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Spectra of multiple bunches coupled by head-on and long range beam-beam interactions

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Summary

A new strong-strong simulation program was written to study the coherent beam-beam interaction of multiple bunches coupled by head-on and long range interactions. In the first step the interaction of rigid bunches was simulated to compute the possible beam-beam modes visible on tune spectra following kicks given to individual or a finite number of bunches. In particular the effect of the symmetry properties of the collision pattern and the phase advance effects were studied in this first report.

1 Introduction

The spectra of the barycentric motion and the mode frequencies of coherent beam-beam modes are well known and understood for the case of a few bunches colliding head-on [1, 2]. Present and future colliders have many bunches and multiple interaction points and a much richer spectrum of modes must be expected [3]. This is in particular true when the collision points are not symmetrically distributed and additional effects due to non-symmetric collision schemes [4, 5] or asymmetric colliders like two-ring schemes [6] must be expected.
In the LHC there are a number of effects which break the symmetry between the collision points:

- Asymmetric configuration of the collision points
- Presence of a large number of parasitic long range interactions
- Unavoidable PACMAN effects [7, 8]
- It is impossible to make the bunches collide exactly head-on [9, 10].

In the case of multiple head-on collisions these modes can be analyzed with a linearized model searching for the eigenmodes of the full single turn map. However, when the non-linear long range interactions are included, the linearized treatment is not adequate. One therefore might expect a fairly large number of modes which may obscure tune measurements or feedback systems. The presence of a large number of modes due to the effect of local, parasitic interactions was already studied in [11, 12] but without possible PACMAN effects and for a simplified LHC collision scheme.
It is therefore important to define possible configurations which minimize the number of modes and provide cleaner spectra.
For the evaluation a strong-strong simulation program is written, using a rigid Gaussian model for the bunches.

2 Simulation program

The simulation program must allow to:

- Track each bunch of both beams independently around the ring
- Apply head-on and long range interactions at bunch encounters
- Give initial kicks to single bunches or a range of bunches to simulate excitation (e.g. for tune measurement)
- Analyze the motion of selected or a range of bunches
- Show the complete set of possible coupled beam-beam modes

In order to evaluate different scenarios, the program must be very flexible to allow easy changes of parameters such as tunes, number of bunches, filling scheme, collision scheme etc. In particular it must allow different crossing planes.
The possibility to change the phase advance between collision points is important.
Statistical fluctuations such as bunch intensity, emittance etc. must be possible to simulate.
It should be possible to simulate and demonstrate PACMAN effects.
In order to get all correct modes of the bunches coupled by head-on and long range interactions, all individual interactions must be simulated in full. In particular, lumping several long range interactions is therefore not adequate.
For future extensions it must be possible to add multi-particles to replace rigid bunches in a straightforward way.

2.1 Parameters

To describe the motion of a rigid bunch the following parameters are used:

- Horizontal position and angle of barycentre: X and X'
- Vertical position and angle of barycentre: Y and Y'
- Horizontal position and angle of single particles: x and x'
- Vertical position and angle of single particles: y and y'
- Longitudinal phase (or position s) and energy deviation: ϕ (or s) and δ

For extension and later use, following parameters are foreseen and stored:

- Bunch intensity (to determine beam-beam kick)
- Bunch emittance (to determine beam-beam kick)
- Tune shift ΔQ_X and ΔQ_Y with respect to a nominal bunch.

2.2 Input description

For the simulation it is necessary to describe the arrangement of the bunches around the machine and their possible interactions with other bunches or machine elements. For simplicity it must be optimized to study beam-beam interactions. However, the description should be very flexible to allow the study of different filling or collision schemes as well as optical properties of the machine. I have followed the strategy designed for beam-beam tracking and the computation of self-consistent properties [9, 10, 13, 14] and included all the necessary extensions.

2.2.1 Bunches in the ring and description of filling scheme

The description of the bunch filling scheme is given in the form of *groups*. Each group has two parameters: the first specifies the number of slots n and the second whether the n slots are occupied by a bunch (1) or whether the slots are empty (0). The total number of slots must be equal to the machine circumference devided by the bunch spacing. It is therefore vital that all empty slots are defined as well as all filled slots. The number of groups per line is specified at the beginning of the description file. To define 1 bunch followed by 39 empty slots one could use:

```
# bunch filling example 1
#Number of groups
2
 1 1 39 0
 1 1 39 0
 1 1 39 0
 1 1 39 0
```

This example describes 4 equidistant bunches spread out in 160 slots (possible bunch positions) while the example below shows 30 bunches arranged in 6 trains of 5 bunches each, filling 20% of the available slots in the whole machine.

```
# bunch filling example 2
#Number of groups
2
 5 1 45 0
 5 1 45 0
 5 1 45 0
 5 1 45 0
 5 1 45 0
 5 1 45 0
```

The scheme below represents the actual LHC bunch filling scheme [7, 18, 19].

```
# bunch LHC filling example
# number of groups
8
72 0  8 0  72 1  8 0  72 1   8 0 30 0   0 0
72 1  8 0  72 1  8 0  72 1   8 0 30 0   0 0
72 1  8 0  72 1  8 0  72 1   8 0 72 1  39 0
72 1  8 0  72 1  8 0  72 1   8 0 30 0   0 0
72 1  8 0  72 1  8 0  72 1   8 0 30 0   0 0
72 1  8 0  72 1  8 0  72 1   8 0 72 1  39 0
72 1  8 0  72 1  8 0  72 1   8 0 30 0   0 0
72 1  8 0  72 1  8 0  72 1   8 0 30 0   0 0
72 1  8 0  72 1  8 0  72 1   8 0 72 1  39 0
72 1  8 0  72 1  8 0  72 1   8 0 30 0   0 0
72 1  8 0  72 1  8 0  72 1   8 0 30 0   0 0
72 1  8 0  72 1  8 0  72 1   8 0 72 1  39 0
```

The number of slots in this case is 3564 which is one tenth of the LHC harmonic number. The description should maximize the readability, although any format is possible.

2.2.2 Positions and actions

When one is interested in beam-beam interactions, only every half bunch spacing something can happen (i.e. where two bunches from the two beams could meet). For N slots defined by the filling scheme (i.e. number of possible bunch positions), one has 2N positions where such actions can occur. In the description the numbering of the positions goes from 1 to 2N in the direction of the clock-wise beam.

2.2.3 Definition of actions

At any position, an action can be requested for a bunch when it is in that place. For beam-

beam interactions (head-on or long range) two bunches (i.e. one from each beam) must be at this position. The different actions are specified by a code number. Possible actions are:

- Head-on collision (at the specified position, code 2 or -2)
- Head-on and long range collisions (left and right of a specified head-on collision)
- Multiple long range collisions (left and right of a specified position, code 4 or -4)
- Single separated collision (code 5 or -5)
- Linear matrix transfer of a bunch (code 3)
- No action (default)

Additional actions, e.g. non-linear elements or correction devices, can easily be defined.

Head-on collision:

The code for a head-on collision point is either **2** or **-2**. The positive sign indicates horizontal and the negative sign vertical separation of the associated long range interactions, i.e. crossing plane in the case of the LHC. The strength of the head-on collision is determined by the beam-beam parameters which is either taken from the general input file or calculated from the bunch intensities, emittances and positions of the two colliding bunches. Before and after a head-on collision, the bunches are advanced in transverse phase space by $\pi/2$.

Long range collisions left and right of a head-on collision:

When a head-on collision point is defined like above, a number of long range collisions left and right of the collision point can be specified on the action statement for the head-on collision by specifying the number of collision points, i.e. the number of positions where long range interaction can occur. E.g. the line:

```
161  2  -15  +15
```

specifies a head-on collision at position 161 with horizontal crossing and 15 long range interactions on each side.

Long range collisions left and right of a specified position:

When an action code of **4** or **-4** is specified, only the long range interactions left and right of a specified position are active, the central head-on collision is ignored. This can be used to simulate a crossing angle configuration when the central head-on collision point is separated and the bunches experience long range interactions left and right of the symmetry point. However the rotation by $\pi/2$ before and after the specified position is performed to ensure the correct phase relationship between the long range interactions before and after.

Separated collisions

An action code of **5** or **-5** is used for a single separated interaction (e.g. in a Pretzel scheme). The third and fourth parameters are ignored.

Linear transfer of the bunches:

With the action code **3** a linear transfer is defined. The two parameters are used to control the phase advance of the transfer. The parameters specify the phase advance in units of 2π (tune). The phase advance between any point in the machine and in particular between interaction points can easily be controlled that way. The two rotations of $\pi/2$ for each head-on interaction point must be taken into account to get the correct overall tune.
In the present implementation the phase advance between two points in the machine is assumed to be the same for the forward and backward beams. In a two ring machine like the LHC this is not always the same.

2.2.4 Description of collision scheme

The collision scheme defines the actions to be performed at the possible positions. This description is an extension of the scheme defined for [13]. Every action consists of one line which defines first the position of the action, the second column is the code of the desired action and the third and fourth columns are parameters required by the action. Typical collision descriptions are:

```
#Collision scheme 1 (for filling example 1):

   1   2   -5  +5
  21   3   7.535  6.91375
  41  -2   -5  +5
  61   3   7.785  7.16375
 101   3   8.035  7.41375
 141   3   7.785  7.16375
 161  -2   -5  +5
 181   3   7.785  7.16375
 221   3   8.035  7.41375
 261   3   7.785  7.16375
 281   2   -0  +0
 301   3   7.535  6.91375
```

which defines 4 collision points where three have long range collisions on both sides of the head-on collision points. The machine has an eightfold symmetry in geometry and phase advance.

```
#Collision scheme 2 (for filling example 2):

   1   5    -0  +0
  26   3   2.2258 2.3070
  51   5    -0  +0
```

```
 76   3   2.2258 2.3070
101   5    -0   +0
126   3   2.2258 2.3070
151   5    -0   +0
176   3   2.2258 2.3070
201   5    -0   +0
226   3   2.2258 2.3070
251   5    -0   +0
276   3   1.9758 2.0570
301   2    -0   +0
326   3   1.7260 1.8100
351   2    -0   +0
376   3   1.7260 1.8100
401   2   -0  +0
426   3   1.9758 2.0570
451   5    -0   +0
476   3   2.2258 2.3070
501   5    -0   +0
526   3   2.2258 2.3070
551   5    -0   +0
576   3   2.2258 2.3070
```

This example resembles a machine with 3 head-on collision points and 9 separated collisions like in a machine with 6 equidistant bunches and a Pretzel separation scheme (SPS collider). As a further example, a collision scheme representing the LHC with its present filling scheme and layout of the four experiments is shown below.

```
#Collision scheme LHC (for LHC filling scheme):

   1  -2   -15  +15
 447   3    8.046   6.940
 892  -2   -0  +0
2229   3   23.015  21.821
3565   2   -15  +15
4902   3   23.533  20.689
6235   2   -0  +0
6684   3    7.716   7.870
```

Since the filling scheme defines the number of bunches and positions, the collision definition scheme must always follow the definition of the filling pattern.

2.2.5 Parameter input

At the start of the program, a parameter file is read in to define the basic input data. The name of this file is taken as a command line argument of the program.

```
collision:  coll_ref.in                          // input collision scheme
filling:    fill_ref.in                          // input filling scheme
use bunch:   1                                   // define bunch for analysis
number of turns: 14                              // number of turns: 2**14
bunches to kick:   5                             // kick 5 consecutive bunches
beam-beam parameter: 0.0025                      // beam-beam parameter
```

2.3 Actions

2.3.1 Linear transfer

At a position requiring a linear transfer I use a linear transfer map:

$$\begin{pmatrix} X \\ X' \\ Y \\ Y' \end{pmatrix}_{n+1} = \begin{pmatrix} \cos(\Delta\mu_X) & \sin(\Delta\mu_X) & 0 & 0 \\ -\sin(\Delta\mu_X) & \cos(\Delta\mu_X) & 0 & 0 \\ 0 & 0 & \cos(\Delta\mu_Y) & \sin(\Delta\mu_Y) \\ 0 & 0 & -\sin(\Delta\mu_Y) & \cos(\Delta\mu_Y) \end{pmatrix} \begin{pmatrix} X \\ X' \\ Y \\ Y' \end{pmatrix}_{n} \tag{1}$$

where $\Delta\mu_X$ and $\Delta\mu_Y$ are taken from the input files (i.e. collision scheme).

2.3.2 Head-on beam-beam interaction

To calculate the head-on beam-beam kick on a bunch, the counter-rotating beam distribution is assumed to have a Gaussian density distribution in the two planes with barycentres at (X^*, Y^*) and squared transverse sizes $\Sigma^*_{xx} =< (x-X)^2 >^*$ and $\Sigma^*_{yy} =< (y-Y)^2 >^*$. In that case the beam-beam force can be expressed analytically. The * denotes parameters of the opposing beam. In the case of rigid bunches the transverse sizes are kept constant. We apply a horizontal beam-beam kick at the IP (equivalent for the vertical beam-beam kick):

$$\Delta X' = \frac{2 r_p N_p^*}{\gamma} \frac{\beta_x}{\sigma_x^2} F_x(X - X^*, Y - Y^*, \Sigma^*_{xx}, \Sigma^*_{yy}) \tag{2}$$

with r_p the classical proton radius, N_p^* the bunch population (* indicates parameters of the counter-rotating beam), γ is the relativistic Lorentz factor, β_x the horizontal betatron function at the IP, σ_x the horizontal rms size and F_x (or, equivalently, F_y for the vertical beam-beam kick) given by

$$F_{\{x,y\}}(X - X^*, Y - Y^*, \Sigma^*_{xx}, \Sigma^*_{yy}) = \frac{\{X, Y\}}{(X^2 + Y^2)} \left[1 - \exp\left(-\frac{X^2 + Y^2}{\Sigma^*_{xx} + \Sigma^*_{yy}} \right) \right]. \tag{3}$$

which is the expression for round beams when $\Sigma_{xx} \approx \Sigma_{yy}$. When the beams are not round, we use the Bassetti-Erskine formula for the evaluation of the kick [22]. In the horizontal plane. The map at the beam-beam interaction is then:

$$\begin{pmatrix} X \\ X' \\ Y \\ Y' \\ s \\ \delta \end{pmatrix}_{n+1} = \begin{pmatrix} X \\ X' + \Delta X' \\ Y \\ Y' + \Delta Y' \\ s \\ \delta \end{pmatrix}_n \tag{4}$$

The beam-beam parameters are defined by

$$\xi_{\{x,y\}} = \frac{N_p r_p \beta_{\{x,y\}}}{2\pi\gamma\sigma_{\{x,y\}}(\sigma_x + \sigma_y)} \tag{5}$$

With the nominal LHC parameters we have $\xi \approx 0.0034$.

Before and after each head-on collision, I apply a phase advance of $\pi/2$ in each plane.

2.3.3 Long range beam-beam interaction

For the calculation of the long range beam-beam kick, the expressions for the head-on interaction must be modified to take the separation into account. The constant part of the kick in the plane of separation must be subtracted. Assuming a constant horizontal separation d and using the expression (3):

$$\Delta X' = \frac{2r_p N_p^*}{\gamma} \frac{\beta_x}{\sigma_x^2} \left[F_x(X + d - X^*, Y - Y^*, \Sigma_{xx}^*, \Sigma_{yy}^*) - F_x(d, 0, \Sigma_{xx}^*, \Sigma_{yy}^*) \right] \tag{6}$$

one gets the deflection $\Delta X'$ and for the other plane we have:

$$\Delta Y' = \frac{2r_p N_p^*}{\gamma} \frac{\beta_y}{\sigma_y^2} \left[F_y(X + d - X^*, Y - Y^*, \Sigma_{xx}^*, \Sigma_{yy}^*) \right] \tag{7}$$

2.4 Tracking strategies

2.4.1 Initial conditions

The barycentres of the bunches of the two beams can be set all to zero at the start of the program or distributed according to a Gaussian distribution. Furthermore, a single bunch or a small number of bunches can be excited at the beginning, simulating e.g. a tune measurement. This is specified in the input files.

2.4.2 Rotation of bunches in both rings

Beam 1 bunches travel increasing number of positions, beam 2 bunches decreasing number of positions.

At each step, every bunch is advanced by one position, i.e. half a bunch spacing. One complete turn in the machine therefore requires 2N steps.
The calculations for all bunches of a beam at each step are independent and it can be envisaged to make use of parallel processing, in particular when the bunches consist of many macro-particles in a later version of the program.

2.4.3 Data processing

By a Fourier analysis of the barycentre of the bunches, as calculated turn by turn, we obtain the tune spectra of the dipole modes. For only one bunch per beam the two spectra of the two bunches are equivalent. For more than one bunch per beam the spectra of bunches with the same collision scheme are also equivalent. Analyzing the sum $(X^{(1)} + X^{(2)})$ or the difference $(X^{(1)} - X^{(2)})$ of the barycentre of two colliding bunches of the two beams (denoted by (1) and (2)) show the spectra of the 0- and π-modes separately. This is useful to analyze the details of the modes.

2.5 Program validation

2.5.1 Head-on effects

To validate the program, I have simulated two head-on collisions in two interaction points, opposite in azimuth. A value of 0.0025 was used for the linear beam-beam parameter. The results are shown in Figs. 1 and 2. Equal charges of the two colliding beams are assumed and the frequencies are therefore shifted downwards from the unperturbed tunes. In Fig. 1

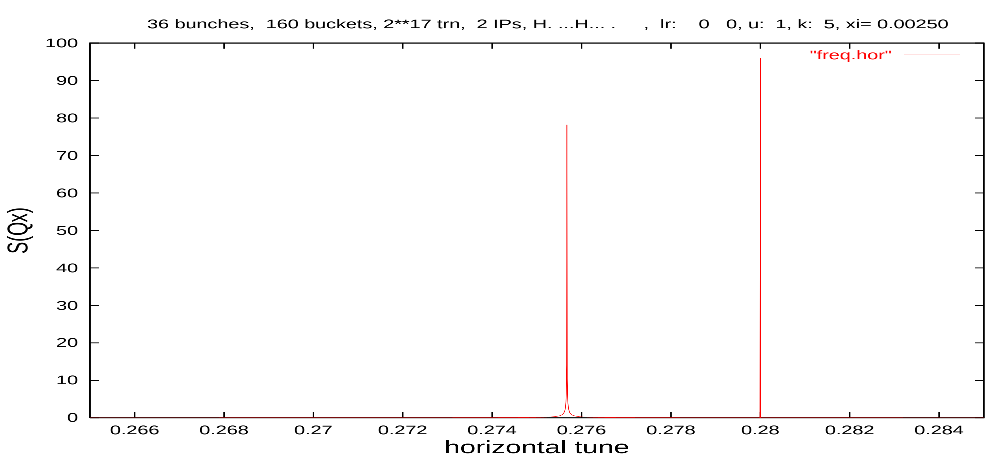

Figure 1: Head-on collisions in IPs 1 and 5.

the spectrum of the first bunch of beam 1 is shown while in Fig. 2 the sum and the difference of the barycentres of the colliding bunches in the two beams are shown. The Fig. 1 clearly shows the two coherent beam-beam modes. The sum signal in Fig. 2 shows only the 0-mode while the difference signal in Fig. 2 shows only the π-mode signal. This is in agreement

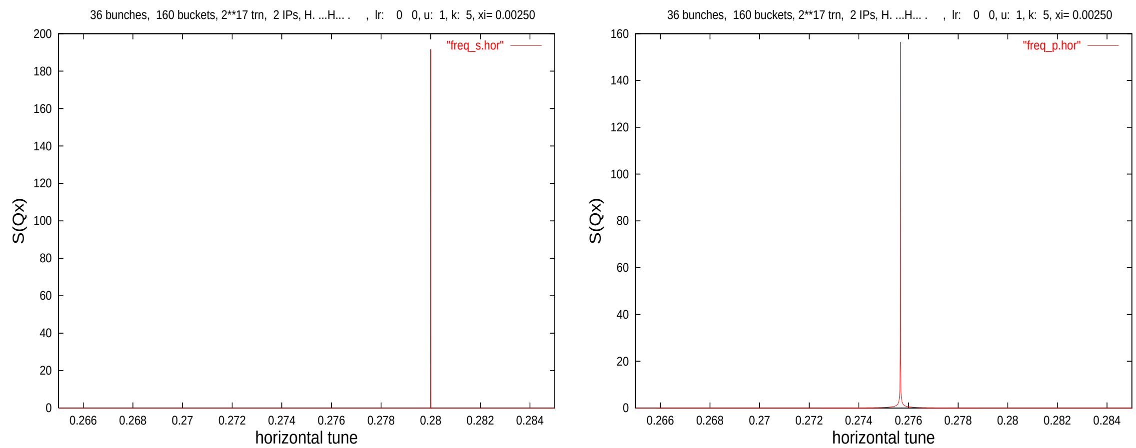

Figure 2: Head-on collisions in IPs 1 and 5. Sum of two bunches (left). Difference of two bunches (right).

with the expectations. The frequency shift between the 0-mode and the π-mode is however not correct in a rigid bunch model and the forces must be calculated from the real field distribution [16, 17]. For the purpose of this report to study the spectra of dipole oscillations the rigid Gaussian model is adequate.

2.5.2 Expected long range effects

The first simulation of long range interactions uses 4 bunch trains of 9 bunches each (bunch filling scheme example 1). However the bunches collide only in two interaction regions opposite in azimuth. Only long range interactions are simulated. The separation is assumed to be in the horizontal plane for both interaction regions. In the plane of separation the

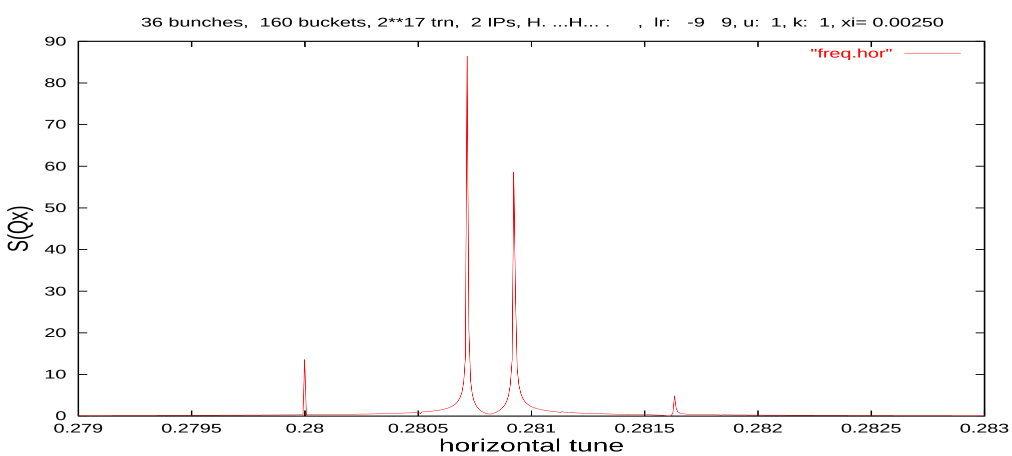

Figure 3: Horizontal spectrum with long range collisions in two IPs.

long range tune shift has a opposite sign relative to the head-on tune shift. This is visible in the spectra (Fig.3) and all modes are shifted to higher frequencies. The separate analysis

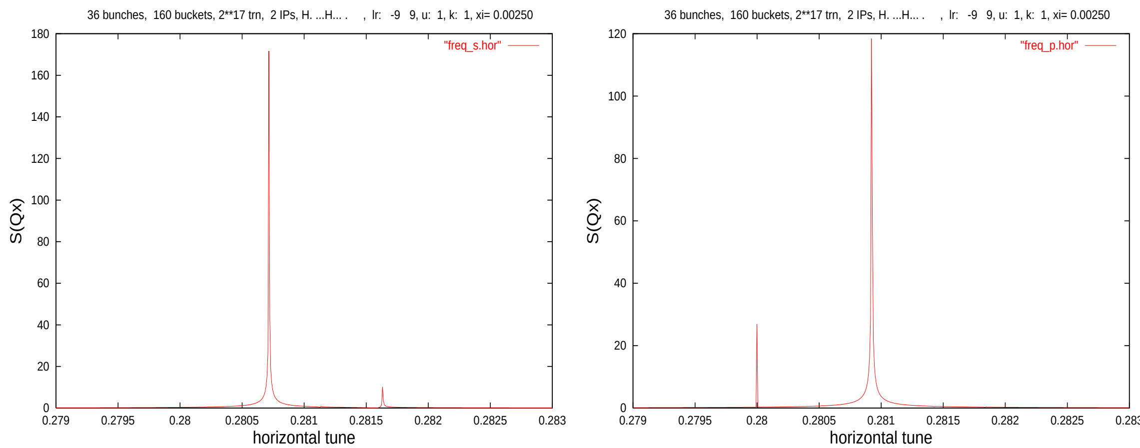

Figure 4: Horizontal spectrum with long range collisions in two IPs. Sum of the two bunches, 0-mode (left).Difference of the two bunches, π-mode. (right)

of the sum and difference of two colliding bunches shows the signals of the 0- and π-modes (Fig. 4).

2.5.3 Reproduction of PACMAN effects

When some bunches do not experience all possible long range interactions or at least fewer than the regular bunches, this results in a different beam-beam effect for those bunches which are then called PACMAN bunches. Such PACMAN conditions can arise when the beam is made up of bunch trains followed by gaps without bunches and when the number of positions with possible long range interactions is limited. More precisely, it happens when this number on each side of an interaction point is smaller than the number of bunches in a train. For the LHC this is the case where typically 15 long range interactions are possible due to the geometry and a bunch train is made up of 72 bunches. In this case the 15 leading and trailing bunches of the train miss long range interactions while the 42 bunches in the centre of the train experience 15 long range interactions on each side, i.e. 30 in total. To demonstrate this and to test the program, I have simulated trains of 9 bunches and allowed up to 15 long range interactions on each side. In this case no PACMAN effects should be visible and all bunches experience 8 long range collisions. In Fig. 5 I show the spectra of the bunches number 1 (upper left figure, beginning of the train) and 5 (upper right figure, centre of the train). The frequencies in the spectra are identical and no PACMAN behaviour is visible.

The spectrum for bunch number 1 is shown in Fig. 5 (lower left figure) when only 5 long range interactions are possible on each side. It can experience only 4 interactions and the frequency spectrum is now shifted. The bunch number 5 in the centre of the train should experience 4 long range interactions on each side and is therefore a nominal bunch. Its spectrum is shown in Fig. 5 (lower right). The comparison of the Figs. 5 (upper right) and (lower right) shows that the two are equivalent.

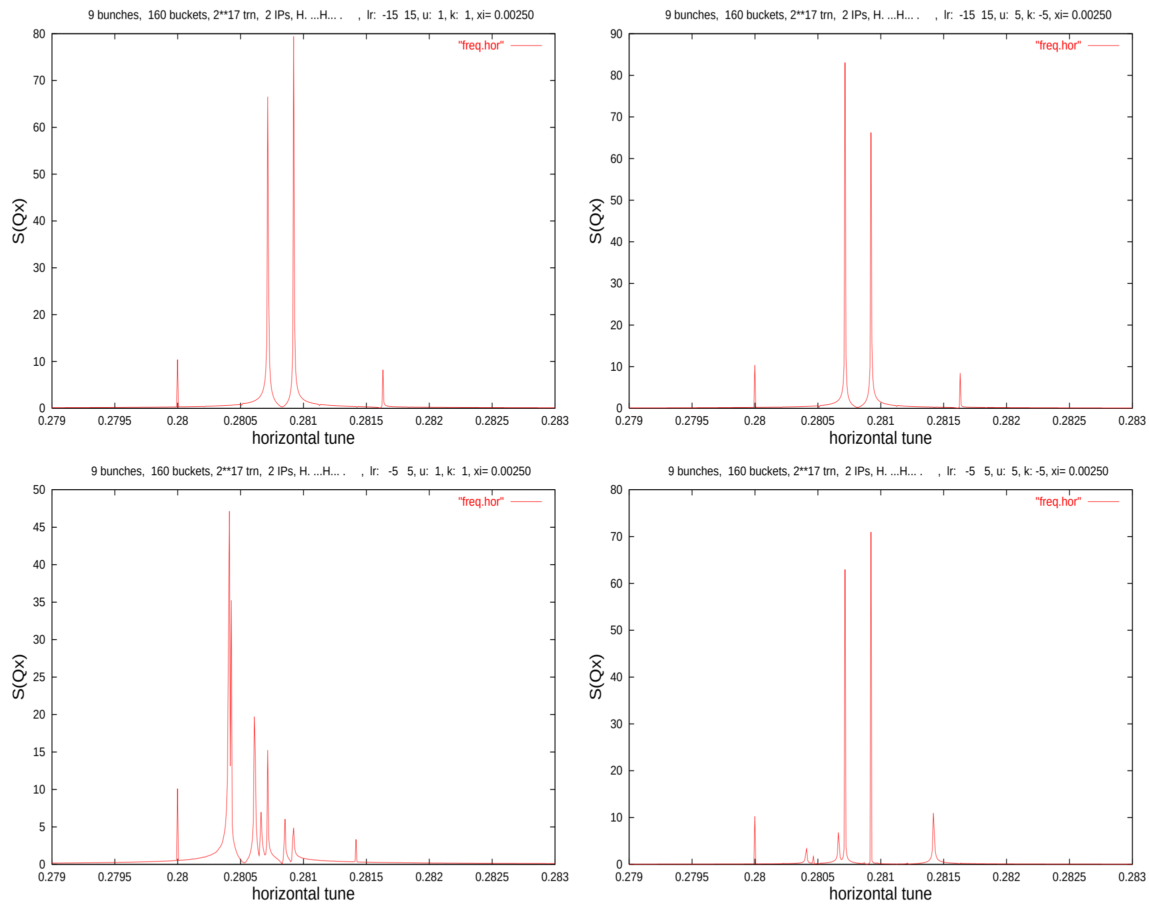

Figure 5: Long range collisions in IPs 1 and 5. Spectra of bunch number 1 (left) and bunch number 5 (right).

3 Results

With the available simulation program, the following effects can be studied and the dependence of the results on the optical and collision configuration can be evaluated.

- Head-on interactions only (one bunch per train or no long range positions)
- Head-on and long range interactions (multiple bunches per train)
- Excitation of single and multiple bunches in a train for measurement purposes

3.1 Multiple head-on interactions

In the case of multiple head-on collisions in a machine, the symmetry properties of the layout are very important for the spectra. A high degree of symmetry can lead to the degeneracy of modes, i.e. identical frequencies, and their suppression in the spectra. Breaking the symmetry by choosing a non-symmetric collision scheme or phase advance differences between the interaction points may cancel this effect and leads to the appearance of additional modes in the spectra. In the following I assume a collider with an eightfold symmetry of the possible collision points and number the interaction regions from 1 to 8. In this case the interaction points 1 and 5 are opposite in azimuth. This resembles the geometrical layout of the LHC straight sections. The Fig. 6 shows the spectra for a single head-on collision (left)

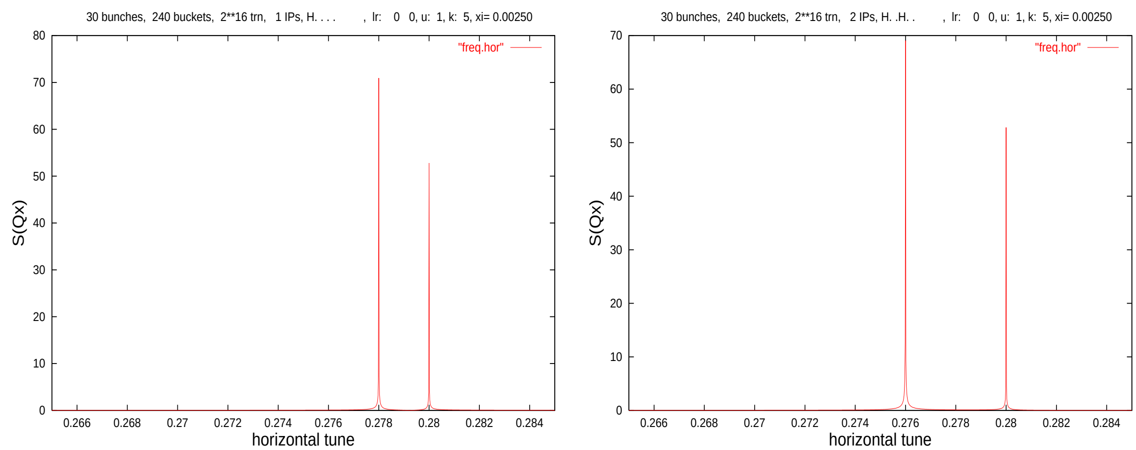

Figure 6: Single head-on collision in IP 1 (left). Symmetric head-on collisions in IPs 1 and 5. (right)

and two head-on collisions opposite in azimuth with symmetric optical layout (right). In this simple case the second collision just doubles the distance between the two basic modes. The effect of additional head-on collisions is shown in the horizontal spectra in Fig.7 where various configurations with different degree of symmetry are explored. It can be observed that a higher degree of symmetry (or periodicity) leeds to degeneracy of mode frequencies and fewer spectral lines. This confirms earlier findings [4, 5, 11, 12] and the importance of symmetries for coherent modes. The number of lines in the spectra can be qualitatively understood by analysing the collision pattern of the bunches. The number is closely related to the number of bunches to which the measured bunch couples directly or indirectly (i.e. via other bunches). For example this explains the number of spectral lines when collisions occur only in interaction points 1 and 2 (Fig.7, lower left). A more detailed analysis will follow in another report.

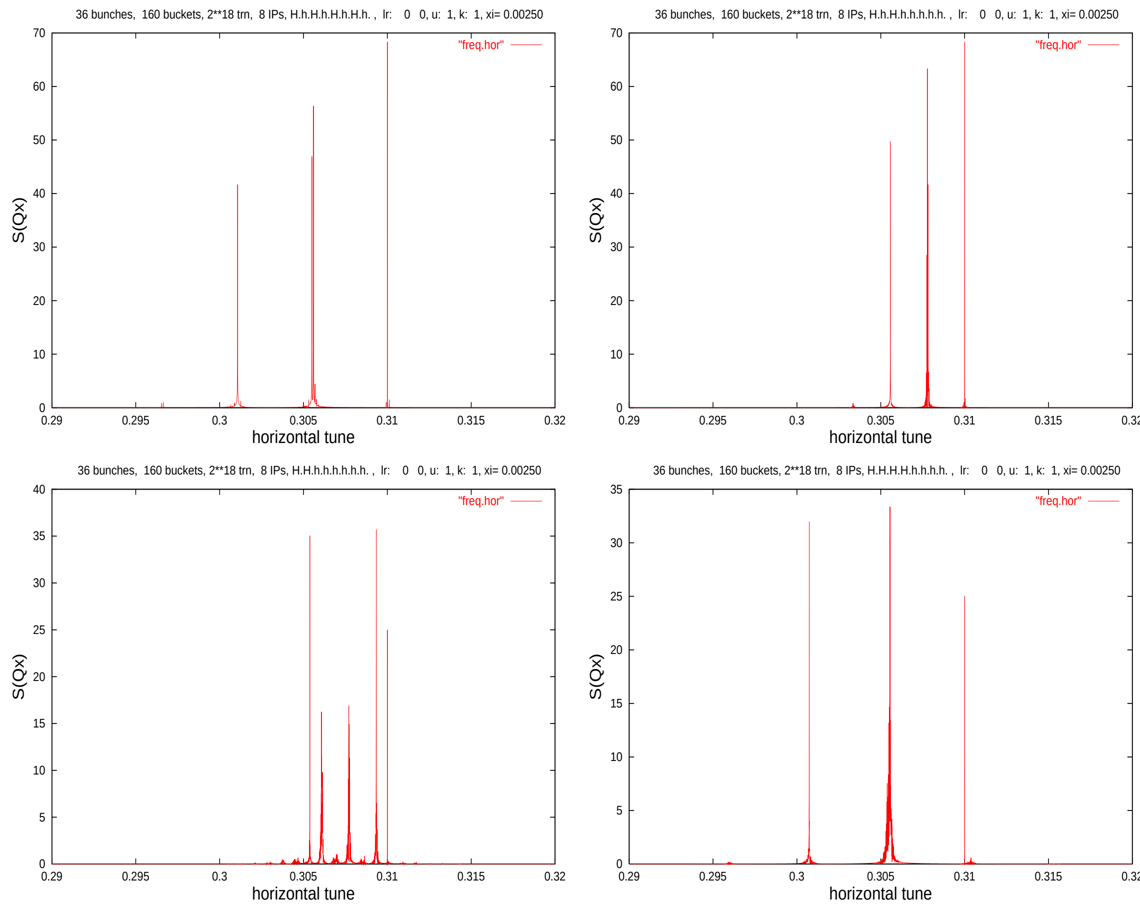

Figure 7: Multiple head-on collisions in IPs 1, 3, 5 and 7 (upper left), IPs 1 and 3 (upper right), IPs 1 and 2 (lower left), IPs 1, 2, 3 and 4 (lower right).

3.2 Collisions with the LHC interaction region layout

The collision scheme of the LHC with its four interaction regions was illustrated as an example already. Although the geometry has an eightfold symmetry, the phase advances between the interaction points break this symmetry and we must expect a richer spectrum of modes.

3.2.1 LHC interaction region layout with standard phase advance

The standard LHC collision scheme was already used as an example before. For the tracking studies, the arcs can be compressed since no action can happen except a single linear transfer. The number of bunches is reduced to 9 per train and to observe PACMAN effects, the number of long range positions is 5 on each side of the collision point. This will strongly reduce the required computing time but has no qualitative effect on the results. The nominal collision definition scheme used in the simulation is then:

```
  1   2   -5  +5
 41   3    8.046   6.940
 81  -2   -0  +0
202   3   23.015  21.821
321  -2   -5  +5
441   3   23.533  20.689
561   2   -0  +0
601   3    7.716   7.870
```

together with a filling scheme:

```
#Number of groups
2
 9 1 71 0
 9 1 71 0
 9 1 71 0
 9 1 71 0
```

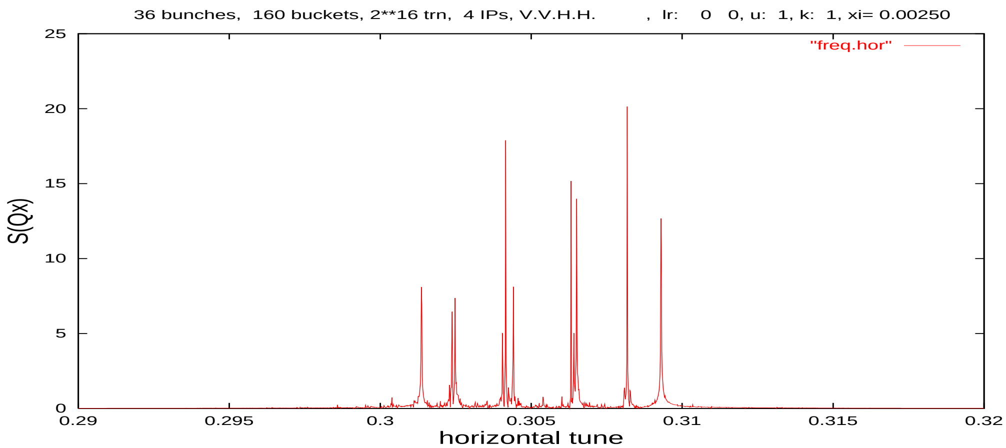

Figure 8: Head-on collisions in IPs 1, 2, 5 and 8 with nominal LHC phase advance between interaction points.

3.2.2 LHC interaction region layout with symmetry between IP1 and IP5

Starting from the scheme above, it can be partially symmetrized to fulfill:

$$\Delta Q_x^{1\rightarrow 5} \quad = \quad \Delta Q_x^{5\rightarrow 1} \quad = \quad Q_x/2 \tag{8}$$

and we use:

```
  1  -2   -0  +0
 41   3   8.046  6.940
 81  -2   -0   +0
201   3  23.109 21.720
321   2   -0  +0
441   3  23.439 20.790
561   2   -0   +0
601   3   7.716  7.870
```

The comparison between Fig.8 and 9 shows the effect of the symmetry between interaction points 1 and 5. Although the number of modes is not really changed, it must be expected that the Landau damping of modes with frequencies just below the 0-mode will "clean" the spectra around the 0-mode, i.e. the nominal tune, and therefore simplifies the tune measurements.

A further improvement is possible by adjusting the phase advance between interaction points 2 and 8 as shown below.

```
  1  -2   -0 +0
 41   3   8.046    6.940
 81  -2   -0  +0
201   3  23.109   21.720
321   2   -0 +0
```

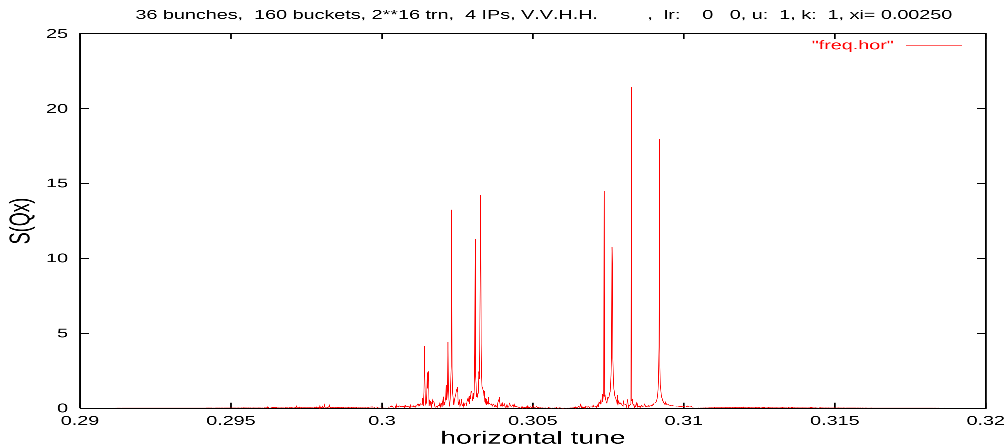

Figure 9: Head-on collisions in IPs 1, 2, 5 and 8. Phase advance symmetry restored between IP1 and IP5.

```
 441   3  23.6235   21.270
 561   2    -0  +0
 601   3   7.5315    7.390
```

The spectra for such a scheme are shown in Fig.10.

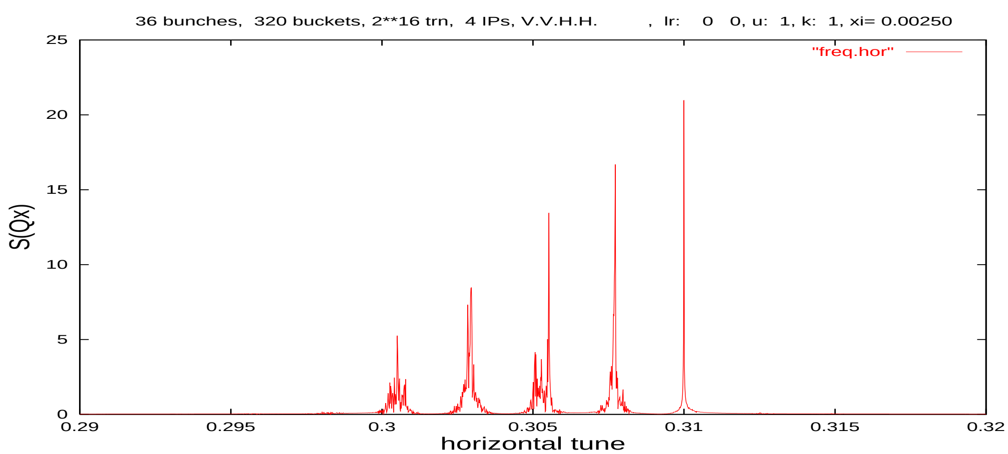

Figure 10: Head-on collisions in IPs 1, 2, 5 and 8. Phase advance symmetry restored between IP1 and IP5 and adjusted between 2 and 8.

3.2.3 LHC interaction region layout with full eightfold symmetry

The fully symmetric version with eightfold symmetry in the phase advances is:

```
   1  -2    -0  +0
  41   3   7.78875  7.165
  81  -2    -0   +0
```

```
201   3  23.36625 21.495
321   2   -0   +0
441   3  23.36625 21.495
561   2   -0    +0
601   3   7.78875  7.165
```

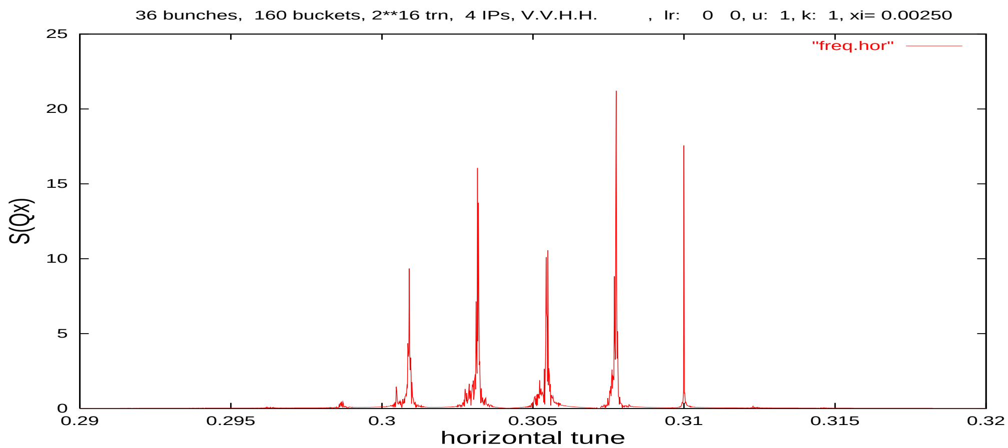

Figure 11: Head-on collisions in IPs 1, 2, 5 and 8 with full eightfold symmetry of phase advances.

The spectra for the fully symmetric machine are very similar to those obtained with the "tuned" collision scheme shown in Fig.10.

3.3 Long range interactions

Long range interactions are very important for the LHC due to their large number: in each interaction region 30 parasitic encounters must be taken into account. An important feature of long range interactions is the sign of the induced tune shift, which is different in the plane of separation and the orthogonal plane. The LHC layout relies on compensation effects between the two low β interaction points where long range interactions are most severe [8, 20]. The crossing planes in the two interaction regions are alternating, i.e. vertical in IP1 and horizontal in IP5. Since these interaction points are exactly opposite in azimuth the same pairs of bunches collide in the two points. The linear tune shift due to the long range interactions is well compensated and should result in a zero net tune shift when the configuration is exactly symmetric. Small deviation from the symmetry can come from:

- Different size of separation in the two interaction points, i.e. different strength of the long range interactions.

- Unsymmetric phase advance between the interaction points.

The consequences of such loss of symmetry and compensation can be studied and may provide limits to the adjustment of the relevant parameters.

When bunch trains experience long range interactions, it becomes important whether only the measured (analyzed) bunch is excited or a finite number of bunches receives and initial kick. In the latter case a strong coupling of the other bunches into the single bunch spectra must be expected. Unless stated otherwise, in the following results I show the spectra of the first bunch in a train, following an initial kick given to only this bunch.

3.3.1 Loss of compensation by different separation

The Figs. 12 and 13 show the spectra of long range interactions only (i.e. no head-on collisions) in the two collisions points 1 and 5 which are opposite in azimuth. First I want to test the effect of different separation and keep the separation constant in IP1 and reduce it in steps in IP5. The loss of compensation is very clearly observed when the difference

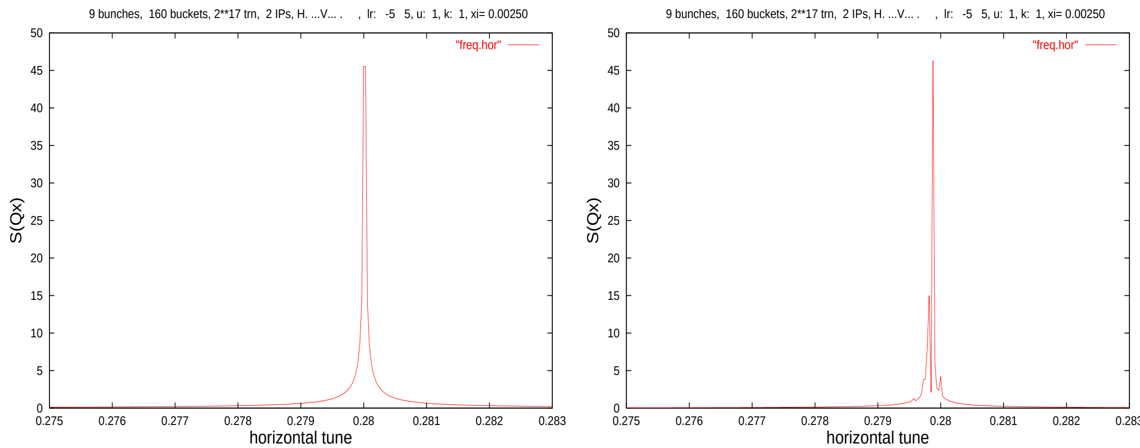

Figure 12: Long range collisions in two IPs 1 and 5. One horizontal and one vertical crossing. Horizontal separation is always 6σ, vertical separation is varied and shown for 6σ (left), and 5σ (right).

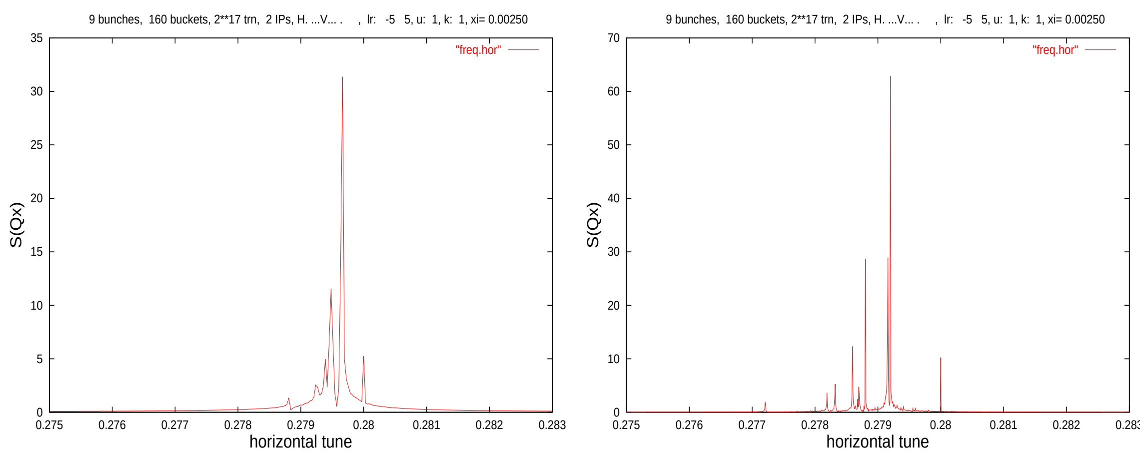

Figure 13: Long range collisions in two IPs 1 and 5. One horizontal and one vertical crossing. Horizontal separation is always 6σ, vertical separation is varied and shown for 4σ (left), and 3σ (right).

becomes large. For a separation of 5σ in IP5 a good compensation and degeneracy of the frequencies is still maintained. For the compensation of first order PACMAN effects the requirements for similar separation in IP1 and IP5 are much less stringent.

3.3.2 Loss of compensation by phase advance differences

The effect of phase advance differences can be studied using a similar strategy. Starting from symmetric phase advance:

$$\Delta Q_x^{1\to5} \;=\; \Delta Q_x^{5\to1} \;=\; Q_x/2 \tag{9}$$

Keeping the overall tune unchanged, the phases are varied in steps to:

$$\Delta Q_x^{1\to5} \;=\; Q_x/2 \;+\; \Delta Q_x \;\;\text{and}\;\; \Delta Q_x^{5\to1} \;=\; Q_x/2 \;-\; \Delta Q_x \tag{10}$$

and the spectra are computed. The results show that a phase split of $\approx \Delta \mathrm{Q}_x = 0.020$ is

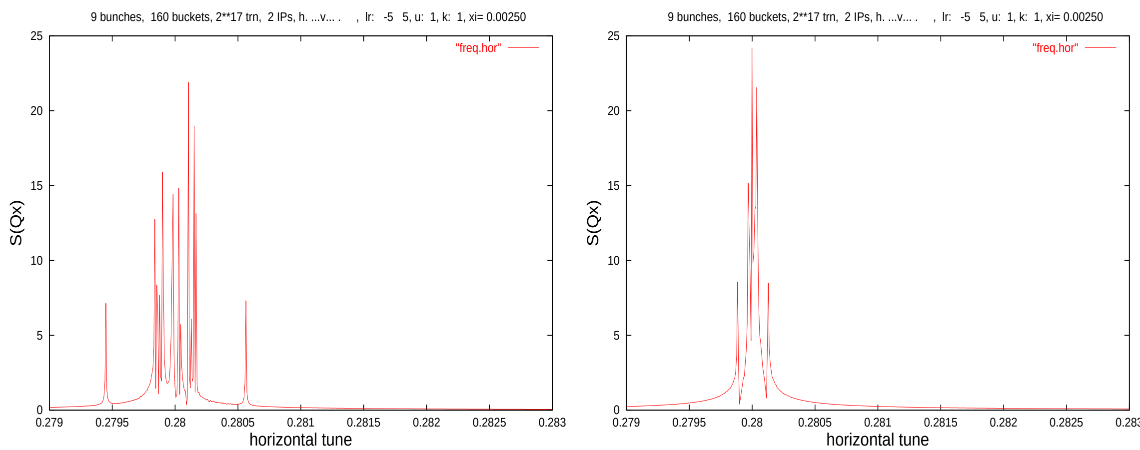

Figure 14: Long range collisions in two IPs. One horizontal and one vertical crossing. Symmetric and unsymmetric phase between the IPs. $\Delta \mathrm{Q}_x = 0.100$ (left) and $\Delta \mathrm{Q}_x = 0.020$ (right)

sufficient to break the symmetry. The difference in the LHC configuration is presently larger and it should be studied whether it can be made more symmetric. For the compensation of first order PACMAN effects [20] (e.g. tune and orbit differences) this symmetry is not required.

3.4 PACMAN effects

We have already seen the PACMAN effects due to the different number of long range interactions. These bunches play an important role for the measurement of the machine tune. The spectra are different compared to the nominal bunches. When the tune is measured, the bunches are excited by a kick. In the case the bandwidth of the exciter is not large enough it is not possible to excite individual bunches. Usually one excites bunches at the beginning or end of a train, e.g. typical PACMAN bunches. This may lead to richer frequency spectra, more difficult to interprete [21].

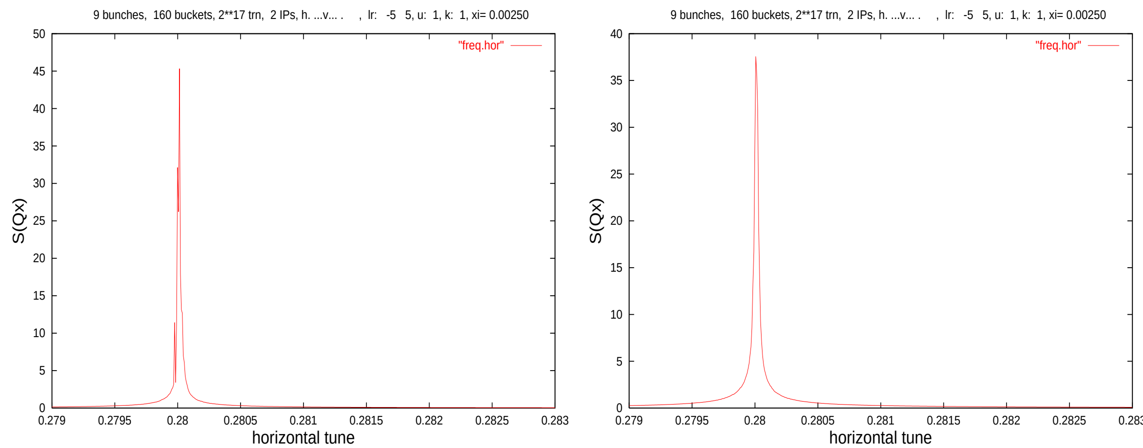

Figure 15: Long range collisions in two IPs. One horizontal and one vertical crossing. Symmetric and unsymmetric phase between the IPs. $\Delta Q_x = 0.005$ (left) and $\Delta Q_x = 0.002$ (right)

3.4.1 Long range interactions and PACMAN effects

It was already demonstrated that PACMAN bunches have different spectra, in particular in the case of crossings in equal planes. When a finite number of bunches at the beginning of a bunch train, (i.e. the PACMAN bunches !) are excited together, one must expect a different result, depending on the symmetry properties as before. In Fig. 16 I show the horizontal and vertical tune spectra of the first bunch when the first bunch of a train is excited. The nominal LHC optics is used. The upper two spectra correspond to horizontal-horizontal crossing planes in interaction regions 1 and 5 and the lower spectra are shown for the standard crossing schemes, i.e. vertical crossing in points 1 and 2 and horizontal crossing planes in regions 5 and 8. The effect of the alternating crossings is visible and provides cleaner spectra around the peaks. However, the compensation is less pronounced due to the missing symmetry. The Fig. 17 shows the equivalent spectra when the first 5 bunches of a train are excited simultaneously. For the nominal LHC optics the difference between the excitation of a single bunch or a finite number of bunches at the beginning of a train is not very significant. For the full collision scheme many bunches are already coupled together and the excitation of additional bunches has a small effect. In the next step I have made the optics fully symmetric and show the equivalent spectra (Fig. 18). As expected and already demonstrated before the spectra contain much fewer pronounced frequencies.

For a symmetric case with alternating crossings, the detrimental effects of an excitation of several bunches is strongly reduced.

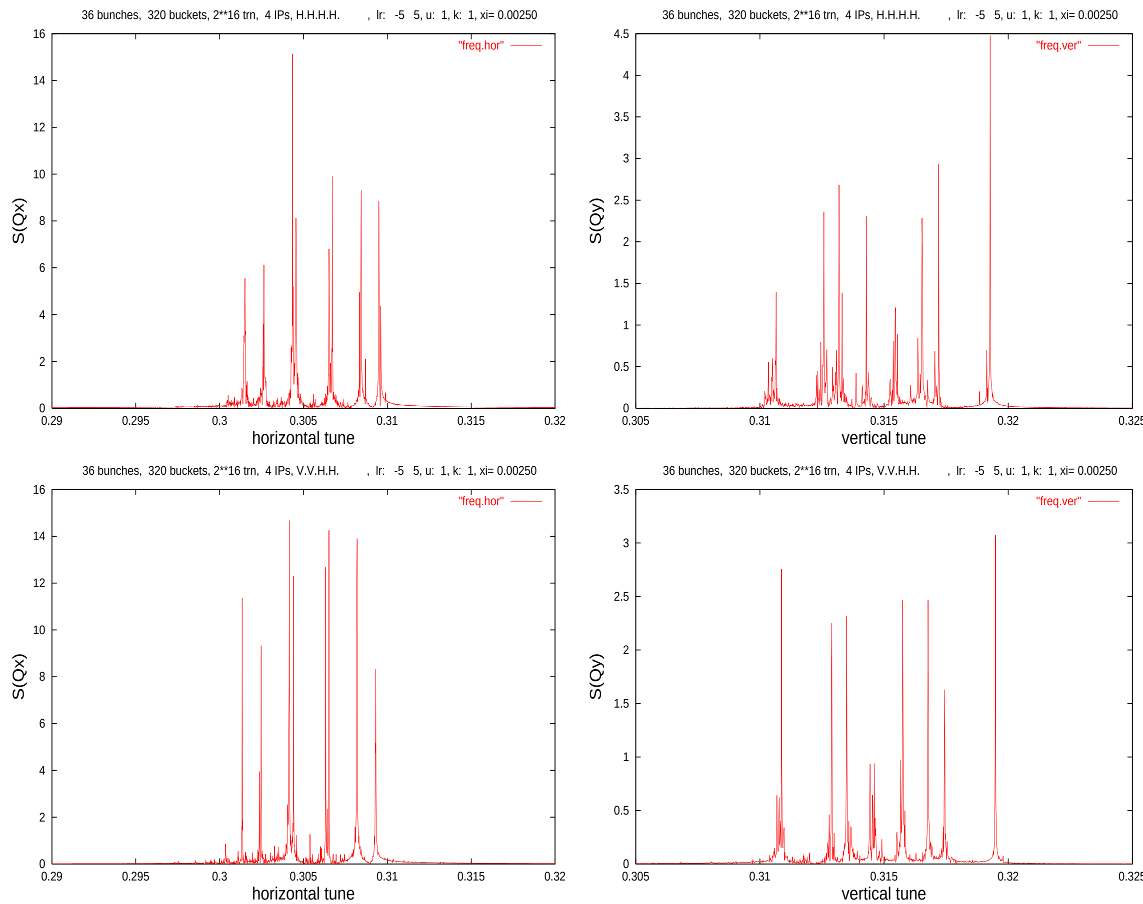

Figure 16: LHC in IPs 1, 2, 5 and 8. Excitation of 1st bunch at beginning of a train. Nominal LHC optics. Top figures for horizontal crossings only, lower figures for alternating horizontal and vertical crossings.

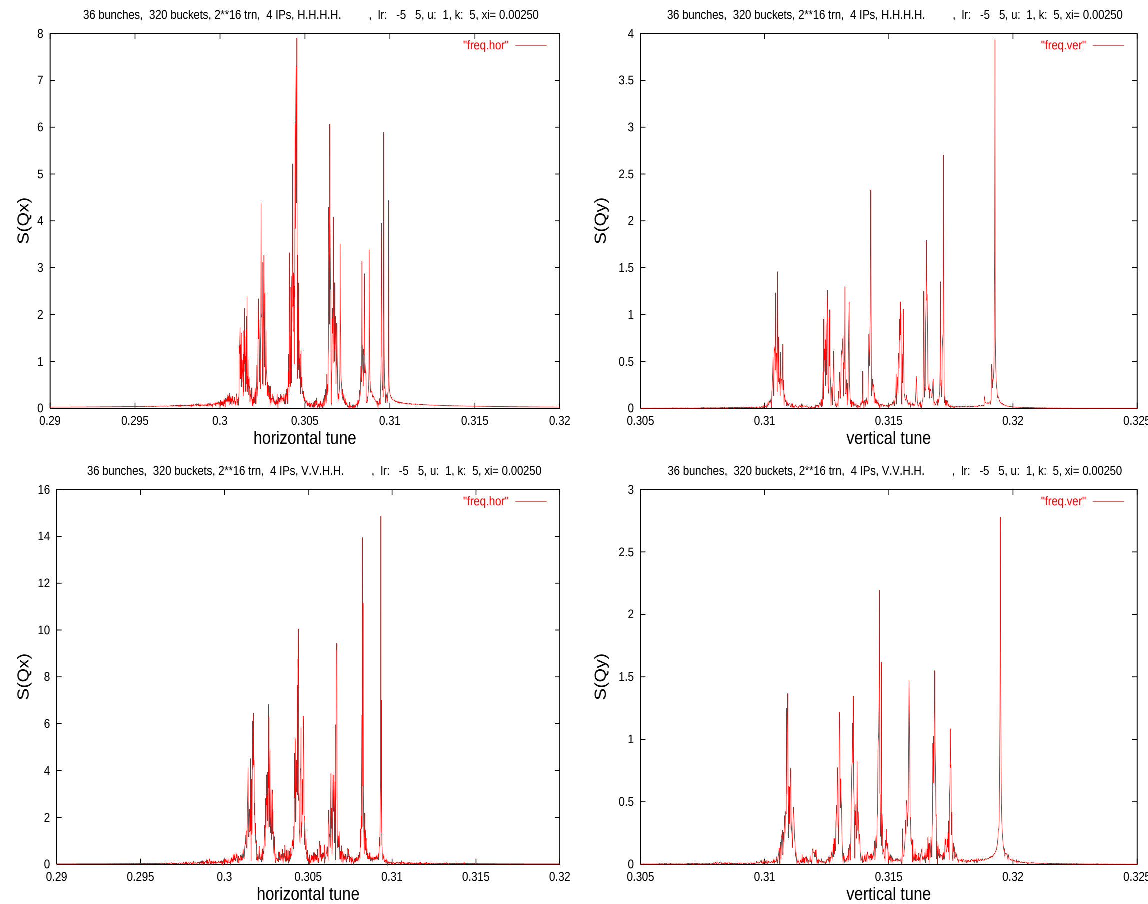

Figure 17: LHC in IPs 1, 2, 5 and 8. Excitation of 5 bunches at beginning of a train. Nominal LHC optics.Top figures for horizontal crossings only, lower figures for alternating horizontal and vertical crossings.

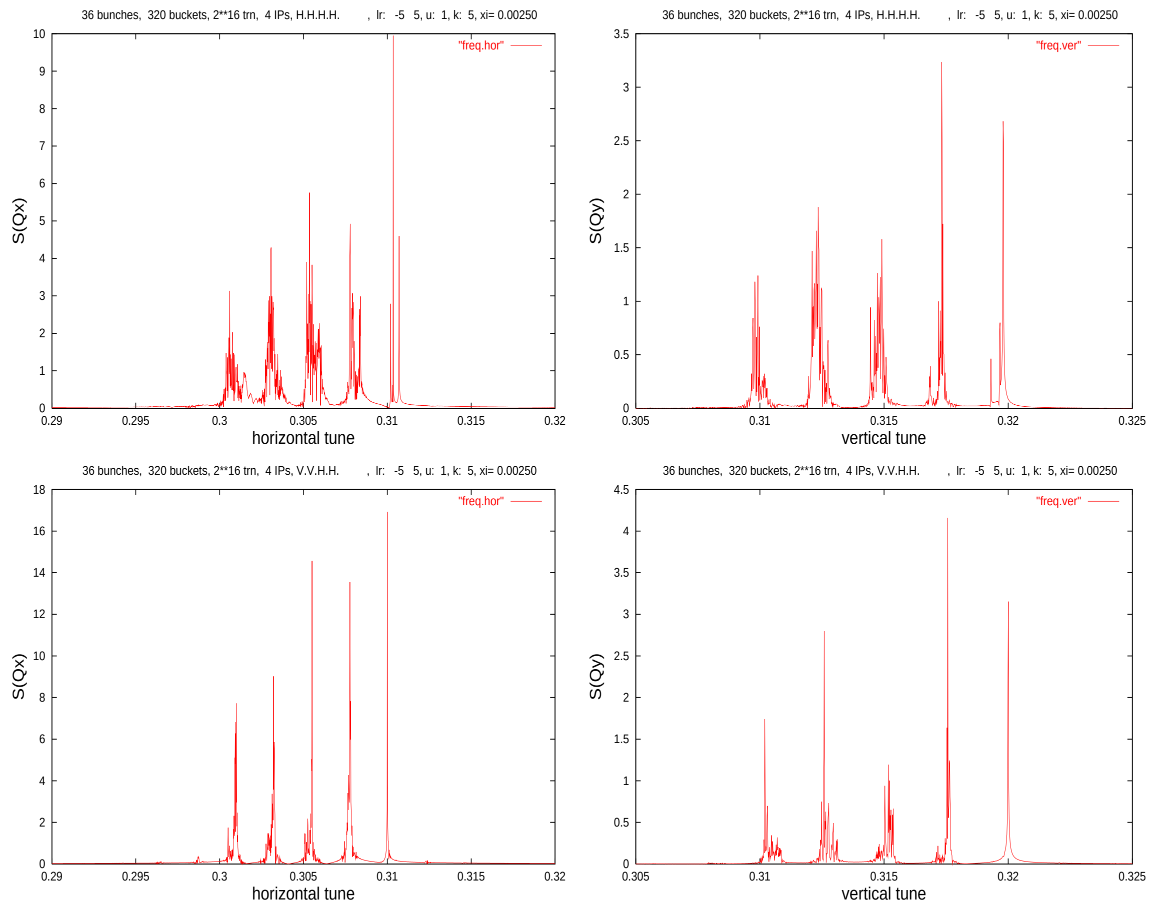

Figure 18: LHC in IPs 1, 2, 5 and 8. Excitation of 5 bunches at beginning of a train. Fully symmetric (eightfold) optics. Top figures for horizontal crossings only, lower figures for alternating horizontal and vertical crossings.

4 SUMMARY

I have used a multi bunch simulation to compute the spectra of dipole oscillations driven by head-on and long range beam-beam interactions. The spectra largely depend on these interactions and the main observations can be summarized:

- Configuration of collisions should be symmetric to reduce number of dipole modes.
- Phase advance between low β interaction regions should be symmetric to allow degeneracy and compensation of coherent modes.
- Although not required for the compensation of first order PACMAN effects ([20]) or suppression of resonances ([5]), some flexibility of the phase adjustment between interaction points is desirable.
- In the case of symmetric layout of the interaction points, low β interaction regions with alternating horizontal and vertical crossing planes provide cleaner spectra.
- Measurement should be on a single bunch following an excitation of this bunch if possible.

These should serve as recommendations when it becomes important to keep the spectra clean.
However, damping effects such as Landau damping due to the incoherent tune spread are not included in the present rigid bunch model and will be studied in the future using a multi-bunch, multi-particle simulation. It must be expected that these damping effects suppress a significant number of modes, in particular in the immediate neighbourhood of the 0-mode.

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