ELECTRON CLOUD EFFECTS IN THE CERN PS

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Abstract

The beam-induced electron cloud build-up is one of the major concerns for the SPS and the design of the future LHC. Recently, this effect has been observed also in the PS with the nominal LHC-type beam, consisting of a batch of 72 bunches of 1.1×10^{11} p/b spaced by 25 ns. The electron cloud induces baseline distortion in electrostatic pick-up signals that is observed, both in the last turns of the PS when the full bunch length is reduced to less than 4 ns, and in the transfer line between the PS and the SPS rings. Experimental observations are presented and compared to simulation results and predictions from theory. Furthermore, possible cures, such as variation of the bunch spacing, inserting gaps in the bunch train and applying weak solenoidal fields, are also discussed.

1 INTRODUCTION

The electron cloud build-up is a non-resonant single-pass effect, which can be triggered by photo-electrons due to synchrotron radiation, as predicted for LHC, or simply by a few primary ionisation electrons, as seen in the SPS during the past two years [1]. The primary electrons are accelerated by the proton beam bunches up to few tens of eV and cross the vacuum pipe in a few ns. A significant fraction of secondary electrons is lost between two successive bunch passages, but slow secondary electrons with energies of a few eV survive until the next bunch arrives and can be accelerated again. This mechanism may lead to an electron cloud build-up if the maximum secondary electron yield of the pipe wall is larger than a critical value. Then the electron cloud is amplified at each bunch passage and reaches a saturation value determined by space charge repulsion. The electrons 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.

Once this electron cloud is formed, it acts as an additional impedance for the proton beam, and it can drive single-bunch and/or coupled-bunch instabilities.

In the present paper, the observations made in the PS with the LHC-type beam [2] are described in Section 2 and compared to simulations and theory in Section 3. The possible cures are then discussed in Section 4.

2 OBSERVATIONS

2.1 In the Last Turns of the PS

The nominal LHC beam at the exit of the PS consists of a train of 72 bunches, each of 1.1×10^{11} protons, spaced by 25 ns and with a momentum of 26 GeV/c. The longitudinal emittance at 2σ is 0.35 eVs, and the normalised rms transverse ones are 2.5 μm. Just before extraction, the bunches are compressed from ~16 to ~4 ns total ($4\sigma_z/c$) length, within about 100 turns. This is achieved by bunch rotation after a non-adiabatic increase of the RF voltage. The rotating bunches in the mis-matched bucket are ejected after one quarter of the synchrotron period, when the minimum length is reached.

An electron cloud build-up has been observed in the last turns of the PS, during this bunch compression. The electron cloud induces baseline distortions in electrostatic pick-up signals. The effect is essentially visible in the vertical plane, as illustrated in Fig. 1. The pick-up has the bandwidth 0.2-30 MHz, and it is located in a vertical dipole field region.

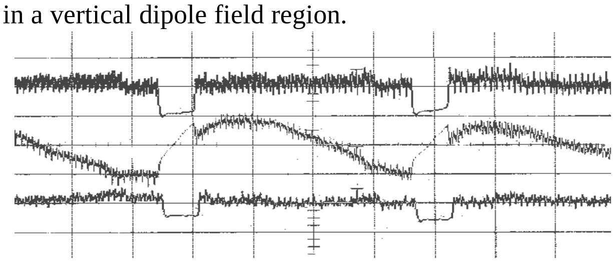

Figure 1: *Measured baseline drift in a PS electrostatic pick-up during bunch compression prior to extraction. From top to bottom, Σ, Δy, and Δx. Time scale: 500 ns/div. The 30 MHz bandwidth of the pick-up does not allow to discriminate the 4 ns bunches. The bunch train lasts 1.8 μs and the gap is 320 ns.*

2.2 In the TT2 Transfer Line Towards SPS

This effect has also been observed in the TT2 (single-pass) transfer line between PS and SPS (see Fig. 2). Here the pick-up is located in a field-free region, and its bandwidth is 0.006-400 MHz. The number of electrons pulled out of the electrostatic pick-up electrodes (on the Σ signal) is estimated as $n_e \approx 10^9$ (the capacitance is C = 500 pF and the voltage corresponding to the drift of the baseline is $V \approx 300$ mV).

Electron cloud effects seem however to lead only to instrumentation problems, as preliminary observations indicate that the beam quality is not affected. This is probably due to the fact that the time of electron cloud-beam interaction is short compared to the rise-time of a potential instability (see Section 3).

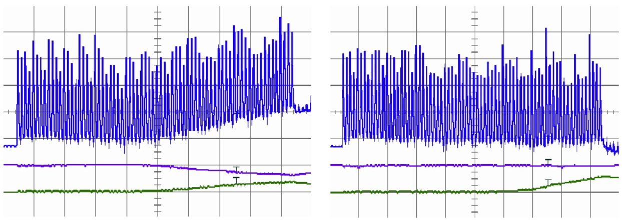

Figure 2: *Measured baseline drift in a TT2 electrostatic pick-up: solenoid OFF (left) and ON, with about 50-100 Gauss, (right). From top to bottom, Σ, Δx, and Δy. Time scale: 200 ns/div. This pick-up has a larger bandwidth than the one of Fig. 1, which allows to discriminate the short bunches. The bunch structure is not observable on Δx and Δy signals, as the beam is centred in the pick-up.*

3 COMPARISON WITH SIMULATIONS AND THEORY

3.1 Electron Cloud Build-Up

Figure 3 depicts the evolution of the electron cloud line and central densities in a PS dipole chamber, with inclusion of the elastically scattered electrons. Various proton bunch lengths are considered, representing different snap-shots during bunch compression prior to beam extraction.

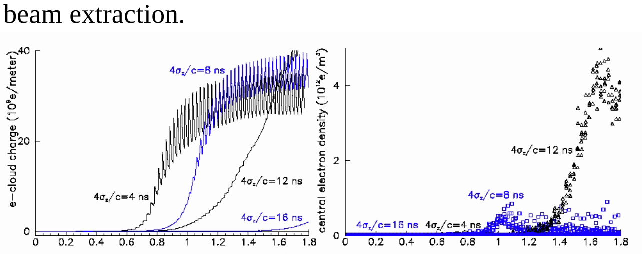

Figure 3: *Simulated evolution of electron cloud line (left) and central (right) densities in units of* m^{-1} *and* m^{-3} *respectively, as function of time during the passage of the 72 proton bunches through a PS dipole chamber. Four bunch lengths (4, 8, 12, and 16 ns) are considered, taking into account elastic electron scattering.*

The parameters used for the simulations [3], in addition to those given in Section 2, are the average transverse betatron functions $\beta_{x,y} \approx 15$ m, the vacuum chamber half height and half width, $h_x = 7$ cm and $h_y = 3.5$ cm, the maximum secondary emission yield $\delta_{\max} = 1.9$, and the incident electron energy for which the secondary emission yield is maximum $\epsilon_{\max} = 300$ eV. As in the SPS case, the primary electron production may be dominated by ionisation of the residual gas. Assuming a vacuum pressure of 10 nTorr and an ionisation cross section of 2 Mbarn, the number of primary electrons created per proton and per unit length is $d\lambda_e/ds = 0.05\times10^{-6}$ m^{-1}.

The simulations demonstrate that the electron line density grows faster, the shorter the bunch. However, the central density is highest for the intermediate bunch lengths (8 and 12 ns), and not for the shortest. This indicates that electrons once generated can be more easily "trapped" by longer bunches, which is consistent with the prediction based on over-focusing [4].

3.2 Instabilities

The threshold electron density for the strong head-tail instability is estimated as [5] $\rho_{e,th}^{TMC} = 2\gamma\, Q_s / (\pi T_0\, r_p\, c\, \beta_y)$. Here, r_p is the classical proton radius and c the velocity of light. Inserting the relativistic mass factor $\gamma = 27.7$, the synchrotron tune $Q_s = 0.0045$, and the revolution period $T_0 = 2.1$ μs, the threshold $\rho_{e,th}^{TMC} \approx 5.5\times10^{12}$ m^{-3} is obtained. It is about the maximum value of the central density found in the above simulations.

The rise-time of the conventional head-tail instability for the l = 1 mode is given, for the vertical plane, by $\tau_y^{HT,l=1} \approx 3T_0\,\eta\gamma / (64\rho_e\,\beta_y\, r_p\,\sigma_z\, Q_y')$. Inserting the slippage factor $\eta \approx 0.026$, an electron density $\rho_e \approx 10^{12}$ m^{-3}, and the chromaticity $Q_y' = \xi_y\, Q_y \approx 1$, a rise-time of about 10 ms is found.

Finally, the rise-times of the multi-bunch instability can be estimated as [6,7] $\tau_{x,y}^{MB} \approx 4\pi\gamma\, Q_{x,y} / (N_b\, r_p\, c W_{x,y}(\tau_{sep}))$, using the most critical formula for a bunch train, which is obtained for a uniformly populated ring. Here, $Q_{x,y} \approx 6.25$ are the transverse betatron tunes, N_b is the number of protons per bunch, and $W_x(\tau_{sep})$ = 5200 m^{-2} and $W_y(\tau_{sep})$ = 1500 m^{-2} denote the bunch-to-bunch wake fields (estimated from the simulations). Inserting the wake field computed after the 72nd bunch for a total bunch length of 8 ns, the approximate rise-times are 9±5 ms and 30±15 ms for the horizontal and vertical planes respectively. The case with 72 bunches of 4 ns length, and the most critical one with 84 bunches in the 84 buckets, have not been simulated successfully yet, but preliminary indications show that it could be much faster.

4 POSSIBLE CURES

4.1 Variation of Bunch Spacing

A beam with 50 ns bunch spacing was tested during 2000, but its intensity was only half the nominal one due to longitudinal instabilities. No electron cloud build-up was observed at this intensity with such a bunch spacing. This beam, with higher intensity, will be studied again in the near future.

4.2 Gaps in the Bunch Train

The evolution of the baseline drift in a TT2 electrostatic pick-up is depicted in Fig. 4, when gaps of 12 bunches (320 ns) are introduced. It shows that the electron cloud build-up remains at the end of the bunch train, wherever the gap is.

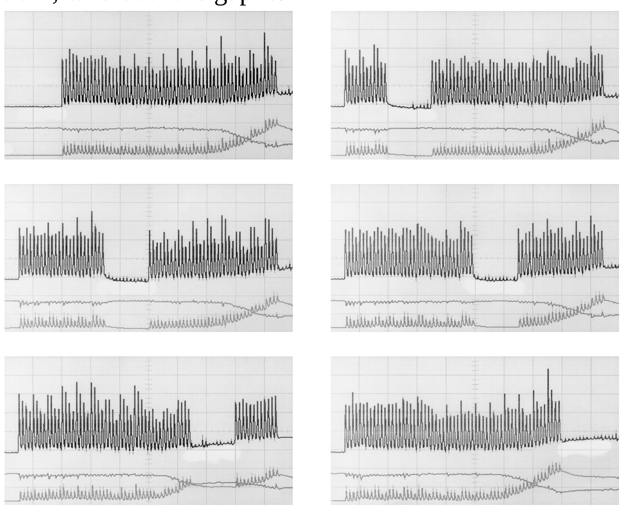

Figure 4: *Measured baseline drift in a TT2 electrostatic pick-up, with the six possible cases of 12 missing bunches (i.e. one PS-Booster ring). From top to bottom, Σ, Δx, and Δy. Time scale: 200 ns/div*.

Consistent with these measurements, simulations show that a gap of 320 ns is not sufficient to reset the memory of the electron cloud (see Fig. 5). The electron cloud density is rapidly re-established behind the gap.

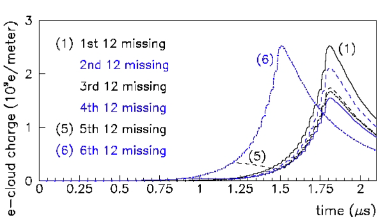

Figure 5: *Simulated evolution of electron cloud line density in unit of m^{-1}, as function of time during the passage of the bunch train through a field-free region in TT2. The six possible cases of 12 missing bunches are represented. The total bunch length is 4 ns, and elastic electron scattering is taken into account*.

Observations performed in the presence of 6 gaps of 120 ns, and the corresponding simulated case, are shown in Fig. 6. It is seen that the effect remains at the end of the bunch train, as predicted.

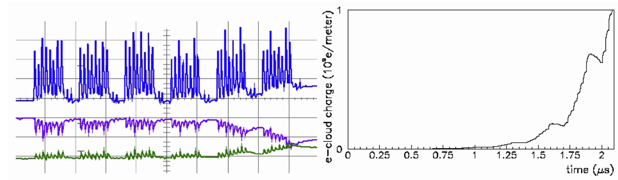

Figure 6: *(left) Measured baseline drift in a TT2 electrostatic pick-up with 6 gaps of 120 ns. From top to bottom, Σ, Δx, and Δy. Time scale: 200 ns/div. (right) Corresponding simulated electron line density*.

Finally, the case of 84 bunches, i.e. without any gap, has also been studied. It has been observed that the baseline drifts in the PS and TT2 pick-ups were more pronounced, but the beam was still stable.

4.3 Solenoidal Field

By applying a weak solenoidal field in the TT2 electrostatic pick-up, the baseline distortion could be eliminated (see Fig. 2), as predicted in Fig. 7. The effect remains, however, on the vertical signal, which may be due to the non-ideal solenoidal field created (~70 windings before and after the 25 cm long pick-up).

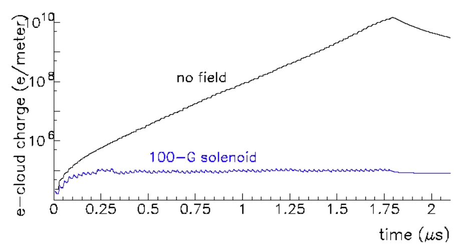

Figure 7: *Simulated electron cloud line density in a TT2 field-free region, without and with a solenoidal field of 100 Gauss*.

5 CONCLUSION

For a realistic choice of parameters, the simulations reproduce most of the PS observations with the LHC-type beam. These electron cloud effects seem to lead only to diagnostics problems as they appear at the very end of the PS cycle. The beam is then fast extracted towards the SPS in few μs, without any measurable quality deterioration.

Preliminary simulations with the PS beam for CNGS (CERN Neutrinos to Gran Sasso) [8] show that electron cloud effects will probably be a matter of concern, which should be carefully studied.

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