LHC Luminosity Upgrade: Cryogenic Parametric Studies of a He II Cooling System for a Forward Q0 at ATLAS/CMS

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For a forward Q0, either NbTi or Nb_3Sn can be used for the coil conductor. Parametric studies have been carried to estimate coil temperatures and to estimate some of the cryogenic system characteristics: required He II cross-sections, pipe lengths, and pipe sizes.

Coil Temperatures

The coil surface temperatures are estimated for both NbTi and Nb_3Sn coils. Coil temperatures are first calculated assuming the He II cooling is in the annular space between the beam pipe and the coils.

For a NbTi coil, it is assumed that there is little penetration of helium into the coils and any cooling channels through or along the Kapton wraps are closed due to the large mechanical forces. This has been confirmed elsewhere [1]. The coil surface temperature is then governed by the Kapitza resistance between the He II and the Kapton and conduction through the Kapton wraps. A Kapton thickness of 125 μm is assumed.

For a Nb_3Sn coil, there is no penetration of helium into the coils. The coil surface temperature is governed by the Kapitza resistance between the He II and the epoxy and the conduction through a thin layer of epoxy insulating the coils from the beam pipe. An epoxy thickness separating the coil from the He II bath is assumed to be 125 μm.

The Kapitza heat transfer between the He II and Kapton and epoxy surfaces is given by [2]:

$$q`` = 47.43\left(T_{Kap}^4 - T_{He}^4\right)$$

where q`` is the heat flux [W/m^2], T_{Kap} is the Kapton temperature [K], and T_{He} is the helium temperature [K].

Figure 1 plots the estimated coil surface temperatures for both NbTi and Nb_3Sn coils as a function of heat flux into the He II. The Kapton wraps raise the surface temperature of the NbTi coil by up to several hundred mK. The epoxy raises the surface temperature of the Nb_3Sn coil by up to 200 mK.

Temperatures within the coils are governed by the volumetric heat deposition and the thermal conductivities of the coil materials. Detailed analyses of conduction-cooled coils (NbTi and Nb_3Sn) are required to determine the limiting operating temperature margin.

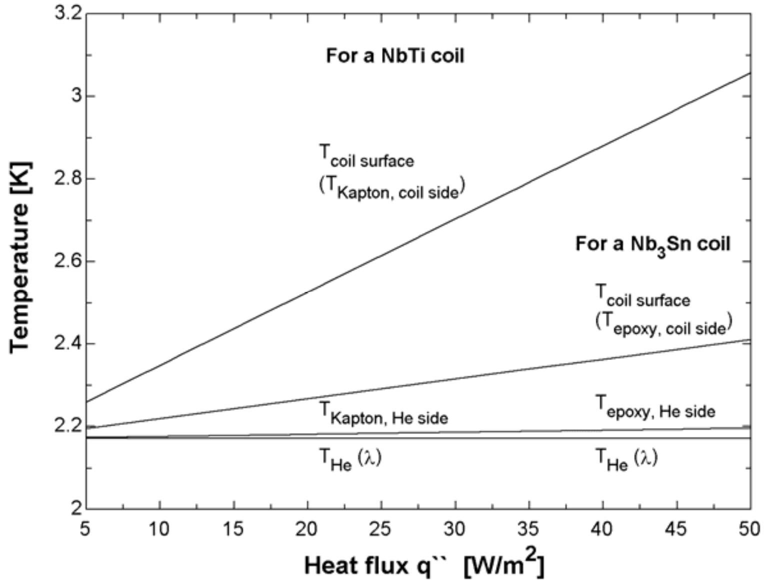

Figure 1 Estimated coil surface temperatures vs. heat flux for NbTi and Nb_3Sn coils.

If the He II cooling is located outside the stainless steel collars, the coil temperatures are expected to be similar to Figure 1 provided sufficient radial cooling channels through the collars are present.

The stainless steel collars have an inner radius of 10.5 cm and an outer radius of 16.5 cm. Radial cooling channels through the collars would have a length of 6 cm. Assuming a ΔT of 10 mK at a temperature of 2.15 K, Figure 2 plots the number of required 2 mm diameter cooling channels as a function of the total heat load for magnet lengths of 3 m, 5 m, and 7 m. This is the total number of cooling channels, so the number of cooling channels per quadrant is one-fourth this number.

It is important to note that because the He II thermal conductivity function is strongly dependent on temperature (especially near the lambda point), the number of cooling channels required is also strongly dependent on temperature. For example, at 2.13 K the number of cooling channels required is a factor of five less than at 2.15 K.

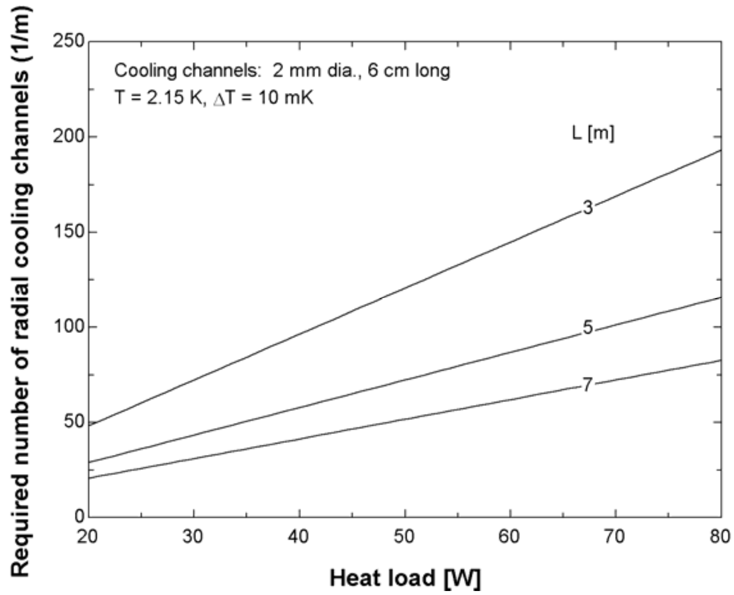

Figure 2 Required number of radial cooling channels for a 10 mK ΔT (2.16-2.15 K)

Pressurized He II Cooling System

A very basic flow schematic for a pressurized He II cooling system is presented in Figure 3. A rough temperature profile is also included.

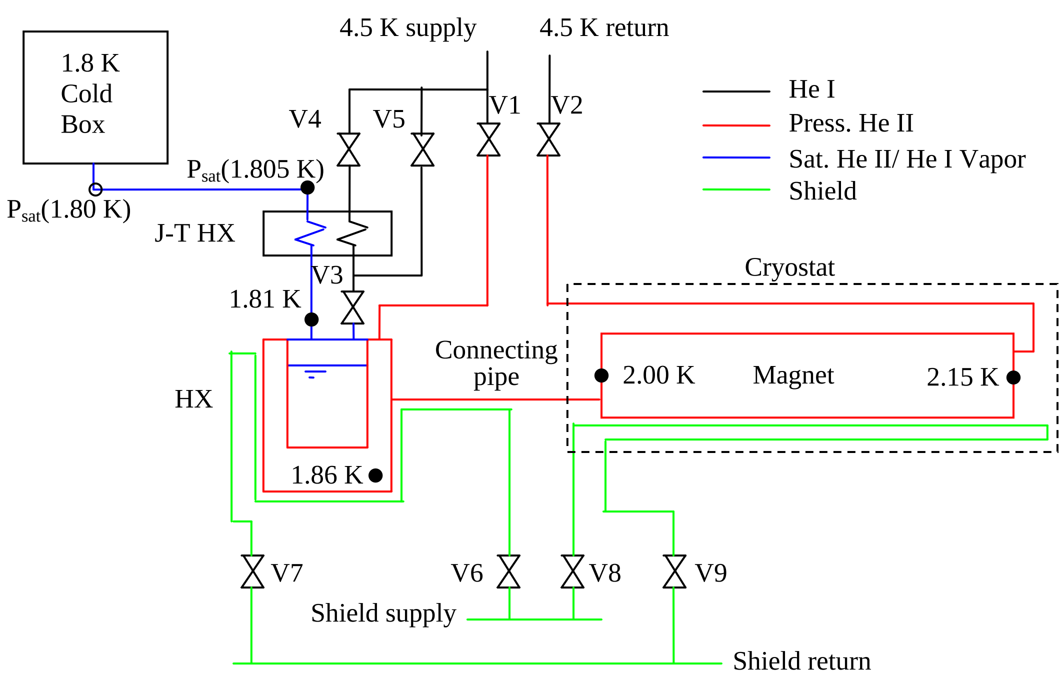

Figure 3 1.9 K static bath cooling system flow schematic.

- A 150 mK temperature drop (2.15-2.00 K) is allocated to the magnet.
- A 140 mK temperature drop (2.00-1.86 K) is allocated to the connecting pipe. This pipe connects the magnet to the 1.8 K heat exchanger and can impose a significant temperature drop on the system. This effect would be minimized by putting the heat exchanger inside the cryostat, but space restrictions in this application may eliminate this possibility.
- A 50 mK temperature drop (1.86-1.81 K) is allocated across the heat exchanger wall. This is the temperature drop from the pressurized He II to the saturated He II and is composed of two Kapitza resistances (pressurized He II to HX wall, and HX wall to saturated He II) and a conduction resistance through the heat exchanger wall material.
- A 5 mK (equivalent) temperature drop (1.81-1.805 K) is allocated across the J-T heat exchanger. The J-T heat exchanger precools the He I before it is expanded into the saturated He II bath. This reduces flashing losses from ~40% to ~5%.
- A 5 mK (equivalent) temperature drop (1.805-1.800 K) is allocated to the pumping line to the 1.8 K cold box.

The last two items are equivalent temperature drops, meaning they are not actual temperature drops but pressure drops corresponding to 5 mK drops in saturation temperature.

It is assumed that a thermal shield will be integrated into the cryostat.

Parametric Studies

Figure 4 plots the required He II cross-section to longitudinally conduct the heat load from the magnet to the connecting pipe. The temperature range is 2.15 K at the IP-end of the magnet and 2.00 K at the non-IP end of the magnet. The heat load is assumed to be uniform longitudinally and azimuthally. Three magnet lengths are included: 3 m, 5 m, and 7 m. For reference, a 0.005 m^2 area corresponds to a 70 mm OD beam pipe with 106 mm ID coils.

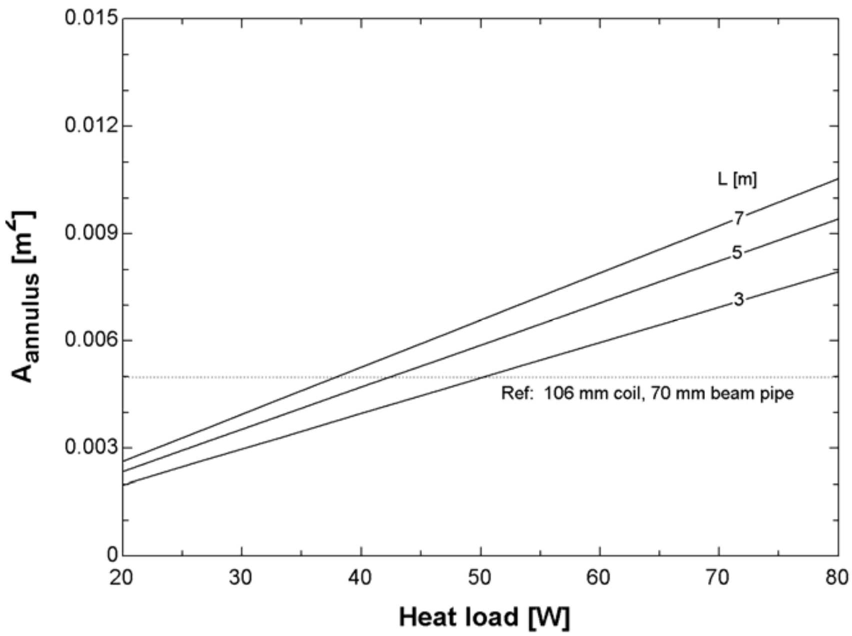

Figure 4 Required magnet He II cross-section vs. heat load for a 150 mK ΔT (2.15-2.00 K)

Figure 5 plots the required inner diameter of the connecting pipe to conduct the heat load from the magnet to the heat exchanger. The temperature range is 2.00 K at the magnet end and 1.86 K at the heat exchanger. Pipe lengths ranging from 1 m to 20 m are included.

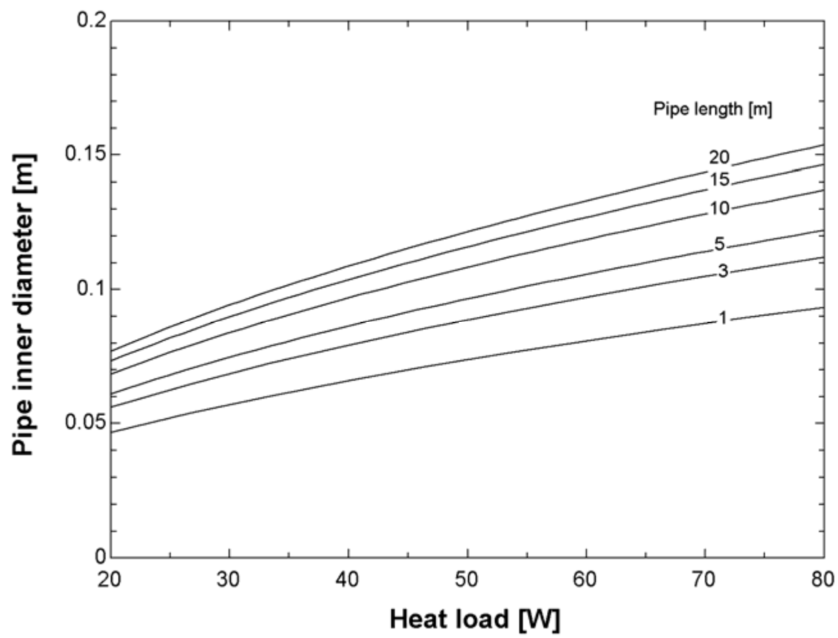

Figure 5 Required connecting pipe inner diameter vs. heat load for a 140 mK ΔT (2.00-1.86 K)

Figure 6 plots the required inner diameter of the pumping line from the 1.8 K heat exchanger to the 1.8 K cold box. The temperature range is 1.805 K (equivalent) at the heat exchanger end and 1.800 K (equivalent) at the cold box end. Pipe lengths ranging from 10 m to 100 m are included.

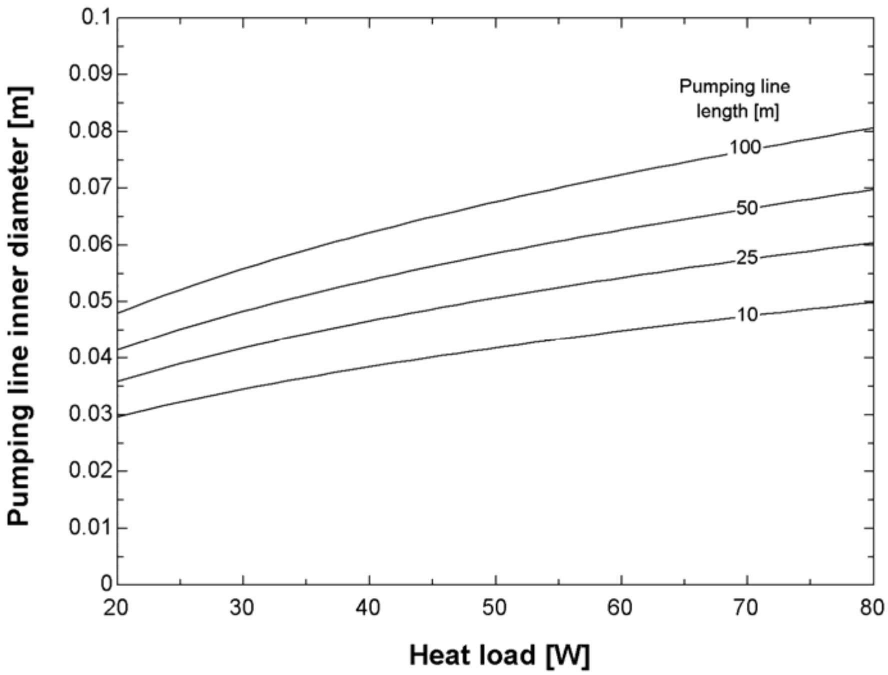

Figure 6 Required pumping line inner diameter for magnet He II cross-section vs. heat load for a 5 mK ΔT (equivalent) (1.805-1.800 K)

Physical Installation

In addition to the magnet itself, space must be allocated for several additional items:

- 4.5 K return line. This line is used during cooldown of the magnet from 300 K to 4.5 K and will be filled with He II during normal operations. An estimated size for this vacuum-jacketed line is 38 mm inner line and 88 mm outer line.
- He II connecting pipe. An estimated size for this vacuum-jacketed line is 100 mm inner line and 175 mm outer line.
- Thermal shield supply and return. An estimated size for these vacuum-jacketed lines is 25 mm inner line and 50 mm outer line.
- The pressurized He II volume is bounded by valves V1 and V2. V1 is a control valve, and V2 is an isolation valve. Placing these valves as close as possible to the heat exchanger and magnet, respectively, will minimize the He II volume.
- The heat exchanger, J-T valve, and J-T heat exchanger can be integrated into one unit. The connecting pipe between the magnet and the heat exchanger could

present a significant He II volume, so the HX unit should again be placed relatively close to the magnet.

- Pumping line. An estimated size for this vacuum-jacketed line is 50 mm inner line and 100 mm outer line.

It is preferable to thermally shield the 4.5 K return line and the He II connecting line because these lines will be filled with liquid helium.

Shielding can be integrated into flexible lines by companies such as Nexans Deutschland Industries GmbH & Co [3]. Another option is to use thermally-shielded hard piping sections with bellows, indium seals, etc. Using hard piping sections is more complicated, but these connections will need to be assembled/disassembled infrequently, only when the detector is opened or closed.

References

1. L. Chiesa, et al., "Thermal Studies of a High Gradient Quadrupole Magnet Cooled with Pressurized, Stagnant Superfluid," Fermilab Technical Division Note TD-00-064 (2000).
2. M. La China, "Modeling of Heat Transfer from SC Coils to He II: Nb-Ti vs. Nb_3Sn," Review on the Thermal Stability of Accelerator Superconducting Magnets, CERN, November 14, 2006.
3. K. Schippl, "Flexible transfer lines," Symposium for the Inauguration of the LHC Cryogenics, CERN, May 31-June 1, 2007.