

THE HIGH ENERGY LHC BEAM-BEAM EFFECTS STUDIES

T. Pieloni *, C. Tambasco, J. Barranco, L. Rivkin, EPFL, Lausanne, Switzerland
D. Amorim, S. A. Antipov, X. Buffat, B. Salvant, F. Zimmermann CERN, Geneva, Switzerland

Abstract

We present in this paper the studies of beam-beam effects for the High Energy Large Hadron Collider. We will describe and review the different aspects of beam-beam interactions (i.e. orbit effects, Landau damping, compensation schemes and operational set-up). An operational scenario for the collider will also be given as a result of the study.

INTRODUCTION

A conceptual design study for a future high-energy frontier circular collider at CERN for the post-LHC era is carried out by a world-wide international collaboration. The studies should be made available in time for the next update of the European Strategy for Particle Physics in 2019. The High Energy Large Hadron collider is an option of the design study parameters and description can be found in [1]. The main concept is to re-use the existing underground tunnel of the present Large Hadron Collider and apply the 16 T dipole magnets to reach a center of mass energy of 27 TeV. The collider will consist of two high luminosity experiments [2] placed opposite in azimuthal along the 27 Km circumference. The two beams will share a common beam pipe and collide at the two Interaction Point (IPs) called A and B. While in the common beam pipe the two counter rotating, as in the LHC, will experience beam-beam effects.

BEAM-BEAM EFFECTS

The beam will experience two types of beam-beam effects: the head-on collisions at the two IPs corresponding to the two experiments and several Long-Range (LR) encounters left and right of the head-on collisions. Due to the 25 ns the beams will meet each other every 3.75 m resulting in up to 72 LR beam-beam encounters up to the first separation dipole. To avoid long range encounters a minimum separation is needed and this is obtained by operating at a finite crossing angle as in the LHC [3]. The crossing angle reduces the overlapping region between the two bunches crossing each other at the IP resulting in a reduction of the luminosity. To compensate for this geometric luminosity reduction of approximately 70%, a crab crossing scheme is foreseen similarly to the HL-LHC baseline [4]. In this study we assume an horizontal-vertical alternating crossing scheme between IPA and B as implemented in the LHC [5]. This choice is made to profit of the passive compensation of LR tune and chromaticity spread over the different bunches of the order of $3 \cdot 10^{-3}$ and 2-3 units, respectively. Possibilities for alternative crossing scheme have been explored and can be integrated [6] easily following an optimization of the optics (i.e phase advance and working point).

* tatiana.pieloni@epfl.ch

HEAD-ON INTERACTIONS

For the beam parameters and optics defined in [1] a beam-beam parameter of 0.01 per IP should be expected. The two head-on collisions will result in a total beam-beam tune shift of 0.02 as visible in Fig. 1, where the two dimensional detuning with amplitude up to 6σ amplitude particles due to head-on collisions is compared to the LHC 2012 operation case and the HL-LHC baseline of [4]. As a result of the HL-LHC simulation studies the above parameters result to be feasible giving a minimum dynamic aperture largely above the 6σ goal [7]. In addition it has been experimentally proved in the LHC during dedicated experiments without LR encounters that beams can collide with a total beam-beam tune shift of 0.02 with lifetimes larger than 10-20 hours [8]. In Fig. 1 we also compare to the largest tune spread ever reached in the LHC during regular collider operation in 2012 (black lines).

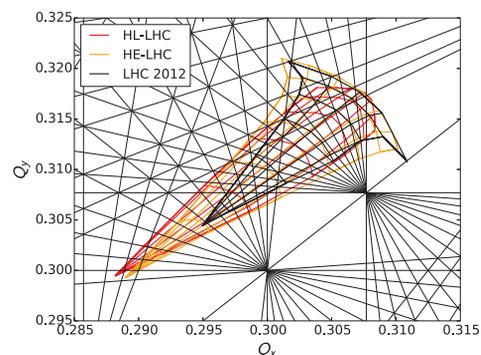


Figure 1: Two dimensional detuning with amplitude up to 6σ particles due to two beam-beam effects. The HE-LHC proposed scenario (orange) with $d_{sep} = 13.7\sigma$ (half crossing angle of $180\mu rad$) is compared to the LHC 2012 operational case (black) and the HL-LHC baseline scenario of [4] (red).

A major concern of head-on collisions are the linear and non-linear implications to the optics. Two head-on collisions will result in a strong β -beating. The maximum beating expected is of 15%. As a consequence a reduction of the machine aperture is expected and implications to the collimation system have to be studied in details as in [9]. The possibility to apply linear and non-linear correction schemes is explored and findings for the HL-LHC case [10] can be easily applied to the HE-LHC design.

LONG-RANGE INTERACTIONS

The beam-beam LR separation at the first encounter can, for the high luminosity experiments, be defined as:

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

where α is the crossing angle, β^* the beta function at the interaction point and ϵ_{norm} is the normalized emittance at the IP. This approximation is valid only for the case where the β^* is much smaller than the s location of the first long-range encounter (for a 25 ns beam spacing, this corresponds to 3.75 m from the IP). The real separations at the LR encounters are shown in Fig. 2 for the LHC 2012 physics case where beam-beam effects were the strongest (black dots), the HL-LHC case at beginning of collisions (red dots) and for the HE-LHC case with two half crossing angles for 210 μrad and orange dots for the 180 μrad .

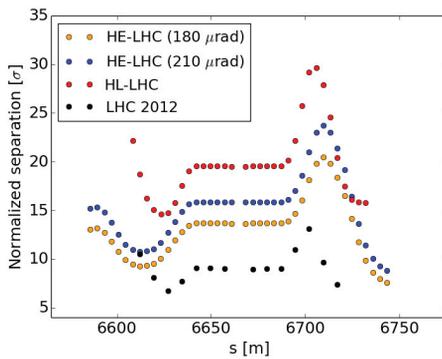


Figure 2: Beam-beam long-range radial separation at the LR encounters left and right of the IP in units of the transverse RMS beam size (σ) at the LR beam-beam encounters for two different half crossing angles for the HE-LHC case (180 μrad orange dots and 210 μrad blue dots). The separations are compared to the HL-LHC case (red dots) [4] and the LHC 2012 (black dots).

For the HE-LHC a minimum half crossing angle of 180 μrad (equivalent to a d_{sep} of 13.7 σ) is necessary. Such angle/separation has been chosen to guarantee that all LR encounters will have a separation equal or larger than 8 σ that guarantees a dynamic aperture above the target value (6 σ). The first consideration comes from the LHC observations made during dedicated experiments [11, 12]. For very small crossing angles the particle losses are highly non linear with respect to the number of encounters. This highlights the dominant effect of the closer encounters in the triplet that start approaching a head-on collision with consequences on the tunes, chromaticity etc. The second condition is obtained scaling from the HL-LHC simulation campaigns of Ref. [7]. In Fig. 3 the minimum dynamic aperture as a function of the crossing angle is shown for the HL-LHC case for the case with and without multipolar errors. The HE-LHC equivalent case corresponds to the crossing angle of 650 μrad in the plot for which the DA is around 7 σ . A similar behaviour is expected for the HE-LHC lattice.

Beam to beam separation equal to 17 σ will bring the beam-beam effects identical to the HL-LHC baseline case

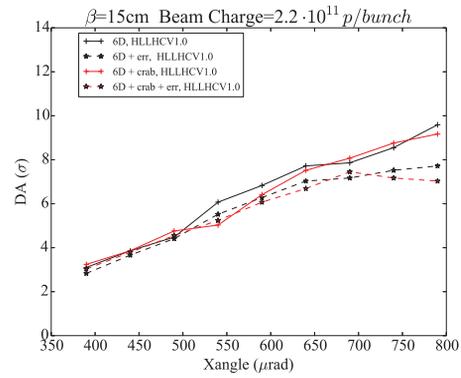


Figure 3: Minimum dynamic aperture for the HL-LHC study case of Ref. [7] as a function of the crossing angle in the presence of multipolar errors and crab crossing scheme. The d_{sep} of 13.7 σ is equivalent to the crossing angle of 650 μrad .

as shown in Fig. 4 where the nominal scenario (orange) is compared to an increased d_{sep} case (blue line), to the HL-LHC case (red line) and to the 2015 LHC operational case (orange) for reference.

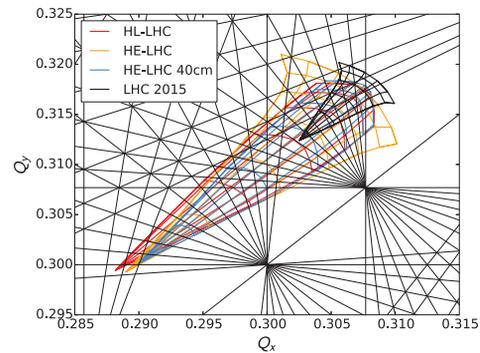


Figure 4: Two dimensional detuning with amplitude up to 6 σ particles due to two beam-beam effects for the LHC 2015 operational case (black lines), the HL-LHC baseline scenario [4] (red line), HE-LHC (orange line) with $d_{sep} = 13.7 \sigma$ (180 μrad half) and for $d_{sep} = 17 \sigma$ (blue line).

BEAM-BEAM AND LANDAU DAMPING

The accelerator impedance can be source of coherent instabilities. The general strategy applied is very similar to the FCC-hh case where the coupled-bunch instability modes will be cured by a transverse feed-back, while single-bunch instabilities will be suppressed by Landau damping [13]. As in the LHC, Landau octupoles, which have been implemented in the HE-LHC lattice, will provide the necessary Landau damping. For the octupole magnets the main parameters are listed in Table 1. A system of 264 Landau octupoles with maximum gradient of 220000 T/m³ and length of 0.32 m will provide enough integrated strength to damp coherent impedance modes.

The coupled-bunch beam stability in the presence of the transverse feedback, chromaticity, and Landau octupoles

Table 1: Main Octupole Magnet Features for HE-LHC and LHC

	LHC (7 TeV)	HE-LHC (13.5 TeV)
Gradient [$T \cdot m^{-3}$]	53000	220000
Length [m]	0.32	0.32
Av. β -function (arcs)	100	200
Int. strength [m^{-3}]	0.726	1.42
N. Octupoles	168	264

using the NHT [14], DELPHI [15] and BIM-BIM [16] has been described in [17]. Figure 5 shows the stability diagrams obtained from the dispersion relation of [18] and the impedance modes computed with BIM-BIM. This case reflects the situation for single beam at top energy without beam-beam effects. One third of the octupole strength is sufficient to stabilise the impedance modes. No limitation in dynamic aperture are expected scaling the FCC-hh studies where 15σ is reached [19,20].

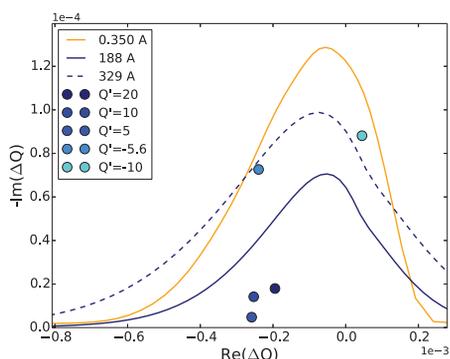


Figure 5: Impedance coherent modes for different values of chromaticity (blue dots) and stability diagrams. The detuning with amplitude is given by the Landau octupoles powered in negative polarity at one third (blue solid) and half (blue dashed) of their strength. The stability diagram of an electron lens of 0.35 A is also compared (orange line).

During the betatron squeeze the LR beam-beam interaction will counter act the octupole detuning with amplitude and reduce the stability area as know from LHC experience [17,21]. To avoid this reduction larger strength of the octupoles magnets can be used or alternatively a collide and squeeze sequence can be applied to guarantee the head-on collision spread for Landau damping as integrated in the HL-LHC baseline [4,22]. The use of octupole magnets is also positive in terms of dynamic aperture since they compensate in a global scheme the LR effects as described in [23,24] and clearly visible in Fig. 6 where the minimum DA is shown for different phase advances between the main IPs for an FCC study case with negative polarity of the Landau octupoles. An optimization of the phase advance from DA studies will be needed to allow for the compensation. A total DA of 8σ can be reached with beam-beam and octupole magnets allowing for a possible reduction of the crossing angle.

An alternative approach has been proposed in Ref. [25] and it is plotted for comparison (orange line) for an electron

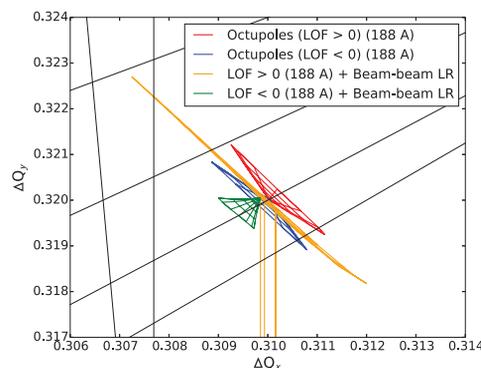


Figure 6: Minimum dynamic aperture over 10^6 turns for different set's of phase advances between the two main IPs for the case with negative octupole polarity.

current of 0.35 A. Similarly to the head-on collisions electron lenses are very efficient in producing spread and could represent an interesting alternative in case of limitations from the octupole system.

CONCLUSION

A set of studies have been performed to evaluate the beam-beam effects for a possible operational cycle of a HE-LHC design. A crossing angle of minimum $360 \mu\text{rad}$ has been proposed based on scalings from the LHC and the HL-LHC studies. Such crossing angle will guarantee all LR encounters at a separation $d_{\text{sep}} > 8\sigma$ and a dynamic aperture above the target value of 6σ . A maximum tune shift of 0.02 is expected from the two head-on collisions. From experimental evidences in the LHC and simulations of DA the parameter set of the HE-LHC are in within reach. The main concern comes from the LR effects. For this reasons possible compensation schemes (i.e. octupoles, pulsed e-lenses or wires) should be studied in details together with the evaluation of a collide and squeeze option [26] as for the HL-LHC baseline scenario. The single and two-beam stability of the HE-LHC beams can be guaranteed by a system of 264 Landau octupoles integrated in the baseline lattice. The total strength is sufficient to damp impedance coherent modes with the same strategy used for the FCC-hh study [13,20]. Octupole magnets compensating LR interactions are a more favourable choice because they provide the largest stability area for single beam and they allow for a global compensation of long-range beam-beam effects which results is a larger DA. The baseline scenario proposed for the HE-LHC design in terms of beam-beam effects is feasible and in line with the beam dynamics requirements. Detailed simulations are foreseen to confirm these preliminary studies.

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