ELECTRON CLOUD IN THE SPS
SUMMARY

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1 INTRODUCTION

The session summarised here was devoted to electron cloud effects in the SPS and LHC. Eight talks were presented, covering recent experimental observations in the SPS with LHC type beams with 25 ns bunch spacing, measurements of surface properties, simulation results, potential remedies for the SPS vacuum system, and alternative filling schemes from the PS.

- The first talk by F. Ruggiero [1] gave a short introduction to some key concepts relevant to the discussion of electron cloud effects and their implications for PS, SPS and LHC operation.
- This was followed by a talk given by W. Höfle [2] who reported about strong perturbations on pick-up signals of the SPS transverse feedback system (damper), observed with LHC type beams and attributed to the electron cloud effect. He also presented observations with a solenoid magnetic field and encouraging tests with new electronics, working at a multiple of the bunch frequency.
- SPS vacuum observations and, in particular, the dependence of the measured strong pressure rise on various beam parameters were reported in the third talk by J.M. Jimenez [3]. Also electron currents collected by a dedicated, shielded pick-up as well as first indications of some conditioning effect were discussed.
- The last talk on SPS experimental observations by G. Arduini [4] focussed on a fast instability, accompanied by emittance blow-up and beam losses. The effect is more pronounced in the horizontal plane and affects mainly the tail of the batch.
- N. Hilleret [5] gave an overview of secondary electron yield (SEY) measurements for pure metals versus technical surfaces, performed by an electron gun and a collector cage, with very low primary electron currents. He discussed the effect of oxide layers, adsorbed water, and special surface treatments, including bake-out, freon processing, glow discharge, low emissivity coatings, electron and photon dosing.
- Simulation results for SPS and LHC were presented by F. Zimmermann [6], who explained how the electron cloud build-up is modelled and what are the potential implications for the heat load on the LHC beam screen and for beam stability in the SPS and LHC.
- I.R. Collins [7] discussed possible remedies, including surface conditioning by photon scrubbing and electron bombardment.
- Finally R. Cappi [8] reported about methods to produce gaps in the bunch train of the LHC beam via RF manipulations in the PS.

2 PHYSICAL MECHANISM OF THE ELECTRON CLOUD BUILD-UP

In the LHC, photoelectrons created at the pipe wall are accelerated by proton bunches up to 200 eV and cross the pipe in about 5 ns. Depending on the bunch spacing, a significant fraction of secondary electrons is lost in between two successive bunch passages, but slow secondary electrons survive until the next bunch and are again accelerated up to several keV (see Fig. 1 in Ref. [1]). This *non resonant* mechanism may lead to an electron cloud build-up with implications for beam stability, emittance growth, and heat load on the cold LHC beam screen.

The average number of secondary electrons generated when a primary electron hits the pipe wall with a given incidence angle depends on the chemical composition of the surface and on its roughness [5]. It is described by a universal curve characterised by two material parameters: the maximum secondary emission yield $\delta_{\rm max}$ and the energy at which the yield is maximum (see Fig. 11 in Ref. [6]). Each bunch passage can be considered as the amplification stage of a photo-multiplier: a minimum gain is required to compensate for the electron losses and this corresponds to a *critical secondary electron yield* $\delta_{\rm cr}$, typically around 1.3 for nominal LHC beams (see Fig. 18 in Ref. [6]). When $\delta_{\rm max} > \delta_{\rm cr}$, the electron cloud is amplified at each bunch passage and reaches a saturation value, determined by space charge repulsion.

The electrons are *not* trapped in the proton beam potential, but form a time-dependent cloud extending up to the pipe wall. In field-free regions this cloud is almost uniform, while in the dipole magnets the electrons spiral along the vertical field lines, with typical Larmor radii ranging from a few μm in the LHC to a few hundreds μm in the SPS, and tend to form two stripes at about 1 cm away from the beam axis, where the average energy gain corresponds to the maximum SEY (see Figs. 29 and 30 in Ref. [6]). Since the vertical dimensions of the LHC beam screen and of the SPS vacuum chamber are very similar, the corresponding critical SEY is the same for both machines. However the mechanism that triggers the electron cloud build-up is different. In the LHC at 7 TeV, each proton generates 10^{-3}

photoelectrons/m, while in the SPS the critical photon energy is not sufficient to create photoelectrons and the primary yield is dominated by ionization of the residual gas: at 10 nTorr the latter is only 10^{-7} electrons/m per proton [6]. This is one reason why electron cloud effects were not anticipated in the SPS, the other reason being that it was reasonable to expect a substantial surface conditioning of the SPS vacuum chamber after so many years of operation, especially with leptons (photon scrubbing). However the SPS vacuum chamber is often vented and this may create oxide and/or condensed water layers with high SEY (see Figs. 5 and 6 in Ref. [5]). In addition, synchrotron radiation masks reduce or prevent photon scrubbing.

3 ELECTRON CLOUD EFFECTS IN THE SPS: EXPERIMENTAL EVIDENCE

Here is a rather convincing list of SPS observations supporting the conclusion of an electron cloud build-up with LHC type beams:

- A *similar threshold bunch intensity* $N_{\rm b} = 2.5 \div 5 \times 10^{10}$ is observed for damper pick-up signals, distributed pressure rise and beam instability, when the bunch spacing is 25 ns. This is in good agreement with electron cloud simulation results, assuming a maximum SEY $\delta_{\rm max} \simeq 1.9$ (compare the simulated electron cloud build-up of Fig. 23 in Ref. [6] with the signals measured at the damper pick-ups, shown in Figs. 4a and 5b of Ref. [2], or with the observed relative pressure rise of Fig. 7 in Ref. [3]).
- Ion effects are excluded, since they would depend on the integrated charge over several bunches, while no effect is observed with different bunch spacings and the same total batch intensity [2]. Moreover the observed threshold bunch intensity has a *weak dependence on the residual gas pressure*, contrary to ion effects and in agreement with electron cloud simulations (see Fig. 26 in Ref. [6]).
- There is direct evidence of *negative charge* (electrons), collected by a dedicated pick-up with a shielding grid, correlated with beam intensity and bunch pattern (see Fig. 14 in Ref. [3]).
- There is *no correlation* of the damper pick-up signals with local orbit, beam losses, or previous operation with lepton beams.
- The threshold intensity for damper pick-up signals *doubled* by applying a 100 Gauss *solenoid field*.

First observations of anomalies in the behaviour of the SPS damper with LHC type beams date back to September 1998. In June 1999 the problem persisted and could be attributed to baseline jumps in the signals of all the eight electrostatic pick-ups, as shown in Figs. 1 and 2 of Ref. [2]. This phenomenon occurs only beyond a threshold bunch intensity $N_{\rm b} \sim 4 \div 5 \times 10^{10}$ of the 2 μs LHC batch with 25 ns bunch spacing and the baseline drift starts after the passage of some 30-40 bunches. No baseline drift was observed with 130 ns bunch spacing and $N_{\rm b} \sim 2.5 \times 10^{11}$, nor with 5 ns bunch spacing and $N_{\rm b} \sim 10^{10}$, in agreement with simulation results (see Fig. 28 in Ref. [6]).

A modest solenoid field was effective in curing the baseline jumps, but limited to 100 Gauss (20 A) by heating problems. Above an LHC batch intensity of 5×10^{12} protons, the solenoid field was insufficient. This is qualitatively understandable in view of the keV energies acquired by electrons near the beam axis and is in marked contrast to the results of multipacting tests, performed with a multiwire chamber and a 100 W wide-band amplifier [7]. In the last case, the maximum electron energies are limited to about 100 eV and a week solenoid field completely suppresses the electron cloud build-up.

The observations of the damper pick-up signals show that the baseline jumps are not present at multiples of the 40 MHz bunch frequency. An effective solution to provide a clean signal for the damper in the year 2000 is therefore to mix the beam position Δ-signals with a beam synchronous RF reference signal at a multiple of the bunch frequency, for example 120 MHz, down to baseband for further processing (see Fig. 8 of Ref. [2]).

3.1 Do we understand all SPS observations?

In spite of the experimental evidence for an electron cloud effect in the SPS and of the significant agreement with simulations, there are some observations that still require analysis and understanding. For example, the threshold for baseline jumps in the damper pick-up signals *decreased* by about 30% during summer 1999 and then increased during the ion run in autumn, going back to its original value of the beginning of the 1999 run. Also the influence of a bias voltage applied to the pick-up electrodes is not completely understood, since the optimum voltage changed from day to day [2].

Moreover, violent baseline jumps in the damper pick-up signals are observed *at injection* or when the beam is transversely kicked. The reason is *unclear*, although there may be some relation with the narrow vertical strips shown by electron cloud simulations in the dipole magnets. A tentative conclusion is that transverse RF beam shaking during surface conditioning might be beneficial and improve the uniformity of the beam scrubbed surface.

A fast horizontal instability with a rise time of 20-25 turns is observed in the SPS above a threshold LHC batch intensity of 4×10^{12} protons (see Fig. 10 of Ref. [4]). The observations have been performed with couplers equipped by a 200 MHz receiver, not affected by the electron cloud induced baseline distortions of electrostatic pick-ups, and beam oscillations have been monitored at six consecutive slices along the batch. The instability mainly affects the batch tail, saturates and leads to emittance blow-up and beam losses. There is a slower instability also in the vertical plane, possibly associated with non-optimum adjustment of the transverse feedback gain. Vertical oscillations in the range 400 to 800 MHz are observed with a vertical wide-band pick-up and may be associated with single bunch activity. This fast instability might be interpreted as a single bunch, *beam break-up* instability caused by the short range wakefield in the electron plasma; preliminary estimates [6] assuming an electron cloud density of 10^{11} electrons/m^3 lead to a rise time of 500 μs, or 20 turns, very close to the observed instability rise time. If this instability mechanism is confirmed, it can not be easily cured by the damper. On the other hand it should disappear after surface conditioning, since the electron cloud build-up would then be suppressed.

3.2 Cures against the electron cloud build-up

Laboratory measurements indicate that electron bombardment at a few hundred eV is one of the most effective means to reduce the SEY of a technical surface. For example an *electron dose* of about 1 mC/mm^2 leads to a significant reduction of $\delta_{\max}$ and to a positive shift of the energy corresponding to the maximum yield (see Fig. 16 of Ref. [5]). An *electron dose* of 5×10^{-5} C/mm^2 is the observable limit for surface conditioning [7]. With the present 5% duty cycle, an observable surface conditioning by the electron cloud bombardment is expected within a 12 hour running period: this prediction seems in agreement with SPS vacuum observations (see Fig. 10 of Ref. [3]), although only three gauges out of twenty show a modest pressure decrease between 7 and 13%. It appears that a substantially higher duty cycle will be needed in the year 2000 for surface conditioning.

Other possible remedies against the electron cloud build-up include clearing electrodes, plasma conditioning with memory effect (e.g. with Freon11), ex-situ coating with low emissivity materials (e.g. TiN or TiZrV) and ex-situ or in-situ bake-out [7]. The latter is not practical for the SPS dipole vacuum chambers.

An alternative solution is to produce gaps in the LHC batch by means of RF manipulations in the PS [8]. For example, starting from seven PS Booster bunches and applying three subsequent bunch splittings yields a modified LHC bunch train consisting of 56 bunches with gaps of four missing bunches every eight bunches. As shown by the simulation of Fig. 39 in Ref. [6], the electron cloud build-up would be suppressed for a maximum SEY of 1.5. For a higher maximum SEY of 1.9, one should resort to a reduced fill pattern consisting of a sequence of four LHC bunches followed by four missing bunches, etc. (see Fig. 41 in Ref. [6]. Alternatively the bunch spacing could be 50 ns and the bunch intensity $\sqrt{2}$ higher than the nominal intensity. This solution would still provide the design luminosity to three of the four LHC experiments, but the event multiplicity would be doubled. However two beams with 50 ns bunch spacing would not collide at IP8, since LHCb is longitudinally displaced by 3/2 of an RF bucket. Satellite bunches with a few per cent of the nominal intensity could then be added at the empty nominal positions to provide the required low luminosity. As shown in Fig. 37 of Ref. [6], there would still be suppression of the electron cloud build-up.

4 DISCUSSION AND CONCLUSIONS

During the discussion, F. Caspers pointed out that one physical mechanism not included in the simulations is the possible ‘magnetron effect’ associated with the electron cyclotron motion in the magnetic field of the dipoles. The latter has a frequency of about 28 GHz/Tesla and, under special resonance conditions, may give rise to a coherent RF modulation of the beam. The incoherent radiation due to the electron cyclotron motion can not exceed the kinetic energy of the electron cloud and is therefore already included in the estimated heat load on the LHC beam screen.

The electron cloud build-up is a *single pass* effect and, as shown by the SPS experience, it can be triggered by a few primary ionization electrons. Therefore, for a maximum SEY above the critical value, the build-up may take place also in the *transfer lines* and in the *LHC at injection*.

4.1 Heat load on the LHC beam screen

An effective solution to reduce the maximum SEY below its critical value is to condition the LHC screen surface, either by synchrotron radiation photons or using electrons [5] accelerated by a special proton beam, with increased bunch spacing or weak satellite bunches, thus clearing slow secondary electrons. To keep the heat load due to electron cloud build-up in the LHC dipoles within the cooling capacity of the cryogenic system (about 1 W/m per beam), it is foreseen a beam screen with ribbed surface and reduced reflectivity [9]. For example, with a reflectivity of 10% and nominal LHC beam parameters, the heat load in the dipoles goes from 5 W/m for an initial $\delta_{\max} = 2.3$ down to 42 mW/m for a final $\delta_{\max} = 1.1$, after surface conditioning (see Table 2 in Ref. [6]). It is clear that the nominal LHC beam can not be used during the initial conditioning phase, since the cryogenic limit would be largely exceeded. However, one can control the electron cloud build-up and operate the LHC with a special ‘conditioning beam’. Assuming a tolerable heat load around 200 mW/m, the beam scrubbing time would be about 35 hours.

To clarify the relative merits of a dipole screen with low reflectivity, let me recall that synchrotron radiation photons travel practically in synchronism with the proton bunch from which they are emitted, even after several reflections. These photons hit the LHC beam screen along a strip extending a few mm above and below the horizontal plane. Photoelectrons created near the horizontal plane are harmless in the dipole magnets, since their effective acceleration depends only on the small vertical component of the beam electric field. For low screen reflectivity only a few photons are scattered away from the horizontal plane, towards the (flat) top and bottom regions, where they can create ‘dangerous’ photoelectrons and contribute to the heat load. A low screen reflectivity does not significantly reduce the heat load unless $\delta_{\rm max} < \delta_{\rm cr}$, as shown by the simulation in Fig. 32 of Ref. [6]. On the other hand, a low screen reflectivity may have the drawback that photon scrubbing takes longer to condition the most sensitive, top and bottom regions.

4.2 *SPS strategy for the year 2000 and needs for future MD's*

In conclusion, I report here a list of recommendations and comments to study, understand and master electron cloud effects in the SPS during the year 2000. Before the SPS start-up:

- Install a few vacuum chambers with special *low-emissivity coatings*.
- Remove some of the synchrotron radiation masks?
- Install solenoids and/or clearing electrodes in (some) straight sections, *measure SEY in situ*.
- If possible, adopt a *more strict policy* for vacuum chamber opening. P. Collier remarked that this will not be possible before 2-3 years.

At the SPS start-up:

- Fix baseline drift of damper pick-up $\Longrightarrow$ *work at 120 MHz*.
- Repeat measurements of *beam emittance and instability*, vary beam parameters (RF voltage, chromaticity, etc.) and develop minimum software for *fast correlation plots*.
- Compare with simulations and draw conclusions for LHC.

As soon as possible in the SPS:

- Condition beam pipe surface by beam scrubbing $\Longrightarrow$ need dedicated MD time (several hours) with *high duty cycle*.
- Monitor electron cloud threshold (increase acquisition rate on more vacuum gauges, measure treated chambers, etc.).
- If threshold does not increase with beam scrubbing after several A h $\Longrightarrow$ as a last resort, try local injection of Freon?
- Test suppression of electron cloud in straight sections by solenoid fields and/or clearing electrodes.

As soon as possible for the PS and/or SPS:

- Test *satellite bunches* at 3 ns distance from nominal LHC bunches. T. Linnecar reported that it may be possible to generate such satellites in the SPS, using the 800 MHz cavities.
- Test new PS schemes for LHC type beams with *gaps and/or 50 ns spacing*.
- Repeat measurements of *beam emittance and instability*, vary residual gas pressure, bunch intensity, etc.

5 REFERENCES

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