TD-01-035

VLHC Thermal Shield Cooling

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Keywords: ***VLHC, thermal shield, beam screen, cooling system, and refrigeration power optimization.***

Abstract

The Very Large Hadron Collider (VLHC) - stage 2 cooling system has been optimized regarding the ability to minimize the total refrigeration power. The stage 2 VLHC synchrotron radiation dictates a high optimal beam screen temperature. LHC dipole cryostat thermal model results provide data to characterize the behavior of the stage 2 VLHC cooling system. In the cryogenic concept pursued here, the same helium gas cools the cryostat thermal shield and the beam screen in series. This report also focuses on different scenarios that could be used to extract the heat loads from the thermal shield and the beam screen.

1 INTRODUCTION

The Very Large Hadron Collider (VLHC) stage 2 machine is designed to provide a 10 T magnetic field, guiding two protons beam of 87.5 TeV each, around the 233 km circumference ring. Nb_3Sn superconducting magnets will operate in supercritical helium at 4.5 K. The stage 2 VLHC luminosity considered in this report, is $2 \cdot 10^{34} cm^{-2}s^{-1}$. According to the VLHC concept feasibility studies [1], the working assumption for the stage 2 cryogenic system layout considers 12 cryogenic plant locations around the ring. Such an arrangement creates 24 cryogenic strings of approximately 9.7 km length each. The stage 2 VLHC half-cell (~135 m long) is composed of seven ~17-m long dipoles and one ~9-m long quadrupoles. The two proton beams are guided inside the two beam screens.
The heat generated by synchrotron radiation (SR) is the dominant source of heat in the stage 2 VLHC and needs to be extracted by the beam screen cooling system. The large synchrotron radiation heat load of ~ 5 W/m/beam (as compared to 0.32 W/m/beam in the LHC), dictates a high optimal beam screen temperature. The stage 2 VLHC beam-screen cooling system and the influence of the synchrotron radiation were presented elsewhere [2].
Furthermore, the heat loads to be extracted on the low temperature levels are essential to be minimized in order to reduce the total refrigeration power cost. Therefore, we characterized the heat loads to be extracted at each temperature level. In addition, we can express the optimization functions in the process of determining the optimal thermal shield and beam screen temperatures. The different powers at the plugs are discussed for the beam screen and especially for the thermal shield.
As proposed in [1] a single cryogenic circuit will extract the heat loads from the thermal shield and the beam screen. Additional scenarios where the thermal shield and the beam screen are individually cooled are also discussed in the report. The modelization of the cryogenic system takes into account the dynamic

heat loads (mostly synchrotron radiation) and the static heat loads, scaled from measurements on LHC cryostat thermal models to the stage 2 VLHC system.

2 COMPONENTS DESCRIPTION

The stage 2 VLHC dipole and quadrupole cold masses are protected from the ambient by cryostats. The cryostat serves to support the magnet accurately and reliably within the vacuum vessel, to provide all required cryogenic piping, and to insulate the cold mass from heat radiated and conducted from the environment. For this latter function, a thermal shield is used, composed of an aluminum upper shield welded to an extruded lower tray. This assembly is wrapped with superinsulation composed of Multi LayerInsulation (MLI). Three and two composite posts support the stage 2 VLHC dipoles and quadrupoles, respectively [1]. The beam screen is housed in the dipole and the quadrupole cold mass within the ∅ 40 mm apertures of the magnets.

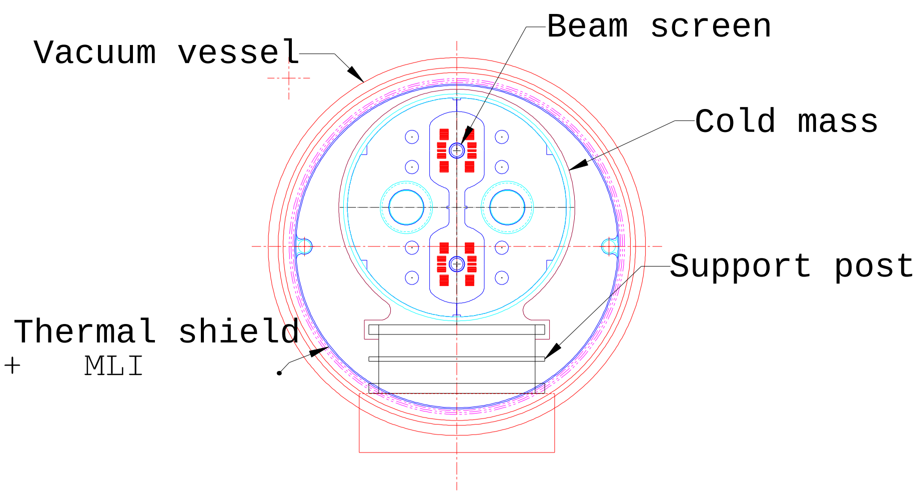

Figure 1: Cross-section of a Stage 2 VLHC dipole

Table 1 defines the thermal and geometric properties of the thermal shield. Most of the cryostat components are scaled from the LHC design.
Since we want to determine the influence of the thermal shield temperature, T_{ts}, this temperature is the principal variable used in the following.

Table 1: Thermal shield functional parameters

Symbol	Definition	Unit	Value
T_{ts}	Thermal shield average temperature	K	variable
T_{vv}	Vacuum vessel temperature	K	300
Per_{ts}	Perimeter of the thermal shield	m	2.5
L	Length of the dipole and quadrupole	m	18, 10
t	Thickness of the aluminum shield	mm	3
N	Number of MLI layers		30
DT_{ts}	Allowable temperature gradient in the thermal shield cooling pipe	K	5
DP_{ts}	Allowable pressure drop in the thermal shield cooling pipe	bar	0.1

As for the LHC, we foresee to use gaseous helium flowing in the lower tray extrusion of the stage 2 VLHC thermal shield in order to extract the static heat load coming from the ambient.
Then, the flow of helium cools the beam screen and permits us to extract the high synchrotron radiation heat load.
Table 2 defines the thermal and geometric properties of the beam screen system. As for the thermal shield parameters, the allowable temperature gradients and pressure drops were selected in order to optimize the refrigeration cycle.

Table 2: Beam screen functional parameters

Symbol	**Definition**	**Unit**	**Value**
T_{bs}	Beam screen average temperature	K	$T_{ts}+DT_{bs}/2+DT_{ts}/2$
T_{cb}	Cold bore temperature	K	5
d_{cb}	Cold bore inner diameter	mm	34
d_{bs}	Beam screen outer diameter	mm	32.5
g	Thermal conductance coefficients (*)	$W/m/K^{2.32}$	$3.1 \cdot 10^{-6}$
e	Emissivity of stainless steel surfaces		0.1 @ 4 K 0.2 @ 300 K
e	Emissivity of aluminum surfaces		0.04 @ 4 K 0.15 @ 300 K
s	Stefan-Boltzmann constant	$Watt/m^2/K^4$	$5.67 \cdot 10^{-8}$
ΔT_{BS}	Allowable temperature gradient in the beam screen cooling pipe	K	20
ΔP_{ts}	Allowable pressure drop in the beam screen cooling pipe	bar	1.1

(*) g *is* deduced from measurements on the LHC beam screen system with the support-less (“touching”) beam screen design [6]

3 HEAT TRANSFER LAW EQUATIONS

3.1 THERMAL SHIELD

The heat loads are scaled up from measurements performed at CERN on the LHC Cryostat Thermal Model (CTM) [4-5]. The LHC supporting system performance is detailed in [6]. These performances permit us to determine the stage 2 VLHC heat transfer law equations. The process to calculate the heat loads to be extracted at room temperature is detailed below:

First, we define the power to be extracted at each temperature level.
The total power due to the static heat loads, *Pts(Tts),* is equal to the sum of the radiative heat loads, *Ptsrad*, and the conductive heat loads, *Ptscond*. The conductive term of (1) is due to the heat transfer through support posts and the radiative term is due to the radiation and conduction through residual gas from the ambient to the thermal shield. The static heat loads are functions of the thermal shield temperature.

$$P_{ts}(Tts) = Ptsrad(Tts) + Ptscond(Tts) \quad (1)$$

$$Ptsrad(Tts) = \left[a \; \frac{(Tvv^2 - Tts^2)}{2 \cdot N} + b \; \frac{(Tvv^4 - Tts^4)}{N} \right] \cdot Per_{ts} \tag{2}$$

$$Ptscond(Tts) = \left(-7 \cdot 10^{-5} - 0.006 \cdot Tts + 8.19 \right) \cdot \frac{2}{10} \tag{3}$$

where:
α,β are coefficients taking into account the thermal conductivity of the superinsulation system and the emissivity factor of superinsulation, respectively. Both coefficients are deduced from the type of superinsulation and the residual gas pressure in the vacuum vessel.
Equations (2), (3) are determined from the LHC full-scale thermal measurements. For instance, the CTM run permitted us to measure the heat loads for a thermal shield at 65 K and an insulation vacuum equal to 10^{-3} Pa. We measured a total heat load of 4.2 W/m, extracted from the thermal shield temperature level. The heat loads were distributed as following:

Ptsrad(65K) = 2.8 W/m

Ptscond(65K) = 1.4 W/m

Based on these CTM measurements, we can determine α and β equal to $2.06 \cdot 10^{-4}$ W/K^{2}m^2 and $3.14 \cdot 10^{-9}$ W/K^{4}m^2, respectively.
Then, we can determine the heat to be extracted at room temperature, *PRT(T)*, by using the Carnot factor (4). The Carnot factor *f* assumes a refrigerator efficiency of 0.3. This approach is repeated for each heat load in the current thermal system.

$$f(T) = \frac{1}{0.3\left(\frac{T}{300 - T}\right)} \tag{4}$$

$$PRT(T) = f(T) \cdot P(T) \tag{5}$$

Figure 2 shows the heat load coming from ambient to the thermal shield. Figure 3 shows the electrical power needed at room temperature to extract the thermal shield heat load. Both functions are plotted versus the thermal shield temperature.

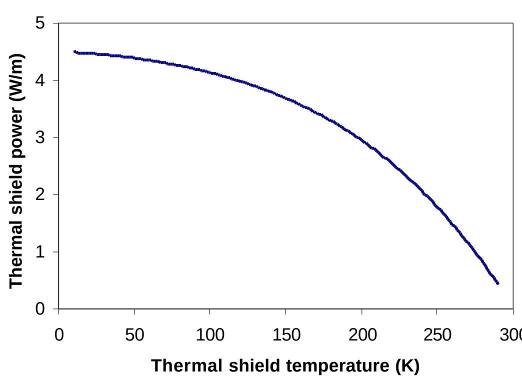

Fig.2. Total power to be extracted from the thermal shield vs. temperature

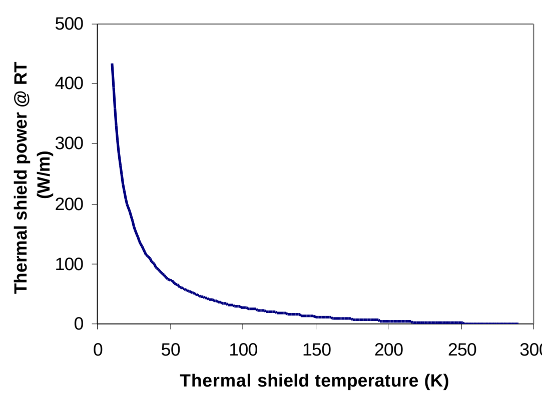

Fig.3. Equivalent of the thermal shield heat loads at room temperature vs temperature

3.2 BEAM SCREEN

The heat load on the beam screen, $P_{bs}(T_{bs})$, can be expressed as a function of the beam screen temperature (6). This latter is dependent on the thermal shield temperature if only one circuit provides the cooling of both the beam screen and thermal shield (7). $P_{bs}(T_{bs})$ corresponds to the beam induced heat load on the beam screen, *Po*, minus the heat load transferred to the cold bore. The static heat load on the cold bore, $P_{cb}(T_{bs},T_{cb})$, emanating from the beam screen depends mainly on the temperature difference between beam screen (T_{bs}) and the cold bore (T_{cb}). Nevertheless, we note that in the case of the stage 2 VLHC that the heat load induced by the synchrotron radiation, *Po*, will in general be much larger than other beam related heat loads, P_{bs}, such as multipacting or resistive wall heat load transferred to the cold bore. Although the LHC beam screen design serves as a baseline for the calculations presented in the following, new requirements arise with the large synchrotron radiation heat load of ~ 5 W/m/beam. Therefore we considered the beam induced heat load, *Po*, to be equal to the synchrotron radiation heat load (*Po*=5 W/m/beam).

$$P_{bs}(T_{bs}) = Po - P_{cb}(T_{bs}, T_{cb}) \tag{6}$$

$$\mathrm{T_{bs}} = \mathrm{T_{ts}} + \frac{\Delta \mathrm{T}_{ts}}{2} + \frac{\Delta \mathrm{T}_{bs}}{2} \tag{7}$$

The static heat load on the cold bore $P_{cb}(T_{bs},T_{cb})$ is due to the conduction through the support system contact points between the beam screen and the cold bore (first term in (8)) and from radiation (second term in (8)).

$$P_{cb}(T_{bs}, T_{cb}) = g\left(T_{bs}^{2.32} - T_{cb}^{2.32}\right) + s\left(T_{bs}^{4} - T_{cb}^{4}\right)pd_{cb}\,\frac{1}{\dfrac{1}{e(T_{bs})} + \dfrac{d_{bs}}{d_{cb}}\left(\dfrac{1}{e(T_{cb})} - 1\right)} \tag{8}$$

4 OPTIMIZATION FUNCTIONS

The optimum temperature results in a minimum refrigeration power cost and can be found by minimizing P_{tot}, at a fixed cold bore temperature (T_{cb}). In our model we did not take into account the helium transfer lines (the optimal temperature would be higher in that case) and we did not use over-capacity factors (safety-margins). Therefore we calculate the operating wall power expressed in W/m.

4.1 THERMAL SHIELD OPTIMIZATION - NO BEAM SCREEN IN SERIES

Consider that the thermal shield cooling system is independent of the beam screen cooling system. We estimate that 0.5 W/m is the additional heat load, *Q1*, on the two cold bores due to resistive heating in the magnet, beam gas scattering, radiation from the shield, conduction through the cold mass supports.
So, we only need to take into account the heat loads to the cold bore and the heat load to the thermal shield. The heat load on the thermal shield and the static heat load on the cold bore define the total cooling power, *P*1, as a function of the thermal shield temperature, T_{ts}.

Therefore, the optimization function of the operating wall plug power can be expressed by the following equation (9):

$$P1(T_{ts}) = f(T_{ts})P_{ts}(T_{ts}) + f(T_{cb}) \cdot [2 \cdot P_{cb}(T_{bs}, T_{cb}) \ + Q1] \qquad (9)$$

Figure 4 illustrates the influence of the thermal shield temperature on the operating wall plug power. The resulting optimal temperature is 63 K for an operating wall power plug of 187 W/m.

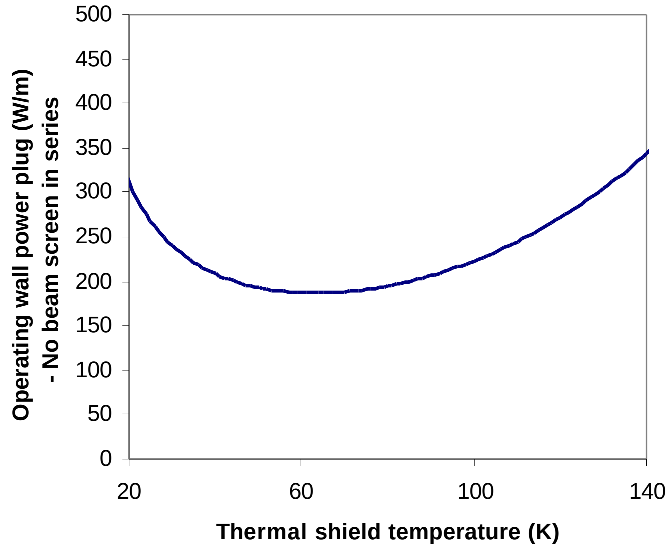

Fig.4. Operating wall power plug when the beam screen is independent from the cryogenic system.

This optimal temperature of the thermal shield is equivalent to the one of the LHC for which the synchrotron radiation power is much lower.

For a temperature of 63 K, the thermal shield and cold mass operating wall plug power is equal to 43.5 MW over the 233 km of the stage 2 VLHC circumference.

4.2 THERMAL SHIELD OPTIMIZATION - BEAM SCREEN IN SERIES

In this section we will consider that the thermal shield cooling system is connected to the beam screen cooling system. So, we need to take into account the heat loads to the cold bore, to the beam screen, and to the thermal shield.
We estimate that 0.5 W/m is the additional heat load, *Q1*, on the two cold bores due to resistive heating in the magnet, beam gas scattering, radiation from the shield, conduction through the cold mass supports. Therefore, the optimization function of the operating wall plug power can be expressed by the following equation (10):

$$P2(T_{ts}) = f(T_{ts}) \cdot P_{ts}(T_{ts}) + f(T_{bs}) \cdot [2 \cdot P_{bs}(T_{bs})] + f(T_{cb}) \cdot [2 \cdot P_{cb}(T_{bs}, T_{cb}) \ + Q1] \qquad (10)$$

Figure 5 illustrates the influence of the thermal shield temperature on the operating wall plug power. The optimal temperature is 83 K for an operating wall plug power of 265 W/m.
Hence, if we applied (7) the optimal beam screen temperature rises to 97 K.

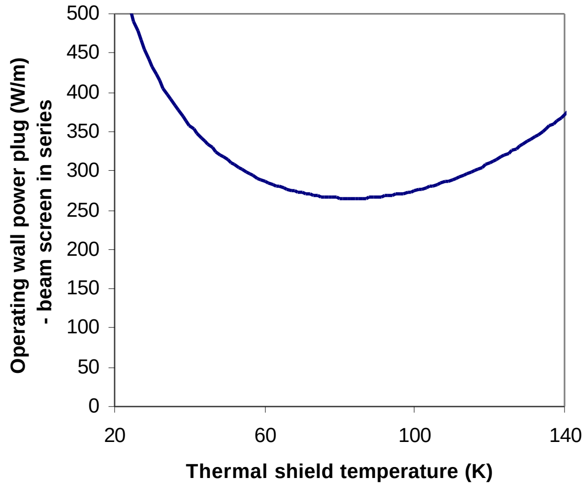

Fig.5. Operating wall power plug with the beam screen in series with the thermal shield.

For the thermal shield temperature of 83 K, the thermal shield and cold mass operating wall plug power is equal to 52.4 MW over the 233 km of the VLHC circumference. In this calculation we consider that the synchrotron radiation only applied on a length equivalent to the perimeter of radius 29.9 km.

5 CONCLUSIONS

This report underlines the influence of the synchrotron radiation in the determination of the optimal thermal shield operating temperature. If we consider using the thermal shield and the beam screen in series, the optimal temperature of the thermal shield would be 20 K higher than in the case where the beam screen is independent.

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