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TRANSVERSE MODE-COUPLING INSTABILITY IN THE CERN SPS: COMPARING MOSES ANALYTICAL CALCULATIONS AND HEADTAIL SIMULATIONS WITH EXPERIMENTS IN THE SPS

B. Salvant [1], G. Arduini, R. Calaga[2], R. Jones, E. Métral, G. Papotti, G. Rumolo, R. Steinhagen, R. Tomás

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Abstract

Since 2003, single bunches of protons with high intensity (1.2e11 protons) and low longitudinal emittance (0.2 eVs) have been observed to suffer from heavy losses in less than one synchrotron period after injection at 26 GeV/c in the CERN Super Proton Synchrotron (SPS) when the vertical chromaticity is corrected.
Understanding the mechanisms underlying this instability is crucial to assess the feasibility of an anticipated upgrade of the SPS, which requires bunches of 4e11 protons. Analytical calculations from MOSES and macroparticle tracking simulations using HEADTAIL with an SPS transverse impedance modelled as a broadband resonator had already qualitatively and quantitatively agreed in predicting the intensity threshold of a fast instability. A sensitive frequency analysis of the HEADTAIL simulations output was performed using SUSSIX, and revealed the fine structure of the mode spectrum of the bunch coherent motion. A coupling between the azimuthal modes “-2” and “-3” was clearly observed to be the reason for this fast instability.
The aim of this contribution is to compare the HEADTAIL simulations with dedicated measurements performed in the SPS in 2007.

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Since 2003, single bunches of protons with high intensity (1.2e11 protons) and low longitudinal emittance (0.2 eVs) have been observed to suffer from heavy losses in less than one synchrotron period after injection at 26 GeV/c in the CERN Super Proton Synchrotron (SPS) when the vertical chromaticity is corrected.

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INTRODUCTION

A campaign for the reduction of the SPS impedance took place between 1999 and 2001 to allow high-intensity LHC-type beams to be accelerated in the SPS without suffering from longitudinal microwave instability [1]. Subsequent measurements in 2003 [2] and 2006 [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 ($\varepsilon_L \sim 0.2$ eVs), and the vertical chromaticity is corrected ($\xi_y \sim 0$).

This vertical instability presented the signature of a Transverse Mode Coupling Instability (TMCI): (i) The resulting heavy losses appeared within less than a synchrotron period; (ii) they could be avoided if the vertical chromaticity was increased ($\xi_y = 0.8$); and (iii) a travelling-wave pattern propagating from the head to the tail of the bunch could be observed on the data recorded on the SPS "HeadTail" monitor, a fast intra-bunch beam position 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] agreed in predicting the intensity threshold of a single bunch interacting with a BroadBand (BB) transverse impedance [4]. The MOSES and HEADTAIL codes also agreed in predicting the behaviour of most of the bunch spectral lines for a round chamber, and in particular agreed in predicting a fast instability due to a coupling between modes '-2' and '-3' [7].

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.

SIMULATING THE 2006 SPS KICKERS

With ZBASE [9], it is now possible to calculate the dipolar, and quadrupolar parts of the vertical and horizontal resistive wall impedance of the SPS kickers, using Zotter's formalism [10]. These impedances can then be inverse Fourier-transformed into wake fields, and all the data tables and plots stored in the database for further use. The wake fields created by the 20 kickers present in the SPS ring in 2006 were summed - taking into account the beta function for each kicker -, leading to two wake field contributions for each plane (dipolar and quadrupolar). HEADTAIL was modified to allow importing dipolar and quadrupolar wake fields separately, in order to study collective phenomena resulting from these summed wake fields. Scanning the intensity and analyzing the vertical coherent motion with SUSSIX [8] resulted in the plot in Fig. 1. The vertical tune shift $Re(Q - Q_y)$ with respect to the zero-current-tune Q_y is normalized to the synchrotron tune Q_s.

The HEADTAIL input parameters were chosen to be as close as possible to the SPS machine measurements parameters (low beam current betatron tunes, longitudinal emittance, RF Voltage). However, the simulated bunch needs to be matched to the non linear SPS bucket in order to observe the modes clearly. This means that the bunch length can not be fixed to the measured value of $\sigma_t = 0.7$ ns, but to $\sigma_t = 0.5$ ns instead.

As can be seen on Fig. 1, a weak coupling between azimuthal modes '0' and '-1' is observed for a bunch population (N_b) of 6.5 10^{10} protons (p), resulting in a slow instability. These modes decouple for N_b = 7.5 10^{10} p, resulting in a stabilization of the vertical motion. Finally a strong coupling between azimuthal modes '-2' and '-3' occurs for N_b = 9.3 10^{10} p, leading to a significant growth rate. This general behaviour is similar to the case of a simulated BB impedance in a flat chamber [7]. Therefore, in this case of a more realistic transverse impedance model taking into account the 20 SPS kickers, we can again conclude that a TMC instability is observed.

Besides, as in the case of a BB impedance in a round chamber [7], it can be noticed that the main spectral line is subject to an abrupt step when this TMCI threshold is met, i.e. for $N_b = 9.3\ 10^{10}$ p (see red dots in Fig. 4).

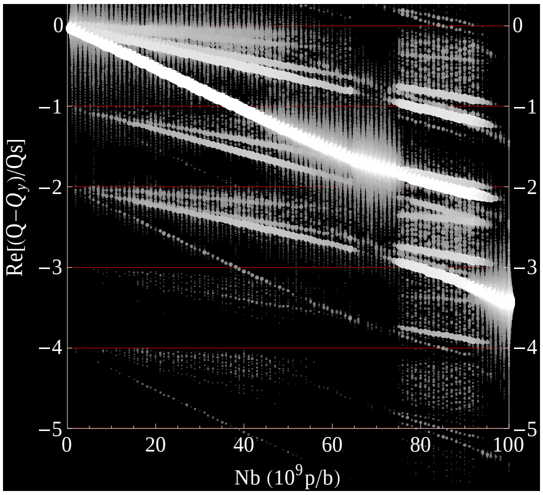

Figure 1: HEADTAIL simulated bunch mode spectrum vs. bunch population Nb for $\varepsilon_L = 0.16$ eV.s, $\sigma_t = 0.5$ ns, $V_{RF} = 1$ MV and $\xi \sim 0$. The size and brightness of the white dots depend on the spectral amplitude. The bunch interacts with the sum of the Resistive-Wall impedance of the 20 SPS kickers of 2006.

SPS EXPERIMENTS

Single bunches of protons with low longitudinal emittance ($\varepsilon_L = 0.16$ eV.s) were prepared by the PS complex with variable intensities, through vertical shaving in the PS Booster. As in 2003 and 2006 [3], if the SPS vertical chromaticity is corrected to $\xi_y \sim 0$, a fast vertical instability was observed to occur if the bunch population is raised to 7.6 10^{10} p. The SPS “HeadTail monitor” revealed a travelling wave pattern along the bunch, and the instabilility could be avoided if the SPS vertical chromaticity was raised. These patterns are typical of TMC instabilities.

As simulations showed, the mode analysis relies on clean data (many turns with low amplitude decoherence, i.e. low chromaticity, and low amplitude detuning), with the acquisition of both the coherent position and momentum. In addition, the bunch extracted from the PS was not matched to the SPS bucket, and “wavy” longitudinal distributions could be observed. Then, the ideal conditions for observing mode shifting was not met in 2007.

However, two additional patterns observed in the experiments were found to be typical of the simulated TMC instabilities showed in the previous paragraphs.

Existence of two instability thresholds

As can be seen in Fig. 2, for Nb $\in$ [1;6] 10^{10} p, negligible losses are visible : the bunch motion is stable. For $N_b \in$ [6; 6.3] 10^{10} p, slow proton losses occur. However, for $N_b \in$ [6.3; 7.6] 10^{10} p, the bunch motion becomes again stable. Finally, for $N_b > 7.5\ 10^{10}$ p, fast heavy losses occur. It should be noted that the first point measured by the SPS Beam Current Transformer (BCT) is performed 10 msec after injection, and not right at injection. Beam losses may then have occurred before the first measurement point. Also, the 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.

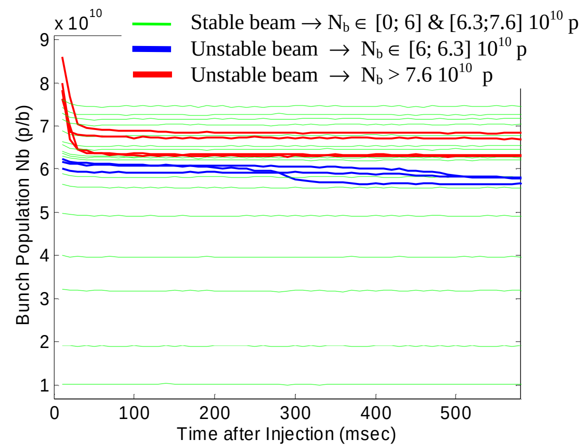

Figure 2: Particle losses pattern measured by the SPS BCT for various cycles, SPS parameters $\varepsilon_L = 0.16$ eV.s, $\sigma_t = 0.7$ ns, $V_{RF} = 1$ MV and $\xi \sim 0$. Low N_b lead to stable bunch motion (in green). Two distinct unstable ranges (slow instability in blue and fast instability in red) are separated by another stable range of bunch population (in green).

Besides, the comparison of simulated and measured growth rates calculated for the 200 turns immediately following the injection oscillations is shown in Fig. 3. Only these 200 turns were relevant, as inevitable injection oscillations perturb the measurement of the growth rate, and, unfortunately, the interesting pickup oscillations are damped rapidly after a synchrotron period. Nevertheless, a very similar – however shifted in N_b - sharp growth rate decrease before the onset of the main instability can be observed. The shift can be explained by the current impedance model, which only takes into account the SPS kickers. Therefore the rest of the machine should be included in the model through ZBASE and then input into HEADTAIL [11].

As a consequence, the TMC typical pattern of stable and unstable ranges predicted by the HEADTAIL simulations, is observed right after injection with the Tune Meter, and at a few tens of msec with the BCT.

Sharp tune step at the fast instability threshold

As can be seen in Fig. 4, the main spectral line seems to be subject to the same tune step when the instability threshold is met, both in the experiment and the simulation. The tune slope with intensity and the instability threshold differ between experiment and simulations. This is expected as the impedance model only takes into account the SPS kickers.

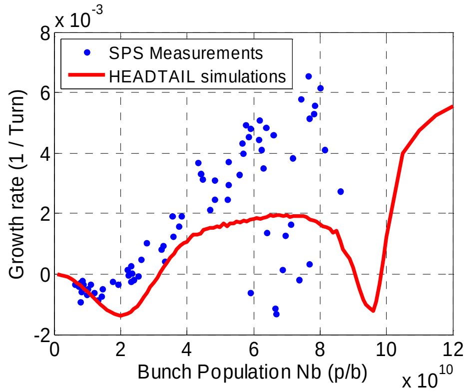

Figure 3: Comparison of growth rate vs. bunch population Nb for a 2007 SPS experiment (blue dots) and HEADTAIL simulations for the 20 2006 SPS kickers (red line). Parameters $\varepsilon_L = 0.16$ eV.s, $V_{RF} = 1$ MV and $\xi \sim 0$, $\sigma_t = 0.7$ ns (measurement) and $\sigma_t = 0.5$ ns (simulations).

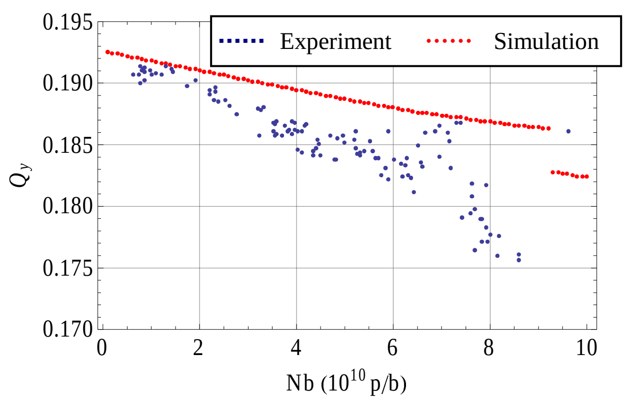

Figure 4: Comparison of bunch stronger vertical mode vs. bunch population Nb. 2007 SPS experiment (blue dots) and HEADTAIL simulations for the 20 2006 SPS kickers (red dots). Parameters $\varepsilon_L = 0.16$ eV.s, $V_{RF} = 1$ MV, $\xi \sim 0$, $\sigma_t = 0.7$ ns (measurement) and $\sigma_t = 0.5$ ns (simulations). The simulated tune data was normalized by the experimental bunch length data to be able to compare the tune slope.

All these observations are not yet proofs, but the hypothesis that this fast vertical SPS instability is a TMCI is gaining more weight.

CONCLUSION AND FUTURE WORK

Coupling between azimuthal modes "-2" and "-3" is observed to be the cause of the instabilities simulated with HEADTAIL, both in the case of the BB impedance in a round or flat chamber, and in the case of the 20 SPS kickers present in 2006.

Measuring the mode spectrum in the SPS is tricky, as many parameters have to be carefully tuned to get very clean data, in particular the amplitude detuning. However, a double instability threshold, and a tune step were observed on both simulations of the 20 2006 kickers impedance and on SPS experiments performed in 2007. These two typical features of TMC instabilities are yet again other indications that the fast instability observed in the SPS could be explained by a coupling between modes "-2" and "-3".

The next steps are to improve the SPS impedance model through careful calculations, simulations, and localization of the impedance sources. Besides, in order to try and obtain a cleaner mode spectrum, measurements will be performed again in 2008, with an emphasis on finding two BPMs that are separated by a betatron phase of 90 degrees, on measuring the intensity from injection, and on controlling better the amplitude detuning and the longitudinal parameters.

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