STUDY OF BEAM-BEAM EFFECTS IN HERA WITH SELF-CONSISTENT BEAM-BEAM SIMULATION

J. Shi* and L. Jin, University of Kansas, Lawrence, KS 66049
G.H. Hoffstaetter, Cornell University, Ithaca, NY 14850

Abstract

The beam-beam effect in HERA was studied with a self-consistent beam-beam simulation by using the particle-in-cell method. A remarkable agreement between the experimental measurement and the simulation result was observed on the emittance growth, luminosity reduction, and coherent tune shifts. The simulation study also showed that the chaotic coherent beam-beam instability could occur in HERA and this collective beam-beam instability could be avoided with a slightly different working point.

INTRODUCTION

In the current luminosity upgrade of HERA, the luminosity is expected to increase roughly by a factor of 4.5. To achieve this goal, the beam-beam parameter of the electron beam $(\xi_{e,x},\ \xi_{e,y})$ will be increased to (0.034, 0.052). To examine any possible luminosity reduction due to beam-beam effects, several beam experiments were performed on HERA [2, 1, 3]. In order to have a better understanding of those experimental data and to evaluate the beam-beam effect in the HERA upgrade, the dynamics of beam-size growth and the stability of the coherent beam-beam oscillation in HERA were studied with a self-consistent beam-beam simulation. A remarkable agreement between the experimental measurement and the simulation result was observed on the emittance growth, luminosity reduction, and coherent tune shifts. The simulation study also showed that the chaotic coherent beam-beam instability [4] could occur in HERA. It was found that when the beam-beam parameter of the electron beam exceeds a threshold that corresponds to an overlap of the electron beam with a low-order single-particle beam-beam resonance, the onset of the collective beam-beam instability results in an enhanced growth of the proton-beam emittance. After the onset of this collective beam-beam instability, the phase-space area near the origin (closed orbit) becomes unstable for beam centroids and two initially centered beams could develop a spontaneous chaotic coherent oscillation due to beam-beam interactions. A study of the dynamics of beam particle distributions showed that after the onset of the beam-beam instability, the distributions significantly deviate from Gaussian distribution due to beam halo. The formation of the beam halo is a result of chaotic transport (chaotic diffusion) of particles from beam cores to beam tails. In the HERA Upgrade, the beam-beam parameter of the positron beam is over 20 and 100 times larger than that of the proton beam in the horizontal and vertical direction, respectively, and the two rings have a very different working point. Traditionally, the beam-beam effect in such situation is considered as a typical strong-weak or very unsymmetrical case. For the strong-weak beam-beam interactions, it is commonly believed that the coherent beam-beam effects is not important. This study showed that the traditional boundary between the strong-strong and strong-weak beam-beam interactions is no longer valid in the nonlinear regime of beam-beam interactions. For high-intensity beams, the nonlinear beam-beam perturbation could dominate the beam dynamics and the collective beam-beam instability could therefore occur in both cases of strong-strong (symmetrical or nearly symmetrical) and strong-weak (very unsymmetrical) beam-beam interactions.

In the simulation, the linear HERA lattice with one or two IPs was used. The beam-beam interaction at each IP was represented by a kick in transverse phase space and the beam-beam kick was calculated by using particle-in-cell method with 5×10^5 macro-particles in each beam. The code used in this study is an expanded version of [4] that is currently capable of studying beam-beam effects of proton or lepton beams with any aspect ratio. The motion of particles was tracked in 4-dimensional transverse phase space without synchrotron oscillation and momentum deviation. For lepton beams, the quantum excitation and synchrotron damping are treated as kicks in each turn during the tracking [5].

NON-COLLECTIVE BEAM-BEAM EFFECTS

The beam experiment in HERA Accelerator Study 2000 studied the beam-beam effect at a very large beam-beam tune shift of the electron beam [1]. In the experiment, the vertical beam-beam parameter of the e^+ beam was varied from 0.047 to 0.272 by changing the vertical beta-function $\beta^*_{e,y}$ of the e^+ beam at IPs from 0.7 m to 4.0 m. Detailed experimental parameters can be found in Ref. [1]. In the experiment, the emittance of the e^+ beam after collision and the luminosity were measured as functions of $\beta^*_{e,y}$ at both HERA IPs, H1 and ZEUS. To have a better understanding of those measured data, we have reconstructed the HERA beam experiment with the beam-beam simulation. This study also served a detailed benchmark of our beam-beam simulation code with the experimental measurement.

Figure 1 plots the emittance growth of the e^+ beam and the specific luminosity as a function of $\beta^*_{e,y}$ measured in the experiment and calculated by the beam-beam simulation. For each $\beta^*_{e,y}$ where the measurement was performed, two data points correspond to the measurement at H1 and

* Supported by the US DOE under Grant No. DE-FG03-00ER41153.

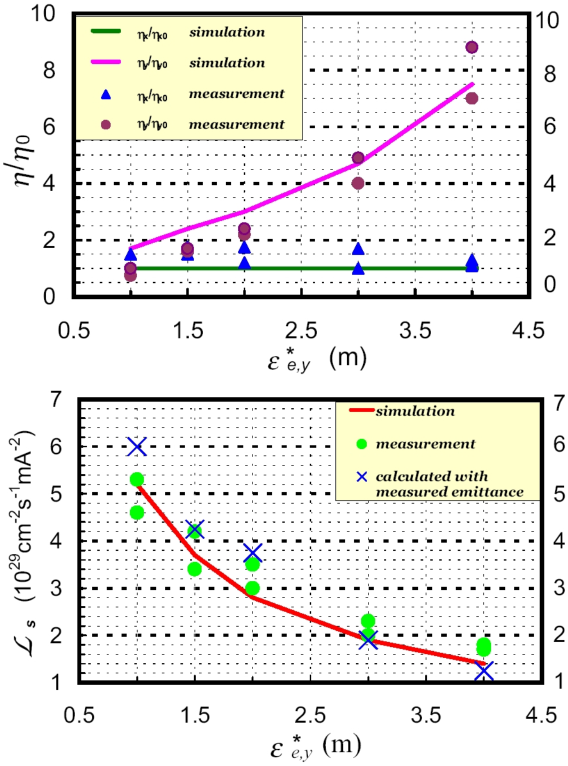

Figure 1: Emittance of the e^+ beam (upper figure) and specific luminosity (lower figure) v.s. $\beta^*_{e,y}$. ϵ_0 is the emittance without collision. Discrete points are from the experiment and continuous curves from the simulation. In the emittance plot, the upper (lower) curve is the vertical (horizontal) emittance.

Table 1: Coherent tune of the e^+ beam at $\beta^*_{e,y} = 4.0$ m. "Gaussian Beams" is the tune calculated with the measured e^+-beam emittances by using the derived formula for two non-symmetrical Gaussian beams

	ν_x	ν_y
Experiment	52.160	52.233
Simulation	52.162	52.232
Gaussian Beams	52.156	52.227

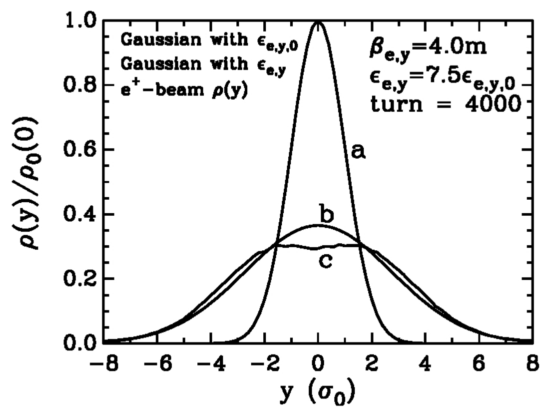

Figure 2: The vertical projection of the e^+-beam distribution at $\beta^*_{e,y} = 4.0$ m. (a) The initial beam distribution (Gaussian); (b) the Gaussian distribution with enlarged e^+-beam emittance; and (c) the e^+-beam distribution.

ZEUS, respectively. Both the emittance and the luminosity plot show a remarkable agreement between the experiment and the simulation. In the experiment, the coherent tune was also measured at $\beta^*_{e,y} = 4.0$ m. Table 1 lists the coherent tune measured in the experiment and calculated by the simulation and it shows a very good agreement between the experiment and the simulation. In order to understand such the small coherent tune shifts, the eigen-frequencies of the coherent oscillation was derived for the un-symmetrical case of beam-beam interaction based on the assumption of rigid Gaussian beams [2]. With the enlarged e^+-beam emittance in Fig. 1, however, the coherent tune calculated from the derived formula does not agree well with the experimental or simulation result (see Table 1). The discrepancy here is due to a non-Gaussian distribution of the e^+ beam. A study of the dynamics of particle distributions during the beam-beam simulation showed that the distribution of the e^+ beam deviated from a Gaussian distribution with a significant drop at beam core and a growth of beam tails (see Fig. 2). Compared with the distribution of the e^+ beam, a Gaussian beam has more particles in the core. The coherent beam-beam tune shift calculated from the derived formula is therefore larger than the real tune shift of the e^+ beam.

COLLECTIVE BEAM-BEAM INSTABILITY

Simulation has been conducted for the HERA Upgrade with two e-p collisions. When the working point of the e beam is at $\vec{\nu}_e = (54.14,\ 51.21)$, the onset of the chaotic coherent beam-beam instability results in an emittance blowup on the p beam and a significant luminosity reduction (see Fig. 3). Moreover, the two initially centered beams developed a spontaneous chaotic coherent oscillation (see Fig. 4). A study of the dynamics of beam-beam tune spread of the e beam showed that this collective beam-beam instability is due to an overlap of the e beam and the 4th-order resonance (see Fig. 5). It can be clear seen in Fig. 5 that many particles in the e beam are trapped inside the resonance. A simulation with a slightly different working point $\vec{\nu}_e = (54.072,\ 51.107)$ of the e beam was therefore performed. At this new working point, the e-beam is away from the 4th-order resonance. The beam centroid motion is stable and no significant emittance growth was observed on the p beam. Consequently, the luminosity is recovered to the design value (see Fig. 3). The collective beam-beam instability in this case can be therefore avoided by eliminating the crossings of major beam-beam resonance. To determine the threshold of the onset of the coherent beam-beam instability, the emittance growth of the p beam was studied as a function of bunch current of the p beam in the case of one interaction point. It was found that the threshold is at 50% design p-beam current. This further confirms the effect of the 4th-order resonance on the collective beam-beam instability since at 50% design p-beam current the e beam avoids the crossing of the 4th-order resonance. To verify the effect of the 4th-order resonance, a beam experiment was performed on HERA recently [3]. In the experiment, the emittance of the p beam and luminosity were measured and compared at two different working points of the e^+ beam. When the working point of the e^+ beam is at $\vec{\nu}_e = (0.140,\ 0.210)$, the e^+ beam does not cross any major beam-beam resonance. In this case, no significant emittance growth of the p beam and the luminosity reduction were observed. When the working point of the e^+ beam was moved to $\vec{\nu}_e = (0.215,\ 0.296)$, on the other hand, the e^+ beam overlaps with the 4th-order resonance and a more than 30% emittance growth was observed in both horizontal and vertical emittance of the p beam. We were able to reconstruct this experiment with the beam-beam simulation. The phenomena observed in the experiment agree well with that of the beam-beam simulation.

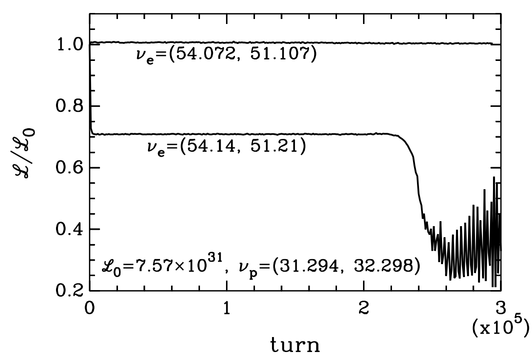

Figure 3: Luminosity in HERA Upgrade with two e-p collisions.

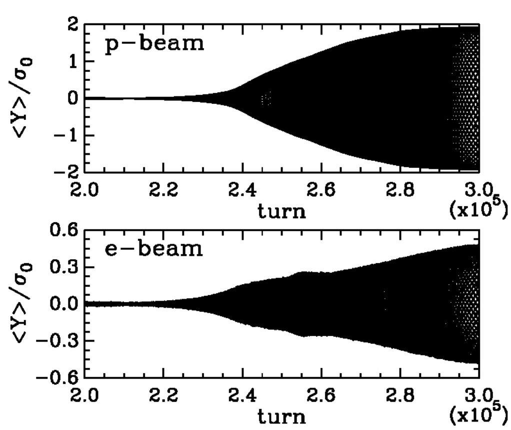

Figure 4: Chaotic coherent beam oscillation in HERA Upgrade with two e-p collisions at $\vec{\nu}_e = (54.14,\ 51.21)$.

Another aspect of the collective beam-beam instability is the importance of the beam-beam tune spread to the beam instability [6]. The simulation study suggested that having

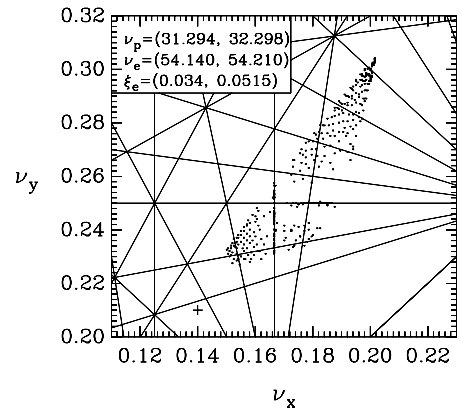

Figure 5: Tune spread of the e beam in HERA Upgrade with two e-p collisions when $\vec{\nu}_e = (54.14,\ 51.21)$.

a large beam-beam tune spread may benefit the stability of beams in certain situation. One such example is when the working point of the e^+ beam is such that the e^+ beam crosses only the 4th-order resonance of $2\nu_x + 2\nu_y = 1$ when there is one IP in the ring while crosses three 4th-order resonance lines including $2\nu_x + 2\nu_y = 1$ when there are two IPs in the ring. Note that the incoherent beam-beam tune shift as well as the beam-beam tune spread in the case of two IPs is about twice as large as that in the case of one IP. It was found in the simulation that the collective beam-beam instability occurs in the case of one IP but in the case of two IPs. Similar phenomenon has also been observed in the recent HERA experiment [3]. In the near-linear regime of beam-beam interactions, the beam-beam tune spread is the dominant beam-beam effect and a smaller beam-beam tune spread could benefit beams by reducing the possibility of resonance crossings. In the nonlinear regime of beam-beam interactions, however, the phase-dependent perturbation of beam-beam interactions could lead to the onset of the chaotic coherent beam-beam instability. In this situation, having a large tune spread could benefit the beam stability since the existence of a sizable tune spread is one of necessary conditions for the Landau damping that could suppress the coherent beam-beam instability and, moreover, the existence of a large tune spread reduces the possibility of trapping particles inside a bad resonances.

REFERENCES

[1] G.H. Hoffstaetter, *HERA Accelerator Studies 2000,* DESY HERA 00-07, (2000).

[2] G.H. Hoffstaetter, *HERA Accelerator Studies 1999,* DESY HERA 00-02, (2000).

[3] M. Minty, “ Summary of Recent Beam-Beam Experiments After the Luminosity Upgrade”, preprint, (2003).

[4] J. Shi and D. Yao, Phy. Rev. E**62**, 1258 (2000).

[5] K. Hirata and F. Ruggiero, CERN/LEP-TH/89-43 (1989).

[6] L. Jin and J. Shi, “Importance of Coherent Beam-Beam Effects to the Compensation of Beam-Beam Tune Spread in Hadron Colliders”, submitted to Phys. Rev. E, (2003).