BEAM INSTABILITIES STUDIES AT TRANSITION CROSSING IN THE CERN PROTON SYNCHROTRON

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Abstract

The CERN PS crosses transition energy at about 6 GeV by using a second order gamma jump performed with special quadrupoles. However, for high-intensity beams, and in particular the single bunch beam for the neutron Time-of-Flight facility, a controlled longitudinal emittance blow-up is still needed to prevent a fast single-bunch vertical instability from developing near transition. A series of studies have been done in the PS in 2008 to measure the beam behaviour near transition energy for different settings of the gamma transition jump. The purpose of this paper is to compare those measurements with simulations results from the HEADTAIL code, which should allow to understand better the different mechanisms involved and maybe improve the transition crossing.

INTRODUCTION

The gamma transition jump of the CERN Proton Synchrotron (PS) consists of doublet and triplet pulsed quadrupoles which change the natural gamma transition of the accelerator [1]. This scheme was performed to cure instabilities which constituted an intensity limitation. These mechanisms in the longitudinal plane involved excitations of bunch length oscillations due to longitudinal space charge forces and impedance effects. Bunch length simulations through transition with HEADTAIL[2] allow to predict, by taking into account the longitudinal space charge forces and a broad band impedance, the beam behaviour when these collectives effects are combined. For instance, the simulations can determine together with measurements whether there is a compensation of those effects and which one is driving the longitudinal behaviour as a function of the intensity. The first section is devoted to the study of the bunch length evolution near transition with neither collective effects nor γ_{tr}-jump, while the second and the third section investigate the cases of space charge only and broad band impedance only.

NEITHER COLLECTIVE EFFECTS NOR γ_{TR}-JUMP

Consider a bunch which starts in an equilibrium condition, i.e. a well matched beam with the accelerating bucket, far from below transition and without any space charge forces. The bunch length has been simulated during the acceleration with HEADTAIL and nToF parameters [3] without neither collective effects nor gamma jump. The results are presented in Fig. 1 and compared with analytical formulas [4]. The simulation shows a good agreement with theory. The bunch becomes shorter and longer while approaching transition, but restores its shape afterwards. In addition, its length reaches a minimum at the transition energy and is a symmetric function with respect to transition time.

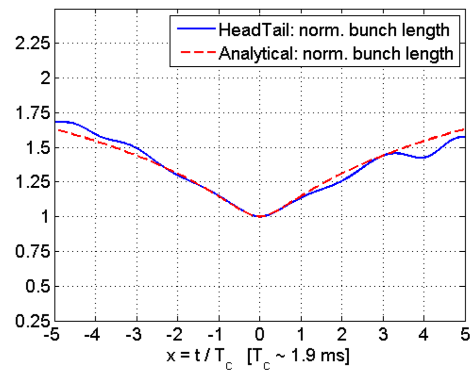

Figure 1: Evolution of the bunch length normalized to the minimum bunch length. The time in the abscisses has been normalized to the nonadiabatic time T_c.

WITH SPACE CHARGE ONLY

When the beam intensity becomes high, the mutual forces between particles in the bunch cannot be neglected anymore. HEADTAIL simulations have been done with the PS parameters to determine the effect of the longitudinal space charge forces on the bunch length for different beam intensities. The results of those simulations are presented in Fig. 2. The first remark is that at the lowest intensty, i.e. $0.01 \cdot 10^{12}$ protons, the space charge influence on the bunch is negligible. For the other cases, the bunch length oscillations due to space charge are amplified by increasing intensity. Due to the space charge, the bunch length will be larger below transition and shorter afterwards than the case without space charge. This force is defocusing below transition and focusing above [4]. This asymmetry causes a bunch to bucket mismatch, inducing bunch length oscillations. Note small oscillations on the simulated bunch length below the transition energy which are due to a poor matching of the bunch in the bucket in HEADTAIL.

This simulation can be compared to analytical formulas. The evolution of the bunch length near transition can be found by solving the following equation [4]

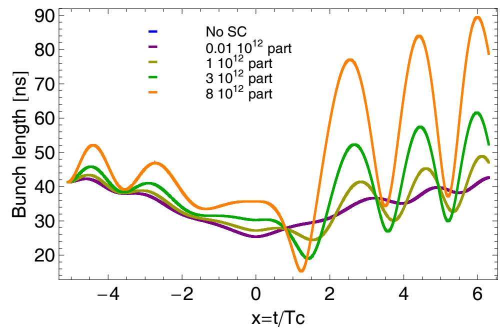

Figure 2: Evolution of the 4σ bunch length through transition at different intensities with space charge only and compared to the case without any collective effects from HEADTAIL simulations.

$$\frac{d}{dx}\left(\frac{1}{|x|}\frac{d\tau_b}{dx}\right)+\tau_b+\frac{10^{27}K_{SC}}{\tau_b^2}-\frac{10^{36}|x|S}{\tau_b^3}=0 \quad (1)$$

with

$$K_{SC}=\frac{3N_b r_0 E_0 g_0 sgn(\eta)}{\pi^2 h f_0^3 R\gamma_{tr}^2 \hat{V_{RF}}|\cos\phi_s|} \quad (2)$$

$$S=\frac{64\epsilon_l^2\dot{\gamma}T_c^4}{\pi\beta^4\gamma_{tr}^8 E_0^2} \quad (3)$$

$$T_c=\left(\frac{\beta^2 E_0\dot{\gamma_t^4}}{4\pi f_0^2 h\hat{V}_{RF}|\cos\phi_s|}\right)^{1/3} \quad (4)$$

Here, τ_b is the total (4σ) bunch length in ns, $x = t/T_c$ where t is the time and T_c the nonadiabatic time, N_b the number of protons per bunch, $r_0 = 1.54\ 10^{-18}$ m the classical proton radius, $E_0 = 0.938\ 10^9$ the rest mass energy in eV, $g_0 = 1 + 2\log\left(\frac{b}{a}\right)$ the longitudinal space charge factor where b is the beam pipe radius and a the beam radius, $sgn(\eta) = 1$ if $\eta \geq 0$ or -1 if $\eta < 0$ where $\eta = \gamma_{tr}^{-2} - \gamma^{-2}$ is the slip factor with $\gamma(\gamma_{tr})$ the relativistic factor (at transition), h is the RF harmonic number, f_0 the revolution frequency, R the machine radius, $\hat{V}_{RF}$ the peak RF voltage, ϕ_s the synchronous phase, ϵ_l the longitudinal emittance in eVs, $\dot{\gamma}$ is the time derivative of γ and β the relativistic velocity factor.

The bunch length for the intensity case $8\cdot10^{12}$ protons has been compared with the one found from (1) and plotted in Fig.3. A good agreement is obtained in spite of a difference in the oscillation frequency and in the amplitude which could be explained by the poor longitudinal bunch to bucket matching in HEADTAIL. This induces a bunch length oscillation which is superposed to the one caused by the space charge.

WITH A BROAD BAND IMPEDANCE ONLY

The same simulation of the bunch length evolution had been done in HEADTAIL with a model of broad band resonator with a shunt impedance of 20 Ohm, a resonance frequency f_r of 1000 MHz with a quality factor Q of 1. The results for different intensities are shown Fig. 4. Bunch length oscillations are observed as well, producing a longitudinal mismatch through transition. However, in opposition of the longitudinal space charge, the broad band impedance effect is focusing, below transition and defocusing above [5]. The intensity cases $3\cdot10^{12}$ and $8\cdot10^{12}$ protons are not presented for the reason that the beam becomes instable and the bunch length grows rapidly. The threshold in intensity is therefore at about $3\cdot10^{12}$ and is due to the fact that the broad band impedance has also a real part in HEADTAIL, whereas the analytical formula considers only a pure inductive impedance.

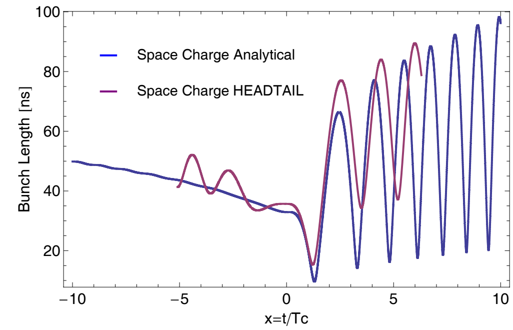

Figure 3: Comparison between the bunch length simulated with HEADTAIL with an intensity of $8\cdot10^{12}$ protons with the one computed with the analytical formula (1).

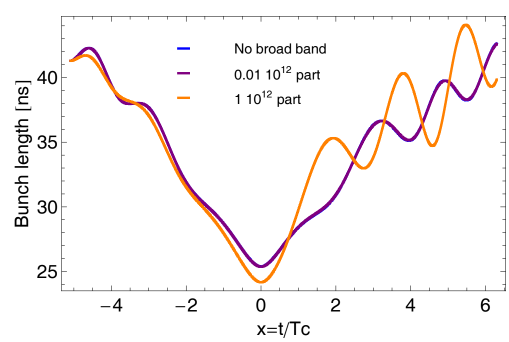

Figure 4: Bunch lengths simulated with HEADTAIL at two intensities with a broad band impedance $R_s = 20$ Ohm, $f_r = 1000$ Mhz, $Q = 1$.

Like the case with space charge, the simulations can be compared with the theory near transition with a broad band impedance, as shown in Fig. 5. Again, a fairly good agreement between the theory and the simulation is found, in particular in the way how the bunch length reaches the minimum bunch length at transition. The difference could again come from the poor longitudinal matching but also from the fact that the analytical calculation takes into account only the imaginary part of the impedance.

Since the focusing forces of the two effects are in an opposite direction on the bunch length, we expect a compen-

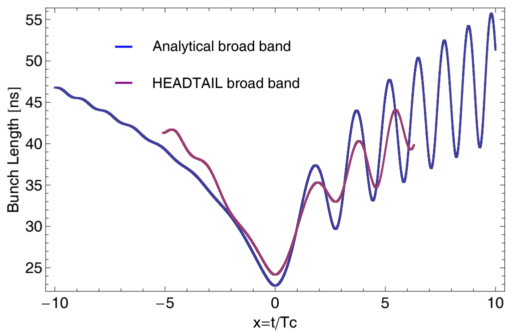

Figure 5: Comparison between the bunch length simulated with HEADTAIL with an intensity of $1 \cdot 10^{12}$ protons with the one computed with analytical formulas for a broad band impedance.

sation of the space charge impedance by the broad band one if the induced oscillations are out of phase and if the amplitudes are the same. In Fig. 6, the bunch length with space charge and with the broad band impedance computed with analytical formulas are compared for an intensity beam of $1 \cdot 10^{12}$ protons. A compensation of the collectives effects can be expected by making a simulation including both effects but it has to be checked.

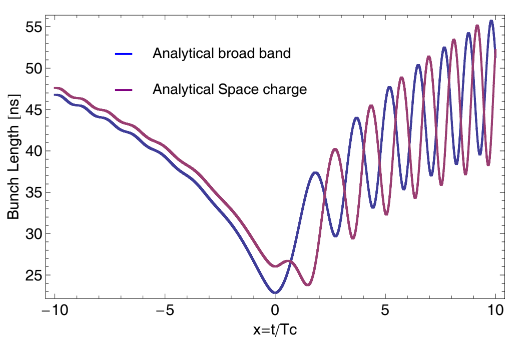

Figure 6: Comparison of the cases with space charge and broad band impedance with analytical formulas for a beam of $1 \cdot 10^{12}$ protons

Since the space charge forces are mainly energy and intensity dependent ($K_{SC} \propto N_b/\gamma^2$), this means that the bunch length oscillations due to space charge could be canceled by increasing the broad band impedance if the bunch length in the measurements is oscillating. By comparing with simulations, it will determine the effect which drives the present longitudinal beam behaviour in the PS. As an example the measured bunch length of a nToF beam through transition at an intensity of $3.5 \cdot 10^{12}$ protons with the gamma jump is plotted in Fig. 7. From Fig. 6, a different pattern has been noted near transition $x = 0$ with space charge or broad band. When the bunch length reaches a minimum at $x = 0$, the driving effect is the broad band impedance. Otherwise, if it atteins the minimum after $x = 0$, the driving effect is the space charge. The measurements in Fig. 7 show that the minimum is reached after transition therefore the bunch length oscillations might be dominated by the space charge effect. However, since the gamma jump was performed, this case has to be studied in more detail.

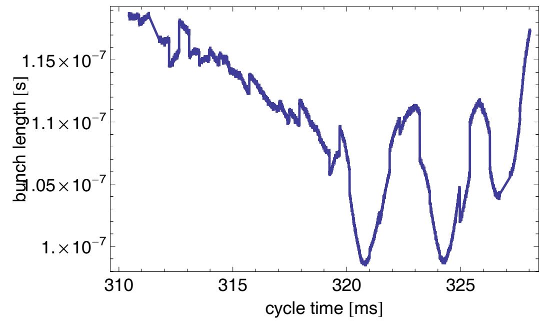

Figure 7: Bunch length measurement of a nToF beam with an intensity of $3.5 \cdot 10^{12}$ protons through transition ($t_{transition} \approx 318$ ms).

CONCLUSIONS AND OUTLOOKS

The measurements made in the PS with the nToF beam show a mismatch at the transition for the bunch length, inducing oscillations. Since good agreements have been found between HEADTAIL simulations and analytical formulas, the gamma jump can be implemented in the code to predict the beam behaviour for different settings of the scheme. The case space charge and broad band impedance together is still under study. With these results, it will be possible to check if a compensation of the two effects can be done. By adding the gamma jump into the code will allow to fit the measurements and deduce the machine impedance. The following of this study will be to measure the longitudinal microwave instability, but also transverse mechanims which perturbs the transition crossing. Improvements in the simulation are planned, like to find a better beam to bucket matching to avoid residual oscillations observed below the transition crossing.

ACKNOWLEDGEMENTS

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