PUSHING THE LIMITS: BEAM

E. Métral (for the ABP/ICE section)

Abstract

Many collective effects were observed in 2010, first when the intensity per bunch was increased and subsequently when the number of bunches was pushed up and the bunch spacing was reduced. After a review of the LHC performance during the 2010 run, with a particular emphasis on impedances and related single-beam coherent instabilities, but mentioning also beam-beam and electron cloud issues, the potential of the LHC for 2011 will be discussed. More specifically, the maximum bunch/beam intensity and the maximum beam brightness the LHC should be able to swallow will be compared to what the injectors can provide.

INTRODUCTION

The highest LHC peak luminosity (~ 2.07 10^{32} cm^{-2}s^{-1}) was achieved on Monday 25/10/10 on the fill number 1440 with a total intensity per beam of ~ 4.35 10^{13} p and beam parameters given in Table 1 [1]. The missing factor 50 to reach the nominal peak luminosity can be explained by the missing number of bunches (~ 8) and the missing factor for the β* (~ 6), realizing that the loss by a factor 2 from the beam energy was compensated by transverse emittances which were about two times smaller than nominal.

Parameter	Achieved	Nominal	Missing factor
Bunch population [p/b]	1.15 10^{11}	1.15 10^{11}	1
Number of bunches / beam	368	2808	
Bunch spacing [ns]	150	25	
Colliding bunch pairs	348	2808	8.07
Beam energy [TeV]	3.5	7	*2*
β* [m]	3.5	0.55	6.36
Norm. trans. emittance [μm]	~ 2.1	3.75	*~ 0.56*
Full crossing angle [μrad]	200	285	
Rms bunch length [cm]	9	7.55	
Peak luminosity [cm^{-2}s^{-1}]	2.07 10^{32}	10^{34}	50

Table 1: Parameters used for the LHC maximum peak luminosity performance in 2010.

The integrated luminosity goal for 2011 is 1 fb^{-1} (even if the experiments are now asking for few fb^{-1}). Assuming the same peak luminosity as the maximum reached in 2010 (see Table 1), a total of ~ 100 operational days (see [2] where ~ 120 days are anticipated, i.e. about half of the total run length) and a Hubner (overall run) factor of 0.2 would lead to an integrated luminosity of ~ 1/3 of the 2011 goal. This means that one should aim at least at gaining a factor ~ 3 in peak luminosity, meaning that one should reach at least ~ 6 10^{32} cm^{-2}s^{-1}. To have some margin one should therefore aim for ~ 10^{33} cm^{-2}s^{-1}, which was also said in the past to be a goal for 2011. Hence, a factor 5 should be gained compared to last year.

Many collective effects were observed in 2010. The first in spring when the bunch intensity was increased to the nominal value. Accelerating a single-bunch, an horizontal single-bunch coherent instability from the machine impedance was observed and stabilized with Landau octupoles. The second collective effect appeared in summer when the number of bunches was increased and the crossing angle was scanned. First analyses revealed that the Head-On (HO) beam-beam effects alone seem to be fine, but the Long Range (LR) effects remain to be studied in detail [3]. Furthermore, when the transverse feedback was removed at top energy in the presence of many bunches (and small chromaticities, i.e. few units), the beam was lost which seems to indicate that a transverse coupled-bunch instability was stabilized by the transverse feedback, but this instability was not studied in detail yet. Finally, the third collective effect occurred in autumn when the batch spacing was reduced to 150 ns, 75 ns and finally 50 ns, which revealed some electron cloud effects (the smaller the batch spacing the more significant the electron cloud effects) [4-6]. In these conditions, which parameters can therefore be realistically used in 2011 to increase the peak luminosity by a factor 5 and reach the goals? A reduction of the β* from 3.5 m down to 2 m seems a reasonable assumption, and this value will be assumed for the rest of this paper (in fact 1.5 m is also contemplated at the moment) [7,8]. Furthermore, the energy is assumed to increase from 3.5 TeV to 4 TeV (even if the final decision will only be taken after the Chamonix2011 workshop), as the effect is rather small (14% increase in luminosity). These two effects would already increase the peak luminosity to ~ 4 10^{32} cm^{-2}s^{-1}. This means that "only" a factor ~ 2.5 remains to be gained, playing with the beam intensity and/or beam brightness, i.e. with 3 parameters: the bunch population, the number of bunches and the transverse beam emittance.

This paper is structured as follows. In Section 1, the predictions for the LHC impedances and single-beam instabilities are compared to the observations made in 2010. As the particular item of the Landau octupoles was raised on the Monday morning of the workshop, some more information are given to try and explain why the Landau octupoles had to be used already with a single nominal bunch. In Sections 2 and 3, the electron cloud and beam-beam predictions are compared to the observations made in 2010. Finally, a scenario is proposed in Section 4 to reach the goals for 2011 together with a fallback plan.

IMPEDANCES AND SINGLE-BEAM INSTABILITIES

It is worth reminding that when we discuss “the impedance of a machine”, we speak in fact of (at least) 5 impedances, which are needed to correctly describe the beam dynamics, and these 5 impedances are all complex functions of frequency: (1) the longitudinal impedance, (2) the horizontal dipolar (or driving) impedance, (3) the horizontal quadrupolar (or detuning) impedance, (4) the vertical dipolar (or driving) impedance, and (5) the vertical quadrupolar (or detuning) impedance. Nevertheless, two interesting quantities (numbers) are given by taking the imaginary part of the effective impedance (i.e. the impedance weighted by the bunch spectrum) in both longitudinal and transverse (most critical of the horizontal and vertical) planes. These numbers are referred to as the longitudinal and transverse (sum of the dipolar and quadrupolar impedances) imaginary effective impedances and the predictions were the following: ~ 0.09 Ω in the longitudinal plane at both injection and 7 TeV/c and for the transverse plane, ~ 3.5 MΩ/m at 450 GeV/c, ~ 7.5 MΩ/m at 3.5 TeV/c and ~ 30 MΩ/m at 7 TeV/c (i.e. a value larger than in the SPS, where ~ 20 MΩ/m are now obtained [9], and which comes from the numerous collimators with very small gaps [10]). First measurements in 2010 revealed that in the longitudinal plane, a value very similar to the predicted one (i.e. ~ 0.09 Ω) was measured from the loss of Landau damping leading to undamped bunch oscillations at the beginning of the run with small longitudinal emittance [11]. The imaginary part of the effective transverse impedance has been evaluated from tune shift measurements vs. intensity and revealed that it was within less than 40% compared to theoretical predictions. Furthermore, moving all the collimators of IR7 only, an even better agreement was obtained (as was already obtained in 2004 and 2006 in the SPS with a LHC collimator prototype [12]): closing all the collimators from 15 σ to 5 σ a transverse coherent tune shift of - 2.4 10^{-4} was measured while - 2.0 10^{-4} was predicted (with an about nominal bunch). The real part of the transverse effective impedance was measured through the instability rise-time of an instability studied at 3.5 TeV/c (see below) and it seems to be very close to expectations. All these measurements reveal therefore a good agreement with predictions. There was only one exception recorded so far, which concerns the TDI and the two TCLIs (all of them used only at injection): it seems that their induced tune shift is a factor ~ 2 - 2.5 larger than expected. This issue is followed up [13]. No measurements of the imaginary part of the effective transverse impedance at high energy (3.5 TeV/c) are available yet. One should try and have an estimate of it in 2011, even if no big surprise is anticipated (to be confirmed!), as it should be dominated by the collimators, for which our impedance model is the more precise. But, what could happen if the impedance is larger than expected (or if more critical beam parameters are used)? The answer is: (i) in the longitudinal plane, we could observe a loss of Landau damping leading to undamped bunch oscillations (as observed at the beginning of the run with small longitudinal emittance) [11]; (ii) in the transverse plane, this could lead to a Transverse Mode Coupling Instability (TMCI). From Fig. 1, which depicts the predicted (in 2006) real and imaginary parts of the transverse complex tune shifts (due to the machine impedance and for nominal beam parameters) at 7 TeV/c for the first head-tail modes, for both single-bunch and coupled-bunch instabilities and vs. chromaticity, it can be seen that for 0 chromaticity the single-bunch (SB) real tune shift for mode 0 is ~ - 5 10^{-4}. Assuming that the TMCI intensity threshold is reached when the tune shift of the mode 0 is ~ equal to - Q_s (the synchrotron tune, whose value is ~ 2 10^{-3} at 3.5 TeV/c), one can deduce that the intensity threshold should be a factor ~ 4 higher than nominal. This is confirmed by recent HEADTAIL simulations, as can be seen from Fig. 2, where an intensity threshold of ~ 3.5 10^{11} p/b is obtained, i.e. a factor ~ 3 higher than nominal.

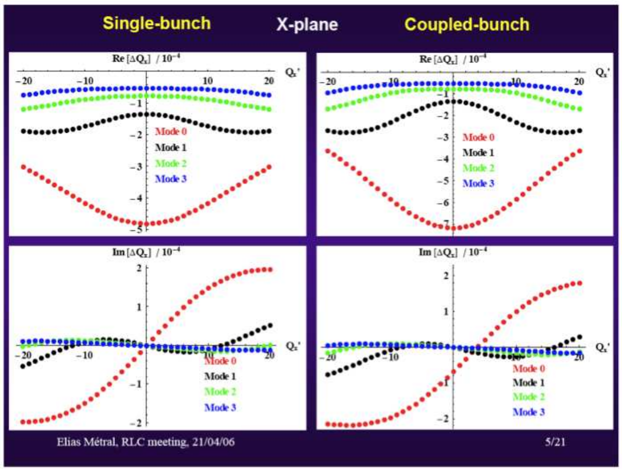


Figure 1: Predicted (in 2006) real and imaginary parts of the transverse complex tune shifts (due to the machine impedance and for nominal beam parameters) at 7 TeV/c for the first head-tail modes, for both single-bunch and coupled-bunch instabilities and vs. chromaticity (without any Landau damping mechanism).

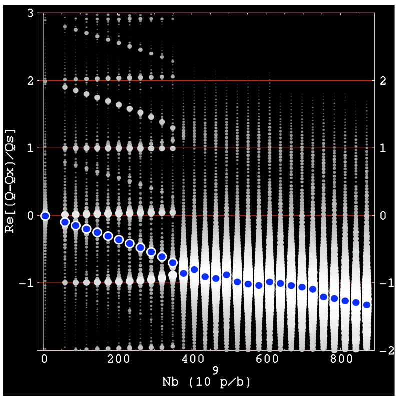


Figure 2: Horizontal modes vs. bunch intensity for 0 chromaticity and TMCI intensity threshold (when modes 0 and -1 couple).

It is worth mentioning that contrary to other machines, the TMCI is more critical at top energy than at injection energy (factor ~ 7 there) due to the fact that the transverse impedance increases with energy (collimators!). Furthermore, with many bunches the coupled-bunch (CB) TMCI intensity threshold could be lower [14], as can already be anticipated by looking at Fig. 1, where the coupled-bunch tune shift for mode 0 and 0 chromaticity is ~ - 7 10^{-4} instead of ~ - 5 10^{-4} for a single-bunch. This mechanism will be studied in detail soon, with the HEADTAIL code which was recently extended to multi-bunch operation by N. Mounet, but the intensity threshold should be higher than nominal.

However, chromaticity is never 0 in a real machine and a single bunch is always potentially unstable (for any beam parameter!) as can be seen on Fig. 3, where the single-bunch (and coupled-bunch) instability rise-times vs. chromaticity (computed in 2006) are shown for the case at 7 TeV/c (same case as the one shown in Fig. 1). A rise-time of less than 1 s is predicted (with nominal beam parameters and Q' ~ 6), with neither intrinsic nonlinearities nor Landau octupoles (i.e. without any Landau damping mechanism). The solution is to reduce the chromaticity as much as possible (but still positive, if not using a transverse feedback) and use Landau octupoles (if the "unknown" intrinsic nonlinearities are not sufficient). The latter are "unknown" and therefore this is why we could not answer (precisely) in the past to the following two questions: (1) for which bunch current do we need to put some octupoles?; (2) for which number of bunches do we need to put the transverse feedback on (related here to the coupled-bunch instability)? The "unknown" intrinsic nonlinearities depend on the machine and it is therefore also very difficult to compare between different machines. What will make the beam stable or not is: (i) the natural (uncontrolled) lattice nonlinearities; (ii) the fact that the bunch is kept in the machine for a time with is shorter than ~ the instability rise-time; (iii) external (controlled) nonlinearities through (Landau) octupoles to provide Landau damping; (iv) other spreads could help: internal (i.e. from space charge, nonlinear synchrotron motion, etc.), from impedances etc; (v) linear coupling between the transverse planes (as e.g. in the PS where this method replaced the octupoles). Examples of head-tail instabilities are shown in Fig. 4, where several superimposed consecutive traces are depicted to reveal the (absolute value of the) head-tail mode number equal to the number of nodes: mode 0 in the PSB in ~ 1974 and mode 6 in the PS in 1999. A simple visualization of the Landau damping mechanism is shown on Fig. 5, explaining why above a certain "unknown" (at least before detailed studies) intensity, Landau octupoles are needed to keep the transverse coherent (i.e. of the whole bunch) tune inside the incoherent (i.e. of the individual particles) tune spread to absorb (incoherently) the energy and stabilize the beam through Landau damping. It is said in the LHC Design report [15, pages 103 and 104] that the higher order head-tail modes have to be stabilized by Landau damping or (slightly) negative chromaticity and that all the single-bunch head-tail modes at injection should be Landau damped by the lattice nonlinearities (space charge can also help under some conditions). The fact that at higher energy the situation is more critical is due to the fact that the lattice nonlinearities are smaller (the beam size is smaller) and the space charge tune spread reduces. For the nominal bunch intensity, the bunch will become unstable (without Landau octupoles) at the energy where the incoherent tune spread will become ~ smaller than the transverse coherent tune shift. Detailed analyses will continue on this subject in 2011.

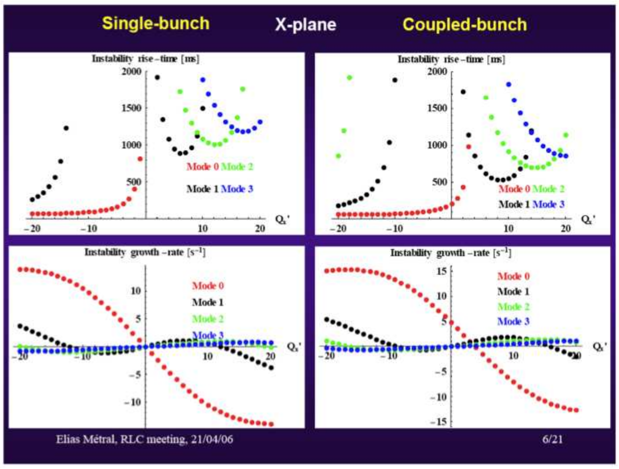


Figure 3: Predicted (in 2006) instability rise-times and growth rates corresponding to the case of Fig. 1.

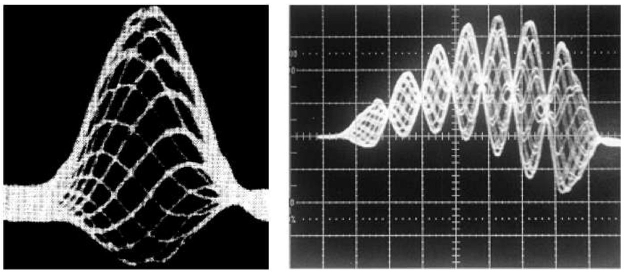


Figure 4: Example of head-tail modes: (left) in the PSB in ~ 1974 by Gareyte and Sacherer; (right) in the PS in 1999.

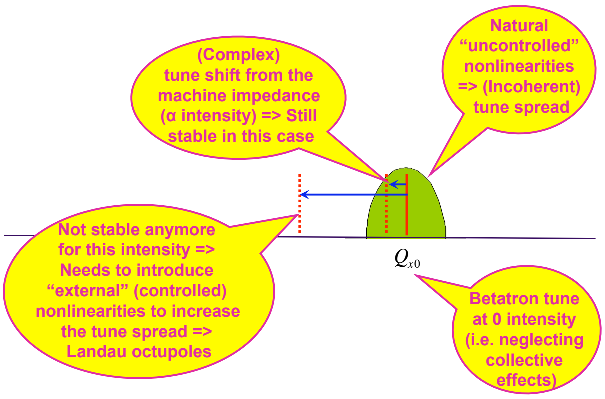
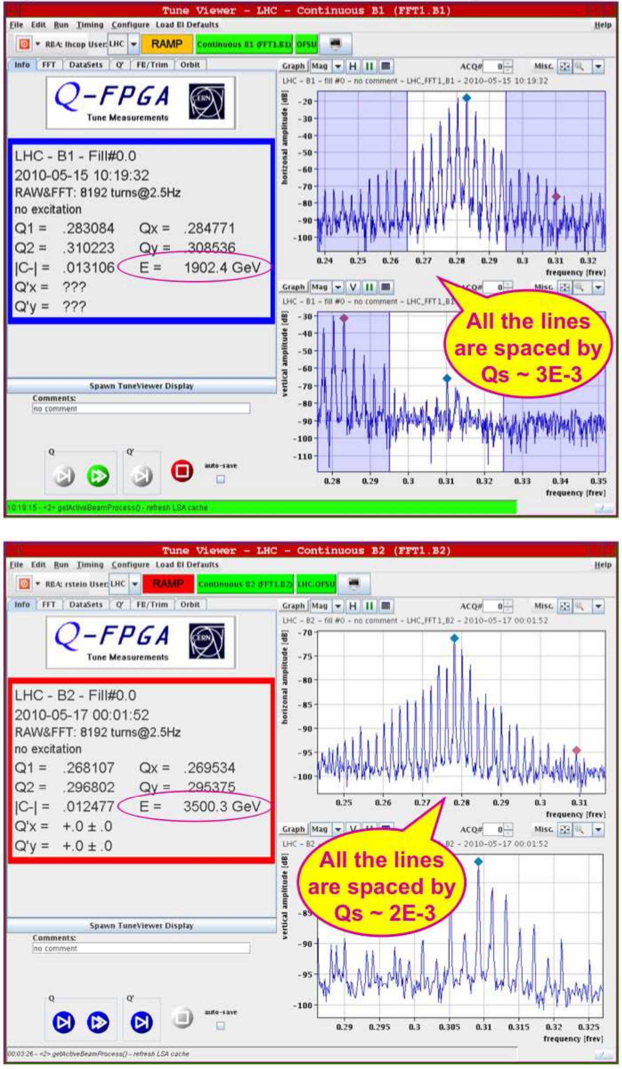

(Complex) tune shift from the machine impedance (α intensity) => Still stable in this case
Natural "uncontrolled" nonlinearities => (Incoherent) tune spread
Not stable anymore for this intensity => Needs to introduce "external" (controlled) nonlinearities to increase the tune spread => Landau octupoles
Q_{x0}
Betatron tune at 0 intensity (i.e. neglecting collective effects)

Figure 5: Visualization of the transverse Landau damping mechanism.

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. This led to the famous "Christmas tree" (see Fig. 6) together with beam losses in IR7: can we explain it?



LHC - B1 - Fill#0.0
2010-05-15 10:19:32
RAW&FFT: 8192 turns@2.5Hz
no excitation
Q1 = .283084 Qx = .284771
Q2 = .310223 Qy = .308536
|C-| = .013106 E = 1902.4 GeV
Q'x = ???
Q'y = ???

LHC - B2 - Fill#0.0
2010-05-17 00:01:52
RAW&FFT: 8192 turns@2.5Hz
no excitation
Q1 = .268107 Qx = .269534
Q2 = .296802 Qy = .295375
|C-| = .012477 E = 3500.3 GeV
Q'x = +.0 ± .0
Q'y = +.0 ± .0

Tune Viewer - LHC - Continuous B1 (FFT1.B1)
Tune Viewer - LHC - Continuous B2 (FFT1.B2)
Q-FPGA
Tune Measurements
RAMP
Spawn TuneViewer Display
Comments:
no comment
horizontal amplitude [dB]
vertical amplitude [dB]
frequency [frev]
All the lines are spaced by Qs ~ 3E-3
All the lines are spaced by Qs ~ 2E-3

Figure 6: "Christmas tree" observed on 15/05/2010 at 1.9 TeV/c (upper) and on 17/05/2010 at 3.5 TeV/c (lower).

A detailed study was performed on Monday 17/05/10 at 3.5 TeV/c (the acceleration was done with some octupole current equal to - 200 A at 3.5 TeV/c corresponding to a K_3 = - 12 m^{-4}). The bunch was stable and then the octupole current was reduced by steps (see Fig. 7). The bunch was still stable for I_{oct} = - 20 A (may be we could redo this measurement by waiting longer) and became unstable for I_{oct} = - 10 A, for which a rise-time of ~ 10 s (with Q' ~ 6 and a transverse emittance of ~ 5 μm, but there are some doubts on this measurement) was measured (see Fig. 8, upper). The stabilizing octupole current seems therefore to be between - 20 A and - 10 A.

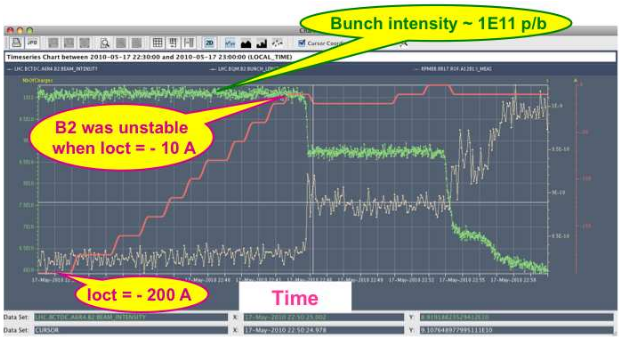
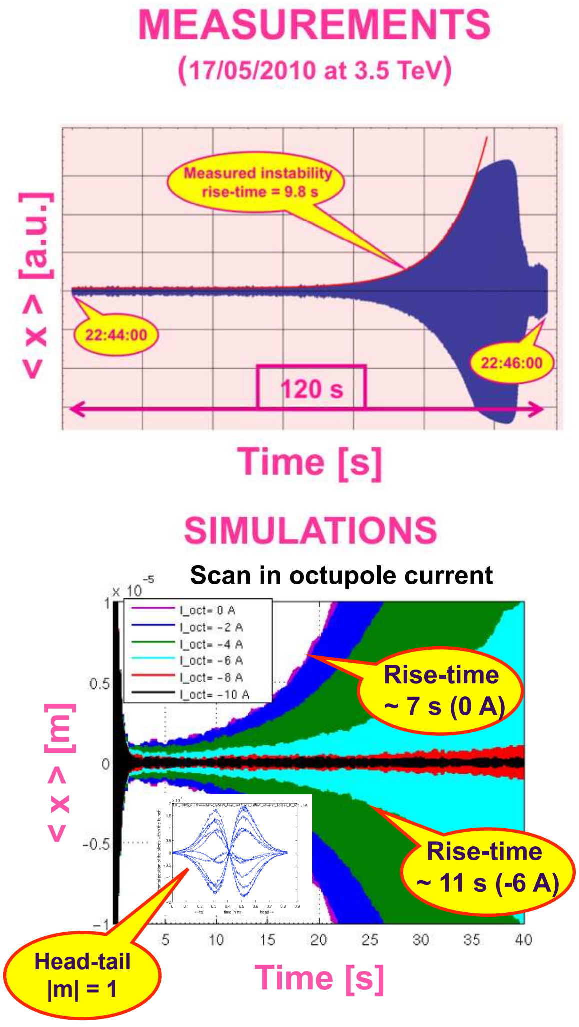


Figure 7: Correlation between the octupole current which was reduced by steps, from - 200 A to - 10 A (red curve) and the bunch intensity (green curve).



MEASUREMENTS

(17/05/2010 at 3.5 TeV)

SIMULATIONS

Scan in octupole current

Figure 8: (Upper) Measured horizontal single-bunch instability for a current in the octupoles of - 10 A for a chromaticity Q' of ~ 6 and an emittance of ~ 5 μm (however there are some doubts about this value as the transverse emittances were overestimated at the beginning of the 2010 run. To be checked…). (Lower) Corresponding HEADTAIL simulations assuming the nominal horizontal emittance of 3.75 μm.

HEADTAIL simulations (see Fig. 8, lower) 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. Therefore, a similar rise-time (of ~ 10 s) is observed in both cases, for $I_{oct} = - 6$ A in the simulations and for $I_{oct} = - 10$ A in the measurements (here again with some doubts on the transverse emittance value). Furthermore, 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. Looking at the frequency domain, Fig. 9 was measured. 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. Note that the instability rise-time can also be estimated from these pictures in the frequency domain [16]: 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. 9 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, as found in the time domain (see Fig. 8, upper).

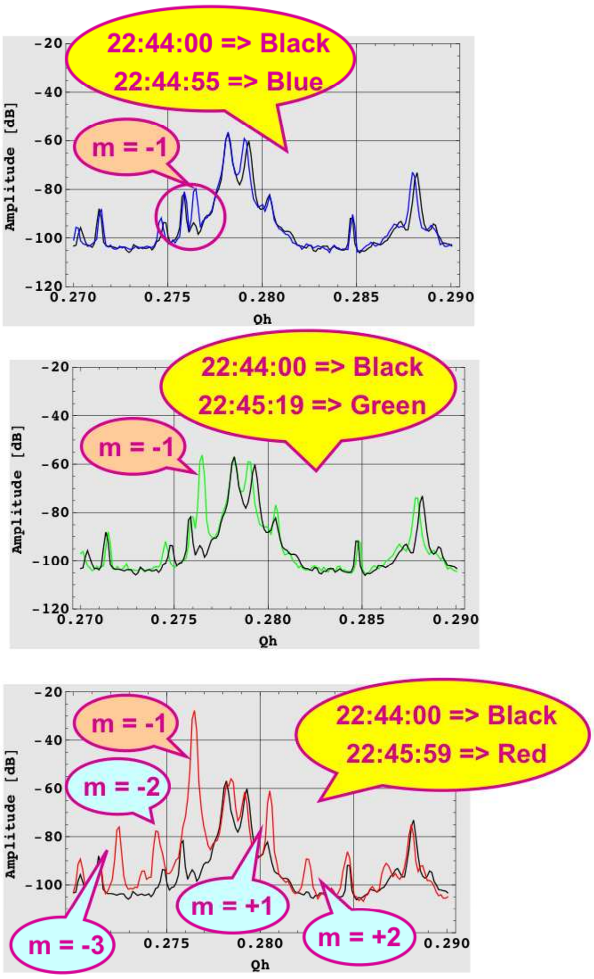


Figure 9: Frequency analysis of the measured Fig. 8.

Everything seems therefore to be consistent with a head-tail instability of mode m = - 1. HEADTAIL simulations were nevertheless performed to try and see if we could reproduce two observations linked to this instability: (i) the famous "Christmas tree" (see Fig. 6) and (ii) a 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 there…) and it is found that the "Christmas tree" appears when the beam losses are included (see Fig. 10). The exact mechanism still needs to be understood to have a full understanding but it is only a consequence and not the cause of the instability.

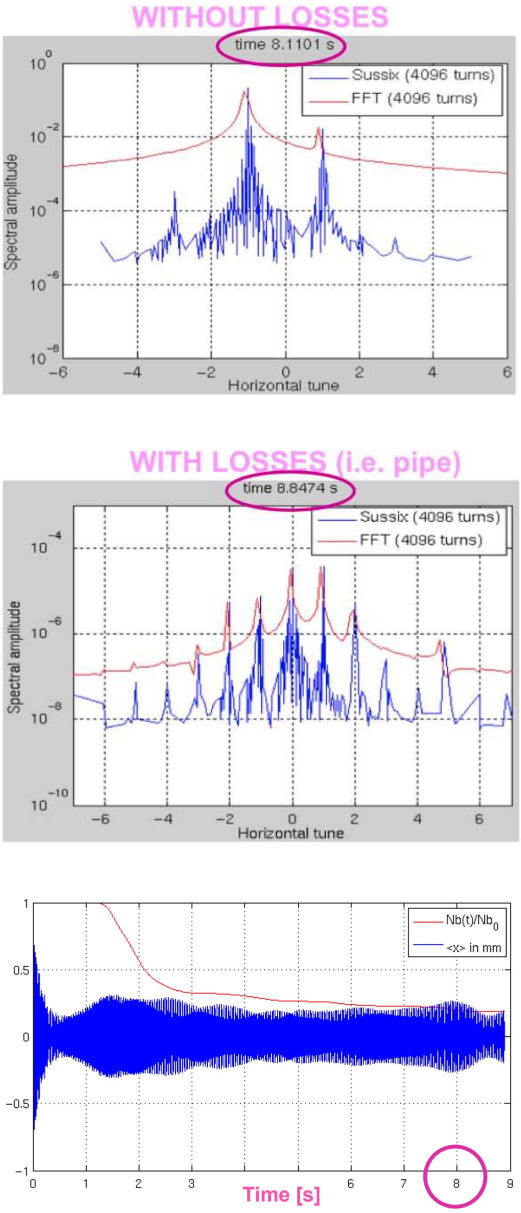


Figure 10: HEADTAIL simulations for the case of the nominal bunch at 7 TeV/c without and with beam losses (i.e. including the beam pipe in the simulations).

The bunch length increase appearing during the instability was studied with the bunch parameters of Fig. 8 (lower) without octupole current (see Fig. 11). It is seen that when beam losses start to appear (after ~ 40 s of simulation) the rms bunch length increases from ~ 0.06 m to ~ 0.09 m. In the measurements, the rms bunch length increased from ~ 0.06 m to ~ 0.07 m (see Fig. 12). Therefore, a similar behavior is observed. The exact mechanism still needs to be understood to have a full understanding but it is, again, only a consequence and not the cause of the instability.

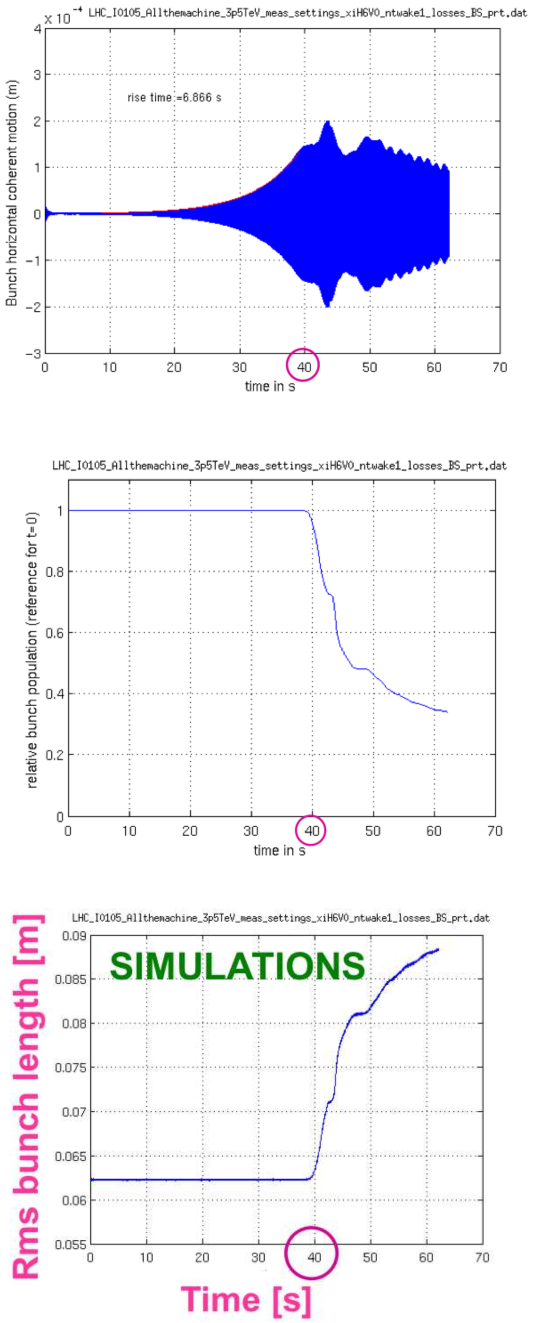


Figure 11: HEADTAIL simulations for the case of Fig. 8 (lower) without octupole current including beam losses (i.e. with a beam pipe).

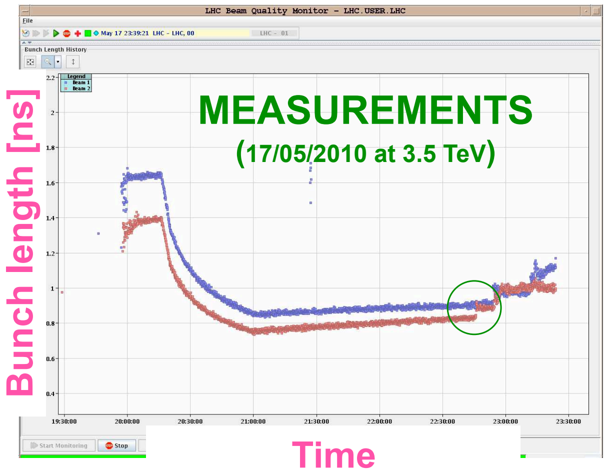
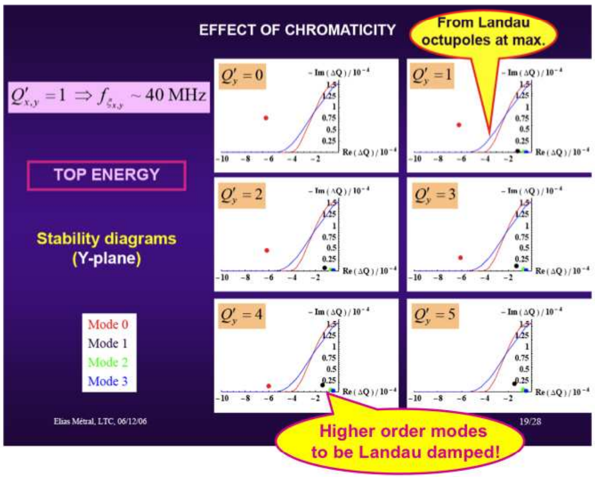

LHC Beam Quality Monitor - LHC.USER.LHC
File
Bunch Length History
Legend
Beam 1
Beam 2
MEASUREMENTS
(17/05/2010 at 3.5 TeV)
Bunch length [ns]
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
19:30:00
20:00:00
20:30:00
21:00:00
21:30:00
22:00:00
22:30:00
23:00:00
23:30:00
Start Monitoring
Stop
Time

Figure 12: Measurements of bunch length increase during the instability studies performed on Monday 17/05/10.

In summary, we “believe” we understand this instability because it was predicted: Head-Tail instability m = - 1 with a rise-time of ~ 10 s (note that it should be close to 1 s at 7 TeV). The Christmas tree and the bunch length increase seem to be consequences of the beam loss: the exact mechanisms still need to be understood to have a full understanding but they are not essential as they are consequences of the instability and not causes. 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. It is worth mentioning at this point that transverse coupled-bunch instabilities are also predicted in the absence of Landau damping and transverse feedback. The transverse feedback should be able to damp the mode 0. However, (as already mentioned above), the higher order head-tail modes have to be Landau damped by natural nonlinearities or Landau octupoles, otherwise the beam will be unstable (see Fig. 13).


EFFECT OF CHROMATICITY

From Landau octupoles at max.

$Q'_{x,y} = 1 \Rightarrow f_{\xi_{x,y}} \sim 40$ MHz

TOP ENERGY

Stability diagrams (Y-plane)

Mode 0
Mode 1
Mode 2
Mode 3

Elias Métral, LTC, 06/12/06

19/28

Higher order modes to be Landau damped!

Figure 13: Apparition of higher order head-tail modes for the transverse coupled-bunch instability when chromaticity is increased (computation in 2006).

ELECTRON CLOUD

Electron cloud effects were expected in the LHC but the 2010 observations came may be earlier than anticipated because most of the time a Secondary Emission Yield (SEY) smaller than 1.7 was considered. The legitimate question to ask would then be: why did we make our electron cloud estimates for SEY between 1.1 and 1.7, as (i) for unbaked copper tube, ~ 2 < SEY < ~ 2.5 (see Fig. 14) and (ii) using ~ 2 < SEY < ~ 2.5, the electron cloud team can reproduce some of the observations [17]? As already mentioned at the beginning of the workshop [5], a huge simulation campaign has restarted. Our best estimate for the moment is an initial SEY between 2 and 2.5 (which would be compatible with an unbaked copper tube) to explain the 2010 measurements, but many other parameters play also an important role (more news soon…).

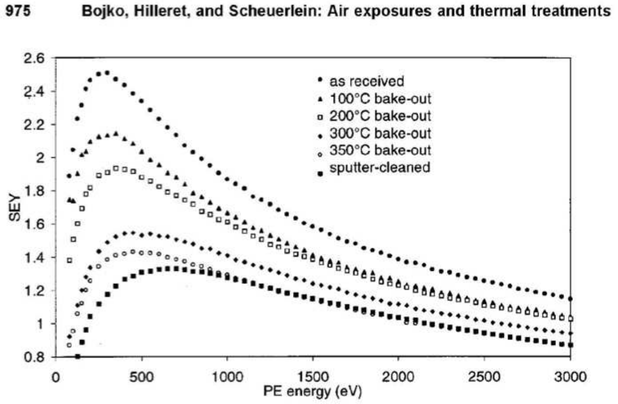


Figure 14: Influence of 24 h bakeouts at various temperatures on the SEY of technical copper [18].

It is worth mentioning that the LHC design has adopted a fourfold strategy for suppressing the formation of an electron cloud [15, page 116]: (i) NEG coating in the warm sections (i.e. ~ 10% of the total circumference) to have a SEY of ~ 1.1; (ii) sawtooth surface in the arcs to reduce the forward reflectivity from ~ 80% to 2%; (iii) the pumping slots in the beam screen are shielded by baffles to avoid, in dipoles, a direct electron path along the magnetic lines between the beam region and the cold bore; (iv) scrubbing (i.e. surface conditioning) to reduce the SEY.

For the predicted coherent and incoherent effects, the 2010 observations and for the scrubbing run proposal in 2011, see Refs. [5] and [6], which were devoted to these subjects.

BEAM-BEAM

Many predictions were made in the past (see for instance Refs. [3] and [15, page 117]. Did we have some surprises in 2010? The answer is no: the good results obtained with a HO tune shift about 2 times larger than nominal can be explained by smaller lattice nonlinearities than expected (as confirmed also from the observed single-bunch instability from the machine impedance). In Ref. [3], it is mentioned that a typical tune shift per collision of 0.006 to 0.007 imposed no lifetime problems in the SPS (with p-pbar operation) and that similar numbers are reported from the Tevatron. Therefore, it should be expected that similar values can be reached in the LHC. It is worth reminding that the nominal HO tune shift was derived from the SPS experience, taking into account possible contributions from the lattice nonlinearities and significant LR contributions. The nominal value of the beam-beam parameter $\xi = 0.0037$ was defined to provide a coherent set of parameters to reach the target luminosity of 10^{34} cm^{-2}s^{-1}. It should be considered as conservative and not as an expected upper limit, in particular in the absence of strong LR interactions. In the presence of strong LR interactions, the situation is more involved as the tune footprint (i.e. the area occupied in the tune diagram by all the particles due to the nonlinear beam-beam force) is much bigger (see Fig. 15) and there are thus more possibilities of interaction with lattice resonances and subsequent beam lifetime problems [3].

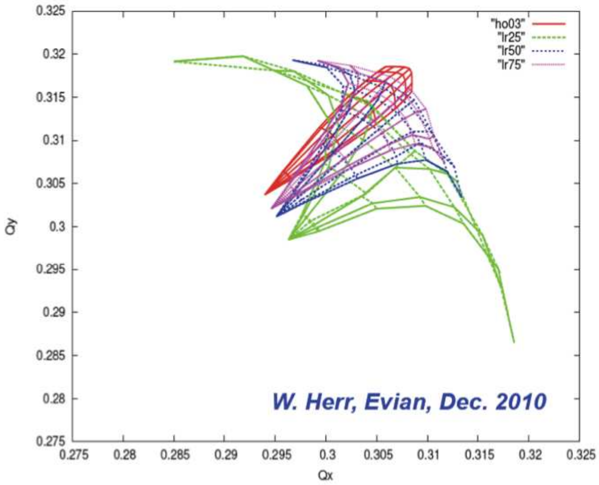


Figure 15: Beam-beam tune footprints (for HO collisions only and both HO and LR) for different bunch spacings at 3.5 TeV/c and β* = 3.5 m.

The optimization strategy for 2011 depends on the first beam-beam limit which will be reached, i.e. HO or LR. The HO tune shift is proportional to the beam brightness, i.e. the intensity to emittance ratio, and is independent of β* and the energy as can be seen from Eq. (1), while the LR tune shift depends on β*, the crossing angle and energy, as can be seen from Eq. (2)

$$\Delta Q_{\mathrm{HO}} \propto \frac{N_b}{\varepsilon_n}, \qquad (1)$$

$$\Delta Q_{\mathrm{LR}} \propto \frac{N_b}{d_{sep}^2} = \frac{N_b\,\varepsilon_n}{\alpha^2\,\beta^*\,\gamma}, \qquad (2)$$

where N_b is the number of protons per bunch, ε_n the normalized transverse emittance, α the crossing angle and γ the relativistic mass factor. If the HO interaction is the beam-beam limit, it is therefore advantageous to increase the bunch intensity together with the transverse emittance since this would keep the HO tune shift unaffected, but increases the luminosity proportionally to the intensity. The luminosity is further increased by a reduction of β*, without affecting the beam-beam parameter ξ. The situation is very different for the contribution of LR interactions where the tune shift is still proportional to the bunch intensity but is inversely proportional to the square of the beam separation d_{sep} (see Eq. (2)). This means that any change of β* or the energy requires to adjust the crossing angle to keep the LR tune shift constant.

PROPOSED SCENARIOS FOR 2011

As already discussed in Introduction, a factor 5 needs to be gained in 2011 to reach the goal luminosity of 10^{33} cm^{-2}s^{-1}. Assuming a beam energy of 4 TeV (instead of 3.5 in 2010, even if the final decision will only be taken after the Chamonix2011 workshop), as the effect is rather small (14% increase in luminosity), a β* of 2 m (whereas 1.5 m is even currently discussed), leads already to a gain of a factor 2 (~ 4 10^{32} cm^{-2}s^{-1}). A factor ~ 2.5 remains to be gained, playing with the beam intensity and/or beam brightness. Figure 16 shows the link between the number of bunches, the intensity per bunch and the transverse normalized emittance to reach 10^{33} cm^{-2}s^{-1}, together with what the SPS can provide [1,19,20]. Based on Fig. 16 and on the 2010 experience, the proposed scenario (plan A) and the fallback solution (plan B) are given in Table 2. The idea is essentially to multiply the number of bunches by ~ 3 (after the re-commissioning, scrubbing run etc., i.e. in production mode).

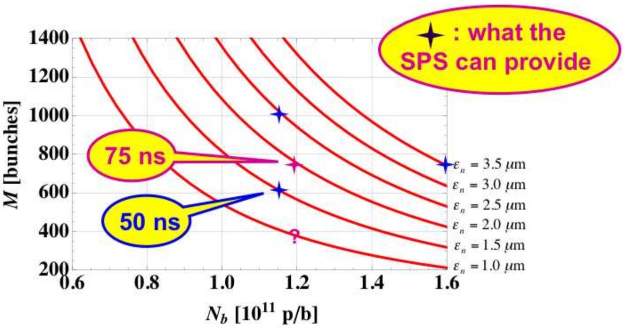


Figure 16: Relation between the bunch population, the number of bunches and the transverse normalized beam emittance to reach a peak luminosity of 10^{33} cm^{-2}s^{-1}, assuming a beam energy of 4 TeV and a β* of 2 m. The blue star is used for the 50 ns beam while the red one is for the 75 ns beam.

Parameter	PLAN A	PLAN B
Bunch population [p/b]	1.15e11	1.15e11
Number of bunches / beam		936 (max)
Bunch spacing [ns]	50 ns	75 ns
Colliding bunch pairs	1000 (max = 1404)	936 (max)
Beam energy [TeV]	4	4
β* [m]	2	2
Norm. trans. emittance [μm]	2.3	2.2
Full crossing angle [μrad]	285	285
Rms bunch length [cm]	9	9

Table 2: Proposed scenarios for 2011: Plan A is more challenging but it has more potential and 108 bunches were already accelerated in 2010; Plan B is less challenging (824 bunches were already injected in 2010) but it has also less potential.

SUMMARY AND OUTLOOK

The small lattice nonlinearities have one “detrimental” and one beneficial effect: (i) Landau octupoles are needed to stabilize the single-bunch instability from the transverse impedance; (ii) the HO tune shift can be ~ 2 times larger than nominal (without strong LR interactions). All the observations made so far are in good agreement with predictions and more detailed measurements will be done in 2011 to try and fully understand the single-bunch instability observed around ~ 2 TeV without Landau octupoles (i.e. the effect of the smaller transverse beam size, smaller lattice nonlinearities, smaller space charge tune spread, etc.). Nevertheless, most of it seems to be already understood and recommendations were already given in Ref. [1], in particular for the use of chromaticity. The next steps should consist in: (i) trying to fully understand the single-bunch instability, i.e. why (quantitatively, see above) it develops around 2 TeV; (ii) measuring the transverse coherent tune shift at 3.5 TeV/c to try and estimate the TMCI intensity threshold (the prediction for the single-bunch TMCI is around 3.5 10^{11} p/b); (iii) measuring the coupled-bunch complex tune shifts at both injection and top energy without transverse feedback; (iv) identifying the beam-beam limits which are very important for the LHC performance and which are vital ingredients for the LHC upgrade studies.

The electron cloud observations in 2010 are certainly due to ~ 2 < SEY < ~ 2.5, whereas 1.7 was usually the maximum value studied in the past. A huge simulation campaign has restarted and our best estimate for the moment is an initial SEY between 2 and 2.5 (which would be compatible with an unbaked copper tube) to explain the 2010 measurements, but many other parameters play also an important role (more news soon…). Detailed studies should be performed during the 2011 LHC scrubbing run.

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