LHC Project Note 321

August 26, 2003

Werner.Herr@cern.ch

Effect of missing head-on collision on beam-beam effects in the LHC

W. Herr, AB Division, CERN

Keywords: luminosity, beam-beam

Summary

Changes to the bunch filling pattern in the LHC have consequences for the number of long-range and head-on beam-beam interactions. In particular changes of the symmetry of the pattern have significant effects, especially the number of bunches with missing head-on collisions. The consequences of a recent change are presented together with an assessment of possible implications for the beam dynamics.

1 Introduction

The bunches in the LHC do not form a continuous train of equidistant bunches spaced by 25 ns, but additional space must be provided to allow for the rise time of kickers. These gaps and the number of bunches per batch are determined by requirements from the LHC injectors (PS, SPS etc.) and the preparation of the LHC beam (bunch splitting). The whole LHC bunch pattern is composed of 39 smaller trains of 72 bunches separated by gaps of various length followed by a large abort gap for the dump kicker at the end. The Figs. 1 and 2 show the previous [1] and actual filling scheme [2] with the various gaps in the train.

2 Filling schemes

The old scheme resembled a fourfold symmetry and the abort gap was provided by omitting that last batch of the otherwise symmetric pattern. The new scheme fullfils the requirement that the abort gap follows four instead of three consecutive batches [2]. The first bunches in each beam are always assumed to collide in the symmetry points in interaction regions 1 and 5. The Fig. 3 shows the new scheme, but with an increased bunch spacing of 75 ns. This scheme is foreseen for the early days of the LHC. Each bunch collides with another bunch

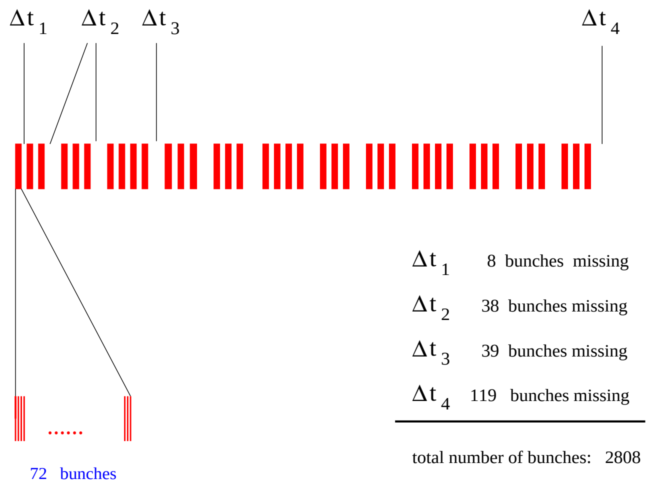

Figure 1: Old LHC filling scheme (April 2000) for 25 ns bunch spacing.

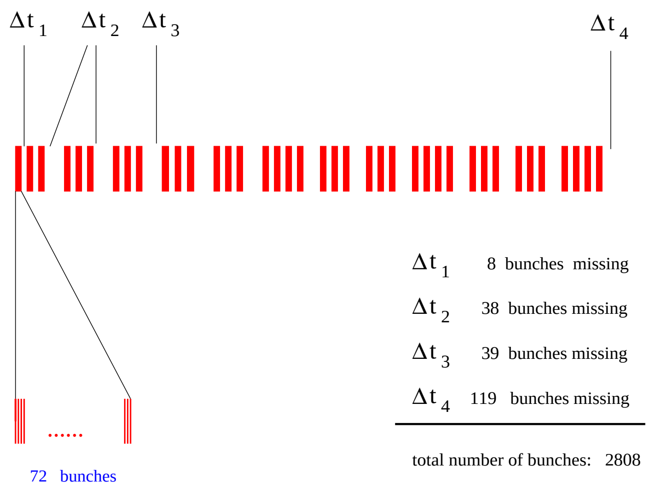

Figure 2: New LHC filling scheme (February 2003) for 25 ns bunch spacing.

in the two high luminosity regions of the machine. However, bunches at the beginning and end of a train suffer only half the long-range interactions at each interaction point [3]. As a consequence, some bunches experience only half the accumulated beam-beam effects and may have a different dynamics [3].

3 Missing head-on collisions

The number of missing head-on collision depends largely on the intrinsic symmetry of the filling pattern while the number of missing long-range interactions depends on the sizes of the various gaps. A complication is introduced by LHCb in interaction point 8 where the collision point is displaced by 11.22 m ($\equiv$ 75 ns) from the symmetry point. Therefore the first three bunches of each train in one beam and the last three bunches of the other beam do not collide head-on in interaction point 8. Further missing head-on collisions are introduced

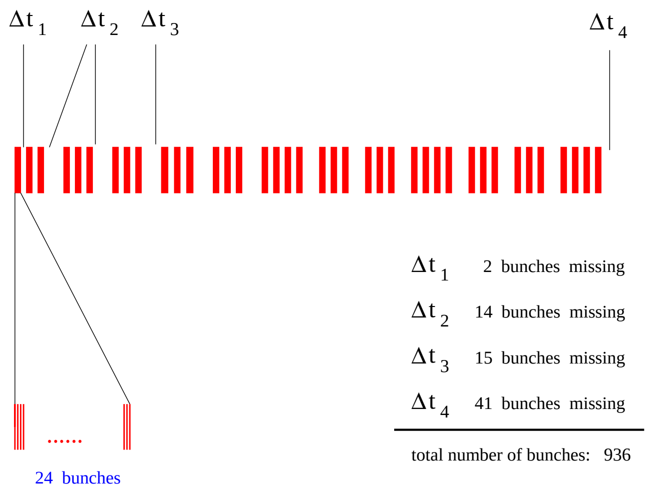

Figure 3: New LHC filling scheme for 75 ns bunch spacing.

by the abort gap and as a consequence a significant number of bunches experience three or only two out of the four head-on collision. Instead of 2808 bunch crossings per revolution as in interaction points 1 and 5, only 2616 will happen in interaction point 2 and only 2514 in 8. Bunches which do not have the regular collision pattern have been named PACMAN bunches in the literature. For the new base line scheme only 1275 bunches are regular bunches with 4 head-on and 120 long range interactions, i.e. more than half of the bunches are not regular. The identification of regular bunches is important since measurements such as tune, orbit or chromaticity should be selectively performed on those. A comparison of the number of

Scheme	total	4 HO	3 HO	2 HO	LR^{max}	LR^{min}	regular
Old 25 ns	2808	2553	252	3	120	43	1443
New 25 ns	2808	2385	360	63	120	44	1275
New 75 ns	936	783	128	25	40	15	413

Table 1: *Numerology of head-on (HO) and long-range (LR) collisions for different filling schemes.*

missing head-on and long range collisions for the three filling schemes under consideration is made in Tab. 1. The main difference is the large increase of missing head-on collisions and a reduced number of regular bunches for the present base line scheme. The reason for this rather larger number of missing head-on collisions is the lack of symmetry in the new filling pattern, while the previous scheme resembled a four-fold symmetry.

3.1 Collision pattern

The head-on collision pattern along the whole bunch train and details are given in Figs. 4 to 7. For the previous filling scheme the effects of the displaced interaction point and the

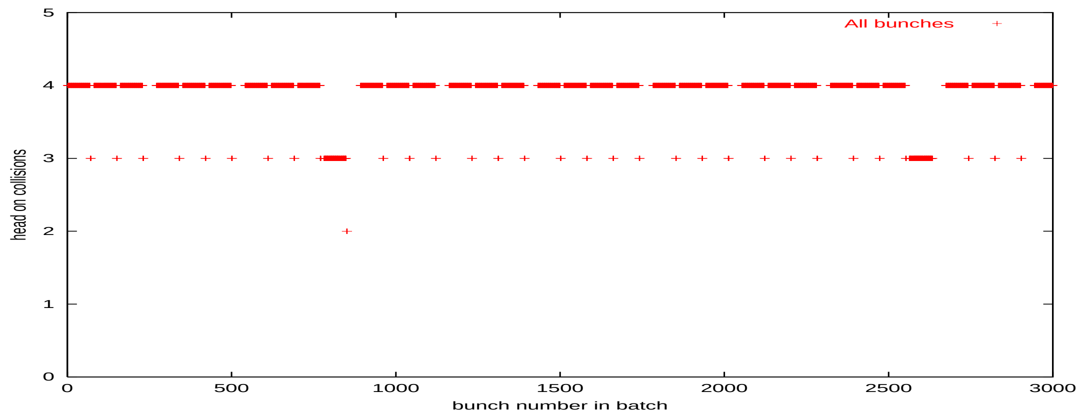

Figure 4: Number of head-on collisions along the bunch train for the old filling scheme.

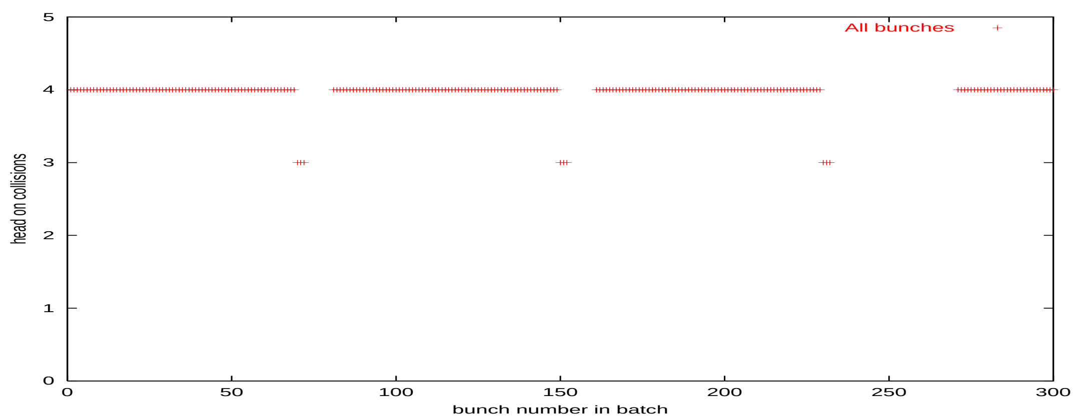

Figure 5: Number of head-on collisions along the bunch train (details) for the old filling scheme.

abort gap are rather obvious and clearly visible in Fig. 4 where the full train is shown and Fig. 5 where some details are given. The new scheme exhibits a much less regular pattern (Fig. 6). In Fig.7 I show some details of this pattern and have added the positions of the regular bunches. It should be noted that removing the bunches with two head-on collisions does not improve the situation. Their position would be taken by other bunches. Only restoring a fourfold symmetry, including the abort gap, would suppress the double missing head-on collision.

As already mentioned, missing long-range interactions complicate the picture and for simulations (e.g. [3, 4, 5, 6]) both have to be taken into account. The Figs. 8 and 9 show the number of head-on versus long-range collisions for each bunch in the train. The so-called nominal or regular bunches have all long-range and all head-on collisions and their positions are marked explicitly in the pictures. An interesting consequence of the (missing)

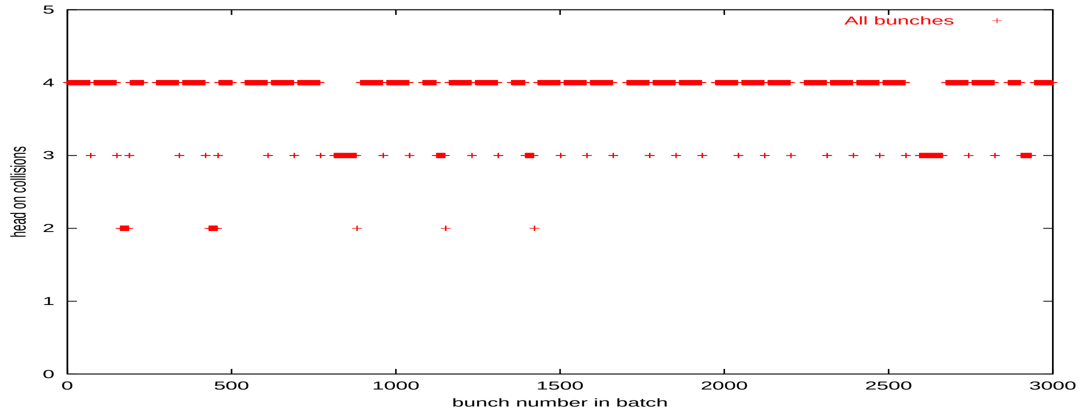

Figure 6: Number of head-on collisions along the bunch train for the new base-line filling scheme.

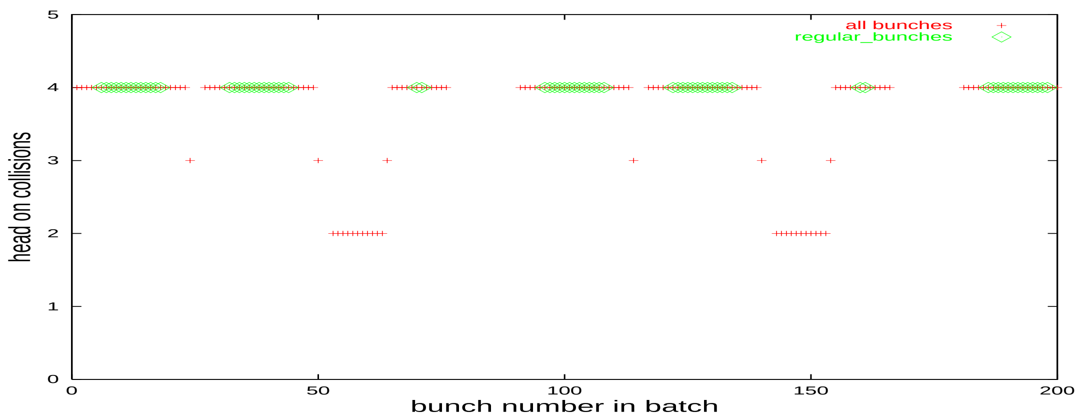

Figure 7: Number of head-on collisions along the bunch train (details) for the new base-line filling scheme.

symmetry is shown in these figures. For the more symmetric scheme the bunches with the fewest head-on collisions have in general also much fewer long-range collision. Such a strong correlation is missing in the new base-line scheme in particular when a bunch spacing of 75 ns is considered. However, the significance of missing long-range interactions is rather independent of the filling pattern since they are mainly determined by the size of the gaps. This can easily be seen in Fig.8 where the minimum and maximum number of long-range collisions is practically the same for both cases. For a passive compensation of bunch to bunch effects caused by long-range interactions alternating crossing planes are very desirable [4].

For simulations it is usually required to study the behaviour of extreme bunches and therefore those at the top and bottom of the vertical bars must be chosen, depending on the purpose of the simulation. Suggested candidates would be nominal bunches (top, right bar), all head-on but half the long-range interactions (”classical” PACMAN bunches, at bottom, right bar), and last but not least the bunches with the fewest head-on as well as long-range collisions (bottom, left bar).

For the study of dynamic or diffusive aperture the nominal bunches are usually investi-

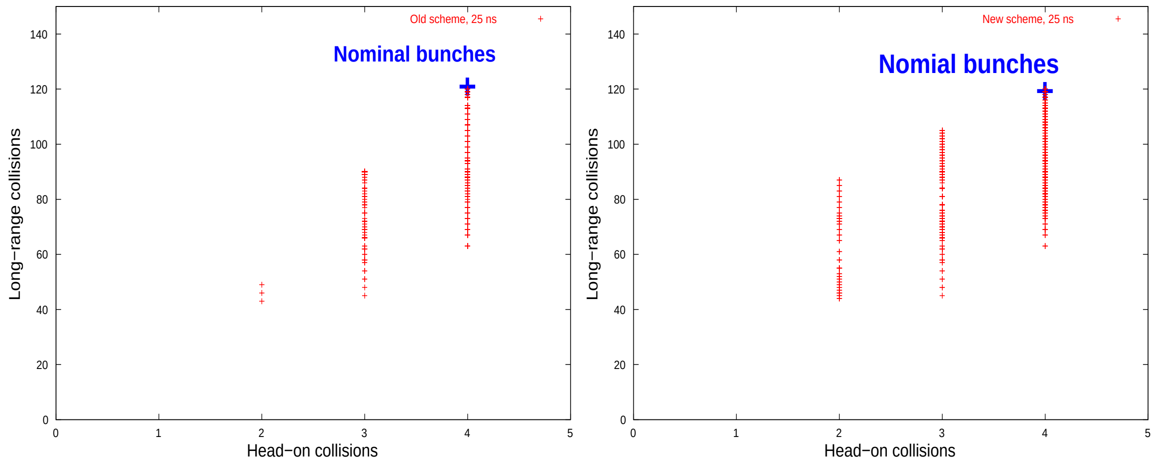

Figure 8: Head-on versus long range collisions. Old (left) and new (right) schemes with 25 ns spacing.

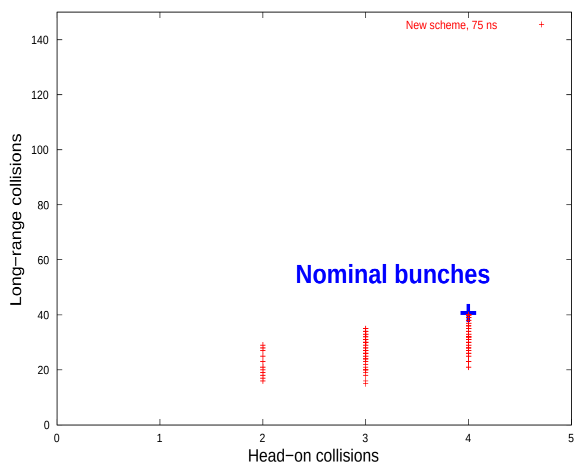

Figure 9: Head-on versus long range collisions. New scheme with 75 ns spacing.

gated. For the study of tune spreads (footprints) the first two classes have been considered up to now. The full effect of the last class was included only in studies where the parameters of all bunches were calculated self-consistently using the TRAIN [8] program.

4 Footprints and bunch to bunch variation

As a result of the different accumulated beam-beam effects, we must expect a bunch to bunch variation of vital parameters such as orbit, tune and chromaticity. Such variations have been observed in LEP and have limited the performance [7]. While tune or orbit changes of the whole beam can be corrected, this is not possible on a bunch to bunch basis. It is therefore important to minimize these effects.

4.1 Tune variation and tune spread

To demonstrate these effects, we show results from the self-consistent calculation [8] for the horizontal tune for two horizontal (Fig. 10) and alternating crossings (Fig. 11). Since the

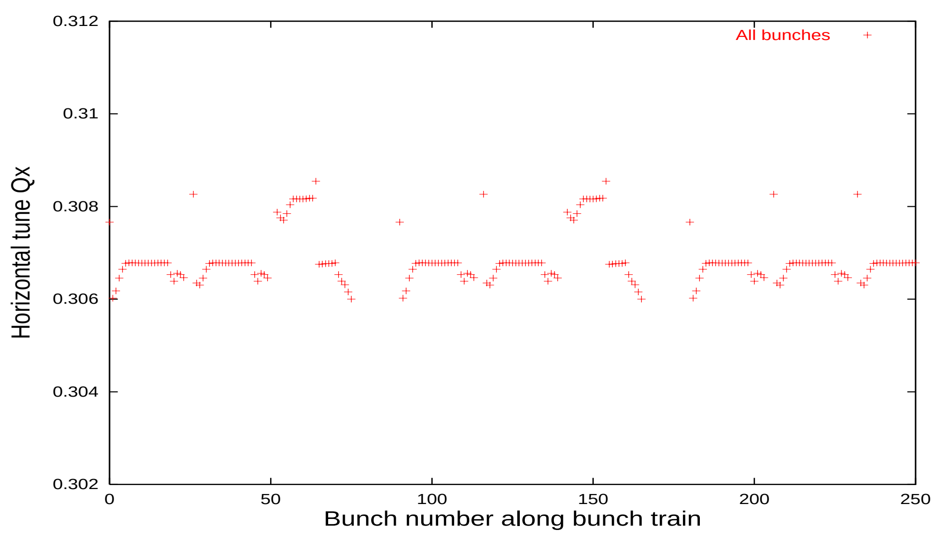

Figure 10: Tune variation along bunch train, new scheme with 75 ns spacing. Two horizontal crossings.

relative effect of missing head-on collisions is largest for the new collision scheme together with 75 ns bunch spacing I have chosen this option for the example. For the case of two horizontal crossings we have the well known variation of the tune along a batch [4]. While all regular bunches have practically the same tune, the PACMAN bunches show significant differences. For the case of alternating crossings the coherent tune of the bunches is practically constant along the batch with the exception of bunches with missing head-on collisions. Their tunes are shifted by the coherent beam-beam tune shift as expected. For the bunch spacing of 25 ns the spread is dominated by long range interactions.

The **coherent** tune of the bunches will therefore depend on their position in the train. However this does not increase (or decrease) the overall operational tune spread. This is shown in Fig. 12 where I show a tune footprint for the nominal conditions for nominal bunches, PACMAN bunches (missing long-range collisions) and for bunches which have the fewest collisions in total, i.e. the least number of head-on as well as long-range collisions. The footprint for the latter is entirely in the shadow of the regular footprint and therefore does not increase the overall tune spread. This is practically independent of the crossing

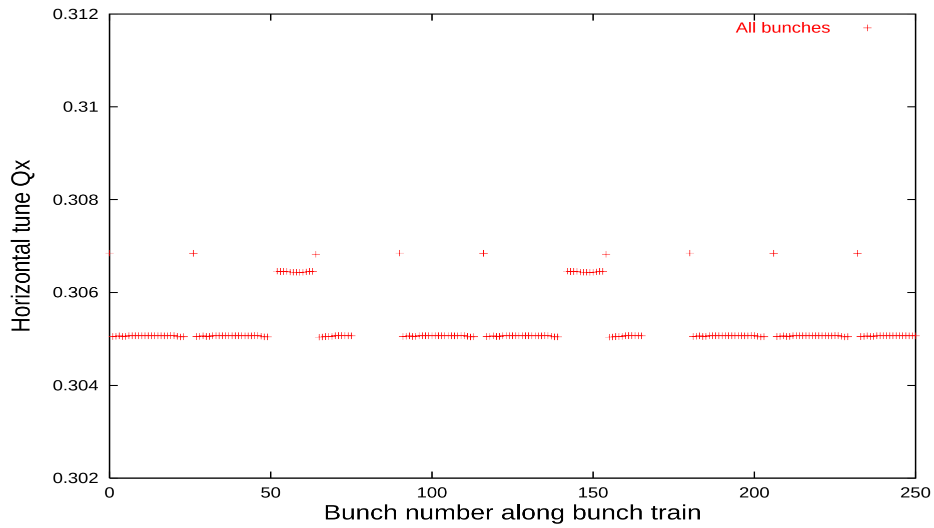

Figure 11: Tune variation along bunch train, new scheme with 75 ns spacing. Alternating crossings.

scheme. The Fig.13 shows the footprint for a bunch spacing of 75 ns and the tune spread is dominated by the head-on collisions.

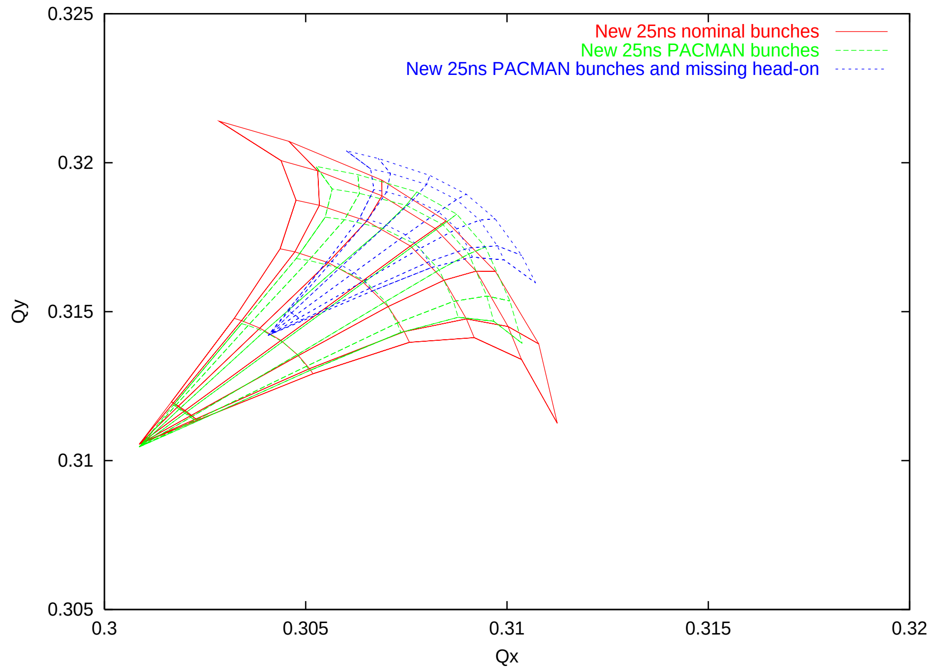

Figure 12: Tune footprint for nominal, PACMAN and missing head-on collisions. New scheme with 25 ns spacing.

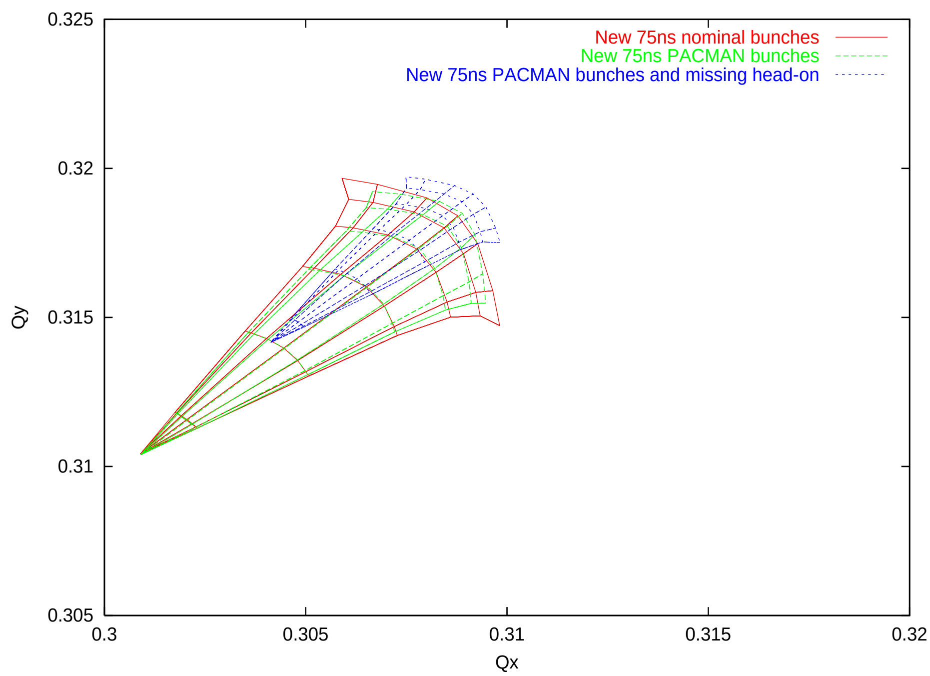

Figure 13: Tune footprint for nominal, PACMAN and missing head-on collisions. New scheme with 75 ns spacing.

4.2 Possible effects on Landau damping

Examining the Figs. 12 and 13, it is worth noting that the reduced tune spread of some individual bunches may have other implications. Should this tune spread be considered as a source of Landau damping [11] it must be remembered that the effective tune spread [11] can vary significantly from bunch to bunch. Furthermore, it was shown [11] that the effective tune spread mainly comes from the head-on collisions. With the increased number of bunches with missing head-on collisions this may become an issue. When the overall tune spread is important like for the Landau damping of coupled bunch modes, no detrimental effects are expected because the full tune spread inside and across bunches is practically unchanged.

Single bunch instabilities such as head-tail instabilities do not rely on Landau damping from beam-beam tune spread and should not be affected.

These differencs could become even larger when the intensity is increased, e.g. for the ultimate luminosity. However, operating only with two experiments opposite in azimuth avoids the problems of missing head-on collisions.

4.3 Consequences for beam instrumentation

The large number of bunches with missing head-on collisions make it even more important to be able to select individual bunches for the measurement of vital beam parameters, such as the tune or chromaticity. A list of the bunches or bucket numbers and their collision schedule must be available to all instruments where a bunch to bunch variation is important.

5 Summary

Changes to the filling pattern of the LHC can have significant effects on the collision schedule of the bunches, in particular on bunches missing one or more head-on collisions.

- Filling patterns without a symmetry largely increase the number of missing head-on collisions.
- Bunches with missing head-on collisions have very different coherent tunes and orbits.
- The overall, operational tune spread is not increased by missing head-on collisions and there is no reason to believe that they are more unstable than regular bunches.
- The reduced tune spread for some bunches could have consequences for Landau damping, although not for coupled bunch modes.
- Beam-beam simulations and measurements must take into account the different collision pattern.

At present we believe that changes to the filling pattern do in general not pose any problems for the beam dynamics, but the two last points must always be considered and action taken if needed.

References

[1] R. Garoby; *Base line proton filling scheme with 72 bunches*, Minutes of the 59th LHC Parameters and Layout Committee, 12.4.2000.

[2] P. Collier; *New base line proton filling scheme*, Minutes of the 2nd LHC Technical Committee, 19.2.2003.

[3] W. Herr; *Effects of PACMAN bunches in the LHC*, LHC Project Report 39 (1996)

[4] W. Herr; *Features and implications of different LHC crossing schemes*, LHC Project Report 628 (2003)

[5] W. Herr and J. Miles; *A Comparative Study of Beam-beam Tune Footprints for Colliding Beams with a crossing angle and offset vertex in LHC V4.1*, LHC Project Note 04 (1995)

[6] H. Grote and O. Meincke; *Tune footprints for collision optics 5.0*, LHC Project Note 161 (1998)

[7] W. Herr; *Beam-beam issues in the LHC and relevant experience from the SPS proton antiproton collider and LEP* Proc. of the 2001 workshop on beam-beam effects, FNAL, 25.6.-27.6.2001, (2001)

[8] H. Grote and W. Herr; *Self-consistent orbits with beam-beam effects in the LHC*, Proc. of the 2001 workshop on beam-beam effects, FNAL, 25.6.-27.6.2001, (2001)

[9] H. Grote and W. Herr; *Nominal and ultimate luminosity performance of the LHC*, LHC Project Note 275 (2002)

[10] H. Grote; *Comparing beam-beam effects in three LHC injection schemes*, LHC Project Note 267 (2001)

[11] W. Herr and L. Vos; *Tune distributions and effective tune spread from beam-beam interactions and the consequences for Landau damping in the LHC*, LHC Project Note 316 (2003)