TRANSVERSE MODE-COUPLING INSTABILITY IN THE CERN SPS: COMPARING HEADTAIL SIMULATIONS WITH BEAM MEASUREMENTS

B. Salvant (EPFL and CERN) and D. Quatraro (INFN, Bologna University and CERN),
G. Arduini, E. Métral, G. Papotti, G. Rumolo, R. Steinhagen, R. Tomás, (CERN), R. Calaga (BNL)

Abstract

Since 2003, single bunches of protons with high intensity and low longitudinal emittance have been observed to suffer from heavy losses in less than one synchrotron period after injection in the CERN Super Proton Synchrotron (SPS) when the vertical chromaticity is corrected ($\xi_y \sim 0$).

This fast instability does not limit the current performance of the SPS, but would be a major limitation in case of an anticipated upgrade of the SPS, which requires bunches of 4e11 protons (p). Besides, the characteristics of this instability are also complementary indicators of the value of the SPS beam coupling impedance.

MOSES analytical calculations, HEADTAIL macroparticle tracking simulations, as well as several measurement campaigns in the SPS indicate that this instability may be due to a coupling between transverse modes ‘-2’ and ‘-3’.

The aim of this contribution is to report improvements of the SPS impedance model used by HEADTAIL simulations, and to find out more characteristics of the measured instability in order to assess whether the observed instability in the SPS is indeed a Transverse Mode Coupling Instability (TMCI).

INTRODUCTION

Measurements in 2003, 2006 and 2007 [1-3] showed that the SPS intensity is now limited by a fast vertical single bunch instability at injection energy (26 GeV/c) if the bunch longitudinal emittance is low (ε_L~0.2 eVs), and the vertical chromaticity is corrected.

This vertical instability presented the signature of a TMCI: (i) the losses appeared within less than a synchrotron period; (ii) they could be avoided if the vertical chromaticity was increased; and (iii) a travelling-wave pattern propagating from the head to the tail of the bunch could be observed on the fast intra-bunch beam position “Headtail” monitor [4].

Calculating the coherent bunched-beam modes with the MOSES code [5] and simulating the coherent behaviour of a single bunch with the HEADTAIL code [6] for a bunch interacting with a round chamber modelled as a broadband impedance agreed in predicting the behaviour of most of the bunch spectral lines and in particular the onset of a fast instability due to a coupling between modes ‘-2’ and ‘-3’ [7], thanks to a sensitive SUSSIX frequency analysis [8].

A more realistic model of the impedance of the SPS (taking into account the 20 kickers present in 2006) was simulated with HEADTAIL, and these simulations were compared to dedicated measurements performed in the SPS in 2007 [3]. The simulated TMC instability indeed shared very similar qualitative patterns with the instability observed in the SPS, giving more weight to the hypothesis that a TMCI is indeed limiting the SPS single bunch population (Nb).

Now, a more accurate model of the SPS impedance is needed in order to get a more quantitative estimate. This is why the single-kick approach in HEADTAIL is compared with a recently implemented multi-kick approach [9]. Moreover, further HEADTAIL simulations with losses were performed to compare the measured Beam Current Transformer (BCT) pattern obtained in [3].

MULTI-KICK APPROACH IN HEADTAIL

The dipolar, and quadrupolar parts of the vertical and horizontal resistive wall impedance of the SPS kickers was calculated with ZBASE [10] using Zotter’s formalism [11].

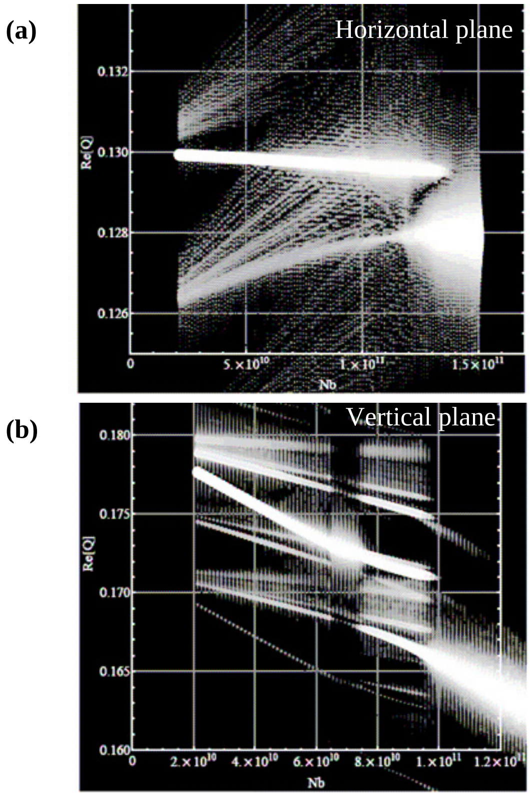


Figure 1: HEADTAIL simulated bunch mode spectrum vs. bunch population Nb for $\varepsilon_L = 0.16$ eV.s, $\sigma_t = 0.5$ ns, and $\xi = 0$, using the multi-kick approach. (a) horizontal plane, (b) vertical plane. The size and brightness of the white dots depend on the spectral amplitude. It is important to notice that the x-axis scale differs for the two plots.

These impedances were then inverse Fourier-transformed into wake fields. In [3], the wake fields created by the 20 kickers present in the SPS ring in 2006 were weighed by the beta function at their location and summed, leading to two wake field contributions for each plane (dipolar and quadrupolar). HEADTAIL simulation campaigns were performed, in which the intensity was scanned, and the vertical coherent motion was analyzed with SUSSIX.

A new version of HEADTAIL was implemented to import a machine lattice from a MAD-X output file, and to let the bunch interact with multiple impedance sources [9]. The individual wake fields obtained from ZBASE for each SPS kicker were then input into HEADTAIL. Over one turn, the HEADTAIL simulated bunch could then interact separately with each of these 20 kickers taking into account the beta function at their location. The horizontal and vertical coherent motions analyzed with SUSSIX are displayed in Fig. 1.

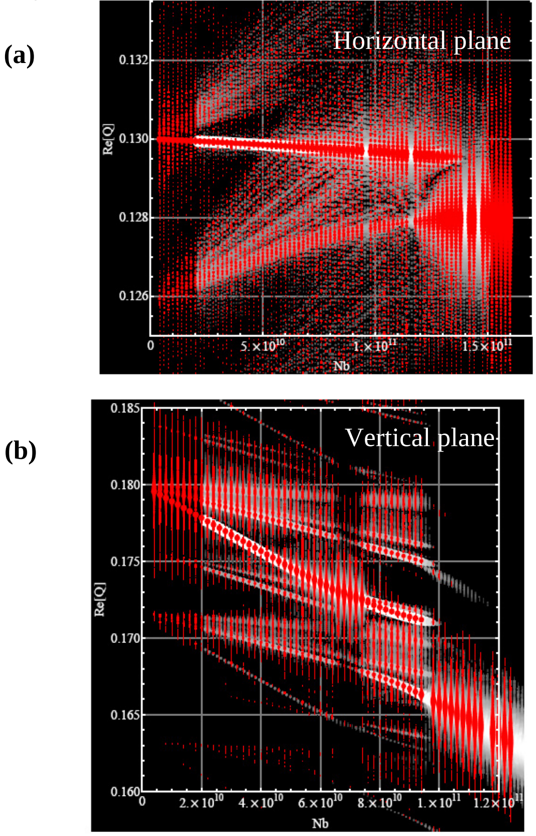


Figure 2: HEADTAIL simulated bunch mode spectrum vs. bunch population Nb for $\varepsilon_L = 0.16$ eV.s, $\sigma_t = 0.5$ ns, and $\xi = 0$, using the multi-kick approach (white) and the single-kick approach (red). (a) horizontal plane, (b) vertical plane. The size and brightness of the white dots depend on the spectral amplitude. The size of the red dots depends on the spectral amplitude, but their brightness does not. The x-axis scale differs for the two plots.

The comparison between the older version of HEADTAIL, which uses a single kick per turn to model the interaction of the bunch with the 20 SPS kickers' Resistive Wall impedance, and the new version of HEADTAIL, which uses 1 kick per kicker per turn (i.e. 20 kicks per turn) is shown in Fig. 2 (horizontal and vertical mode spectra), and Fig. 3 (growth rates). The good agreement between the two approaches validates, if needed, the 1-kick approach that was used in previous impedance studies with HEADTAIL.

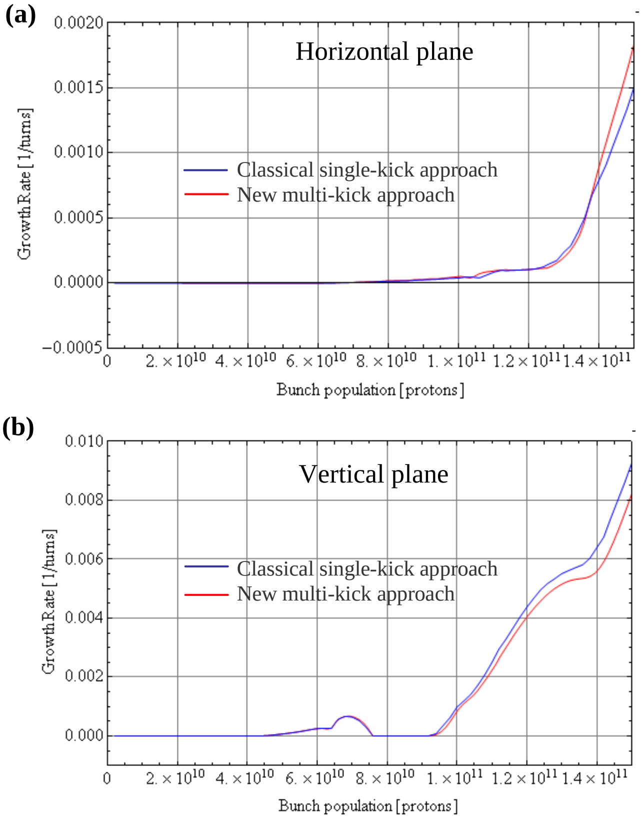


Figure 3: HEADTAIL simulated growth rates vs. bunch population Nb for $\varepsilon_L = 0.16$ eV.s, $\sigma_t = 0.5$ ns, and $\xi = 0$, using the multi-kick approach (red) and the single-kick approach (blue). (a) horizontal plane, (b) vertical plane.

MEASURED AND SIMULATED BCT DATA

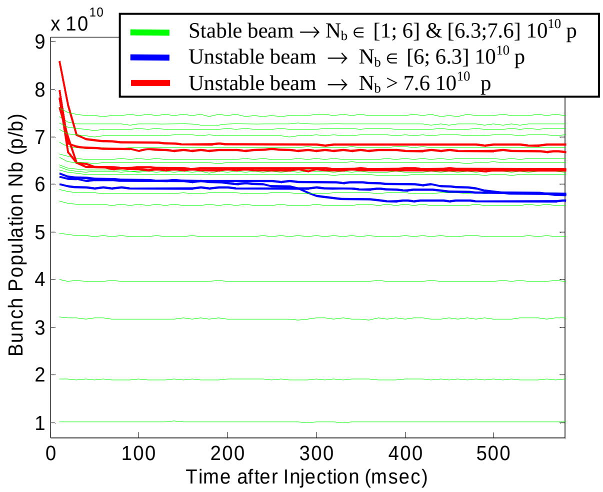
As already reported in the introduction, the vertical instability observed during the dedicated experiments in the SPS in 2007 presented typical characteristics of a TMCI. In addition, it was also reported in [3] that this measured instability showed two distinct unstable bunch population ranges separated by a stable bunch population range (see Fig. 4 (a)), as well as a tune step when Nb reaches the main instability threshold. These rather unusual instability patterns were in qualitative agreement with the HEADTAIL simulated instability, for which the cause was clearly a coupling of transverse modes.

In order to compare the measured and simulated losses, single-kick HEADTAIL simulations were performed, in which macroparticles are lost if their distance from the beam pipe axis gets over 2 cm (approximating the position of the vacuum chamber). The bunch population over the simulated 10,000 turns (i.e. 230 msec) is presented in Fig. 4 (b).

It should be noted that the first point measured by the SPS BCT is performed 10 msec after injection, and beam losses may have occurred before this first measurement point. Also, HEADTAIL simulations do not take into account space charge, amplitude detuning and other stabilization mechanisms which may damp instabilities in the machine, and therefore reduce the bunch population ranges for which the beam is unstable. Nevertheless, as in HEADTAIL simulations, a threshold for a slow instability is followed by a stable range, and finally by a threshold for a fast instability.

This new element joins in the growing list advocating for a TMCI observed in the SPS.

(a) SPS measurements (BCT) :



(b) HEADTAIL simulations :

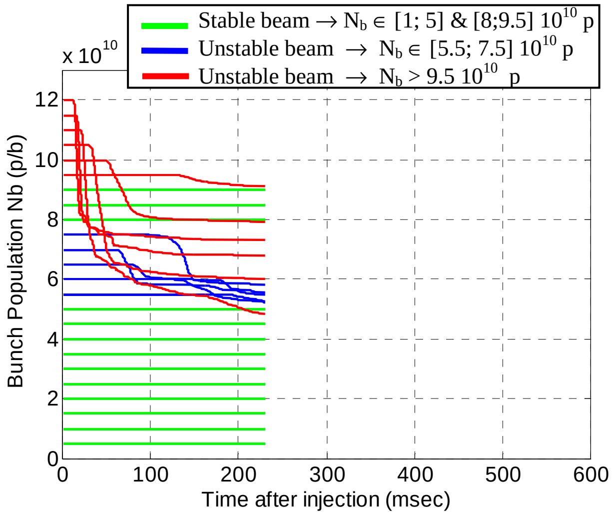


Figure 4: Bunch population (a) measured by the SPS BCT for various cycles, SPS parameters $\varepsilon_L = 0.16$ eV.s, $\sigma_t = 0.7$ ns, and $\xi \sim 0$, (b) simulated with HEADTAIL for $\varepsilon_L = 0.16$ eV.s, $\sigma_t = 0.5$ ns, and $\xi = 0$. Low bunch currents N_b lead to stable bunch motion (in green). In both simulations and measurements, two distinct unstable ranges (slow instability in blue and fast instability in red) are separated by a stable range of bunch population (in green).

CONCLUSION AND FUTURE WORK

A new version of HEADTAIL is able to import a lattice from MAD-X and wakefields from ZBASE in order to get a more realistic model of the SPS impedance [9]. This new HEADTAIL multi-kick approach was successfully benchmarked with the current single-kick approach for the case of the 20 SPS kickers installed in 2006.

Besides, single-kick HEADTAIL simulations with losses predict loss patterns, which qualitatively agree with the BCT loss patterns measured in the SPS. This is another element advocating for a TMCI in the SPS.

The next steps are to carry on improving the SPS impedance model, and to perform more realistic HEADTAIL simulations.

ACKNOWLEDGMENTS

We would like to thank T. Bohl and the OP team for their contributions to the measurements in the SPS, J. Jowett for useful tips on *Mathematica*, as well as D. Brandt, Y. H. Chin, R. de Maria, A. Hoffman, A. Grudiev, R. Jones, Y. Papaphilippou, L. Rivkin, E. Shaposhnikova, Y. Shobuda, and B. Zotter, for fruitful discussions and advice.

REFERENCES

[1] E. Métral, *et al.*, “Transverse Mode Coupling Instability in the CERN Super Proton Synchrotron”, ICFA Beam Dynamics Workshop, “High Intensity and Brightness Hadron Beams”, Bensheim, Germany, 2004.

[2] G. Arduini, *et al.*, “Fast Vertical Instability at Injection in the CERN SPS - an Update”, PAC’07, Albuquerque, 2007.

[3] B. Salvant et al., “TMCI in the CERN SPS: comparing MOSES analytical calculations and HEADTAIL simulations with experiments in the SPS”, EPAC’08, Genova, Italy, 2008.

[4] E. Métral, *et al.*, “The Fast Vertical Single-Bunch Instability after Injection into the CERN Super Proton Synchrotron”, EPAC’06, Edinburgh, UK, 2006.

[5] Y. H. Chin, “User's guide for new MOSES version 2”, CERN/LEP-TH/88-05, 1988.

[6] G. Rumolo and F. Zimmermann, “Practical user guide for HEADTAIL”, CERN-SL-Note-2002-036-AP, 2002.

[7] B. Salvant, *et al.*, “Transverse Mode Coupling Instability in the SPS: HEADTAIL Simulations and MOSES Calculations”, Proc. BEAM’07, CERN, Geneva, 2007.

[8] R. Bartolini, F. Schmidt, “Computer Code for Frequency Analysis of Non-Linear Betatron Motion" SL-Note-98-017-AP. CERN, 1998.

[9] D. Quatraro et al., “Headtail upgrade”, CERN internal report, to be published.

[10] O. Brüning, “ZBASE User's Guide Version 1.1”, CERN-SL-96-069-AP, 1996.

[11] E. Métral *et al.*, “Resistive-Wall Impedance of an Infinitely long Multi-Layer Cylindrical Beam Pipe”, PAC’07, Albuquerque, USA, 2007.

[12] E. Métral *et al.*, “CERN SPS impedance in 2007”, EPAC08, Genoa, Italy, 2008.