

# THE ELECTRON CLOUD INSTABILITY OF THE LHC BEAM IN THE CERN SPS

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## Abstract

The electron cloud induced by the LHC beam in the SPS occurs mainly in the dipoles and it is responsible for strong transverse instabilities. In the horizontal plane a coupled bunch mode instability develops in a few tens of turns at injection. Tune shift measurements, mode number and phase space analyses have been performed at different energies and provide information about the electron cloud distribution and its dynamics. In the vertical plane a single bunch head-tail like instability occurs. The equivalent ‘electron-cloud wake field’ is inferred from the analysis of the head-tail motion of the bunches of the LHC beam train.

## INTRODUCTION

Because of the large bunch population ( $N_{\text{bunch}}$ ) and of the bunch spacing the LHC beam [1][2], when injected in the SPS, induces electron multipacting for  $N_{\text{bunch}}$  higher than a given threshold ( $N_{\text{th}}$ ) depending on the secondary emission yield of the vacuum chamber. Above the multipacting threshold the following phenomena are observed when the LHC beam is injected:

- dramatic dynamic pressure increases (by more than a factor 100), mainly in the arcs, and build-up of an electron cloud along the LHC beam bunch train (72 bunches) [3];
- in the dipoles (covering 70% of the SPS circumference) the electron cloud surrounds the beam for  $N_{\text{th}} < N_{\text{bunch}} < 5\text{--}6 \times 10^{10}$  p. For larger  $N_{\text{bunch}}$  electrons concentrate in two stripes centred on the beam and parallel to the magnetic

field lines and for  $N_{\text{bunch}} > 11 \times 10^{10}$  p a third stripe centred on the beam appears [4];

- horizontal and vertical transverse instabilities [5][6].

## TRANSVERSE INSTABILITIES

The transverse instabilities developing for  $N_{\text{bunch}} > N_{\text{th}}$  start from the tail and progress to the head of the batch. For a single batch with nominal bunch population all the bunches except the first 10-15 are affected. The lower the bunch population is, the smaller will be the number of bunches affected by the instability. When more batches are injected with nominal batch spacing the instability affects a larger and larger number of bunches as we move from the first to the last (fourth) batch. These observations are compatible with the measured build-up and decay of the electron cloud density along and between successive bunch trains [3].

The properties of the instability are significantly different in the horizontal and vertical plane. In the horizontal plane it manifests itself as a coupled-bunch instability while in the vertical plane a single bunch head-tail like instability occurs [7].

### Horizontal plane

Fig. 1 shows the two most important spatial and temporal patterns of the horizontal oscillations of the batch obtained by Singular Value Decomposition of the 72 bunch positions recorded over 1000 consecutive turns for  $N_{\text{bunch}} = 3 \times 10^{10}$  p, just above the multipacting threshold [8].

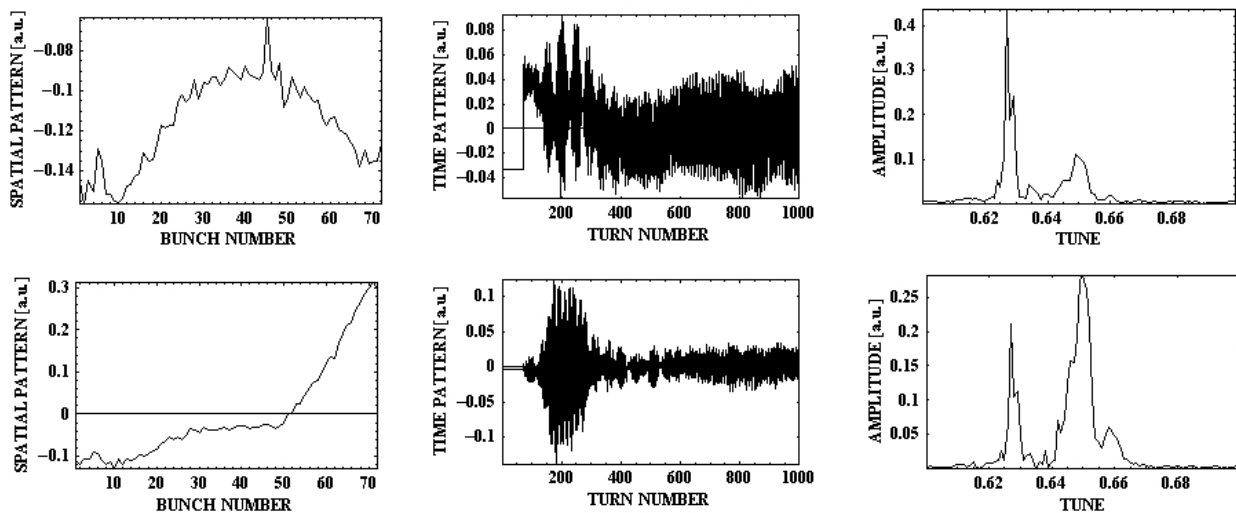


Figure 1. Two dominant spatial and temporal patterns together with the Fourier transform of the temporal patterns of the horizontal oscillation.  $N_{\text{bunch}} = 3 \times 10^{10}$  p and  $q_H = 0.18$ ,  $q_V = 0.13$ . Injection occurs 71 turns after the start of the acquisition.

Only low order coupled-bunch modes contribute to the above spatial patterns that oscillate with two main tunes:

the unperturbed fractional tune (0.627) and 0.65. The transverse feedback is designed to damp these low

frequency modes (few MHz). A “knee” is clearly visible in the second spatial pattern at about bunch 50 where the oscillations start to have significant amplitude. This corresponds with the position along the batch where the electron cloud starts to build-up.

The rise time of the instability is a few tens of turns and is only weakly dependent on the bunch population. Measurements at  $5 \times 10^{10}$  p/bunch show that the rise time is even by about 50% longer than at  $3 \times 10^{10}$  p/bunch while at the nominal bunch population ( $11 \times 10^{10}$  p) the rise time is again comparable with that measured at  $3 \times 10^{10}$  p/bunch.

At higher intensity the two well-separated frequencies of oscillation are no more visible. Measurements of the tune of each bunch as a function of its amplitude of oscillation evidence an important detuning (Fig. 2). At the nominal intensity a significant positive detuning is measured for low amplitudes ( $\sim 0.01$  in 1 beam sigma for nominal beam emittance) followed by a negative detuning. A sort of hysteresis is also observable. These are clear indications of non-linear behaviour of the coupling force between bunches in the tail of the LHC batch.

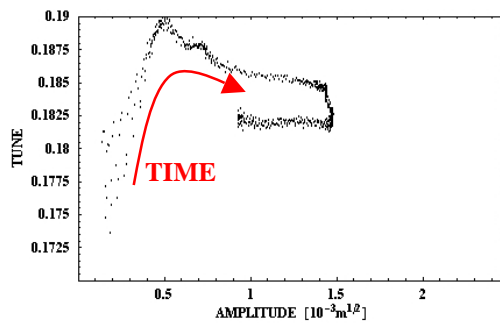


Figure 2. Tune vs. amplitude of oscillation for a bunch in the tail of the batch and  $N_{\text{bunch}}=11 \times 10^{10}$  p. This measurement was performed with the LHC beam high intensity working point ( $q_H=0.18$ ,  $q_V=0.13$ ). The data for the first 700 turns after injection are plotted (each point represents a sliding average over 32 turns of the amplitude and phase advance per turn).  $\beta_H \sim 21$  m at the monitor.

The characteristics of the electron cloud instability in the SPS are a consequence of the fact that multipacting mainly occurs in the arcs. In a dipole field electrons are bouncing up and down in the vacuum chamber and are tightly bound to the magnetic field lines around which they spiral. For the lower intensities ( $N_{\text{th}} < N_{\text{bunch}} < 5-6 \times 10^{10}$  p/bunch) the electron cloud can be approximated as a vertical ribbon of uniform density developing along the batch and starting from a given bunch  $n$ . Any transverse movement of the bunch, or of a slice of it, affects the electron cloud distribution which, in turn, affects the trailing bunches, or trailing slices, generating bunch-to-bunch or head-tail coupling. Due to the presence of the magnetic field no net horizontal motion is imparted to the electrons during the bunch passage. Consequently no significant distortion of the electron cloud distribution

occurs in the horizontal plane during the bunch passage and the electron cloud can couple only subsequent bunches. When a bunch has a horizontal displacement with respect to the preceding one, it will go through the electron cloud ribbon off-centre and will experience a linear force  $F$  (in the approximation of a uniform electron cloud distribution with density  $\rho_{ec}$ ) [7]:

$$F = -\frac{e\rho_{ec}}{\epsilon_0}(x_{j+1} - x_j)\chi(j-n)$$

where  $x_j$  and  $x_{j+1}$  are the horizontal positions of bunch  $j$  and  $j+1$ , respectively and  $\chi$  is the step function. The strength of the electron cloud coupling does not depend directly from the bunch population but only indirectly via  $\rho_{ec}$  which depends on  $N_{\text{bunch}}$ . In general the range of the coupling due to the electron cloud can be longer than the bunch spacing and one bunch can couple to more than one trailing bunch. The behaviour of the 72 bunches can therefore be described by a set of coupled linear differential equations of second order. The solution of such a system, including terms approximating the effect of the resistive wall wake, allows determining the most unstable modes. A tune shift of  $+0.025$  (with respect to the unperturbed tune) and a growth time of 60 turns are estimated assuming that the electron cloud has a density  $\rho_{ec}=1 \times 10^{12}$  e/m<sup>3</sup> and develops after 50 bunches (as observed experimentally for  $N_{\text{bunch}}=3 \times 10^{10}$  p). This is in good agreement with the observations.

For  $N_{\text{bunch}} > 5 \times 10^{10}$  p the electron cloud distribution takes the form of two stripes symmetrically placed with respect to the beam and the uniform approximation is no longer valid, except for small amplitudes where the electron cloud density is nevertheless reduced as compared to the lower intensity case. This explains why the growth time for  $N_{\text{bunch}}=5 \times 10^{10}$  p is longer than that measured for  $N_{\text{bunch}}=3 \times 10^{10}$  p. Significant detuning with amplitude is expected for oscillation amplitudes comparable with the electron stripe half-separation (few mm for the  $N_{\text{bunch}}=5 \times 10^{10}$  p). The non-linear behaviour is exacerbated for the nominal bunch intensity where an additional central stripe appears.

The growth rate of the instability has been measured at different energies and decreases almost linearly with the momentum of the beam. This is in good agreement with the simple model described above.

### Vertical plane

In the vertical plane the electron cloud instability is a single bunch instability: a measurement of the position of the bunches of the batch over several turns does not show any phase correlation among subsequent bunches. The instability mainly affects the tail of the batch and the rise time is decreasing with increasing  $N_{\text{bunch}}$  (the maximum amplitude of oscillation is achieved in  $\sim 600$  turns for  $N_{\text{bunch}}=3 \times 10^{10}$  p and in 300 turns for  $5 \times 10^{10}$  p). Several sidebands are visible close to the main tune line with separation close to the synchrotron frequency  $Q_s \sim 0.004$  indicating the head-tail nature of the instability. The comparison of the spectra of the signals provided by a

wide-band strip-line coupler for a bunch of the head and one of the tail of the batch reveals vertical motion inside the bunch at frequencies of about 700 MHz (full bunch length = 4 ns) particularly enhanced in the trailing bunch as a result of the electron cloud.

The difference with respect to the horizontal plane is due to the fact that in the vertical plane the motion of the electrons under the influence of the electric field of the bunch is not constrained by the presence of the magnetic field as for the horizontal plane. For that reason any motion of the head of the bunch will couple to the tail similarly to what a short-range wake field does.

Electrons are pinched during the bunch passage and the density of the cloud in the region traversed by the bunch is significantly enhanced. The density evolution of the electron cloud with time depends strongly on the bunch population and this explains the dependence of the growth rate of the instability on the bunch population.

Because of the strong electron cloud density modulation during the bunch passage the effect is very different from that of conventional wake fields, the electron cloud wake depends strongly on the position along the bunch from where it is excited and cannot be expressed simply in the form  $W(z_s - z_w)$ , where  $z_s$  and  $z_w$  are the longitudinal positions of the source and witness particles, respectively [9][10].

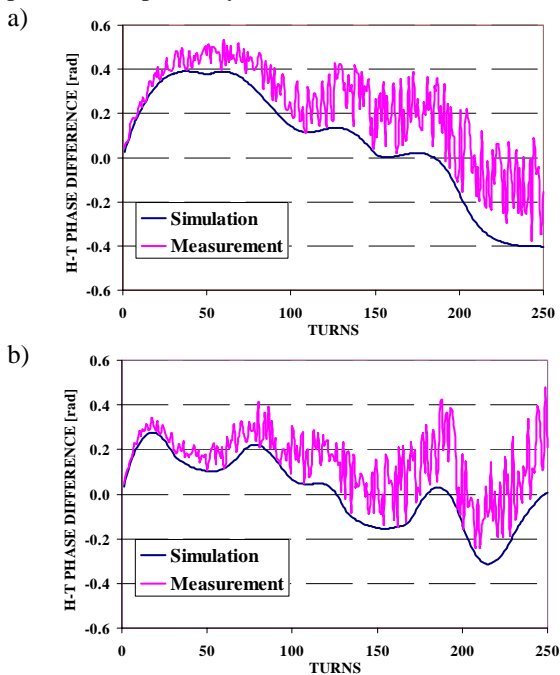


Figure 3. Calculated and measured head-tail phase difference for a bunch of the head (a) and a bunch of the tail (b) of the LHC batch [7].

Within this approximation an effective wake field associated with the electron cloud can be inferred by comparing the head-tail phase difference evolution with time for a bunch with and without electron cloud. Fig. 3 presents such a comparison for a bunch of the head of the

batch (no electron cloud) and a bunch of the tail (electron cloud).

The measurement can be reproduced if a wake field with interaction length 0.3 to 0.5 times the bunch length is introduced to model the electron cloud head-tail coupling.

Simulations taking into account the interaction of electron cloud with the beam [9] and simple head-tail models based on the effective electron cloud wake seem to indicate that the electron cloud enhances the effects of the machine impedance and that the combination of the electron cloud and impedance wake is responsible for the fast growth rate of the vertical instability.

Simulations confirm also the beneficial effect of high positive chromaticity to fight the vertical instability as observed experimentally [9].

## SUMMARY

In the SPS the different behaviour of the electron cloud instability of the LHC beam in the horizontal and vertical planes is a consequence of the confinement of multipacting in the dipoles. In the horizontal plane low order coupled bunch instabilities are observed and can be cured by the transverse feedback. In the vertical plane a single bunch head-tail instability develops as a result of the interplay of the electron cloud and of the machine impedance, coupling the motion of the head and the tail of the bunch. The only cure found so far is running at high positive vertical chromaticity ( $\xi = (\Delta Q/Q)/(\Delta p/p) > 0.1$ ).

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