SIMULATION OF COLLIDING BEAMS WITH FEEDBACK IN LHC*

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Abstract

The particle tracking code BeamBeam3D is used to simulate beam-beam effects in the Large Hadron Collider (LHC). In order to simulate the emittance stability, a feedback model was implemented in BeamBeam3D. For test purposes beams in the present LHC were simulated. Initially the beam-beam force was computed self-consistently for both beams. However, significant numerical noise obscured the results. Therefore the beam-beam force was then evaluated assuming a Gaussian particle distribution instead. In this report, the feedback model, the problem with numerical noise and first simulation results with the soft Gaussian model are presented.

INTRODUCTION

LHC is performing very well, and the high luminosity (HL)-LHC project aims at increasing the luminosity well beyond the nominal $10^{34}\text{cm}^{-2}\,\text{s}^{-1}$ [1]. Increasing the luminosity inevitably enhances the beam-beam effects in the machine as well. The crab cavities that are foreseen to avoid the geometric luminosity loss, innate to the high-intensity collision optics with large crossing angles, have an impact on the beam dynamics, too. Therefore simulations studying the impact of the beam dynamics is pursued in parallel to the design and prototyping of crab cavities [2].

Here we concentrate on the beam emittance and how it is affected by the feedback (FB) system. The FB system is designed to suppress the coherent beam motion, which is also beneficial for the emittance because non-linear fields, like the self-field of the opposite beam in collisions, transfer energy from the coherent beam motion into the incoherent particle motion. In order to include the effect of LHC's FB system into beam simulations, a FB model was implemented in the code BeamBeam3D [3]. The FB model is described in the first section.

At present, simulations of the beam dynamics in LHC with crab cavities cannot be benchmarked against experiments. In order to validate the simulations, the present LHC (without crab cavities) was simulated. These simulations suffered significantly from numerical noise due to the self-consistent computation of the self-fields, as shown in Sec. 2. The beam-beam force was therefore computed using a less noisy soft Gaussian model. First simulation results with the soft Gaussian model are discussed in Sec. 3.

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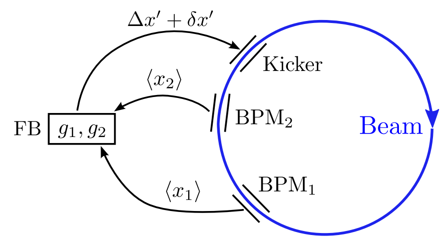

Figure 1: Feedback model implemented in BeamBeam3D.

FEEDBACK MODEL

The beam's offset is measured with a beam position monitor (BPM), and a kicker applies a correction kick which changes the beam's momentum. Following the layout of LHC's FB system, the FB model features two BPMs and one kicker for each beam and each transverse plane. For one beam the setup is illustrated in Fig. 1.

Without loss of generality we discuss the horizontal coordinate x. The correction kick is determined by applying a notch and Hilbert filter to the offsets during 7 earlier turns. The kick associated with BPM i during turn n is calculated following Ref. [4] with modifications pertaining to LHC [5],

$$\Delta x'_{i,n} = \frac{g_i}{\sqrt{\beta_i \beta_k}} \sum_{k=0}^{6} h_k \times (x_{i,n-d-k} - x_{i,n-d-k-1}), \quad (1)$$

where h_k are the Hilbert coefficients, g_i is the gain, and d is a delay (in units of turns). Taking the difference between two consecutive offsets acts like a high pass filter thus avoiding a beam excitation due to an orbit or BPM misalignment. The total kick applied is given by $\Delta x_{1,n} + \Delta x_{2,n}$.

Imperfections of the hardware, in particular those of the BPMs, prevent the FB from damping a coherent oscillation below arbitrary limits. In the model these imperfections are taken into account by adding random numbers δx_n of a Gaussian distribution at every turn. As a result the offset experiences a fluctuation around the equilibrium orbit.

The efficiency of the FB model depends not only on g and the tune, Q, but also on a phase that determines the values of the Hilbert coefficients h_k. The optimization of these parameters is not trivial but for the standard LHC optics (injection and collision) good values were obtained [6]. For small gains (¡1.5) an approximate analytic expression can be used to determine h_k as a function of Q.

A FB model based on Eq. 1 was implemented in BeamBeam3D. A disadvantage of the model is that running the code with the FB model requires additional information about the beam optics, like phase advances between the

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BPMs and the kicker. For the computation of the beam-beam interaction these parameters are usually not relevant because a linear transfer map based on the tune is used to transfer the beams from collision to collision. The simulations discussed in the following sections were done using the aforementioned FB implementation.

NUMERICAL NOISE

The simulation of the present LHC permits the validation of BeamBeam3D with the new FB model. According to data shown at the 5^{th} LHC Crab Cavity Workshop [7], the transverse beam size does not increase by more than 40 % in 25 hours. Assuming that the emittance grows linearly, the corresponding emittance growth is maximal 3.8 % in the first hour. The parameters listed in Tab. 1 represent typical values for the LHC operation in 2011, with two exceptions for practical purposes. The numerically most expensive part of our simulations is the evaluation of the beams' self-fields. In order to reduce the computation time, only one interaction point (IP) was used in the simulations presented here instead of 2 IPs. The effective beam-beam parameter for the entire ring was maintained by doubling the actual particle number of 1.5×10^{11}. This approximation increases the simulated emittance growth non-negligibly. However, for the following discussion the accuracy is sufficient.

Table 1: Beam Parameters and Numerical Parameters Used in the Simulations Presented Here

Number of protons	3×10^{11}
Number of IPs	1
Energy	3.5 TeV
Normalized emittance	2.5 μ m
Bunch length	7 cm
Momentum spread	1.1×10^{-4}
Beta function at IP	1 m
Number of macro particles	8×10^6
Number of slices per bunch	8
Number of transverse grid cells	128×128

In the first simulations the mutual interaction of the beams was evaluated self-consistently. Thus systematic errors due to limiting assumptions about the particle distribution were avoided. The disadvantages of the self-consistent computation are its high numerical costs and the emergence of noise in the self-fields because of the low number of macro particles (compared to the number of physical particles).

Figure 2 shows the horizontal emittance of one of the beams simulated with the FB system where no BPM (or other) noise was added. Initially the emittance jumps up as a consequence of the particles rearranging in response to the perturbation of the lattice by the beam-beam effect. Then the emittance continues to grow linearly in good approximation with a growth rate of 13 %/h. This growth exceeds the observation in LHC although the noise in the real system was included in this simulation. The driver for this growth is numerical noise, which was already observed in earlier simulations but to a much lower extent. The reason for the increased impact of the noise is the change of the beam parameters which yields a larger beam-beam parameter.

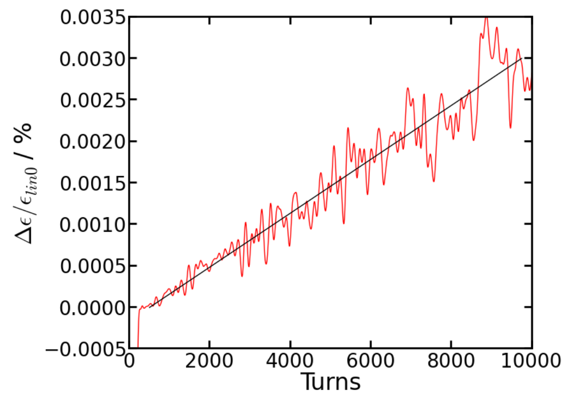

Figure 2: Emittance growth in a self-consistent simulation. The data were smoothed to suppress noise.

In order to avoid numerical noise, the self-consistent field computation was replaced by an analytic field calculation based on the assumption that the particles are normally distributed. Self-consistency was abandoned in this way but the Gaussian approximation seems reasonable for several reasons. Firstly, the cores of the beams in LHC are well described by a Gaussian function. Secondly, the beams were also initialized with a Gaussian distribution in the self-consistent simulations. Thirdly, the simulations consider stable beams and short time scales.

An additional advantage of this method is its higher speed, which allows the simulation of longer storage times. Due to the slowness of self-consistent simulations only 10^4 turns were simulated, corresponding to a strorage time of only about 1 s. The much faster soft Gaussian method allows to extend the simulated storage time by a factor of about 10. The results in the next section were obtained using the soft Gaussian approach.

SOFT GAUSSIAN SIMULATIONS

Switching from the self-consistent to the soft Gaussian collision model drastically changed the results. The numerically driven emittance growth disappeared—the emittance shrinked instead. As Fig. 3 shows for the horizontal plane for one beam, the emittance shrinking rate depends on the number of macro particles. Note the ten fold simulation time compared to the self-consistent case in Fig. 2 Since an emittance drop was found in the x and y planes of both beams, the beams seem to be cooled. Figure 4 reveals that the cooling rate as a function of the number of macro particles is well approximated by a hyperbola, i. e. the cooling

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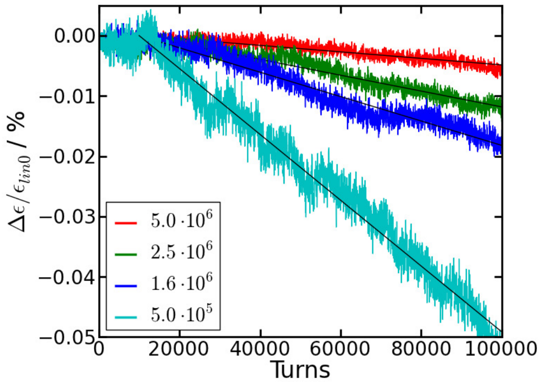

Figure 3: Decreasing emittances of beams with different numbers of macro particles. The data were smoothed to suppress noise.

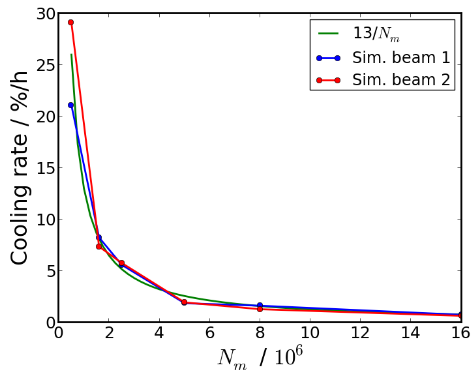

Figure 4: Cooling rate as a function of the number of macro particles and a hyperbola.

is inversely proportional to the number of macro particles in the beam.

This relation between particle number and cooling rate is known from stochastic cooling theory [8]. With its innate simplifications the FB model used in these simulations actually does not differ from an equally reduced model of a stochastic cooler. Hence the cooling is an artifact of the FB model and the comparably low number of macro particles. This effect has been seen in other FB simulations before [5]. In studies of emittance growth, this effect needs to be minimized, and the simulated emittance growth rates needs to be corrected. The model may need further improvements.

Being aware of the spurious cooling, one can examine the emittance when BPM noise impairs the FB's function. An example with a rms noise amplitude of 5 nm at a beta function of 1 m is shown in Fig. 5 for both emittances and for both transverse planes. These data have not been corrected for artificial cooling. Initially the beams had circular cross sections and the planes differed only by the tunes, the fractional parts being $Q_x = 0.31$ and $Q_y = 0.32$.

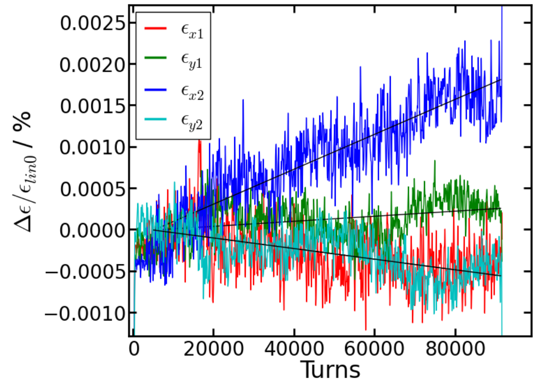

Figure 5: Simulation with noisy FB system. The data were smoothed to suppress noise.

The distinct behavior of the different emittances is not fully understood. Random effects due to random particle distributions (although macroscopically equal) may be involved.

CONCLUSIONS

To simulate the impact of noise on beams in LHC, the particle tracking code BeamBeam3D has been equipped with a FB model. Excessive numerical noise, obscuring the physically originated emittance growth, is avoided using the soft Gaussian collision model. The FB model introduces artificial stochastic cooling, which has to be taken into account when interpreting data. The simulation results referring the current LHC have to be well understood before the HL-LHC with crab cavities can be studied.

ACKNOWLEDGMENT

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