BEAM-BEAM EFFECTS LONG-RANGE AND HEAD-ON.

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Abstract

The 2015 LHC run has shown the beauty of having weaker beam-beam effects with respect to 2012 physics run. The 2015 set-up has been defined to allow Landau octupole and chromaticity to be powered at maximum currents to fight coherent instabilities. Quantitative studies of the impact of reduced crossing angles on the beam and luminosity lifetimes have been used to compare to expectations from Dynamical Aperture studies. Possible scenarios for the 2016 RUN will be presented highlighting the beam-beam limits expected from long range and head-on.

BEAM-BEAM EFFECTS IN THE LHC EXPERIENCE FROM 2012 PHYSICS RUN

The 2012 Physics run of the LHC has shown losses and emittance blow-up which are related to beam-beam effects. The analysis of the bunch by bunch luminosity and specific luminosity decay rates during collisions has shown a clear dependency on the beam-beam interactions long-range and head-on [1]. An example of such relation is shown for the physics fill 2710 in Figure 1 and 2. In Figure 1 the ATLAS bunch by bunch luminosity decay rates (blue dots) over the first hour of collision is shown as a function of the slot position of the bunch pairs colliding in the experiment. The green line shows the number of long-range encounters each bunch undergoes at the interaction point 1. Bunches that undergo the maximum number of long-range interactions are the ones with reduced lifetimes since they fill stronger non-linearities from the long-range interactions. Head and tails of bunch trains show a slower decay rate since the number of beam-beam long-range interactions are reduced for them. Luminosity lifetimes can vary from 1.5 to 0.6 hours for the bunches, depending on the number of long-range interactions they experience.

In Figure 2 the bunch by bunch decay rates of the specific luminosity are shown as a function of the bunch pair position in the filling scheme and as for the luminosity decay rates it shows a similar beam-beam dependency. The decay rates of the specific luminosity (the luminosity normalized respect to the intensity of the bunch pairs colliding) show that the emittance increase is more pronounced for bunches in the centre of a train while it is much reduced for head and tail bunches. Emittance lifetimes from luminosity measurements show a range between 5 and 0.5 hours for bunches, depending on the number of long-range encounters. The emittance blow-up in the first 1-2 hours of collision was shown also in [2,3], where a clear difference between unstable and stable bunches was highlighted.

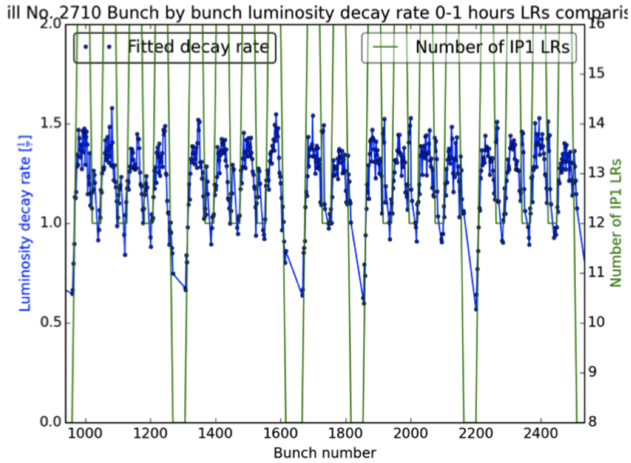

Figure 1: Bunch by bunch luminosity decay rate computed for first hour in stable beams during a representative physics fill number 2710 of the LHC physics fills of 2012.

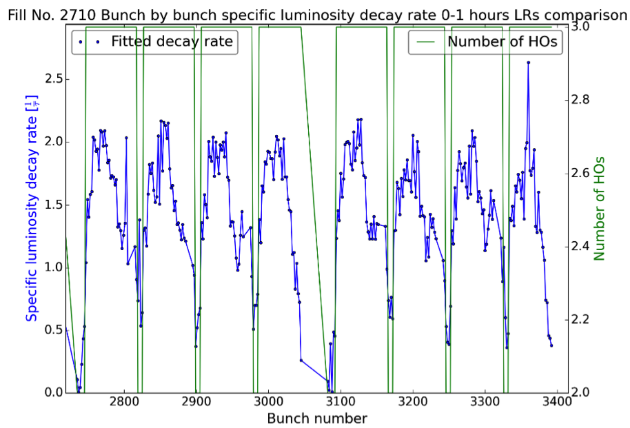

Figure 2: Bunch by bunch specific luminosity decay rate computed for first hour in stable beams during a representative physics fill number 2710 of the LHC physics fills of 2012.

In Figure 3 the luminosity decay rates are computed using different time windows along the physics fill of approximately 8-9 hours. One can notice that only the data accumulated over the first hours (blue dots) show a clear dependency on the beam-beam effects. Long-range effects are visible over trains while the missing collisions (head-on and long-range) in ALICE and LHCB experiments are visible in the ranges of 700-1000 and 2500-2700 ns slots. The different

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Figure 3: Bunch by bunch luminosity decay rates for different time intervals (see legend) for the LHC physics fill number 2710 of 8 hours in stable beams. The decay rates are computed using different time intervals to show the impact of long range beam-beam effect (blue dots pattern) dominant in the first hour of physics fill and disappearing after (red, green dots as expressed in the legend).

behaviour of these bunches can be related to the different tune shift they have with respect to the nominals. This comes from the missing long-ranges but mainly from the missed head-on collision (IP2 and IP8 collide at the IP with transverse offset). The associated tune shifts are of the order of 10^{-3} and these can easily lead to changes in dynamic aperture of the level of 1-2 σ [4]. As a consequence of the intensity reduction and emittance blow-up the beam-beam interaction become weaker and therefore the effects coming from beam-beam interactions disappear already at the second hour of the physics fill. In [1] a brightness dependent model for the luminosity evolution is proposed to describe the luminosity evolution in a beam-beam dominated regime. The model has been shown to describe well the luminosity evolution for the physics fills of 2012 and has been used to analyse the data presented in this paper and in [1].

In 2012 strong instabilities have been present during the whole physics run [5]. To mitigate such effects the Landau octupoles have been powered at maximum strength with currents of 590 A and high chromaticity operation has been put in place (from 2 to 15-17 units increase) as summarised in [2]. These strong non-linearities have negative effects on the beams dynamics of colliding beams but were necessary to mitigate the instabilities. The implications to the dynamic aperture is shown in Figure 4, where the dynamic aperture as a function of the crossing angle in IP1 and IP5 with strong beam-beam (red solid line for bunches with 1.6×10^{11} protons per bunch, emittances of $2.2\mu m$ and chromaticity $q^{'}$ of 2 units) is compared to the cases with high chromaticity ($q^{'}$ = 15 dashed lines) and for different polarity of the Landau octupoles (black for positive and red for negative polarity). The dynamic aperture is already strongly reduced below the 6 σ safe limit due to the very high intensities used. The beam-beam effects together with the strong octupoles and high chromaticity operation have reduced it to 4 σ. This value has been identified in several experiments [6–9] as the limit of chaotic motion for which important losses and emittance effects have been measured. At a dynamic aperture so reduced one should also expect resonance excitation and possibly diffusive mechanism which can modify the particle distributions and eventually create holes in the stability diagram [12] reducing the stability of beams.

SET-UP CHOICES FOR THE 2015 PHYSICS RUN

With the worry of coherent instabilities, the 2015 physics run set-up from beam-beam point of view was defined such as to allow for high octupole current and high chromacity operation at top energy and in collision. This was defined with dynamic aperture studies scanning the beam parameter space and operational configurations. The beam-beam long-range effects have been kept weaker than in the nominal design report. A beam-beam separation of 11σ for beams with normalised emittance of $3.75\mu m$ has been proposed and implemented using a crossing angle of 290 μrad for the optics of 80 cm β^{*}. This separation allows to reach a dynamic aperture of roughly 5.5 σ in the presence of maxi-

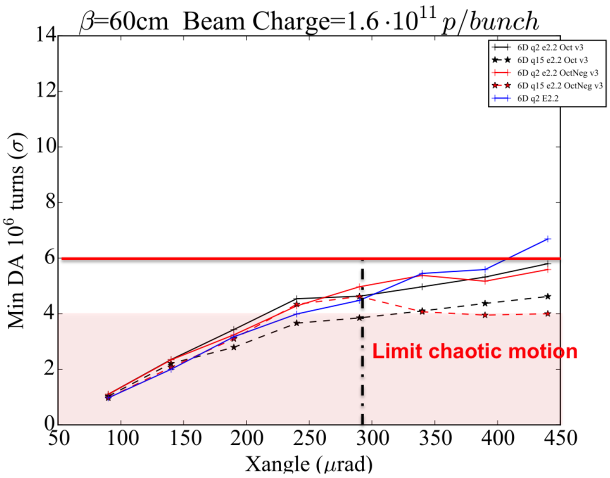

Figure 4: Dynamic aperture calculations as a function of the crossing angle α in IP1 and IP5 for the LHC standard configuration during the 2012 physics run: 60 β^* at the two IPs, bunch intensities of 1.6 $\times 10^{11}$ protons and normalized transverse emittances of 2.2 μ m. The different lines corresponds to beam-beam alone (blue line), with positive octupole polarity operation (black lines) and negative octupole polarity operation with 550 A current (red lines). The solid lines refer to operation with low chromaticity ($Q^{'} = 2$ units) while dashed lines are for high chromaticity operation ($Q^{'}$ = 15 units). The limit of chaotic motion identified empirically during experiments [6–9] is highlighted as the red area below 4σ dynamic aperture.

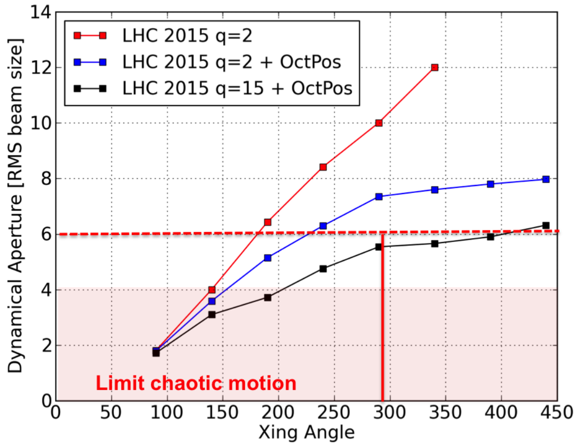

Figure 5: Dynamic aperture calculations as a function of the crossing angle α in IP1 and IP5 for the LHC standard configuration during the 2015 physics run: 80 β^* at the two IPs, bunch intensities of 1.3 $\times 10^{11}$ protons and normalized transverse emittances of 3.75 μm. The different lines corresponds to beam-beam alone (red line), with octupoles at 550 A in positive polarity operation (blue lines) and high chromaticity 15 units (black lines). The limit of chaotic motion identified empirically during experiments [6–9] is highlighted as the red area below 4 σ dynamic aperture.

mum current in the octupoles (550 A), chromaticity of 15 units and for bunches with intensities up to 1.3$\times 10^{11}$ protons. This is visible in Figure 5 where the dynamic aperture as a function of crossing angle is shown for the case with beam-beam alone (red line), with octupoles at 550 A (blue line) and when chromacity is set to 15 units (black line). At the crossing angle of 290 μrad the DA results to be between 5 and 6 σ of the RMS beam size leaving 1.5 σ margins to the chaotic limit. An optimisation fo IP2 and IP8 beam-beam effect is also putted in place ensuring tune shifts and spread below the 10^{-4} level till the end of the betatron squeeze as discussed later on.

An analysis similar to the one shown in Figure 1 shows for a typical physics fill of the 2015 physics run, no evident long-range contribution to the luminosity lifetimes. This is shown in Figure 6 where the bunch by bunch luminosity decay constants (blue line) are plotted as a function of the bunch pairs slot number in units of 2.5 ns. One can notice also that the average of the luminosity lifetimes has improved compared to the 2012 cases giving better integrated luminosity. The luminosity lifetimes are around 20 hours in collision, while in 2012 we had lifetimes going down as 0.5 hours in the first 1 hour of collision. At an energy of 6.5 TeV such intensity decays could lead easily to beam dumps.

LONG-RANGE BEAM-BEAM TEST: MARGINS AND POTENTIAL LUMINOSITY REACH FOR RUNII

During the 2015 physics run we have tested and quantified the impact of a reduced crossing angle, chromaticity and octupole current operation [8, 11]. This test goal was to explore the limits due to long-range beam-beam effects for a possible reduction of the crossing angle and therefore to define the maximum achievable peak and possibly integrated luminosity in the LHC for RUNII [14]. From models it is known that high octupole and high cromaticity operation will reduce the achievable minimum crossing angle. Moreover we wanted to quantify how fast the beam intensities and emittances are affected by a reduced crossing angle to define the needed margins from the chaotic limit identified in previous experiments [6, 7, 9].

A summary plot of the experiment is shown in Figure 7 where the beam 1 (blue line) and beam 2(red line) losses lifetimes in hours are plotted as a function of time during the machine development study. We have reduced in steps the crossing angles in IP1 and IP5 simultaneously to keep the passive compensation of tunes and chromatcity and observe only the effect of increased spread and orbit effects. The angles reduction started from 290 μrad down to 130 μrad, each step is indicated in the yellow boxes. On can notice that the losses show two regimes. A first fast drop due to a scraping of tail particles since the bunches are getting closer to each other and a second where the loss rate is

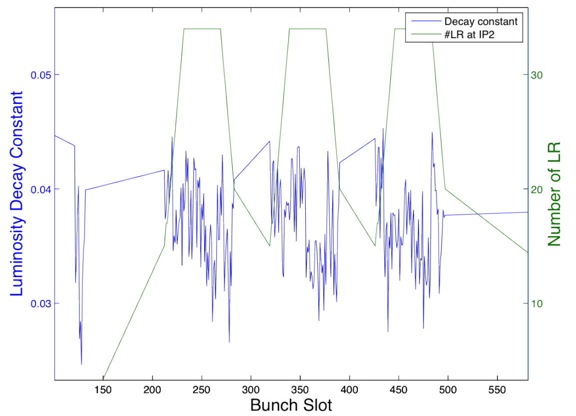

Figure 6: Bunch by bunch luminosity decay rates computed for first hour in stable beams during a representative physics fill of the LHC physics fills of 2015. The number of long-ranges encounters expected per slot number are also indicated (green line) to show the expected pattern.

almost constant during our time range of roughly 15-20 minutes. The change in loss lifetimes indicates an increased diffusion rate of particles and it's visible from a crossing angle of 158 μrad. At the minimum crossing angle of 130 μrad chromaticity has been reduced to 2 units (beam 2 tune optimised to recover a decay of the lifetime) and finally the octupole magnets currents reduced from 476 to zero A. A detailed description can be found in [8].

From simulations in Figure 12 we expected a reduction of the dynamic aperture due to the increasing long-range effects when the separation is reduced as

$$d_{sep} = \alpha \cdot \sqrt{\gamma \cdot \beta^{*}/\epsilon_n}. \tag{1}$$

To calculate the intensity and luminosity decay constants λ, a c variable simple exponential decay model was used to fit to the intensity and luminosity data.

$$N(t) = N_0 e^{(-\lambda t)} + c(t) \tag{2}$$

The lifetime in hours is given by the inverse of the decay constant $\tau = \lambda^{-1}$ Among other decay models tested and described in [1] for the LHC luminosity, the one described above was sufficient in this case. The exponential model has

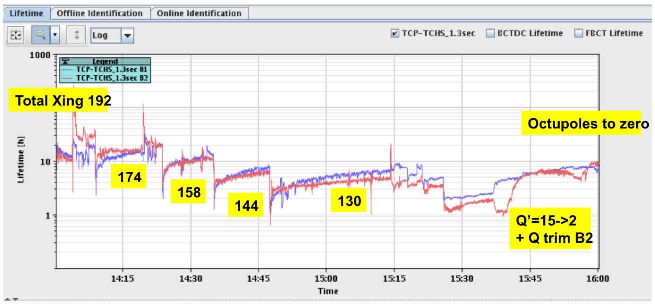

Figure 7: Beam 1 (blue line) and beam 2 (red line) loss lifetimes in hours as a function of time during the long-range test done on 15th September 2015 in the LHC. In yellow the steps can find the reduced crossing angles at IP1 and IP5 during the MD. The reduction of chromaticity from 15 to 2 units and octupole magnet current from 476 A to zero are also highlighted as last two steps of the experiment.

proved to model well the intensity as well as the luminosity lifetimes [8, 11]. Results of the analysis on the bunch by bunch intensities are shown in Figure 8 and 9. One can notice that for angles down to 158 μrad no change in lifetimes can be notice which are linked to long-range beam-beam. Drops of the decay constant before this angle are due to orbit drifts at the IPs as described in details in [8].

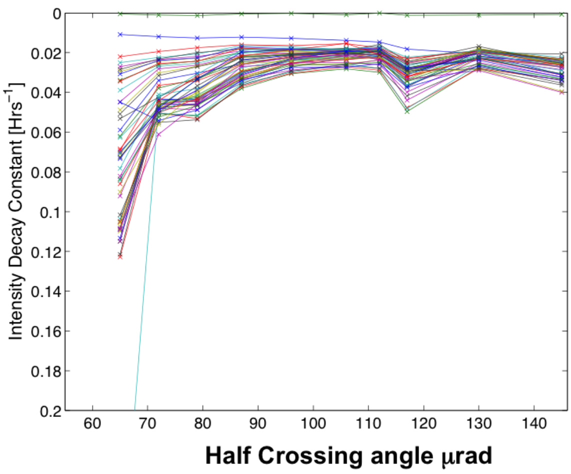

Figure 8: Beam 1 bunch by bunch intensity decay rates as a function of the half crossing angle $\alpha/2$ at IP1 and IP5 .

Beam 1 and 2 bunches intensity lifetimes are reduced from 25 hours at the larger angle to 8 and 4 hours at the minimum angle, respectively. On top of the reduction in lifetimes one can notice from Figure 10 that the lifetimes depend on the number of long-range encounters (black and blue line). Bunches with maximum number of long-range parasitic encounters suffer most. An asymmetric behaviour has been observed between bunches of the head and tail of the train. This difference can be due most probably to different emittances between the bunches (e.g. as with electron could effects larger emittances for tail bunches respect to head). Another possible explanation for such observation can be the measured error of roughly 20% on the crossing angles in crossing and separation plane in IP1 and IP5 [15]. Such an error can give an asymmetric configuration to the long-range effects. Future studies should be performed with better control of the transverse emittances and the optics configuration at the IPs. Beam 2 seems suffering stronger the long range effects with intensity lifetimes worse by a factor two respect to beam 1 (at the minimum crossing angle lifetimes are around 4 hours for beam 2 and 8 for beam1).

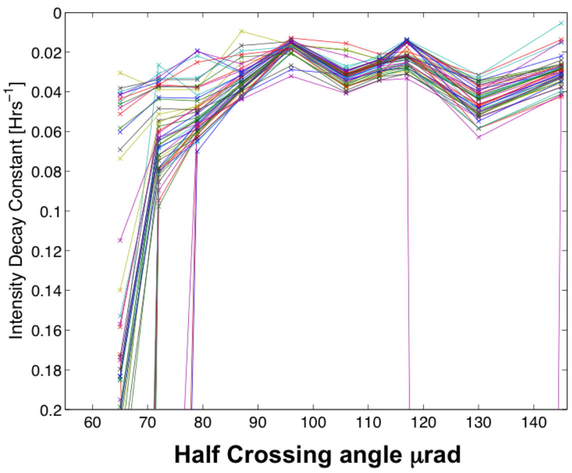

Figure 9: Beam 2 bunch by bunch intensity decay rates as a function of the half crossing angle $\alpha/2$ at IP1 and IP5.

At the minimum crossing angle we reduced chromaticty from 15 to 2 units and observed an improvement of the beam intensity lifetimes but still keeping the long-range number dependency as shown in Figure 10 red line. The lifetimes have improved from 4-8 back to above 20 for both beams after a tune correction for beam 2. A second test performed was to reduce the octupole current from 476 A to zero A (pink line in Figure 10). In this last step also the long-range number dependency has disappeared and lifetimes have gone back to values comparable to the initial crossing angle case of 290 μrad black line. With this test we wanted to demonstrate and quantify the impact of high chromaticity and high octupole operation to the beam parameters since in simulations they do show an important contribution. The high chromaticity and octupole operation costs 2 σ in beam-beam separation.

In Figure 12 we show the expected dynamic aperture for the experiment performed. The initial dynamic aperture for beams of 2.4 μm and intensities around $1.2{\times}10^{11}$ protons per bunch with octupoles at 500 A and chromaticity of 15 units is of 6 σ. Long-range separations at the nominal crossing angle of 290 μrad is around 14 σ. Reducing the crossing angle from 290 to 180 μrad we have a dynamic aperture always above the 4σ limit. Below the angle of 180 μrad, corresponding to a separation of 8.4 σ, we enter in the regime where bunch by bunch losses follow the long-range encounters. Below the 4σ limit we observe a reduction of

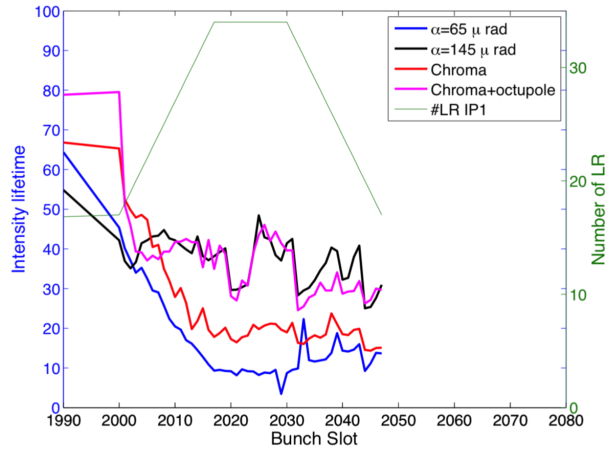

Figure 10: Beam 1 bunch by bunch lifetimes in hours as a function of the bunch slot position for the operational half crossing angle ($\alpha/2$ = 145μ rad black line), for the reduced angle ($\alpha/2$ = 65μ rad blue line), reduced chromaticity (Q' reduced from 15 to 2 units, red line) and for reduced current in the octupole magnets (from 476 A to zero, pink line). The number of long-range encounters as a function of the 25 ns slot number are also shown (green line).

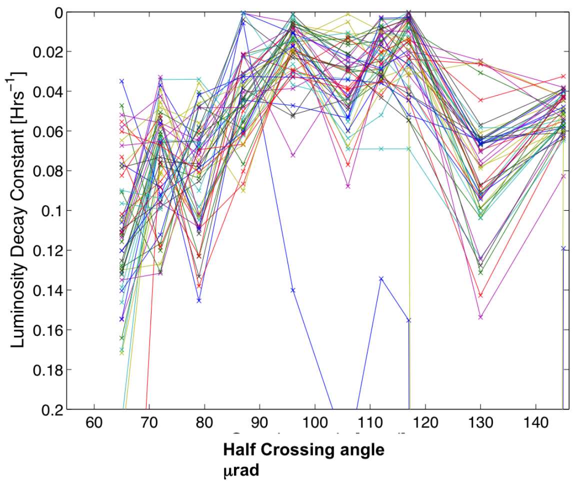

Figure 11: Bunch by bunch luminosity decay rate as a function of the half crossing angle $\alpha/2$ at IP1 and IP5.

the intensity lifetimes in both beams with a clear long-range pattern as shown in Figure 10.

IP1 and IP5 set-up proposal For the 2016 physics run a reduced crossing angle is proposed to achieve a long range separation of 10 σ in IP1 and IP5. This corresponds to the crossing angles of 370 and 330 μrad for the 40 and 50 cm β^* optics respectively. With such crossing angles for a beam with characteristics similar to one obtained at the end of 2015 (normalized emittances of 3.5 μm, intensities of 1.2 $\times 10^11$ protons per bunches and a total number of bunches of 2736) one should expect a peak luminosity of 1.1-

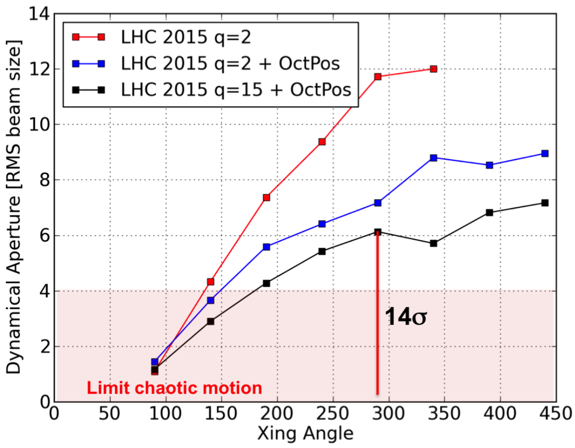

Figure 12: Dynamic aperture calculations as a function of the crossing angle α in IP1 and IP5 for the LHC standard configuration during the 2012 physics run: 80 cm β^* at the two IPs, bunch intensities of 1.2 $\times 10^{11}$ protons and normalized transverse emittances of 2.4 μ m. The different lines corresponds to beam-beam alone (red line), with chromaticity of 15 units (blue line) and positive octupole polarity with 550 A (black lines). The limit of chaotic motion identified empirically during experiments [6, 7, 9] is highlighted as the red area below 4 σ dynamic aperture.

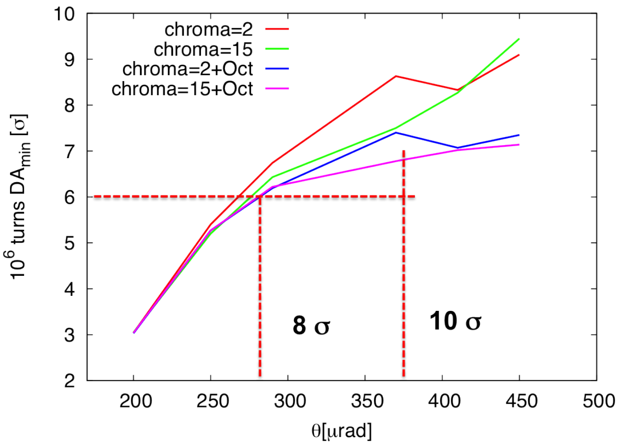

Figure 13: Dynamic aperture calculations for a 4D case (without longitudinal motion) as a function of the crossing angle α in IP1 and IP5 for the 2016 LHC configuration: 40 β^* at the two IPs, bunch intensities of 1.3 $\times 10^{11}$ protons and normalised transverse emittances of 3.75 μ m. The different lines corresponds to beam-beam head-on and long-range interactions with chromaticity of 2 units (red line), with chromaticity of 15 units (green line), with octupoles at current of 476 A in positive polarity (blue line) and with chromaticity of 15 units and octupole at 476 A (pink line). The proposed crossing angle of 370 μrad corresponding to 10 σ beam to beam separation at the first long-range encounter is high lighted with the potential lower limit of 8 σ separation.

$1.0 \times 10^{34} cm^{-2} s^{-1}$ for the 40 and 50 cm β^* optics respectively. Figures 13 and **??** show the dynamic aperture for the 40 cm optics option as a function of the crossing angle. The different lines correspond to the various contributions to DA coming from chromaticity (2 units red and blue lines or 15 units green and pink) and the effects of octupoles powered in positive polarity (with 0 A red and green lines compared to 476 A blue and pink). The two plots relate to the effect of the longitudinal motion (RF system) the crossing angle proposed will guarantee a DA between 5-6 sigma with high chromaticity and high octuple current. This will ensure also lifetimes above 20 hours as a consequence of the observations during the long-range MD described above. And problems of losses should appear at and below 4 sigma DA.

From beam-beam considerations no differences are expected between the optics options of 40 and 50 cm β^*. Simulation studies have shown similar behaviour if the same normalized separation is maintained. An illustration of the differences between the two options is shown on the tune footprints of Figure 14 where one can notice a reduced head-on shift for the 40 cm optics since the geometric reduction factor is larger and slightly larger detuning of tail particles.

The footprint of the 40 cm option is compared to the reached 80 cm case of the 2015 physics run in Figure [**?**]. While in Figure15 we show the footprint when octupoles are reduced in collision.

Based on the results and findings described above and in [8] the option with a 40 cm β^* will give larger potentials on the luminosity reach of the LHC. From the beam-beam testes performed on the minimum achievable crossing angle it results that a crossing angle of 8σ might be possible when all other sources of non-linearities are reduced, e.g. octupole currents and chromaticity. A test to verify this is strongly needed since many problems have been encountered during the 2015 experiment. The step in crossing angle should be done also when the beam emittances are stable (e.g. electron cloud free conditions) and as small as possible to reduce the separations to the actual beam RMS sizes. A reduction of the crossing angle from 370 to 300 μrad will provide a further increase of luminosity of roughtly10-14% depending on the bunch lenght.

IP2 and IP8 set-up proposal For the LHCB and ALICE experiments the strategy is to keep them in the shadow of the main high luminosity experiments, CMS and ATLAS. This is obtained by ensuring that the contribution from the beam-beam interactions of these two experiments to the tune shifts and spread is below few 10^{-4} in units of the tunes. This is dictated by the strong sensitivity of dynamic aperture to the beams working points. It is known [4] that a reduction of 2 σ DA is expected for shifts of the order of 3×10^{-3}. In Figure 17 and 18 the results of the simulated tune shift expected from LHCB and ALICE are shown as a function of the respective half crossing angles for the two polarities of

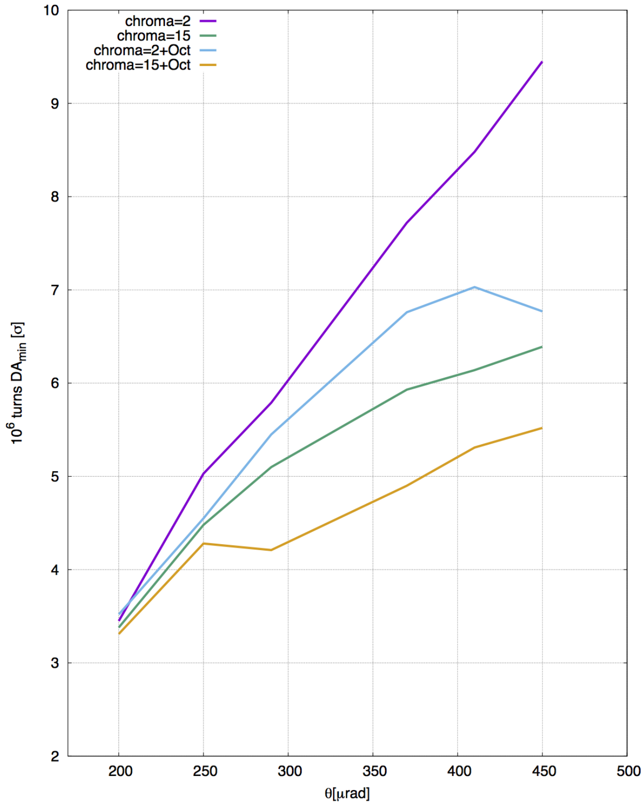

Figure 14: 6 D Dynamic aperture calculations as a function of the crossing angle α in IP1 and IP5 for the 2016 LHC configuration: 40 β^* at the two IPs, bunch intensities of 1.3×10^{11} protons and normalised transverse emittances of 3.75 μ m. The different lines corresponds to beam-beam head-on and long-range interactions with chromaticity of 2 units (red line), with chromaticity of 15 units (green line), with octupoles at current of 476 A in positive polarity (blue line) and with chromaticity of 15 units and octupole at 476 A (pink line). The proposed crossing angle of 370 μrad corresponding to 10 σ beam to beam separation at the first long-range encounter is high lighted with the potential lower limit of 8 σ separation.

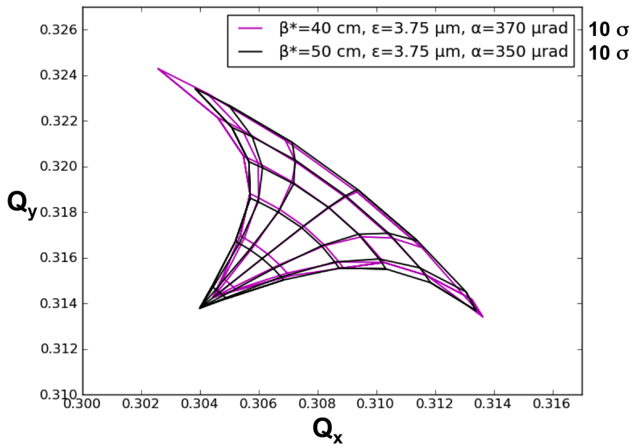

Figure 15: 2 Dimensional detuning with amplitude, footprint, for a separation of 10 σ in IP1 and IP5 for two possible optics the 40 (pink line) and 50 cm (black line).

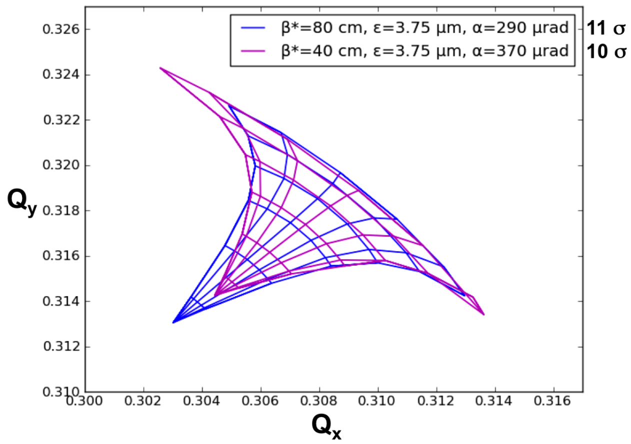

Figure 16: 2 Dimensional detuning with amplitude, footprint, for two configurations: the 2015 physics run (11 σ separation black line) and te possible 2016 configuration with 10 σ separation pink line.

their spectrometer magnets. The spectrometer polarities are normally changed during the physics year and the chosen external angles should be defined to allow for the different combinations.

The simulations shown in Figure 17 and 18 are for the case with largely separated head-on collision. The maximum effects from these two experiments will come from the single beam-beam interaction at the IP which will result in 10^{-3} tune shifts of the beam core.

LHCB experiment should operate with an external crossing angle of 500 μrad as during the 2015 since their conditions have not changed and no effects from this experiment has been identified so far.

ALICE detector have asked to operate with both polarities of the spectrometer and while it is changed no synchronised change of the crossing angle should be applied. This puts this experiment in a similar condition as LHCB where the external and spectrometer angles compensate each other reducing the long-range separations. A larger crossing angle is needed for ALICE to allow this changes. An angle of 400 μrad will guarantee a transparent polarity swap during the year and an overall effect of the long-ranges from this experiment below the 10^{-4} level as shown in Figure18.

INSTABILITY OBSERVATIONS ON COLLIDING BEAMS

During the 2015 physics run colliding beams have shown to be stable thanks to the Landau damping provided by the beam-beam head-on collisions. Few cases have shown instabilities on colliding beams: instabilities during the OP-scans and instabilities due to emittance asymmetries in collision.

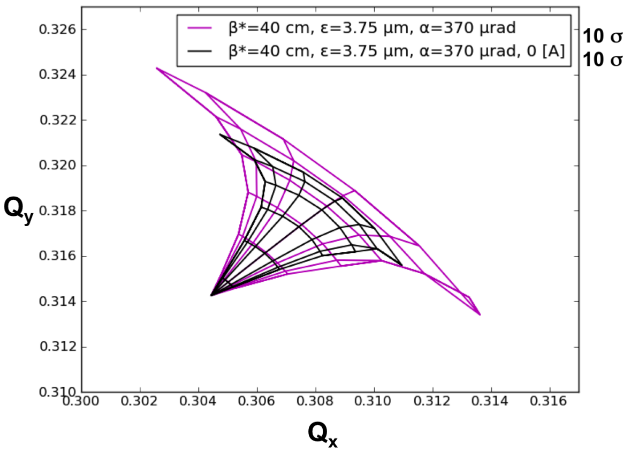

Figure 17: 2 Dimensional detuning with amplitude, footprint, for the 2016 physics run with (pink line) and without (black line) octupole magnets detuning.

The first instability occurs while separating the beams during OP-scans, in particular during ATLAS horizontal scans. It happened systematically at around a separation of 1.5-2σ and it appeared as a coherent oscillation with a consequent blow-up of the transverse emittance as shown in Figure 19. A possible explanation is of course the fact that when doing an OP-scan one is reducing the Landau damping stable area as shown in Figure 20, where the horizontal (left plot) and vertical (right plot) stability diagrams are shown as a function of the transverse separation (legend color) and compared to the case with only octupole magnets (black dashed lines). One can notice that at a separation of 2σ the stability diagram is strongly reduced approaching the single beam case and even smaller in the horizontal plane. However instabilities were not observed in the single beam conditions, e.g. during the squeeze, possibly the transverse feedback reduced gain identified lately and corrected for, have removed such instabilities. This points to a possible ADT responsibility together with the reduced stability diagram as a in explaining such observation.

Another type of instability has been observed in the physics fill 4231 in stable beam. This has been observed in the vertical plane after instabilities occurred before (e.g. during the squeeze and at injection) with an important emittance blow-up. This is due to a condition that changes the stability of the colliding beams which go to a so called weak-strong situation. The blown-up bunch will see from the colliding companion a full head-on collision while this is not true for the strong beam who will undergo a much weaker beam-beam head-on effect, and consequently weaker stability. The blow-up of beams before stable beams will create an asymmetric configuration in collision and the larger head-on stability will not be guaranteed. When e-cloud effects on the emittances and single beam instabilities have been mitigated, no observations of such instability have occurred during stable beams.

BEAM TRANSFER FUNCTION MEASUREMENTS AND STABILITY DIAGRAMS

In the LHC, the Landau octupole magnets are powered to provide the necessary tune spread to stabilize the beams by the Landau damping mechanisms. In order to predict the Landau damping and quantify the stability threshold, the SDs are analytically evaluated by solving the dispersion integral for a given detuning $\omega_{x,y}(J_x, J_y)$ and particle distribution $\psi(J_x, J_y)$ as a function of the transverse actions J_x and J_y in each plane [20]:

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \frac{J_{x,y}}{\Omega - \omega_{x,y}(J_x, J_y)} \frac{d\psi}{dJ_{x,y}} dJ_x dJ_y \qquad (3)$$

where $\Delta Q_{x,y}$ are the complex tune shifts at the stability limits for each frequency Ω. The term $\omega_{x,y}(J_x, J_y)$ contains the information about the spread that can be affected by other sources of non-linearities in the accelerator machine such as the beam-beam interaction, space charge and electron cloud.

The transverse BTF system of LHC was developed and installed in the LHC during the first part of 2015. During a BTF acquisition the chosen beam is safely excited, i. e. without causing losses or emittance blow up, within a betatron frequency range of interest in both planes. The beam is excited by the kickers of the transverse damper (ADT), while the beam response is recorded by the Beam Position Monitors of the BBQ (Base Band Q measurements) system. The measured SD is reconstructed through the relation: $SD = 1/R(\Omega)$, where $R(\Omega)$ is the complex BTF response at each excitation frequency Ω and it is defined as the dispersion integral in Eq.(3).

BETA-BEATING DUE TO HEAD-ON BEAM-BEAM EFFECTS

The other beam represents an electromagnetic lens and therefore can cause a change of the β function the so called dynamic beta [21]. This results in a local change of the β^* at the IPs with a direct consequences on the luminosity reach. For the LHC during 2015 an imbalance of maximum 1-2% has been evaluated and presented in [22].

A part of the change on the β^* a beating should be expected all along the accelerator. This is shown for the LHC case in Figure 22 where due to the two collisions in IP1 and IP5 a maximum beating of 7% is expected. The standard beta-beating corrections are assumed to be better that 5% without beam-beam effects. Studies have started to understand the impact of such beta beating since it involves the beam core and not tail particles. In particular for the HL-LHC project since this can easily exceed the 15-26%, depending on the operation mode.

CONCLUSION

The 2015 run has shown the beauty of relaxed beam-beam effects. A reduced beam-beam separation of 10σ is proposed for the 2016 physics run for the optics of 40 cm β^* which corresponds to a crossing angle of 370 μrad as also discussed in [14]. From beam-beam effects the choice of 40-50 cm β^* is equivalent if the same separation is maintained. The 40 cm β^* option is strongly supported due to the potential luminosity reach for reduced crossing angle operation in a second step during the physics run. Based

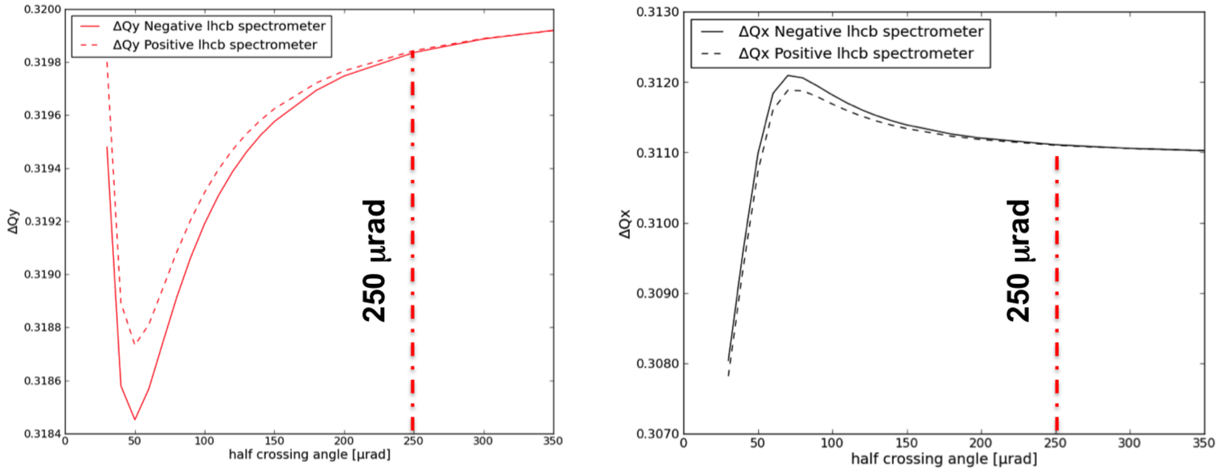

Figure 18: Vertical (left picture) and horizontal (right picture) tune shifted caused by the beam-beam effects at IP8 (the lhcb experiment). The solid lines refer to the case with positive polarity of the spectrometer while the dashed line to the case with negative polarity. The proposed half crossing angle for IP8 to be transparent to the the spectrometer polarity change is indicated.

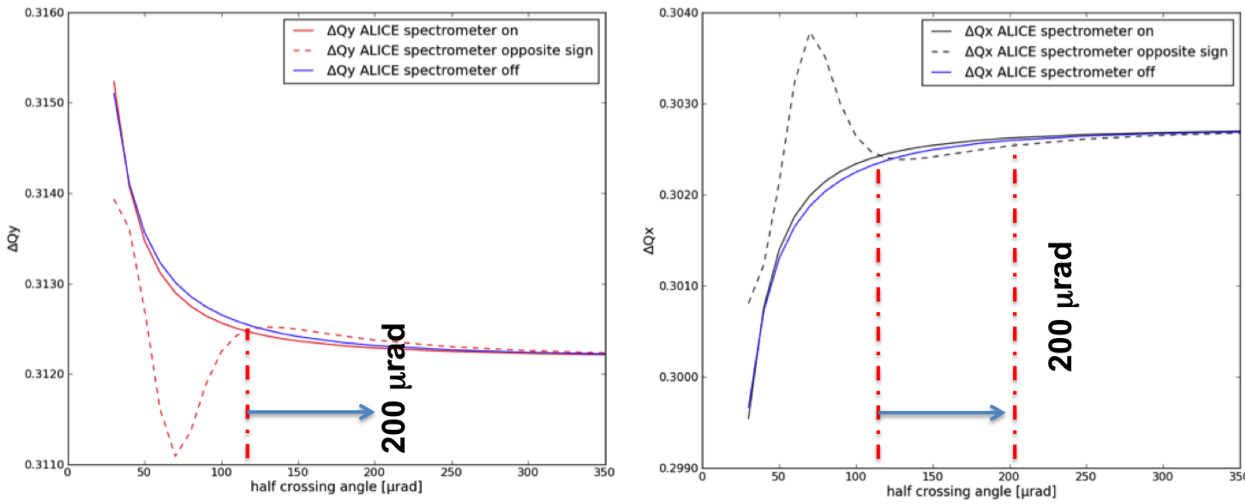

Figure 19: Vertical (left picture) and horizontal (right picture) tune shifted caused by the beam-beam effects at IP2 (the Alice experiment). The solid blue lines refer to the case without the spectrometer, red solid line to the case with spectrometer with polarity that sum up with the long-range beam-beam while the dashed line to the case with polarity that reduces the separation of the beam-beam encounters. The proposed half crossing angle to allow swap of spectrometer polarity is shown and is 200 μrad.

on the observations during the long-range limit tests a separation of roughly 8.0 σ can be achieved for reduced octupole and chromaticity values with intensity and luminosity lifetimes of 10-20 hours. The test should be repeated during the 2016 run to confirm the observation and specially to define the margins. Instabilities during collisions are understood and always linked to a loss of the head-on induced Landau damping due to transverse separation and/or mismatched emittances. Keeping beams into collision and small differences between the beams emittance can mitigate such effects. The transverse feedback might also play a role in the instabilities observed during OP-scans.

ACKNOWLEDGEMENT

The authors would like to thank G. Arduini, R. Bruce, R. Tomas, W. Herr, J. Wenninger, S. Fartoukh, M. Giovannozzi, Y. Papaphilippou, M. Lamont, S. Redaelli for several usefull discussions. And all the RF ADT, BI and OP teams for support over the various test and activities.

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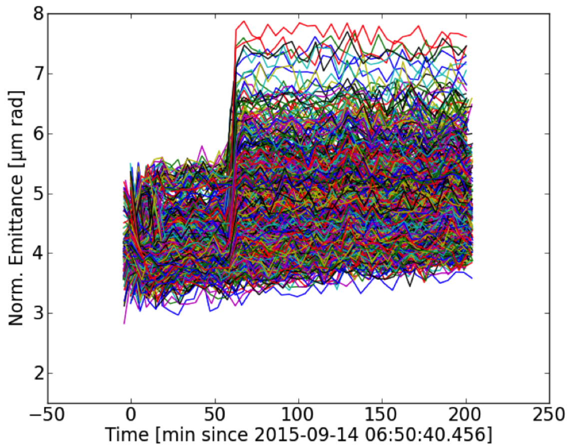

Figure 20: Bunch by bunch emittances in μm as a function of time during a physics fill of 2015 physics run. The emittances are measured by the BSRTs showing a sudden increase on selected bunches while beams were separated.

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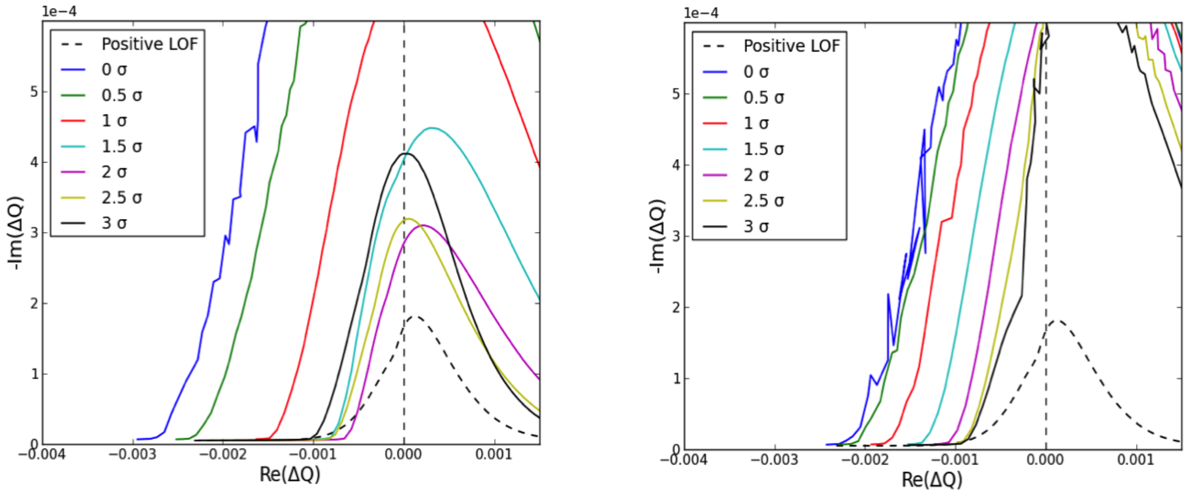

Figure 21: Horizontal (left) and Vertical Stability diagrams computed for a typical physics fill for different transverse separations at IP1 (legend). In dashed black lines the stability diagrams due to octupoles alone are plotted as a reference.

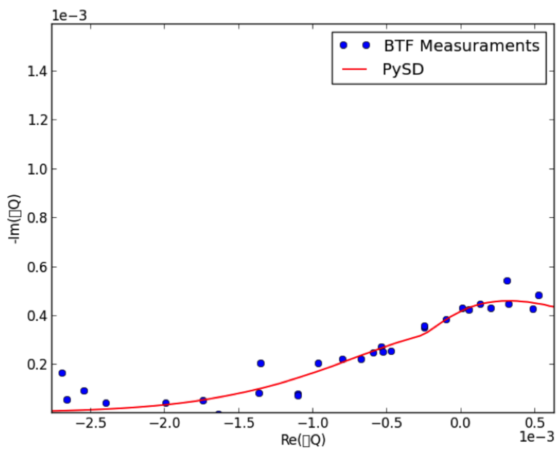

Figure 22: Computed (red line) versus measured (BTF reconstruction) stability diagram.

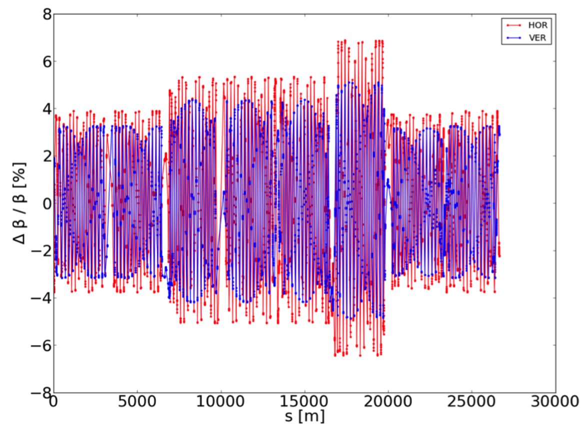

Figure 23: Horizontal (red) and Vertical (blue) beta-beating percentage due to beam-beam effects for a typical 2015 physics fill along the LHC circumference starting from IP3.