

# ELECTRON CLOUD EFFECTS IN THE CERN SPS AND LHC

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## Abstract

Electron cloud effects have been recently observed in the CERN SPS in the presence of LHC type proton beams with 25 ns bunch spacing. Above a threshold intensity of about  $4 \times 10^{12}$  protons in 81 consecutive bunches, corresponding to half of the nominal ‘batch’ intensity to be injected into the LHC, an intense electron bombardment gives rise to a strong perturbation of the transverse feedback pick-up signals and to significant pressure rises. Also the intensity and emittance along the bunch train is affected. We compare experimental results with simulations of the electron cloud build-up and discuss possible solutions.

## 1 INTRODUCTION

In the LHC, photoelectrons created at the pipe wall are accelerated by proton bunches up to 200 eV and cross the pipe in about 5 ns. For the nominal bunch spacing of 25 ns a significant fraction of secondary electrons is lost in between two successive bunch passages, but slow secondary electrons with energies below 10 eV survive until the next bunch and can be again accelerated up to several keV. This non resonant, single pass mechanism may lead to an electron cloud build-up if the maximum secondary electron yield (SEY)  $\delta_{\max}$  of the pipe wall is larger than a critical value, typically around 1.3 for nominal LHC beams [1]. Then the electron cloud is amplified at each bunch passage and reaches a saturation value determined by space charge repulsion, with implications for beam stability, emittance growth, and heat load on the cold LHC beam screen.

The electrons are not trapped in the proton beam potential, but form a time-dependent cloud extending up to the pipe wall. In field-free regions this cloud is almost uniform, while in the dipole magnets the electrons spiral along the vertical field lines, with typical Larmor radii ranging from a few  $\mu\text{m}$  in the LHC to a few hundreds  $\mu\text{m}$  in the SPS, and tend to form two stripes where the average energy gain corresponds to the maximum of the SEY. Since the vertical dimensions of the LHC dipole beam screen and of the SPS vacuum chamber are very similar (about 2 cm half height), the corresponding critical SEY is the same for both machines. However the mechanism that triggers the electron cloud build-up is different. In the LHC at 7 TeV, the generated synchrotron radiation creates  $10^{-3}$  photoelectrons/m per proton, while in the SPS (and in the LHC at injection energy) the primary electron production is dominated by ionization of the residual gas: assuming an ionization cross section of 2 Mbarn, at 10 nTorr the primary yield is only

$6.4 \times 10^{-8}$  electrons/m per proton. This is one reason why electron cloud effects were not anticipated in the SPS, the other reason being that it was reasonable to expect a substantial surface conditioning of the SPS vacuum chamber after so many years of operation, especially with leptons (photon scrubbing). However the SPS vacuum chamber is often vented and this creates oxide and/or condensed water layers with a high SEY [3]. In addition, tungsten synchrotron radiation masks located at the extremities of the SPS dipole chambers reduce or prevent photon scrubbing.

## 2 EXPERIMENTAL EVIDENCE

There is a rather convincing list of SPS observations supporting the conclusion of an electron cloud build-up with LHC type beams [2]. In particular, a similar threshold bunch intensity  $N_b = 2.5$  to  $5 \times 10^{10}$  is observed for damper pick-up signals, distributed pressure rise and beam instability, when the bunch spacing is 25 ns. This is in good agreement with electron cloud simulation results [2], assuming a maximum SEY  $\delta_{\max} \simeq 1.9$ : compare the simulated electron cloud build-up of Fig. 1 with the signals measured at the damper pick-ups, shown in Fig. 2a, or with the observed relative pressure rise of Fig. 3. As for the LHC, the simulated electron cloud density in the SPS grows significantly after about 30-40 bunch passages and reaches a saturation value of a few  $10^9$  electrons/m, consistent with the observed pressure rise and with the charge deposition measured on the damper pick-up. Ion effects are excluded, since they would depend on the integrated charge over several bunches, while no effect is observed with different bunch spacings and the same total batch intensity. Moreover the observed threshold bunch intensity has a weak

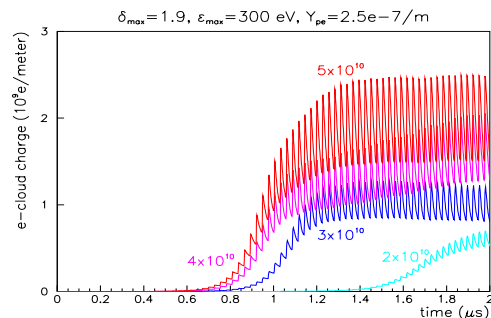


Figure 1: Simulated electron cloud build-up in the SPS for four different bunch populations,  $\delta_{\max} = 1.9$  and a primary electron yield (at the pipe wall)  $Y_{pe} = 2.5 \times 10^{-7}/\text{m}$  per proton, corresponding to a gas pressure  $p = 40$  nTorr.

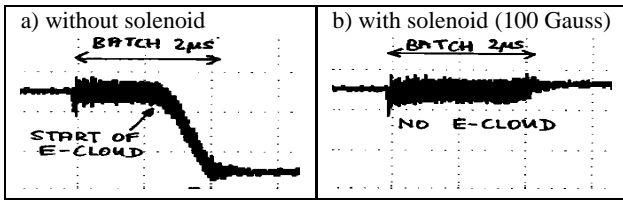


Figure 2: Vertical pick-up signal ( $\Delta$ -signal) for a batch intensity of  $5.5 \times 10^{12}$  protons, in 81 bunches with 25 ns spacing, measured with high impedance FET amplifiers at the electro-static pick-ups for the SPS damper system: a) without and b) with a solenoid field of 100 Gauss.

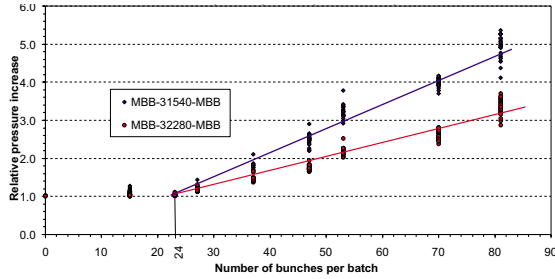


Figure 3: Relative pressure rise vs. number of bunches with  $N_b = 7.5 \times 10^{10}$  protons in an LHC type batch, measured at different gauges placed between two SPS dipoles.

dependence on the residual gas pressure, contrary to ion effects and in agreement with electron cloud simulations. There is also direct evidence of negative charge (electrons), collected by a dedicated pick-up with a shielding grid, correlated with beam intensity and bunch pattern. Finally, a modest solenoid field was effective in curing the damper pick-up, but limited to 100 Gauss by heating problems (see Fig. 2b). Above an LHC batch intensity of about  $5.5 \times 10^{12}$  protons, the solenoid field was insufficient. This is qualitatively understandable in view of the keV energies acquired by electrons near the beam axis.

Early observations of anomalies in the behaviour of the SPS damper with LHC type beams in 1998 were confirmed in 1999 and the problem could be attributed to baseline jumps in the signals of all the eight electrostatic pick-ups. This phenomenon occurs only beyond a threshold bunch intensity  $N_b \sim 4$  to  $5 \times 10^{10}$  of the  $2 \mu\text{s}$  LHC batch with 25 ns bunch spacing and the baseline drift starts after the passage of some 30-40 bunches (see Fig. 2a). No drift was observed with 130 ns bunch spacing and  $N_b \sim 2.5 \times 10^{11}$ , nor with 5 ns bunch spacing and  $N_b \sim 10^{10}$ , in agreement with simulation results shown in Fig. 4. The observations of the damper pick-up signals show that the baseline jumps are not present at multiples of the 40 MHz bunch frequency. An effective solution to provide a clean signal for the damper, already successfully implemented for the horizontal damper, is therefore to mix the beam position  $\Delta$ -signals with a beam synchronous RF reference signal at a multiple of the bunch frequency, for example 120 MHz, down to baseband for further processing [2].

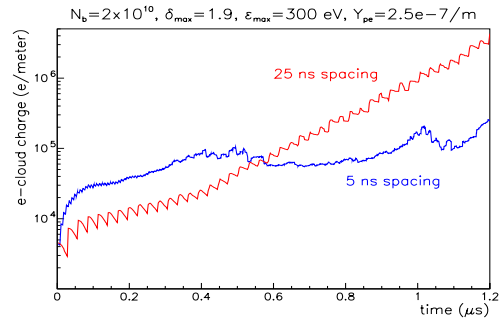


Figure 4: Simulated electron cloud build-up in the SPS for a bunch population  $N_b = 2 \times 10^{10}$  and  $p = 40$  nTorr, comparing bunch spacings of 5 ns and 25 ns. In both cases the maximum SEY  $\delta_{\text{max}} = 1.9$  exceeds the critical value, but the build up of the electron cloud is more regular and much faster for the 25 ns spacing than for the 5 ns spacing.

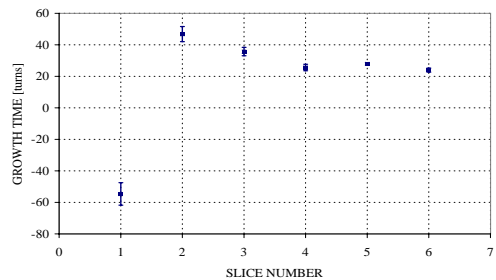


Figure 5: Growth time of the horizontal instability observed at injection vs. position in the batch, for a batch intensity of  $4 \times 10^{12}$  protons. Slice 1 corresponds to the head and slice 6 to the tail of the batch.

A fast horizontal instability with a rise time of 20 to 25 turns is observed in the SPS above a threshold LHC batch intensity of  $4 \times 10^{12}$  protons (see Fig. 5). The observations have been performed with couplers equipped by a 200 MHz receiver, not affected by the electron cloud induced baseline distortions of electrostatic pick-ups, and beam oscillations have been monitored at six consecutive slices along the batch. The instability mainly affects the batch tail, saturates and leads to emittance blow-up and beam losses. There is a slower instability in the vertical plane too, also affecting the tail of the batch. Vertical oscillations around 700 MHz are observed with a wide-band pick-up and may be associated with single bunch activity (this happens to be close to the transverse oscillation frequency of the electrons inside the LHC proton bunches and there is also a known SPS impedance source around the same frequency). This fast instability might be interpreted as a single bunch, beam break-up instability caused by the short range wakefield in the electron plasma; preliminary estimates [5, 6] assuming an electron cloud density of  $5 \times 10^{11}$  electrons/ $\text{m}^3$  lead to a rise time of  $500 \mu\text{s}$ , or 20 turns, very close to the observed instability rise time. This is compatible with recent SPS measurements of single bunch head-tail phase shift, indicating that bunches near the tail of a batch are affected by a significant short range wakefield.

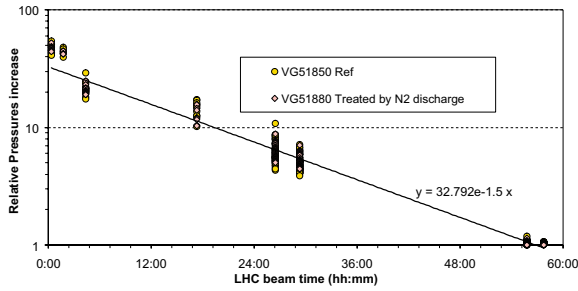


Figure 6: Relative pressure rise vs. LHC beam time with a batch intensity above  $3.8 \times 10^{12}$  protons. The measured pressure is practically the same for a reference vacuum chamber and for a special chamber treated with  $N_2$  discharge, both located in a field-free region of the SPS.

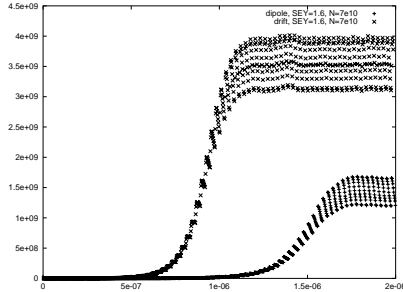


Figure 7: Simulated electron cloud build-up in the SPS for  $N_b = 7 \times 10^{10}$ ,  $\delta_{\max} = 1.6$  and  $p = 40$  nTorr: comparison of field-free regions (top curve) and dipoles (bottom curve).

### 3 POSSIBLE CURES

Laboratory measurements indicate that electron bombardment at a few hundred eV is one of the most effective means to reduce the SEY of a technical surface. For example an electron dose above  $1 \text{ mC/mm}^2$  leads to a significant reduction of  $\delta_{\max}$  [3]. An electron dose of  $5 \times 10^{-5} \text{ C/mm}^2$  is the observable limit for surface conditioning, in agreement with early SPS observations during 14 hours with a duty cycle of 3.4% [2, 4]. The effect of dosing has been confirmed by irradiation tests with synchrotron light from the EPA ring [3]. A reduction of  $\delta_{\max}$  down to a saturation value below 1.3 is observed for a copper sample positively biased at 100 V and for a primary photon dose around  $10^{22}$  photons/m, corresponding to 30 hours of nominal LHC operation at 7 TeV. In the SPS the accumulated photon dose during lepton cycles after one year of LEP filling, with synchrotron radiation masks in place, is only  $10^{21}$  photons/m.

Recently a clear indication of surface cleaning has been observed in the SPS during an equivalent period of 60 hours with 100% duty cycle and a batch intensity above  $3.8 \times 10^{12}$  protons in 81 bunches: Fig. 6 shows a marked reduction of the relative pressure rise vs. LHC beam time. In spite of the reduced pressure rise after electron bombardment, it is not clear which fraction of this reduction can be attributed to the SEY or to the molecular desorption yield of the vacuum chamber wall. Comparing recent SPS measurements of pressure rise vs. intensity to early measurements in 1999,

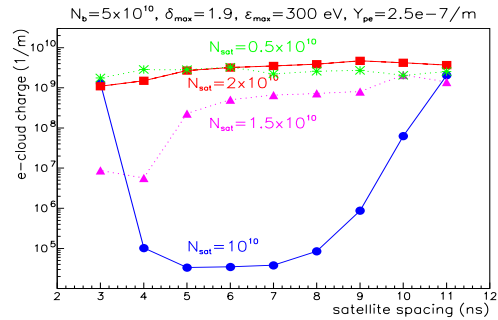


Figure 8: Simulated suppression of electron cloud build-up in the SPS by low-intensity satellite bunches with intermediate spacings from the main bunches, for  $N_b = 5 \times 10^{10}$ ,  $\delta_{\max} = 1.9$ , and  $p = 40$  nTorr. The full bunch length is 3 ns both for the main and the satellite bunches.

i.e. before surface cleaning, it appears that the threshold LHC batch intensity for electron cloud build-up in the field-free regions has increased from about  $4 \times 10^{12}$  to more than  $5 \times 10^{12}$  protons. A possible interpretation of the observation that surface conditioning is more effective in field-free regions than in regions with strong dipole magnetic field is that the electron cloud build-up in the dipoles is slower and reaches a lower saturation value, as shown in Fig. 7.

Another possible solution is to produce gaps in the LHC batch by means of RF manipulations in the PS [2]. For example, starting from 7 PS Booster bunches and applying 3 subsequent bunch splittings yields a modified LHC bunch train consisting of 56 bunches with gaps of 4 missing bunches every 8 bunches. Simulations show that the electron cloud build-up would be suppressed for a maximum SEY of 1.5. For a higher  $\delta_{\max}$  of 1.9, one should resort to a reduced fill pattern consisting of a sequence of 4 LHC bunches followed by 4 missing bunches. Alternatively the bunch spacing could be doubled. Such schemes could be used for the initial beam conditioning of the LHC.

As shown in Fig. 8, low-intensity satellite bunches with a population around  $10^{10}$  protons and intermediate spacings from the main bunches would be very effective against electron cloud build-up. In the SPS it may be possible to generate satellite bunches at 3-5 ns distance from nominal LHC bunches, using the 800 MHz cavities.

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