TWO BEAM EFFECTS

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Abstract

In this talk we propose possible scenarios for operation of beams during the betatron squeeze, adjust and stable beam mode at 6.5 TeV energy for the 2015 LHC physics run. The available parameter space in term of intensity, emittances, chromaticity, octupole current, damper gain will be explored for the 25 ns bunch spacing. Conclusions on possible settings for the operation will be based when possible on experimental experience from the LHC 2012 physics run. Limitations and possible countermeasures will be considered in the choices of possible scenarios in order to provide the highest integrated luminosity.

INTRODUCTION

The 2012 run of the Large Hadron Collider (LHC) has shown, despite the great physics discovery of a Higgs-like boson, several instabilities that 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 [2]. Moreover to cure the instabilities several other parameters have been changed experimentally (i.e. chromaticity from approximately 2 units to larger values of 15) and the transverse feedback gain increased from 200 turns up to 50 turns.

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

Table 1: LHC Operational Parameters

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_n [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

In this paper we show the impact of all the operational changes on the beam-beam interactions via simulations and try to compare to 2012 observables where possible. Predictions for 2015 operation are also shown and possible limits highlighted. The studies are focused on two main domains: incoherent beam-beam effects and the role of beam-beam effects during the coherent instabilities observed during the LHC Run1 at the end of the betatron squeeze, the adjust beam process and during stable beams. The origin of these instabilities is still not understood however some observations have led to considerations on the beam stability to help defining the LHC possible future scenarios. Based on the experience from the 2012 Run, we use the predictions for 2015 to define a set of parameters for the start-up of the LHC (i.e. beam-beam separations for different brightness of the beams, chromaticity, octupoles) and propose a possible strategy to ensure the most robust performances.

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INCOHERENT BEAM-BEAM

Long range experiments versus simulations

The Beam-Beam Interactions (BBIs), head-on and long range, lead to a detuning with amplitude of the beam particles [3]. In Fig.1 we show the two dimensional detuning with amplitude for particles up to 6σ due to beam-beam interactions head-on and long ranges, the so called tune footprints [3]. The different tune footprints are calculated for bunches with intensities of 1.3$\cdot 10^{11}$ protons per bunch and a long range beam-beam separation of 10 σ at the first encounter defined as:

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

where α is the crossing angle, γ the relativistic factor, β^* the beta function at the Interaction Point (IP) and ϵ_n the normalized emittance.

The different footprints correspond to different operational scenarios of the LHC: the 2012 Run1 case with 50 ns bunch spacing (blue lines) is compared to the nom-inal LHC design report case with 25 ns bunch spacing with emittances of 3.75 μm (red lines) and with emittance of 1.9 μm (green lines). As one can notice, despite the smaller emittances the wings of the footprint are larger for the transversally smaller bunches (in green) because their head-on contribution to the spread is much larger respect to the case with almost twice the emittances (nominal LHC case in red) even for identical separations at the long range encounter of 10 σ. This picture is used to illustrate why the choice of the crossing angle α, β^* and or the beam emittances ϵ should be taken together to ensure no surprises when pushing the beam brightness during the physics run. The common idea that reduced emittances are always better has to be compared to the contribution given by the head-on spread to the overall footprint.

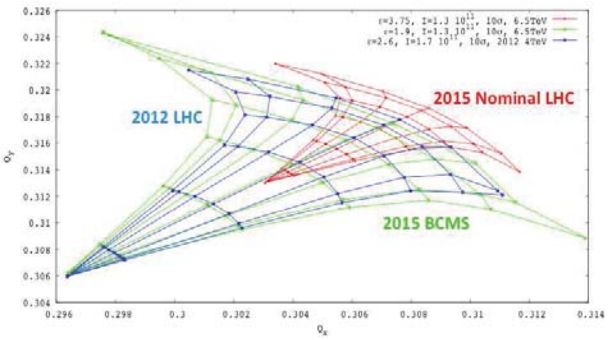

Figure 1: Beam-beam tune footprints: for the 2012 case at 50 ns bunch spacing (blue lines), for the nominal LHC emittances of 3.75 μm rad (red lines) and for reduced emittances of 1.9 μm rad (green lines) both for 25 bunch spacing.

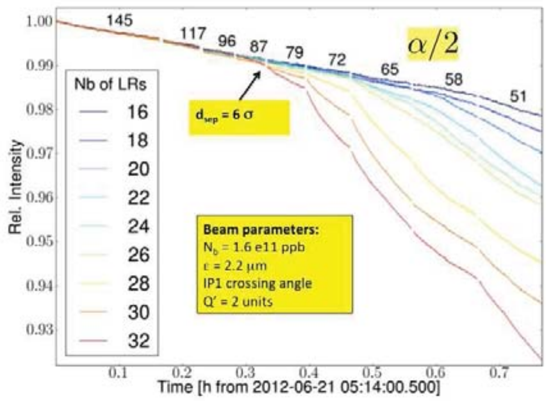

Figure 2: Bunch by bunch relative intensity losses as a function of time for different crossing angles α. The number of long-ranges interactions per bunch are indicated in the legend.

Several experiments aiming to characterize the long range interactions have been carried during the 2011 and 2012 LHC runs. These experiments were performed to probe our Dynamic Aperture (DA) simulation in order to get confidence in the use of these tools for predicting the performances of future scenarios and for the general understanding of the non-linear dynamics of beam-beam. Details of the experiments could be found in several papers [4, 5, 6]. The experiments were done with trains of bunches so that the full set of long ranges interactions were applied, the crossing angle α, and therefore the beam-beam separation d_{sep}, was reduced in steps till detrimental effects, large losses with impact on beam lifetimes, were observed. An example of such an experiment is shown in Fig. 2 where the relative intensity drop for a train of different bunches experiencing different numbers of long range interactions are shown as a function of time while the crossing angle at the IPs is reduced in steps of approximately 1 σ in beam-beam separation. The onset of losses starts at a beam-beam separation of approximately 6 σ for this specific case with the beam parameters as indicated.

This type of experiment has been repeated for different intensities, β^* and bunch spacing (50 and 25 ns). A summary of the different results is given in Tab. 2. We will call lately this limit at which the deep losses and lifetime drops occur as the limit of chaotic motion, which identifies the limit from which we should define our margins for beam-beam effects to not deteriorate significantly and drastically the beam properties. At these separations particles from the tails are lost and also core particles diffuse, due to beam-beam, to larger amplitudes feeding the tails and therefore reducing the beam lifetimes. We compare then the onset of losses identified by the experiments with our dynamic aperture simulations. The DA is defined as the region, in units of beam size, of phase space where particles are stable. Comparing the experimental point to DA simulation show that the limit of chaotic motion is around a value of DA of $\approx 4\,\sigma$. This means that when we reach this limit particles at 4 σ are not stable and particles at 2 σ start showing chaotic spikes [7].

Table 2: Summary of onset of losses measured during long-range beam-beam experiments.

Spacing (ns)	β^*(m)	N_p (10^{11} p/b)	$\alpha(\mu$rad)	$d_{sep}(\sigma)$
50	1.5	1.2	240	5-5.5
50	1.5	1.2	240	5-5.5
50	0.6	1.2	290	5-5.5
50	0.6	1.6	290	6-6.5
25	1.0	1.0	290	6.5-7.5

This is visible in Fig. 3 where the DA calculations for 50 (green line) and 25 (red line) ns bunch spacing are shown for a nominal LHC case ($1.15 \cdot 10^{11}$) while the experimental points (cyan dots) are shown on top of the simulations. A detailed analysis of the different cases have been shown at [8] where simulations of the different experimental conditions have been compared to the experimental data.

From the dedicated experiments we have learned that:

- measurements of the limit of chaotic motion are reproducible and it seems to be settled at a DA of 4-5 σ
- changing β^* does not change the limit (what counts is the normalized separation d_{sep} of Eq.1)
- changing the crossing angle doesn't change the limit (what counts is the normalized separation d_{sep} of Eq.1)
- increasing the intensity from 1.2 to 1.6 10^{11} anticipates the limit by 1σ, the dependency is known to be linear and approximately 1 σ more separation is need to have the same DA

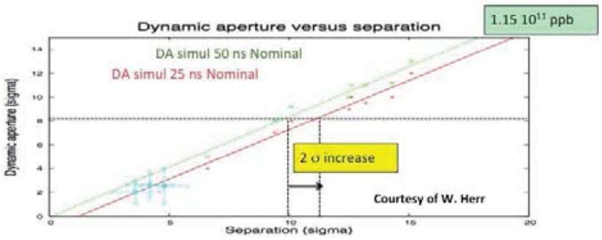

Figure 3: Dynamic Aperture as a function of the first beam-beam long range encounter separation in units of beam size. The red dots are simulations for a 25 ns bunch spacing while the green points are for 50 ns bunch spacing. Simulations were performed for IP1 and IP5 interaction regions with head-on and long-range interactions for an intensity of $1.15{\cdot}10^{11}$ ppb and a transverse emittance of 3.75μm rad. The blue points corresponds to experimental points collected during dedicated experiments where beam losses were appearing [5].

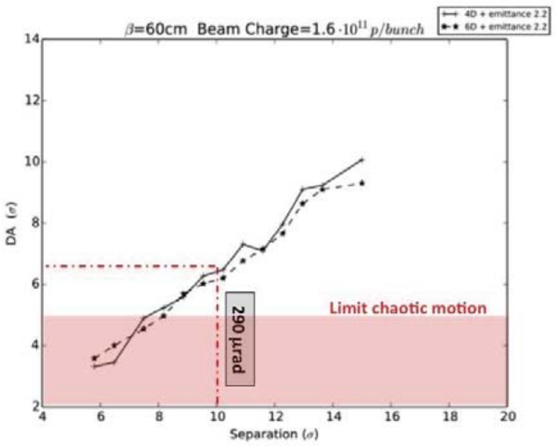

Figure 4: Dynamic Aperture as a functions of the beam-beam separation at first long range encounter for a beam with $1.6{\cdot}10^{11}$ proton per bunch. The red region identifies the chaotic motion region.

- doubling the long range encounters (from 50 to 25 ns) anticipates the limit by approximately 2 σ in simulations, from measurements caused by big uncertainties on the beam emittances it has been measured at 4-6 σ
- the lower limit for 25 ns beams has not been identified yet.

The absolute value of DA simulations is very difficult to relate to a machine observable. On the other hand it is very powerful if used in relative to predict the impact of changes in the machine configurations (i.e. impact of intensity, crossing angle, β* and bunch spacing). The lower limit, which defines our margins, can be identified only experimentally. However for the 25 ns case the 2012 measurements were not conclusive and therefore an experiment of long range interactions in 2015 will be needed to identify the limits in order to decide the margins to take from that.

2012 Physics run: impact of chromaticity

Another important change that occurred during the 2012 run was the increase of the machine chromaticity Q' to cure coherent instabilities. Q' was raised from 2 units up to approximately 15 in the August 2012 [9]. In Fig.5 the bunch by bunch emittances, computed from the specific luminosity, is shown as a function of time. One can notice the faster blow up of the high brightness bunches respect to the blown up ones with emittances of around 3.4 μm. The smaller picture shows the bunch by bunch emittances after 30 minutes in stable beams to distinguish between bunches stable (blue dots) during the betatron squeeze and those unstable (green dots). This observation has raised the question if maybe could be beam-beam provoking a blow-up of the bunches [10]. A detailed analysis of the bunch by bunch emittance blow-up and lifetime evolution in stable beams is still on going , however simulations have been carried to characterize the DA for this case.

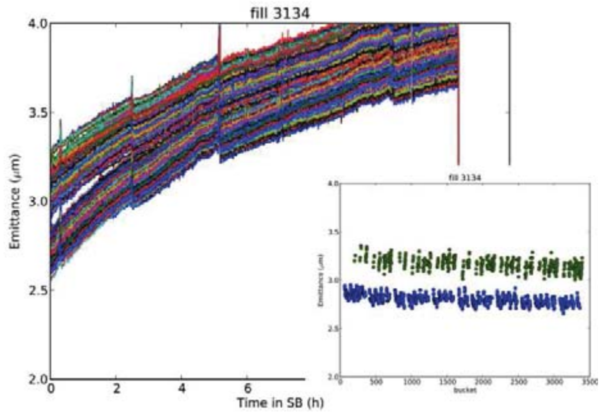

Figure 5: Bunch by bunch luminosity convoluted emittance versus time during physics fill 3134 of the LHC in 2012.

High values of the chromaticity deteriorates significantly the DA. Results of simulations are shown in Fig. 6 where we compare the DA of the first part of the year with Q'= 2 units (black lines, dots) versus the case with Q' = 15 units (blue and red lines). The high chromaticity plots are for two beam emittances: for bunches with 2.5 μm (red lines) and for the bunches with 3.5 μm emittance. This scenario corresponds to the physics fills of 2012 , second part of the year. One can notice that the DA for both cases is reduced and for the bunches with smaller emittance much closer it is on top of the limit of chaotic motion. The chromaticity change during the year might be the explanation for a deprecation of the integrated luminosity per fill due to a stronger blow-up of the emittances and reduced lifetimes.

Stron-strong simulations also confirm the emittance blow-up. In Fig.7 the simulated emittances are shown as

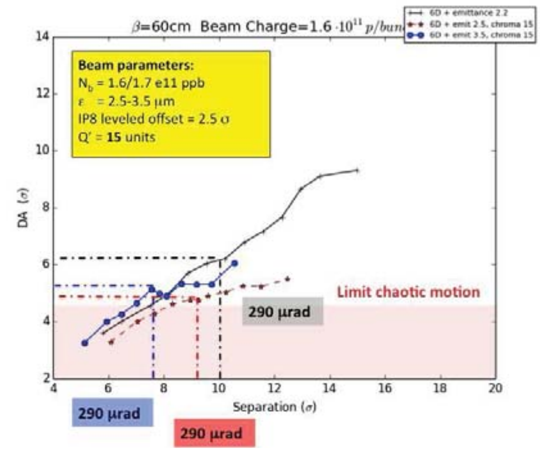

Figure 6: Dynamic aperture simulations for 1.6·10^{11} proton bunches as a function of the long range beam-beam separation in units of the beams size. Black line correspond to the first part of the 2012 Run with chromaticity of 2 units and a separation of 10 σ while the other two lines are for the second part of the year with Q'=15 units. Red and blue lines correspond to beams with transverse emittances of 2.5 ($d_{sep} = 9.2\,\sigma$) and 3.5 ($d_{sep} = 7.8\,\sigma$) μm rad, respectively.

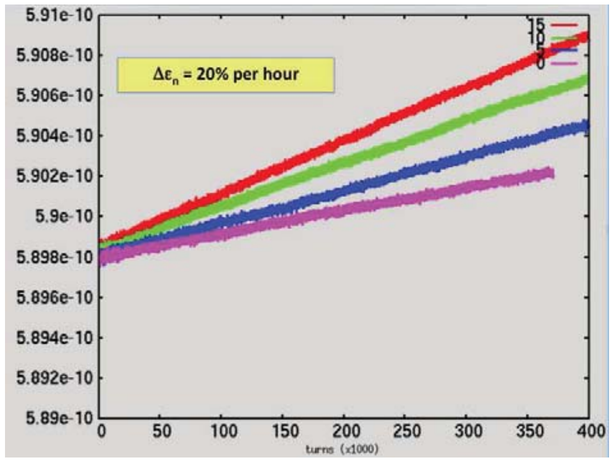

Figure 7: Emittance blow-up for different values of chromaticity Q'. Simulations are performed with Beam-Beam3D.

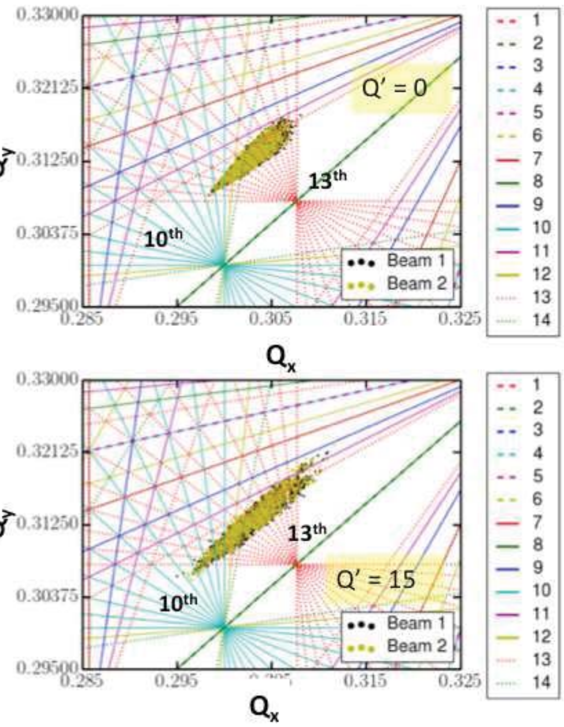

Figure 8: Footprints of head-on collision for different values of chromaticity. Upper plot for Q'=0 and lower for Q'=15 units.

a function of the time in collision (two head-on collisions) for different values of chromaticity. One can notice that up to a 20% per hour blow up due to the head-on collisions only is expected. A possible explanation to this phenomenon is that it is due to the crossing of the 10^{th} order resonance (as highlighted in Fig. 8). The beam lifetime deprecation could then be linked to the long range and high chromaticity values and octupole setting during collision which should result in larger detuning for large amplitude particles which are responsible for bad lifetimes. The effect of the emittance blow-up is linked to another observation, the bunch shortening in collision, which was reproduced with this model and therefore gives us confidence that it is a good representation of the machine set-up. The detailed study could be found at [11].

As a result of these studies we can conclude that chromaticity has to be settled as low as possible close to zero (slightly positive) when in collision and head-on beam-beam interactions are granted. If this is not possible due to instabilities on non colliding bunches then these bunches will set the lowest limit, to avoid instabilities, however this highest value of the chromaticity will deteriorate the beam lifetimes and an emittances blow-up should be expected when pushing the beam brightness. An experimental verification of the resonances driving the beams blow-up in collision will help delimiting the available space in tune diagram in within we should keep the footprints to avoid these effects.

2015 Scenario

Simulations of the dynamic aperture expected for the LHC 2015 possible scenarios are shown in Fig.9 for bunches with intensities of maximum 1.3·10^{11} protons and transverse emittances of 1.9 μm (black lines, dots) and 3.75 μm (red lines and dots) to cover the whole range of possible beam parameters. We have settled the chromaticity to 2 units in all cases.

If one wants to set the dynamic aperture as in 2012 for

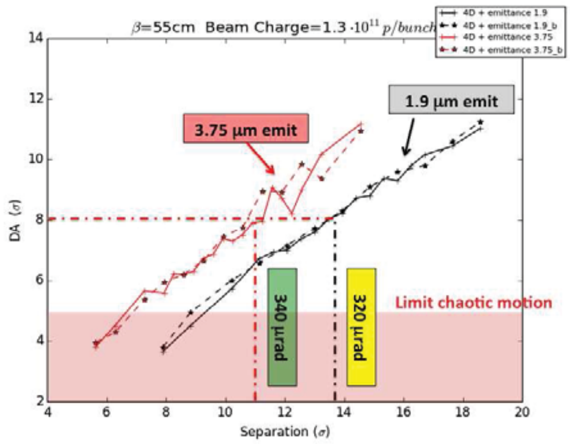

Figure 9: Dynamic aperture simulations as a function of the beam-beam separation d_{sep} for bunches of intensity of maximum $1.3{\cdot}10^{11}$ protons and transverse emittances of 1.9 μm (black lines, dots) and 3.75 μm (red lines and dots). A relaxed dynamic aperture of 8 σ is highlighted red dashed line and the corresponding crossing angle required for two beam emittances.

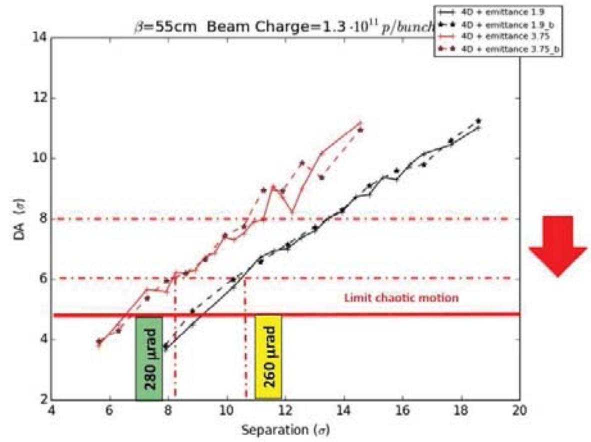

Figure 10: Dynamic aperture simulations as a function of the beam-beam separation d_{sep} for bunches of intensity of maximum $1.3{\cdot}10^{11}$ protons and transverse emittances of 1.9 μm rad (black lines, dots) and 3.75 μm rad(red lines and dots). A pushed dynamic aperture of 6 σ is highlighted with red dashed line and the corresponding crossing angle required for the two beam emittances.

beams of $1.15{\cdot}10^{11}$ protons per bunch and transverse emittance between 2 and 3.5 σ one should increase simply by 2 σ the beam beam separation to take into account the doubling number of long range encounters. This can be deduced from Fig.3 moving from the 50 to the 25 ns curve to keep the same value of DA one needs to move from 10 to 12 σ beam-beam separation d_{sep}. However the 2015 run should have beams with bunch intensity never exceeding $1.3{\cdot}10^{11}$ protons, therefore a slightly reduced separation could be applied. To start as in the 2012 run we need to guarantee a dynamic aperture value of 8 σ, which corresponds for the larger emittance beams to 11σ beam to beam separation (for 55 cm beta* this corresponds to a crossing angle of 340 μrad). This is visible in Fig.9 where we highlighted the d_{sep} at which one will keep a 8 σ DA. This separation might not be the smallest achievable.

For the 25 ns beams (twice number of long ranges respect to 2012 case) the limit of chaotic motion has not been defined yet. Uncertainties in the emittance measurements and bunch by bunch blow-up due to e-cloud effects put large error bars on the measurements. During a specific MD we measured it between 4-6 σ DA, details can be found in [8]. A reduced d_{sep} could be proposed in a second stage after a dedicated experiment with the goal to identify the limit of chaotic motion when the beam parameters (mainly emittances and intensities at collision) and machine parameters (chromaticity) are settled and under control. This possible step is sketched in Fig.10 where assuming a chaotic limit at 5 σ DA, we could aim, if no lifetime deprecation is visible in experiments, to a beam-beam separation of approximately 8.5 σ.

INSTABILITIES

The LHC beams were accelerated in 2012 from injection energy (450 GeV) to a top energy of 4 TeV. The β^* at the different 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 that 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 [9, 12]), the polarity of the Landau octupoles (changed from negative to positive [13]) and the transverse feedback gain (from 200 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 at minute 16 from the start of the betatron 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. In Fig.11 we show the fills with instabilities during the β squeeze (red dots) and fills without instabilities (black dots). In the plot we highlight the middle of the year changes (octupole polarity, chromaticity and feedback gain).

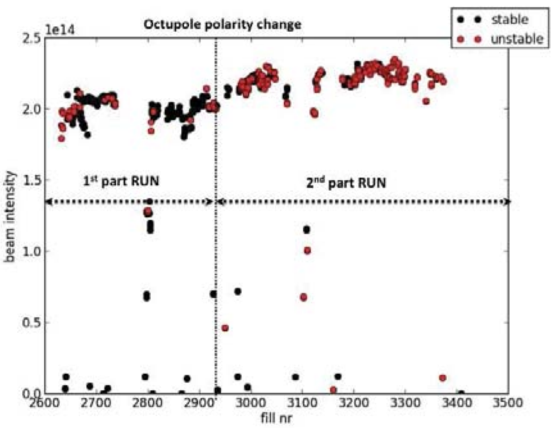

Figure 11: Beam intensity per physics fill of the LHC 2012 run. Red dots correspond to a fill that had an end of squeeze instability while black dots correspond to fills without instabilities during the squeeze.

2012 case and change of polarity

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 , not stabilized by the transverse feedback, should be dumped. In the LHC the stability diagram at the beginning of the betatron squeeze are illustrated in Fig. 12 (black lines) for both octupoles polarities (left negative and right positive). The negative polarity was preferred before the squeeze since it provides larger area for the expected modes, having negative real tune shift [14]. However, the long-range interactions also contribute to the non-linearities and affect the stability diagram at the end of the β squeeze (red and blue lines in Fig. 12). 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 [13].

In Fig.13 we show a comparison of the worst stability diagram for both polarities of the Landua octupoles. The smaller stability diagram at the end of the squeeze is the one where long range are strongest (nominal bunch with full long range encounters) for the negative polarity (red line) and the one of a pacman bunch (least number of long range encounters) for the positive polarity of the octupoles (blue line). The change of polarity of the Landau octupoles have moved reduced stability diagrams from nominal (central bunches of a train) to pacman bunchs (head and tails of a train). The total area is very similar as visible in Fig. 13. This might also be proved with a clear pattern of un-

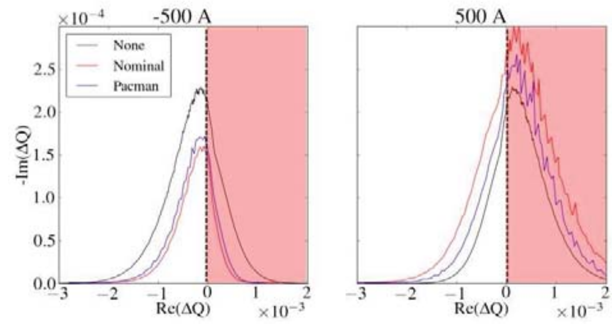

Figure 12: Stability diagrams for negative (left plot) and positive (right plot) polarity of the Landau octupoles (black lines) compared to the stability diagram reduced by long range interactions for a nominal bunch (red lines) and a pacman bunch (blue lines).

stable bunches for the second part of the year with positive polarity in the octupoles where tail bunches were the one unstable [9].

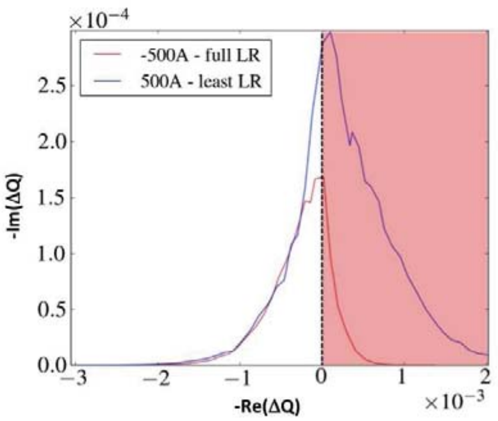

Figure 13: Stability diagram for negative polarity and full long range encounters (red line) and for positive polarity and least number of long range (blue line).

2015 run with twice long range encounters

The 25 ns beams will lead to twice the number of long ranges, moreover the energy increase will lead to less effective Landau octupoles. Depending on the octupole polarity the stability diagrams will be reduced by long range detuning if the polarity is negative and will add up if it will be positive. In Fig.14 we show the stability diagrams (Re(ΔQ) and -Im(ΔQ)) for different beam-beam separation d_{sep}. Stability diagrams are defined by the octupoles when the long range separation is large (from 25 to 15 σ separation) and they are modified by the long ranges when the separation is further reduced to 10 σ. From beam-beam point of view there is a clear preference in this case for the positive polarity of the octupoles.

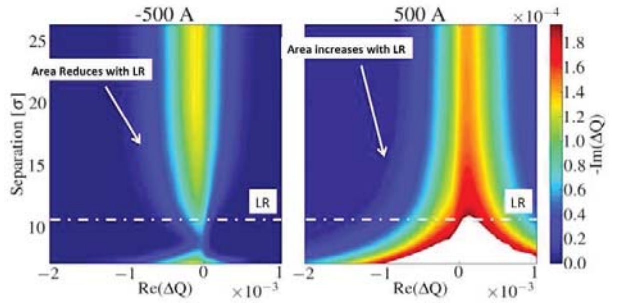

Figure 14: Stability diagrams (Re(ΔQ) and -Im(ΔQ)) as a function of the long range beam-beam separation d_{sep} for negative polarity (left plot) and positive polarity (right plot) of the octupoles.

One can see in details in Fig15 the worse stability diagram a bunch could have for positive (blue lines) and negative (red lines) octupole polarity for the 2012 configuration (left plot) and for the 2015 case (right plot). The 2015 case is characterized by stronger long range interactions which will redude significantly the area with respect to the 2012 case (two red curves). The positive polarity for 2015 will give a stability diagram, which is the largest, and therefore the preferred with beam-beam.

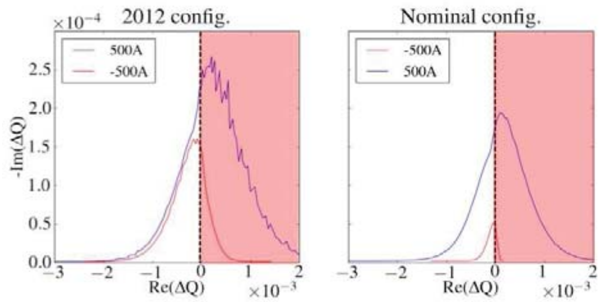

Figure 15: Comparison of the stability diagrams for both polarities of the octupoles at the end of the squeeze with long range effects. The left plot refers to the 2012 case while the right plot to the 2015 possible run at 6.5 TeV. The red lines are the worse stability diagrams for negative polarity while the blue are for the positive polarity.

Positive versus negative polarity

It is clear however from Fig.16 that the negative polarity of the octupoles is preferred to the positive for single beams (larger area for negative than positive polarity: dashed lines). A question raised by S. Fartoukh is: can we push out of the squeeze the long range effects. In Fig.16 we show the reduction of the stability diagram from a pure octupole contribution (largest area with dashed line) to the different reductions while squeezing the β^* (coloured lines). The arrow shows the direction in time during the squeeze. This has been repeated for two crossing angles, larger than nominal 340 and 400 μrad. As a comparison the stability diagram for the positive polarity is shown (dashed line with smaller area). One can notice that stopping at a β^* of 65 cm with a crossing angle α equal to 340 μrad the stability diagrams will always be larger or equal to the one obtained in case of positive octupole polarity. For the case with crossing angle equal to 400 μrad the $\beta*$ can be reduced to 50 cm. The stability diagrams are smaller than the one with positive polarity for separations below 12 σ.

Since the single beam stability prefers the negative octupole polarity and based on the study of the stability diagram we could accept this choice and relax the long range effects to assume their effects are smaller than going for a positive octupole polarity. The choice of relaxed long range interactions is at around 12 σ. This proposal is also in line with the conclusions made from the DA beam-beam studies.

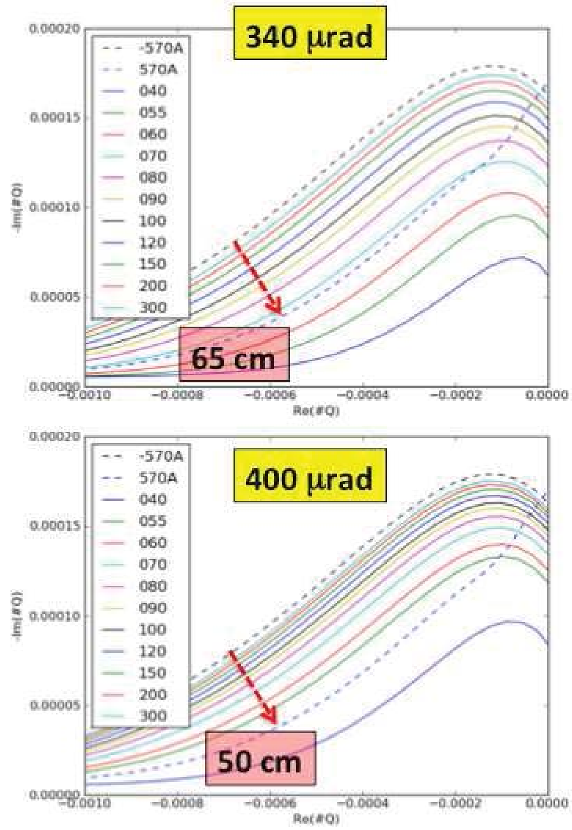

Figure 16: Stability diagrams for nominal bunch during the β squeeze for two different crossing angles for the negative octupole polarity.

Collide and squeeze

While the end of squeeze instability has not been understood yet observations of the LHC 2012 instability have also demonstrated the head-on collision to be the only mean 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. It would be therefore profitable to have the beams colliding during (part of) the squeeze in order to avoid the instabilities, details on this possibility are discussed in [15]. An operational effort should be done at the start-up to explore the possibility of making the collide and squeeze procedure operational in order to gain experience in case of real need.

Instabilities and beam dumps during the adjust beam process

The end of squeeze instability, was lasting also during the collision beam process. At the beginning 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 first collapse a separation in the crossing plane and 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 more recent analysis (question raised by G. Arduini) of these instabilities it has been noticed that at the end of the squeeze a separation in the crossing plane was still on during the adjust beam process and was collapsed only in the first part of the adjust beam process. In Fig. 17 we show the beam to beam separations at the long range encounters with parallel separation (at the end of the squeeze blue dots) and without (red dots) for two cases if a separation in the crossing plane is added (bottom plot) or not (top plot). For the 50ns beams this was not giving detrimental effects since the separation at the first encounter was reduced from 11 to 7 σ, however the effect was not negligible. In a configuration at 25 ns bunch spacing this would have given a first long range at 5 σ with very detrimental effects. A separation in the crossing plane has to be avoided during operation since it could give reduced long range separations due to a longitudinal shift of the beam-beam parasitic encounter locations.

In Fig.18 we show the instabilities observed during the adjust beam process as a function of time (middle plot) to be compared to the collapse of the separation bumps in the crossing planes and separation planes (plotted in the top figure). For this configuration the stability diagrams are plotted (bottom figure) as a function of the collapse of the bumps. One can notice that the stability diagram is reduced further when the separation in the crossing planes is collapsed then it is stable till the head-on component becomes important which occurs around 1.5 σ. Therefore instabilities during the adjust could be counted as end of squeeze instabilities. Studies are on-going to quantify the expected variations in chromaticity due to the collapse of a separation in the crossing plane.

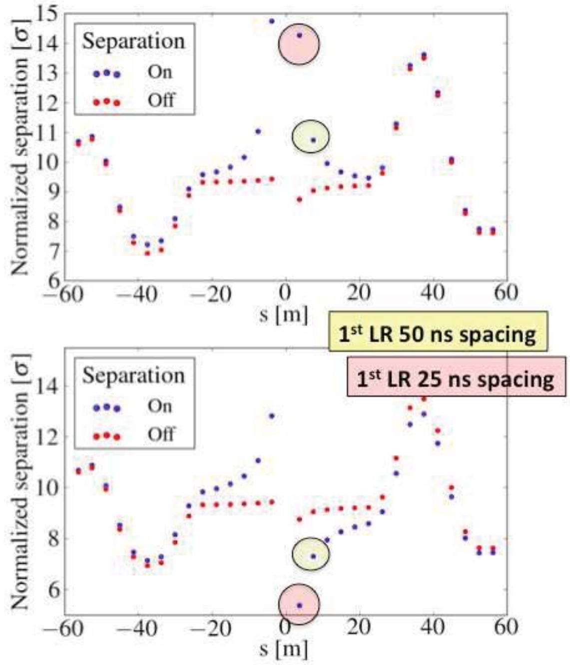

Figure 17: Beam to beam separation in units of the beam size at the end of the squeeze with the parallel separation (blue dots) and without (red dots). Top plot is without a separation in the crossing plane while bottom with a separation in the crossing plane.

Instabilities during stable beams

Another instability was occurring during stable beams the so called ”snowflake” instability [9]. This instability was involving only special bunches colliding head-on only in IP8. The instability was arriving after several hours in stable beams. A more recent analysis [17] has shown that the IP8 special bunches are colliding with a transverse offset to level the luminosity. The range of the offsets was from approximately 4 σ to zero. The expected stability diagrams for such a configuration are shown in Fig. 19. As for the case of the adjust beam process a minimum of stability is expected when fully separated above 2.5 σ and at around 1.3 σ separation the picture deviates a bit from a collapse of a separation dump, because of the tilted plane of collision in the LHCb experiment. One can notice that due to the geometry of the collision the minimum is expected in the vertical plane and data analysis shows the instability always in this plane. The data analysis also shows a pick of the instabilities occurring at a separation of 2 and 1.3 σ separation. The instabilities have not disappeared after the middle of the year change of 2012 but just became very weak (very small intensity drops) and since the beam lifetimes were very bad, they became very difficult to be detected.

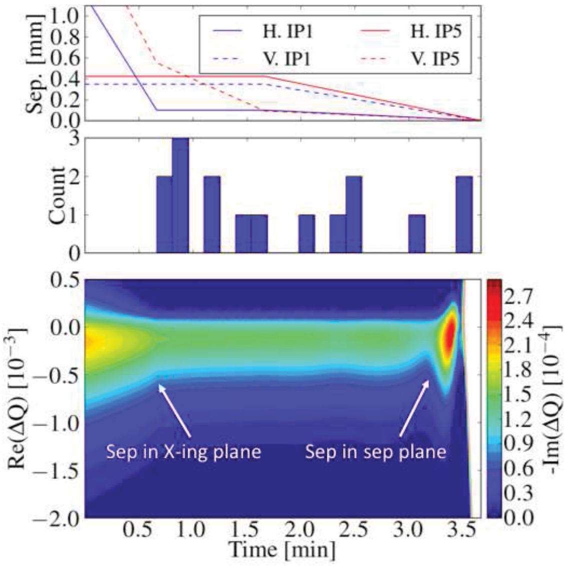

Figure 18: Dumps counting (middle plot) as a function of the time during the adjust beam process compared to the separation bump evolution (top plot) and the corresponding stability diagrams (lower plot).

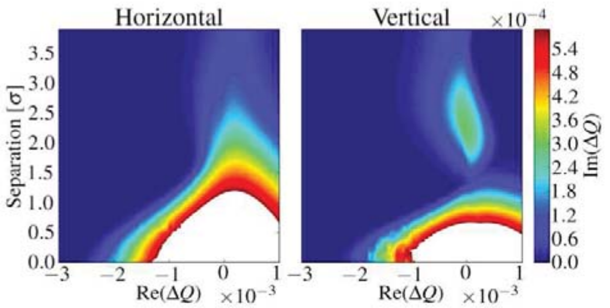

Figure 19: Stability diagrams for bunches colliding in IP8 with a transverse offset as a function of the offset. Left plot is in the horizontal plane while right plot vertical.

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. The feedback modeling is fundamental for our understandings. In Fig. 20 we show simulation results of the growth rate of the most unstable mode (color code) versus chromaticity and feedback gain when the LHC impedance and long range beam-beam effects (settled at a separation of 10σ) are interplaying. The upper plot is for a perfect model of the damper while the lower plot is for a damper with a sensitivity to head-tail motion as shown in [18].

The right plot of Fig. 20 shows how deprecated becomes the zero and negative chromaticity area for high damper gains.

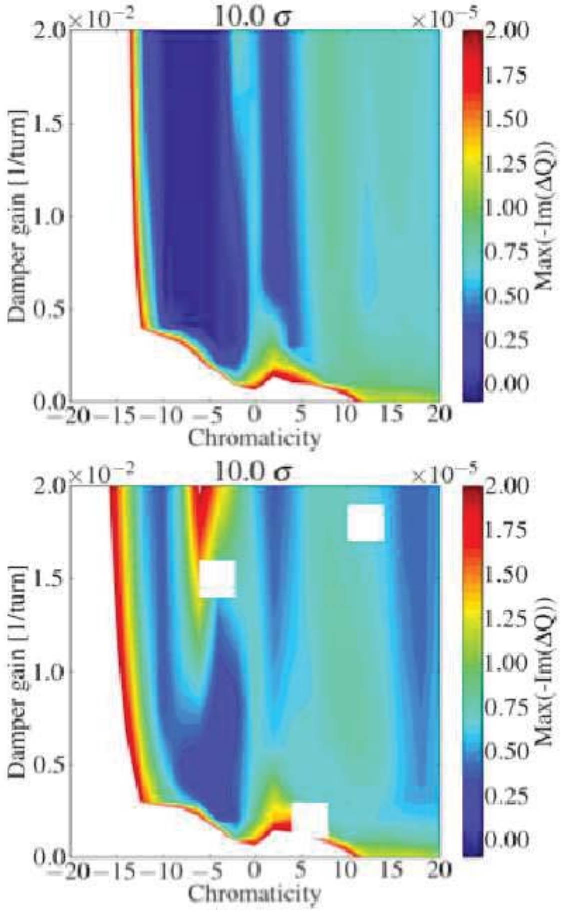

Figure 20: Growth rate of the most unstable mode (color code) versus chromaticity and feedback gain when the LHC impedance and long range beam-beam effects (setted at a separation of 10σ) are interplaying at the end of the squeeze. Upper plot is for a perfect feedback while lower plot is with a non-perfect feedback.

The area with high chromaticity and ADT gain is still the most promising in terms of stability. A deeper knowledge of the feedback dynamics will be fundamental to address the instabilities observations. On top of suppressing the co-herent motion arising from the interplay of beam-beam and impedance driven modes the ADT shows also an impor-tant role in enhancing diffusion of particles. This diffusion mechanism affects strongly the stability diagrams even for small variations of the beam tail profiles of which we have no knowledge.

CONCLUSIONS

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 have being developed to allow a better understanding of the observations [12, 19]. Nevertheless, some time should be dedicated to the testing of these models with beams after

LS1. 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.

An up-date of the data analysis of the instabilities led us to some conclusions:

- all instabilities during end of squeeze and adjust can be considered as end of squeeze instabilities due to a separation in the crossing plane collapsed in the first part of the adjust process
- only two dumps occurred during the collapse of the separation bumps in the adjust beam process, during the intensity ramp up.
- the reduction of the stability diagram could not explain the instabilities observed in 2012 the impedance modes should have been stable inside the area even if reduced by long range [2]
- The instabilities in IP8 were present the whole year and seem to be well explained with the minimum of stability diagram due to the missing head-on collision due to the offset leveling
- 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 the only efficient damping mechanism, therefore the collide and squeeze procedure should be explored in operation to face possible difficulties before a possible need

Single beam prefers the negative polarity since it gives larger margins for pushing the beam brightness [2]. The beam-beam interactions will reduce the stability diagrams however keeping the long range effects relaxed will allow to have a stability diagram always larger or equal to the positive polarity case for single beam. Therefore we are confident that the negative polarity stopping the beam-beam separation at 12 σ will be better in terms of stability diagrams than the positive polarity. High chromaticity should be preferred and high damper gain. 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 and have shown to be sensitive to a tune split. A study to determine if it is a tune effect of coherent beam-beam mode related should be followed. The stability at the end of the squeeze will, therefore, strongly rely on colliding during the squeeze if the instability will appear again. Testing this procedure during early stages of commissioning would help identifying possible problematics (offsets at the IP) and take countermeasures. The relaxed long range separations will also keep orbit effects from beam-beam much more relax and this will be also beneficial for a possible collide and squeeze procedure.

If the collide and squeeze procedure shows problems then we will need to step back to positive polarity and reduce the beam brightness.

For incoherent beam-beam considerations a minimum separation of 11 σ is mandatory to avoid going to close the limit of chaotic motion. A two stage approach is preferred where relaxed settings 11-12 σ beam to beam separation is requested and lately, only after a long range experiment, one could maybe reduce the separation to smaller values approaching the identified limit.

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. Over the 2012 year moreover evidence of selective losses on bunches with long range interactions in IP2 were visible and presented in [21]. For these two IPs we therefore suggest separations larger than 13-14 σ in all cases if not limited by hardware constrains.

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