STUDY OF THE WIRE COMPENSATION OF LONG-RANGE BEAM-BEAM INTERACTIONS IN LHC WITH A STRONG-STRONG BEAM-BEAM SIMULATION

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Abstract

The wire compensation of long-range beam-beam interactions in LHC was studied with tracking of one million particles over 100 thousand turns by using the particle-in-cell method. The robustness of the wire compensation with static and random errors in the current on the wire was investigated based on the growth of the beam-size.

1 INTRODUCTION

Many studies have shown that the long-range beam-beam interactions due to parasitic collisions inside interaction regions have significant adverse effects on the beam stability in LHC [1, 2]. A wire compensation scheme has been proposed to compensate the long-range beam-beam effects [3]. Because of a large beam separation at the parasitic collisions, the long-range beam-beam interaction is dominated by a force with the form of $1/r$ in the phase-space region occupied by the beam (the phase-space region near the closed orbit), where r is the distance from a particle in one beam to the center of the counter-rotating beam. In the wire compensation scheme, an electrical wire is thus installed on each side of an IP to provide the beam with a similar $1/r$ force but an opposite sign to the beam-beam interaction. The use of the wire compensation can significantly improve the linearity of the phase space-region near the closed orbit, especially in the case that the phase advance among the parasitic collision points is very small such as in LHC. A tracking study with a strong-weak model of beam-beam interactions showed that the wire compensation of the long-range beam-beam interactions is effective in improving the stability region of beams in LHC [4]. When dynamic aperture is close to the beam separation, however, the $1/r$ force does not dominate the long-range beam-beam interaction in the phase-space region relevant to the dynamic aperture. The principle of the wire compensation is no longer valid there and, therefore, a study of the dynamic aperture is not sufficient for the evaluation of the wire compensation scheme. In order to exam the effectiveness of the wire compensation in the phase-space region occupied by the beam, we have studied the evolution of the beam size in LHC including beam-beam interactions and multipole field errors in the lattice with a self-consistent beam-beam simulation. The robustness of the wire compensation with static and random errors in the current on the wire has been studied based on the beam-size growth.

2 SIMULATION MODEL

The lattice used in this study is the LHC collision lattice in which the fractional parts of horizontal and vertical tunes are chosen to be $(\nu_x,\ \nu_y) = (0.31,\ 0.32)$. Head-on and long-range beam-beam interactions at two high luminosity interaction points (IP1 and IP5), were included. The crossing angle of two counter-rotating beams was taken to be 300 μrad with vertical crossing at IP1 and horizontal at IP5. For the long-range beam-beam interactions, there are 15 parasitic collisions on the each side of an IP. In the simulation, the first 5 parasitic collisions were calculated individually and, due to an almost zero phase advance among them, the rest of the parasitic collisions were lumped into one single kick at the location of the sixth parasitic collision point. In this study, a beam-beam parameter of $\xi = 0.02$ was used in order to be more conservative.

The head-on beam-beam interactions were calculated with our self-consistent (strong-strong) beam-beam simulation code that was fully tested and presented in detail in a previous paper [5]. In this code, each beam is represented by a large number of macro-particles with a given initial distribution in transverse phase space. In this study, a half million macro-particles were used for each beam and the initial beams have a round Gaussian distribution in the normalized transverse phase space with standard deviation σ_0 and truncated at $\pm 4\sigma_0$. $\sigma_0 = \sigma^*/\sqrt{\beta^*}$ where σ^* and $\beta^* = 0.5$ m are the nominal transverse beam size and beta function at IP, respectively. During the tracking, head-on beam-beam kicks in four-dimensional transverse phase space were calculated at each IP by using the particle-in-cell method. The detail can be found in Ref. [5].

Because of a large beam separation at the parasitic collision points, the momentum kicks in transverse phase space due to the long-range beam-beam interactions can simply be calculated with the strong-weak formula

$$\Delta\vec{p} = G_0 \frac{\vec{r}+\vec{r}_0}{|\vec{r}+\vec{r}_0|^2} \left[1 - \exp\left(-\frac{|\vec{r}+\vec{r}_0|^2}{2\sigma^2}\right)\right] \qquad (1)$$

where $\vec{r}$ is transverse coordinate and $\vec{r}_0$ the horizontal and vertical beam separation. σ is the rms beam size at the parasitic collision point. For LHC, $|\vec{r}_0| \sim 9\sigma$. The kick strength G_0 is related to the beam-beam parameter ξ by $G_0 = 8\pi\sigma^{*2}\xi/\beta^*$. Since $|\vec{r}_0| >> \sigma$, the long-range beam-beam interaction is dominated by the $|\vec{r}+\vec{r}_0|^{-1}$ term in the phase-space region occupied by the beam ($|\vec{r}| < 3\sigma$).

For the wire compensation of the long-range beam-beam interactions, in the simulation model an electrical wire is

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placed on each side of an IP before the insertion quadrupole (MQX) Q1. The horizontal or vertical distance from the wire to the beam is 9.46σ that is about the same as the beam separation at parasitic collision points. The maximal phase advance from the location of the wire to the location of the parasitic collision points is about 3^o. An almost perfect local compensation can therefore be achieved in the phase-space region where $|\vec{r}+\vec{r}_0| >> \sigma$. The current on the wire provides the beam a kick equivalent to the total contributions of 15 parasitic collisions. Dipole components of all the long-range beam-beam kicks and wire kicks were subtracted during the tracking.

3 THE RESULTS

Figure 1 plots the initial tune spread of the beams in the case that includes both head-on and long-range beam-beam interactions without or with the wire compensation. It shows that after the wire compensation eliminates the beam tune spread due to the long-range beam-beam interactions. This result is consistent with that in Ref. [4]. In Fig. 2 the evolution of the beam size is plotted for the case that includes only the head-on collisions and for the case that includes both the head-on and long-range collisions but without the wire compensation. As these two curves are roughly parallel to each other during the period of the tracking, the dominant effect of the long-range beam-beam interactions in this case is a large increase in the initial beam-size blowup due to the nonlinear beam filementation in phase space. With the wire compensation, this increase in the beam-size blowup was completely eliminated and the evolution of the beam size coincides with that for the case of the head-on collisions only.

In the application of the wire compensation, there are always fluctuations or errors in the current on the wire. The applicability of the wire compensation depends on the robustness of the compensation to the errors in the current. Cases of the wire compensation with different strength of the static and random errors were thus studied. Fig. 3 shows the beam-size growth at the 10^4th turns as a function of the static error in the current for the compensation, where the beam-size growth is scaled by that for the case of the head-on collisions only. For a comparison, the case including both head-on and long-range collisions but without the wire compensation is also plotted. It shows that the wire compensation with a static error in the range of 0 to -10% has a perfect compensation in terms of the beam-size growth. The unsymmetry of this window of the perfection for the compensation could be due to the small phase advances between the location of the wire and the parasitic collision points. Moreover, in cases of the wire compensation with up to 50% static error in the current, there is only up to 20% increase in the beam-size growth due to the long-range beam-beam interactions. Without the wire compensation, on the other hand, the long-range beam-beam interactions result in a 60% increase in the beam-size growth when compared with the case of the head-on collisions only. This indicates that the wire compensation with up to 50% error in the current always improves the linearity of the phase-space region occupied by the beam so that the initial beam filementation due to the nonlinear long-range beam-beam perturbations is greatly suppressed. Previous study on the improvement of the stability region by the wire compensation suggested that the static error in the range of 0 to -10% appears acceptable [4]. Our study on the beam-size growth, however, indicates that the tolerance of the static error in the current could be loosened.

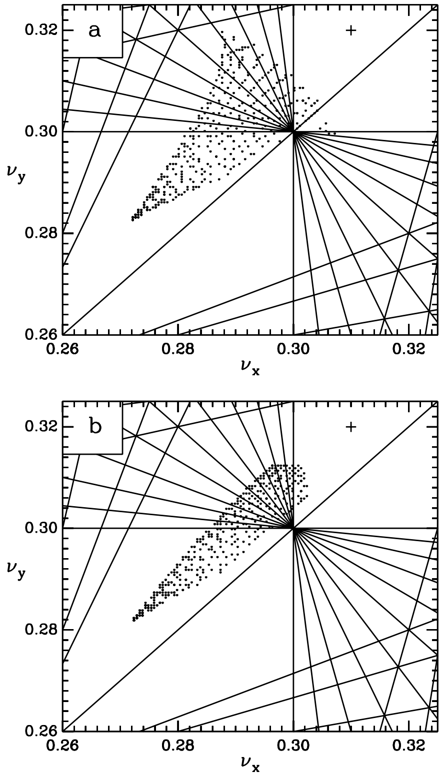

Figure 1: Beam tune spread in the case including both head-on and long-range beam-beam interactions (a) without the wire compensation and (b) with the wire compensation. Two IPs were included. The cross indicates the working point, $(\nu_x,\ \nu_y) = (0.31,\ 0.32)$. $\xi = 0.02$. The tune spread was calculated in the first 2000 turns with 500 particles that have amplitude up to 4σ initially.

Figure 4 plots the evolution of the beam size for different magnitude of current fluctuation in the wire compensation. The current fluctuation used in the simulation is an uniform random noise. Fig. 4 shows that a very small current fluctuation even less than 1.0% can heat up the beam and result in a larger growth rate of the beam size when compared with the case without the wire compensation. A much strict requirement on the current fluctuation has therefore to be imposed in order to use the wire compensation scheme. The requirement of the current fluctuation should at least be $< 0.5\%$ or smaller. The study of Ref. [4] also showed a similar strict tolerance on the current fluctuation.

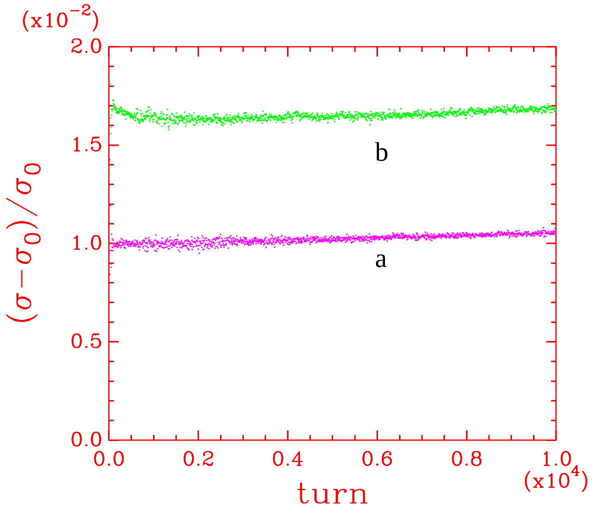

Figure 2: Evolution of the average of the horizontal and vertical beam size with (a) the head-on collisions and (b) both head-on and long-range collisions but without the wire compensation. σ_0 is the initial beam size.

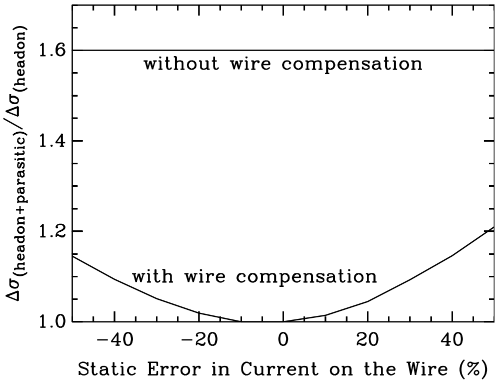

Figure 3: The increase of the average of the horizontal and vertical beam size at the 10^4th turn vs. the static error of the current for the wire compensation. $\Delta\sigma_{\text{(headon+parasitic)}}$ and $\Delta\sigma_{\text{(headon)}}$ are the increase in the beam size for the case including both head-on and long-range collisions and for the case including only the head-on collisions, respectively.

4 CONCLUSIONS

The wire compensation of long-range beam-beam interactions in LHC is very effective in reducing the beam-size growth due to long-range beam-beam interactions. The compensation is not sensitive to static current errors but is very sensitive to current fluctuations. A current fluctuation of 0.5% or more can heat up the beams and make the situation worse than that without the wire compensation. The use of the wire compensation thus requires a very strict tolerance on the current fluctuation. The wire compensation scheme is a good option for the compensation of long-range beam-beam effects from localized parasitic collisions such as in LHC. It is, however, very difficult if not impossible to apply this scheme to the case when there is a large number of parasitic collisions around ring such as in Tevatron. To control the nonlinear effects of such non-localized long-range beam-beam interactions, a global compensation of long-range beam-beam interactions with multipole correctors based on a minimization of nonlinearities in one-turn maps has been studied and found to be very effective [6].

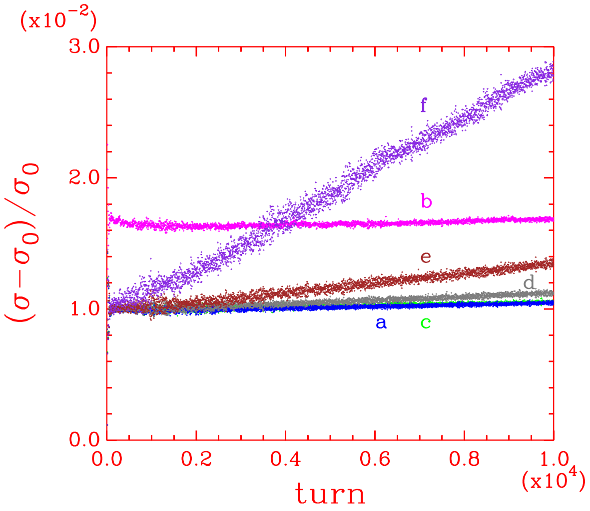

Figure 4: Evolution of the average of the horizontal and vertical beam size for the cases with different strength of current fluctuation in the wire compensation. (a) Include only head-on collisions. (b) Include both head-on and long-range collisions but without the wire compensation. (c)–(f) are the cases that include head-on and long-range collisions and the wire compensation with (c) 0%, (d) 0.5%, (e) 1.0%, and (f) 2.5% current fluctuation on the wire.

ACKNOWLEDGMENTS

This work is supported by the US Department of Energy under Grant No. DE-FG03-00ER41153 and the University of Kansas General Research Fund. We would like to thank the Center for Advanced Scientific Computing at the University of Kansas for the use of the Supercomputer.

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