# STUDY OF BEAM-BEAM LONG RANGE COMPENSATION WITH OCTUPOLES

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## *Abstract*

Long range beam-beam effects are responsible for particle losses and define fundamental operational parameters of colliders (i.e. crossing angles, intensities, emittances, $\beta^*$). In this study we propose octuple magnets as a possible scheme to efficiently compensate long-range beam-beam interactions with a global correction scheme. The impact and improvements on the dynamic aperture of colliding beams together with estimates of the luminosity potentials are discussed for the HL-LHC upgrade and extrapolations made for the FCC project.

## INTRODUCTION

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 [1, 2]. The larger the detuning with amplitude larger is the Landau damping provided by the beams, in the LHC the detuning with amplitude is given by the Landau octupole magnets. Being forced to operate with high octupole and chromaticity due to collective instability in the LHC requires the need to quantify better the impact of such non-linearities on the beam lifetimes also in the presence of beam-beam effects [3, 4]. Differently than for the LHC case, despite the expected reduction of the tune spread (as discussed in [5]) a negative impact on dynamic aperture has always been observed for both polarities in simulations and also in data [2]. Studies have been performed on LHC, HL-LHC as case studies for a possible application to the FCC. For the HL-LHC case with ATS [6] optics (squeezed below 30 cm $\beta^*$ with enhanced betas in the arcs) we observe for the first time a compensation between beam-beam long-ranges and octupole magnets powered in negative polarity. The study is based on long term tracking simulations and it is not due to the spread reduction present for example also in the LHC. The cases studied in this paper, if not differently specified, use the fully squeezed ATS optics at 15 cm $\beta^*$, 2.2 $10^{11}$ protons per bunch, 2.5 µm emittances, crossing angle of 590 µrad and chromaticity of 2 units. Details of the study can be found in [7].

## LONG-RANGE COMPENSATION WITH OCTUPOLE MAGNETS

For the first time simulation results for the HL-LHC pointed out the possibility of using the octupoles magnets to improve the Dynamic Aperture (DA) by compensating the long range encounters effects as shown in Fig. 1 where the minima DA as a function of the octupole strength is plotted for the nominal crossing angle (purple line) and reduced ones (green and blue). The DA improves using negative polarity in the Landau 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 or not of the tune spread. Compensating long-range beam-beam with multiples is not a new idea [8–10] and has been studied extensively, however the new results for the HL-LHC case have shown strong effects and opens room for alternative scenarios using a set of octupole magnets to compensate the long-range beam-beam effects. In Fig. 1 the compensation is shown for even reduced crossing angles respect to the baseline. The octupoles can recover dynamic aperture from 4 to 7 $\sigma$ (transverse RMS beam size) for example with reduced angle (550 µrad).

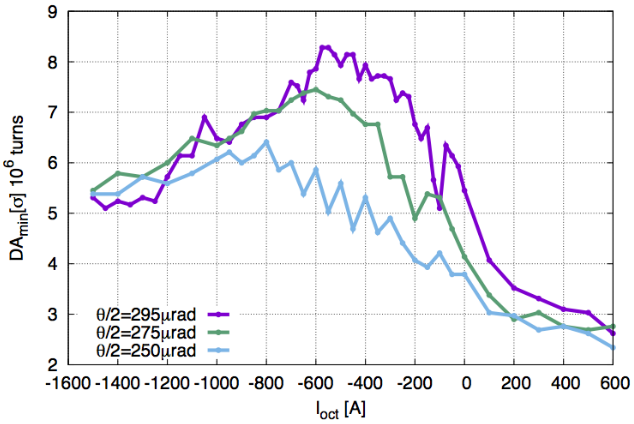

Figure 1: Minimum DA as a function of the octupole current for different crossing angles with a full compensation with crab crossing at the IPs for the head-on interactions at the IP1 and IP5. Case 1 is the nominal half crossing angle of 295 µrad (purple line). Case 2 if for a reduced half crossing angle of 275 µrad (green line). Case 3 for a half crossing angle of 250 µrad (blue line).

A Frequency Map Analysis (FMA) [11] 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. 1 for the nominal case (purple line). In Fig. 2 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 Fig. 1 at zero current in the octupoles and fully crabbed crossed head-on collisions corresponding to a

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DA of 5.5 $\sigma$. When we use octupole magnets with negative polarity, Fig. 2 top right, DA improves to 8 $\sigma$ 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.

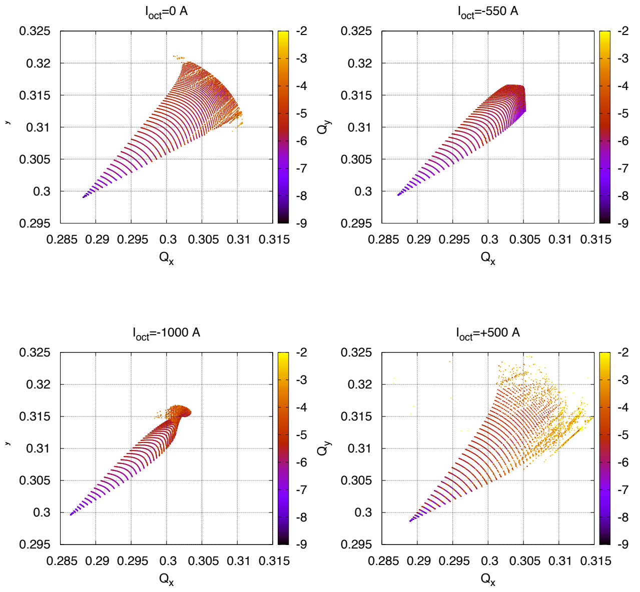

Figure 2: FMA for different currents and polarities in the octupoles for particles up to amplitudes of 6 $\sigma$. Top left shows the FMA expected from the beam-beam long-range effects when the octupoles are not powered, resonances are excited. Top right picture shows when octupoles are powered with 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.

Another important result is that using negative octupoles will allow to use also higher beam intensities as shown in Fig. 3 where the goal of 6 $\sigma$ dynamic aperture is reached with an intensity of 3.7 $\times 10^{11}$ protons per bunch using the maximum strength of the existing octupoles system.

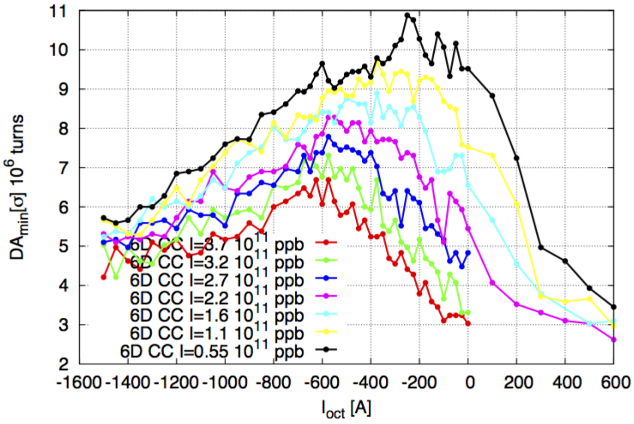

Figure 3: Minimum DA as a function of the powering current in the octupole circuits with negative polarity for an HL-LHC study case using different intensities from $0.55\times10^{11}$-$3.7\times10^{11}$ protons per bunch: The crossing angle is set to nominal value of 590 μrad.

## IMPACT OF CHROMATICITY

Another interesting finding is the interplay with the machine chromaticity. 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. 4 pointing to a deeper involvement of the chromatic properties of the ATS optics to the overall compensation scheme.

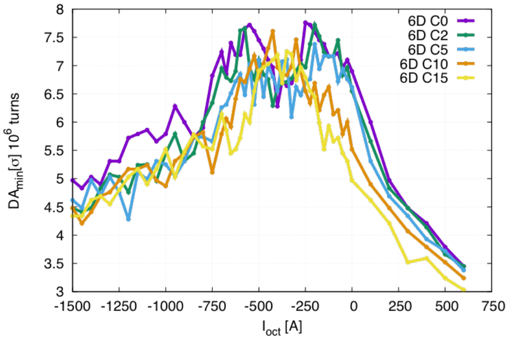

Figure 4: Minimum DA as a function of the Landau octupole powering current for different chromaticity values.

## OPTICS AND LONG-RANGE SEPARATION DEPENDENCY

There is a clear dependency of the compensation of long-ranges beam-beam with octupole magnets on the optics used as visible in Fig. 5. This happens because of the three effects: first the increased strength of the octupoles while reducing $\beta^*$, the second due to long-range beam-beam getting stronger due to reduced separation and finally due to the optics change while squeezing. One can notice two regimes for the non-linearities of the machine. For $\beta^*$ 42 cm (dark blue line) one can notice that adding octupoles to the system will reduce the dynamic aperture because the octupoles represent the strongest non-linearity in the system and therefore dictates the DA. In this case the long-range beam-beam effects are weak with separations of 21 $\sigma$. Reducing the $\beta^*$ at the IPs the long-range beam-beam effects become stronger and the compensation starts taking over as visible in Fig. 5 orange line where the two effects start compensating (at long-range separations of approximately 15 $\sigma$). 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 strength 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 to almost 6 $\sigma$ using the available octupole magnets powered to roughly 600 A in negative polarity.

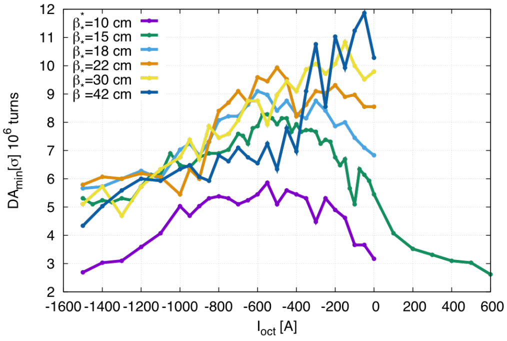

Figure 5: Minimum DA for different ATS squeezed optics cases. The different lines refer to the different $\beta^*$ reached at the IP1 and IP5 and they go from 42 cm to 10 cm .

For the available LHC optics standard or ATS compatible no compensation is observed despite the spread reduction as been made equivalent to the HL-LHC case. This points to the clear differences in the optics properties of the beta functions at the octupoles and sextupoles magnets due to the telescopic squeeze.

## DIFFERENT LANDAU OCTUPOLE CIRCUITS

In Fig. 6 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). The best dynamic aperture corresponds to the case where the vertical particles tails are completely suppressed by the octupole magnets. This is enough to improve drastically the DA. If one correlates the dynamic aperture plotted in Fig. 6 to the corresponding footprints 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 [7].

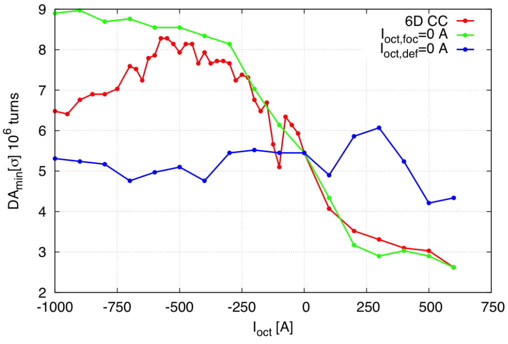

Figure 6: Minimum DA as a function of the powering current in the Landau octupoles for three different set-ups of the circuits. Red line is in the case of equal powering of the ROF and ROD circuits, green line if with the ROF circuit is set to zero current while blue line if the ROD circuit is kept to zero current.

## CONCLUSIONS

Studies of dynamic aperture in the presence of beam-beam effects, 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 using the ATS HL-LHC optics. The detailed studies can be found in [7].

The compensation scheme shows that the compensation of long-ranges can be achieved with a global scheme using the existing Landau octupole circuits or a reduced subset. The compensation works mainly for the ATS optics only when the telescopic part is enabled and it is maximum using only one of the Landau Octupole circuit families (powering the ROF to zero Ampere). 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. This finding can be applied to the LHC and the FCC colliders if the optics properties at the octupoles and sextupoles are brought to a similar level as for the HL-LHC optics with the telescopic squeeze (i.e. beta values).

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