BEAM-BEAM EFFECT FOR THE LHC PHASE I LUMINOSITY UPGRADE

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Abstract

The Phase I Luminosity Upgrade of the LHC will be based on a new Nb-Ti inner triplet for the high luminosity region ATLAS and CMS. The new proposed layout aims at pushing β^* down to 30 cm replacing the current LHC inner triplet, with longer ones operating at lower gradient (123 T/m) and therefore offering enough aperture for the beam to reduce β^* to its prescribed value. As a consequence of this new longer interaction region, the number of parasitic encounters will increase from 16 to 21 in front of the separation dipole D1, with an impact on the dynamic aperture of the machine. In this paper the effect of the beam-beam interaction is evaluated for the Phase I layout and optics, at injection and in collision, evaluating the possible impact of a few additional parasitic collisions inside and beyond the D1 separation dipole till the two beams do no longer occupy the same vacuum chamber. Whenever needed, a comparison with the nominal LHC will be given. In addition a possible backup collision optics will be discussed for the Phase I upgrade, offering a much wider crossing angle at an intermediate β^* of 40 cm in order to reach a target dynamic aperture of 7.5 σ.

INTRODUCTION

The Large Hadron Collider is being commissioned and it is planned to reach the nominal luminosity of 10^{34} $cm^{-1}s^{-1}$ in its final configuration.

A first phase of luminosity upgrade (Phase I) is focused on the possibility to reduce the transverse size of the beam at the interaction point, squeezing the β^* from its nominal value of 0.55 cm, down to 0.30 cm [1]. This new squeeze is performed replacing the nominal inner triplet with a new longer triplet with a lower gradient and a larger aperture, leaving unchanged the other quadrupoles of the long straight section (the so-called matching section and dispersion suppressors). A consequence of a longer triplet are new parasitic encounters between the beams, with an impact on the stability due to the long-range beam-beam interaction. This paper presents the stability of the beam, in term of Dynamic Aperture, with the beam-beam scheme of the Phase I Luminosity Upgrade.

SIMULATION SETUP

A comparison between the new and old interaction region, in terms of length, is reported in Tab. 1. Q1, Q2 and Q3 are the three quadrupoles of the Inner Triplet. IR is the Interaction Region calculated from the magnetic entry of the left D1 to right D1, where D1 is the separation dipole.

Table 1: Length comparison Phase I IR vs. nominal.

Element	nominal	Phase I
Q1	6.37 m	9.135 m
Q2a and Q2b	5.50 m	7.735 m
Q3	6.37 m	9.135 m
IR	119.244 m	149.316 m

A relevant parameter to be considered is the number of beam-beam (BB) encounters: for the nominal bunch spacing of 25 ns [2] the number of parasitic encounters between the Interaction Point (IP) and the edge of the separation dipole D1 is 16 for the nominal layout optics and 21 for Phase I. Nevertheless, in the simulations discussed later, the first 5 parasitic encounters after the magnetic entry of D1 are also implemented, till the two beams are fully separated.

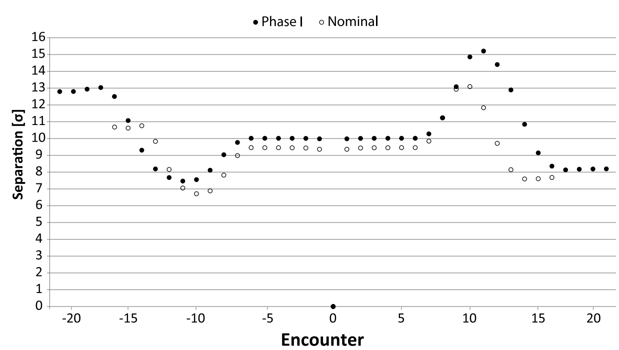

Figure 1: Normalized separation at collision of the BB encounters for the nominal and Phase I optics. This example is the horizontal plane for IP5.

The BB interactions depend critically on the crossing angle: it changes both at injection and collision for the new Phase I optics with respect to its nominal value. For the nominal optics the full crossing angle is 340 μrad at injection ($\beta^* = 11$ m) and 285 μrad in collision ($\beta^* = 0.55$ m), that corresponds, for collision, to a normalized separation of 9.5 σ in the drift spaces. For the Phase I optics the crossing angle is kept constant from injection ($\beta^* = 14$ m) to collision ($\beta^* = 0.30$ m) and at collision it is 410 μrad with a normalized separation of 10 σ. The normalized separation of the two beams along the interaction region is

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illustrated in Fig. 1.

For the new layout, it is worth noting that, out of the 32 first parasitic encounters on either side of the IP, only three show a smaller separation compared the nominal layout. This larger separation can partially compensate for the additional 5+5 parasitic encounters due to the longer triplet.

The head-on BB interaction has a strong impact on the tunes: the fractional part of the tune without BB is the same for the nominal and the Phase I optics (.31 and .32 for the horizontal and vertical plane respectively). Therefore the tune footprint can be directly compared as in Fig. 2. The overall tune footprint, due to the head-on collision, is smaller for the new optics because the crossing angle is larger.

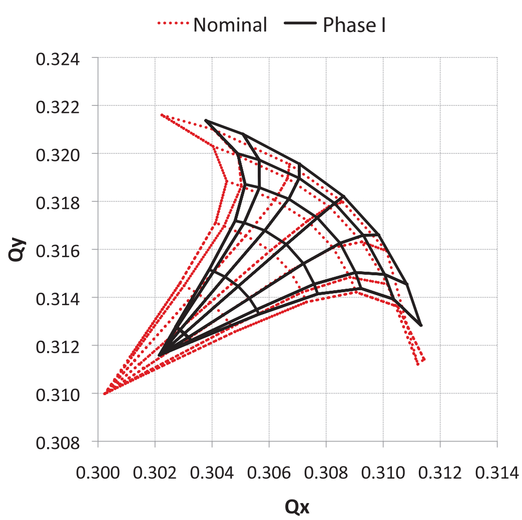

Figure 2: Head-on BB tune shift in the nominal and Phase I optics.

To verify the long term stability of the beam in the presence of the weak-strong BB effect tracking studies are required: the particles are tracked with different configurations based on different initial conditions and 60 different representations of multipolar components, called seeds in the following. The initials conditions are selected considering steps of 15° between 15° and 75° in the x-y plane. For each angle the amplitude is varied in small steps (30 pairs of particles equally spaced over 2 σ): at injection the normalized amplitudes of the particles are chosen between 8 and 14 σ, and between 4 and 18 σ in collision. The magnetic errors are selected according to the study in [3] and the random errors are generated using 60 different seeds. For each configuration of angle, amplitude and seed, the particles are tracked for 10^6 turns. The Dynamic Aperture (DA) is defined as the minimum amplitude with particle loss. Lastly, we use in the simulations a fixed relative momentum deviation of two thirds of RF bucket.

The particles in the LHC will have to survive for some 10^9 turns in collisions which is inaccessible for today's computing facilities. However, we find that the DA seems to saturate between 10^6 and 10^7 turns.

This issue needs a rather involved analysis following those of earlier studies (see Ref. [4]). For a full understanding of what happens with the particle dynamics in presence of BB and enlarging the maximum number of turns from 10^6 to 10^7 it is mandatory to do such a thorough analysis of the tracking results. At the time it was understood why the DA decreases significantly when increasing the turn number form 10^5 to 10^6 and we have to make sure that nothing similar will happen when the turn number is increased further. To complement the present study we are therefore planning to write an analysis paper in the near future.

Of course, no proof can be given for particle stability over a 100 times larger time scale. Moreover, subtle effects would have to be taken into account like diffusive processes, let alone the fact that the LHC operates in the strong-strong BB regime.

SIMULATION RESULTS

Three cases are considered both at injection and in collision: the DA without BB effect serves as a reference and is compared to the DA including BB interactions at nominal current (1.15×10^{11}) and ultimate current (1.7×10^{11}) respectively.

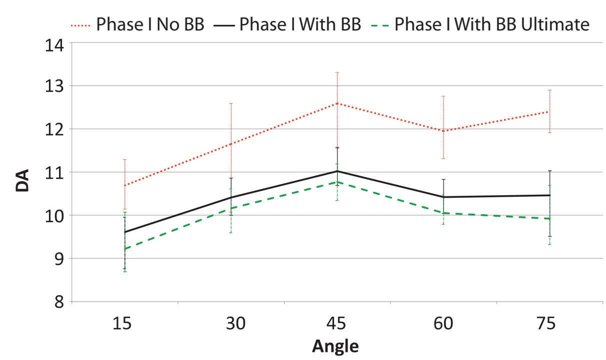

Figure 3: DA at injection.

The tracking for Phase I at injection is shown in Fig. 3. The three lines represent the average DA over 60 seeds versus the angle for the three cases. The vertical bars give the range between the maximum and the minimum of the 60 seeds. The minimum DA is particularly significant because it is an estimation of the worst possible combinations of errors in the machine. At injection the BB force decreases the average DA by 1.5 σ for the nominal current and 2 σ for the ultimate current, compatible with the equivalent study which was performed for the nominal LHC.

In collision the effect of the BB force is stronger because of the tune spread induced by the head-on collisions that can push the particles towards the resonance excited by the long-range BB interactions. Consequently the layout and optics of the new insertion, with 21 parasitic encounters and a β^* of 30 cm, present some issues to be considered carefully (Fig. 4): the average DA with BB at nominal current drops by 6 to 10 σ compared to the case without BB. Moreover, the minimum DA at nominal current is around

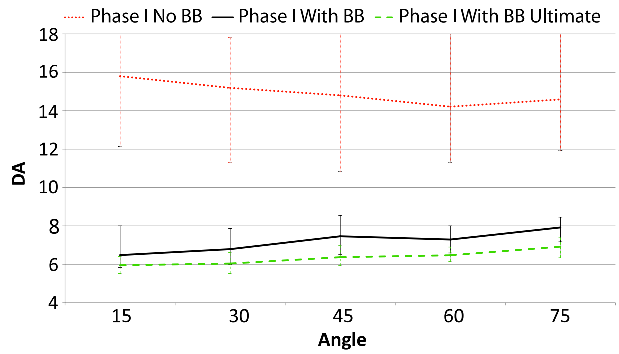

Figure 4: DA in collision with $\beta^* = 30$ cm and $\theta_c = 410$ μrad

6 σ which must be considered as a bare minimum for the stable region of the LHC beam (the primary collimators of LHC in collision are set to 6 σ). The situation is further degraded for ultimate intensity where the minimum DA is, for some seeds, below 6 σ. The average DA of the nominal LHC in collision [2] is around 7 σ and the minimum DA roughly 6 σ, i.e. not far from the results of the tracking obtained for the Phase I upgrade. In essence, however, the DA of the upgrade is barely acceptable and one should aim at improving the situation, in particular for higher current (the ultimate and beyond).

To this end, a back-up collision optics (proposed in [1]) shall be attempted with the intention to reduce the long-range BB effect, with a larger crossing angle. This optics should increase the DA up to the target value of 7.5 σ, which corresponds to the reach of the secondary halo in the LHC [2]. This alternative optics is designed to work with the same new inner triplet (IT) imposing to relax β^* in order to preserve the IT aperture in the presence of a larger crossing angle. The new parameters for the back-up solution are: $\beta^* = 40$ cm and a crossing angle of 560 μrad that corresponds to a normalized separation of about 16 σ.

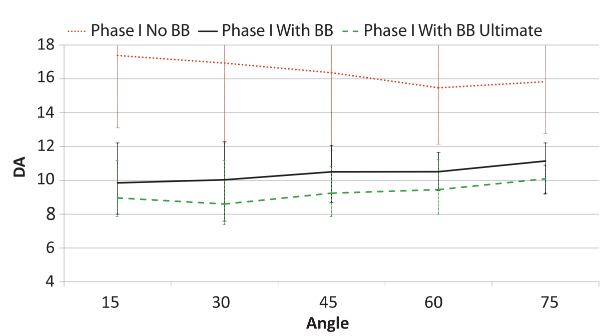

Figure 5: DA in collision with $\beta^* = 40$ cm and $\theta_c = 560$ μrad.

The tracking for this optics is shown in Fig. 5. The reduction of the average DA due to the BB effects is still sizable, in between 5 and 7 σ but the minimum DA remains above 7.5 σ for both nominal and ultimate currents.

The luminosity can be defined as in Eq. 1 [2]:

$$L \approx \frac{1}{\sqrt{1+\frac{(\theta_c\sigma_z)^2}{4\beta^*\epsilon}}}\frac{\mathrm{n_b N_b}^2\mathrm{f_{rev}}}{4\pi\beta^*\epsilon}, \tag{1}$$

with $\mathrm{n_b}$ the number of bunches circulating in the machine, $\mathrm{N_b}$ the number of protons per bunch, $\mathrm{f_{rev}}$ the revolution frequency of the machine, β^* the β function at the collision point, ϵ the transverse emittance of the beam, θ_c the crossing angle and σ_z the RMS bunch length.

The increase of the crossing angle θ_c and β^* reduces the luminosity for the back-up optics compared to the nominal upgrade optics. However, since the back-up optics allows for higher current ($\mathrm{N_b}$ in Eq. 1) an overall gain of luminosity might be achievable.

CONCLUSIONS

As expected, the BB effect in the LHC is one of the most important limiting factor. Any upgrade of the machine will have to face this issue, in particular due to the obvious request for more luminosity. The optics proposed for the Phase I upgrade is close to the limit of the DA acceptable for the LHC, while the back-up collision optics offers more margin. Indeed, thank to the increased aperture of the new triplet, the normalized crossing angle can be pushed up to about 16 σ and the optics still squeezed down to β^* =40 cm resulting in a substantially reduced sensitivity of the dynamic aperture with respect to the beam-beam effects. The upgrade optics at 30 cm, or more precisely a crossing angle limited to only 10 σ (as in the nominal LHC) seems to push the limits of what can be done in a future LHC upgrade.

REFERENCES

[1] S. D. Fartoukh, "Layout and Optics Solutions for the LHC Insertion Upgrade Phase I," *these proceedings*.

[2] O. S. Brüning *et al.*, *LHC Design Report*. Geneva: CERN, 2004.

[3] B. J. Holzer *et al.*, "Dynamic Aperture Studies and Field Quality Considerations for the LHC Upgrade Optics," *these proceedings*.

[4] Y. Luo and F. Schmidt, "Weak–Strong Beam–Beam Tracking for LHC V6.0," Beam-Beam Workshop Fermilab, Batavia, USA, Tech. Rep., 2001.