

ELECTRON CLOUD IN 2016: CLOUDY OR CLEAR?

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Abstract

The proton physics run in 2015 confirmed that electron cloud poses a significant challenge to LHC operation with beams of 25 ns bunch spacing. Despite evident conditioning of the electron cloud during the 2015 run, full suppression did not occur, and hence also the 2016 proton physics run suffered the presence of e-cloud. This contribution reviews the electron cloud situation throughout the 2016 run. The conditions at the beginning of the run, including the scrubbing and intensity ramp-up, are covered and compared to 2015. Studies and observations of the evolution during the run are described, along with ongoing efforts to interpret them. Finally, some future implications are discussed. Detailed considerations and plans for 2017 operation are presented elsewhere [1].

INTRODUCTION

As anticipated, electron cloud caused important limitations to the performance of the LHC in 2015, the first year of luminosity production with 25 ns beams at a top energy of 6.5 TeV [2]. Initially, the electron cloud severely degraded the beam quality at injection, whereas the induced heat load on the beam screens in the cryogenic magnets limited the amount of beam that could be stored at 6.5 TeV throughout the year. Although a clear reduction of electron cloud build-up could be observed over the 2015 run, significant electron cloud was evidently still present at the end of year.

Since the LHC arcs were kept under vacuum during the 2015-2016 Year End Technical Stop (YETS), a complete reset of the Secondary Electron Yield (SEY), as observed at the beginning of operation in 2015, was not expected for 2016. Some de-conditioning of the beam screens could nevertheless be foreseen; de-conditioning was regularly observed in 2015 after breaks in standard proton physics, in particular when running with relatively high-intensity beams with low or no e-cloud formation. In these cases, however, the previous condition of the beam screens could typically be recovered with only a few hours of scrubbing with standard 25 ns beams.

Based on these considerations up to four days of dedicated scrubbing at 450 GeV were allocated in 2016. The scrubbing could be implemented prior to and interleaved with the intensity ramp-up in physics, as needed, with the aim of achieving sufficient beam quality for efficient luminosity production. Continued scrubbing dose to further reduce the heat load in the arcs could subsequently be accumulated in parallel with physics, as was done during the 2015 run.

START UP

The dedicated scrubbing run took place on the 25th of 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 [3]. Strong e-cloud instabilities occurred at injection, often triggering beam dumps. When beam dumps were avoided, significant emittance growth and beam degradation was seen. The de-conditioning could be confirmed also through the measurements of arc heat loads and bunch-by-bunch energy loss from the RF stable phase measurement.

The scrubbing was interrupted after about 24 hours, due to the detection of a vacuum leak in the SPS high energy beam dump (TIDVG) [4]. At this point up to 1800 bunches per beam, in trains of 216 bunches per injection, had been stored in the machine at 450 GeV, without significant beam degradation. Injections of 288 bunches, which were planned to be used during the scrubbing, could initially not be set up due to instabilities, and were thus not used.

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 LHC bunches, allowing for injections of a single batch of 72 bunches, or two batches of 48 bunches into the LHC [5]. The conditioning achieved during the initial 24 hours of scrubbing was sufficient to carry out the intensity ramp-up at 6.5 TeV up to 2040 bunches per beam, the maximum number that could be stored in trains of 72 bunches, without any major problems caused by e-cloud effects.

The arc heat loads during a fill at the end of the intensity ramp-up (Fill 4980) are shown on the bottom right in Fig. 1. On the left in the same figure are the heat loads during a similar fill with 2040 bunches at the end of the 2015 proton run (Fill 4536). In both fills, the heat loads are significantly larger than the dashed curve in the bottom right graph, which shows the expected heat load due to impedance and synchrotron radiation. This indicates a dominant contribution to the heat load due to electron cloud. Furthermore, the comparison shows very similar heat loads for the two fills, confirming the expectation that any de-conditioning observed after the YETS could be quickly recovered. Also the difference in heat load between the machine sectors that was observed during 2015 remains essentially the same. The origin of this difference could not be determined in 2015 (see [2]) and is still unclear.

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

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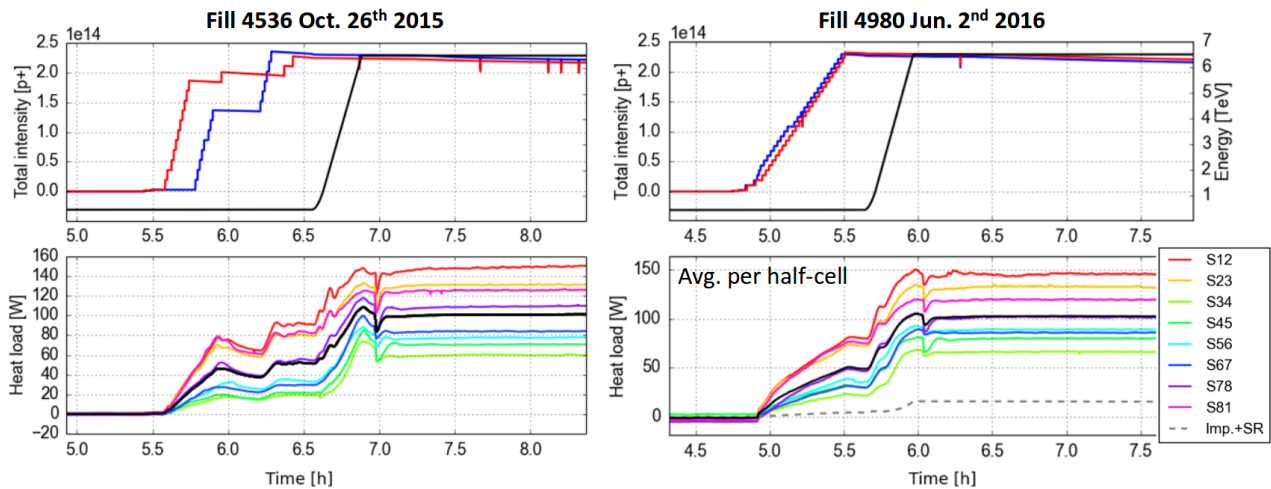


Figure 1: Heat loads measured in two similar fills with 2040 bunches: Fill 4536 at the end of proton physics in 2015, and Fill 4980 right after the intensity ramp-up in 2016. Average values for the heat loads in each sector of the machine are shown, given in W/half-cell.

YETS. In addition, further improvements of the cryogenic feed-forward control effectively limited problems with the cryogenics at injection [6], while beam stability and lifetimes were 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 [2, 7]. The dynamic pressure in the injection kicker (MKI) area in Point 8 still occasionally reached the interlock values, preventing further injections [8]. However, the issue could effectively be mitigated by limiting the bunch intensity to roughly 1.1×10^{11} p/bunch.

EVOLUTION DURING PHYSICS

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. 2, 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. Simultaneously, the target bunch length for the controlled longitudinal blow-up on the ramp was gradually decreased from 1.25 ns to 1.1 ns.

The middle graph in Fig. 2 shows the average heat load measured on the arc beam screen, sector by sector. The

maximum heat load allowed by the cooling capacity, roughly 160 W per 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.

To assess if an evolution of the conditioning with the accumulated dose can be observed, Fig. 3 shows the value of the normalized average heat load per sector, measured at the end of the “Squeeze” beam mode for fills during the 2015 and 2016 proton runs. In 2015, a reduction of approximately 30% can be seen over the run, which took place over a period of roughly two months. In 2016, a slightly smaller reduction occurred over the full period, spanning nearly six months. Furthermore, the majority of the reduction in 2016 seems to have occurred during the beginning of the run, whereas only a small change can be seen over the latter part. In all sectors, the heat load remains significantly larger than the estimate due to impedance and synchrotron radiation.

Although Fig. 3 does not distinguish between reduction in heat load due to changed beam parameters and reduction due to conditioning, even after a careful analysis, the change in rate of heat load reduction cannot be correlated with any apparent change in settings, implying that it very likely is due to a change in the rate of conditioning with scrubbing dose.

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, marked with blue arrows in Fig. 2, were performed with as similar beam parameters as possible. The full operational cycle to bring the beams into collision was performed, and the fills were used for luminosity production. The filling

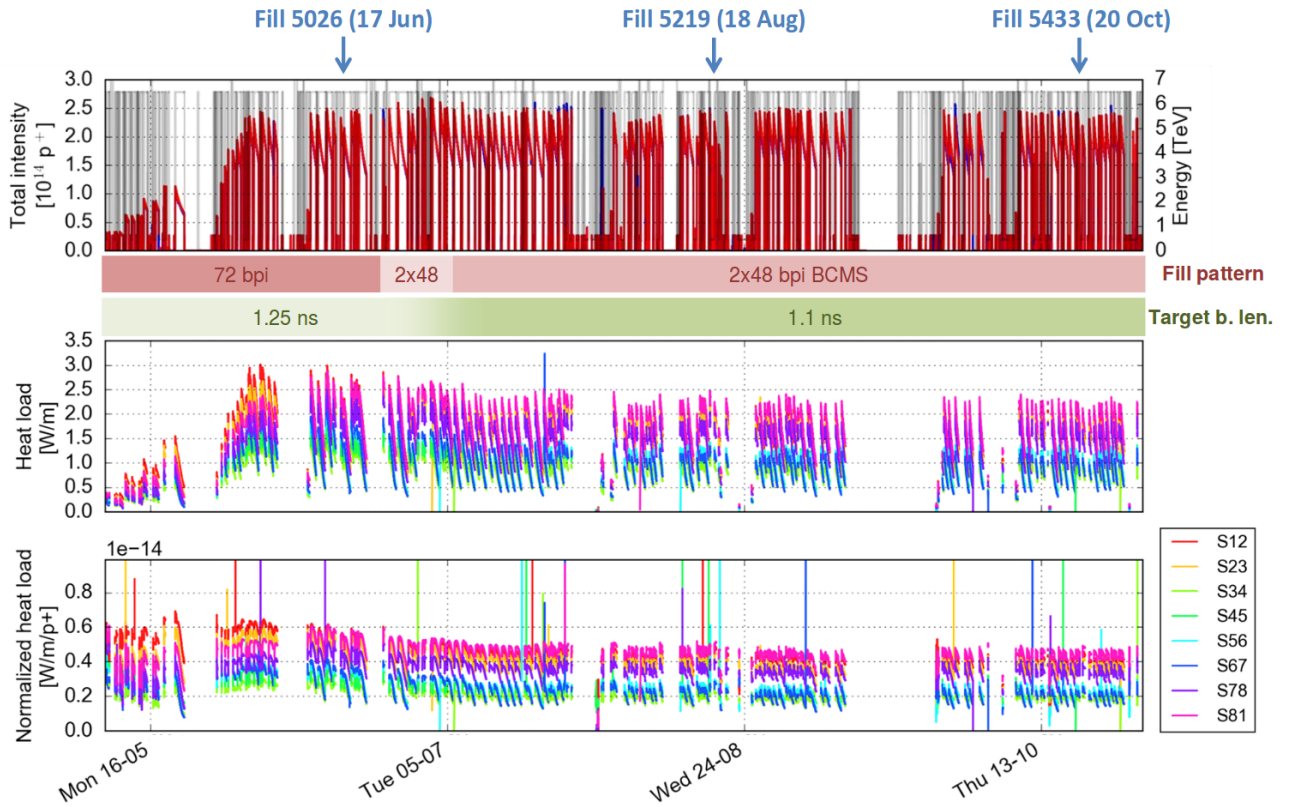


Figure 2: Evolution of the beam intensity (top), average heat loads in the arcs (middle), and average arc heat loads normalized to the beam intensity (bottom) during the 2016 proton run.

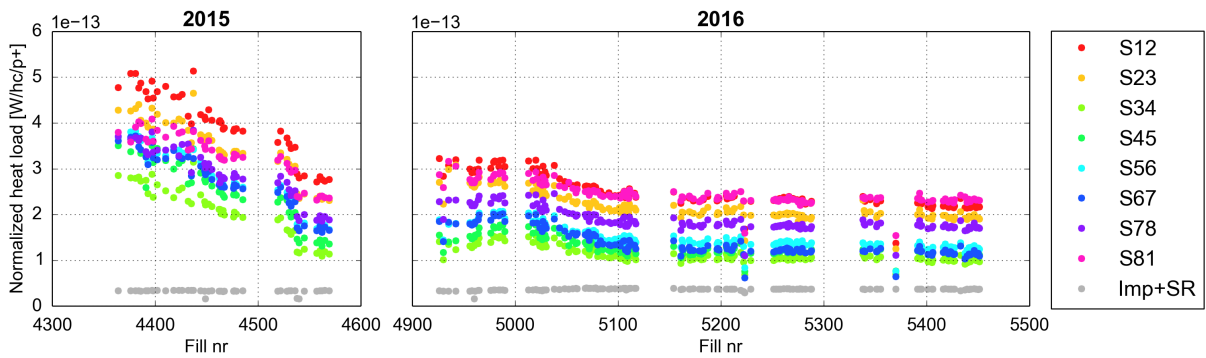


Figure 3: Instantaneous normalized average heat load per sector at the end of the “Squeeze” beam mode for proton fills in 2015 and 2016. Calculated heat load estimate due to impedance and synchrotron radiation in grey.

pattern consisted of 2040 bunches per beam, in trains of 72 bunches, using the standard production scheme in the PS. The target bunch length for the controlled blow-up on the ramp was set to 1.25 ns, and settings for chromaticity, octupole current and the transverse damper were identical.

In Fig. 4, on the top left, the evolution of the bunch length at 6.5 TeV during the reference fills can be seen, given as a function of the average bunch intensity, which decreases during the fill due to the luminosity burn-off. The bunch lengths are nearly identical, especially for the first and last

of the fills, whereas the second fill has slightly shorter bunch lengths. The remaining graphs in the figure show the evolution during the reference fills at 6.5 TeV of the average arc heat loads due to electron cloud per sector, i.e. with the expected contribution from impedance and synchrotron radiation removed from the measured values.

A reduction of the heat load over the four month period covered by the reference fills can be observed in all sectors. In most sectors, there is a larger reduction in heat load between the first two reference fills compared to the latter

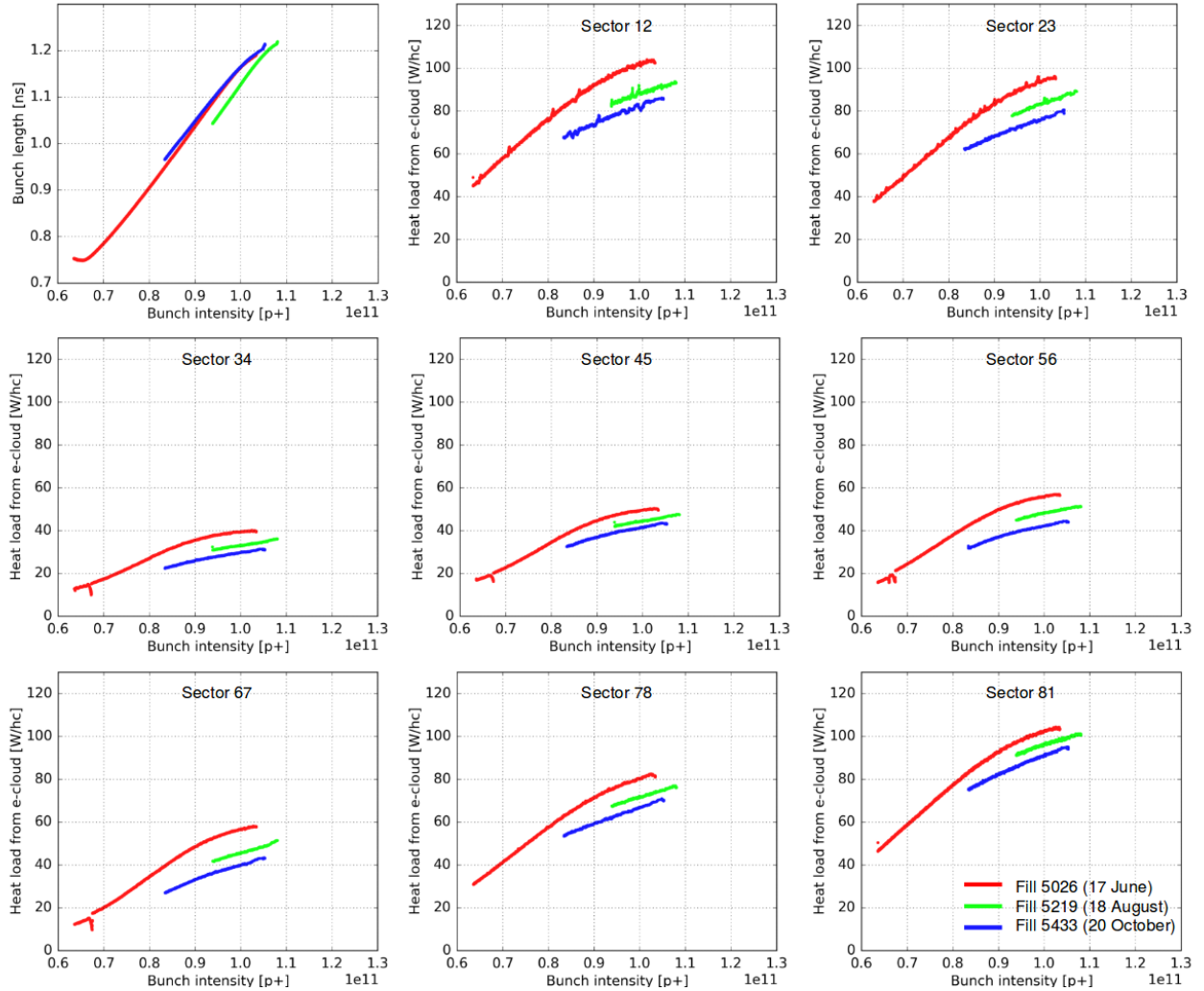


Figure 4: Bunch length (top left) and average arc heat loads due to electron cloud at 6.5 TeV, as a function of the average bunch intensity during the reference fills.

two, supporting the conclusion that the conditioning rate decreased during the run.

Dedicated studies of the scrubbing process in the laboratory indicate that the rate of conditioning achieved with a given electron dose decreases as the conditioning progresses [9], providing a possible interpretation for the observations described above. The effective scrubbing dose of electrons deposited on the beam screens during machine operation can be inferred from the integrated heat load, combined with information on the geometric distribution and energy spectrum of the impacting electrons from PyELOUD simulations [2]. The accumulated dose during 2016 proton operation, estimated in this way, is roughly a factor four times larger than the corresponding dose in 2015.

DEDICATED STUDIES

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) 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 [10].

In general, the cell-by-cell heat load pattern along the machine is very reproducible from fill to fill, in particular for a given bunch configuration [11]. Figure 5 displays the heat loads at injection and top energy for individual cells in Sector 23, during a fill before the beam screens were warmed up (top) and a similar fill after the warm-up (bottom). The cells marked with blue bands belong to the family of cells in which the beam screen temperature was changed. As in the cells shown here, 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 [12, 13]. Based on this study there is no indication that the temperature plays a role

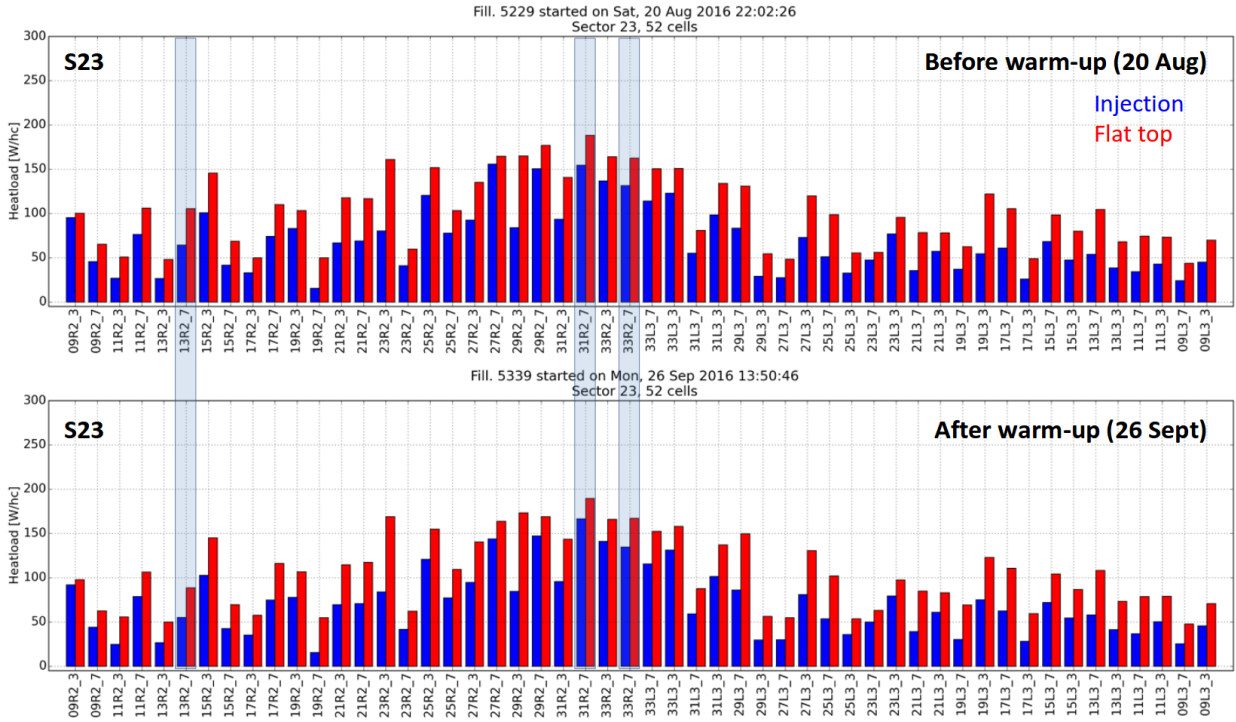


Figure 5: Cell-by-cell heat loads in Sector 23, at 450 GeV and 6.5 TeV. Measured values shown before (top), and after (bottom) the beam screens of selected cells, marked by blue bands, were operated at a temperature of 50–80 K.

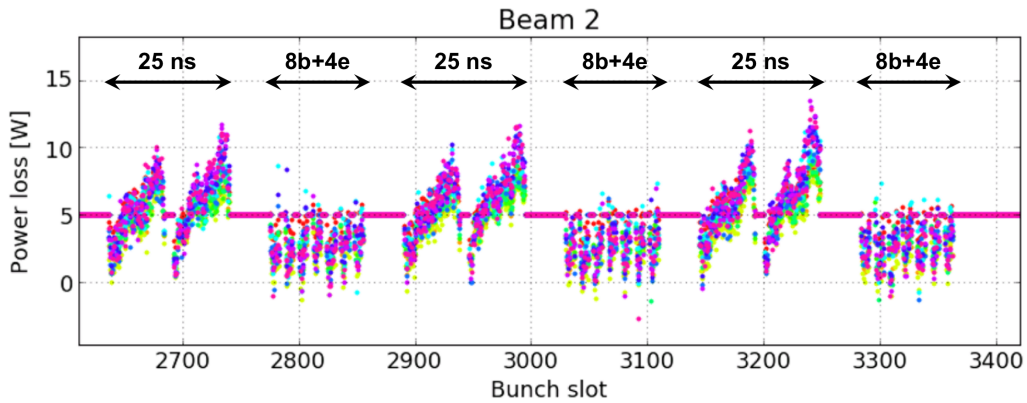


Figure 6: Bunch-by-bunch beam power loss, as estimated from the RF stable phase measurements, for a hybrid filling scheme alternating trains of 25 ns BCMS beam and 8b+4e beam.

on the conditioning, but it cannot be excluded that exposure to higher temperatures or for a longer period of time could show an effect.

In the event that the beam screens cannot be conditioned sufficiently to keep the heat load of the nominal filling pattern (2760 bunches) within the cooling capacity, it may be necessary to use bunch patterns that reduce the electron cloud build-up. The "8b+4e" bunch pattern, with trains of 56 bunches made of short trains of eight bunches with 25 ns bunch spacing separated by four empty slots, was shown in 2015 to effectively suppress the e-cloud [2]. Since the 8b+4e filling scheme has roughly 30% fewer bunches than the nominal 25 ns scheme, a hybrid scheme tailored from

standard 25 ns and 8b+4e beam, has the potential to maximize the beam current while keeping the heat load within the available cooling capacity.

The effectiveness of such a filling scheme was tested during Machine Development in 2016. A hybrid filling scheme with 1908 bunches was used, consisting to 55% of 25 ns BCMS beam and to 45% of 8b+4e beam, resulting in 15% fewer bunches than the equivalent standard filling scheme. The e-cloud suppression could be confirmed both through the measured arc heat load and the beam energy loss estimated from the RF stable phase. A 40% reduction of the heat load was observed in the most critical sector of the machine,

and the bunch-by-bunch pattern of the beam energy loss (Fig. 6) shows that the 8b+4e trains stay e-cloud free [14].

CONCLUSION

Although significant electron cloud was present in the LHC during the 2016 run, the machine performance was not severely affected. As a result of the conditioning of the beam screens in 2015, as well as the experience acquired in operating with e-cloud, problems due to e-cloud instabilities and transients on the beam screen temperature were mostly avoided.

With the number of bunches that could be stored in the machine restricted by the SPS, the total beam current was not limited by the available cooling capacity, but by the constraint on the bunch intensity due to the pressure rise in the MKI area. In 2017, on the other hand, when both of these constraints are foreseen to be relaxed, the heat load on the arc beam screens is again expected to limit the total current [1].

The beam screens continued to condition in 2016, but a significant decrease in the rate of conditioning was observed after the first months of operation. A test where selected beam screens were kept at a higher temperature showed no improvement in their condition. It remains to be seen in 2017, if operating with longer bunch trains and/or higher bunch intensities can enhance the conditioning again.

If this is not the case it may be beneficial, in particular after Long Shutdown 2 when higher bunch intensities will be available, to use hybrid filling schemes to tailor the heat load to the available cooling capacity.

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