# REVIEW OF THE INSTABILITIES OBSERVED DURING THE 2012 RUN AND ACTIONS TAKEN

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### *Abstract*

Despite the excellent performance of the LHC in 2012, with a record peak luminosity at 4 TeV corresponding to 77% of the 7 TeV design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$, the intensity ramp-up was perturbed by several types of instabilities. All the observations (during both physics cycles and dedicated MDs) are critically reviewed, comparing them to past predictions and new findings. The lessons learned and actions taken are then discussed in detail.

## INTRODUCTION AND MAIN LIMITATION AT THE END OF THE RUN

The LHC luminosity has been considerably increased in 2011 and 2012 and the peak luminosity record was ~ 7.7 $10^{33}$ cm$^{-2}$s$^{-1}$, corresponding to 77% of the 7 TeV design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$, but at 4 TeV, i.e. 4 / 7 = 57% of the design energy. This great achievement led to the discovery of a Higgs-like boson, announced on July 4th, 2012, and to a total integrated luminosity of ~ 23 fb$^{-1}$ for the two high-luminosity experiments, ATLAS and CMS. Furthermore, only half of the design number of bunches has been used (1374), using a beam with 50 ns bunch spacing instead of the nominal 25 ns bunch spacing. However, and this is the reason of the success, the bunch brightness was up to ~ 2.4 times larger than nominal, as bunches with ~ 1.6 $10^{11}$ p/b within ~ 2.2 µm (transv. r.m.s. norm. emittance) were successfully put in collision, instead of the nominal bunches of 1.15 $10^{11}$ p/b within 3.75 µm. Finally, tight collimators settings (collimator apertures close to nominal ones at 7 TeV) have been used in 2012, leading to larger impedances and more critical instabilities (a factor ~ 2.3 was computed for the transverse plane compared to 2011 [1]).

Despite the excellent performance of the LHC in 2012, 3 types of instabilities perturbed the intensity ramp-up, which are discussed below.

### *In collision: "Snowflakes"*

These instabilities happened always in the horizontal plane only, for both beams and could happen after several hours of stable beam (see an example in Fig. 1). It concerned initially only the IP8 private bunches, i.e. the bunches colliding only at the Interaction Point 8. This was rapidly identified and these instabilities disappeared once the filling scheme was modified (reducing first the number of private bunches and then removing them all). The interpretation of this mechanism is that it happens on selected bunches with insufficient tune spread (and thus Landau damping) as they have no Head-On collisions in IP1/2/5 and have a transverse offset in IP8 to level luminosity.

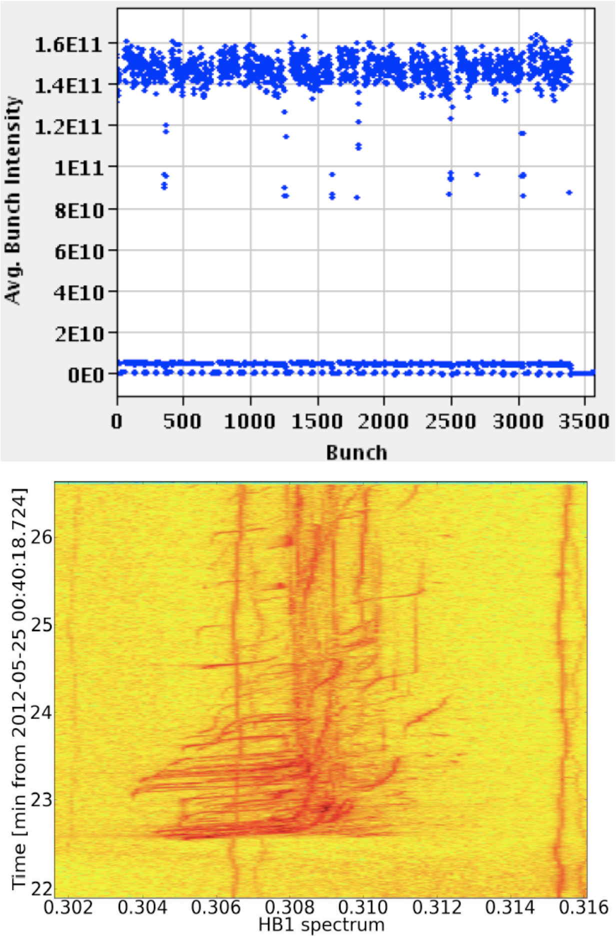

Figure 1: Example of "snowflakes" instability: (a) bunch intensity vs. number of the bunch (25 ns slot) and (b) horizontal frequency spectrum vs. time. Courtesy of X. Buffat.

### *During the collapsing process (putting the beams into collision)*

A second type of instabilities happened at the end of the collision process when ending with residual separations of ~ 2.1 σ in IP1 and ~ 1.2 σ in IP5 (values estimated from luminosities at the moment of the dump).

These instabilities happened also in the horizontal plane and an example is given in Fig. 2.

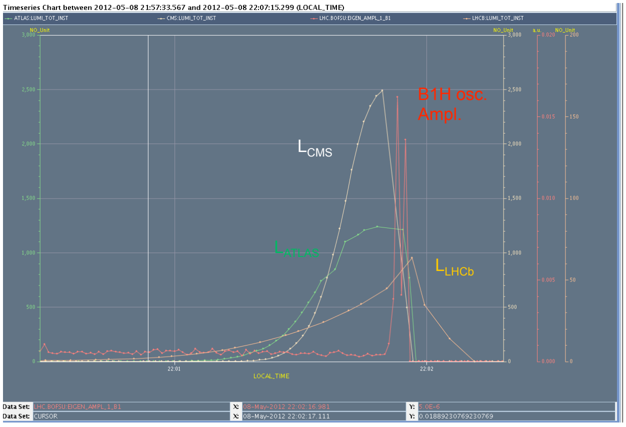

Figure 2: Example of instability during the collision process (putting the beams into collision): the luminosities vs. time are represented for the different experiments as well as the horizontal oscillations amplitude for beam 1. Courtesy of G. Arduini.

### *During or at the end of the squeeze process: EOSI (End Of Squeeze Instability)*

A third type of instability happened during or at the end of the squeeze, called EOSI (End Of Squeeze Instability), also in the horizontal plane. A characteristic picture is shown in Fig. 3, where 3 lines spaced by the (small-amplitude) synchrotron tune can be observed.

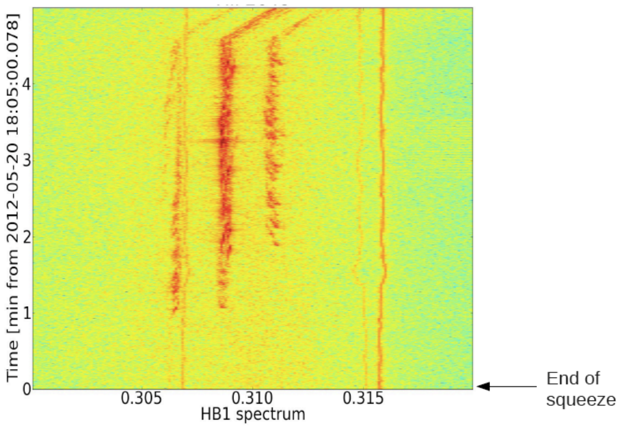

Figure 3: Example of instability observed at the end of the squeeze: horizontal frequency spectrum vs. time after the end of the squeeze. Courtesy of X. Buffat.

The first and second types of instabilities did not appear anymore after the change of the Landau octupoles polarity (moving from negative to positive detuning with amplitude) on August 7th (fill #2926) and the increase of the chromaticities and the transverse damper (ADT) gain. Unfortunately these 3 parameters have been modified more or less at the same time and it is therefore not possible to identify the main beneficial effect. The third type of instabilities could not be cured during the entire run despite the increase of the octupoles current close to its maximum value (550 A), the increase of chromaticities from ~ 2 units to ~ 15-20 units and the increase of the ADT gain to its maximum value (50 turns damping time). Note however that this instability appeared then mostly in the vertical plane of beam 1. Furthermore, it became then very reproducible at the end of the squeeze (with even more synchrotron sidebands), when β* is already at 60 cm, and after ~ 16 min from the start of the squeeze process. Examples of this instability are shown in Fig. 4.

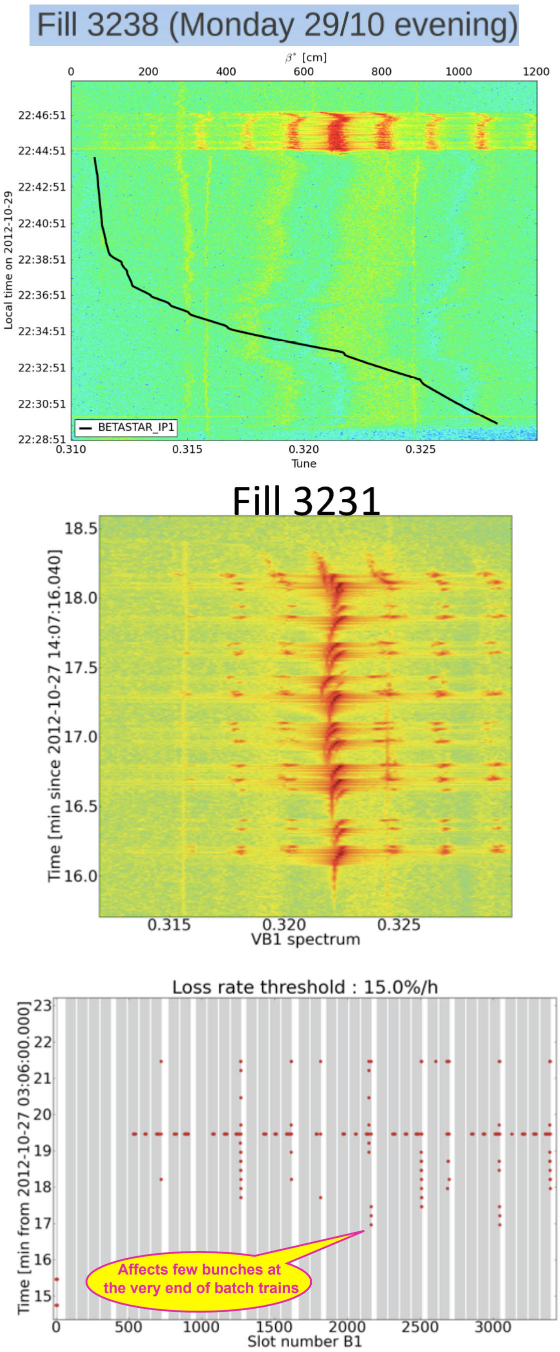

Figure 4: Examples of the EOSI instability at the end of the run, which could not be cured: (a) Courtesy of N. Mounet and (b) and (c) courtesy of T. Pieloni.

## PAST PREDICTIONS, NEW FINDINGS AND ACTIONS TAKEN

Based on the past work done before the LHC commissioning [2,3], the first measurements of transverse coherent instability with a single bunch [4] and with a train of 12+36 bunches [5], the initial recommendations at the beginning of the run were the following [6]:

1) Chromaticities: ~ 1-2 units (with the wish to make some controlled studies during the run with negative values as the possibility of running with slightly negative chromaticities was proposed in the past [2]).

2) Landau octupoles current (in the focusing ones): ~ -450 A (as ~ - 200 A was used at the end of 2011 and the impedance should have been increased by a factor ~ 2.3 with the tight collimators settings).

3) Bunch length (rms): increase it from 9 cm (i.e. 1.2 ns total) in 2011 to ~ 10 cm (i.e. ~ 1.35 ns total) in 2012 for beam-induced RF heating reasons [7].

4) ADT gain: reduce it as much as we can (to minimize the possible noise introduced and the associated transverse emittance growth).

However, several issues rapidly appeared during spring and several actions were taken to continue and push the performance:

1) To avoid the beam dumps triggered during the collision process, it was proposed to change the sign of the Landau octupoles such that the tune spreads from beam-beam and octupoles add up instead of compensating each other and therefore do not fight against each other (for both Long Range - LR - and HO, IP8 and nominal bunches) [8].

2) New values for the ADT gain, chromaticities and Landau octupoles current were then suggested after a new analytical approach from A. Burov [9,10]. Figure 5 shows the latest results obtained by A. Burov for the 50 ns beam, with 1.5 $10^{11}$ p/b within 2 $\mu$m. Several conclusions can be drawn from this figure. In the absence of transverse damper, the usual results for both single-bunch and coupled-bunch head-tail instabilities are obtained and some Landau damping is needed [3]. In the presence of the transverse damper, a valley with zero Landau octupoles current is found for negative chromaticities as discussed for instance in Ref. [11] and proposed as a possible remedy in Ref. [2]. The interpretation being that for slightly negative chromaticities, the higher-order head-tail modes are intrinsically damped and the enhanced instability of mode 0 is damped by the transverse damper. However, if the transverse impedance is twice the nominal one, the valley disappears and the best operational location seems to be at high chromaticities, i.e. ~ 15 - 20 units for a sufficiently high ADT gain (with its initial bandwidth [12]). Finally, another very interesting observation is that for sufficiently high ADT gain and chromaticities, the stabilizing Landau octupoles current is the same for both single-bunch and coupled-bunch instabilities.

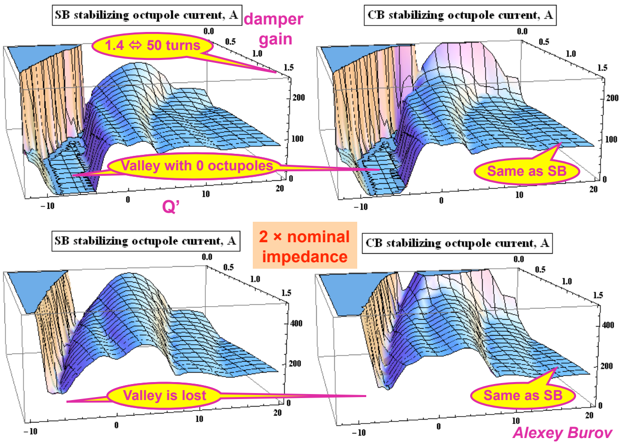

Figure 5: Stabilizing Landau octupoles current (in A) vs. chromaticity and ADT gain for (upper left) a single bunch with nominal transverse impedance, (lower left) a single bunch with twice the nominal transverse impedance, (upper right) the 50 ns beam with nominal transverse impedance, (lower right) the 50 ns beam with twice the nominal transverse impedance. Courtesy of A. Burov.

The conclusions of all the 1-beam studies are the following:

1) The current model (for the transverse impedance and the Landau damping mechanism) seems consistent and disagreements with dedicated measurements never exceeded a factor ~ 2. This is why most of the time now we consider the impedance as being a factor 2 larger than nominal. This result was already obtained in the past in several studies without ADT [5] and it seems to be confirmed this year including the effect of the ADT [10].

2) It happened several times that the situation was much better than predicted, which can be explained by larger transverse tails (for the previous negative octupoles polarity) or longitudinal tails.

The problem with the EOSI comes in the presence of 2 beams, below a $\beta^*$ of few m. Much more octupoles current than for 1 beam is needed, and the maximum available value was in fact not enough to completely suppress the instability. It was however sufficient in 2012 to reach the HO collisions, which then stabilizes everything but we might be limited at higher energies, and this is therefore a potential worry/showstopper for the future [13].

Therefore, the remaining question is: why is the beam unstable at the end of the squeeze? Do we understand well the ADT? Recent simulation studies are shown in Fig. 6, revealing in particular the effect of a flat gain [12] over all the coupled-bunch frequency range. Do we lose Landau damping due to the interplay with other mechanisms? Either because the stability diagram is modified (shifted, deformed, collapsing etc.) due to other nonlinearities: (i) beam-beam (LR and/or HO), but it seems it cannot explain the EOSI [14]; (ii) machine nonlinearities, but it seems also that it cannot explain the EOSI; (iii) e-cloud in IRs? This is the recent hypothesis from A. Burov, which he just started to study [15];

(iv) others? Or, because the coherent tune shift (of some modes) is underestimated: (i) a 2-beam impedance MD was performed [16], which remains without clear conclusions; (ii) beam-beam coherent modes (mode coupling), see below and Fig. 7; (iii) e-cloud in IRs? Recent hypothesis from A. Burov; (iv) others? The study of the mode coupling between the beam-beam coherent modes and the impedance-induced modes has been done by S. White by including the impedance model of Ref. [5] into the beam-beam code BeamBeam3D [17] (see Fig. 7). In case of such a problem, the solution is to introduce a tune split between the 2 beams to decouple the machine, as usual when coherent beam-beam modes are involved, as it is simply explained for instance in Ref. [18]. It is seen indeed from Fig. 7 that introducing a tune split shifts the mode coupling instability threshold to a higher number of LR interactions and that therefore the unstable bunches should move from the tail (original observed positions) to the centre of the batches. Some studies have been suggested and performed, starting with the fill #3259 (see Fig. 8), where the unstable bunches seemed indeed to move from the tail to the centre, as expected. Other studies are shown in Fig. 9. It is difficult to conclude on the effect of the tune split (and its sign) due to the small statistics and the fact that some fills with tune split behaved very similarly to other fills. It is worth noting that simulation studies show that this instability should be suppressed by the ADT (as studied by A. Burov [19] and S. White [20]) and therefore a tune split should even not be needed. However, is it really true in reality in the presence of other effects such as noise etc.? This will be followed up with multi-bunch tracking studies.

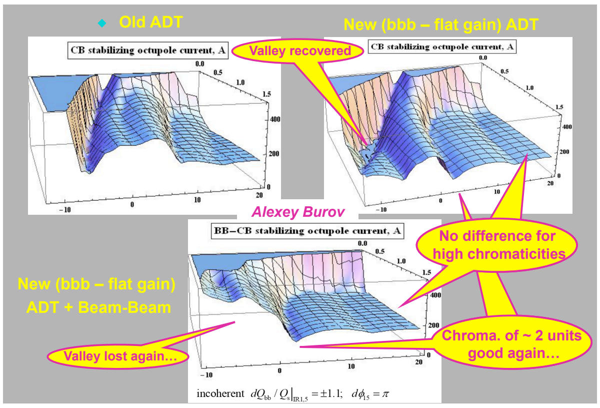

Figure 6: Recent studies on ADT with initial gain and flat gain [12]. Courtesy of A. Burov.

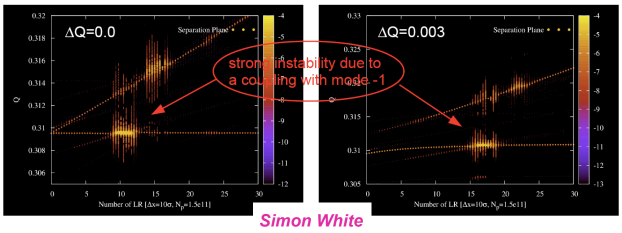

Figure 7: Interplay between the LHC impedance and beam-beam coherent modes, leading to mode coupling (a) without tune split and (b) with a tune split. Courtesy of S. White.

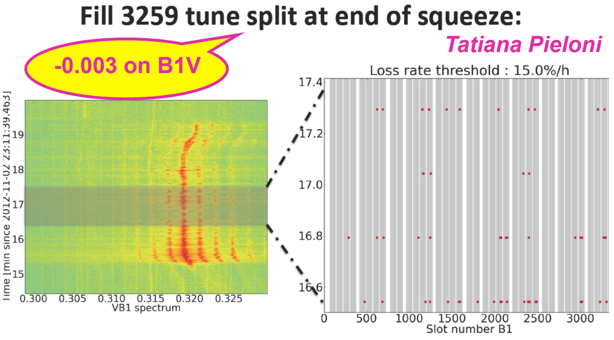

Figure 8: Measurements of the unstable bunches in the presence of a tune split of -0.003 in the vertical plane of beam 1.

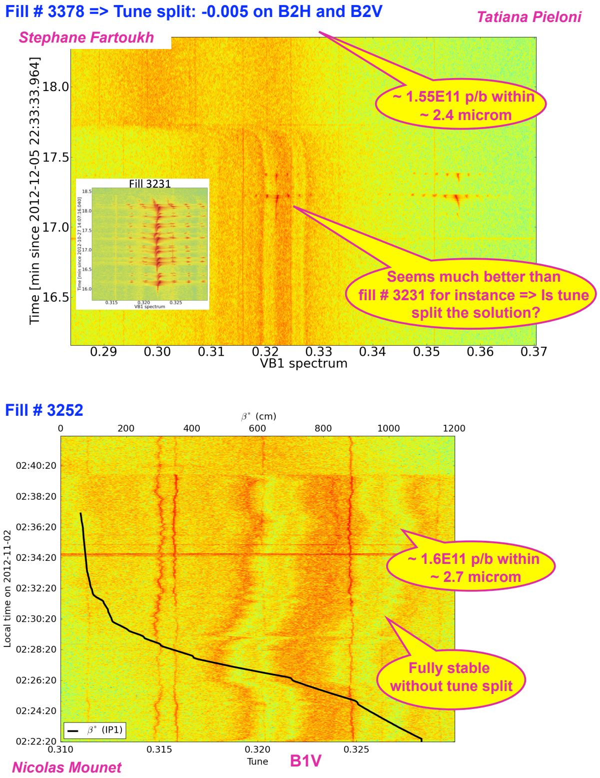

Figure 9: Other studies than in Fig. 8, (a) with and (b) without tune splits, where it is therefore difficult to conclude about the beneficial effect of the tune split.

## CONCLUSIONS AND LESSONS LEARNED FROM 2012

The impedance model and Landau damping mechanism with 1 beam only is reasonably well understood as measurements never revealed a factor more than ~ 2 over the last few years. Furthermore, we have also now a new global instability model including the transverse damper, which gives us a better understanding of the single-beam phenomena. This factor ~ 2 will need however to be better understood in the future.

The main problem concerns the 2-beam operation, for which much more octupoles current than predicted is needed and the reason has not been identified yet. Several observations have been made: some of which are clear and some of which are less clear. The clear observations are summarized below:

i) Instabilities are observed only for β* smaller than few m;

ii) Increasing the Landau octupoles current helps. As we should be limited at higher energies, could we have more octupoles current in the future? It seems that a factor ~ 2 could be gained with the spool piece correctors MCO and MCOX (the dynamic aperture should also be watched out) [21];

iii) Increasing chromaticities to ~ 15-20 units helped a lot (but according to A. Burov's theory a plateau has been reached now and no further stability gain can be expected by increasing the chromaticity);

iv) Once in collision, no instability is observed anymore due to large beam-beam HO tune spread (see also Ref. [14]);

v) No beam dumps have been observed anymore with the new (positive) Landau octupoles polarity, higher chromaticities and ADT gain, which have been modified at the same time. Note that there were also discussions to modify the collision beam process to go faster through the critical points [22], but this was implemented later.

The plan for the future is to continue the data analyses (trying for instance to identify the tunes which were lost by using the trims, the head-tail modes excited, etc.), and try and understand / work more on interplays between different mechanisms (incoherent and coherent): impedance, nonlinearities (machine and Landau octupoles), space charge (at low energy), ADT, longitudinal bunch distribution, beam-beam when the beams start to see each other, e-cloud… One needs also to understand better how the ADT works [12] and to continue and benchmark the new results [10] with tracking codes. This already started and will be continued by including the ADT in the HEADTAIL code [23] (ongoing) and including the impedance and ADT in the beam-beam COMBI code [24].

Finally, based on the 2012 experience, it is also fundamental to try and benchmark some of the main theoretical/simulation results at an early stage of the (re-)commissioning as things get then rapidly very intricate and it becomes more difficult to apply the proper corrections.

# APPENDIX A

The other beam spectra of the fill #3252 (see Fig. 9c), which was fully stable without tune split, are shown in Fig. A.

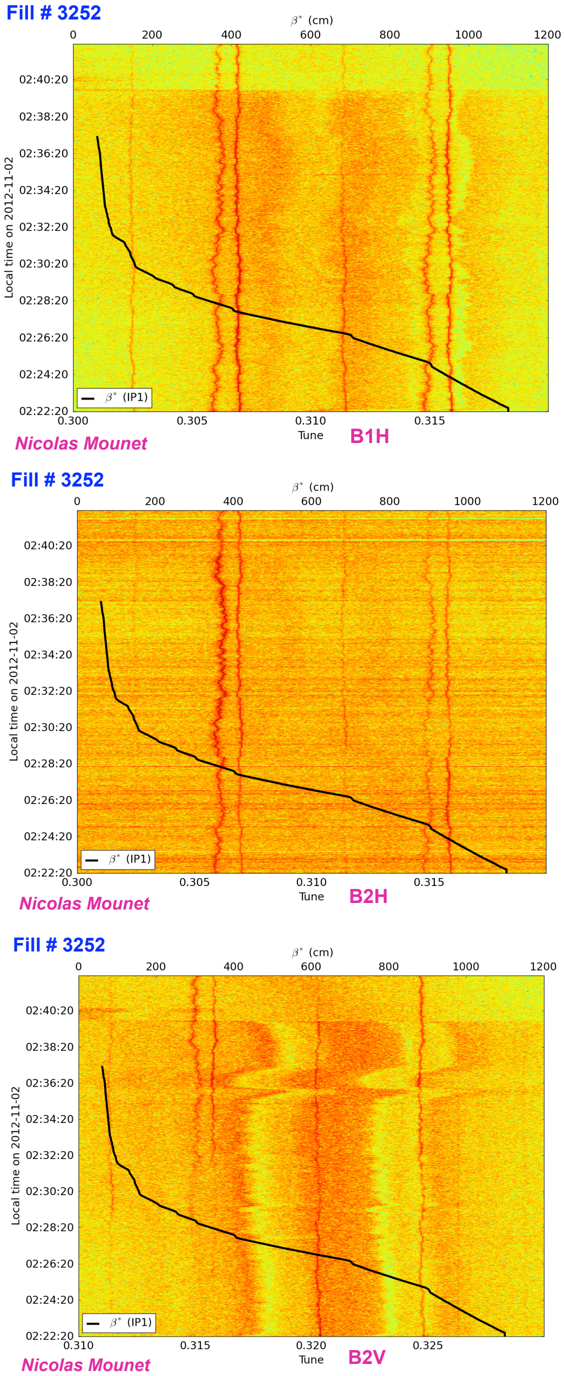

Figure A: Beam spectra for the fill #3252 in the horizontal plane for both beams and vertical plane for beam 2. The vertical plane for beam 1 is shown in Fig. 9c.

# APPENDIX B

There were several examples of fills without instability with the old/previous (negative) polarity of the Landau octupoles with intensities per bunch between ~ 1.47 $10^{11}$ p/b and 1.51 $10^{11}$ p/b: e.g. #2717, 2718, 2719, 2720, 2723, 2724, 2725, 2726, 2728 and 2729. They all came after good chromaticities measurements all along the cycle and proper corrections to ~ 2 units applied at all stages.

## APPENDIX C

In addition to the 3 types of instabilities discussed in the paper, there were also 2 other types of instabilities:

i) A 4th type of instability was observed at injection (leading to transverse emittance blow-ups of some injected batches). This is the reason why 6.5 A in the Landau octupoles are used at injection. Note that this value has been found to work but it was not optimized and the reason why it works not yet understood. Note also that the octupoles current had to be increased even more (by a factor ~ 4) during the 25 ns scrubbing run in the presence of electron cloud. This should be followed up in the future.

ii) A 5th type of instability was also observed at flat-top before the squeeze in some cases before the re-optimization of the octupoles current as the 1-beam instability was expected to be more critical with the current (positive) sign of Landau octupoles (e.g., a factor ~ 1.6 was anticipated for a Gaussian transverse profile).

## APPENDIX D

During the 2012 run, there were a lot of discussions about the crossing, during a certain time, of a zero or small tune spread: this can be the case for instance when the Landau octupoles had the negative polarity and beam-beam and octupoles fought against each other or during the collision process (whatever the octupoles current). Is crossing a zero (or very small) tune spread a problem? Yes, in principle it is a potential weakness but several other aspects should be considered at the same time. For instance, what is important in the end is the stability diagram, as the spread has to be at the correct place (with the coherent tunes inside). Furthermore, the time of the process and the most critical instability rise-time should be compared, as the instability might not have the time to develop.

For instance, the PS machine is crossing a zero tune spread every cycle at transition (see Fig. D). The solutions (if this is really a problem, i.e. above a certain intensity) are:

i) Don't cross the zero tune spread if possible. This is what was implemented in the LHC for the very small tune spread due to beam-beam and octupoles compensation by changing the sign of the octupoles. In the PS, to avoid crossing transition it would require to modify the optics.

ii) Cross faster and/or cleaner (e.g. IP1&5 first and then IP8), as it was proposed and implemented during the year. For the PS, the transition is crossed faster by using a gamma transition jump (see Fig. D) and therefore the time, during which the tune spread (proportional to the slip factor) is small, is considerably reduced and the intensity threshold is then significantly increased.

iii) Another possibility is also to try and increase the instability rise-times by reducing the impedance (opening the gaps, changing the collimators materials etc.) and/or by playing with the chromaticities and transverse damper gain (as was done also at the same time when the octupoles current was changed).

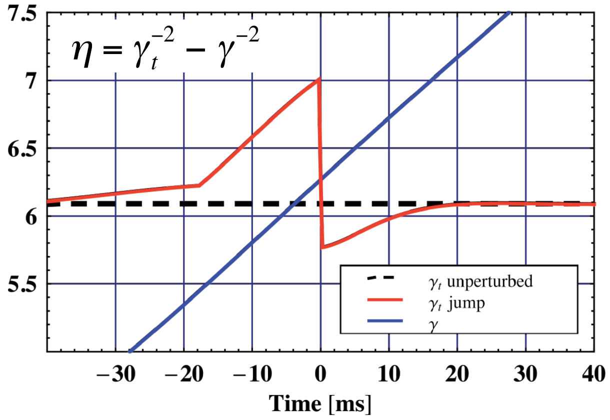

Figure D: Example of the PS transition crossing. Evolution of the relativistic gamma transition (and of the of the relativistic gamma of the beam) near transition crossing without and with the present relativistic gamma transition jump.

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