COHERENT BEAM-BEAM EFFECTS IN THE LHC

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Abstract

In the Large Hadron Collider (LHC) two proton beams of similar intensities collide in several interaction points. It is well known that the head-on collision of two beams of equal strength can excite coherent modes whose frequencies are separated from the incoherent spectrum of oscillations of individual particles. This can lead to the loss of Landau damping and possibly to unstable motion. The beam-beam effect in the LHC is further complicated by a large number of bunches (2808 per beam), a finite crossing angle and gaps in the bunch train. The coherent beam-beam effects under various conditions and operational scenarios are studied analytically and with multiparticle simulations. We give an overview of the studies and present proposals to overcome these difficulties together with possible side effects.

1 INTRODUCTION

Two colliding beams exert a force on each other which is defocusing for beams of equal charge as in the case of LHC. Solutions of the linearized Vlasov equation show that for round beams and in the case of one bunch per beam with equal parameters (intensity, beam size, betatron tune) two coherent dipole modes of oscillations appear: the σ mode, with a frequency equal to the unperturbed betatron tune, and the π-mode with a tune shift of $Y = 1.21$, where Y is the Yokoya factor [1], times the beam-beam parameter ξ. In the LHC the situation is complicated by some specific features which affect coherent beam-beam effects:

- The LHC is operated in the strong-strong regime, i.e. equally strong beams.
- It has four interaction regions and two independent rings.
- It has parasitic (long range) interactions and many (2808) bunches.
- The beams cross at horizontal and vertical angles at the collision points.

It has been predicted [2, 3] that the coherent π-mode may not be Landau damped for certain strong-strong conditions. Therefore an accurate knowledge of the Yokoya factor and the conditions for the excitation or suppression of coherent modes is highly desirable. In this report we present a selection of the main coherent effects.

2 SIMULATION AND TOOLS

In a self-consistent model of the coherent interaction, the distributions of both beams evolve as a consequence of the mutual interaction and are used at the interaction points to calculate the force on the individual particles. To evaluate the coherent effects we employ two basic types of approaches: we study the solutions of the Vlasov equation using analytic and numerical models such as perturbation theory or its numerical integration [3, 4]. We further study the effects using multiparticle tracking. A number of studies have been done for LHC using the so-called "soft Gaussian model" [5]. This model assumes the force experienced by a particle when traversing the counter- rotating beam as originating from a Gaussian beam distribution with variable barycenters and rms beam sizes. This allows the use of an analytical expression for the forces. This Gaussian model cannot take into account the non-Gaussian deformations of the distribution and as a result underestimates the force and yields a Yokoya factor that is slightly smaller ($Y = 1.1$ in our case). We therefore use a different approch for the field evaluation to get quantiatively correct results. A Hybrid Fast Multipole Method is applied [10] and the results agree extremely well with the analytical prediction.

3 COHERENT BEAM-BEAM MODES

As a first results we show in Fig.1 the Fourier spectrum of two bunches colliding head on in one interaction point (IP). We show the spectral density of the barycentric motion of 10^4 particles as a function of the distance to the unperturbed tune Q, normalized by the beam-beam parameter ξ: $\omega = \nu - Q/\xi$. The two modes (0-mode, right peak; π-mode, left peak) are clearly visible with the incoherent spectrum between, extending between 0 and $-\xi$. The 0-mode is at the unperturbed tune ($\omega = 0$) and the π-mode is outside the incoherent spectrum ($\omega = -1.21 \pm 0.002$) and therefore cannot be Landau damped. This result accurately confirms the analytic calculation.

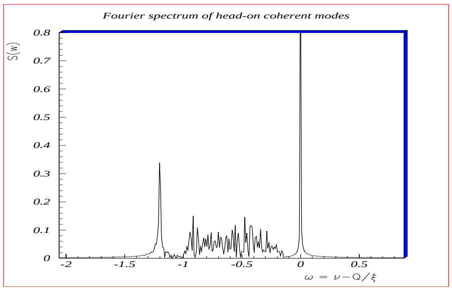

Figure 1: Head on beam-beam coherent modes.

4 EFFECT OF BROKEN SYMMETRIES

An isolated, discrete π-mode is a potentially dangerous situation and various proposals were made to suppress this mode [7, 8]. All proposals rely on the breaking of some symmetry between the beams. This makes it more difficult to organize and maintain a collective motion and the mode cannot develope. Such proposals in pure or modified form are:

- Different fractional tunes of the two beams.
- Different integer tunes of the two beams for multiple interaction points.
- Phase advance adjustments of different type for multiple interaction points.

Although all proposals can succeed to suppress the coherent modes, they may have unwanted side effects which may lead to operational difficulties or loss of luminosity.

4.1 Intensity differences

The coherent modes only exist in the real strong-strong regime where the two beams have equal intensities and beam sizes. For beams of unequal intensities the π-mode moves closer and closer to the incoherent continuum and merges into it [2] when the ratio becomes less than 0.6. As a result the mode can be Landau damped and disappears. This is illustrated in Fig.2 where we plot the coherent modes again, but for intensity ratios of 0.65 (top) and 0.55 (bottom). While for a ratio of 0.65 the mode is at the edge of the incoherent spectrum, it has merged for 0.55. The analytical prediction is completely confirmed.

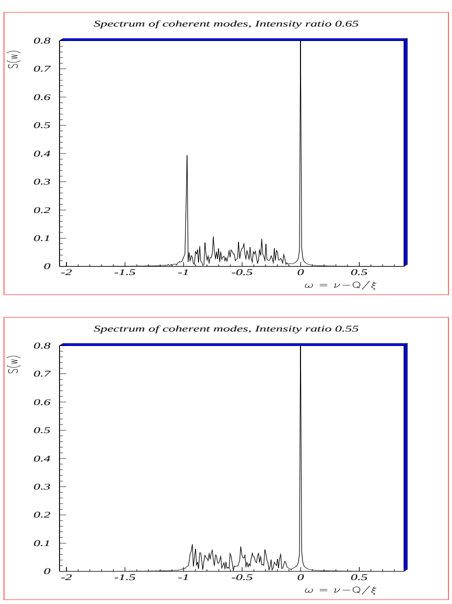

Figure 2: Head on beam-beam coherent modes for two different beam intensity ratios.

5 OPTICS MODIFICATIONS

Breaking the symmetry between the bunches is an efficient method to avoid coherent motion of bunches. Changes to the beam optics such as different tunes of the two beams, phase advance differences between the interaction point etc., help to suppress the coherence. Some of these possible measures we investigate in some more detail.

5.1 Tune differences

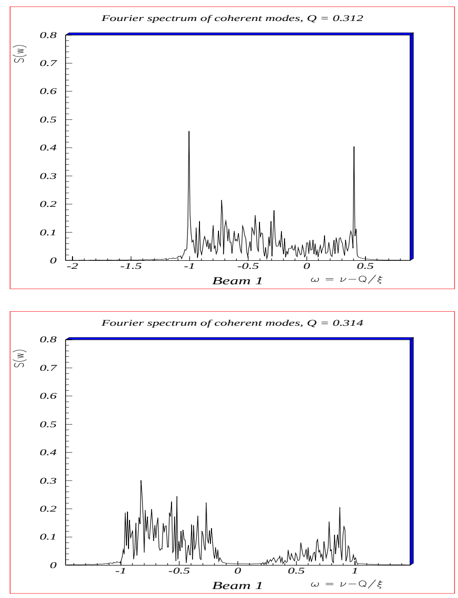

Figure 3: Coherent modes with different fractional tunes.

In Fig.3 we show the effect of different fractional tunes. While the horizontal tune of beam 1 was kept at 0.31, we have changed the tune of beam 2 to 0.312 (upper figure) and 0.314 (lower figure). The strong coherent modes disappear for a tune difference above 0.75ξ, proving the principle in this simply case.

5.2 Separate working points

The LHC has two separate beams colliding in the interaction points, and therefore it is possible to run the two beams with different working points. Three working points (WP) have been proposed, based on studies of the incoherent single particle dynamics::

WP 1 $(Q_{x,1}, Q_{y,1}) = (0.232, 0.242)$

WP 2 $(Q_{x,2}, Q_{y,2}) = (0.310, 0.320)$

WP 3 $(Q_{x,3}, Q_{y,3}) = (0.385, 0.395)$

However the study [8] has shown that this strategy excites a new type of resonances where the two beams couple to resonances of the type: $nQ_{x,i} + mQ_{x,j} = r$, e.g.: $1Q_{x,1} + 2Q_{x,3} = 1.002$ or $2Q_{x,2} + 1Q_{x,3} = 1.005$. It can be shown that the coherent mode is moved back into the incoherent spectrum and is Landau damped, but at the expense of a small emittance growth. Details can be found in [8]. This is demonstrated in Fig.4 where we plot the dipole

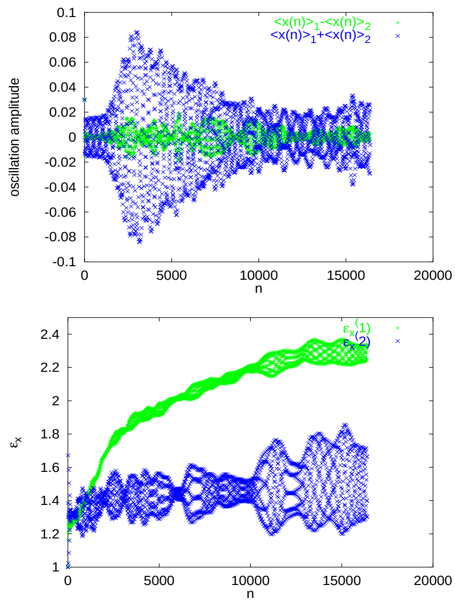

Figure 4: Dipole oscillations and emittance growth for working points 1 and 3.

oscillations and the emittances of the beams as a function of the number of turns. The working points 1 and 3 are used in this example. The dipole oscillation does not grow in time, but the emittance is steadily increased. In Fig.5 we show

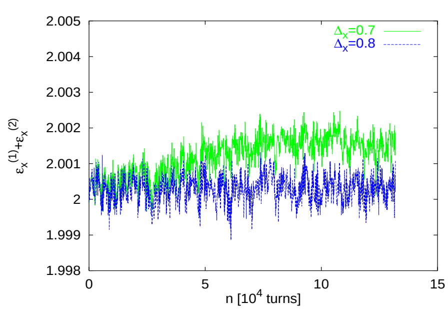

Figure 5: Emittance growth for working points 2 and 3. The emittance growth until the beams size is larger and the beam-beam effect lower and outside the resonance stopband. Δ_x is the distance to the resonance stopband as defined in [8].

another example with the combination of working points 2 and 3. We show the emittance as a function of the turn number for two distances to the resonance stopband. In the first case where the distance if large enough ($\Delta_x = 0.8$), no oscillation or emittance growths is seen. In the second case ($\Delta_x = 0.7$) no oscillation is observed but the emittance of one beam grows until the beam-beam parameters becomes lower and the beam is outside the stopband of the resonance and the growth stops.

5.3 *Multiple interaction regions*

In case of multiple interaction points additional measures can be employed to break the symmetry. Such possibilities are phase advance differences and integer tune changes. Details of the many possible options are given in [11]. We

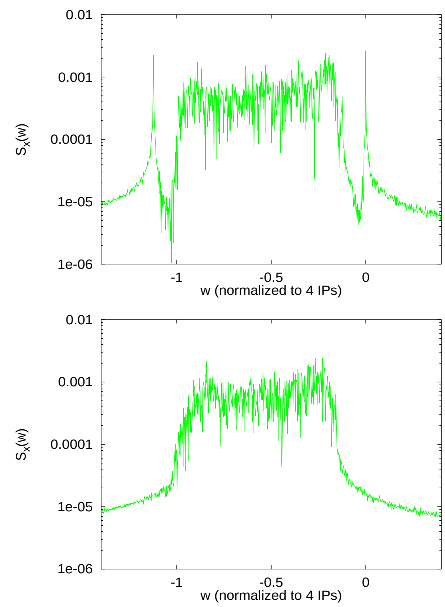

Figure 6: Coherent modes for 4 collisions and with different integer tunes. Horizontal axis as before but normalized to 4ξ.

give one instructive example in Fig.6. In the upper figure we have used the standard tunes ($Q_x = 64.31, Q_y = 59.32$) and collide 2 bunches per beam in 4 interaction points. The modes are again very prominent. The horizontal axis is $\omega = \nu - Q/4\xi$ and therefore the π-mode appears at ω = -1.21. The symmetry hides some of the additional modes. In the lower figure the integer tunes are swapped between the two planes ($Q_x = 59.31, Q_y = 64.32$) and the modes have disappeared. For the used collision symmetry it is enough to have unequal parity (odd and even) for the two beams to obtain practically complete suppression.

5.4 *Small tune split*

Finally, we present the effect of a small tune split of 0.02 between the two beams. This time both beams have the same working point to avoid the above problems, but are separated by $\pm\, 0.01$. No more growth is observed, however a small beam size asymmetry has developed in both planes, usually called a flip-flop situation (Fig.7).

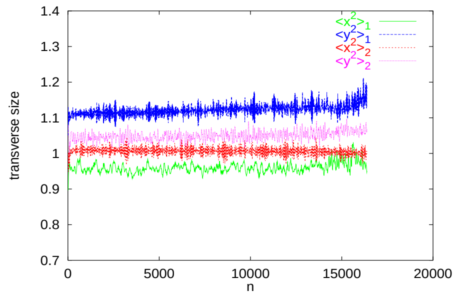

Figure 7: Coherent modes with small tune split, showing a flip-flop effect.

6 COHERENT MODES FROM LONG RANGE INTERACTIONS

A feature that is important for colliders with many bunches is the existence of parasitic (long range) interactions. In the LHC we have about 120 parasitic interactions around the 4 interaction points. Apart from many other effects, they can excite coherent modes, just like head on collisions. However, while in the head on case and for small separation, the beam-beam force is basically linear, the long range forces are rather non-linear. Their effects can be studied using Vlasov perturbation theory or multi particle tracking. Details about the two methods are found in [3, 10]. As an example we show in Figs.8 and 9 the coherent modes from multi-particle tracking for single bunches with separation of 10 σ and 6 σ in the horizontal plane. The basic modes (0-mode and π-mode) are again visible as in the head-on case and can be identified as such by analysing the sum or difference of the centroid motion of the beams. A basic difference is the sign of the π-mode tune shift. It has the opposite sign as for the head on case in the plane of separation and the same sign in the other plane. This is due to the different focussing properties of separating beams, a very well-known result. One can now speculate, and it was also believed in the past, that the tune shifts of opposite sign of the head on and long range modes can compensate, at least partially, and return the π-mode into the incoherent spectrum, which would allow Landau damping. In the Fig.10 we now plot the coherent modes for combined head on and long range interactions. The horizontal modes are plotted for horizontal (left column) and vertical crossing (central column). The right column shows the spectra for alternating crossings, i.e. one crossing with horizontal and another with vertical crossing. The contribution from long range interaction increases from top (no long range interactions) to bottom. We observe that while the head on modes remain visible, although their amplitude becomes smaller, a second coherent mode appears on the other side of the incoherent spectrum. The whole picture is shifted due to the long range tune shift. Instead of a compensation we have now two apparently independent modes on both sides of the incoherent continuum, a somewhat unexpected result. An explanation of the above is given in Fig.11 where we

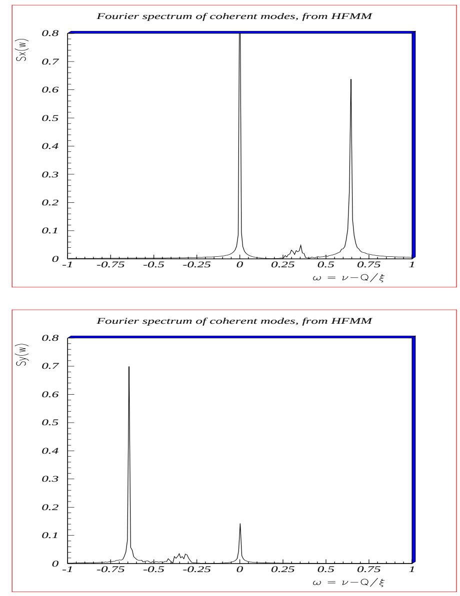

Figure 8: Coherent beam-beam modes from long range interactions with 10 σ separation in the horizontal plane.

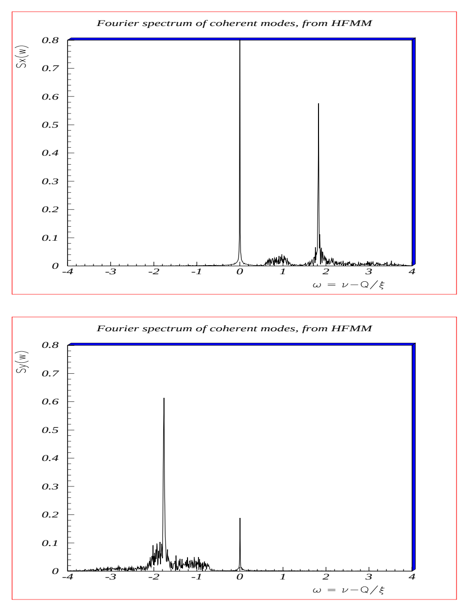

Figure 9: Coherent beam-beam modes from long range interactions with 6 σ separation in the horizontal plane.

show the eigenfunctions of the two discrete modes appearing at the bottom left of Fig.10. The corresponding eigenfunctions as a function of the amplitude are very different. While in the first mode (head on case) mainly core particles participate, the second (long range) mode involves mainly tail particles with large amplitude J_x. Therefore different parts of the bunch contribute to the two modes and this is why the two modes do not compensate. In the case of vertical separation (centre column) only the head on mode is visible and rapidly increasing its amplitude with increasing

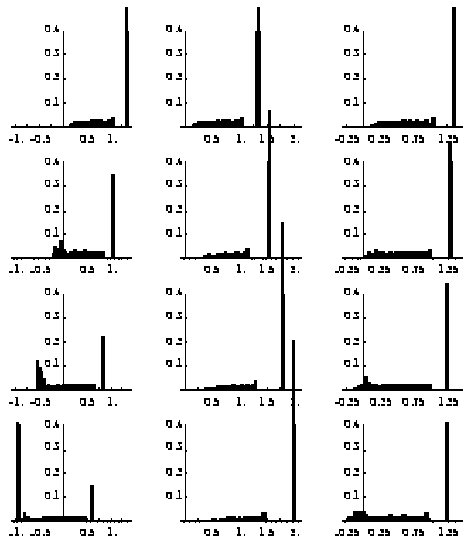

Figure 10: Head on and long range coherent modes in the horizontal plane with increasing long range contributions (top to bottom) from crossings in the horizontal plane (left), vertical plane (centre) and alternating crossing (right).

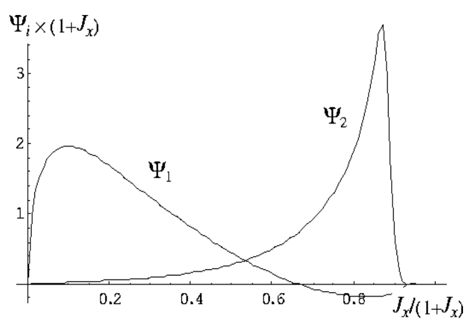

Figure 11: Coherent beam-beam eigenmodes for head on (ψ_1) and long range (ψ_2) modes.

long range contributions. Therefore if the separation is in the same plane in all interaction regions, the stability in the other plane may be strongly deteriorated. The problem is solved with alternating crossings as proposed for the LHC (right column). Here we observe a small decrease of the horizontal mode (and the same for the vertical, since now both planes are equivalent.

7 EFFECT OF CROSSING ANGLE AND SYNCHROTRON MOTION

So far we have ignored the effect of the crossing angle and the synchrotron motion. The latter can couple to the transverse motion through the crossing angle, leading to synchro-betatron resonances. This coupling affects the coherence in two ways: first the additional degree of freedom weakens the coherence and reduces the Yokoya factor. Secondly, since the synchrotron tune (Q_s = 0.00212) is comparable to the beam-beam tune shift, the discrete modes can overlap with synchritron sidebands, leading to Landau damping [3]. The finite crossing angle of ± 150 μrad also reduces the tuneshift from the head-on collision and therefore the Yokoya factor.

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