STABILIZATION OF THE LHC SINGLE-BUNCH TRANSVERSE INSTABILITY AT HIGH-ENERGY BY LANDAU OCTUPOLES

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Abstract

When the first ramp was tried on Saturday 15/05/2010 with a single bunch of about nominal intensity (i.e. ~ 10^{11} p/b), the bunch became unstable in the horizontal plane at ~ 2 TeV. The three main observations were: (i) a "Christmas tree" in the transverse tune measurement application (with many synchrotron sidebands excited), (ii) beam losses (few tens of percents) in IR7, and (iii) an increase of the bunch length. This transverse coherent instability has been stabilized successfully with Landau octupoles. Comparing all the measurements performed during this first year of LHC commissioning with the theoretical and simulation predictions reveals a good agreement.

INTRODUCTION

A first ramp was tried with a single bunch of ~ 10^{11} p/b (on both beams B1 and B2) on Saturday 15/05/2010 without Landau octupoles. The bunch was unstable at ~ 1.8 TeV/c for B1 and ~ 2.1 TeV/c for B2, leading to beam losses of few tens of percents in the Interaction Region (IR) 7 where the protecting collimators are. It was then decided to put some current in the Landau octupoles (dedicated magnets used to provide more Landau damping and whose maximum absolute current is 550 A) during the ramp to try and reach the collision energy of 3.5 TeV/c, which worked successfully. A detailed study was performed on Monday 17/05/10 at 3.5 TeV/c to try and understand better the different mechanisms involved, which is discussed in some detail in Ref. [1].

OBSERVATIONS

The acceleration was done with an octupole current equal to I_{oct} = - 200 A at 3.5 TeV/c corresponding to an octupole strength K_3 = - 12 m^{-4}. The bunch was stable and then the octupole current was reduced by steps (see Fig. 1a). The bunch was still stable for I_{oct} = - 20 A (even if we should have waited maybe a bit more) and became unstable for I_{oct} = - 10 A, for which a rise-time of ~ 10 s (with a chromaticity Q' ~ 6 and a transverse emittance of ~ 5 µm) was measured (see Fig. 1b) together with a "Christmas tree" on the tune measurement (see Fig. 1c). Note that there were some doubts on the emittance measurement, which might have been overestimated. The stabilizing octupole current seems therefore to be between - 20 A and - 10 A. Looking at the frequency domain, Fig. 2 was obtained. It can be seen there that the mode *m* = - 1 (at - Q_s from the tune) clearly grows up alone (Q_s ~ 2 10^{-3}) and the other head-tail modes follow afterwards.

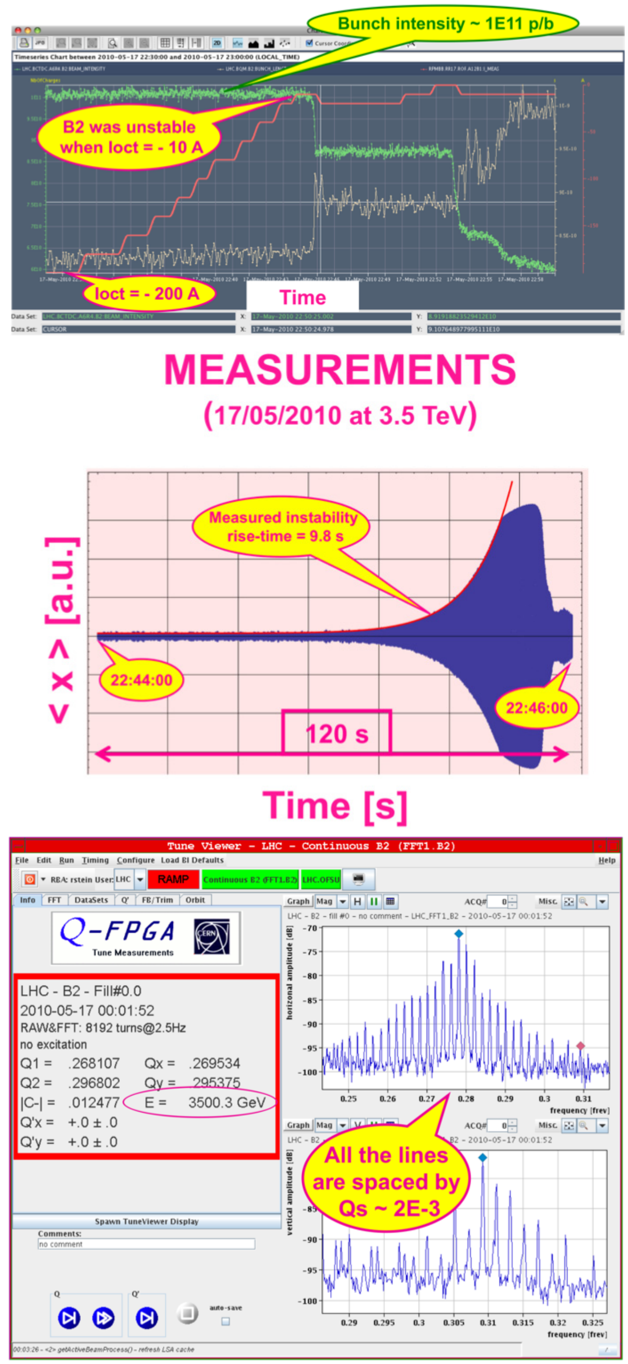


Figure 1: (a) Correlation between the octupole current which was reduced by steps, from - 200 A to - 10 A (red curve) and the bunch intensity (green curve); (b) Measured horizontal single-bunch instability and (c) "Christmas tree" observed in the tune measurement.

The instability rise-time can also be estimated from Fig. 2: the instability rise-time is given by the time needed for the amplitude of the unstable line to be increased by ~ 9 dB. We see from Fig. 2 (a and b) that it is increased by ~ 24 dB in 24 s, i.e. by ~ 9 dB in ~ 9 s. Therefore, the instability rise-time is ~ 9 s, in agreement with the ~ 10 s estimated from time-domain measurements.

Another observation during this instability was an rms bunch length increase from ~ 0.06 m to ~ 0.07 m (see circle in Fig. 3).

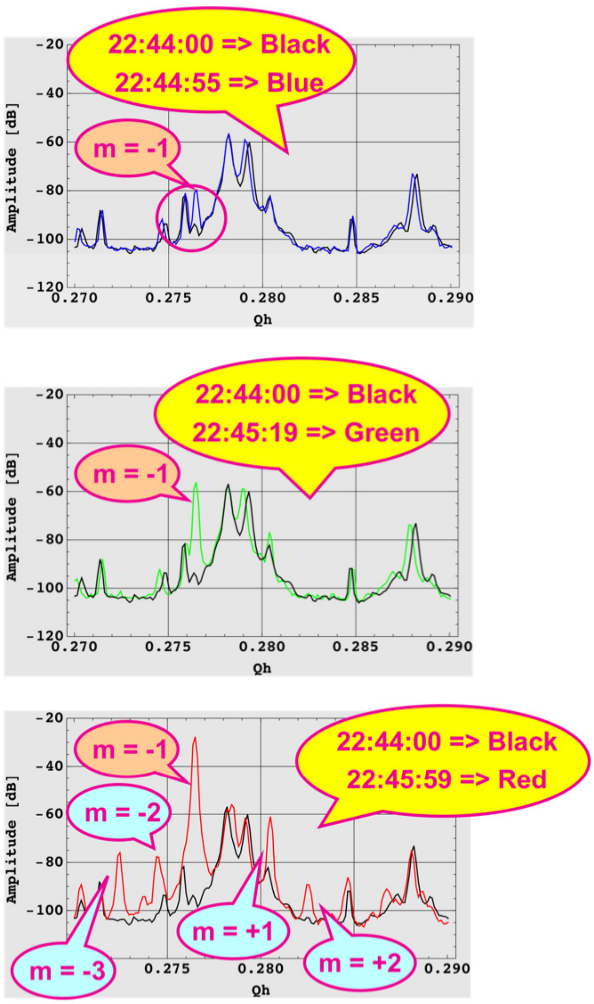


Figure 2: Frequency analysis of the data of Fig. 1b.

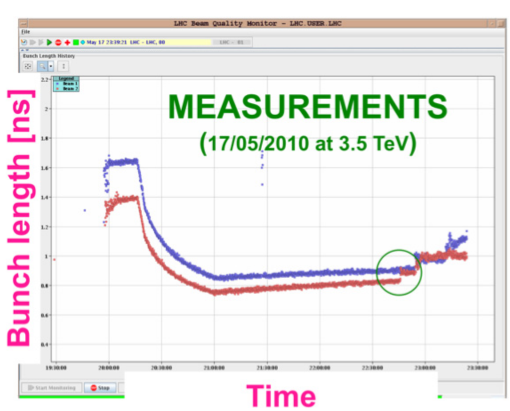


Figure 3: Bunch length increase during the instability.

HEADTAIL SIMULATIONS

HEADTAIL [2] simulations predict an unstable bunch (with Q' ~ 6 and a nominal transverse emittance of 3.75 μm) for I_{oct} > - 10 A, with a rise-time of ~ 11 s for I_{oct} = - 6 A (see Fig. 4). Therefore, a similar rise-time (of ~ 10 s) is observed in both cases: ~ - 6 A in the simulations and ~ - 10 A in the measurements (with some doubts on the measured transverse emittance, this is why the nominal emittance was used in the simulations). It is worth reminding that if the transverse emittance is two times larger the induced tune spread is two times larger. Bunch stability is obtained in the measurements for a current in the octupoles between - 20 A and - 10 A, whereas HEADTAIL simulations predict bunch stability for ~ - 10 A. Therefore, we can say that a good agreement between measurements and HEADTAIL simulations is obtained, with the current knowledge of the beam parameters.

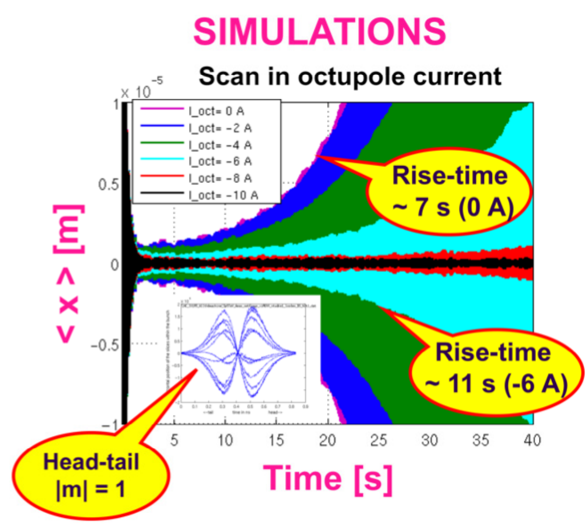


Figure 4: Simulated (with HEADTAIL) horizontal single-bunch instability for a chromaticity Q' of ~ 6 and assuming the nominal horizontal emittance of 3.75 μm.

Everything seems therefore to be consistent with a head-tail instability of mode $m = -1$. Additional simulations were performed to try check if we could reproduce the two observations linked to this instability, i.e. the "Christmas tree" and the bunch length increase. To study the "Christmas tree", HEADTAIL simulations were performed for the case of the nominal bunch at 7 TeV/c (as the instability is faster in this case due to the collimators which are closer to the beam) and it is found that the "Christmas tree" appears when the beam losses are included (see Fig. 5). The exact mechanism still needs to be understood; anyway the "Christmas tree" seems to be only a consequence and not the cause of the instability. As concerns the bunch length increase it was studied with the beam parameters of Fig. 4 without octupole current. It is seen from Fig. 6 that when beam losses start to appear (after ~ 40 s) the rms bunch length increases from ~ 0.06 m to ~ 0.09 m (compared to ~ 0.07 m measured).

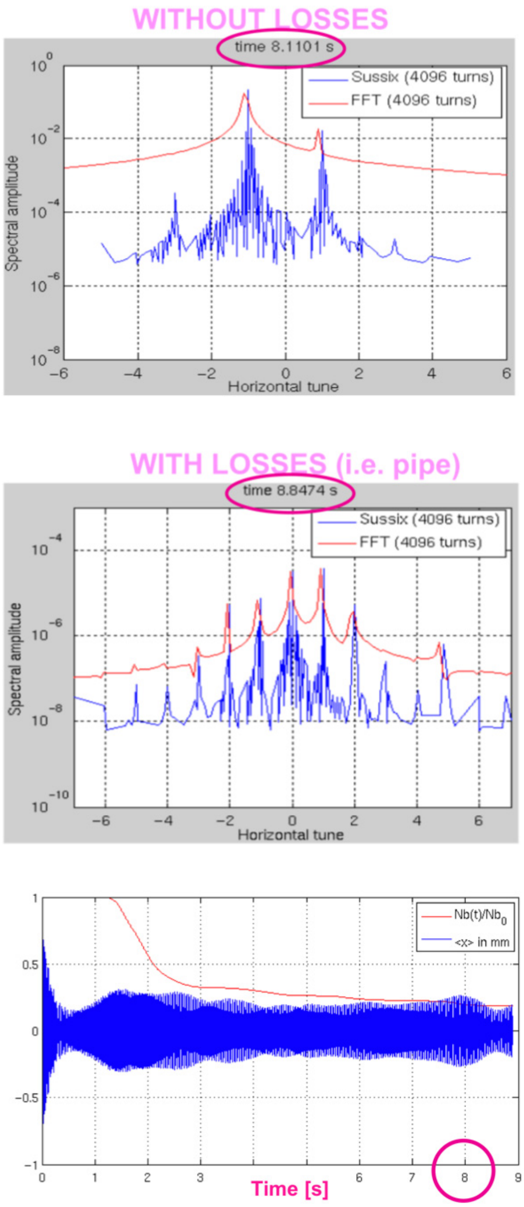
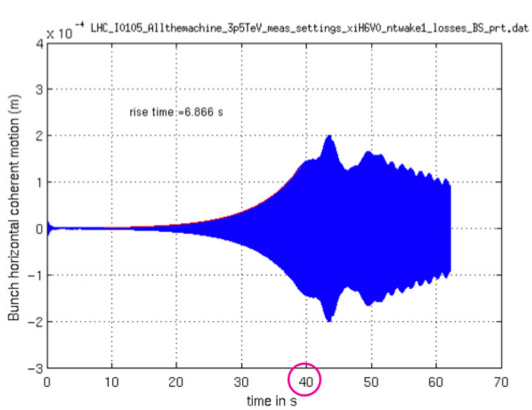
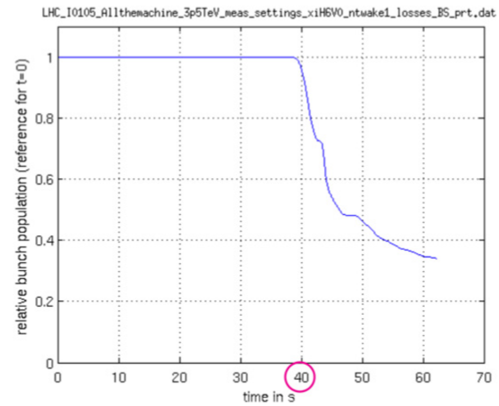


Figure 5: HEADTAIL simulations for the case of the nominal bunch at 7 TeV/c without and with beam losses (i.e. including a beam pipe's aperture in the simulations).





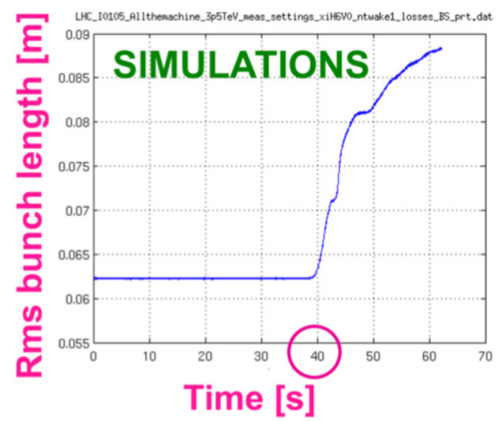


Figure 6: HEADTAIL simulations for the case of Fig. 4 without octupole current, including beam losses.

CONCLUSION

This instability was predicted in the past [1] and is therefore believed to be understood quite well: Head-Tail instability m = - 1 with a rise-time of ~ 10 s (note that it should be close to 1 s at 7 TeV with the nominal beam parameters and collimators' settings). The Christmas tree and the bunch length increase seem to be consequences of the beam losses and their exact mechanisms still need to be understood. These measurements and simulations reveal that the intrinsic nonlinearities of the LHC are not sufficient to provide Landau damping (i.e. the field quality is too good!) and external ("controlled", i.e. coming from the Landau octupoles) nonlinearities need to be introduced to stabilize the beam.

ACKNOWLEDGEMENTS

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REFERENCES

[1] E. Métral, Pushing the limits: beam, Chamonix 2011 LHC Performance Workshop, 24-28 January 2011, Chamonix, France.

[2] G. Rumolo and F. Zimmermann, Phys. Rev. ST Accel. Beams 5, 121002 (2002).