CALCULATIONS ON DEPOLARIZATION IN HERA DUE TO BEAM-BEAM EFFECTS

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Abstract

Polarized beams will play an important role in the HERA physics program in the next years. First, the HERMES experiment will use longitudinally polarized electrons (or positrons) for collisions with a polarized gas target while at the detectors H1 and ZEUS these particles undergo collisions with the proton beam in a transversely polarized state. Later, spin rotators will be installed around the H1 and ZEUS experimental regions, allowing for collisions of longitudinally polarized electrons/positrons with the proton beam. Measurements show that for present HERA beam intensities the beam-beam effect does not reduce polarization by more than 5%. We present calculations using the spin tracking code SITROS which explore depolarization due to beam-beam effects towards higher beam intensities and luminosity.

I. INTRODUCTION

Beam collisions in HERA occur at the two interaction points of the experiments H1 and ZEUS. The transverse dimensions of electron[1] and proton beams have to be matched, otherwise the lifetime of the proton beam would suffer. Especially the naturally small vertical size of the electron beam has to be increased. For that purpose, vertical beam bumps are used to increase vertical dispersion at bending magnets and thus vertical emittance. About 10% of emittance coupling (ratio between vertical and horizontal emittance) is needed to match the height of the proton beam.

The strength of the beam-beam interaction is characterized by the vertical tune-shift parameter of the electron beam:

$$\xi_z = \frac{N r_e}{\gamma} \cdot \frac{\beta_{zIP}}{2\pi \sigma_{zIP} \, (\sigma_{xIP} + \sigma_{zIP})}$$

where x and z are the horizontal and vertical coordinates, N denotes the number of particles per proton bunch, r_e is the classical electron radius and γ the Lorentz factor.

A beam-beam tune shift of $\xi_z = 0.04$ is generally considered to be the performance limit, at present luminosities typical values of 0.01-0.02 are reached. For the calculations presented in this paper, the optics and beam sizes at the IP remain constant, so ξ_z is only a function of the bunch charge. For the optics we used, a tune shift of 0.04 corresponds to single bunch currents of 0.5 mA.

II. THE COMPUTER MODEL

The spin tracking code SITROS[3] traces an ensemble of particles through sections of the storage ring, simulating the emission of synchrotron radiation between sections. Orbit motion and the variation of the spin rotation axis and angle through a section are calculated to second order, the rotation of the spins around these axes is treated correctly to all orders. The polarization is calculated as a function of time by taking the vector sum of the tracked particles spins. An exponential fit to these numbers then yields a depolarization time constant τ_d. The equilibrium polarization is then calculated from

$$P_{eq} = P_{ST} \frac{1}{1 + \frac{\tau_p}{\tau_d}}$$

where P_{ST} is the Sokolov-Ternov level[2] and τ_p the polarization rise time.

In SITROS, a so called 'weak-strong' model is used to describe the beam-beam interaction. The particles of the tracked beam experience the oncoming beam as a fixed gaussian charge distribution. The resulting particle deflections are treated in a thin lense approximation:

$$\begin{aligned} \Delta x' &= \tfrac{2Nr_e}{\gamma} x \int_0^\infty \sqrt{q_x^3 \cdot q_z} \exp\left(-\tfrac{x^2}{q_x} - \tfrac{z^2}{q_z}\right) dq \\ \Delta z' &= \tfrac{2Nr_e}{\gamma} z \int_0^\infty \sqrt{q_x \cdot q_z^3} \exp\left(-\tfrac{x^2}{q_x} - \tfrac{z^2}{q_z}\right) dq \end{aligned} \qquad (1)$$

with $q_x = 2\sigma_x^2 + q$ and $q_z = 2\sigma_z^2 + q$.

Since the 820 GeV proton beam is much more rigid than the 27.5 GeV electron beam and the particle deflections per bunch crossing are small, this model should be adequate.

III. SIMULATION RESULTS

The following results are calculated for the HERA electron ring with an energy of 27.52 GeV, the betatron tunes are 47.1 in the horizontal plane and 47.2 in the vertical. The synchrotron tune is 0.06 with a total gap voltage of 125 MV. The optics is the luminosity optics used in this years running period. One pair of spin rotators provides longitudinal polarization for the HERMES experiment.

Care was taken not to be dominated by vertical emittance growth due to orbit resonances. For each calculation, the tunes were empirically fine-tuned to keep the vertical emittance stable and matched to the proton beam as close as possible, just as it would be done in real machine operation.

The results are presented as energy scans over a range of about 440 MeV around the operating energy, corresponding to a spin tune range of one integer. The spin tune, which is plotted on the horizontal axes, is, in an ideal planar storage ring without spin rotators, the number of spin precessions around the magnetic field axis in the bending magnets and is given by $\nu_s = a\gamma$. On the vertical axes, the results for equilibrium polarization are plotted. The dotted lines are first order polarization calculations using a matrix algorithm[4]. The points with error bars connected with a solid line are tracking results from SITROS.

In figure 1 the HERA electron storage ring is modeled with realistic imperfections, the simulation with the present running

[1]HERA collides electrons or positrons with protons. Throughout the paper, we will only refer to electrons, but everything also holds for positrons.

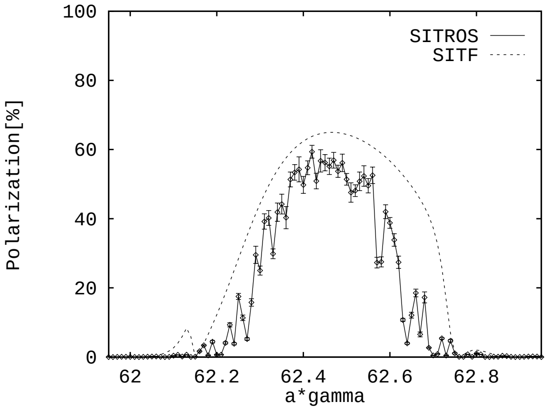

Figure. 1. HERA electron ring with realistically modeled imperfections with a beam-beam tune shift of 0.01

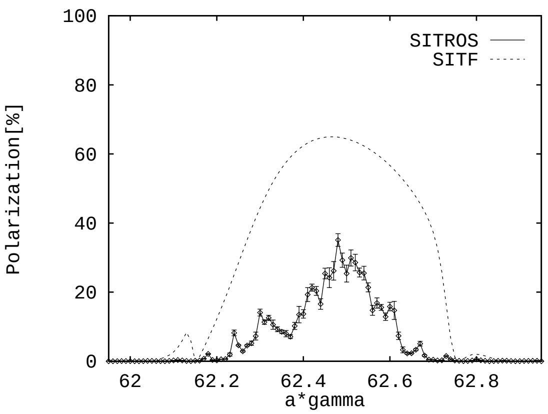

Figure. 2. HERA electron ring with realistically modeled imperfections at the beam-beam limit (ξ_z=0.04).

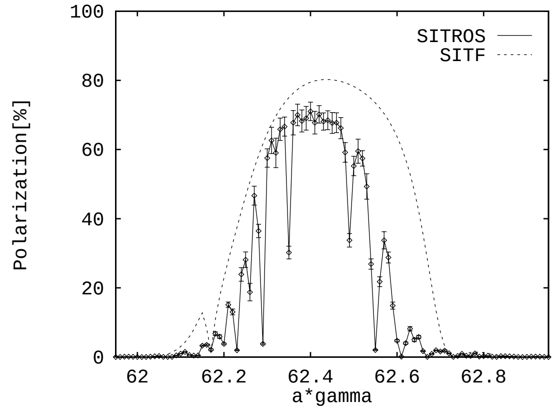

Figure. 3. HERA electron ring without imperfections but with dispersion generating vertical bump. No beam-beam effect.

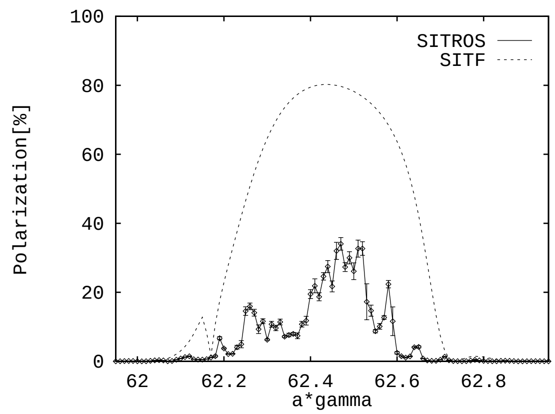

Figure. 4. HERA electron ring without imperfections but with dispersion generating vertical bump at the beam-beam limit (ξ_z=0.04).

conditions agree within a few percent with polarization measurements. The beam-beam tune shift is 0.01. Figure 2 shows the same machine operating at the beam-beam limit, with 0.5 mA current per proton bunch and a beam-beam tune shift of ξ_z=0.04.

Figure 3 shows a calculation for the HERA electron ring without imperfections, only the vertical dispersion bump presently used in the real machine generates vertical emittance. The beam-beam effect is less than 0.01 in this calculation. Although polarization is improved at low currents (compared to the realistic machine in figure 1), figure 4 shows that at the beam-beam limit the equilibrium polarization is not higher than in the realistic machine (figure 2).

In figure 3, the linear calculation shows that the first order synchrotron resonances are strong. We optimized the harmonic content of the dispersion trajectories[5] to weaken the synchrotron resonances and side bands. Figure 5 indeed shows a further improvement for the low current case, both width and height of the polarization plateau improved compared to figure 3. The curve labeled 'SITF Ideal' is the first order result for a perfect machine with one spin rotator pair without dispersion bumps.

Figure 6 shows a somewhat artificial result in that only one of the two ways the beam-beam force acts on the spins is taken into account: the spins of the particles are rotated according to fields experienced in the colliding bunch, but the particle orbit is artificially left untouched. Therefore, the spins do not experience additional fields and rotations in the quadrupoles and sextupoles around the ring due to a slightly changed particle trajectories.

In figure 7, the full effect of the beam-beam force is applied, like in figures 2 and 4. Still an improvement can be seen in comparison with figure 4. The polarization peaks at 45% instead of 35%.

Figure 8 gives an overview of measured and simulated equilibrium polarization versus beam-beam tune shift in the HERA electron ring. The simulation results are averaged values for the polarization 'plateaus'. The simulation results indicated with circles are calculated for the machine with realistic imperfections like in figures 1 and 2. The triangular point is the improved result with an optimized harmonic content of the vertical dispersion trajectories.

IV. CONCLUSION AND OUTLOOK

Without measures taken SITROS indicates a loss of about 20% of polarization if the operating currents of HERA are increased towards reaching the beam-beam limit with the present optics. An optimization of the harmonic content of the vertical dispersion trajectories improves polarization by about 10%. Further work will concentrate on pushing this gain further and to inves-

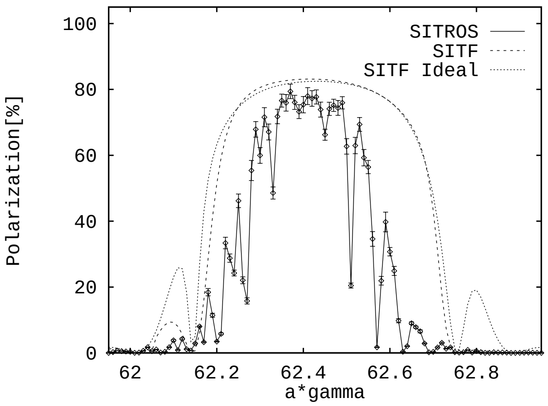

Figure. 5. HERA electron ring with improved dispersion generating vertical bump with optimized spin harmonic content, no beam-beam effect.

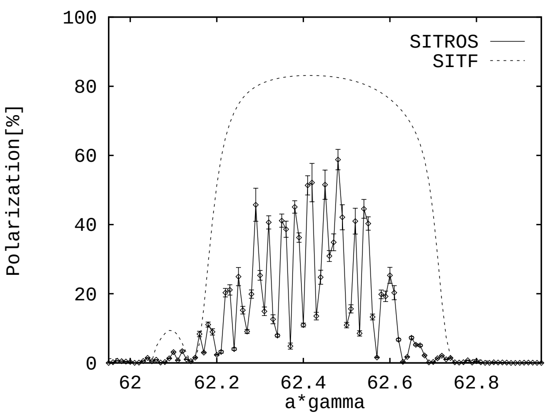

Figure. 6. HERA electron ring with improved dispersion generating vertical bump with optimized spin harmonic content at the beam-beam limit (ξ_z=0.04). Only the spins are deflected by the beam-beam force, not the particle trajectories.

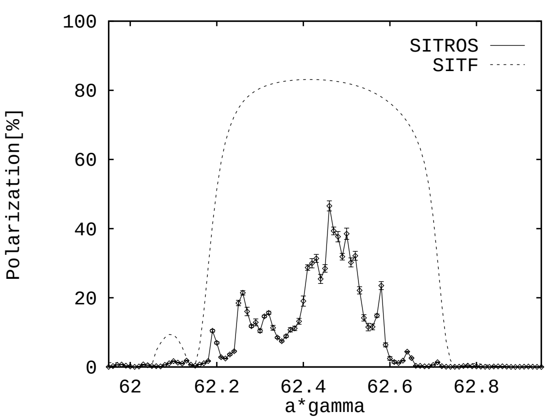

Figure. 7. HERA electron ring with improved dispersion generating vertical bump with optimized spin harmonic content, at the beam-beam limit (ξ_z=0.04).

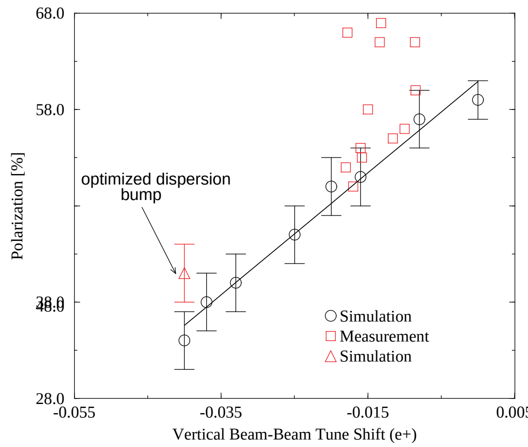

Figure. 8. Polarization versus ξ_z for a machine with realistic distortions. Simulation (SITROS) results and measurements made in 1994 [1] are shown.

tigate a possible cancellation between the direct spin kick at the IP and the integrated kick due to the subsequently different orbit [6].

V. ACKNOWLEDGMENTS

We would like to thank Drs. D.P. Barber and R. Brinkmann for fruitful discussions.

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