Study of Beam-Beam Effects in HERA With Self-Consistent Beam Simulations*

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Abstract

By the luminosity upgrade for HERA, the horizontal and vertical beam-beam parameter of the electron beam have approximately doubled. To examine any possible luminosity reduction due to beam-beam effects, several beam experiments were performed [1]. In order to have a better understanding of those experimental data and to evaluate the beam-beam effect in the HERA upgrade, a self-consistent beam-beam simulation in HERA was conducted by using one million macro-particles with the particle-in-cell method. The dynamics of beam-size growth and the stability of the coherent beam-beam oscillation were studied. A remarkable agreement between the experimental measurement and the simulation result was observed. For the current HERA upgrade parameters, the simulation showed that the beam-beam interaction could induce a chaotic coherent beam-beam instability that could result in emittance blowup and roughly 50% luminosity reduction. HERA could easily be affected by this instability since it depends sensitively on the working-point. In the HERA upgrade, the horizontal beam-beam parameter of the electron beam is over 25 times larger than that of the proton beam and the two rings have a very different working point. Traditionally, the beam-beam effect in HERA is considered as a typical strong-weak or highly un-symmetrical case. But for high intensity beams, nonlinear beam-beam effects could dominate the beam dynamics and results in a coherent beam-beam instability even in a strong-weak situation.

INTRODUCTION

With a length of 6335m, HERA is the largest accelerator at DESY in Hamburg. It provides collisions between a 920GeV proton beam and a 27.5GeV polarized electron or positron beam and supplies four high energy physics experiments. Since all data that will be shown has been obtained with positrons, we only refer to positrons in the following, even though HERA can also accelerated electrons. H1 and ZEUS are the world's only high-energy e/p collider experiments; and here we will be concerned with the beam-beam force in their interaction points.

After the design luminosity of the electron-proton collider HERA had been exceeded [2, 3], the interaction regions were rebuilt to obtain smaller β^* at the two interaction points (IPs) [4]. In order to focus the proton beam stronger in the experimental region, the positron beam has to be separated from the proton beam as early as possible. Whereas the first proton quadrupole had been 26m after the IP, this distance is now 11m. Additionally the upgrade project included 60m long spin rotators at both sides of the H1 and ZEUS detectors. The complete upgrade involved 448m of new vacuum pipes, 4 superconducting magnets for early separation of the e and p beams inside the detectors with a distance of only 2m from the IP, and 54 normal conducting magnets. The desired increase in specific luminosity was quickly obtained after the upgrade of the interaction regions (IRs) [5], but operating the detectors with full beam currents has not been possible due to too large background signals in H1 and in ZEUS. Currently a number of improvements are being implemented to reduce this background.

Table 1: HERA after the lumi upgrade

Parameters	HERA-e	HERA-p
E(GeV)	27.5	920
I(mA)	58	140
$N_{ppb}(10^{10})$	4.0	10.3
β_x^*(m)	0.63	2.45
β_y^*(m)	0.26	0.18
ϵ_x(nm)	20	5000/γ
ϵ_y/ϵ_x	17%	1
σ_x/σ_y(μm)	112/30	112/30
σ_z(mm)	10.3	191
$2\Delta\nu_x$	0.068	0.0031
$2\Delta\nu_y$	0.103	0.0009

BEAM-BEAM EXPERIMENTS

Since the vertical beam-beam tune shift of the lepton beam will increase by 50% compared to the year 2000 operation, when nominal proton currents are filled, the tune shift limit has been explored with the old IRs by increasing the positrons' β^*_{ey} [1, 6]. Values of $\beta^*_{ex} = 2.5$m (corresponding to the expected horizontal tune shift with 140mA of protons) and β^*_{ey} =1m,1.5m,3m, and 4m have been implemented and collided with a 90mA proton beam. The e and p beam sizes were not matched. We observed a monotonically increasing blow-up of the vertical lepton emittance with increasing β^*_{ey} by factors up to 8 as shown in Fig. 1 (top). At the value of $\beta^*_{ey} = 1.5$m which corresponds to a vertical beam-beam tune shift of 0.069, the blow-up factor was 1.5. Figure 1 (bottom) shows the measured specific luminosity and the luminosity computed from the measured beam emittances. The lifetime and operation conditions were good even with the tune shift of 0.5. This is probably due to a depopulation of the bunch center so that the tune spread is less than it would be for a Gaussian beam. This is also indicated by the fact that the shift in the coher-

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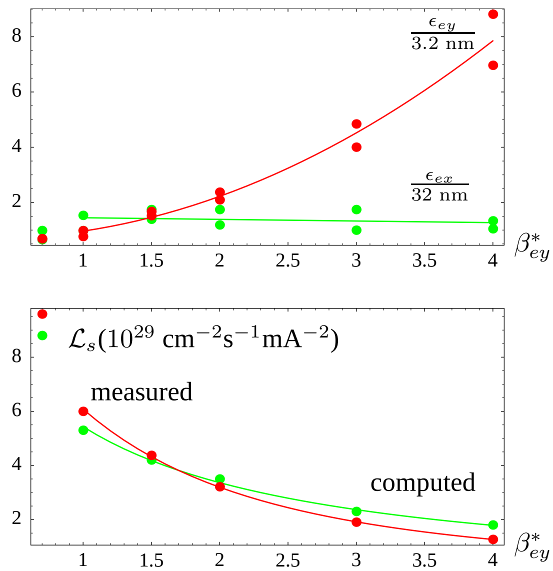

Figure 1: Top: Measured emittances of the lepton beam as a function of the vertical beta function. Bottom: Measured and computed specific luminosity.

ent oscillation frequency for $\beta^*_{ex} = 2.5$m and $\beta^*_{ey} = 4$m was measured to be only $\Delta\nu_x = 0.009$ and $\Delta\nu_y = 0.013$ while it would be $\Delta\nu_x = 0.027$ and $\Delta\nu_y = 0.082$ if both beams were Gaussian. The latter values were computed with a simple formula for the coherent beam-beam tune shift for Gaussian beams of unequal sizes [7] in the weak-strong limit, i.e. under the assumption that the proton beam acts as a fixed nonlinear lens. The here presented simulations with the specified beam parameters have yielded a coherent tune shift of $\Delta\nu_x = 0.003$ and $\Delta\nu_y = 0.013$. While the horizontal tune shift is close to the resolution of the calculation and therefore not very trustworthy, the agreement of the vertical tune shift with the measurement is quite remarkable.

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