TRANSVERSE INSTABILITIES OF THE LHC PROTON BEAM IN THE SPS

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Abstract

The availability from the injectors of the proton beam required for the LHC era has allowed studying its transverse behaviour in the SPS. Profile and beam oscillation measurements evidenced the existence of strong transverse instabilities developing along the batch and inducing an emittance blow-up of increasing importance from the head to the tail of the batch. An intensity threshold, comparable to that observed for the development of the beam induced electron cloud, has been found for the onset of the above phenomena. The results of the measurements and their possible interpretation are presented.

1 INTRODUCTION

Since the beginning of 1999 a proton beam with characteristics comparable with those required for the LHC era has been available from the injectors for the SPS. The basic parameters of this beam can be found in ref. [1]

Four types of transverse instabilities are observed for the LHC beam:

- Head-tail instability. The m=0 mode becomes unstable for negative chromaticities. Adjusting the chromaticity to slightly positive values can damp this dipole mode. The damping constant is proportional to the intensity and to the transverse impedance.
- Resistive wall instability. For batch intensities (I_{batch}) higher than 2 x 10^{12} p the fundamental mode is unstable and the transverse feedback (damper) is needed to damp it.
- Horizontal instability due to short range wake [2]. For I_{batch}>2 x 10^{12} p a horizontal instability develops at the end of the batch a few hundred milliseconds after injection. This instability appears also for beams with 5 ns bunch spacing for linear densities above 10^{12} p/µs. The frequency of this instability (about 6 MHz) is just above the bandwidth of the present damper. The foreseen increase of its bandwidth to 20 MHz should allow controlling this instability.
- A fast horizontal and vertical instability developing at injection. This has been observed only for the LHC beam for batch intensities I_{batch}> 3-4 x 10^{12} p (less than half the nominal intensity). This instability could not be damped by the transverse feedback and strong negative octupole radial strength[1] was required in order to get decent injection efficiency. In order to get better understand this phenomenon beam measurements and simulations were performed.

2 BEAM MEASUREMENTS

Profile measurements of different slices along the batch (2 µs total length) were performed by means of a wire scanner. One horizontal and one vertical damper were ON, low positive chromaticity $((\Delta Q/Q)/(\Delta p/p) < 0.02)$ and strong negative radial octupole component were set. The results of the profile measurements at 4 different positions in the batch and for different batch intensities are shown for the horizontal and vertical planes a few ms after injection (Fig. 1 and 2). For I_{batch} > 4 x 10^{12} p the tail of the batch is affected by a significant blow-up in the horizontal plane mainly at injection. The blow-up is present, but to a smaller extent, also in the vertical plane where it continues all through the 600 ms injection plateau used during the machine studies.

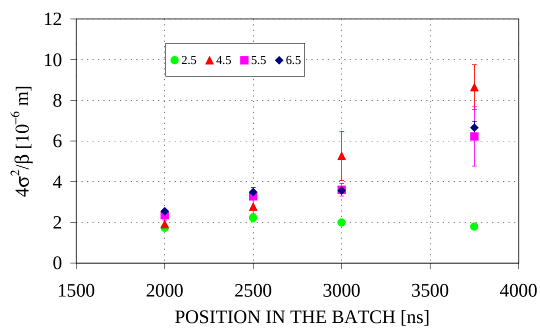

Figure 1: Horizontal profile measurement along the batch a few ms after injection for different batch intensities (expressed in 10^{12} p)

In order to understand the source of the blow-up of the tail of the batch the beam oscillations have been measured. As for the beam profiles the measurement was gated and beam positions could be acquired for six equidistant slices of the batch over 1024 turns. Measurements were performed using a coupler equipped with a 200 MHz receiver of 2 MHz bandwidth. Slice 1 corresponds to the head of the batch and slice 6 corresponds to the tail of the batch. The measurements were performed with I_{batch} ~ 4 x 10^{12} p. One vertical and two horizontal dampers were active and no octupole component was introduced. The chromaticity was small and positive (< 0.02).

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

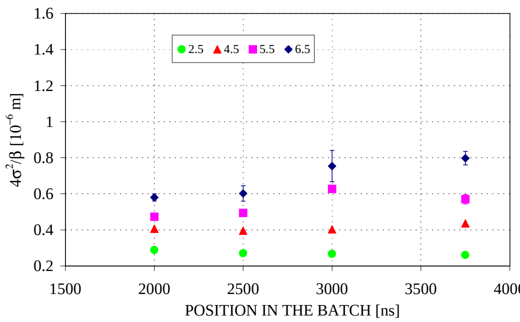

Figure 2: Vertical profile measurement along the batch a few ms after injection for different batch intensities (expressed in 10^{12} p).

The results of the measurements for the horizontal plane at injection are shown in Fig. 3. A rapidly growing oscillation affects mainly the tail of the batch just after injection. It saturates and then it is damped. The most likely damping mechanism is the horizontal blow-up of the beam. 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. 4.

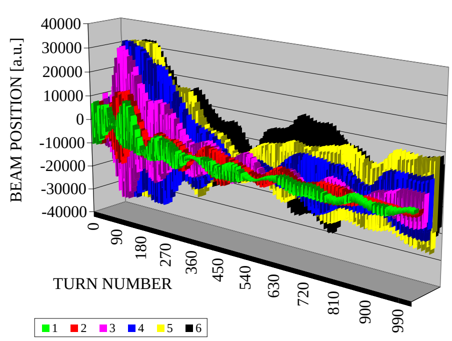

Figure 3: Horizontal beam oscillations for six consecutive slices of the batch at injection.

While the head of the batch undergoes a damped oscillation the rest of the batch becomes unstable. The growth time is getting shorter and shorter going from the head to the tail of the batch and saturates at about 25 turns[2] in the second half of the batch. The evolution of the spectral power with time shows that after 30 ms the tail of the batch (slice 6) is not oscillating any more while slice 5 is still oscillating as it is not yet fully blown up. After 600 ms the maximum spectral power of the oscillations is localised at the centre of the batch but now it is more than two order of magnitudes smaller than at injection.

[2] The revolution period of the beam in the SPS is 23 μs

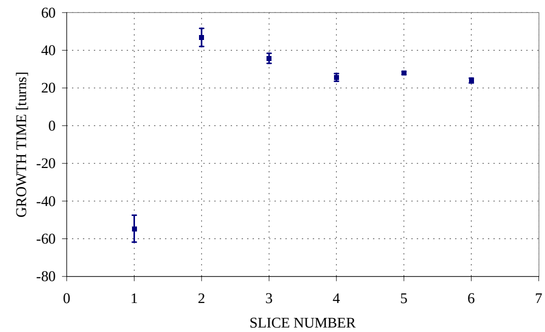

Figure 4: Growth time of the horizontal instability observed at injection vs. position in the batch.

Similar measurements were performed in the vertical plane. The Fourier analysis of the data shows that the oscillation amplitude grows from the head to the tail of the batch at injection. It is also interesting to observe that the peaks corresponding to both the horizontal and vertical tunes are visible and have comparable amplitudes. The reason for the appearance of oscillations in the vertical plane at the frequency corresponding to the horizontal tune is not yet clear as the betatronic coupling was corrected to less than 0.005 (closest-tune approach) before the measurement. The possibility that this signal is due to a tilt of the coupler used for the oscillation measurements is being investigated. A strong signal corresponding to a tune of 0.5 points to an excessive gain of the transverse feedback loop as was confirmed later by measurements performed without vertical damping.

Beam oscillation measurements confirm the result of the beam profile measurements showing that the tail of the batch blows-up horizontally and, to a minor extent, vertically mainly at injection. The continuous blow-up of the vertical size all through the injection plateau can be traced back to an incorrect setting of the gain of the vertical damper.

During one of the sessions dedicated to the study of the behaviour of the LHC beam in the SPS, 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. Preliminary more recent observations seem to confirm these results, which indicate a coherent motion within a bunch.

3 SIMULATIONS AND ESTIMATES

The threshold for the presented instability coincides well with that for the onset of the beam induced electron cloud in the SPS [3].

If a bunch is offset with respect to the other bunches, it will perturb the electron-cloud distribution, and the next bunch will receive an additional deflection caused by this perturbation. Thus, similar to a multi-bunch wake field, the electron cloud couples the motion of subsequent bunches [4]. The electron-cloud can also act as a short-range wake-field and drive single bunch instability. While a multi-bunch instability could be controlled by the transverse feedback a single-bunch instability could not be dealt by such a system. A campaign of simulations was launched to determine the electron distribution in the SPS [5]. Using the simulation results, growth rates expected for different kinds of expected instabilities can be compared with experimental observations.

According to simulations, the electron-cloud density increases exponentially along in the batch and then saturates towards the tail of the batch (see Fig. 5). The saturation density depends primarily on bunch intensity (I_{bunch}), bunch spacing and the secondary emission yield (SEY) and to a lesser extent on beam size and vacuum chamber geometry. The residual pressure does not affect significantly the saturation density but it affects the 'threshold position' along the bunch train. A similar behaviour is obtained for the total number of electrons in the vacuum chamber and, assuming 50 nTorr residual pressure, for SEY=1.9 it fits well with the signals provided by electrostatic high-impedance pick-ups installed in the SPS [6]. For I_{bunch}= 7.5 x 10^{10} (corresponding to I_{batch}= 6 x 10^{12}) the saturation electron cloud density near the beam is about 5 x 10^{11} m^{-3}.

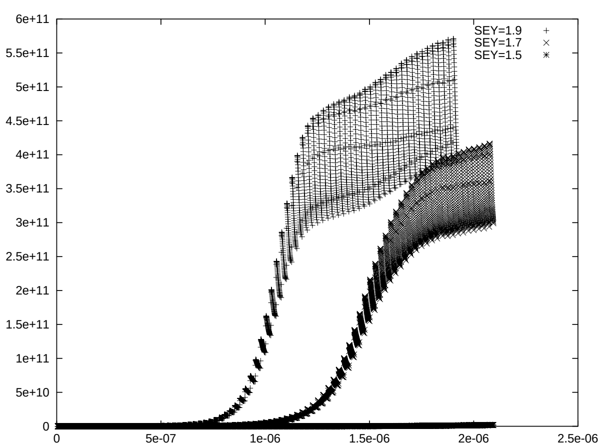

Figure 5: Simulated electron cloud density along the batch for different SEY.

Typical growth rates for multi-bunch instability calculated on the basis of the above simulations are of the order of a few hundred of milliseconds. On the other hand the expected electron oscillation frequency inside a bunch and therefore the characteristic frequency of the "single-bunch" instability is 730 MHz. The expected growth rates [7] for a beam break-up instability (ignoring the synchrotron motion) is 500 μs, that for the m=1 head-tail mode is 7.7 ms for a chromaticity $(\Delta Q/Q)/(\Delta p/p)=0.01$. The threshold electron-cloud density for the onset of the strong head-tail (TMCI) instability is estimated to be about 8 x 10^{11} m^{-3} which can be reached for LHC nominal bunch intensities. The observations performed on the LHC beam seem therefore to be compatible with single bunch instabilities driven by the electron cloud. The observed beam oscillations and blow-up of the tail of the batch are also in qualitative agreement with this image.

4 SUMMARY

Most of the transverse instabilities observed for the LHC beam in the SPS can be controlled by adequate tuning of the machine parameters or by operating the transverse feedback, whose bandwidth will be increased. Most worrying is a fast horizontal instability developing at injection with growth times of about 30 turns. This produces an important blow-up of the tail of the LHC batch and for intensities higher than 6 x 10^{12} p important losses at injection occur even when applying strong octupole fields. The same phenomenon appears, though to a smaller extent, also in the vertical plane. The threshold for the onset of this instability (I_{batch}= 4 x 10^{12} p) is comparable with that for the appearance of beam induced electron cloud. Simulated electron density distributions and growth-rates estimated for electron-cloud driven single-bunch instabilities appear to be roughly consistent with the observations.

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