IMPEDANCE EFFECTS ON BEAM STABILITY

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Abstract

In 2012, attempts to increase the bunch intensity, decrease the emittance and reduce the collimators gaps in the LHC, will potentially make the detrimental effects due to the machine impedance more critical. Extrapolating the data accumulated in 2010 and 2011, in several foreseen scenarios, the headtail modes at top energy will require an increase of the current in the octupoles installed in the LHC. In the worst case, instead of around 200 A in the defocusing octupoles and -200 A in the focusing ones as at the end of the 2011 physics run, the octupoles' current will have to be increased to around ± 450 A.

INTRODUCTION

Several kinds of impedance-related instabilities may affect the LHC beam operation:

- Headtail intrabunch modes, which develop in principle at any intensity, but are also relatively weak. They are slightly stronger when many bunches fill the machine [1]. While absent at zero chromaticity, they become more critical when going to higher chromaticities, and have to be stabilized by Landau damping. We will mainly focus on these modes here, as they have been observed so far to be the only impedance-related instability affecting the beam operation in the LHC. In particular, observation of these modes in 2010 with a single bunch at nominal intensity led to the use of the LHC octupoles during normal operation in 2010 and 2011 [2].
- Coupled-bunch rigid-bunch modes, which develop at any intensity and any chromaticity (including zero), and are stronger than the intrabunch modes. They are damped by the transverse feedback system, and we will therefore not consider them here.
- Transverse mode coupling (TMC) instability [3], which occurs only above a certain intensity threshold. The threshold becomes lower (by $\sim 20\%$ according to simulations with a 50 ns beam [1]) in the coupled-bunch regime. This kind of instability is very difficult to cure as a feedback upgrade would be needed.

The complex tune shifts related to these instabilities can be evaluated thanks to the LHC impedance model [1] together with either a beam dynamics simulation code such as HEADTAIL [4] or a theory such as Sacherer's [5]. The HEADTAIL code has been recently extended to allow the simulations of many bunches [6]. The LHC impedance model presently [1] includes the resistive-wall impedance of the 44 collimators, of the beam screens covering 86% of the ring, and of the vacuum pipe for the remaining 14% with various cross sections, together with a broad band impedance model to account for most of the smooth transitions around the ring [7].

In these proceedings we will first compare various beam-based observations with the results obtained from the LHC impedance model to date together with the HEADTAIL macroparticle simulation code. Then we will summarize the tests already done with the tight collimator settings, giving in particular hints of explanations about the high losses that happened on August 29$^{\text{th}}$, 2011, and what can be done to avoid such problems in 2012. Finally we will review the possible impedance-related limitations in 2012.

COMPARISONS BETWEEN BEAM-BASED MEASUREMENTS AND THE IMPEDANCE MODEL

We compare here the results from the simulation code HEADTAIL using the wake fields from the LHC impedance model, with beam-based measurements of tune shifts and instability rise times performed in 2010 and 2011. We review both the single-bunch and coupled-bunch cases.

Single-bunch

At 450 GeV$/c$, tune shifts measurements were performed on May 28$^{\text{th}}$, 2010 [8]. The total tune shift due to the impedance of the machine was measured using either an overinjection of a high-intensity bunch on a previously injected low-intensity one or an intensity scraping done thanks to one collimator. The specific contributions given to the tune shift by certain collimators were separately quantified, by moving groups of collimators together, in particular the injection protection collimators – TDI, TCLIA and TCLIB – and the collimators in the IR7 insertion region. On November 1$^{\text{st}}$, 2011 [9] additional measurements were done on the TDI alone, by moving this collimator and measuring the corresponding tune shift. At 3.5 TeV$/c$ some measurements of the tune shift due to a subset of collimators (in particular those of IR7) were performed on May 7$^{\text{th}}$, 2011 [10]. An instability rise time measurement took place on May 17$^{\text{th}}$, 2010 [2, 11].

Results of all these experiments, compared to HEADTAIL simulations using the LHC impedance model, are shown in Figs. 1 and 2 in respectively horizontal and vertical. The tune shifts normalized by the bunch intensity are then shown in Figs. 3 and 4. Note that the other beam or machine parameters (e.g. bunch length and chromaticity) can

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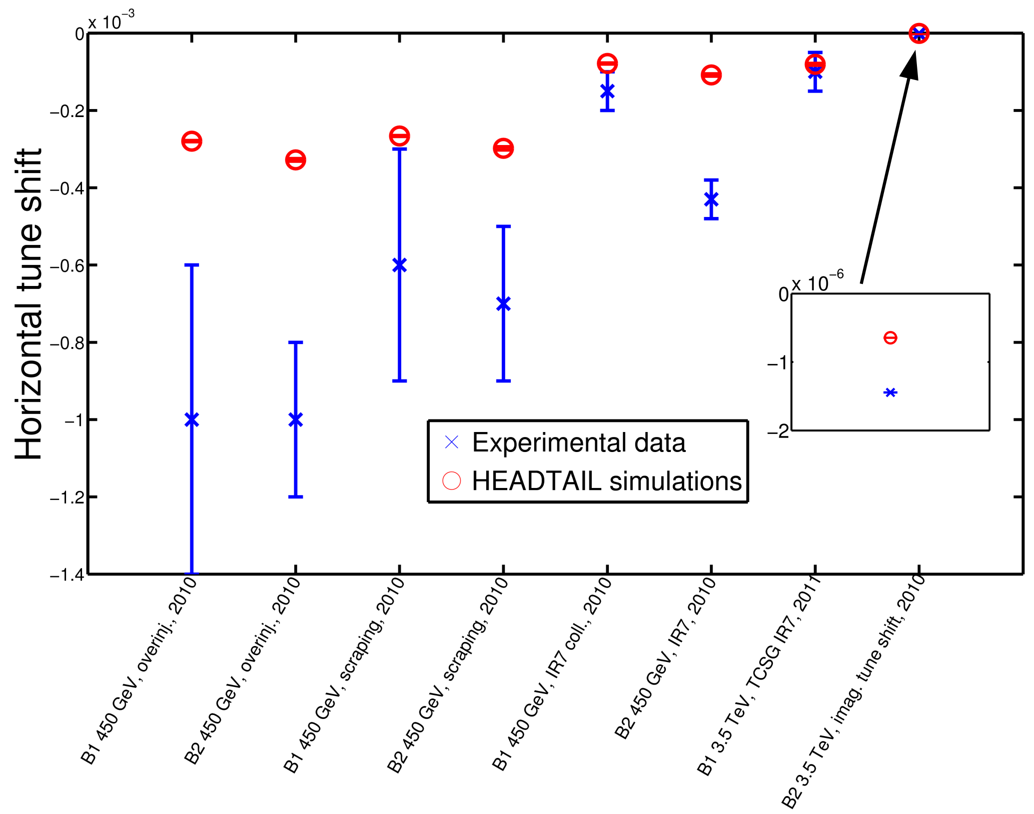

Figure 1: Horizontal tune shifts measured and simulated, in various cases.

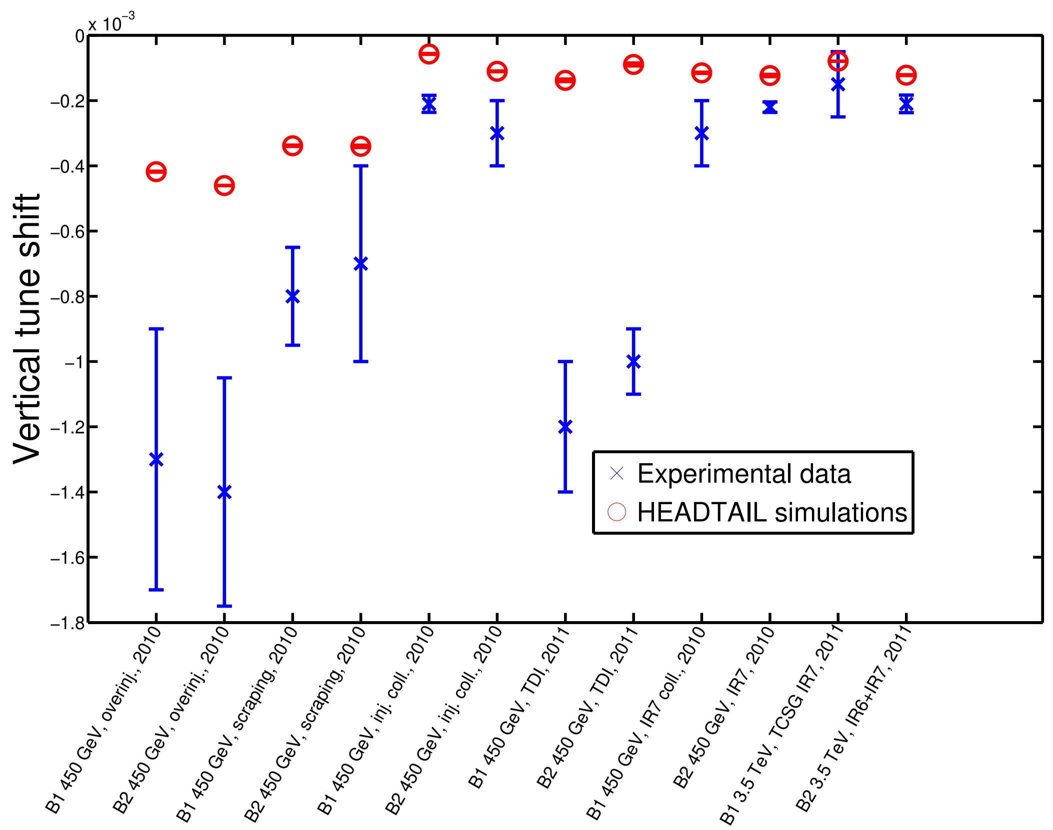

Figure 2: Vertical tune shifts measured and simulated, in various cases.

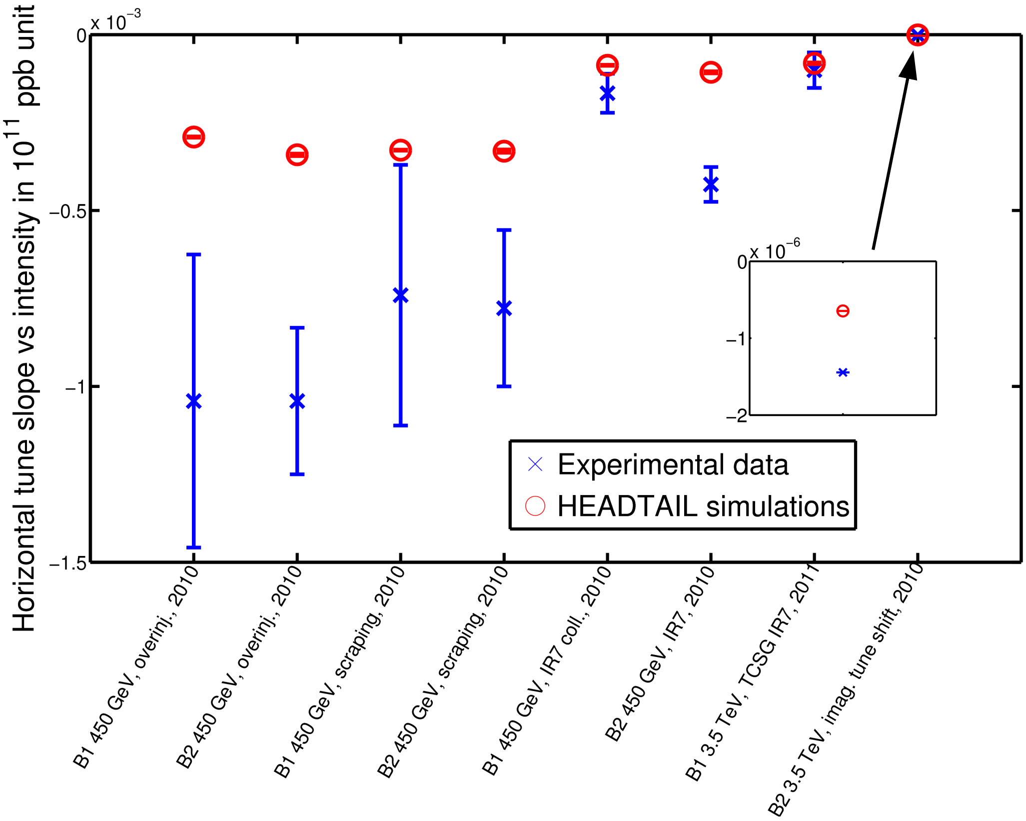

Figure 3: Horizontal tune shifts measured and simulated in various cases, normalized with the bunch intensity in units of 10^{11} particles per bunch.

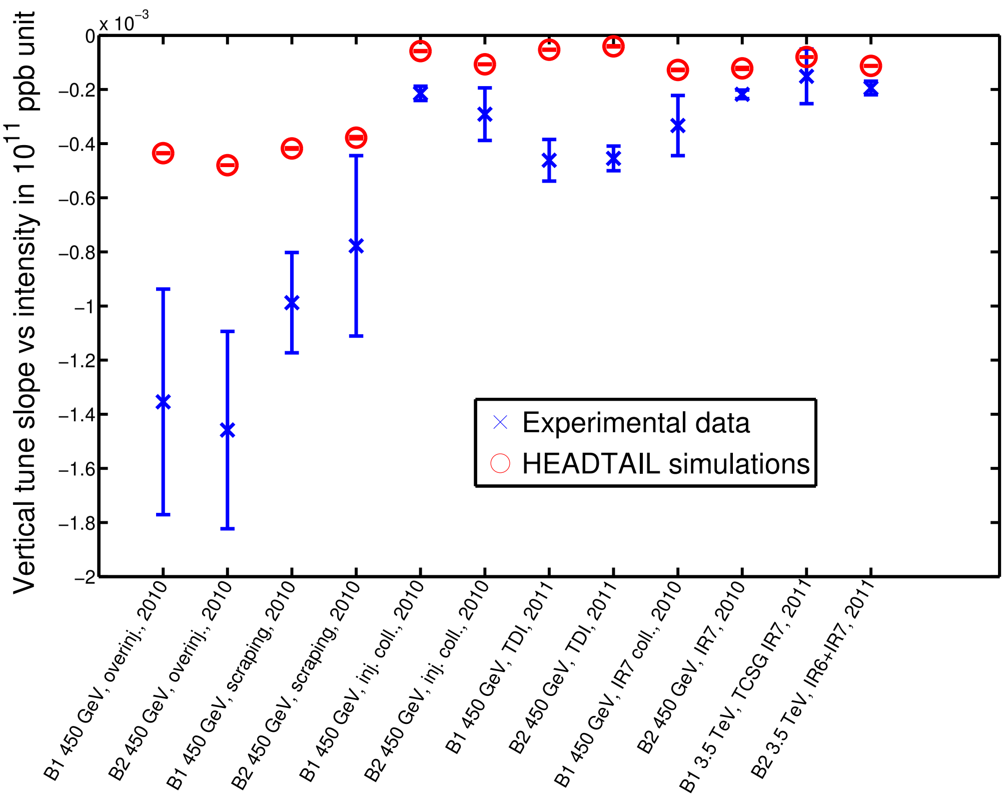

Figure 4: Vertical tune shifts measured and simulated in various cases, normalized with the bunch intensity in units of 10^{11} particles per bunch.

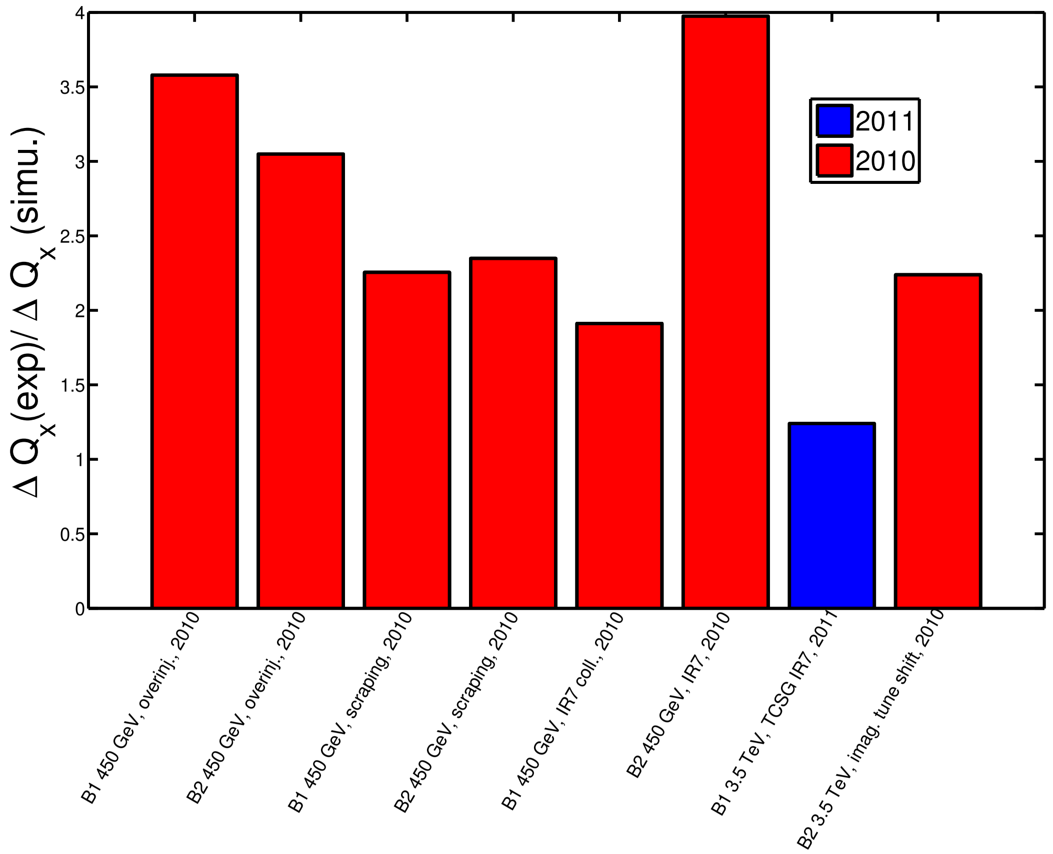

Figure 5: Discrepancy factor between the horizontal tune shifts measured and simulated, in various cases.

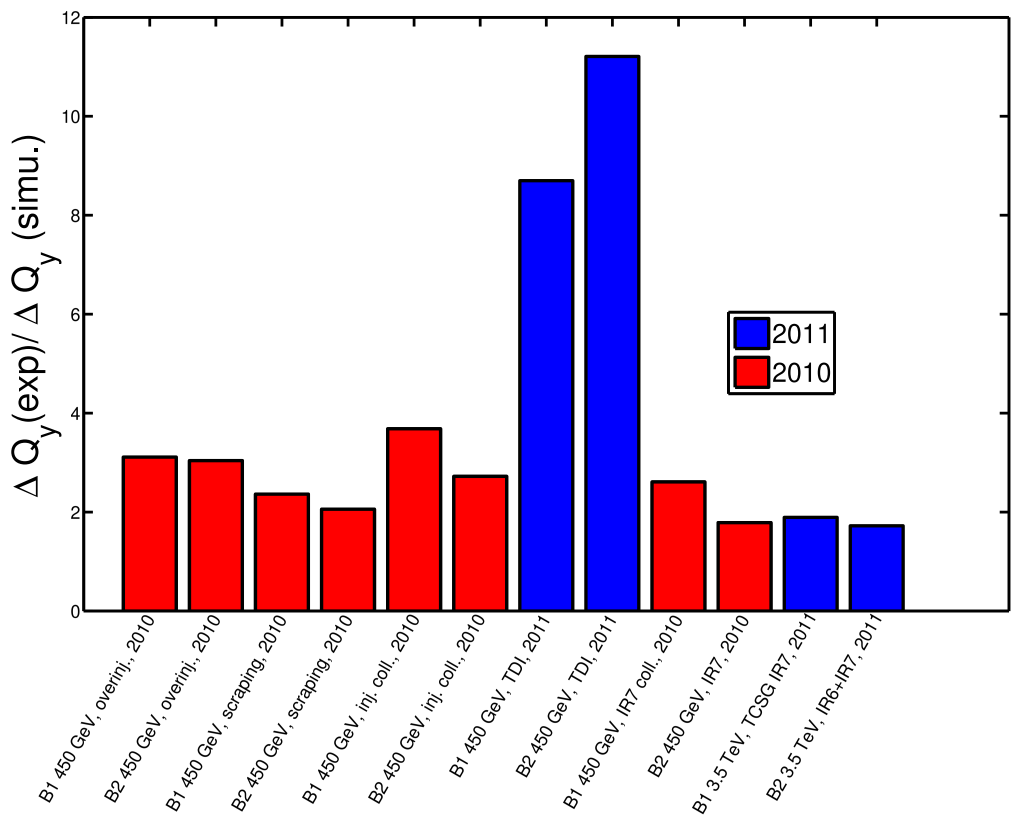

Figure 6: Discrepancy factor between the vertical tune shifts measured and simulated, in various cases.

differ slightly between the various measurements, and this was taken into account in the simulations. Finally, the discrepancy factors between the measurements and the simulations are exhibited in Figs. 5 and 6. In most cases, we find a disagreement between the model and the measurements by a factor 2-3. At 3.5 TeV$/c$, simulations tend to be closer to the measurements than at 450 GeV$/c$, especially when taking into account the experimental error bars which are visible in Figs. 1 and 2. One can also note the systematic and yet unexplained discrepancy between the overinjection measurements and the scraping ones, the former giving a higher discrepancy factor with respect to the model than the latter. Finally, the tune shift due to the injection protection collimators, which is expected to be dominated by the TDI contribution (in particular its ceramic block) has changed drastically between 2010 and 2011. This could be explained either by a rather bad quality of the measurement in 2010 with respect to that of 2011, or by some damage done to the titanium coating on the ceramic part of the TDI jaw, resulting in a reduction of its thickness [9][1].

Note that the discrepancy factor between the 2011 measurements on the TDI and the model (which is around 10 in Figs. 5 and 6) decreases to around a factor 3 when taking into account the geometrical part of the TDI impedance [9], instead of only its resistive-wall part as in the LHC impedance model presently used. Also, it was found recently that the titanium coating is actually thicker than what was expected (5 μm instead of 3 μm), which decreases the TDI impedance, but on the other hand it got contaminated by the hBN ceramic, possibly increasing its resistivity by a factor 6 [12], thus increasing its impedance. The overall effect is expected to be an increase of the impedance, but this has still to be evaluated quantitatively.

The LHC impedance model has not yet been changed to take into account the geometrical impedance nor the updated properties of the titanium coating. Still, such modifications of the model would affect in the same way the results of both the 2010 and 2011 cases. Therefore, they can not explain the change in discrepancy factor between the 2010 and 2011 TDI tune shift measurements.

Coupled-bunch

In the coupled-bunch regime (i.e. when many bunches are present in the machine), only the instability rise times of the rigid-bunch modes have been measured, on May 8th, 2011 [13]. This has been done at both 450 GeV$/c$ and 3.5 TeV$/c$, with 48 bunches at nominal intensity (one batch of 12 bunches and one of 36 bunches), the bunch separation being 50 ns.

In Figs. 7 and 8 we show a comparison between measurements and simulations for the coupled-bunch instability rise times at 450 GeV$/c$ for various chromaticities.

[1] After the workshop, visual inspection of the TDI jaws did not reveal any absence of coating, but its thickness has not been measured. On the other hand, the beam screens around the jaws were observed to be deformed; the impact of this deformation on the impedance will be assessed in future studies.

Note that the rise times from the simulations were obtained thanks to three different methods [1], taking in the end the average of the three methods. A rather good agreement is found between simulations and measurements, except for beam 2 when $Q' \geq 1$. In the same graphs we also show the single-bunch instability rise times obtained from the simulations, indicating that even for negative chromaticities the coupled-bunch instabilities are significantly faster that the single-bunch ones.

In Figs. 9 and 10 we show the measurements of the vertical rise times at 3.5 TeV$/c$, for different values of the current in the octupoles. The x axis indicates the current in the defocusing octupoles, while the focusing octupoles are always set to a current opposite to this value. For zero octupole current, the simulation results in vertical are also given, showing a discrepancy by about a factor 3 for both beams.

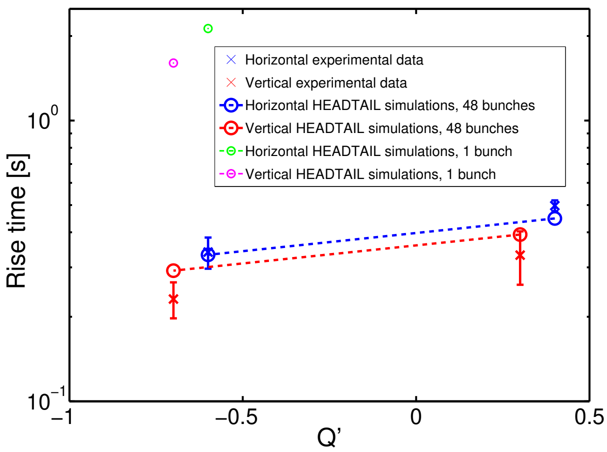

Figure 7: Coupled-bunch instability rise times vs. Q' for beam 1, at 450 GeV$/c$, from both measurements and simulations. We also show simulations results in the single-bunch case.

Summary

Single-bunch tune shifts and rise time measurements show a discrepancy by a factor 2-3 with respect to the model. Coupled-bunch instability rise times are much closer to the model at 450 GeV$/c$, but also at a factor around 3 at 3.5 TeV$/c$. Since the HEADTAIL code has been benchmarked against theory [6, 14], revealing a good agreement, the discrepancy factor probably comes mainly from the LHC impedance model, which is still in its early stage of development and needs improvements to better describe the machine. Studies are ongoing to add other machine elements not yet taken into account and perform more accurate electromagnetic simulations for those already included.

Given the current discrepancy between simulations and mesurements, we suggest that predictions made with the LHC impedance model should be taken in relative terms, i.e. to anticipate the effect of parameter changes with re-

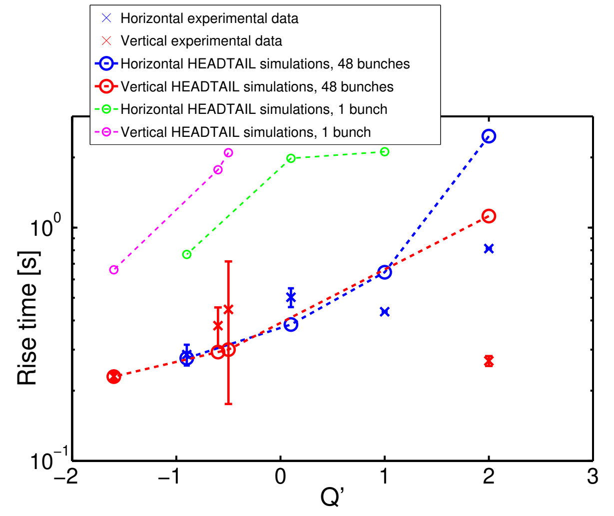

Figure 8: Coupled-bunch instability rise times vs. Q' for beam 2, at 450 GeV$/c$, from both measurements and simulations. We also show simulations results in the single-bunch case.

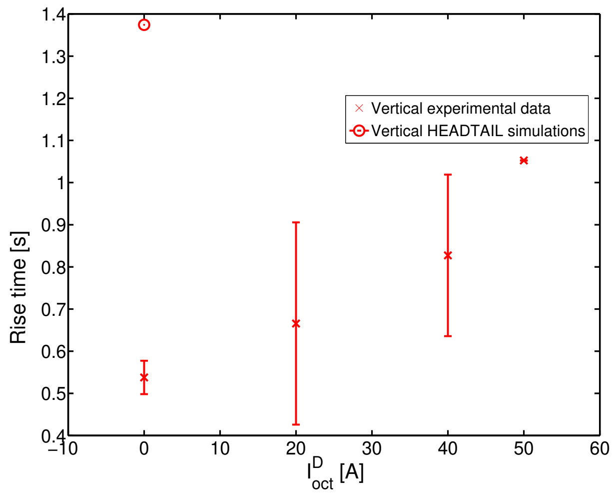

Figure 9: Coupled-bunch instability rise times vs. current (in A) in the defocusing octupoles for beam 1 vertical, at 3.5 TeV$/c$, from measurements. Simulations results at zero octupole current are shown as well.

spect to a reference situation (e.g. the 2011 physics run). Note finally that further measurements will have to be performed in coupled-bunch regime, in particular to obtain the coupled-bunch tune shifts, as they are a key parameter for the transverse mode coupling threshold, as well as for the loss of Landau damping threshold.

TESTS ALREADY PERFORMED WITH THE TIGHT COLLIMATOR SETTINGS

The tight collimator settings [10] are new settings to be used at top energy. With the tight settings, the primary collimator is set to 4 nominal sigma, which at 3.5 TeV$/c$ corresponds to the nominal opening in mm at 7 TeV$/c$. The other collimators have larger than nominal retractions (e.g. secondary collimators at 6 sigma at 3.5 TeV$/c$) in order to

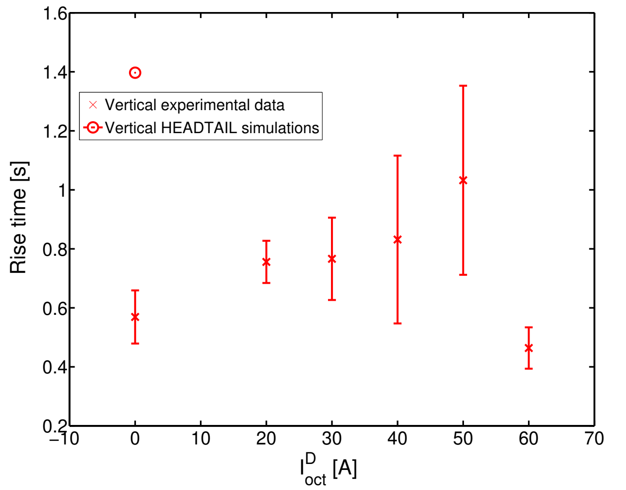

Figure 10: Coupled-bunch instability rise times vs. current (in A) in the defocusing octupoles for beam 2 vertical, at 3.5 TeV$/c$, from measurements. Simulations results at zero octupole current are shown as well.

allow the machine drifts observed in 2011. Since with tight settings most of the collimator half gaps are narrower than those of the intermediate (or relaxed) settings used during the 2011 physics run in the LHC, using these settings will increase the machine impedance.

Such tight settings were tested four times in 2011: during the machine development studies (MD) of May 7$^{\text{th}}$ [10], of August 29$^{\text{th}}$ [15] and of November 5$^{\text{th}}$ [16], as well as during the end-of-fill study (EOF) of August 21$^{\text{st}}$ [17]. The tests were performed for both beams except for the EOF study, when only beam 1 was set to the tight settings.

These tests give a lower limit for the transverse mode coupling (TMC) instability threshold. The highest intensity per bunch achieved in those tests without any visible detrimental effect from the impedance was around 10^{11} protons per bunch, obtained for both beams in single bunch during the MD on November 5$^{\text{th}}$ and for beam 1 with 1380 bunches during the EOF study of August 21$^{\text{st}}$. In both cases the total average bunch length was around 1.2 ns. During the MD on August 29$^{\text{th}}$ a higher bunch intensity was achieved ($1.3 \cdot 10^{11}$ protons per bunch), with 84 bunches, but losses were observed as we will discuss below. Therefore, one can infer from the 2011 tests that with the tight collimators settings, the TMC threshold must be above 10^{11} protons per bunch, both in single-bunch regime and in coupled-bunch regime (50 ns spacing) when the two beams are colliding.

The case of August 29th, 2011 (fill 2060)

During this MD, after the ramp to 3.5 TeV$/c$ the collimators were set to their tight settings and the beam squeezed to $\beta^* = 1$ m at the ATLAS and CMS interaction points. High losses were then observed at the end of the squeeze, before closing the separation at the interaction points (i.e. before the beams were brought into collision) [18], as visible in Fig. 11. Around one minute later a "Christmas tree" was observed in the tune spectra (i.e. reg-

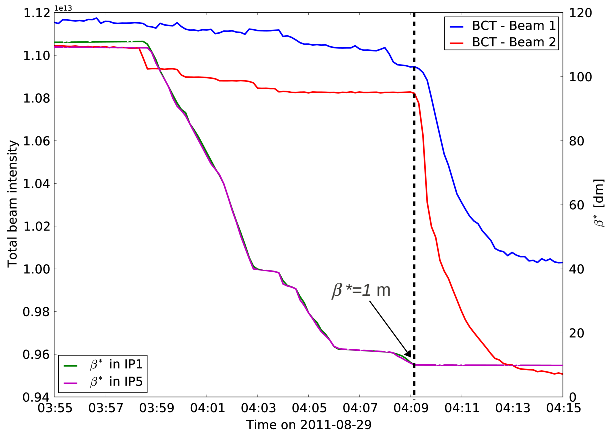

Figure 11: β^* and total beam intensity (from the Beam Current Transformers) around the time of the losses on Aug. 29th.

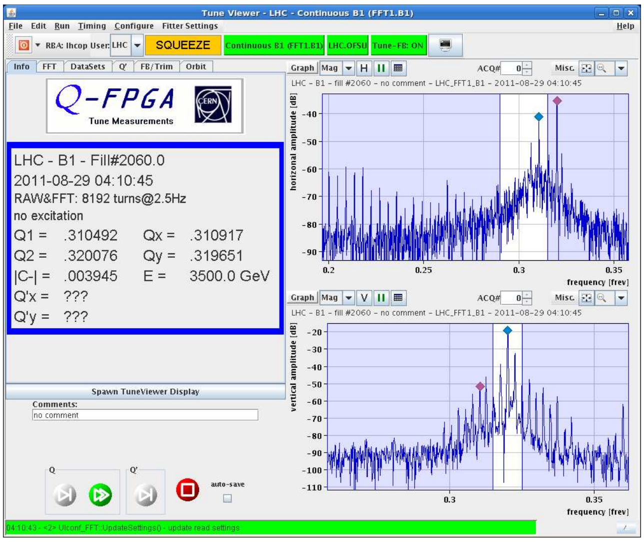

Figure 12: BBQ tune spectra of beam 1 right after the losses on Aug. 29th (extracted from the LHC OP log book).

ularly spaced peaks symmetrically placed around the main tune line) as shown in Fig. 12.

Note that the separation at the interaction points was not yet collapsed at the time when the losses were observed (around 4:09 AM local time). This means that the beams were not colliding head-on when the losses occurred. However, long range beam-beam effects are present also when the beams are separated.

To investigate the possible reasons of the losses, we first show in Figs. 13 and 14 the bunch by bunch population from the Fast Beam Current Transformer (FBCT) data, before and after the losses. It appears that the losses affected mainly the bunches in the middle of the first batch of 36 bunches. This is rather unlikely to be caused by an impedance-related instability, since the most unstable bunches would be in that case those at the end of the batch in coupled-bunch regime, or the ones with the highest in-

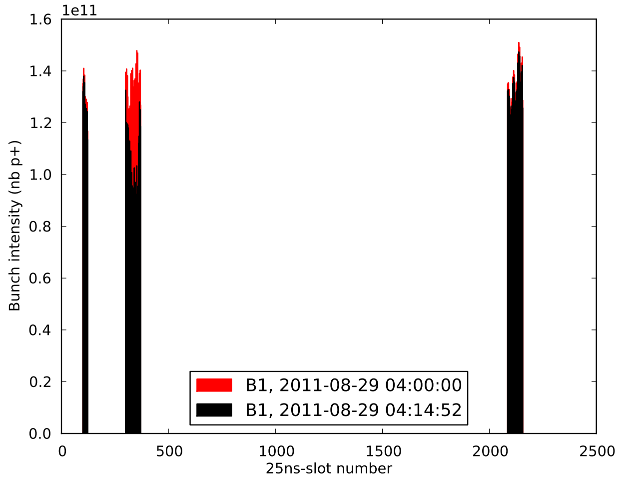

Figure 13: Beam 1 bunch by bunch population before and after the losses on Aug. 29th.

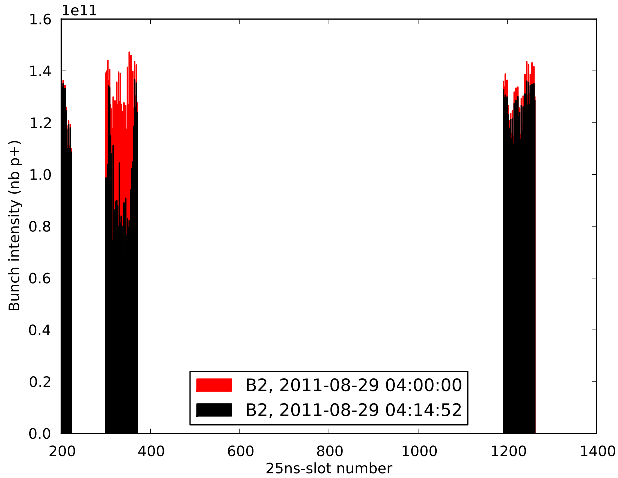

Figure 14: Beam 2 bunch by bunch poulation before and after the losses on Aug. 29th.

tensity if the instability is single-bunch. On the other hand the bunches losing intensity seem to correspond to those that undergo long range collisions in IP1 and IP5 [18]. Simultaneously to the losses, a rapid growth of the BBQ signal is visible for both beams and both planes in Figs. 15 to 18, which tends to show that the losses were due to a coherent instability. The rise time of this instability is of a few seconds [19]. Note that the BBQ signal seems to saturate in vertical but not in horizontal.

As visible in Figs. 19 and 20, at the time of the losses several bunches of beam 1 were lengthened while for beam 2, some were lengthened and other shortened. From Figs. 21 and 22 we see that for beam 1 the bunches with numbers 21 and 23 to 42 (in the middle of the first batch of 36 bunches) get lengthened, while for beam 2 the bunches with numbers 13, 14 and 36 to 43 get lengthened and the bunches with numbers 19, 20, 22, 23, 25, 27 to 35 get shortened.

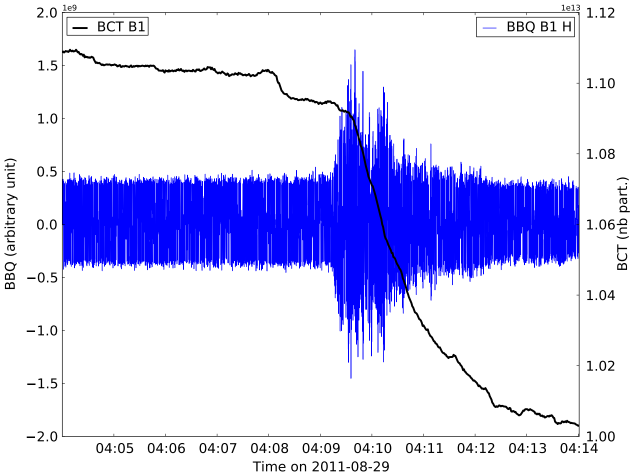

Figure 15: Raw horizontal BBQ data of beam 1, together with the total beam intensity from the BCT, on Aug. 29th.

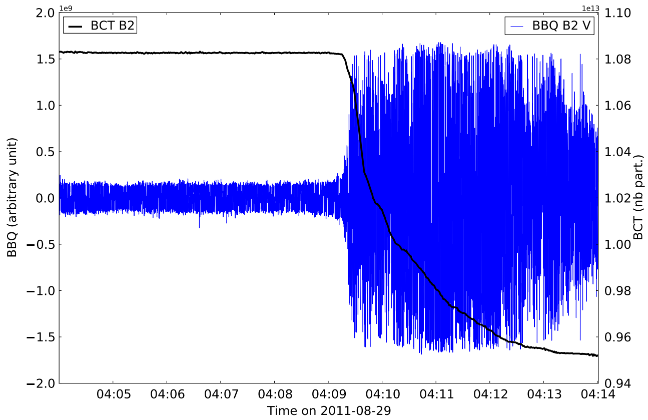

Figure 18: Raw vertical BBQ data of beam 2, together with the total beam intensity from the BCT, on Aug. 29th.

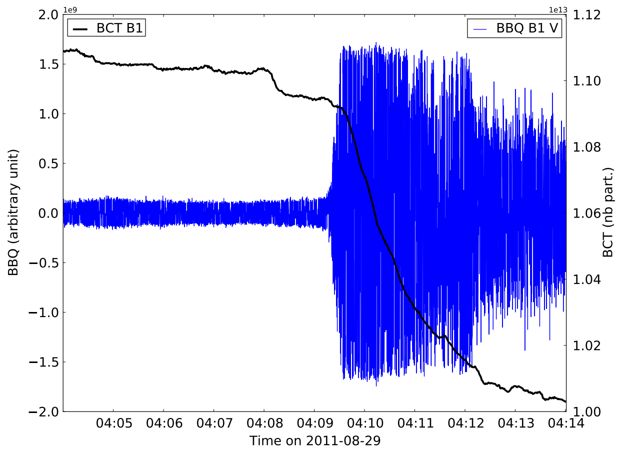

Figure 16: Raw vertical BBQ data of beam 1, together with the total beam intensity from the BCT, on Aug. 29th.

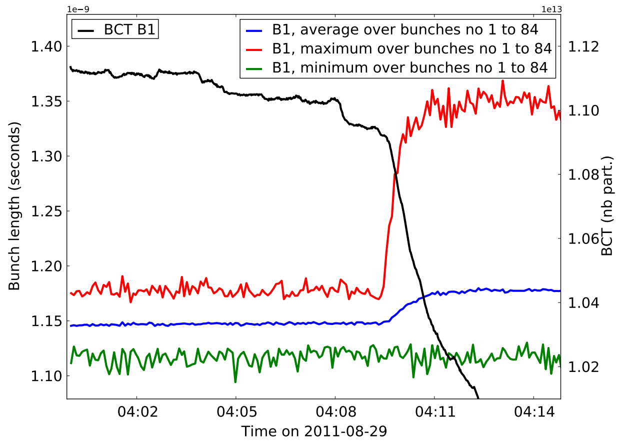

Figure 19: Maximum, minimum and average bunch lengths of beam 1, together with the total beam intensity from the BCT, on Aug. 29th.

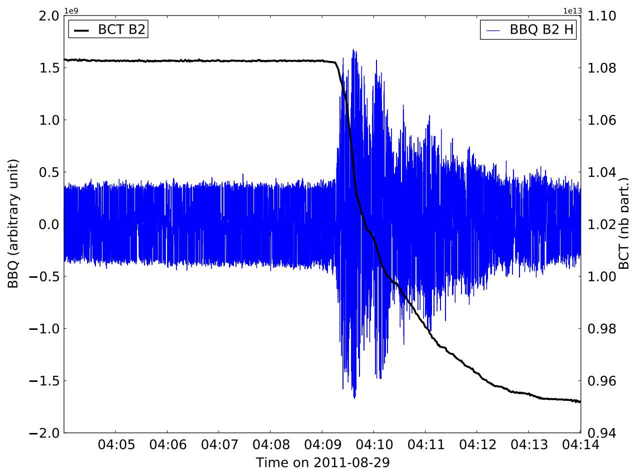

Figure 17: Raw horizontal BBQ data of beam 2, together with the total beam intensity from the BCT, on Aug. 29th.

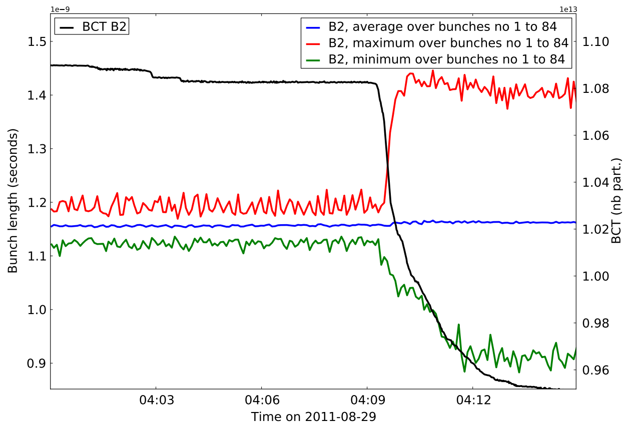

Figure 20: Maximum, minimum and average bunch lengths of beam 2, together with the total beam intensity from the BCT, on Aug. 29th.

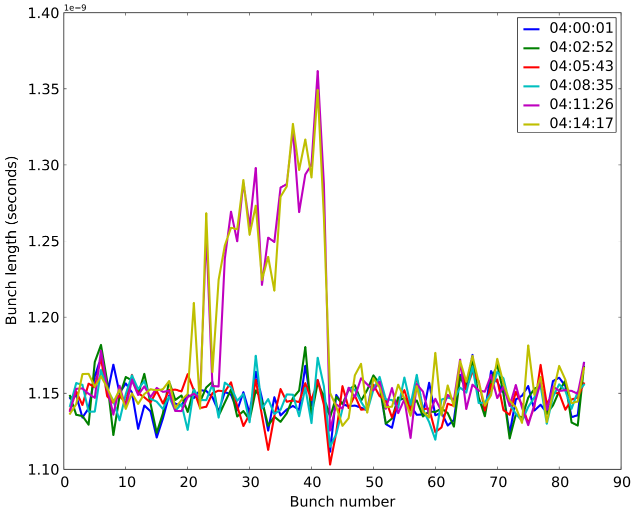

Figure 21: Bunch lengths along the bunch train of beam 1 at various times, on Aug. 29th. The bunches are numbered from 1 to 84 (batch of 12 bunches first, then the two batches of 36 bunches).

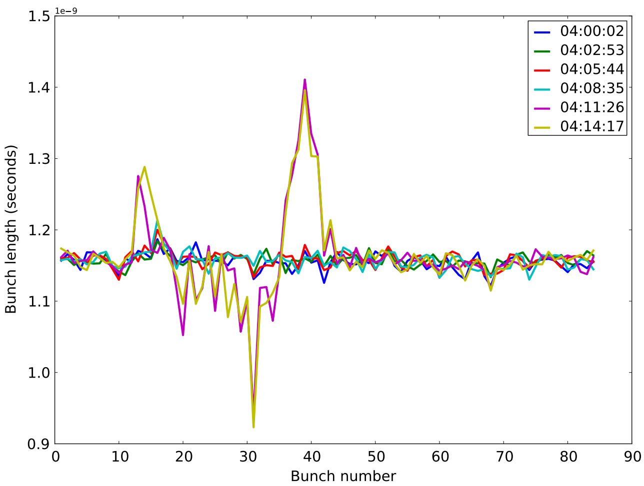

Figure 22: Bunch lengths along the bunch train of beam 2 at various times, on Aug. 29th. The bunches are numbered from 1 to 84 (batch of 12 bunches first, then the two batches of 36 bunches).

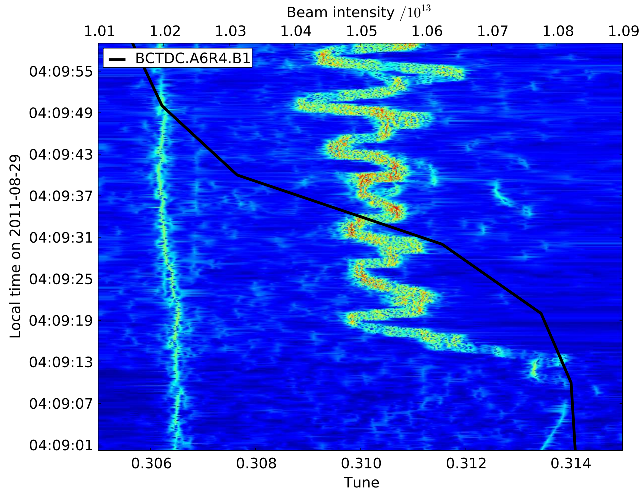

Figure 23: BBQ horizontal tune spectrum evolution with time for beam 1, at the time of the losses on Aug. 29th. The black curve gives the total bunch current from the BCT.

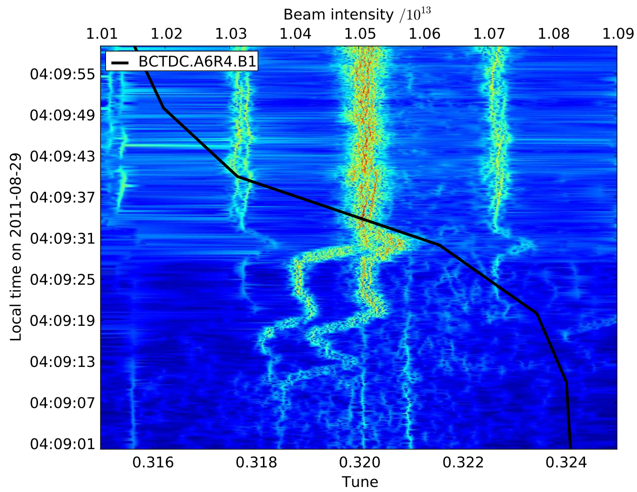

Figure 24: BBQ vertical tune spectrum evolution with time for beam 1, at the time of the losses on Aug. 29th. The black curve gives the total bunch current from the BCT.

Figures 23 to 26 show the evolution of the tune spectra calculated with SUSSIX [20] from the BBQ position data during the losses (the color indicates the amplitude of the spectrum lines, from blue – low amplitudes – to red – high amplitudes). In the same plot a black curve indicates the total intensity from the BCT (Beam Current Transformer). For all beams and all planes, a strong coherent line close to the main tune (within around $2-4\cdot10^{-3}$) appears at the time when the losses begin. At the very beginning of the losses, this line has a frequency higher than the main tune in the horizontal plane, and lower than the main tune in the vertical plane. Note that the frequency of this line changes with time during the losses, getting in a few seconds indistinguishable from the main tune line. A tentative explanation of this line would be that it is a long range beam-beam coherent mode [21], which indeed could have provoked the losses. The beam-beam parameter is around $3\cdot10^{-3}$ with a normalized emittance equal to 5 mm.mrad, which takes into account the emittance blow-up that we will discuss below. Therefore, the distance between this coherent line and the main tune is similar to the beam-beam parameter, which is consistent with the long range coherent modes simulated in Ref. [21].

Before the losses actually occur, another phenomenon seems to have happened. A lifetime reduction was observed during the squeeze [18]. In Figs. 27 to 30, we show the evolution of the tune spectra calculated with SUSSIX [20] from the BBQ data during several minutes before the losses. It appears that strong lines are present in the spectra, on each side of the tune and at a distance of about $5\cdot10^{-3}\approx2Q_s$ from it (Q_s being the synchrotron tune). An example of tune spectrum is plotted in Fig. 31 for the case of beam 2 in horizontal, where these two peaks are clearly

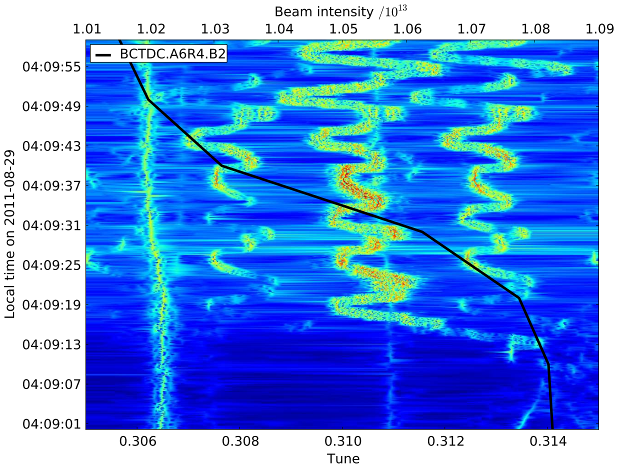

Figure 25: BBQ horizontal tune spectrum evolution with time for beam 2, at the time of the losses on Aug. 29th. The black curve gives the total bunch current from the BCT.

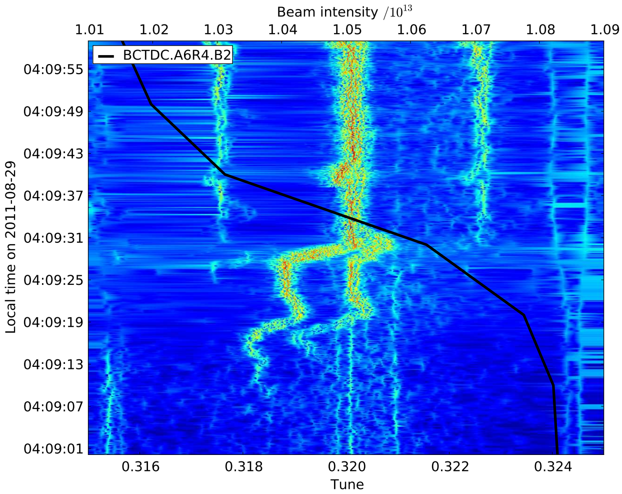

Figure 26: BBQ vertical tune spectrum evolution with time for beam 2, at the time of the losses on Aug. 29th. The black curve gives the total bunch current from the BCT.

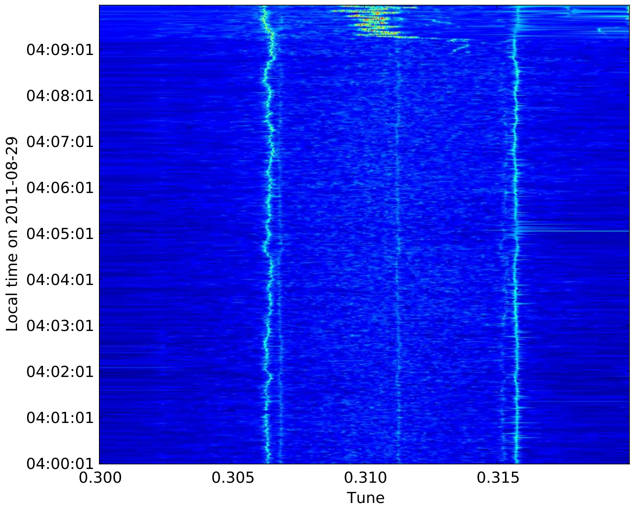

Figure 27: BBQ horizontal tune spectrum evolution with time for beam 1, before the losses on Aug. 29th.

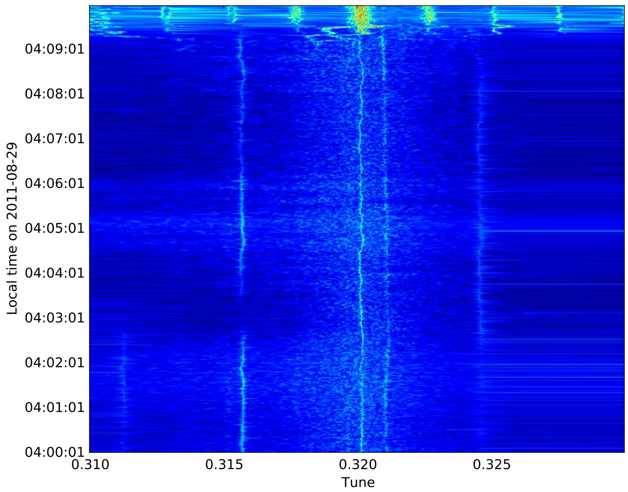

Figure 28: BBQ vertical tune spectrum evolution with time for beam 1, before the losses on Aug. 29th.

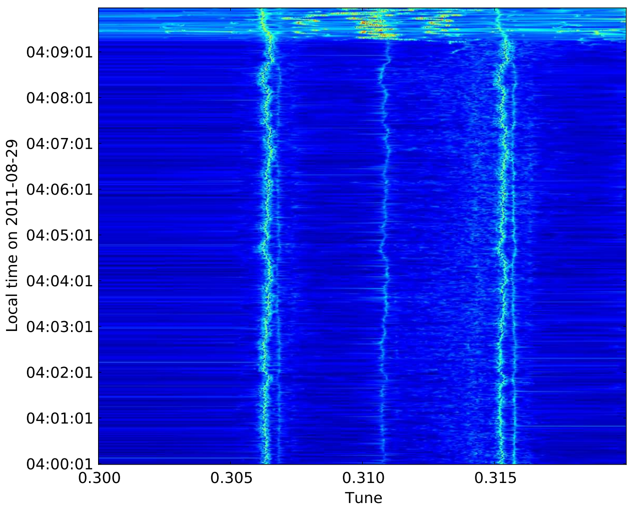

Figure 29: BBQ horizontal tune spectrum evolution with time for beam 2, before the losses on Aug. 29th.

visible. Simultaneously a strong emittance blow-up was also observed, as visible in Fig. 32. Both the lines in the BBQ spectra and the emittance blow-up could have been triggered by a headtail instability of azimuthal mode number $m = \pm 2$, but this is still to be confirmed. Another possible explanation for the lines in the BBQ spectra (but not for the emittance blow-up) could be that it is a quadrupolar longitudinal oscillation due a longitudinal mismatch.

In any case, the observed blow-up has decreased the beam-beam distance, which was already small ($7.7\,\sigma$ instead of $9.3\,\sigma$ in the physics fills that were done later on in 2011) due to the small crossing angle set in this MD ($100\,\mu$rad). With such a blow-up, the beam-beam separation might well have gone down to $5\,\sigma$, which could affect long range beam-beam coherent modes [21] and could therefore explain the losses.

More studies and MDs are required to give a more definite explanation of these obervations. Nevertheless, there are some general guidelines for future operation:

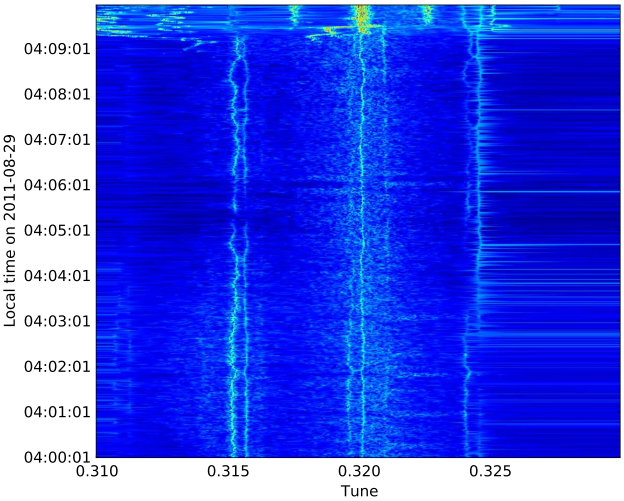

Figure 30: BBQ vertical tune spectrum evolution with time for beam 2, before the losses on Aug. 29th.

- to prevent long range beam-beam coherent modes to appear, avoid too small beam-beam separation,
- to damp headtail modes, do not run with too high chromaticities or too small octupole currents. In particular, at the end of 2011, the octupole currents were increased to ± 200 A and Q' corrected down to 1-2 units.

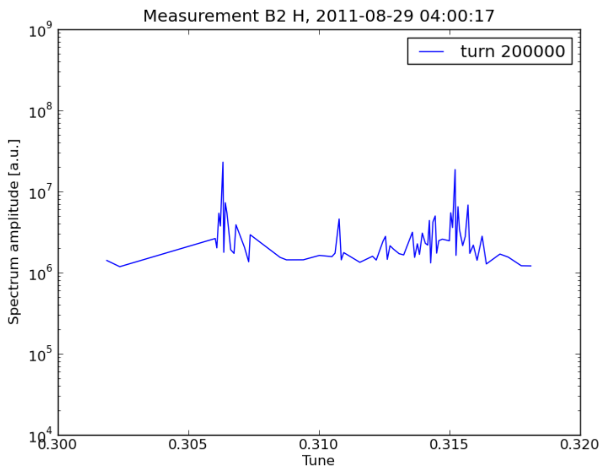

Figure 31: BBQ horizontal tune spectrum for beam 2 during the squeeze on Aug. 29th.

POSSIBLE IMPEDANCE LIMITATIONS IN 2012

With the LHC impedance model and Sacherer's formula [5] (note that we also tested Laclare's formalism [22], obtaining very similar results), we computed the complex tune shifts with the tight collimator settings. We used the settings obtained for beam 1 during the MD of May 7th, 2011, knowing that they are very similar to the tight settings tested at other times in the year, at least for the most

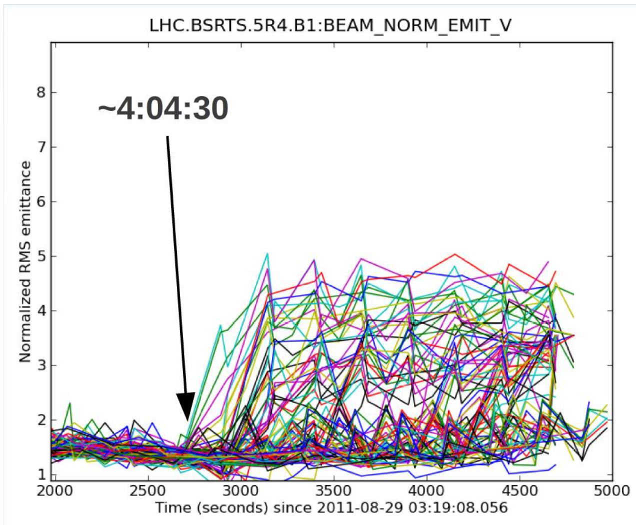

Figure 32: Beam 1 vertical emittance of each bunch from the BSRT (Beam Synchrotron Light Telescope), on Aug. 29th.

critical collimators (those closest to the beam). We scaled the half-gaps with $\gamma^{-\frac{1}{2}}$ (γ being the relativistic mass factor) for the 4 TeV$/c$ case. We tested the most critical headtail mode[2] $m = 1$ for three different situations likely to occur in 2012:

- momentum 3.5 TeV$/c$, 1782 bunches (50 ns spacing), intensity $1.7 \cdot 10^{11}$ protons per bunch,
- momentum 4 TeV$/c$, 1782 bunches (50 ns spacing), intensity $1.7 \cdot 10^{11}$ protons per bunch,
- momentum 4 TeV$/c$, 3564 bunches (25 ns spacing), intensity $1.2 \cdot 10^{11}$ protons per bunch.

Note that Q' was set to 2 and the total bunch length to 1.2 ns in each of these scenarios. First results show that there is almost no difference between the 4 TeV$/c$ and the 3.5 TeV$/c$ cases. Then, the 25 ns case is 30% less critical than the 50 ns one, which is due to the lower intensity while the bunch spacing (and therefore the number of bunches) has a rather small impact on the complex tune shift. Finally, for the worst case (50 ns with 4 TeV$/c$), the complex tune shift is in absolute value 2.3 times higher than the one we would have obtained with the same model for the situation at the end of the physics run in 2011, i.e. 1380 bunches and $1.45 \cdot 10^{11}$ protons per bunch, intermediate collimator settings, same Q', bunch length and transverse emittances as above. Note that we neglected the difference between a partially filled machine with 1380 bunches and a fully filled one with 1782 equidistant bunches.
Finally, knowing that the detuning coefficients and therefore the stability diagram are proportional to the current in the octupoles [11, 23], we expect the beams to be stable with 2.3 times the octupole current of 2011, i.e. ~ 450 A

[2] According to the current LHC impedance model, the modes $m = \pm 2$ are less critical than the $m = \pm 1$ ones.

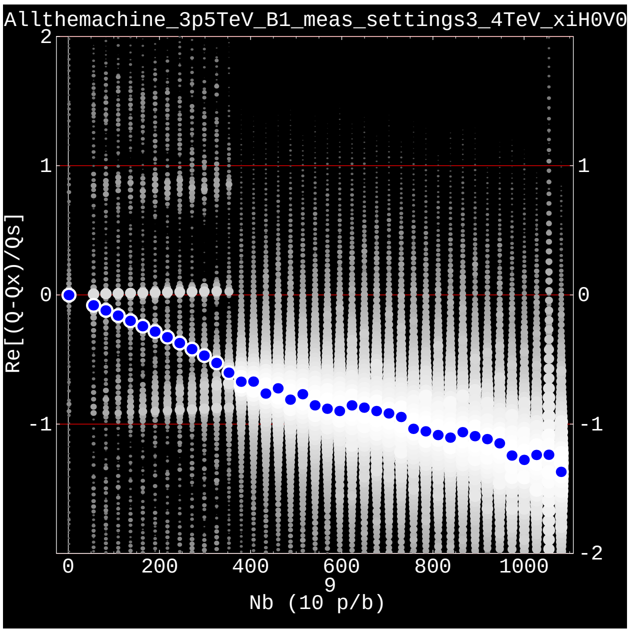

Figure 33: Tune spectrum (normalized by the synchrotron tune Q_s) in the horizontal plane vs. bunch intensity, for a single-bunch at 4 TeV/c with tight collimator settings, at zero chromaticity and without octupoles. The brightness of the points reflects the spectrum line amplitude.

in the defocusing octupoles and -450 A in the focusing ones.

Concerning the transverse mode coupling (TMC) threshold, it is estimated (from the LHC impedance model with HEADTAIL simulations) to be at an intensity of $3.8 \cdot 10^{11}$ protons per bunch, in the single-bunch case, as can be inferred from Fig. 33. The coupled-bunch TMC theshold is estimated to be around 20% smaller [1] with 50 ns spacing, that is to say around $3 \cdot 10^{11}$ protons per bunch. These values have to be considered with care since it was seen in the first section that the model underestimates the machine impedance by a factor 2-3. At least we know from 2011's experience that the TMC threshold is above 10^{11} protons per bunch (see previous section).

CONCLUSION

In the LHC, beam-based measurements of tune shifts and instability rise times show a discrepancy of factor 2-3 with respect to the impedance model and HEADTAIL simulations. More measurements are needed, in particular concerning Landau stabilization at flat top, coupled-bunch tune shifts and transverse mode coupling thresholds. Tight collimator settings that might be used in 2012, were tested four times in 2011, both in single-bunch and coupled-bunch regimes. These tests did not reveal any impedance-related problem except for one of them, on August 29th, when high beam losses were observed. The observed phenomena during this MD were, in order of appearance: 1) during the squeeze, two lines in the tune spectra, at $\sim 2Q_s$ from the main tune and at each side of it; 2) an emittance blow-up several minutes before the losses; 3) at the end of squeeze, rapid losses on several bunches in the middle of the first batch of 36 bunches together with a large coherent signal in the BBQ and new lines appearing in the tune spectra; 4) at the end of the losses, a "Christmas tree" characterized by regularly spaced peaks at $\pm Q_s$ from each other, visible only in vertical. With such tight collimator settings, we finally compared, thanks to the model, the worst case scenario (50 ns, $1.7 \cdot 10^{11}$ protons per bunch, same emittances as during the 2011 physics run) with respect to the end of the 2011 physics run, finding that ~ 450 A are required in the defocusing octupoles (and -450 A in the focusing ones) to stabilize the beam. We could improve the situation with chromaticities closer to zero (i.e. $Q' < 2$) or with the 25 ns beams with a lower bunch intensity.

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