and outer conductor maximum temperatures of 2.07 K. The increased luminosity maximum conductor temperatures were 1.860 K and 2.97 K for the inner and outer conductors respectively. The thermal model results at increased luminosity heat load show some outer conductor layers at greater than 2.0 K temperature due to the assumption of heat transfer by conduction only. Some future experimental work is recommended to measure the extent of outer row thermal coupling with the static superfluid bath.

SUMMARY

As a result of the above, our study recommended that the "Adapted CERN" design should be selected over other investigated designs because of: workable concept for increased luminosity design, i.e., there is room for growth, greatest design margin, design concentrated cryogenic resources at one end, baseline design would require only two heat exchangers. The recommended design parameters are: four 88-mm cooling channels in yoke, liquid supply line routed outside of the cold mass, 78-mm diameter corrugated cooling ducts, two heat exchangers for baseline heat load; the design is upgradable with the addition of a beam cooling insert and two additional heat exchangers.

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