DYNAMIC BETA AND BETA-BEATING EFFECTS IN THE PRESENCE OF THE BEAM-BEAM INTERACTIONS

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Abstract

The Large Hadron Collider (LHC) has achieved correction of beta beat down to better than 5%. The beam-beam interactions at the four experiments result as extra quadrupole error in the lattice. This will produce a change of the beta* at the experiments and a beating along the arcs which for the High Luminosity LHC (HL-LHC) will be very large. Estimations of these effects will be given with the characterisation of the amplitude dependency. A first attempt to correct his beating is also discussed.

INTRODUCTION

Head-On (HO) Beam-Beam (BB) collisions as well as Long-Range (LR) interactions induce a force on the particles that depends on their amplitude. For small amplitude particles (i.e. below $\approx 1\sigma$), the force is approximately linear which means that the particles traveling see the beam coming from the opposite direction as a defocusing quadrupole when they are close enough to the beam center. Beam-beam interactions will induce a change in the β-function all along the accelerator [1]. In the simplest case for small amplitudes, one can derive analytically the change of the β-function coming from N small quadrupole errors (i.e. head-on collisions at small amplitudes) at positions s_i (i = 1,...,N) [2]:

$$\frac{\Delta\beta(s)}{\beta_0(s)} = \frac{2\pi\xi}{\sin(2\pi Q_0)} \sum_{i=0}^{N} \cos(2 \mid \mu_0(s) - \mu_0(s_i) \mid - 2\pi Q_0). \tag{1}$$

During the 2015 LHC Physics Run a study of possible impacts of the dynamic beta effects of beam-beam on the collider performances, modifying the β^* at the two high luminosity experiments. While the effect on the LHC performances has been shown to be of maximum 1% level the study has highlighted a much more relevant contribution to the beating along the circumference with possible implications to machine protections. The LHC β-beating from the lattice imperfections is measured and corrected in commissioning phase to a level beetween the 5-7% [5, 6]. The measurements and corrections are performed with single beams and beam-beam effects are not accounted for. Studies of the implications in β-beating for the LHC configuration of 2015 have shown that in collisions a beating of up to 8% is expected mainly due to the head-on collisions with a beam-beam parameter ξ of approximately 0.0037 per Interaction Point (IP) . The computed β-beating for the LHC set-up of 2015 are shown in Figure 1. The beating comes mainly from the head-on collisions at the IPs, two in the cases shown in this paper. The maximum beating expected is obtained when full head-on collision is established.

A similar effect is expected for the High Luminosity LHC (HL-LHC) case, where due to the much stronger head-on (ξ_{bb} ≈0.01 per IP), a maximum β-beating of approximately 15% and 24% is expected for the case of two and three head-on collisions, respectively. In Figure 2 the β-beating for the HL-LHC is shown for the baseline scenario defined in [3] with two head-on collisions in the ATLAS and CMS experiments. For the HL-LHC the effect is independent on the β^* as the beam-beam parameter is when no crossing angle is present at the IP as for the crab-crossing scenario.

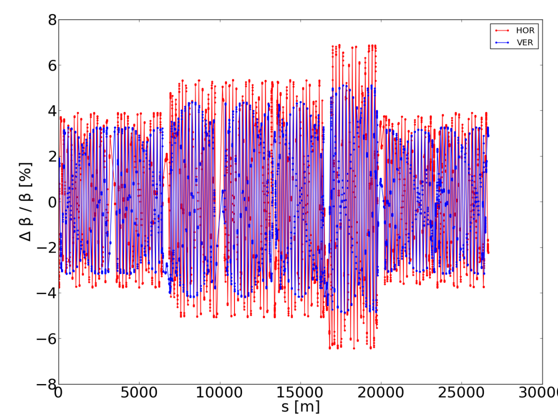

Figure 1: Beta-beating as a function of the longitudinal coordinate in the LHC for two head-on collisions at IP1 and IP5.

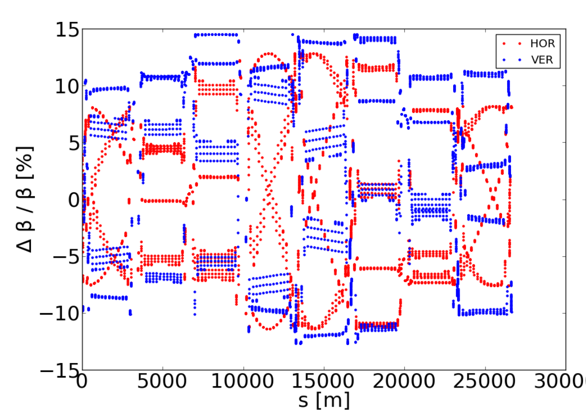

Figure 2: Beta-beating computed for the HL-LHC baseline scenario as a function of the longitudinal coordinate.

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Figure 3: Particles detuning with amplitude due to two head-on collisions. The particle amplitudes go from 0 to 8 σ RMS beam size. The different curves show the behaviour for oscillations at different angles in the X-Y plane.

Figure 4: Particles detuning with amplitude due to two head-on collisions and long-range encounters. The particle amplitudes go from 0 to 8 σ RMS beam size. The different curves show the behaviour for oscillations at different angles in the X-Y plane.

There are two aspects to study one related to luminosity performances and one related to the impact to the collider protection systems. The first can profit of such an effect since by optimizing the phase advance between the beam-beam interactions and keeping the beating corrections and errors at minimum one can obtain a reduction of the β_* at the IPs as done for example in [4]. For the HL-LHC case reductions of the beta function at the IP of maximum 9% have been evaluated with the present optics. The possible effects to the protection system need a careful understanding of the dynamics since the different interactions HO and LR act differently on core and tail particles. Figures 3 and 4 show the detuning with amplitude of particles colliding head-on and with long range interactions, respectively. The different lines show the behaviour of the particles with different angle in the x-y plane.

NON-LINEAR β BEATING

Due to the non-linearity of the beam-beam forces, the motion of particles oscillating at different amplitudes will be affected differently. In order to evaluate the impact of beam-beam interactions in terms of optics function, we compute the effective β function at a given point in the lattice using single particle tracking simulations. A matrix containing the phase space coordinates at the Poincaré section of interest for 5000 consecutive turns is obtained using MAD-X. The singular value decomposition of this matrix provides the transformation matrix to normalised coordinates which, when compared to the Floquet transformation, determines the optics functions. Figures 5 and 6 show the results of such an analysis in the presence of head-on and long-range beam-beam interactions in the LHC, in a configuration similar to the regular operational conditions during the 2016 run. As expected the variations of the optics function at zero amplitude correspond to those obtained with the linear model.

Figure 5: Horizontal tune shift and β beating at the interaction point 1 due to head-on beam-beam interactions in interaction points 1 and 5 in the LHC, for particles oscillating at different amplitudes. The different curves show the behaviour for oscillations at different angles in the X-Y plane.

In the presence of head-on beam-beam interactions only, the tune shift is maximum for particles oscillating at small amplitudes and vanishes asymptotically for large oscillation amplitudes. This behaviour of the tune shift is visible in Figure 5, the β-beating follows the same trend. While reasonably small in the case of the LHC, the head-on beam-beam tune shift considered for the HL-LHC as well as the FCC-hh is significantly larger. In such condition the maximum linear β beating induced by head-on beam-beam interaction could exceed the achieved correction of the bare optics and

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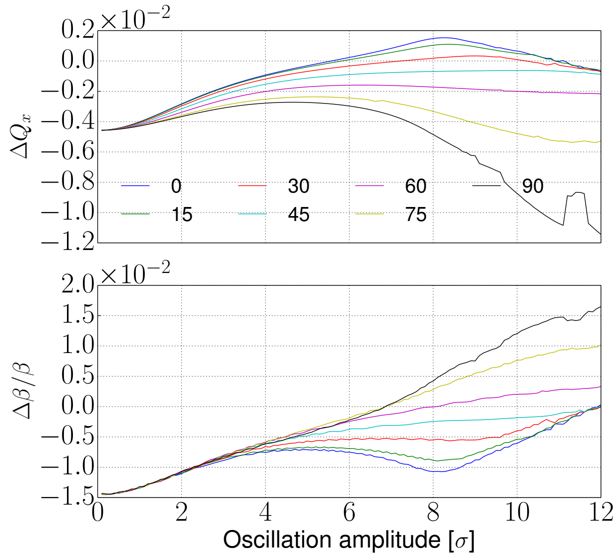

Figure 6: Horizontal tune shift and β beating at the interaction point 1 due to head-on and long-range beam-beam interactions in interaction points 1 and 5 in the LHC, for particles oscillating at different amplitudes. The different curves show the behaviour for oscillations at different angles in the X-Y plane.

possibly the tolerances imposed by the collimation system. Nevertheless, the effect on halo particles remains negligible. As opposed to head-on interactions, the forces due to long-range beam-beam interactions do not vanish for large amplitude particles. As a result, both the tune shift and the β-beating do not vanish at large amplitude. Figure 6 illustrates this behaviour, in the case of the LHC. While important optics distortions are visible for amplitudes above 6 σ, they will not affect the machine performance since particles with such an amplitude would be collimated. The efficiency of the cleaning could nevertheless be affected in case the β-beating below 6 σ approaches the tolerances.

The effect of the phase advance between the interaction points on the β-function has also a strong effect. Preliminary studies have showed that the maximum of the β-beating can be adjusted by varying the phase advance between the interaction points. The simulations also revealed that the maximum of the β-beating on a given plane could be very different from one side of the ring to the other which should be taken into account in the design phase, for example of the collimation system.

OPTICS CORRECTION

Beta-beating of up to 8 % and 6 % in the horizontal and vertical planes, respectively, is caused by head-on and long-range beam-beam effects in the four interaction points of the LHC at 7 TeV with a bunch population of 1.3×10^{11} particles and $\beta^* = 0.6$ m. The correction of the β-beating [7] is computed by rematching the interaction region (IR) with the closest quadrupole magnets to the IP, however using the triplet to perform the correction for LR BB is not possible because it would require opposite polarities in common magnets for the beams.

Table 1: Correction of the Peak β-beating due to LR BB at IP1 and IP5 (LHC Beam 1)

	ΔK_1	ΔK_2	Peak β-beating [%]	
	[10^{-6} m^{-2}]	[10^{-3} m^{-3}]	**Horizontal**	**Vertical**
IP1				
Uncorrected	-	-	1.81	1.87
Q4	+7	-	0.32	0.30
Q5	+15	-	0.52	0.54
MCSSX	-	9	0.08	0.20
IP5				
Uncorrected	-	-	1.81	1.86
Q4	−7	-	0.31	0.30
Q5	−15	-	0.52	0.49
MCSX	-	2	0.17	0.10

For the case of only LR-BB at IP1 (vertical crossing angle), the results on the variation of the strengths from their nominal values, $K + \Delta K$, of Q4, Q5, and MCSSX –at the left/right of the IP–, show a significant reduction of the peak β-beating (Table 1). The correction of the case of LR BB at IP5 by means of Q4 and Q5 is analogous to the former, resulting in ΔK of similar magnitude and opposite polarity due to the horizontal crossing angle. For the same reason, MCSX is used instead of MCSSX for the correction at IP5.

Rematching of the optics at the start/end of the interaction region (as well at the IP), where the HO BB effect is present, was the strategy adopted to correct the induced β-beating. Different configurations involving the quadrupole strengths of Q4 to Q7 were tested, and beams 1 and 2 were studied separately. As seen in Figure 7, the correction achieved

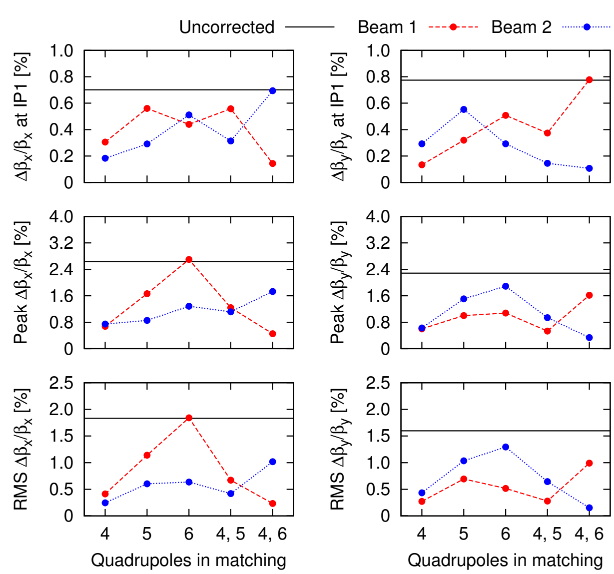

Figure 7: Correction of the beta-beating at IP1, peak beta-beating, and rms beta-beating, due to HO-BB at IP1.

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by the adjustment of a single quadrupole, such as Q4 or Q5, proved to be the most efficient: the peak- and rms- β-beating are reduced by a factor of 4 for both planes, and the β-beating is decreased by a factor of 2.5 or more, depending on the plane and beam under consideration. Similarly, the correction by the pair Q4-Q5 is also noticeable, and the corresponding tune-shift is lower, i. e. $\Delta Q_x = -0.0068$ and $\Delta Q_y = -0.0064$ (beam 1), compared to -0.0086 horizontally and -0.0066 vertically, for the correction with Q4 exclusively. Matchings involving Q6 do not perform satisfactory due to its strength being very close, in the case of LHC, to its limit.

Refined matchings and further studies as a function of the bunch population and β^*, for the LHC and HL-LHC, are ongoing.

CONCLUSIONS

Beam-beam effects can lead to important beating of beta functions. The maximum beating for the LHC and its upgrade is of the order of 8% and up to 24%, respectively. This could lead to important consequences in terms of machine protection, collimation and performances. A preliminary study shows the amplitude dependent beating for the case with head-on and long-range interactions. The phase advance between the beam-beam interactions have also an important role changing the location of the maximum beating. This could be optimized in the lattice design of colliders in the design phase. The beam-beam induced beating is very different from normal single beam effect and needs further investigations to understand the impact on other systems (i.e. collimation). A first proposal to correct for the beam-beam induced beating has been explored and the procedure described. Preliminary results for the LHC case have been presented and shows the possibility to reduce the beating due to long-range interactions by a factor 2.5. Further studies and an experimental verification is foreseen to prove the correction proposal for the LHC.

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