ELECTRON CLOUD EFFECTS, VACUUM (SPS+LHC) SUMMARY

F. Ruggiero, SL Division, CERN, Geneva, Switzerland

1 OVERVIEW

The session summarised here was devoted to Electron Cloud Effects and Vacuum in the SPS and LHC. Seven talks were presented, covering recent experimental observations of electron cloud effects at the KEK-B Low Energy Ring (LER), measurements of surface properties at EPA, simulations of electron cloud build-up and heat load, vacuum observations and electron scrubbing in the SPS with LHC type beams, SPS measurements of electron cloud impedance, and theory and simulations of the electron cloud instability.

- In the first introductory talk [1] I shortly reviewed the main conclusions and recommendations on electron cloud effects in the SPS and LHC from the last Chamonix workshop. One important recommendation was to devote several days of LHC type beam with high duty cycle to the conditioning of the SPS beam pipe: this recommendation was implemented in April 2000. However it was possible to schedule dedicated electron cloud MD's and systematic beam measurements (reported in Session 3) only several months later, after the SPS beam pipe had been vented.
- In the following talk K. Oide [2] presented recent observations and cures of electron cloud effects at the KEK-B positron ring. In particular, he reported about unexplained memory effects in the observed blow-up of the single-beam vertical size, successful reduction of the blow-up by permanent magnets and weak solenoids, having a positive impact on the luminosity, nonlinearity of the vacuum pressure versus beam current, tune-shift due to the electron cloud, observation of electron current and energy spectrum.
- Experiments performed at cryogenic temperature with the COLDEX apparatus, installed on an external EPA synchrotron radiation beam line and in the EPA ring itself, were reported in the third talk by V. Baglin [3], together with 'scrubbing' results obtained by photon irradiations of LHC beam screen samples at room temperature. In addition to a significant reduction of the photoelectron and secondary electron yield (SEY) after an accumulated electron dose of a few mC/mm^2, these measurements indicate a probability of nearly 60% of elastic reflection at the beam screen surface for electrons with energies around 10 eV. It was reported that, after scrubbing, this probability is reduced to about 40%.
- New simulation results for SPS, PS, and LHC were presented by F. Zimmermann [4], who explained how the electron cloud build-up and its persistence after a long gap in the bunch train can be dramatically enhanced by elastically reflected or re-diffused low-energy electrons. The consequent heat load on the LHC beam screen is correspondingly increased. From these simulations one can derive the local cloud density on the beam axis, for further studies of the induced single bunch instability, and the rate of electron bombardment on the pipe surface, to estimate the duration of surface conditioning implied by the different filling patterns. In addition, F. Zimmermann discussed the possible perturbation of beam diagnostics by incident electrons, the requirements for dedicated electron-cloud monitors, and the suppression of the electron cloud in field-free regions by a weak solenoid.
- SPS vacuum observations during 2000 and, in particular, the dependence of the measured dynamic pressure rise on various LHC type beam parameters as well as the electron current collected by a dedicated pick-up, were reported in the fifth talk by J.M. Jimenez [5]. These vacuum observations clearly indicate a reduction of dynamic pressure rise after electron scrubbing, but this is not (yet) accompanied by a corresponding increase of the threshold intensity for beam instability and emittance growth.
- In the following talk, K. Cornelis [6] discussed the contribution of the electron cloud to the total SPS transverse impedance, based on betatron phase advance differences between the head and tail of an LHC bunch measured by a wide-band pick-up. Comparing data for bunches at the beginning and at the end of the batch gives an empirical measurement of the electron cloud impedance and indicates a short-range wakefield in the vertical plane and a horizontal wakefield extending over several bunches.
- In the last talk, G. Rumolo [7] reported about computer simulations of single bunch instabilities driven by a quasi-stationary electron cloud. The proton (or positron) bunch and the electron cloud are modelled by two sets of macro-particles that interact at discrete locations along the beam orbit. Consistently with analytic estimates, the emittance growth depends on the number of electron oscillations during a bunch passage and saturates when the latter approaches unity,

as in the case of the SPS. For a cloud density of 10^{12} electrons/m^3, the predicted emittance growth is modest and only weakly dependent on chromaticity (above transition). Preliminary results including an additional broad-band impedance, to model conventional wakefields, indicate that this is a key ingredient to account for the dipole beam instability observed in the SPS. Such additional broad-band impedance, possibly in conjunction with a higher electron cloud density, may also lead to predicted emittance growths closer to SPS observations [8].

- These talks were followed by a general discussion triggered by short presentations on surface treatments, solenoids, and multipacting tests (by O. Gröbner and N. Hilleret), and electron cloud diagnostics for the LHC (by H. Schmickler).

2 DISCUSSION

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. Electron cloud effects have been recently observed also in the PS, during bunch compression prior to extraction of the LHC type beam, and in the TT10 transfer line (leading to some perturbation of beam diagnostics).

2.1 Measurements of surface properties and electron scrubbing

COLDEX results in EPA have demonstrated the effectiveness of the perforated LHC beam screen, in conjunction with the external cold bore, in maintaining the residual gas density at the desired low level (around $10^{15}\,\mathrm{m}^{-3}$ for H_2 molecules) even under synchrotron radiation bombardment.

Irradiation measurements at room temperature, on samples of the LHC beam screen with saw-tooth structure, show that the forward reflectivity is reduced down to 6-8% (from 77% for a Cu colaminated smooth surface). The photoelectron yield is 0.03 electrons per absorbed photon (at 45 eV) before irradiation and drops to 0.015 after a dose of 1.5×10^{22} photons/m, corresponding to about two days of nominal LHC operation at 7 TeV. Measurements of total electron emission yield indicate that an electron dose of $10\,\mathrm{mC/mm}^2$ is necessary to scrub the surface and achieve a maximum yield of 1.2; in the LHC this dose corresponds to three days in the dipoles and ten days in the field-free regions, assuming an electron cloud bombardment with mean energy of 100 eV and power deposition limited to $0.2\,\mathrm{W/m}$. Low-energy electrons or reflected photons scrub the surface much less efficiently than electrons with energies above 100 eV.

The Seiler formalism alone can not fit the total electron yield measured at EPA for low primary electron energies, which can be explained only by a substantial probability of elastically reflected or re-diffused electrons. The results of a fit for these low-energy data were presented in the talk by V. Baglin and have been used in the simulations by F. Zimmermann (see Eqs. (2) and (3) in Ref. [4]). However, there seems to be a discrepancy between these EPA results and the results of SEY laboratory measurements by N. Hilleret (although the controversy may turn out to be mainly semantic, and associated with the difference between *total* and *secondary* electron emission). N. Hilleret pointed out in subsequent discussions that one should also make a clear distinction between surface *cleaning* after electron bombardment, associated with the reduction of residual gas pressure due to electron stimulated desorption, and surface *conditioning*, i.e., the reduction of SEY. This is not merely a semantic distinction, since the two physical processes are different and require different electron doses. In particular this implies that, to achieve a significant reduction of SEY, electron scrubbing should continue even after the vacuum pressure has significantly dropped.

2.2 Experimental evidence for an electron cloud effect in the SPS

The experimental evidence accumulated during 1999 for an electron cloud effect in the SPS with LHC type beams with 25 ns spacing [10] has been confirmed during the year 2000. Above a threshold bunch intensity of about $4 \div 5 \times 10^{10}$ protons, a transverse beam instability is accompanied by distributed pressure rise, baseline jumps in the damper pick-up signals and electron current collected by a dedicated electron probe. Simulations are in qualitative agreement with observations, assuming a maximum SEY $\delta_{\max} \simeq 1.9$ and a substantial probability (around 50%) of elastic reflection for low-energy electrons.

The transverse instability is observed only for a bunch spacing of 25 ns[1] and the growth rate increases from the head to the tail of the LHC batch [8]. An additional, very convincing observation by K. Cornelis in favour of electron cloud rather than conventional (say resistive wall) instability is that among the bunches in the tail of the LHC batch, the one with the highest intensity also has the highest instability growth rate. For a conventional instability, driven by short-range wakefields, one would rather expect that bunches *following* the one with the highest intensity should be more unstable.

During the year 2000, the baseline jumps in the damper pick-up signals have been successfully overcome by signal processing at 120 MHz and the performance of the SPS damper with LHC type beam has improved [9]. Above the instability threshold, a *positive* coherent vertical tune shift is observed, increasing from the head to the tail of the LHC batch. For an LHC batch of 72 bunches and a bunch population $N_\mathrm{b} = 8 \times 10^{11}$ protons, the vertical tune shift reaches a maximum value of more than 0.01 (the value measured with the damper under the same conditions and reported in Ref. [9] is 0.03). Since the observed horizontal tune shift is

[1] A beam with 50 ns bunch spacing was tested during 2000, but its intensity was too low.

much smaller, the horizontal and vertical tunes come closer at the end of the batch (and they started to overlap with the working point adopted in 1999). Assuming an electron cloud density of 10^{12} electrons/m^3, the coherent vertical tune shift estimated for the SPS at 26 GeV is 0.011, while for the LHC at 450 GeV it is 0.07 (see Sec. 6.2 of Ref. [4]).

2.3 Electron cloud build-up vs bunch length and gaps in the bunch train

The simulations presented at the last Chamonix workshop did not include elastically reflected electrons and assumed shorter bunch lengths[2] compared to the nominal SPS and LHC values. With the correct SPS bunch length of 30 cm, only a modest electron cloud build-up is predicted in the dipoles over the 1.8 μs duration of an LHC batch. With elastically reflected electrons (or shorter bunch lengths) the build-up is much faster and saturates after about 40 bunch passages, reaching a value of 1.6×10^{10} electrons/m for a nominal LHC bunch population $N_{\rm b} = 10^{11}$ protons and an assumed maximum secondary electron yield $\delta_{\rm max} = 1.9$ (see Fig. 4 in Ref. [4]).

The prediction of a faster electron cloud build-up for shorter bunches agrees with qualitative observations performed with the SPS damper pick-ups during tests with mismatched RF voltage (see Fig. 2 in Ref. [9]). The simulated build-up in a PS dipole chamber is also faster for the shorter (4 ns) bunch length prior to beam extraction.

The effect of a gap of 12 missing bunches has been found insufficient to completely reset the electron cloud memory, both by vacuum observations [5] and beam observations [8] in the SPS. This is consistent with simulation results, indicating that the electron cloud density is rapidly re-established behind the gap and saturates only a few bunches later. From Fig. 8 in Ref. [4], the exponential decay time of the electron cloud in the gap is estimated to 100 ns without elastically reflected electrons and becomes roughly three times longer with elastically reflected electrons.

2.4 Electron scrubbing in the SPS and LHC

According to simulations (see Sec. 5 in Ref. [4]), the electron dose accumulated in the SPS during the 50 hours scrubbing experiment in April 2000 is 0.5 mC/mm^2. This is sufficient to reduce the molecular desorption yield by about a factor two and agrees with the observed, significant reduction of dynamic pressure rise [5], especially in the field-free regions. However the maximum SEY is still expected to be between 1.4 and 1.8 (see Fig. 4 in Ref. [3]): in other words such an electron dose is sufficient for surface cleaning, but insufficient for surface conditioning, consistently with the absence of any observable increase in the threshold intensity for beam instability (presumably dominated by electron cloud build-up in the dipoles). It should also be noted that this estimated dose is obtained assuming that the LHC beam intensity was constantly above the electron cloud threshold.

The dynamic pressure rise initially observed in the SPS dipoles was higher than in the field-free regions and remained such even after the scrubbing experiment, with a lower threshold bunch intensity (tentatively 3.5×10^{10} protons, in contrast to 6×10^{10} protons in the field-free regions). This seems to contradict simulation results, that predict a faster electron cloud build-up in the field-free regions (see Fig. 11 in Ref. [4]). However, the uniform electron bombardment of the beam pipe in the field-free regions is likely to provide a more effective surface cleaning than the scrubbing concentrated over two narrow electron stripes, as predicted in the dipole magnets. Surface recontamination (that should be absent in the LHC) may then explain the reduced scrubbing efficiency observed in the SPS dipoles.

In view of LHC commissioning strategies, simulations of average heat load deposition in the LHC arcs are reported in Fig. 20 of Ref. [4]. They indicate that a bunch population of about 3×10^{10} protons should not be exceeded in the early conditioning phase of the beam screen, while the bunch intensity can reach 6×10^{10} protons when the maximum SEY has dropped to about 1.3 and, later, 1.1×10^{11} protons for $\delta_{\rm max} = 1.1$. These results assume a nominal 25 ns bunch spacing and take into account the available cooling capacity at 7 TeV.

2.5 New ingredients in electron cloud simulations

To obtain reliable simulation results, one needs reliable input for the surface properties and in particular reliable information about the elastically reflected or re-diffused electrons, for primary energies as low as a few eV's, including their angular distribution and the dependence on the incidence angle. In addition to a careful scrutiny of past and future SEY measurements, this may require complementary approaches. An interesting idea [11] consists in sending low-energy electrons through a 1 m long metallic pipe, possibly with a well defined energy and incidence angle, and collecting them on the other side, after a few bouncings on the pipe surface. The experimental set-up would be relatively simple and cheap, and may incorporate a few refinements such as masks and DC-bias voltages along a segmented pipe. The results may require some simulation work for a proper interpretation.

A gap of at least 24 bunches is needed in the SPS to completely reset the electron cloud generated by the previous bunches [8] and a gap of about 1 μs is needed at the KEK-B LER. This observations may hint at some missing ingredient in the electron cloud simulations, especially if a significantly lower probability of elastic reflection for low-energy electrons is ascertained by forthcoming measurements. O. Gröbner and F. Zimmermann have suggested to include the ionization of the residual gas by low-energy

[2] Owing to an error arising from inconsistent relations between different parts of the simulation code [4] and associated with a weight function for arbitrary bunch profiles, the bunch length was shorter by a factor $1/\sqrt{5}$.

electrons in the cloud as an additional, significant source of electrons. O. Gröbner has recently also suggested that the ions may trap some electrons during long inter-bunch gaps and F. Caspers has underlined the possible role of the dipole magnetic field in the dynamic trapping of the ions. F. Zimmermann has observed that the ions should be cleared in the SPS with a single LHC batch followed by a very long empty gap, but he has recently speculated that the hysteresis effect observed for the vertical beam size at the KEK-B positron ring, characterised by a typical delay time of some 100 s, could be related to the ionization process by the cloud electrons.

3 SPS STRATEGY FOR THE YEAR 2001

3.1 Needs for new diagnostics and future MD's

With the installation of a special bypass in the SPS, in-situ SEY measurements will be possible in 2001, as well as calorimetric measurements at room temperature of the heat load deposited by the electron cloud in field-free regions, equipped with a weak solenoid, and possibly also in a special dipole corrector, as recently suggested by G. Arduini. Other important diagnostics for electron cloud MD's include adequately shielded electron probes (so-called Rosenmberg detectors), synchronised with the beam signal. In addition, the horizontal position of the two predicted vertical electron stripes could be measured in a special dipole corrector by means of SEM grids or wires; this would directly confirm our understanding of the basic physical mechanism for the build-up of the electron cloud and would give an independent value for the energy corresponding to the maximum SEY, possibly during surface conditioning (this may have important implications for the positioning of the pumping slots on the LHC beam screen).

Beam manipulations and measurements in 2001 should profit from the enhanced damper bandwidth and possibly from a variable gain along the LHC batch. The injection of longitudinally mismatched beams should be repeated to calibrate the peak detected signal as a function of the varying bunch length and to measure the corresponding variation of the electron cloud threshold intensity. Alternative beam manipulations could include debunching an LHC batch above threshold intensity and correlating bunch length measurements with electron probe signals. The aim is to obtain a direct quantitative comparison with simulations.

3.2 Electron scrubbing in 2001

During discussions at Chamonix and later at CERN, it was agreed that electron scrubbing with LHC type beams of adequate duty cycle should be repeated in 2001. Vacuum and beam measurements should be regularly performed before, during and after the scrubbing to monitor the effect of an accumulated electron dose of several mC/mm^2 and to distinguish surface cleaning from surface conditioning. Special care should be taken to ensure that the proton bunch intensity be always significantly above the electron cloud threshold, even after the initial scrubbing phase.

Concerning the strategy to be followed, one could decide to perform this scrubbing either at the beginning or in the second half of the 2001 run. The second option would have the advantage of better controlled machine conditions, in contrast to an immediate start after the long shutdown and the complete renovation of the Faraday cage. An additional advantage would be the possibility to compare the usual surface cleaning before the scrubbing to the expected surface cleaning *and* surface conditioning after beam scrubbing. Another strategic choice is to fill the SPS with one or more LHC batches, for a faster scrubbing. One possibility would be to have *two batches* during the parasitic cycle. K. Cornelis suggested either to start and finish on Wednesday MD's (after one week of scrubbing) or to stop physics and give access to the machine for a few hours, to measure SEY in-situ. Possible ways to condition wider horizontal regions of the dipole vacuum chamber include running with varying rather than fixed batch intensity, and possibly with some beam shaking.

4 ACKNOWLEDGEMENTS

I would like to thank Frank Zimmermann for his invaluable help as Scientific Secretary of this workshop session and for many interesting discussions. Some of the new ideas reported in this summary have actually been proposed after the Chamonix workshop by several people: in particular I want to thank Oswald Gröbner for his inspiring hints and contributions.

5 REFERENCES

[1] F. Ruggiero, "Electron cloud effects: introduction and motivation", these proceedings.

[2] K. Oide, "Observations and cures of electron cloud effects at KEKB-LER", these proceedings.

[3] V. Baglin, I.R. Collins, O. Gröbner, C. Grünhagel, B. Heinrist, N. Hilleret, and B. Jenninger, "Measurements at EPA of vacuum and electron-cloud related effects", these proceedings.

[4] F. Zimmermann, "Electron-cloud simulations: an update", these proceedings.

[5] J.M. Jimenez, "SPS vacuum observations and electron scrubbing with LHC beams", these proceedings.

[6] K. Cornelis, "Measurement of the electron cloud impedance", these proceedings.

[7] G. Rumolo and F. Zimmermann, "Theory and simulations of the electron cloud instability", these proceedings.

[8] G. Arduini, "Observations on transverse instabilities", these proceedings.

[9] W. Höfle, "Progress with the SPS damper", these proceedings.

[10] F. Ruggiero, 'Electron Cloud in the SPS: Session Summary', Proc. Chamonix 10, CERN-SL-2000-007-DI, p. 9.

[11] Sam Heifets, private communication (November 2000).