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Heat load profile estimates on LHC beam screens by thermal transient analysis

To cite this article: B. Bradu *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **502** 012116

IOP Conf. Series: Materials Science and Engineering **502** (2019) 012116 doi:10.1088/1757-899X/502/1/012116

Heat load profile estimates on LHC beam screens by thermal transient analysis

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Abstract. The LHC beams are producing significant dynamic heat loads on the LHC cryogenic system. These heat loads are deposited on beam screens, where they must be properly extracted with dedicated cooling loops between 4.6 K and 20 K. Since 2015, unexpected beam-induced heat loads are observed in specific locations of the machine and their origin is still not completely understood. In order to improve our understanding on the heat load origin and on the spread between them on different areas of the accelerator, the thermal transients occurring after the beam dumps have been analyzed to reconstruct the heat load profiles of the beam screens. Following a description of this specific issue, the paper presents the methodology used for the measurements and estimates of the heat load profiles and its validation against some experimental data and dynamic simulations.

1. Introduction

Since 2015, the LHC (Large Hadron Collider) runs with a proton bunch spacing of 25 ns generating important heat loads on the cryogenic beam screens located inside the beam pipes. These beam screens are maintained between 4.6 K and 20 K during the beam operation using supercritical helium [1].

The heat loads deposited on the beam screen are monitored in real-time around the machine and very large variations of beam-induced heat loads have been observed along the ring without any satisfactory explanation [2]. Using the current scaling laws for the different beam-induced heat load contributors (synchrotron radiations, image current and electron clouds), the future LHC Run 3 from 2021 and the HL-LHC (High-Luminosity LHC) from 2026 could be compromised due to the limited cryogenic cooling capacity available. In order to identify the possible root cause of this phenomenon and to mitigate it, a *beam-induced heat load task force* composed by about 20 CERN members representing the concerned fields of expertise has been setup. In the framework of this task force, it was asked to locate as precisely as possible these abnormal heat loads along the beam screens.

Heat loads are computed on each of the 485 half-cells of 53 m each. In order to locate more precisely the heat loads along these loops, four half-cells (called 13R4, 33L5, 13L5 and 31L2) have already been equipped with additional thermometers between each magnet and aperture in order to obtain a resolution of about 15 m in dipoles and 8 m in quadrupoles. Results in these extra-instrumented half-cells showed again very variable heat loads from one aperture to another one without any satisfactory explanation, see Figure 1. In order to go further in the heat load localization, thermal transients occurring after the beam dumps can be analysed.

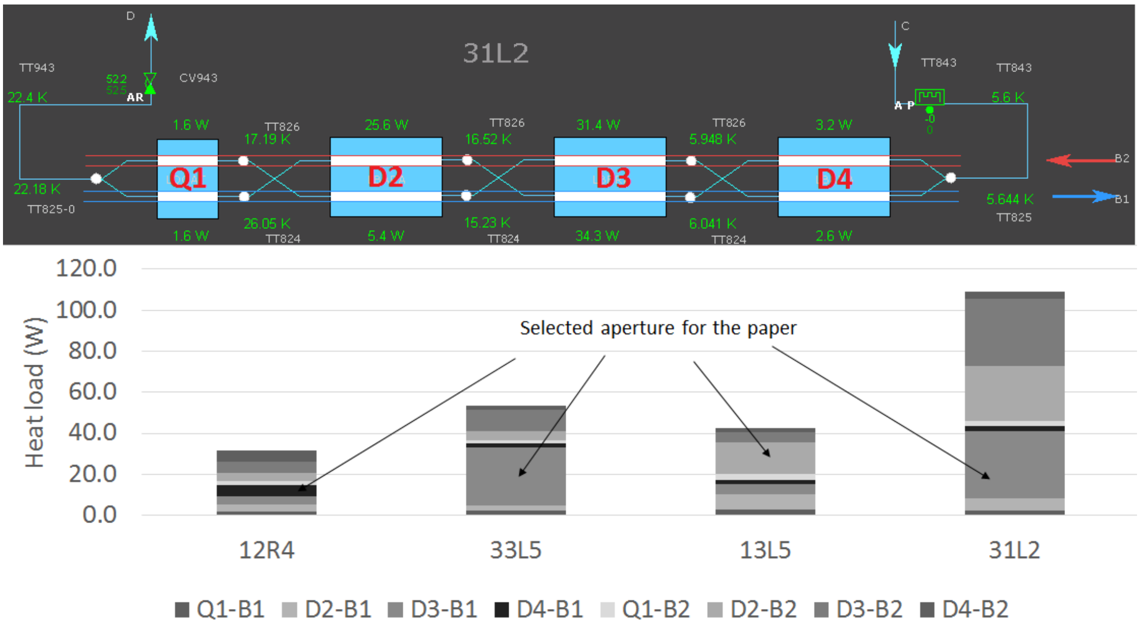

Figure 1. Typical scheme of an instrumented half-cell composed by one quadrupole $Q1$ and three dipoles $D2$, $D3$, $D4$ (top). Summary of heat loads measured in each aperture ($B1$, $B2$) of the 4 instrumented half-cells during Fill 6737 the 28^{th} May 2018 (bottom).

2. Methodology to estimate heat load profiles

2.1. Experimental setup

When a beam is dumped, the beam-induced heat loads suddenly disappear from beam screens resulting by a fast re-cooldown of the beam screens as the cooling circuit is supplied by supercritical helium at 5 K. To prevent a strong temperature disturbance in cryogenic refrigerators, electrical heaters located at the entrance of the beam screen cooling loops are automatically powered at the beam dump to compensate the missing heat loads and reducing the undesirable transient, see [3] for details.

Nevertheless, if the electrical heater is not powered just after the beam dump, the re-cooldown transient of the beam screen at the supercritical helium supply temperature could provide useful information. This thermal transient clearly depends on the beam screen temperature profile just before the dump as the heat capacity of the beam screen mass is changing significantly during the cooldown between 20 K and 5 K. The heat load repartition along the magnets could be then reconstructed consequently. To validate the method, some dynamic simulations were performed using the cryogenic beam screen cooling loop model described in [4]. The Figure 2 illustrates a simulation of this re-cooldown over one dipole aperture where we can see the different dynamics depending on the heat load repartition: uniformly distributed over the 15 meters of the dipole, located on the first meter only and located on the last meter only.

It was consequently decided to delay the heater powering after the beam dumps and to freeze the regulation valve by about 15 min in the four extra-instrumented cells around the machine in order to preserve this re-cooldown transient.

2.2. Algorithm to identify possible heat load profiles

To reconstruct the heat load profile along a magnet aperture just before the beam dump, the first task consists in computing the total heat load on this aperture and to compute the amount of energy that was necessary to re-cooldown the entire beam screen after the dump.

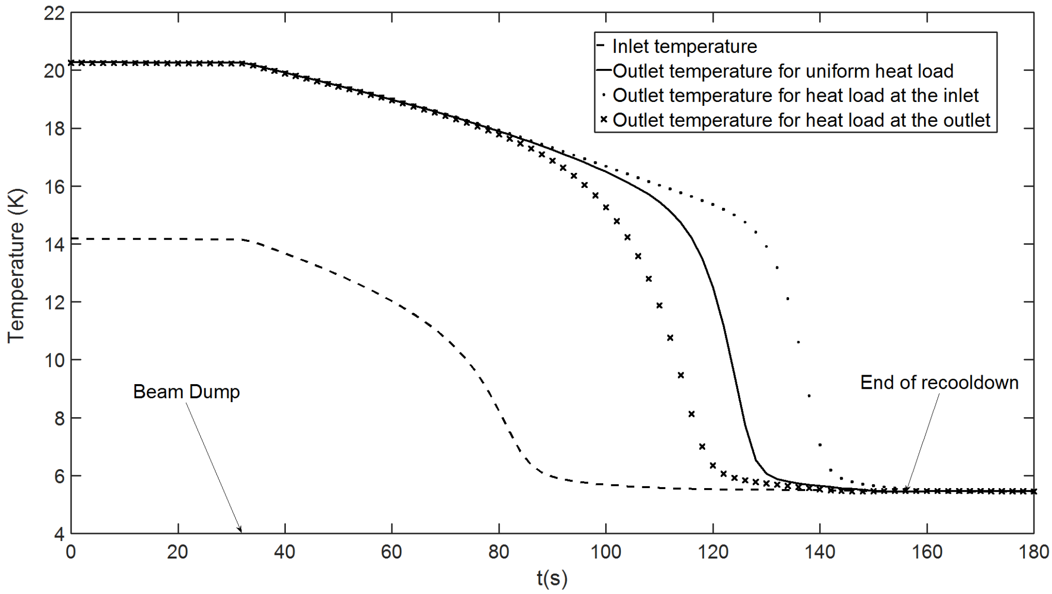

Figure 2. Simulation of beam screen temperatures on one dipole aperture after a beam dump

The following steps are performed:

- Extract the valve position and all temperature and pressure sensors connected to the concerned magnet aperture.
- Computation of the massflow passing in the cooling circuit: $\dot{m}$, see [5] for details.
- Compute the total heat load of the aperture with a simple energy balance: $Q_{BS} = \dot{m} \cdot (h_{out} - h_{in})$ where h_{in} and h_{out} are the inlet and outlet enthalpies calculated from the corresponding pressures and temperatures.
- Identify the starting time of re-cooldown t_0 when proton beam intensities are below $10^{10} p^+$.
- Identify the ending time of re-cooldown t_{end} when $|T_{in} - T_{out}| < 10\ mK$ and both temperatures reached their minimum value.
- Compute the extracted energy in the helium cooling loop to re-cooldown the beam screen:

$$E_{He} = \sum_{t=t_0}^{t=t_{end}} Q_{BS}(t) \cdot \Delta t \tag{1}$$

where Δt is the time step between two measurements (about 5 sec).

Then, to identify all compatible temperature profiles with this re-cooldown energy E_{He}, about 1000 heat load profiles are randomly generated over n nodes having a length Δx and a sum equal to $Q_{BS}(t_0)$. In addition to this, a minimum heat load is applied over each node, corresponding to the the synchrotron radiation and the image current heat loads, see [6] for details. To obtain a resolution of about 1 meter in dipoles, it was decided to use 15 nodes to discretise the magnets. Once these heat load profiles are generated, the corresponding temperature profiles are deduced and the energy needed to re-cooldown the beam screen mass is computed for each profile:

$$E_{BS} = \sum_{x=1}^{x=n} \sum_{T=T_0}^{T=T_{end}} M_l \cdot Cp(T,x) \cdot \Delta T \cdot \Delta x \tag{2}$$

where T_0 and T_{end} are the initial and final temperatures of the beam screen, ΔT is the temperature step taken as 0.1 K, M_l is the specific mass of the beam screen ($M_l = 1.32\ kg/m$) and Cp is the specific heat of the beam screen, depending of the temperature in the node x.

The possible profiles are the ones where $E_{He} = E_{BS}$ with a tolerance of about ± 5 % corresponding to the relative error done of the massflow calculation.

3. Experimental results

From May 2018, electrical heaters were switched off and all valves were frozen 15 minutes after beam dumps in the four instrumented half-cells giving 32 available beam screen re-cooldown to execute this thermal transient analysis.

To illustrate the results, two beam dumps were selected with a beam energy of 6.5 TeV and at different beam intensities during June 2018:

- **Dump 6737** at high intensity ($2.7 \cdot 10^{14} p^+/beam$)
- **Dump 6772** at low intensity ($1.5 \cdot 10^{14} p^+/beam$)

Then, we have selected one dipole beam screen aperture in each of the instrumented half-cell showing different heat load values:

- **13R4-D2-B2** showing an average of about 0.25 W/m during fill 6737
- **33L5-D3-B1** showing an average of about 1.90 W/m during fill 6737
- **13L5-D2-B2** showing an average of about 1.05 W/m during fill 6737
- **31L2-D3-B1** showing an average of about 2.20 W/m during fill 6737

The Figures 3 and 4 represent all the heat load profiles found in four selected dipole apertures during the 2 selected beam dumps. All profiles found within the 5% of error are displayed and if any profile is found, the profile with the lowest error is displayed with its associated error. Note that in case of several possible profiles, the profile with the smallest heat load peak is represented with a black dash-line.

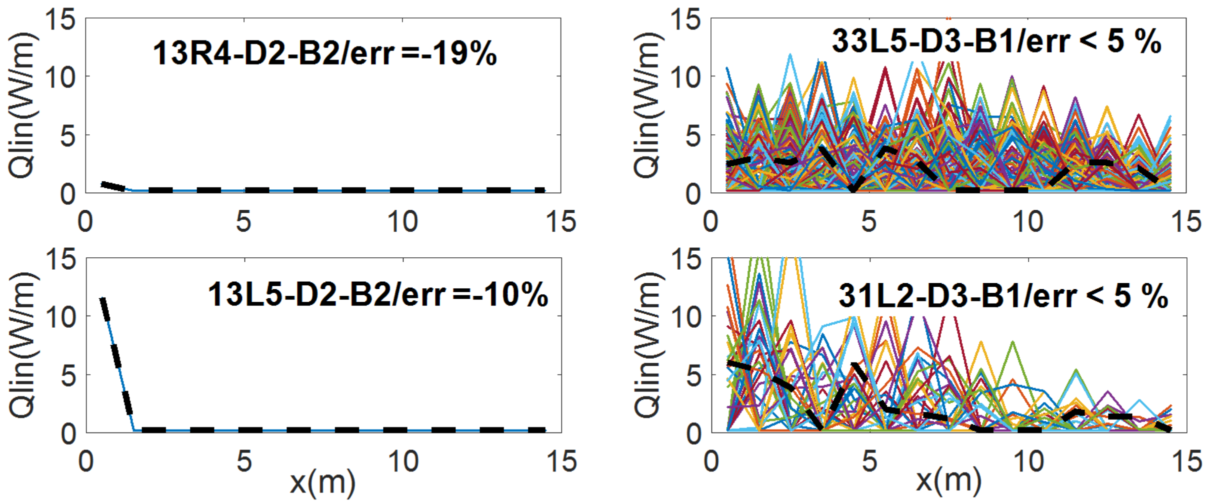

Figure 3. Potential heat load profiles after beam dump 6737 (high beam intensity - 6.5 TeV)

We observe that the low heat load half-cell 13R4-D2-B2 shows rather flat profiles with relatively low linear heat loads as expected. On the other hand, the high heat load half-cells are showing quite significant peaks localized in only few meters indicating that the abnormal heat

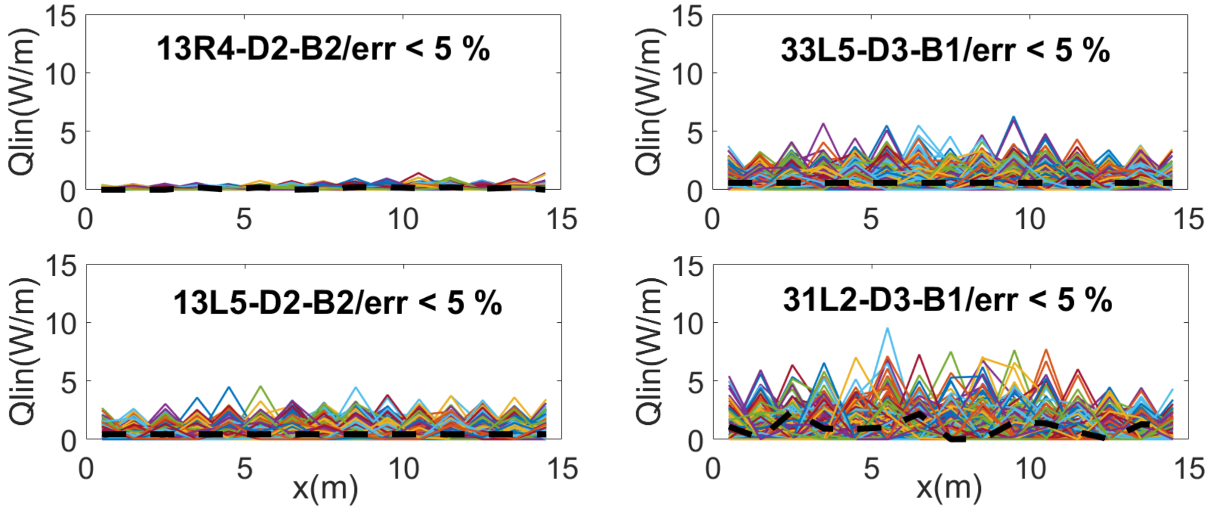

Figure 4. Potential heat load profiles after beam dump 6772 (low beam intensity - 6.5 TeV)

loads observed on the magnets are deposited on only few meters, inducing a very high specific heat load, up to 10 W/m. It can be also noticed that the heat load peaks can be localized at different locations according to all possible profiles but the most probable ones (dash-lines), demonstrate heat load peaks located at the entrance of the magnet, close to the interconnections, but this observation cannot be extrapolated due to the small available statistics.

4. Conclusion

LHC beams are producing abnormal beam-induced heat loads along the beam screens with a very variable distribution. In order to understand this phenomenon and finding a solution for the future, the cooldown transients of the beam screens occurring after the beam dumps having been analyzed using a stochastic method to estimate the possible heat load profiles with the available measurements. Results have shown some local phenomena on only few meters responsible for these high heat load observations.

If the abnormal heat loads are due to electron clouds effect as the experts believe, such a high value can be explained only by a very important SEY (Second Electron Yield) of the surface, which can be difficult to explain for the beam screen copper surface in the LHC, especially after a significant accumulated electron dose, as all beam screens should condition together to reach the same SEY value around the machine[7].

Acknowledgments

The authors would like to thank all the members of the CERN beam-induced heat load task force who contributed to setup and analyse the results of this thermal transient analysis and also the cryogenic control support team for the needed software modifications.

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