COHERENT BEAM-BEAM MODES IN THE CERN LARGE HADRON COLLIDER (LHC) FOR MULTIPLE BUNCHES, DIFFERENT COLLISION SCHEMES AND MACHINE SYMMETRIES

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Abstract

In the LHC almost 3000 bunches in each beam will collide near several experimental regions and experience head-on as well as long range beam-beam interactions. In addition to single bunch phenomena, coherent bunch oscillations can be excited. Due to the irregular filling pattern and the unsymmetric collision scheme, a large number of possible modes must be expected, with possible consequences for beam measurements. To study these effects, a simulation program was developed which allows to evaluate the interaction of many bunches. It is flexible enough to easily implement any possible bunch configuration and collision schedule and also to study the effect of machine imperfections such as optical asymmetries. First results will be presented and future developments are discussed.

INTRODUCTION

Coherent beam-beam effects for few bunches are well understood [1, 2, 3, 4]. In order to get high luminosity, future machines rely on a large number of bunches. The consequences are long range interactions and a large number of possible modes of oscillations because many bunches couple through long range interactions. They are further complicated due to PACMAN effects, beam parameter variations (e.g. emittance, intensity), unsymmetric collision schedules and synchrotron motion [3]. It must be expected that these effects lead to different coherent modes and in particular to a different Landau damping behaviour. Furthermore, the coherent spectra might obscure beam measurements. To evaluate the different modes and possibly their damping, it is important to simulate a large variety of options, in particular different bunch filling and collision schemes. We have written the COherent Multi Bunch Interactions program (COMBI) which can simulate easily a large number of bunches for any arbitrary collision or filling scheme. This program is a strong-strong, fully self-consistent simulation and allows for both, the simulation of rigid bunches as well as multi particle simulations. As part of the program development, an input structure was defined which allows the specification of rather complicated filling and collision patterns and possible imperfections. To keep the computing time within limits, a parallel processing is foreseen from the design stage. In this report we assume Gaussian bunches and field calculation, however the program is not limited to this approximation.

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COMBI SIMULATION PROGRAM

In this paper we will focus on the features of the soft Gaussian version and on the differences to the rigid bunch model which is described in detail in [5] and that will be used as comparison. The COMBI program allows to:

- Track individual particles of different bunches independently recalculating bunch parameters at each interaction point for a self consistent field evaluation
- Apply head-on and long range interactions at bunch encounters
- Analyze the motion of selected or range of bunches of the beams structure, e.g. emittances, barycentres

In order to evaluate different scenarios, the program allows easy changes of several parameters e.g. tunes, number of bunches, filling scheme, collision scheme and crossing planes. Statistical fluctuations of the bunch intensity, emittance etc. can also be simulated. The filling structure also permits to demonstrate PACMAN and super PACMAN bunches effects which could play an important rule in complex hadron colliders as for example the LHC [6].

Parameters

To describe the motion of particles in a Gaussian bunch the following parameters are used:

- Particle horizontal and vertical position and angle
- Barycentre horizontal and vertical position and angle
- Bunch intensity (may vary from bunch to bunch)
- Bunch emittance (may vary from bunch to bunch)

The following parameters are stored for extentions:

- Longitudinal phase (or position) and energy deviation: ϕ (or s) and δ
- Tune shifts ΔQ_x and ΔQ_y with respect to a nominal bunch can be foreseen and stored

The bunch arrangement in the machine and their possible interactions with other bunches or machine elements are very flexible to allow the study of different filling or collision schemes as well as optical properties of the machine.

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Beam filling scheme

To simplify the implementation, the whole circumference is devided into an equally spaced number of possible bunch positions, i.e. slots. 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 following example describes a beam with two bunch trains of 6 bunches each, filling 20% of the ring.

```
 # Bunch filling example (60 slots, 12 filled)
6  1  24  0  6  1  24  0
```

The number of slots is 60. The slots define the step size for the tracking of particles and bunches. The LHC full bunch filling scheme can easily be described with 3564 slots [5].

Beam collision scheme

In the collision scheme we define what happens to the beam. 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 meet). For N slots defined by the filling scheme, at 2N positions an action can occur and be defined. Actions can be requested for a bunch when it is in that place where the action is defined. For beam-beam interactions two bunches, one from each beam, must be at this position. A possible collision scheme for the bunch filling shown above can be:

```
#Collision scheme example (120 positions)
  1  -2   -5  +5
 31   3   36.655  29.160  36.155  29.160
 61   2   -0  +0
 91   3   36.655  29.160  36.155  29.160
```

An action is described by a line where the first column defines its position. The second defines the desired action while extra columns are parameters required by the action. In the example above:

- A linear transfer is defined by code 3 (position 31). The 4 parameters express the phase advances in units of 2π horizontally and vertically for the 2 beams
- Head-on collisions in the horizontal or vertical plane are defined by code 2 (as in 61) or -2 (in 1) respectively, additional parameters define the number of long range interactions left and right
- User defined actions, e.g. wake fields, can be added

Linear transfer

At a position requiring a linear transfer we use a linear transfer map for both planes, e.g. for a particle horizontal position and angle (x and x') of beam 1 is like:

$$\begin{pmatrix} x \\ x' \end{pmatrix}^1_{n+1} = \begin{pmatrix} \cos\Delta\mu_{x_1} & \sin\Delta\mu_{x_1} \\ -\sin\Delta\mu_{x_1} & \cos\Delta\mu_{x_1} \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}^1_{n} \quad (1)$$

where $\Delta\mu_{x_1}$ is taken from the collision scheme and represents the horizontal phase advance of beam 1.

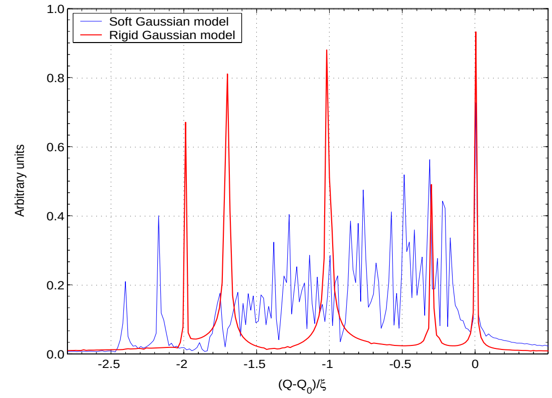

Figure 1: Tune spectra of rigid bunch (red line) and soft Gaussian bunch (blue line) coupled by two head-on collisions in IPs 1 and 2 in a eightfold symmetry.

Head-on beam-beam interaction

To calculate the head-on beam-beam kick, the counter-rotating particle distribution is assumed to be Gaussian 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 this case the beam-beam force can be expressed analytically (* denotes parameters of the opposing beam). For the soft Gaussian model the bunch barycentres and the bunch transverse sizes are calculated at each interaction while in the case of rigid bunches the transverse sizes are constant. The horizontal beam-beam kick looks like:

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

with r_p the classical proton radius, N_p^* the bunch population, γ is the relativistic Lorentz factor, β_x the horizontal betatron function at the IP, σ_x the horizontal rms size of the observed bunch and F the beam-beam force given for round beams when $\Sigma^*_{xx} \approx \Sigma^*_{yy}$ by

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

The vertical kick is equivalent. More details are in [5].

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. Assuming a constant horizontal separation d we substitute x by $x + d$ in Eq. 2 and 3. The constant part of the kick in the plane of separation is subtracted [5], since it changes only the closed orbit, it can be neglected for this study.

SIMULATION RESULTS

To demonstrate the basic features we studied multi head-on and multi long range effects and the dependencies on the collision configuration focusing on the differences between

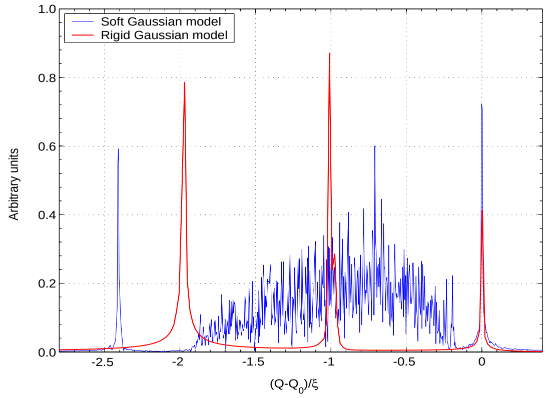

Figure 2: Tune spectra of rigid bunch(red line) and soft Gaussian bunch (blue line) coupled by two head-on collisions in IPs 1 and 3 in a fourfold symmetry.

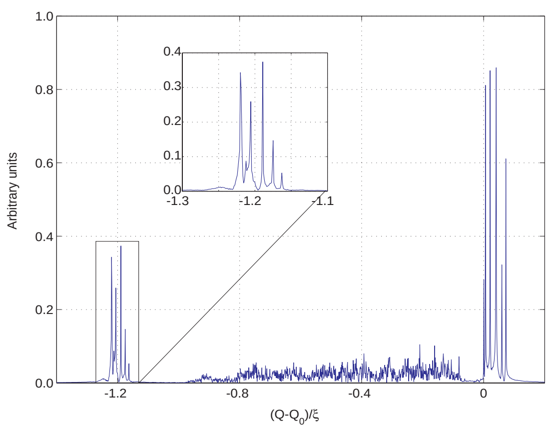

Figure 3: Tune spectrum of a train of 6 soft Gaussian bunches coupled by one head-on collision in IP 1 and one long range interaction in IP 5.

the rigid bunch model and the soft Gaussian. For the simulations we assume a collider with an eightfold symmetry of the possible collision points and number them from 1 to 8, as the LHC straight section geometrical layout.

Multiple Head-on Interactions vs Symmetry

In the case of multiple head-on collisions, the symmetry and periodicity properties of the layout are very important. Unsymmetric collisions lead to multi peak spectra while a higher order symmetry leads to the degeneracy and suppression of modes. This, already demonstrated in [5] for rigid bunches, is reproduced here in Figs. 1 and 2 (red lines) where we show the horizontal coherent spectra of 4 bunches undergoing two head-on collision in IP1 and IP2 and in IP1 and IP3, respectively. The abscissa shows the tune shift normalized to the linear beam-beam parameter ξ. The same simulations were performed with the soft Gaussian model (blue lines) in order to see the effects of damping mechanims on the coherent modes. Differences in the absolute value of the tune shifts between rigid and soft spectra are well understood and due to the Yokoya factor [2]. In Fig. 2 some modes are already suppressed due to the higher symmetry of the collision scheme. Moreover, damping effects suppress a significant number of modes in the neighbourhood of the σ-mode. Modes outside the incoherent spectrum $[0, 2\xi]$ are still present while modes inside the incoherent spectrum are completely damped.

Head-on and Long Range Coupling

Fig. 3 represents the tune spectrum of a train of 6 bunches colliding head-on in IP 1 and long range in IP 5. Without the long range coupling the spectrum presents only two coherent modes and an incoherent spectrum of $[0, \xi]$. The effects of the long range coupling of many bunches is visible in the larger number of additional modes around the original positions of the σ and π modes, detail in Fig. 3.

CONCLUSIONS AND OUTLOOK

We have written a simulation program to compute the spectra of dipole oscillations driven by head-on and long range beam-beam interactions. Both, rigid bunch and self consistent multi particle bunch model are implemented. The spectra obtained with the two models are consistent and understood within the approximations. Symmetric collision schemes lead to a reduced number of dipole modes. In addition, damping effects such as Landau damping suppress a significant number of coherent modes in the neighbourhood of the σ-mode. Multiple bunches coupled by head-on and long range interactions lead to a larger number of modes depending on the number of long range interactions and on the number of bunches interacting. In the LHC several effects break the symmetry between the collision points: asymmetric configuration of the IPs, large number of parasitic long range interactions and unvoidable PACMAN effects and offset collisions. It is important to study and understand these effects to define possible configurations which minimize the number of modes and provide cleaner spectra. In this framework a further extension is the HFMM (Hybrid Fast Multiple Method) [7] for a correct quantitative treatment of the beam-beam force, possibly in parallel mode.

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