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ASSESSMENT OF LINEAR AND NON-LINEAR OPTICS ERRORS DUE TO BEAM-BEAM WITH MULTIPOLES FOR THE HIGH LUMINOSITY LHC*

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Abstract

Study of the head-on and long-range beam-beam effects in the High Luminosity LHC (HL-LHC) is of interest to evaluate their potential impact on performance (in the form of luminosity imbalance) and machine operation (collimator system), and, depending on their magnitude, correction schemes might be necessary to minimize them. In this work, both the β-beating at zero amplitude and its amplitude-dependence are computed for the current HL-LHC baseline optics and parameters, as well as the amplitude detuning, at the main interaction points and collimators. Correction of the β-beating, tune shift and footprint for the HL-LHC, as originally proposed for the LHC, via compensation of the multipolar terms of the beam-beam force with corrector magnets, is also discussed.

INTRODUCTION

Stronger beam-beam forces are expected for the High Luminosity LHC (HL-LHC) [1, 2], in comparison with the current LHC, mainly due to the increased bunch population. The beam-beam interactions give rise to a series of effects such as tune shift, tune spread and β-beating [3]. Depending on their magnitude, these in turn may have an impact on the protection system or limit the performance of the machine. Measurements of these effects have been conducted in the LHC [4–6] in view of the HL-LHC upgrade.

In the first section of this paper the β-beating at zero amplitude is reviewed for a configuration corresponding to the current HL-LHC baseline at the beginning of the fill [7]. The nonlinear terms of the beam-beam kick yield to a dependence of the β-beating with particle amplitude. This case is evaluated in the subsequent section at primary and secondary collimators, as well as at the interaction points (IPs); a discussion on the detuning [8] of the machine is also presented.

Correction techniques can be implemented to control and reduce the beam-beam effects. In the last section, the correction scheme via compensation of the multipolar terms of the long-range beam-beam force with magnets, introduced in [9, 10], is revised for the HL-LHC.

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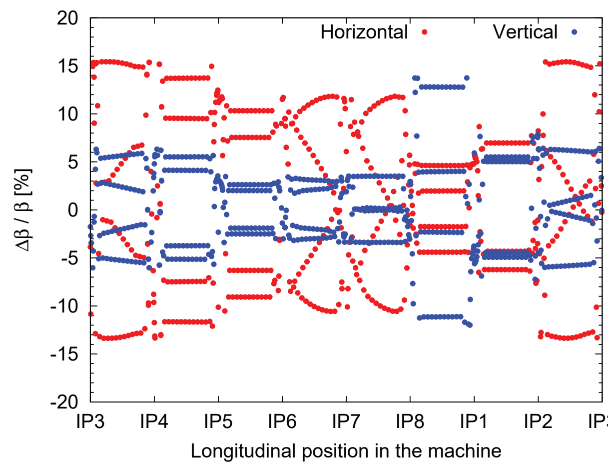

Figure 1: Horizontal and vertical β-beating at zero amplitude along the machine for the HL–LHC baseline at the start of the fill.

β-BEATING AT ZERO AMPLITUDE

Studies on the β-beating are performed assuming head-on (HO) and long-range (LR) interactions at the two main interaction points of the machine; their longitudinal positions around the corresponding IP are determined by the bunch separation of 25 ns, and their magnitude by the beam sizes and bunch population. Head-on and long-range beam-beam encounters at the two other IPs are also present, but their effect is smaller due to the offset for levelling (as in ALICE) luminosity and their larger normalized crossing angle (as in LHCb).

In the HL-LHC baseline [2, 7] the luminosity is levelled at a maximum value of 5×10^{34} cm^{-2} s^{-1}, compatible with the maximum pile-up acceptable by the two main experiments. This is done via reduction of β^* as the beam is burnt-off and the intensity decreases. Due to the large bunch population (2.2×10^{11} protons per bunch), β-beating is larger at the beginning of the fill ($\beta^* = 64$ cm) –and thus more of a concern– with respect to that at the end of the levelling, when the minimum β^* is reached (15 cm) and the bunch population has reduced by almost a factor of 2. The horizontal and vertical β-beating generated by the beam-beam interactions at the beginning of the fill is shown in Fig. 1; its peak value reaches a magnitude of 15 % and 14 % in the horizontal and vertical planes, respectively, or, in terms of RMS values,

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about 8 % for the horizontal and 5 % for the vertical beating. These figures decrease at the end of the levelling stage (after around 7.4 h) to 6 % (10 %) for the horizontal (vertical) peak β-beating, corresponding to RMS values of 3 % for both planes.

The β-beating depends also on the phase advance between IPs; by a proper adjustment of this phase advance, a global compensation can be found. The margins for these adjustments are, however, limited [11]. Local corrections using quadrupole around the IPs can also be implemented [12].

AMPLITUDE-DEPENDENT β-BEATING

Amplitude-dependent β-beating is evaluated via single-particle tracking with MAD-X [13]. Due to the non-linearity of the beam-beam forces, particles oscillating at different amplitudes will be affected differently. Equally-spaced particles with amplitudes up to 10σ, positioned at different angles from 0° to 90° in the physical xy plane, are tracked in the HL-LHC lattice for 4000 turns. A matrix containing the phase space coordinates is obtained for a series of observation points of interest (Poincaré sections); the singular value decomposition of each matrix provides the transformation matrix to normalized coordinates which, when compared to the Floquet transformation, determines the optics functions at this point [9].

In the present work, such observation points are the two main IPs, as well as the primary and secondary collimators. Results (Fig. 2) show a large detuning with amplitude, mostly along the diagonal: a dominating effect from the head-on

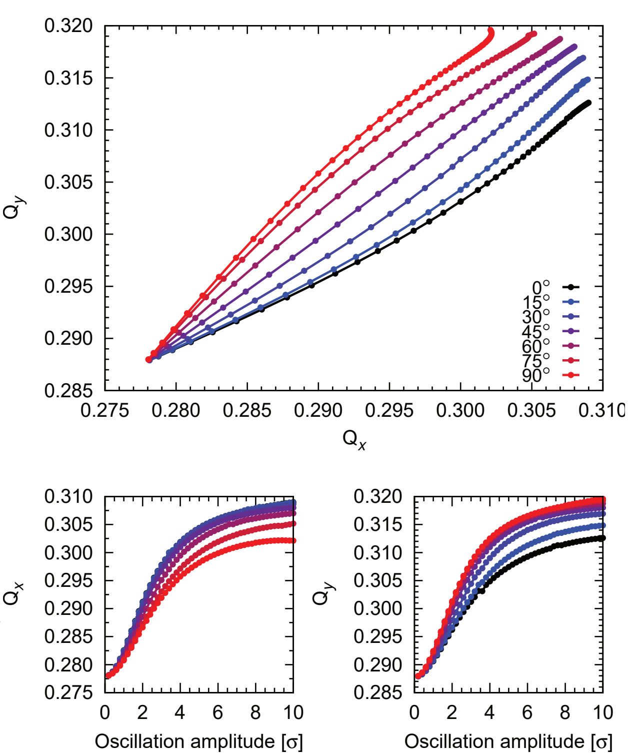

Figure 2: Detuning with amplitude for the HL-LHC baseline at the start of the fill.

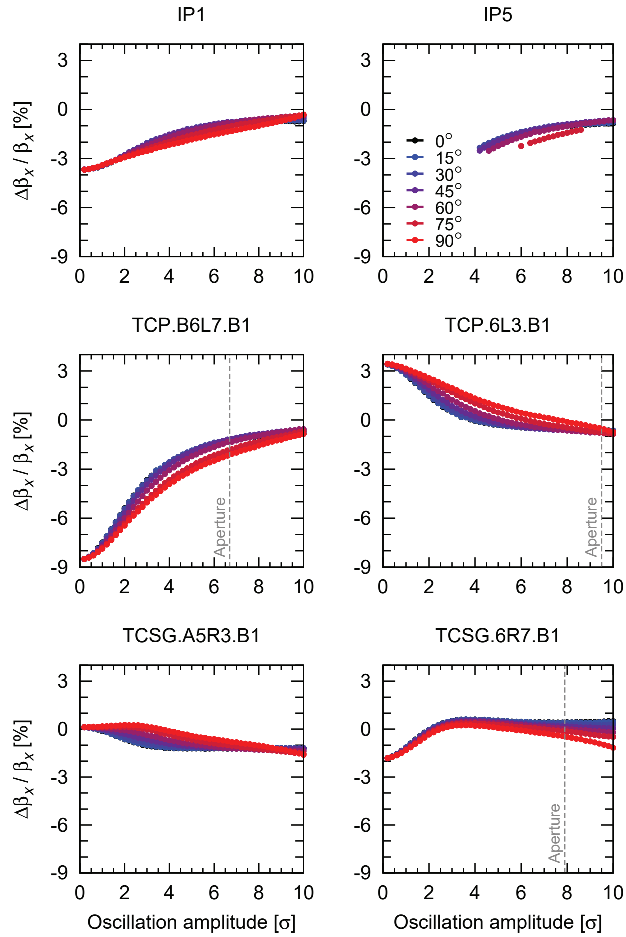

Figure 3: Horizontal amplitude-dependent β-beating at the interaction points of the HL-LHC baseline, and at selected primary (TCP) and secondary (TCSG) collimators, at the start of the fill.

contributions, and a smaller effect from the long-range contributions that becomes more significant as the amplitudes get larger.

Figure 3 illustrates the amplitude-dependent β-beating evaluated at selected primary and secondary collimators and the main IPs; as in the previous plot, the different lines show the behaviour of the particles with different angle in the xy plane; some points have been omitted due to numerical errors. As it can be observed, the resulting values are within the tolerance of 20 % [14]; also, the maximum of the β-beating as a function of amplitude does not necessarily reaches its maximum at zero-amplitude (which magnitude corresponds, as expected, to that from the linear model). The latter is observed, in particular, at the secondary collimators. The non-linear β-beating does not necessarily vanish with particle amplitude. Significant optics distortions are found for some collimators at amplitudes well below the corresponding aperture, represented in the plots as a vertical line. Hence, the collimator efficiency is not expected to be compromised; only if the β-beating below 6 σ approaches the tolerances it might pose a concern.

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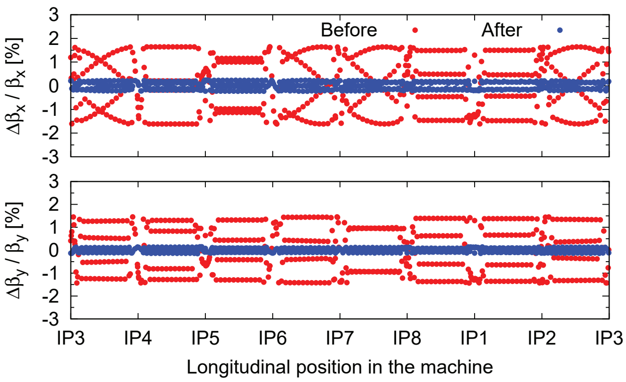

Figure 4: Horizontal and vertical β-beating before and after correction of the quadrupolar term of the BBLR with a sextupole magnet with offset.

CORRECTION SCHEME

It has been shown for the LHC that β-beating at zero amplitude, coming from the linear component of the head-on beam-beam force, can be corrected with quadrupoles [9]. This technique could be similarly applied to the HL-LHC to significantly reduce the β-beating, using the quadrupoles in the interaction region (IR) around the main IPs. These corrections however would deteriorate β for particles at large amplitudes, rising in turn concerns over the collimators.

In the case of the long-range beam-beam (BBLR) effects, a technique currently has been proposed [10], aiming at the compensation, term-by-term, of the Taylor expansion of the beam-beam kick, using the magnetic field from the feed-down of corrector magnets at the IR. In MAD-X notation [13], the strength of a normal magnetic field of order m ($m = 0$ for a dipole, $m = 1$ for a quadrupole, etc.), resulting from the feed-down of a normal magnet of order n, due to an offset between the centers of the magnet and the beam passing through it (d_x), is given by

$$\frac{\mathtt{KN}_m^{(n)}}{m!} \equiv \frac{\mathtt{KN}_n}{n!} \binom{n}{m} d_x^{n-m} . \tag{1}$$

Hence, the necessary field strength in the multipole corrector of order n to compensate the m-term of the BBLR kick is

$$\mathtt{KN}_n = \frac{n!}{\binom{n}{m} d_x^{n-m}} \frac{K_m}{m!} , \tag{2}$$

where K_m is the corresponding coefficient of the Taylor expansion [10], a function of the bunch population, the beam-beam separation, etc. A sum over the total number of long-range encounters, and a scaling factor with $\beta_{x,y}$ due to their different positions and the position of the corrector, and the order of the effect to be corrected, has also to be taken into account.

In order to illustrate this correction scheme for the HL-LHC, compensation of the linear effects of the beam-beam encounters in one side of IP5 (horizontal crossing) is studied. Nominal beam and machine parameters corresponding to the start of the levelling process are assumed. The linear term of the BBLR force is compensated by the adjustment of a local sextupole corrector, recovering the original tune (62.31, 60.32) and reducing the β-beating (Fig. 4). Moreover, contrary to the LHC, the HL-LHC is equipped with decapoles in the triplet region, which allow to locally compensate the octupolar component of the BBLR via feed-down, reducing the footprint. Correction of higher order terms is ongoing; in this case, the impact on dynamic aperture, via single-particle long-term tracking, has to be addressed since the correction makes use of the adjustment of non-linear optics elements.

CONCLUSION

Beam-beam interactions affect the β-beating as a function of the betatronic amplitude. These effects have been estimated for the current HL-LHC; the maximum linear β-beating induced by head-on and long-range beam-beam, with the set of the parameters corresponding to the beginning of the fill (full intensity), is found to be a few percents at the amplitude corresponding to the collimator aperture, and therefore it is not considered an issue. The impact of beam-beam interactions on the luminosity imbalance between the ATLAS and CMS experiments will be relevant only at the end of the levelling process, but it is expected to be negligible due to the lower bunch population.

A first proposal to correct the linear and non-linear effects induced by long-range beam-beam forces has been outlined. This scheme makes use of the careful adjustment of corrector magnets in the interaction regions. Further studies are needed to fully prove its viability.

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