Study of Offset Collisions and Beam Adjustment in the LHC Using a Strong-Strong Simulation Model

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Abstract

The bunches of the two opposing beams in the LHC do not always collide head-on. The beam-beam effects cause a small, unavoidable separation under nominal operational conditions. During the beam adjustment and when the beams are brought into collision the beams are separated by a significant fraction of the beam size. A result of small beam separation can be the excitation of coherent dipole oscillations or an emittance increase. These two effects are studied using a strong-strong multi particle simulation model. The aim is to identify possible limitations and to find procedures which minimise possible detrimental effects.

1 INTRODUCTION

Under nominal operational conditions, the beam-beam effect causes a small, unavoidable separation, as shown in Fig. 1, the closed orbit is subject to variations. Therefore the bunches collide with a small offset between $0-0.2\sigma$, and, as a result the emittance may increase or the beam stability may suffer. In the simulation described below, both

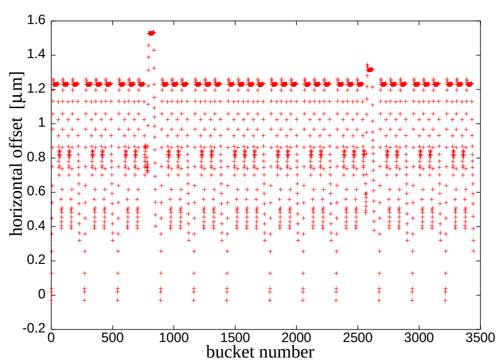

Figure 1: Horizontal offset at IP1 for all bunches. The offset is caused exclusively by long-range beam-beam interactions (courtesy of H. Grote)

constant and varying separations for the beams were considered as this may also be a way of bringing the beams into collision. A separation could also be a way of optimising luminosity [1] by, for example, sweeping the beam [2]. So one of the main objectives of the simulation is to find separations which have a clearly beneficial or detrimental effect on the beam.

The simulation is explained in 2 followed by the results with the nominal LHC parameters in 3. The same code was also run for increasing intensities, up to 10 times the nominal, and the results are summarised in 4. Section 5 summarises the results obtained.

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2 SIMULATION

The simulation used had only one interaction point and one bunch per round beam. This bunch was made of 10000 macro-particles following a Gaussian distribution in all four transverse coordinates (x, x', y, y'). The simulation was soft Gaussian meaning that a kick was given to each particle at every turn, namely

$$\Delta(x^{'}, y^{'}) = -8\pi\xi\sigma^2 \frac{(x, y)}{r^2}\left[1-\exp\left(-\frac{r^2}{2\sigma^2}\right)\right]$$

with $r^2 = x^2 + y^2$, σ the r.m.s. beam size and the beam-beam parameter $\xi = 0.0034$. The normalisations $\alpha = 0.0$, $\beta = 1.0$ were used.

The program is a strong-strong model, so both beams mutually affect each other and the beam sizes σ are updated at every turn. The number of turns is currently (131072), representing 12 seconds of machine time for the LHC. After passing the interaction point, both beams undergo a linear transfer in the arcs (with different tunes), so that the beam-beam interaction is the only nonlinearity considered.

The beam size and emittance are calculated after every turn, as well as the particles in the halo, in this way, it is possible to determine if the current distribution deviates from the initial Gaussian one and by how much. Finally, the program makes an FFT of the centre of mass motion and looks at the 0 and π modes respectively as shown in Fig. 2 (for one beam and one transverse coordinate). This provides a comparison with the already existing code Hybrid Fast Multipole Method (HFMM) [3] due to Herr, Zorzano and Jones as can be seen from Fig. 3. The Yokoya factor found by the present simulation is about 10% smaller than the true Yokoya factor found by [3] (1.09 instead of 1.21 for 0 separation). This is understood and due to the fact that the Gaussian assumption means the beam size is overestimated at every turn, leading to a smaller kick. The clear advantage of the present simulation over the others is that it is an order of magnitude faster, meaning more ideas can be verified faster and the code may be run for longer. The results are qualitatively correct and the strategy should be to use the present simulation where possible and to refer to [4] or [3] when exact results are required.

3 CONSTANT AND VARYING OFFSETS AND RESULTS

The types of separations used may be divided into two: constant ones which ranged from 1 to 3σ (in steps of 0.1σ)

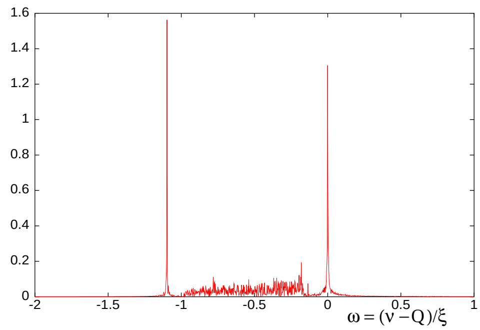

Figure 2: FFT of the centre of mass for no separation in units of normalised tune shift (abscissa) and arbitrary (ordinate) using the soft Gaussian simulation

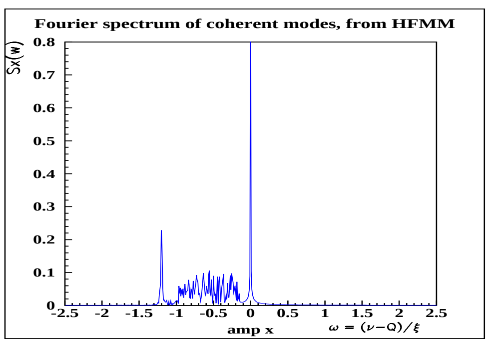

Figure 3: FFT of the centre of mass for no separation using HFMM (courtesy of W. Herr)

and varying ones with the beams separated by 10σ and being slowly or rapidly brought into collision. Many varying separations (time dependent) were considered and only the results of one are shown below. The results for the constant separations from the soft Gaussian program were compared to those obtained using HFMM [3] and were found to be qualitatively the same as shown below in Fig. 4 for one particular case. The emittance and beam sizes were also looked at and found to be in good agreement. Some of the

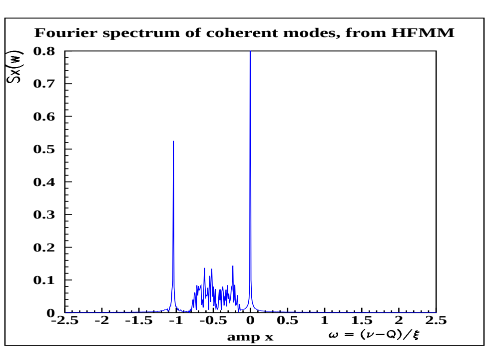

Figure 4: FFT of the centre of mass for a separation of 0.5σ using HFMM (courtesy of W. Herr)

varying separations were linearly decreasing and some, as shown in Fig. 5, had an overshoot. The linearly decreasing ones can be directly compared to already existing results using J. Shi's PIC code [4]. Some random separations (white noise) were considered , equivalent to random kicks, again for comparison with J. Shi's program. One can see from the centre of mass motion, Fig. 6, when the beam was actually brought into collision. However, this was the only observed effect and there was no significant ($> 0.1\%$) beam size blow up, as shown in Fig. 7, for any of the separations considered except for the ones with linear random or Gaussian random ($\pm 1/10\sigma$) kicks, where a blow up was expected.

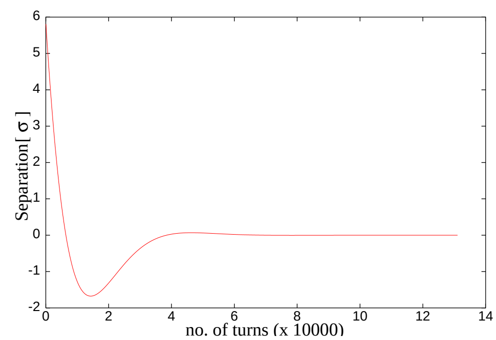

Figure 5: Typical varying separation (x plane)

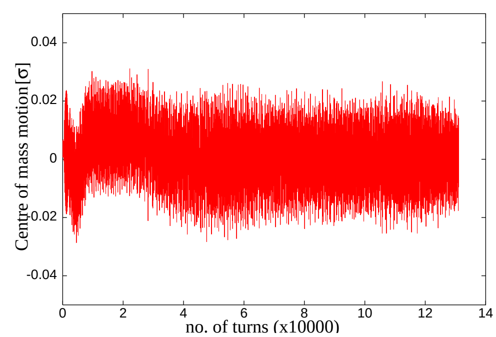

Figure 6: Centre of mass motion (x plane) for separation given by Fig. 5

4 HIGHER INTENSITY STUDIES

The code was run with the same settings, but with increasing intensities and assuming the same emittance (ϵ^*). This time only constant separations were considered, however, it is not expected that the results change any of the varying ones considered above. The results are summarised in Figs. 8, 10, 11. The abscissa represents varying intensity given in multiple units of the beam-beam parameter ξ for 2^{17} turns and the ordinate is the percentage increase of the beam size. Also shown is the beam size blow up for an increase in intensity by a factor of 10 (Fig. 9) for 0σ separation. Note that this blow up is very similar to the one

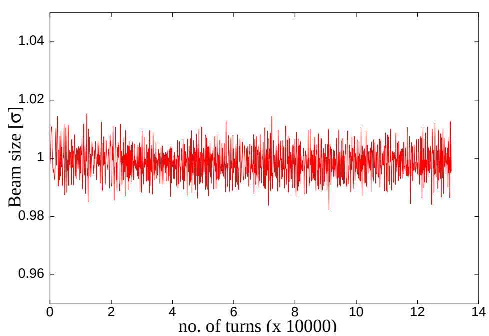

Figure 7: Fluctuations of beam size (x plane) for separation given by Fig. 5

observed for nominal intensity and Gaussian random noise.

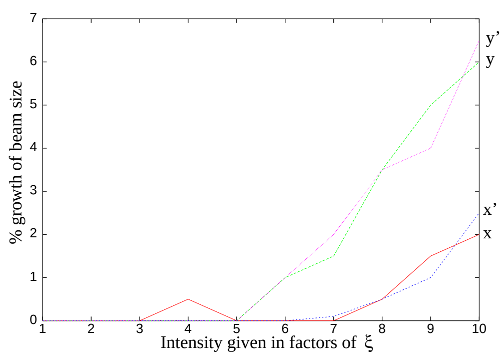

Figure 8: Varying intensity with 0σ separation

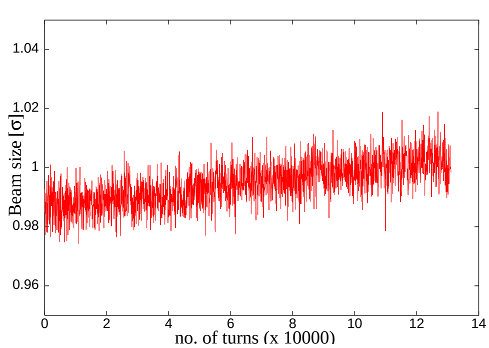

Figure 9: Beam size blow up for 10 times the nominal intensity and 0σ separation

It may be concluded from these figures that the intensity can be increased by a factor of at least 3 for all the separations considered.

5 CONCLUSIONS

The main advantage of the present simulation is that it is up to 20 times faster than other existing programs [3, 4], enabling more ideas to be verified faster. Despite

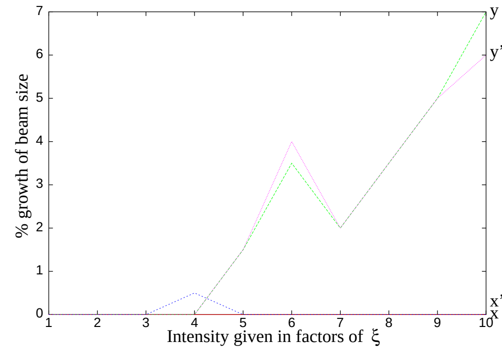

Figure 10: Varying intensity with 1σ separation

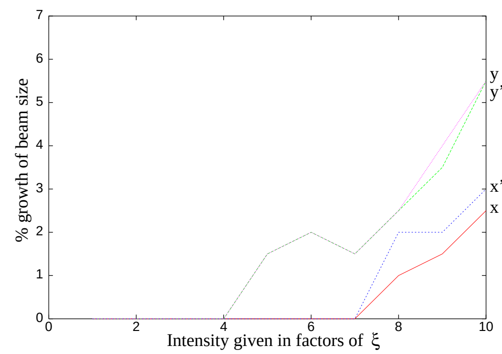

Figure 11: Varying intensity with 2σ separation

the Gaussian approximation, the simulation shows qualitatively, though not quantitatively, correct results and is in full agreement with [3, 4]. There is a beam blow up in some cases at higher intensities and with random noise.

From the results, it can be seen that the intensity may be increased by at least a factor of three, though no significant beam size increase was seen up to and including five times the nominal intensity. Only constant separations were considered for the increasing intensities cases, however, it is not expected that varying the separations will change the results significantly.

6 REFERENCES

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[4] J. Shi, "PIC code", private communication.