ELECTRON LENS FOR BEAM-BEAM COMPENSATION AT LHC *

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Abstract

Head-on beam-beam effect may become a major performance limitation for the LHC in some of the upgrade scenarios. Given the vast experience gained from the operation of Tevatron electron lenses, a similar device provides significant potential for mitigation of beam-beam effects at the LHC. In this report we present the results of simulation studies of beam-beam compensation and analyze potential application of electron lense at LHC and RHIC.

INTRODUCTION

In the nominal LHC operating scenario with $1.15 \cdot 10^{11}$ protons per bunch, the transverse emittance of 3.75 μm, and 30 long-range collision points per one main IP the total beam-beam tune shift will not exceed 0.015 and the beam-beam effects are not expected to cause any adverse effects in the beam dynamics. A naive approach with doubling the bunch intensity, decreasing the transverse emittance by a factor of 2, and running two experiments would increase the beam-beam tune shift to 0.03 and provide the luminosity of 10^{35} cm^{-2} s^{-1} [1]. In this case, however, the beam-beam effects would become a strong limiting factor deteriorating the machine performance.

Beam-beam compensation with electron lenses could be an effective and relatively inexpensive solution [2]. Over the years of operation at the Tevatron, electron lenses provided vast experience and proved to be reliable devices that can be effectively used for correction of bunch-to-bunch tune differences induced by long-range beam-beam interactions and significant improvement of the life time of proton bunches [3]. Due to the change of the operating conditions at the Tevatron which shifted the focus of beam-beam effect from antiprotons to protons [4], electron lenses have not been used for nonlinear head-on compensation, and the proof-of-principle experiment has yet to be performed. Head-on compensation with electron lenses has been recently adopted by the RHIC upgrade program, and the device installation is scheduled to be completed by the end of 2011 [5].

In the past decade a number of beam-beam simulation codes were developed which are capable of accurate consideration of various effects in the beam dynamics. Together with the increase of the available computing power, they are now a powerful tool for consideration of different collider operation scenarios.

At Fermilab, the tracking code LIFETRAC [6] was successfully used to describe and predict beam-beam effects in the Tevatron, including the effects of electron lenses.

In this paper the results of simulation studies of beam-beam effects in RHIC and LHC are presented, and possible prospects of head-on beam-beam compensation with electron lenses is discussed.

SIMULATION MODEL

The weak-strong macro particle code LIFETRAC is described in more detail in [6]. The model uses a three-dimensional Gaussian strong bunch. The ring is represented by a series of linear 6D transformations between the IPs. Also included are the first and second order chromaticity, and thin multipoles up to 10th order. The machine lattice is read from MAD-X decks and a full account of coupling and collision sequence is taken. In order to evaluate the beam life time an aperture restriction is placed at the distance of 5-6 σ of the beam and particles reaching this aperture are counted and their coordinates collected.

A number of electron lens configurations were coded, including a Gaussian profile and different versions of smooth-edge-flat-top profiles. In the simulations reported here the electron lens was treated as a thin element, but a provision exists for inclusion of the edge effects.

For the LHC simulations the V. 6.5 optics was used with the total number of IPs equal to 124. A Gaussian electron lens was placed at the “bbc” section near IP1.

The RHIC model included two head-on IPs and 540 thin high-order multipoles. Electron lens element was located at IP10.

In both cases 10^4 particles were tracked over 10^7 turns in a typical simulation run.

RESULTS FOR RHIC

For the RHIC simulations, the total beam-beam tune shift of 0.02 was used. Figs. 1-3 present the tune footprint and bunch intensity and transverse emittance evolution for the cases of no beam-beam compensation and 50% compensation with a Gaussian e-lens. Even though no improvement in the beam life time is observed, the emittance growth is strongly suppressed by the e-lens and the overall effect on the luminosity is positive. Other groups studying the same problem came to a similar conclusion that a partial compensation improves the beam life time [7, 8].

COMPENSATION AT THE LHC

For the sake of simplicity of simulations the machine configuarion was kept constant and only a limited number of parameters was varied, including the proton beam intensity and parameters of the electron lens. The first goal

* Work supported by the Fermi Research Alliance, under contract DE-AC02-07CH11359 with the U.S. Dept. of Energy.

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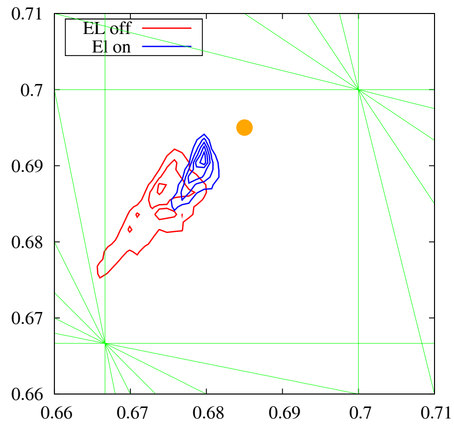

Figure 1: Tune footprint for RHIC with e-lens on (50% compensation) and off. $\xi = 0.02$.

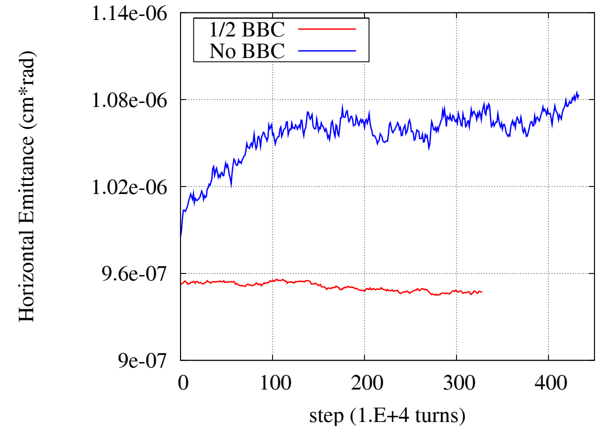

Figure 3: Horizontal beam emittance in RHIC with e-lens on (50% compensation) and off. $\xi = 0.02$.

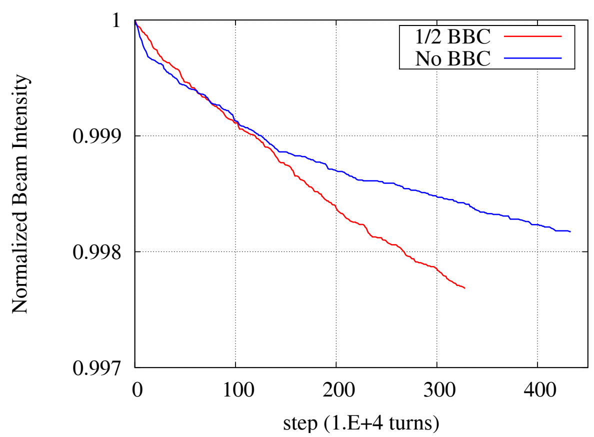

Figure 2: Beam life time in RHIC with e-lens on (50% compensation) and off. $\xi = 0.02$.

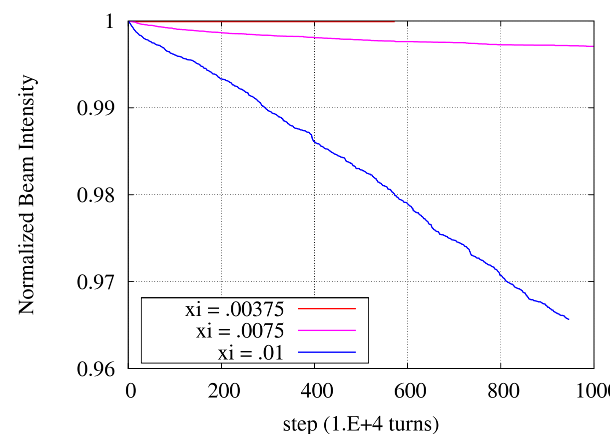

Figure 4: LHC beam life time for different values of beam-beam parameter per IP without beam-beam compensation.

was to determine the approximate magnitude of the adverse beam-beam effects. One has to keep in mind that no machine imperfections were included at this stage, hence the provided values of the beam life time most probably represent the upper boundary estimate. It is known that the final focus nonlinearities could cause additional beam losses [9]. In Fig. 4 the simulated bunch intensity evolution is plotted for tree values of the beam-beam parameter. The value of 0.00375 per IP corresponds to the nominal LHC bunch intensity of $1.15 \cdot 10^{11}$. The simulation time of 10^7 turns corresponds to approx. 900 s. Thus for the doubled bunch intensity the non-luminous fraction of the beam life time drops to $\sim$100 hours, and to $\sim$10 hours for the tripled intensity.

Fig. 5 demonstrates that it is the combination of long-range and head-on beam-beam effects that causes particle losses. So, in the absence of long-range collisions the large tune spread generated by the head-on interaction does not lead to life time degradation.

In Fig. 6 the vertical tune spectra are plotted for the full compensation and no compensation at $\xi = 0.03$.

The dependence of compensation on different e-lens parameters was studied, for example on the size of e-beam, number of electron lenses in the ring, and betatron phase advance between the main IP and the location of e-lens (Fig. 7).

The chart in Fig. 8 summarizes the effect of full beam-beam compensation with a Gaussian e-beam on the proton life time for different proton beam intensities. The proton losses are reduced by almost a factor of two for the doubled bunch intensity, and by a factor of four for the tripled intensity.

SUMMARY

Long-term particle tracking studies with a weak-strong code showed that head-on beam-beam effects will have a detrimental effect on the performance of RHIC and LHC if the beam-beam parameter exceeds $\sim$0.02.

In the RHIC case particle losses are caused by the combined action of beam-beam force and high order nonlinearities of the final focus triplets. For the LHC, it is the com-

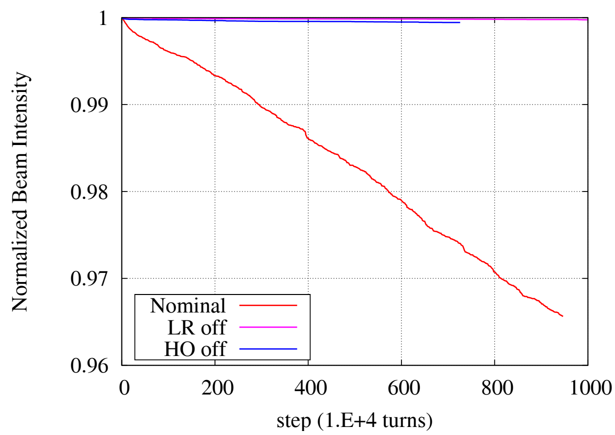

Figure 5: LHC beam life time with long-range (LR) or head-on (HO) collisions switched off. $\xi = 0.04$.

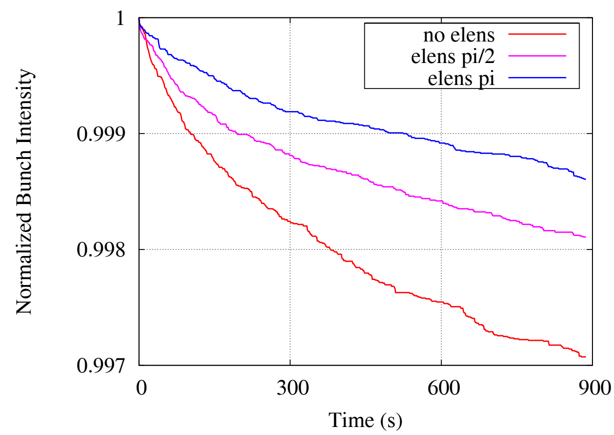

Figure 7: Effect of the phase advance between IP1 and the e-lens on the LHC beam life time. $\xi = 0.03$.

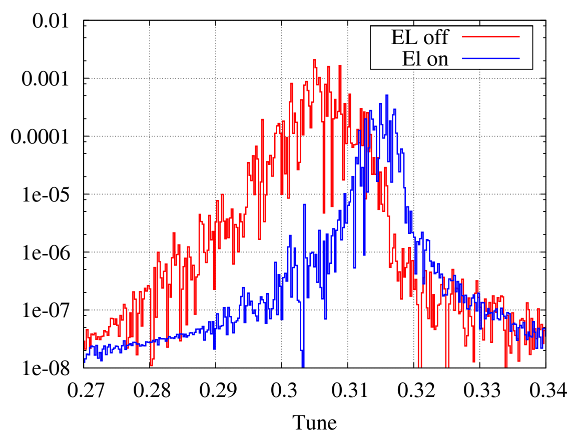

Figure 6: Vertical Shottky spectra with e-lens on (full compensation) and off. Total beam-beam tune shift $\xi = 0.03$.

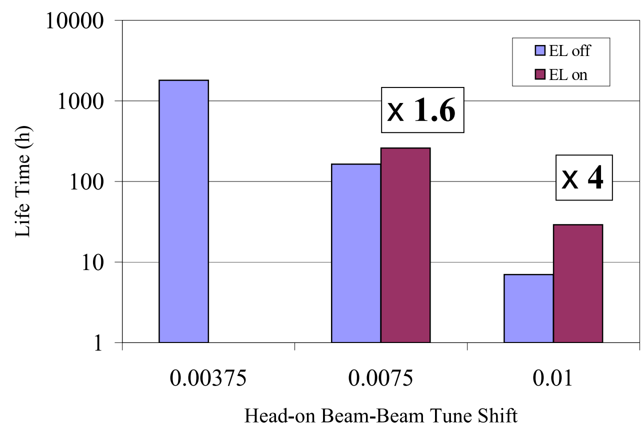

Figure 8: LHC beam life time for different values of beam-beam parameter with e-lens on (100% compensation) and off. The quoted value of beam-beam parameter is per IP (1/4).

bination of head-on and parasitic collisions that degrades the beam life time. In both cases simulations predict that a single electron lens with a Gaussian beam profile acting on the proton beam would mitigate some of the life time degradation.

To further develop the compensation schemes, a more detailed consideration is necessary of such factors as the machine optics imperfections, electron beam stability, quality of the electron and proton beam alignment.

ACKNOWLEDGMENTS

The authors thank W. Fischer, A. Kabel, J.-P. Koutchouk, H.J. Kim, Y. Luo, G. Robert-Demolaize, and T. Sen for collaboration on the subject and fruitful discussions.

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