STABILITY OF COLLIDING BEAMS AT 6.5 TeV

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Abstract

In this paper we will try to propose some possible scenarios for operation of beams during the betatron squeeze, adjust and stable beam mode at 6.5 TeV energy for after the LS1. The available parameter space in term of intensity, chromaticity, octupole current, damper gain, bunch spacing and length will be explored and conclusions on possible settings for the operation will be based when possible on experience from the LHC physics runs. Different luminosity leveling scenarios will be considered. Techniques to mitigate instabilities when beam-beam effects are involved will also be discussed.

INTRODUCTION

The 2012 run of the Large Hadron Collider (LHC) has shown, despite the great physics discovery of a Higgs-like boson, several instabilities which have perturbed the accelerator performances. To achieve the required integrated luminosity several parameters had been changed and pushed compared to 2011: reduced β^*, from 1 m to 0.6 m, and higher brightness beams (approximately two times larger than nominal). To ensure protection of the triplets collimator gaps have been reduced to tight settings corresponding to apertures close the nominal 7 TeV configuration, leading to larger impedances [1]. A first type of instabilities occurred during stable beams after many hours of physics and affected specific bunches colliding only in the LHCb experiment. A second type was developing at the end of the betatron squeeze (after 3 m β^*) and while bringing the beams into collision as described in [2]. The origin of these instabilities is still not fully understood however some observations have led to considerations on the beam stability to help defining LHC possible future scenarios.

INSTABILITIES

The main beam parameters, compared to those of 2010 and 2011, are summarized in Tab. 1.

Parameter	2010	2011	2012	Nominal
N$_p$[10^{11} p/b]	1.2	1.45	1.58	1.15
N$_b$	368	1380	1380	2808
Spacing [ns]	150	75/50	50	25
ϵ [μ m rad]	2.4-4	1.9-2.4	2.2-2.5	3.75
β^* (IP1/5) [m]	3.5	1.5-1	0.6	0.55
L [10^{32} cm$^2 s^{-1}$]	2	35	76	100

Table 1: LHC Operational Parameters

The LHC beams were accelerated in 2012 from injection energy (450 GeV) to a top energy of 4 TeV. The β^*s at the different Interaction Points (IPs) were then lowered (from 10 m to 3 m in IP2 and IP8 and from 11 m to 0.6 m in IP1 and IP5). This process, known as β squeeze, lasted around 15 min. At the beginning of the year at a β^* value of $\approx$ 1.5 m during the execution of the β squeeze several bunches were becoming unstable, losing their intensity in a non reproducible manner. In particular the instability was observed only during a subset of the physics fills. The bunches have become unstable one after the other for several minutes till the head-on collision was established. In some cases, the instabilities generated losses high enough to cause a beam dump. An important parameter for stability is chromaticity which might explain the non reproducibility of the instability when operating with small positive value (LHC was operating at Q' $\approx$ 2 units till the beginning of August 2012). At the beginning of August 2012 the machine configuration has been changed drastically in terms of chromaticity (changed from 2 units to 15 units [2, 6]), the polarity of the Landau octupoles (changed from negative to positive [9]) and the transverse damper (from 100 to 50 turns). The changes have been implemented within a few fills since fill number 2926, making difficult the analysis of the implications of the different parameters. As a result of these changes the instability has significantly changed. It became extremely reproducible, occurring after two minutes before the end of the squeeze and in the vertical plane only. Many bunches were affected by the instability, causing reduced intensity drops, as opposed to large losses on few bunches in the previous configuration. Two examples of the bunch by bunch intensity losses versus time during this type of instability is shown in Fig. 1.

The coherent mode is shown in Fig. 2 where several frequencies are visible all spaced by $Q_s \approx 0.002$, the synchrotron tune. Several bunches were loosing up to half their intensity while coherently oscillating. Bunches where going unstable at different moments and the instability could last till the head-on collision was established and coherent motion stopped.

The stability of the beams before going through the β squeeze and during the squeeze is given by the Landau octupoles which ensure a given stability diagram, defining a limit under which all impedance driven modes should be stabilized. In the LHC the stability diagram at the beginning of the betatron squeeze are illustrated in Fig. 3 (dashed lines) for both octupoles polarities. In red we show the stability diagram with negative octupole polarity and in blue the positive polarity effect. The negative polarity was preferred before the squeeze since it provides larger area for

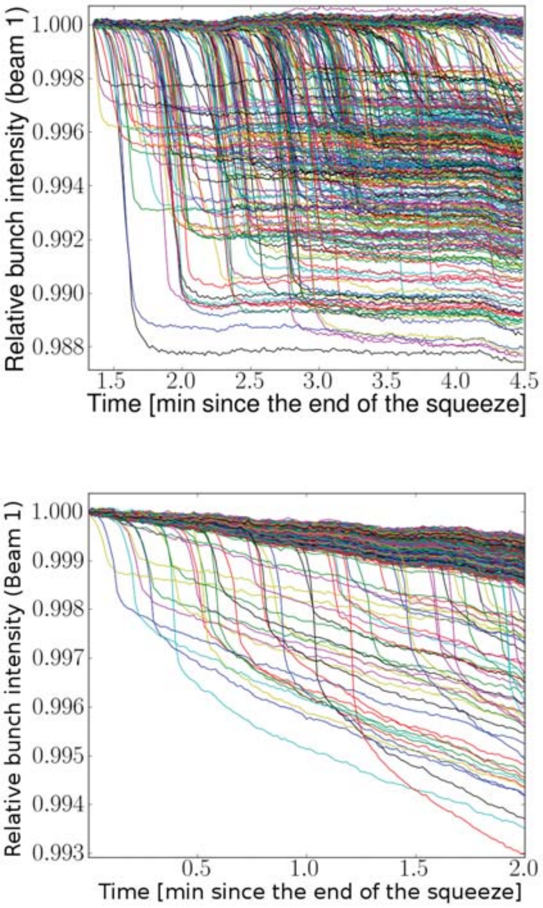

Figure 1: Bunch by bunch losses in beam 1 during an end of squeeze instability as a function of time for Fill 2648 with negative octupole polarity (top picture) and Fill 3250 with positive polarity(bottom plot).

the expected modes, having negative real tune shift [10]. However, the long-range interactions also contribute to the non-linearities and affect the stability diagram at the end of the β squeeze (solid lines in Fig. 3). For the case of negative polarity they reduce the stability area while for the positive polarity they increase it. This was the motivation for inverting the polarity of the Landau octupoles [9] but the instabilities observed at the end of the squeeze is still present in the new configuration, despite the larger stability diagram at the end of the squeeze, increased damper gain and larger positive chromaticity, and remains unexplained.

COLLIDE AND SQUEEZE

Observations of the LHC 2012 instability have also demonstrated the head-on collision to be very efficient to stabilize the beams. Indeed, the tune spread due to a head-on collision is much larger than the one due to octupoles or beam-beam long range interactions or any other non-linearity present in the LHC. Moreover, the detuning is more important on the core particles of the beam rather than the tails, which significantly enhances its contribution to the stability diagram, as shown by Fig. 4. An observation of this effect is shown on Fig. 2 where the coherent oscillations is visible all along the end of the betatron squeeze and disappears when the beams are brought into collision. It would be therefore profitable to have the beams colliding during (part of) the squeeze in order to avoid instabilities, details on this possibility are discussed in [5].

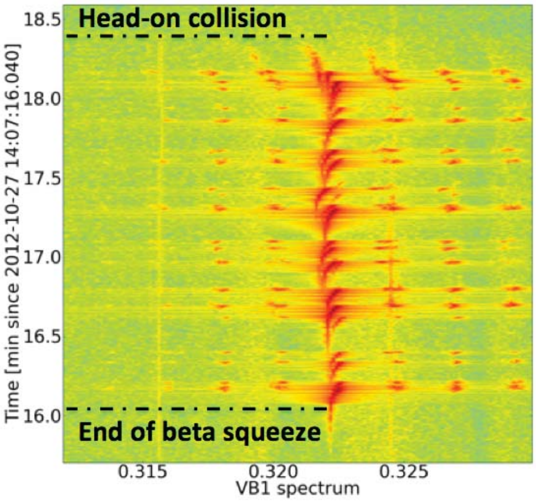

Figure 2: Beam 1 vertical frequency spectrum as a function of time during an end of squeeze instability.

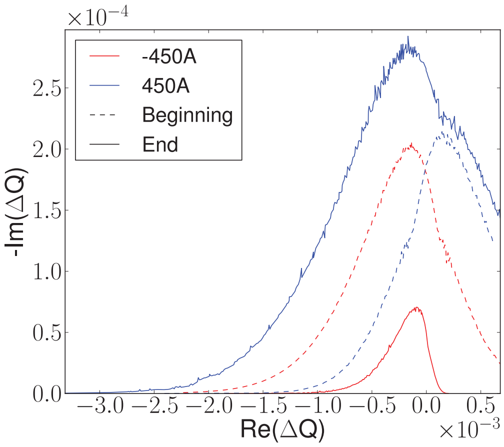

Figure 3: Beam stability diagrams for the two LHC octupole configurations: positive (blue lines) and negative (red lines) before the betatron squeeze (dashed lines) and at the end with long-range contribution (solid lines).

GOING INTO COLLISION

The end of squeeze instability, as shown in Fig. 2, was lasting also during the collision beam process. At the be-

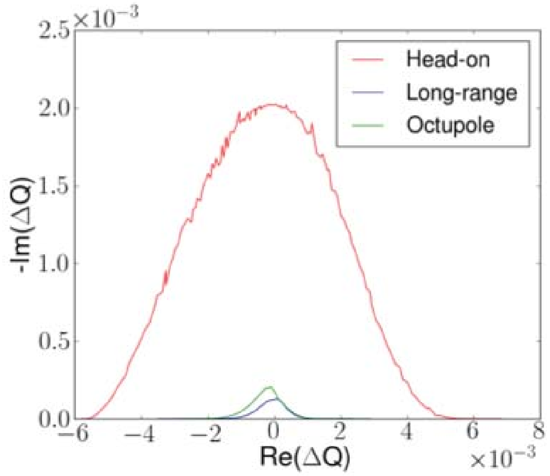

Figure 4: Beam stability diagrams provided by one head-on collision compared to octupoles and long-range.

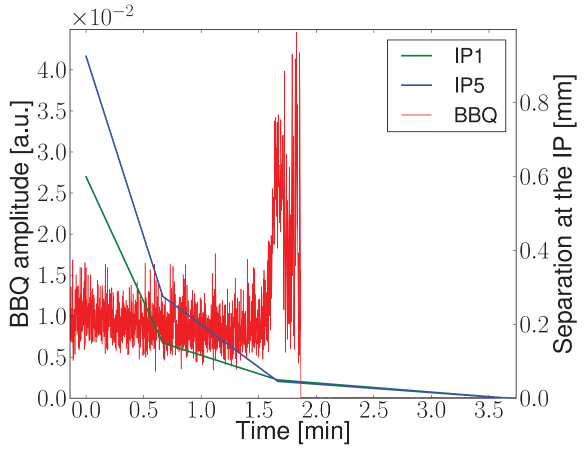

Figure 5: Oscillation amplitude of beam1 during the collapse of the separation bumps as a function of time.

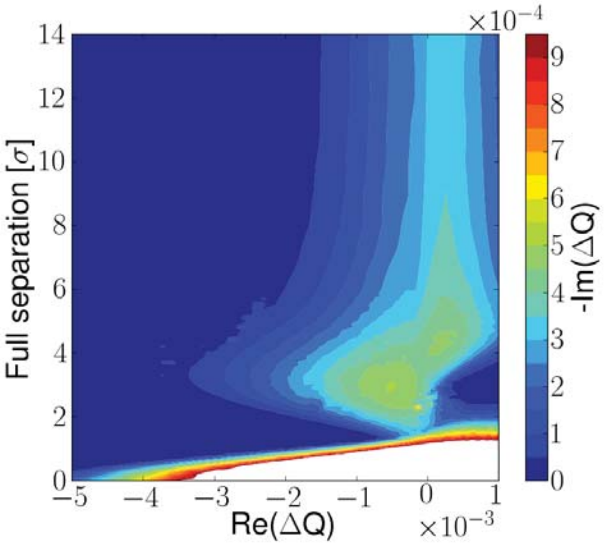

Figure 6: Evolution of the stability diagram in the horizontal plane during separation collapse in both IP1 and IP5 synchronously. In other words, the color indicates the maximum imaginary tune shift that can be stabilized for a given real tune shift and separation.

ginning of the year the process was long (≈ 200 s) and was not directly going for head-on collisions in IP1 and IP5 but was slowed down to allow the tilting of IP8 crossing angle and only at the end optimized for luminosity. Several instabilities were observed while IP1 and IP5 were staying almost steady at an intermediate separation. In Fig. 5 we show the beam amplitude of oscillation and IP1 and IP5 separation reduction as a function of time. The beams are not yet in head-on collision and an exponential growth of the oscillation amplitude can be observed, causing a dump which occurred for a separation of $\approx 1 - 2\ \sigma$. These instabilities may be explained by the variation of the stability diagram as a function of the beams separation, as shown on Fig. 6. Indeed, there exists a minimum of stability around $1 - 2\sigma$ separation. A significant amount of time was spent at such separations, leaving the time for an instability to develop.

Over the year a change of the collision beam process has been proposed and implemented in the second half of the run. The purpose of the new process is to speed up the collapse of the separation bumps and to go straight to head-on collision in IP1 and IP5 to ensure stability.

However to guarantee a stronger stability several configurations have been tested with simulations and have shown that a synchronous collapse of both horizontal and vertical plane separation will lead to a minimum (magenta dots) of stability in both planes at the same time, as shown in Fig. 7 upper plot, where we show the beam footprint for different beam separations equal in both planes. The lower plot shows how one can avoid to have this minimum simultaneously in both planes by collapsing one plane at the time. The stability for this second configuration has been studied for both cases and results from multi-particle tracking simulations are shown in Fig. 8. The figure shows the amplitude of oscillation as a function of time for the different separations in either both planes at the same time (upper plot) or only the horizontal plane (lower plot). One can see that when only one plane goes through the stability minimum the other plane helps in the damping making this option more robust compared to the one going both planes together (or as for the LHC both IP1 and IP5 together) where for a defined separation of $\approx\ 1.5\ \sigma$ separation in both planes the system in not stable.

LUMINOSITY LEVELING

In Fig. 9 the different luminosities as a function of the β^* at IP1 and IP5 are shown for the four beam configurations of Tab. 2. As is visible a possible 50 ns operation of

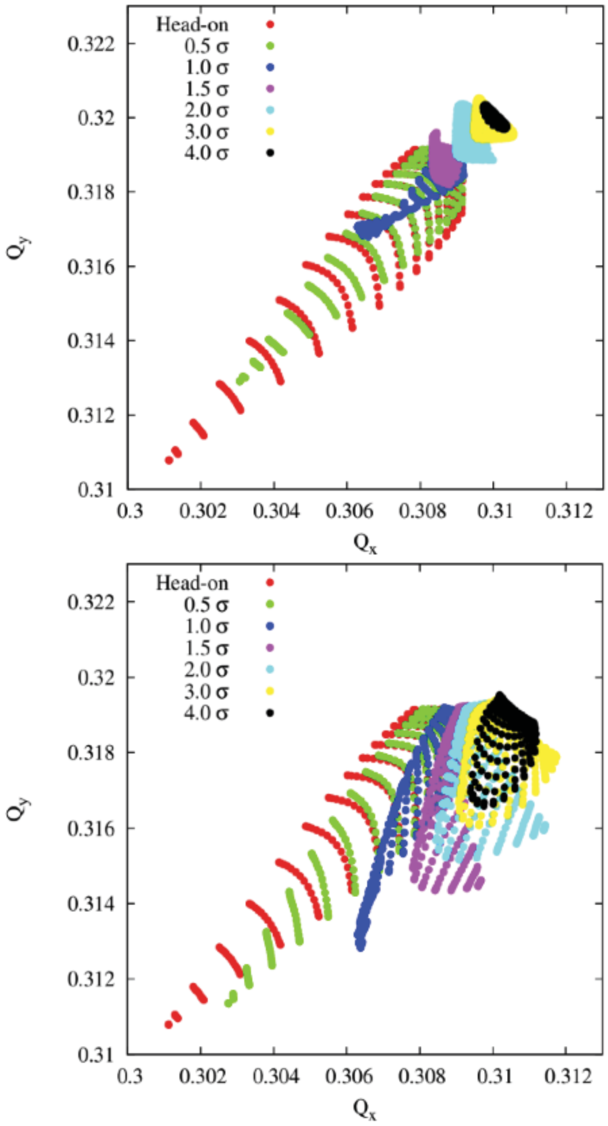

Figure 7: Footprint evolution during separation collapse in both planes synchronously (upper figure) and only in the horizontal plane (lower figure).

Beam spacing	LHC emittance (SPS)	Intensity
25 [ns]	1.9 (1.4) [μm·rad]	1.15 10^{11} [p/b]
25 [ns]	3.75 (2.8) [μm·rad]	1.15 10^{11} [p/b]
50 [ns]	1.6 (1.2) [μm·rad]	1.6 10^{11} [p/b]
50 [ns]	2.3 (1.7) [μm·rad]	1.6 10^{11} [p/b]

Table 2: Possible LHC Operational Parameters after LS1.

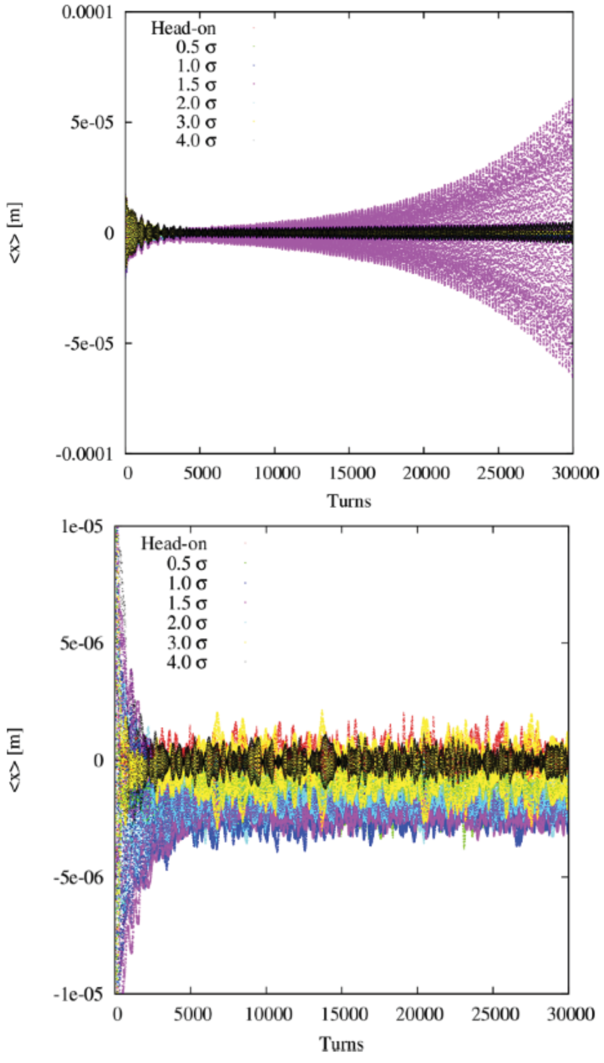

Figure 8: Beam oscillation amplitude as a function of time for different separations at the interaction point, the separation being either in both horizontal and vertical plane (upper figure) or in the horizontal plane only (lower figure).

the LHC will rely strongly on luminosity leveling since the pick luminosity is much larger than what the experiments can process. Therefore robust leveling techniques should be explored. Leveling with a transverse offset is operationally robust and flexible and has the advantage of lowering the maximum beam-beam tune shift, in case of problems due to head-on beam-beam. However, this technique may lead to instabilities during the leveling procedure due to a reduction of stability diagram, similarly to instabilities during the collapse of the separation. In this case, however, the procedure cannot be sped up. This type of instability was already observed in 2012 due to luminosity leveling with a transverse offset in IP8. Indeed, the LHC configuration included few bunches without head-on collision in IP1 and IP5, the stability diagram of these bunches was significantly reduced during the leveling procedure, leading to instabilities during luminosity production. This has enforced the usage of strong octupoles and the transverse feedback during luminosity production. There is great interest in avoiding the usage of such techniques in future scenarios since they have shown detrimental effects on the luminosity lifetime. Ensuring at least one head-on collision for every bunch would allow to reduce the need for other stabilizing technique and therefore improve the luminosity lifetime.

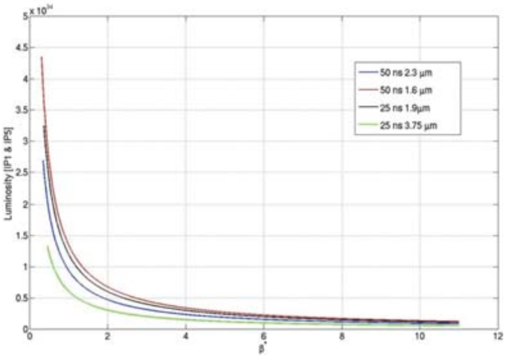

Figure 9: Luminosity as a function of β^* for the four beam parameters of Tab.2. Luminosity of calculated for IP1 and IP5 only.

TRANSVERSE DAMPER

During 2012 operation, the transverse feedback, the Landau octupoles and the chromaticity have been set to high values to ensure the beams stability. However a deep study of the different contributions is fundamental in the first commissioning period of the LHC in 2015 since few observations have shown they could act differently and that the machine luminosity can be deteriorated by using them operationally at maximum strength.

A test has been performed on single bunches separated in steps with constant chromaticity and octupoles set to their maximum strength. An instability appeared for specific separations where the stability diagram is minimum and was always cured with the transverse feedback while the octupoles were insufficient [8]. This suggests to keep the transverse feedback on when the beams are not colliding and demonstrates that it is not needed when beams are colliding head-on. Further tests are needed to identify the effect of chromaticity, set for this case to 5 units, and of different values/polarities of the octupole current.

On Fig. 10 we show the amplitude of oscillation of beam 1 in the horizontal plane as a function of time during consecutive Van deer Meer scans followed by a test during which the transverse damper gain was halved and finally turned off. After a transition period the oscillation amplitudes of the beams stayed constant. The spikes are due to few bunches not colliding which developed an instability while the rest of the beam was stable. With this observation we can state that the transverse damper is not needed if all bunches collide head-on. It is however fundamental for separated beams instabilities also without long-range beam-beam interactions.

Another important point is the feedback bandwidth which was increased in the second half of the 2012. While before collisions no detrimental effects have been visible, in collision, it is evident that the high bandwidth can be detrimental to the beams. An end of fill test has been performed where the transverse feedback at high bandwidth was turned on while the beams were colliding, the measured luminosity is shown on Fig. 11. The transverse feedback was set to high bandwidth at time 11:00 and a significant deterioration of luminosity lifetime is visible, suggesting to avoid this set-up for operation.

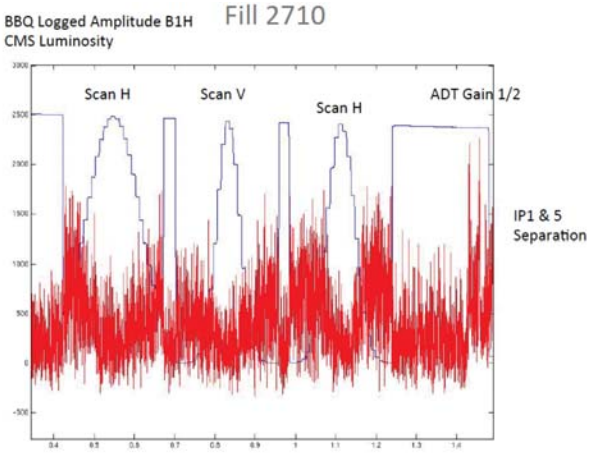

Figure 10: CMS luminosity (blue line) and BBQ logged amplitude of oscillation of beam1 horizontal plane as a function of time. The first part shows the oscillation amplitude during a Van deer Meer scans. During the second part the beams are colliding head-on, the transverse damper gain was reduced then turned off. Only non-colliding bunches start to oscillate coherently leading to an instability (high amplitude peaks at t = 1.45) the rest of the beams were stable.

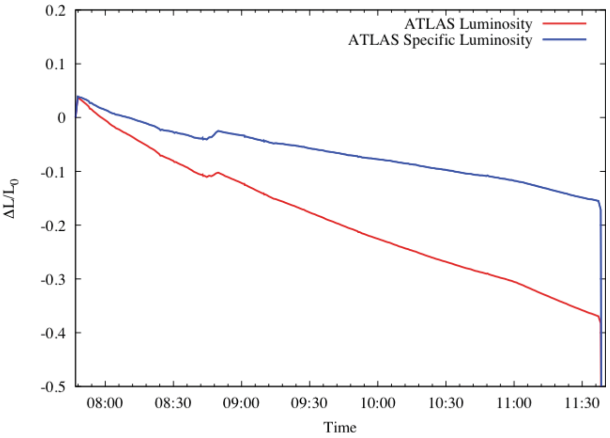

Figure 11: Atlas luminosity as a function of time while the transverse feedback was changed (at time 11:00) to high bandwidth. A deterioration of luminosity lifetime is visible and directly related to the change of bandwidth.

Moreover the lifetime deterioration is directly related to the number of beam-beam parasitic encounters as shown in Fig. 12 where the bunch by bunch deterioration of luminosity lifetime is evaluated and compared to the number of long-range encounters. It is visible that the deterioration is more important for bunches with larger number of long-range interactions suggesting an interplay between the transverse damper and the beam-beam interactions which has to be studied in details.

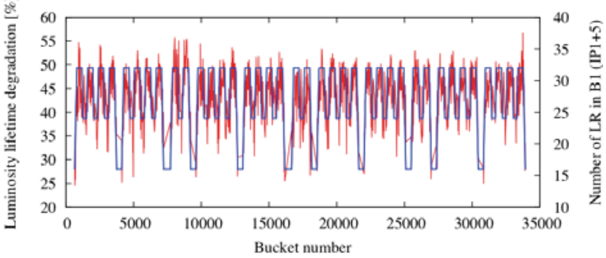

Figure 12: Bunch by bunch luminosity lifetime degradation and number of long range parasitic encounters as a function of the bunch RF bucket. The plots shows a clear dependency of the lifetime degradation with the number of parasitic encounters.

OCTUPOLES AND CHROMATICITY

In 2012, the time allocated for systematic studies on the effect of the octupoles, as well as on the effect of chromaticity was not sufficient to conclude on possible settings for 2015. An initial period of commissioning should be devoted to study the parameter space in order to properly assess potential stability issues during the run. Nevertheless, the observations described here and in [2] brings us to two possible scenarios.

The first possibility is going back to settings similar to the initial setting of 2012 where no sign of instability where observed during several fills. This configuration rely on a small positive chromaticity, around 2 units. While more stable than at high chromaticity, the stability strongly depends on the chromaticity variations [6]. Therefore a good control of this parameter is required in order to operate in this configuration. The octupole current should be minimized, not only for lifetime optimization, but also because the feed down effect leads to a strong dependency of the chromaticity on the orbit, which should be avoided to minimize chromaticity variations. The choice of the polarity results from a compromise between the stability before and after the squeeze. A lower current is required before the squeeze with the negative polarity. This option is therefore preferred, in case the stability at the end of the squeeze can be insured by colliding during the squeeze.
It is important to note that variations of the chromaticity also occur due to beam-beam interactions, as explained in [12], the variation of chromaticity along the bunch trains should be taken into account.

A second possibility, preferable in case chromaticity variations cannot be avoided, would essentially rely on a high positive values of the chromaticity, similarly to the end of the 2012 run. In this configuration the machine should be less sensitive to chromaticity variations. However, no cure for the instabilities at the end of the squeeze have been found in this configuration, at the end of 2012 run. Indeed, the end of squeeze instability was visible during all fills. The stability at the end of the squeeze will, therefore, strongly rely on colliding during the squeeze.

High chromaticity, octupole current and damper gain have potential detrimental effect on the beam and luminosity lifetime, there is therefore a great interest in finding an optimized parameter set, for which experimental time should be devoted.

CROSSING ANGLES AND LONG-RANGE BEAM-BEAM

Crossing angles in the high luminosity experiments (IP1 and IP5) are defined by setting the beam to beam separation at the first long-range beam-beam encounter equal to 10σ for the 50 ns bunch spacing and 12σ for the 25 ns, according to the following equation :

$$d_{sep} = \frac{\sqrt{\beta^*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha. \qquad (1)$$

The beam-beam separation is particularly sensitive to the beam emittance, any deterioration of transverse emittance (i.e. electron cloud, transverse emittances) will reduce the separation and might lead to higher losses due to several parasitic encounters at too small separation. In particular, one should remember that the separation at the first encounter is not the minimum separation the beams encounter. The separation is reduced at some encounters also by 1.5-2.0 σ. In these considerations however intensity effects are not considered, higher intensities will require larger separations at the parasitic encounters. The 2012 operation has shown that setting the separation at 10 sigma was leaving enough margin for the intensity range covered (allowing higher intensities available from the injectors without recommissioning the crossing angle). From studies of long-range interactions we have found a deterioration of $1.0\text{-}1.5\sigma$ in the on-set of losses when moving from 1.15 to 1.6 10^{11} protons per bunch [7]. Also, the separation required depends on the beams intensity. For these reasons, some margin should be kept in the initial configuration, in order to avoid delays during operation caused by the re-commissioning of procedures with new parameters.

In Tab. 2 one has the corresponding crossing angles per corresponding β^* for the four scenarios as calculated in [1].

For the low luminosity experiments (IP2 and IP8) the effect of parasitic encounters should be kept in the shadow of the high luminosity experiments. Therefore a larger separation at the long range encounters is required. These two IPs do not have passive compensation of the tune shifts and chromaticity leading to enhanced pacman effect. In particular, the difference between bunch families, in particular in term of tune and chromaticity, may become significant rendering difficult the optimization of the machine. For these two IPs we therefore suggest separations larger than 12-14 σ in all cases.

Beam [ns],[μm]	β^*_{cross} [cm]	β^*_{sep} [cm]	$\beta^*_{sep,2}$ [cm]	$\alpha/2$ [μrad]
25, 1.9	35	33	30	150
25, 3.75	31	33	30	127
50, 1.6	46	33	30	205
50, 2.3	37	33	30	163

Table 3: LHC Operational Parameters for after LS1 [1]. β^*_{cross} and β^*_{sep} are the β^*s in the crossing and separation plane respectively, during the standard squeeze. The $\beta^*_{sep,2}$ is the β^* reach in the separation plane with collide and squeeze.

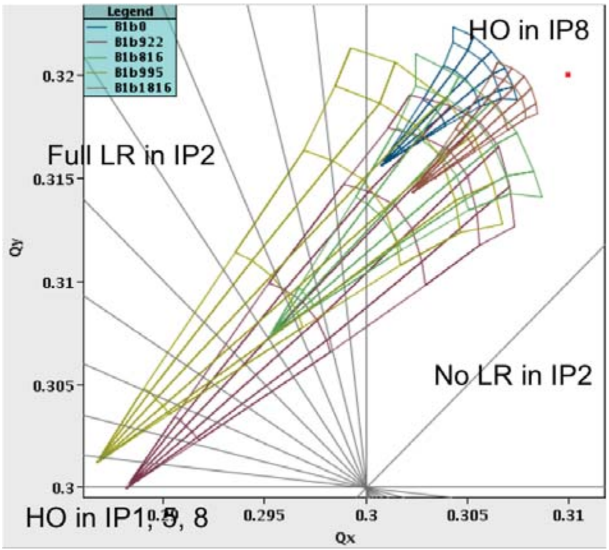

Figure 13: Footprints for extreme packman families to illustrate the separations in tune among the different bunches. The different tune shifts are due to IP8 and IP2 long ranges since for IP1 and IP5 a passive compensations cancels this effects on tunes and chromaticity.

An example of the 2012 configuration is visible in Fig. 13 where the effect of IP2 and IP8 long ranges are visible showing a larger occupancy of the tune area. Over the 2012 year moreover evidence of selective losses on bunches with long range interactions in IP2 were visible and presented in [11].

CONCLUSION

There are many unknowns concerning the instabilities observed during the 2012 run of the LHC. Models including the machine impedance, the transverse damper, Landau octupoles and beam-beam interactions are being developed to allow a better understanding of the observations. Nevertheless, some time should be dedicated for the testing of these models with beams after LS1. In particular, most stabilizing technique have shown detrimental effects on the beam, therefore finding a set of optimized parameters might be necessary to keep the luminosity lifetime under control.

The beams stability greatly depends on the chromaticity, a good control of this parameter will be required in any event. Head-on collision have shown to be an efficient damping mechanism. The stability may therefore be ensured by bringing the beams into collision during the squeeze, while ensuring at least one head-on collision for each bunch. In such configuration, the needs for other stabilizing techniques is drastically reduced.

Luminosity leveling in both the low and high luminosity experiments rises important beam stability issues that should be addressed in the early stage of the LS1 in order to find operational procedures that meet the experiments desiderata.

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