ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPME026

TMCI THRESHOLDS FOR LHC SINGLE BUNCHES IN THE CERN-SPS AND COMPARISON WITH SIMULATIONS

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Abstract

At the beginning of 2013 an extensive measurement campaign was carried out at the SPS in order to determine the Transverse Mode Coupling Instability thresholds of LHC-type bunches in a wide range of intensities and longitudinal emittances. The measurements were performed in two different configurations of machine optics (nominal and low gamma transition) with the goal to characterize the differences in behavior and performance. The purpose of this paper is to describe in detail the measurement procedure and results, as well as the comparison of the experimental data with HEADTAIL simulations based on the latest SPS impedance model. Beside the impedances of the resistive wall, the beam position monitors (BPMs), the RF cavities, and the flanges, an advanced model of the impedance of the kicker magnets is included, which are found to play a major role in the definition of the stability region of the LHC-type bunches in the two optics configurations studied.

INTRODUCTION

The LHC Injectors Upgrade project (LIU) aims at consolidating and upgrading the existing accelerator chain at CERN for higher beam intensity and brightness in preparation for the future needs of the LHC. In this respect, the transverse mode coupling instability (TMCI) at SPS injection due to the vertical beam coupling impedance has been identified as potential intensity limitation in the SPS [1]. For a given longitudinal emittance ε and a matched RF bucket, the TMCI intensity threshold is expected to scale linearly with the slippage factor $\eta \equiv 1/\gamma_t^2 - 1/\gamma^2$. The SPS optics configuration used by default until 2012 has a gamma transition of $\gamma_t = 22.8$ and is called Q26 according to the integer part of the betatron tunes $(Q_x = 26.13, Q_y = 26.18)$. In the frame of the LIU project, a new optics with lower transition energy has been developed [2]. Compared to the Q26 optics, the working point is lowered by 6 integer units in both planes $(Q_x = 20.13, Q_y = 20.18)$ in this so-called Q20 optics and the transition energy is reduced to $\gamma_t = 18$. Since LHC beams are always injected above transition in the SPS, reducing the transition energy of the lattice results in a higher slip factor throughout the acceleration cycle and consequently better beam stability in the transverse and longitudinal planes. This has been demonstrated both in extensive machine experiments and in simulation studies [3]. In the following, a detailed study of the TMCI in the two SPS optics configurations is presented.

SPS TRANSVERSE IMPEDANCE MODEL

An accurate model of the SPS beam coupling impedance is needed in order to determine its effect on the beam stability and assess the impact of new devices to be installed in the machine. The transverse impedance model is obtained by summing the contributions of the different devices along the machine weighted by the β functions at their respective locations. Since the TMCI in the SPS is observed only in the vertical plane, the horizontal impedance is not of concern here and will thus not be discussed.

Measurements of the coherent tune shift with intensity give integrated information about the effective impedance of a machine, which depends on both its full impedance and the length/shape of the bunch used for the measurements. The effective impedance is calculated for the 0-mode assuming a bunch with a Gaussian distribution and is directly related to the tune shift. In 2012, a vertical effective impedance of 18.3±0.7 MΩ/m was measured for a single bunch beam in the Q20 optics. Figure 1 shows a direct comparison between these measurements and the different contributions included in the present SPS impedance model as indicated by the legend. The SPS kicker magnets are the most important sources for the broad band impedance in the SPS, as they account for about 40% of the measured tune shift. The model of the SPS ferrite loaded kickers has been developed in CST 3D simulations starting from a simplified geometry, which has been benchmarked with analytical calculations. In a step-by-step approach, the realistic geometry of the kickers (C-shape), the longitudinal cell structure (segmentation) and the serigraphy in the case of the SPS extraction kickers has been taken into account [4].

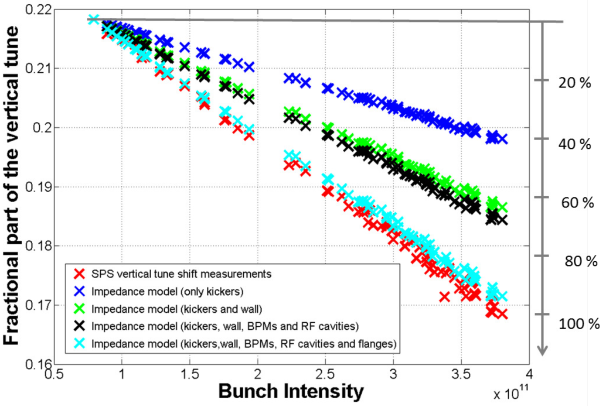

Figure 1: Vertical tune versus bunch intensity measured with the Q20 optics in 2012 in comparison with the SPS impedance model.

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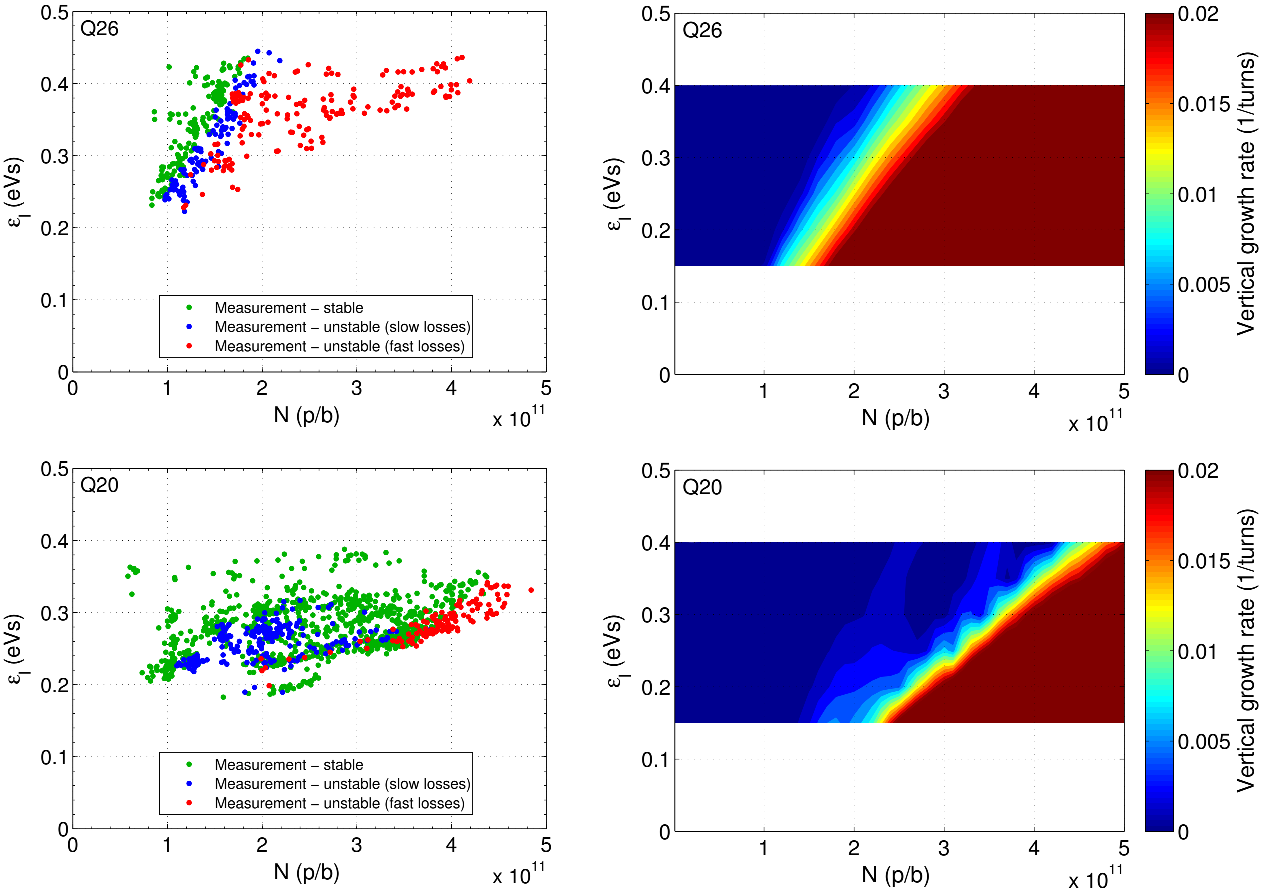

Figure 2: Measurements of the beam stability at injection with low vertical chromaticity (left) and comparison with the growth rate as predicted by HEADTAIL simulations (right) for the Q26 optics (top) and Q20 optics (bottom).

The model of the wall impedance (resistive wall and indirect space charge) is based on analytical calculations taking into account the different SPS vacuum chambers and accounts for another 20% of the total measured vertical tune shift. Beam position monitors and RF cavities are modeled in CST 3D simulations. However, their contribution to the total impedance is rather small. Finally, it was discovered recently that the step transitions between the different types of SPS vacuum chambers and flanges represent a significant part of the total SPS broadband impedance. CST 3D simulations have been performed for each transition type. Slightly more than 20% of the total vertical tune shift can be explained by these step transitions. Note that the present SPS impedance model including all the above contributions reproduces more than 90% of the measured vertical tune shift.

INSTABILITY STUDIES

The vertical single bunch TMCI at injection is one of the main intensity limitations for LHC beams in the Q26 optics. The instability results in emittance blow-up and fast losses. Analytical models based on a broadband impedance predict that the instability threshold with zero chromaticity scales like $N_{th} \propto |\eta|\varepsilon/\beta_y$ [5], where ε is the longitudinal emittance and β_y denotes the vertical beta function at the location of the impedance source. Thus, a significant increase of the instability threshold is expected in the Q20 optics, since the product of the slip factor and the vertical beta function at important impedance sources $(\eta\beta_y)$ is about 2.5 times higher compared to the Q26 optics.

Measurements have been performed with the Q26 and the Q20 optics in the same experimental conditions in order to allow for a direct comparison of the instability thresholds. In Q26, the RF voltage of the main 200 MHz RF system was set to $V_{200} = 1.4\,\mathrm{MV}$. In order to achieve the same bucket area in the two optics, the voltage was increased to $V_{200} = 4.0\,\mathrm{MV}$ in Q20. In both optics, the 800 MHz cavity was operated in bunch shortening mode at 10% the voltage of V_{200}. In these conditions and with (linear) chromaticity close to zero, the TMCI intensity thresholds in the Q20 and the Q26 optics were characterized as a function of the longitudinal emittance and the bunch intensity at PS extraction [6], as shown in Figure 2 (left). Each measurement point corresponds to the injection of a single bunch into the SPS. The longitudinal emittance was calculated from the bunch length measured in the PS before the bunch rotation and the bunch intensity was measured by the bunch current transformer in the PS before extraction. Cases in which the beam was stable are indicated by green dots. Injections where the beam was unstable are marked by red dots if losses occurred within the first 1000 turns (“fast losses”) and blue dots if losses occurred later in the cycle (“slow losses”).

In the case of the Q26 optics, a linear dependence of the intensity threshold as a function of the longitudinal emittance is observed, as expected from the analytical models. Note that the TMCI intensity threshold for the nominal longitudinal emittance of $\varepsilon = 0.35$ eVs at injection was found at $N_{th} \approx 1.6 \times 10^{11}$ p/b in the Q26 optics in good agreement with previous studies [1]. For the same longitudinal emittance the TMCI intensity threshold is about 2.5 times higher in the Q20 optics, i.e. at around $N_{th} \approx 4.5{\times}10^{11}$ p/b. However, in addition to the strong TMCI at high intensity, an area of “weak instability” is observed in the Q20 optics for longitudinal emittances below $\varepsilon \approx 0.32$ eVs and intensities in the range $1.1{\times}10^{11}$ p/b $< N < 2.3{\times}10^{11}$ p/b. It should be emphasized that this slow instability is not of concern for the multi bunch LHC beams, as they have larger longitudinal emittance.

The experimental observations in the two SPS optics are compared with numerical simulations using the wake functions obtained from the SPS impedance model described above. In particular, the impedance contributions from the kicker magnets, the wall impedance, the BPMs and the RF cavities have been taken into account. Note that in the beam stability simulations presented here the impedance of the transition pieces is not yet included. However, preliminary simulation results indicate that they play a minor role for the TMCI instability thresholds. Figure 2 (right) shows the vertical growth rate as a function of longitudinal emittance and intensity for the two optics as obtained with the macroparticle code HEADTAIL. Both the 200 and the 800 MHz RF systems and the non-linear chromaticity up to third order measured in a separate experiment [6] are taken into account. The threshold intensities in the two optics are very similar to those observed in the measurements. Furthermore, the area of slow instability experimentally found in the Q20 optics is reproduced in the simulations. Figure 3 shows the intra bunch motion measured with the SPS Head-Tail monitor for a few example cases in comparison with the results of HEADTAIL simulations. A clear traveling wave pattern without nodes is observed in the measurement for high intensity in the Q26 optics, which is a typical signature of a TMCI. A very similar intra bunch motion is also observed in the simulation for comparable beam parameters. In this case, (azimuthal) mode -1 couples with mode -2 and mode -3. Two cases are shown for the Q20 optics: for high beam intensity, where the strong instability appears, a traveling wave pattern is observed. In the simulation, the instability is caused by coupling of the modes -1 with -2 and later also -3. For an intermediate intensity at which the weak instability occurs, the intra bunch motion has one node in the center of the bunch, which indicates that mode -1 is dominating.

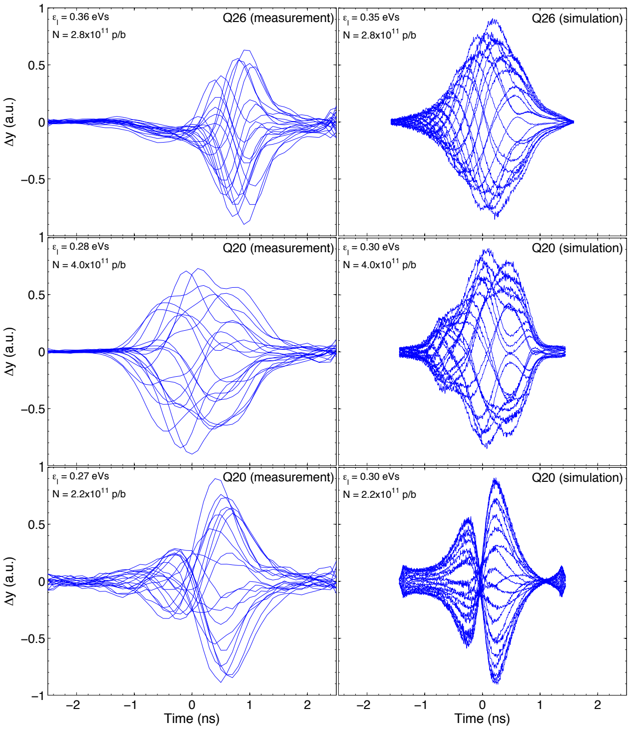

Figure 3: Vertical intra bunch motion in the SPS Head-Tail monitor measurement (left) in comparison with the corresponding HEADTAIL simulations (right) for one case of the Q26 optics and two cases of the Q20 optics.

SUMMARY AND CONCLUSIONS

The TMCI at SPS injection can be a serious intensity limitation for future LHC beams in the SPS when using the Q26 optics. With the Q20 optics the TMCI is not of concern for the beam parameters envisaged by the LIU project. The instabilities observed in the two optics for different ranges of intensities and longitudinal emittances are reproduced in excellent agreement by HEADTAIL simulations with the detailed SPS impedance model. This model reproduces furthermore almost completely the measured vertical coherent tune shift with intensity.

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