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Global compensation of long-range beam-beam effects with octupole magnets: dynamic aperture simulations for the HL-LHC case and possible usage in LHC and FCC.

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Abstract

The Large Hadron Collider has shown with various experimental verifications that one of the main limitations to the collider performance and to a possible upgrade can come from the long-range beam-beam effects which will define the operational parameters (intensities and emittances) and machine set-up (crossing angles and the minimum beta function at the interaction points). The High Luminosity project aims at very high intensities and will therefore need much larger separations to keep the long range effects weak. In the past several studies of possible active compensators have been carried out and experimental studies are planned to explore such schemes in the LHC. In this note we show the feasibility of using octupole magnets to compensate the effects of long range beam-beam interactions by use of dynamical aperture simulations. A prove of principle of such a compensation scheme is shown for the HL-LHC optics. Preliminary studies for the LHC optics ATS and standard are also presented pointing to the importance of the machine optics choices to make this compensation effective. Considerations of a possible use of such a scheme for the FCC case are also discussed.

Keywords: Accelerator Physics, beam-beam effects, long-range compensation, HL-LHC, Dynamic Aperture

Contents

1 Introduction

The High Luminosity upgrade of the Large Hadron Collider (HL LHC) aims at achieving a peak luminosity of 5×10^{34} cm^{-2}s^{-1} with levelling allowing an integrated luminosity of 250 fb^{-1}, enabling i.e. the goal of 3000 fb^{-1} in its 10-12 years of lifetime [1].

Recently a change of the baseline have set different values for the β^*, now 20cm, but studies presented in this note have been done conservatively for the old value of 15 cm that the HL-LHC project still aims and for parameters mentioned in [2]. The compensation is a general effect and can be easily scaled to the newer baseline.

The luminosity goal of the HL-LHC can be achieved by colliding 2.2 $\cdot 10^{11}$ protons per bunch, 2384 bunches per beam and low beta functions at the interaction points all colliding at a finite crossing angle of 590 μrad to minimise the effects linked to parasitic encounters left and right of each experiment. The luminosity reduction due to this large crossing angle is estimated to be around 70%. It is therefore foreseen to compensate this loss of luminosity by the use of crab cavities [1]. The HL-LHC operation at low β^* is possible thanks to the ATS scheme [3]. The corresponding peak luminosity would exceed the limit of 5×10^{34} $cm^{-2}s^{-1}$ imposed by the detectors to avoid high pile-up operation, for this reason a strategy for levelling the luminosity is fundamental. Results have been summarised for the baseline and ultimate scenario in [2] and used for [4]. Beyond the general studies of beam-beam effects for the HL-LHC baseline and ultimate scenario with beta start levelling of [5], one needs to address also the impact of high octupoles and chromaticity effects. Operational observations of coherent instabilities during the 2012, 2015 and 2016 physics run of the LHC [6] shows that large octupoles and chromaticity values are needed to suppress coherent instabilities. Simulations in these conditions are needed to define the LHC optimal running scenario [7] and it is fundamental to assess if the HL goal is achievable. In this note we summarise the results of these studies for the baseline scenario of the HL-LHC were the impact of high octupoles magnets and high chromaticity is addressed.

The transverse Dynamic Aperture (DA) is defined as the maximum transverse amplitude where the particles perform stable motion for 10^6 turns. Even if the DA does not provide direct information regarding the emittance growths, it is an important indicator to predict the beam lifetimes imposed by the nonlinear beam dynamics at collision. In the LHC collider the use of DA simulations is very important to define the margins needed in units of RMS beam size when changing the beam properties (e.g. beam charge and emittances) and machine optics (e.g. crossing angle and β^*). In Table 1 we summarise the HL-LHC beam parameters and compare to the LHC nominal design values and the operational parameters of the 2012 physics run. We compare to the 2012 run because it has been by far the most challenging in terms of long-range and head-on effects together with a very low dynamic aperture due to high Landau octupoles and chromaticity operation as summarised in [8].

All the simulations shown are performed using Sixtrack [9] with the beam-beam 6D kick computed with the Hirata formalism with energy change [10]. The Hirata 6D formalism has been chosen as the baseline for beam-beam studies since it is the model which better describes the beam-beam interactions in the HL-LHC scenarios and because, compared to the 4D Bassetti-Erskine formalism [11], used for the LHC design, it has been shown to be the most conservative when evaluating the dynamical aperture.

Table 1: HL-LHC, LHC nominal and LHC 2012 operational parameters

Parameter	LHC Nom	LHC 2012	HL-LHC
$N_p(10^{11}$ p/b)	1.15	1.65	2.2
N_b	2808	1380	2808
Spacing (ns)	25	50	25
ε (μrad)	3.75	2.2-2.5	2.5
β^* (m)	0.55	0.6	0.15
α μrad	285	290	590
Q_x	64.31	64.31	62.31
Q_y	59.32	59.32	60.32
ξ_{bb}/IP	0.0034	0.007	0.0033(0.011 with crab crossing)

We use as the design goal of having the minimum DA equal or bigger than 6σ: this value have been chosen as a minimum requirement as used in the optimisation phase of the LHC design and also as experimentally proved to be a robust assumption in terms of stability and lifetimes during the LHC 2012, 2015 and 2016 experiments [12]. Machine set-ups that give a simulated minima dynamic aperture of 6 σ leaves margins from the chaotic limit which has been identified empirically in the LHC to be at a simulated DA of roughly 4-3 σ. For configurations with minima DA below this value the beams and luminosity lifetimes start deteriorating and lifetimes drop below 10 hours with important losses related to long-range beam-beam [**?**, 7, 13–16, 18]. These findings are used to define future set-ups as presented in [19] and confirms the easier operation of the collider when larger margins are kept in operation. The HL-LHC assumes beam lifetimes of 10 hours to achieve the designed performances. It is therefore fundamental to guarantee at a design stage enough margins to meet the goal till a more robust criterion will be established thanks to the deeper understanding of the LHC observations. Studies correlating measured and expected losses due to dynamic aperture can be found in [18].

2 Compensating beam-beam long range effects with the Landau Octupoles

Due to coherent instabilities observed during the LHC RUN I and II the LHC operates with high chromaticity and Landau octupole strength to guarantee stability [6–8]. In 2012 it was proposed the idea of octupole tune spread cancelled by long-range effects [20] as a possible explanation fo the instabilities observed, this has shown not to be a possible explanation as described in [6]. While the interplay between octupole and long-range beam-beam effects on the tune spread is evident as shown in Figure1 where the larger footprint occurs when the octupoles add up with the long-range spread. The long term tracking has always shown a negative impact on the dynamic aperture, highlighting the fact that the reduction of spread was not a real compensation of the beam-beam effects. Differently than for the LHC case [7], despite the expected reduction of the tune spread (as discussed in [21]) a negative impact on dynamic aperture has always been observed for both polarities. For the HL-LHC case it will be shown to be different and a real compensation between the two effects occurs thanks to the ATS optics property which is not related to the only compensation of tune spread. For the first time in [22] some preliminary results for the HL-LHC pointed out the possibility of using the octupoles magnets in the HL-LHC lattice to improve the Dynamic Aperture (DA) by compensating the long range encounters effects. Figure 2 shows how the DA improves using negative polarity in the octupoles for the maximum current allowed (I_{oct}=-550 A). These results have never been obtained for the LHC optics, which was always pointing to a negative effect of the octupoles independent of their compensation and not of the tune spread. These new and preliminary results have boosted an extensive study to understand the differences and find a possible configuration suitable and testable in the LHC as a prove of principle for the HL-LHC project. Compensating long-range beam-beam with multiples is not a new idea [23–25] and has been studied extensively, however the new results for the HL-LHC case have shown strong effects and opens room for alternative scenarios to the use of crab cavities with very competitive performances [26].

The compensation appears to be effective at the end of the betatron squeeze with and without head-on collisions. Based on these results the negative polarity of the octupoles has been chosen for the HL-LHC baseline scenario described in [2]. The results of a more detailed simulation campaign are summarised in this note were the effects of multipolar errors are not included. A complete study to define the robustness of such a scheme should be repeated taking into account the machine non-linearities. Only sextupole magnets are used and Landau octupoles for different beam-beam configurations.

In Figure 2 the dynamic aperture for the HL-LHC operational scenario at the end of the betatron squeeze to 15 cm β^*. Simulations include the beam-beam long-range effects in IP1 and IP5 (black lines) and Landau octupoles at 550 A powered in negative polarity (blue lines) and positive polarity (red lines) for different values of chromaticity. The studies have been performed for two different intensities 1.0 10^{11} proton per bunch (dashed lines) and 2.2 10^{11} protons per bunch (solid lines). As visible in the figure the negative octupole polarity improves the dynamic aperture for beams with higher intensities from around 6 σ to above 8 σ, while for the case with lower intensities 1.0 10^{11} protons per bunch the compensations does not appear. This could be due to the fact that the dynamic aperture with beam-beam alone is already at a large value and no effects need to be compensated.

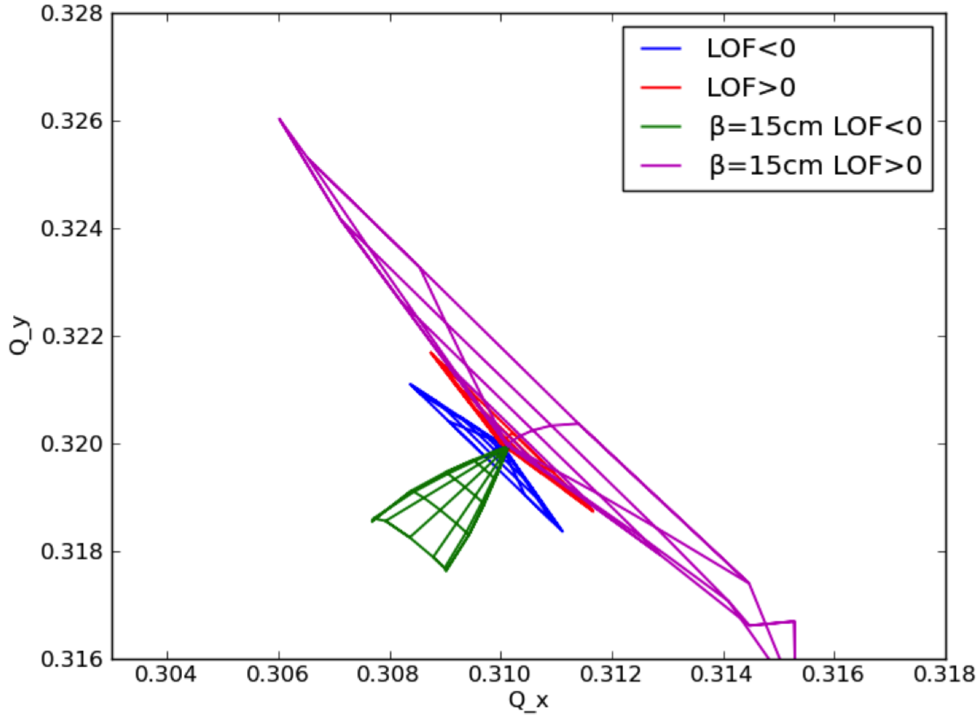

Fig. 1: Footprints for different polarities of the Landau octupoles powered at 550 Ampere at a β^* of 15 cm. The $LOF < 0$ refers to the negative polarity of the octupoles while $LOF > 0$ to the positive. Red and Blue Footprints show the detuning with amplitude (up to 6 σ) from octupole magnets and sextupoles alone, while Green and Pink in combination with the long-range beam-beam effects for the HL-LHC operational baseline as described in [2].

A similar study with the head-on collisions is shown in Figure 3 where one can notice two effects: first that the two head-on collisions do not affect strongly the DA which is mainly dominated by the long-range, octupole and high chromaticity effects, second, we notice that the compensation is preserved also in the presence of the head-on collisions. This shows that the effective improvement in DA comes from a real compensation of the long-range effects by use of the octupolar field and it is robust enough to apply also in the presence of strong head-on effects.

To further understand the dynamics and potential of such scheme a scan of the octupoles current is performed increasing the octupole current range also to currents beyond the limits of the present hardware which is of 590 Ampere. Figure 4 shows the minimum DA for the cases with (green line) and without (purple line) crab crossing for a scan of the octupoles current. The current move from positive polarity of the octupoles (i.e. +600 Ampere) to negative polarity (-1500 Ampere). Dynamic aperture moves from 2.5 σ for the positive polarity case where long-range and octupoles adds up, to 8 σ DA for octupoles powered at -600 Ampere. The maximum compensation appears at a current of -600 Ampere. In the presence of a crossing angle (i.e. without crab cavities) the head-on dynamics change (purple line) and the compensation is slightly reduced and actually the optimum set-up for the octupole currents changes. The DA has an important improvement by using the existing octupoles circuit powered at their maximum current of 590 Ampere in negative polarity.

A Frequency Map Analysis (FMA) [27] for different values and polarities of the octupoles for a crab crossing scenario provides an interesting insight to what is happening to the particle distribution in frequency for the different points of DA simulations shown in Fig. 4. In Figure 5 top left, we see the frequency map analysis of a typical HL-LHC case with full head-on crab-crossed and the full long-range effects, this corresponds to the DA point of Figure 4 at zero current in the octupoles and fully crabbed

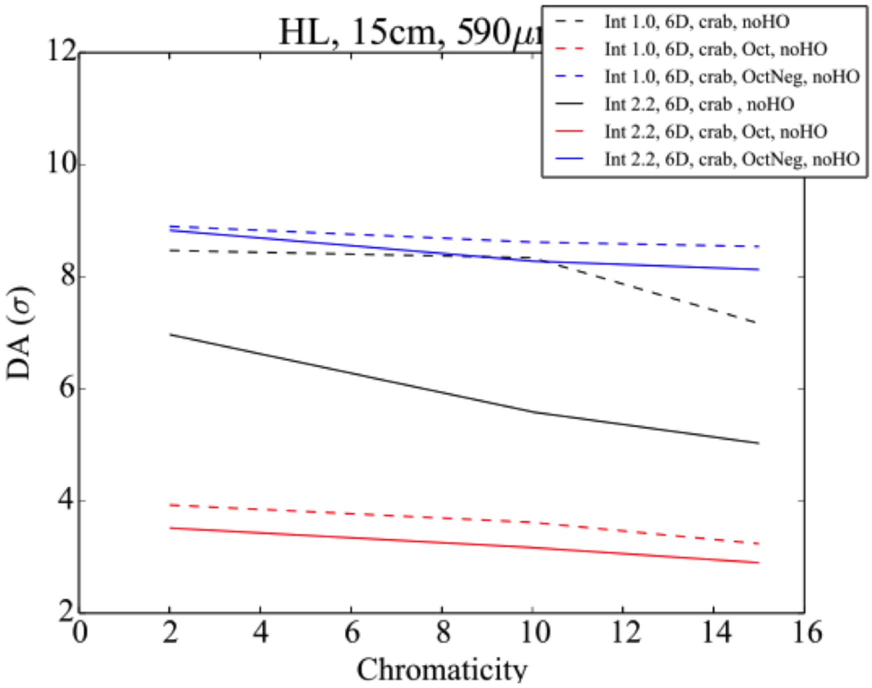

Fig. 2: Dynamic aperture studies for the HL-LHC operational scenario at the end of the betatron squeeze to 15 cm β^*. Simulations include long-range beam-beam effects in IP1 and IP5 (black lines) and Landau octupoles at 550 A powered in negative polarity (blue lines) and positive polarity (red lines) for different values of chromaticity. The studies have been performed for two different intensities 1.0 10^{11} proton per bunch (dashed lines) and 2.2 $\times 10^{11}$ protons per bunch (solid lines).

crossed head-on collisions corresponding to a DA of 5.5 σ. When we use octupole magnets with negative polarity, figure 5 top right, DA improves to 8 σ and this comes from a contraction of the footprint with a clear compensation of the resonance excited by the long-range effects. Despite the frequency spread is reduced but still covering resonances excited without octupoles, they disappear when octupoles are used. However if we continue increasing the octupole current (bottom left) the overcompensation makes the tails to fold on each other and increasing the diffusion index similar to the original case with resonances, causing the DA to deprecate again. Finally for the case of positive polarity (bottom right) the tails are not compensated actually they are further pushed to larger tune values leading to a visible larger footprint covering additional and stronger resonances which results in a loss of DA. The effect of octupoles is not improving DA because of a reduction of the tune spread but an effective compensation of resonances as visible with the FMA shown.

The possibility of compensating long-ranges beam-beam effects with the existing octupole families opens the possibility of reducing the crossing angle in the HL-LHC scenarios and relax consequently the crab cavity needs while keeping the 6 σ constraint on the dynamic aperture as a safe margin. Figure 6 shows that in case of being able to power the octupoles to larger currents than nominal it could be possible to reduce the half crossing angle from 295 μrad to 250 μrad while fulfilling the 6 σ goal in minimum dynamic aperture which is used for the design of the HL-LHC. The cases studied here are the worse case since a fully squeezed with maximum intensity of 2.2 10^{11} protons per bunch is used. Using β^* levelling leaves even larger margins on the minimum crossing angle achievable.

Reducing the crossing angles further as shown in Figure 6, the compensation is still effective but a stronger octupole system should be foreseen to obtain the maximum compensation. In the study we have artificially modelled an enlarged octupole effect by exceeding the magnets powering limits to show the principle of such a compensation. In Figure 6 it is proved that a crossing angle of 500 μrad will still fulfil the minimum 6σ dynamic aperture requirements using a current of -800 A in the octupole magnets. Experimental evidence in the LHC might also open the possibility of reducing the

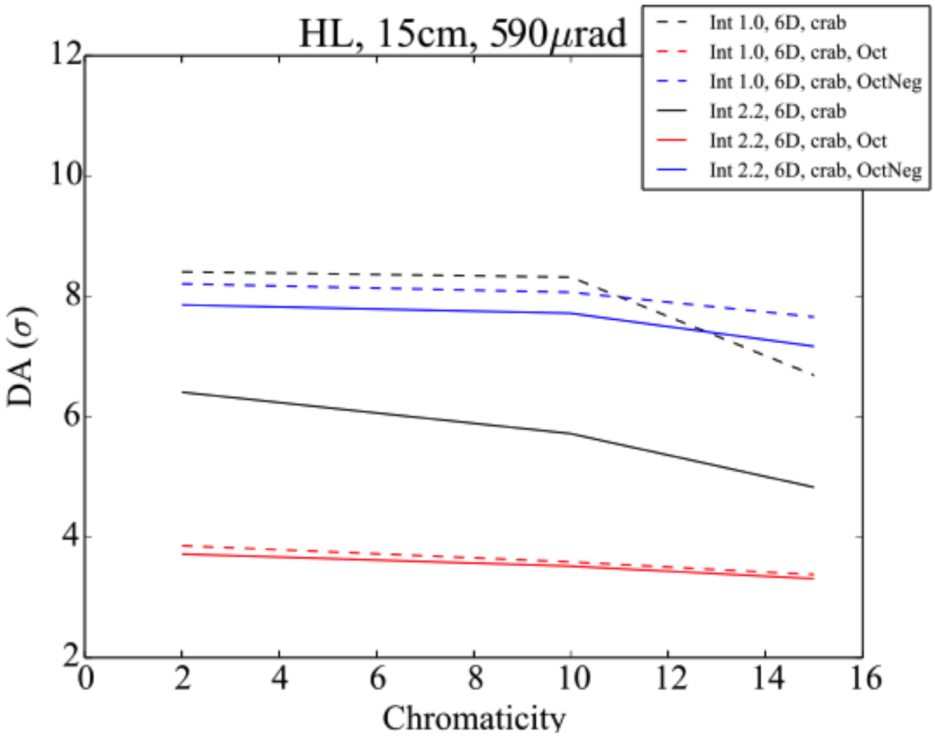

Fig. 3: Dynamic aperture studies for the HL-LHC operational scenario at the end of the betatron squeeze to 15 cm β^*. Simulations include head-on and long-range beam-beam effects in IP1 and IP5 (black lines) and Landau octupoles at 550 A powered in negative polarity (blue lines) and positive polarity (red lines) for different values of chromaticity. The studies have been performed for two different intensities 1.0 10^{11} proton per bunch (dashed lines) and 2.2 $\times 10^{11}$ protons per bunch (solid lines).

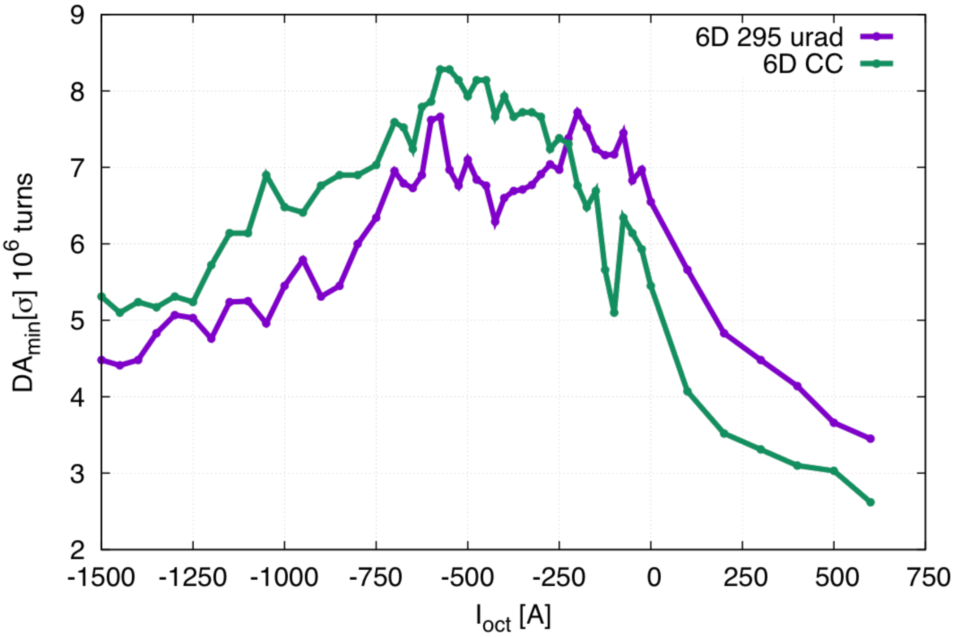

Fig. 4: Minimum DA for two collisions schemes for the 15 cm β^* optics and 2.2 10^{11} protons per bunch: with an angle (purple) and crab crossing (green). It is clear the benefit from powering at collision the octupoles with negative polarity for the crab crossing case. For the case of collision with an angle there is an improvement at a current of -250 Ampere. The hardware limit for the octupoles current is of 590 Ampere as indicated by the red solid lines. The chromaticity is set to 2 units.

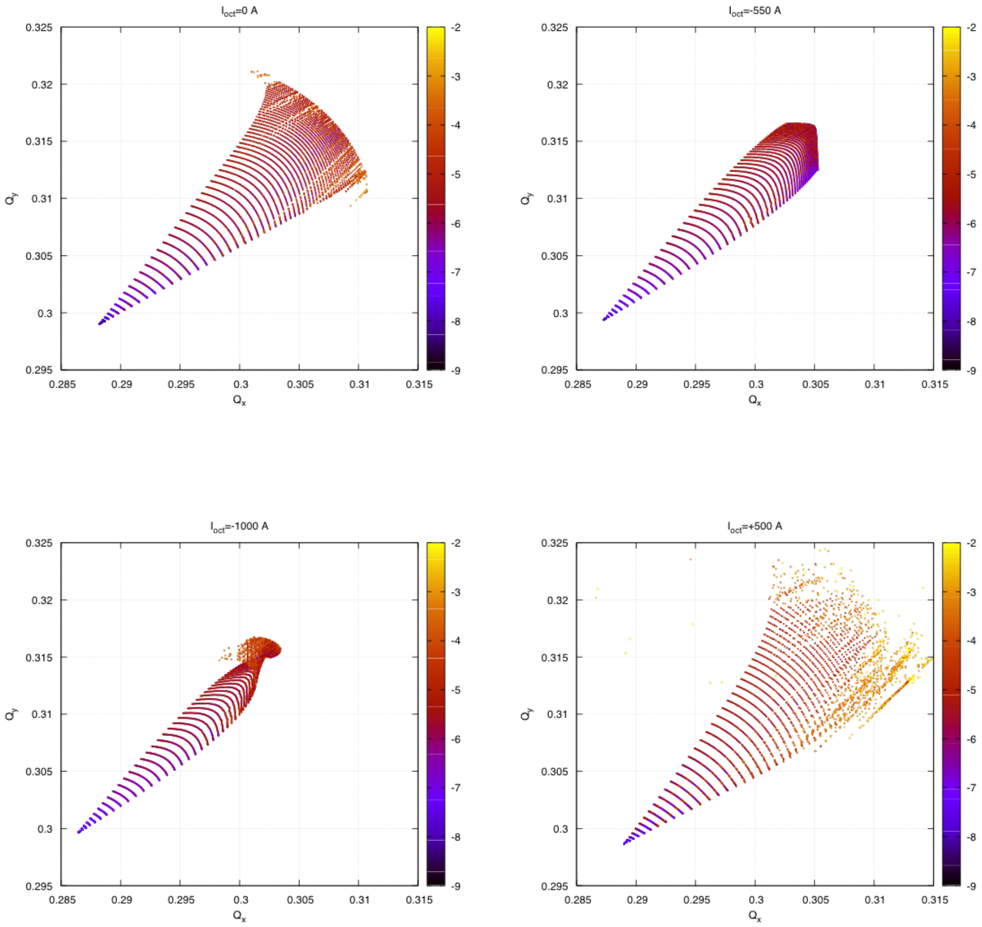

Fig. 5: FMA for different currents and polarities in the octupoles for particles up to amplitudes of 6 σ. Top left shows the FMA expected from the beam-beam effects Long-range with 15 cm β^* optics and 2.2 10^{11} protons per bunch when the octupoles are not powered, resonances are excited. Top right picture shows when octupoles are powered with negative polarity and compensate clearly the tune spread and resonances at the optimum current of -550 A. Bottom left shows the cases when an overcompensation occurs for currents of -1000 A. Bottom right shows the further deterioration when octupoles are powered in positive polarity at +500 A. The chromaticity is set to 2 units and no multipolar errors are present.

target dynamic aperture to 5 σ DA. If this is confirmed it might be still safe a even further reduction of the crossing angle to 450 μrad, as visible in Figure 6 (orange line) however a stronger Landau octupole system should be foreseen for crossing angles below 500 μrad with full intensity beams of 2.2 10^{11} protons per bunch.

Another important result is that using negative octupoles will allow to use also higher beam intensities as shown in Figure 7 where the goal of 6 σ dynamic aperture is reached with an intensity of 3.7 $\times 10^{11}$ protons per bunch. One can notice the important impact of the crossing angle at the head-on collision indicating a deep involvement of odd resonance which are not excited with crab-crossing with respect to a finite crossing angle at the IPs.

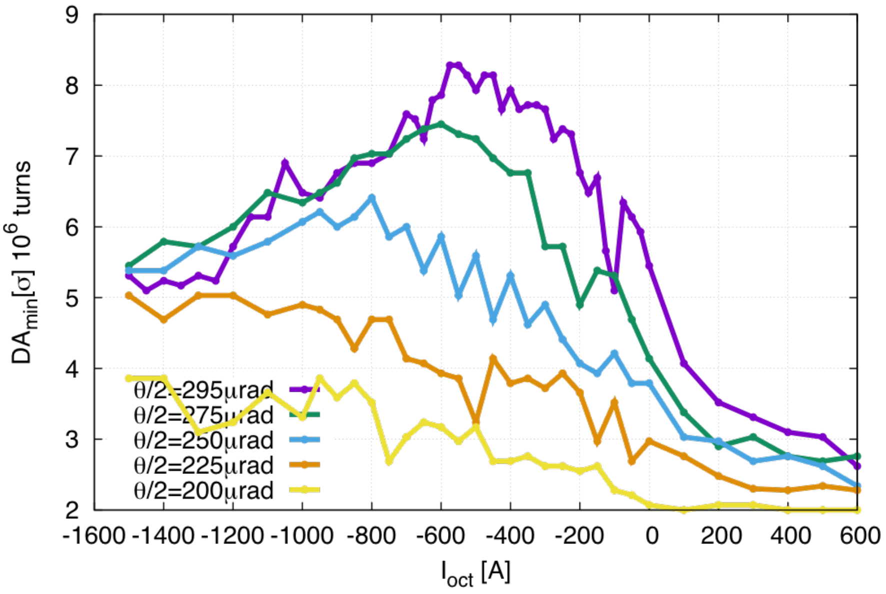

Fig. 6: Minimum DA as a function of the octupole current for different crossing angles with a full compensation with crab crossing at the IPs for the head-on interactions at the IP1 and IP5. The 15 cm β^* optics and 2.2 10^{11} protons per bunch is used. Case 1 is the nominal half crossing angle of 295 μrad (purple line). Case 2 if for a reduced half crossing angle of 275 μrad (green line). Case 3 for a half crossing angle of 250 μrad (blue line). Case 4 for a half crossing angle of 225 μrad (orange line) and case 5 for half crossing angle of 200 μrad (yellow line). Chromaticity is of 2 units for these cases.

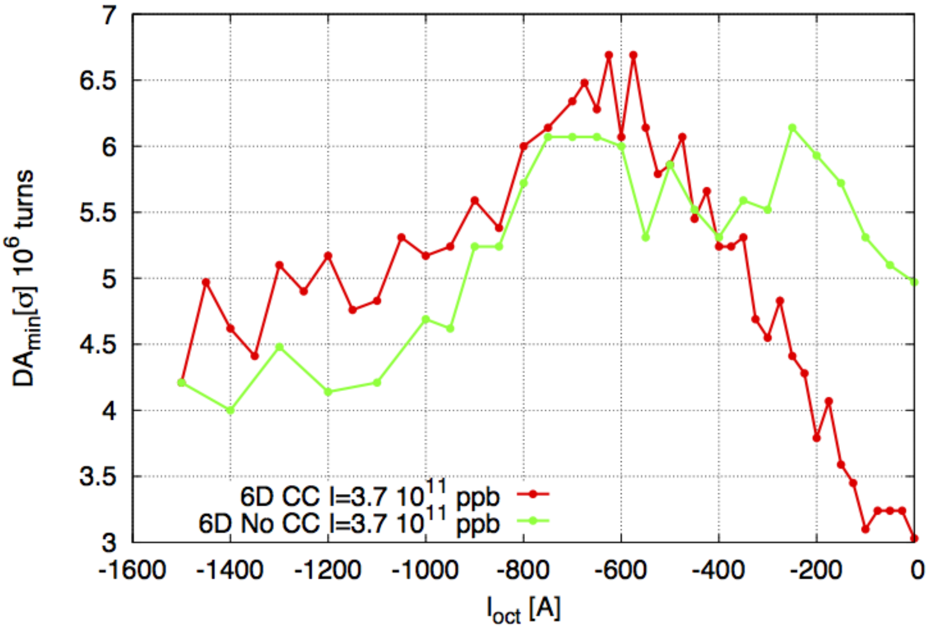

Fig. 7: Minimum DA as a function of the powering current in the octupole circuits with negative polarity for an HL-LHC study case using the ATS 15 cm β^* optics, 3.7 10^{11} protons per bunch and chromaticity of 2 units: with crab crossing at the head-on collision (red line) and no crab crossing (green line). The crossing angle is set to nominal value of 590 μrad.

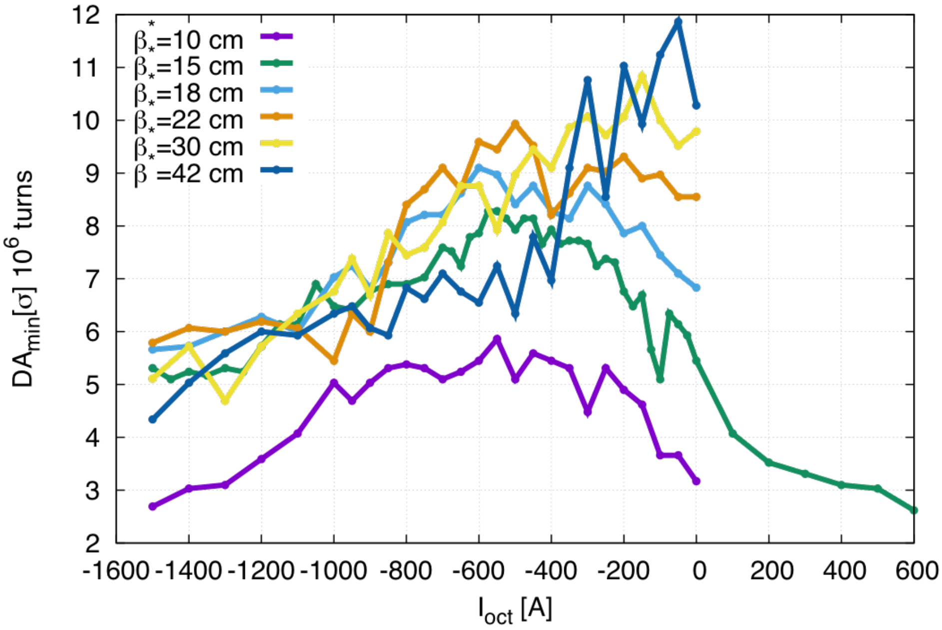

Fig. 8: Minimum DA for different ATS squeezed optics cases. The different lines refer to the different beta* reached at the IP1 and IP5 and they go from 42 cm to 10 cm beta*. The intensity is set to 2.2 10^{11} protons per bunch and chromaticity is set to 2 units for these studies.

3 Compensation dependency of the optics, intensities, chromaticity and octupole circuits

The long-range beam-beam effects depend on the normalised separation at the encounters and for a given crossing angle this separation depends on the beta function at the location of the encounters. In Figure 8 we show how the compensation changes as a function of the beta* at the IPs simulating an operational case of beta* leveling for the HL-LHC as described for the operational scenario of [2] for the maximum intensity of 2.2 10^{11} protons per bunch. The long-range encounters separation goes for these cases from 21 (dark blue case) to 10 σ (purple line case). Two important observations can be drown from the study: first that the compensation with octupole works more effectively for the nominal case with beta* of 15 cm with a current in the Landau octupoles equivalent to the maximum possible of 590 A confirming the robustness of the HLLHC baseline scenarios proposed and giving the possibility to reduce the crossing angle and relax the crab cavities requirements in terms of crab crossing voltage. Second point is that there is a clear dependency on the optics used. One can notice two regimes for the non-linearities of the machine. For β^* 42 cm (dark blue line) one can notice that adding octupoles to the system will reduce the dynamic aperture because the octupoles actually represent the strongest non-linearity in the system and therefore dictates the DA. In this case the long-range beam-beam effects are weak since the separations are around 21 σ separation. Reducing the beta* at the IPs the long-range beam-beam effects become stronger and the compensation starts taking over as visible in Fig. 8 orange line where the two effects start compensating (at long-range separations of approximately 15 σ). Reducing further the beta* the beam-beam separations the compensation becomes more evident (22 cm orange line and 15 cm green line). The optimum compensation is obtained for the nominal 15 cm optics with Landau octupoles powered at their maximum strenght of approximately 590 Ampere. An important result is the possibility of using also a squeezed optics with beta* of 10 cm (purple line) increasing the DA to a close to acceptable level from 3.5 σ to almost 6 σ using the available octupole magnets power of roughly 600 A in negative polarity.

In Figure 9 we show the same study but compared to a reduced crossing angle case for the 42 cm β^* optics to compare the same long-range effects but different optics. This shows how it is not possible to recuperate the dynamic aperture by just reducing the tune spread due to long-range effects with the octupoles powered in negative polarity. A fundamental role comes from the optics properties of ATS

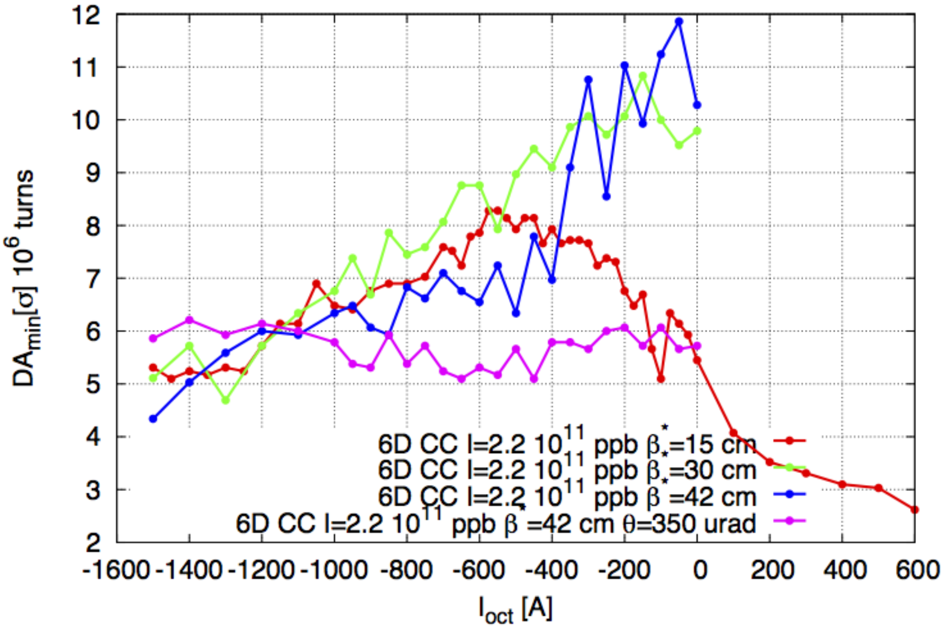

Fig. 9: Minimum DA for different ATS squeezed optics cases as a function of the octupole currents. The different lines refer to the different beta* reached at the IP1 and IP5 for a crossing angle of 590 μrad. The optics are: 42 cm (blue line), 30 cm (green line) and 15 cm (red line) beta*. For the case with 42 cm β^* we compare to the case with crossing angle of 350μrad which is equivalent to a 12.5 σ beam-beam separation. The intensity is set to 2.2 10^{11} protons per bunch and chromaticity is set to 2 units for these studies.

with the telescopic part, not present for the 42 cm case. This study shows the compensation is not related to tune spread reduction.

Important to notice that the compensation is valid also for smaller intensities. The improved DA observed with the ATS optics of HL-LHC for the case with 1.110^{11} protons per bunch has never been observed for LHC type of optics neither for an ATS compatible optics for the LHC as will be shown later. The octupole current in the octupoles will have to be adjusted depending on the intensity of the beam-beam long-ranges consequently with respect to the intensities of the bunches. The upper limit in intensity in this simplified case is at 3.710^{11} protons per bunch.

Another interesting finding is the interplay with the machine chromaticity. The HL-LHC as the LHC will have to be designed and possibly operated with high chromaticity (i.e. 15 units) to suppress coherent instabilities observed during the LHC run II [4, 7] therefore margins should be taken to allow for such an operational scenario. This study shows that octupoles magnets could be used to improve the dynamic aperture deterioration due to the high chromaticity operation. The octupoles, by compensation of the long range effects, give larger DA allowing to operate with larger chromaticity (which has the effect of reducing DA). The optimum compensation for high chromaticity then occurs at different currents of the octupoles as visible in Fig. 12 pointing to a deeper involvement of the chromatic properties of the ATS optics to the overall compensation scheme. For low chromaticity runs the required octupole strength for a full compensation of the long-range effects is of -250 Ampere, while for a high chromaticity runs the required strength of octupole is around -450 Ampere which is in reach with the existing octupole system. The dynamic aperture is improved from a value of 5 σ to above 7 σ. Using the positive polarity is not an option since it gives an evident degradation of the dynamic aperture for all cases analysed in this note. The results for the case with crab crossing can only improve the results as shown in Figure 4.

Normally in physics operation both octupoles families, focusing (ROF) and defocusing (ROD), are powered equally. We now explore what happens if we power them to different values and polarities. In Figure 13 both scenarios with (right) and without (left) crab crossing are shown scanning versus

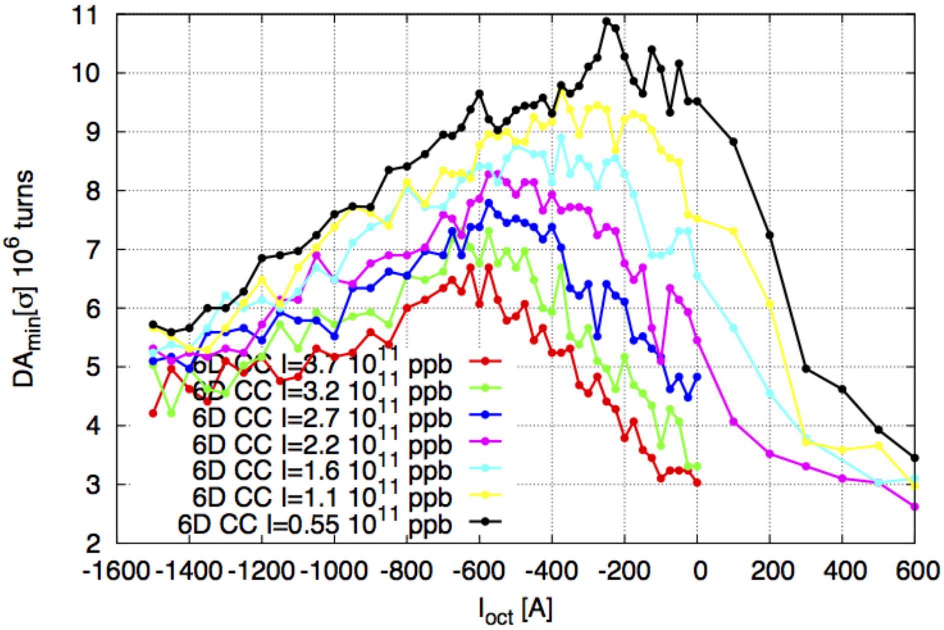

Fig. 10: Minimum DA as a function of octupole powering current in negative polarity for different bunch intensities for the ATS 15 cm β^* squeezed optics with nominal crossing angle of 590 μrad, full crab crossing at the IPs. The different lines refer to different intensities per bunch. The pink line refers to the HL-LHC 2.2 10^{11} protons per bunch while the yellow one to the standard LHC case. Chromaticity is set to 2 units for these studies.

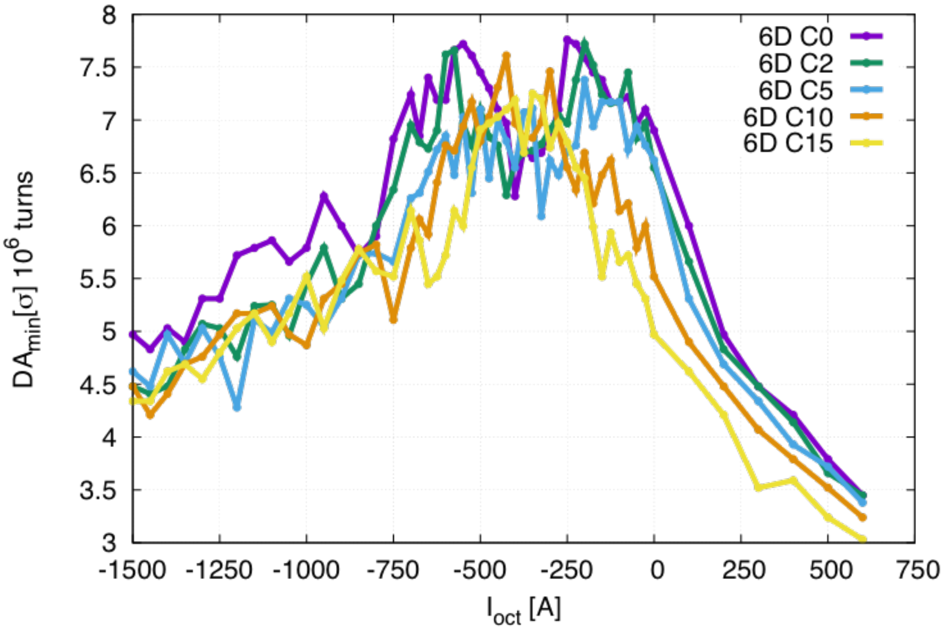

Fig. 11: Minimum DA as a function of the Landau octupole powering current for different chromaticity values for the nominal ATS squeezed optic of 15 cm β^*, 590 μrad crossing angle and full intensity of 2.2 10^{11} protons per bunch no crab crossing is applied.

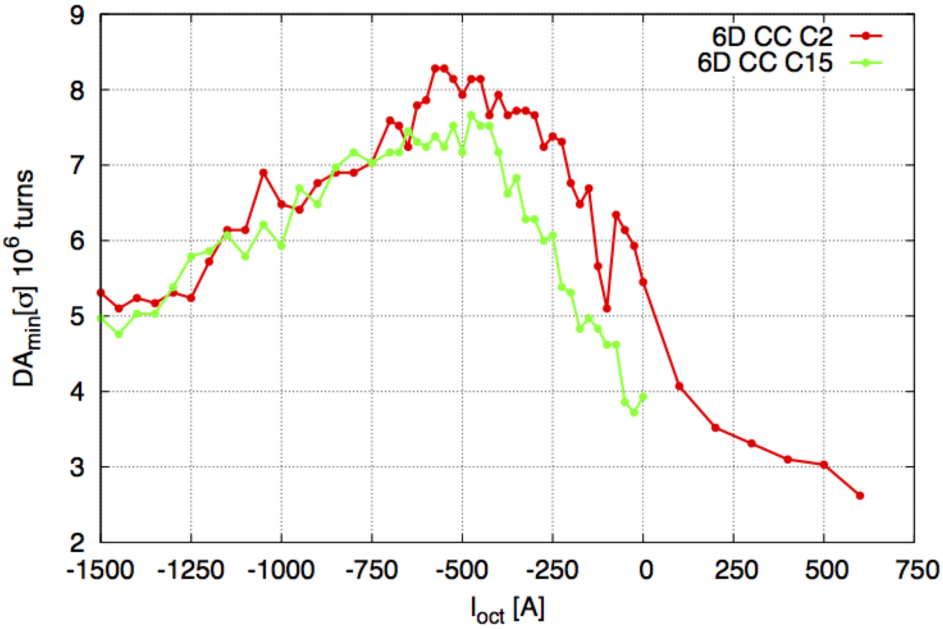

Fig. 12: Minimum DA as a function of the Landau octupole powering current for chromaticity values of 2 units (red line) and 15 units (green line) for the nominal ATS squeezed optic of 15 cm β^*, 590 μrad crossing angle and full intensity of 2.2 10^{11} protons per bunch with crab crossing at the IPs.

the octupole current in focusing and defocusing octupoles independently. Again it is clear that the crab crossing scheme is the one that benefits more from the compensation in both relative and absolute values. As well it is interesting to see that main improve of the DA comes from the contribution of the defocusing octupoles. Achieving the absolute maximum DA with almost no current in the ROF family and improving the DA from around 5 σ to above 8 σ depending on the magnets current. This highlights an important ingredient to the overall compensation scheme since it depends strongly on the head-on contribution and in particular to the compensation of synchro-betatron coupling mechanisms which are suppressed with a crab crossing scheme scheme or by the fact the head-on effect is stronger when the angle is compensated (i.e. to the beta beating contribution). Studies of beam lifetimes for separated Landau octupole families should be foreseen in the LHC to understand and experimentally verify this new feature together with the stability margins in a reduced octupole configuration. Possibly reducing the crossing angle and apply the compensation in collision where the head-on collision will give the needed spread for stability.

In Figure 14 we highlight the minimum DA as a function of the octupole current for the nominal case with both octupole families equally powered (red line) and compare to the case we power only the ROF circuit (green line) or the ROD (blue line).

If one correlates the dynamic aperture plotted in Figure 14 to the corresponding footprint of Figure 15 it is evident that an asymmetric compensation of the footprint tails seems more efficient pointing to the actual suppression of resonances in that area of the tune diagram that involves principally the larger amplitude particle of the vertical plane. A deeper study of the FMA and of the excited and suppressed resonances could give more details on the subject for a possible optimisation of the Landau octupole current strength. The best dynamic aperture corresponds to the case shown with red lines in Figure 15 where the vertical particles tails are completely suppressed by the octupole magnets. This is enough to improve drastically the DA.

4 HL-LHC versus LHC optics and potential applications

The principle of compensating long-range beam-beam effects by use of a global scheme and multipolar magnets demonstrated for the HL-LHC optics could be used also for the LHC case if the optics properties of the two lattices are brought to a similar level. As visible in the study of the optics dependency of

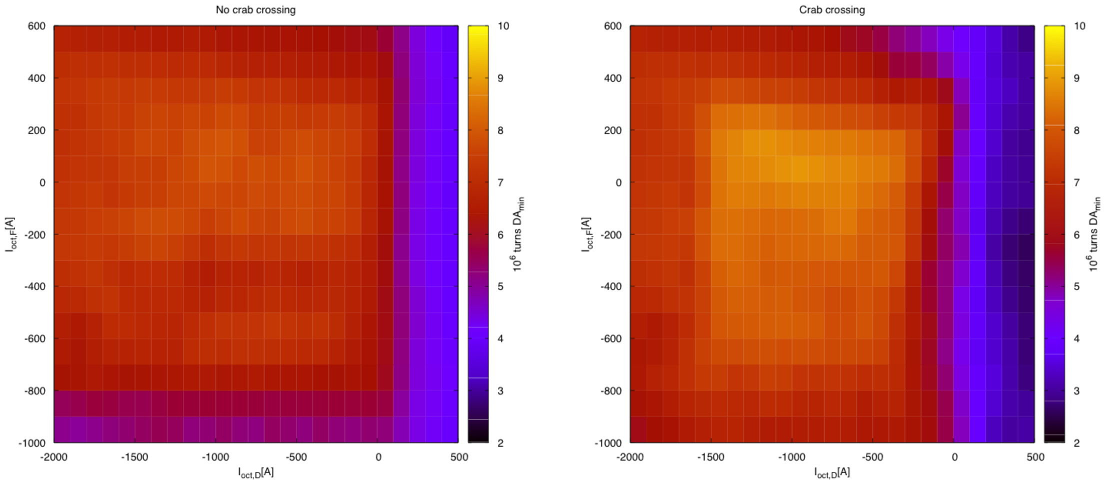

Fig. 13: Minimum DA for different powering set-ups of the Landau octupoles focusing (ROF) and defocusing (ROD) circuits for the HL-LHC baseline case without (left plot) and with (right plot) crab crossing at the IPs. Nominal ATS squeezed optic of 15 cm β^*, full intensity of 2.2 10^{11} protons per bunch and chromaticity of 2 units.

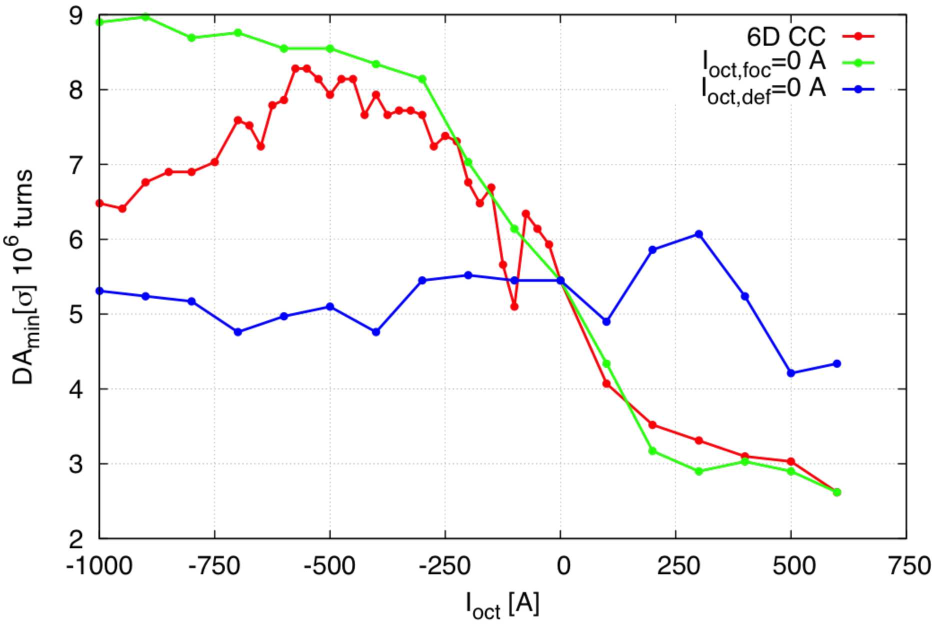

Fig. 14: Minimum DA as a function of the powering current in the Landau octupoles for three different set-ups of the circuits. Red line is in the case of equal powering of the ROF and ROD circuits, green line if with the ROF circuit is set to zero current while blue line if the ROD circuit is kept to zero current.All studies are done for the HL-LHC baseline case with full crab crossing at the IP1 and IP5. Nominal ATS squeezed optic of 15 cm β^*, full intensity of 2.2 10^{11} protons per bunch and chromaticity of 2 units.

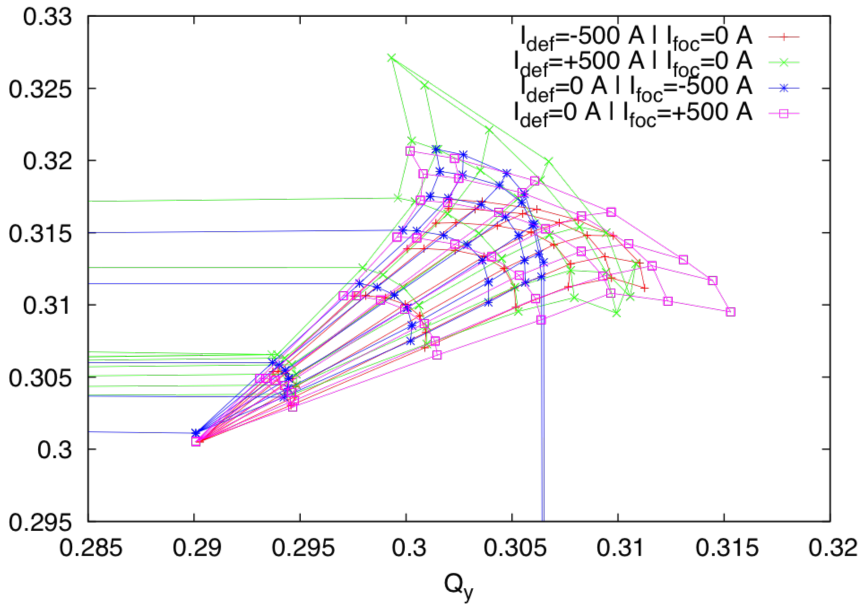

Fig. 15: Tune footprints in the presence of beam-beam head-on and long-ranges for different set-ups of the Landau octupole families and different powering currents. The best compensation case (with maximum DA values) corresponds to the cases with zero A current in the focusing and -500 A in the defocusing family (red line).

Figure9 of such compensation it is clear that the telescopic part of the ATS [3] optics is fundamental, therefore a complete study with modified LHC optics should be pursuit. Preliminary studies have been shown at [28, 29]. The global compensation starts for the squeezed optic with beta* below 22 cm this is where the telescopic part of ATS optics takes place changing the optics properties in the IPs adjacent arcs and therefore at the location of the Landau octupoles. Very small or no compensation is observed between long-range beam-beam and octupoles magnets for the ATS 42 cm optic as well as for a ATS LHC 40 cm case of Figure 16. Similar test have been performed also for standard LHC optics with similar results. A maximum improve of 30% in DA is observed for a case very similar to the HL-LHC fully squeezed for wich the dynamic aperture could reach values of 8 σ. Preliminary tests of the effect on the beams lifetimes coming from octupoles and chromaticity has been carried out in the LHC and have shown it is consistent with expected larger DA for reduced octupoles and chromaticity [7, 13]. However more detailed tests are fundamental to explore these effects.

The compensation scheme with octupole magnets depends then on the actual optics used and on the strength of the beam-beam long-range interactions. A first verification if this comes only from the increased strength of the octupole magnets or from the other specific properties of the ATS optics (i.e. sextupoles chromatic correction due to the telescopic squeeze) was done and it is shown in Figure 16 . Based on the known larger betas in the arcs the overall effect of the octupole magnets will be stronger than for a non telescopic optic as the LHC for example. This is shown in the footprints of Figure17 where the larger spread in the HL-LHC case is compared to the LHC case. The effect coming from the larger betas in the arcs can be estimated from the detuning with amplitude dependency on the beta functions at the Landau octupoles [31] as shown in the telescopic part of ATS gives stronger spread at the location of the octupoles thanks to the larger beta functions, so for the same powering currents and beam emittance the actual spread is increased by a factor of roughly 2.6 for the 15 cm fully squeezed case respect to a non-telescopic optic.

We have performed a scan in octupole currents exceeding the current limits of the circuits to verify if the different behaviour observed between HL-LHC and LHC optics was due to the differences in effective strength of the octupoles. Figure 16 shows the results in terms of dynamic aperture for different powering current in the octupole magnets. The configuration is very similar to the HL-LHC scenarios

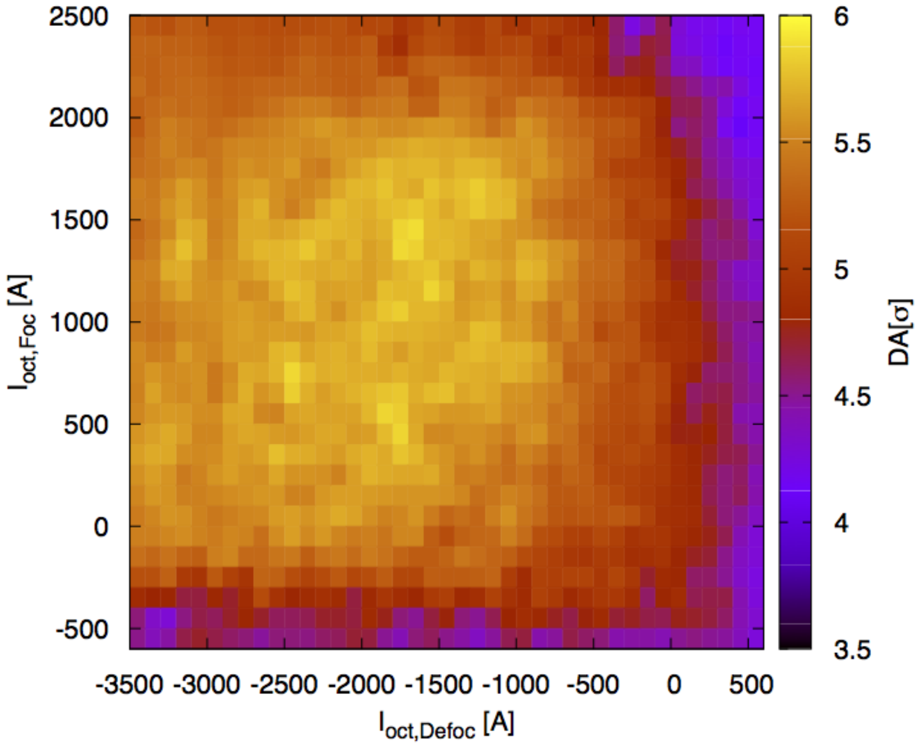

Fig. 16: Minimum DA as a function of different powering currents of the Landau octupole circuits. The optics used is an ATS compatible optics 40 cm for the 2017 run, intensities of 2.2 10^{11} protons per bunch, crossing angle of 290 μrad and chromaticity of 2 units.

analysed in the previous section (beam-beam separations of 12.5 σ, intensities of 2.2 10^{11} protons per bunch and transverse emittances of 2.5 μm). The overall footprint is shown in FIgure 18 which if compared to Figure5 (top left and right plots) shows how similar is the problem in terms of footprint but so different in terms of dynamic aperture. This is mainly due to the suppression of beam-beam driven resonances which is possible with ATS optics with the telescopic part respect to ATS compatible optics without the telescopic part. A second test was done repeating the study for a modified ATS compatible optic with a re-matched phase advance from the long-ranges to the octupoles and still no improvements have been observed. These results point to a deeper involvement of the telescopic part of ATS which will need modification of the LHC optics to make it as much similar to the HL-LHC case to profit of this compensation scheme. Further studies should look into this details to make it feasible for the LHC and in general for any circular collider since it is evident from this studies that the effective compensation seems robust and controllable with a ATS optics with telescopic part active.

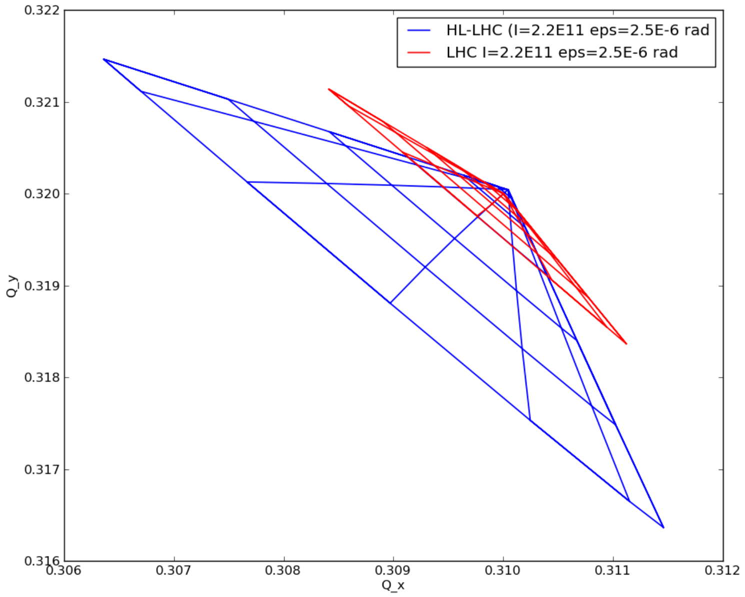

Fig. 17: Amplitude detuning from Landau Octupoles powered at 590 Ampere for the HL-LHC ATS optics squeezed at 15 cm(blu lines) and for the LHC optics squeezed at 80 cm (red lines) for same beam parameters 2.2 10^{11} protons per bunch and transverse emittances of 2.5 μm.

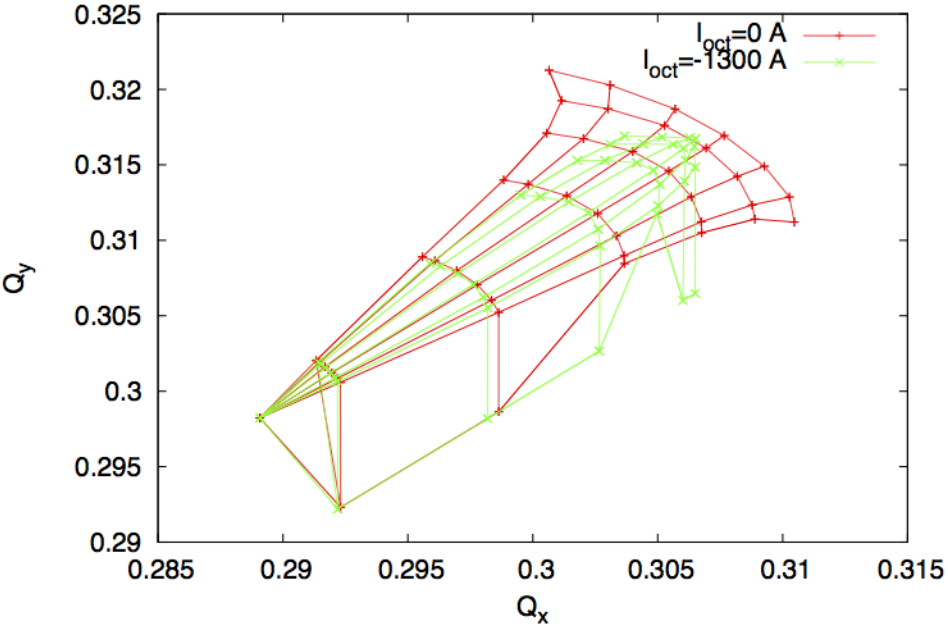

Fig. 18: Footprints at 6 σ particles for the case of beam-beam effects and octupoles powered in negative polarity at 0 A (red lines) and 1300 Ampere the equivalent of the HL-LHC case (500 A times 2.6 due to the telescopic squeeze). The LHC ATS optics squeezed at 40 cm is used with beams of intensity 2.2 10^{11} protons per bunch and transverse emittances of 2.5 μm. The crossing angle is set to have long-range beam-beam separation of 12.5 σ.

5 Conclusions

Studies of the effect of long-range dynamic aperture in the presence of strong Landau octupoles and high chromaticity have been presented and have shown for the first time the possibility to use the Landau octupoles circuits to compensate long-range beam-beam effects in the HL-LHC. The compensation works mainly for the ATS optics used for the HL-LHC and it is maximum using only one of the Landau Octupole circuit families (powering the ROF to zero Ampere). The compensation scheme shows that the compensation of long-ranges can be achieved with a global scheme using the octupole magnets. A distributed set of octupole magnets can compensate the bad effects on dynamic aperture due to long-range beam-beam effects in a very effective way if ATS optics is used. As a further result it is shown that the octupoles magnets can be used to improve the high chromaticity negative effects on dynamic aperture as well becoming an important and powerful tool to be used for defining the HL-LHC operational scenarios.

The presently installed octupole magnet system with a maximum powering current of around -590 Ampere in the FOD is by chance at the optimum value for a long-range compensation for the HL-LHC baseline and ultimate scenarios for both most challenging 15 and 10 cm β^* squeezed optics. Reducing to half the octupole circuits (ROF switched off) the compensation can even improve further the dynamic aperture in the presence of strong beam-beam effects and strong chromaticity. The Landau octupoles prove to be an important knob to operate with strong beam-beam long-range effects and high chromaticty as also shown experimentally in the LHC [13]. However a detailed study on the consequences of such a reduced octupole system on the beam stability should be foreseen.

The case studied in this note shows the possibility of reducing the beam-beam long-range separations requirements for HL-LHC from the nominal 12.5 σ to around 8.5 σ with a consequent reduction of the needed crossing angles at the two high luminosity experiments from 590 to 500 μrad for the round optics case. If similar values in normalised separation will be possible for a flat optics this gives the possibility to have for free a very promising back-up scenario for the HL-LHC project.

This compensation for the HL-LHC gives the possibility to reduce the crossing angle for the round optic case of HL-LHC by a large amount reducing the overall crab cavities power needs. It becomes a even more appealing possibility if applied to the flat optic alternative scenarios proposed in [26] where a standard 10 σ separation was always assumed when no octupole magnets are used. Further optimisation could be done with flat optics to reduce the needed separation to the round case by use of octupole magnets.

We have studied also the compensation for the LHC standard and ATS compatible optics available [29]. The dynamic aperture is always similar (maximum 0.5 σ improvement in within the error bars of such simulations) or worse in the presence of octupole magnets independently of the polarity. The telescopic part of the HL-LHC ATS makes the compensation possible. In this note we checked the effect of the stronger octupoles (due to the larger betas) and of the phase advance to the octupoles magnets and both have not changed the results. The dynamic aperture is not improved with negative octupoles and no strong compensation is visible. Other possible ingredients which might explain the conpensation being so effective for HL-LHC ATS respect to an ATS compatible LHC optic are for example the beta ratios at the octupoles and/or the contribution of the sextupoles which needs to be studied.

The findings obtained for the HL-LHC study case have a strong implication also for the FCC project since this highlights the best performances of an ATS type of optics respect to a standard LHC in terms of effective Landau octupoles and compensation of long-range effects by use of octupoles. The possibility to design the appropriate optics and Landau octupole set-up to be possibly used to compensate for the long-range beam-beam effects if needed, will give, together with the experimental verification of this effect, in the LHC, the possibility to have a mitigation to beam-beam effects at zero costs.

Further studies are needed to define the basic needs from the optics design to have the best optical properties to use such compensation and to prove its robustness in the presence of multipolar errors in the machine model.

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