

Electron Cloud with LHC-type beams in the SPS: a review of three years of measurements

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Abstract

In August 1999, high bunch intensities LHC-type beams were injected for the first time in the SPS inducing strong vacuum pressure rises, perturbations on the electrostatic pick ups and beam instabilities. Evidences of the electron cloud phenomenon as the mechanism responsible for these instabilities are reviewed. This paper present also the results obtained with several detectors installed in the SPS machine to improve the understanding of the electron cloud mechanism and refine the simulations. The spatial distributions of the electrons in the cloud are shown in presence of and without a dipole magnetic field. The effects of the beam intensity and filling pattern on the behaviour of the electron cloud are presented. The scrubbing effect is studied using an in-situ measurement of the secondary electron yields. Finally, the potential limitations due to the electron cloud in the SPS and the issues for the LHC are discussed. Possible remedies will be presented, i.e. nitrogen and argon glow discharges or new filling schemes. A table of contents located at the end of this paper gives detailed information on the subjects covered.

1 Introduction

Pressure rises in presence of LHC-type¹ beams were highlighted in August 1999 [1]. Fig.1 shows that the pressures increase only in presence of the LHC type beams. With the fixed target SPS² proton beams, the pressures recover with a time constant consistent with the effective pumping speed. Pressure increases by a factor of 50 to 60 were recorded in the arcs and in the long straight sections. The maximum pressure measured was 10^{-5} Pa for a proton bunch intensity of 5.8×10^{10} p/b and a duty cycle close to 62%. The average static pressure in the SPS was 10^{-7} Pa.

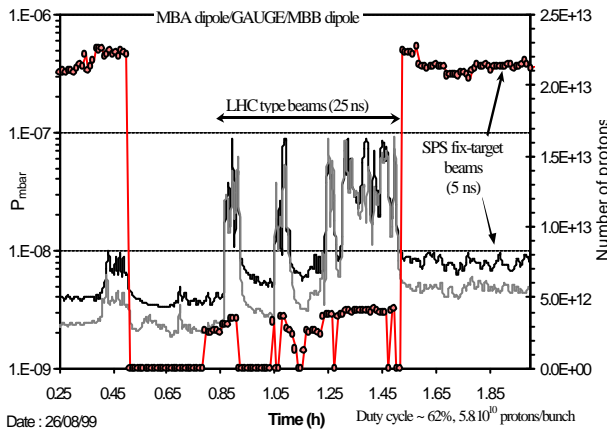


Fig. 1: Pressure rises versus time, 5.6×10^{10} p/bunch, single batch (81 bunches), duty cycle 62 %.

Below a given threshold (4.0×10^{10} p/b in August 99 in field free regions), no pressure rise was observed and a biased pick-up collector shielded from the beam

¹ 3-4 batches of 72 bunches separated by 225 ns, 25 ns bunch spacing, $1.1-1.7 \times 10^{11}$ p/b (81 bunches in 1999), bunch length: 4 ns.

² 2 trains of 2100 bunches separated by 1 ms, 5 ns bunch spacing, $1.0-2.0 \times 10^{10}$ p/b

by a metallic grid detected no signal. Above the threshold of the electron cloud, pressures raise and with a single batch, the shielded pick-ups detected peaks of current separated by $23 \mu\text{s}$ which corresponds to the revolution time in the SPS. Fig.2 shows the signal detected at 7.5×10^{10} p/b.

The transverse feedback system (“damper”) used in the SPS to damp injection oscillations and to stabilize the beam against transverse coupled bunch instabilities was also strongly perturbed [2]. The vertical position signal induced by a single batch showed a drift of the signal starting half through the 2- μs batch (Fig.3). This drift is due to electrons hitting the pick-up electrode. The threshold intensity of this phenomenon, around 4.0×10^{10} p/b, was increased up to 7.0×10^{10} p/b by applying a longitudinal solenoid magnet field of 100 Gauss (10^{-2} T) giving a clear indication that electrons, in the vacuum chamber, were at the origin of the effect.

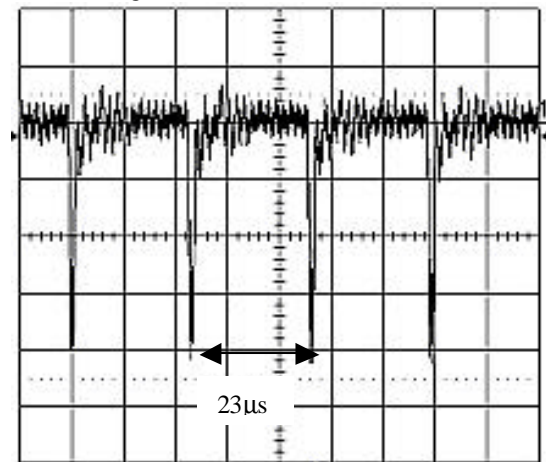


Fig.2: Structure of the current collected by the pick-up with a proton bunch intensity of 7.5×10^{10} (bias +45V)

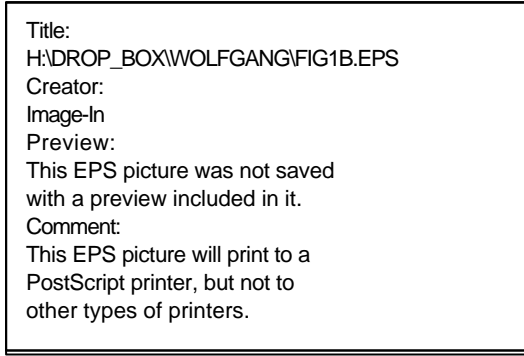


Fig.3: Vertical damper pick-up signal perturbed by electron cloud effect (6.8×10^{10} p/bunch) [2].

In the SPS or in the LHC, electrons created at the vacuum chamber wall, will be accelerated by the proton bunches up to 200 eV and will need less than 5ns to cross the chamber³. A significant fraction of the electrons will be lost with the nominal spacing of 25ns, except the electrons with an energy below 10eV, which will survive and be kicked up to several keV by the following bunches. This non resonant single pass mechanism may lead to an electron cloud build up if the maximum secondary electron yield (SEY) δ_{max} of the chamber wall is larger than a critical value, typically around 1.3 [3][4]. The critical value is 1.15 [5] if the contribution of the reflected electrons is taken into account in the secondary electron yield coefficient (SEY). Then, the electron cloud is amplified at each bunch passage and reaches a saturation value determined by the space charge repulsion with implications for the beam stability, emittance growth [6] and heat load on the LHC cryogenic system [7][8].

The observed threshold bunch intensity has a weak dependence on the residual gas pressure, contrary to ion effects and is in agreement with electron cloud simulations. Measurements showed that for bunch intensities above 7.0×10^{10} p/bunch, the weak solenoid field becomes insufficient in view of the keV energies acquired by the electrons near the beam axis.

An issue for the vacuum system of the SPS, as the LHC injector, is to avoid any emittance growth due to the gas density since this emittance will be preserved in the LHC leading to a degradation of the luminosity. The emittance growth due to a residual pressure (N_2 equivalent) is given by:

$$\frac{\partial \epsilon}{\partial t} = 1.2 \cdot 10^{-3} \langle \mathbf{b} \rangle \frac{P(Pa)}{g} \quad [9]$$

where g is the relativistic factor. For a \mathbf{b} of 40 mand an average pressure below 10^{-6} Pa, the emittance growth due to the beam-gas interaction is negligible⁴. The electron cloud can drive multi [10][11] and single bunch instabilities [12][13][14][15][16], and it can

³ SPS dipoles chambers: MBA: h=34.5mm/l=152mm,

MBB: h=48.5mm/l=129mm, drift ID=φ156mm

⁴ Injection cycle for the LHC: ~15 seconds.

also induce coherent and incoherent tune shifts. Electrons near the beam are thought to be responsible for the single bunch instability. A broadband pick-up at the SPS has allowed the detection of motion inside the bunch, and to fit for the period of the effective wakefield [17]. The result is consistent with the estimated electron oscillation wavelength, and with the proposed instability model based on a head-tail interaction [13][14][16].

Beam instabilities induced by the electron cloud will not be covered in this paper, which aims to resume the observations in the SPS, to crosscheck and give inputs to refine the simulations and to validate the scrubbing scenario proposed for the LHC.

2 Measurable and Set-ups description

Table 1 shows the different types of detectors, which were used to study the electron cloud phenomena and to measure the beam effects.

Electron cloud phenomena	Field free region	Dipole field region
e ⁻ cloud activity (intensity)	Electrons energy analyser, strip detectors	
e ⁻ cloud build-up	Pick-ups	-
Energy distribution of the electrons	Electrons energy analysers	
	Electrostatic energy analyser	-
	Retarding field detector	-
Spatial distribution of the electrons	Strip detectors (16 channels)	
Secondary electron yield measurements (δ)	Secondary Electron Yield (δ) set-up	
Surface treatment to cure e ⁻ cloud	Pressure, pick-ups	-
Beam effects		
Bunch intensity	Pressures, strip detectors	
Filling pattern		
Batch length		
Missing bunches		
Bunch spacing		
Bunch length		
Batch spacing		
Filling factor		
Scrubbing	Secondary Electron Yield (δ) set-up, pressures	

Table 1: Different types of detectors and the corresponding measurable parameters.

2.1 Pressure gauges and pick-ups

The majority of the electrons from the cloud will be lost on the vacuum chamber walls inducing pressure rises by the electron stimulated desorption (ESD) phenomenon. In the SPS, the pressure rises are a direct signature of the electron cloud activity and therefore, the 70 pressure gauges installed all around the SPS ring give an indication of the electron cloud activity. This simple technique is sensitive to a small variation of the beam parameters, i.e. 5% of variation of the bunch intensity above the electron cloud threshold is measurable. Nevertheless, variations of less than 10 seconds duration of the beam parameters cannot be studied due to the time constant imposed by the conductance of the vacuum chambers. Real pumping speed should also be taken into account when comparing $\Delta P/P$ at different locations in the SPS ring.

The electron cloud build up in the field free regions is studied using pick-up buttons screened from the beam by a grounded grid. A fraction of the electrons from the cloud are collected by a current integrator or measured using a scope. The 20 mm diameter buttons allow low RC time constant and therefore a single bunch can be seen using a scope (see Fig.4).

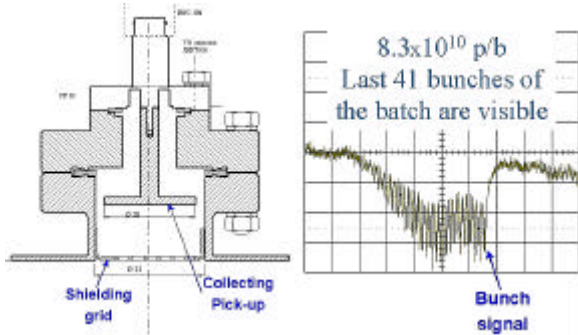


Fig.4: Drawing of a shielded pick up and a typical signal (-) obtained in presence of the electron cloud.

2.2 Strip detector: Spatial distribution of the electrons

Preliminary measurement on the electron cloud indicates different behaviours in presence or not of a dipole magnetic field and simulations predicted the appearance of two strips above a given bunch intensity: 5.5×10^{10} p/bunch.

To confirm these simulations and study the spatial distribution, a 16 copper strips detector was installed in the SPS. The copper strips, deposited on a MACOR™ substrate in the longitudinal plane, allow the collection of a fraction of the electrons from the cloud. The strips, which remain under vacuum, are separated from the beam by the vacuum chamber wall in which hundreds of holes ($\phi 2\text{mm}$) are drilled with a total transparency of 7.5 % to avoid the extinction of the multipacting by an excessive collection of electrons. The distribution of the holes was calculated to minimize the interference with the strips arrangement. The resulting sensibility shows a fluctuation of the transparency below 20%. The signal collected by each channel is measured individually using a current integrator with a minimum integrating time of 2 ms (~ 100 turns in the SPS). The detection limit of the current integrator is about 10^{-8} A for each individual channel. Fig.5 shows the signal of the electron cloud following a controlled beam bump of 8mm.

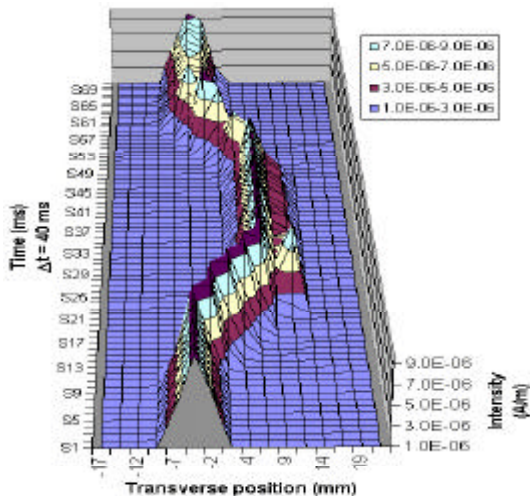


Fig.5: Signal of the electron cloud following a controlled beam bump of 8 mm.

3 Main results - Beam effects

3.1 Bunch intensity

Pressures in the SPS do not vary up to a threshold bunch intensity above which the pressures increase with the bunch intensity (Fig.6 and Fig.7). The amplitudes of the negative current signals measured on the pick-ups also increase with the bunch intensity (Fig.8a and Fig.8b). In August 1999, the threshold in the long straight section (field free region) was about 4.3×10^{10} p/b and increased up to 6.4×10^{10} p/b in April 2000 after several days of operation with high bunch intensity LHC-type beams. In the arc, the dipole magnetic field affects the behaviour of the pressure versus the bunch intensity (Fig.7). In presence of a dipole magnetic field, the measurements give consistently a lower threshold value, between 3.0 and 4.0×10^{10} p/b and higher-pressure rises.

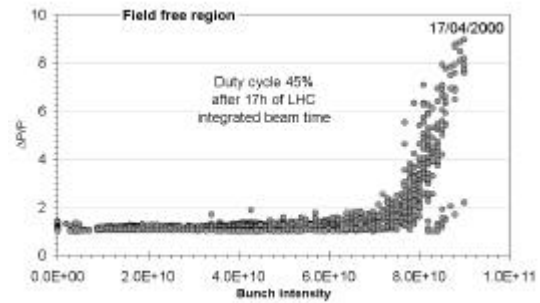


Fig.6: Pressure rise versus bunch intensity in a field free region. Static pressure 10^6 Pa, MBB-type aperture.

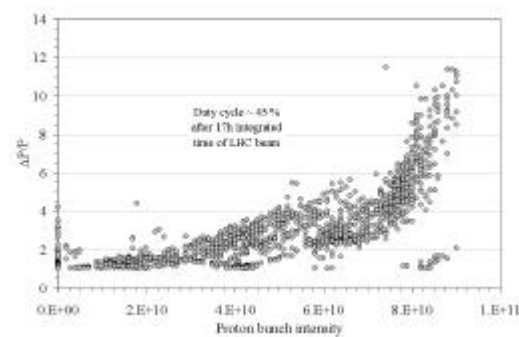
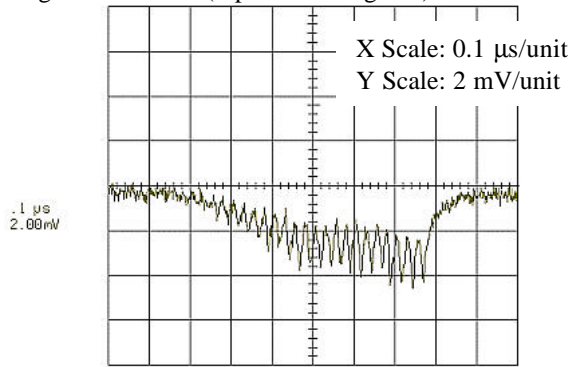


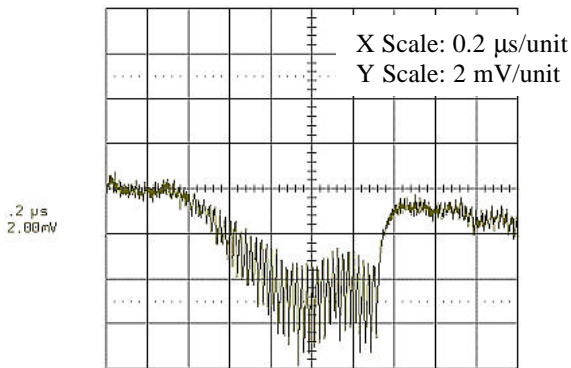
Fig.7: Pressure rise versus proton bunch intensity in a dipole region (arcs). Static pressure 10^6 Pa, MBB-type aperture.

The difference observed between the field free and the dipole regions has not been understood but cannot be attributed to systematic errors since the gauges are not influenced by the dipole magnetic field. One explanation could come from the simulations [7] which showed that, in a dipole magnetic field, the electrons are confined in the vertical plane. The number of electrons and their distribution in energy in the cloud will depend on the bunch intensity and therefore, in a dipole field, the impinging surface will depend on the bunch intensity. The entire vacuum chamber will not be bombarded and recontamination should be expected.

In the SPS and in presence of a strong electron cloud activity, the pressure limitations were mainly coming from the arcs (dipole field regions).



8a) Pick-up signal, bunch intensity of 6.9×10^{10} p/b



8b) Pick-up signal, bunch intensity of 8.3×10^{10} p/b

Fig.8: Pick-up signals showing the effect of an increase of the bunch intensity

3.2 Filling pattern – Electron Cloud build up

3.2.1 Batch length – Electron cloud build up

The initial results obtained in the SPS [1] showed that the number of bunches needed to build up the electron cloud decreased when the bunch intensity increased. As an example, 32 bunches were needed at 6.5×10^{10} p/b, only 20 bunches at 7.9×10^{10} p/b (see Fig.9 and Fig.10). These results were confirmed also by observations on pick-ups (see Fig.8a and Fig.8b) which showed that the number of detectable bunches on the pick up signal increased with the bunch intensity.

3.2.2 Missing bunches

The batch of 72 bunches is made out of 6 trains of 12 bunches (Fig.11) and allowed the suppression of one of these trains. During the measurements, the 3rd and the 4th train were removed. The results showed that the pick up signals were affected by the 12 missing bunches (Fig.12) and the pressure rises decreased by a factor 8 (Fig.13). The pick-ups showed that the 4th missing train is more efficient than the 3rd one (Fig.12a and Fig.12b). No difference in the pressure rises could be seen between the two missing trains (Fig.13).

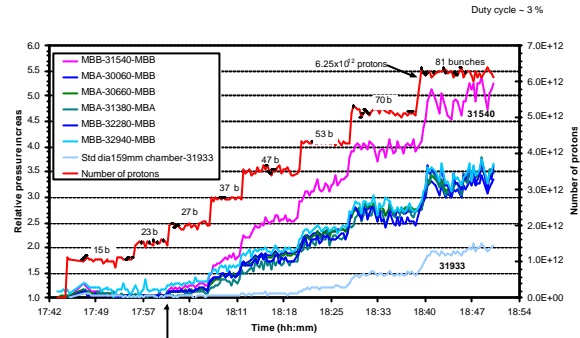


Fig.9: Relative pressure increase DP/P versus number of bunches at 7.7×10^{10} protons per bunch.

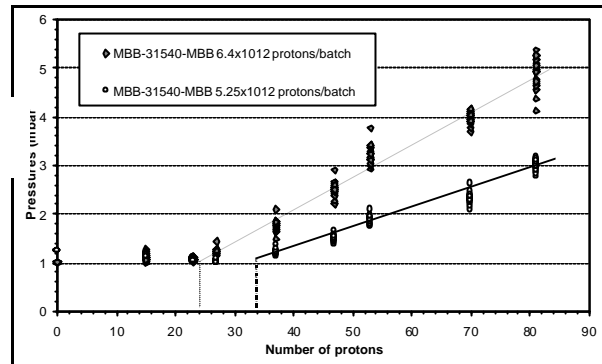


Fig.10: Relative pressure increase DP/P versus number of bunches in the batch (81 bunches) at 6.5×10^{10} and 7.7×10^{10} p/bunch.

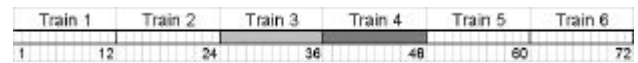
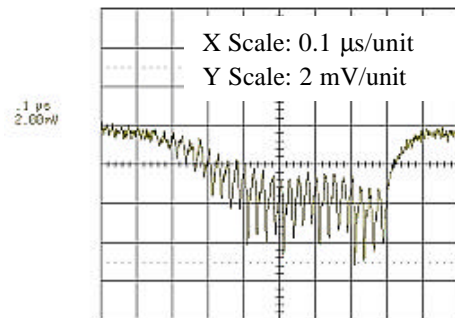
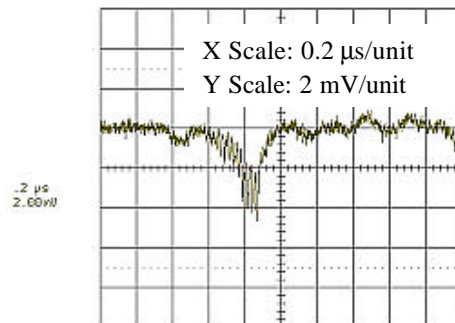


Fig.11: Filling pattern with 72 bunches made out of 6 trains of 12 bunches each.



12a) 3rd missing train (12 missing bunches)



12b) 4th missing train (12 missing bunches)

Fig.12: Pick-up signals with 12 missing bunches.

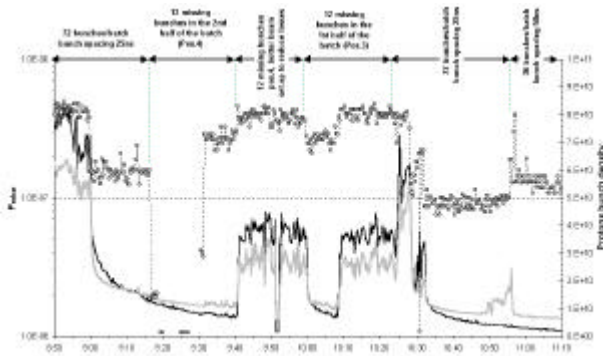


Fig.13: Pressures behaviour versus time with 12 missing bunches in 3rd and 4th positions.

3.2.3 Bunch spacing

The nominal LHC bunch intensity (10^{11} p/bunch) was achieved using the 50 ns bunch spacing and 36 bunches per batch instead of the nominal 72 bunches per batch. The resulting electron cloud activity was 10 times below as compared to the level measured with 5×10^{10} p/b and 72 bunches per batch.

The electron cloud effect was also observed both by the strip detector and by the pressure gauges with the SPS fixed target beam with 5ns spacing. The presence of the electron cloud was only observed in specific conditions during the ramp from 26 to 450 Ge V where the beam is squeezed in all dimensions and therefore the bunch density is maximized. In normal operation, the bunch intensity is much below the threshold and this explains why the electron cloud is not observed in the SPS with the fixed target-type beams.

Using the nominal LHC bunch spacing, i.e. 25ns, the maximum intensity achieved in 2001 with a single batch was 8.0×10^{10} p/bunch. With 3 batches, the maximum bunch intensity achieved was 5.5×10^{10} p/bunch. Above these intensities, the pressure interlock was reached and the beam dumped. In addition, the strong electron cloud activity induced strong beam oscillations, which could not be damped by the RF damper [18].

The origin of the pressure limitations will be discussed in the paragraph on beam scrubbing.

3.2.4 Bunch length

Qualitative measurements on the effect of the bunch length on the electron cloud were made using the strip detector. Fig.14 shows an enhancement of the electron cloud activity when the bunch length was decreased from 5ns down to 2ns. As the transverse emittance remained stable, this is easily understandable since in these conditions, a decrease of the bunch length result in an increase of the bunch density leading to a stronger electron cloud activity [19].

3.2.5 Filling factor - Batch spacing

Three to four batches of 72 bunches will be injected into the SPS, ramped from 26 GeV to 450 GeV and then injected into the LHC. The standard LHC 8 bucket spacing [225ns] showed that the electron cloud did not disappear between two successive batches. All

this was evidenced by pick up measurements with 2, 3 and 4 successive batches (see Fig.15). The pick-ups even showed that the build up of the 2nd, 3rd or 4th batch profits from the cloud created left behind by the previous batch resulting in a faster build up.

Other batch spacing have been studied to reduce the electron cloud effect, i.e. 21 bucket [550 ns] and ¼ of the SPS evolution time [5.25 μ s] instead of the standard 8 buckets spacing [225 ns]. Results obtained on the pick ups (see Fig.16) showed that a batch spacing bigger than 550 ns [21 bucket spacing] is required to decouple the effect of two successive batches on the electron could build up. Fig.17, obtained using the strip detector, shows no difference between the two batch spacings 225ns and 550ns on the total electron cloud activity.

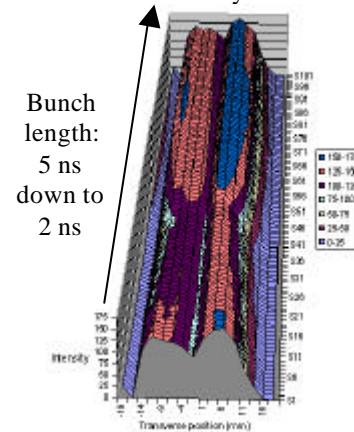
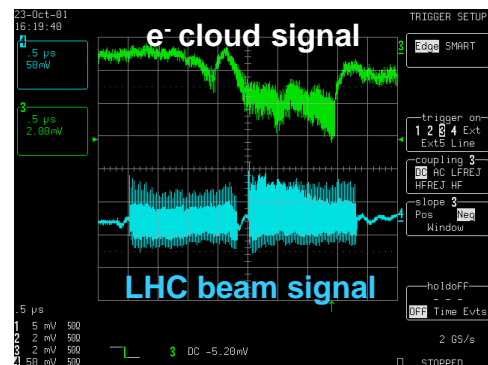
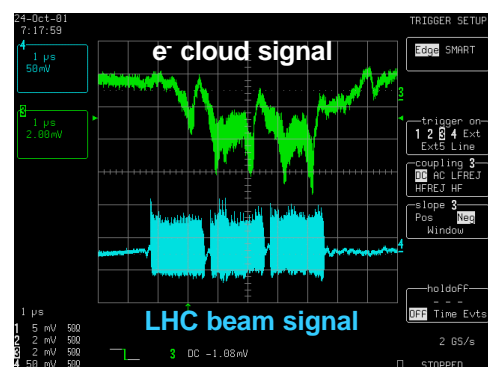


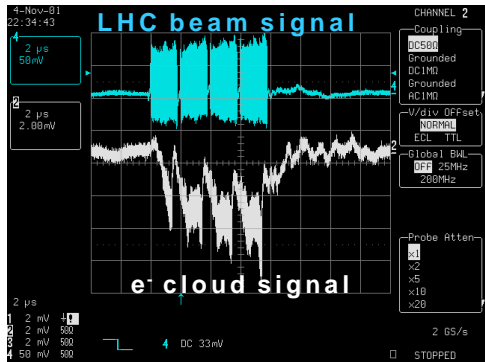
Fig.14: Effect of the bunch length on the electron cloud activity. Results obtained with the strip detector.



15a) 2 batches of 72 bunches [225ns batch spacing]

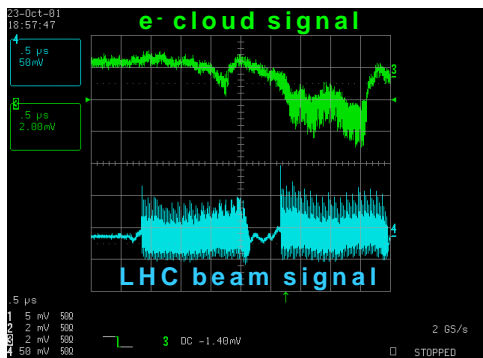


15b) 3 batches of 72 bunches [225ns batch spacing]

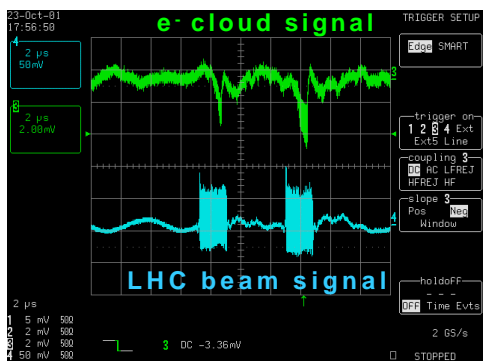


15c) 4 batches of 72 bunches [225ns batch spacing]

Fig.15: Pick up signals with a multi-batch injection [nominal 225 ns LHC batch spacing].



16a) 2 batches [550 ns spacing]



16b) 2 batches [5.25 ns spacing]

Fig.16: Pick up signals of the electron cloud build up with two different batch spacing [550 ns and 5.25 ns].

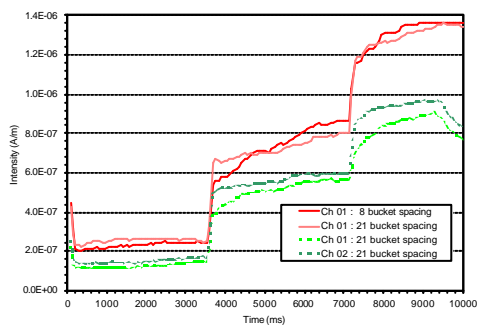


Fig.17: Results obtained using the strip detector, showing no difference between the two batch spacing [225 ns and 550 ns] on the total electron cloud activity.

Fig.18 obtained with the strip detector shows the increase of the electron cloud activity after injecting the 2nd and 3rd batch. The two strips (or bands) visible in Fig.18 will be discussed later on in the paragraph on dipole field effects.

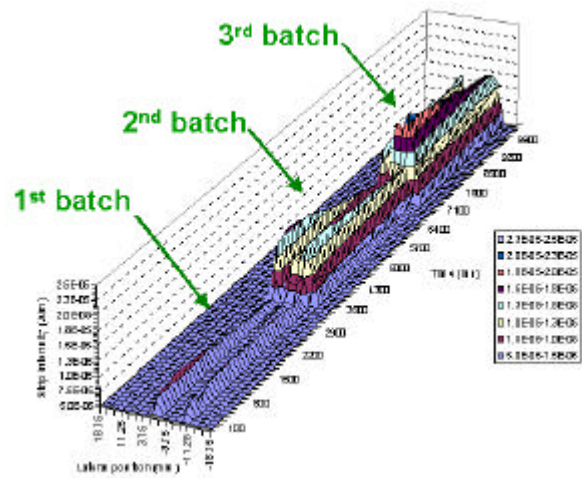


Fig.18: Electron cloud activity measured using the strip detector with a multi-batch injection in a dipole field.

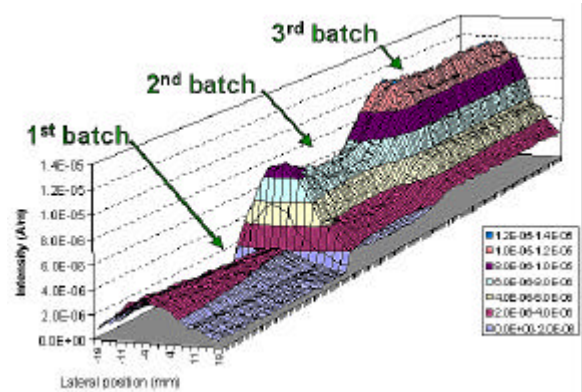


Fig.19: Electron cloud activity measured using the strip detector with a multi batch injection in a field free region.

Above the threshold in the field free regions, the strip detector can also be used to visualise the electron cloud in a field free region. Fig.19 gives a 3D view with 3-batch injection. As for the dipole regions, the electron cloud activity increased after the 2nd and 3rd batch injection. The non-isotropic angular acceptance of the strip detector resulted in a non-flat distribution. A flat distribution is expected in the field free regions.

4 Effect of a dipole magnetic field

The simulations made for the LHC [5] pointed out the strong effect of a dipole magnetic field on the electron cloud. A longitudinal magnetic field has been successfully used in *B* factories, e.g. KEKB, PEP-II [20][21][22] and SPS [2] to reduce the electron cloud activity. A transverse dipole field will force the electrons to follow a cyclotron motion depending mainly on the beam potential and on their lateral position before being kicked by the beam. This cyclotron motion will, also influence all the detectors

including the strip detector used to study the electron cloud in a dipole field. The effect of the dipole field on the electron cloud behaviour and the limitations of the different detectors used will be discussed.

4.1 Appearance of two strips at high intensities

Above a given threshold, which is related to the energy of the δ_{\max} (secondary electron yield) of the chamber wall and to the energy of the electrons, simulations predicted the appearance of two strips in the cloud in a dipole field (see Fig.20). The distance between the two strips will increase with the beam potential and does not depend on the magnetic field strength. If the bunch dimensions are assumed to remain constant (bunch length, transverse emittance), the bunch potential varies as the bunch intensity. The minor variations observed with the strip detector with the magnetic field strength arise from the dependence of the acceptance of this detector on the magnetic field. This dependence is mainly due to the diameter of the holes ($\varnothing 2\text{mm}$), which at a field of $B = 10^{-2}$ T is close to the Larmor radius of the high-energy electrons (> 200 eV).

The increase of the width of the electron cloud when decreasing the magnetic field strength is not yet understood (Fig.21) and will be studied in the future with a higher resolution strip detector.

Fig.22 shows the position of the two strips at two different bunch intensities.

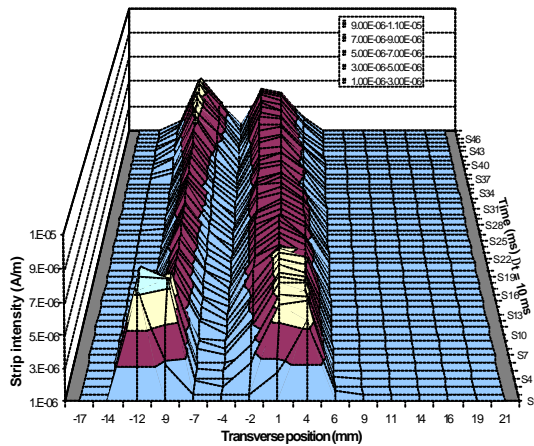
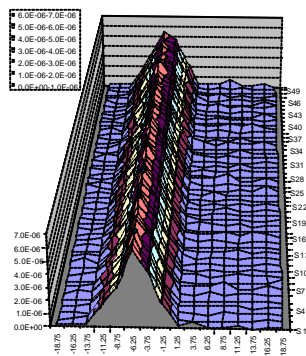
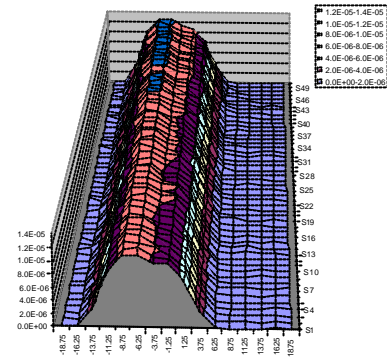


Fig.20: Appearance of two strips in a dipole field above a threshold, in this case: 6.0×10^{10} p/bunch.

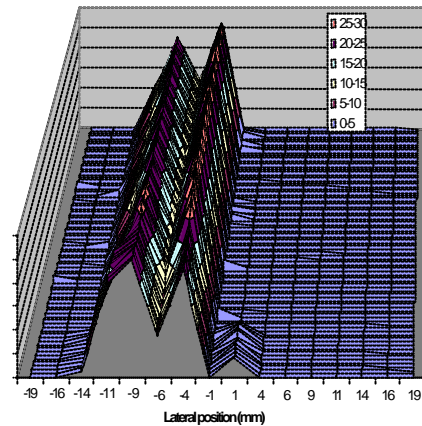


21a) Dipole field of 0.2 T

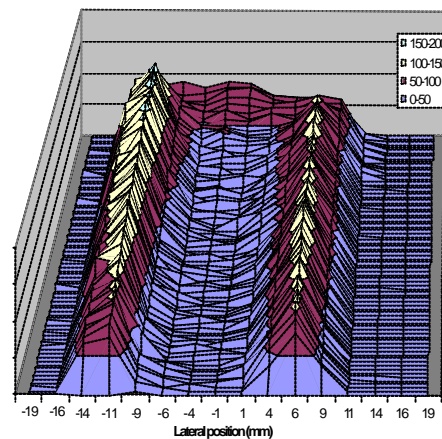


21b) Dipole field of 2×10^{-2} T

Fig.21: Effect of the magnetic field strength on the electron cloud (5.0×10^{10} p/bunch, single batch)



22a) Position of the two strips at 5.0×10^{10} p/bunch



22b) Position of the two strips at 8.6×10^{10} p/bunch

Fig.22: Position of the two strips depending on the bunch intensity.

4.2 Threshold of the dipole field effect

The strip detector showed that weak dipole field strength has a strong effect on the electron cloud. The strip detector used at bunch intensities below the threshold for the field free regions showed that a dipole field of 20 to 30 Gauss is required to trigger the electron cloud (see Fig.23 and Fig.24).

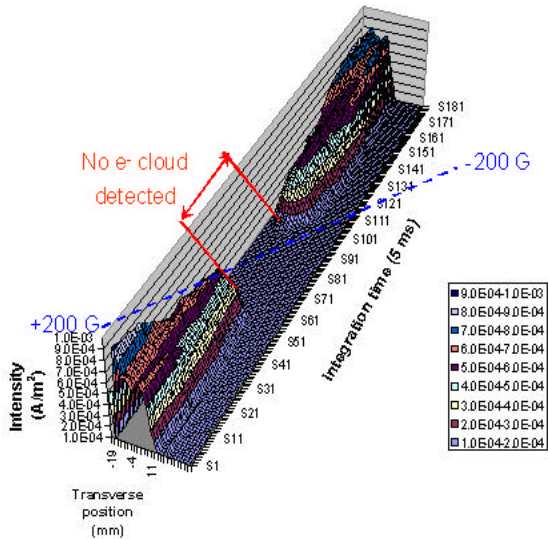


Fig.23: 3D view showing the disappearance of the electron cloud below 20 Gauss (2×10^{-3} T).

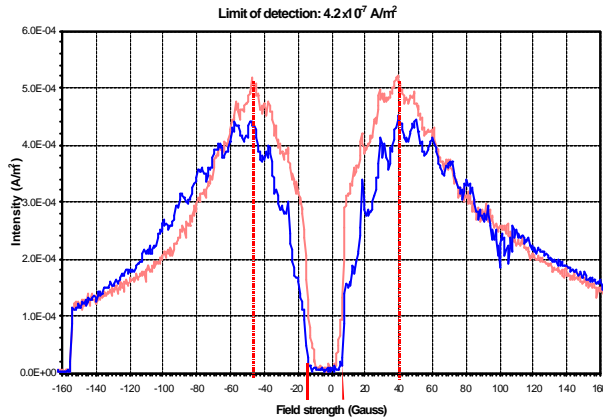


Fig.24: Intensities collected by two different strips as a function of the dipole field strength.

5 Beam scrubbing

In the SPS, the pressure rises ($\Delta P/P$) are a direct signature of the electron bombardment. The beam scrubbing (or the scrubbing) effect characterises a decrease of these pressure rises. This decrease of $\Delta P/P$ results from both a cleaning of the surface (gas desorbed by the electron bombardment and pumped) and a reduction of the electron cloud activity as a result of the decrease of secondary electron yield (δ) of the inner chamber walls.

The scrubbing effect was studied in details to quantify the scrubbing time required in the SPS, after a shutdown, before being able to inject the LHC. Another objective of these measurements is to validate the “scrubbing scenario” proposed for the LHC. This scenario is based on the decrease of the SEY (δ) with the subsequent reduction of the heat load in the LHC cryogenic circuit.

In addition to the variation of the $\Delta P/P$ of the 70 gauges around the SPS, the scrubbing effect was quantified using a set up which allowed an in-situ measurement of the secondary electron yield (δ) of a

copper sample exposed to the bombardment of the electrons from the cloud (see Fig.25). After receiving a controlled dose, the copper sample was rotated towards the electron gun to measure the SEY. When required, the sample was masked from the beam to avoid any exposure with non-optimal beam conditions.

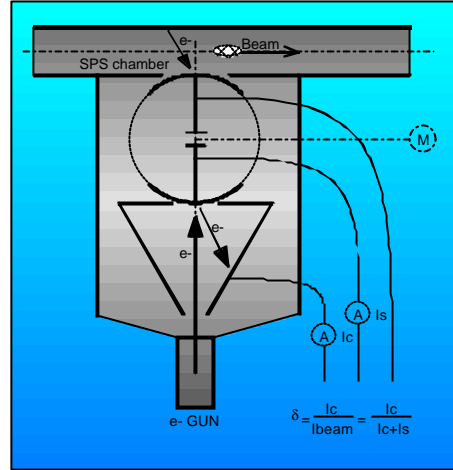


Fig.25: Schematic view of the in-situ SEY detector installed in the SPS

First measurements presented in 2000 [1][23] were made with a total integrated LHC beam time of about 60 hours. The decrease of the pressure rises was significant both in the field free and in the dipole field regions [23] (see Fig.26). An increase of the threshold bunch intensity was observed indicating a decrease of the SEY (δ) since the reduction of the outgassing rate by the electron stimulated desorption (ESD) can not explain this shift.

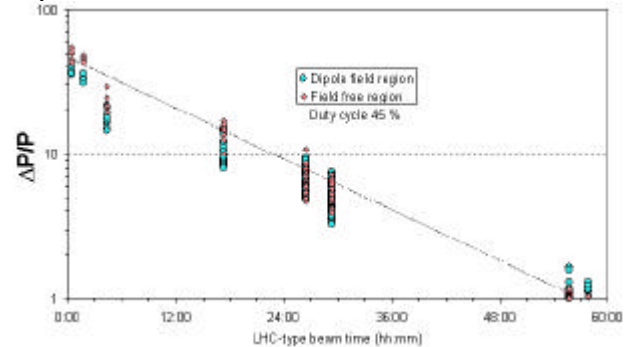


Fig.26: Pressure decrease observed both in the dipole and field free region with the LHC beam time in 2000.

The measurements have shown that the pressure rise decrease by a factor of 30 after about 2.5 integrated days of LHC-type beams. The beam scrubbing efficiency depends on the electron cloud activity and therefore on the bunch intensity. The higher the bunch intensity, the higher is the scrubbing effect. The beam time in Fig.26 corresponds to the cumulated time in presence of LHC-type beams with bunch intensities higher than 5.0×10^{10} , which corresponded to the threshold of the electron cloud in the field free regions. Fig.26 shows a clear evidence

of a cleaning effect and no pressure increase can be seen after 60 hours of LHC-type beams.

The measurements have shown that the scrubbing effect is effective up to the bunch intensity used for the commissioning. If a beam with higher bunch intensity is injected, the pressure will increase. This observation is consistent with the displacement of the electron strips in the magnets when the bunch intensity increases.

Results obtained in 2001 were less encouraging in terms of pressure decrease versus LHC-beam time. The reduced scrubbing observed could be explained by the lower bunch intensities injected in the SPS in 2001 as compared to 2000 (Fig.27). In winter 2000-2001, the whole SPS was vented to air during about 5 months for an installation of the pumping port shielding⁵[24]. Fig.28 shows a smaller threshold after venting which implies a higher electron cloud activity for the same bunch intensity. Measurements made in the Laboratory (Fig.29)[25] confirmed that a venting to air resets the SEY (δ) of a sample submitted to an electron beam scrubbing.

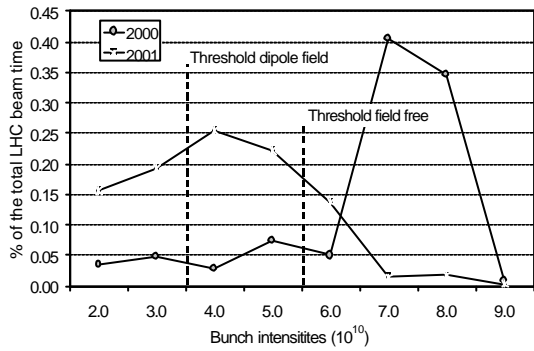


Fig.27: Distribution of the bunch intensities in 2000 and 2001

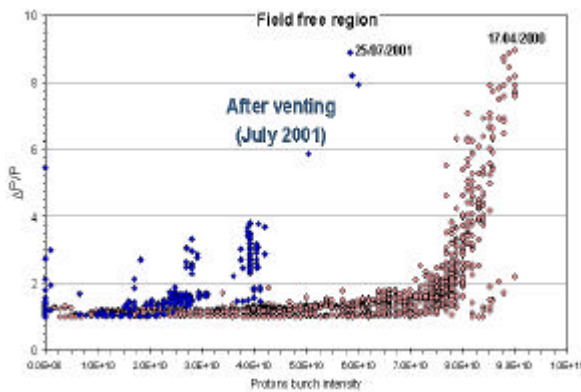


Fig.28: Threshold of the electron cloud in 2000 and in 2001 after a long venting to air of the SPS machine.

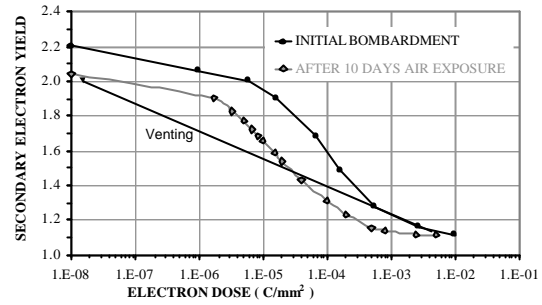


Fig.29: Measurements made in the laboratory showing the scrubbing effect with electron dose and the reset induced by a venting to air.

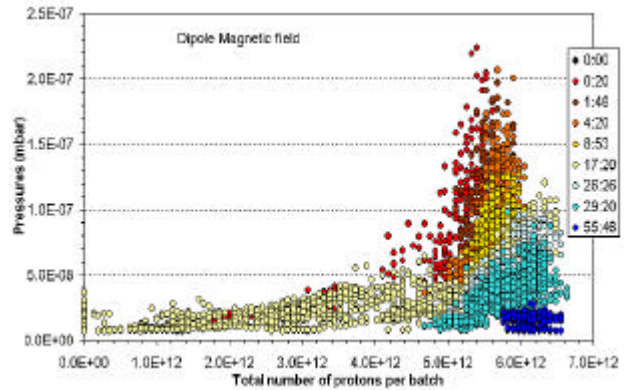


Fig.30: Threshold increasing with the LHC beam time.

The increase of the threshold of the electron cloud, as shown in Fig.30 is a clear indication of a decrease of the SEY. More recent measurements made in 2001 in the SPS with the in-situ SEY detector gave evidence of the decrease of the SEY with the LHC-Type beam time (Fig.31).

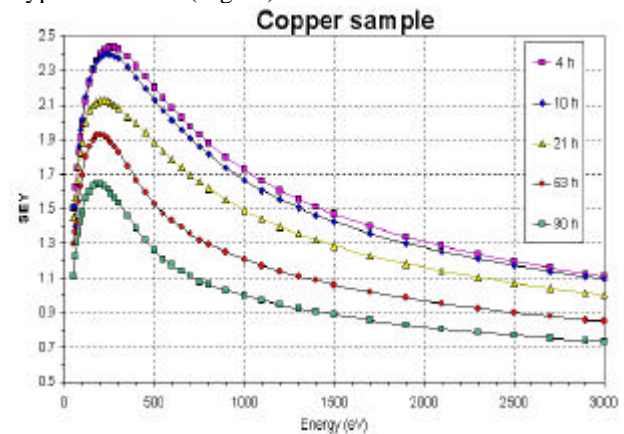


Fig.31: Decrease of the SEY of a copper sample exposed to the bombardment of the electrons from the cloud in the SPS as a function of the LHC-beam time.

Even with the relatively low bunch intensities injected in the SPS in 2001 (see Fig.27), the decrease of the SEY (δ_{\max} and $E[\delta_{\max}]$) is significant (see Fig.32). The value of the δ_{\max} decreased from 2.4 down to 1.6 after less than 100 hours. More relevant is the evolution of the integral of the curve above a δ of 1.3, which is considered as the threshold of the

⁵ Installed between all magnets to decrease the impedance of the SPS machine

multipacting effect [3][4][5]. Fig.33 shows that the reservoir of secondary electrons decreased by more than 80% after about 100 hour of LHC beam time.

All the results presented above gave evidence of the scrubbing effect in the SPS. The lower efficiency observed in 2001 can be explained by the statically lower bunch intensities and therefore, the lower energies of the electrons impinging on the inner wall of the vacuum chambers.

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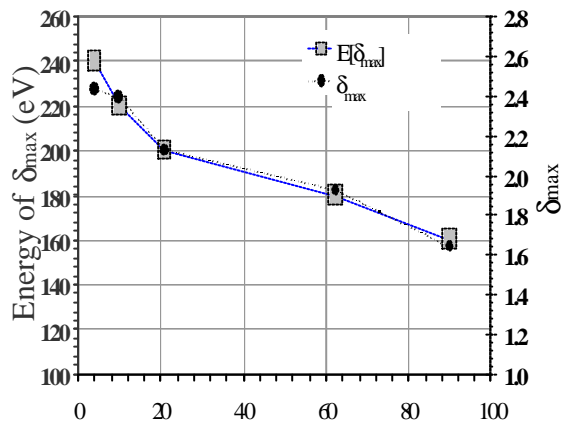


Fig.32: Decrease of the d_{max} and $E[d_{max}]$ with the LHC beam time

An important issue for the scrubbing is obviously the existence of the electron cloud effect. The higher the bunch intensity, the higher the electron cloud activity and the higher will be the scrubbing effect. Operating the SPS and the LHC below the electron cloud threshold will never be a solution since the SEY (δ_{max}) will remain high i.e. 2.3-2.4 for a copper sample.

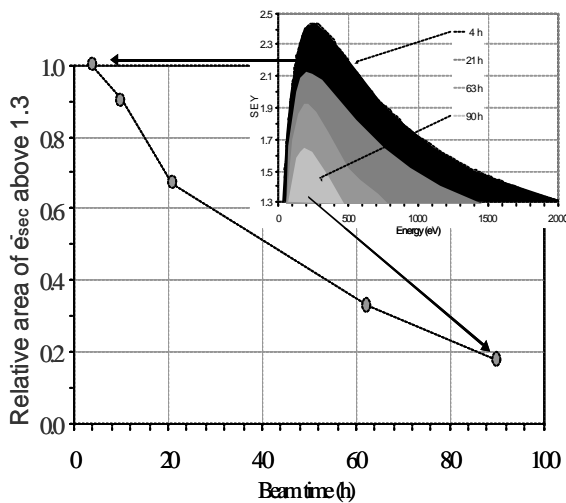


Fig.33: Decrease of the reservoir of secondary electrons with the LHC-beam time

5.1.1 Nitrogen discharge - Memory effect

No difference in the pressure rises nor in an increase of the scrubbing effect could be seen between the non treated vacuum chambers and the two chambers treated with a N_2 discharge.

Nevertheless, the chambers treated with a N_2 discharge and submitted to a beam scrubbing showed a faster conditioning compared to the non-treated chambers after an exposure to air and pressure rises were 4 times smaller.

More recent measurements were made to study the effect of an Ar/O_2 discharge and of a N_2 discharge followed by a $300^\circ C$ bake out. These results confirmed that the N_2 discharge even after the bake out at $300^\circ C$ during 24h had a behaviour identical to the non treated chambers. On the other hand, the Ar/O_2 discharge gave satisfactory results. The $\Delta P/P$ measured was 2.5 times smaller than the one measured on the identical non-treated chambers (see Fig.34).

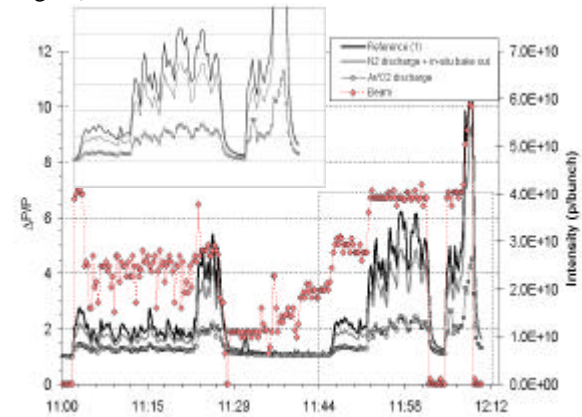


Fig.34: $\Delta P/P$ measured in dipole regions and in field free regions. Effect of an Ar/O_2 discharge and N_2 discharge followed by a $300^\circ C$ bake out. Static pressure 10^{-6} Pa, MBB-type aperture.

6 Conclusions - Discussions

All the measurements confirmed the electron cloud as the mechanism being responsible for the pressure rises in the SPS: pick-ups measured an electron current signal, pressure rises occurred only in the presence of LHC-type beams and the strip detector gave a 3D view of the cloud. In addition, the behaviour of pressure rises versus bunch intensity is consistent with observations made in B factories, i.e. KEKb, PEP-II [20][21][22]. As for KEKb, a small longitudinal magnetic field (10^{-2} T) partly cured the limitations induced by the electron cloud.

The electron cloud is a threshold mechanism, which depends on the existence or not of a dipole field. In presence of a dipole field, the threshold was around $2.0-3.0 \times 10^{10}$ p/bunch⁶ and it was $5.5-6.0 \times 10^{10}$ p/bunch⁵ for the field free regions. The threshold mechanism was confirmed by the measurements using the strip detector with bunch intensities between 3.0

⁶ Nominal bunch length of 4 ns

and 5.5×10^{10} p/bunch. In presence of a dipole field, the electron cloud was observed and it disappeared immediately after suppressing the dipole field.

The beneficial effect of a 50 ns bunch spacing was evidenced. The nominal LHC bunch intensity (10^{11} p/bunch) was achieved with a single batch and the observed electron cloud activity was 10 times below the level expected. But the used of a higher bunch spacing will require an increase of the bunch intensity to keep constant the luminosity.

All the other parameters of the filling pattern were tested and showed a low efficiency in suppressing the electron cloud. Missing bunches did not suppress the electron cloud but decreased its intensity by a factor of 8. This is consistent with other measurements which showed that the electron cloud would need much more time to decay. Increasing the batch spacing would be effective only with a batch spacing higher than 550 ns which would lead to an unacceptable decrease of the LHC luminosity.

The cleaning effect or "scrubbing" was evidenced in the SPS using pressure gauges, pick-ups and in-situ SEY detector. In the SPS, the scrubbing effect results from the bombardment of the electrons from the cloud on the inner chamber wall. The higher the electron cloud activity, the higher will be the scrubbing efficiency. The measurements showed that, in less than three days of scrubbing in 2002, the pressure rises in presence of LHC-type beams become negligible in the SPS. This effect was visible both in the field free and in the dipole field regions with bunch intensities above 6.0×10^{10} p/bunch. A recontamination by the non-bombarded surface could explain the lower efficiency in the dipole regions due to the existence of two strips. All the measurements have shown an increase of the threshold bunch intensity, a decrease of the SEY (δ) from 2.3 down to 1.6 after 100 hours of LHC-beam time and a decrease by a factor 30 of the relative pressure increase $\Delta P/P$.

Operating any machine limited by the electron cloud below its threshold, in particular the SPS and the LHC, will never be a solution since the SEY (δ_{\max}) will not decrease and will stay at 2.3 for a copper surface.

To reduce the scrubbing time, chambers treated by N_2 and Ar/O_2 discharges were installed in the SPS. In the first cycle of experiments no difference between the non-treated chambers and the two chambers submitted to a N_2 glow discharge have been observed. After an air exposure, only the treated chamber (N_2 discharge) seems to have a memory of the scrubbing effect. The in-situ bake out at $300^\circ C$ did not improve the efficiency of this treatment. The Ar/O_2 discharge was more efficient; a reduction of the $\Delta P/P$ by a factor of 2.5 was measured.

The measurements in the SPS also confirmed that a venting to air will reset the scrubbing effect, i.e. the SEY (δ_{\max}) value will increase back to its initial value 2.3.

7 Issues for the LHC machine

Contrary to the SPS machine which is limited by the pressure rises and beam instabilities in presence of a strong electron cloud activity, the LHC will be mainly limited by the heat load on the cryogenic system. Different parameters of the filling pattern could be used to decrease the heat load but measurements showed that the cloud was never suppressed. In addition, the bunch intensities should be increased above the nominal value (1.1×10^{11} p/bunch) to reach the nominal luminosity.

However, the strip detector gave issues for the design of the beam screen as the expected position of the electron cloud strips at nominal intensity coincides with the position of the pumping holes in the beam screen (Fig.35).

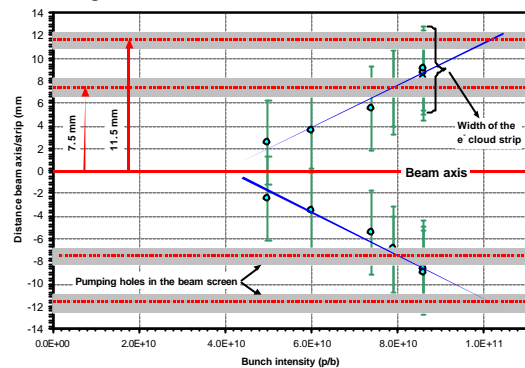


Fig.35: Measured position and width of the two strips on the SPS and their expected position at the nominal LHC-bunch intensity. The expected position is in coincidence with the position of the pumping holes in the initial design of the beam screen.

To avoid that the beam screen no longer ensures the interception of the heat load and that a non-negligible fraction of the electrons from the cloud impinge directly the cold bore, the position of the holes has been reviewed and an additional screen is being studied (see Fig.36).

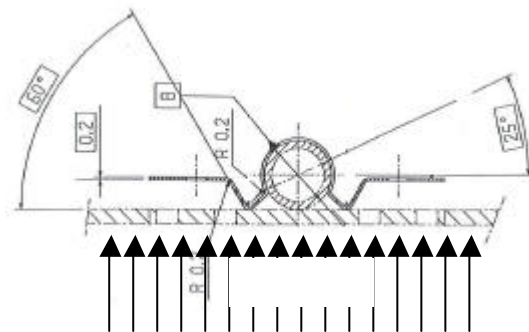


Fig.36: Additional screens (baffles) on the LHC beam screen to intercept the electrons from the cloud to reduce the heat load to the cold bore (1.9 K) [26].

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