LHC BEAM PARAMETERS: PUSHING THE ENVELOPE?

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Abstract

The goal for 2011 is to deliver an integrated luminosity of one inverse femtobarn to the experiments. This will require to gain an order of magnitude in peak luminosity, i.e. run with values of more than 10^{33} $cm^{-2}s^{-1}$, whereas a maximum of ~ 2.07 10^{32} $cm^{-2}s^{-1}$ was achieved so far. Many collective effects were observed this year, first when the intensity per bunch was increased and subsequently when the number of bunches was pushed up and the bunch spacing was reduced. A critical review will be made to examine which parameters can be realistically used to increase the luminosity, analysing the risks and the consequences. A scenario is proposed as well as a back-up solution.

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. 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}. Assuming the same peak luminosity as the maximum reached in 2010 (see Table 1), a total of ~ 100 operational days (see [1] 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 [2]. 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) [3]. 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) [4]. 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.

EXECUTIVE SUMMARY

Potential from the injectors (SPS)

All the possibilities are shown in Fig. 1, where the potential from the SPS injector is also mentioned. Several combinations should therefore be possible, neglecting for the moment the collective effects and the induced beam quality degradation. Note that with the current status of the injectors it is not possible to reach 10^{33} $cm^{-2}s^{-1}$ using the 150 ns beam, which was used last year, because of the limited maximum intensity per bunch which can be delivered from the PS at the moment. With the maximum possible number of bunches (i.e. 468 bunches) and assuming a transverse emittance of ~ 2.5 µm (in collision), a bunch intensity of ~ 1.7 10^{11} p/b would be needed, whereas the current limit with the 150 ns beam is ~ 1.1 10^{11} p/b [5]. The intensity limit comes from a longitudinal coupled-bunch quadrupolar instability due to the high-frequency 40 and 80 MHz RF cavities. The reason why it went so well this year (according to the PS RF experts) is because the LHC asked for batches of only 8 bunches (and not 12) and because the LHC never asked for more than ~ 1.1-1.2 10^{11} p/b. In fact increasing the intensity to more than ~ 1.1 10^{11} p/b could work (even if the beam is unstable at the PS) but then some satellites might be created: it would then be up to the SPS and LHC to say if these satellites are fine or not. As concerns the 75 ns and 50 ns beams the potential from the injectors is summarized in Table 2.

75 ns	N_b [10^{11} p/b]	ε_n [µm]	L [10^{33} cm^{-2} s^{-1}]
1-batch	1.2	2	1.2
2-batch (to be studied)	1.2?	1?	2.3?
50 ns	N_b [10^{11} p/b]	ε_n [µm]	L [10^{33} cm^{-2} s^{-1}]
1-batch	1.15	2.5	1.4
1-batch	1.6	3.5	1.9
2-batch	1.15	1.5	2.2

Table 2: Potential from the injectors (SPS). In both cases, from 1 to 4 batches (of up to 36 bunches for the 50 ns beam and 24 bunches for the 75 ns beam) can be sent. For the 75 ns beam, the bunch intensity it limited to ~ 1.2 10^{11} p/b due to another longitudinal coupled-bunch instability on the PS flat top. The PS RF colleagues have some ideas for next year, but they still have to make the detailed studies [5].

Current constraints from the LHC

The impedance effects should be under control as first measurements revealed that they are very close to predictions (see next Section): (i) in the longitudinal plane, the loss of Landau damping can be avoided using a sufficiently large (closer to nominal) longitudinal emittance; (ii) Landau octupoles are needed to stabilize the transverse single-bunch instability (and higher order head-tail modes) and the transverse feedback is needed to damp the transverse coupled-bunch instability with small chromaticity (i.e. few units), otherwise some higher head-tail modes might develop which cannot be damped by the transverse feedback due to the bandwidth limitation.

As concerns beam-beam effects, which have been discussed in detail in Ref. [2], it seems that the HO tune shift (alone, i.e. without LR effects) can be larger than the nominal value by a factor more than ~ 2, meaning that we could increase the bunch brightness (i.e. intensity to emittance ratio) by a factor ~ 2, compared to the nominal situation (see Table 1). It is also worth reminding that we have more flexibility with the 50 ns beam than with the 75 ns beam as concerns the luminosity delivery to all the experiments. Finally, small transverse emittances are better for the LR effects (taking into account the aperture and the crossing angle).

As concerns electron cloud effects, which have been discussed in detail in Ref. [3], the 75 ns beam is safer for the production mode (824 bunches were already injected

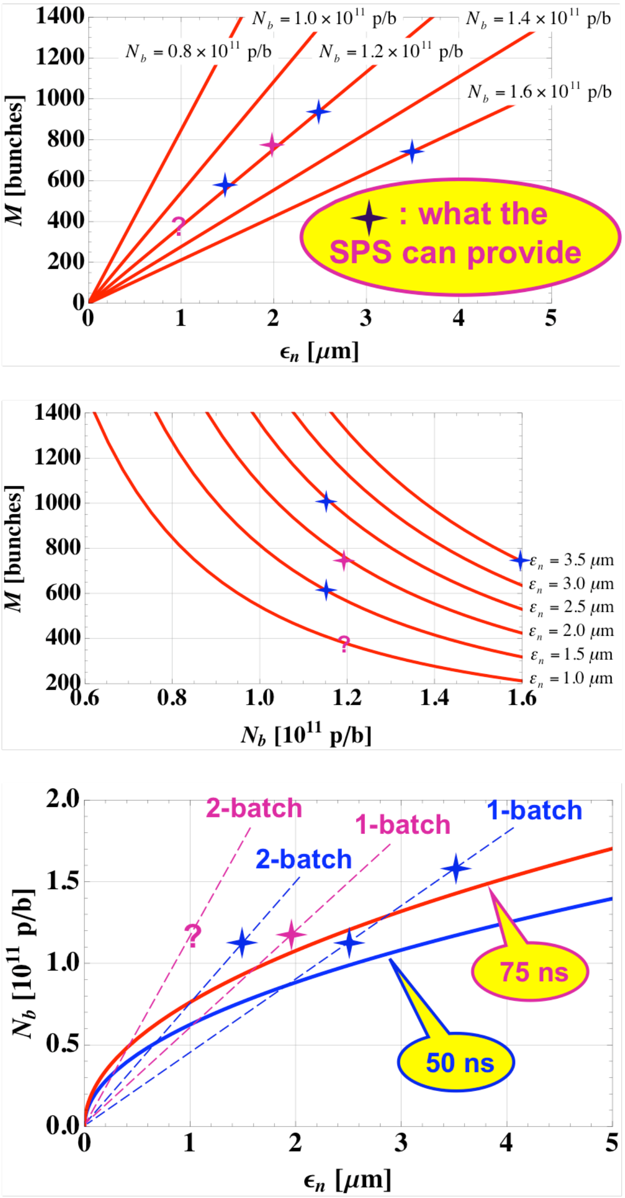


Figure 1: Relation between the bunch population, the number of bunches and the transverse beam emittance to reach a peak luminosity of 10^{33} cm^{-2}s^{-1}, assuming a beam energy of 4 TeV and a β* of 2 m. The blue star is used for the 50 ns beam while the red one is for the 75 ns beam. In the 3rd plot, the maximum number of bunches is assumed, i.e. 936 bunches for the 75 ns beam and 1404 bunches for the 50 ns beam.

in 2010). It is however proposed to do a scrubbing run with the 50 ns beam (note that 108 bunches were already accelerated in 2010) as no scrubbing was observed in the arcs with the 75 ns beam with about nominal bunch intensity, and as some margin should be provided for acceleration etc. Furthermore, knowing that the electron cloud build-up is almost independent of the transverse emittances (far from the build-up threshold!) [6], and that the induced single-bunch instability is less critical for large transverse emittances, it is proposed to start with the largest (~ nominal) emittances at least at the beginning.

Proposed scenario to reach 10^{33} $cm^{-2}s^{-1}$

A scrubbing run of ~ 1 effective week should be performed as soon as possible in the run (may be after a recovery phase from last year performance). Some time should also be reserved to scrub at top energy if needed, as the situation at top energy is not exactly the same as at injection energy (even if it was observed in 2010 that a scrubbing run at injection energy was also effective at top energy). It is proposed to use the 50 ns beam with a bunch intensity of ~ 1.4 10^{11} p/b and a transverse emittance (rms. norm.) of ~ 4 µm (i.e. the maximum which is compatible with injection losses: may be this is too much in which case we should reduce it to the nominal value of 3.5 µm). A transverse controlled emittance blow-up should be used in the injector chain (for instance in the SPS, as was done in the past [7]). Then, the idea is to increase the number of bunches looking at the vacuum pressure gauges, remaining below the vacuum interlocks. Finally, the transverse emittance could be slowly decreased as the secondary emission yield decreases.

Concerning the production mode (MDs are not discussed here), either a staged approach can be used (as was done in the past) or a challenging plan can be proposed (with a plan B as fallback solution). In the staged approach, the idea would be to run with the 75 ns beam and then move to the 50 ns beam (which could be studied during MDs). In the challenging mode discussed here it is proposed to try and run after the scrubbing run with the 50 ns beam (see Table 3), with ~ nominal bunch intensity (1.15 10^{11} p/b) and a large transverse emittance at the beginning (~ 3.5 µm, provided by controlled transverse emittance blow-up from the injectors). Then we should try and increase the number of bunches up to ~ 1000 to reach a luminosity of ~ 6 10^{32} $cm^{-2}s^{-1}$. This scenario with the 50 ns beam is better than with the 75 ns beam for the luminosity flexibility between the different experiments. Decreasing the transverse emittance (reducing the controlled transverse emittance blow-up from the injectors) will increase the luminosity (LR effects will reduce/disappear and HO ones increase but there is some margin as previously mentioned). The goal luminosity of 10^{33} $cm^{-2}s^{-1}$ will be reached when the transverse emittance will be equal to ~ 2.3 µm (the SPS should be able to deliver ~ 2.5 µm in 1 batch and ~ 1.5 µm in 2 batches, which means that the double-batch beam with controlled transverse emittance blow-up would be needed). Finally, one should try and increase the number of bunches as much as we can (up to 1404) and then one could even try to increase the intensity per bunch.

In this case, the fallback solution (plan B) would be to use the 75 ns beam with a bunch intensity of ~ 1.2 10^{11} p/b and the largest transverse emittance at the beginning (~ 3.5 µm, provided by controlled transverse emittance blow-up from the injectors). Then the idea is to increase the number of bunches up to 936 (i.e. the maximum) to reach a luminosity of ~ 6 10^{32} $cm^{-2}s^{-1}$. Decreasing the transverse emittance (reducing the controlled transverse emittance blow-up from the injectors) will increase the luminosity (LR effects will reduce/disappear and HO ones increase but there is some margin as previously mentioned). The goal luminosity of 10^{33} $cm^{-2}s^{-1}$ will be reached when the transverse emittance will be equal to ~ 2.2 µm (the SPS should be able to deliver ~ 2 µm in 1 batch and ~ 1? µm in 2 batches; the latter case still need to be studied in detail during MDs).

Parameter	PLAN A	PLAN B
Bunch population [p/b]	1.15 10^{11}	1.15 10^{11}
Number of bunches / beam		936 (max)
Bunch spacing [ns]	50	75
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 3: Possible parameters to reach 10^{33} $cm^{-2}s^{-1}$ in 2011.

LHC IMPEDANCES

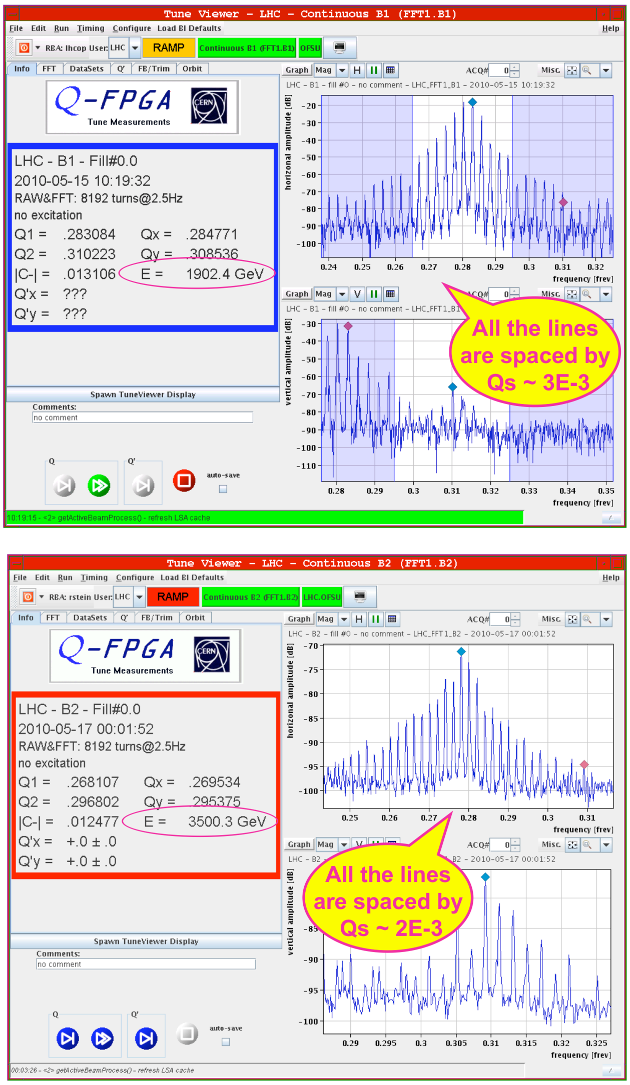
The imaginary part of the effective transverse impedance has been evaluated from tune shift measurements vs. intensity and revealed that it was within less than 40% compared to theoretical predictions. Furthermore, moving all the collimators of IR7 only, an even better agreement was obtained (as was already obtained in 2004 and 2006 in the SPS with a LHC collimator prototype [8]). The real part of the effective impedance was measured through the instability rise-time of an instability studied at 3.5 TeV (see next Section) and it seems to be within less than a factor of 2 compared to theory. All these measurements revealed therefore a good agreement with theoretical 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 [9].

As concerns the longitudinal impedance, a first estimate of the imaginary part of the longitudinal effective impedance was deduced from the loss of Landau damping leading to undamped bunch oscillations at the beginning of the run with small longitudinal emittance: both theoretical predictions and measurements point to a similar value of ~ 0.09 Ω [10].

LHC BEAM COHERENT INSTABILITIES

Christmas tree in May!

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. The bunch was unstable at ~ 1.8 TeV for B1 and ~ 2.1 TeV for B2. This led to the famous “Christmas tree” (see Fig. 2), which could be reproduced by simulations (when beam losses are introduced in the simulations). The Christmas tree is a consequence of a head-tail instability *m* = - 1 from the machine impedance predicted with a rise-time ~ 5 s without octupoles and intrinsic nonlinearities. This instability was measured in detail on Monday 17/05/2010 on the 3.5 TeV magnetic flat-top. The bunch was accelerated with some current in the (Landau) octupoles. At 3.5 TeV, the octupole current was



LHC – B1 – fill #0 – no comment – LHC_FFT1_B1 – 2010-05-15 10:19:32

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 = ???

Comments: no comment

10:19:15 - <2> getActiveBeamProcess() - refresh LSA cache

LHC – B2 – fill #0 – no comment – LHC_FFT1_B2 – 2010-05-17 00:01:52

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

Comments: no comment

00:03:26 - <2> getActiveBeamProcess() - refresh LSA cache

Figure 2: Observation of “Christmas trees” (with all the synchrotron sidebands excited) when the nominal intensity bunch was unstable at ~ 1.9 TeV (upper) and 3.5 TeV (lower).

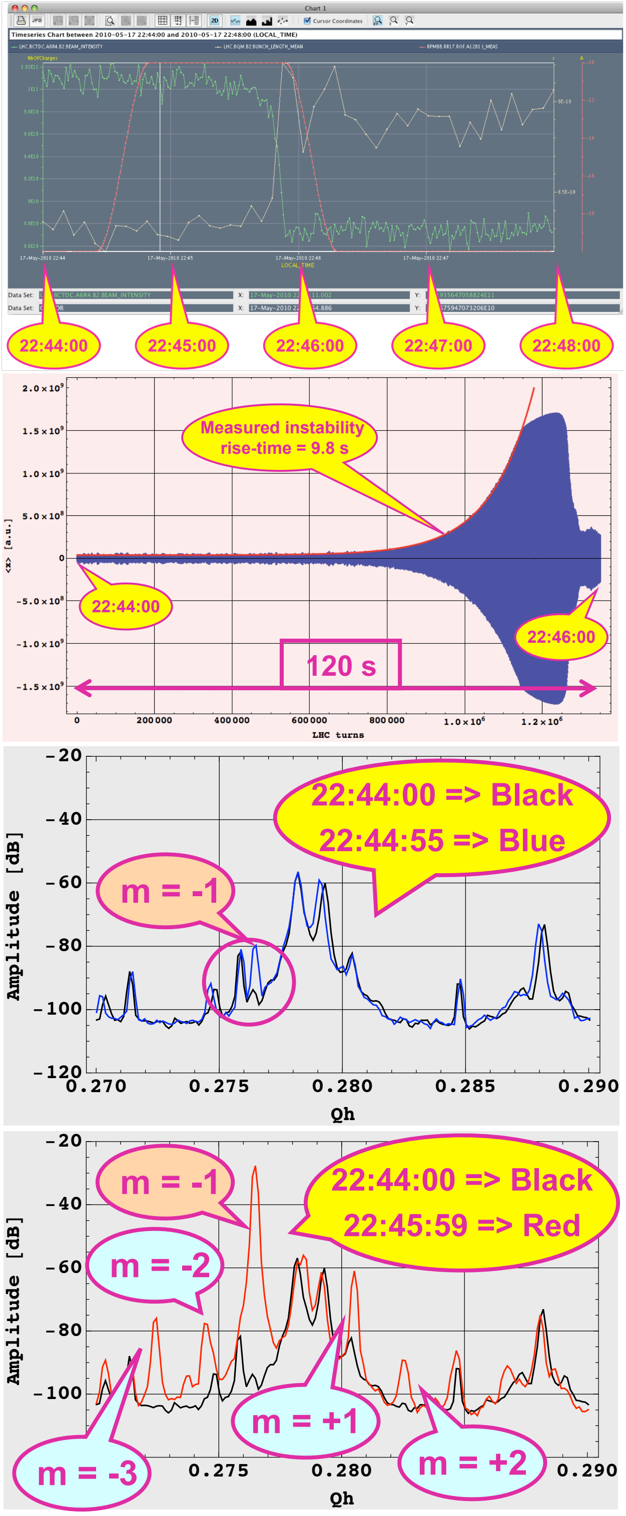


Figure 3: Beam losses observed at 3.5 TeV with a single-bunch when the octupole current reached – 10 A (a). The measured instability rise-time was ~ 10 s in the presence of an octupole current of – 10 A (b), and only one mode (*m* = - 1) clearly starts alone (c) before all the others (d).

"increased" (i.e. the effect decreased, as a negative current was used) from – 200 A to – 10 A by steps (see Fig. 3a). At – 20 A, the bunch was still stable whereas at – 10 A it was unstable with a rise-time of ~ 10 s and it could be clearly observed that only one mode (m = - 1) was first unstable and then, when the beam losses started to be observed, all the synchrotron sidebands were excited, leading to the Christmas tree (see Fig. 3d).

Transverse coherent instability induced by beam-beam?

A vertical instability was observed at 3.5 TeV in stable-beam conditions (see Fig. 4). A possible qualitative explanation could be a loss of Landau damping (whose origin is not clear yet), as the observed instability rise-time was ~ 10 s, i.e. very similar to the one observed in Fig. 3. Note that in the present case the instability appeared in the vertical plane, whereas it was in the horizontal plane in Fig. 3, but similar rise-times are predicted in both transverse planes.

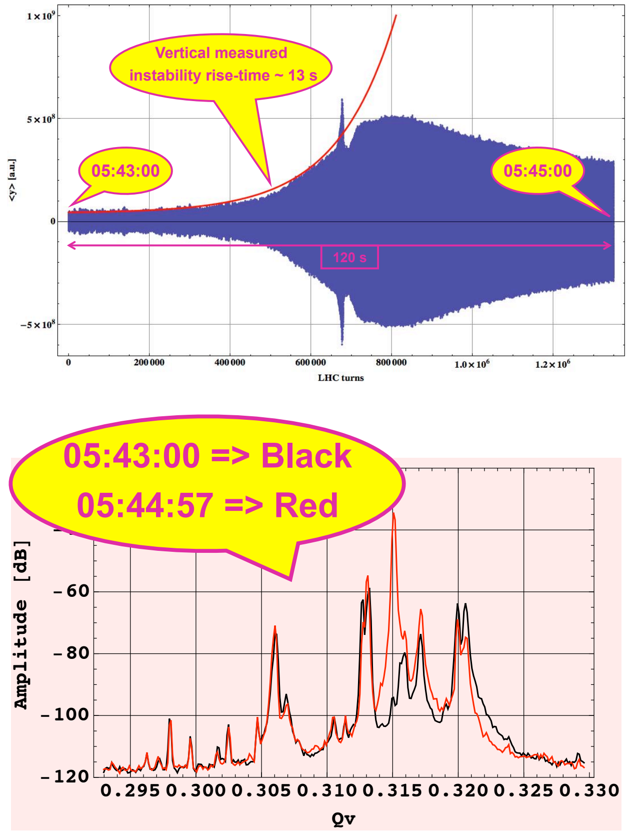


Figure 4: Observation of a single-bunch instability in stable-beam conditions, whose origin is not yet clear.

Transverse coupled-bunch instability with the 75 ns beam at 450 GeV?

During some machine studies, only the beam B1 was studied with 11 batches of 2 times 24 bunches spaced by 225 ns (with a batch spacing of 1.85 µs). The chromaticities were set to Q' ~ 10 in both transverse

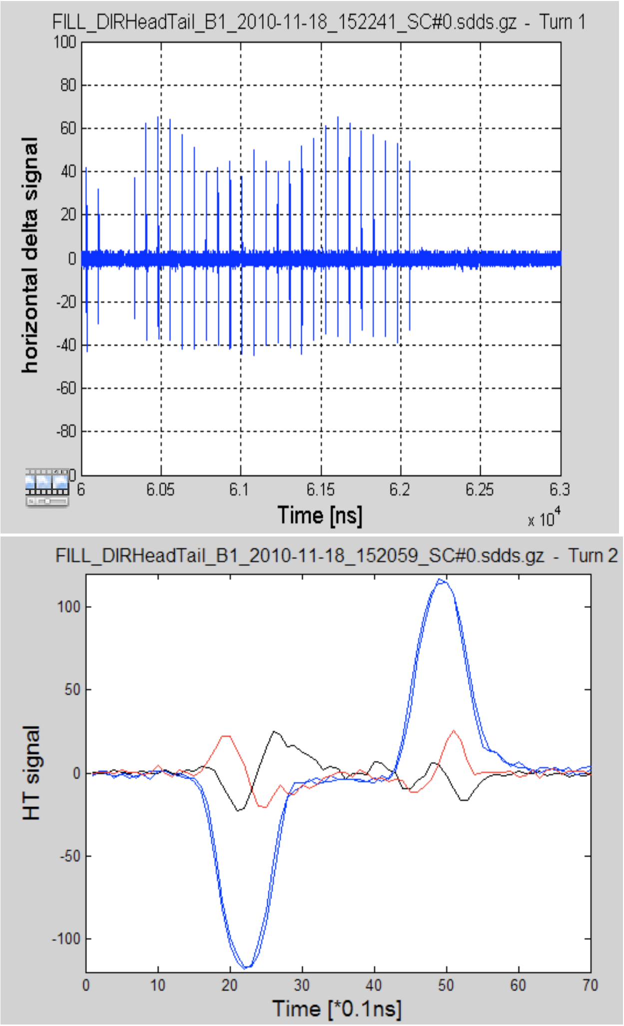


Figure 5: Observation of a transverse coupled-bunch instability (with the coupled-bunch pattern "clearly" visible on the upper plot) with a measured head-tail (within bunch) mode |m| = 1 from the Headtail monitor (lower plot). Note that the second signal of the second plot comes from the reflection. Courtesy of Benoit Salvant.

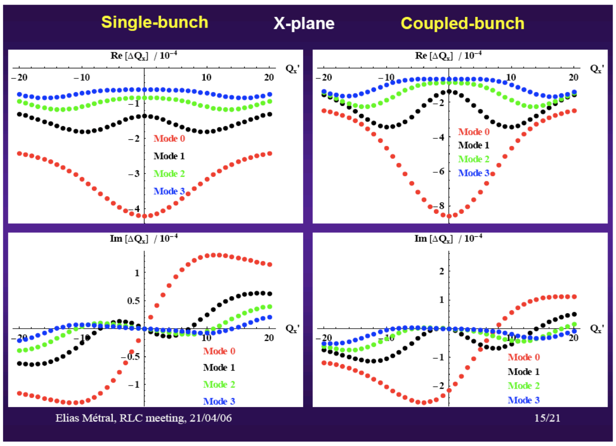


Figure 6: Theoretical predictions for the complex tune shifts of the nominal (25 ns) beam at injection.

planes. The beam was observed to be unstable with coupled-bunch coherent oscillations along the last batches (see Fig. 5a), without growing oscillations but with beam losses. This instability could be stabilized (and the beam losses removed) by increasing the chromaticities to Q’ ~ 20. This observation is qualitatively compatible with a coupled-bunch instability *m* = 0 damped by the transverse feedback and the mode |*m*| = 1 which cannot be damped by the transverse feedback (see Fig. 5b). This would explain why there were no growing coherent oscillations (mode 0 is correctly damped by the transverse feedback) but still losses observed (mode 1 is growing). This is qualitatively what would have been expected from Fig. 6 (right), which was computed for the case of the nominal beam (25 ns beam) at injection: for Q’ ~ 10, mode 1 could develop if not Landau damped (either by intrinsic lattice nonlinearities or by powering Landau octupoles). Increasing the chromaticity reduces the effect of mode 1 which might even become stable if the intrinsic nonlinearities are sufficient.

RECOMMENDATIONS

In the case of transverse coupled-bunch instabilities from the machine impedance and/or the electron cloud, the transverse feedback should be able to damp them [11]. Therefore, it is better to have the smallest chromaticity in order not to excite the higher order modes, which cannot be stabilized by transverse feedback (see Fig. 6 for a qualitative picture).

Moreover, one should not have a Transverse Mode-Coupling Instability (TMCI) from the machine impedance, and there is thus no reason to increase the chromaticity to stabilize the beam.

The only reason to increase the chromaticity could come from the electron cloud induced vertical single-bunch “TMCI-like” instability, which was most probably observed during the first MD with the 50 ns beam on 02/11/10. However, in this case a possible issue could come from transverse coupled-bunch instability from the machine impedance with head-tail mode |m| = 1 which could develop, and which cannot be damped by the transverse feedback. In this case, one should increase the chromaticity even more if mode 1 is not Landau damped (but in this case the beam lifetime will most probably be reduced) or increase the tune spread through Landau octupoles.

ACKNOWLEDGEMENTS

Many thanks to all the people who worked on impedances in the past (F. Ruggiero, L. Vos, F. Caspers, vacuum people etc.), and in particular B. Salvant and N. Mounet for the recent studies on impedances and single-beam coherent instabilities.

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