Analysis of the beam induced heat loads on the LHC arc beam screens during Run 2

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Summary

During Run 2 the Large Hadron Collider (LHC) has been routinely operated with 25 ns bunch spacing. In these conditions large heat loads have been measured on the beam screens of the superconducting magnets, which together with other observations indicates that an electron cloud develops in the beam chambers. The analysis of these heat loads has revealed several interesting features allowing to pinpoint peculiar characteristics of the observed beam-induced heating. This document describes the main findings of this analysis including the evolution taking place during the run, the observed dependence on the beam conditions and the results from special tests and dedicated instrumentation. The differences observed in the behavior of the eight LHC arcs are also discussed.
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1 Introduction

After the Long Shutdown 1 (LS1), the Large Hadron Collider (LHC) restarted operation in March 2015 aiming at colliding 25 ns beams with the maximum number of bunches at 6.5 TeV during Run 2. As had been suggested by simulation studies and by the brief experience with 25 ns beams at the end of Run 1, electron cloud effects made the operation with these beams very challenging [1–6]. Four weeks in 2015, 24 hours in 2016 and one week in 2017 were necessary to condition the beam chambers of the LHC and enable a smooth intensity ramp-up with 25 ns beams for physics production. In spite of that, the electron cloud still visibly affected the beam quality and limited the number of bunches and the intensity per bunch at 6.5 TeV, especially at the beginning of the runs, due to its adverse effects on the beam and to its strong contribution to the heat load in the cold regions [6,7].

In particular, the heat load on the beam screens of the arcs reached values comparable to the full cooling capacity available from the cryogenic systems [8, 9] and posed significant challenges when increasing the number of bunches used for the luminosity production fills. Surprisingly, it has been observed throughout Run 2 that the different LHC sectors respond differently to 25 ns beams and exhibit different heat loads when the machine is filled with this type of beams. This difference does not decrease with beam conditioning (scrubbing), as the offset between the normalized heat loads (i.e. heat load per stored proton) of the various sectors has basically remained constant since the first physics fills with 25 ns beams in 2015. The causes of these differences, which were not expected as the eight LHC sectors are by design identical, are still unknown.

The Electron Cloud Working Group [10], with the support of the cryogenics team (TE-CRG), has been regularly following up the evolution of the measured heat loads.

The main findings of this work are reported in this document, which is structured as follows: Sec. 2 presents an overview of the relevant beam operations in the period 2015-2017; in Sec. 3 we analyze the main features observed on the heat loads when operating with 25 ns bunch spacing including the effect of the beam energy and of the bunch intensity, as well as the cell-by-cell behavior; in Sec. 4 we analyze the effect of the thermal cycle performed in Sector 12 during the Extended Year-End Technical Stop (EYETS) between 2016 and 2017; in Sec. 5 we compare the data from Run 2 with measurements collected with 25 ns in Run 1; Sec. 6 reviews the main results from specially instrumented cells where the heat load in each magnet can be measured separately; in Sec. 7 we summarize observations made with different filling patterns, which allow disentangling the contributions from the different heat load sources; Sec. 8 presents a collection of data acquired with a single circulating beam; Sec. 9 compares the heat load data from the cryogenics system against the beam energy loss measured by the RF system; Sec. 10 reports the outcome of an experiment during which selected arc cells were operated with higher beam screen temperature. Finally in Sec. 11 the main observations and findings are summarized and conclusions are drawn.
2 Overview of proton beam operation in Run 2

While most of the luminosity production for the LHC Run 1 (2009-2012) was achieved with 50 ns bunch spacing, it was decided for Run 2 to operate with nominal 25 ns beams, as defined in the LHC Design Report [11]. Tests performed before the Long Shutdown 1 (LS1) as well as extended simulation studies clearly suggested that electron cloud effects were likely to pose important challenges to the operation of the machine with this type of beams [1–6]. For this reason, a significant time of the 2015 machine schedule (four weeks) was devoted to scrubbing runs at 450 GeV for the mitigation of the electron cloud. While no extended scrubbing period was then necessary in 2016 since the machine had not been vented during the Year-End Technical Stop (YETS) 2015-16, another longer period (one week) had to be devoted to scrubbing in 2017 due to the opening of Sector 12 during the Extended YETS 2016-17 necessary to exchange a faulty dipole magnet. Furthermore, since important scrubbing was also parasitically accumulated during physics production, in the following we will briefly describe not only the dedicated scrubbing runs but also the physics operation in 2015, 2016 and 2017, highlighting the changes of beam parameters and machine settings with potential impact on electron cloud production and related effects.

2.1 2015 scrubbing runs

After the usual period of commissioning with low intensity beams, the first post-LS1 scrubbing run took place in the period 24 June – 5 July 2015, with the aim of preparing the machine for a first intensity ramp-up in physics with 50 ns beams [6]. With this bunch spacing only about 450 bunches per beam could be accelerated to 6.5 TeV, due to radiation to electronics faults in the Quench Protection System (fixed during the following Technical Stop). A longer scrubbing period took place later on in the period 25 July – 10 August, aiming at enabling physics production with 25 ns beams.

Due to the full machine venting during LS1, the Secondary Electron Yield (SEY) of the LHC beam screens was not surprisingly found to be reset to the values observed at the beginning of Run 1. Electron cloud induced instabilities were observed even with 50 ns beams, which were used routinely for physics production before LS1. Figure 1 (top) shows the beam intensity evolution during the scrubbing periods. Apart from an initial 48 hours with 50 ns bunch spacing, scrubbing was performed with 25 ns beams. The progress during scrubbing was mainly determined by pressure increase in the injection kicker (MKI) regions, vacuum spikes at the injection stoppers (TDI), strong transients on the beam screen temperature slowing down injection speed and dump/refill cycles, and beam losses due to electron cloud driven instabilities. The intensity in the machine could be steadily increased over the two weeks up to about 2500 bunches per beam.

The evolution of the SEY of the beam screens in the main dipoles could be reconstructed by comparing heat load measurements with PyECLoud buildup simulations and is shown in the bottom plot of Fig. 1. The SEY reduction is much faster at the early stages of the scrubbing process when the SEY is larger. This is a known feature of the surface behaviour. Nevertheless, an evident improvement of the beam quality was also observed during the later stages, when the curve of the reconstructed SEY effectively flattens off.
2.2 2015 operation with 25 ns beams

The scrubbing runs provided sufficient mitigation to control the beam degradation at 450 GeV and start the intensity ramp-up with 25 ns beams at 6.5 TeV, although full suppression of the electron cloud was not achieved [6]. Instabilities at injection could be kept under control with fully functional transverse damper as well as high enough chromaticity and octupole settings. The beam degradation caused by the larger tune spread generated by the anti-instability settings could also be avoided with a lower vertical tune ($Q_y = 0.295$ instead of the nominal $Q_y = 0.31$). However, the electron cloud still appeared to pose important challenges to the beam intensity ramp-up at 6.5 TeV due to the unprecedented heat loads on the beam screens of the cryogenic magnets (both in terms of fast transients of the beam screen temperatures, when injecting or dumping the beams, and absolute values of the heat load that would quickly approach the cryogenic limit in the sectors with the highest heat load).

A dedicated feed-forward loop had to be implemented to automatically adapt the cryogenics regulation based on the expected heat loads from the measured beam parameters [12]. By the beginning of October, the LHC could be operated with 1450 bunches per ring with a total beam intensity of about $1.5 \times 10^{14}$ p per ring. At that point, the limit of the available cooling capacity on the arc beam screens was almost reached. To keep increasing the beam current, it was necessary, on one hand, to rely on further conditioning of the beam screens, and on the other hand to fine tune the beam parameters in order to maximize the beam intensity within the constraints posed by the available cooling capacity. This was achieved mainly by two actions, as highlighted in Fig. 2:

- The target bunch length for the controlled longitudinal blowup in the ramp was in-
creased from 1.25 ns to 1.35 ns;

- The filling scheme was gradually relaxed by spacing farther apart the SPS trains (in Fig. 2 “72g72” stands for injection of two trains of 72 bunches spaced by 1 µs instead of the nominal 225 ns) and eventually shortening them (moving to injections of four trains of 36 bunches spaced by 225 ns), thus minimizing the number of bunches with saturated electron cloud (and hence the heat load).

By the end of the proton run it was possible to operate with 2244 bunches per ring in short trains of 36 bunches, with bunch intensities of about $1.2 \times 10^{11}$ p/bunch. The center plot in Fig. 2 shows the average heat load measured on the arc beam screens over the whole 2015 physics run. While from this plot it is difficult to draw conclusions on the scrubbing, as the beam intensity was constantly increased along the year (top plot), a global reduction of about a factor of two can be clearly observed on the heat load per proton (bottom plot in Fig. 2). This is a combined effect of the accumulated scrubbing dose and of the tuning of the beam parameters (bunch length and filling pattern). In order to isolate the effect of scrubbing, the heat load of a reference fill performed at the end of the p-p run was compared
with that of a fill with the same beam conditions (filling pattern, bunch intensity, bunch length) at an early stage of the intensity ramp-up. This comparison revealed a net reduction by 30 to 60% of the heat load in the arcs [6].

2.3 2016 Mini-scrubbing Run

In 2016, the dedicated scrubbing run took place on the 25 April, following a period of commissioning with low-intensity beams. In the first few fills clear signs of beam screen de-conditioning with respect to the situation at the end of proton physics in 2015 could be observed [7]. The de-conditioning could be seen in the strong e-cloud instabilities occurring at injection, the significant emittance growth and beam degradation, as well as through the measurements of arc heat loads and bunch-by-bunch energy loss from the RF stable phase measurement. However, with respect to 2015, re-conditioning also appeared to take place very quickly. Though the scrubbing had to be interrupted after only 24 hours due to a vacuum leak in the SPS high energy beam dump (TIDVG), by that point up to 1800 bunches per beam, in trains of 216 bunches per injection (composed of three trains of 72 bunches spaced by 225 ns), had been stored in the LHC at 450 GeV without significant beam degradation. As a consequence of the vacuum leak, the intensity that could be accelerated in the SPS was limited for the remainder of the run to 96 bunches, allowing for injections of a single batch of 72 bunches, or two batches of 48 bunches into the LHC.

The conditioning achieved during the 24 hours of scrubbing was sufficient to carry out the intensity ramp-up at 6.5 TeV up to 2040 bunches per beam, i.e. the maximum number that could be stored in trains of 72 bunches, without any major problems from e-cloud effects.

2.4 2016 operation

Despite the significant levels of electron cloud present in the machine, both the scrubbing run and the intensity ramp-up suffered less from electron cloud effects compared to the corresponding periods in 2015. This can be mainly attributed to the conditioning that took place during the 2015 run, which was evidently mostly preserved over the YETS. In addition, further improvements of the cryogenic feedforward control effectively limited problems with the cryogenics at injection, while beam stability and lifetimes were also improved by adopting, immediately at the start of the 2016 run, the settings found beneficial during 2015: high chromaticity and octupole current, along with adjusted transverse tunes to accommodate the large tune footprint.

During most of the proton physics run in 2015, the LHC was operated at the limit of the available cooling capacity on the arc beam screens, and several measures were taken to reduce the heat load per proton in order to allow for a higher beam current in the machine. In 2016, by contrast, the beam current was limited by the SPS, and instead measures were taken to maximize the luminosity for a given current. The evolution of the total beam intensities during the 2016 run is shown at the top of Fig. 3, below which the main changes made in beam parameters are outlined. Injections of single trains of 72 bunches were replaced by two trains of 48 bunches, which could still be accelerated in the SPS, allowing for a maximum of 2220 bunches in the LHC. With this filling pattern, the Batch Compression Merging and Splitting (BCMS) production scheme could be used in the PS, in order to increase the
beam brightness [13]. Simultaneously, the target bunch length for the controlled longitudinal blowup on the ramp was gradually decreased from 1.25 ns to 1.1 ns. The middle graph in Fig. 3 shows the average heat load measured on the arc beam screens, sector by sector. The maximum heat load allowed by the cooling capacity, roughly 160 W/half-cell or 3 W/m, was reached only briefly at the beginning of the run. The graph on the bottom of the figure shows the evolution of the heat loads, normalized to the total beam intensity. An overall reduction of the heat load of roughly 25% over the full run can be observed. This is the combined effect of the conditioning due to the accumulated scrubbing dose and the adjustments to beam parameters. In order to evaluate the conditioning independently of the beam parameters, three reference fills were performed during the run, at roughly two-month intervals. The three fills were performed with as similar beam parameters as possible. More information about these tests can be found in [14]. The reduction of the heat load over the four month period covered by the reference fills ranged between 10 and 20% according to the sector. In most sectors the heat load decrease between the first two reference fills was significantly larger than the decrease recorded between the second and the third reference fill. This means that the conditioning rate decreased during the run.

Figure 3: Evolution of the beam intensity (top), sector-by-sector averaged heat loads (middle), and the same normalized to the beam intensity (bottom) during the 2016 proton run.
2.5 2017 scrubbing run

In 2017, again a longer scrubbing run was needed to re-condition Sector 12, which was vented during the EYETS to exchange a faulty dipole. Therefore, six full days were devoted to LHC scrubbing from 6 until 12 June [15, 16]. The scrubbing run was carried out with long trains from the SPS (up to 288 bunches per injection) in order to test the potential for more efficient scrubbing. Even more strikingly than in the previous year, the beneficial effect following the operational experience accumulated with 25 ns beams (e.g. in terms of cryogenic feedback and operational settings) and the actions taken during the EYETS (e.g. the improved pumping in the vacuum sensitive MKI areas) was immediately visible. Figure 4 shows how the intensity in the LHC could be rapidly increased up to about 3.4e14 p/beam, with the record number of 2820 bunches in trains of 288b for both beams. From Fig. 4, one can also see that by the end of the scrubbing run the heat load in Sector 12 (vented during the EYETS), initially higher due to the surface recontamination, was reduced to the levels measured at injection at the end of 2016 (which means about the same value as that of Sector 81). It also exhibited the same cell-by-cell distribution, showing that the 2016 situation had been fully restored, as it will be discussed in detail in Sec. 4. Remarkably, the beam quality over the length of an operational injection period looked very good even with 2820 bunches. The degradation driven by e-cloud could be observed only over longer time scales. An important margin with respect to the chromaticity and octupole settings, and even in damper gain, was explored and proven with the last fill of the scrubbing run. During this fill, which was carried out with chromaticities lowered to 7 units in both planes, octupole setting reduced by one third and halved damper gain, the beam was perfectly stable and its lifetime was better than in previous fills. Obviously, these settings could not be transferred directly to operation with 25 ns beams, as the variant used for physics production was the BCMS beam (like in 2016), which has lower transverse emittance and is therefore more prone to electron cloud degradation.
Figure 5: Evolution of the beam intensity (top), sector-by-sector averaged heat loads (middle), and the same normalized to the beam intensity (bottom) during the 2017 proton run (until August 2017).

2.6 2017 operation

The evolution of the LHC beam intensity, heat loads and normalised heat loads in the different sectors for the 2017 physics run is displayed in Fig. 5 [16]. Data collected after the 10 Aug 2017 are not included, due to frequent changes in beam conditions related to intensity limitations from fast losses in the 16L2 cell of Sector 12 [17]. Observations made with 8b+4e beams in this period will be discussed in detail in Sec. 7.

At the beginning of the physics run, the beam current was rapidly ramped up to $3 \times 10^{14}$ p/beam, with a record number of 2556 bunches per beam in injections of 144 bunches from the SPS (made of three trains of 48 bunches spaced by 200 ns, with BCMS production scheme) and peak luminosity values exceeding by 60% the LHC design value. After reaching the highest number of bunches, the heat load at the beginning of the fills exceeded 150 W/half-cell. During the first phase and well into the physics run, it can be observed that Sector 12 became again the largest heat load producer. This is because by ramping the energy to 6.5 TeV, photoelectrons are generated (and can multipact) in regions previously not cleaned by the electron cloud at 450 GeV. The further conditioning of Sector 12 took place later on with the long physics stores. Fill after fill, it can be seen that the heat load value in Sector 12 gently decreases, until it lands back on a very similar value as Sector 81, thus reproducing the 2016 (pre-EYETS) situation. Over the effective two months of LHC running until 9 August, 2017, while the parasitic scrubbing with physics is clear for Sector 12, the heat load in the other sectors hardly showed signs of further decrease. These aspects will be discussed in detail in Secs. 3 and 4.
3 Arc heat loads with 25 ns bunch spacing

In order to quantitatively trace the evolution over the entire Run 2, the heat loads for each cooling circuits have been recalculated for the entire 2015-2017 period using the most recent calibration provided by the cryogenics team [18–20]. For all fills for which ”Stable Beams” was declared, the heat loads at selected moments of the cycle were saved in a reduced database (for all cooling circuits) together with relevant beam parameters. This allowed studying their long term evolution without having to handle too large amounts of data [18].

The analysis presented in this section includes fills performed with 25 ns spacing and more than 800 bunches in the period 2015-2017. Observations from fills performed using different bunch patterns are described in Sec. 7.

3.1 Global evolution

In Fig. 6 the evolution of the heat loads measured at 6.5 TeV is shown. The top left plot shows the evolution of the total number of bunches per beam in the considered period. The top right plot shows the evolution of the average heat load per half-cell measured in the eight LHC arcs at the end of the 'Squeeze' process (i.e. shortly before colliding the two beams). Strong differences among the sectors are evident throughout the entire period with a group of sectors around Point 1 (S12, S23, S78, and S81) showing significantly larger loads compared to the others, with differences exceeding a factor of two.

In the bottom-left plot in Fig. 6 the heat load values are normalized by the total beam intensity of the two beams at the moment of the measurement. This allows visualizing the conditioning effect that is expected on the e-cloud contribution to the heat loads. A clear reduction can be observed in all sectors over the 2015 run and in the initial part of 2016. After that, the normalized heat loads stayed practically constant, with the exception of Sector 12, which was warmed up and vented in the 2016-17 EYETS. The de-conditioning of S12 due to this process can be clearly observed between the end of 2016 and the beginning of 2017, as can the re-conditioning over the 2017 run (the effect of this thermal cycle for Sector 12 will be discussed in more detail in Sec. 4). In the bottom-right plot in Fig. 6 the normalized heat load is plotted as a function of the integrated heat load on the beam screens. This gives an indication of the evolution with respect to the accumulated electron dose.

3.2 Cell-by-cell analysis

A striking feature in the bottom plot in Fig. 6 is that the differences in normalized heat load between sectors stay practically constant during the conditioning process, with the heat load decrease stopping at different levels for the different sectors. This behavior is observed also at a cell-by-cell level, as shown in Fig. 7, where all the half-cells in the LHC are regrouped according to their heat load as measured at the end of 2016. The plot clearly shows that cells having high heat loads at the beginning of 2015 continued showing high loads over the entire analyzed period with their conditioning stopping at very high heat load values.

The strong correlation observed in the normalized heat load decrease, for which the differences practically consist only in a constant offset, seems to suggest the presence of at least two heat load components, one that is similar for all sectors and cells and shows the
Figure 6: Top left: number of bunches in the LHC for all the proton physics fills with more than 800 bunches. Top right: average heat load measured at 6.5 TeV in the eight LHC arcs (measurements are taken at the end of the squeeze process, when the heat load transient from the energy ramp is extinguished). Bottom-left: average heat load normalized to the total intensity of the two beams. Bottom-right: normalized heat loads as a function of the accumulated heat load (the dip observed on all curves around $0.1 \times 10^9$ J corresponds to operation with trains of 36 bunches at the end of 2015, see Sec. 2). All heat load values are given per half-cell.

Figure 7: Heat loads (top) and heat loads normalized to the total intensity of the two beams. Each color represents the average heat load of a group of cells having similar heat loads at the end of 2016.
In order to illustrate the evolution at a cell-by-cell level we have compared the heat loads measured at high energy for all cells in three selected fills from 2015, 2016 and 2017. Beam properties and other relevant quantities measured at the time selected for the comparison are reported in Table 1. The corresponding heat loads normalized to the total intensity are displayed in Figs. 8 and 9. Consistently with the observations on the arc averages (see Fig. 6), for most of the cells a significant change is observed only between 2015 and 2016, while the heat loads are very similar between 2016 and 2017. The cell-by-cell pattern is found to be very reproducible over the considered period and affected only marginally by scrubbing, by the beam-screen flushing performed at the beginning of each operational year and, for Sector 12, by the de-conditioning and re-conditioning cycle related to the warm-up and venting of the sector in the 2016-17 EYETS (discussed in detail in Sec. 4). Notably, instead, the Long Shutdown 1 (LS1, 2013-2015) is observed to have a significant impact on the average heat loads in the arcs, as well as on the cell-by-cell pattern. This will be discussed in detail in Sec. 5.

Qualitative differences between sectors are clearly visible in Figs. 8 and 9. A larger spread in the measured heat loads is observed within the sectors showing higher average loads (S12, S23, S78 and S81). The difference in average heat load observed between these high load sectors and the others is found to be larger than the spread observed within the low-load sectors (see also Figs. 12–16).

<table>
<thead>
<tr>
<th>Fill</th>
<th>4552</th>
<th>5264</th>
<th>6054</th>
</tr>
</thead>
<tbody>
<tr>
<td>Started on</td>
<td>24 Oct 2015 15:00</td>
<td>30 Aug 2016 23:43</td>
<td>07 Aug 2017 14:15</td>
</tr>
<tr>
<td>$T_{\text{sample}}$ [h]</td>
<td>3.40</td>
<td>1.80</td>
<td>3.10</td>
</tr>
<tr>
<td>Energy [GeV]</td>
<td>6000</td>
<td>6499</td>
<td>6499</td>
</tr>
<tr>
<td>$N_{\text{bunches}}$ (B1/B2)</td>
<td>1825/1824</td>
<td>2220/2220</td>
<td>2556/2556</td>
</tr>
<tr>
<td>Intensity (B1/B2) [p]</td>
<td>2.08e14/2.04e14</td>
<td>2.46e14/2.47e14</td>
<td>2.91e14/3.01e14</td>
</tr>
<tr>
<td>$\text{Bun.len.}$ (B1/B2) [ms]</td>
<td>1.30/1.34</td>
<td>1.05/1.06</td>
<td>1.07/1.07</td>
</tr>
<tr>
<td>H.L. exp. imped. [W]</td>
<td>5.02</td>
<td>8.27</td>
<td>10.15</td>
</tr>
<tr>
<td>H.L. exp. synrad [W]</td>
<td>8.76</td>
<td>10.49</td>
<td>12.61</td>
</tr>
<tr>
<td>H.L. exp. imp. × SR [Wip+]</td>
<td>3.35e-14</td>
<td>3.61e-14</td>
<td>3.84e-14</td>
</tr>
<tr>
<td>$T_{\text{nobeam}}$ [h]</td>
<td>1.50</td>
<td>0.05</td>
<td>1.90</td>
</tr>
</tbody>
</table>

Table 1: Relevant parameters measured at high energy for three selected fills from 2015, 2016 and 2017 (here $T_{\text{sample}}$ is the time of the measurement with respect to the start of the fill, $T_{\text{nobeam}}$ is the time before injection at which the heat loads without beam are evaluated, the bunch length ($4\sigma$) is measured by the LHC Beam Quality Monitor [21], the heat loads expected from impedance and synchrotron radiation is also reported). The selected fills are used for cell-by-cell comparisons in Figs. 8 and 9.
Figure 8: Heat loads normalized to the total intensity of the two beams measured at high energy for three selected fills in 2015, 2016 and 2017 (see table in Fig. 1) for Sectors 12, 23, 34 and 45.
Figure 9: Heat loads normalized to the total intensity of the two beams measured at high energy for three selected fills in 2015, 2016 and 2017 (see table in Fig. 1) for Sectors 56, 67, 78 and 81.
Figure 10: Heat load evolution at 450 GeV for all proton physics fills with more than 800 bunches. For a detailed explanation of the different subplots see caption of Fig. 6.

3.3 Dependence on the beam energy

The dependence of the heat loads on the beam energy is illustrated in Figs. 10–16. The observed heat load differences between LHC sectors are already present at injection energy, as shown in Fig. 10. The difference in average heat load between injection energy and collision energy is shown for the eight arcs in Fig. 11. No strong difference is observed among the arcs in this respect (apart from the already mentioned S12 deconditioning), showing that not only do the differences among arc averages appear already at injection, but they also stay constant as a function of the energy. Nevertheless, as it can be seen in Fig. 12, the heat load distribution within each sector is changing when moving from injection to collision energy. In particular, Figs. 13–16 show that, although a heat load increase is observed in all cells after the energy ramp, significantly different behaviors are observed at a cell-by-cell level.
Figure 11: Evolution of the heat load increase observed between 450 GeV and 6.5 TeV beam energy. For a detailed explanation of the different subplots see caption of Fig. 6.
Figure 12: Comparison of the cell-by-cell heat load distribution (curves) and average (dots) for the eight arcs of the LHC before and after the acceleration from 450 GeV to 6.5 TeV. The measurements are normalized by the total beam intensity. The total heat load expected from impedance and synchrotron radiation is shown for reference. Bottom: table with the relevant quantities at the time of the two measurements.
Figure 13: Cell-by-cell heat loads normalized to the total intensity of the two beams for Sectors 12 (top) and 23 (bottom). A histogram of the load distribution and a table with different relevant quantities at the time of the measurements are also shown.
Figure 14: Cell-by-cell heat loads normalized to the total intensity of the two beams for Sectors 34 (top) and 45 (bottom). A histogram of the load distribution and a table with different relevant quantities at the time of the measurements are also shown.
Figure 15: Cell-by-cell heat loads normalized to the total intensity of the two beams for Sectors 56 (top) and 67 (bottom). A histogram of the load distribution and a table with different relevant quantities at the time of the measurements are also shown.

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Figure 16: Cell-by-cell heat loads normalized to the total intensity of the two beams for Sectors 78 (top) and 81 (bottom). A histogram of the load distribution and a table with different relevant quantities at the time of the measurements are also shown.
3.4 Dependence on the bunch intensity

The heat load dependence on the bunch intensity was measured during a Machine Development (MD) session in 2016, with three consecutive fills performed with the same bunch length and filling scheme but with different bunch intensities. The results of these measurements are shown in Fig. 17. The average heat loads measured in the eight LHC arcs are fitted quite well with a linear dependence with an intensity threshold. The intensity threshold is in the range from 0.35 to $0.5 \times 10^{11}$ p/bunch, depending on the sector. This behavior is not expected from impedance and synchrotron radiation, while it is consistent with e-cloud effects. More details about these tests can be found in [14].
4 Impact of the thermal cycle to room temperature for Sector 12

During the EYETS 2016-17, the Sector 12 had to be warmed up to room temperature, opened in order to exchange a faulty dipole identified during the 2016 run, and finally cooled back down to resume operation. As a consequence, the full sector was exposed to air and the SEY of the inner part of the beam screen returned to high values. Direct SEY measurements carried out later in the year on the beam screen of the extracted dipole revealed SEY values of around 1.8-2.0 uniformly both azimuthally and longitudinally after air exposure [22]. Consistently, the heat load measured in Sector 12 in the first phase of the scrubbing run in 2017 appeared to be much higher than that of the other sectors and, as expected, also higher in normalised terms than what was measured at the end of 2016. This behaviour is illustrated in Fig. 18. While the normalised heat loads of the sectors that were not opened during the EYETS appear to have barely moved from the values they had just before the EYETS, the normalised heat load of Sector 12 exhibited a value that was more than twice the value measured at the end of 2016.

The reconditioning of Sector 12 took place during the 2017 scrubbing run for the injection energy, and subsequently during the physics run at 6.5 TeV. The scrubbing of Sector 12 at 450 GeV is clearly visible in Fig. 19. Here we have chosen to plot the evolution of the normalized heat load as measured for each scrubbing fill at an instant after the end of the
injection process and after all transients on heat loads are extinguished. From Fig. 19, it is clear that the sectors that remained cold during the EYETS slightly reconditioned only over the first 24 hours, in a typical fast deconditioning-reconditioning cycle that was already previously observed in LHC [6,7]. Furthermore, the difference between these sectors appears to be very similar to the difference at the end 2016 and it does not evolve during the scrubbing run. Sector 12, instead, evidently conditioned over the first four days of scrubbing. As from day 4, the measured heat load at the end of the injection process appeared to have become again very similar to the value at at the end of 2016. The fact that no further evolution was observed after day 4 could be fed back into the planning of future scrubbing runs after “short” and partial machine openings. The other interesting feature that we should highlight from Fig. 19 is that the use of long trains of 288 bunches from the SPS during the last three full days of scrubbing had unfortunately no visible impact on the heat load levels of the different sectors, and therefore on the difference between them.

Finally, it is also worth looking into the heat load distribution in Sector 12 and how it evolved over the scrubbing run. Figure 20 shows the cell-by-cell normalised heat load at 450 GeV along Sector 12. The top plot shows the direct comparison between two fills that took place at the end of the 2016 (blue) and at the beginning of the 2017 scrubbing run (red). A clear increase in the normalised heat load is observed on all cells, such that the loss of conditioning due to the venting appears to have basically equalised the heat loads across the sector. However, the pre-EYETS situation is then fully restored with scrubbing. The distribution of the normalised heat loads at the end of the scrubbing run is practically identical to the one measured at the end of 2016, as displayed in the bottom plot of Fig. 20.

In conclusion, the thermal cycle undergone by Sector 12 temporarily changed the heat load distribution between sectors, but the situation was quickly restored to what it was beforehand by means of the scrubbing run at 450 GeV and by parasitic scrubbing in physics at
Figure 20: Cell-by-cell distribution of the normalised heat load along Sector 12 at the end of 2016 (blue) and at the beginning of the 2017 scrubbing run (red) in the upper plot, and at the end of 2016 (blue) and at the end of the scrubbing run 2017 (red) in the lower plot.

6.5 TeV. If on one hand it can be considered good that the thermal cycle has not deteriorated the surface behaviour and the previous SEY could again be reached after a reasonable amount of scrubbing, it is also disappointing on the other hand that it could not produce any improvement (e.g. due to the cooling procedure) with respect to 2016. In general, based on this one experience, one might conclude that the difference in normalised heat load measured between sectors, which seemed to stay constant while the sectors were all at the same stage of their scrubbing history (see previous section), is not permanently altered by a thermal cycle, but it is recovered once a vented sector has reached an advanced scrubbing state again.
Figure 21: Beam intensity and energy (top), average heat load per half-cell measured in the eight arcs of the LHC (middle), and the same heat-load normalized by the total beam intensity (bottom) during two fills performed with trains of 72 bunches in 2012 (left) and in 2017 (right).

5 Comparison of heat load data against Run 1

In Run 1 luminosity production was carried out using bunch spacings larger than 25 ns (most of the operation was made with the 50 ns spacing). Nevertheless, at the end of 2012 a test period with 25 ns bunch spacing took place (a detailed description of the performed tests is available in [23]).

During the three-day scrubbing run performed in 2012, beam configurations were very similar to those used for scrubbing in Run 2 and, in particular, in 2017. This allows for a direct comparison of the heat loads.

In 2012 heat load data were not regularly logged, therefore the heat loads needed to be recomputed from the raw data saved by the cryogenics system (helium temperatures, pressures, settings of the heater and of the valves installed on the cooling circuits). With the support of the cryogenics team, the GasFlowHLCalculator tool [24] has been configured according to the Run 1 conditions of the LHC cryogenic system. This allowed reconstructing the heat loads deposited on the arc beam screens during the 2012 scrubbing run. The obtained results are in agreement with recalculations made independently by the cryogenics team [20].

In Fig. 21 we compare the average heat load measured in the arcs during two fills performed with trains of 72 bunches from the SPS in 2012 (on the left) and in 2017 (on the
Figure 22: Top: comparison between the average heat loads (dots) and cell-by-cell distributions (curves) measured in the LHC arcs in 2012 (in blue) and in 2017 (in red), at selected instants of the fills shown in Fig. 21. The measurements are normalized by the total beam intensity. The total heat load expected from impedance and synchrotron radiation is shown for reference. Bottom: table with different relevant quantities at the time of the two measurements.

right). The differences between the two fills are striking. In 2012, the average heat loads measured in the eight arcs were very similar. In 2017, instead, consistently with what was observed throughout the entire Run 2, large differences are visible. In particular, the normalized heat loads measured in the low-load sectors (S34, S45, S56, S67) are very similar to those observed in 2012. Instead, the normalized heat loads from the high-load sectors (S12, S23, S78, S81) are significantly larger than the corresponding 2012 measurements.

Selected snapshots from the two fills are compared in more detail in Figs. 22-26. In Fig. 22 the average normalized heat loads are shown together with the distribution of the cell-by-cell heat loads measured in each sector. The different behavior of the two groups of sectors is again evident: for S34, S45, S56 and S67 the average heat loads and the cell-by-cell spreads measured in 2017 are similar to 2012. For S12, S23, S78 and S81 an increase between 2012 and 2017 is observed both in the average load and in the cell-by-cell spread.
Figures 23-26 compare the heat loads measured in each cell in 2012 and in 2017. We notice that in S12, S23, S78 and S81, an increase in heat load is observed for most of the cells, while this feature is not present in the other sectors.

It is worth underlining explicitly that, while the activities performed during the LS1 had an important impact on the heat loads measured after the reconditioning, such an effect was not observed after the venting and the thermal cycle performed in S12 during the 2016-17 EYETS, as discussed in Sec. 4.
Figure 23: Cell-by-cell heat loads normalized to the total intensity of the two beams for Sectors 12 (top) and 23 (bottom) in 2012 (blue) and in 2017 (red). A histogram of the load distribution and a table with different relevant quantities at the time of the measurements are also shown.

30
Figure 24: Cell-by-cell heat loads normalized to the total intensity of the two beams for Sectors 34 (top) and 45 (bottom) in 2012 (blue) and in 2017 (red). A histogram of the load distribution and a table with different relevant quantities at the time of the measurements are also shown.
Figure 25: Cell-by-cell heat loads normalized to the total intensity of the two beams for Sectors 56 (top) and 67 (bottom) in 2012 (blue) and in 2017 (red). A histogram of the load distribution and a table with different relevant quantities at the time of the measurements are also shown.
Figure 26: Cell-by-cell heat loads normalized to the total intensity of the two beams for Sectors 78 (top) and 81 (bottom) in 2012 (blue) and in 2017 (red). A histogram of the load distribution and a table with different relevant quantities at the time of the measurements are also shown.
6 Data from special instrumented cells

While in general in the LHC we can only measure the heat loads on a cell-by-cell basis (with every half-cell being formed by three 14.2 m long dipole magnets, one 3 m long quadrupole magnet, miscellaneous short multipole magnets and field-free interconnections), a few selected half-cells have been equipped with extra thermometers to separately measure the heat loads on a magnet-by-magnet basis within the given half-cell (even distinguishing between Beam 1 and Beam 2). In particular, the following cells were selected:

- Three cells in Sector 45 (13R4, 13L5, 33L5), which were instrumented during LS1. They were chosen randomly to sample both the extremities and the middle of the sector, but turned out to belong to a low-load sector. They practically always showed relatively low heat loads.

- One cell in Sector 12 (31L2), which was instrumented during the EYETS 2016-17 using the opportunity of the dipole exchange already mentioned in previous sections. This cell shows a large heat load.

Figure 27 shows the evolution of the normalised heat load measured in all the instrumented dipoles at the end of the injection process during the 2017 scrubbing run. All the dipoles in the cells of Sector 45 exhibit basically no heat load because they were previously conditioned by the 2015-16 runs. The dipoles in the 31L2 cell, freshly instrumented and recently opened to air, undergo a clear scrubbing, which however seems to behave differently for the three different dipoles. While the newly exchanged dipole 31L2-D4 begins from a high value of heat load and then scrubs completely within the first two days, the other two dipoles (which were not exchanged) already start from higher heat load values and after 4-5 days seem to saturate their scrubbing, landing however at a non-zero value of heat load. This type of behaviour is likely to be the origin of the higher heat loads measured in the high-load sectors with respect to the low-load sectors.

Figure 27: Evolution of the normalised heat load in the instrumented dipoles as measured at the end of the injection process for every fill over the 2017 scrubbing run (right plot). The left plot shows the number of bunches injected (blue for Beam 1 and red for Beam 2) and the numbers above it specify the length of the trains injected from the SPS.
Figures 28 and 29 show the evolution of the normalised heat load measured in all the instrumented dipoles both at the start of the ramp (450 GeV) and at the end of the squeeze process (6.5 TeV) for every physics fill over the years 2015, 2016 and 2017. Obviously, the data relative to the instrumented 31L2 cell are only available as from 2017. At injection energy, the dipoles of Sector 45 exhibit a quick scrubbing in 2015 and then their heat load values appear to hit the measurement resolution later on. At 6.5 TeV a clear scrubbing trend is observed in all the dipoles of the instrumented cells of Sector 45 all throughout 2015, which continued for at least half of the 2016 run. Afterwards, the values level off and exhibit a spread between 0.2 and $5 \times 10^{-13}$ W/p according to the cell (much larger than the very small values at injection, which indicates that the heat loads in these dipoles increases significantly along the energy ramp). Conversely, both data at injection and at 6.5 TeV show that the dipoles in 31L2 start from visibly larger values (by at least a factor two) and scrub throughout 2017. However, while 31L2-D4 (the exchanged magnet) seems to follow the same scrubbing slope as all other instrumented dipoles in Sector 45 did in 2015 at the beginning of their scrubbing, 31L2-D2 and 31L2-D3 progress much more slowly. While the slope of their decrease might seem just slightly lower, we should also consider that they are receiving much more electron dose. This is visible in the plots of the heat load as a function of the integrated heat load, bottom right of Fig. 29. It should be mentioned that the present heat load of the 31L2 cell is very close to that measured last year, suggesting that the magnet that was removed was also well behaved in terms of electron cloud and had scrubbed down to normalised heat load values typical of low-load magnets [25].

Figure 30 shows the evolution of the normalised heat load measured in all the instrumented quadrupoles at the end of the injection process during the 2017 scrubbing run. The quadrupoles in the cells of Sector 45 exhibit a low heat load because they were previously conditioned by the 2015-16 physics runs. The quadrupole in the 31L2 cell, freshly instrumented and recently opened to air, starts from a very high heat load value and undergoes a light scrubbing over the first two days before landing at a value that is still more than three times higher than that of the other instrumented quadrupoles. This value has remained constant over the 2017 physics run, as shown in Fig. 31. However, the heat load measured at injection in the instrumented quad vanishes over the energy ramp, as can be seen in Fig. 32. This is consistent with simulations showing a lower SEY threshold for electron cloud build up at 450 GeV than at 6.5 TeV, and therefore a higher heat load value if the SEY of the beam screen in the quadrupole is assumed to be between 1.15 and 1.25 [25].

Figure 33 shows the evolution of the normalised heat load measured in all the instrumented quadrupoles at 6.5 TeV for every physics fill over the years 2015, 16 and 17. From here we can see that the quadrupoles in Sector 45 were basically scrubbed to their lowest value (i.e. $0.05 \times 10^{-13}$ W/p) during the first half of the 2015 physics run. Their heat load values remained then practically the same ever after. The quadrupole in 31L2 seems to be undergoing the same process and has almost reached the final value.

In conclusion, if we assume that what we see in the cell 31L2 is representative of the behaviour of a typical half-cell in a high-load sector, then the analysis on the heat load of the single magnets compared with the same analysis made for two half-cells of a low-load sector would suggest that at 6.5 TeV the larger heat load of the high-load sectors is mainly due to the dipoles, which do not reach the same advanced scrubbed state as those in the half-cells of the low-load sectors. At 450 GeV quadrupoles might also play a role.
Figure 28: Evolution of the heat loads in the dipoles of the instrumented cells at 450 GeV, for all proton physics fills with more than 800 bunches. For a detailed explanation of the different subplots see caption of Fig. 6.

Figure 29: Evolution of the heat loads in the dipoles of the instrumented cells at 6.5 TeV, for all proton physics fills with more than 800 bunches. For a detailed explanation of the different subplots see caption of Fig. 6.
Figure 30: Evolution of the normalised heat load in the instrumented quadrupoles as measured at the end of the injection process of every fill over the 2017 scrubbing run (right plot). The left plot shows the number of bunches injected (blue for Beam 1 and red for Beam 2) and the numbers above it specify the length of the trains injected from the SPS.

Figure 31: Evolution of the heat loads in the quadrupoles of the instrumented cells at 450 GeV, for all proton physics fills with more than 800 bunches. For a detailed explanation of the different subplots see caption of Fig. 6.
Figure 32: Heat load in the quadrupoles of the instrumented cells during a physics fill with 25 ns beams.

Figure 33: Evolution of the heat loads in the quadrupoles of the instrumented cells at 6.5 TeV, for all proton physics fills with more than 800 bunches. For a detailed explanation of the different subplots see caption of Fig. 6.
7 Effect of the bunch pattern

An important feature for identifying the source of the observed heat loads (and of the differences between arcs) is the dependence on the bunch spacing. During Run 2, most of the luminosity production has been performed with 25 ns spacing. Nevertheless a certain number of fills were performed with other bunch patterns, for special runs, tests and studies.

In Tab. 2 we list a set of fills performed with different bunch spacings together with the relevant beam parameters. For these fills, we compare in Fig. 34 the average heat load per bunch measured at high energy in each sector, and the corresponding load expected from impedance and synchrotron radiation effects.

<table>
<thead>
<tr>
<th>Beam type</th>
<th>Fill n.</th>
<th>N. bunches</th>
<th>Avg. bun. intensity</th>
<th>Avg. bun. length</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 ns</td>
<td>4511</td>
<td>685</td>
<td>0.86e11 p/b</td>
<td>1.18 ns</td>
</tr>
<tr>
<td>50 ns</td>
<td>5980</td>
<td>1284</td>
<td>1.07e11 p/b</td>
<td>1.08 ns</td>
</tr>
<tr>
<td>8b+4e</td>
<td>6259</td>
<td>1916</td>
<td>1.07e11 p/b</td>
<td>1.08 ns</td>
</tr>
<tr>
<td>25 ns</td>
<td>6079</td>
<td>601</td>
<td>1.08e11 p/b</td>
<td>1.09 ns</td>
</tr>
<tr>
<td>25 ns</td>
<td>6123</td>
<td>2220</td>
<td>1.13e11 p/b</td>
<td>1.08 ns</td>
</tr>
</tbody>
</table>

Table 2: List of analyzed fills with different bunch spacings together with the relevant beam parameters. The corresponding arc heat loads are shown in Figs. 34–43.

In the fills with 100 ns and 50 ns bunch spacing, the measured heat loads per bunch are very similar and consistent with the expected values from impedance and synchrotron radiation. Moreover no significant differences are observed between sectors.

In the fills performed with 25 ns bunch spacing, instead, the heat load differences between sectors become apparent. In these cases the heat loads per bunch are much larger compared to the 50 ns and 100 ns cases and exceed by a large factor the expectation from impedance and synchrotron radiation. Comparing the two considered 25 ns fills we observe that the total number of bunches affects only marginally the measured heat load per bunch.

The case of the 8b+4e scheme, made of short trains of eight bunches with 25 ns spacing interleaved by four empty slots, shows an intermediate behavior between the 50 ns and the 25 ns spacings.

The large increase observed with the 25 ns bunch spacing with respect to 50 ns bunch spacing allows us to exclude that impedance heating (for any arbitrary impedance, including High Order Modes) could be the source of the observed heat loads [26]. The observations are instead compatible with e-cloud effects for which different multipacting thresholds are expected for different bunch spacings [23]. The difference between cells, under this hypothesis, corresponds to different surface properties, in particular SEY, of the installed beam screens.

Figure 35 shows the cell-by-cell distributions observed in the eight arcs with 25 ns, 50 ns and 8b+4e beams. With 50 ns beams, not only are the arc averages very close to each other and consistent with the expectations from impedance and synchrotron radiation, but also the observed spreads are extremely similar and compatible with the accuracy of the measurement. Differences in averages and spreads are instead very strong for the 25 ns fills. Also with respect to these aspects, the 8b+4e pattern shows an intermediate behavior, where differences among sectors are present but significantly less pronounced compared to the 25 ns fills.
Figure 34: Average heat load measured in the eight LHC arcs with different filling patterns (in blue), compared against the expected load from impedance (in grey) and synchrotron radiation (in green).
Figure 35: Comparison of the cell-by-cell heat load distribution and average among fills with 25 ns bunch spacing (in red), 50 ns bunch spacing (in blue in the top picture) and 8b+4e bunch pattern (in blue in the bottom picture).
In Figs. 36-43 the normalized heat loads measured with 25 ns, 50 ns and 8b+4e beams are compared for all cells in the LHC arcs. Again different qualitative behaviors are observed for different arcs. A large increase in normalized heat load is observed with the 25 ns spacing with respect to the 50 ns and 8b+4e cases in most of the cells of the high-load sectors.
Figure 36: Cell by cell heat loads measured in Sector 12 with 25 ns bunch spacing (in red), with 50 ns bunch spacing (in blue in the top picture) and with the 8b+4e scheme (in blue in the bottom picture).
Figure 37: Cell by cell heat loads measured in Sector 23 with 25 ns bunch spacing (in red), with 50 ns bunch spacing (in blue in the top picture) and with the 8b+4e scheme (in blue in the bottom picture).
Figure 38: Cell by cell heat loads measured in Sector 34 with 25 ns bunch spacing (in red), with 50 ns bunch spacing (in blue in the top picture) and with the 8b+4e scheme (in blue in the bottom picture).

<table>
<thead>
<tr>
<th>Sector 34</th>
<th>50 ns</th>
<th>25 ns</th>
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</thead>
<tbody>
<tr>
<td>Fill</td>
<td>5980</td>
<td>5979</td>
</tr>
<tr>
<td>Started on</td>
<td>22 Jul 2017 10:34</td>
<td>21 Jul 2017 15:41</td>
</tr>
<tr>
<td>T_sample [h]</td>
<td>3.00</td>
<td>3.30</td>
</tr>
<tr>
<td>Energy [GeV]</td>
<td>6499</td>
<td>6499</td>
</tr>
<tr>
<td>N_bunches (B1/B2)</td>
<td>1284/1284</td>
<td>2556/2556</td>
</tr>
<tr>
<td>Intensity (B1/B2) [p]</td>
<td>1.36e14/1.38e14</td>
<td>2.80e14/2.84e14</td>
</tr>
<tr>
<td>Bunch len. (B1/B2) [ns]</td>
<td>1.08/1.09</td>
<td>1.07/1.07</td>
</tr>
<tr>
<td>H.L. S34 (avg) [W]</td>
<td>13.98</td>
<td>56.41</td>
</tr>
<tr>
<td>H.L. S34 (std) [W]</td>
<td>6.16</td>
<td>14.79</td>
</tr>
<tr>
<td>H.L. exp. imped. [W]</td>
<td>4.33</td>
<td>9.20</td>
</tr>
<tr>
<td>H.L. exp. synrad [W]</td>
<td>5.57</td>
<td>12.01</td>
</tr>
<tr>
<td>T_nohean [h]</td>
<td>0.63</td>
<td>2.90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sector 34</th>
<th>8b+4e</th>
<th>25 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>6247</td>
<td>6057</td>
</tr>
<tr>
<td>Started on</td>
<td>27 Sep 2017 08:01</td>
<td>08 Aug 2017 16:12</td>
</tr>
<tr>
<td>T_sample [h]</td>
<td>2.80</td>
<td>2.80</td>
</tr>
<tr>
<td>Energy [GeV]</td>
<td>6499</td>
<td>6499</td>
</tr>
<tr>
<td>N_bunches (B1/B2)</td>
<td>1916/1916</td>
<td>2556/2556</td>
</tr>
<tr>
<td>Intensity (B1/B2) [p]</td>
<td>2.19e14/2.22e14</td>
<td>2.98e14/3.05e14</td>
</tr>
<tr>
<td>Bunch len. (B1/B2) [ns]</td>
<td>1.07/1.09</td>
<td>1.08/1.06</td>
</tr>
<tr>
<td>H.L. S34 (avg) [W]</td>
<td>24.86</td>
<td>60.69</td>
</tr>
<tr>
<td>H.L. S34 (std) [W]</td>
<td>9.54</td>
<td>15.37</td>
</tr>
<tr>
<td>H.L. exp. imped. [W]</td>
<td>7.45</td>
<td>10.51</td>
</tr>
<tr>
<td>H.L. exp. synrad [W]</td>
<td>9.40</td>
<td>12.83</td>
</tr>
<tr>
<td>T_nohean [h]</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Figure 39: Cell by cell heat loads measured in Sector 45 with 25 ns bunch spacing (in red), with 50 ns bunch spacing (in blue in the top picture) and with the 8b+4e scheme (in blue in the bottom picture).
Figure 40: Cell by cell heat loads measured in Sector 56 with 25 ns bunch spacing (in red), with 50 ns bunch spacing (in blue in the top picture) and with the 8b+4e scheme (in blue in the bottom picture).
Figure 41: Cell by cell heat loads measured in Sector 67 with 25 ns bunch spacing (in red), with 50 ns bunch spacing (in blue in the top picture) and with the 8b+4e scheme (in blue in the bottom picture).
Figure 42: Cell by cell heat loads measured in Sector 78 with 25 ns bunch spacing (in red), with 50 ns bunch spacing (in blue in the top picture) and with the 8b+4e scheme (in blue in the bottom picture).
Figure 43: Cell by cell heat loads measured in Sector 81 with 25 ns bunch spacing (in red), with 50 ns bunch spacing (in blue in the top picture) and with the 8b+4e scheme (in blue in the bottom picture).
8 Observations with a single circulating beam

It is interesting to check whether the peculiar heat load distribution between sectors depends on both beams or if it is dominated by one of the two beams. Separated data for Beam 1 and Beam 2 in identical running conditions are not available in 2015 and 2016. However, in both years there were fills with Beam 1 alone, from which we can draw at least some conclusions by comparison with similar fills in which both beams were injected. In 2017 there were a few instances during the scrubbing run, in which the behaviour of the two beams could be observed separately.

Figure 44 shows the direct comparison between two fills that took place only one day apart. In fill 4532, displayed on the right side, both beams were injected and used for physics production. In fill 4535, depicted on the left side, only Beam 1 was injected and ramped to 6.5 TeV for a specific test, with the same intensity as in the previous day. The middle plots show the heat loads measured in the different sectors for these two fills, while the bottom plots show the same heat loads normalised to the beam intensity. No striking difference seems to stand out. The heat loads measured with two beams are about twice the values measured with the single beam both at injection and top energy, and the normalised values along the cycle are very similar. The spread between the sectors seems to be also the same for both cases with single or with two beams. Looking into the cell-by-cell distribution for the different sectors, again the normalised heat loads look very similar for both fills both at injection energy (Fig. 45) and top energy (Fig. 46), with perhaps a slight tendency towards
higher values for the fill with Beam 1 only but with no outstanding difference.
In Fig. 47 two fills that took place during the same day at the end of the 2017 scrubbing run are shown. In Fill 5813, displayed on the left side, only Beam 1 was injected (2760 bunches in trains of 288 bunches from the SPS). In Fill 5812, on the right side, only Beam 2 was injected using the same filling pattern. The sector-by-sector heat loads displayed in the middle plots show that there is no striking difference in the distribution of the heat loads among sectors in the two cases. In general, one could say that the values for Beam 1 are slightly higher than for Beam 2 (10-15%), especially for Sector 12. However, these minor differences could be easily ascribed to either a slight asymmetry in the scrubbing history (especially for Sector 12, still in the scrubbing process after being opened to air during the EYETS) or to the slightly longer bunches during the fill with Beam 2 only. A detailed view of the cell-by-cell distribution of the heat loads across the 8 sectors is provided in Figs. 48 to 51. While looking at these pictures one can identify specific cells in which the heat load is not symmetrically distributed over the two beams (apertures) and the high load is basically due to one beam only, the general picture of the heat load distribution over the machine and the separation between low-load and high-load sectors from their average heat loads remain basically the same for both beams.
Figure 45: Cell-by-cell distribution of the normalised heat loads in the eight LHC sectors. These data were taken at 450 GeV for the fills 4532 and 4535 shown in the previous picture.
Figure 46: Cell-by-cell distribution of the normalised heat loads in the eight LHC sectors. These data were taken at 6.5 TeV for the fills 4532 and 4535 shown in the previous picture.
Figure 47: Comparison between two fills that took place on 11 June, 2017. Fill 5813, on the left side, was made with Beam 1 only. Fill 5812, on the right side, was made with Beam 2 only. Both fills took place during the last day of the 2017 scrubbing run and were made with a full machine (2760 bunches) in trains of 288 bunches.
Figure 48: Cell-by-cell heat loads measured in Sectors 12 and 23 for the fills in Fig. 47, i.e. fill 5813 only with Beam 1 (in blue) and fill 5812 only with Beam 2 (in red).
Figure 49: Cell-by-cell heat loads measured in Sectors 34 and 45 for the fills in Fig. 47, i.e. fill 5813 only with Beam 1 (in blue) and fill 5812 only with Beam 2 (in red).
Figure 50: Cell-by-cell heat loads measured in Sectors 56 and 67 for the fills in Fig. 47, i.e. fill 5813 only with Beam 1 (in blue) and fill 5812 only with Beam 2 (in red).
Figure 51: Cell-by-cell heat loads measured in Sectors 78 and 81 for the fills in Fig. 47, i.e. fill 5813 only with Beam 1 (in blue) and fill 5812 only with Beam 2 (in red).
Figure 52: Bunch-by-bunch energy loss for Beam 1 estimated from the measured RF stable phase for two fills performed with 25 ns bunch spacing (top) and with 8b+4e beam pattern (bottom). Different colors correspond to different moments during the energy ramp, as indicated by the vertical bars on the left plot.

9 Comparison against beam power loss

The power deposited through different mechanisms on the beam screen walls necessarily needs to translate into an energy loss for the LHC proton beam. In a synchrotron, an energy loss generates a shift of the particle stable phase with respect to the RF system. As a consequence, the bunch power loss can be measured by detecting the stable phase of the bunches. A sophisticated method has been developed to accurately measure the bunch-to-bunch relative phase in the LHC with an accuracy below one degree [27].

As an absolute phase reference is not available, the bunch stable phases are measured with respect to the average of the first 12 bunches in the filling scheme. Assuming that all bunches have the same intensity, this means that the average energy loss for these bunches is subtracted from the energy loss of all bunches.

Figure 52 shows the bunch-by-bunch power loss measured for Beam 1 during a fill with 25 ns bunch spacing (top) and during a fill with the 8b+4e bunch pattern (bottom). The same measurements for Beam 2 are shown in Fig. 53. With 25 ns spacing, a clear e-cloud signature can be observed, with a clearly visible increase of the power loss along the bunch trains. Much lower bunch power losses are instead observed with the 8b+4e bunch spacing for which the e-cloud buildup is expected to be strongly suppressed [6].

In Fig. 54 the total power loss of the two beams is compared against the total heat
Figure 53: Bunch-by-bunch energy loss for Beam 2 estimated from the measured RF stable
phase for two fills performed with 25 ns bunch spacing (top) and with 8b+4e beam pattern
(bottom). Different colors correspond to different moments during the energy ramp, as
indicated by the vertical bars on the left plot.

load measured on the beam screens of all the cold magnets in the machine. It can be
noticed that the two quantities are very similar (in fact well within the uncertainties of both
measurements). This means that a large fraction of the beam power loss goes into energy
deposited on the beam screen. Furthermore, this confirms, as expected from e-cloud effects,
that the heat load generation is very uneven along the bunch trains and is actually generated
mainly by the bunches at the tail of the trains.
Figure 54: Comparison between the total beam power loss estimated from the measured RF stable phase and the total heat load on the beam screens of all cold magnets in the LHC.
10 Controlled warm-up of selected cells

The LHC beam screens are typically kept at a temperature of 5–20 K during operation. In order to investigate if the operating temperature of the beam screens might have an effect on their conditioning process, a dedicated study was performed. For roughly two weeks of luminosity production (26th of August – 12th of September 2016) the beam screens in selected cells in the arcs were operated at a temperature of 50–80 K, to observe if any impact on the conditioning could be detected [28]. Figure 55 shows the temperature measured in the selected cells in the period of the test. As the cryogenics control loops had to be disabled during the test, large oscillations in temperature are observed as a consequence of the heat load changes on the beam screens.

Figures 56–59 display the heat loads at injection and top energy for all cells in the LHC arcs, during a fill before the beam screens were warmed up and a similar fill after the warm-up. The cells marked with blue bands belong to the family of cells in which the beam screen temperature was changed. No evident effect on the measured heat load can be observed in any of the cells that underwent a temperature change, neither immediately after the exercise nor after a longer period of time.
Figure 56: Heat loads on the beam screens in the different cells of Sectors 12 (top) and 23 (bottom), before and after operation of selected cells with higher beam-screen temperature. The cells for which the temperature increase was applied are marked with vertical blue bands.
Figure 57: Heat loads on the beam screens in the different cells of Sectors 34 (top) and 45 (bottom), before and after operation of selected cells with higher beam-screen temperature. The cells for which the temperature increase was applied are marked with vertical blue bands.
Figure 58: Heat loads on the beam screens in the different cells of Sectors 56 (top) and 67 (bottom), before and after operation of selected cells with higher beam-screen temperature. The cells for which the temperature increase was applied are marked with vertical blue bands.
Figure 59: Heat loads on the beam screens in the different cells of Sectors 78 (top) and 81 (bottom), before and after operation of selected cells with higher beam-screen temperature. The cells for which the temperature increase was applied are marked with vertical blue bands.
11 Conclusions

In this document we have presented a comprehensive overview of the heat load measurements in the eight LHC sectors during Run 2. Following the evolution and dedicated comparisons between different operating conditions, the following points can be retained:

- During Run 2, the eight LHC sectors have consistently exhibited significantly different heat load values when the machine is operated with 25 ns spaced beams.

- The sectors can be grouped in low-load sectors (S34, S45, S56, S67) and high-load sectors (S78, S81, S12, S23). The difference between the heat loads measured in these sectors can be as high as a factor 4. Both low- and high-load sectors have average heat load values at least a factor 2 above those expected from impedance and synchrotron radiation.

- With the presently achieved scrubbing state, when 50 or 100 ns beams are used in the LHC, there is no spread between the heat loads of the different sectors and the measured values match those expected from impedance and synchrotron radiation heating. When running with 8b+4e beams, which are made of short trains of bunches spaced by 25 ns (8b) separated by even shorter gaps (4e), the heat loads exhibit the same distribution as with full 25 ns beams but significantly lower values for the same number of bunches.

- With 25 ns beams, the heat load differences between sectors are observed already at injection energy and remain constant during the energy ramp.

- This difference of heat loads among sectors was not present before LS1. Even when running with 25 ns beams (e.g. during the 2012 scrubbing run), all the sectors exhibited very similar heat load values, which are compatible with the values measured nowadays in the low-load sectors.

- The measured heat loads lead to a total power deposited on the cold beam screen that is fully consistent with the value estimated from the bunch-by-bunch stable phase shift measurements. This confirms that the power seen by the cryogenic system is indeed lost by the beam.

- Sector 12, which was vented to air during the EYETS 2016-17 in order to exchange a faulty dipole magnet, was found largely deconditioned at the beginning of 2017, as seen in the much larger heat load value than that measured at the end of 2016 (the additional load was uniformly distributed over its various half-cells). When it then reconditioned during the 2017 scrubbing run, the cell-by-cell heat load values returned to exactly the same values they had in 2016. This means that Sector 12 has remained a high-load sector and it still exhibits the same cell-by-cell heat load distribution as before its venting. The EYETS thermal cycle of Sector 12 did not have any beneficial effect on its heat load distribution with 25 ns beams, but it also did not further degrade it (unlike LS1).
• The data from the instrumented cells in Sector 45 show how both dipoles and quadrupoles can be efficiently scrubbed using 25 ns beams and lead to low heat load values. The half-cell newly instrumented during the EYETS 2016-17, which was located in the middle of the high-load Sector 12, shows a remarkably different type of dynamics. The newly installed dipole has undergone the same scrubbing as the dipoles in the other instrumented cells. The two neighbouring dipoles have gone through a light scrubbing and finally settled on heat load values much above the value of the other dipole. The quadrupole has also landed at a heat load value still very high at injection energy. The behaviour of magnets such as these could be the culprit of the high heat load in the high-load sectors and should be investigated in further detail.

• The spread of heat load values among the different sectors is equally seen when a single beam (either Beam 1 or Beam 2) is stored in the LHC. Barring minor differences in the distributions and values (including a few cells that exhibit high load for one beam and low load for the other beam), the statistical distribution of the heat loads turns out to be very similar for both beams.

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