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STUDIES OF TRANSVERSE INSTABILITIES IN THE CERN SPS

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Abstract

In the framework of the LHC Injectors Upgrade (LIU), beams with about twice the intensity compared to the present values will have to be accelerated by the CERN SPS and extracted towards the LHC. Machine studies with intensity higher than the nominal LHC beam have shown that coherent instabilities in both transverse planes may develop at injection energy, potentially becoming a limitation for the future high intensity operation. In particular, a transverse mode coupling instability is encountered in the vertical plane, the threshold of which can be sufficiently increased by changing the machine optics. In addition, a headtail instability of individual bunches is observed in the horizontal plane in multi-bunch operation, which requires stabilization by high chromaticity. The PyHEADTAIL code has been used to check if the present SPS impedance model reproduces the experimental observations. The instability growth rates have been studied for different machine optics configurations and different chromaticity settings. In addition, other stabilizing mechanisms like tune spread from octupoles or the transverse damper have also been investigated.

INTRODUCTION

To achieve higher luminosity in the experiments of the Large Hadron Collider (LHC), CERN has launched the High Luminosity LHC (HL-LHC) project [1]. To satisfy the increased demands of the collider, the LHC injectors have to be adapted. These modifications are warped up in the LHC Injector Upgrade (LIU). For the Super Proton Synchotron (SPS), the last injector in the LHC injector chain, the intensity accelerated after the upgrade is supposed to nearly double with respect to currently operated intensities.

The Transverse Mode Coupling Instability (TMCI) represents one of the most important intensity limitations in the SPS at injection. Before the LHC era the SPS was operated with the so called Q26 optics with an integer tune of 26 and characterized by its low TMCI threshold would have limited the maximum intensity delivered to the LHC. To improve the intensity threshold, enabling operation with LHC intensities and even leaving margins for future intensity goals, the low gamma transition optics, the Q20 optics with an integer tune of 20, were introduced. However, the low gamma transition in combination with LIU intensities leads to an increased beam loading that probably cannot be compensated by the RF power amplifiers, not even after the upgrade of the RF system foreseen by LIU [2]. Therefore, a Q22 optics with an integer tune of 22 and intermediate transition energy has been proposed, relaxing the demands on the RF power amplifiers but also leading to a intermediate stability threshold. The intensity threshold the TMCI imposes has already been studied for the Q26 and the Q20 optics [3]. Here, for the first time, it has been investigated in depth for the newly proposed Q22 optics.

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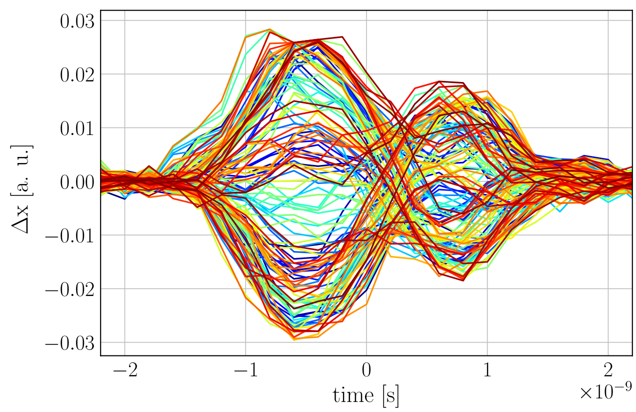

Figure 1: Measured horizontal mode 1 instability. The amplitude of the instability is plotted over time with respect to the center of the bucket over 140 consecutive turns.

In the present injector chain configuration the LIU intensity cannot be reached therefore the only way to predict the behavior of the machine after the upgrade is simulations. In the case of the SPS mainly beam dynamics simulations in PyHEADTAIL [4] are used. These simulations rely on models of the machine. Due to its small vertical aperture, transverse instability studies in the SPS historically concentrated on the vertical plane. To verify the models of the horizontal plane a measurement campaign has been launched. In recent high intensity multi-bunch runs in the SPS a horizontal single-bunch instabilities (see Fig. 1) were observed and are currently being studied and characterized. As the horizontal plane could become a potentially limiting factor, the campaign to verify the horizontal models has been extended to also investigate high intensity instabilities and possible damping mechanisms. Its current status is presented here. The horizontal studies concentrate on the Q20 optics as that is the baseline for LIU [2].

TMCI MEASUREMENTS

The TMCI intensity threshold can be estimated by Eq. 1 [5]. It is dependent on the machine radius R and revolution frequency ω_0, the slippage factor η, the longitudinal emittance ϵ_z, the transverse betatron function β_y ,vertical chromaticity Q_y' and on Z_y^{BB} the broadband impedance res-

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onator model of the machine and its resonance frequency ω_r.

$$N_{thr}^{TMC} = \frac{16\sqrt{2}}{3\pi}\frac{R|\eta|\epsilon_z}{\beta_y e\beta^2 c}\frac{\omega_r}{|Z_y^{BB}|}\left(1+\frac{Q_y'\omega_0}{\eta\omega_r}\right) \quad (1)$$

The influence of the changeable machine parameters on the threshold is investigated here.

For the measurements, the optics are set up with a slightly positive vertical chromaticity ($Q_y' = 0.7$) to ensure the suppression of the mode zero head-tail instability excited at negative chromaticity. The nominal value of 2.7 MV for the RF voltage was found scaling the voltage used in the Q20 optics with the ratio of the gamma transitions. The nominal longitudinal emittance for the measurements is $\epsilon_z = 0.32$ eVs.

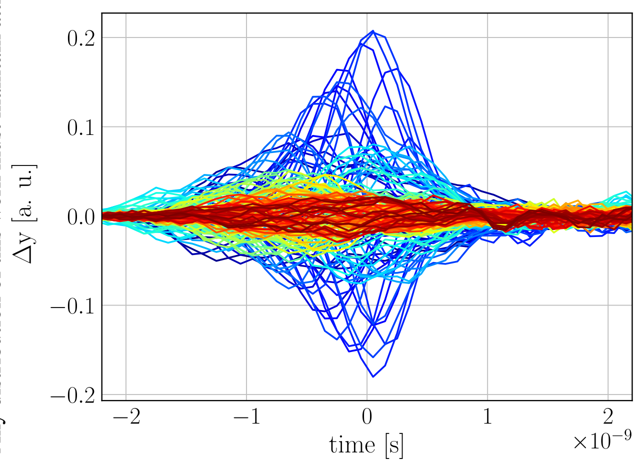

Figure 2: Measured TMCI in the vertical plane. The amplitude of the instability is plotted over time with respect to the center of the bucket over 200 consecutive turns.

The TMCI threshold is measured by injecting a single bunch into the SPS and ramping up its intensity over consecutive shots. The intensity measured in the SPS after 200 ms by the beam current transformer, is then compared to the intensity extracted from the Proton Synchotron (PS), its injector. Whenever the intensity in the SPS is significantly lower, a very fast TMCI is observed. The head-tail monitor then shows the typical traveling wave pattern as displayed in Fig. 2.

Influence of Emittance

First the machine is run with nominal longitudinal emittance ($\epsilon_z = 0.32$ eVs). The TMCI threshold for this case is found at 2.5e11 protons per bunch (ppb) as shown in Fig. 3.

For the next measurement the emittance is changed by reducing the RF-bucket size in the PS-Booster, the second accelerator in the CERN proton accelerator chain. Figure 4 shows a TMCI threshold of about 1.7e11 ppb for a longitudinal emittance of 0.22 eVs. The linear dependency predicted by Eq. 1 is confirmed as the ratio of emittance to intensity threshold is constant for both emittance measurements.

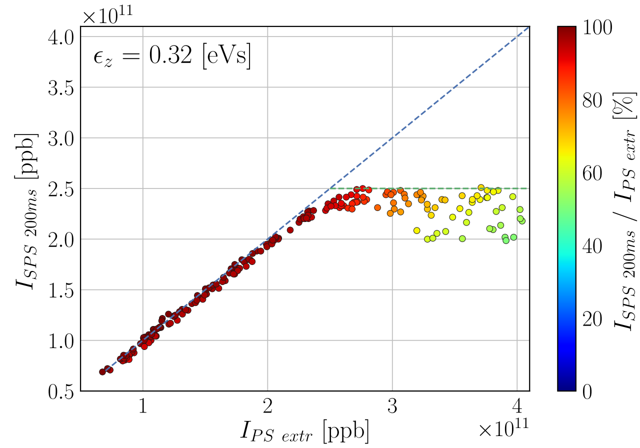

Figure 3: Intensity in the SPS left 200 ms after injection over the intensity extracted from the PS. Color-coded is the percentage of particles left in the SPS after 200 ms with respect to the number of particles extracted from the PS. The green dashed line represents the TMCI threshold obtained from the measured data.

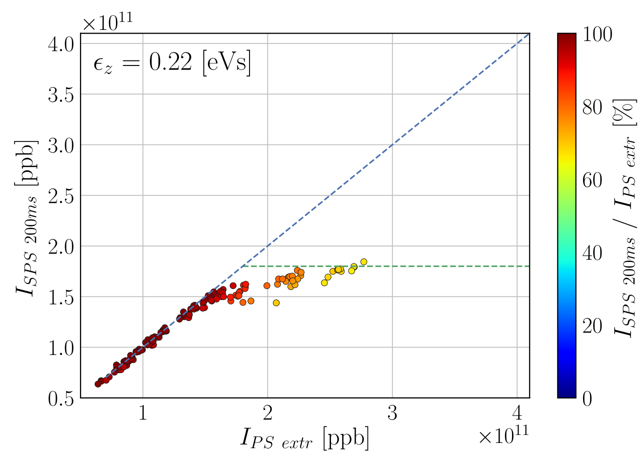

Figure 4: Intensity in the SPS left 200 ms after injection over the intensity extracted from the PS. Color-coded is the percentage of particles left in the SPS after 200 ms with respect to the number of particles extracted from the PS. The green dashed line represents the TMCI threshold obtained from the measured data.

Influence of RF Voltage

A change of the cavity RF voltage influences the synchrotron motion of the particles, which affects the TMCI threshold. A particle with faster synchrotron motion is affected by the coupling modes for a shorter time, leading to a slower instability development.

$$\epsilon_z = 4\pi\frac{Q_s}{\eta R}p_0\sigma_z^2 \quad (2)$$

The longitudinal emittance is linearly dependent on the synchrotron tune Q_s (Eq. (2) [6]) which scales with the square

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root of the RF voltage V (Eq. (3) [6]).

$$Q_s = \sqrt{\frac{eV\eta h}{2\pi E_0 \beta^2}} \tag{3}$$

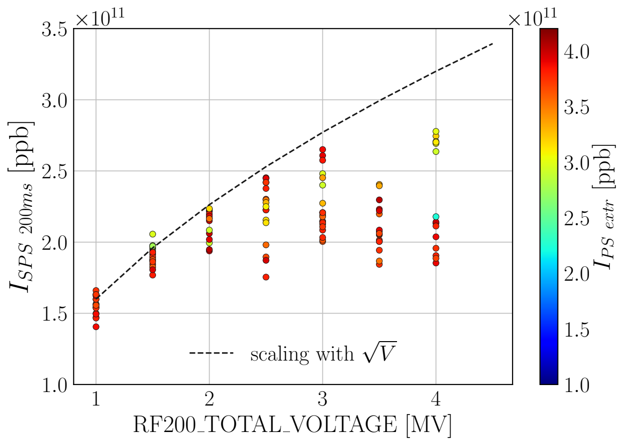

Figure 5: Intensity in the SPS left 200 ms after injection over the RF voltage of the SPS main cavities (RF200). Color-coded is the number of particles extracted from the PS. The dashed black line scales with the square root of the voltage.

As expected, the measurements show a square root dependency of the threshold on the RF voltage (see Fig. 5). This scaling does not hold for voltages over 3 MV as injection losses already dominate in this case.

Influence of Chromaticity

The TMCI threshold is dependent on the chromaticity (Eq. (1)). To confirm this dependency different values of Q_y' have been probed for their threshold.

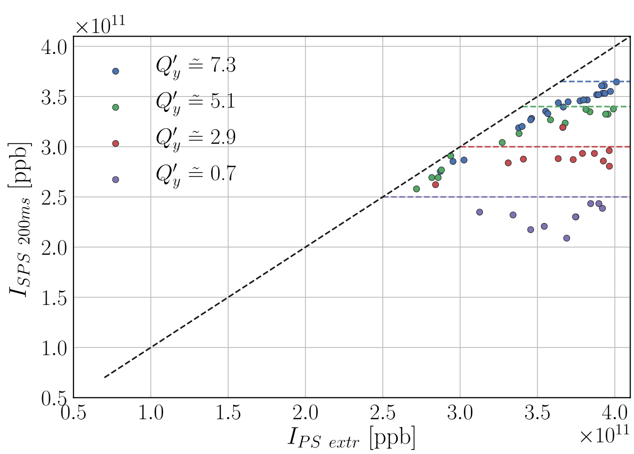

Figure 6: Chromaticity scan. Again the intensity in the SPS left 200 ms after injection is plotted over the intensity extracted from the PS. Shots with different chromaticity are represented with different colors.

The results of this scan shown in Fig. 6 confirm the prediction. The threshold is clearly increased for higher chromaticity values.

Compare Measurements with Simulations

To compare the measurements with PyHEADTAIL a scan over intensity and emittance has been executed. The results are shown in Fig. 7. A general behavior where lower emittance results in a lower TMCI threshold is observed. The lower the emittance the lower the TMCI threshold. As TMCI is an extremely fast instability it was not possible to fit its growth-rate. Here the ratio of intensity measured in the SPS after 200 ms and the intensity extracted from the PS is used as a substitute.

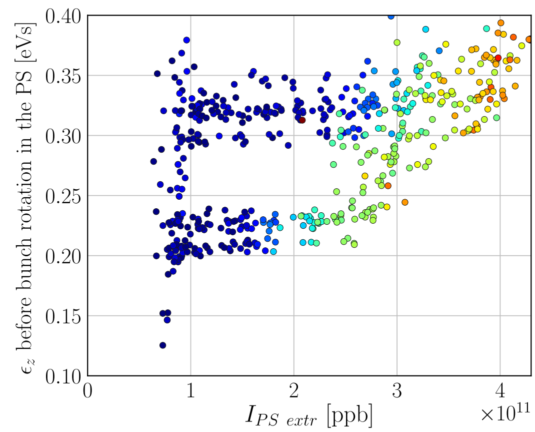

Figure 7: Measured longitudinal emittance against intensity extracted from the PS. Color-coded is the percentage of particles left in the SPS after 200 ms with respect to the number of particles extracted from the PS.

The simulations of the TMCI threshold in PyHEADTAIL are done employing the same parameter values as used for the measurement in the machine. Simulations (Fig. 8) and measurements show a good agreement. Even if the growth-rate is compared to the ratio between particles after 200 ms in the SPS and particles extracted from the PS, the general behavior of the TMCI threshold is well reproduced. On the other hand, the island of slow growth-rate seen in Fig. 8 could not be observed in measurements.

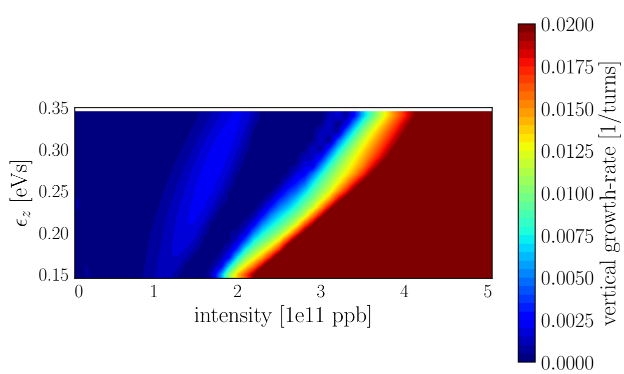

Figure 8: Simulated scan of the longitudinal emittance against intensity. Color-coded is the vertical growth-rate of occurring instabilities.

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Beam Condition After TMCI

To investigate the beam condition after the occurrence of TMCI, emittance studies have been done. For this purpose, horizontal and vertical rotational wire scanners are used in the SPS to measure the emittance of a beam developing TMCI. A rotational wire scanner measures the emittance two times, once swinging into the beam and once going back to its parking position. Unfortunately, as the TMCI is very fast, it was not possible to measure the emittances before and after the instability. Therefore the emittance of shots with intensities below the TMCI threshold are compared to the shots with intensities above it.

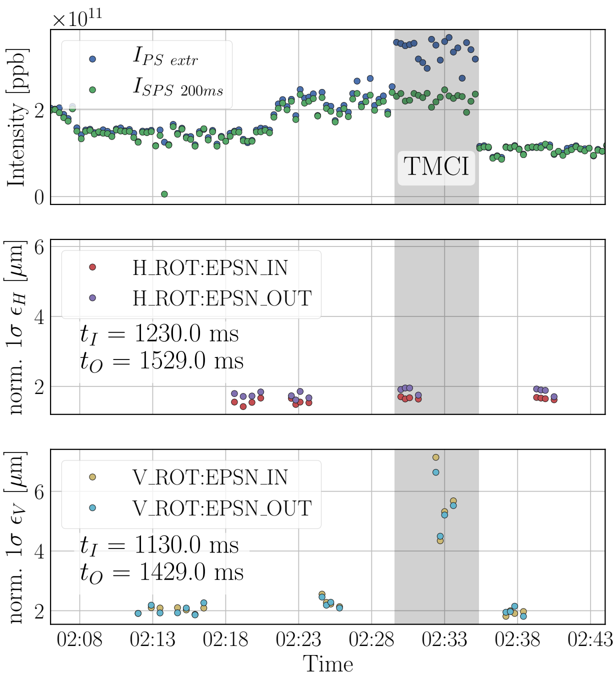

Figure 9: Intensity history and rotational wire-scans in horizontal and vertical plane over time. t_I and t_O denote the time in the SPS cycle when the in- and outgoing scan took place (injection at 1015 ms).

In Fig. 9 the results of the measurements are plotted. The blow-up in the vertical plane due to the instability is clearly observed. The emittance in the horizontal plane is not changed by the instability.

STUDIES OF THE HORIZONTAL PLANE

The influence of the damper and the linear chromaticity on instabilities in the horizontal plane has already been published in [7]. For the future operation of the SPS with LIU intensities the octupole could become an important tool to keep the beam stable. The stabilization mechanism is based on the amplitude detuning introduced by the octupoles. That crates a tune spread leading to Landau damping. The focus here lies on the effect the octupoles have on instabilities in the SPS.

Octupole Studies

The possibility to stabilize the beam using octupoles has been investigated in measurements. In this case single bunches with intensities of 2e10 ppb are used. While the vertical chromaticity was kept at a positive value, the horizontal chromaticity was set to -2 to provoke a mode zero head-tail instability in the horizontal plane. The aim is to cure this instability using the octupoles.

Three groups of Landau octupoles in the SPS are used for the measurements; the group next to the focusing quadrupoles (LOF) the one next to the defocusing quadrupoles (LOD) as well the Landau octupoles for extraction (LOE). As the LOE are not used during operation anymore, not all of them are connected to a power supply. For these studies only the octupoles LOE1202 and LOE3302 were used. They are situated in regions with a small horizontal dispersion so that they mainly create amplitude detuning and hardly any second order chromaticity. The LOF act mainly on the horizontal plane, the LOD mainly on the vertical plane.

First a scan over the magnetic strength value K of the LOFs is done (blue curve in Fig. 10). For absolute K_{LOF} values of 6 m^{-4} the instability is damped. However, the LOFs do not only produce amplitude detuning (a_{xx}) but also second order chromaticity (Q_x'') in the horizontal plane. To investigate the damping mechanism, only a_{xx} respectively only Q_x'' shall be introduced. The optics simulation software MADX [8] and the optics model of the SPS are used to calculate K values for the LODs, LOFs and LOEs to compensate a_{xx} respectively Q_x'' in the machine.

To measure the effect of Q_x'' on the mode 0, the general idea is to set up the LOEs to compensate the a_{xx} introduced by the LOFs and the LODs to compensate the introduced amplitude detuning cross term a_{xy}. For a scan over second order horizontal chromaticity a set of values for all three octupole groups is calculated with MADX. For every measurement point Q_x'' is set to the value needed as well as a_{xx} and a_{xy} to zero. To crosscheck a_{xx} has been verified to be compensated well at different settings of Q”. The results of this Q_x'' scan results in the green curve in Fig. 10. The curve follows remarkably well the blue curve of the K_{LOF} scan in the same figure. This leads to the impression that the damping of the LOFs is mainly due to the second order chromaticity.

For the scan over a_{xx} the compensation strategy is different; the LOEs are used to create the a_{xx} as they produce only little Q_x''. a_{xy} is then compensated manly by the LODs (supported by the LOFs). MADX is used again to determine K values producing the desired amount a_{xx} with zero Q_x'' and a_{xy}. To compare the results to the K_{LOF} scan MADX is also used to calculate the K values that would be needed for the LOFs to produce the same a_{xx} values (the effects of Q_x'' and a_{xy} these values introduce, too are ignored). The horizontal chromaticity during the last measurement was -1.3, which produces a mode zero with a lower growth-rate. That is the reason for the lower value of the a_{xx} scan curve

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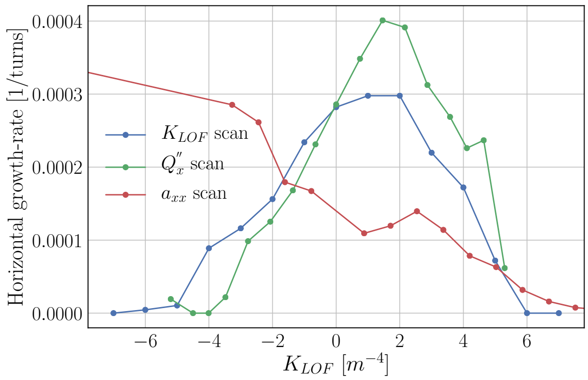

Figure 10: Octupole scan for different settings. The measured growth-rate is plotted over the the K_{LOF} value set. For the Q''_x / a_{xx} scan the LOE and LOD octupoles have been used to compensate the a_{xx} / Q''_x produced by the LOF. The growth-rate for every measured point is averaged over multiple shots.

in Fig. 10 for deactivated octupoles ($K_{LOF} = 0\,\mathrm{m}^{-4}$). For the two other scans (with Q'_x = -2) the values obtained without octupoles are nearly identical, speaking for a good quality of the measurement.

For positive values of K_{LOF} up to $6\,\mathrm{m}^{-4}$ the second order chromaticity seems to drive the beam unstable, working against a_{xx}. Negative amplitude detuning values do not seem to be able to stabilize the beam meaning that for negative values Q''_x is the stabilizing mechanism. A possible explanation for the inability of negative a_{xx} to stabilize the beam that is the tune spread introduced by the amplitude detuning enlarges an existing tune spread driving the beam into a resonance. This would also explain the losses observed during the measurements. For that reason simulations are very complicated and still ongoing.

CHECKING THE IMPEDANCE MODEL

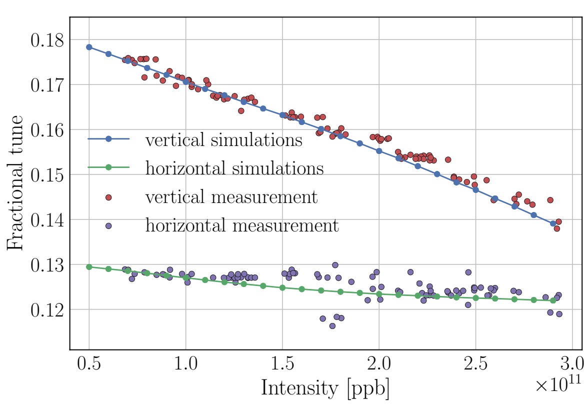

Figure 11: Scan of the fractional tune over the intensity for the Q20 optics. Simulations are compared to the measured fractional tune of shots with different intensities.

To be sure that the impedance model of the simulations is correct and to keep track of the changes in the machine, verification measurements were executed. In [7] the effect of first order chromaticity on a provoked instability has been investigated and the results were compared to the model finding a good agreement and confirming the impedance model. Here the fractional tune in both planes has been measured for different intensities and compared to simulations. The settings of the machine were reproduced in simulations and compared to the measurements.

Figure 11 shows the results. The simulations reproduce the measurements in both planes. The fluctuation of the measured values around the simulation is due to measurement error and the fact that the limited number of turns used to determine the fractional tune.

CONCLUSION

To crosscheck the SPS impedance model, tune shift versus intensity scans have been compared to measurements. The good agreement speaks for a highly realistic machine model. The effect of the SPS octupoles on a deliberately created beam instability has been investigated in measurements. The different damping mechanisms introduced by the octupoles have been also looked at separately by compensating the others. The TMCI threshold of the newly proposed Q22 optics has been studied in depth for the fist time and was found at 2.5e11 ppb. Furthermore the dependency of the threshold on multiple parameters has been investigated.

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