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1.9 K HEAT INLEAK AND RESISTIVE HEATING MEASUREMENTS ON LHC CRYOMAGNETS

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This paper describes the method applied to perform these measurements, compares the results with the expected specified values and discusses the impact of the measured values on cryo-plant tuning and operational margins.

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G. Ferlin, S. Claudet, L. Tavian, U. Wagner

Technology Department, CERN,
1211 Geneva 23, Switzerland

ABSTRACT

The superconducting magnets of the Large Hadron Collider (LHC) distributed over eight sectors of 3.3-km long are cooled at 1.9 K in pressurized superfluid helium. During the commissioning campaign of the sectors in 2008, cold standby periods at nominal operating temperature have allowed to measure the overall static heat inleaks reaching the magnet cold masses at 1.9 K by enthalpy balance in steady-state operation. In addition, during electrical powering of the different magnet circuits, helium II calorimetry based on precision thermometry has been implemented to assess with an accuracy of 100 mW/m the additional heat loads due to resistive heating and to detect possible abnormal heat dissipation during powering.

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KEYWORDS: Superfluid helium, Calorimetry, Heat inleak, Resistive heating, Cryomagnet.

INTRODUCTION

The main superconducting magnets of LHC are cooled at 1.9 K in pressurized superfluid helium baths. The accelerator is divided in eight sectors, each of them constituted of a 2.9-km continuous cryostat (CC) containing the cryomagnets and segmented in 27 cells: 23 standard cells constituting the arc and 2 x 2 specific cells constituting the dispersion suppressors at both arc extremities. At the vicinity of the LHC particle detectors the sectors include also special cryomagnet strings containing the final-focusing inner-triplet quadrupoles (IT) cooled as well at 1.9 K.

For cooling the sectors, the LHC features the largest helium cryogenic system in the world [1], with 140 kW at 4.5 K and 20 kW at 1.8 K installed refrigeration capacity, a cold mass of 37’000 t with a cold surface area of 50’000 m^2, and some 130 t of total helium inventory.

The long lead times for industrial procurement of such complex plants, combined with the need for early refrigeration capacity at the location of the test station for LHC magnets, impose to pre-define the sizing of the plant at a time when the thermal design of the machine components is not fully validated. At that time, the thermal design has been established from first principles and experimental work, the final configuration of the accelerator was not yet confirmed, and some of the basic processes for beam-induced heat loads were still largely speculative.

TABLE 1 gives the main heat loads at 1.9 K of the LHC sectors as defined in the Design Report [1].

The confirmation of available capacity at 1.9 K for beam-induced heat loads requires to know the built-in heat inleaks and resistive heating.

These systematic heat inleaks and resistive heating measurements were conducted in autumn 2008, after magnet powering test campaigns.

OVERALL STATIC HEAT INLEAKS MEASURMENT AT 1.9 K

During the commissioning campaign of the LHC sectors in 2008, the cold standby period has been used to optimize the cryo-plant tuning. One of the main data necessary to optimize the cryo-cycle is to confirm the expected overall thermal losses. In particular 1.9 K heat inleak were specifically measured. This chapter describes this measure.

The method is described for one sector of LHC. Measurements were done on five sectors. Results and summary will describe five sectors.

Description of the Method

Static heat inleaks are a function of the design of the cryostat. Under stable thermal conditions, static heat inleaks at 1.9 K on pressurized helium produce a constant evaporation of saturated helium. Mass-flow of saturated helium is a direct picture of the thermal losses at 1.9 K (1).

$$\dot{m}(cell) = {\left(Q_{HI} + Q_{EH}\right)} \big/ {H2 - H1} \qquad (1)$$

where Q_{HI} is the heat inleak of the cell, Q_{EH} is the electrical heating added to the cell and $H2-H1$ is the enthalpy balance of cooling helium as defined in FIGURE 1.

Saturated helium vaporized by heat inleaks is collected to the pumping line every cryo-cell connection (107 m). One continuous cryostat is constituted of 27 connections for cryo-cells to which it is necessary to add the inner triplet connection and the return module connection.

Instrumentation installed does not allow measuring individually the saturated helium mass flow generated by each cell. The unique option consists to measure the global helium flow for the continuous cryostat (2).

$$\dot{m}_{CC} = \sum_{n=1}^{27} \dot{m}(cell)_n \qquad (2)$$

TABLE 1. Main 1.9 K heat loads from LHC design report

	High load sectors [W]	**Low-load sector [W]**
Heat inleaks	623 to 667	594 to 639
Resistive heating	289 to 292	287 to 289
Nominal beam-induced heating	462 to 504	269 to 313
Ultimate beam-induced heating	847 to 951	369 to 473
Total nominal	1380 to 1460	1150 to 1240
Total ultimate	1760 to 1910	1250 to 1400
Installed	2400	2100

The saturated helium pumping line is connected to the cold compressor cold box, FIGURE 2, in which a continuous saturated helium flow is as well generated to allow fast reconnection in case of cold compressor trip. The total mass flow pumped is the sum of the mass flow generated in the continuous cryostat to be added with all the others circuits linked to the pumping line (3).

$$\dot{m}_{T} = \dot{m}_{CC} + \dot{m}_{IT} + \dot{m}_{CB} + \dot{m}_{RM} \qquad (3)$$

where $\dot{m}_{T}$ is the total mass flow measured upstream of warm screw compressor, $\dot{m}_{CC}$ is the saturated helium mass flow from the 27 cells constituting the continuous cryostat, $\dot{m}_{IT}$ is the saturated helium mass flow from the inner triplet(s), $\dot{m}_{CB}$ is the saturated helium mass flow from cold compressor box and $\dot{m}_{RM}$ is the saturated helium mass flow from return module.

Mass flow $\dot{m}_{IT}, \dot{m}_{CB}$ and $\dot{m}_{RM}$ are measured by stopping the helium cooling flow and measuring the corresponding total flow decrease during this phase.

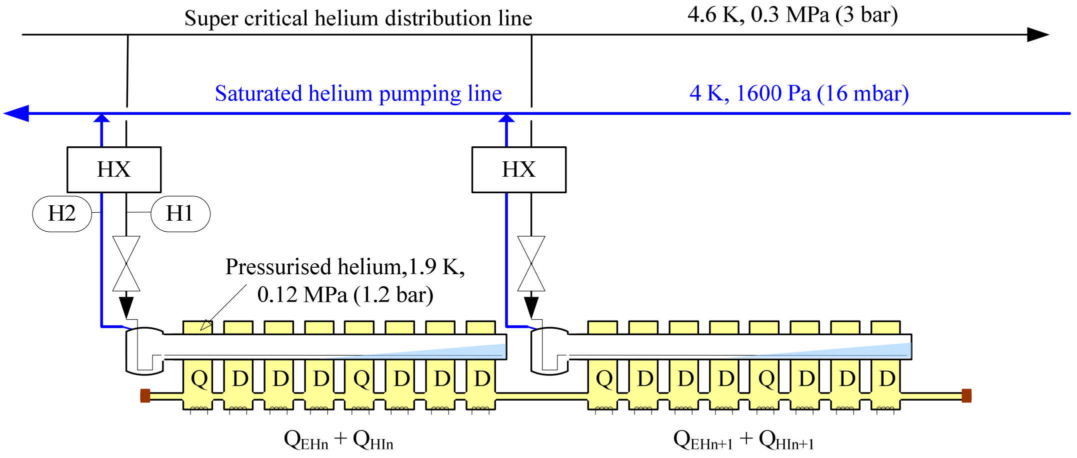

FIGURE 1. Cryogenic flow-scheme at 1.9 K level of a LHC sub-sector composed of two cryo-cells.

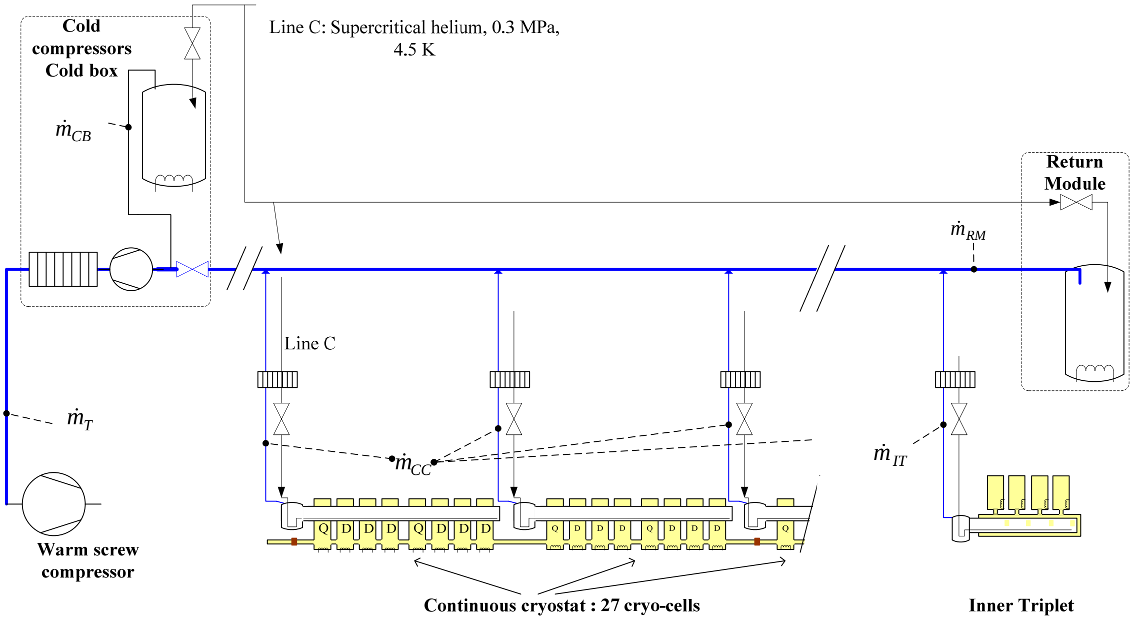

FIGURE 2. Cryogenic flow-scheme at 1.9 K level of one LHC sector

Results of the Test Campaign Done in Autumn 2008

Static heat inleaks measured for one test-sector S5-6 are given in TABLE 2. As the minimum operational range of the cold compressor system is 42 $g.s^{-1}$[2], the measurement without any added electrical power is not possible. The measured values are used to calculate the overall heat inleaks without added heating in FIGURE 3. By using this method, systematic errors such offset and proportional error linked to electrical heaters are removed. The other important error origin is the accuracy of measurement for the total mass flow. Total mass-flow sensor used for the calculation is duplicated by a second mass flow meter and cross checked by the volumetric flow measured on the warm screw compressor. The total mass flow error could be estimated to +/- 2 $g.s^{-1}$.

TABLE 2. Typical measurements done on sector S5-6_October 2008

Measurement	unit	**A**	**B**	**C**	**D**
$\dot{m}_T$	[$g.s^{-1}$]	81.9	69.2	57.0	64.5
$\dot{m}_{CB}$	[$g.s^{-1}$]	4.6	4.6	4.6	4.6
$\dot{m}_{IT}$	[$g.s^{-1}$]	2.4	2.4	2.4	2.4
$\dot{m}_{RM}$	[$g.s^{-1}$]	2.4	2.2	3.0	15.0
$\dot{m}_A$	[$g.s^{-1}$]	72.5	60.0	47.0	42.5
enthalpy balance	[J]	18.6	18.65	18.63	18.65
Q_{EH}	[W]	892	652	407	317
Q_{IT}	[W]	45	45	45	45
Q_{CC}	[W]	457	466	469	475
Estimated error	[W]	+/- 37	+/- 37	+/- 37	+/- 37

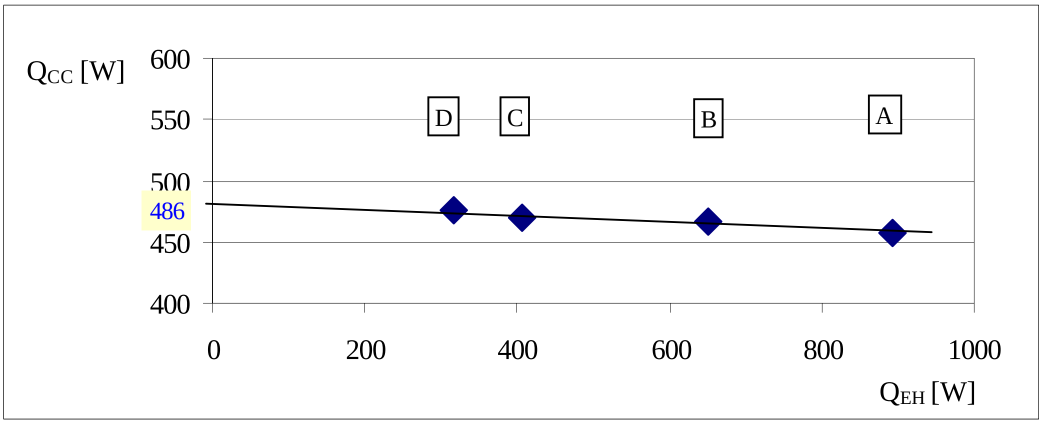

FIGURE 3. Extrapolation to get the continuous cryostat heat inleak value (sector S5-6) without added electrical heater

Only five of eight sectors had been measured during autumn 2008 campaign. FIGURE 4 shows comparison between the foreseen and the measured heat inleaks for these 5 sectors. The measured static heat inleaks are in average 125 W lower in comparison to budgeted static heat inleaks defined in design report.

RESISTIVE HEATING MEASUREMENT

Resisting heating was defined for all the current circuits of LHC based on superconducting-cable splice resistances which are connected in series. TABLE 3 gives the resistive heating of the main electrical circuits according to the Design Report for a sector. At nominal conditions, the resistive heating in a sector is about 290 W including 243 W coming from the main dipole and quadrupole electrical circuits. The difference of 47 W is coming from corrector magnets and individually powered magnets which have dedicated electrical circuits.

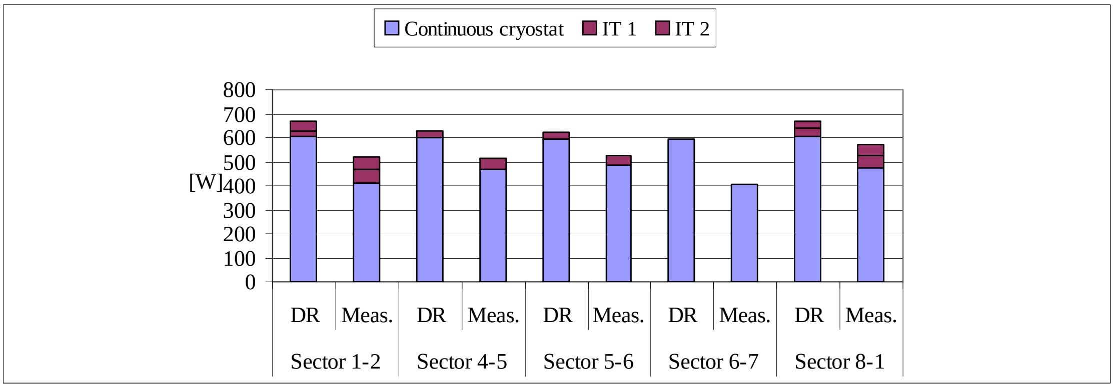

FIGURE 4. Global comparison of the static heat inleaks on 5 LHC sectors

TABLE 3. Resistive heating of the main electrical circuits in a sector according to the Design Report

Electrical circuits	**Nominal current [A]**	**Average splice resistance [nΩ]**	**Number of splices [-]**	**Resistive heating [W]**
Dipole interconnect	11850	0.6	420	35.4
Dipole cold mass	11850	0.5	1396	98.0
Total dipole	11850	0.52	1816	133
Quadrupole interconnect	11870	0.6	840	71.0
Quadrupole cold mass	11870	0.5	552	38.9
Total quadrupole	11870	0.56	1392	110
Total main circuits		0.54	3208	243

Calorimetry Measurement

Following the incident on a LHC sector due to an electrical arc on the main dipole bus-bar circuit, a detection method based on calorimetry using available precision cryogenic thermometers has been first validated by applying calibrated heating in the magnet cold-mass and then implemented in the different sectors [3].

This method allows detecting abnormal dissipation in the W-range and is able to assess the heat load due to the resistive heating during powering plateaus. In 2008, measurements of the main dipole and quadrupole circuits have been performed respectively on 5 and 4 sectors, each of them containing 23 standard cells distributed in 11 sub-sectors. FIGURE 5 shows the histogram of the specific resistive heating measured at 7 kA in the different sub-sectors for the main dipole and quadrupole circuits. The calorimetry measurement has allowed detecting 2 non-conform dipoles having extra resistance of internal splices of respectively 100 and 50 nΩ. These magnets have been removed. Consequently, the specific resistive heating of the corresponding sub-sectors has been accordingly corrected. TABLE 4 gives the average values of the measurements for a standard cell of 107 m. The average specific resistive heating is 8.4 mW/m for the dipole circuit and 9.1 mW/m for the quadrupole circuit. The average splice resistance is about 2 times lower than defined in the Design Report. Consequently, some cooling capacity will be saved in nominal conditions.

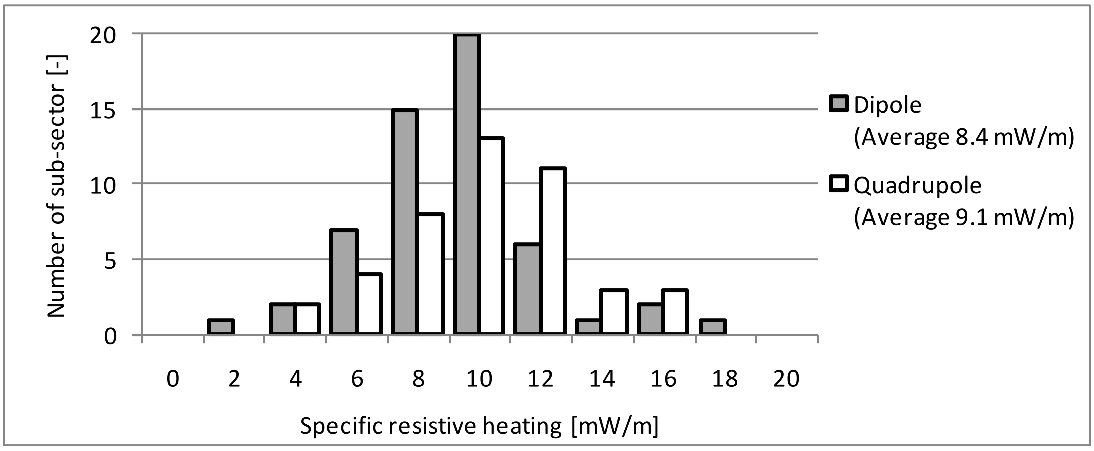

FIGURE 5. Histogram of specific resistive heating measured on sub-sectors at 7 kA

TABLE 4. Measured resistive heating at 7000 A

Electrical Circuit	Current [A]	Average resistive heating [mW/m]	[W/cell]	Number of splices per cell [-]	Average splice resistance [nΩ]
Dipole	7000	8.4	0.90	70	0.26
Quadrupole	7000	9.1	0.98	56	0.36
Total		17.5	1.87	126	0.30

Scaling to Nominal Current

The calorimetry measurements can be scaled to assess the new expected resistive heating of the main magnet circuits at nominal current. For the scaling, it is assumed that the splice resistance remains constant with the applied current and that the magneto-resistance effect on splices which are under magnetic field is negligible. TABLE 5 gives the scaling of resistive heating measurement to nominal current for the main circuits. In total, a heat load of 137 W is assessed representing a heat load saving of 106 W, i.e. a reduction of 44 % of the corresponding load. FIGURE 6 shows the nominal resistive heating per sector to be compared with the Design Report (DR) data.

SUMMARY AND CONCLUSION

Measurements done confirm and validate the design report [1] estimations concerning 1.9 K static heat inleaks and resistive heating. An average margin of 125 W for static heat inleak and of 106 W for resistive heating (total 231 W per sector with respect to the LHC design report) has been demonstrated. Cryo-plant tuning is already adapted to compensate the missing flow (12.5 $g.s^{-1}$) linked to low heat inleak and resistive heating, by using electrical heating in cold mass during beamless magnet tests in order to keep the Cold compressor chain in his operational range. On the other hand, the 231 W margin will be used as operational margin during the phase with high intensity beam to allow 15 to 20 % increase of dynamic losses with respect to design report data.

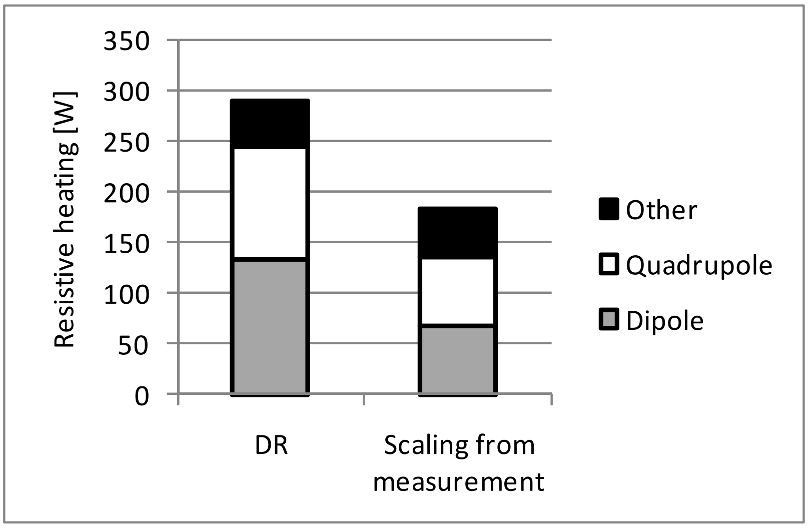

FIGURE 6. Nominal resistive heating per sector

TABLE 5. Scaling of resistive heating measurement to nominal conditions

Scaling to nominal conditions (per sector)		
Resistive heating on dipole circuit	[W]	66.7
Resistive heating on quadrupole circuit	[W]	69.9
Total resistive heating on main magnet circuits	[W]	137
Saving w/r to Design Report data	[W]	106

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