Beam-beam effects in the LHC

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Abstract

The LHC model has been studied in collision with 4- and 6-dimensional beam-beam elements. Orbit effects, tune footprints, and emittance behaviour are shown for different crossing angles (horizontal, vertical, large, small), without and with pacman-effect.

1 INTRODUCTION

When the LHC is operated with all bunches in collision, its dynamic aperture is largely constrained by the beam-beam effects, and by the multipole field errors in the low-β triplet quadrupoles [1].

The beam-beam effects cause tune shifts that can be visualized best in the form of "footprints" showing a tune shift diagram for particles launched at different points in action-angle space, typically covering six σ (transverse) beam size in action, and one quadrant (horizontal to vertical) in angle. The footprint can then be used to detect resonance lines that will cross it when it is placed in a tune diagram at the correct working point. This results mainly in a maximum tolerable "tune rectangle" which in the case of the LHC is the square $-0.01 \leq \Delta Q_x \leq 0, -0.01 \leq \Delta Q_y \leq 0$. The beam-beam tune shift decreases with increasing crossing angle: the effect of the parasitic encounters is reduced because of the larger bunch separation, and the head-on is reduced because the opposite bunch is seen under an angle and has therefore parts that are further away than at zero crossing angle [2].

The effect of the higher order multipole errors in the low-β quadrupoles increases with increasing angle since both the direct effect of a higher order component, and its feed-down caused by the angular separation get stronger and stronger. Therefore, leaving other considerations aside, there exists an optimum crossing angle.

2 DESCRIPTION OF THE LHC MODEL USED

LHC version 5 has been used for the studies presented here, on one hand because they started before version 6 existed, on the other hand because this version 5 was used in similar studies elsewhere [3]. However, the results remain valid for version 6 since the optics of the most important interaction points (1 and 5) are essentially the same. Very slight (if any) changes may come from the new operational tunes: whereas in version 5 $Q_x = 63.31$, $Q_y = 59.32$, Q_x is one unit higher in version 6.

The LHC model used here has the following specific features:

- Thin lens
- No matched optics for ring 2, therefore assuming:
  - Perfect anti-symmetry at IP1, IP2, IP5, and IP8
- Head-on collisions at IP1, IP5, and IP8
- Halo collision at IP2
- Vertical crossing at IP1, IP2, and IP8
- Horizontal crossing at IP5
- Crossing angles between $\pm 125 \mu rad$ and $\pm 150 \mu rad$ at IP1 and IP5, $\pm 100 \mu rad$ at IP2 and IP8
- All footprints calculated at injection tunes and then moved because of the tune-finding procedure (this has been checked to give the same footprints as the ones at collision tunes)
- At each of IP1, IP2, IP5, + IP8: 14 parasitic crossings on either side (at the workshop the correct number turned out to be 16)
- 4D (MAD [4] standard) and 6D (Hirata [5]) thin beam-beam elements (added to MAD), but all tracking always 6D (MAD)
  - Head-on split into five in both cases
  - Parasitic not split
- "Pacman effect": simulated by switching all parasitic off left of each IP
- Low-beta quadrupoles in triplets:
  - Split in four at IP1 and IP2, in two at IP2 and IP8
  - low-β quadrupole errors from the BNL Web page as valid on March 20, 1999, random errors added to systematic

The orbit with the separation bumps can be seen in Figure 1. The corresponding Twiss parameters are given in Table 1.

pos.	β_x[m]	β_y[m]	x[mm]	y[mm]
IP1	0.5	0.5	0	0
IP2	15	10	0.195	0
IP5	0.5	0.5	0	0
IP8	13	15	0	0
pos.	x_p[mm]	y_p[mm]	α_h $[\mu rad]$	α_v $[\mu rad]$
IP1	-0.002	0	0	±150
IP2	-	-	-	±100
IP5	0	-0.002	±150	0
IP8	-	-	0	±100
	Q_x	Q_y	Q_s	U_{RF}[MV]
	63.31	59.32	0.002	16

Table 1: Main Twiss parameters of the nominal LHC collision machine.

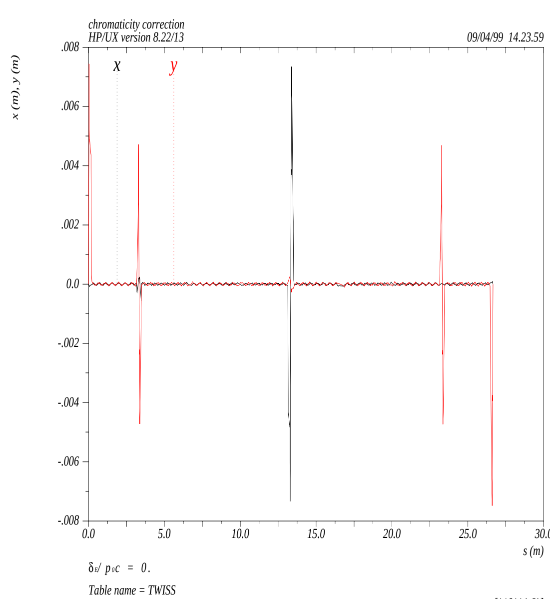

Figure 1: Orbit of nominal LHC collision with full beam-beam at $\pm150\mu rad$.

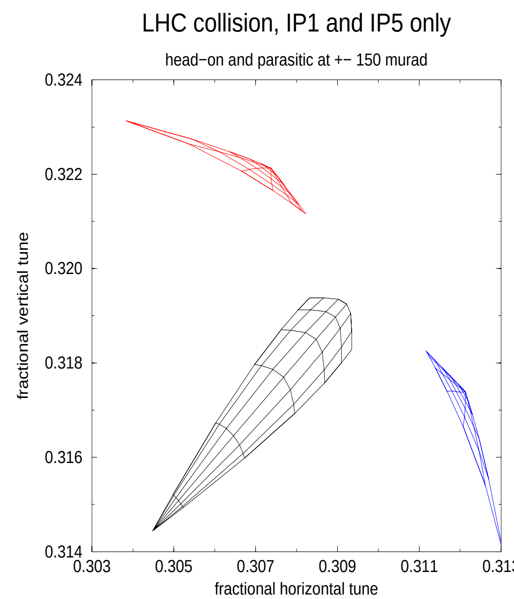

Figure 2: Footprints of head-on in IP1+IP5, parasitic in IP1, and in IP5.

3 TUNESHIFTS AND FOOTPRINTS

A comparison of the 4D beam-beam elements in MAD and the 6D beam-beam element of Hirata's shows no marked difference in the footprints in the case where both types are cut into five slices at the IPs (head-on collisions). In the following, the footprints are therefore given for 4D beam-beam elements only. However, in tracking studies it is probably preferable to use the 6D beam-beam elements since they may lead to long-term effects that are not yet visible in the 1024 turns used to calculate the footprints.

The tuneshifts are calculated for a weak-strong interaction, i.e. the bunches of the opposite beam remain unchanged. Since the charges in the two beams are both positive, the effect is defocussing in both planes for head-on collisions. For a bunch separation above 2σ the effect becomes focussing in the plane of the separation, but stays defocussing in the other plane. This can be seen nicely in Figure 2 where the combined head-on, and the parasitic footprints are shown for IP1 and IP5. One sees as well that the parasitic footprints lie symmetrically to the diagonal because of the effect just mentioned, since the crossing at IP1 is vertical, and at IP5 horizontal.

Table 2 shows the tuneshifts for different combinations of crossing angles and collision schemes for closed orbit particles (zero amplitude). For the angle of $\pm150\mu rad$ the tune shifts show the expected behaviour, i.e. they add up, and are antisymmetric in IP1 and IP5; this still holds approximately at an angle of $\pm100\mu rad$. At $\pm50\mu rad$, however, this is no longer the case, since there the orbit distortions are so strong that the beam-beam encounters can no longer be regarded as antisymmetric with respect to the IPs.

angle	type	IP1 ho	IP5 ho	IP1+5 ho
$\pm150\mu$	ΔQ_x	-0.00306	-0.0025	-0.0055
$\pm150\mu$	ΔQ_y	-0.0025	-0.00306	-0.0056
$\pm100\mu$	ΔQ_x	-0.0033	-0.00293	-0.0062
$\pm100\mu$	ΔQ_y	-0.0030	-0.00324	-0.0062
$\pm50\mu$	ΔQ_x	-0.0034	-0.00328	-0.0066
$\pm50\mu$	ΔQ_y	-0.0032	-0.00326	-0.0067
angle	type	IP1 all	IP5 all	IP1+5 all
$\pm150\mu$	ΔQ_x	-0.0057	-0.0003	-0.00595
$\pm150\mu$	ΔQ_y	-0.0003	-0.0057	-0.00599
$\pm100\mu$	ΔQ_x	-0.0100	+0.019	-0.0074
$\pm100\mu$	ΔQ_y	+0.0191	-0.0093	-0.0072
$\pm50\mu$	ΔQ_x	-0.02676	+0.0117	-0.0181
$\pm50\mu$	ΔQ_y	+0.01188	-0.0265	-0.0083

Table 2: LHC tune shifts for different crossing angles; only IP1 and IP5 have beam-beam elements and separation bumps.

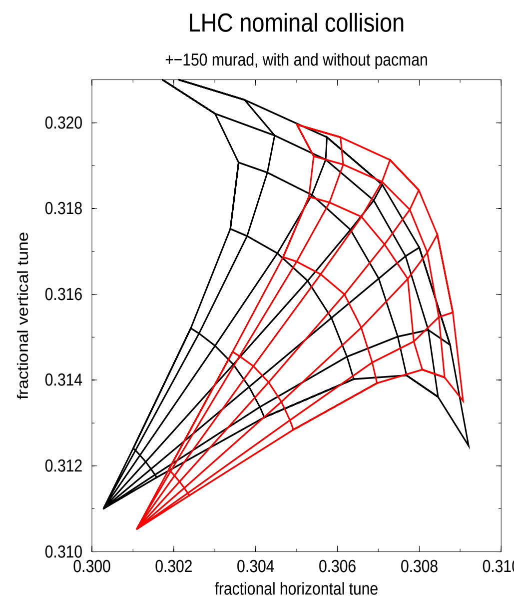

Figure 4: Full and pacman footprints at nominal angle.

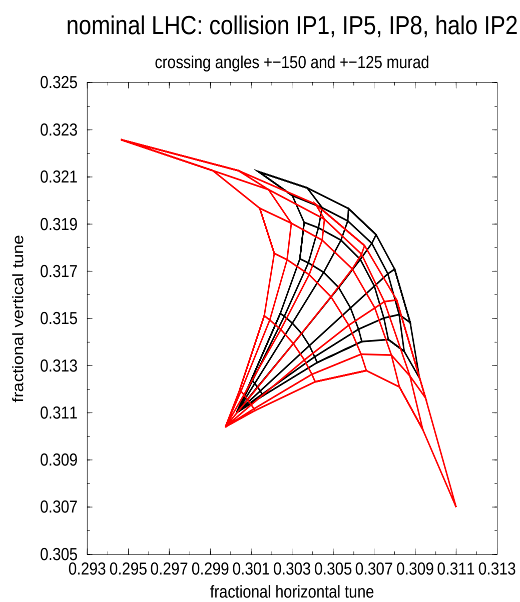

Figure 3: Full footprints for two angles.

As was mentioned before, the total footprint (here given for particle amplitudes up to 6σ) should fit into a square $-0.01 \leq \Delta Q_x \leq 0, -0.01 \leq \Delta Q_y \leq 0$. This is the case as long as the crossing angle in IP1 and IP5 is $\pm150\mu rad$ or above, as can be seen in the remaining Figures:

- Figure 3 shows the full footprints for the angles $\pm150\mu rad$ and $\pm125\mu rad$. The strongly enhanced influence of the parasitic encounters can clearly be seen in the (larger) footprint at the smaller angle.
- Figure 4 shows the full footprint together with a "pacman" footprint as experienced by leading and trailing bunch particles
- Figure 5 shows the footprint in case a head-on collision is missed out (sometimes called "super-pacman")
- Figure 6 finally shows the full footprint with the effect of the b10 errors in the low-β quadrupoles added. This is still acceptable even for the uncorrected b10 errors used here.

4 QUESTIONS RAISED AT THE WORKSHOP

Several questions arising during the workshop were answered "on the spot" by running the corresponding simulations over night.

- Question: is there an emittance blow-up beyond 10000 turns? Answer: tracking with
  - LHC collision at $\pm150\mu rad$, all 4D beam-beam elements present
  - full error table for triplet quadrupoles including systematic and random, KEK at IP1 and IP8, FNAL at IP2 and IP5
  - tracking one particle at 5σ and 7σ each, $\Phi = 45^\circ$ (angle in the x-y plane), $\Delta_p = 2\sigma$ over 100000 turns
  - resulted in no observable emittance growth

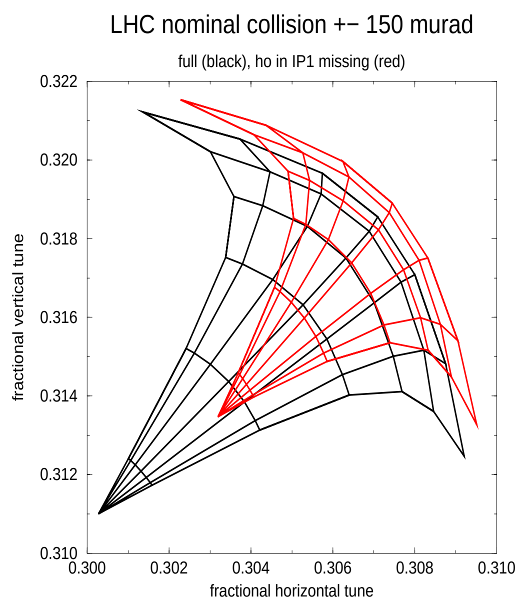

Figure 5: Full footprints with and without missing head-on at IP1.

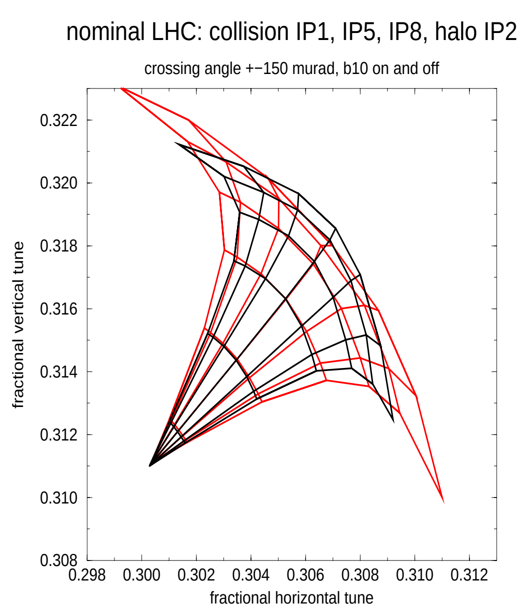

Figure 6: Full footprints with and without b10 at nominal angle.

- Question: do the triplet errors allow angles higher than $\pm 150\mu rad$? Answer: Tracking with the LHC above, particle amplitudes 7σ, showed loss of the particles above $\Phi = 45^\circ$ for $\pm 175\mu rad$ (and for $\pm 200\mu rad$). However, with the fractional tunes swapped, i.e. $Q_x = 63.32$, $Q_y = 59.31$ the particles survived at $\pm 175\mu rad$ and were only lost at $\pm 200\mu rad$ above $\Phi = 45^\circ$. So the answer is: no with the current collision tunes, maybe with different tunes.
- Question: what effect has a missing head-on collision? Answer: The footprint in Figure 5 shows that at least the tune shift poses no problem.

5 CONCLUSION

The constraint of the "magic tune square" $-0.01 \leq \Delta Q_x \leq 0, -0.01 \leq \Delta Q_y \leq 0$ rules out crossing angles much below $\pm 150\mu rad$ at IP1 and IP5. The low-β quadrupole errors (and probably luminosity considerations, and the geometric aperture as well) forbid to go much higher. These results therefore suggest that a crossing angle of $\pm 150\mu rad$ at IP1 (vertical) and IP5 (horizontal) is optimal for the current LHC model.

6 REFERENCES

[1] A. Verdier, A. Faus-Golfe *Multipole compensation in the LHC low-β insertions*; Proceedings of 1997 Part.Acc.Conf., Vancouver, 12.5.-16.5 1997; LHC Project Report 1997.

[2] H. Grote, Olaf Meincke *Tune Footprints for Collision Optics 5.0*; LHC Project Note 161, 1998.

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