E-CLOUD DIAGNOSTICS & OBSERVATIONS

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Abstract

In 1998 and for the first time, an electron cloud build up was limiting the beam intensity in the Super-Proton Synchrotron (SPS) when operated with LHC-type beams.

This limitation was expected since predicted by various simulations. Some quantitative discrepancies were identified leading to the installation of several detectors in the SPS ring in order to provide the required input parameters for the simulations. This paper describes all types of detectors used since 1998 and highlights the major results obtained. Some ideas for future studies will also be addressed.

INTRODUCTION

The simulations have predicted an electron cloud build up when running with LHC-type beams in the SPS. Indeed, the electron build-up was observed by an indirect effect 1998 on the RF damping system, the pressure rises [Fig.1] in the beam vacuum pipes, the bunch instabilities and the emittance blow-up.

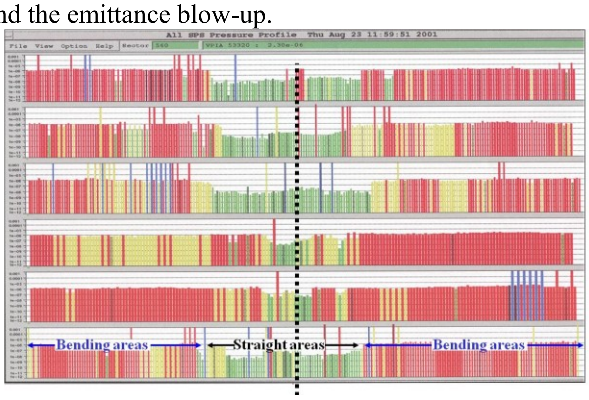

Fig. 1: *Pressure rises in the SPS ring in presence of high bunch intensities and LHC-type beams. The red colour corresponds to pressures higher than 10^{-4} Pa.*

The pressures increased very fast by several order of magnitude from 10^{-6} Pa up to 10^{-3} Pa in the arcs (bending sections), the increase was less pronounced in the long straight sections, e.g. about a factor of 10.

Following that alarming observation, it was decided to install diagnostics to measure directly the electron cloud (E-Cloud) such as pick-ups with and without bias, retarding field, strip detectors and to test mitigation techniques like solenoids. The idea was to provide as much as result to benchmark the simulation code.

The preliminary measurements confirmed that the electron cloud is a threshold phenomenon which depends on the magnetic field conditions. A solenoid field (>20-30 Gauss) kills the E-Cloud build-up as a dipole field (bending areas of the SPS ring) reduces the threshold (around 3.10^{10} p/bunch for a 4 ns bunch length and 25 ns bunch spacing) as compared to the field free regions (threshold at 5.10^{10} p/bunch) in similar beam conditions. The quadrupole field regions behave in a different way.

The build-up depends on the beam potential e.g. bunch intensity, bunch length and emittance, the beam filling pattern e.g. bunch spacing, number of bunches per batch, length of the injection and extraction gaps. The simulations did reproduce all these observations.

Already in 2000, it appeared clearly that the E-Cloud would be a limitation for the SPS operation with LHC-type beams. The beam scrubbing periods were added to the SPS schedule after each shutdown e.g. 10 days of operation with LHC-type beams up to 1.7×10^{11} protons/bunch and 4 batches (72 bunches/batch). This scrubbing period aimed to produce a surface conditioning e.g. a decrease of the secondary electron yield of the inner vacuum pipe surface resulting from the electron bombardment.

The vacuum cleaning e.g. pressure improvement resulting from the induced electron stimulated desorption benefited the operation. As expected, the measurements confirmed that the venting to atmosphere or long time without LHC-type beams reset partly or totally the scrubbing benefits.

While operating with high bunch intensities (>10^{11} p/bunch), an E-cloud build-up was also observed in the Proton Synchrotron (PS), the injector of the SPS right before the extraction.

REVIEW OF DIAGNOSTICS AND MAJOR OBSERVATIONS

Pressure sensors

The electron from the cloud, getting energy from the beam potential will induce a local gas desorption when impacting the vacuum beam pipe walls. Therefore, the pressure sensors allowed measuring indirectly the E-Cloud build-up. Differences can be seen between dipole and field free regions as well as when varying the beam characteristics. The pressure increase can be plotted as a function of the bunch intensity to illustrate the threshold effect (Figs. 2 and 3) or as a function of time to show the fast pressure rises (Fig. 4).

When impacting the beam pipe walls, the electrons with an energy ranging from a few eV to 1 keV will induce a vacuum cleaning (decrease of the desorption yield by the electrons) and a beam conditioning (decrease of the secondary electron yield of the surface). Both effects are competing and lead to a decrease of the pressure rise with time as shown by Fig. 5.

The main limitation of this indirect observation is that the quantity of gas released depends both on the electron flux characteristics (number of electrons and energies) and on the gas surface coverage which evolve continuously.

The environment of the pressure sensor has to be taken into account: such as small aperture beam pipe with a limitation in conductance or the available pumping speed and type of pumps at the gauge location. And, not least, the beam pipe material and surface treatment.

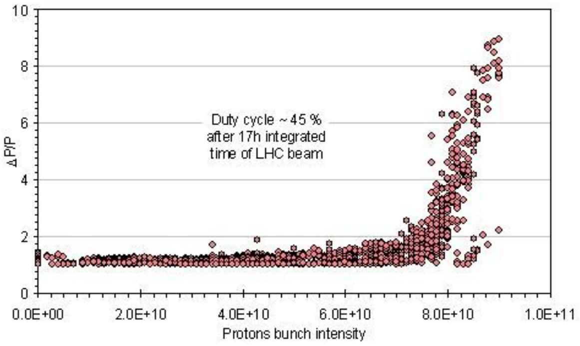

Fig. 2: *Pressure increase observed in the long straight sections (field free) of the SPS as a function of the bunch intensity.*

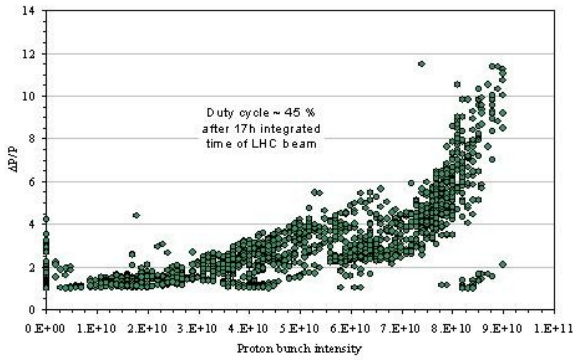

Fig. 3: *Pressure increase observed in the bending sections (dipole field) of the SPS as a function of the bunch intensity. The threshold of the E-cloud is around 3.10^{10} p/bunch.*

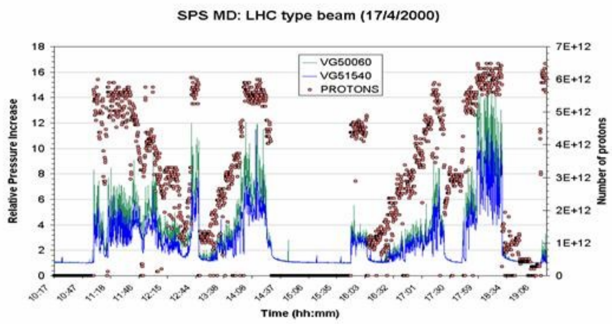

Fig. 4: *Pressure increase in the dipole field (VG50060) and field free (VG51540) regions as a function of time and of the bunch intensity.*

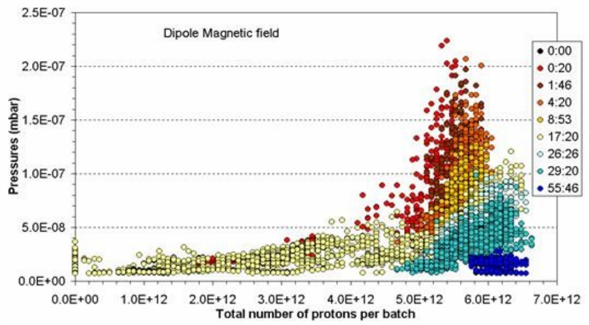

Fig. 5: *Pressure decrease resulting from the vacuum cleaning effect which results from the bombardments of the beam pipe walls by the electrons from the E-cloud. Beam conditioning and bunch dependence are observed, but the results not easily understandable*

Pick-ups

A simple pick-up design (Fig. 6) allows measuring the E-Cloud build-up with a turn-by-turn resolution (Fig. 7). Its operation in large accelerators requires the use of low impedance cables with an excellent shielding against electromagnetic perturbations. Using a slightly more complex design (Figs. 8-10) which includes a high voltage filtering grid and a collector repeller, the energy distribution of the electrons of the cloud can be measured (Fig. 11).

The energy distribution of the electrons is a parameter of major importance for the simulations since it allows determining the number of secondary electrons generated by the primaries when impacting the beam pipe walls after being accelerated by the beam potential.

As mentioned above, the signal-to-noise ratio is the limiting factor to use this type of diagnostics in the accelerators. In fact, increasing the collector transparency, e,g, increasing the detection signal, can lead to the perturbation of the E-cloud build-up and even to its extinction by an excessive collection of electrons. Using a moderate bias (<50 V) is an alternative which has been studied but the results showed clear indications that the E-cloud build-up gets perturbed. Under such condition, turn-by-turn measurements are excluded.

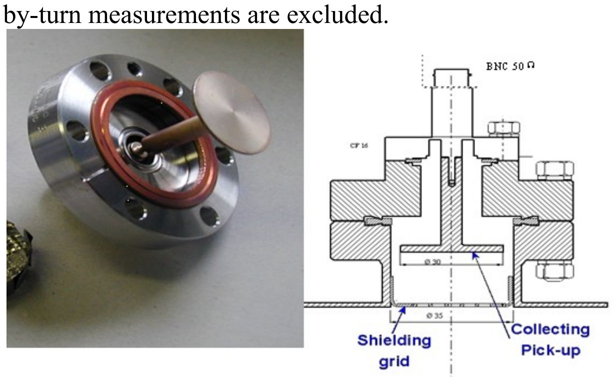

Fig. 6: *Design and picture of a simple shielded pick-up.*

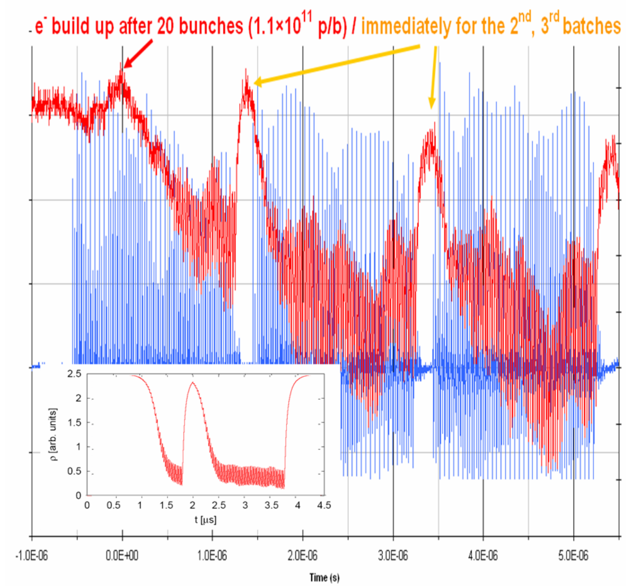

Fig. 7: *Electron cloud build up during a single passage of three LHC bunch trains (batches) measured by the shielded pick up, compared with a simulation for two batches (insert).*

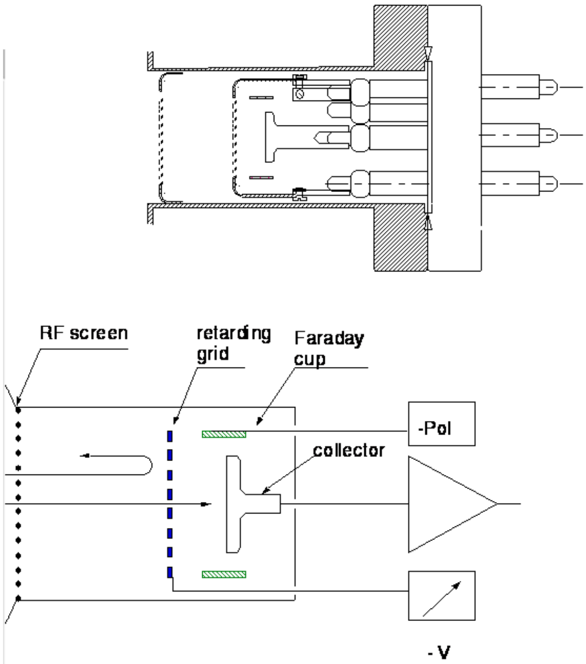

Fig. 8: *Design and operating principle of a shielded pick-up equipped with a HV filtering grid.*

Fig. 9: *Picture of a shielded pick-up equipped with a HV filtering grid.*

A screening against the beam is essential to get read off the beam potential contribution which is much larger than the one induced by the electron flux impinging the collector.

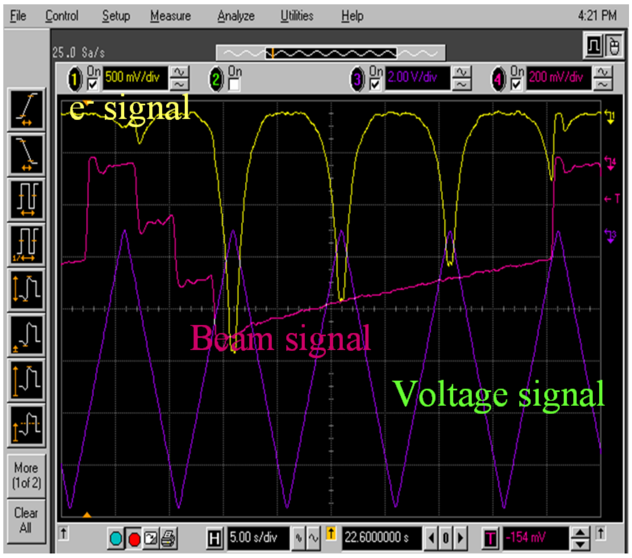

Fig. 10: *Operating principle of the pick-up equipped with a HV filtering grid. The HV is modulated by a triangular signal while the collector signal is acquired. The energy distribution is obtained by deriving the collector current against the HV voltage.*

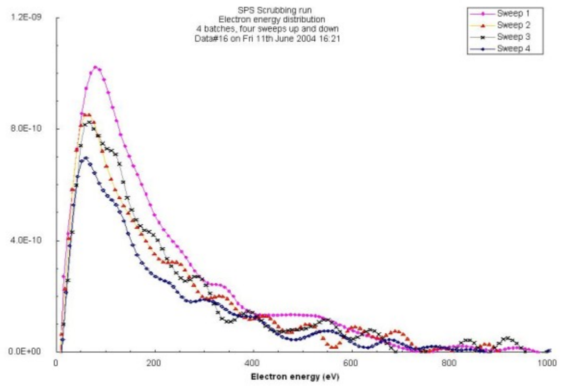

Fig. 11: *Energy distribution of the electrons in the E-cloud as a function of the number of batches injected in the SPS ring.*

Strip detectors

The strip detectors design (Fig. 12) was developed in 1999 to allow measuring quantitatively and with a transversal resolution, the E-cloud flux to the walls of the beam pipes. This detector was designed to use the fast and challenging electronic developed for the SemGrid detectors which are extensively used in CERN accelerators. Getting read off the design of a dedicated electronic saved two years and allows measurements already in 1999.

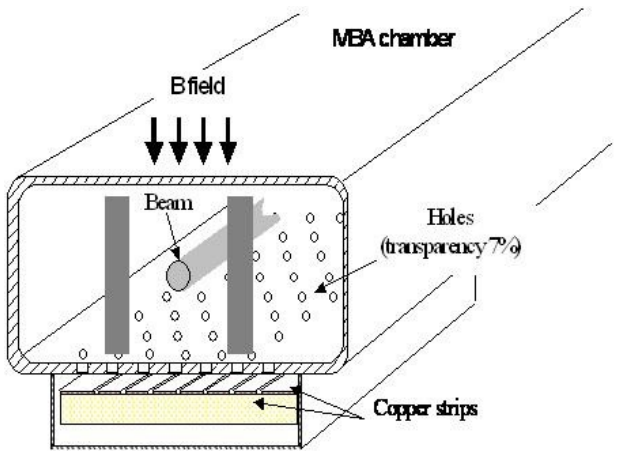

Fig.12*: Schematic view of the strip detector design.*

This type of detector which provides quantitative and reproducible measurements of the E-cloud flux to the wall of the beam pipes, appeared to be easy to use. As a consequence, the number of detectors installed amount nowadays to 8 units, 6 at CERN and 2 at RHIC (BNL Brookhaven National Laboratory-US).

The results provided by the strip detectors can be visualised in a 3-D plot where the x-axis (transversal axis) corresponds to the transversal position along the beam pipe, the y–axis to the time and the z-axis to the electron flux.

The compact design allowed its insertion inside dipole magnets to allow studying the E-cloud in dipole field conditions. Figures 13 and 14 show the typical signals obtained in field-free and dipole filed conditions respectively.

In field-free conditions, an homogeneous transversal electron density is expected which does not correspond to the result of Fig.14. The discrepancy is explained by the rectangular shape of the SPS dipole beam pipes.

In field free conditions

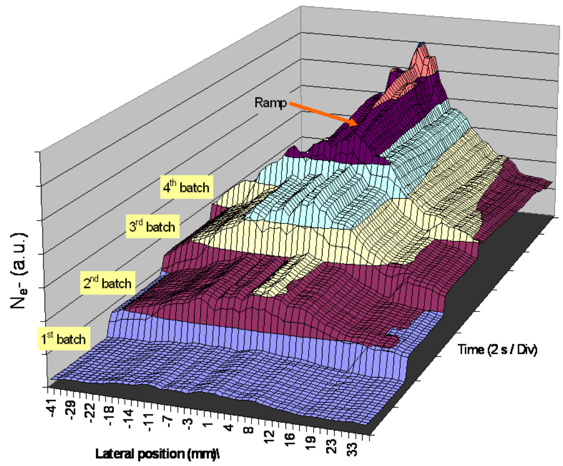

Fig. 13: *Typical output signal given by the strip detector when operated without a dipole field. Looking toward the time axis, the E-cloud build-up by steps results from the injection of a new batch (72 bunches) in the ring. After the 4th injection, the beam energy is ramped to 450 GeV.*

In dipole field conditions

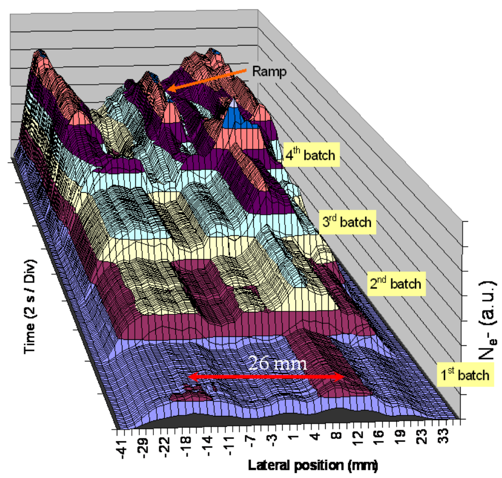

Fig. 14: *Typical output signal given by the strip detector when operated with a dipole field. Looking toward the time axis, the E-cloud build-up by steps results from the injection of a new batch (72 bunches) in the ring. After the 4th injection, the beam energy is ramped to 450 GeV.*

In the dipole field, the simulations had predicted two or three transversal strips depending on the bunch intensity. The two lateral strips will move away from the beam while increasing the bunch intensity. This transversal structure in two or three strips results from the confinement of the electrons along the magnetic field lines.

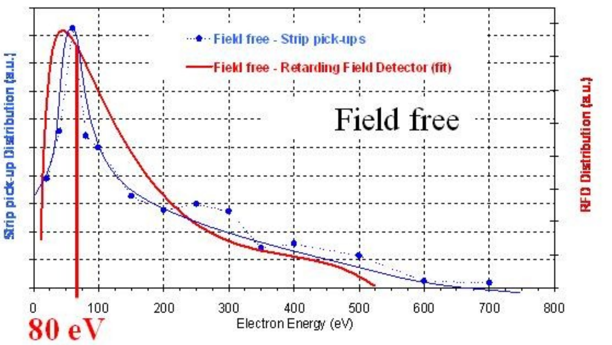

Fig. 15: *Energy distribution in a field free region measured by the strip detector equipped with a HV filtering grid.*

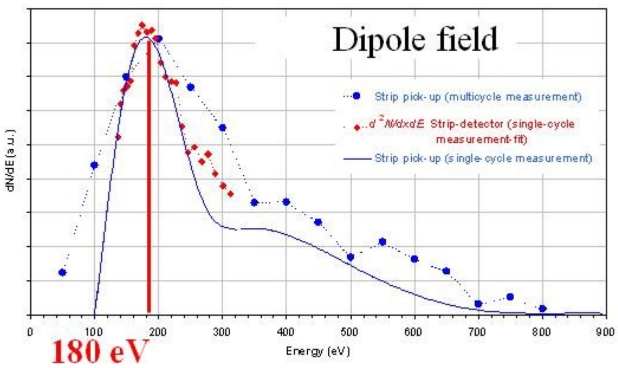

Fig. 16: *Energy distribution in a dipole field region measured by the strip detector equipped with a HV filtering grid.*

A more complex design installed in the SPS ring allowed a combined measurement of the spatial and energy distribution of the electrons in the cloud. These results were of major importance for the benchmarking of the simulation codes. Figs. 15 and 16 show the energy distribution in field free and dipole field respectively. These measurements match the one obtained with the pic-ups equipped with a HV filtering grid. The 3-D plot combining the measurement of the spatial distribution of the electrons and of their energy distribution is given by Fig. 17. It appears that the high energy electrons are concentrated in the central strip. This observation could explain why the central strip disappear faster as the high the electron energy and the faster the surface conditioning.

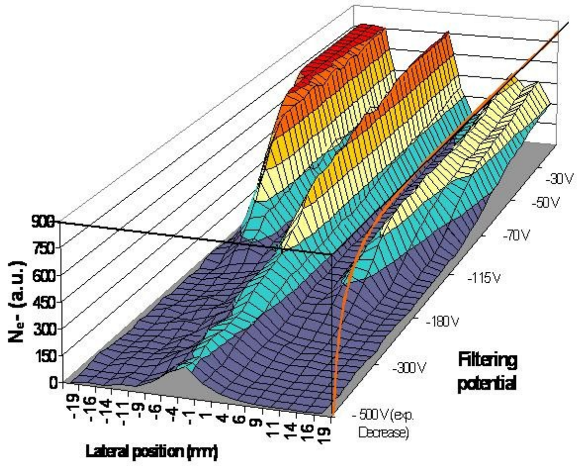

Fig. 17: *3-D plot obtained with a strip detector equipped with a HV filtering grid. The red curve on the right axis indicates the filtering potential in Volts.*

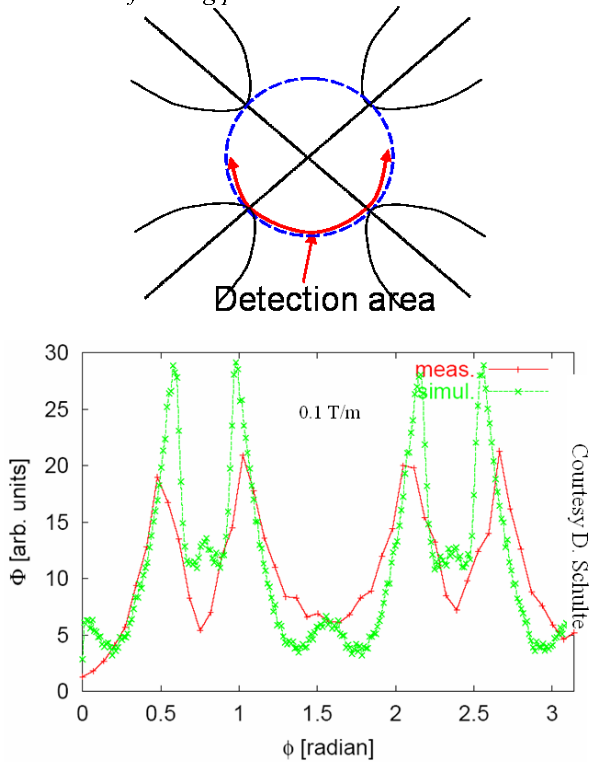

Fig. 18: *Simulations made for the quadrupole configuration.*

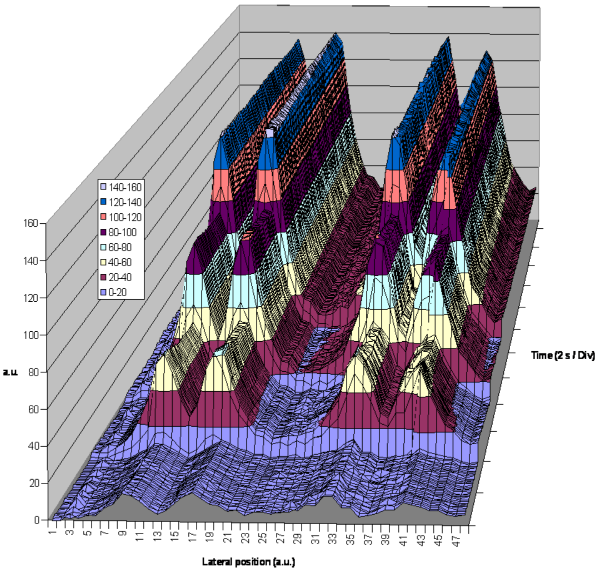

Fig. 19: *3-D plot obtained with the strip detector installed in a quadrupole. The detector covers half of the perimeter of the quadrupole.*

The results showed that the transversal electron density varies with beam position, the beam parameters (bunch intensity and length) and the magnetic field.

The energy distribution depends on the magnetic configuration and all these detectors are now installed inside remotely operated dipoles in order to compare the behaviour with and without a dipole field.

Similar measurements were made with a strip detector installed inside a quadrupole magnet and results were used for the benchmarking of the simulation codes (Figs. 18 and 19).

Any variation of the beam orbit can also be detected since, in dipole field, the two strips structure centered on the beam will follow any orbit displacement. Fig.20 shows an orbit displacement while ramping the beam energy to 450 GeV.

Another variant developed and used in the SPS allowed for measurements at cryogenic temperature (>20 K) in order to study the effect of condensed gasses (Fig. 21) at the exception of hydrogen and helium which require a much lower operating temperatures.

The main limitation of the strip detector is that it does not provide a quantitative measurement of the electron density through the entire energy spectrum. In fact, the low energy electrons lying nearby the beam pipe wall, commonly called surviving electrons, are not collected.

Another limitation is that this detector provides integrated measurements other thousands of turns. Due to the long distances in the SPS and to avoid an exposure of the electronics to the radiation in the tunnel, only integrated measurements are done e.g. integrating electron signal over several seconds (2 s minimum). Turn-by-turn observations are not possible since there require an installation of the electronic nearby (<50 cm) the detector.

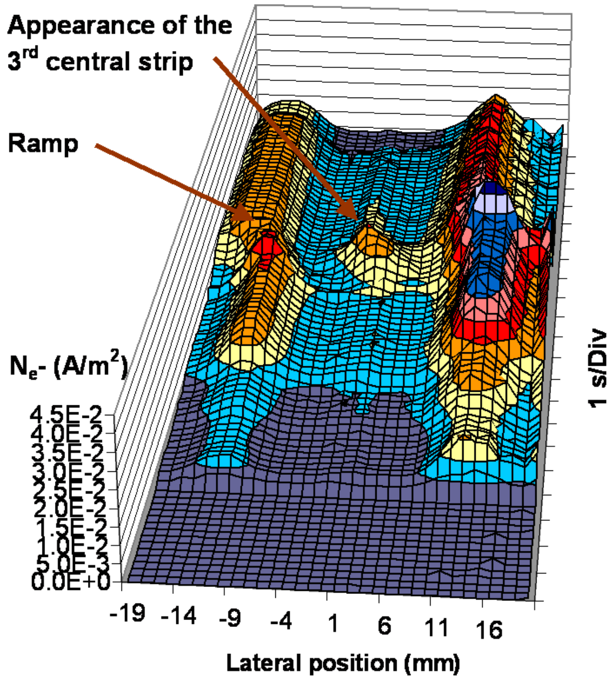

Fig. 20: *Orbit displacement measured by the strip detector while ramping the beam energy to 450 GeV.*

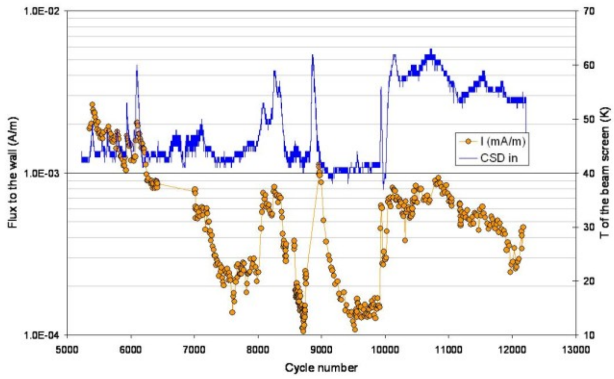

Fig. 21: *E-cloud density and temperature variation as a function of time measured with a strip detector operated between 20 and 40 K to study the effect of the condensed gasses.*

Secondary electron yield (SEY) measurements

The secondary electron yield (SEY) value of the inner surface of the beam pipe wall is one the key values together with the bunch intensity which defines the E-cloud build-up. The SEY value provides also indications of the conditioning state of the surface. This conditioning results from the bombardment of the surface by the electrons.

To measure and follow the evolution of the SEY in an accelerator, a SEY detector (Figs. 23 and 24) was installed in-situ to measure the SEY of a surface exposed to an electron bombardment inside the beam pipe. The set-up allowed measurements during the conditioning process (Fig.25) and confirmed that any exposure of the surface to air, e.g. during a venting of the vacuum system to atmosphere, will reset the SEY back to its initial value before starting the conditioning.

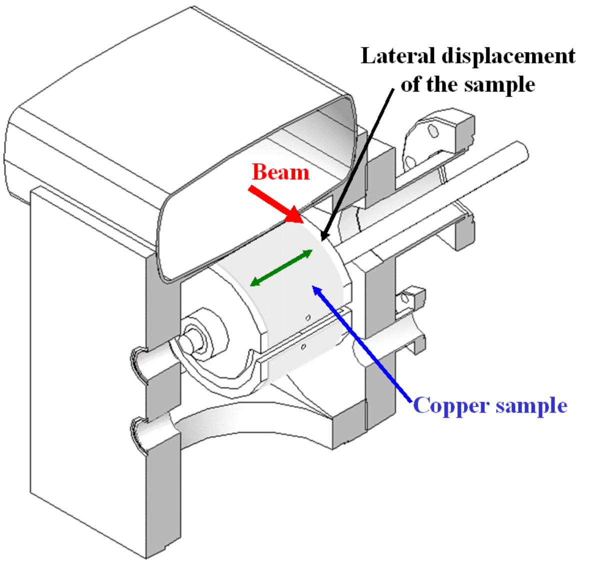

Fig. 23: *Design of the SEY detector with his rotating sample which allows for an in situ measurement of the SEY of the exposed surface. The transversal motion aimed to measure the impact of the two strips which build-up in presence of a dipole field.*

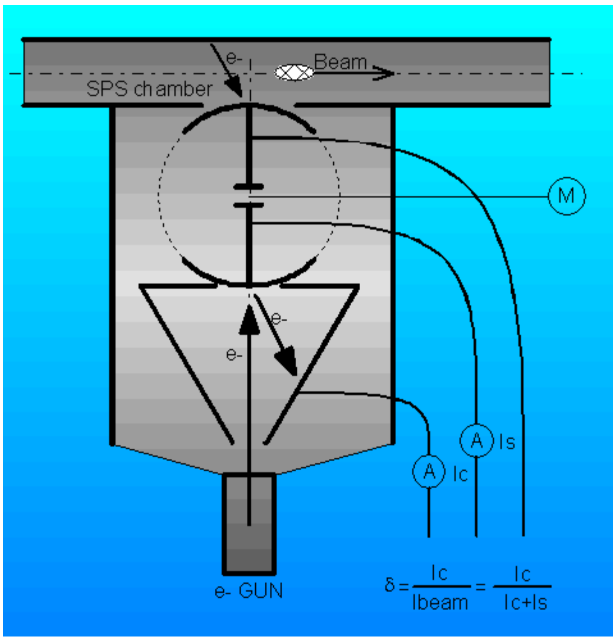

Fig. 24: *Schematic view of the SEY detector for in situ measurement.*

Due to the perturbations induced by the bunched beam circulation, caring on the measurements required several 5-8 minutes periods without beam. The size of the electron collector prevents the installation inside a dipole magnet and therefore only measurements in field free conditions were made.

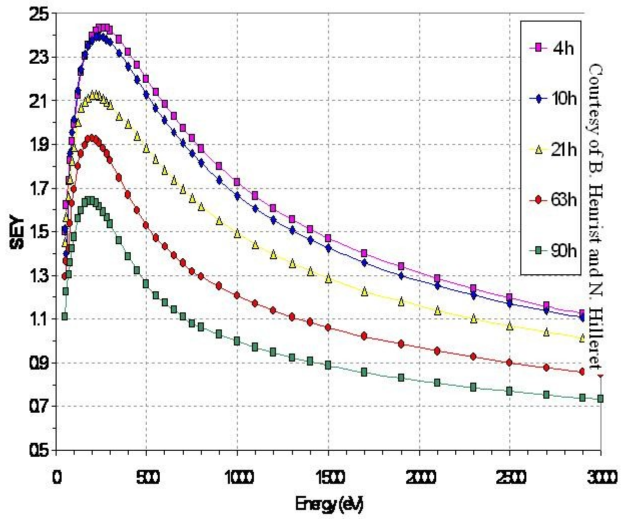

Fig. 25: *Curves showing the SEY as a function of the electron energy. The SEY decrease with time illustrates the conditioning effect.*

As a side effect from beam losses, the electronics which was installed inside the SPS tunnel suffered a lot and lead to the removal of these expensive diagnostics immediately after the completion of the measurement campaign.

An alternative solution has been installed in a dipole magnet which allows the exposure of a sample to the electron bombardment and then its transportation to the measuring stand in the laboratory. This transportation is made under vacuum to prevent changes of the surface characteristics.

RF transmission measurements

This experiment was initially proposed and implemented in the SPS tunnel to qualify and quantify this set-up for its future use in the LHC arcs, in which no diagnostics apart from the heat load measured on the cryogenic system is available.

Very soon, it appears that this system will also be of use in the SPS to qualify the new coatings for E-cloud mitigation.

The principle consists in injecting an RF signal inside the beam pipe through a dedicated antenna and to collect the signal at another antenna. The distance between antennas in the SPS is limited by the quality of the RF shielding inside the vacuum pumping ports.

In presence of an E-cloud, the RF signal get perturbed proportionally to the electron density and cloud length.

The measurements carried on in the SPS were successful and confirmed the potentialities of this technique as an E-cloud diagnostic tool. The calibration against the pick-up signals will allow extracting quantitative measurements.

As it can be expected, the length of the signal and electromagnetic perturbations is a limitation in addition to the quality of the RF continuity, already mentioned above.

Future Diagnostics

During the SPS shutdown 2008-09, the instrumentation in the PS and SPS accelerators will be completed by a new version of the repeller detector (pick-up with a HV repeller) to complete the measurements of the electron density and energy distribution of the electrons in the cloud. This new version has been optimised to reduce the electromagnetic noise and allows for a fast extraction of the electrons from the cloud.

In the PS, a calibration stand has been installed for quantitative measurements of electron densities using the RF transmission method.

The area with 4 strip detectors in the SPS has been rearranged as a test bench to validate mitigation coatings on dipole magnets, new coatings, surface roughness, clearing electrodes, etc.

As a complement, laboratory stands have been set- up to study the SEY of condensed gasses on cold surfaces and the dose effects.

APPLICATIONS OF E-CLOUD STUDIES

The E-cloud studies which started in 1999 at CERN, have already resulted in practical applications on existing or new accelerators.

The best example is the modification of the LHC beam screen to avoid additional heat loads induced by electrons impacting directly the cryodipole cold bore inducing an unacceptable additional load to the cryogenic system. It is expected that the electron shields implemented on all LHC arc beam pipes will prevent from an E-cloud early limitation of the LHC performances.

In the SPS and aiming to increase the bunch intensity and reducing the beam instabilities, a “Beam scrubbing” period, about 10 days in total, was introduced in the operation schedule.

Experience has been gain on the optimisation of the RF gymnastics and damping of the beams to reduce instabilities and emittance blow-up and for the benchmarking of simulation codes.

Finally, the existing instrumentation allows validating the mitigation techniques which are being studies for the SPS upgrade and onward for the new accelerator projects using high bunch intensity proton beams.

E-CLOUD LIMITATIONS

As already mentioned, the beam conditioning which decreases the SEY of the beam pipe surfaces is the most efficient way to reduce the E-cloud build up. However, this process has an intrinsic auto limitation since the electron dose reduces the SEY resulting in a decrease of it. Then, the SEY will decreases slower until the E-cloud threshold is reached leading the SEY to stays constant.

Therefore, starting at a lower SEY could save beam time but does not solve the E-cloud induced limitations. In addition, venting to atmosphere will reset the SEY.

On high energy proton accelerators or photon factories, the electron reduction can be partly compensated by other source of electrons: the low-energy electrons surviving the gap between bunches and accumulating close the beam pipe walls (high reflectivity), the photo-electrons resulting from the synchrotron radiation and the beam losses. The electron trapping in quadrupole could still be an issue, more than 2 km in the LHC.

The cold surfaces e.g. LHC bending areas have additional constraints. The retrofitting of a mitigation technique would take time and will be very expensive (beam screens) and the configuration of the cold/cryostat makes difficulties to install E-Cloud instrumentation.

Finally, the benchmarking of simulation codes shall continue but this require to develop new instrumentation to provide measurements of the E-cloud density over the entire energy spectrum, with special focussing on the low energy < 20 eV) range.

ACKNOWLEDGEMENTS

The work presented here is the result of several years of work and studies of many colleagues working with and in the field of accelerator physics at CERN and in the world through collaborations. It will be a challenge in itself to cite all the people involved.

After many years of studies, conceptions, designs, procurements, installations and measurements, the progresses made is the result of their efforts. Among these contributors, I would like to acknowledge the work carried out by B. Henrist who has actively contributed to the design and installation of the hardware in the SPS tunnel.