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LHC NOTE 149

COMPUTER SIMULATIONS OF THE COHERENT BEAM-BEAM EFFECT IN THE LHC

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Abstract

For the Large Hadron Collider in the LEP tunnel (LHC) a non-zero crossing angle is foreseen to avoid multiple collisions outside the interaction point. The two beams can however suffer from range beam-beam interactions during the time they are in one common vacuum chamber. These long range interactions can excite coherent beam-beam modes and due to the finite separation they are in general non-linear leading to possible coherent resonances of higher order. A computer simulation has been developed and was used to investigate this coherent beam-beam effect. Possible constraints on the LHC parameters are investigated and discussed.

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Computer simulation of the coherent beam-beam effect in the LHC

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Abstract

For the Large Hadron Collider in the LEP tunnel (LHC) a non-zero crossing angle is foreseen to avoid multiple collisions outside the interaction point. The two beams can however suffer from long range beam-beam interactions during the time they are in one common vacuum chamber. These long range interactions can excite coherent beam-beam modes and due to the finite separation they are in general non-linear leading to possible coherent resonances of higher order. A computer simulation has been developed and was used to investigate this coherent beam-beam effect. Possible constraints on the LHC parameters are investigated and discussed.

1 Introduction

The LHC is designed to reach very high luminosities above $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [1] and to achieve this a very large number of closely spaced bunches (4725) is foreseen. Normally, the two beams are separated into two beam pipes except in the interaction regions where they share a vacuum chamber. To avoid that all those bunches collide, a crossing angle of $200 \mu\text{rad}$ is foreseen. However, long range beam-beam effects cannot be avoided between the incoming and outgoing bunches and it was shown [2] that these long range forces constrain the choice of parameters for the crossing angle and the β^* functions at the interaction point. In this paper the coherent effect of long range interactions will be examined. The excitation of coherent bunch oscillations induced by the beam-beam effect is well known and studied extensively [3, 4] for the case of head-on collisions where the coherent motion is excited by a small transverse displacement of the colliding bunches. For the LHC these coherent oscillations can be excited by long range collisions since they are dipolar kicks and one can expect the excitation of coherent rigid dipole oscillations, i.e. small deviations from the nominal orbit. Their stability is investigated with a simulation program.

2 LHC parameters

Parasitic long range collisions in interaction region

The bunch spacing of 15 ns corresponds to a bunch distance of 4.5m and for the LHC geometry one calculates a total number of 19 parasitic collisions on each side of the collision point. The actual kicks received from opposing bunches are relatively small but since their effect is cumulated over many collisions, the total kick can become very significant [2]. Because a given bunch "collides" with many other bunches in every interaction region, a coupling of all bunches and a large number of coherent modes can be expected. To ensure a stable system, the motion of all these modes with different frequencies must be stable independently.

Beam separation in interaction region

The normalised emittance of the LHC beams is $\epsilon = 3.75 \mu\text{m}$ ($\epsilon = \sigma^2 \gamma / \beta$) and with a β^* value of 0.5 m this results in a beam size of about $15 \mu\text{m}$. The separation between the two orbits

$d(s)$ increases linearly with the distance from the interaction point and the normalised separation $d_{sep} = d(s)/\sigma(s)$ is constant between the interaction region and the first quadrupole and can be written as $d_{sep} = \alpha \beta^* / \sigma^*$ with α the full crossing angle and β^* and σ^* , the betatron function and beam size at the interaction point (see e.g. [2]). For the nominal LHC parameters this gives a separation of about 6.5σ for all long range collisions.

3 Simulation model

Phase space variables and particle transport

The variables used for the simulation are the transverse coordinate and angle of a bunch with respect to the design orbit (x, x'). The bunches are considered as rigid objects in this simulation since only the coherent dipole oscillation is considered. A complete simulation with more than 4000 bunches is unrealistic since the computer time required for the simulation would be too large. The maximum number of bunches in the simulation was 256 per beam. For the particle transport a linear, uncoupled machine is assumed. All the interaction regions are considered identical in the simulation, i.e. same length and same β^* . Details about the simulation can be found in [6].

Beam-beam interaction

For a given bunch the distance from its design orbit can be written as x_1 , the distance of the opposing bunch to its design orbit as x_2 and the distance of the two design orbits is $d(s)$. The distance between the two bunches is then given as $\delta x = x_2 - x_1 + d$. The beam-beam interaction between the two bunches is approximated by rigid dipole kicks of the form:

$$f(r) = \frac{8\pi\epsilon\sigma^2 x_1 x_2}{r\beta} (1 - e^{-\frac{r^2}{2\sigma^2}})$$

where: $r = \sqrt{x^2 + z^2}$, σ is the transverse beam size and ξ is the linear beam-beam tune shift.

The transverse kick $\delta x'$ is computed as $\delta x' = f(x_2 - x_1 + d(s)) - f(d(s))$. The term $f(d(s))$ has to be subtracted since it is an orbit kick caused by the beam-beam interaction and has to be compensated by other means. In this study we are only interested in oscillations of bunches around the orbit.

The separation for the nominal LHC parameters is about 6.5σ and a linearised beam-beam force as it is usually used to study coherent beam-beam effects from head-on collisions is not sufficient since it would suppress all resonances of orders higher than two and result in too optimistic limits for the stability (for details see [6]). In order to make the model realistic for a smaller number of bunches, several parasitic collisions have been accumulated into a single kick for the test bunch. The phase advance between the long range collisions on one side of the interaction region is small and such a cumulation is justified but the total effect is overestimated since the bunches normally collide with different phases.

Simulation strategy

The program has been written for two dimensions, but the stability was only studied in the horizontal plane where the

two beams cross at an angle. The initial orbit displacements of all bunches were chosen as random numbers in the range of $\pm 0.1\sigma$. The results have been shown to be not very sensitive to the initial displacement. For the results presented in the next section only the long range forces are considered.

The program follows all bunches of both beams and keeps track of the phase space variables. An unstable situation is assumed whenever a bunch exceeds a certain limit on the displacement, in most cases a limit of twice the initial deviation from the design orbit is enough and the detection of instability is relatively insensitive to the actual choice of this value. For this detection, the number of turns tracked in each case is in the order of 250 - 1000, but in some cases up to 16000 turns have been tracked to study the possible dependence of the number of turns on the onset of unstable motion. Should the motion remain stable, i.e. bound, then the linear beam-beam tune shift ξ is increased in small steps to find the maximum value where the motion remains stable. To find stability diagrams in the (Q, ξ) -plane, the initial Q -values of the machine are scanned.

4 Results

Equally spaced interaction regions

Although equally spaced interaction regions with a limited number of bunches are not a good model for the LHC, such a scheme is treated for completeness and to compare with the results obtained for clustered interaction regions and many bunches.

Spectrum and stability A simulation has been performed to investigate the stability of a scheme with four bunches and equally spaced interaction regions, in this particular example with 4 collision points, i.e. every second collision is omitted. Fig.1 shows a Fourier spectrum of a bunch where the beam-beam tune shift used was $\xi = -0.0034$, i.e. the nominal LHC tune shift, the separation was 6.5σ and 19 long range collisions were cumulated on each side in every interaction region. The horizontal tune was $Q_h = 71.28$. Three peaks in

Figure 1: Mode spectrum for four bunches and equally spaced interaction regions

the spectrum can be seen: the peak at the lowest frequency corresponds to the so-called 0-mode without a frequency shift where the bunches move together and which is always stable. The mode where the bunches move maximally out of phase is the so-called π -mode which experiences the maximum frequency shift. This mode can become unstable. Between the 0-mode and the π -mode are the multi-bunch modes and in this

very simple case of equally spaced and equal bunches these modes are degenerated into a single mode. The symmetry of the system is the reason for this degeneracy and breaking the symmetry by using two non equidistant interaction points or different phase advances between the interaction points the other modes become visible [5]. The instability is usually presented in the form of a (Q, ξ) -diagram where for every value of the tune Q the tune shift ξ is plotted where instability occurs, i.e. at values of ξ for which the π -mode (or any other mode) is shifted onto a resonance which can be driven by the force. The stability diagram in the (Q, ξ) -plane is shown in Fig.2. Two re-

Figure 2: Stability diagram for four bunches and equally spaced interaction regions

gions are visible where the bunch motion becomes unstable: the regions for tune values just below the integer and around the third order resonance. The resonances at $1/2$ and $2/3$ are suppressed by the symmetry of the system. The stability plot for a single interaction region would show these resonances. For a linearised beam-beam force the third order resonance disappears. Non-linear resonances of orders higher than three have not been seen in the simulations.

Frequency shift An important quantity is the frequency shift of the π -mode since it determines the frequency span of the coherent beam-beam modes. From simulations with simple configurations it can be shown that this shift is only dependent on the total number of long range collisions, the linear beam-beam tune shift ξ , the number of interaction points and the normalised separation. This frequency shift is independent of the total number of bunches as long as the above parameters are kept constant, i.e. for smaller number of bunches the long range kicks are accumulated into a single kick. This allows a simple extrapolation of the frequency span to the nominal LHC parameters.

Clustered interaction regions

In the SSC and the LHC the interaction points are clustered (SSC) or not equally distributed around the ring (LHC), i.e. with different phase advance. In addition, the long range collisions are clustered around the interaction regions since normally the two beams are separated elsewhere.

Frequency shift Assuming three identical interaction regions with a phase advance of $Q/2$, $Q/4$ and $Q/4$ between the collisions, a separation of 6.5σ and 19 long range collisions on both sides of the collision point, a frequency shift of the π -mode of about 11ξ is found, i.e. with the current tune values of

$Q_x=71.28$ and $Q_z=70.31$ this results in a shift to 71.317 of the horizontal π -mode. The coherent tune shift from the head-on collision at the interaction point however has a opposite sign and partially compensates the long range tune shift. The total shift is therefore $\approx 7.5 \xi$. It can therefore be extrapolated that a linear tune shift of more than 0.0075 is necessary to get unstable motion. For a linearised beam-beam force a linear beam-beam tune shift as large as $\xi=-0.02$ would be needed since only first and second order resonances would be excited.

Clustered long range interactions with many bunches To investigate the effect of many long range interactions clustered around the collision points, a larger number of bunches has been simulated (up to 256 per beam) and the long range collisions have been localised around the interaction points. Because a given bunch collides with many other bunches, all bunches couple together and a very large number of multi-bunch beam-beam modes can be observed. In Fig.3

Figure 3: Mode spectrum for clustered long range collisions

the spectrum is shown for 256 bunches and one interaction point with eight clustered long range collisions. A large number of beam-beam modes can be seen between the 0-mode and the π -mode. For the limit of a very large number of bunches the spectrum will become a continuum of modes and the entire tune region up to the π -mode is potentially unstable if a low order resonance is in this region. The stability diagram for the above conditions is shown in Fig.4. The resonances of

Figure 4: Stability diagram for clustered long range collisions

orders one, two and three are clearly visible. No resonances are

suppressed since the symmetry is broken. The widths of the individual resonances are decreasing very fast with the number of parasitic collisions: the long range collisions all occur at different phases between the bunches and a decoherence effect is observed. For larger number of collisions (≥ 6) the linear beam-beam tune shift in the input has to be adjusted with a precision of $\approx 10^{-5}$ to get unstable motion. The limit of instability in Fig.4 had to be carefully searched since with a too coarse scan of ξ the instability could be missed and only the first and second order resonance would be seen. A scan with the required granularity in ξ would not be feasible since the computer time required would be enormous. A method was therefore implemented in the simulation program to find the stability limit for the required resonance by adjusting the π -mode on to the required frequency. Higher order resonances were also studied using this method, but have not been identified, at least not with the number of turns studied (up to 16000 turns). With the nominal LHC parameters, i.e. almost 40 long range kicks per interaction region, a strong decoherence can be expected and the excitation of resonances with orders higher than two will be weak or non-existing.

Dependence on separation The separation determines not only the total frequency shift of the π -mode and therefore the frequency span of the beam-beam modes, but also the non-linearity of the beam-beam potential. For the working point of $Q_h = 71.28$ a separation of more than 5σ is necessary in order to remain stable [6]. For the nominal separation of 6.5σ the motion is stable for $\xi \leq 0.0075$.

5 Conclusion

The coherent dipole oscillations induced by long range beam-beam interactions for the LHC have been investigated and the results can be summarised as follows:

- Coherent dipole oscillations can be excited by long range collisions.
- The separation of several sigma causes the excitation of non-linear coherent resonances of low (3rd) order.
- Clustered interaction regions increase the number of beam-beam modes which can potentially become unstable. The frequency space between the 0-mode and the π -mode should be free from low order resonances.
- For the LHC parameters a linear tune shift of $\xi = 0.0075$ per interaction is necessary for unstable motion.
- However, strong decoherence from long range collisions and other damping mechanisms will make it unlikely that the coherent beam-beam effect is a limitation for the LHC with the current working point.

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Proton antiproton collisions at a finite crossing angle in the SPS

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Abstract

Future high luminosity hadron colliders such as the LHC at CERN and the SSC will have many bunches and therefore require a non-zero crossing angle to avoid multiple bunch crossings outside the interaction point. Long range beam-beam interactions as well as the possible excitation of synchrotron resonances due to this crossing angle have been studied theoretically and with computer simulations. However, very little experimental data is available on the effect of a crossing angle in hadron colliders with bunched beams. The electrostatic separators of the CERN SPS used to separate the orbits in its normal operation as a proton-antiproton collider were used to establish a horizontal crossing angle in one of the interaction regions. We have studied the effect of the crossing angle on the beam dynamics to compare with the expectations from theory and to identify possible limitations for future high luminosity colliders, in particular for the Large Hadron Collider currently under study at CERN

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1 Introduction

At the LHC a very high luminosity in the order of $10^{34} \text{cm}^{-2} \text{s}^{-1}$ is expected [1] and this requires a large number of bunches: for the design luminosity of $1.7 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1}$ more than 4000 bunches are necessary. These bunches are normally separated in two vacuum chambers but near the experimental interaction points they share a common beam pipe. It is therefore unavoidable that there will be always a certain number of bunches simultaneously in the same vacuum chamber leading to long range beam-beam interactions. These long range interactions have been studied previously [2] and it has been shown that a crossing angle of $\alpha = 200 \mu\text{rad}$ is required to reduce the tune spread due to the long range interactions in the high luminosity intersection regions. However, a finite crossing angle can excite synchro-betatron resonances since the beam-beam interaction depends on the longitudinal position of the particle in the bunch [3, 4] and therefore couples the transverse and longitudinal planes. Simulations have been performed for the LHC [5] to test the stability of particles under these conditions and it was shown that the non-zero crossing angle probably has no detrimental effect on the beam.

Figure 1: Schematic view of SPS separation scheme

During the last collider run of the SPS with protons and antiprotons in 1990 it was possible to study the effect of a crossing angle experimentally for a hadron collider. In this report we shall describe the experiment and present the results and a short discussion of the implications.

2 Experimental procedure

2.1 Crossing angle with electrostatic separators

For the operation of the SPS as a proton antiproton collider with 6×6 bunches it was necessary to separate the two beams in most of the ring to avoid parasitic collisions which would effect the beam life time. The schematic layout is shown in Fig.1. For this purpose three electrostatic separators are used to produce a horizontal pretzel orbit in $5/6$ of the ring

and only at the experiments and in the middle between the experiments the bunches collide head-on [6].

To successfully collide protons and antiprotons with a finite horizontal crossing angle in one of the interaction regions several constraints have to be met simultaneously:

- The bunches should collide **only** in the interaction region used for the experiment to avoid a large total tune shift and complicated spectra.
- The crossing angle should be variable over a large range of values, i.e. zero to several hundred μrad
- The separation at the interaction point with the crossing angle should be zero.

To simplify the problem we have used only one bunch in each beam, i.e. we have to deal with two collision points only. The above problem can be solved if three independent separator units are available. In order to get to very large crossing angle above 500 μrad we had to reduce the high voltage gap in some of the tanks to increase the field for the separation. By these means we obtained crossing angles up to 600 μrad (full crossing angle). The theoretical values of the crossing angle were verified with orbit measurements with and without the electrostatic separators.

2.2 Parameters for the experiment

The bunch length in the SPS is in the order of 3 ns (4σ). The emittances for the experiments varied by a factor of three since some of the experiments were done after a normal physics run and the beams were already diluted after 10 hours of collisions. Two dedicated experiments were done with fresh beams with smaller emittances (normalised emittance $\approx 10\pi \cdot 10^{-6}$ m rad) for both particle types. For the nominal emittances ($4\sigma\gamma^2/\beta$) and $\approx 10^{11}$ particles per bunch the linear beam-beam tune shift ξ is in the order of ≈ 0.005 , i.e. 1.5 times larger than expected for the LHC.

Another important parameter is the characteristic angle, which is the crossing angle at which the ratio between the longitudinal and transverse dimensions is such that the ends of the bunches separate when the bunch centres collide. The ratio $\alpha\sigma_s/2\sigma_{x,z}$ should be smaller than one to avoid a significant reduction of the available luminosity and strong excitation of synchro-betatron resonances. The longitudinal and transverse beam sizes are expressed as the r.m.s. values σ_s and $\sigma_{x,z}$ and α is the full crossing angle. For the nominal LHC crossing angle of 200 μrad this ratio is ≈ 0.5 . With the above parameters it was possible to test ratios between 0 and about 0.7, i.e. we could explore the entire interesting range of this parameter.

The working point of the LHC is in the neighbourhood of the 12th order resonance and in order to explore resonances of comparable strength we studied the behaviour near the 10th order resonance i.e. for tunes around 26.70 horizontally and 27.69 vertically.

The synchrotron frequency for the SPS is up to around ≈ 180 Hz corresponding to a synchrotron tune of ≈ 0.004 , i.e. about 2-3 times the values for the LHC.

2.3 Preparation

For all runs at the end of a normal physics run the unwanted bunches had to be killed and this was done with the SPS damper system [7]. However, the remaining bunches always slightly suffered and their emittances increased, making a scraping of the bunches necessary.

2.4 Measurements

With the very small values for the synchrotron tune Q_s , one could probably not expect to see individual satellite resonances, but the excitation of synchro-betatron sidebands would appear as a broadening of the non-linear resonances driven by the head-on beam-beam effect. The experimental verification therefore is to scan the horizontal tune across the resonance and measure the beam lifetime with and without the crossing angle. The background signals measured at the experiments are a good and very sensitive measure of the beam lifetime and of possible particle losses. The background rates coming from the proton and antiproton beam can be measured individually. For the experiment we have chosen the UA2 area since the background and luminosity counters of the UA2 experiment were made available in the SPS control room.

The tune was measured with the SPS Schottky system and the spectra for both planes were recorded during the entire experiment [8] and could be inspected later during the analysis. The emittances were measured using the standard wire scanner and if necessary reduced by scraping.

Synchro-betatron resonances also have an effect on the longitudinal phase space and we have used the pickups for the longitudinal feedback system to look for possible changes in the longitudinal spectrum.

3 Experimental results

To compare we have made several scans with a zero crossing angle and in Fig.2 we have plotted such a scan for a crossing angle of $500 \mu\text{rad}$ and head-on crossing, i.e. $0 \mu\text{rad}$.

Figure 2: Tune scan with $\alpha = 500 \mu\text{rad}$

This value gave a ratio $\alpha\sigma_s/2\sigma_{x,z} \approx 0.45$ i.e. close to the one expected for the LHC. Taking into account the (purely statistical) errors, no significant change in the behaviour of the background can be seen.

In Fig.3 we have plotted a similar measurement for a smaller crossing angle of $\alpha = 250 \mu\text{rad}$. The absolute values of the background cannot be easily compared because the geom-

Figure 3: Tune scan with $\alpha = 250 \mu\text{rad}$

etry of the background measurement system changes when a crossing angle is established. It is therefore only meaningful to look for the onset of particle losses when a resonance is approached. For the crossing angle of $250 \mu\text{rad}$ no significant change can be observed as for the previous diagram. The two above measurements were taken during the same run, but later experiments with the same crossing angles gave no different results and are therefore not presented here.

In the last experiment we were able to establish a crossing angle of $600 \mu\text{rad}$ with a relatively small emittance. We could therefore reach values for the ratio $\alpha\sigma_s/2\sigma_{x,z}$ of more than 0.7. The results are shown in Fig.4.

Figure 4: Tune scan with $\alpha = 600 \mu\text{rad}$

As it was shown for smaller values of the crossing angle, no significant broadening of

the resonances can be seen. The small peak at horizontal tune values around $Q_h \approx 0.692$ is the 13th order resonance $13Q_x = 347$ and is stronger in this case as compared with the previous measurements. The Fourier spectra of the horizontal and vertical motion showed no difference to the head-on case.

4 Conclusion

We shall try to conclude as follows:

- We have shown that electrostatic separators can be used to establish proton-antiproton collisions at a finite crossing angle in a hadron collider like the SPS.
- Crossing angle up to $600 \mu rad$ have been reached.
- The comparison between tune scans with and without crossing angle shows no significant difference.
- For the nominal LHC parameters (i.e. β^* function at the interaction point, crossing angle α and separation) it seems unlikely that synchro-betatron resonances significantly affect the beam stability.
- To establish the existence of synchro-betatron resonances in hadron colliders, more experiments are probably necessary.

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