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SELF-CONSISTENT ORBITS WITH BEAM-BEAM EFFECT IN THE LHC

H. Grote

Abstract

In part of the straight sections of the LHC the two beams share a common beam tube. Therefore the bunches cross each other not only at the interaction point, but as well at many places on either side, with a typical transverse separation of 10 times the transverse beam size. These ”parasitic” encounters lead to orbit distortions and tune shifts, in addition to higher order effects. Since the string of bunches from the injection machine contains gaps, not all possible 3564 ”buckets” around the machine are filled, but only about 3000. This in turn causes some bunches to not always encounter bunches in the opposite beam at one or several parasitic collision points (so-called ”pacman” bunches), or even at the head-on interaction point (”super-pacman” bunches). With a special program self-consistent orbits in the LHC have been calculated for the first time with the full beam-beam collision scheme resulting from various injection scenarios. The offsets at the interaction points, and the tune shifts are shown to be small enough to be easily controlled.

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Abstract

In part of the straight sections of the LHC the two beams share a common beam tube. Therefore the bunches cross each other not only at the interaction point, but as well at many places on either side, with a typical transverse separation of 10 times the transverse beam size. These ”parasitic” encounters lead to orbit distortions and tune shifts, in addition to higher order effects. Since the string of bunches from the injection machine contains gaps, not all possible 3564 ”buckets” around the machine are filled, but only about 3000. This in turn causes some bunches to not always encounter bunches in the opposite beam at one or several parasitic collision points (so-called ”pacman” bunches), or even at the head-on interaction point (”super-pacman” bunches). With a special program self-consistent orbits in the LHC have been calculated for the first time with the full beam-beam collision scheme resulting from various injection scenarios. The offsets at the interaction points, and the tune shifts are shown to be small enough to be easily controlled.

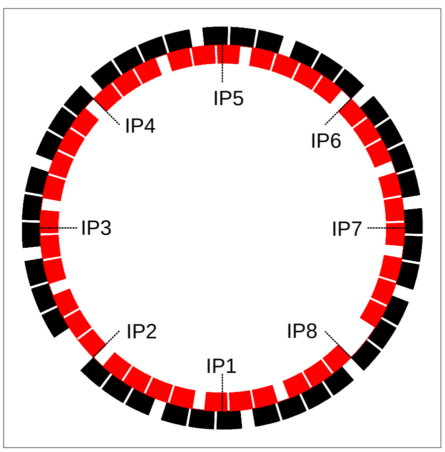

Figure 1: Latest injection scheme with bunches in ring-1 (outside, clockwise) and ring-2 (inside, anti-clockwise). The picture catches the instant at which the first bunch of ring-1 arrives at IP2.

1 INTRODUCTION

In the LHC [5] the two opposite beams share a common beam tube for roughly 50 m on either side of the four interaction points. Since the bunch spacing is only 7.5 m, in order to avoid unwanted head-on collisions the beams cross with an angle. Even so, in addition to the one head-on encounter at each interaction point there remain 15 positions on either side of it where the closed orbits at nominal energy are only about 10 σ apart, and even less in the focusing quadrupoles at either side of each interaction point. Various effects (alignment errors, field errors, momentum errors, imperfect injection, beam-beam kicks) may lead to significant orbit distortions and further distance reduction. Because of “holes” in the filling scheme the situation differs from bunch to bunch. The principal effects on the bunches caused by the beam-beam encounters are tune shifts and orbit offsets at the interaction points. The former are potentially dangerous because they may shift the tune of a bunch onto a resonance which may lead to its loss; the latter reduce the luminosity, and the offset at the head-on collision creates an extra orbit kick that adds to the distortions already present. Further possible causes for worry are changes in the chromaticity, non-zero dispersion at the interaction point, odd order resonances, and possibly higher order effects. The aim of the current study was therefore to see whether acceptable closed orbits exist for all bunches in both beams, whether the coherent tune shifts remain small enough to be of no concern, and the other effects mentioned can be corrected if necessary. The study provides as well input for the layout of the correction system in that it gives typical values for orbit errors caused by beam-beam effects.

The results are presented in graphical form because of the large number of bunches. The bucket number for ring-1 is constructed as follows: bucket number zero is at IP5, bucket number one to the left of it (seen from top), number two further to the left and so on backwards through IP4, IP3, IP2, IP1, IP8 etc. until to the right of IP5. The beam rotates clockwise. For ring-2 the numbering is done from IP5 to the right, the beam rotates anti-clockwise.

2 BUNCH FILLING SCHEME

$72 \times 1 \;\; 8 \times 0 \;\; 72 \times 1 \;\; 8 \times 0 \;\; 72 \times 1 \;\; 38 \times 0$
$72 \times 1 \;\; 8 \times 0 \;\; 72 \times 1 \;\; 8 \times 0 \;\; 72 \times 1 \;\; 38 \times 0$
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Whatever the bunch filling scheme, as long as it is the same for both rings, and the injection is symmetric to IP1 and IP5, every bunch in ring-1 will collide with a bunch in ring-2 (and vice versa) at IP1 and IP5. For this to be true as well at IP2 and IP8, the following condition has to be fulfilled:

The distance from IP to IP is 891 half-buckets (bunches collide every half-bucket since both beams move) except for IP8 which is 888 from IP7 and 894 from IP1. If the injection scheme repeats itself every 891 buckets, then at all IPs a bunch will always meet a bunch. Super-pacman bunches are only created at IP8. The filling scheme shown here respects this symmetry almost fully, only at the end a few bunches are missing creating super-pacman bunches at IP2 and IP8. In symbolic form it can be written as above (1 means bunch present, 0 absent).

3 ALGORITHM

The calculations are performed with two programs, MAD [3] and TRAIN, the latter being a heavily modified version of the program TRAIN [4] developped for LEP. Both programs communicate via a database DOOM.

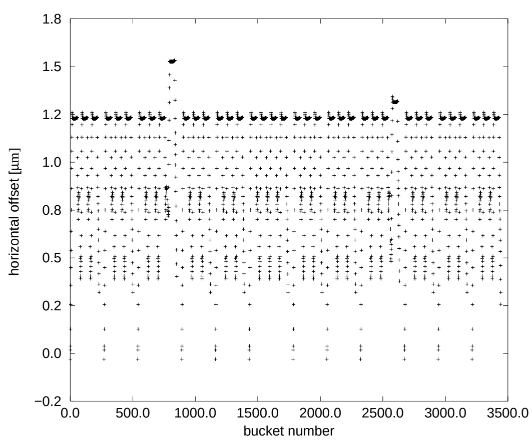

Figure 2: Horizontal offset at IP1 for all ring-1 bunches. The offset in caused exclusively by beam-beam interactions. The spread is about 1/10 of the beam size.

For the results presented here, a thin-lens model of the LHC version 6.0 was used, containing the latest separation and crossing schemes of version 6.1 [1], [2]. In the first step, the two LHC lattice and optics files are prepared for the TRAIN program: the lattice file for LHC ring-1 is read, the crossing and separation bumps are matched, tunes and chromaticities are adjusted, the places of head-on and parasitic encounters are marked, and the second order maps between all these beam-beam interaction points are lumped. This is justified since the optics under study contains only dipoles, quadrupoles, and sextupoles; field and alignment errors are not present. The Twiss parameters, element, lattice, force, and map tables are then stored in DOOM. For ring-2 the same procedure is followed using a matched thin-lens version for ring-2. At the end of this step, then, the database contains the necessary information for both rings to perform the self-consistent orbit finding.

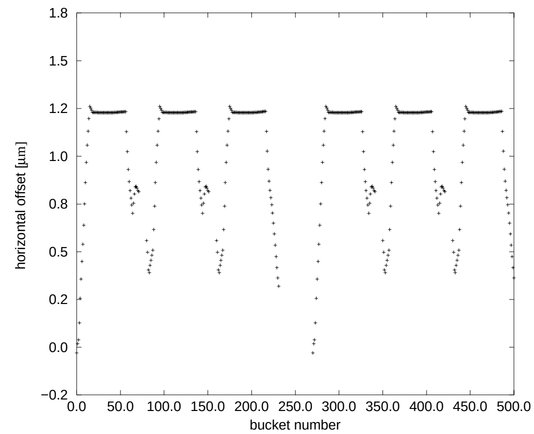

Figure 3: Detail of Figure 2. The 15 pacman bunches at either end of each bunch packet of 72 bunches can clearly be seen. The small irregularities are caused at IP2 and IP8.

This second step is performed by the program TRAIN. It first reads the description of the two rings from the database, and in particular the number and position of all beam-beam encounters. It then reads the injection schedule from an independent file and establishes the "encounter list" for all bunches in both beams. Next the program finds an initial closed orbit from the linear one-turn matrices with beam-beam encounters switched off. The program then iterates in a double loop over all bunches in both rings, with beam-beam encounters switched on. Where which bunch meets which bunch in the other ring is known from the bunch filling scheme. The inner loop is iterated with fixed distances between bunches at the beam-beam encounters, i.e. fixed beam-beam kicks. When it has converged to closed orbits for all ring-1 and ring-2 bunches, then the bunch positions at the beam-beam encounters are updated, and the outer loop is iterated until these positions do not change anymore. The bunch sizes are kept fixed as calculated from the undisturbed beta-functions, their change in size is negligible. Once all orbits (i.e. their six-dimensional initial coordinate vectors) are known, each bunch pair is tracked with the second order maps to get the tunes, chromaticity, and dispersion. The total CPU time for 2808 bunches in each beam is of the order of a few minutes on a fast workstation (e.g. Pentium III).

4 COHERENT TUNES, CHROMATICITY, LUMINOSITY, AND DISPERSION

The coherent horizontal and vertical tunes for all bunches are shown in Figure 4. The offset batch stems from the super-pacman bunches at IP8; IP2 has practically no effect since there the beams are separated by about 4σ. The offset of the normal bunches is as expected, i.e. roughly $-3 \times 0.00342/2 = -0.0051$ (the undisturbed fractional tunes are 0.31 and 0.32, respectively). When the bunch currents in both rings have a Gaussian distribution rather

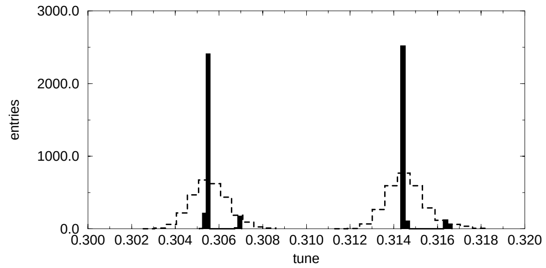

Figure 4: Solid: horizontal (left) and vertical tunes for all 2808 bunches in ring-1. The two offset bumps belong together. They represent the 186 super-pacman bunches occuring at IP8. Dashed: tune spread resulting from a Gaussian beam current distribution.

than being equal as in the results presented up to now, this has very little effect on the orbit offsets, since they are caused by over one hundred parasitic encounters and are thus averaged; however, there is a visible effect on the coherent tune shift which is caused by the head-on collisions only of which there are up to three (the separation of 4σ at IP2 makes this head-on collision insignificant for the tune shift). Figure 4 shows the coherent horizontal tune shift resulting from a Gaussian bunch current distribution with $\sigma = 0.2\, c_{nom}$ ($c_{nom} = 0.189\, [mA]$ is the nominal bunch current). The spread doubles with respect to the case with fixed beam current, but is still within $\pm 2 \times 10^{-3}$ which is not dramatic. Bunch current variations of this order can therefore be tolerated, provided there are no other effects not studied here that give reasons for concern.

The change in the dispersion is below $1\, mm$ for all bunches. The luminosity resulting from the offset at the collision points lies between 0.98 and 1 without correction. When the average offset (see Figure 3) is corrected, the overall luminosity drops by less than 0.001.

The horizontal and vertical chromaticity without beam-beam effect were adjusted to 1.6 and 1.8, respectively. The chromaticities with beam-beam effect are given in Figure 5. This effect can be tolerated since the range of acceptable chromaticities is between one and two.

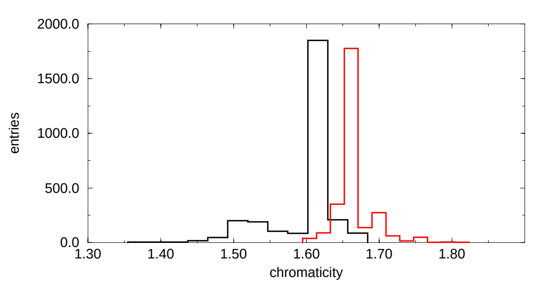

Figure 5: Horizontal (black) and vertical chromaticities for bunches in ring-1.

5 FROM SEPARATED TO COLLIDING BEAMS

One might fear that instabilities occur when the beams in the two rings are brought into collision. However, as far as the self-consistent orbits are concerned, this effect should be small since changing one of the head-on collisions into a parasitic one cannot have much impact in view of all the other parasitic encounters already present. This is confirmed when this effect is simulated: at IP5, the beams have been separated by zero to ten σ in steps of one σ. The maximum offset occurs at a separation of three σ in the form of an overall shift of about 0.2 μm. Obviously, this can easily be compensated by a slight beam position adjustment.

6 CONCLUSIONS

The self-consistent bunch orbits presented here for the latest bunch filling scheme allow the following conclusions which of course concern only the closed orbits for zero phase-space amplitude, and not any other parameter such as long-term stability, lifetime, emittance blow-up, dynamic aperture etc.:

- the bunch offsets lie within $\pm 0.1\sigma$ at the physics collision points
- the effects on the luminosity are negligible
- the effects on other parameters (tune, chromaticity, dispersion) are small, and their shifts can easily be corrected (not their spread)

7 REFERENCES

[1] O. Brüning, W. Herr, R. Ostojic, “A beam separation and collision scheme for IP1 and IP5 at the LHC for optics version 6.1”, CERN LHC Project Report 315

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[5] The LHC Study Group, “The Large Hadron Collider - Conceptual Design”, CERN/AC/95-05