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SIMULATION AND MEASUREMENT OF THE TMCI THRESHOLD IN THE LHC

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Abstract

The Transverse Mode Coupling Instability (TMCI) occurs in individual bunches when two transverse oscillation modes couple at high bunch intensity. Simulations predict an instability threshold in the LHC at a single bunch intensity of $3 \cdot 10^{11}$ protons. The TMCI threshold can be inferred by measuring the tune shift as a function of intensity. This measurement was performed in the LHC for different machine impedances and bunch intensities. The impedance was changed by varying the primary and secondary collimators gaps to increase their contribution to the resistive wall impedance. The experiment also allowed to assess the validity of the LHC impedance model in the single bunch regime, at low chromaticities.

INTRODUCTION

The transverse mode coupling instability (TMCI), also named strong head-tail instability, can affect high intensity single bunches in circular accelerators. The instability mechanism can be described with a two particle model [1, p. 180], assuming a broad-band impedance (i.e short-range wakefield). During the first half of the synchrotron period, the electromagnetic field induced by the particle at the head of the bunch perturbs the particle at the tail of the bunch. The same happens during the second half of the synchrotron period but the two particles have swapped their positions. Below a certain bunch intensity, the disturbance is not strong enough and the perturbations do not accumulate. However above a certain intensity threshold the perturbations accumulate and the particles motion grows exponentially. This description can be reproduced and visualized with the tracking code PyHEADTAIL [2], an example is made available in the PyHEADTAIL examples repository [3, 4].

The TMCI can clearly be observed in electron machines [1, p. 184] because of the short length of the bunches [5]. In proton machines, such an instability was observed in the CERN SPS but with higher order azimuthal oscillation modes [6, 7]. However in the LHC, because of the relatively short length of the bunches (1.08 ns in 2017 and 2018), a coupling between mode 0, i.e the mode where the bunch head and tail oscillate in phase, and -1 i.e where the bunch head and tail oscillate in counter-phase, may occur. As the High Luminosity LHC project plans to increase the bunch intensity by a factor of two compared to the nominal LHC value [8, 9], the transverse mode coupling instability could become a limitation to the machine operation. The study can also be used to assess the validity of the accelerator impedance model and thus help to understand discrepancies between predicted stability limits and instability observations [10]. The problem was first studied by performing stability simulations with the LHC impedance model and the Vlasov solver DELPHI [11]. In a second step, the tune-shift as a function of intensity was measured in the LHC for different collimator settings, allowing to modify the machine impedance. This measurement allows to infer the TMCI intensity threshold and notably for the HL-LHC case.

SIMULATION OF THE TMCI INTENSITY THRESHOLD

To understand and predict beam instabilities, an impedance model of the LHC has been developed [12] and is extensively used. It has also been extended to the HL-LHC case [13]. It models many contributors to the beam coupling impedance, among which the main ones are the beam screens, the vacuum chambers and the collimation system. At the top energy of 6.5 TeV, the collimation system is the main contributor to the overall machine impedance. This results from the scaling of the resistive wall impedance in $1/b^3$ in the frequency range of interest and in the presence of a transverse damper, where b is the collimator gap [1, p. 38]. The collimator gap itself scales with the transverse beam size as:

$$b = n\sigma_t = n\sqrt{\frac{\epsilon_n}{\beta\gamma}\left(\beta_x \cos(\theta)^2 + \beta_y \sin(\theta)^2\right)} \qquad (1)$$

where σ_t is the RMS transverse beam size, n the collimator position setting, ϵ_n the beam normalized emittance, β the ratio of the beam velocity to the speed of light c, γ the Lorentz factor, β_x and β_y the Twiss functions at the collimator position, θ the azimuthal angle of the collimator. These scaling laws highlight that in the LHC the impedance is higher at top energy because of the tighter gaps in the collimators. In turns the stability margins are tighter at top energy than at injection energy [10].

The fact that the collimators can mechanically adjust their aperture to follow the beam size makes it possible to modify the machine impedance by moving in or out the collimators. This will allow to change the TMCI threshold and possibly reach it with nominal LHC beams. To quantify this effect as well as the influence of other beam parameters such as chromaticity, stability simulations were performed with the Vlasov solver DELPHI [14]. The treatment of Vlasov's equation leads to an eigensystem which is solved by the code which then outputs complex eigenvalues and eigenvectors. The eigenvalues give informations on the azimuthal and radial modes frequency shifts and growth rates. The eigenvectors allow to reconstruct the longitudinal bunch profile for

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each oscillation mode. DELPHI simulations were performed for different machine chromaticities and collimators settings. To find the TMCI intensity threshold, the single bunch intensity was scanned between 0 p.p.b. to 5×10^{11} p.p.b. (protons per bunch). The beam parameters are summarized in Table 1.

Table 1: Stability Simulations Parameters

Parameter	**Value**
Number of bunches	1
Bunch intensity / 10^{11} p.p.b	0 to 5
Full bunch length / ns	1.08
Unnormalized chromaticity	0 to 5
Damping rate	no damper, 100 turns, 50 turns

In Figs. 1, 2 and 3, the top plot shows the real tune-shift of the different oscillation modes as a function of bunch intensity and the bottom plot shows the growth rate associated to these modes, both obtained with DELPHI. Figure 1 shows the case with the nominal collimator settings at zero chromaticity. The plot clearly shows the mode coupling occurring for a single bunch intensity of 3×10^{11} p.p.b.: the mode 0 and -1 have their growth rates suddenly increasing for this intensity value and beyond. While the LHC injector chain can create LHC type bunches with an intensity up to 3×10^{11} p.p.b., it is at the moment impossible to reach in the LHC a single bunch intensity higher than 2.2×10^{11} p.p.b.. But as exposed previously, the machine impedance can be modified by changing the collimators gaps. Simulations with tighter collimators settings were thus performed: Fig. 2 shows the results for a configuration in which the primary (TCP) collimators are brought in closer to the beam by $0.5\sigma_t$ and the secondary collimators (TCSG) by $1\sigma_t$. In this case the TMCI threshold appears at 2×10^{11} p.p.b., an intensity reachable in the LHC.

These two cases assume that the machine chromaticity is equal to zero units. Operational experience shows that the unnormalized chromaticity can be controlled within ~ 2 units [15] so to ensure beam stability, the LHC is operated with a positive chromaticity. To measure the tune-shift as a function of intensity while ensuring beam stability, a slightly positive chromaticity should be used. Simulations were made with DELPHI taking into account this effect. Figure 3 shows the results for the same collimator configuration as in Fig. 2, but with a unnormalized chromaticity of 5 units. For intensities below 2×10^{11} p.p.b., the real part of the eigenvalues are not too affected by the chromaticity effects. The imaginary part however shows that the mode -1 has a small growth rate for all intensity values: as the chromaticity is now non zero, this mode is affected by a classic head-tail instability [1, p. 197].

In conclusion, stability simulations with the LHC impedance model indicate that:

- In the nominal configuration, the TMCI intensity threshold is at a single bunch intensity of 3×10^{11} p.p.b., currently impossible to reach in the LHC;
- Closing further the machine collimators gaps can reduce the threshold to 2×10^{11} p.p.b.;
- Because of the operational uncertainties, a slightly positive chromaticity should be used to ensure beam stability;
- This positive chromaticity affects the modes shifts, but the tune-shift as a function of intensity remains similar to the cases with zero chromaticity, it can thus be measured to infer the TMCI threshold.

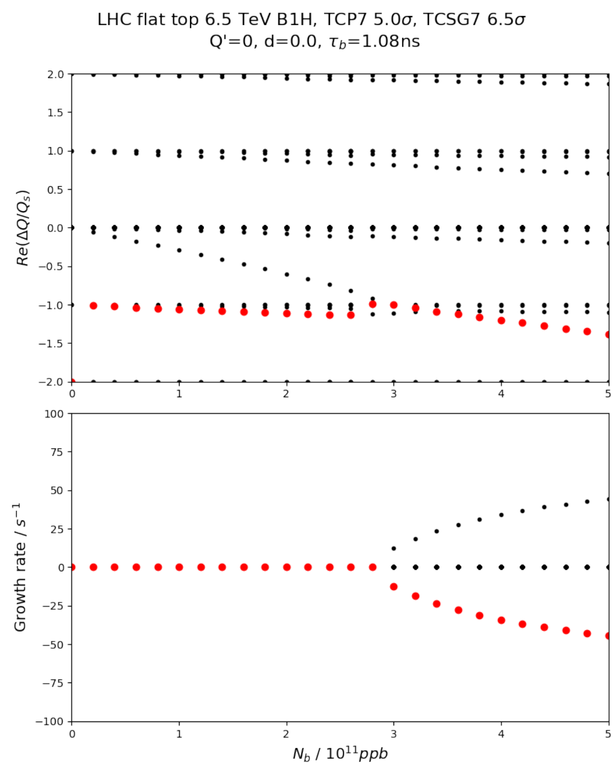

Figure 1: Complex Tune Shift as a Function of Intensity. The nominal LHC collimators configuration is showed, for a chromaticity of zero units.

MEASUREMENT OF THE TUNE-SHIFT VERSUS INTENSITY

In the framework of the LHC Machine Development program, an 8 h time slot was approved to measure the tune shift as a function of bunch intensity for different collimators settings. The measurement took place on the night of the 15th to 16th September 2017. Because of the setup and energy ramping time taken by the machine, two sets of measurement at top energy could be performed. The first set used 3 bunches of different intensities, the second set two. These numbers were constrained by machine protection requirements: the total intensity in each beam could not exceed 3×10^{11} p.p.b. if some collimators were to be moved in or out. Doing so

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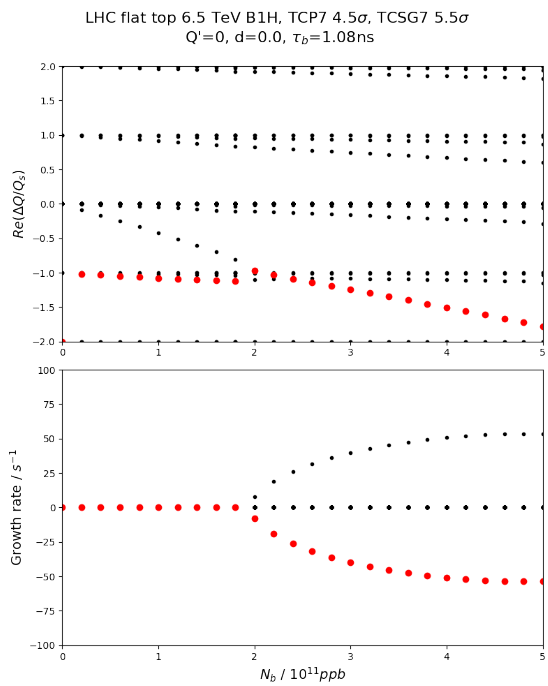

Figure 2: Complex Tune Shift as a Function of Intensity. Results for tighter collimators settings are showed, for a chromaticity of zero units.

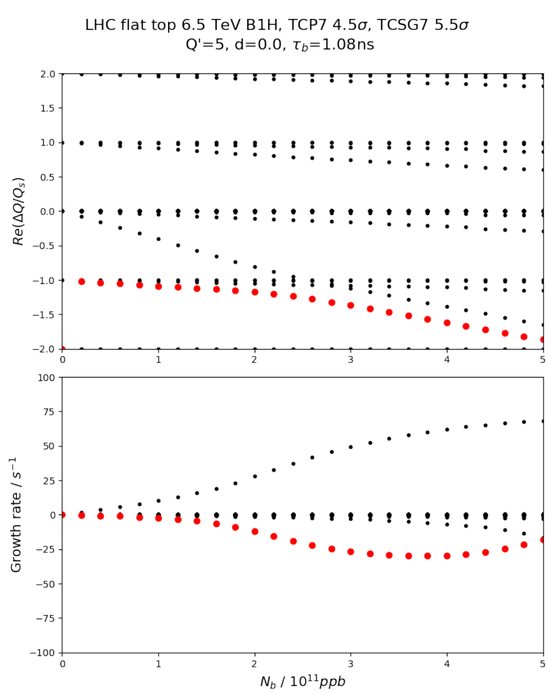

Figure 3: Complex Tune Shift as a Function of Intensity. Results for tighter collimators settings are showed. The unnormalized chromaticity is now 5 units.

with a higher beam intensity would have led to a beam dump from the interlock system. The beam parameters for the two measurements are given in Tables 2 and 3.

Table 2: Beam Parameters During the First Measurement

Parameter	**Value**
Number of bunches	3
Bunch intensities / 10^{11} p.p.b	0.6, 1.0 and 1.3
Full bunch length / ns	1.1
Normalized emittance / µm	3
Unnormalized chromaticity	5

Table 3: Beam Parameters During the Second Measurement

Parameter	**Value**
Number of bunches	2
Bunch intensities / 10^{11} p.p.b	0.9 and 1.9
Full bunch length / ns	1.1
Normalized emittance / µm	3
Unnormalized chromaticity	5

During the first measurement, selected collimators were moved closer to the beam in several steps in order to increase the machine impedance and so the tune-shift. The primary (TCP) and secondary (TCSG) collimators were the ones moved, the steps taken are reported in Tables 4 and 5 respectively for the first and second measurement. The gap settings are given in number of transverse beam size at the collimators position σ_t: the gap in mm can then be computed using Eq. 1. During the second measurement, which included a higher intensity bunch (see Table 5), the collimators were first moved out from the beam. This was done to reproduce an equivalent HL-LHC impedance [13] and so to assess the impact of the planned impedance reduction on the tune-shift [16].

Table 4: Primary and Secondary Collimators Gaps Settings During the First Measurement

Step	**TCP gap / σ_t**	**TCSG gap / σ_t**
1	5	6.5
2	5	6
3	4.5	6

At every step in the collimators position, the bunches were coherently excited multiple times with the LHC transverse damper (ADT) operated in AC-dipole mode [17]. The bunch-by-bunch and turn-by-turn position at the ADT pick-up was recorded with the ADTObsBox [18]. The data were then post-processed with PySUSSIX [19], a Python wrapper of SUSSIX [20]. The intensity of each bunch being recorded over time with the Fast Beam Current Transformer (FBCT), it is then possible to compute the tune-shift versus intensity slope, after having removed the baseline tune from the one computed for each bunch.

The measurements results are given in Table 6. Both beam and planes are reported for the different steps in the collimators gaps. Each table entry shows two values: the

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Table 5: Primary and Secondary Collimators Gaps Settings During the Second Measurement

Step	TCP gap / σ_t	TCSG gap / σ_t
1	5	14
2	5	6.

top one reports the simulated values obtained from DELPHI simulations with the LHC impedance model, the bottom one the measurement result. The reduction of the tune-shift versus intensity for larger collimators gaps (first row of Table 6) is clear, highlighting the potentially large gain in impedance from coating the collimators [16]. Measurements with nominal or tighter than nominal collimators settings (second, third and fourth rows of Table 6) show that the measured values are consistently higher than the simulated ones. The more critical situation in terms of stability margins in 2017 [10] could thus be partly explain by a higher impedance than used in the simulations.

Table 6: Measured Tune-shifts for the Two Beams and Planes. The values are given in $(10^{11}\text{p.p.b} * Q_s)^{-1}$ where Q_s is the synchrotron tune ($Q_s = 2 \cdot 10^{-3}$ in the LHC). For the measured value, the number inside the parenthesis is the uncertainty of the measurement. The first column indicates the TCP/TCSG collimators gaps for the measurement.

Gaps	B1H	B1V	B2H	B2V
5/14	-0.17 −0.20(4)	-0.12 −0.17(5)	-0.18 −0.25(4)	-0.12 −0.13(3)
5/6.5	-0.30 −0.34(3)	-0.23 −0.38(4)	-0.32 −0.37(3)	-0.24 −0.27(2)
5/6	-0.34 −0.41(5)	-0.27 −0.38(5)	-0.36 −0.39(3)	-0.27 −0.30(2)
4.5/6	- -	- -	-0.38 −0.45(4)	-0.29 −0.30(3)

As for the TMCI threshold, the measurement of the tune-shift implies that it would be lower than simulated. Figure 4 shows for the horizontal plane of Beam 1 the simulated and the measured tune-shifts as a function of intensity. From simulations with an unnormalized chromaticity of +5 units, the TMCI threshold for the nominal LHC case lies at 3.2×10^{11} p.p.b.. For the simulated HL-LHC case it lies at 6×10^{11} p.p.b.. Measurement results plotted alongside show that the TMCI intensity threshold in the nominal LHC case might be closer to 3×10^{11} p.p.b.. The HL-LHC case however shows a clear improvement and the inferred TMCI threshold is above 5×10^{11} p.p.b.. The foreseen impedance reduction for HL-LHC would therefore increase the TMCI threshold and help maintain a factor 2 safety margin in terms of single bunch intensity.

An attempt to observe a mode coupling instability was made at the end of the first measurement by reducing the collimators gaps even further. The LHC head-tail monitor [21] is used to record the intra-bunch motion if an instability is detected. In the case of a mode coupling instability, a

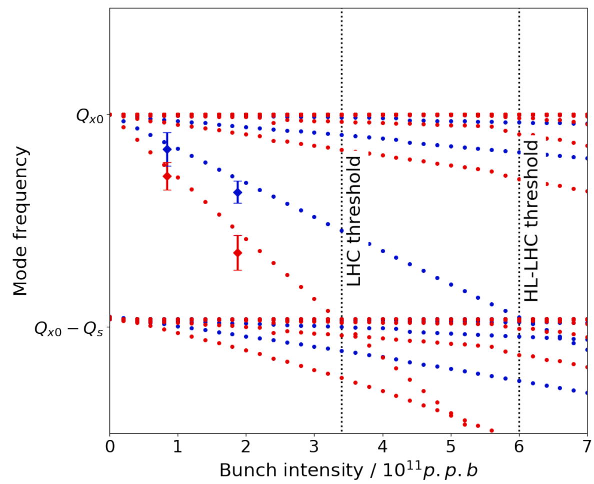

Figure 4: Measured (diamonds) and simulated (dots) tune-shifts as a function of intensity for the nominal LHC collimators settings (in red) and for the equivalent HL-LHC impedance collimators settings (in blue). The plane showed is B1H, for an unnormalized chromaticty of +5, without damper.

traveling wave pattern would be seen along the bunch, as showed in Fig. 5. However because of the slightly positive chromaticity and the lower bunch intensities in the first measurement, a classic head-tail instability was observed. This measurement with a higher intensity bunch during the second ramp could not be attempted because of a beam dump triggered by a superconducting magnet quench before the end of the measurement session.

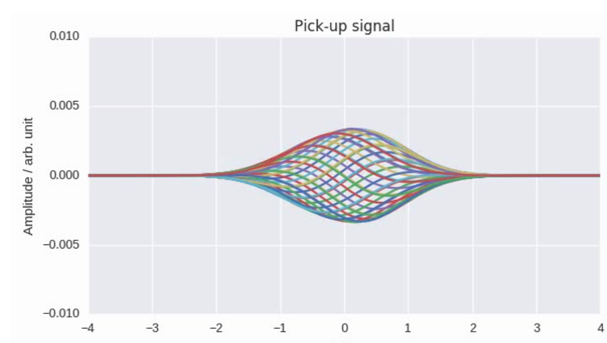

Figure 5: Intrabunch motion in the mode coupling regime, with a positive chromaticity and above transition. The signal is reconstructed from the eigenvectors output of DELPHI. The horizontal axis is the bunch length.

CONCLUSION

The Transverse Mode Coupling Instability threshold was simulated using the LHC impedance model and the Vlasov solver DELPHI. Different cases of machine impedance were assessed by varying the collimators gaps. They showed that for tight enough settings, the mode coupling instability is within the intensity reach of the LHC.

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Measurements of the tune-shift versus intensity were performed at the LHC top energy for these different collimators settings. The resulting values appear to be 10% to 20% higher than the simulations for the nominal and tight collimators settings. This could partly explain the discrepancies observed between instabilities observations and predictions during the year 2017. A measurement with larger collimators gaps was also carried out to mimic the HL-LHC impedance. A clear tune-shift reduction could be observed, highlighting the positive impact of the planned upgrade of the LHC collimation system.

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