Experimental studies on the SPS electron cloud

G. Rumolo*, G. Arduini, E. Métral, E. Shaposhnikova, E. Benedetto, R. Calaga[(a)], G. Papotti, B. Salvant[(b)]
CERN, Geneva, Switzerland, [(a)] BNL, Brookhaven, USA, [(b)] EPFL, Lausanne, Switzerland

Abstract

One of the most important limitations in the performances of the CERN-SPS is presently the Electron Cloud Instability (ECI). Hence, defining its dependence on energy with confidence is an indispensable asset to direct the efforts for all the upgrade studies.
Macroparticle simulations carried out with the HEADTAIL code [1] have shown that the ECI mechanism is subtle and the scaling laws valid for the Transverse Mode Coupling Instability cannot be applied to it [2]. The reason lies in the fact that the electron dynamics, while a bunch is going through an electron cloud, is heavily affected by the transverse beam size. In fact, transversely smaller beams can enhance the electron pinch and lower the intensity threshold for the bunch to be unstable. Hence, higher energy beams, though more rigid, can be more unstable due to their smaller transverse size (with constant transverse normalized emittance).
During the 2007 run a measurement campaign has been carried out at the CERN-SPS to prove experimentally the outcomes of macroparticle simulations.

INTRODUCTION AND MOTIVATIONS

Plans for the Large Hadron Collider (LHC) performance upgrade include the improvement of the existing LHC injectors and/or the design of possible new rings in the injector chain [3]. Several scenarios, aimed at overcoming the existing bottlenecks, are presently being taken into consideration. One option, based on the replacement of the Proton Synchrotron (PS) ring with the PS2 [4], foresees an increase of the injection energy into the existing SPS from the present 26 GeV/c to 50 GeV/c. This is believed to be beneficial for the machine in many regards (e.g., less space charge and intra beam scattering, more rigid beams against coupled bunch instabilities, no transition crossing, lower injection and capture losses) [2]. Furthermore, it would allow for an upgrade of the SPS to a 1 TeV extraction energy ring, with the related advantages for injection into the LHC.
However, the SPS upgrade plan crucially depends on the effect of a higher injection energy on the collective phenomena that are presently believed to be the real limitation in the SPS performance. One of them is TMCI, which was observed in the SPS for special intense bunches with low longitudinal emittance [5, 6]. Therefore, it could be a potential limiting factor in the future, especially taking into account the enhancement of the impedance of the SPS caused by the installation of 9 new extraction kickers in the ring since 2003 and the higher charge per bunch that should be injected into the SPS [7]. In addition, the vertical single bunch ECI has been limiting for a long time the number of batches that could be injected into the SPS and it could be overcome by beam scrubbing and subsequently operating the ring with a high vertical chromaticity (which nonetheless can be harmful for the beam lifetime) [8]. A detailed study on the energy dependence of the threshold for the onset of these instabilities is essential to assess a global beneficial effect of the pre-injector upgrade without unwanted side effects.
The scaling law of the TMCI threshold with energy was already addressed in [9]. Under conservation of the longitudinal emittance and assuming bunches always matched to their buckets, the TMCI threshold only depends linearly on the slip factor $|\eta|$, and therefore a higher injection energy would certainly help to operate the machine farther from this limitation. Besides, preliminary studies of the dependence of the ECI threshold on energy were done, which showed that the related scaling law cannot be trivially derived from the existing TMCI theories. In fact, a first attempt of analytical approach using a broad-band resonator with beam dependent parameters showed that it may become surprisingly unfavourable at high energies far from transition, under the further assumptions of conservation of the bunch length and the normalized transverse emittances. A comprehensive study of the effect of higher injection energy on the ECI has been therefore carried out numerically and experiments are being done in the CERN-SPS with an LHC-type beam to verify it.

SUMMARY OF SIMULATION RESULTS AND CODE-TO-CODE BENCHMARK

Table 1 shows a list of the essential parameters used for the numerical study (typical LHC-type bunch in the SPS). The main assumptions of our model are:

- The longitudinal emittance and the bunch length are kept constant. The momentum spread $\Delta p/p_0$ is re-scaled and the matched voltage re-adjusted accordingly when changing the energy. The matched voltage goes like $|\eta|/\gamma$ with energy. This constraint could be relaxed by increasing the longitudinal emittance.
- The normalised transverse emittances are constant.

* Giovanni.Rumolo@cern.ch

Consequently the transverse beam sizes are scaled down $\propto \sqrt{1/\gamma}$ when changing the energy. This constraint comes from the LHC requirements in terms of transverse emittance.

Table 1: Parameters used in our study

Parameter	Symbol	Unit	Value
Circumference	C	km	6.9
Momentum	p_0	GeV/c	14–450
Norm. transv. emitt.	$\epsilon_{x,y}$	μm	2.8
Long. emitt. (2σ)	ϵ_z	eVs	0.35
Bunch length	σ_z	m	0.3
Bunch population	N		1.1×10^{11}
Number of bunches	N_b		72
Bunch spacing	T_b	ns	25
Number of trains			4
Train spacing		ns	200
Vertical tune	Q_y		26.13
Momentum comp.	$\alpha = 1/\gamma_t^2$		0.00192
Av. cloud density	ρ_e	m^{-3}	10^{12}

HEADTAIL simulations

The dependence of the ECI threshold on energy has been simulated with the HEADTAIL code [1]. The kick approximation is used for the action of the electron cloud on the bunch, namely the action is lumped in one or more points along the ring. The N_{sl} slices of which the bunch is made, interact with the electrons (modeled as N_e macro-particles and uniformly distributed with zero initial speed in the cross-section of the pipe) after one another. Each slice sees the electron cloud as deformed by the interaction with the preceding slices. The distortion of the cloud distribution induced by the bunch traversing it, is the mechanism that couples body/tail motion of the bunch with the head motion and potentially causes instability. To gain an insight into the physical mechanism that determines the type of dependence of the instability threshold on energy, we have first looked for thresholds at different energies assuming an electron cloud with initial uniform density (and fixed average value) concentrated in the dipole regions of the machine (which is supported by the SPS experimental observations). Figure 1 shows that the ECI threshold drops down with energy like $1/\gamma$ under the given assumptions. A very weak dependence on $|\eta|$ seems to be hinted to by the two points at 20 and 26 GeV/c (equidistant from transition), which exhibit the same threshold. Our explanation for this unusual behaviour is that, although the bunch becomes more rigid at a higher energy, and therefore less sensitive to collective effects, it also becomes transversely smaller, which enhances the effect of the electron cloud pinch. As a result, the "head wake" of the EC (calculated as the response, in terms of electric field averaged over the beam cross section, to a small displacement of the bunch head) has a higher frequency and amplitude at higher energies. Besides, the matched voltage changes like $|\eta|/\gamma$, which causes a decrease of the synchrotron tune far from transition. This translates into a slower motion in the longitudinal plane and therefore larger time scales for natural damping.

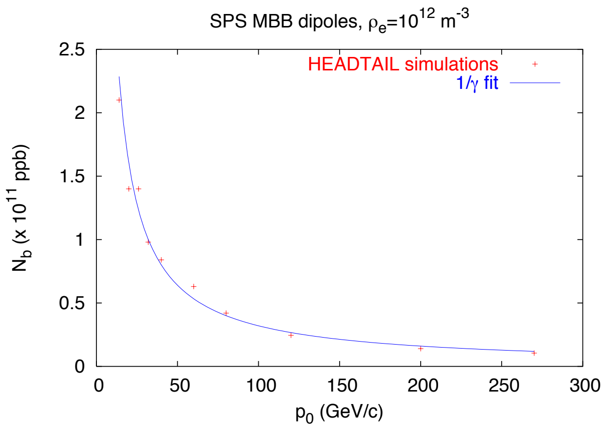

Figure 1: Simulated ECI threholds at different energies, study done with fixed e-cloud density.

The HEADTAIL code has been recently upgraded to deal with more realistic initial distributions of the electrons. The necessity of a more refined model to gain more confidence in the predictions was evident, because the average electron density over the full pipe cross section can significantly differ from the local density around the bunch, which is more directly related to the development of instabilities. Therefore, HEADTAIL can now load the 4D electron distribution as produced by the build up code ECLOUD [10] and use it for the instability simulation. The integration ECLOUD-HEADTAIL, though not completely self-consistent, is certainly a significant step forward with respect to the old model, which only interfaced the two codes through the value of the average density over the pipe section.
The result of a scan extending to 270 GeV/c over a few points is shown in Fig. 2 for a maximum SEY δ_{max} of 1.4. The decreasing trend of the threshold with increasing energy is confirmed. Nevertheless, the strong $1/\gamma$ decaying law found with the fixed density cloud model turns into a smoother decrease of the threshold with energy, which simply levels off to the threshold for electron cloud build up at energies higher than ≈ 100 GeV/c.

Comparison with the PEHTS code

To cross-check the validity of this result a benchmark was carried out with the PEHTS code [11], which was separately developed by K. Ohmi and can also simulate the interaction of a positively charged bunch with an electron cloud. Two reference cases from Fig. 1 (and parameters from Table 1), far apart from each other, were chosen to be simulated with the PEHTS code. The two values of beam energy used for the benchmark are 40 and 270 GeV/c. Figures 3 shows the beam vertical rms-size evolution for dif-

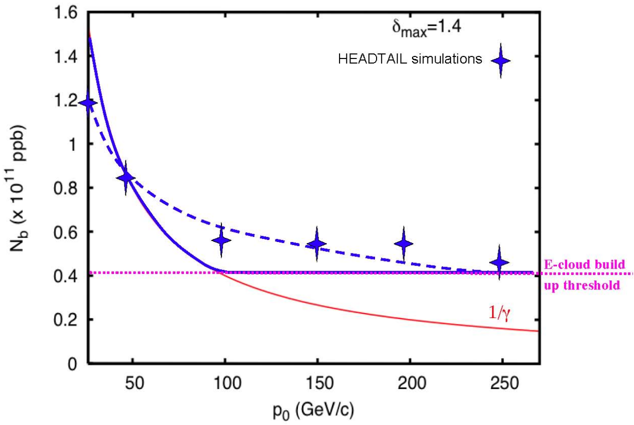

Figure 2: Simulated ECI thresholds at different energies, study done with quasi-self-consistent e-cloud distribution.

ferent bunch populations, as resulting from PEHTS simulations [12]. It can be deduced that the thresholds for instability lie at around 7×10^{10} and 2×10^{10} for 40 and 270 GeV/c, respectively. Therefore, these values are very close to those calculated with HEADTAIL and confirm the decreasing trend of the ECI threshold with energy, as was anticipated in our study.

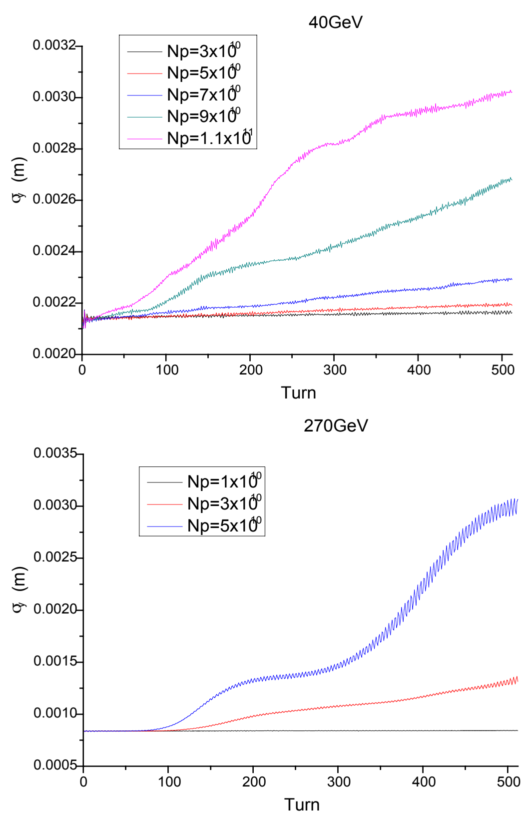

Figure 3: Emittance evolution for different bunch population at 40 (top) and 270 GeV/c (bottom). Courtesy of H. Jin and K. Ohmi

EXPERIMENTAL CAMPAIGN AT THE SPS (AS OF SEPTEMBER 2007)

An experimental study to prove the scaling law found by simulations has been carried out at the CERN-SPS during the 2007 run. The studies were essentially done using two possible SPS cycles (see Fig. 4). In the short MD1 cycle (top part of Fig. 4), parallel to physics, only one batch of the LHC beam was injected in the SPS at 26 GeV/c and then accelerated to 37 GeV/c. Two flat parts of about 1 s were available at bottom and top energy, during which it was attempted to induce ECI. With this cycle it was expected to see a larger effect before the scrubbing run, when the electron cloud could be potentially a problem already at the tail of one batch alone. In the long dedicated supercycle for MDs (bottom part of Fig. 4) we used an LHC-type beam made of 1 to 3 batches with 72 bunches each. The beam was injected into the SPS at 26 GeV/c during a flat bottom of 10.86 s, then accelerated to an intermediate plateau of 55 GeV/c (about 6 s) and eventually taken to 270 GeV/c and sent onto a dump. The 55 GeV/c flat portion would serve to show that the beam still suffers from ECI at this higher energy. Observing the beam behaviour at this energy would be specially interesting, because it lies close to a potential value as new SPS injection energy after the upgrade of the pre-injectors.

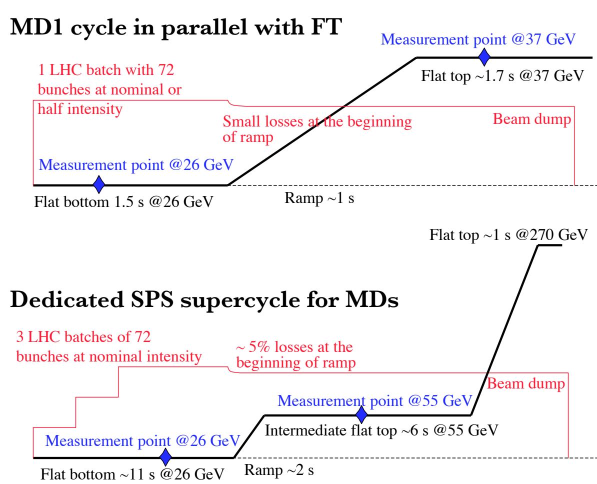

Figure 4: SPS cycles that were used to carry out ECI measurements at different energies in the SPS.

Measurements at 26 and 37 GeV/c

The experiment at 26 and 37 GeV/c was conducted using the short MD1 cycle. After having one batch injected into the SPS in stable conditions, a vertical chromaticity bump was created, which quickly lowered chromaticity in the middle of the flat bottom or of the flat top. No significant difference was observed between the measurement sessions that took place before scrubbing and those after the scrubbing run. Also the damper gain settings did not appear to influence the results. In this way we could determine the limit value of vertical chromaticity below which the beam would become unstable at both energies. Threshold chromaticity values were therefore identified to be 2.2 and 3.3 (in Q' units) at 26 and 37 GeV/c, respectively, and did not change over the different MD sessions done with this cycle. The instability manifested itself with beam loss in the tail of the batch at both energies. Figure 5 shows that, after the instability developed, the last part of the batch is quickly lost. This feature points to an electron cloud as possible source of the instability, but does not rule out possible coupled bunch instabilities caused by a long range wake field that can extend over one batch length but does not accumulate the effect turn after turn. Actually, the electron cloud signal as observed from the e-cloud monitor appears on the ramp, where the bunch gets shorter, and significantly extends to the flat top, as well (see Fig. 6). No strong signal is observed at 26 GeV/c in standard operation. However, during one of the MD sessions a successful attempt was made to trigger a stronger electron cloud at 26 GeV/c by means of a voltage bump, which causes a localized bunch shortening on the flat bottom (Fig. 7). No significant difference in the instability evolution at 26 GeV/c was observed under these conditions (nor depending on whether the chromaticity bump was created within the voltage bump or outside of it). This induced us to believe that the main driving force for the instability observed at 26 GeV/c was not electron cloud.

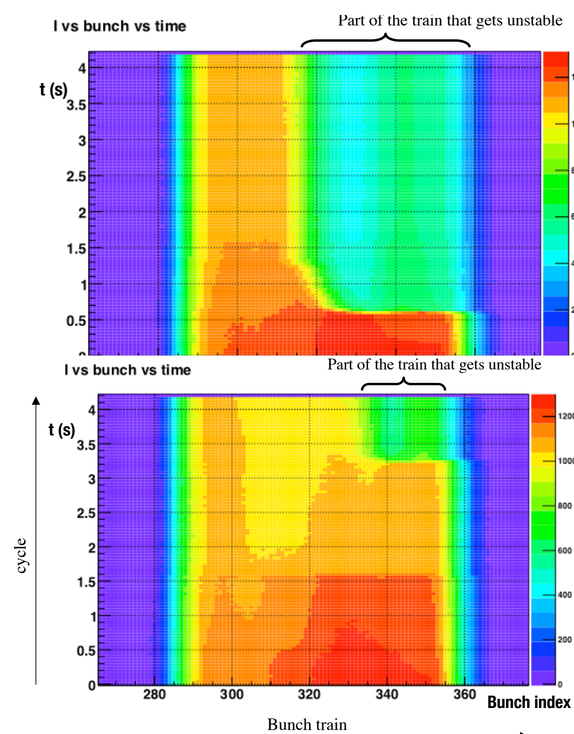

Figure 5: Bunch by bunch intensity evolution with an unstable beam. Top picture shows the intensity evolution when the instability is driven at 26 GeV/c, the bottom picture corresponds to an instability driven at 37 GeV/c

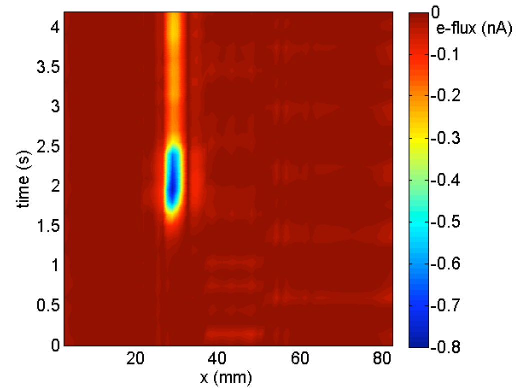

Figure 6: Measured electron cloud build up during the MD1 cycle.

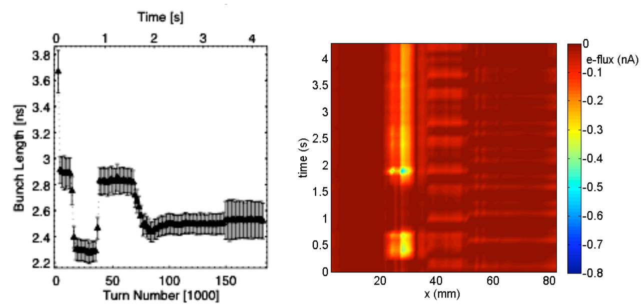

Figure 7: Bunch length (left) and measured electron cloud build up during the MD1 cycle (right) when a voltage bump is appled at the flat bottom in order to shorten the bunch and enforce the electron cloud at 26 GeV/c.

Figure 8 shows the typical bunch by bunch centroid evolution over 1000 subsequent turns, acquired with the LHC-BPMs (i.e., beam position monitors that can provide turn by turn and bunch by bunch measurements). It is evident that the intra-batch motion exhibits some correlation and a traveling wave pattern at 26 GeV/c, with a possible single bunch component at the very end of the batch. However, at 37 GeV/c there was no evident sign of coupled bunch motion and the unstable bunch by bunch motion at the tail of the batch looked uncorrelated, possibly induced by a single bunch effect. The difference between the two cases becomes more evident plotting the spectra of the LHC-BPM signals, Fig. 9. The upper pictures show the individual Fourier transforms of the time traces of each bunch separately (for 26 and 37 GeV/c), whereas the lower graphs are the complete 2D Fourier transforms of the signals. In the spectra of the bunch by bunch time traces, a coherent signal is obviously visible only in the tail of the batch, where bunches have acquired a coherent motion due to the instability. Two lines can be seen at 26 GeV/c, whereas one line (with possible side-bands) is visible at 37 GeV/c, which shifts upwards with the bunch number. The full 2D Fourier

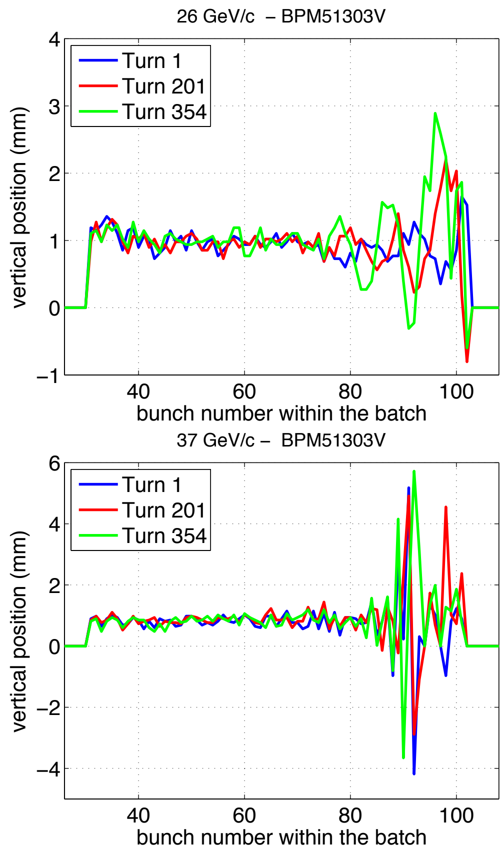

Figure 8: Bunch by bunch Δ_y signal of an unstable beam. Top picture shows three snapshots of the instability evolution along the batch at 26 GeV/c, the bottom picture corresponds to an instability driven at 37 GeV/c. Acquisition starts at turn 1.

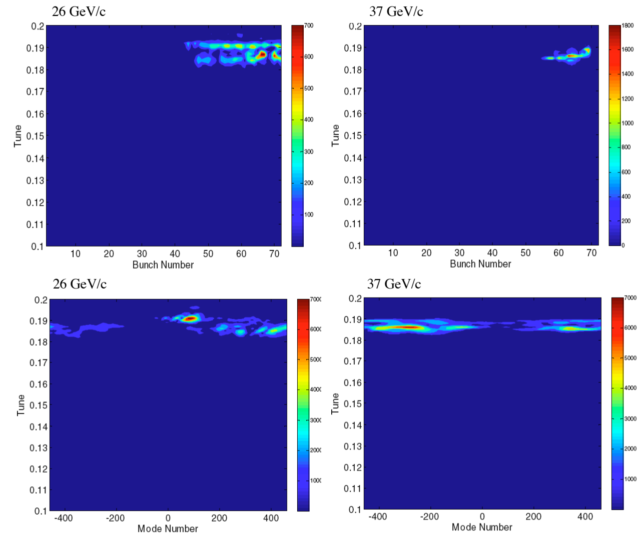

Figure 9: Fourier transforms of the bunch by bunch BPM signals from an unstable bunch at 26 (left) and 37 GeV (right). The top plots are the Fourier transforms of the bunch by bunch signals carried out indivdually over the acquisition time, whereas the bottom pictures represent the full 2D Fourier transforms of the 2D signal.

transform reveals one main peak at 26 GeV/c associated to the upper tune line (with a weaker component of the signal spread over all the bunch numbers and mainly associated to the lower tune line) and appears uniformly smeared over the bunch numbers at 37 GeV/c. The presence of a high peak in the 2D Fourier spectrum of the 26 GeV/c signal translates into a coupled bunch instability component dominant at this energy. The signal spread over all bunch numbers at 37 GeV/c indicates a dominant single bunch instability.

Measurements at 26 and 55 GeV/c

Using the LHC-type beam in the SPS on a long MD cycle as the one shown in the bottom illustration of Fig. 4, we tried to excite the ECI at 26 and 55 GeV/c. Figure 10 shows that, when injecting one (top) or 2 (bottom) batches into the SPS, a strong signal from the e-cloud monitor could be observed. The 2-stripe signal would be growing along the cycle. With 2 batches (Fig. 10, bottom picture) a sharp increase could obviously be seen at the flat bottom when the second batch got injected into the machine, but later on it would continue also over the ramp to the intermediate 55 GeV/c plateau, and become even more pronounced over the second ramp to 270 GeV/c. The reason could be a combined effect of bunch shortening and reduction of the transverse beam size. It is interesting to observe that, with one single batch inside the machine, the electron cloud evolution looks rather similar, but with one remarkable difference: the curious sudden appearance of a quite strong electron cloud signal after about 6 s from injection (Fig. 10, top picture). The reason of this puzzling behaviour was investigated, and it was found out that the signal appears when the uncaptured beam has completed a full turn and has smeared all over the machine. This coasting beam component can therefore trap the electrons between two subsequent passages of the batch through one section and allow a multi-turn electron cloud build up. The suspicion that this could be the cause was then easily confirmed by cleaning the gap with a kicker and thus observing the complete absence of any electron cloud signal all along the flat bottom.

To excite the instability, the chromaticity would be quickly reduced toward the end of the flat bottom (after all batches have been injected and possible transients have damped out) or in the middle of the intermediate plateau at 55 GeV/c. It was expected to observe ECI below some positive chromaticity value at both energy values. The transverse feedback system was kept on during these measurements. The outcome was that Q' could be set to a slightly negative at 26 GeV/c before an instability would set in, whereas at 55 GeV/c a Q' of about 4 units was the observed threshold for instability. The instability always started from the tail of the batch (or of the batches) and measurements with a different batch distribution (3 batches uniformly distributed around the ring) seemed to significantly stabilize

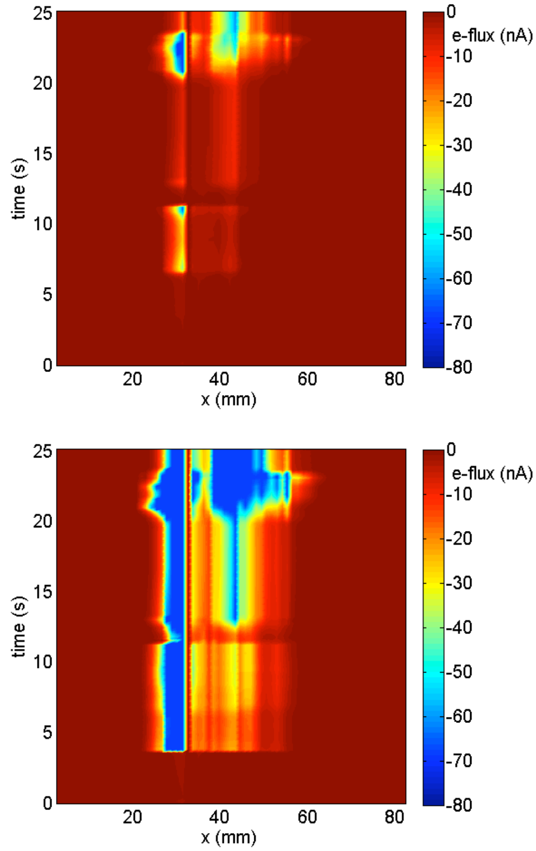

Figure 10: Measured electron cloud build up during the long dedicated MD cycle with only one batch (top picture) and with 2 batches injected into the SPS (bottom picture).

the beam at 55 GeV/c. Both elements pointed once again to either electron cloud or a coupled bunch phenomenon, or a combination of the two. A preliminary analysis of the bunch by bunch centroid evolution shows that the instability was of coupled-bunch type with a dominant low mode number both at 26 and 55 GeV/c. In some cases, a variety of modes could be seen, with a possible single bunch component. Nonetheless, these minor modes, where present, could not be easily disentangled from the dominant coupled bunch low number mode. Although these modes should have been damped by the transverse feedback, there is a strong suspicion that actually they appeared because they were induced by an incorrect setting of the damper.

CONCLUSIONS

In conclusion, experiments carried out at the SPS until September 2007 have given evidence of electron cloud inside the machine (depending on the operating conditions), but they are not conclusive on the scaling law of the instability threshold, because of the presence of other collective phenomena in most of the measurements, which made it difficult to isolate the contribution coming from the electron cloud.

In particular, the electron cloud was observed in the SPS with the e-cloud monitor

- At 26 GeV/c with a bunch shortening voltage bump or enhanced by uncaptured coasting beam
- A clear signal could be seen especially at higher energies (shorter bunch, smaller transverse sizes)

Concerning the instability, it can be concluded that the LHC beam was observed to be vertically unstable in the SPS at

- 26 GeV/c for vertical $Q' < 0$–2 (with 1 to 3 batches, and depending on the feedback system settings)
- 37 GeV/c for vertical $Q' < 3.3$ (with 1 batch)
- 55 GeV/c for vertical $Q' < 4$ (with 1 to 3 batches)

In most of these cases it was observed that only the tail of the bunch train(s) is affected by the instability. However, the pattern of the instability along the bunch train shows a coupled bunch instability (not excluding that single bunch effects were also present but not dominant) both at 26 and 55 GeV/c. In particular, the measurements conducted at 26 and 55 GeV/c were probably affected by a not optimum setting of the transverse feedback, which induced coupled bunch oscillations instead of damping them. Only at 37 GeV/c the principal instability seems to be of single bunch type and can be associated with electron cloud, since it only affects the last few bunches of the batch and does not seem to have any coherent bunch to bunch pattern.

Therefore, drawing conclusions on the dependence of the electron cloud instability on the beam energy is not straightforward from the data so far collected. It is foreseen in the next dedicated MD sessions to try to observe ECI at 55 GeV/c and assess its dependence on the beam transverse size by using controlled transverse emittance blow up with the transverse damper. This would be the easiest indirect proof of the mechanism responsible for the scaling law of the ECI threshold with energy, as was found with our simulations.

ACKNOWLEDGMENTS

The authors would like to thank T. Bohl, D. Quatraro, F. Roncarolo, R. Tómas and F. Zimmermann for inspiring discussions, help and support. Special thanks go to H. Jin and K. Ohmi for their availability in benchmarking our codes.

REFERENCES

[1] G. Rumolo, and F. Zimmermann, Phys. Rev. ST Accel. Beams **5**, 121002 (2002)

[2] G. Rumolo, E. Métral, and E. Shaposhnikova, in Proc. of the LUMI'06 Workshop, Valencia, Spain, 16-20 October 2006, edited by W. Scandale, T. Taylor and F. Zimmermann, published as CERN Yellow Report CERN-2007-002

[3] Proceedings of the LUMI'05 Workshop "Scenarios of the LHC Luminosity Upgrade", Arcidosso, Italy, 31 August-3 September 2005, http://care-hhh.web.cern.ch/CARE-HHH/LUMI-05/default.html

[4] M. Benedikt *et al.*. "Preliminary accelerator plans for maximizing the integrated LHC luminosity", PAF, January 2006, http://paf/web.cern.ch/paf

[5] G. Arduini and A. Verdier, "Poor man pilot and TOTEM bunches", CERN AB-Note-2003-017 (MD)

[6] G. Arduini, H. Burkhardt and E. Métral, "Observation of a fast single-bunch transverse instability on protons in the SPS", CERN AB-Note-2003-093 (MD)

[7] G. Rumolo, E. Shaposhnikova and V. G. Vaccaro, CERN-AB-2005-088-RF (2005)

[8] G. Arduini *et al.*, CERN-SL-2001-003-DI (2001)

[9] G. Rumolo, E. Métral, E. Shaposhnikova, "Simulation Study on the Energy Dependence of the TMCI Threshold in the CERN-SPS", in Proc. EPAC'06, Edinburgh, Scotland, June 26-30, 2006

[10] G. Rumolo and F. Zimmermann, CERN-SL-Note-2002-016-AP (2002)

[11] K. Ohmi and F. Zimmermann, Phys. Rev. Lett. **85**, 3821 (2000)

[12] H. Jin and K. Ohmi, private communication, 2007.