ELECTRON CLOUD EFFECTS AT THE CERN ACCELERATORS

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Abstract

Electron cloud effects have been identified as one of the main performance limitations for some of the synchrotrons of the CERN accelerator complex. The tools for the simulation of the electron cloud build-up and its effects on beam stability have significantly evolved in recent years, leading to a much better understanding of all machine observations. At the same time, electron cloud mitigation measures have been tested (e.g. surface treatments) and implemented in operation (e.g. beam induced scrubbing). The combination of a deeper understanding of the electron cloud and a handle on its mitigation has been the key to reach and exceed the nominal luminosity in the LHC during Run 2 as well as to define strategies to cope with the High Luminosity (HL) operation of the LHC as from 2026.

INTRODUCTION AND HISTORY

General concept and early studies

Electron production in a closed environment with an oscillating electromagnetic field can lead under certain circumstances to multipacting, i.e. avalanche multiplication of the number of electrons due to their acceleration in the electromagnetic field and subsequent impact against high Secondary Electron Yield (SEY) surfaces. This phenomenon can significantly degrade the performance of RF devices (e.g. in applications for space satellites [1]) as well as that of accelerator (or storage) rings operating with closely spaced positron or proton bunches [2].

Figure 1 illustrates schematically how an electron cloud (e-cloud) builds up at a certain location (transversal cut) in the vacuum chamber of an accelerator ring.

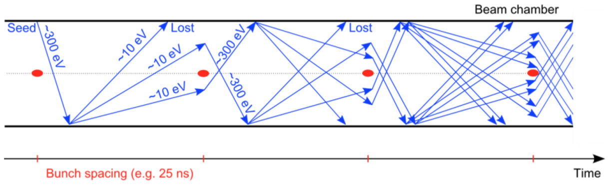

Figure 1: Sketch of electron cloud formation in the vacuum chamber of an accelerator ring.

Each passing bunch generates a number of primary electrons (e.g. photoelectrons), which are accelerated by the beam field and fly across the chamber cross section. Each electron produces secondaries when it hits the inner wall of the vacuum chamber, provided that the SEY is greater than unity at the impact energies. The number of electrons in the vacuum chamber thus increases by the arrival of the next bunch, and eventually grows exponentially as more bunches go through. The e-cloud build up stops when a dynamical steady state is reached, at which the space charge repulsion of the e-cloud itself prevents the electrons newly emitted at the surface from being accelerated in the beam field, and the net electron production and loss rates become equal. E-cloud build up in an accelerator is associated to pressure rise, heat load in cryogenic regions, stable phase shift, beam instability and emittance growth.

Observations and first studies of beam-induced multipacting at CERN date back to 1977, when a pressure rise at the Intersection Storage Ring (ISR) after installation of an aluminum test chamber was ascribed to electron accumulation [3]. Based on the ISR experience, concerns about the Large Hadron Collider (LHC) operation already started at the very first design stages in the 1980's. These worries were then reinforced over the next two decades, when beam instabilities due to photoelectrons were observed at the KEK Photon Factory [4,5] and a series of e-cloud studies including both simulations and experiments were launched both at the Beijing Electron Positron Collider [6] and for the positron ring (LER) of the PEP-II B Factory [7].

E-cloud studies at CERN before LHC (1996-2009)

In the second half of the 90's first estimates were published, predicting a serious effect on heat load and beam stability for LHC (e.g. [8–11]). The existence of conditions for beam-induced multipacting in the LHC was first mentioned in 1996 [8]. About the same time, mainly motivated by the e-cloud observations in e^+ storage rings, the e-cloud build up code ECLOUD was developed [9]. The code gradually grew and new features were added over the years to improve its modelling [10] and reproduce different observables (e.g. heat load on chamber, effect on pick up electrodes [12]) as well as to explore possible mitigation techniques (e.g. satellite bunches). In parallel to the numerical effort, advanced analytical models were also developed to describe the e-cloud formation and evolution as well as the effects of its interaction with a particle beam [13–15]. After 1998, e-cloud effects were directly and systematically observed at the CERN Super Protron Synchrotron (SPS) with the LHC beam (25 ns bunch spacing) [16].

In the early 2000's, the e-cloud was observed also in the upstream injector, the Proton Synchrotron (PS) in its late stages of the preparation of the 25 ns spaced beams [17–19]. At the same time, since beam stability and lifetime turned

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out to be significantly affected by the presence of an e-cloud in the CERN accelerator rings, the HEADTAIL code was developed in order to study the interaction of an e-cloud with a bunch of positively charged particles [12,20]. As a novelty with respect to existing codes (e.g. the one described in [21]), the HEADTAIL code had several distinctive features:

- It could model both the e-cloud and the particle bunch as ensembles of macroparticles with a finite transverse size (strong-strong approach), such that the emittance growth due to e-cloud could also be studied alongside with coherent beam stability;
- Although the code was originally intended to only model the interaction of a particle bunch with an e-cloud, its scope was soon extended to include other types of sources of collective interactions, like beam coupling impedances and space charge, which in turn benefited from the slice modeling. The study of the interplay between any of these effects became possible;
- HEADTAIL was also interfaced with ECLOUD to receive the electron distribution just before a bunch passage in the saturation stage of the electron cloud build up, to be used as initial distribution for the interaction with the bunch.

The beam transport in the transverse planes and the longitudinal motion, which had been initially modelled through simple decoupled one-turn linear transfer matrices, were upgraded over the years to include more detailed lattices, nonlinearities (multipoles, different RF systems), coupling between transverse planes and damping. The ECLOUD and HEADTAIL codes were intensively used over the first decade of the 2000's not only to interpret the observed e-cloud effects in the SPS [22–24], but also to study future upgrade scenarios and mitigation techniques [25–27]. The data recorded during the SPS experimental studies also served as a benchmark for the validation of the simulation tools, steering the assessment of the models to be used for the LHC predictions. It also became increasingly clear that the electron cloud was a potential danger for the LHC operation in terms of heat load on the cold beam screen, beam stability and beam quality degradation [28–30]. Extensive simulation studies showed that the heat load in the beam screen of the dipoles would exceed the cryogenic capacity already for a maximum SEY of 1.3 with nominal beam parameters (much lower value than the known SEY of "as received" Cu, but considered attainable through conditioning). Furthermore, while it was found that the e-cloud driven instability could be efficiently controlled with transverse feedback and/or high chromaticity, the e-cloud was also identified as responsible for a slow emittance growth induced by periodic crossing of resonances, leading to an intolerable degradation of the beams in collision also in the absence of a strong instability. However, a reliable assessment of the impact of all these predictions on the future LHC operation was made very difficult by the sensitivity of the results to the model parameters and the numerical accuracy [28]. The following strategy was therefore laid out and applied to the LHC (fully detailed in the LHC Technical Design Report [31]):

- Use sawtooth pattern in the beam screen of the dipoles to reduce photon reflectivity and photoemission yield;
- Shield the pumping slots on top and bottom of the beam screen in the cryogenic regions in order to avoid multipacting (and heat deposition) on the cold bore;
- Coat all warm sections with Non-Evaporable Getter material (NEG) having low SEY;
- Rely on surface scrubbing (from electron bombardment while running within the limits of the cryogenic system) to eventually lower the maximum SEY close enough to its estimated e-cloud build up threshold value;
- Keep the back-up options to run with larger bunch spacing (50 ns) or to use cleaning satellite bunches, if they can be produced in a clean manner in the injectors, compatibly with the requirements from the experiments.

The LHC era

After the LHC was fully installed and commissioned, and its regular operation started as of November 2009, the years 2010 – 2013 (Run 1) and 2015 – 2018 (Run 2) were characterised by the following main facts:

- **SPS**: The LHC beams with 25 ns bunch spacing were successfully produced within specifications (i.e. without visible degradation from e-cloud even for the lower transverse emittances achieved in the pre-injectors) [32]. The future operation with double intensity and brightness was extensively investigated by means of both experimental and numerical studies [33, 34]. It was concluded that beam induced scrubbing would be the baseline choice also for operation in the new beam parameter range, while making sure that all the logistics for a-C coating would be fully developed in case of need for post-LS2 implementation due to persisting e-cloud issues in Run 3;
- **LHC**: Apart from some cases of localised pressure rise in the common beam chambers, operation in presence of e-cloud in the LHC was first experienced when the bunch spacing was reduced from 150 ns to 75 and then 50 ns, which required the first LHC scrubbing run in 2011. As first tests of injection of 25 ns spaced beams revealed severe e-cloud effects, which required further understanding and scrubbing, the 50 ns bunch spacing was kept for operation throughout Run 1. After a successful scrubbing run and a pilot physics run with 25 ns beams at the end of 2012, operation eventually switched to 25 ns in Run 2 (2015-2018) [35–39]. Run 2 was characterised by the progress in the understanding of the observed heat loads and beam instabilities, the arising of puzzling observations like the difference of

heat loads between the LHC sectors, and the establishment of predictions for the HL-LHC operation beyond 2025 [40–42].

The simulation tools used over the previous decade underwent an important upgrade and re-write, evolving into the modular Python based codes PyECLOUD and PyHEADTAIL [43, 44] – more robust, performant, reliable and flexible. These codes have been eventually merged into a common set of accelerator library modules that can be combined to provide simulations of e-cloud build up and multi-bunch beam dynamics under collective effects (including e-cloud and ions) [45, 46]. This development was necessary, and turned out to be instrumental to interpret and explain all the SPS and LHC observations, steer their current operation and make all the required extrapolations for the future operation of both machines in the HL-LHC era. The success of this project was the result of a long standing effort and, unlike previous attempts to modernise and speed up the e-cloud tools (both in-house and through external collaborations), has produced a maintainable and durable set of tools.

THE ELECTRON CLOUD IN THE CERN ACCELERATORS

The Proton Synchrotron (PS)

The production scheme of the LHC beams in the PS is based on two or three steps of bunch splitting in order to obtain at the exit of the PS bunch trains with 50 ns or 25 ns spacing, respectively. In either case, the final stage of bunch splitting takes place at top energy (26 GeV) and is followed by adiabatic bunch shortening and fast bunch rotation shortly before extraction [47]. These two processes are meant to reduce the bunch length from the initial 15 ns after the last splitting to 12 and then 4 ns, respectively, and make the bunches fit into the 5 ns long SPS buckets. The beam parameters are summarized in Table 1.

Table 1: PS beam parameters at 26 GeV for 50 and 25 ns beams

	50 ns	**25 ns**
Bunch intensity ($\times 10^{11}$ ppb)	1.3-2.0	1.3-2.0
Bunch length (ns)	15 → 12 → 4	
Number of bunches	36	72
Transv. rms emittances (μm)	1-2	2-3

The LHC beams in the PS are prone to e-cloud formation only during the last few tens of milliseconds of the production cycle, as was confirmed in several observations and dedicated studies conducted between 2000 and 2009 [19, 48–50]. A measurement campaign to reveal e-cloud at 26 GeV and the related beam instabilities was conducted right before LS1 to assess the possible impact of the e-cloud on future beams [34]. To clearly observe the instability rising, the flat top had to be extended by several ms with respect to an operational cycle. Figure 2, upper plot, shows for example the amplitude of the horizontal oscillation as a function of the bunch and turn number for a typical train of 72 bunches with 25 ns spacing right after the bunch rotation. It is possible to see that the bunches at the end of the train are the first to become unstable, and then the instability appears with lower rise times to the middle of the train. The unstable motion propagates in a correlated fashion between bunches, while the head of the train remains stable. The bottom plot shows the horizontal cut of the upper picture, where one can see the exponential rise.

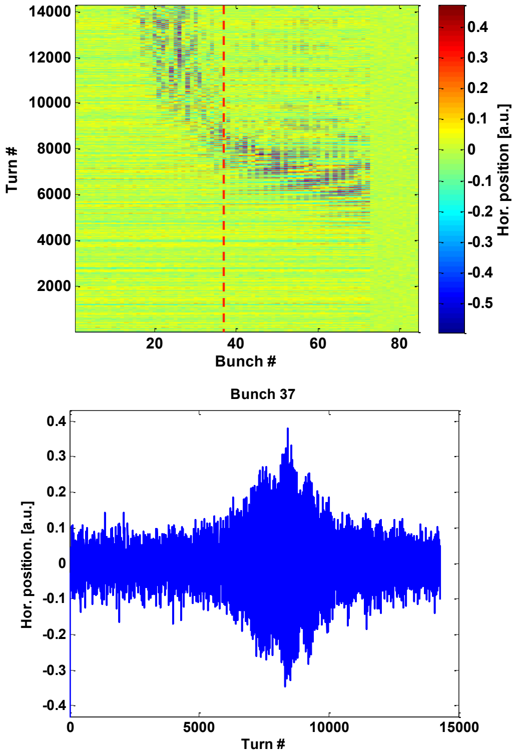

Figure 2: Instability along a 72 bunch train in the CERN PS. The evolution of the horizontal oscillation amplitude is plotted as a function of bunch and turn number (top) and the horizontal cut displayed with a red dashed line in the top plot is shown in the bottom plot.

However, during Run 2 (2014-2018), thanks to already installed LIU hardware, the PS has successfully produced trains of 72 bunches with 2.6e11 p/b at the PS extraction, which represent the beam structure and bunch intensity targeted for post-LS2. Although no problem of transverse beam stability has emerged for these beams at 26 GeV, it must be noticed that their transverse emittance was still about twice lower than the future post-LS2 beams.

The Super Proton Synchrotron (SPS)

Since the early 2000's, observations of pressure rise, beam instability and emittance growth in the SPS pointed to the presence of an e-cloud limiting the capability of this accelerator of handling LHC-type beams [51]. Stabilising the beam with the transverse damper and sufficiently high chromaticity, regular scrubbing runs (lasting from few days to two weeks) took place at the beginning of almost every operational year between 2002 and 2010 to achieve the necessary reduction of the SEY of the vacuum chambers. The strategy has proved successful, as the e-cloud indicators (e.g. emittance growth along the bunch train) gradually disappeared and the nominal LHC beams could be produced in the SPS with no significant e-cloud degradation as from 2011. The achieved parameters are summarised in Table 2. The three values of bunch length quoted are the injected value, that after filamentation at flat bottom (RF voltage to 4 MV), and at flat top (after controlled longitudinal emittance blow up during the accelerating ramp, if needed – usually not applied with Q20 optics).

Table 2: SPS beam parameters for 50 and 25 ns beams

	50 ns	**25 ns**
Beam energy (GeV)	26 → 450	
Bunch intensity ($\times 10^{11}$ ppb)	1.2-1.8	1.3
Full bunch length 4σ (ns)	4 → 2.8 → 1.5	
Number of bunches	144	288
Transv. rms emittances (μm)	1-2	1.5-2.5

Many studies were conducted in the SPS, both as a testbench for LHC [22, 23] and in the framework of the LHC injector upgrade (LIU) program [26, 27, 32]. During LS1, the SPS was opened and the vented surfaces of the beam chambers were expected to return to high values of SEY. However, the post-LS1 experience showed that scrubbing can be recovered fairly quickly (1 week) for the nominal intensity, while higher intensities, like those required in the HL-LHC era, are still affected by losses and further scrubbing will be needed [33].

A key point to be addressed for the SPS was to determine the values of SEY thresholds for e-cloud formation in the different beam chambers and define what parts are critical for present and future LHC beams. Figure 3 shows the electron flux to the wall as a function of the SEY for four different values of bunch current and for the main types of SPS chambers, i.e. MBA and MBB-type for dipoles plus QD and QF for quadrupoles (shapes and sizes of these chambers can be found in [43]). The following features can be observed:

- The e-cloud build up is fairly insensitive to bunch intensity for dipoles (though the position of the stripes changes), while thresholds in quadrupoles exhibit a non-monotonic behaviour with bunch intensity;

- Above the SEY threshold, the electron flux always becomes quickly larger for larger bunch currents;

- MBA-type chambers have higher SEY threshold value and therefore are the easiest to scrub, while MBB-type and quadrupole chambers have lower SEY threshold (comparable or lower values than those to which StSt potentially scrubs) and might suffer from large e-cloud build up even after extensive scrubbing.

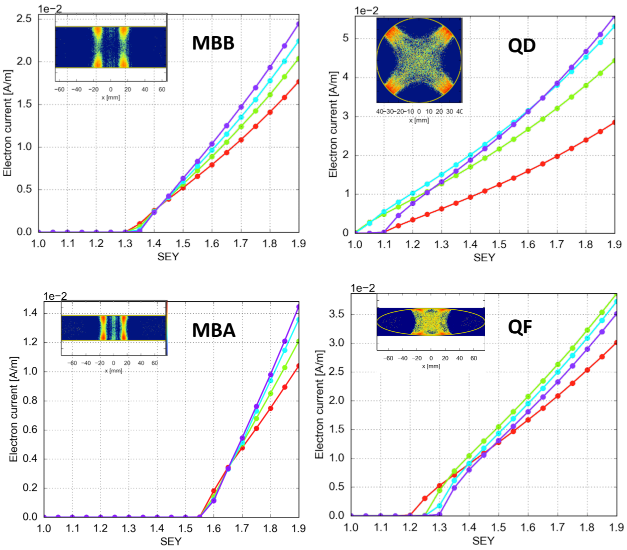

Figure 3: SEY curves for e-cloud formation for four types of SPS chambers and four different bunch intensities (red 1.0×10^{11} p/b, green 1.5×10^{11} p/b, turquoise 2.0×10^{11} p/b, purple 2.5×10^{11} p/b).

Considering all the results of the above study as well as the encouraging results from the scrubbing campaigns in 2014 and 2015 with larger bunch currents than nominal (2.0×10^{11} p/b), it was decided to apply a-C coating [27] only to the quadrupole chambers and some of the drift chambers during the Long Shutdown 2 (LS2), while relying on scrubbing for the long term operation of the SPS with HL-LHC beam intensities. Further experience with high intensity beams in the SPS (>2e11 p/b) has shown that scrubbing is indeed effective to reduce the emittance growth, however a horizontal instability has been also observed to limit the bunch intensity to about 1.8e11 p/b and a stabilisation strategy has to be laid out. While the source of this instability has not yet been pinned down, its features might point to e-cloud to play a role in its onset. Coating of the MBB chambers in LS3 is kept as an option if scrubbing will turn out not to be sufficient to guarantee the desired beam quality during Run 3 [33].

The Large Hadron Collider (LHC)

In mid 2010 LHC started operating with 150 ns spaced bunches for physics. During this period of operation, a pressure rise was observed in uncoated parts of the common vacuum chamber, which could be suppressed by installation of solenoids. Injection of 75 ns and 50 ns beams showed initially strong e-cloud effects [35]. At the beginning of 2011, a ten day scrubbing run with 50 ns beams took place in order to prepare the machine to operate with this type of beams and thus extend the luminosity reach for the 2011 run. The scrubbing run was successful and by end June the number of bunches collided in the LHC reached its maximum value of 1380 per beam, while the intensity per bunch and the transverse emittances remained constant at their nominal values (i.e., 1.15×10^{11} ppb and 2.5 μm). Over 2011 and 2012, the 50 ns beams were gradually made brighter (to about $(10^{11}$p/b)/(1 μm)) and more intense (up to 1.7×10^{11} p/b at collision) without causing any significant recrudescence of the e-cloud effects. Experience with 25 ns beams prior to LS1 was only limited to few MD sessions in 2011 and 2012, and a scrubbing run followed by a pilot physics run at the end of 2012. The 25 ns beams appeared to suffer from strong instabilities at injection (damped with transverse damper and high chromaticity) and exhibited poor lifetime and blown up emittances. Using the heat load measurements, the SEY on the beam screen in the arcs was estimated to decrease from an initial value above 2.0 to about 1.4 [36, 37], with little deconditioning between 2011 and 2012.

During LS1, the LHC chambers were vented and the SEY was reset to its initial values. That's why an extended scrubbing of four weeks with 25 beams, with very gradual intensity ramp up, was necessary to reach the stage at which the LHC could start producing physics with 25 ns beams. After several cycles of deconditioning/reconditioning, 2242 bunches per beam were successfully put in collision by October 2015. The filling pattern used was relaxed (injection of trains of 36 bunches from SPS) in order to keep the heat load in the beam screen of the arcs below the limit (135 W per half cell (W/hc) for one of the sectors). In 2016, after a 24 hour scrubbing run, the LHC went into physics production. With 2040 bunches per beam (in trains of 72 bunches) and nominal beam parameters, the LHC reached its nominal peak luminosity of 10^{34} cm^{-2} s^{-1}. At this point, the heat load in the beam screen of the arcs was very close to its limit (160 W/hc) and only exhibited a slow decrease thanks to scrubbing accumulated during the physics stores. Finally, the brightness of the beams was increased by switching to the BCMS scheme (trains of twice 48 bunches spaced by 225 ns) [52] and the final fills with 2220 bunches could comfortably exceed the nominal luminosity by up to 40% with heat load within the capacity of the cryogenic system. During this year it was not possible to increase further the number of bunches in LHC, because the SPS could not produce LHC beams in longer trains than 2x 48 bunches, due to a vacuum leak in the internal dump. During the winter shutdown between 2016 and 2017, Sector 12 of LHC had to be opened to exchange a faulty dipole. That's why at the beginning of 2017 a longer scrubbing (about a week) was needed to recondition Sector 12 before moving to physics production. In 2017, the number of bunches injected quickly got to the maximum of about 2600 per beam, and in this configuration the LHC ran during the first part of the year. Unfortunately, in the second part, due to air condensation in both chambers in the cell 16L2, which probably took place while pumping after the shutdown, it was necessary to move to a low e-cloud variant of the 25 ns beam, i.e. the so-called 8b+4e. This beam had the advantage to limit the probability of occurrence of UFO-like events at 16L2, which caused strong beam losses and premature dumps with the standard 25 ns beam. In spite of a partial warm up of the Sector 12, which had been believed to be sufficient to degas the condensed air and pump it out, the 16L2 persisted in 2018 and limited the intensity per bunch in LHC (1e11 p/b).

The general evolution during 2015-18 can be seen in Fig. 4, which displays the bunch number in the top plot and the heat load measured at high energy in the eight arcs for all physics fills in the bottom one. Two puzzling features can be noticed, which are potentially unsettling for future operation:

- While the normalised heat load decreased by a factor two in 2015 (due to both scrubbing and filling pattern relaxation), the evolution in 2016 shows only a limited decrease at the beginning and then it levels off in the second part of the year and throughout 2017-18 (excluding the 8b+4e run at the end 2017, which was intrinsically low e-cloud). This suggests that scrubbing has saturated, even while running at high heat load. Running with trains of doublets (pairs of bunches 5 ns) [52] could perhaps lead to additional scrubbing in the future, but it was not tested again after 2015 due to the SPS dump in 2016 and to 16L2 in 2017-18;
- There is a constant offset between the values of the normalised heat load in different sectors and the "asymptotic" values differ by a factor three. The heat load in the "best" sectors landed to about twice the value expected from impedance and synchrotron radiation, suggesting that the e-cloud is still playing a role everywhere in LHC. In this situation, the sectors with the highest heat load are a limit for the total intensity that can be collided in LHC. The reason of this spread is still under investigation, and it is hoped that the surface analysis of some bad beam screens extracted in LS2 can clarify its origin.

Table 3 shows the achieved LHC beam parameters.

Table 3: LHC beam parameters for 50 and 25 ns beams

	50 ns	**25 ns**
Beam energy (TeV)	0.45 → 3.5/4 → 6.5	
Bunch intensity ($\times 10^{11}$ ppb)	1.1-1.7	1.0-1.2
Bunch length (ns)	1.0-1.5	
Number of bunches	1376	2800
Transv. rms emittances (μm)	1.1-1.7	1.5-2.5

In high e-cloud operation, i.e. with 25 ns beams, the beam stability at injection and along the cycle is usually preserved with large chromaticity values, relatively high octupole currents and a fully functional transverse feedback system [53]. Due to the tune footprint in presence of large chromaticity and strong e-cloud, this also implies that the tunes must be carefully placed to be far enough from any dangerous resonance line. The incoherent losses observed when the vertical tune of the LHC was 0.31 at injection (due to the proximity to the third order resonance) could be easily avoided by lowering the vertical tune at injection to values around 0.29.

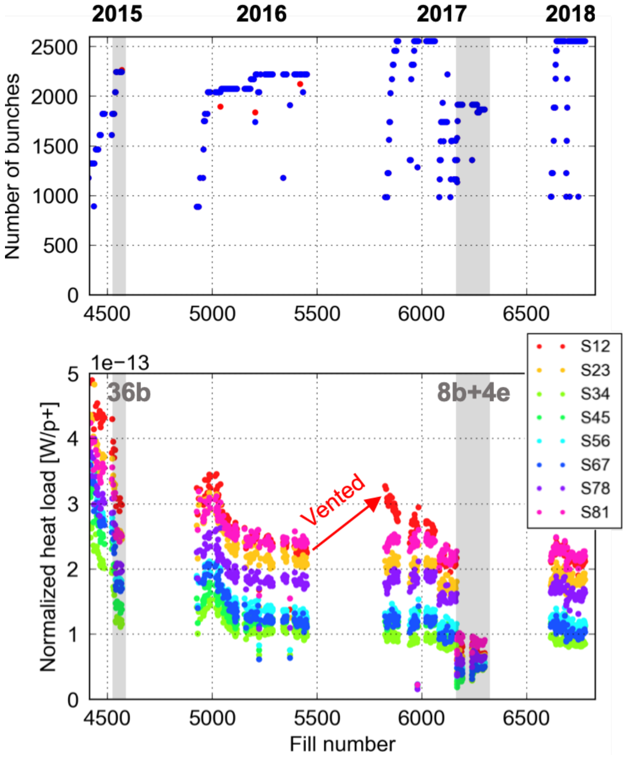

Figure 4: Top: evolution of number of bunches in LHC during Run 2. Bottom: heat load at 6.5 TeV in the eight sectors (as labeled) for all fills with 25 ns bunch spacing normalized to the total intensity of the circulating beam.

The horizontal tune had to be also lowered to keep a safe distance from the vertical one not to trigger instabilities from coupling [54]. Extensive simulation studies were carried out to try to disentangle the role of the e-cloud in the different LHC regions (dipoles, quadrupoles/multipoles, drift chambers) [53]. At nominal intensity it is believed that the two-stripe structure of the e-cloud in the dipoles makes it basically "harmless" for the beam stability (due to the very low central density of electrons) and the beam instability is caused by the e-cloud in the quadrupoles. Conversely, for lower bunch currents a third stripe develops at the center of the chamber and the region around the beam gets quickly densely populated with electrons. This range of bunch intensities is explored, while the beam intensity decreases during the phase of "stable beams", i.e. when the beams are colliding at 6.5 TeV to provide data for the experiments. In practice, this situation resulted in single bunches at the ends of the trains becoming vertically unstable at some advanced point of the store, which was observed systematically in the LHC during the first phase of the 2016 run in spite of the high chromaticity, the current in the octupoles close to its maximum and the presence of the beam-beam head-on tune spread [55]. This instability, which was kept under control by increasing further the chromaticity in stable beams, disappeared during the second part of the run, even with low chromaticity, probably thanks to the scrubbing of the central region of the beam screen accumulated with physics.

For HL-LHC operation, it is essential that the e-cloud with the future beam parameters will: 1) produce heat load in the cold regions that is compatible with the capacity of the cryogenic system; and 2) not cause beam degradation due to instability or incoherent effects. The dependence of the e-cloud with bunch intensity has been found to be favourable in simulations (central density and heat load level off or even drop for higher intensities than the present nominal), and this has been partially experimentally verified up to bunch intensities of 2e11 p/b, but only in trains of 12 bunches. It has been envisaged to make a low SEY treatment of the beam screens of the twin and single bore magnets in the interaction regions, including triplets and matching sections [41] to minimise the impact of these regions on the total load on the cryogenic system. For the arcs, future operation will rely on both the predicted dependence of e-cloud with intensity and efficiency of scrubbing, while keeping the back up option of running with low e-cloud filling patterns, like full or mixed 8b+4e [56], in case of need. The option of adding a 200 MHz RF system to lengthen the bunches, which could make operation possible if the heat load is still limited by the e-cloud in the dipoles [42], is presently not in the baseline of the upgrade project.

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