EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 609

THERMAL DESIGN AND PERFORMANCE OF THE ELECTRICAL DISTRIBUTION FEED BOX OF THE LHC PROTOTYPE CELL

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Abstract

The Electrical Distribution Feed Box (DFBS) is a 4.5 K saturated liquid helium cryostat constructed for the Large Hadron Collider (LHC) Prototype Cell (String 2). The thermal design of the DFBS is presented, with emphasis on the modelling of the cooling of the current lead chimneys via the helium bath boil-off gas and on the design of the lambda plate. The expected performance is compared to measurements done during the first operation phase of the LHC prototype cell.

LHC Division

Geneva,   15 November 2002

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INTRODUCTION

In order to test the magnets, the related cryogenics and the other components of the LHC under realistic operating conditions, CERN has ordered from industry a number of full-scale prototype superconducting magnets, which were installed in a 120 m long string, operated and tested. This facility is the LHC Prototype Cell, hereafter called String 2 [1].

The Electrical Distribution Feed Box (DFBS) [2] is a 6 meter-long liquid helium (4.5 K / 0.135 MPa) cryostat (Figure 1) which supports and cools 32 High-Temperature Superconductor (HTS) current leads [3] used for powering the String 2 main dipole and quadrupole superconducting magnets, together with their correctors. Currents are rated at 13 kA and 600 A.

The DFBS also supports the Lambda-plate that thermally and hydraulically separates its saturated liquid helium bath from the magnet string pressurised superfluid helium bath at 1.9 K / 0.13 MPa.

Figure 1 String 2 Electrical Distribution Feed Box

The DFBS cryostat is subjected to heat inleaks at 50 K (thermal shield), 4.5 K (saturated helium bath), and 1.9 K (shuffling module and magnet baths), each one being the sum of several contributions.

The paper is structured in 4 parts presenting: the DFBS cryogenic design with emphasis on the Lambda plate design, the calculated and then the tested DFBS heat load values and finally, a revised thermal model used to optimize the heat exchange within the current lead chimneys.

DFBS CRYOGENIC DESIGN

Figure 2 gives a schematic layout of the DFBS cryogenic structure and a prototype Lambda plate. The temperature of a current lead is controlled by a regulation valve acting on a flow of externally supplied 20 K gaseous helium. Helium gas from the vessel, produced by heat loads to the 4.5 K bath, is used to cool the HTS part of the lead and exits the latter in the cryostat neck at a temperature of 50 K. A manual valve then limits this flow to a fixed amount (0.03 g/s per chimney – see later for explanations) necessary to cool the cryostat necks, thus reducing the conduction heat load to the bath. The mass flow in excess is returned to the helium vessel, then into the 20 K line via a cold valve, prior to injection into the current lead. Liquid helium is provided from the refrigerator through a regulation valve in order to keep the liquid helium level in the helium vessel constant.
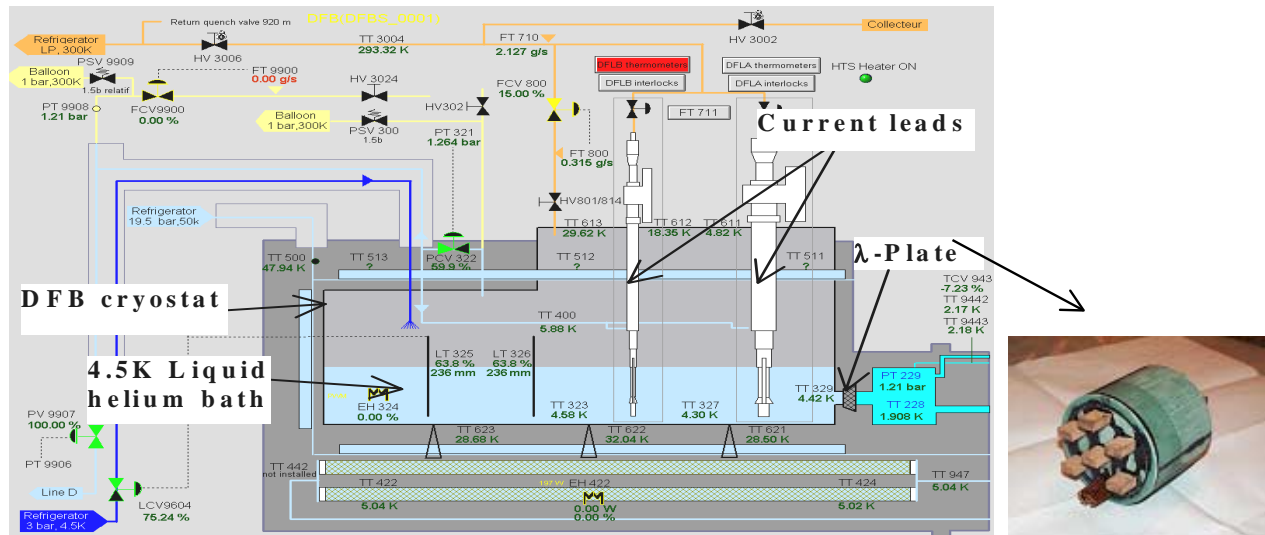
Figure 2 DFBS cryogenic diagram during nominal operation conditions; Lambda plate prototype

6 copper stabilized superconducting cable busbars rated 13 kA and 32 superconducting wires rated 600 A transport the electrical current through the Lambda plate. A hydraulic separation between the DFBS liquid helium at 4.5 K and the magnet bath at 1.9 K is ensured (leak tightness better than 5x10-2 mbar l / s STP) while maintaining the electrical continuity of the superconducting busbars, with no use of resisting splices to avoid Joule heating. It has to withstand hydraulic pressure difference up to 2 MPa in case of magnet quenches and remain leak tight at a level better than 0.16 g/s in superfluid helium with pressure difference of 0.035 MPa [4].

DFBS THERMAL CALCULATIONS (DESIGN VALUES)

Heat loads at 4.5 K
The global thermal loads to the 4.5 K DFB liquid helium bath can be divided into three main parts:
•   thermal loads due to the cryostat itself (including radiation from the thermal shield to the helium vessel, conduction from the cold supports, the pressure control valve, conduction through the 20 K line, instrumentation wires and cryostat chimneys). In static operation (no current in the leads), for the String 2 phase 1 configuration, this thermal load was expected to be ideally 7 W. Additional loads of 1 W (due to electrical splices) and 3.5 W (due to an increase of the 20 K line helium gas temperature) should appear when powering the electrical circuits,
•   thermal loads due to the Current Leads. These values can be estimated from previous measurements performed on the Current Leads on the "test cryostat", giving an estimated global value of 9.5 W [5]. This represents the static thermal loads to the 4.5 K helium bath due to all Current Leads installed on String 2 under the operating conditions,
•   heat sink crossing the Lambda-plate. The expected value is 10 W (thermal conduction through OFHC Copper – RRR = 100).

Heat loads at 1.9 K
The heat loads on the 1.9 K magnet bath are the addition of the radiation through the multi layer insulation (MLI) at the shuffling module (cf. Figure 4) level and of the heat flow crossing the Lambda-plate. The expected value is 0.2 W + 10 W = 10.2 W.

Heat loads at 50 K on the thermal shield
The heat load on the 50 K of the thermal shield was estimated at 117 W. This important value is due to an incident, which forced the replacement of the composite part of the 3 support posts with stainless steel. The value should be reduced to 77W when using composite support posts.

DFBS THERMAL TESTS

Several tests were performed without electrical power, in order to determine the heat loads to the 4.5 K helium bath, due to the cryostat itself as well as the heat load crossing the Lambda-plate. The tests were based on gaseous helium mass-flow measurements for different set-ups.

Global heat loads at 4.5 K

During a first measurement campaign on String 2, the global thermal loads on the 4.5 K helium bath were measured statically (i.e. no current in the leads). The liquid helium supply valve was closed as well as the cold valve separating the gas produced in the helium vessel from the gas in the 20 K external line (see Figure 2). The chimney manual valves were completely opened in order to allow all the helium gas produced by liquid evaporation to be evacuated through the chimneys. Only one chimney valve was closed (housing fragile instrumentation wires).

After system stabilisation, the helium boil-off rate of the pressurised bath results from a balance between the three main heat sources to the 4.5 K bath: cryostat itself, current leads, Lambda plate. The amount of gas produced by liquid vaporisation was determined by two methods (Figure 3): direct measurements (using a flowmeter) of the gas passing through the chimneys and monitoring of the liquid level evolution into the helium vessel.

The global delivered power to the DFBS 4.5 K liquid helium bath was found to be of 12.6 ± 0.5 W.
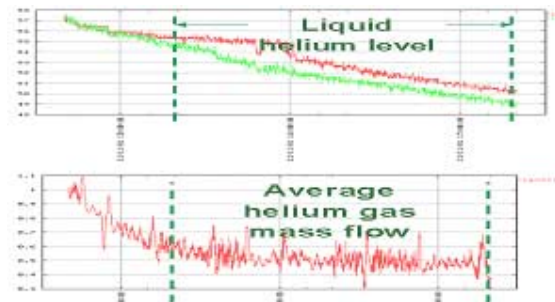

Figure 3 DFBS thermal tests

Heat loads through the Lambda-plate from 4.5 K to 1.9 K

In order to quantify the heat flow through the Lambda-plate by difference between DFBS thermal loads with and without the contribution of the Lambda-plate, the cryomagnet helium bath was warmed up to 4.5 K (see Figure 4) and the measurement presented above was repeated.
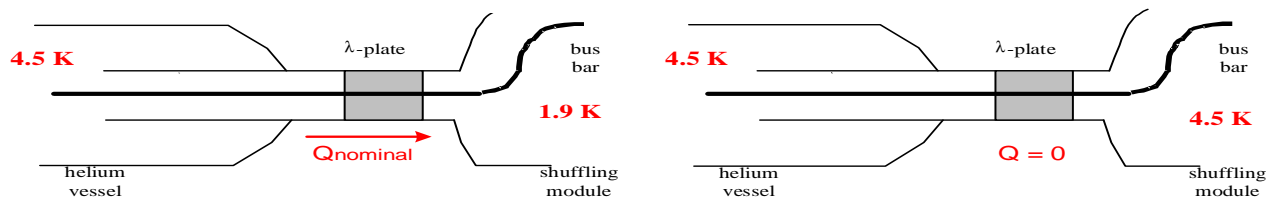

Figure 4 Lambda plate test approach

The measured value of the heat through the Lambda-plate during nominal operation was 7.2 ±1.1 W.

Substituting the Lambda plate and current leads contributions from the global measurement, the thermal load due to the DFBS cryostat itself was determined to be 10.3 ±1.1 W.

OPTIMISATION OF THE CHIMNEY NECK HEAT FLOW: THERMAL MODEL AND TESTS

As said above, during the measurements, one chimney was kept closed because it houses fragile instrumentation wires. That chimney was not cooled by helium gas, thus the heat conduction through its neck represents a non-negligible contribution.

Since solid conduction through the chimney neck from 300 K (chimney upper flange) to the helium bath is a very important factor for the final value of the heat load to the 4.5 K bath, a detailed thermal model of 13000 A chimney was established (Figure 5) and validated by a measurement campaign.

Presently on the DFBS, the enthalpy of the vapour resulting from liquid helium evaporation is used to absorb some of the heat leaking into the vessel, thus cooling the neck.
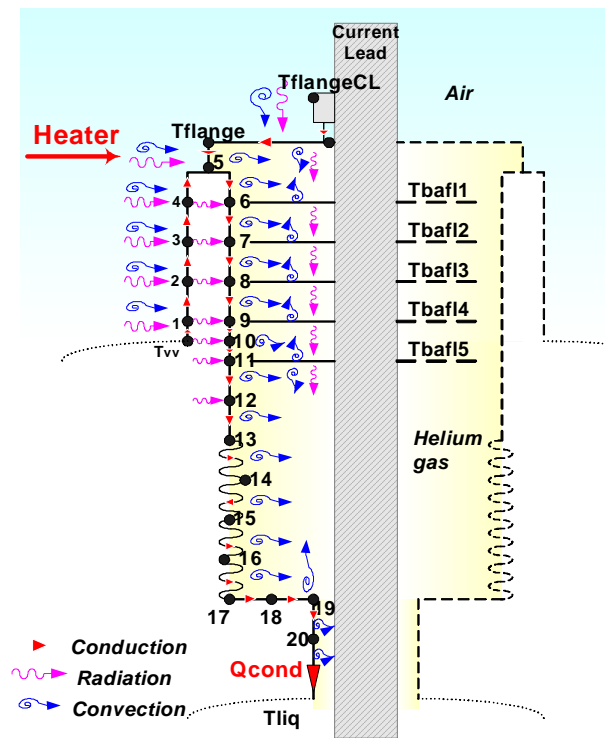
Figure 5 Chimney neck analytical model

However, an undesired effect may appear if the gaseous helium flow passing through the chimney is too important: the neck becomes too cold at the upper flange level and ice appears. In order to avoid it, heaters were installed at that location maintaining the chimney upper flange at a temperature of 26 ºC. Heater power as well as flange temperature variation with gas massflow were determined by calculations and validated by tests.

Heat loads to the helium bath were calculated for different values of gas flow cooling the chimney neck. Refer to Figure 6 for some calculation results. For an optimum operation, compromise had to be found between the heat load to the helium bath (minimised), chimney flange temperature (maximised) and the top gas temperature (maximised to avoid ice on the pipe collecting the gas at the chimney upper flange).

To completely suppress heat load to the bath, 0.030 g/s through each chimney was found to be the optimum value.
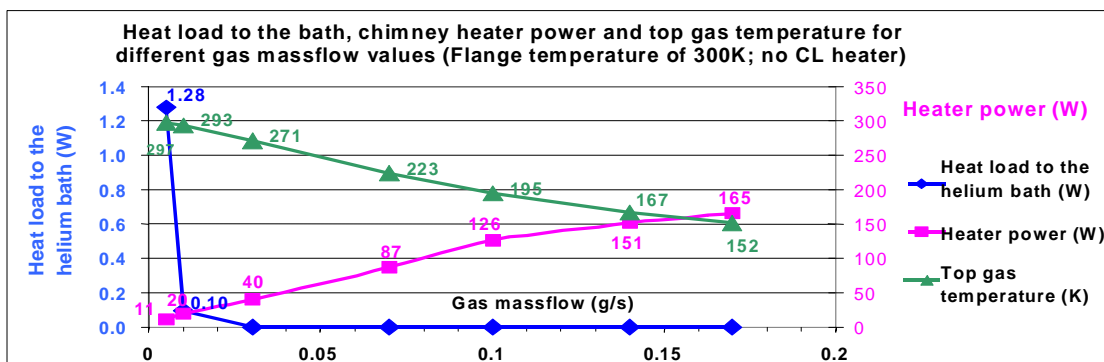

Figure 6 Chimney neck thermal calculation results

CONCLUSIONS

Good correlation between the measured and calculated thermal loads values of the DFBS was shown. The DFBS cryostat static heat load measured value is 10.3±0.6 W and the expected value was 7 W. The heat load crossing the Lambda-plate was also measured and the value is 7.2 ±1.1 W while the expected value was 10 W.

The heat loads due to conduction through the chimney neck can be reduced to zero. The analytical model built can be used to optimise the chimney design of the DFBs to be installed in the LHC.

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