THE FAST VERTICAL SINGLE-BUNCH INSTABILITY AFTER INJECTION INTO THE CERN SUPER PROTON SYNCHROTRON

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Abstract

Since 2003, high-intensity single-bunch proton beams with low longitudinal emittance have been affected by heavy losses after less than one synchrotron period after injection. The effects of the resonance frequency of the responsible impedance, longitudinal emittance and chromaticity on the intensity threshold were already discussed in detail in 2004, comparing analytical predictions with simulation results. In this paper the evolution of the instability between injection and the time of beam loss is our main concern. Measurements are compared with HEADTAIL simulations. A travelling-wave pattern propagating along the bunch, which is the signature of a Beam Break-Up or Transverse Mode Coupling Instability (TMCI), is clearly identified. The oscillating frequency, near ~1 GHz, is in good agreement with the usual broad-band impedance model deduced from beam-based measurements like the head-tail growth rate vs. chromaticity.

INTRODUCTION

The low-frequency longitudinal impedance of the SPS has been reduced by a factor of ~2.5 from 1999 to 2001 by modification and shielding of over thousand elements like vacuum ports [1]. The threshold for the longitudinal microwave instability increased even more. However, the transverse impedance has only been reduced by ~40% [2] and this improvement was since then partially cancelled by the re-installation of the equipment needed for the SPS as LHC injector (5 MKE extraction kickers installed in 2003 and 4 installed for the 2006 start-up).

Measurements have been performed in 2003 in the SPS right after injection at 26 GeV/c, where a fast single-bunch vertical instability develops if the longitudinal emittance of the beam is too small [3]. Figure 1 is an example of what was observed with a high-intensity single bunch ($\sim 1.2 \times 10^{11}$ p/b) of low longitudinal emittance (~ 0.2 eV.s). The RF voltage was $\hat{V}_{RF} \approx 0.6\,\mathrm{MV}$, which corresponds to the synchrotron period $T_s = 7.1\,\mathrm{ms}$. Keeping the chromaticity close to zero, the bunch was stabilized when the intensity was reduced to $\sim 6 \times 10^{10}$ p/b.

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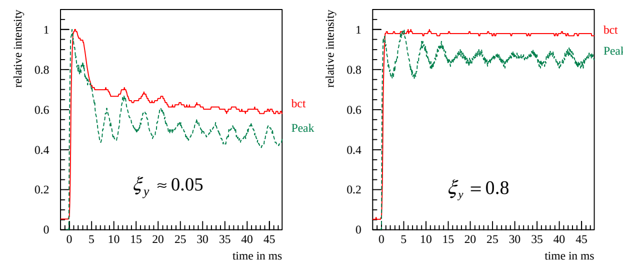

Figure 1: Plot of the measured relative (normalized to the value at injection) bunch intensity vs. time in the SPS machine in 2003. bct stands for beam current transformer and Peak stands for peak intensity. The bunch, which is unstable when $\xi_y \approx 0.05$ (left) is stabilized by increasing the (relative) chromaticity to $\xi_y = 0.8$ (right).

MEASUREMENTS

The evolution of the vertical centroid position along the bunch has been recorded turn by turn using the “Head-Tail” monitor (with a sampling period of 125 ps) [5]. An animation has been produced, clearly revealing a travelling-wave pattern propagating from the head of the bunch to the tail, with a frequency of ~ 1 GHz [6]. As the animation could not be reproduced here, only the picture with 150 traces superimposed is shown in Fig. 2. The oscillation frequency is clearly visible on Fig. 3.

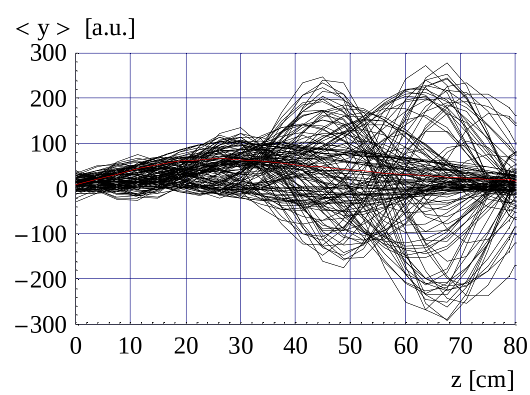

Figure 2: Measured evolution of the vertical centroid position along the bunch < y > = N (z) × y_{av} (z), where N (z) is the longitudinal bunch profile, using the “Head-Tail” monitor (with the traces of all the 150 turns superimposed), for a vertical (relative) chromaticity close to zero (see Fig. 1). The first turn after injection is shown in red. The head of the bunch (truncated at ± 2 σ_z) is on the left and the tail on the right.

Increasing the chromaticity above a certain value prevents the instability from developing (see Fig. 4). Here again, it is nicely seen in the animation [6] that the travelling-wave pattern does not succeed to propagate along the bunch. Only the picture with the traces of all the 150 turns superimposed is shown in Fig. 4.

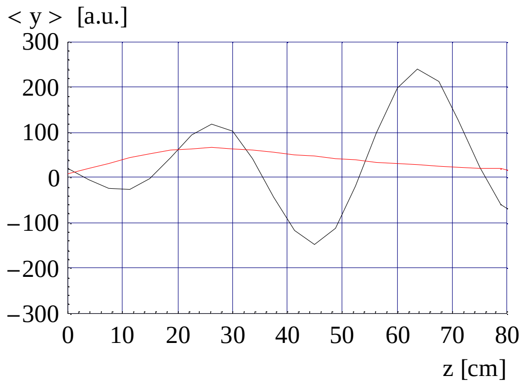

Figure 3: Measured evolution of the vertical centroid position along the bunch using the “Head-Tail” monitor (only the trace of turn 99 is shown), for a vertical (relative) chromaticity close to zero (see Fig. 1).

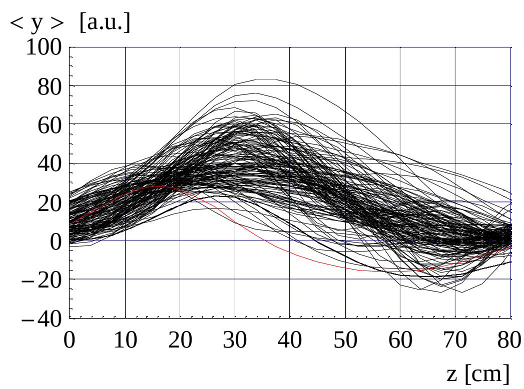

Figure 4: Measured evolution of the vertical centroid position along the bunch using the “Head-Tail” monitor (with the traces of all the 150 turns superimposed), for a vertical (relative) chromaticity of ~2. Note the difference in vertical scale.

SIMULATIONS

Simulations have been performed using the HEADTAIL code [7], assuming the beam and SPS parameters reported in Table 1. The cases of round and flat geometry (which is the real case in the SPS) have both been simulated, but revealed no significant difference concerning the evolution in time of the instability. The evolution of the vertical centroid position along the bunch has been simulated turn by turn, and an animation has also been produced, clearly revealing a travelling-wave pattern propagating from the head of the bunch to the tail, with a frequency of ~ 1 GHz [6]. The picture with all the traces superimposed is shown in Fig. 5, where the same kind of picture as the measured Fig. 2 is reproduced from simulation using the “classical” Broad-Band (BB) impedance model deduced from several beam-based measurements.

Table 1: Basic beam and SPS parameters relevant for this simulation study. The BB shunt impedance is given here for a round chamber.

Parameter	Value	Unit
Circumference	6911	m
# of bunches	1	
Relativistic γ	27.7286	
# of protons per bunch	$1.2\ 10^{11}$	
Vert. tune	26.13	
Vert. relative chromaticity	0	
Rms bunch length	20	cm
Rms long. mom. spread	0.00093	
Synchrotron tune	0.00323	
Cavity harmonic number	4620	
Mom. compaction factor	0.00192	
BB tr. shunt impedance	20	MΩ/m
BB resonance frequency	1	GHz
BB quality factor	1	

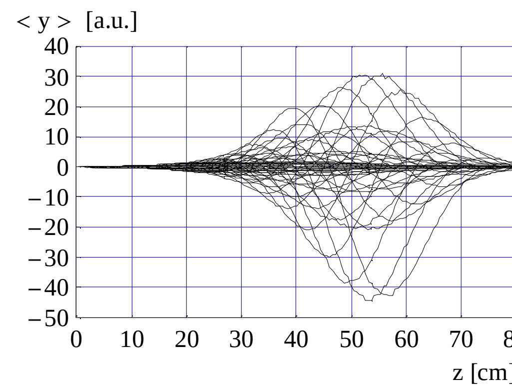

Figure 5: Simulated evolution of the vertical centroid position along the bunch using the HEADTAIL code (with the traces of all the turns superimposed). The head of the bunch (truncated at ± 2 σ_z) is on the left.

The effects of space charge and RF voltage have also been studied in detail with predictions for the LHC beam, whose longitudinal emittance is 0.35 eV.s instead of ~ 0.2 eV.s used here [8]. For the simulations a BB impedance model with a resonance frequency f_r = 1.3 GHz and a quality factor $Q = 1$ was used. The transverse shunt impedance Z_t was scanned to try to fit observed thresholds with different beam parameters. The results are shown in Fig. 6, which reveals that the nominal LHC beam (with the estimated impedance of ~ 20 MΩ/m) should be close to the instability with matched longitudinal voltage (~ 0.7 MV). However, capturing the beam in a 2 MV bucket, as normally done in operation, should considerably help.

Space charge seems beneficial since it raises the TMCI threshold, but it also gives rise to a fast emittance blow-up below TMCI threshold. This effect should be studied in detail in future machine studies as this could considerably degrade the LHC beam quality.

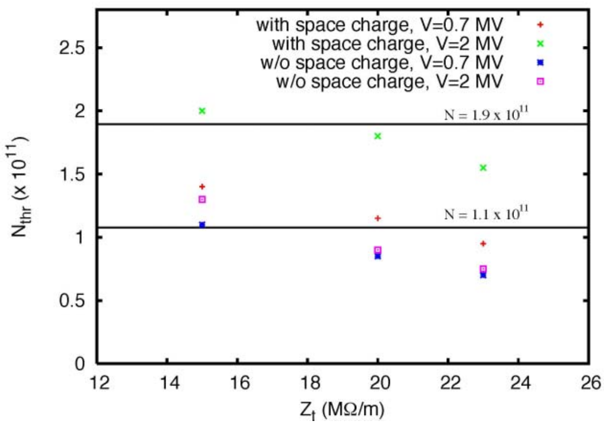

Figure 6: Simulated TMCI intensity threshold for the LHC beam with/without space charge for two different RF voltages, using the HEADTAIL code.

A more precise model of the SPS transverse impedance is under development. For the moment only the transverse impedances of the MKE kicker and the Beam Position Monitors (BPMs) have been computed and/or measured. The results of analytical prediction and measurements using two wires [9] for one MKE kicker are shown in Fig. 7. It is seen that the measurements are close to the theoretical (2D) prediction, which is close to a BB impedance with a resonance frequency near 1.8 GHz, a quality factor Q ~ 1, and a shunt impedance of ~ 0.5 MΩ/m. As there are nine MKE kickers in the SPS, it leads to ~ 4.5 MΩ/m in total.

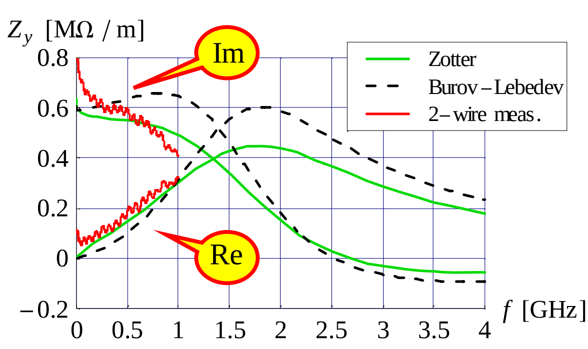

Figure 7: Theoretical predictions of the transverse resistive-wall impedance of one SPS MKE kicker, using both Zotter's [10] and Burov-Lebedev's [11] formalisms.

Concerning the 108 horizontal and 108 vertical BPMs, simulations with MAFIA have been performed, revealing the presence of four potentially dangerous transverse trapped modes (two from the horizontal and two from the vertical BPMs). The basic parameters of these modes are listed in Table 2. HEADTAIL simulations, considering only the four trapped modes, revealed that the TMCI intensity threshold is one order of magnitude higher that the observed one. Therefore, the BPMs alone cannot explain the observed fast instability.

Table 2: The four most dangerous transverse trapped modes per BPM from MAFIA simulations.

	β_x (m)	β_y (m)	f_r (GHz)	R (MΩ/m)	Q
BPH	103	21	0.537	4.6	1951
BPH	103	21	1.836	2.35	3367
BPV	22	101	0.786	1.67	2366
BPV	22	101	2.27	2.05	5880

CONCLUSION

The measured evolution of the vertical centroid position along the bunch can be reasonably reproduced using the "classical" broad-band impedance model deduced from several beam-based measurements. A detailed analysis of this evolution in time will be used in the future to refine our SPS transverse impedance model, which is under development. For the moment only the transverse impedance of the 9 SPS MKE kickers has been computed and measured, and the impedance of the 108 horizontal and 108 vertical BPMs simulated.

The nominal LHC beam in the SPS could be unstable after the installation of the last four MKE kickers before the 2006 start-up. Capturing the beam in a 2 MV bucket, as normally done in operation, should considerably increase the intensity threshold. The TMCI threshold is certainly increased by space charge, however there is an emittance blow-up associated below threshold, which could degrade the beam quality. Another possibility to increase the instability threshold could be the use of linear coupling [12].

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