TUNE SPREADS AND SHIFTS DUE TO THE LONG RANGE BEAM-BEAM EFFECT IN THE LHC

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Abstract:
The performance of existing and proposed colliding hadron beam facilities is often limited by the non-linear effects arising from beam-beam interactions, in particular for high intensity beams as proposed for the LHC. In addition to the normal head-on collisions, the beam-beam interaction in the LHC is complicated by a non-zero crossing angle in the collision points and a large number of bunches. This leads to long range beam-beam collisions near the interaction regions where the two beams are not fully separated into different vacuum chambers. The tune shifts and spreads from these long range interactions are studied with a simulation program and the results obtained are presented. Possible limitations imposed by these long range effects are discussed.

INTRODUCTION

The performance of a colliding hadron beam facility is often limited by the non-linear effects arising from the beam-beam interaction, in particular for high intensity beams as proposed for the LHC. Such limitations have been observed and intensively studied for the CERN SPS collider [1]. The beam-beam interaction introduces a tune shift which is largest for small amplitude particles while large amplitude particles experience almost no shift. This results in a tune spread in the beam. Studies have shown [2] that for the LHC a total tune spread $|\Delta Q|$ of ≤ 0.01 is desirable. Assuming a total number of three interaction regions, a maximum beam-beam tune shift of $\xi = -0.0034$ per crossing was proposed and was used to determine the LHC parameters [3,4]. In contrast to the CERN SPS the two beams travel in separate vacuum chambers and collide at a non-zero horizontal crossing angle in the interaction regions. A detailed analysis of the beam-beam effects in the LHC has to include two effects: the influence of the crossing angle between the particle beams and the presence of coherent long range interactions near the intersection points, where the beams are not yet separated into different vacuum chambers. The bunches feel an electromagnetic dipolar force when they pass each other in the vacuum chamber. This becomes important when the inter-bunch spacing is very small (< 8 m for the LHC) and a larger number of bunches are simultaneously in the same vacuum chamber near the interaction regions. A given bunch interacts with many incoming or outgoing bunches before it leaves the interaction region (Fig.1).

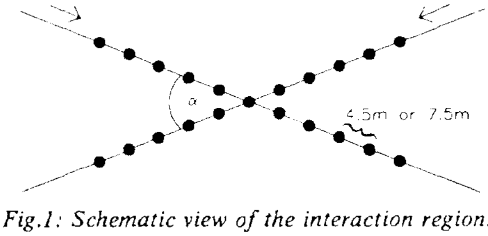


Fig.1: Schematic view of the interaction region.

The aim of this study is to investigate in detail the effect of long range interactions and to calculate the tune shifts and spreads caused by these effects. The implications and possible constraints on the LHC parameters such as the crossing angle or bunch spacing are examined.

LONG RANGE BEAM-BEAM INTERACTIONS

The short range beam-beam interaction gives a incoherent kick to the test particle at the moment when the two bunches cross each other. Apart from these kicks, the bunches experience the electromagnetic forces of other bunches travelling in the same beam pipe when they pass without actually crossing each other. These can be understood as kicks where the bunches are considered as rigid objects. Such kicks cannot be avoided when the crossing angle is very small and the number of bunches large.

Beam separation

An important parameter for this study is the normalised bunch separation d_{sep}, i.e. the distance of the two beam centres divided by the transverse r.m.s. bunch size.
Between the interaction point and the first focusing element the path can be considered as a drift space (field free region) and the betatron amplitude becomes

$$\beta(s) = \beta^* \cdot (1 + s^2/\beta^{*2}) \qquad (1)$$

where β^* is the betatron amplitude at the interaction point and it can be easily shown that the normalised separation becomes constant for large distances and can be expressed as [6, 7]:

$$d_{sep} = \alpha \cdot \beta^* / \sigma^* \qquad (2)$$

The beam size at the interaction point is σ^*. With the original design parameters of the LHC [3] the separation is calculated as 7.68 σ, very similar to the SSC value of 7.5 σ. All long range interactions give the same effect as long as the separation is the same. For studies of long range interactions beyond the field free region into the focusing triplet the actual betatron amplitude has to be used to calculate d_{sep} and the separation changes with s [5]. It is found that the separation varies between 7.7 σ and 10.2 σ. For the LHC high luminosity version and the high luminosity interaction region the separation in the field free region would be only $\approx 2.2\ \sigma$ with a maximum separation of 3.4 σ in the focusing triplet if the same crossing angle of $\alpha = 96\ \mu$rad is retained. This is caused by the smaller value of β^* (0.25m instead 1.0m) (2). One should expect severe problems, especially for particles where the transverse oscillation amplitude is close to the horizontal beam separation.

Number of long range interactions

The number of long range collisions, N_{lr}, can easily be derived from the path lengths inside the same vacuum chamber, L, and the bunch spacing as

$$N_{lr} = 4L/B \qquad (3)$$

where B is the bunch spacing in metres (e.g. 7.5 m for the original LHC or 4.5 m for LHC high luminosity version). The numbers obtained are 27 long range collisions for the original LHC design and around 40 for the high luminosity version. The distance between the interaction point and the beam separator magnet is taken for L.

Long range kicks

The long range kicks can be written as

$$\Delta x' = -8\pi\xi\sigma^2 \cdot \beta_x \cdot (1 - \exp(-r'^2/2\sigma^2)) \cdot (x + d_{sep})/r'^2$$
$$\Delta z' = -8\pi\xi\sigma^2 \cdot \beta_z \cdot (1 - \exp(-r'^2/2\sigma^2)) \cdot z/r'^2 \qquad (4a,b)$$

(with: $r' = ((x + d_{sep})^2 + z^2)^{1/2}$)

respectively. In the limit of very small separation, $d_{sep} \rightarrow 0$, the kicks will be the same as for a head-on collision.

SIMULATION MODEL

A linear, uncoupled machine is simulated and the beam-beam interactions are represented by kicks. The variables used for the simulation are the horizontal and vertical displacements (x and z) and angles (x′ and z′). Between the interaction regions the transverse phase space coordinates are transformed linearly and without coupling. No higher multipole fields or non-linearities other than the beam-beam effect is taken into account.

Beam-beam kicks

When the particles enter the interaction region the first long range kicks are calculated according to (4a,b) and x′ and z′ are updated. In the drift space part of the collision region the long range kicks can be represented as the accumulated kick of several parasitic bunch passings since the beam separation remains constant (4). Before and after this drift space the long range kicks have to be computed individually with the appropriate beam separation calculated from the betatron amplitudes given in [5]. After a linear transfer of 180° the next long range kicks are applied and the particle is tracked to the next interaction region. The effect of the beam-beam kicks on the orbit is neglected in the simulation. The position of the particle is recorded after each turn and a fast Fourier transform is applied to determine the tune.

Parameters

The parameters used for the simulation of the original LHC design are taken from the report [3] and for the high luminosity version from [4].

SIMULATION RESULTS – SINGLE INTERACTION

In this chapter the effect of the long range beam-beam interactions will be investigated for a single interaction region.

Long range interaction

The long range tune diagram for the original LHC parameters is shown in Fig.2 for the parameters given in [3].

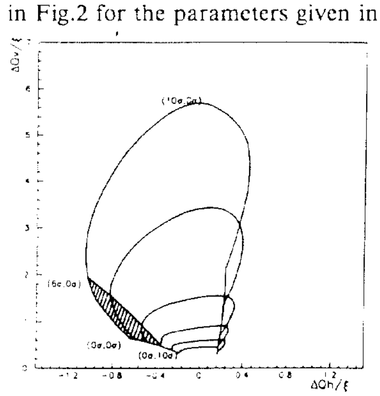


Fig.2: Long range beam-beam tune diagram for original LHC.

The betatron amplitudes run from 0 to 10 σ for both planes in order to illustrate the shape of the tune diagram. The interesting range is for amplitudes from 0 to 6 σ and is indicated as the hatched area in Fig.2. The maximum tune shifts are experienced by particles around 8 to 10 σ where the amplitudes are close to the horizontal separation and they fold over for larger amplitudes. Due to the scaling in d_{sep} all tune diagrams for long range interactions look the same for the same separation. The short range interaction, head-on or with a crossing angle, produces a maximum tune spread of ξ, where the shift is largest for particles at small amplitudes (see e.g. [1]). For large amplitude particles the long range force is stronger than the short range force and it has a focusing effect in the vertical plane and a defocusing effect in the crossing plane. For particles with amplitudes of less than 6 σ the spreads induced by the short and long range forces are comparable, i.e. < 1·ξ. This situation is expected to change drastically with the parameters for the high luminosity option of the LHC. The corresponding tune diagram for long range collisions is shown in Fig.3. with a bunch spacing of 15 ns [4].

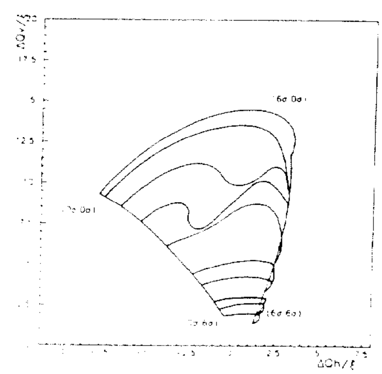


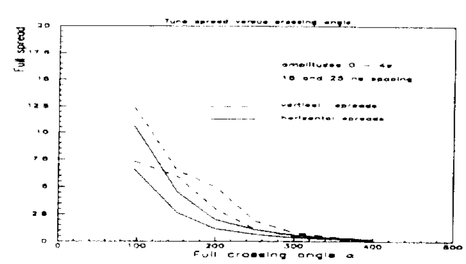
Fig.3: Long range beam-beam tune diagram for high luminosity

The transverse amplitudes used for this diagram range from 0 to 6 σ. The folding over already occurs for much smaller amplitude particles but with larger absolute values for the tune spread. The tune spread for these parameters is obviously dominated by the long range beam-beam interactions and is much larger than the desired value of $|\Delta Q| \approx 0.01$.

Variation of the crossing angle

From (4) it can be seen that the separation can be increased by increasing the crossing angle α or the betatron function β^* at the interaction point. The overall horizontal and vertical long range tune spreads for particles in the amplitude ranges from 0 to 4 σ in both planes are plotted in Fig.4 as a function of the crossing angle. Two different values for the bunch spacing were assumed, i.e. 15 ns and 25 ns.

Figure 4: Tune spreads as function of crossing angle



The functional dependence is approximately $\approx \alpha^{-2}$ (or $\approx d_{sep}^{-2}$, which is equivalent) as the angle is increased. Such a dependence is theoretically expected [6]. To achieve a tune spread comparable to the tune spread of the old LHC design an angle of about $\alpha \approx 300$ μrad should be chosen for 15 ns bunch spacing and ≈ 250 μrad for 25 ns. Because of the scaling behaviour, Fig.3 would reduce approximately to Fig.2 with this crossing angle.

Alternating crossing angles

The global tune spread can be reduced by alternating horizontal and vertical bunch crossings because the beam-beam effect is focusing in the crossing plane and defocusing in the other plane. A scheme with alternating crossing angles has been studied and for the parameters of the high luminosity LHC a reduction of the tune spread of a factor ≈ 2 (horizontal) and ≈ 2.5 (vertical) has been found. Since the focusing and defocusing effects are of a different magnitude, the compensation cannot be complete.

SIMULATION RESULTS – THREE INTERACTIONS

Standard LHC layout with three interaction regions

Three experimental areas are foreseen in the layout of the LHC. One very low β insertion (0.25 m) and two medium low β insertions (0.5 m). To study the accumulated effect of all long range interactions, this scheme was simulated and the total long range tune shift for particles in the amplitude range of $0 - 4\ \sigma$ was found to be $\Delta Q_v = 36 \cdot \xi$ and $\Delta Q_h = 15 \cdot \xi$ if all crossings are horizontal with a crossing angle of $\alpha = 96$ μrad. Such a tune spread cannot be accepted. The total tune spread can be reduced by having one horizontal crossing and two vertical crossings. The resulting tune spread was $\Delta Q_v = 10 \cdot \xi$ and $\Delta Q_h = 13 \cdot \xi$, which is an appreciable reduction but still too large. To reduce the tune spread from the long range interactions to a value comparable with the head-on spread, it was decided to study the schemes with increased crossing angles. The values chosen were $\alpha = 280$ μrad for the low β crossing and $\alpha = 210$ μrad (180 μrad) for the two crossings with $\beta = 0.5$m. The results are summarised in Table 1.

Crossing scheme:	ΔQ_h [$\cdot\xi$]:	ΔQ_v [$\cdot\xi$]:
All hor., all 96 μrad	15$\cdot\xi$	36$\cdot\xi$
Alternating, all 96 μrad	10$\cdot\xi$	13$\cdot\xi$
All hor., 280 and 210 μrad	2.2$\cdot\xi$	4.0$\cdot\xi$
Alternating, 280 and 210 μrad	4.9$\cdot\xi$	2.9$\cdot\xi$
All horizontal, 280 and 180 μrad	3.6$\cdot\xi$	8.8$\cdot\xi$
Alternating, 280 and 180 μrad	9.8$\cdot\xi$	3.2$\cdot\xi$

Table 1: Tune spreads for different crossing schemes. (three interaction regions, 15 ns bunch spacing)

One could conclude from these results that minimum crossing angles of $\alpha = 280$ μrad and $\alpha = 210$ μrad are required for the three interaction regions. They correspond to values of $\approx 6.5\ \sigma$ for the beam separation. A large crossing angle, however, leads to a loss of luminosity and the possible excitation of synchro-betatron resonances [8]. This will be the subject of a separate study [9].

Increased bunch spacing

Another way to reduce the long range effects would be to consider a increased bunch spacing and/or a larger β^* at the interaction regions. The results are shown in Table 2.

Crossing scheme:	ΔQ_h [$\cdot\xi$]:	ΔQ_v [$\cdot\xi$]:
Three crossings, β^* = 0.25 m and 0.50 m:		
All horiz.,all 96 μrad	8.0$\cdot\xi$	18.0$\cdot\xi$
All horiz.,all 180 μrad	1.6$\cdot\xi$	4.8$\cdot\xi$
All horiz.,200 and 180 μrad	1.5$\cdot\xi$	3.7$\cdot\xi$
All horiz.,200 and 150 μrad	2.3$\cdot\xi$	5.5$\cdot\xi$
Three crossings, all β^* = 0.50 m:		
All horiz.,all 96 μrad	7.0$\cdot\xi$	8.2$\cdot\xi$
All horiz.,all 180 μrad	1.0$\cdot\xi$	1.3$\cdot\xi$
All horiz.,all 150 μrad	1.6$\cdot\xi$	3.5$\cdot\xi$

Table 2: Tune spreads for different crossing schemes. (increased bunch spacing and increased β^*)

CONCLUSION

For the short and long range beam-beam interaction the resulting tune spreads and shifts have been studied for two LHC conditions, the original LHC as layed out in the design report [2] and the new version with increased luminosity [3].

- The amplitude dependence is different for long range interactions as compared with short range effects.
- For the original LHC design the tune spreads induced by short and long range interactions are comparable.
- Tune spreads for the high luminosity LHC interaction regions is too large to be manageable.
- An increased crossing angle increases the separation and reduces the long range effects. A crossing angle as large as $\alpha = 280$ μrad may be necessary.
- Possible alternatives to reduce the necessary crossing angle are alternating crossings, reduced bunch spacing or a larger beta function in the interaction region.

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