THE ELECTRON CLOUD INSTABILITY IN THE SPS

K. Cornelis, CERN, Geneva, Switzerland

ABSTRACT

The beam-induced electron multi-pacting, which is created by the LHC beam in the SPS, occurs mainly in the dipoles. It creates a vertical electron ribbon, which is responsible for strong transverse instabilities. In the horizontal plane a coupled bunch mode instability could be identified. Tune shift measurements and mode number analyses can tell us something on the electron cloud density and the electron survival time. In the vertical plane a single bunch head-tail like instability occurs. A method is described by which we can estimate an equivalent impedance, created by the electron cloud.

1 OBSERVATIONS

In the SPS the e-cloud is mainly created in the dipoles. This can be seen from the vacuum pressure rise in the ion pumps and vacuum gauges, which is only observed in the arcs and not in the straight sections. The instability starts somewhere from bunch number 15 to bunch number 30, depending on the bunch intensity. For high bunch intensities the instability starts earlier in the batch.

The characteristics of the instability are quit different in both planes. In fig. 1 and 2 for example, one can see a snapshot over one turn of the position of the first 48 bunches in the batch. In fig. 1, which is the horizontal plane, the instability starts after some 400 nsec i.e. 16 bunches and it looks like slow wave over more than 20 bunches. In the vertical plane, the instability starts also after ~16 bunches but there is no apparent phase correlation between subsequent bunches.

The two dimensional plots in fig. 3 summarise the main observations on the instability in both horizontal and vertical plane. The first two pictures on the top show the oscillation amplitude as function of bunch number and turn number. One can see that the horizontal oscillation sets on after only 50 turns, whereas in the vertical plane it takes about 500 turns. These pictures were taken for a bunch intensity of $3\ 10^{10}$, just above the threshold. For bunch intensity twice as high, $6\ 10^{10}$, the horizontal rise time stays the same (50 turns), but the vertical rise time reduces to 100 turns.

The second row of plots shows the tune as a function of the bunch number. In the horizontal plane one can see a second distinct tune line appearing as from bunch number ~16, i.e. the bunches which are sitting in the cloud. The second line is 0.03 higher in tune than the first one.

In the vertical plane the tune line widens for the bunches that are sitting in the cloud. Detailed spectra show several synchrotron sidebands around the main tune line.

The two bottom pictures show a two dimensional FFT. It shows the betatron tunes in one dimension and the frequency of the oscillation inside the batch. These plots confirm what is suggested by the snapshots in fig. 1 and 2. The horizontal instability shows up like a low frequency inside the batch, i.e. a coupled bunch instability of low order. The vertical mode spectrum looks like a white spectrum, covering the whole frequency range, suggesting a non-correlated motion between the bunches. In the vertical plane the motion looks like a single bunch instability.

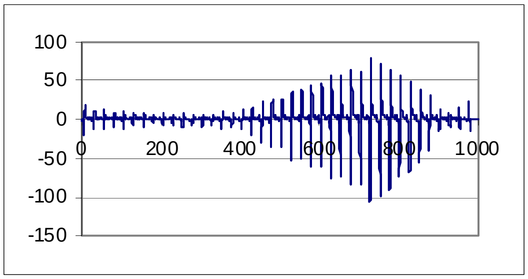


Fig. 1: snapshot of the horizontal position of the first 48 bunches in the batch when the instability is present.

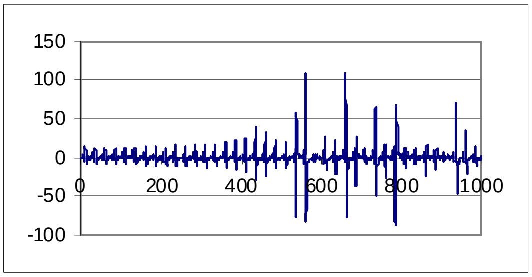


Fig. 1: snapshot of the vertical motion of the first 48 bunches in the batch when the instability is present.

We can summarise the observations as follows:

- In the Horizontal plane the e-cloud provokes a fast growing coupled bunch instability of low order. Growth rate is ~50turn. Does not change with intensity.
- In the vertical plane the instability looks like single bunch instability Growth rate: ~500 turns just above threshold going to ~100 turns at two times the threshold.

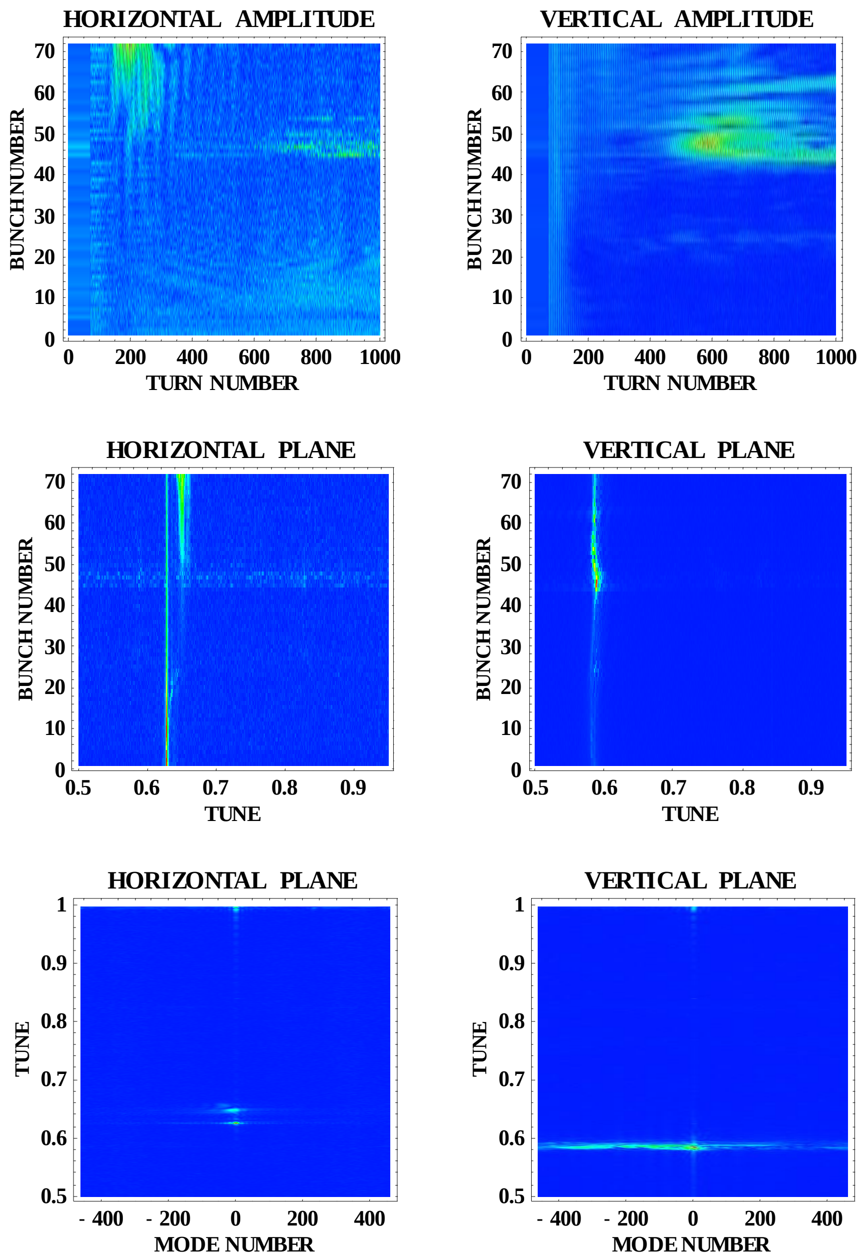


Fig. 3 Two-dimensional plots showing the main characteristics of horizontal and vertical instabilities. The top row shows the oscillation amplitude as function of turns and bunch number. The middle shows the tune versus bunch number and the bottom shows the mode number inside the batch.

1 THE HORIZONTAL INSTABILITY

The difference between horizontal and vertical behaviour comes from the fact that the electron cloud is created in the dipoles. The combination of a vertical magnetic field and the flat vacuum chamber makes that the electrons are mainly bouncing up and down, spiralling around the magnetic field lines, creating a vertical ribbon at the position of the bunches. It is this behaviour, which creates a coupling mechanism between subsequent, bunches in the horizontal plane. When a bunch passes at a different horizontal position than the previous ones, it will go off-centre through the electron cloud and experience a force proportional to the displacement (fig. 4).

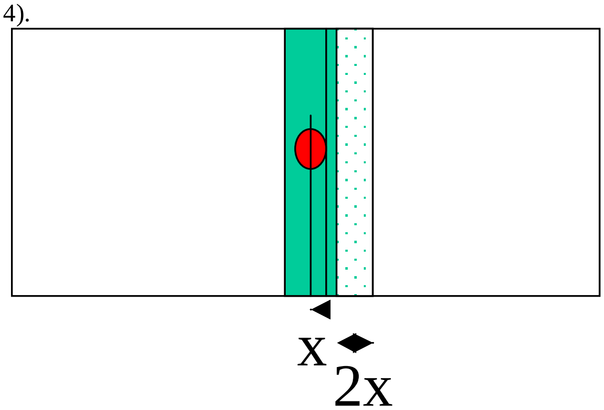


Fig. 4: the force on a bunch displaced by x is equal to force from a slice of the ribbon with thickness 2x (the light green part). The forces in dark green part cancel out because of symmetry.

In a linear approximation the horizontal force of the e/cloud can be expressed as:

$$F = -\rho e.(X_{n+1}-X_n)/2\varepsilon_0$$

With ρ the electron density, Xn the horizontal position of the nth bunch.
The behaviour of the 72 bunches in a batch can be expressed in the following set of coupled oscillators:

$$X_1'' + \omega_\beta^2 X_1 = 0$$

$$\vdots$$

$$X_n'' + \omega_\beta^2 X_n = 0$$

$$X_{n+1}'' + \omega_\beta^2 X_{n+1} = -k(X_{n+1} - X_n)$$

$$\vdots$$

$$X_{72}'' + \omega_\beta^2 X_{72} = -k(X_{72} - X_{71})$$

ω_β being the betatron frequency. The first n bunches see no electron cloud and they behave like uncoupled oscillators. As from the n+1th bunch there is a coupling via the electron cloud with the previous bunch. This degenerate system gives two eigen-frequencies (Ω) given by:

$$(\Omega^2-\omega_\beta^2)^n(\Omega^2-\omega_\beta^2-k)^{72} = 0$$

One mode is the unperturbed betatron frequency. This is the mode where all bunches move in phase with the cloud. The second mode has a slightly higher frequency and it corresponds to the modes where bunches move with a different phase.
The corresponding tune shift can be calculated from the force exercised by the cloud:

$$dP/dx = dt\ dF/dx = \rho e.ds/\varepsilon_0 c$$

P is the transverse momentum, s de longitudinal coordinate and c the speed of light. The normalised kick can be written as:

$$k = dP/dsdxP = \rho e/\varepsilon_0 cP$$

Expressing P in eV/c this becomes for the SPS energy of 26GeV:

$$k = \rho/\varepsilon_0 26\ 10^9$$

The corresponding tune shift is then:

$$\Delta Q = \rho\{\beta\}L/\ \varepsilon_0 26\ 10^9$$

with L the total length of the dipoles in the SPS.

3 THE VERTICAL PLANE

In the vertical plane things look quit different. During the bunch passage, the electrons are accelerated in the vertical plane towards the centre of the bunch. Some electrons are even trapped inside the bunch leading to an increased electron density inside the bunch [1]. Fig. 5 and 6 show the different behaviour of the electron phase space during the bunch passage. In the horizontal plane (fig.5), the dynamics is completely dominated by the magnetic field creating a cyclotron motion. The bunch passage has no influence on the phase space density. In the vertical plane however (fig 6) there is a build up of electron density inside the bunch. This phenomenon creates a coupling between the head and the tail of the bunch. When the tail passes at a different vertical position as the head, it will experience a force from the displaced electron density. This creates the same coupling mechanism as a wake field, leading to head tail instability. However, there are two major differences with the normal wake field: the longitudinal dependence of the force can not be written as a greens function and the frequency content of the "electron-wake" changes with the bunch intensity. For higher bunch currents the electrons impinge much faster (fig 7)

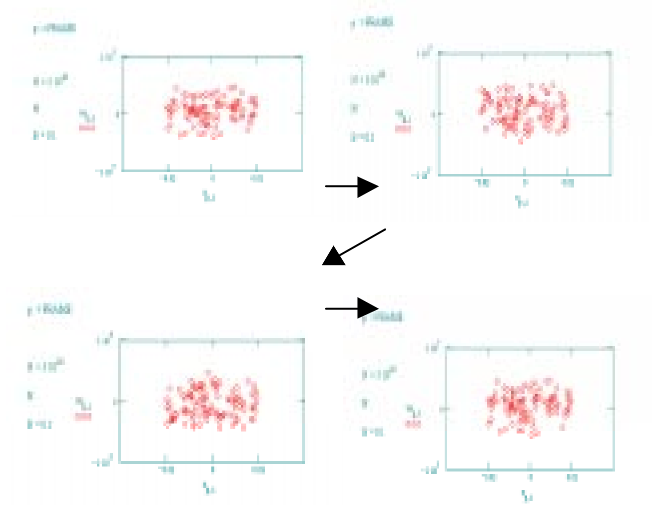


Fig. 5: Evolution of the electron phase space during the bunch passage in the horizontal plane.

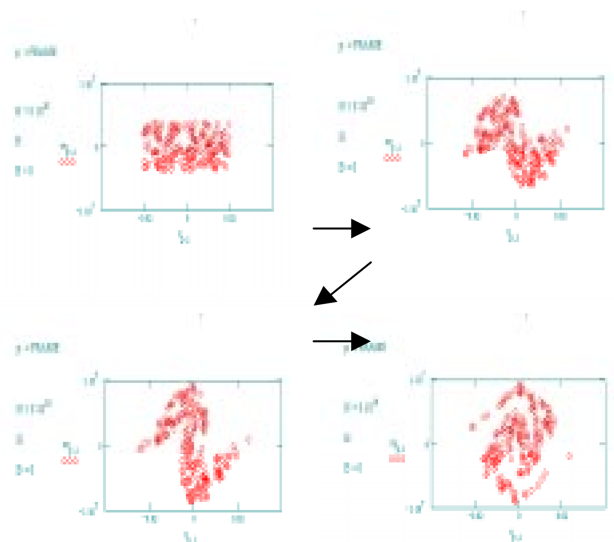


Fig. 6: Evolution of the electron phase space during the bunch passage in the vertical plane.

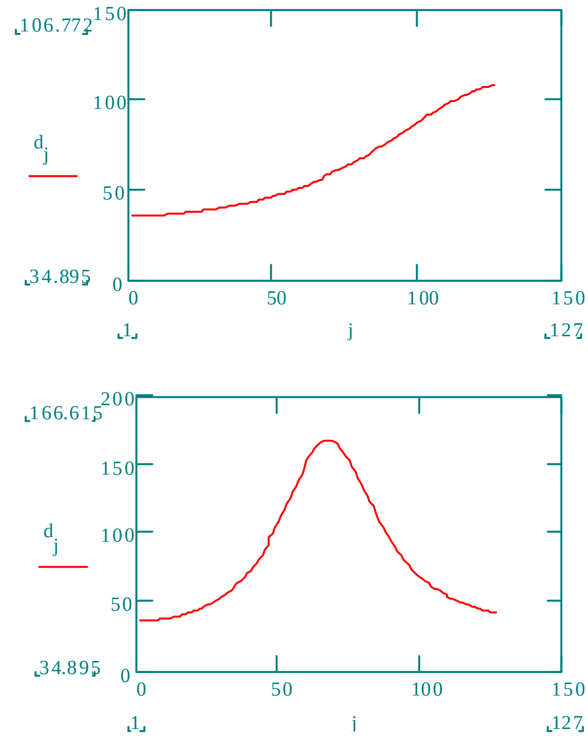


Fig. 7: Evolution of the vertical electron cloud density during the bunch passing. The top is for a bunch intensity of 2.5 10^{10}, the bottom for 8 10^{10}.

If there is something like an equivalent vertical impedance, created by the electron cloud, can we measure it? For this one has to measure de effect of the impedance on an individual bunch inside the cloud. A technique, which can be used, is to look at the betatron phase evolution over one synchrotron period (fig 8) after a vertical kick [2].

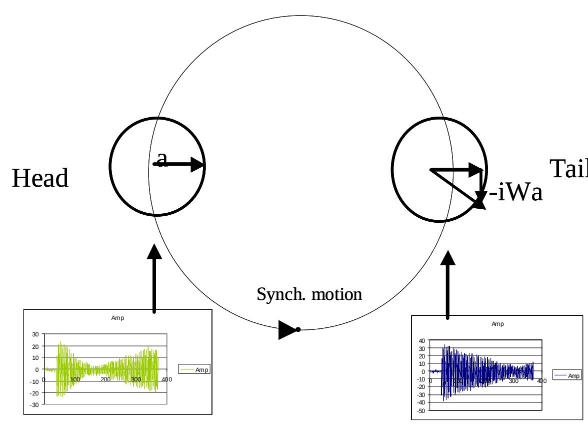


Fig. 8: The wake field W creates a phase advance for the tail depending on the position of the head. Following the phase evolution of head and tail over a synchrotron period can give details about W.

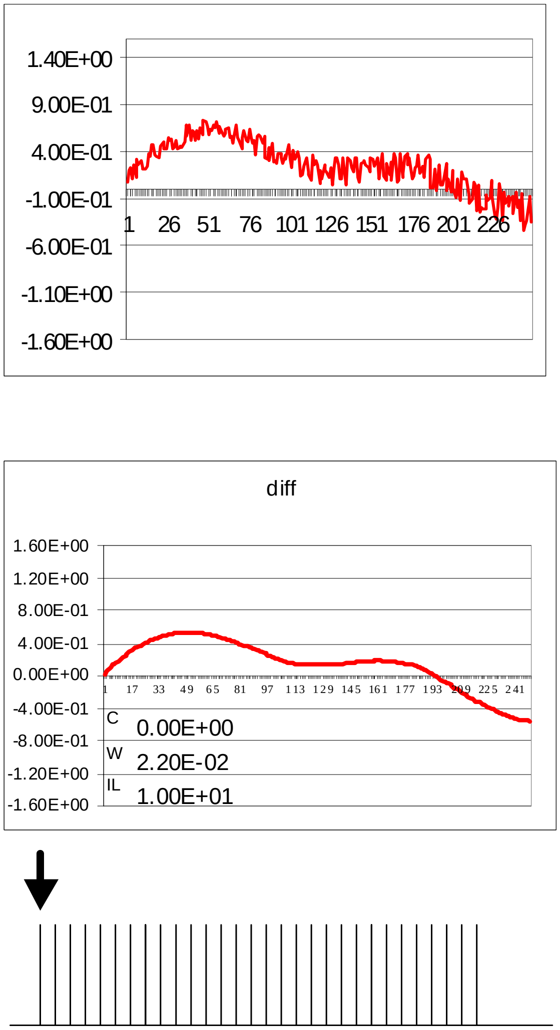


Fig 9: Calculated (bottom) and measured (top) head-tail phase advance difference for the first bunch.

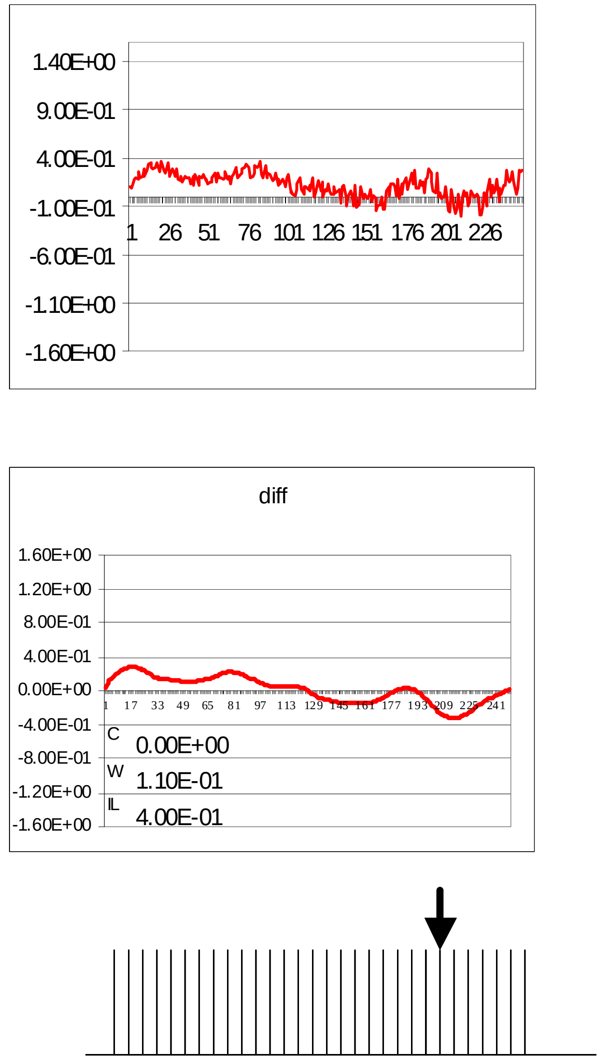
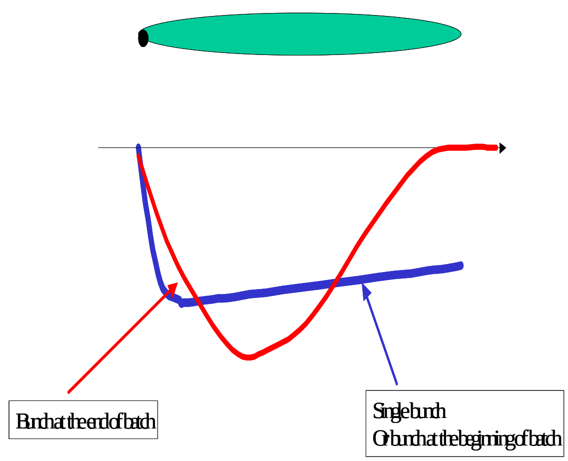


Fig 10: Calculated (bottom) and measured (top) head-tail phase advance difference for a bunch. Sitting in the e-cloud



In fig. 9 de result of such a phase measurement is presented. What is shown is de evolution of the phase difference between head and tail over one synchrotron period and this for the first bunch of the train. The bottom picture shows a calculation of this phase difference using a long wake field, i.e. longer than the bunch.

In fig 10 de same measurement is shown, but for a bunch sitting in the cloud. In order to be able to recalculate the measured data a wake field is needed with a shorter interaction length (0.3 t0 0.5 times the bunch length). This leads to a picture of the wake field as shown in fig 11.

Fig 11: Picture of the equivalent wake field, created by the electrons (red), compared to the machine impedance (bleu).

4 CONCLUSIONS

- In the SPS the electron cloud is created in the dipoles.
- It results in a fast, horizontal coupled bunch instability of low order that can be cured by the existing feedback.
- The vertical instability is of single bunch nature (higher head tail mode). The growth rate depends on intensity.
- The equivalent short wake, created by the electrons could be measured.

REFERENCES

[1] G. Rumolo, *Theory and simulation of electron-cloud instabilities*, proceedings of the 11th Chamonix workshop, CERN, 2001.

[2] K. Cornelis, *SPS measurements of electron cloud impedance*, proceedings of the 11th Chamonix workshop, CERN, 2001.