HELIUM II CALORIMETRY FOR THE DETECTION OF ABNORMAL RESISTIVE ZONES IN LHC SECTORS

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Abstract

Following the incident on a LHC sector due to an electrical arc on the main dipole bus-bar circuit, post-mortem analysis of previous current plateaus has shown abnormal temperature drift in the helium II baths of some magnets in the concerned area. In order to identify other possible risky areas, a detection system based on calorimety 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. On the 3-km long continuous helium II cryostat of each LHC sector, this method allows detecting abnormal dissipation in the W-range , i.e. additional resistive heating due to abnormal resistance of about 40 nΩ at 7 kA and less than 15 nΩ at the nominal current of 12 kA. The paper describes the principle and the methodology of this calorimetric method and gives the results obtained on the LHC sectors.

INTRODUCTION

The LHC accelerator is composed of eight sectors, each containing a 3-km long continuous cryostat. Within a continuous cryostat, the main superconducting dipoles (MB), focusing (QF) and defocusing (QD) quadrupoles are powered in series up to 12 kA via three independent electrical bus-bar circuits.

Nine days after the successful start-up of LHC, on 19 September 2008 during a powering test at 8.7 kA, an electrical arc on the main dipole bus-bar circuit provoked a major incident in Sector 3-4. Post-mortem data-analyses of previous powering tests at lower current of that sector were performed in order to detect possible precursor signs of the incident. By looking at the temperature evolution during a current plateau at 7 kA, abnormal temperature drifts were noticed in the vicinity of the concerned zone (see Fig. 1).

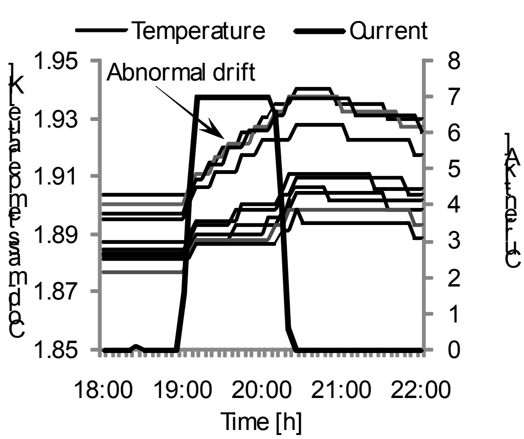

Figure 1: Post-mortem data-analysis of Sector 3-4.

Following this finding, it was decided to develop a detection method based on calorimety in He II, using available precision cryogenic thermometers in order to identify other possible risky areas in the machine.

LHC MAGNET COOLING SCHEME

The main superconducting magnets are cooled at 1.9 K in pressurized superfluid helium (LHe II) baths. The continuous cryostat is segmented in 13 sub-sectors having lengths of 180 to 320 m (see Fig. 2) [1]. A subsector is defined as the length between two hydraulic restrictions on the (otherwise continuous) static He II bath.

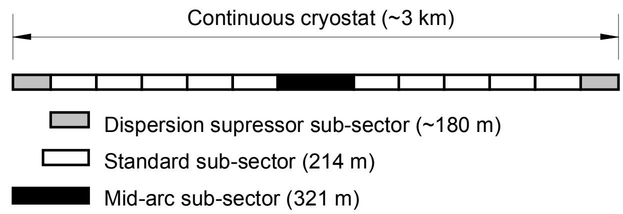

Figure 2: Continuous cryostat sub-sectors.

The cooling loop of a standard sub-sector is shown in Fig. 3. The heat load reaching the static pressurized LHe II bath is extracted by saturated LHe II flowing in two bayonet heat exchangers. The flow of saturated LHe II and consequently the temperatures of the pressurized baths are controlled by two Joule-Thomson valves (JT).

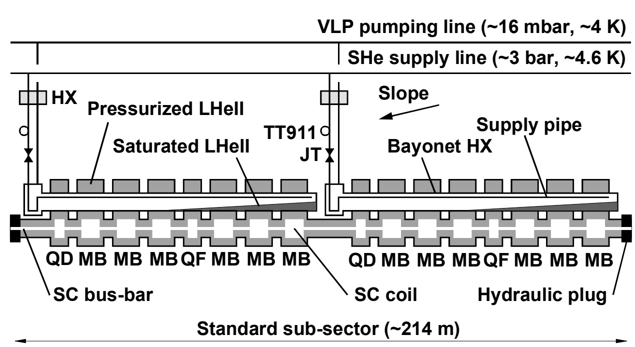

Figure 3: Standard sub-sector cooling loop.

CALORIMETRIC METHOD

When the cryogenic system is in steady-state operation, several hours before the start of powering, the JT valves are blocked at their average opening positions so as to only compensate the static heat inleaks reaching the magnet cold masses. In this condition, any temperature drift on the cold masses can be attributed to dissipation during powering. As the compensation of static heat inleaks is usually not perfect, the residual temperature drift at zero current is used to correct the baseline conditions. Fig. 4 shows a typical temperature evolution of a magnet during a calorimetric test. In the test configuration, the static pressurized LHe II follows an isochoric transformation. Moreover, due to the high thermal conductivity of the LHe II, the temperature within a magnet bath can be considered uniform. Consequently, the resistive heating $\dot{Q}r$ dissipated in the pressurized LHe II bath of a sub-sector during a current plateau can be given by Eq. 1 where:

- T00 is the magnet temperature at the JT-valve blocking start,
- T01 is the magnet temperature at the current ramp start,
- t0 is the time between the JT-valve blocking start and the current ramp start,
- T10 is the magnet temperature at the current plateau start,
- T11 is the magnet temperature at the current plateau end,
- t1 is the duration of the current plateau,
- M is the mass of helium in the magnet cold mass defined according to a specific volume of 26 l/m,
- ρ is the helium density in the magnet cold mass which remains constant with time (closed volume),
- U is the internal energy of helium,
- n is the number of magnet of the concerned sub-sector.

$$\dot{Q}r = \sum_{i=1}^{n} M_i \cdot \left[\left(\frac{U(T11_i,\rho_i) - U(T10_i,\rho_i)}{t1}\right) - \left(\frac{U(T01_i,\rho_i) - U(T00_i,\rho_i)}{t0}\right)\right] \quad (1)$$

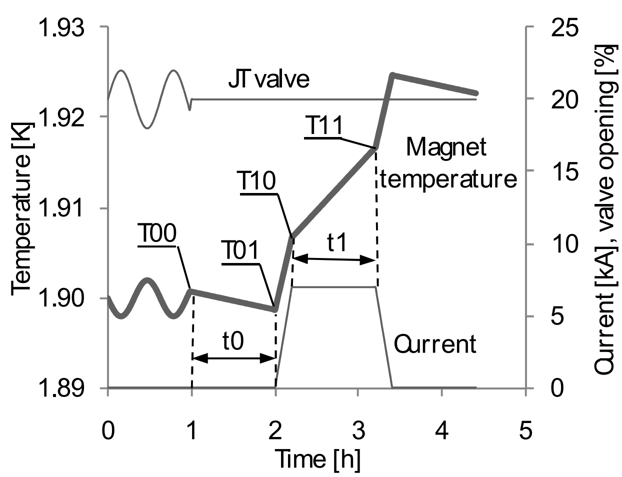

Figure 4: Typical magnet temperature evolution.

Validation by Applying Calibrated Heating

In order to validate the method, a known calibrated electrical heating of 10.0 W has been applied in a standard sub-sector. Fig. 5 shows the magnet temperature evolution and Table 1 gives the other input data. The calorimetric measurement according to Eq. 1 yields 10.0 W, hence confirming the validity of the method which can be applied with confidence during magnet circuit powering.

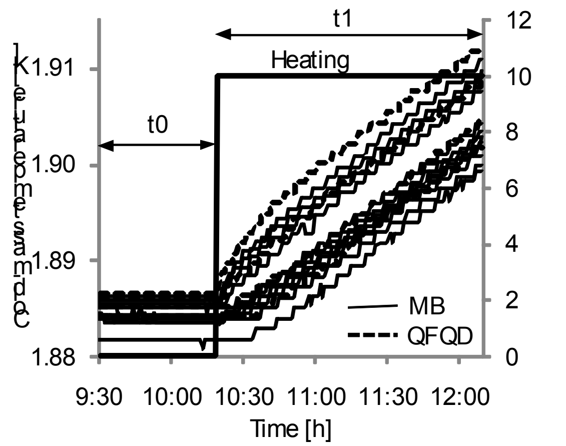

Figure 5: Experimental validation on a standard sub-sector with a known electrical heating.

Table 1: Input Data

Data		
Helium mass M in MB	[kg]	61.4
Helium mass M in QF or QD	[kg]	21.6
Helium density	[kg/m^3]	148
Time t0	[s]	2880
Time t1	[s]	6600

CALORIMETRY DURING POWERING

Following validation, the detection of abnormal heat deposition by calorimetry has been applied during intensive repowering test campaigns conducted in five remaining sectors. The damaged sector (S3-4) as well as the two adjacent ones (S2-3 and S4-5), which had to be emptied in order to allow the repair work, were not available for repowering tests. On the first repowered sector (S1-2) only the main dipole circuit was repowered up to 7 kA, before the sector had to be emptied for magnet transport. On the last four sectors (S5-6, S6-7, S7-8 and S8-1), the three main 12 kA circuits were repowered up to 7 kA. Overall, the main dipole and quadrupole circuits were repowered in 65 and 52 sub-sectors, respectively out of a total of 104.

Fig. 6 and Fig. 7 show the temperature evolution of two standard sub-sectors respectively with normal and abnormal resistive heating during dipole circuit powering at 7 kA. The normal resistive heating of 2.0 W corresponds to an overall electrical resistance of 41 nΩ. The abnormal resistive heating of 6.9 W corresponds to an overall resistance of 141 nΩ i.e., an extra-resistance of 100 nΩ in excess of the normal value. As concerns localization of the defect, the magnet temperatures tend to equalize due to the high thermal conductivity of LHe II, and the calorimetry is not able to precisely locate the resistive zone within the concerned sub-sector. About

50 % of the magnet temperature sensors are not equipped with signal conditioners; the temperatures of the adjacent magnets are then used for assessment of dissipation.

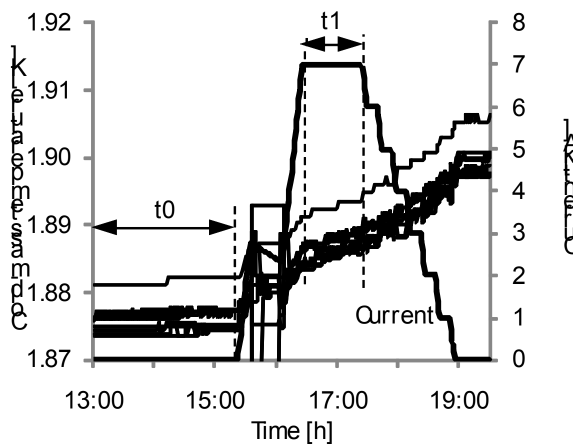

Figure 6: Temperature evolution of a standard sub-sector with normal resistive heating.

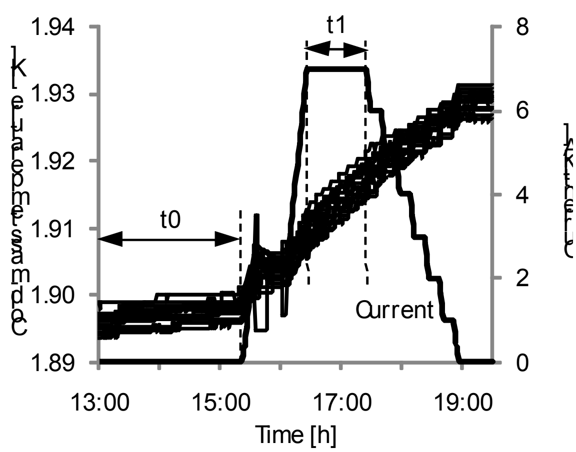

Figure 7: Temperature evolution of a standard sub-sector with abnormal resistive heating.

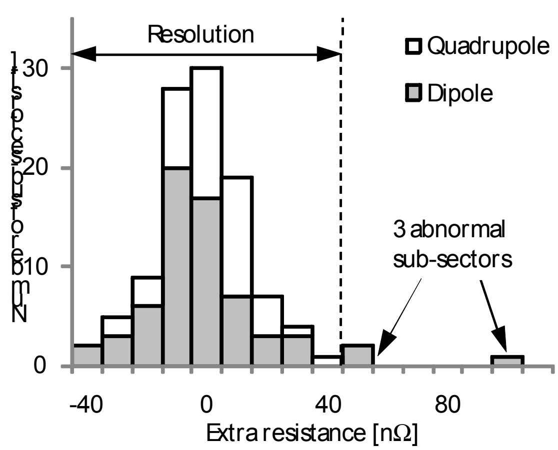

Figure 8: Histogram of extra resistance detected by calorimetry with respect to normal value.

Fig. 8 shows the histogram of the extra electrical resistance estimated by LHe II calorimetry. This histogram shows that the resolution of the calorimetry is about ±40 nΩ at 7 kA, i.e. about 15 nΩ at the nominal current of 12 kA.

During the repowering campaign, three abnormal zones were detected on the dipole circuits. Two of them were confirmed by independent electrical measurements [2]. These abnormal resistances were located inside dipole cold masses and the corresponding cryo-magnets have been removed. The third abnormal zone detected is not yet electrically confirmed and additional measurements will be needed during recommissioning of the sector. On the quadrupoles circuits, all the measurements remain within the detection resolution.

Uncertainties on Measurements

The uncertainty of the measurement is mainly due to the stability of the inlet conditions of the blocked JT-valves and to the resolution of the thermometers. Even with a fixed opening set-point, the valve position can still evolve within a dead-band of ±0.5 % and consequently modify the effective cooling of the subsector during the test. In addition, for some cooling loops, fluctuations were observed in the temperature of the incoming sub-cooled helium (see Fig. 3). These fluctuations also impact on the effective cooling of the subsector. The resulting overall error on the assessment of resistive dissipation can reach up to +/-2 W, coherent with the histogram dispersion.

CONCLUSION

Superfluid helium calorimetry has been validated and intensively used at CERN to detect abnormal resistive zones in the LHC sectors. Making use of the cooling with pressurized superfluid helium, this powerful method allows detecting on the 3-km continuous cryostat extra resistive heating above 2 W with localization within about 200 m. The results are impressively good thanks to the excellent quality of the thermometry and stability of the cryogenic plants and distribution system. At nominal current, the present resolution allows to detect abnormal electrical resistance of about 15 nΩ. The main origins of the measurements uncertainty are identified and actions are under way to further improve the detection resolution to below 10 nΩ at nominal current.

REFERENCES

[1] Ph. Lebrun, Cryogenics for the Large Hadron Collider, IEEE Trans. Appl. Superconductivity 10 1 (2000) pp. 1500-1506
[2] R. Bailey et al, A Method to Detect Faulty Splices in the Superconducting Magnet System of the LHC Sectors, PAC'09, Vancouver, BC, Canada