ELECTRON CLOUD BUILD UP AND INSTABILITY: COMPARISON BETWEEN OBSERVATIONS AND NUMERICAL SIMULATIONS FOR THE CERN PS

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Abstract

Experimental observations on the electron cloud have been collected at the CERN PS machine throughout the last two years. At the same time, an intense campaign of simulations has been carried out to understand the observed electron cloud build-up and the related instability. The results of the numerical simulations are presented in this paper and discussed in detail.
Abstract

Experimental observations on the electron cloud have been collected at the CERN PS machine throughout the last two years. At the same time, an intense campaign of simulations has been carried out to understand the observed electron cloud build-up and the related instability. The results of the numerical simulations are presented in this paper and discussed in detail.

1 INTRODUCTION

Gas ionization and electron multiplication due to the secondary emission process on the inner side of the beam pipe may induce the build-up of an electron cloud, which can significantly degrade the performance of rings operating with closely spaced proton or positron bunches. The undesired electron cloud causes pressure rise and beam instability when the parameters are pushed above certain thresholds [1].

In the case of the CERN PS machine, the electron cloud has been observed since the year 2000 for LHC-type bunch trains (72 bunches of $1.1 \times 10^{11}$ p/b spaced by 25 ns). The baseline drift produced by the electron signal at the pick-up electrodes has given evidence of the presence of electrons in large amount inside the beam chamber [2]. To see the degrading effects of the electron cloud on the machine performance, measurements have been carried out with the LHC beam stored in the PS at high-energy for a longer time (see Ref. [3] for more details on the beam manipulations applied). More data have been recorded concerning not only the build-up process but also the induced instability [3]. The main experimental observations on the electron cloud driven instabilities in the PS can be summarised as follows. The instability manifests itself as a single-bunch phenomenon which sets in above an intensity threshold of about $4 - 5 \times 10^{10}$ p/b and is especially evident in the horizontal plane. Its rise-time $\tau$ is about $3 - 4$ ns and it causes a transverse emittance growth which can be as large as a factor 10 or 20 in the horizontal plane and 2 in the vertical plane.

The two codes developed at CERN, ECLOUD and HEADTAIL (see [4] for details), can simulate both the build-up process of the electron cloud and its expected effect on the single bunch that passes through it [1, 5, 6, 7]. This paper reports on the results of numerical simulations carried out with these two codes.

Section 2 gives a short description of the PS lattice and its main magnets. Section 3 is devoted to results of build-up simulations for both dipole and field-free regions of CERN PS, considering different bunch intensities and lengths. Using the saturation value of the cloud density as obtained in Section 3, a full instability study via computer simulations is presented in Section 4. Emphasis is put on the expected dependency of the unstable evolution on key parameters like bunch intensity, chromaticity and bunch length. Simulations for field-free regions are compared with those for a combined function magnet. Finally, conclusions are drawn in Section 5.

2 PS LATTICE AND MAIN MAGNETS

The PS lattice consists of ten super-periods each made of ten combined function magnets 4.26 m long, interlaced with eight 1.0 m and two 2.4 m drift spaces [8]. Every magnet is composed of two half-units with gradients of opposite sign, separated by a central junction. Each half-unit is made of five blocks with small gaps in between. Additional field adjustment can be made using the three currents of the pole-face winding and figure-of-eight-loop devices located on the magnet poles. These additional current loops allow controlling the machine tunes and chromaticities. The outline of the PS magnet unit in the extraction region is shown in Fig. 1.

The latest PS magnetic field measurements using Hall probes were undertaken in 1992 [9] for different operational settings of the currents in the main coil, pole-face and figure-of-eight-loop windings. The measurements have been carried out in the median plane of the laboratory test PS magnet unit U17 composed of an open half-unit followed by a closed half-unit. The resulting vertical field component data, including measurements of the central field, the end and lateral stray fields, and the field in the junction between the two half-units, produced a discrete 2D field map [9].

The measurements were carried out in a Cartesian coordinate frame. The longitudinal $z$-axis coincides with the magnet axis and its orientation is given by the direction of motion of the protons (see Fig. 1). The radial $x$-axis coincides with the mechanical symmetry axis and it points towards the exterior of the PS ring (see Fig. 1). In this reference system a regular mesh is defined and for each point in the mesh, the value of $B_y$ has been measured in the median plane. The step size is $20$ mm along the longitudinal $z$-axis and $10$ mm along the radial $x$-axis. The mesh extends from $-2.55$ m to $2.73$ m and from $-70$ mm to $310$ mm in the
Figure 1: PS magnet unit 16. This unit is located just downstream of the extraction septum. The overall layout is shown in the upper part. The vacuum pipes for the circulating beam as well as that for the extracted one are visible. The two cross sections of the entry face (with open gap) and exit face (with closed gap) of the magnet are also shown on the left and right respectively.

The fitted 2D field map for the 26 GeV/c working point is shown in Fig. 2 (see Ref. [10] for more details). This field can, in first approximation, be modelled as

\[ B_x = \pm G y \]

\[ B_y = B_{y0} + G x \]  \hspace{1cm} (1)

with values for \( B_{y0} \) and \( G \) given in Table 1.

3 ELECTRON CLOUD BUILD-UP IN CERN PS

The simulation algorithm used in the ECLOUD code has already been discussed in great detail in previous papers (for instance, see [5] for the most up-to-date description). By simulating residual gas ionization and secondary emission at the chamber walls, including elastic reflection of low-energy electrons, the code can predict whether a high density electron cloud is expected to form during the passage of a closely spaced bunch train. To simulate the PS straight sections and dipole chambers, parameters from Table 1\(^1\) have been used. In the build-up simulations, the gradient component has been neglected as this is not expected to affect the build-up process significantly. This point has to be confirmed by additional numerical simulations.

Figure 3 depicts the evolution of the electron line densities in a PS dipole chamber without (upper) and with (lower) inclusion of the elastically back-scattered electrons. Various bunch lengths are considered, representing different snap-shots during bunch compression prior to beam extraction (the bunches in the PS are compressed by a factor 4, from 16 ns to 4 ns within 100 turns). The simulation demonstrates that the electron line density grows faster the shorter the bunch, and that there is no electron cloud build-up for the initial bunch length of \( 4 \sigma_z / c = 16 \) ns.

Comparing Fig. 3 (upper) and (lower), we further notice that with the elastically back-scattered electrons included,

Table 1: PS parameters used in the simulations. As far as the beam emittance is concerned, the rms physical value is quoted here.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>628 m</td>
</tr>
<tr>
<td>Relativistic factor ( \gamma )</td>
<td>27.7</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>72</td>
</tr>
<tr>
<td>Bunch spacing (( T_{sep} ))</td>
<td>25 ns</td>
</tr>
<tr>
<td>Bunch population (( N_b ))</td>
<td>( 3 \times 10^{10} ) protons</td>
</tr>
<tr>
<td>Trans. rms-sizes (( \sigma_{x,y} ))</td>
<td>1.2 - 2.4/1.2 mm</td>
</tr>
<tr>
<td>Chamber half-aperture (( x ))</td>
<td>70 mm</td>
</tr>
<tr>
<td>Chamber half-aperture (( y ))</td>
<td>35 mm</td>
</tr>
<tr>
<td>Maximum SEY (( \delta_{max} ))</td>
<td>1.9</td>
</tr>
<tr>
<td>( E_{max} )</td>
<td>300 eV</td>
</tr>
<tr>
<td>Tunes (( Q_{x,y,s} ))</td>
<td>6.25/6.25/0.0015</td>
</tr>
<tr>
<td>Bunch rms-length (( \sigma_z ))</td>
<td>0.3 - 1.2 m</td>
</tr>
<tr>
<td>Aver. beta functions (( \beta_{x,y} ))</td>
<td>16 m</td>
</tr>
<tr>
<td>Rms-energy spread</td>
<td>1.75 - 7 \times 10^{-4}</td>
</tr>
<tr>
<td>Mom. compaction (( \alpha ))</td>
<td>0.027</td>
</tr>
<tr>
<td>Chromaticities (( \xi_{x,y} ))</td>
<td>up to 0.5 in both planes</td>
</tr>
<tr>
<td>Dipole field (( B_{y0} ))</td>
<td>1.256 T</td>
</tr>
<tr>
<td>Field gradient (( G ))</td>
<td>5.2 T/m</td>
</tr>
<tr>
<td>( T_{rev} )</td>
<td>2.2 ( \mu )s</td>
</tr>
</tbody>
</table>

\(^1\)The horizontal emittance is in reality constant, but the horizontal rms-size is swept through the given range in order to account for dispersion and the different energy spreads.
the simulated equilibrium electron line densities are a factor $3 - 4$ higher than without. Perhaps more surprisingly, the central density is highest for intermediate bunch lengths (not shown, but see Ref. [2]), and not for the shortest. This indicates that electrons, once generated, can be more easily trapped by the potential produced by longer bunches.

Furthermore, the build-up has been simulated at different currents, to identify a possible intensity threshold. Figure 4 shows the averaged cloud density evolution corresponding to different bunch intensities from $3 \times 10^{10}$ to $1.1 \times 10^{11}$ (for a 4 ns long bunch). While the cloud rise-time does not appear to be much affected by this parameter (after the passage of about 40 bunches, corresponding to 1 $\mu$s, the cloud has in all cases already reached saturation), the saturation value tends to decrease with increasing current (from $10^{12}$ m$^{-3}$ for $N_b = 3 \times 10^{10}$ to about $5 \times 10^{11}$ m$^{-3}$ for $N_b = 1.1 \times 10^{11}$). It is worthwhile noting that these transverse averaged values correspond to much higher values of the central density, because the electron cloud is initiated by residual gas ionization and stays therefore mostly localised around the beam due to dipole field confinement. Because of the stripe-like distribution, the central densities can reach values between 2 and 20 times larger than the transverse averaged densities. The influence of this non-uniform distribution of the electron cloud in the pipe cross-section has not been taken into account in the instability simulation of next Section.

The difference between the build-up in a field-free region and inside a strong dipole is shown in Fig. 5: the electron cloud builds up more rapidly in a dipole but saturates around a value which is about two thirds of that reached in a field-free region.

![Figure 3: Electron cloud build-up in a PS dipole for different bunch lengths and without (upper) and with (lower) elastic reflection of the electrons.](image)

![Figure 4: Electron cloud build-up in a PS dipole for different bunch intensities. The electron cloud reaches saturation after the passage of about 40 bunches.](image)

![Figure 5: Electron cloud build-up inside a PS dipole and in a PS field-free region.](image)

### 4 SIMULATION OF THE ELECTRON-CLOUD INDUCED SINGLE-BUNCH INSTABILITY IN CERN PS

The electron cloud driven single-bunch instability in the PS has been studied using the HEADTAIL code. As input for these simulations we have assumed an electron cloud density of about $2 \times 10^{12}$ m$^{-3}$, consistent with the central density values given by the simulations described above. Instability simulations were originally performed in field-free regions to explore whether the parameters were in the...
correct range to excite the electron cloud instability. The combined function magnetic field configuration was introduced only in a second stage.

Scans with different bunch intensities, chromaticities and bunch lengths have been made in order to isolate the dependence of the instability on each of these parameters. If not mentioned otherwise, the rms bunch length has been set to 2.5 ns (0.75 m), which is the value for which an instability at the PS was observed and monitored. The chromaticity is zero in both planes.

We first evaluate the expected oscillation frequency of the electrons very close to the bunch transverse centre, and therefore the number of oscillations that they perform during one bunch passage. These values for a field-free region can be computed according to [11]:

\[
\omega_{ex} = \sqrt{\frac{N_b r_e e^2}{2 \sigma_{x(y)} \sigma_z (\sigma_x + \sigma_y)}}.
\] (2)

Equations (2) and (3) yield \( \omega_{ex} = 2 \pi \times 195 \) MHz and \( \omega_{ex} = 2 \pi \times 225 \) MHz, \( n_x = 1.95 \) and \( n_y = 2.26 \) for a PS bunch of \( N_b = 4 \times 10^{10} \) p/b. Figure 6 shows horizontal and vertical wake functions computed from the transverse field on the beam axis by displacing the bunch head (longitudinally located at \( z = 0 \); the bunch centre is at \( -2 \sigma_z \)). The shape of the wake functions considerably changes if the displacement occurs at a different location along the bunch profile [5]: in Fig. 7 the wake functions are plotted for an offset located at \( -4/3 \sigma_z \) (i.e., after one third of the full bunch has already gone through the cloud). The period with which the wake functions oscillate corresponds to the period of oscillation of the electrons in the linear range of the beam force.

Figure 8 shows the horizontal (upper) and vertical (lower) emittance growth over 3000 turns for different bunch intensities. The rise-time of the instability is always on the order of a few milliseconds, spanning between 1.5 ms for the highest intensity (\( N_b = 1 \times 10^{11} \) p/b) and about 5 ms for the lowest (\( N_b = 3 \times 10^{10} \) p/b). It is worthwhile pointing out that in this paper the rise-time is defined in terms of emittance growth due to electron cloud over 3000 turns for different bunch intensities.
growth and not in terms of beam-size increase. The instability appears equally in both planes. Nevertheless, a threshold for the onset at about $N_b = 3 \times 10^{10}$ p/b is more pronounced in the vertical plane.

Figure 9 shows the expected emittance growth for a bunch with $N_b = 4 \times 10^{10}$ p/b and for different values of (positive) chromaticity. From the pictures it appears clearly that a positive chromaticity larger than 0.3 in $\xi = Q'/Q$ can efficiently cure the degrading effect of the electron cloud. In both planes the instability growth time decreases for values of $\xi$ up to 0.25, and finally the bunch becomes stable for higher values. At higher current ($N_b = 8 \times 10^{10}$ p/b), chromaticity can still reduce the instability, but a significant emittance growth can be observed even when $\xi$ approaches 0.5 (see for instance Fig. 10).

The effect of bunch length has been studied by using two different approaches. The first one, which better reproduces what can be actually done on the machine, consists in re-matching the bunch longitudinally each time by keeping the longitudinal emittance constant, and therefore multiplying the synchrotron tune by the square of the ratio $\sigma_{\text{old}}/\sigma_{\text{new}}$. Following this re-matching procedure, we find that for low current, the bunch length $\sigma_{\text{old}} = 0.75$ m is right at the limit of the region where the instability sets in (see Fig. 11): shorter bunches are in fact stable. For higher current ($N_b = 8 \times 10^{10}$ p/b), the threshold is pushed a little lower, as shown for example in Fig. 12. As the synchrotron

Figure 9: Horizontal (upper) and vertical (lower) emittance growth over 3000 turns for different chromaticities and $N_b = 4 \times 10^{10}$ p/b. This current value is slightly above the instability threshold.

Figure 10: Vertical emittance growth over 3000 turns for different chromaticities and $N_b = 8 \times 10^{10}$ p/b. This current value is far inside the instability region.

Figure 11: Horizontal (upper) and vertical (lower) emittance growth over 3000 turns for different bunch lengths and $N_b = 4 \times 10^{10}$ p/b. The bunch has been re-matched for each case by keeping the longitudinal emittance constant and changing the synchrotron tune.
tion magnets, and therefore the magnetic field in Fig. 14, we can observe that, contrary to the pure dipole, the combined function magnet causes a significant horizontal wake which is of lower frequency than the vertical one. The maximum amplitude of the wake strongly depends on the magnetic field gradient, as shown in Fig. 14 (upper to lower), where the wakes for three different gradient values are plotted. However, the results of numerical simulations seem to indicate that the presence of a horizontal wake alone cannot explain why a horizontal instability is observed in the PS machine [3]. Figure 15 shows the horizontal (upper) and vertical (lower) emittance growths for a single bunch interacting with an electron cloud inside a combined function magnet. The rise-time of the instability is shorter in the vertical plane, and the observed vertical emittance increase over 4000 turns is evidently much larger.

5 CONCLUSIONS

Simulations have been carried out with the ECL and HEADTAIL codes to reproduce and interpret the electron cloud observations at the CERN PS. The results show that a train of bunches with the LHC nominal spacing is expected to produce an electron cloud in the PS chamber for bunch rms-lengths in the range $1 - 2$ ns. The equilibrium value reached by the cloud density at saturation is then a function of the single-bunch intensity, showing a higher value for lower currents in the range $3 \times 10^9$ p/b. Such an electron cloud, supposed to be uniformly distributed in the longitudinal direction all along the ring, is able to render the single bunch unstable on a time scale of few milliseconds. The simulation has shown that the instability threshold lies at around $2 - 3 \times 10^9$ p/b. For lower intensities no significant emittance growth is expected; for higher intensities the emittance increases by a factor as large as 20 with a rise-time that becomes shorter as the current is in-

![Figure 12: Vertical emittance growth over 3000 turns for different bunch lengths and $N_b = 8 \times 10^{10}$ p/b. The bunch has been re-matched for each case by keeping the longitudinal emittance constant and changing the synchrotron tune.](image1)

![Figure 13: Horizontal (upper) and vertical (lower) emittance growth over 3000 turns for different bunch lengths and $N_b = 4 \times 10^{10}$ p/b. The bunch has been re-matched for each case by keeping the synchrotron tune constant and scaling bunch length and momentum spread by the same amount.](image2)
creased. Chromaticity seems to be an efficient cure against this kind of instability. Positive values of $\xi$ above 0.3 can completely suppress the instability for moderate currents, whereas at higher currents even a chromaticity of $\xi = 0.5$ cannot efficiently damp it. Furthermore, it was found that shorter bunches and higher synchrotron tunes have a stabilising effect against the electron cloud. A bunch with 4 ns length is expected to remain stable even with a population of $10^{11}$ protons. This case cannot be studied in the PS machine, due to the non-adiabatic process used to achieve the 4 ns long bunch length [3]. Instability simulations carried out in a field-free region show that the beam blow-up should occur symmetrically in the $x$ and $y$ planes, and in a pure dipole field it is expected only in the vertical plane [7]. A further step has been to introduce in the simulation the magnetic field from a combined function magnet acting on the electrons. Though a significant horizontal wake field is generated in this case, numerical simulations indicate that this alone still cannot explain the observation of a stronger instability in the horizontal plane. Work is presently underway and more measurements have been planned at the PS ring to achieve a better comprehension of this phenomenon.

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7 REFERENCES


