Electron cloud effects for PS2, SPS(+) and LHC

G. Rumolo*
CERN, Geneva, Switzerland

Abstract

Electron cloud effects are expected to be enhanced and play a central role in limiting the performance of the machines of the CERN complex after the upgrade that is planned to take place in the next years.

The beam will be injected into the SPS through the chain Linac4-SPL-PS2, replacing the existing Linac2-PSB-PS. The ultimate LHC beam in the PS2 will almost certainly suffer from electron cloud, if the vacuum pipe of this ring is not correctly designed in order to contain this effect. The SPS will be able to digest the higher intensity LHC beams coming from the PS2 only if it will have been upgraded against electron cloud by the time PS2 starts operation, or if a wide-band feedback system capable of coping with electron cloud instabilities will have been developed and successfully tested by that time. In the LHC, the main worries are presently the deposited heat load on the inner wall of the cold dipole chambers, which could exceed the cooling capacity both at nominal and ultimate intensities (and spacings) if the secondary emission yield is sufficiently high, and the slow incoherent emittance growth, which could strongly affect the lifetime of the beams and reduce the efficiency of the physics stores.

INTRODUCTION AND MOTIVATIONS

Plans for the Large Hadron Collider (LHC) performance upgrade include the improvement of the existing LHC injectors and the design of possible new rings in the injector chain [1]. The main motivation for these plans is the necessity to improve the reliability of the injector complex, which is rapidly aging, as well as to prepare it for new physics programs at low energy and for the LHC upgrade. Several scenarios, aimed at overcoming the existing bottlenecks, have been taken into consideration over the last few years [2]. The option presently studied by the combined action of several interfaced working groups is based on the replacement of the present injector chain Linac2-PSB-PS Proton with the new chain Linac4-SPL-PS2 [3]. Civil engineering works for the Linac4 have been already undertaken, and Linac4 is foreseen to replace Linac2 as injector into the PSB by 2012. The higher extraction energy from Linac4 (160 MeV instead of the present 50 MeV produced by the Linac2) is expected to be beneficial for the space charge and aperture limitations of the high intensity beams injected into the 4 rings of the PSB, so that its performances are expected to significantly improve. The SPL and the PS2 (accelerating up to 4 GeV and 50 GeV, respectively) are scheduled to be built later on and start operation by 2017. The PS2 will store and accelerate 25ns spaced LHC beams with 4.4×10^{11} ppb in 168 bunches or 50ns spaced LHC beams with 5.5×10^{11} ppb in 84 bunches. The increased injection energy into the SPS is believed to be beneficial for the machine in many regards (e.g., less space charge and intra beam scattering, more rigid beams against coupled bunch instabilities, no transition crossing, lower injection and capture losses, higher Transverse Mode Coupling Instability threshold) [4]. Furthermore, it would allow for an upgrade of the SPS to a 1 TeV extraction energy ring, with the related advantages for injection into the LHC.

However, electron cloud effects can be enhanced at the different stages of the injection chain, due to the foreseen increased intensity of the LHC beams, and their smaller beam sizes. In the PS2, heat load and induced beam instabilities could be an issue. In the SPS the vertical single bunch electron cloud instability has been limiting for a long time the number of batches that could be injected into the ring and it could be overcome by beam scrubbing and subsequently operating the ring with a high vertical chromaticity (which nonetheless can be harmful for the beam lifetime) [5]. The scaling law of the electron cloud instability threshold with energy was addressed in [6] and again, both theoretically and experimentally, in [7], showing a potentially unfavorable behavior with increasing energy (under conservation of bunch length and 3D phase space volume). The counterintuitive outcome of this study was the driving force for the development of new electron cloud mitigation or suppression techniques on one side, and for the feasibility study of a wide-band feedback. New carbon based coatings have been tested in laboratory and sample liners were also installed in the SPS to study their behavior with the circulating beam. The investigation on a feedback system that could fight quick single bunch electron cloud instabilities has been started. In the LHC the electron cloud could be responsible for an intolerable heat load on the inner walls of the cold dipole chambers and for a luminosity drop induced by incoherent emittance growth.

ELECTRON CLOUD SIMULATIONS FOR THE PS2

Table 1 shows a list of the essential parameters so far used for the electron cloud studies in the PS2 (typical LHC-type bunch in the PS2). The results of these studies are summarized in [8, 9]

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* Giovanni.Rumolo@cern.ch

Table 1: Parameters used in our study

Parameter	Symbol	Unit	Value
Energy	E_0	GeV/c	50 or 75
Transv. sizes	$\sigma_{x,y}$	mm	0.8-1.0
Bunch length	σ_z	cm	50-100
Bunch spacing	T_b	ns	25/50/75
Bunch population	N	$(\times 10^{11})$	4/5.4/6.6
Number of bunches	N_b		72/36/24
Number of trains			4
Train spacing		ns	200
Chamber sizes	(a, b)	cm	(8,4)

Preliminary sets of simulations of the build-up of the electron cloud for various options considered in the above table have been carried out with the code POSINST [10]. They only pertain to the build-up of the ecloud in the chambers of dipole bending magnets, at a magnetic field B corresponding to the specified beam energy E_0. No other regions of the machine nor any effects from the ecloud on the beam were considered at this stage. The first results presented in the LUMI'06 workshop [8] were carried out with rather coarse time steps, predicting questionable heat load values in the order of hundreds of W/m. These simulations were subsequently repeated by dividing the bunch length into a variable number of steps, resulting in far less noisy and more reliable heat values than the old ones. In all cases primary electrons were represented by 1,000 macroparticles per bunch passage, and an upper limit of 20,000 was set for the number of macroparticles allowed in the simulation at any given time.

Beams with 25ns spacing exhibit heat loads between 5 and 20 W/m for maximum secondary emission yields (SEYs) between 1.3 and 1.7. For larger bunch spacings (50 and 75 ns), the heat load always keeps below 5 W/m for the given range of SEYs. The values of heat load are also found to be very sensitive to the used model of SEY. If rediffused electrons are not included in the model, the predicted heat load is always lower than 5 W/m for all spacings and even falls below 1 W/m for 50 and 75ns spaced LHC beams.

ELECTRON CLOUD EFFECTS IN THE SPS(+)

Scaling of electron cloud instability with energy

The dependence of the electron cloud instability threshold on energy was first studied with HEADTAIL [11] simulations, showing an instability threshold decreasing with increasing energy under conservation of the 3D phase space volume and bunch length. A possible explanation for this unusual behaviour is that, although the bunch becomes more rigid at a higher energy, and therefore less sensitive to collective effects, it also becomes transversely smaller, which enhances the effect of the electron cloud pinch. Besides, the matched voltage changes like $|\eta|/\gamma$, which causes a decrease of the synchrotron tune far from transition. This translates into a slower motion in the longitudinal plane and therefore larger time scales for natural damping.

An experimental study to prove the scaling law found by simulations was carried out at the CERN-SPS during the 2007 run. The studies were essentially done using two possible SPS cycles. In particular, in the short MD1 cycle, parallel to physics, only one batch of the LHC beam was injected in the SPS at 26 GeV/c and then accelerated to 37 GeV/c. Two flat parts of about 1 s were available at bottom and top energy, during which it was attempted to induce the electron cloud instability. With this cycle it was expected to see a larger effect before the scrubbing run, when the electron cloud could be potentially a problem already at the tail of one batch alone. In the long dedicated supercycle for MDs, an LHC-type beam made of 1 to 4 batches with 72 bunches each was used. The beam was injected into the SPS at 26 GeV/c during a flat bottom of 10.86 s, then accelerated to an intermediate plateau of 55 GeV/c (about 6 s) and eventually to 270 GeV/c before being sent onto a dump. The 55 GeV/c flat portion would serve to show that the beam still suffers from electron cloud instability at this higher energy. Observing the beam behaviour at this energy would be specially interesting, because it is close to 50 GeV/c, i.e. the value of the new SPS injection energy after the upgrade of the pre-injectors.

The experiment at 26 and 37 GeV/c showed no significant difference between the measurement sessions that took place before scrubbing and those after the scrubbing run. Also the damper gain settings did not appear to influence the results. It was possible to determine the limit value of vertical chromaticity below which the beam would become unstable at both energies. The treshold chromaticity value was slightly higher at 37 than at 26 GeV/c, and values did not change over the different MD sessions done with this cycle. The instability manifested itself with beam loss in the tail of the batch at both energies, while an electron cloud signal was observed with the e-cloud monitor on the ramp, where the bunch gets shorter, and on the flat top. No strong signal was observed at 26 GeV/c in standard operation. However, during one of the MD sessions a successful attempt was made to trigger a stronger electron cloud at 26 GeV/c by means of a voltage bump, which causes a localized bunch shortening on the flat bottom. No significant difference in the instability evolution at 26 GeV/c was observed under these conditions (nor depending on whether the chromaticity bump was created within the voltage bump or outside of it). This induced us to believe that the main driving force for the instability observed at 26 GeV/c was not electron cloud. This seemed to be confirmed by the bunch-by-bunch centroid signals, acquired over 1000 subsequent turns with the LHC-BPMs (i.e., beam position monitors that can provide turn by turn and bunch by bunch measurements). The intra-batch motion of the centroids exhibited some correlation and a traveling wave pattern at

26 GeV/c, with a possible single bunch component at the very end of the batch. However, at 37 GeV/c there was no evident sign of coupled bunch motion and the unstable bunch by bunch motion at the tail of the batch looked uncorrelated, possibly induced by a single bunch effect. The results of these measurements were summarized in Ref. [12].

Finally, given all the uncertainties and the absence of consistent sets of data at two different energies, these measurements did not prove conclusive to assess the experimental verification of the scaling law of the electron cloud instability with energy, as it was found by simulations.

Using the LHC-type beam in the SPS on a long dedicated MD cycle, an electron cloud instability was excited at 55 GeV/c. In fact, since there was no evidence of electron cloud instability at 26 GeV/c, it was decided to concentrate on the measurements at 55 GeV/c. After all 4 batches were injected, the chromaticity would be quickly reduced in the middle of the intermediate plateau at 55 GeV/c. The idea was to show that the electron cloud could be observed at this energy and it could be damped by blowing up the transverse emittance of the beam. This would be an indirect proof of the scaling law of the threshold found with the simulations: in fact, it would prove the physical mechanism believed to cause the unusual behavior explained above. These measurements were carried out both with the feedback system on and off, in order to show that they were not possibly influenced by it. The experiment was successful and proved that: 1) There is an electron cloud instability at 55 GeV/c if the chromaticity is low enough, 2) This instability can be efficiently cured by enlarging the beam transversely [7]

Electron cloud mitigation techniques

In the last two years electron cloud mitigation techniques have been object of an intensive study carried out by the SPSU Study Team [13]. In particular, novel coatings for beam chambers have been both studied in laboratory and tested with circulating beam in the SPS. The new types of coating were chosen following the general guideline that ideally a low SEY coating should also be UHV compatible, compact (i.e. it should not flake off and produce dust in the beam chamber), easy to be deposited on stainless steel, and have low resistivity. It was found that coatings based on carbon (C) sputtering, which have in principle all the above properties, could produce a maximum secondary emission yield even below 1 [14]. Several samples were produced, analyzed in the laboratory and some selected ones were installed in an SPS liner with an electron cloud strip monitor attached. At the same time, two additional liners equipped with electron cloud strip monitors, one in simple stainless steel and the other one with activated NEG coating, were always installed in the SPS and used for reference measurements. All the measurements were taken during long dedicated MD sessions, with one or more batches of 25 ns LHC beam circulating in the machine. The measured electron cloud signals confirmed the laboratory measurements done beforehand. The first C coated liner that was installed exhibited an electron cloud signal much lower than the one in stainless steel, but higher than the one measured with NEG coating. This was expected, because the maximum SEY of this sample, as measured in the laboratory, was 1.3, to be compared with a value above 2 for stainless steel and 1.1 for activated NEG. In the second measurement session, which took place after the C coated sample had been exchanged, the new liner gave the lowest electron cloud signal. Again, this was predicted beforehand, because the laboratory measurement for this sample had given a maximum SEY below one. The C coated sample was not exchanged between the second and third MD session, and the electron cloud measurements gave values of electron cloud in it even below those measured two months before. This was a confirmation that the sample does not deteriorate in vacuum and its maximum SEY stays basically unchanged, or becomes lower, even after several days in vacuum. In ordert to study the effects of aging, another sample was kept in the laboratory and exposed to air during several days and weeks. Also in this case, no large sign of detioration was observed. The maximum SEY would slightly increase in the first days of air exposure, but it would quickly saturate to values generally below or about 1.1.

The results of all these measusements, which will be described in a detailed CERN MD report [15], seem to indicate that the use of this type of coating is promising and could potentially suppress the electron cloud, and all related problems, in the new (or upgraded) generation of machines.

Feedback system for the electron cloud instability

One possible method to control both the single and multi-bunch instability is to implement a feedback system. While the design of a feedback system required to damp transverse multi-bunch instabilities poses certain challenges, similar feedback systems already exist in the SPS and therefore it is believed that implementation of such a system is feasible. More challenging is the implementation a single bunch feedback system. Such a system may require a very large bandwidth and a large number of kicks per turn to sufficiently damp the instability, depending on the behavior and growth rate of the single bunch instability. In order to determine the feasibility of such a system the existing tracking code HEADTAIL [11] was utilized. By implementing a newly written feedback module in the existing HEADTAIL code, it was possible to simulate the effects of simple feedback on the transverse motion of a single proton bunch. Because the electron cloud mainly forms in dipoles and the significant single bunch instabilities are expected (and observed) in the vertical plane, the feedback module was made to only act on the vertical motion.

The feedback studies with HEADTAIL focused on examining the behavior of the electron cloud instability at 55 GeV/c (see above) in the SPS. It was found that in order to cure this instability one must have a large enough bandwidth feedback system to handle the asymmetric oscillation in the bunch difference signal. By implementing a bandwidth limiting feedback module it was possible to determine that the minimum bandwidth required to suppress the instability is actually around 300 MHz. But the normalized gain of such a relatively low bandwidth feedback system is relatively large. The lowest bandwidth for which the gain limit is about or below $1/5$ (maximum feasible value) is about 500 MHz. Therefore, a feedback system with 500 MHz bandwidth and gain of about 0.16 would be the most realistically realizable system.
The details of this study can be found in [16].

ELECTRON CLOUD STUDIES FOR THE LHC

Simulation studies of heat load due to electron cloud in the dipole chambers of the LHC have been done wth the ECLOUD code [17] for several values of the maximum SEY and several bunch intensities, and for bunch spacings of both 25 and 50 ns [18]. Comparing the resulting curves with the cooling capacity curves (for the low and high luminosity schemes), shows that:

- The nominal intensity at 25 ns bunch spacing has a tolerable heat load only if the SEY is below 1.4, whereas the ultimate intensity can in principle still tolerate a SEY of 1.4 in the low luminosity configuration, but would be at the limit for a SEY of 1.3 in the high luminosity configuration.
- The nominal intensity requested by the LPA scheme upgrade with 50 ns (5×10^{11} ppb) has a tolerable heat load with a maximum SEY of 1.5 only in the low luminosity configuration, but it causes basically always intolerable heat load in the high luminosity configuration.

It has to be mentioned that the predictions of the ECLOUD code do not take into account the presence of rediffused electrons. As a consequence, similarly to what observed above in Section 2, if rediffused electrons were taken into account in the calculation of the heat load the tolerable values of the maximum SEY would be reduced for all cases. In particular, the study in Ref. [19] done with the POSINST code shows that the predicted heat load is doubled when rediffused electrons are considered.

Another important concern for LHC operation is the possible incoherent emittance growth resulting from the interaction of a beam with an electron cloud not sufficiently intense as to cause a coherent instability. The mechanism leading to emittance growth was described in Ref. [20] and is based on the periodic crossing of resonances due to synchrotron motion from protons that see differently intense electron clouds depending on their longitudinal position inside the bunch (due to the pinch). This mechanism is very similar to that causing emittance growth from space charge [21]. Simulations run with the MICROMAP code, modified such as to introduce a simplified electron cloud kick in several sections of the LHC, show that the emittance growth can be significant and provoke a non-negligible luminosity drop over the store time of a beam inside the machine [22]. More refined models of the pinch are currently under development, which try to reproduce the real pinch dynamics both in field-free and dipole regions.

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