Transverse Mode-Coupling Instability in the CERN Super Proton Synchrotron

G. Arduini, E. Benedetto*, H. Burkhardt*, E. Métral*, G. Rumolo**, E. Shaposhnikova**

Abstract

A vertical single-bunch instability has been observed in 2003 right after injection at 26 GeV/c in the CERN Super Proton Synchrotron (SPS). High-intensity proton bunches ($\sim 1.2 \cdot 10^{11}$ p/b) with low longitudinal emittance (~ 0.2 eVs) are affected by heavy losses after less than one synchrotron period. Such phenomenon has already been observed with leptons in many machines, e.g. in the SPS, or with protons at transition, e.g. in the CERN Proton Synchrotron (PS). However, to the authors' knowledge, it is the first time with protons far from transition. The absence of transverse mode-coupling instability in hadron machines is generally explained by three mechanisms: (i) the intensity threshold for the longitudinal microwave instability is generally lower than for the transverse mode-coupling instability, (ii) the intensity threshold due to mode-coupling between the two lowest azimuthal modes increases with space charge, and (iii) the intensity threshold increases with bunch length (in the long-bunch regime). In this talk measurements performed in the SPS are compared to analytical and simulation predictions.

Presented at ICFA Beam Dynamics Workshop “*High Intensity and Brightness Hadron Beams*”, Bensheim, Germany, October 18-22, 2004:

* CERN, Geneva, Switzerland

** GSI, Darmstadt Germany

Transverse Mode-Coupling Instability in the CERN Super Proton Synchrotron

E. Métral*, G. Arduini*, E. Benedetto*, H. Burkhardt*, E. Shaposhnikova* and G. Rumolo[◇]

*CERN, Geneva, Switzerland

[◇]GSI, Darmstadt, Germany

Abstract. A vertical single-bunch instability has been observed in 2003 right after injection at 26 GeV/c in the CERN Super Proton Synchrotron (SPS). High-intensity proton bunches ($\sim 1.2 \cdot 10^{11}$ p/b) with low longitudinal emittance (~ 0.2 eVs) are affected by heavy losses after less than one synchrotron period. Such phenomenon has already been observed with leptons in many machines, e.g. in the SPS, or with protons at transition, e.g. in the CERN Proton Synchrotron (PS). However, to the authors' knowledge, it is the first time with protons far from transition. The absence of transverse mode-coupling instability in hadron machines is generally explained by three mechanisms: (i) the intensity threshold for the longitudinal microwave instability is generally lower than for the transverse mode-coupling instability, (ii) the intensity threshold due to mode-coupling between the two lowest azimuthal modes increases with space charge, and (iii) the intensity threshold increases with bunch length (in the long-bunch regime). In this talk measurements performed in the SPS are compared to analytical and simulation predictions.

Keywords: Transverse, Instability, Proton.

PACS: 29.27.Bd.

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 $\sim 40\%$ [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 will be installed in 2006).

Recent data provide strong evidence for a fast vertical single-bunch instability in the SPS at injection [3], which is discussed in detail in this paper. Section 1 is devoted to a review of the theoretical predictions, which are compared to simulations in Section 2. The measurements observed in the SPS in 2003 are discussed in Section 3. An SPS impedance estimate is provided in Section 4, from which the Transverse Mode-Coupling Instability (TMCI) intensity threshold is deduced.

THEORY

Several analytical formalisms exist for fast (compared to the synchrotron period) instabilities. The same formula is in fact obtained (within a factor smaller than 2) from 5 seemingly diverse formalisms for a Broad-Band (BB) resonator impedance ($Q_r = 1$) [4]: (i) Coasting-beam approach with peak values [5], (ii) Fast blow-up [6], (iii) Beam break-up (for 0 chromaticity) [7], (iv) Post head-tail [8], and (v) TMCI with 2 modes in the “long-bunch” regime (for 0 chromaticity) [9]. Two regimes are indeed possible for the TMCI according to whether the total bunch length is larger or smaller than the inverse of twice the resonance frequency of the impedance.

The quasi coasting-beam approach using the peak values of bunch current and momentum spread as input for the coasting-beam formula yields the following threshold for the number of protons per bunch

$$N_b^{th} = \frac{32\sqrt{2}}{3} \times \frac{Q_{y0}|\eta|\varepsilon_l}{e\beta^2 c} \times \frac{f_r}{|Z_y^{BB}|} \times \left(1 + \frac{f_{\xi_y}}{f_r}\right), \quad (1)$$

where Q_{y0} is the unperturbed vertical tune, $\eta = \gamma_{tr}^{-2} - \gamma^{-2}$ is the slippage factor, e is the elementary charge, β and γ are the relativistic velocity and mass factors, c is the speed of light, $\varepsilon_l = \beta^2 E \tau_b (\Delta p / p_0)_{\max} \pi / 2$ is the longitudinal emittance (at 2σ , in eVs), approximated by an elliptic area in the longitudinal phase space, with E the total beam energy (in eV), τ_b the total (4σ) bunch length (in seconds), and $(\Delta p / p_0)_{\max}$ the relative momentum spread at 2σ , $f_{\xi_y} = (\xi_y / \eta) Q_{y0} f_0$ is the chromatic frequency, with $\xi_y = (\Delta Q_y / \Delta p) (p_0 / Q_{y0})$ the chromaticity, and f_0 the revolution frequency, and $|Z_y^{BB}|$ is the peak value of the BB $Z_y^{BB}(\omega) = R_r (\omega_r / \omega) / [1 - j Q_r (\omega_r / \omega - \omega / \omega_r)]$, where $\omega_r = 2\pi f_r$ is the resonance angular frequency, and R_r the shunt impedance (in Ω/m).

COMPARISON THEORY - SIMULATIONS

In this section, Eq. (1) is compared to two kinds of codes. The first is MOSES [10], which is a program computing the coherent bunched-beam modes. The second is HEADTAIL [11], which is a code simulating single-bunch phenomena. These two codes have been compared to the coasting-beam formula with peak values on the following example, using SPS parameters. A BB impedance is assumed, with $Q_r = 1$, $R_r = 20 \text{ M}\Omega/m$, and a variable resonance frequency f_r . The numerical values used for the SPS machine are the vertical tune $Q_{y0} = 26.13$, the beam momentum $p = 26 \text{ GeV}/c$, $\eta = 6.1797 \times 10^{-4}$, $f_0 = 43347.3 \text{ Hz}$, and the transverse rms beam sizes $\sigma_x = \sigma_y = 1.2 \text{ mm}$. Three scans have been made and the results are depicted on Figs. 1 to 3. It is known from Eq. (1) and the two codes that the intensity threshold is inversely proportional to the value of the impedance. The first scan is vs. the resonance frequency of the BB impedance, the second is vs. the bunch longitudinal emittance, and the third one is vs. the chromaticity.

As can be seen on the three figures, the intensity threshold increases with the resonance frequency f_r , and both the longitudinal emittance and the chromaticity can be used to increase the intensity threshold.

FIGURE 1. Intensity threshold vs. the resonance frequency f_r of the BB impedance. CB stands for Coasting-Beam formula, HT for the Head-Tail code, and MO for the MOSES code. The vertical chromaticity is $\xi_y = 0$, the longitudinal emittance is $\varepsilon_l = 0.2 \text{ eVs}$, a round chamber is considered and space charge is neglected.

FIGURE 2. Intensity threshold vs. the bunch longitudinal emittance ε_l . CB stands for Coasting-Beam formula, HT for the Head-Tail code, MO for the MOSES code, RC for Round Chamber, FC for Flat Chamber, and SC for Space-Charge taken into account. The vertical chromaticity is $\xi_y = 0$, and the resonance frequency of the BB impedance is $f_r = 1.3 \text{ GHz}$.

FIGURE 3. Intensity threshold vs. the chromaticity ξ_y . CB stands for Coasting-Beam formula, HT for the Head-Tail code, RC for Round Chamber, FC for Flat Chamber, SC for Space-Charge taken into account, no RF when the RF voltage is zero, 0.2 is for $\varepsilon_l = 0.2 \text{ eVs}$, and 0.3 is for $\varepsilon_l = 0.3 \text{ eVs}$. The resonance frequency of the BB impedance is $f_r = 1.3 \text{ GHz}$.

MEASUREMENTS IN THE CERN SPS

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. Figure 4 is an example of what was observed with a high-intensity single bunch ($\sim 1.2 \cdot 10^{11}$ p/b) of low longitudinal emittance (~ 0.2 eVs). The RF voltage is $\hat{V}_{RF} = 0.6$ MV, which corresponds to the synchrotron period $T_s = 7.1$ ms. Keeping the chromaticity close to zero ($\xi_y \approx 0.05$), the bunch was stabilized if the intensity was reduced to $\sim 6 \cdot 10^{10}$ p/b.

FIGURE 4. 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 chromaticity to $\xi_y = 0.8$ (right).

SPS IMPEDANCE ESTIMATE AND TMCI THRESHOLD WITH MOSES FROM 2002 TO 2006

The vertical impedance of one SPS MKE kicker has been estimated using Burov-Lebedev formalism [12,13]. In 2002, a BB impedance is assumed, deduced from analytical estimates of the inductive part confirmed by measurements [14]: $Q_r = 1$, $R_r = 10$ MΩ/m, $f_r = 1.3$ GHz. In 2003 and 2004, the SPS impedance is considered to be the sum of the BB impedance and 5 MKE kickers. This impedance can be fitted by a resonator, whose parameters are $Q_r = 0.8$, $R_r = 11$ MΩ/m, and $f_r = 1.5$ GHz. In 2006 (2005 is a year of shutdown), the SPS impedance is considered to be the sum of the BB impedance and 9 MKE kickers. This impedance can also be fitted by a resonator, whose parameters are $Q_r = 0.8$, $R_r = 13$ MΩ/m, and $f_r = 1.6$ GHz. The

intensity thresholds from 2002 to 2006 have then been estimated for the LHC beam (see Fig. 5).

FIGURE 5. TMCI intensity threshold from MOSES code for the LHC beam in the SPS at 26 GeV/c, after capture at $\hat{V}_{RF} = 2$ MV ($\sigma_t = 0.75$ ns and $Q_s = 0.006$), for $\xi_y = 0$ and neglecting the space charge.

CONCLUSION

It is shown from Fig. 5, that the TMCI may limit the SPS as injector for LHC. From Figs. 3 and 4, it is seen that this instability can be suppressed by increasing the chromaticity, as it is already done to damp the (similar) vertical single-bunch instability induced by the e^- cloud. However, it would be better to operate with the smallest value of vertical chromaticity as possible, for working-point considerations in the tune diagram.

REFERENCES

1. Bohl, T., et al., Proc. EPAC'02, Paris, France, 2002.
2. Burkhardt, H., et al., CERN-SL-2002-030, 2002.
3. Arduini, G., et al., Proc. EPAC'04, Lucerne, Switzerland, 2004.
4. Métral, E., CERN/PS 2002-022 (AE).
5. Laclare, J.L., CERN Accelerator School, CERN 85-19, 1985.
6. Ruth, R.D., and Wang, J.M., IEEE Trans. Nucl. Sci., Vol. NS-28, No. 3, June 1981.
7. Brandt, D., Gareyte, J., CERN SPS/88-17 (AMS), 1988.
8. Kernel, P., et al., Proc. EPAC'00, Vienna, Austria, 2000.
9. Zotter, B., CERN/ISR-TH/82-10, 1982.
10. Chin, Y.H., CERN/LEP-TH/88-05, 1988.
11. Rumolo, G., and Zimmermann, F., CERN-SL-Note-2002-036 AP.
12. Burov, A., and Lebedev, V., Proc. EPAC'02, Paris, France, 2002.
13. Burov, A., LHC Project Note 353 (revised), to be published.
14. Vos, L., CERN-AB-2003-088 (ABP).