HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

Milestone Report

Study of the Supercritical He Cooling

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MILESTONE REPORT

STUDY OF THE SUPERCRITICAL HE COOLING

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Abstract:

This report addresses the feasibility of an optional cooling method for the inner triplet magnets using supercritical helium. Although having ~10% performance penalty in magnetic field gradient, this option is intended as a project safeguard should there be issues with the baseline option of using superfluid helium. It is shown that supercritical helium cooling is in principle a viable option which, should the project require, could be further developed.

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1. INTRODUCTION

The final focusing magnets for the High Luminosity upgrade of the LHC (HL-LHC [1]) will receive a high heat load due to debris coming from the adjacent particle interaction points: the computed peak heat deposition in the coil is of the order 10 mW/cm^3 [2]. Superconducting magnets based on Nb$_3$Sn cable technology and operating in superfluid helium at temperatures below 2 K are objective of current magnet R&D and constitute the baseline for the project [3]. Use of Nb-Ti cable technology is kept as a backup option, requiring longer magnets due to a 30-% lower magnetic field gradient [4]. Differently from Nb-Ti magnets, Nb$_3$Sn based magnets could be designed to operate at around 4.5 K with limited loss in gradient (10-% only). This opens up the possibility to consider, as an alternative to cooling the magnets with superfluid helium, a more economical cooling system, working at about 4.5 K in supercritical helium. In this report, we will present the cryogenic design alternative for cooling these magnets by using supercritical helium. The requirements for the infrastructure for a roughly 60 m long string of these magnets located in an underground tunnel, as well as the specific constraints which the cooling poses on the magnet design will be addressed.

2. DESCRIPTION OF THE INNER TRIPLET MAGNETS

The magnets have one beam pipe protruding over the full length through which the accelerated particles travel. Separated from it by an annular gap, filled with He, are the superconducting coils, usually two layers, embedded in an iron structure to maintain all the forces and to guide and shape the magnetic field. This whole, so-called cold-mass, is enclosed in a vessel, to be kept at the chosen operating temperature and supported in a vacuum insulated cryostat. In the following we will discuss the cooling channels and their configuration specific to the cold masses only.

The Inner Triplet magnets are installed on both sides of the interaction points IP1 and IP5. They consist of two sets of six cryostats: four inner triplet quadrupoles (Q1, Q2a, Q2b, and Q3), one corrector package (CP) and one dipole (D1). The quadrupoles will be made using Nb$_3$Sn coils whereas the CP and D1 will use Nb-Ti coils. The cryostats are about 4 m to 7 m in length each, with up to 3 m of cold interconnects. One set together forms a continuous cryostat with a total length of 57 m.

The heat loads due to debris from the adjacent particle interaction point are intercepted at two distinct magnet locations and temperature levels. A first heat intercept is on tungsten absorbers which are placed inside the beam pipe vacuum and which will be cooled in the 40 K to 60 K range. This heat intercept is outside of the scope of this report. The remaining heat load will fall on the cold mass volume comprised of the yoke, collars and coils, referred to as "cold masses" for the remainder of this article. The heat loads for only one set of 6 magnets are used for calculation. For the purpose of the evaluation of the cooling the heat load to the cold masses is taken at 500 W, but provision has to be taken for it to increase by up to about 50-%. They will see an average heat load of about 8 W/m and localized peaks of up to 30 W/m.

3.   COOLING BY SUPERCRITICAL HELIUM

With supercritical He cooling, helium is circulated through the magnet structure as close as possible to the coils. Two types of cooling channels are envisaged; the annulus between the outer beam-pipe wall and inner layer of the coils, and holes through the metal collars close to the outer layer of the coils (see Figure 1). Heat is removed by using sensible heat (increase in fluid enthalpy), thereby increasing the temperature of the gas between the inlet and outlet of the magnet. Compared to the superfluid helium option, heat diffusion inside of the magnet towards the cooling channels relies on thermal conductivity of the materials foremost, since the thermal conductivity of supercritical helium itself is negligible. Even though at around 4 K the thermal conductivity of solids is higher than at 1.9 K, it cannot compensate the lack of a superfluid helium-based thermal conductive path. The helium channels have to be located as close as possible to the conductors, and a larger temperature difference between the superconducting material and supercritical helium cooling channels is then required. For this milestone report, 0.5 K is considered a reasonable value, which can be verified in detail in a follow-up study. Instead of detailed thermal calculations as function of a fixed I/Ic margin, we fixed for ease of evaluation the maximum temperature of the superconductor at 4.5. The maximum temperature of the channel wall is then 0.5 K lower: 4.0 K.
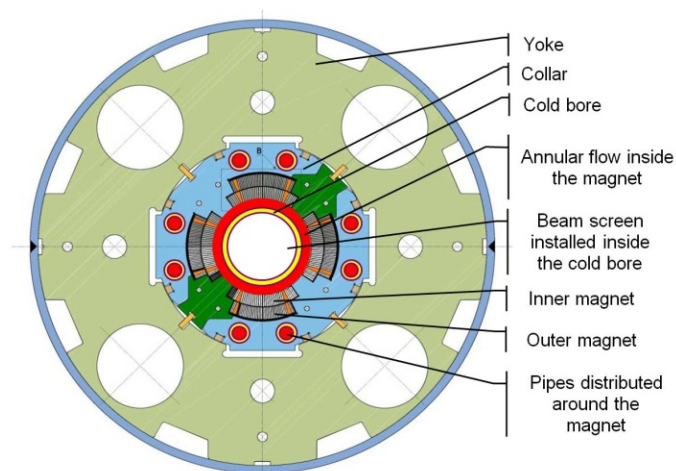

Figure 1: Cross section of the magnet with the supercritical helium cooling channels

At 4 K, the allowable temperature difference along the magnets is less than about 100 mK, and the only parameter to control it is the mass flow.

$$W = \dot{m}.Cp.\Delta T$$

Unfortunately, the supercritical mass flow available at the cold end of the refrigerator would not be sufficient by at least an order of magnitude. Therefore, a dedicated loop with a circulator is required. A typical cooling architecture with supercritical helium is shown in Figure 2 [7], [8].
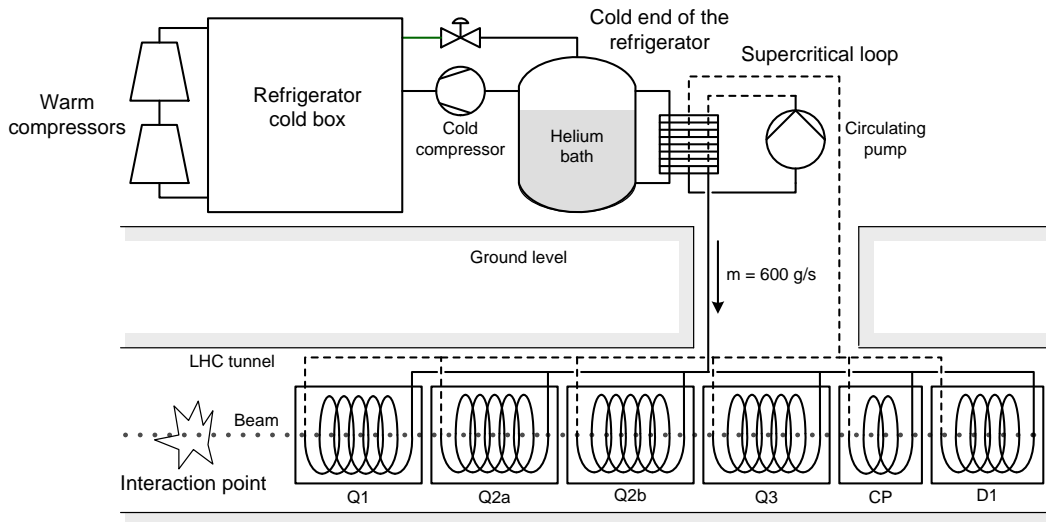
Figure 2: Architecture of the cooling by using supercritical helium with cold circulator

Several parameters have to be optimized, such as the cooling arrangement of the magnets (in series or in parallel), the location of the helium bath (at ground level or in the tunnel), the gap of the annular channel, location of the circulator (at ambient or cold temperature) or the mass flow in each magnet. These points are addressed in the next paragraphs. In a general sense, the different possibilities are compared by using the equivalent power of the refrigerator at 4.5 K expressed as exergy values; these exergy values are minimized.
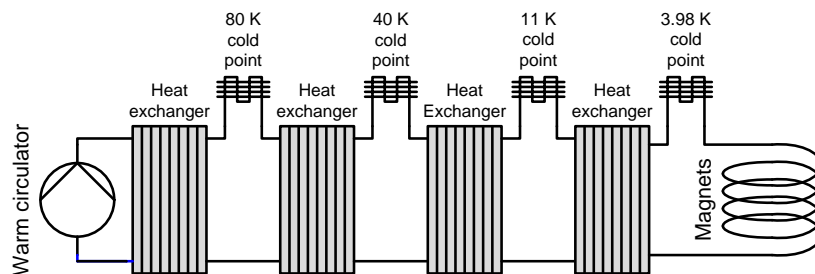

Figure 3: Supercritical loop with the circulator installed at room temperature

Location of the circulator: two options are envisaged: either to install it at room temperature: solution 1 (Figure 3) or at low temperature: solution 2 (Figure 2). In the first case, the compression energy is furnished at room temperature but additional energy is delivered at different temperature levels to compensate heat exchanger inefficiency. In the second case, compression energy (106 W) is rejected at cold. To this value some thermal conduction (50 W) in the circulator has to be added, as often in this type of machine the motor is installed at room temperature and the wheel at cold. The two solutions are compared by computing the electric consumption at room temperature. Energy is delivered at fixed points, and is then converted from low to room temperature by using Carnot efficiency. The load to remove by the supercritical loop is fixed at 600 W (500 W for the magnets + 100 W for cryogenic lines between refrigerator cold point and magnets). Temperatures of intermediate points for the first solution are indicated in Figure 3. Temperature differences of the heat exchangers (HX) are fixed at 1% of the hot temperature (i.e.: 3 K for the HX between 300 K

and 80 K). With these hypotheses, solution 1 requires 168 kW whereas solution 2 requires 58 kW. In addition, the necessary surface of heat exchangers is nearly one order of magnitude lower with the circulator at low temperature. Despite a more complicated rotating machine, solution 2 is retained.

Arrangement of the magnets: strings of six cold-masses have to be supplied at either side of the interaction points. Several hydraulic arrangements are possible. For one magnet string, the typical extremes are a supply in series (solution 3) or in parallel (solution 4). A mixed series/parallel arrangement is not considered. With the supply in series, the temperature differences of each cold-mass are added and the loop has to be cooled at a lower temperature than with the supply in parallel. On the other hand, the supercritical mass flow is higher with solution 4 which requires a larger circulator. From the operating point of view, solution 3 needs to work at a temperature nearing the superfluid transition. It will be difficult to decrease the temperature of the refrigerator if margins have to be increased. With solution 4 the flow in magnets has to be controlled to guaranty a correct magnet outlet temperature. This is generally performed by adding control-valves at the cost of some additional pressure drops and associated a loss of energy. The two solutions have been calculated for a power extracted in the magnets equal to 500 W. With solution 3, the equivalent power at 4.5 K required is about 1500 W whereas with the other solution it is less than 1100 W. Solution 4 has been retained, both for less consumption and for better flexibility in temperature margin.

Location of the helium bath: this component can be installed at ground level or inside the tunnel. With the supercritical operating conditions (3.9 K, 4 to 6 bar), the fluid compression between the ground level and the tunnel altitude (between 50 to 150 m) corresponds to a temperature decrease (around 0.25 K for 100 m). Should the bath be installed at ground level, its temperature will be higher than those of the magnets, which would correspond to a gain in efficiency. Should the bath be inside the tunnel, the compression is applied on the supply and its return which are not in the same thermodynamic state. The return line density is low, so the compression effect is negligible. On the supply line the pressure is similar but the temperature is higher, which corresponds to a lower temperature decrease and a lower efficiency (difference of equivalent power at 4.5 K: around 100 W). It is then more interesting to install the bath at ground level.

Mass flow inside the magnet: the mass flow of the magnet has also been studied and has been correlated to the size of the supercritical channels. Depending on the gap of the annual flow inside the magnet, the diameter of the pipes around is adjusted to obtain identical pressure drop in these parallel circuits. These investigations have demonstrated that an optimum gap is between 1 to 1.5 mm with a required mass flow per magnet of about 125 g/s for Q1, Q2a, Q2b and Q3 and 100 g/s for CP & D1 together: 600 g/s total. The pressure inside the supercritical loop has also been studied; the impact on the power required is negligible for pressures between 3 bar to 10 bar. This is explained by the difference of altitude between all the components of the loop that imposes around 2 bar of pressure difference inside the loop and then smears out the impact of the supercritical pressure.

With the choices retained for the supercritical loop architecture (Figure 2: bath at ground level, supply in parallel, circulator installed at cold temperature, total mass flow fixed at 600 g/s and gap of the annular channel fixed at 1.5 mm) the equivalent cooling power at 4.5 K is just above 1000 W for one set of final focusing magnets.

4. COMPARISON WITH SUPERFLUID HELIUM BASELINE

Table 1 presents the advantages and drawbacks with respect to a 500 W superfluid helium baseline (not detailed in this report). From the magnet point of view, the use of superfluid helium is to be preferred, since for identical field gradient the magnets can be made shorter than with the use of supercritical helium. Under that condition, and with flow distribution verification, supercritical helium remains a very interesting alternative as it allows reducing significantly the investment cost in cryogenics by having less equipment underground, simplifies the cooling architecture, and reduces the operating cost.

	Superfluid		Supercritical	
Energetic consumption	500 W @ 1.9 K, 450 kW electrical	-	650 W @ 3.8 K, 250 kW electrical (if 0.5 K is required for the transfer of the heat from the conductor to the fluid). Additional loads due to circulator and cryolines)	+
Cold rotating machines	4-8 cold compressors	--	1 cold compressor + 1 circulating pump	+
Installation of the cold part of the refrigerator	1.8 K underground	-	Cold box and circulating pump installed at ground level	+
Heat transfer	Superfluid + solid conduction	+	Only solid conduction and at an higher temperature	-
Superconductor margins	The conductor temperature is lower of about 2 K compared to the supercritical cooling	+	10 % decrease in field gradient	-
Experience	Known solution	+	Helium flow distribution through cold-mass to be demonstrated	-

Table 1: Comparison of the cooling solutions

5. CONCLUSIONS

The superfluid helium baseline has already demonstrated its cooling capacity for large accelerators and is clearly the most comfortable solution for performance, heat extraction and superconductor performance. Energy can be removed by solid conduction and by superfluid helium conduction, which is very efficient. On the other hand, this is the most complicated solution for cryogenic aspects: cold compressor trains with limited variability have to be used and need to be installed underground. The temperature is lower, so efficiency is reduced accordingly (roughly a factor 2 compared to supercritical Helium).

With supercritical helium some loads are added by the use of a circulator (20-% more) but that stays in favour of this solution for efficiency. The architecture is simpler, as all the refrigerator components are installed at ground level. The number of cold rotating machines is

also reduced (factor 2) which is positive as they are failure prone devices. Finally this alternative allows a reduction of the investment and operating cost for the cryogenic system.

The feasibility of an optional cooling method for the inner triplet magnets using supercritical helium has been shown and another cooling architecture without circulating pump is under investigation. If the supercritical cooling option is retained a detailed study of the heat flow in the cold masses is to be done including the margin of a +50-% increase in heat loads. Preliminary calculations have been launched to verify that a temperature difference of about 0.5 K in the magnet cold mass is realistic. The cool-down and warm-up of the magnets, and the safety requirements, in particular for managing the behaviour of the system in case of quenches, is to be studied. A full scale demonstrator should be envisaged as a next step.

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