3D STRONG-STRONG SIMULATIONS OF WIRE COMPENSATION OF LONG-RANGE BEAM-BEAM EFFECTS AT LHC*

J. Qiang†, LBNL, Berkeley, USA

Abstract

In this paper, we report on studying wire compensation of long-range beam-beam effects using a fully 3D strong-strong model. The simulations include two head-on collisions with 0.3 mrad full crossing angle and 64 long-range beam-beam collisions near IP 1 and IP5. We found that using conducting wires with appropriate current level will compensate the tail emittance growth due to long-range beam-beam effects. The random fluctuation of current level should be controlled below 0.1% level for a good compensation. Lowering the long-range beam-beam separations by 20% together with wire compensation will improve the luminosity by a few percentage. Further reducing the beam-beam separation causes significant beam blow-up and decrease of luminosity.

INTRODUCTION

Long-range beam-beam effects at LHC can significantly degrade beam lifetime at LHC. These effects were studied using a weak-strong head-on beam-beam model and lumped long-range beam-beam interaction model [1]. Conducting wire was proposed to compensate these effects at LHC [2]. Such a wire compensation has been studied using a weak-strong simulation model [3, 4]and a 2D strong-strong simulation model [5]. In this paper, we studied wire compensation of long-range beam-beam effects using a fully 3D strong-strong beam-beam model.

COMPUTATIONAL AND PHYSICAL MODELS

The computer code used in this study is the BeamBeam3D code [6]. The BeamBeam3D is a parallel three-dimensional particle-in-cell code to model beam-beam effect in high-energy ring colliders. This code includes a self-consistent calculation of the electromagnetic forces (beam-beam forces) from two colliding beams (i.e. strong-strong modeling), a linear transfer map model for beam transport between collision points, a stochastic map to treat radiation damping, quantum excitation, an arbitrary orbit separation model, and a single map to account for chromaticity effects. Here, the beam-beam forces can be from head-on collision, offset collision, and crossing angle collision. These forces are calculated by solving the Poisson equation using a shifted integrated Green function method, which can be computed very efficiently using an FFT-based algorithm on a uniform grid. For the crossing angle collision, the particles are transformed from the laboratory frame into a boosted Lorentz frame, where the beam-beam forces are calculated the same as the head-on collision. After the collision the particles are transformed back into the laboratory frame. The BeamBeam3D code can handle multiple bunches from each beam collision at multiple interaction points (IPs). The parallel implementation is done using a particle-field decomposition method to achieve a good load balance.

In this study, we used version 6.5, baseline optics for the LHC lattice from the website http://www-ap.fnal.gov/t̃sen/RHIC/index.html. There are two major interaction points (IPs), IP 1 and IP 5. Two counter-rotated proton beams collide at IPs with a full crossing angle 0.3 mrad. At each interaction point, there are 16 long-range beam-beam interaction points on each side of the IP. Each long-range beam-beam interaction point is separated by 3.75 meters starting from the interaction point. Figure 1 shows the horizontal and vertical separations of two beams at IP 5. At IP 5, two beams are separated in horizontal plane. At IP 1, two beams are separated in vertical plane (not shown here). A pair of conducting wires are

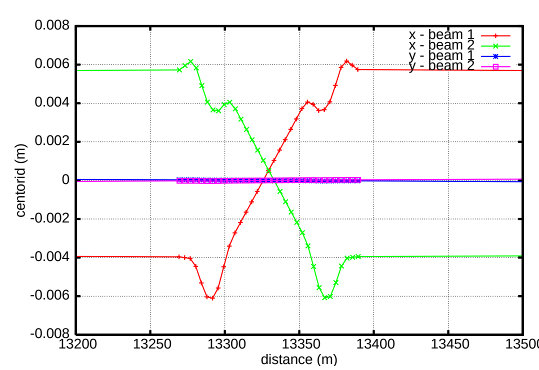

Figure 1: LHC beam-beam separation at IP IP 5.

placed on both sides of the collision points. They are physically located around 105 meters from the interaction points where the horizontal and the vertical beta function values are roughly equal. The distance between the conducting wire and the proton beam is set to 9σ which is the average value of long-range beam-beam separations at LHC. The current of conducting wire is chosen following [7]

$$I_w = \frac{4\pi B_\rho N_p r_p n_{par}}{\mu_0 \gamma L_w} \quad (1)$$

where B_ρ is the magnetic rigidity of the beam, r_p is the classical proton radius, N_p is the number of protons per

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† jqiang@lbl.gov

bunch, n_{par} is the number of long-range beam-beam interactions per side, L_w is the length of conducting wire. For the nominal LHC parameters used here, this results in 84.48 Amper current for the conducting wire.

Using the MAD-X program and the LHC input lattice files, the linear transfer maps between IPs and long-range beam-beam interaction points and the maps between each pair of long-range beam-beam interaction points are extracted. Those linear transfer maps are read into the BeamBeam3D code to transport particles through the lattice of LHC. Figure 2 shows the betatron tunes extracted from the BeamBeam3D simulation without including beam-beam effects. It can be seen that these betatron tunes agree very

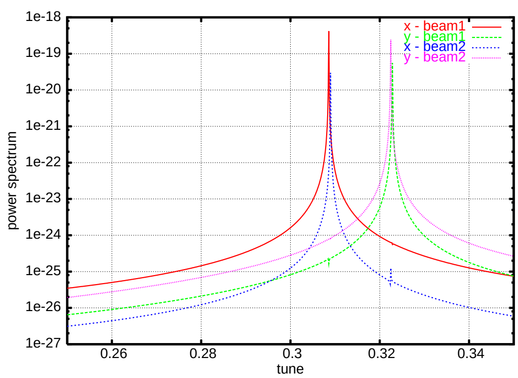

Figure 2: LHC betatron tunes from the BeamBeam3D simulation using a linear transfer map without beam-beam effects.

well with the designed tunes from the output of the MAD-X and the LHC lattice input files. This suggests that we used linear transfer maps correctly in the BeamBeam3D code. Both the head-on collisions at IP1 and IP5 and the long-range beam-beam interactions are included in simulations. For the head-on collision at interaction point, a strong-strong three-dimensional model was used to calculate the beam-beam forces from each beam. Here we have used five longitudinal slices, 128x128 transverse grid points, and 1.3 million macroparticles for each beam. The long-range beam-beam interaction forces are calculated using a soft-Gaussian model. Using a soft-Gaussian model reduces the computational cost of calculating of the long-range beam-beam forces. This is a reasonable model since the two beams are far away enough so that the details of distribution may not be important. The chromatic effects of the LHC lattice were also included in the BeamBeam3D using a one-turn transfer map. The horizontal and vertical chromaticities of each beam were extracted from the output of the MAD-X and the input lattice files. Here, chromaticities for beam one are, $qx = 0.892$, $qy = 0.905$; for beam two, $qx = 1.096$, $qy = 0.927$.

SIMULATION OF CONDUCTING WIRE COMPENSATION OF NOMINAL LONG-RANGE BEAM-BEAM SEPARATION

Using above computational and physical models, we ran simulations for proton beam transport at the LHC. Figure 3 shows the 99.9% emittance growth of proton beams with/without wire compensation together with simulation results without including long-range beam-beam effects. It

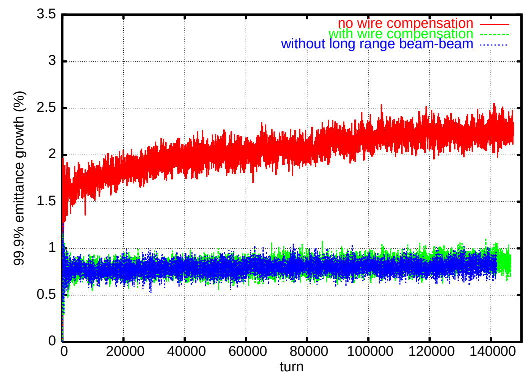

Figure 3: Emittance growth with/without wire compensation and the results without including long-range beam-beam effects.

is seen that using conducting wires has compensated the effects from long-range beam-beam interactions and reduces the 99.9% emittance growth to the level without including long-range beam-beam effects. Here the 99.9% emittance is defined as the emittance that contains 99.9% of particles in a beam. The emittance for each individual particle is given by:

$$\epsilon_i = \gamma x_i^2 + 2\alpha x_i x_i' + \beta x_i'^2 \qquad (2)$$

where Twiss parameters $\gamma\beta - \alpha^2 = 1$, $\alpha = -< xx' > /\epsilon_{rms}$, $\beta =< x^2 > /\epsilon_{rms}$, and ϵ_{rms} is the rms emittance. Using a 99.9% emittance helps to characterize the tail of particle distribution. A larger tail in particle distribution will eventually result in a reduction of beam lifetime.

EFFECTS OF REDUCED LONG-RANGE BEAM-BEAM SEPARATION

Given the success of conducting wire compensation in above nominal parameters, it is natural to ask how good it still will be if we lower separations of long-range beam-beam interactions by reducing the crossing angle of two colliding beams. Reducing the crossing angle of colliding beams helps improve luminosity of the LHC. Figure 4 shows the 99.9% emittance growth without wire compensation, with nominal wire compensation, with 20% reduction of separation, and with 30% reduction of separation. Reducing long-range beam-beam separation by 20% enhances the long-range beam-beam effects. These effects are still well compensated by using conducting wires.

However, further reducing the long-range beam-beam separation by 30% shows significantly large emittance growth. The sudden growth of emittance suggests potential resonance crossing of large amplitude particles. As the beam-beam separation becomes smaller, the electric field profile from a finite size beam and that from a conducting wire is no longer well matched. This mismatch mitigates the compensating capability of conducting wires.

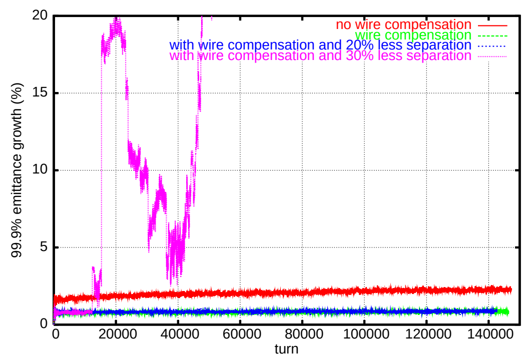

Figure 4: Emittance growth with/without wire compensation, with 20% reduction of nominal separation, and with 30% reduction of nominal separation.

Reducing the crossing angle helps improve the luminosity of colliding beams. Figure 5 shows the luminosity evolution with nominal 9σ long-range beam-beam separation, with 20% reduction of separation, and with 30% reduction of separation. Reducing the original 0.3 mrad crossing angle by 20% improves the peak luminosity by about 3.6%. Further reducing the crossing angle causes significantly decreasing of luminosity.

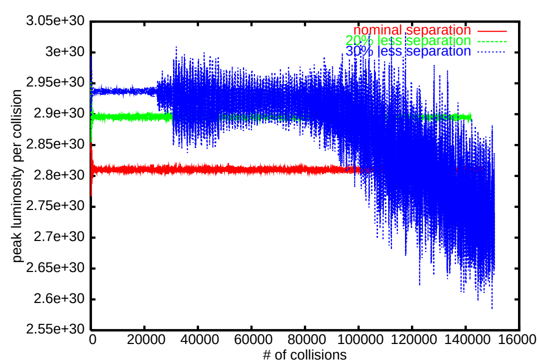

Figure 5: Peak luminosity evolution with nominal 9σ separation, with 20% reduction of nominal separation, and with 30% reduction of nominal separation.

EFFECTS OF WIRE CURRENT FLUCTUATION

In above wire compensation studies, we have assumed an ideal conducting wire model without current fluctuation. To check effects of current fluctuation in the conducting wire, we repeated simulations for the nominal separation with different levels of current fluctuation. Figure 6 shows the 99.9% emittance growth without current fluctuation, with 0.1%, 0.5%, and 1% current fluctuation. Here, we have assumed that the fluctuation is a random white noise. For 1% current fluctuation, it shows more than 2% emittance after $50,000$ turns. During real LHC machine operation, this will result in significant growth of tail distribution after a few minutes. From the current simulation up to about $50,000$ turns, a 0.1% current fluctuation does not show observable more emittance growth than the ideal case. This suggests that the conducting wire current fluctuation should be controlled under a level of 0.1% in order to avoid significant growth of the tail emittance and the reduction of beam lifetime.

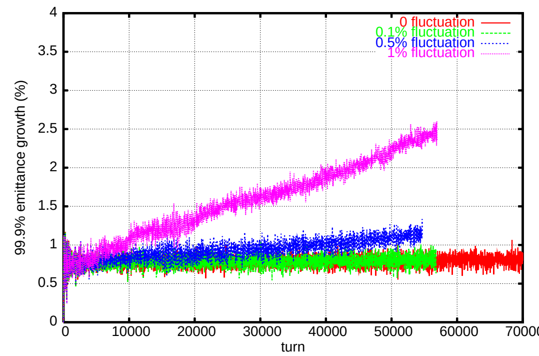

Figure 6: Emittance growth without current fluctuation, with 0.1%, 0.5%, and 1% current fluctuation.

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REFERENCES

[1] Y. Papaphilippou, F. Zimmermann, PRST-AB 2, 104001 (1991).

[2] J.-P. Koutchouk, "Principle of a Correction of the Long-Range Beam-Beam Effect in LHC using Electromagnetic Lenses," Proc. PAC2001, Chicago, P. 1681 (2001).

[3] F. Zimmermann, "Weak-Strong Simulation Studies for the LHC long-Range Beam-Beam Compensation," in Proc. workshop on Beam-beam Effects in Circular Colliders, p. 66, Fermilab, June 25-27, 2001.

[4] U. Dorda, F. Zimmermann, "Simulations of Long-Range Beam-Beam Interaction and Wire Compensation with BB-Track," Proc. EPAC2006, Edinburgh, Scotland, p. 2245 (2006).

[5] L. Jin, J. Shi, Nucl. Instr. Meth. Phys. Res. A, vol. 550, p. 6 (2005).

[6] J. Qiang, M. A. Furman, R. D. Ryne, J. Comp. Phys., vol. 198, p. 278 (2004).

[7] B. Erdelyi and T. Sen, "Compensation of beam-beam effects in the Tevatron with wires," FNAL-TM-2268, 2004.