WEAK-STRONG BEAM-BEAM SIMULATIONS FOR HL-LHC

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Abstract

Various operational scenarios are being currently considered for the future High Luminosity Large Hadron Collider (HL-LHC). In this article we evaluate the expected long term beam stability by means of the dynamic aperture (DA). An extensive simulation campaign was carried out with the SixTrack code [1] including head on and long range beam beam interactions, crab crossing schemes and multipolar errors in the magnets. Parametric scans of the DA are used to determine the impact of each design parameter in the long term stability of the beam. Frequency maps analysis (FMA) are also calculated to characterize the reasons for the values of the DA.

HL-LHC BASELINE SCENARIO

Baseline Scenario: β^* =15 cm with Leveled Luminosity with β^*

The HL-LHC baseline scenario features an Achromatic Telescopic Squeezing (ATS) scheme [2] with $\beta^*_{x,y}$=15 cm, crossing angle θ=590 μrad, beam charge I=2.2$\cdot 10^{11}$p/bunch. The version of the optics used in this paper is `SLHCV3.1b`. In order to fully to profit from the very low β^* provided by the ATS optics, local crab cavity schemes at the interaction points IP1 and 5 are foreseen to ensure head on collisions. All simulations presented here are performed using the SixTrack code [1] and the SixDesk enviroment [3]. The SixTrack code has been updated in order to allow weak-strong simulations in a full crab crossing scenario. The dynamic aperture is computed over 10^6 turns sampling 18 values of the phase space angles with 30 particles every interval of 2σ in amplitude. The energy spread is set to 2.7×10^{-4}. Even if the DA simulations do not provide realistic information regarding the emittance growth, it is an important indicator to predict the beam lifetimes imposed by the non-linear dynamics at collision. From the operational point of view the DA simulations will define the margins in terms of beam properties (e.g. beam charge and emittances) and machine optics (e.g. crossing angle and β^*) to not degrade the beam perfomance. Table 1 summarizes the HL-LHC nominal parameters and compares them to the LHC nominal design values and the operational parameters of the 2012 physics run.

In Fig. 1 the minimum DA as a function of the beam charge is shown for the baseline optics with β^*=15 cm. The different lines represent the minimum DA in a crab crossing scheme (i.e. full head on collision - dashed) and nominal crossing angle scheme (solid) at IP1 and 5. In red the beam-beam 6D kick computed with the Hirata formalism including energy change [4] while in black a 6D kick without energy

Table 1: HL-LHC Nominal, 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	60.31
Q_y	59.32	59.32	62.32

change (i.e. 4D kick longitudinally distributed along the bunch length) is used. The dashed blue lines correspond to the nominal beam charge of the HL-HLC project and the minimum required DA of 6σ. The second value has been chosen following the LHC design Report strategy and also it has been experimentally proved to be a good criterion in terms of stability and lifetimes during the LHC 2012 experiments [5]. A reduction of 2 σ DA is observed in the worst case for the nominal working point of (Q_x,Q_y)=(60.31,62.32). In Fig 2 the FMA for the non-crabbed scenario (left) versus the crabbed crossing at IP1 and 5 (right) is shown. The DA reduction seems to correspond with particles at 4 σ in the vincinity of the 13^{th} and 10^{th} order resonances. Eventually, this could be compensated by an optimization of the working point.

From these results is evident that these optics are not suitable for the nominal beam charge of 2.2$\cdot 10^{11}$p/bunch and crossing angle of 590 μrad. Increasing the crossing angle to 690 μrad allows to recover 1σ, but still is not enough for a good beam stability.

Effects of Magnets Multipolar Errors at Collision

A campaign to evaluate the effect of magnetic field errors on the beam dynamics in the presence of beam-beam interactions has also been performed at top energy. Multipolar errors in the triplets magnets have been set-up following specifications in [6]. Typically 60 different sets (seeds) of the field errors are used for each case. Results in Fig. 3 show an improvement with respect to the case without errors when crab crossing scheme is used. This effect is not yet fully understood and dedicated study are ongoing.

LEVELING

The peak luminosity that the HL-LHC operational baseline scenario can provide is too challenging for the experiment: the need to level the luminosity to a lower value to guarantee the optimum conditions to the detectors to resolve

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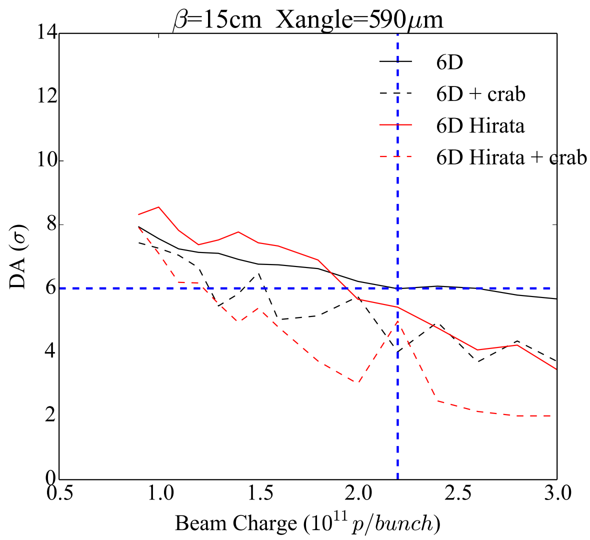

Figure 1: Minimum DA as a function of Beam Charge, for the 15 cm optics and nominal crossing angle of 590 μrad. Red lines refer to the Hirata beam-beam formalism calculation while black line to a 6D without energy change beam-beam model. Dashed lines are for a crab crossing at the IPs while solid represent the same scenario with a head-on with finite crossing angle.

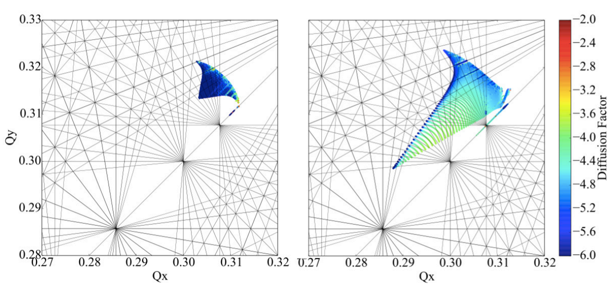

Figure 2: Frequency Map Analysis for the 15 cm optics with nominal crossing angle of 590 μrad and beam charge of $2.2{\cdot}10^{11}$ppb. Left plot, with crossing angle at the IPs while right, with crab crossing schemes at the IPs.

the physics events is crucial. Various techniques are available (e.g. transverse offset, β^*). As baseline scenario for the HL-LHC a leveling with the β^* is assumed.

To simulate the leveling we use 3 steps optics with β^* of 40, 33 and 15cm. A parametric DA study varying beam charge and crossing angle is performed to identify the best scenario. Table 2 shows the β^* leveling parameters for the baseline scenario. The simulations next all include full crabbing scheme at IP1 and 5 and multipolar errors in the triplets.

Figure 4 shows the minimum DA for the β^*=40 cm optics. It is clear that this configuration can fulfill the requirements in Table 2 even with a crossing angle much smaller than the nominal one of 590μrad. Even for higher beam charge than the nominal up to $2.5{\cdot}10^{11}$ p/bunch [7].

Similarly to the 40 cm case, also the β^*=33 cm optics can guarantee the expected performance, still with a significa-

Figure 3: Minimum DA as a function of the beam charge, for the β^*=15 cm optics and nominal crossing angle of 590 μrad including multipolar errors in the magnets

Table 2: β^* Leveling Parameters

β^* (cm)	**fill duration (h)**	**beam-beam separations (σ)**	**bunch population (10^{11} p/bunch)**
40	3	16	1.7
33	4	14	1.5
15	7	11	1.1

Figure 4: Minimum DA as a function of crossing angle, for β^*=40 cm optics including multipolar errors in the triplets.

tive reduction in the crossing angle, as shown in Fig 5 and allowing increased beam charge.

The use of the most challenging optics with β^*=15cm still allows a much more relaxed configuration with large margins as shown in Fig. 6. The expected beam charge of

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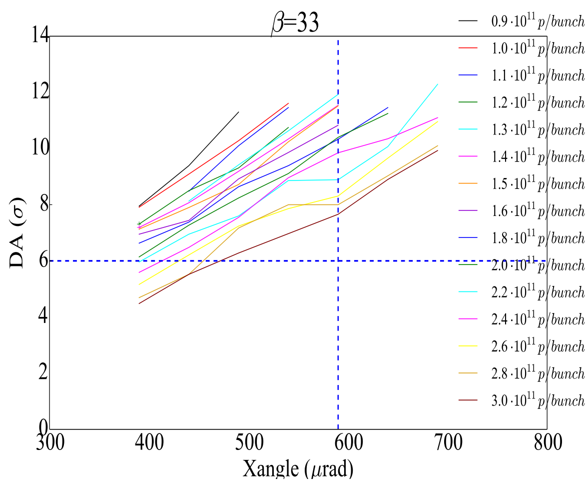

Figure 5: Minimum DA as a function of crossing angle, for β^*=33 cm optics with multipolar errors in the triplets.

$1.1{\cdot}10^{11}$ p/bunch shows a DA of around 8 σ giving margin to reduce the crossing angle and increase the bunch charge.

Figure 6: Minimum DA as a function of crossing angle, for β^*=15 cm optics including multipolar errors in the triplets.

The three optics steps during a β^* leveling scenario studied show this technique relaxes the long range beam-beam effects allowing for reduced crossing angles and increased intensities. The worse case in terms of beam-beam effects for the HL-LHC β^* leveling scenario is still better than the nominal LHC case studied in [8].

PACMAN BUNCHES

Due to the bunch train structure, bunches will experience a different number of long ranges interactions and therefore this could change the DA of the different bunches. A study to evaluate this effect has been performed and the FMA for nominal (maximum number of long-ranges encounters) versus a PACMAN bunch (lowest number of long-ranges) show the very small difference expected. This is also a result of the positive effect of leveling with the β^* since it relaxes significantly the differences. The differences in the DA are within the simulations error bars of 0.5σ.

CONCLUSIONS

Dynamic aperture simulations have been performed using two different models for the head-on beam-beam interactions for the HL-LHC baseline scenario. The HL-LHC baseline scenario with β^* reach of 15 cm and with luminosity leveling with β^* shows a robust dynamic aperture always above the limit of 6 σ. Simulation results show that this is even better than the nominal LHC case studied in [8] and this provides the possibility of increasing the beam charge and reducing the crossing angle at the IPs to relax the needed voltage for the crab cavities.

Tune spread and variation of the DA induced by the PACMAN effects proved to be negligible.

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REFERENCES

[1] F. Schmidt, “SIXTRACK, SINGLE PARTICLE TRACKING CODE TREATING TRANSVERSE MOTION WITH SYNCHROTRON OSCILLATIONS IN A SYMPLECTIC MANNER”, CERN/SL/94-56 (AP).

[2] S.Fartoukh, “ACHROMATIC TELESCOPIC SQUEEZING SCHEME AND APPLICATION TO THE LHC AND ITS LUMINOSITY UPGRADE”, Phys. Rev. ST Accel. Beams, 16, 11, 111002, 2013

[3] L. H. A. Leunissen, F. Schmidt and G. Ripken, “SIX-DIMENSIONAL BEAM-BEAM KICK INCLUDING COUPLED MOTION”, Phys. Rev. ST Accel. Beams 3, 124002 (2000).

[4] K. Hirata, H. Moshammer and F. Ruggiero, “A SYMPLECTIC BEAM-BEAM INTERACTION WITH ENERGY CHANGE”, KEK preprint 92-117 (1992).

[5] W. Herr, et al., "LONG RANGE BEAM-BEAM EFFECTS IN THE LHC", Proceedings of ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders, Geneva, March, 2013.

[6] M. Giovannozzi et al., “DYNAMIC APERTURE PERFORMANCE FOR DIFFERENT COLLISION OPTICS SCENARIOS FOR THE LHC LUMINOSITY UPGRADE”, IPAC2013, Shanghai, China, 12-17 May, 2013.

[7] G. Arduini et al., "HOW TO MAXIMIZE THE HL-LHC PERFORMANCE", Proceedings of the RLIUP Workshop, 29-31 October 2013, Archampe, France.

[8] O. Bruning et al., "THE LHC DESIGN REPORT" Geneva, 2004.