OBSERVATIONS ON TRANSVERSE INSTABILITIES

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Abstract

Machine studies have been conducted in the SPS to better characterise the transverse instabilities observed on the LHC beam by the beam induced electron cloud. Most of the observations have been performed at injection energy. Different beam configurations have been considered as a function of their availability from the injectors. The results of these observations (bunch centroid motion, head-tail oscillations, emittance blow-up, intensity evolution along the batch) and their additional dependence on machine settings (e.g. sextupoles and octupole settings) are presented.

1 INTRODUCTION

In 1999 measurements performed with the TSTLHC[1] beam [1] evidenced an important blow-up of the tail of the batch in both planes. In the horizontal plane this occurred just after injection. In the vertical plane a continuous blow-up was observed all through the injection plateau. The blow-up in the horizontal plane was the result of a strong instability developing just after injection. Its growth time decreased along the batch (going from the head to the tail) and saturated at about 23 turns in the last half of the batch. The amplitude of the oscillations also saturated and than decreased after about 100 turns. At injection the energy transfer from the horizontal to the vertical plane dominated the vertical activity. Though the coupling mechanism was not clear. The arguments in favour of instability induced by the electron cloud were:

- Similar threshold for the onset of the instability and for the electron cloud (I_{bunch} = 4-5 x 10^{10} p).
- 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.

2 BEAM OBSERVATIONS WITH A LINEAR MACHINE

During the year 2000 additional measurements have been performed to confirm the above observations and better characterise the beam behaviour. The evolution of the instability has been studied in a linear machine:

- Chromaticity ($Q' = (\Delta Q/Q)/(\Delta p/p)$) was measured and corrected in both planes to be low and positive (+0.02 - +0.05).
- Detuning with amplitude was measured and minimised by means of machine octupoles.
- Betatron coupling was measured and corrected (down to a closest-tune-approach ~ 0.001) [3].
- RF capture adjusted by RF experts
- The ‘damper’ (transverse feedback) was active in both planes.

All the observations discussed in this report were performed at injection in the SPS (26 GeV/c) and with I_{bunch}~8 x 10^{10} p (i.e. about 75 % of the nominal intensity).

2.1 *Intensity measurements*

When the LHC[2] beam (I_{bunch} ~ 8 x 10^{10} p) is injected in a linear machine, losses occur approximately 4 ms after injection affecting the tail of the batch as can be seen in Fig. 1.

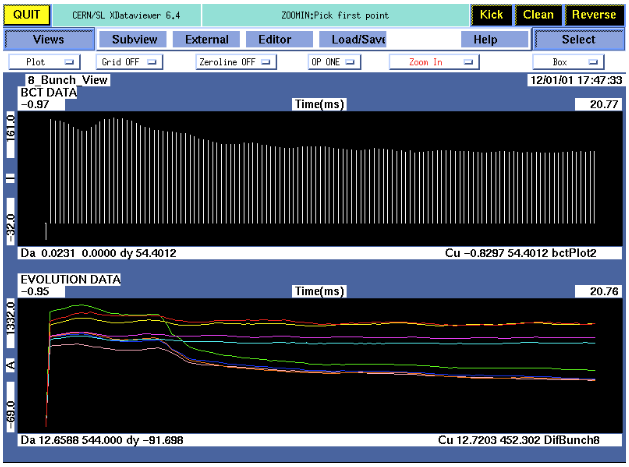

Figure 1: Intensity of the LHC beam vs. time: relative batch intensity (top) and relative bunch intensity for the first 4 bunches and the last 4 bunches (where losses are visible) of the batch (bottom). The intensity measurement is performed every 7 turns for about 20 ms in a linear machine.

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[1] TSTLHC is the name of an LHC type beam consisting of 84 bunches obtained by debunching and recapture and with single batch injection in the PS. Transverse emittances are about twice the nominal value and the longitudinal emittance is up to 50% larger than the nominal one [2].

[2] LHC is the name of the nominal LHC beam obtained by double batch injection in the PS and bunch splitting. It consists of 72 bunches. The transverse and longitudinal emittances are nominal [4].

2.2 *Profile measurements*

Measurements of the beam profile along the MDRF[3] batch have been performed with a rotational wire scanner at injection. The beam profile is measured in a window synchronous to the revolution frequency and 350 ns long. The position of the window can be moved along the batch. The results are shown in Figures 2 and 3. The quantity $4\sigma^2/\beta$ is displayed. The value of σ is determined from the measurement of the FWHM of the beam assuming a Gaussian distribution. A significant blow-up can be observed in the tail of the batch and it is already visible after 20-30 bunches. The spread in the measured size of the tail of the batch (the error bars represent the r.m.s. over a few cycles) is a consequence of the instability and of the jitter (a few ms) in the time at which the wire scanner traverses the beam. In the vertical plane the tail fills-up the physical aperture of the machine ($A_V \sim 4.5$ µm) producing the observed beam losses.

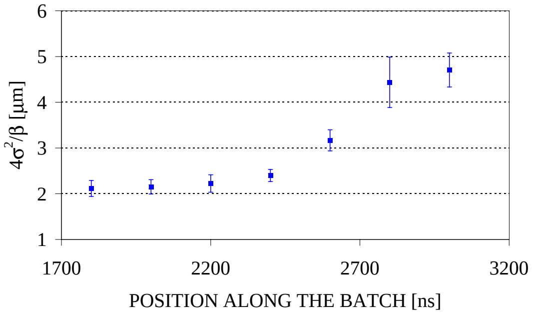

Figure 2: Beam size along the batch for the MDRF beam. Horizontal plane. $I_{bunch} \sim 8 \times 10^{10}$ p.

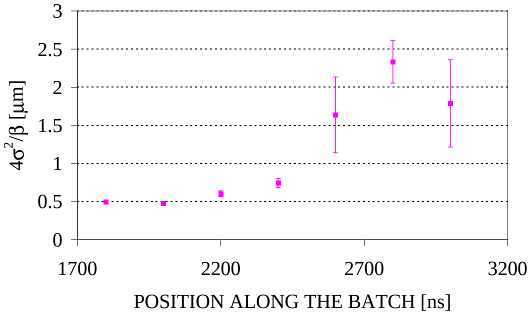

Figure 3: Beam size along the batch for the MDRF beam. Vertical plane. $I_{bunch} \sim 8 \times 10^{10}$ p.

2.3 *Bunch-to-bunch beam position measurement*

Measurements of the position of the centroid of each bunch of the LHC batch have been performed in order to understand the source of the blow-up of the tail. Figures 4 and 5 show the amplitude of the horizontal and vertical oscillations of the first and the last 32 bunches of the LHC beam over 1000 consecutive turns. Each of them was obtained by pasting the measurements performed in two different cycles. The horizontal bands visible in the figure represent the eight central bunches for which no data could be measured.

Injection occurred about 30 turns after the start of the acquisition. The trailing bunches of the batch start to oscillate vertically 30-40 turns after injection and horizontally about 80 turns after injection. The amplitude of the oscillations of the tail of the batch reaches its maximum approximately 150 turns after injection, i.e. 3.5 ms after injection, when the losses occur. The oscillation develops later and later going from the tail to the head of the batch and no significant oscillation is visible for the first 10-15 bunches.

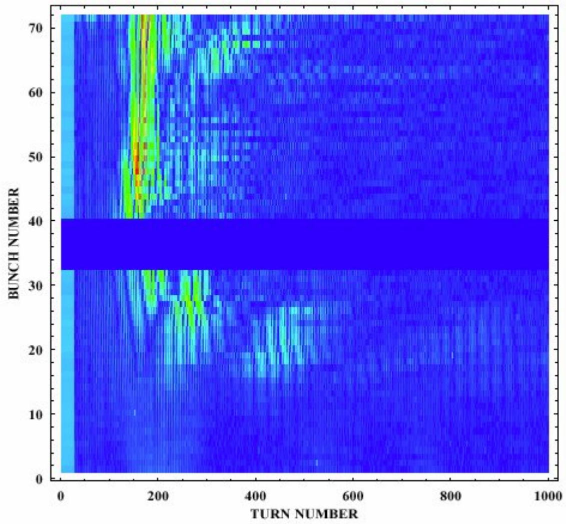

Figure 4: Amplitude of the horizontal oscillations of the centroids of the bunches of the LHC beam.

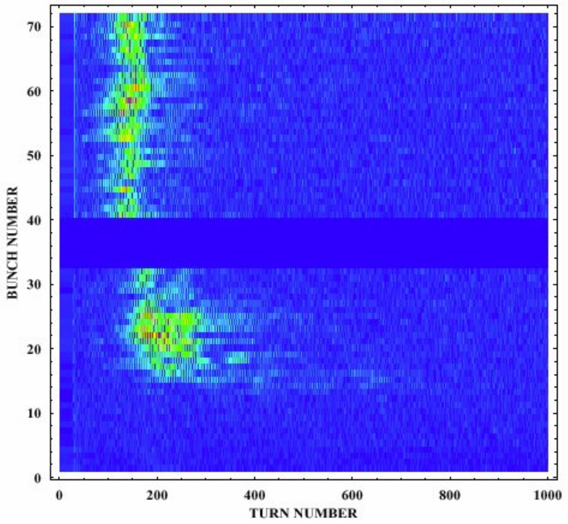

Figure 5: Amplitude of the vertical oscillations of the centroids of the bunches of the LHC beam.

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[3] MDRF beam is the name LHC-type beam obtained by single batch injection in the PS and bunch splitting. It consists of 48 bunches. The longitudinal emittance is nominal while the transverse emittance is twice the nominal [4].

The above observations are consistent with those concerning the beam size evolution along the batch and with the data collected in 1999 concerning the blow-up and the rise-time and saturation of amplitude of the oscillations.

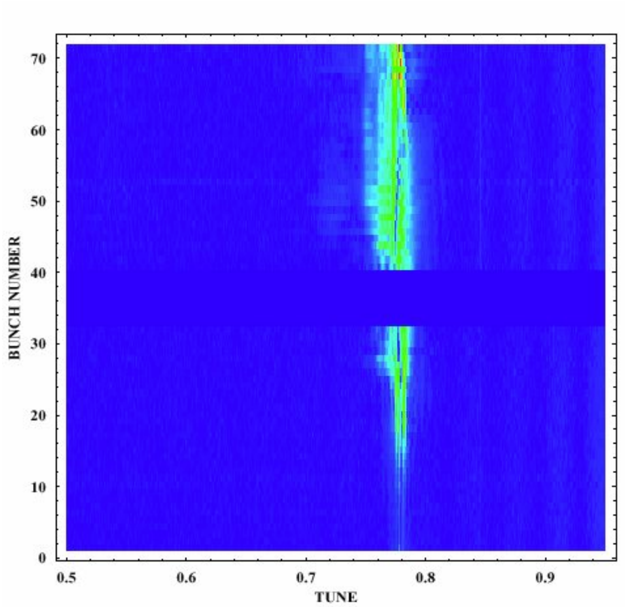

Figure 6: Fourier spectrum of the horizontal oscillations of the centroids of the bunches of the LHC beam as a function of the bunch number.

Figures 6 and 7 show the Fourier spectrum of the horizontal and vertical position of the centroids of the bunches along the batch. No significant oscillation is visible for the first 15 bunches. The vertical tune increases by more than 0.01 from the head to the tail of the batch, a significant step is observed between the 25th and the 30th bunch (see figures 8 and 9).

No transfer of energy from the horizontal to the vertical plane has been observed in 2000 unlike in 1999. This might be the consequence of the different working point (q_H=0.78,q_V=0.60). In 1999 the chosen working point was q_H=0.63, q_V =0.60. The vertical oscillations of the tail of the batch at a frequency corresponding to q_H (1999) can be explained the above-mentioned vertical tune shift bringing the horizontal and vertical tunes closer and closer going from the head to the tail of the batch.

Figures 10 to 13 represent the amplitude of the two-dimensional Fourier transform of the oscillation of the first (respectively last) 10 bunches of the LHC batch. The mode number is the number of wavelengths of the oscillation in one machine turn. The distance between two consecutive bunches in the LHC beam is 25 ns, i.e. 1/924 of a machine turn and therefore the maximum mode number that can be resolved is 462. The minimum and maximum amplitudes corresponding to the extremes of the colour scale are the same for the leading and trailing bunches to allow the comparison of the figures corresponding to the first and last 10 bunches.

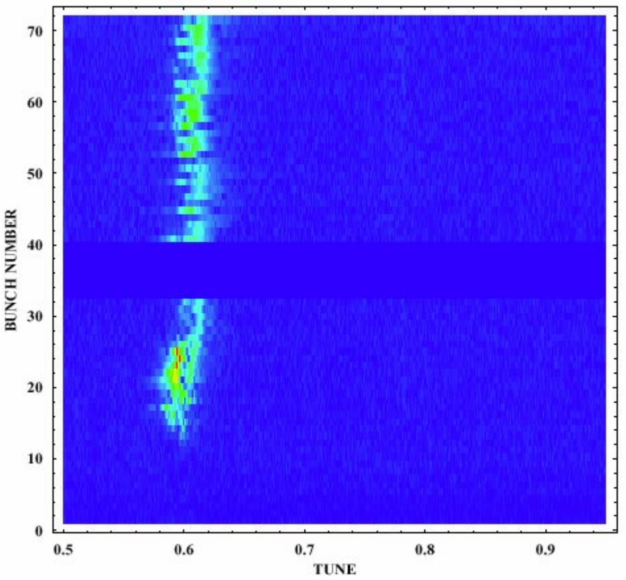

Figure 7: Fourier spectrum of the vertical oscillations of the centroids of the bunches of the LHC beam as a function of the bunch number.

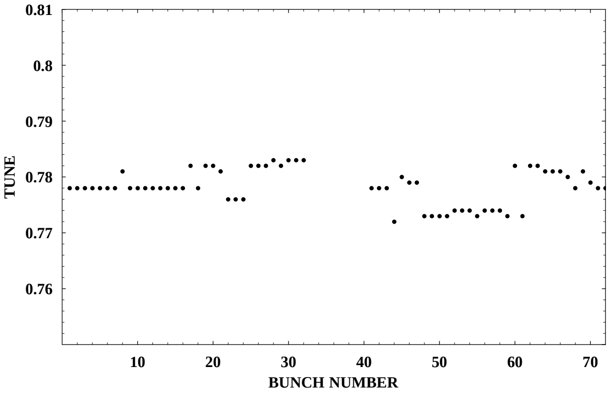

Figure 8: Evolution of the horizontal tune along the batch.

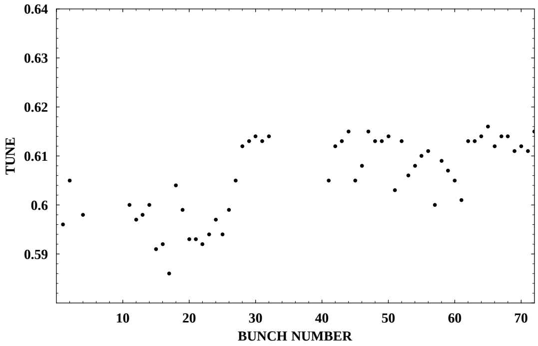

Figure 9: Evolution of the vertical tune along the batch.

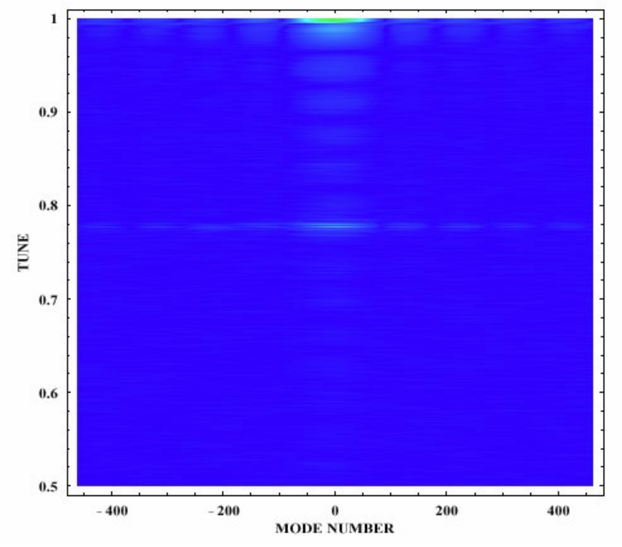

Figure 10: Two-dimensional Fourier spectrum of the horizontal oscillations of the centroids of the first 10 bunches of the LHC beam.

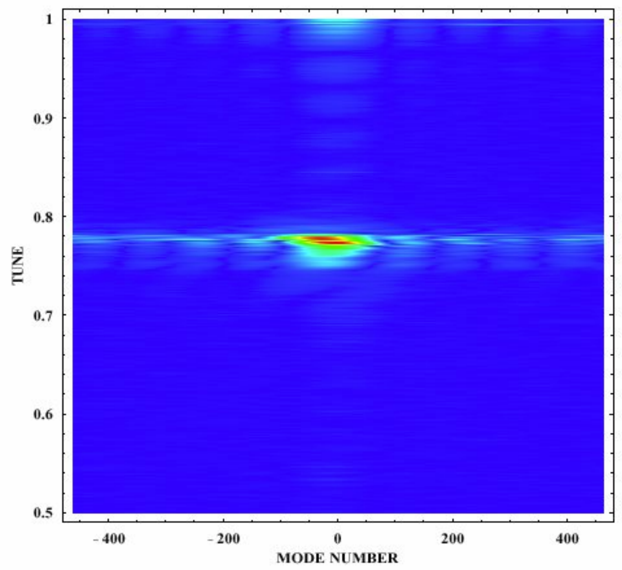

Figure 11: Two-dimensional Fourier spectrum of the horizontal oscillations of the centroids of the last 10 bunches of the LHC beam.

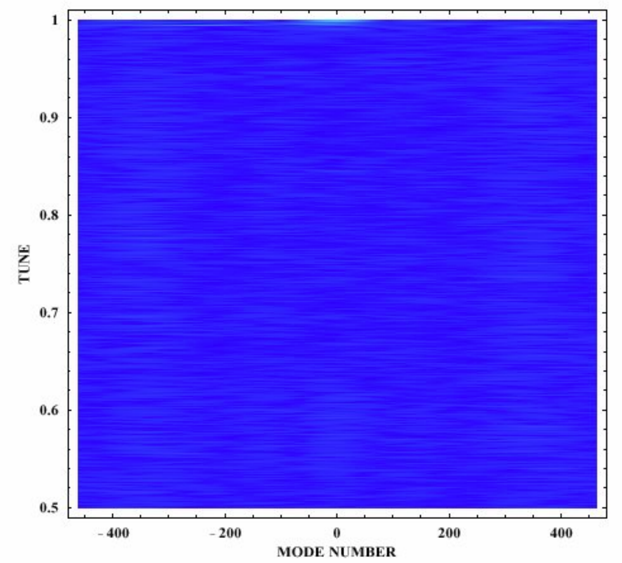

Figure 12: Two-dimensional Fourier spectrum of the vertical oscillations of the centroids of the first 10 bunches of the LHC beam.

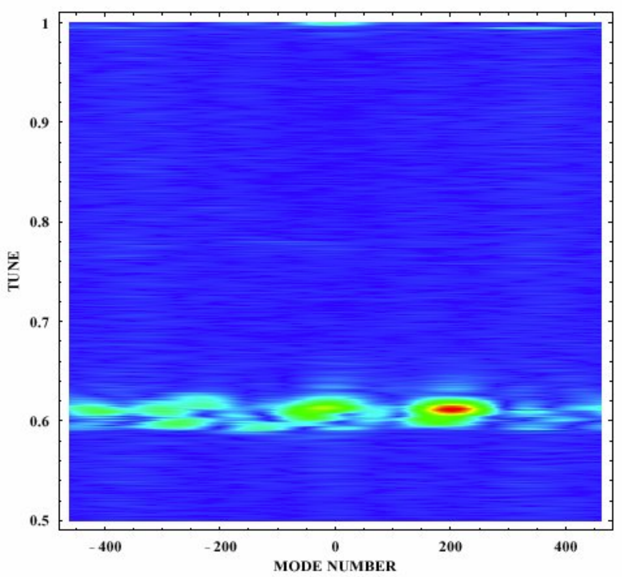

Figure 13: Two-dimensional Fourier spectrum of the vertical oscillations of the centroids of the last 10 bunches of the LHC beam.

The head of the batch is not oscillating while the tail of the batch undergoes oscillations both in the horizontal and vertical planes. In the horizontal plane modes up to number 100 (corresponding to about 4 MHz) are excited, in the vertical plane higher order modes (in particular around mode number 200, corresponding to about 9 MHz) dominate.

Figure 14: Detail of the sum (top) and delta (bottom) signals provided by the wide-band transverse pick-up (vertical plane).

2.4 *Wide-band transverse pick-up*

Measurements have been also performed with a wide-band transverse pick-up. The sum and delta signals provided by such a monitor for the last 39 bunches of the MDRF batch have been sampled every 0.5 ns for 56 consecutive turns approximately 4 ms after injection. Figure 14 shows the details of the raw sum and delta signals for the vertical plane. The signal and the reflection cannot be fully resolved because of the limited length of the strip-line coupler (about 37 cm) [5]. The delta signal (unlike the sum signal) seems to present a finer structure inside the bunch.

The Fourier spectrum of the sum signal (Figure 15) is characterised by lines at multiples of 40 MHz due to the 25 ns spacing between consecutive bunches. The envelope of the spectrum is determined by the bunch length and by the transfer function of the monitor that vanishes at frequencies that are multiples of about 400 MHz. The Fourier spectrum of the delta signal (Figure 16) has side-bands whose distance from the lines at multiples of 40 MHz is approximately 10 MHz thus confirming the existence of coupled bunch mode oscillations. The comparison of the spectra of the delta and sum signals seems also to indicate the presence of transverse motion inside the bunch at frequencies above 800 MHz. Such high frequency components are not measured in the horizontal plane.

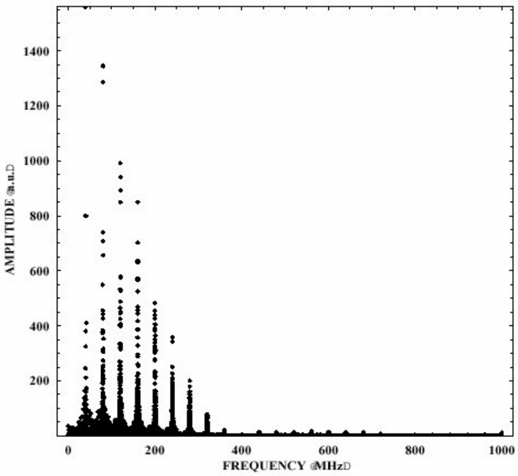

Figure 15: Fourier spectrum of the sum signal provided by the wide-band transverse pick-up (vertical plane) 4 ms after injection.

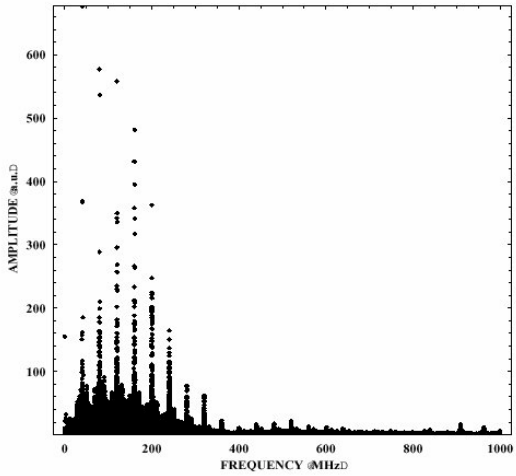

Figure 16: Fourier spectrum of the delta signal provided by the wide-band transverse pick-up (vertical plane) 4 ms after injection.

3 DEPENDENCE ON THE FILLING PATTERN

The nominal LHC filling scheme foresees the injection of 3 or 4 LHC batches in the SPS. The spacing between consecutive batches is 225 ns, corresponding to a gap of 8 bunches [6]. It is therefore interesting to verify if the above spacing is sufficient to completely uncouple the batches with respect to the beam induced electron cloud. For that reason the transverse beam behaviour has been studied when gaps are created in the LHC batch. The injectors can easily create gaps of 12 bunches in the LHC batch by stopping the injection from one of the 4 PS Booster rings into the PS [4].

Figure 17 (bottom) shows the evolution of the intensity of the first and last four bunches of the LHC beam with time. Unlike the full LHC batch no relevant loss is detectable in the tail of the batch (cf. Figure 1).

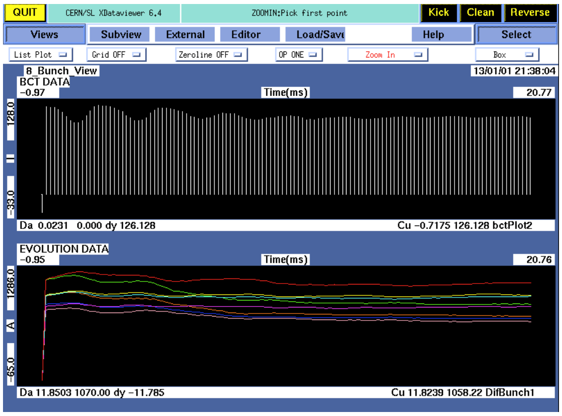

Figure 17: Intensity of the LHC beam vs. time: relative batch intensity (top) and relative bunch intensity for the first 4 bunches and the last 4 bunches of the batch (bottom). A gap of 12 bunches after the first 36 bunches of the LHC beam was created.

The bunch-to-bunch centroid motion has been also measured and its amplitude in the horizontal and vertical planes is shown in Figures 18 and 19, respectively. The behaviour of the head of the batch is similar to that observed for the LHC batch without gap (cf. Figures 4 and 5). The tail of the batch, following the gap, behaves like the head of the batch but the oscillations in the tail start after a smaller number of bunches. This is particularly evident in the vertical plane where oscillations in the head of the batch are visible after 15 bunches. After the gap they appear after less then 10 bunches indicating that a gap of 12 bunches is not sufficient to completely clear off the electron cloud generated by the head of the batch. Similar conclusions can be drawn from the comparison of Figures 20 and 21 with the corresponding Figures 8 and 9.

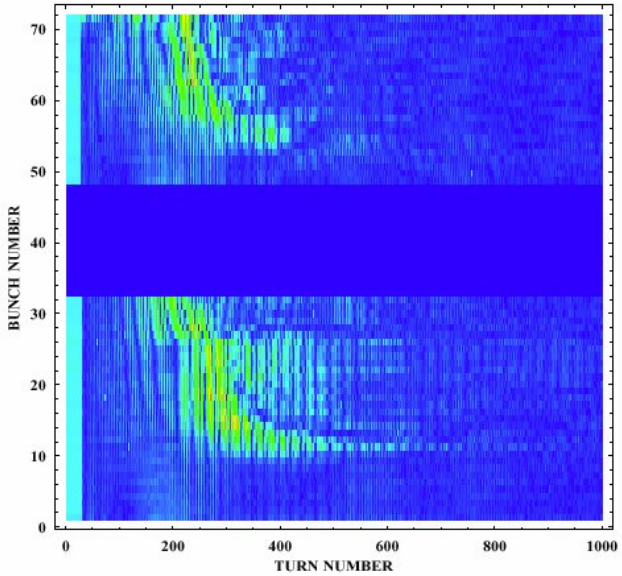

Figure 18: Amplitude of the horizontal oscillations of the bunches of the LHC beam in the presence of a gap of 12 bunches after 36 bunches.

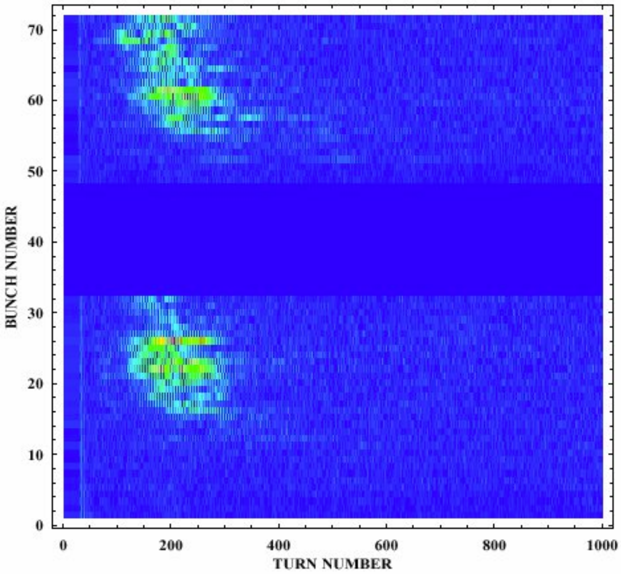

Figure 19: Amplitude of the vertical oscillations of the bunches of the LHC beam in the presence of a gap of 12 bunches after 36 bunches.

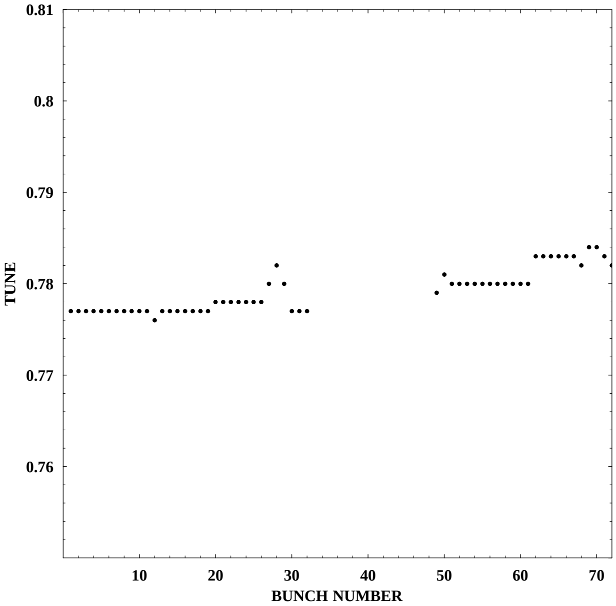

Figure 20: Evolution of the horizontal tune along the LHC batch in the presence of a gap of 12 bunches after 36 bunches.

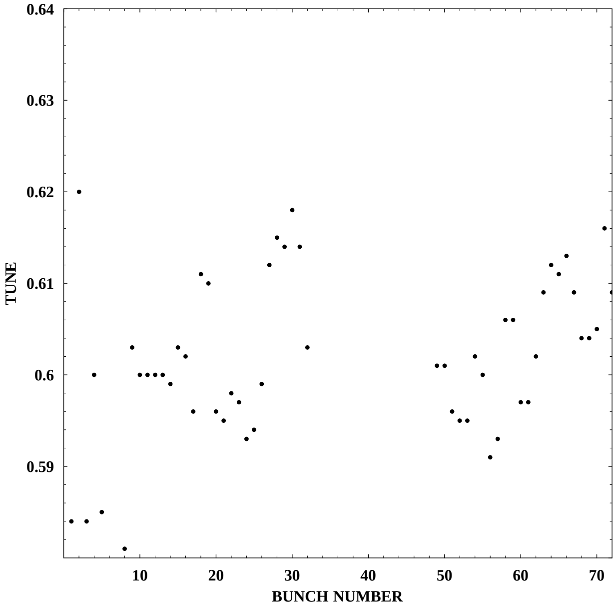

Figure 21: Evolution of the vertical tune along the LHC batch in the presence of a gap of 12 bunches after 36 bunches.

The above behaviour agrees with the electron signal measured by an electron collector installed in a section of the SPS vacuum chamber [7] as well as with simulations [8][9].

A complete reset of the electron-cloud generated by the tail of the batch occurs only when a gap of 24 bunches is created after 36 bunches in the LHC batch.

4 EFFECT OF OCTUPOLES AND CHROMATICITY

The effect of octupoles and chromaticity as means to increase the Landau Damping to fight the instability have been considered.

4.1 Octupoles

Figures 22 and 23 illustrate the dependence of the horizontal and vertical beam size along the batch at injection on different octupoles settings for the MDRF beam in the SPS with low positive chromaticity ($Q_H' \sim Q_V' \sim +0.03$) and the standard working point ($q_H=0.635$ and $q_V=0.567$).

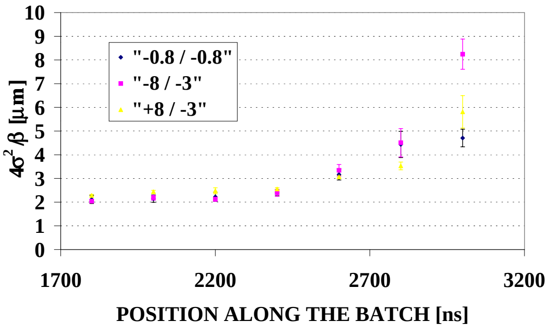

Figure 22: Horizontal beam size along the batch at injection for different control values of the radial and vertical octupole strength (expressed in m^{-3}), respectively.

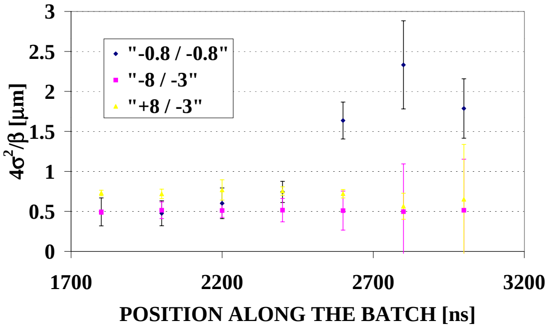

Figure 23: Vertical beam size along the batch at injection for different control values of the radial and vertical octupole strength (expressed in m^{-3}), respectively.

The control settings -0.8/-0.8 m^{-3} for the radial and vertical octupole strength (i.e. the strength of the LOF and LOD families, respectively) correspond to a complete cancellation of the detuning with amplitude. The tail of the batch blows-up significantly in the horizontal plane for high radial strengths with the result of stabilising the beam and of eliminating the vertical blow-up. Nevertheless the tail is filling all the available horizontal aperture of the machine and the beam suffers of slow losses all through the injection plateau.

4.2 Chromaticity

Chromaticity has proven to be the only tool allowing to control the blow-up of the size of the tail of the batch and to obtain a decent lifetime in the injection plateau. Figures 24 and 25 show the horizontal and vertical beam size of the head and the tail of the MDRF batch at injection and 30 ms after injection for a linear machine and standard working point ($q_H \sim 0.62$, $q_V \sim 0.58$).

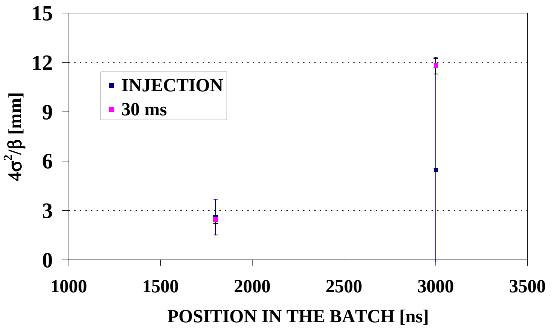

Figure 24: Horizontal beam size of the head and the tail of the MDRF batch at injection and 30 ms after injection in a linear machine (Q_H' ~ Q_V' ~+0.05).

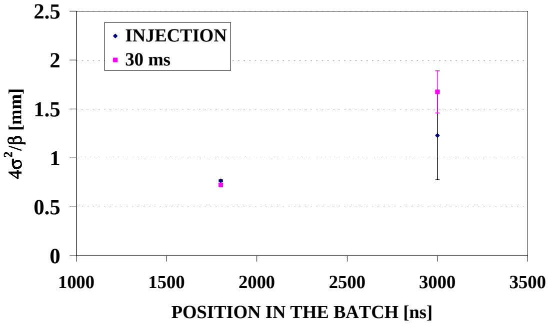

Figure 25: Vertical beam size of the head and the tail of the MDRF batch at injection and 30 ms after injection in a linear machine (Q_H' ~ Q_V' ~+0.05).

The same quantities are displayed in Figures 26 and 27 for high chromaticities (Q_H' ~ Q_V' ~+0.5). In that case no blow-up is observed (the larger size of the head of the batch was a characteristic of the beam extracted from the PS as confirmed by measurements in the injection transfer line).

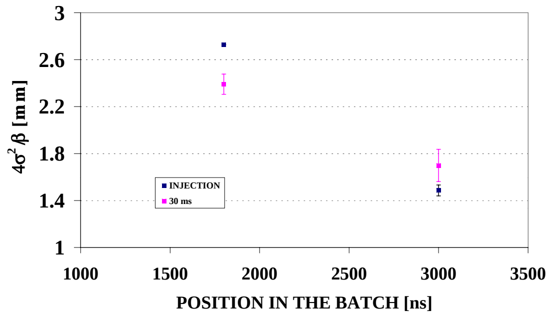

Figure 26: Horizontal beam size of the head and the tail of the MDRF batch at injection and 30 ms after injection with Q_H' ~ Q_V' ~+0.5.

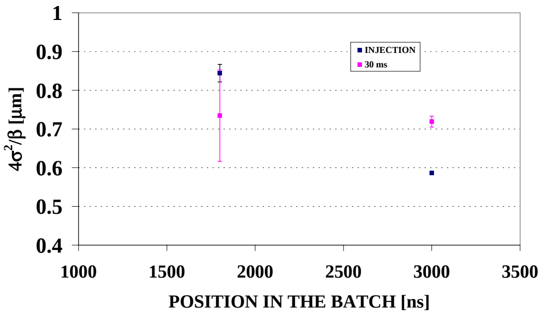

Figure 27: Vertical beam size of the head and the tail of the MDRF batch at injection and 30 ms after injection with Q_H' ~ Q_V' ~+0.5.

In order to control the blow-up in the LHC beam (72 bunches) larger chromaticity values (up to +0.9 in the horizontal plane) than those applied for the MDRF beam (48 bunches) are required, even for the same bunch intensity. The resulting tune spread prevents a stable operation at the standard working point and higher horizontal and vertical tunes must be chosen (q_H=0.78, q_V =0.60) in order to avoid crossing resonances (half-integer for the vertical plane and third-integer for the horizontal plane) with part of the beam. Under these conditions no loss is detectable.

The elimination of the blow-up of the size of the tail of the LHC batch at high values of the chromaticity corresponds to the disappearance of the coupled bunch oscillations observed at low chromaticity (see Figures 4 to 13).

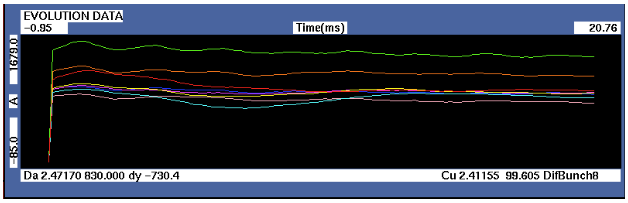

Figure 28: Intensity of the LHC beam vs. time: the relative bunch intensity for the first 4 bunches and the last 4 bunches of the batch is plotted. The intensity measurement is performed every 7 turns for about 20 ms for Q_H' ~ +0.7 and Q_V' ~ +0.5.

The wide-band pick-up still evidences activity at higher frequencies in the vertical plane even for high chromaticity values. Indeed the absence of losses at injection (as compared to the low chromaticity case) seems to enhance the amplitude of the oscillations visible a few ms after injection already for frequencies higher than 600 MHz (see Figures 29 and 30).

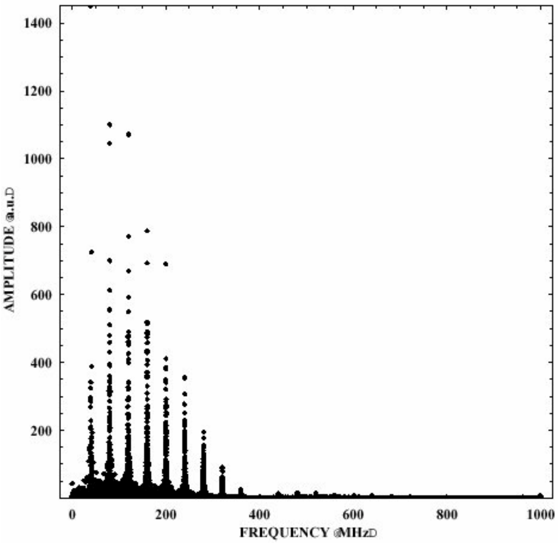

Figure 29: Fourier spectrum of the sum signal provided by the wide-band transverse pick-up (vertical plane) 4 ms after injection. Q_H' ~ +0.7 and Q_V' ~ +0.5.

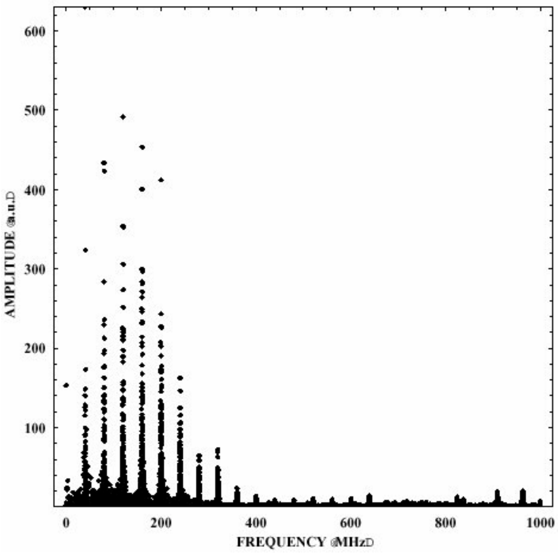

Figure 30: Fourier spectrum of the delta signal provided by the wide-band transverse pick-up (vertical plane) 4 ms after injection. Q_H' ~ +0.7 and Q_V' ~ +0.5.

5 CONCLUSIONS

In a linear machine transverse instabilities affect the trailing bunches of LHC beam in the horizontal and vertical plane. In the horizontal plane coupled-bunch modes up to number 100 (corresponding to about 4 MHz) are excited, in the vertical plane higher order modes (in particular around mode number 200, corresponding to about 9 MHz) dominate. The trailing bunches of the batch start to oscillate vertically 30-40 turns after injection and horizontally about 80 turns after injection. As a result of that a significant blow-up can be observed in the tail of the batch and it is already visible at injection after 20-30 bunches. The amplitude of the oscillations of the tail of the batch reaches its maximum approximately 150 turns (i.e. 3.5 ms) after injection when the tail fills-up the vertical physical aperture of the machine (A_V ~ 4.5 μm) producing beam losses. The oscillation develops later and later going from the tail to the head of the batch. Neither oscillation nor blow-up is detectable for the first 10-20 bunches. This excludes resistive wall as a possible source of the observed behaviour [10].

A positive vertical tune shift of more than 0.01 occurs between the 25th and 30th bunch.

Measurements performed by means of a wide-band transverse pick-up seem also to indicate the presence of vertical motion inside the bunch at frequencies above 600 MHz developing a few ms after injection. Such high frequency components are not seen in the horizontal plane.

The creation of a gap of eight bunches after 36 bunches in the LHC batch reduces the number of bunches undergoing oscillations and no loss is detected. The behaviour of the head of the batch is similar to that observed without gap. The tail of the batch, following the gap, behaves like the head but the oscillations in the tail start after a smaller number of bunches. This indicates that a gap of 12 bunches is not sufficient to completely clear off the electron cloud generated by the head of the batch. The electron cloud generated by the subsequent LHC batches injected in the SPS is therefore expected to add-up if the present filling scheme foreseeing a gap of 8 bunches between consecutive batches is maintained. A complete reset of the electron-cloud is observed if a gap of 24 bunches is created.

Several arguments seem to indicate the beam induced electron cloud as a source of the observed transverse instabilities:

- Similar threshold for the onset of instability and electron cloud (both in terms of bunch intensity and number of bunches required to trigger the electron cloud).
- Compatibility of the observations with the measurements and simulations of the electron-cloud build-up.
- Observation of high frequency (single bunch) activity. The unstable frequencies are comparable with the estimated electron bouncing frequency.

Chromaticity seems for the moment the only tool available to fight the coupled bunch instabilities and to avoid blow-up and losses. The values required to stabilise the beam increase with the number of bunches so that a different working point with higher horizontal and vertical tunes (q_H=0.78, q_V =0.60) has to be used for the LHC beam (72 bunches). It is not yet clear if the above scheme will be viable for the nominal bunch intensities, for more batches and for the acceleration. High chromaticities seem to have no effect on the high frequency oscillations measured in the vertical plane.

ACKNOWLEDGEMENTS

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