EMITTANCE GROWTH DUE TO BEAM-BEAM EFFECTS WITH A STATIC OFFSET IN COLLISION IN THE LHC

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Abstract

Under nominal operational conditions, the LHC bunches experience small unavoidable offset at the collision points caused by long range beam-beam interactions. Although the geometrical loss of luminosity is small, one may have to consider an increase of the beam transverse emittance, leading to a deterioration of the experimental conditions. In this work we evaluate and understand the dynamics of beam-beam interactions with static offsets at the collision point. A study of the emittance growth as a function of the offset amplitude in collisions is presented. Moreover, we address the effects coming from the beam parameters such as the initial transverse beam size, bunch intensity and tune.

INTRODUCTION

The layout of the LHC features four experimental areas where the two counter-rotating beams collide at finite crossing angles [1, 2]. Any growth of the transverse beam emittance in a proton-proton collider is highly undesirable since it reduces the luminosity and increases the background. Possible sources for a growth of the beam emittance are the presence of static as well as time dependent offsets in collision. Coherent oscillations can be excited and amplified by the beam-beam interaction. The decoherence of a finite oscillation in the non-linear fields of colliding beams can lead to emittance growth. For this reason a damping of the oscillations should be foreseen, either with an active feedback system or through the Landau damping mechanism. Under nominal operational conditions, the LHC bunches experience small, unavoidable offsets at the collision points, caused by long range beam-beam interactions [3]. Using the TRAIN [4] program it is possible to calculate self-consistently the orbit effects produced by the long range beam-beam interactions for each single bunch of the LHC beams. Due to beam-beam interactions (BBI) we shall have a global orbit effect on both beams which in operation can be corrected with a global orbit correction to maximize the luminosity. On top of a global orbit effect strong bunch to bunch differences are expected. These offsets at the IPs can become substantial due to the different collision patterns and long range interactions seen by the different bunches and are not negligible since they could reach amplitudes up to 0.3 σ. This spread between the bunch orbits cannot be corrected and therefore a full understanding of the implications is fundamental for the optimization of the accelerator performance during operation. Although the geometric loss of luminosity is very small, one may have to consider an increase of the transverse emittance, leading to a deterioration of the experimental conditions. It is therefore important to evaluate and understand the dynamics of beam-beam interactions with static offsets and if necessary to implement countermeasures. Due to the parasitic encounters, for the LHC case, one should roughly expect offsets in collision of amplitudes between 0.12 and 0.35 σ, where σ is the r.m.s. beam size equal to 16 μm for this case. However, the offset at the collision point need not to be static, but could depend on time, either as a random or systematic (modulated) movement. Typical random offsets can come from noise sources and have been studied previously [5]. A source of modulated, time dependent offset is a deliberate movement of the entire beam in the interaction regions, either as a consequence of orbit corrections or a controlled change of position, e.g. during the luminosity optimization process.

SIMULATIONS SETUP

In a self-consistent model of the beam-beam interaction, the distributions of both beams evolve as a consequence of the mutual interaction. Such self-consistent simulations have been used extensively to study coherent beam-beam effects [6]. A further application of a self-consistent treatment of the BBIs is the evaluation of the beam emittance evolution in time during collision. Here we study the emittance behaviour in the presence of static offsets at the interaction point (IP). For this purpose we make use of the COMBI code in soft Gaussian approximation and with HFMM field solver [9, 7] and the BeamBeam3D code [8]. With the three independent codes we collide only head-on two counter rotating bunches at one or two IPs where an offset is applied. Figure 1 shows the evolution of the normalized vertical emittance as a function of the number of turns for different offsets at the IP.

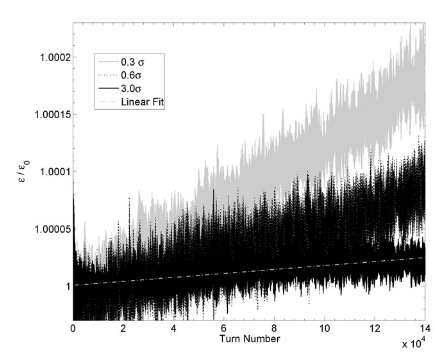

Figure 1: Normalized emittance for different static offsets.

EMITTANCE GROWTH AS A FUNCTION OF OFFSET AMPLITUDE

The vertical and horizontal emittance growth rates are calculated by assuming a linear increase of the emittance in time over 150-500 kturns sample depending on the model used. Transient effects were eliminated where necessary as explained in detail in [9]. In Figures 2, 3 and 4 we show the vertical and horizontal normalized emittance growth rate per second as a function of the offset amplitude. The three plots are results coming from the three different models used for the beam-beam interaction. In Figures 2 and 4 only one beam-beam interaction at IP1 with an offset in the vertical plane is applied. In Figure 3 we heve two beam-beam interactions at IP1 and IP5 and a vertical offset is present only at IP1. We used LHC nominal betatron tunes of $Q_H = 64.31$ and $Q_V = 59.32$, an initial beam size of 16 μm in both planes and a bunch intensity of $N_{1,2} = 1.15 \cdot 10^{11}$. For all models samples of 10^6 or more macro-particles per bunch were used. Predicting absolute values for an emittance increase caused by beam-beam effects is always considered very difficult. However, we found a good qualitative agreement between the results from the three different models and the order of magnitude of the growth rate is consistent.

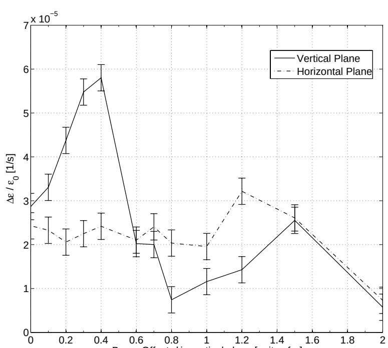

Figure 2: Vertical (solid line) and horizontal (dashed line) emittance growth rate for different beam offsets. Results are obtained with the HFMM.

The vertical growth rate is larger than the horizontal growth rate and is a strong function of the offset applied. While this is not the case for the growth rate in the horizontal plane which seems to be smaller and decreasing as the offsets get larger. The vertical growth is maximum for separations around 0.3-0.4 σ, then it decreases and again it increases significantly for offsets of approximately 1.5 σ. For offsets above 2 σ the growth rate goes to zero. All models reproduce these features very well.

UNDERLYING MECHANISM

The particular trend found for the emittance growth rate as a function of the offset d of Figure 2, 3 and 4 was unexpected. We tried to understand the observations with simple consideration of non-linear dynamics since the beam-beam force is a strongly non-linear element. We do not attempt to derive a complete model of the dynamics, but

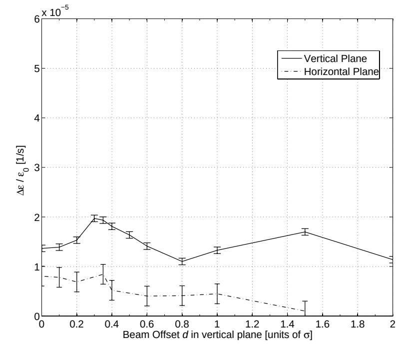

Figure 3: Vertical (solid line) and horizontal (dashed line) emittance growth rate for different offsets. Results are obtained with soft Gaussian model.

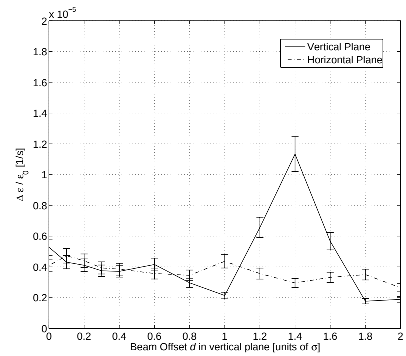

Figure 4: Vertical (solid line) and horizontal (dashed line) emittance growth rate for different beam offsets. Results are obtained with BeamBeam3D code.

rather try to qualitatively understand the observations in a physical picture. To produce an emittance growth due to an offset applied at collision one has to expect it could be a result of the non-linear terms of the beam-beam force on produced by a beam located at a distance d weighted over the opposite beam particle distribution in amplitude. Reducing the problem to the one-dimensional space x we define the particle amplitude distribution of beam 1 as a Rayleigh distribution $R(x)$ centered at $x = 0$. Beam 2 centered at a distance d behaves as a non linear term on the particle distribution of beam 1. As a measure of the strength of the non-linearities of the interaction we take the second derivative F$''(x-d)$ of the beam-beam force. The convolution of the non linear terms of the beam-beam force over the particle amplitude distribution of the opposite beam estimates the overall effect of the non-linear terms of beam 2 distant d from beam 1 on the particle amplitude distribution. The convolution operator as defined assumes the integration of the effect over the collision area. The convolution integral results in a function of the offset d as:

$$C(d) = \int_0^\infty R(x) \cdot F''(x-d)\, dx \qquad (1)$$

In Figure 5 the resulting convolution *C(d)* is plotted as a function of the offset d. In the range between 0 and 5 σ two maxima are found like for the results of the simulations.

Also the location of the two peaks are very similar to those found through multi particle simulation and correspond to offsets of 0.3 and 1.5-2.0 σ.

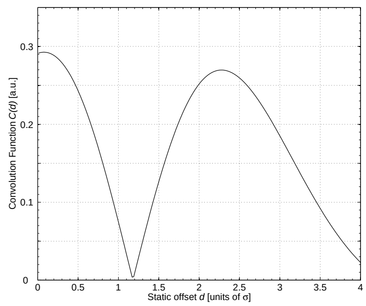

Figure 5: Convolution function *C* as a function of the offset in collision d.

Going for a small change of 10% in the amplitude distribution for beam 1 respect to beam 2 then the *R* $(x/0.9 \cdot \sigma_x^2)$ function shows a maximum density at a $x = 0.9 \cdot \sigma_x^2$ and as a consequence the maxima of *C(d)* move to smaller offsets. Therefore, smaller variations of the maxima locations of Figure 2, 3 and 4 with respect to Figure 5 could be due to the fact that for the physics consideration the amplitude and position variable had been all normalized to the beam σ assumed equal for the two beams. This for the simulation is not completely true since the particle distributions are generated through a random statistical process.

INTENSITY EFFECTS

In order to convince ourselves that the beam-beam effect is the origin of the observed behaviour, we applied the offset in the vertical crossing of IP1 and have studied how changes in the beams intensities influence the emittances increase. A scan of the intensities from $I = 10^{10}$ protons per beam up to $1.2{\cdot}10^{11}$ was performed. For this study we have used $1.5{\cdot}10^6$ macro-particles and tracked the particles for $4{\cdot}10^4$ turns using the HFMM model. As expected if the effect is coming from beam-beam interactions a correlation exists. Figure 6 shows the increase of the relative emittances as a function of the intensity.

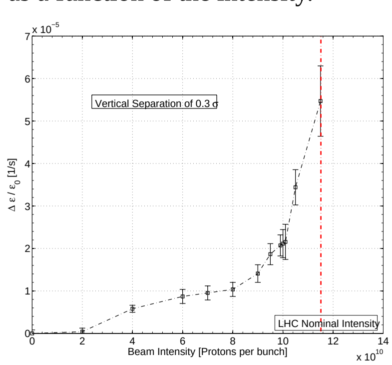

Figure 6: Emittance growth for different bunch intensities in units of 10^{11} protons per bunch and equal initial emittances for a vertical static offset of 0.3 σ.

For the LHC nominal case with bunch intensity of $1.15{\cdot}10^{11}$ protons per bunch we expect an increase of the order of 10^{-4} per second of operation. This absolute value is not very large however a doubling time of the emittance occurs in the most pessimistic case at 30 hour in operation which goes well beyond the most optimistic scenario. However, the strong sensitivity of the growth on the bunch intensities can translate in a much faster increase if it is not kept under control. Further studies [9] have confirmed a dependency of the growth rate to the initial beam emittance.

CONCLUSIONS

We have demonstrated that offsets in collision may lead to emittance growth. Although the emittance growth for a nominal LHC case is very slow, the effect can easily be enhanced and becomes important by changes of beam parameters (beam sizes and intensities) due to a threshold effect. Initial simulation results [9] proved a dependency of the emittance growth rate amplitude on the accelerator optical properties (betatron tunes). Studies are ongoing to characterize the tune dependence in order to define constraints on the accelerator working point. The structure of the relative emittance variation as a function of the offset had triggered a first attempt to explain the observation with a physical picture. With a very simple model for the non-linear beam-beam force and the beam amplitude distribution we can qualitatively explain the emittance growth behavior as a function of the relative beam offset in collision. Further studies should help to optimize the operation and with the expected experimental results we hope to get a better insight into the dynamics of the beam-beam interaction in the case of the LHC.

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