FAST VERTICAL SINGLE-BUNCH INSTABILITY AT INJECTION IN THE CERN SPS - AN UPDATE

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Abstract

Following the first observation of a fast vertical instability for a single high-brightness bunch at injection in the SPS in 2002, a series of detailed measurements and simulations has been performed in order to assess the resulting potential intensity limitations for the SPS, as well as possible cures. During the 2006 run, the characteristics of this instability were studied further, extending the intensity range of the measurements, and comparing the experimental data with simulations that take into account the latest measurements of the transverse machine impedance. In this paper, we summarize the outcome of these studies and our understanding of the mechanisms leading to this instability. The corresponding intensity limitations were also determined.

INTRODUCTION

The LHC proton beam, consisting of up to 4 trains of 72 bunches each, has longitudinal and transverse brightness (i.e. the ratio between the bunch population and its longitudinal and transverse emittances) largely surpassing that of the other multi-bunch beams produced so far by the accelerators of the LHC injector chain. The nominal bunch intensity has already been accelerated in the SPS during p-pbar operation, albeit with different longitudinal emittance and bunch length [1]. The main bunch parameters at SPS injection and at SPS extraction are presented in Table 1 for nominal and ultimate LHC beam operation.

Table 1: Main parameters of the LHC beam in the SPS

	Nominal	Ultimate
Momentum [GeV/c]	26 / 450	
N_b [10^{11} p]	1.15	1.7
1σ–norm. transv. emit. $\varepsilon^*_{H,V}$ [μm]	3 / 3.5	
2σ–long. emit. ε_L [eV s]	0.35 / <0.8	
Full bunch length τ_b [ns]	3 / <2	
Tunes (H/V)	26.13/26.185	
Gamma transition	22.83	

The achievement of the performance required for the ultimate LHC operation or for the LHC luminosity upgrade [2] demands a detailed understanding and control of the single bunch effects and in particular of the machine impedance. For that reason a series of studies has started since the first observation, in 2002, of a fast transverse instability [3] for a single bunch of smaller longitudinal (~0.2 eV.s) and transverse (~1 μm) emittances [4][5][6] leading to losses in less than one synchrotron period. At the same time a systematic monitoring, evaluation and reduction of the machine impedance has started [6][7][8][9] after the impedance reduction campaign that took place in the period 1999-2001 to prepare the SPS as LHC injector [10].

CHARACTERISTICS OF THE INSTABILITY

Studies were performed in 2003 with a single bunch ($N_b=1.2\times10^{11}$ p) of low longitudinal emittance (ε_L=0.2 eV·s) and short bunch length (τ_b=2.7 ns) when captured by the RF 200 MHz system in the SPS with a voltage V_{RF}=0.7 MV corresponding to a synchrotron period T_s=6.6 ms. In that case losses were observed after approximately half a synchrotron period. During that study the beam parameters and machine settings have been varied to better characterize the instability. Measurements with larger bunch populations (up to 2×10^{11} p) have been conducted in 2006.

Dependence on machine settings at injection

The dependence of the losses on the vertical chromaticity and on the capture voltage for constant bunch population, longitudinal emittance and bunch length (see above) have been studied in 2003 and are shown in Fig. 1 [4]. This shows that the instability can be damped by increasing the vertical chromaticity and/or the capture voltage although this leads normally to a reduction of the beam lifetime resulting from the larger tune spread.

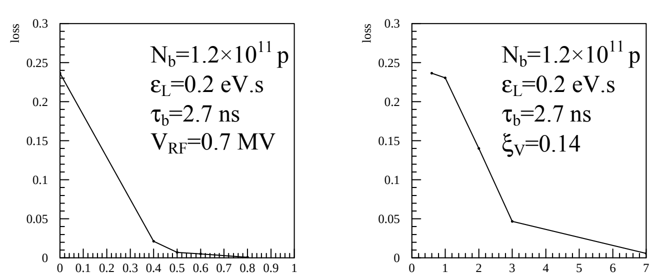

Figure 1: Fraction lost in the first 10 ms vs. vertical chromaticity (left) and capture RF voltage (right). The first point at low vertical chromaticity corresponds to (ξ_V=0.14) while the first point at low RF voltage corresponds to V_{RF}=0.7 MV.

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Dependence on longitudinal parameters of the injected beam.

The threshold of the fast instability has been determined as a function of the longitudinal emittance ε_L for constant capture voltage (0.7 MV) and constant vertical chromaticity (ξ_V=0.14). The threshold for the onset of the instability is 0.3×10^{11} p for ε_L=0.15 eV.s, 0.6×10^{11} p for ε_L=0.19 eV.s and more than 1.2×10^{11} p for ε_L=0.3 eV.s. No significant variation of the threshold has been observed when varying the full bunch length from 3 ns to 4 ns at constant ε_L (0.3 eV.s).

Time evolution of the instability

The time evolution of the horizontal and vertical centroid position along the bunch has been studied. The measured time evolution of longitudinal bunch profile N(t) and of the vertical centroid position $\langle y\rangle(t)=N(t)\times y_{av}(t)$ for $N_b=1.2\times10^{11}$ p, ε_L=0.2 eV·s, V_{RF}=0.7 MV and ξ_V=0.14 are shown in Fig. 2.

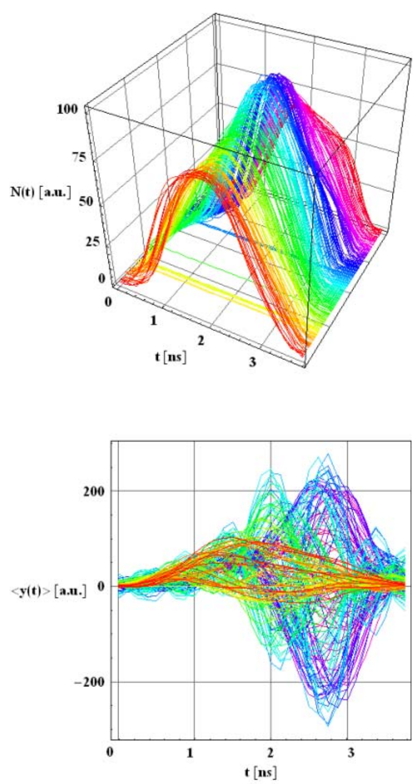

Figure 2: Longitudinal profile and vertical centroid position along the bunch. The head of the bunch is at t=0. The profiles are cut at ±3 σ_t.

An animation of the temporal evolution of the <y>(t) signal [6][11] reveals a travelling-wave pattern with a frequency of ~1 GHz propagating from the head to the tail of the bunch. This behaviour is not observed in the horizontal plane where a standing wave pattern typical of head-tail motion is visible. The same occurs in the vertical plane when the vertical chromaticity is increased.

PRESENT UNDERSTANDING OF THE INSTABILITY

Simulations performed with the HEADTAIL code [12] reproduce very well the observed travelling-wave pattern when a broad band impedance with characteristics (shunt impedance Z_t, resonant frequency f_{res} and quality factor Q) derived from beam-based measurements [13][14] is considered. The same simulations have shown that the threshold of the instability is consistent with the measured one for the same beam characteristics [6].

The travelling-wave pattern propagating along the bunch is believed to be the signature of a Transverse Mode Coupling Instability. Previous studies [15] had shown that the instability threshold as predicted by HEADTAIL (when round chambers and no space charge are considered) is in excellent agreement with the one expected by the MOSES code (based on the numerical solution of the analytical equation for the head-tail modes [16] for round chambers in the absence of space charge). Nevertheless, the occurrence of mode coupling could not be proved due to the limited resolution in the Fourier analysis of the centroid signal.

Fourier analysis of the complex signal constructed from the phase space coordinates by using SUSSIX [17] has provided a significant improvement of the resolution and mode coupling has been observed. The various coherent modes of oscillation (both azimuthal and radial) of the bunch can be disentangled and the shifts of all the spectral lines as a function of the bunch population can be reconstructed with high accuracy and they are found to exactly reproduce the ones calculated with MOSES (Fig. 3) with the exception of a few lines which are not predicted by MOSES. This discrepancy is not yet fully understood although it might be due to the limitations in the analytical approach applied in MOSES.

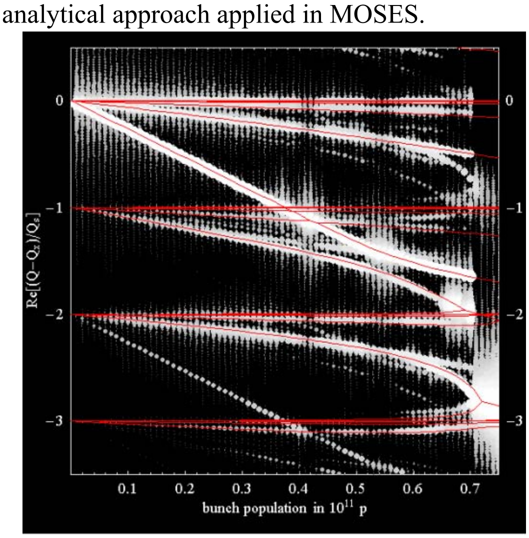

Figure 3: Head-tail modes vs. bunch intensity for ε_L=0.2 eV·s and σ_t=0.67 ns, V_{RF}=0.6MV and ξ_V~0. MOSES (red lines) vs. HEADTAIL (white dots whose size and brightness depend on the spectral amplitude) results analyzed with SUSSIX. Z_t=10 MΩ/m, f_{res}=1 GHz and Q=1.

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The TMCI rise times obtained with HEADTAIL and calculated by simply fitting the time evolution of the centroid with an exponential curve also agree very well with those calculated with MOSES.

HEADTAIL simulations have been performed also for a single bunch with ε_L=0.2 eV·s, V_{RF}=0.6MV and ξ_V~0 for the case of a rectangular vacuum chamber with cross-section similar to the standard SPS main bend vacuum chambers and Z_t=20 MΩ/m, f_{res}=1 GHz and Q=1. These simulations (not possible with MOSES which is limited to a round cross-section and no space charge) show that mode coupling occurs for bunch populations of 0.4×10^{11} p between azimuthal modes -2 and -3. This is typical for long bunches, for which the product between bunch length and resonant frequency of the broad-band impedance is above 1.

IMPLICATIONS FOR THE LHC BEAMS

The larger longitudinal emittance of the LHC beams has a stabilizing effect for the vertical TMCI as well as the larger capture voltage (typically 2MV) which is applied at injection in the SPS. HEADTAIL simulations have been performed for the LHC beam parameters for two different values of the capture voltage (0.7 MV and 2 MV) to determine the threshold for the onset of the TMCI vs. the value of the broad-band shunt impedance. Space charge and the rectangular cross section of the SPS vacuum chamber have been taken into account. The results of these simulations are summarized in Fig. 4 for vertical chromaticity close to 0 [17].

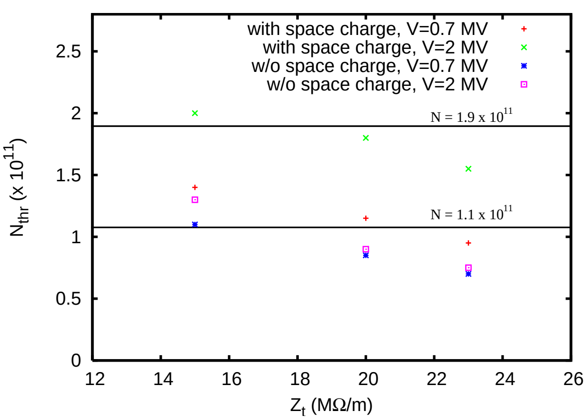

Figure 4: TMCI thresholds vs. broad-band shunt impedance for f_{res}=1 GHz and Q=1 for an LHC bunch.

Measurements of the machine impedance performed in 2006 have shown that Z_t ~ 23 MΩ/m [13][14] and for these values the expected threshold for the TMCI is 1.5×10^{11} p/bunch. These results are in good agreement with measurements performed with a single LHC bunch in 2006 indicating a threshold close to 1.8-1.9×10^{11} p for ξ_V=0.08.

Although this value is close to the ultimate bunch population it must be noted that simulations and measurements indicate that blow-up already occurs for bunch populations smaller than the threshold [18].

SUMMARY AND CONCLUSIONS

Observations and simulations have shown that the fast vertical transverse instability observed in the SPS at injection is very likely a TMCI resulting from the coupling between the head-tail azimuthal modes -2 and -3. An extensive benchmarking between the MOSES and HEADTAIL codes has shown that the latter can very well describe this type of instabilities and it has been used to determine the expected threshold for the TMCI for the LHC beam, based on the present impedance model of the machine. Simulations and measurements indicate that the threshold is close or lower than the ultimate LHC bunch population. Measures (chromaticity and large capture voltage) exist to palliate the effects of this instability (losses and blow-up) but they normally affect the beam lifetime (tail development, slow losses). For that reason an extensive campaign of identification, classification and cure of the possible sources of transverse impedance has started [6] in the frame of the upgrade studies recently launched for the whole LHC injector chain.

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