MEASUREMENTS AND SIMULATIONS OF TRANSVERSE COUPLED-BUNCH INSTABILITY RISE TIMES IN THE LHC

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Abstract

In the current configuration of the LHC, multibunch instabilities due to the beam-coupling impedance would be in principle a critical limitation if they were not damped by the transverse feedback. For the future operation of the machine, in particular at higher bunch intensities and/or higher number of bunches, one needs to make sure the coupled-bunch instability rise times are still manageable by the feedback system. Therefore, in May 2011 experiments were performed to measure those rise times and compare them with the results obtained from the LHC impedance model and the HEADTAIL wake fields simulation code. At injection energy, agreement turns out to be very good, while a larger discrepancy appears at top energy.

INTRODUCTION

Transverse coupled-bunch instabilities [1] occur in general when several bunches interact with their surroundings, creating wake fields that act back on the bunch train in such a way as to give rise to an exponentially growing oscillation. Such instabilities can exhibit intrabunch motion, but usually for chromaticities close enough to zero, the coupled-bunch "rigid-bunch" modes are the strongest modes. Since they develop at any intensity and even for zero chromaticity, they must be damped either by Landau damping or by a transverse feedback system.

In the case of the LHC, the complex tune shifts related to these instabilities can be evaluated thanks to the machine's impedance model [2] together with the beam dynamics simulation code HEADTAIL [3], which has been recently extended to allow for simulations of many bunches [4]. The LHC impedance model presently includes the resistive-wall impedance of the 44 collimators (some being in graphite), of the copper-coated beam screens covering 86% of the ring, and of the copper vacuum pipe for the remaining 14%, together with a broad band impedance model to account for most of the smooth transitions around the ring [5].

Checking the accuracy of both the model and the simulation code against beam-based measurements is obviously highly desirable in order to gain confidence on the predictions that can be made for the future operation of the machine. To do so, a dedicated experiment was carried on on May 8th, 2011 [6] to measure transverse instability rise times of the rigid-bunch modes, as well as the loss of Landau damping threshold in terms of octupole current at top energy. We present in the following a description of the experiment, followed by the results at injection (450 GeV$/c$) and flat top (3.5 TeV$/c$) compared to simulations using HEADTAIL and the impedance model.

DESCRIPTION OF THE EXPERIMENT

The idea of the experiment was to trigger coupled-bunch instabilities and measure their rise times, at both injection energy and flat top, with nominal bunch parameters and 50 ns spaced bunches. As seen in Ref. [2], short trains are expected to give rise to instabilities only a few times weaker than those of a fully filled machine, so the measurements were performed with a quite small number of bunches: a single batch of 36 bunches spaced by 50 ns, preceded by 12 bunches (also 50 ns spaced) and a low intensity pilot bunch, as required by the injection system. Note that for such a small number of bunches and given the "scrubbing" [7] already performed in the machine at that time, the possible effect of electron cloud is thought to be negligible and has not been considered.

During normal operation, transverse coupled-bunch instabilities are prevented by a transverse feedback system; to observe them it is therefore necessary to switch the feedback off for long enough. At injection energy, this was done for both beams and for several chromaticities. At top energy, it was also necessary to reduce Landau damping by decreasing the current in the octupoles, which was done in steps. Note that the defocusing octupoles were set to a positive current and the focusing ones to its opposite.

Several data acquisition processes were triggered during the time window when the feedback was off, acquiring in particular the beam position monitors (BPM) data and those from the transverse feedback pickups (called ADT in the following). The BPMs acquire the positions of the individual bunch centroids for the last 36 bunches of the train during 1000 successive turns (i.e. 89 ms), and the ADT pickups acquire individual bunch centroid positions of the 8 last bunches of the train for 32768 turns (i.e 2.9 s). In addition, the FBCT (fast beam current transformer) gave measurements of the individual bunch intensity, and the BQM (beam quality monitor) provided the individual bunch lengths. Collimator half gaps were continuously monitored, and a few wirescan measurements were also done, to get the beams' normalized emittances along the experiment. All these measured parameters (intensity, bunch length, collimator half gaps and emittances) could vary slightly from one measurement to the next, and this was taken into account into the simulations.

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RESULTS AT INJECTION

Several instabilities were observed with the ADT during the time windows when the transverse feedback was off, for both beams and both planes. We show in Fig. 1 an example of such instabilities, in terms of the turn by turn position of the last bunch of the train measured with the ADT.

From the spectral analysis of the individual bunches, no particular tune shift trend was observed along the 8 bunches. For a given chromaticity (expressed here through the derivative of the tune with respect to the relative momentum deviation Q'), and neglecting the small differences in bunch length and bunch intensities (of at most 8%) between different measurements, we put together all the available ADT measurements showing clear instabilities. We fit them with two different methods, obtaining then the average rise time for the 8 last bunches of the train, and the standard deviation due to both the fitting and the data repetition. We compare in Figs. 2 and 3 those to the rise times obtained at the same chromaticities thanks to HEADTAIL simulations with the same parameters as in the measurements. Note that to analyse HEADTAIL simulation data, three different methods [2] were used to obtain the rise times, taking in the end the average of the three methods. The agreement between the model and the measuremetns is remarkable for chromaticities close to zero or negative, for both beams and both planes. The only significant discrepancy appears for beam 2 in vertical when $Q'_y = 2$. Note that in this latter case only one set of data and one fitting method could be used, hence the absence of error bar.

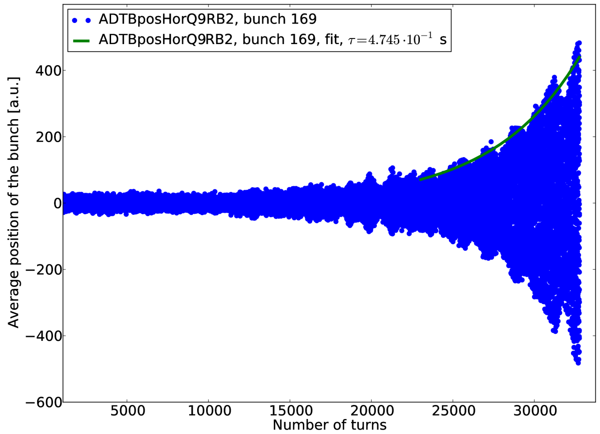

Figure 1: Horizontal signal from the ADT during an instability at injection with $Q'_x = 0.1$ (last bunch of beam 2).

In Figs. 2 and 3, the comparison between the single-bunch and coupled-bunch rise times from the simulations seems to rule out the possibility that the instabilities observed were actually single-bunch. To analyse their coupled-bunch nature, a singular value decomposition (SVD) [8, 9] was performed on the bunch centroid data (vs. bunch number and turn) given by the BPMs along the batch of 36 bunches. In Fig. 4 we show the spatial pattern of the most critical "mode" from the SVD for one of the instabilities, clearly exhibiting a coupled-bunch motion.

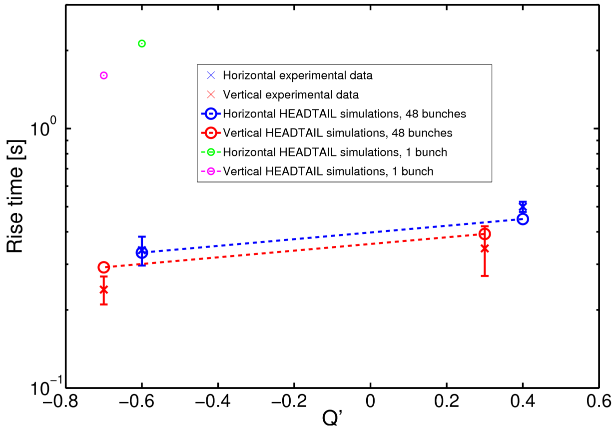

Figure 2: Beam 1 rise times vs. Q' at injection from measurements and HEADTAIL (single-bunch and multibunch).

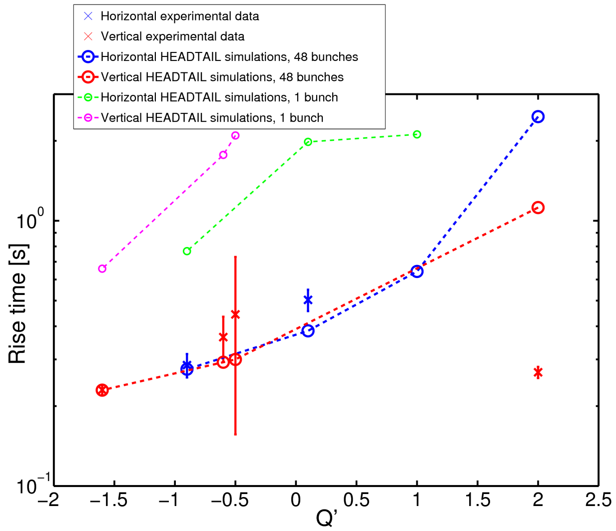

Figure 3: Beam 2 rise times vs. Q' at injection, from measurements and HEADTAIL (single-bunch and multibunch).

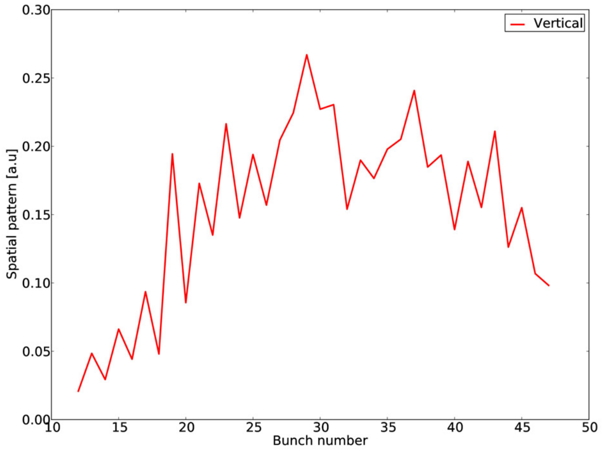

Figure 4: Vertical spatial pattern of the highest "mode" from the SVD of the BPM data, for beam 1 with $Q'_y = 0.3$, at injection.

RESULTS AT FLAT TOP

After the ramp to 3.5 TeV$/c$, decreasing the octupole currents enabled us to observe instabilities on the ADT during the time window when the feedback was off. All the instabilities observed occurred in the vertical plane. On the contrary, HEADTAIL simulations exhibit instabilities only in the horizontal plane for non zero octupole currents, which can be explained by the fact that $Q'_x = 0$ while $Q'_y \geq 1$ (the dipolar wake functions are quite similar for both planes at this energy [2]). Also, a discrepancy of factor $2-3$ between simulations and measurements is visible on the rise times of the 8 last bunches of the train, as shown in Fig. 5. Note the quite large error bars on the simulation data, indicating probably that a higher number of turns would be better to fit the data with a higher accuracy.

All the vertical rise times that could be obtained from the ADT data were collected and are shown in Figs. 6 and 7, together with HEADTAIL simulations results when the octupoles are switched off. The discrepancy between HEADTAIL and the measurements already mentioned appears clearly. On the other hand, the accuracy of the measurement of Q' at 3.5 TeV$/c$ is rather large (of the order of one unit), which could explain the discrepancies observed: if $Q'_y = 0$, these are much reduced.

Finally, measurements show that when the damper is off 60 A (resp. 70 A) in the octupoles are enough to stabilize beam 1 (resp. beam 2), which is less than foreseen in the model (resp. 120 A and 100 A). A possible explanation of the discrepancy is that some sources of non-linearity have been neglected in the simulations, in particular Q'' (second derivative of the tune with respect to the momentum deviation), which is quite high when octupoles are on. The effect of Q'' on beam stability is currently under study.

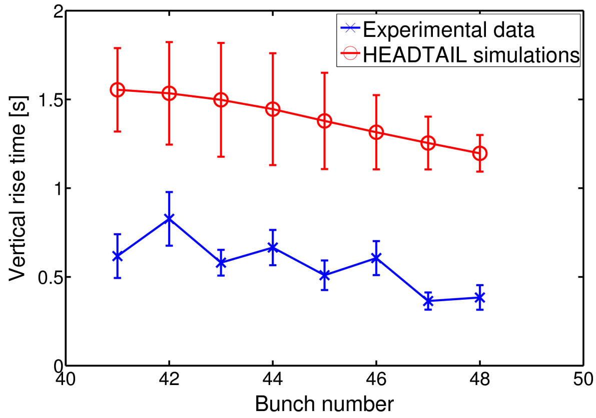

Figure 5: Vertical rise times of the last 8 bunches of beam 2 when octupoles are off at 3.5 TeV$/c$, and comparison with HEADTAIL simulations.

CONCLUSION

The measurements enabled to evaluate the LHC transverse coupled-bunch instability rise times versus chromaticity at injection energy, in good agreement with the LHC impedance model. At top energy, rise times in the vertical plane were obtained as well as the Landau damping threshold, showing a correct order of magnitude with respect to the model.

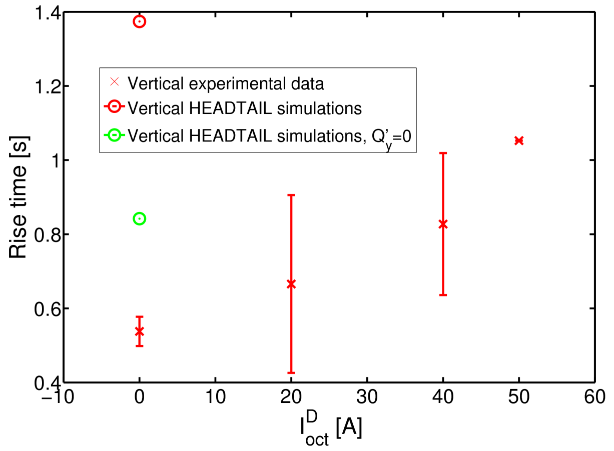

Figure 6: Measured vertical rise times vs. octupole current for beam 1 at 3.5 TeV$/c$, compared to HEADTAIL simulations, both with the measured Q'_y (≈ 2) and with $Q'_y = 0$.

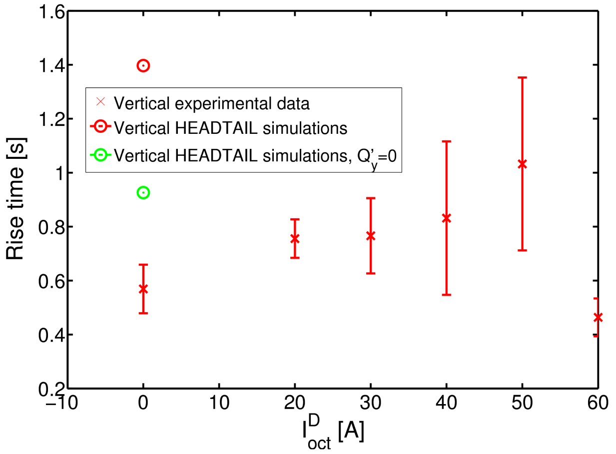

Figure 7: Measured vertical rise times vs. octupole current for beam 2 at 3.5 TeV$/c$, compared to HEADTAIL simulations, both with the measured Q'_y (≈ 1) and with $Q'_y = 0$.

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