SIMULATION STUDY ON THE BENEFICIAL EFFECT OF LINEAR COUPLING FOR THE TRANSVERSE MODE-COUPLING INSTABILITY IN THE CERN SUPER PROTON SYNCHROTRON

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Abstract

The intensity threshold of the transverse mode-coupling instability in a flat vertical chamber, as in the CERN Super Proton Synchrotron, is much higher in the horizontal plane than in the vertical one. This asymmetry between the transverse planes led us to the idea that linear coupling from skew quadrupoles could be used to increase the intensity threshold. This technique is already applied, for instance, in the CERN Proton Synchrotron, where a slow head-tail horizontal instability due to the resistive-wall impedance is stabilized by linear coupling only, i.e. with neither octupoles nor feedbacks. This paper presents the results of the study of the effect of linear coupling on the transverse mode-coupling instability, using the HEADTAIL simulation code.

INTRODUCTION

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 (~ 1.2×10^{11} p/b) with low longitudinal emittance (~ 0.2 eV.s) are affected by heavy losses after less than one synchrotron period. Using a Broad-Band (BB) impedance model, deduced from several beam-based estimates, the measurements data could be reasonably reproduced [1,2]. Furthermore, the almost perfect agreement between MOSES [3], which is a program computing the coherent bunched-beam modes (i.e. computing the Transverse Mode-Coupling Instability (TMCI) intensity threshold for zero chromaticity), and HEADTAIL [4], which is a code simulating single-bunch phenomena, led us to the conclusion that a TMCI is indeed predicted with this impedance model.

In Ref. [1] it was shown that this TMCI may limit the SPS as injector for LHC, as four new MKE kickers had to be installed before the 2006 start-up, and 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 electron 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.

Furthermore, the TMCI intensity threshold in a flat vertical chamber, as in the SPS, is much higher in the horizontal plane than in the vertical one [5]. This asymmetry between the transverse planes led us to the idea that linear coupling from skew quadrupoles could be used to increase the intensity threshold. This technique is already applied, for instance, in the **CERN** Proton Synchrotron (**PS**), where a slow head-tail horizontal instability due to the resistive-wall impedance is stabilized by linear coupling only, i.e. with neither octupoles nor feedbacks [6]. The transverse tunes used were Q_x = 6.22 and Q_y = 6.25, with a linear coupling strength characterized by a "closest-tune approach" (i.e. the tune distance between the 2 normal modes when the horizontal and vertical tunes are set equal) of ~0.05. Note that the beneficial effect of linear coupling was observed in several machines for different kinds of coherent instabilities and for both hadrons and leptons:

- **LANL-PSR** [7]: "Operating at or near the coupling resonance $Q_x - Q_y = 1$ with a skew quad is one of the most effective means to damp our 'e-p' instability".
- **BNL-AGS** [8]: "The injection setup at AGS is a tradeoff between a 'highly coupled' situation, associated with slow loss, and a 'lightly coupled' situation where the beam is unstable (coupled-bunch instability)". The transverse tunes were Q_x = 8.845 and Q_y = 8.890.
- **CERN-SPS** [9]: "A TMCI in the vertical plane with lepton beams at 16 GeV is observed. Using skew quads ('just turning the knobs'), gains in intensity of about 20-30%, and a more stable beam, have been obtained". The transverse tunes were Q_x = 26.62 and Q_y = 26.58. Machine studies were foreseen to examine these preliminary results in detail but were never performed due to lack of time.
- **CERN-LEP** [10]: "The TMCI in the vertical plane at 20 GeV sets the limit to the intensity per bunch. The operation people said that it's better to accumulate with tunes close to each other". The transverse tunes were Q_x = 98.28 and Q_y = 96.26. Machine studies were also foreseen to examine these preliminary results in detail but were never performed due to lack of time.

This paper presents the results of the study of the effect of linear coupling on the TMCI, using the HEADTAIL simulation code. A comparison with previous analytical estimates [11] is also shown.

WITHOUT LINEAR COUPLING

The HEADTAIL simulations were performed using the beam and SPS parameters reported in Table 1. A BB impedance is assumed and the study is performed with zero chromaticity, no space charge, no octupoles and no feedback. Note that the value given in Table 1 for the BB transverse shunt impedance is for a round geometry. For a flat geometry, as it is the case in the SPS, Yokoya factors [12] have to be applied to obtain the horizontal and vertical impedances.

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	
Horiz. tune	26.180	
Vert. tune	26.185	
Horiz. / vert. relative chromaticities	0 / 0	
Rms bunch length	0.2	m
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	

Assuming first a round geometry yields a TMCI intensity threshold of $N_b^{th,x} = N_b^{th,y} \approx 2.8\times10^{10}$ p/b. In the case of a vertically flat geometry the corresponding transverse intensity thresholds become $N_b^{th,x} \approx 8.0\times10^{10}$ p/b and $N_b^{th,y} \approx 3.3\times10^{10}$ p/b. Therefore, one sees that the vertical intensity threshold is increased by the vertical dipolar Yokoya factor $12/\pi^2$ ($2.8 \times 12/\pi^2 = 3.4$), whereras the horizontal intensity threshold is increased slightly more than the horizontal dipolar Yokoya factor $24/\pi^2$ ($2.8 \times 24/\pi^2 = 6.8$). The (beneficial) effect of the detuning impedance [5] seems small and in the plane of higher threshold, which is not useful in practice. This was the starting point of our study on the effect of linear coupling, trying to profit from the much higher intensity threshold in the horizontal plane.

WITH LINEAR COUPLING

Theory

In the presence of linear coupling between the transverse planes, three conditions need to be fulfilled in order to increase the TMCI intensity threshold [11]:

- **Asymmetry between the two planes**. This yields different impedances and then different intensity thresholds. Otherwise no gain is expected.
- **Resonance condition for the working point**. The horizontal and vertical (low-intensity) tunes should be at a certain distance from each other (sign important!). This distance depends on the tune shifts of the modes which couple (due to mode-coupling and not linear coupling) in both planes.
- **Optimum linear coupling strength**. The beam is stable only in a certain range of coupling values.

Assuming $Z_y = \lambda Z_x$, the approximate gain in intensity is given by [11]

$$N_b^{th,y,with} = N_b^{th,y,without} \times \frac{2\lambda}{\lambda+1}, \qquad (1)$$

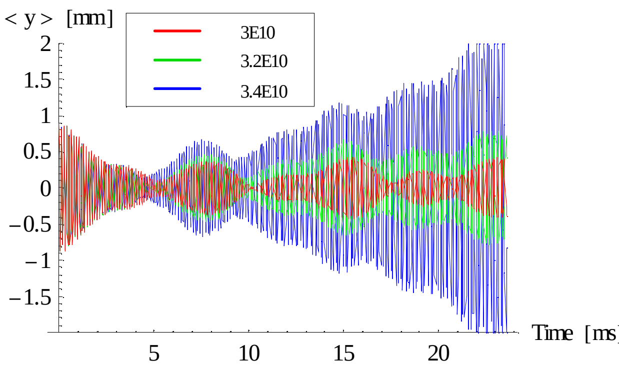
where $N_b^{th,y,with}$ is the vertical intensity threshold with (optimum) linear coupling and $N_b^{th,y,without}$ the vertical intensity threshold without linear coupling. Therefore, one sees that when $\lambda = 1$ no gain is predicted (as expected) and that at maximum, when $\lambda >> 1$, the intensity can be increased by a factor 2. If one applies Eq. (1) to our present case (with $\lambda = 2$, given by the ratio between the transverse dipolar Yokoya factors), one expects a gain in the vertical intensity threshold of 33%. Note that this gain comes only from the different transverse dipolar impedances, with no effect from the detuning impedances.

HEADTAIL Simulation

The usual working point in the SPS for LHC-type beams was Q_x = 26.18 and Q_y = 26.13. A better working point has then been found by exchanging the two tunes, which considerably improved the beam lifetime (in the case of the nominal multi-bunch LHC beam) [13]. Here, a new working point, given in Table 1, is proposed, with a linear coupling strength of $K_{skew}^{\mathrm{HEADTAIL}} = 0.005\,\mathrm{m}^{-1}$. This normalized integrated linear coupling strength corresponds to a “closest-tune approach” of 0.033. The result of the simulation is depicted in Fig. 1. Note that a typical number of linear coupling strength in the SPS when the coupling has not been properly corrected by skew quadrupoles is $K_{skew}^{\mathrm{HEADTAIL}} = 0.015\,\mathrm{m}^{-1}$ [4], i.e. 3 times more than what is required here for beam stabilization. As can be seen in Fig. 1, a small kick of 0.9 mm is initially given at time t = 0 in both transverse planes. The conclusion is that the vertical intensity threshold is increased from $N_b^{th,y,without} \approx 3.3\times10^{10}$ p/b to $N_b^{th,y,with} \approx 4.5\times10^{10}$ p/b, i.e. an increase of 36%, which is in good agreement with the previous theoretical prediction of 33%.

In Ref. [1] it was shown that this instability can be damped by increasing the chromaticity, but a potential drawback is then an emittance growth and/or beam losses due to the interaction between the (increased) incoherent tune spread and resonances. It is proposed to use linear coupling in the SPS to replace the use of chromaticity or help reducing its value, which is better for the lifetime. Machine studies are foreseen this year and detailed simulation studies will be performed including also space charge and a more precise impedance model of the SPS machine, which is under development.

Note that the use of linear coupling was also proposed in Ref. [11] for the similar "TMCI-like" instability induced by an electron cloud, as the (equivalent) horizontal "impedance" is much smaller than the vertical one in 2/3 of the SPS, i.e. in the dipole-field regions. This possibility should also be looked at in detail, as a vertical (relative) chromaticity of ~0.4 is still necessary, even after scrubbing, to stabilize the beam [13]. Here again, linear coupling should allow replacing the use of chromaticity or at least reducing its value.



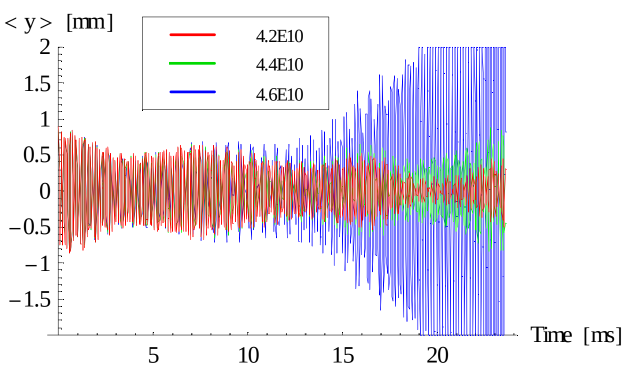


Figure 1: Evolution of the vertical centroid position vs. time (up to 1024 SPS turns, i.e. ~ 23 ms): (upper) without linear coupling, (lower) with optimum linear coupling. In the legend the numbers refer to the number of protons per bunch.

CONCLUSION

A gain in intensity of 36% is predicted for the SPS with the HEADTAIL simulation code in the presence of (optimum) linear coupling (due to the flat vertical chamber), assuming the beam and machine parameters listed in Table 1. The new proposed (low-intensity) working point is Q_x = 26.180 and Q_y = 26.185, and the linear coupling strength is $K_{skew}^{\text{HEADTAIL}} = 0.005\ \text{m}^{-1}$, corresponding to a "closest-tune approach" of 0.033. These simulation results confirm previous analytical estimates, which predicted a gain of 33%, and emphasize the potential interest of using linear coupling to increase the TMCI intensity threshold in asymmetric structures.

Simulations of this instability with the fully nominal LHC bunch, which has a longitudinal emittance of 0.35 eV.s instead of ~ 0.2 eV.s here, show that the intensity threshold should be close to the nominal intensity of 1.15×10^{11} p/b [14]. If this were the case, and if the beneficial effect of linear coupling is confirmed by future measurements, then this could bring us close to the ultimate intensity of 1.7×10^{11} p/b, as a gain in intensity of 48% is required in this case.

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