OBSERVATIONS IN THE SPS: BEAM EMITTANCE, INSTABILITIES

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Abstract

The build-up of electron cloud observed for the LHC beam in the SPS might induce instabilities and therefore emittance blow-up and losses. The results of beam observations performed in the SPS are presented.

1 PRELIMINARY OBSERVATIONS

During the machine development studies performed on the injection and acceleration of the LHC beam in the SPS strong distortions of the signal provided by the pick-ups driving the damper were observed for batch intensities I_{batch} > 2-3 x 10^{12} p. This phenomenon could be suppressed by the application of a solenoidal magnetic field at the pick-up location [1]. Furthermore significant increments of the vacuum pressure were correlated to the presence of the LHC beam for I_{batch} > 4 x 10^{12} p [2]. These observations were soon correlated to the build-up of an electron cloud induced by the LHC beam as a consequence of its bunch spacing.

The machine studies also evidenced the need of strong negative octupole radial strength[1] in order to get a decent injection efficiency for I_{batch} > 4 x 10^{12} p even with dampers ON and with the pick-up solenoidal magnetic field to guarantee proper signals for the dampers. Furthermore an important emittance blow-up was observed during injection and acceleration.

In order to get a better understanding of the above observations profile and beam oscillation measurements have been performed for the LHC beam.

2 PROFILE MEASUREMENTS

Profile measurements were performed by means of a rotational wire scanner read by a photomultiplier with gated reading. The gate, 350 ns long, repeats every turn with a constant delay with respect to the revolution frequency of the beam so that a given part of the batch can be measured. The observation slice can be moved along the batch by modifying the delay of the gate with respect to the revolution frequency. In order to verify the time constant of the read-out electronics a measurement of the profile peak height was performed as a function of the gate delay for a beam of given intensity. The result is shown in Fig. 1 and shows that the time constant is of the order of a few hundreds of ns.

[1] This implies a positive detuning with amplitude, i.e. an increase of the horizontal tune with the amplitude of oscillation.

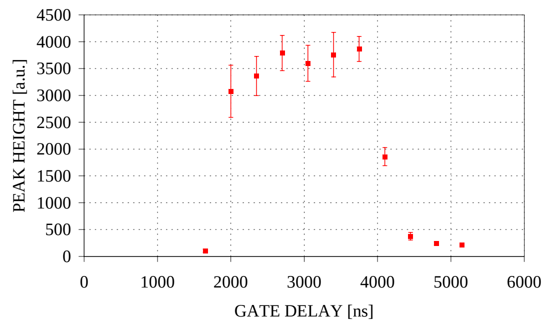

Figure 1: Measurement of the time constant for the read-out electronics of the wire scanner.

The wire scanner is located in a dispersive region (D_H= 2.9 m, D_V= 0 m). The measurements were performed with the TSTLHC beam [3][4], with one horizontal and one vertical damper ON, low positive chromaticity ($(\Delta Q/Q)/(\Delta p/p)$ < 0.02) and strong negative radial octupole component. The results of the profile measurements at 4 different positions in the batch (i.e. 4 different gate delays) and for different batch intensities are shown for the horizontal plane a few ms (Fig. 2) and 600 ms after injection (Fig. 3). The data for the vertical plane are presented in Fig. 4 and 5.

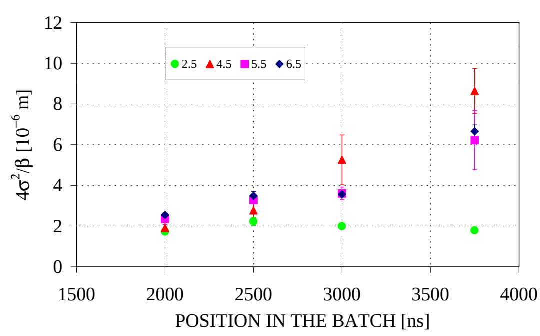

Figure 2: Horizontal profile measurement along the batch a few ms after injection for different I_{batch} (expressed in 10^{12} p).

For I_{batch} > 4 x 10^{12} p the tail of the batch is affected by an important blow-up both in the horizontal and vertical planes. In the horizontal plane the blow-up mainly occurs at injection. In the vertical plane it continues all through the injection plateau as can be clearly seen considering the ratio between the beam size after 600 ms and that at injection for the horizontal (Fig. 6) and vertical plane (Fig. 7).

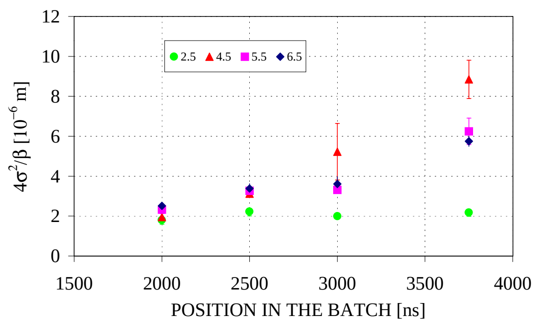

Figure 3: Horizontal profile measurement along the batch 600 ms after injection for different I_{batch} (expressed in 10^{12} p).

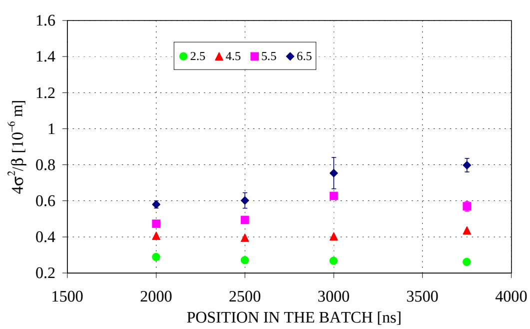

Figure 4: Vertical profile measurement along the batch a few ms after injection for different I_{batch} (expressed in 10^{12} p).

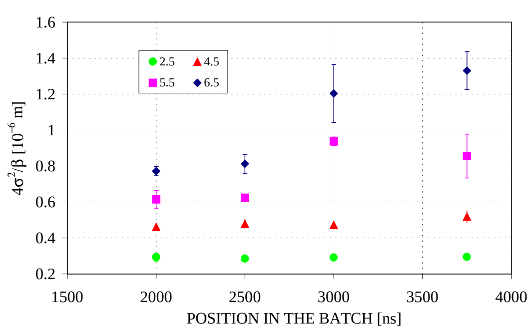

Figure 5: Vertical profile measurement along the batch 600 ms after injection for different I_{batch} (expressed in 10^{12} p).

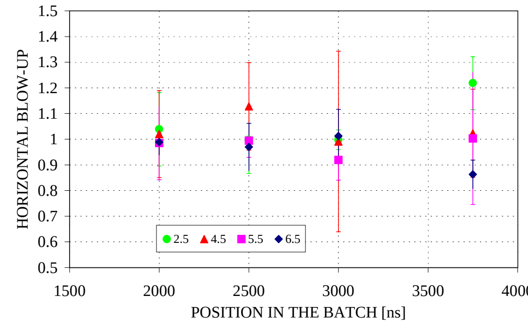

Figure 6: Beam blow-up in the horizontal plane during the injection plateau.

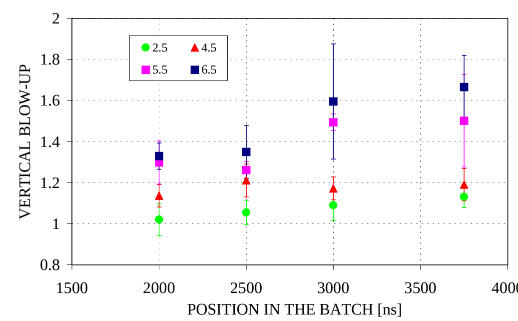

Figure 7: Beam blow-up in the vertical plane during the injection plateau.

3 BEAM OSCILLATION MEASUREMENTS

In order to understand the source of the blow-up of the tail of the batch the oscillations of the batch have been measured. As for the profile measurements the beam position measurement has been gated and six different gate delay could be selected allowing to see six different slices of the batch at the same turn. 1024 consecutive turns could be acquired at every cycle. Measurements were initially performed with an electrostatic pick-up read by a FET amplifier. This set-up is similar to the damper pick-ups and indeed the signals it provided also showed an important baseline distortion. A second attempt was conducted by using couplers equipped by a 200 MHz receiver having a 2 MHz bandwidth. In that case no disturbance of the signal was observed.

The beam oscillations were observed at 6 consecutive slices, each 400 ns long. In this paper slice 1 corresponds to the head of the batch and slice 6 corresponds to the tail of the batch. The measurements were performed with the TSTLHC beam [3][4] with I_{batch} ~ 4 x 10^{12} p. Two horizontal dampers and a vertical one were active and no octupolar component was introduced, the chromaticity was small and positive (< 0.02). The chosen beam intensity offers the following advantages:

- losses at injection are small, even without octupoles;
- the machine has a linear behaviour and interpretation of the measurements is easier;
- the machine is operated above the threshold for the onset of the beam induced electron cloud.

The results of the measurements for the horizontal plane are shown in Fig. 8. A rapidly growing oscillation is affecting mainly the tail of the batch just after injection. It saturates and then it is damped. The damping mechanism is not clear: injection losses are small at this intensity, no significant detuning with amplitude is present. Possible damping mechanisms are the horizontal blow-up of the beam and/or the action of the damper. The frequency of the oscillation corresponds to the horizontal tune as can be observed from the Fourier analysis of the data in Fig. 9.

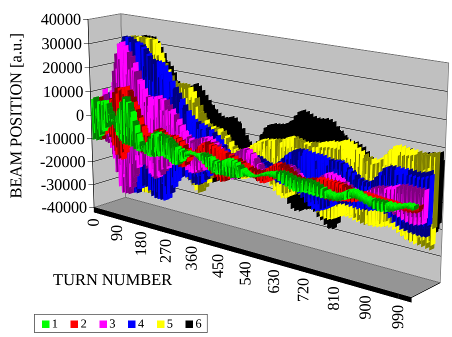

Figure 8: Horizontal beam oscillations for six consecutive slices of the batch at injection.

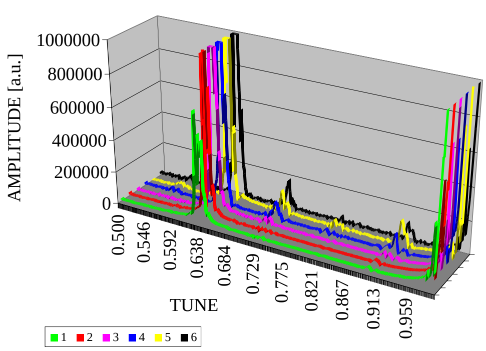

Figure 9: Fourier analysis of the horizontal beam oscillations at injection. The scale of the amplitudes has been artificially compressed to show the fine structure of the spectrum.

The growth rate of the oscillation has been estimated for the different slices of the batch by fitting an exponentially growing (damped) sinusoidal function to the data. The results are shown in Fig. 10. While the head of the batch undergoes a damped oscillation the rest of the batch gets unstable. The growth time is getting shorter and shorter going from the head to the tail of the batch and saturates to about 25 turns in the second half of the batch.

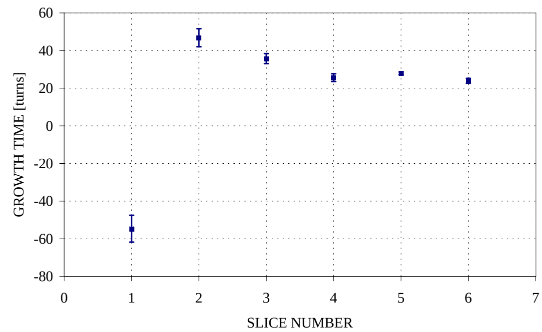

Figure 10: Growth time of the horizontal instability observed at injection vs. position in the batch.

The Fourier analysis (Fig. 9) evidenced the presence of several peaks of smaller amplitude with respect to that corresponding to the horizontal tune and to the harmonics of the synchrotron frequency (the monitor is located in a dispersive region). These peaks are more and more intense as one moves from the head to the tail of the batch. The frequencies of the peaks of the Fourier spectra and their evolution along the batch are shown in Fig. 11 (harmonics of the synchrotron frequency excluded).

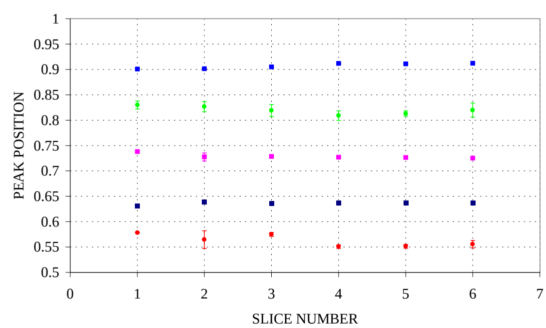

Figure 11: Position of the peaks of the Fourier spectrum of the oscillations observed at injection vs. position along the batch.

An interesting feature of these peaks is that they are equidistant. A more detailed analysis shows that the appearance of these peaks is typical of an exponentially growing sinusoidal function that saturates at a given threshold. Fig. 12 shows the Fourier spectrum of an exponentially growing sinusoidal function oscillating with a tune 0.637 (corresponding to the measured horizontal tune) and a growth time of 22.7 turns (as measured for the tail of the batch) for two different saturation levels. The secondary peaks can be easily individuated.

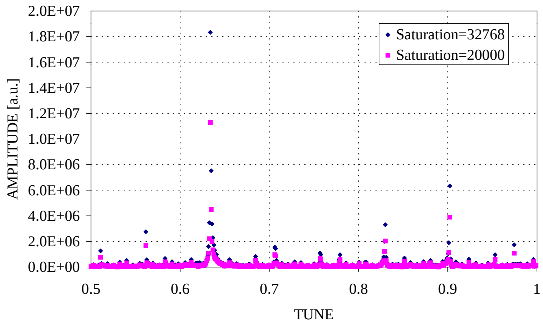

Figure 12: Fourier spectrum of an exponentially growing sinusoidal function for two saturation levels. The tune of the oscillation is 0.637 and the growth time is 22.7 turns.

Another interesting feature of the measured data is the dependence of the horizontal tune on the position along the batch. The horizontal tune increases slightly from the head to the tail of the batch as can be observed in Fig. 13 which is simply a copy of Fig. 11 but with an expanded vertical scale. This could explain why a negative radial octupolar component is needed to stabilise the beam; in fact the detuning with amplitude induced by the octupoles enforces the tune spread observed from the head to the tail of the batch as the tail is oscillating at larger amplitudes.

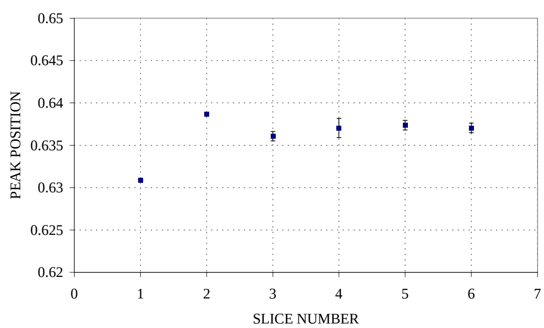

Figure 13: Horizontal tune vs. position along the batch.

Measurements performed after 30 ms (Fig. 14) and 500 ms (Fig. 15) after injection show that the oscillation is creeping from the tail into the head of the batch and than disappears.

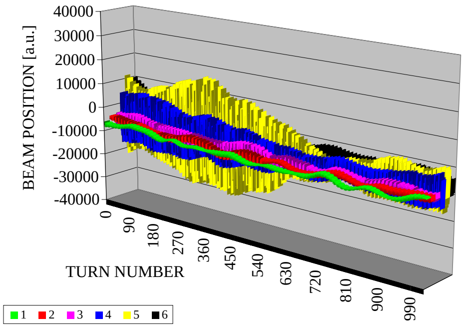

Figure 14: Horizontal oscillation 30 ms after injection for different slices of the batch.

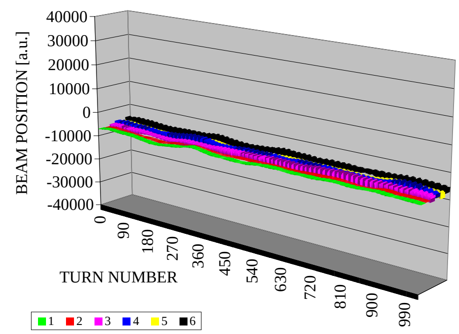

Figure 15: Horizontal oscillation 500 ms after injection for different slices of the batch.

Similar measurements were performed in the vertical plane. These show a strong damping of the injection oscillations (Fig. 16) followed by a residual oscillation lasting for hundreds of ms (Fig. 17). The Fourier analysis of the data shows that the half-integer is the dominating frequency (Fig. 18-19).

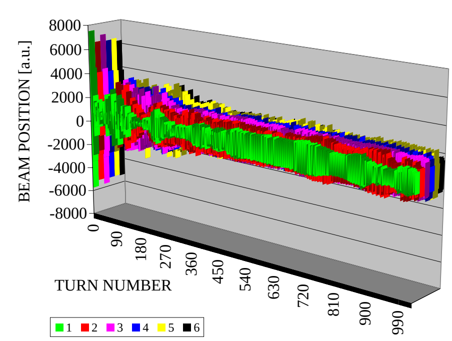

Figure 16: Vertical oscillation at injection for different slices of the batch.

This behaviour points to a non-optimum tuning of the vertical damper as the line on the half integer can be explained by an excessive gain of the feedback loop.

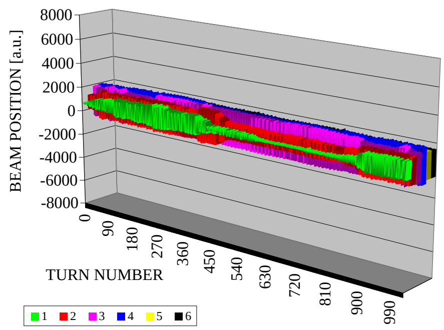

Figure 17: Vertical oscillations 500 ms after injection for different slices of the batch.

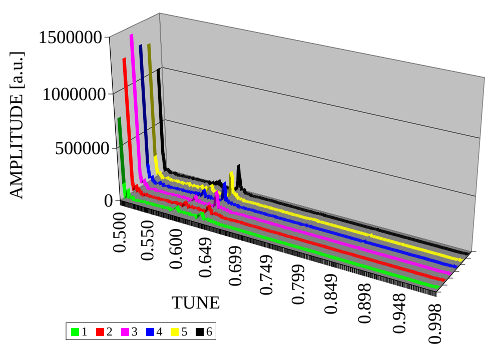

Figure 18: Fourier spectra of the vertical oscillation at injection for different slices of the batch.

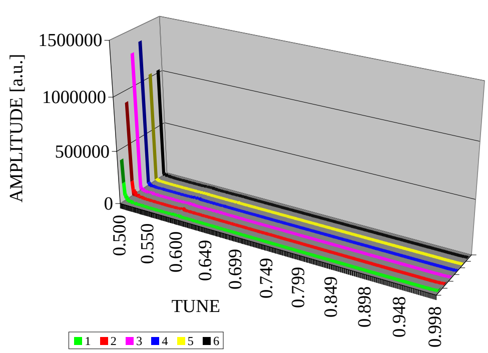

Figure 19: Fourier spectra of the vertical oscillation 500 ms after injection for different slices of the batch.

Some measurements (at higher intensity - I_{batch} = 6 x 10^{12} p of which 5-5.5 x 10^{12} p were injected - and with strong negative radial octupolar component), were performed after having switched off the vertical damper to confirm the above hypothesis. These do not show any more the residual oscillation already 30 ms after injection (Fig. 20) and the line on the half-integer disappears completely already at injection (Fig. 21).

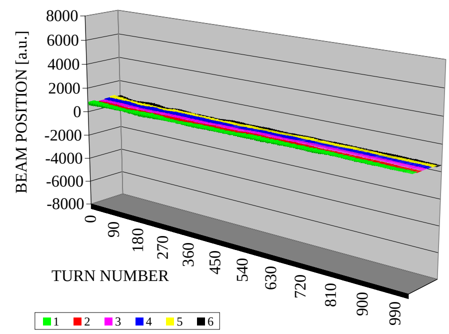

Figure 20: Vertical oscillations 30 ms after injection for different slices of the batch. Vertical dampers OFF.

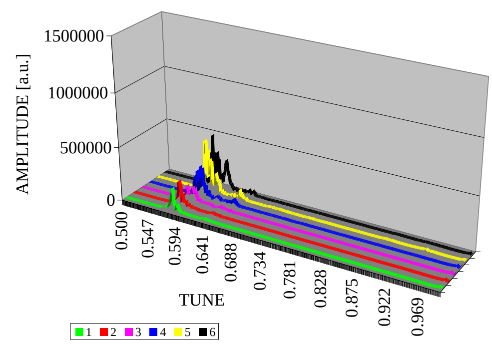

Figure 21: Fourier spectra of the vertical oscillation at injection for different slices of the batch. Vertical dampers OFF.

A part from the half integer line those corresponding to the horizontal (q_H= 0.637) and vertical (q_V=0.602) tunes are also visible (see Fig. 18-19). The horizontal tune peak dominates at injection but its amplitude decreases with time faster than that of the vertical tune. This can be observed in Fig. 22 where the spectral power in two intervals centred on q_H and q_V is considered as a function of the time elapsed from injection.

The spectral power considered for each point is the sum of the spectral powers of the six slices constituting the batch.

The reason for the appearance of such strong oscillations in the vertical plane at the frequency corresponding to the horizontal tune is not clear as the betatronic coupling was corrected to less than 0.005 (closest-tune approach) before the measurement.

The beam oscillation measurements confirm the result of the beam profile measurements, presented in Section 2, showing that the tail of the batch blows-up horizontally mainly at injection while the vertical size suffers of a continuous blow-up all through the injection plateau. This is consistent with the evolution of the spectral power of the oscillation along the batch as a function of the time elapsed from injection (Fig. 23 - horizontal plane and Fig. 24 - vertical plane). These figures show that at injection the tail of the batch is unstable mainly horizontally. This instability whose strength saturates in the second half of the batch creeps into the head of the batch after a few ms and then decays so that after 500 ms vertical oscillations, mainly of the tail of the batch, dominate.

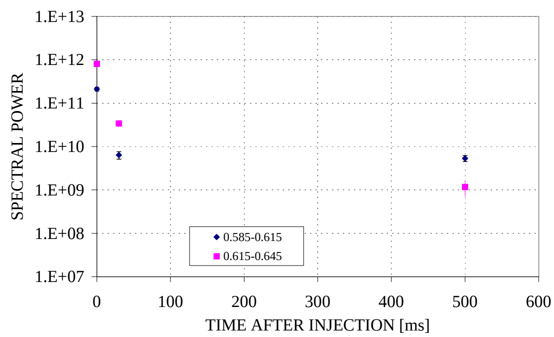

Figure 22: Spectral power vs. time for the tune intervals 0.585-0.615 and 0.615-0.645.

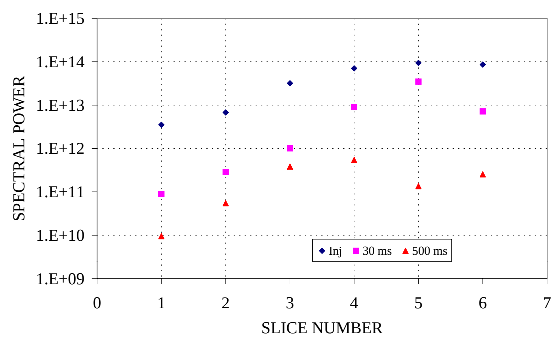

Figure 23: Spectral power along the batch vs. time from injection (horizontal plane).

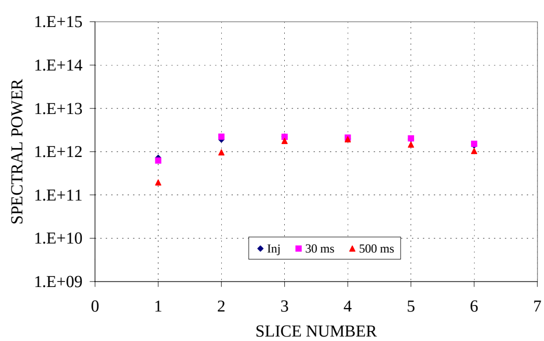

Figure 24: Spectral power along the batch vs. time from injection (vertical plane).

In Fig. 23 and 24 the spectral power has been integrated between 0.5 and 0.95 to exclude the contribution of the synchrotron frequency and its harmonics which are not relevant for this context.

4 OTHER OBSERVATIONS

In occasion of other machine development sessions performed with the TSTLHC beam additional observations were performed:

- For I_{batch} = 6 x 10^{12} p losses were observed in the last third of the batch during a few minutes after injection. These losses might occur at high intensity as a consequence of the blow-up of the tail of the batch observed horizontally and vertically [5].
- Vertical oscillations in the range 400 to 800 MHz were observed by means of a vertical wide-band pick-up. These occurred at injection and then slowly disappeared [5].

5 CONCLUSIONS

A series of measurements were performed with the TSTLHC beam to understand its behaviour at injection and individuate possible correlation with the onset of the electron cloud. An important blow-up of the tail of the batch has been evidenced in both planes. In the horizontal plane this occurs just after injection. In the vertical plane a continuous blow-up has been observed all through the injection plateau.

While the behaviour in the vertical plane is very likely due to a non-optimum adjustment of the gain of the transverse feedback the blow-up in the horizontal plane is due to a strong instability developing just after injection. Its growth time decreases along the batch (going from the head to the tail) and saturates at about 23 turns in the last half of the batch. The amplitude of the oscillations also saturates and than decreases after about 100 turns. This might be the result of the blow-up of the beam or to the action of the transverse feedback. After a few ms the instability creep towards the head of the batch and then dies. At injection the energy transfer from the horizontal to the vertical plane dominates the vertical activity. The coupling mechanism is not clear as the betatronic coupling was minimised (closest tune approach < 0.005) before the experiment took place.

No clear correlation with the electron cloud build-up has for the moment been found. Possible qualitative arguments in favour of an instability induced by the electron cloud are:

- Similar threshold for the onset of the instability and for the electron cloud.
- Stronger effect in the horizontal plane
- Increase of the growth rate of the instability along the batch (from the head to the tail) and saturation in the second half of it.

- Observation of high frequency (single bunch) activity.

ACKNOWLEDGEMENTS

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