A Simulation Study for the Beam-Beam Interaction of Protons with a Flat Electron Beam in HERA

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Abstract

The results of a particle tracking study for the interaction of protons with a flat ($\varepsilon_z/\varepsilon_x = 0.04$) electron beam in HERA are presented. The simulation takes transverse beam separation, linear coupling and random tune modulation into account. For tunes in a region free of resonances up to 10th order a significant growth of proton emittance after tracking over up to several 10^6 turns is observed. Some implications for the HERA interaction parameters and luminosity are discussed.

1 Introduction

In context with studies of spin polarization in the electron ring of the HERA e-p collider, (presently under construction at DESY), it has been pointed out that the electron beam emittance has to be kept as small as possible for a high degree of polarization [1,2]. Although the mechanisms responsible for the correlation between large vertical emittance and small degree of polarization are not yet quite clear and the possibility of having both a "round" beam and polarization is still discussed [2,3], one may have to face the situation where the protons would collide with a very flat electron beam (see Table 1). According to experience made at CERN [4,5] in such a case of unmatched beams, the larger one can be blown up by high order non-linear resonances driven by the space charge force of the opposing smaller one. In order to get an idea of how severe these effects might be in HERA, a simulation study for the "flat beam" situation was done. The simulation procedure is described in the following chapter. After that the results are presented and finally some implications for HERA are discussed.

	protons	electrons
β_x^*	10.0	2.0
β_z^*	1.0	0.7
σ_x	0.27 mm	0.27 mm
σ_z	0.08 mm	0.03 mm
N_b	1.0×10^{11}	3.7×10^{10}
ΔQ_x(perIP)	0.0013	0.016
ΔQ_z(perIP)	0.0012	0.018

Table 1: HERA interaction parameters with a flat ($\varepsilon_z/\varepsilon_x = 4$ %) electron beam. A Proton emittance of 30 π mm $\times$ mrad (normalized, 2 σ) and $E_e = 30$ GeV, $E_p = 820$ GeV is assumed.

2 Simulation Procedure

The simulation is performed by tracking an ensemble of 10^3 protons with initial Gaussian distribution (σ's as in Table 1) over up to 3×10^6 turns (about 1 min of real time in HERA) and recording the time evolution of emittance and luminosity. In this weak-strong approximation, a time-independent Gaussian distribution is assumed for the electron beam and the three interaction points of HERA are concentrated in one (with triple beam-beam strength, $\Delta Q \approx 0.004$). The ring is represented by a single (linear) 4×4 transfer matrix with off-diagonal elements resulting from a skew quadrupole component which simulates a coupling resonance of width $W(Q_x - Q_z) = 2.5 \times 10^{-3}$.

$$M_i = \begin{pmatrix} \cos\mu_{x,i} & \beta_x \sin\mu_{x,i} & k_s\beta_x \sin\mu_{x,i} & 0 \\ -\sin\mu_{x,i}/\beta_x & \cos\mu_{x,i} & k_s \cos\mu_{x,i} & 0 \\ k_s\beta_z \sin\mu_{z,i} & 0 & \cos\mu_{z,i} & \beta_z \sin\mu_{z,i} \\ k_s \cos\mu_{z,i} & 0 & -\sin\mu_{z,i}/\beta_z & \cos\mu_{z,i} \end{pmatrix} \quad (1)$$

$$\mu_{x/z,i} = 2\pi Q_{x/z,i} \quad (2)$$

The interaction with the electron beam is simulated by giving each particle kicks $\delta x'$, $\delta z'$ which are calculated using the complex error function representation of the space charge force for a

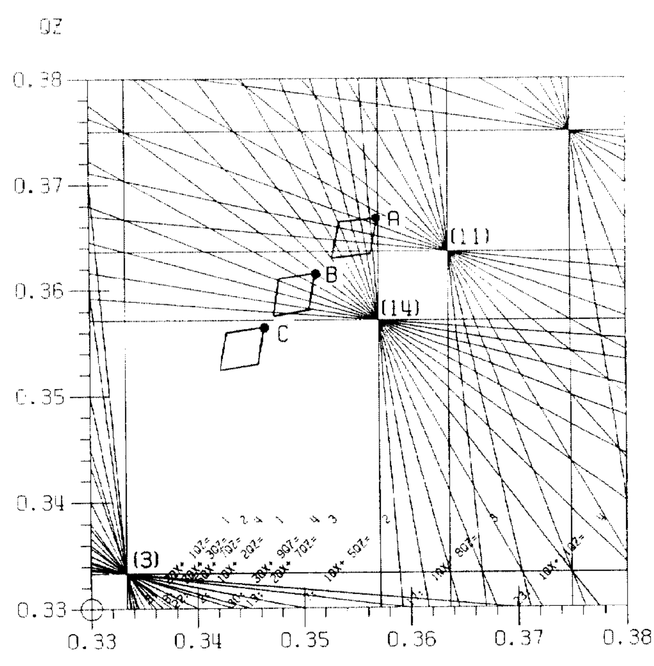

Figure 1: Diagram of sum resonances up to 14th order. Tracking simulations have been done for the three tunes denoted by A, B, C.

Gaussian beam [6]. In order to avoid look-up tables and problems of non-continuous derivatives of interpolation procedures, the complex error function is approximated by elementary functions (see [7] for details).

Special attention is paid to the importance of an external modulation of parameters, which occurs in a real machine due to various kinds of "noise". A random drift of the tunes is simulated by changing the Q-values from turn to turn such that

$$Q\,(\mathrm{turn}\,\#\,i) = Q_0 + \Delta Q_i \tag{3}$$

with

$$\langle \Delta Q_i^2 \rangle^{\frac{1}{2}} = 5 \times 10^{-4}, \; \langle \Delta Q_i \rangle = 0 \tag{4}$$

and

$$\langle \Delta Q_i \Delta Q_j \rangle = \langle \Delta Q_i^2 \rangle \times \exp\left(-\frac{|j-i|}{n_c}\right) \tag{5}$$

where the correlation length of the random tune modulation is set to $n_c = 10^4$ (see ref. [7]). Such a random modulation of the Q-values turns out to be much more dangerous than a modulation with a single frequency (e.g. the synchrotron frequency, if the chromaticity is not perfectly compensated), see below. The drift of the tunes Q_x and Q_z is assumed to be independent and the Matrix M_i is recalculated after each turn.

Another external modulation which is specific for a two-ring collider has been taken into account. Due to ground motion (and possibly also due to correction power supply drifts), the closed orbits in the electron and the proton ring will vary with time such that a time-dependent transverse beam separation at the interaction points results. This effect is simulated by changing the transverse beam separation after each turn using data of an orbit motion measurement that was taken in the HERA electron ring during the last commissioning run [8]. This transverse separation (typically a few tenth of $\sigma_{x,z}$) destroys the symmetry of the space charge force seen by the protons and leads to the additional excitation of odd order resonances.

3 Results

The simulation was done for three different tunes in the region between the 3rd and the 8th order resonance which is clear of all sum-resonances of up to order 10 (Fig. 1). The results for the emittance growth rate and the luminosity lifetime are summarized in Table 2. In case of tune A (overlapping 11th and 14th order resonances) a rapid diffusive growth of the proton beam emittance is observed (Fig. 2), and after 10^6 turns the particle distribution in the vertical plane has developed tails, indicating a strong dependence of emittance growth rate on particle amplitude (Fig. 3). Therefore the decrease in luminosity is much slower than the increase of average particle emittance (Fig. 2). Remarkably, the emittance diffusion completely disappears if the tune modulation is switched off and it goes down by about an order of magnitude if the random modulation is replaced by a harmonic modulation with the synchrotron frequency (see Table 2).

For tunes B and C, the emittance growth rates are much smaller but still statistically significant after tracking over 3×10^6 turns (Table 2). For tune C, however, the estimated luminosity lifetime is rather uncertain due to the poor statistics. As in the case of tune A, the major part of emittance growth occurs in the vertical plane, but the difference between the two planes is less pronounced.

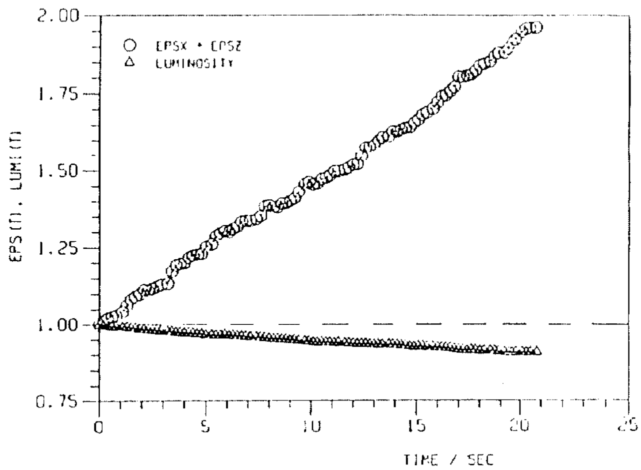

Figure 2: Time dependence of average proton emittance and luminosity over 10^6 turns for tune A. About 90 % of the emittance growth occurs in the vertical plane.

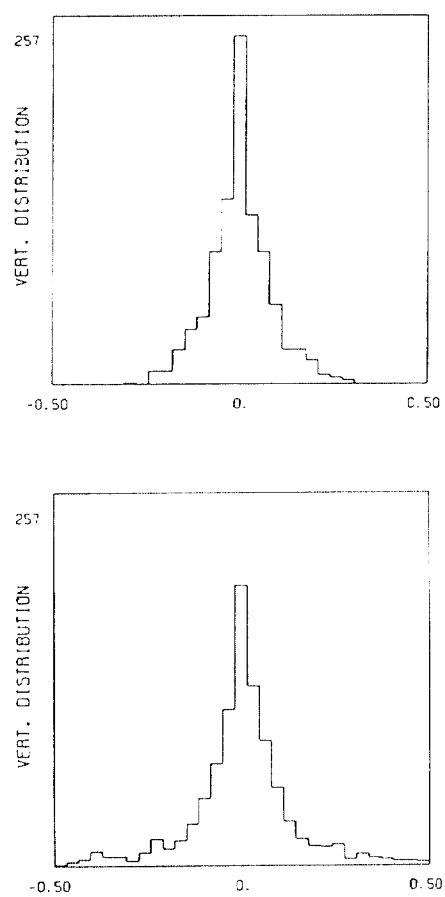

Figure 3: Initial (upper) and final (lower, after 10^6 turns) particle distribution in the vertical plane.

tune	$\frac{\Delta\epsilon}{\epsilon}/\Delta t$	$\frac{\Delta L}{L}/\Delta t$	remarks
A	$4.6 \times 10^{-2}s^{-1}$	$-5 \times 10^{-3}s^{-1}$	with random tune modulation,
B	$1.2 \times 10^{-2}s^{-1}$	$1 \times 10^{-3}s^{-1}$	time-dependent transverse
C	$\approx 0.2 \times 10^{-2}s^{-1}$	$\approx -5 \times 10^{-4}s^{-1}$	separation
A	$\approx 4 \times 10^{-3}s^{-1}$		constant separation, harmonic tune modulation with $Q_s = 10^{-3}$, amplitude 5×10^{-4}
A	$< 10^{-3}s^{-1}$	--	no tune modulation

Table 2: Summary of simulation results

4 Discussion

As the simulation results indicate, the luminosity lifetime in HERA can be severely limited by the beam-beam interaction with unmatched electron and proton beam sizes. Although some of the model assumptions are rather crude (e.g. the pessimistic approximation of a single interaction point with triple ΔQ), one may express some doubts whether a working point with sufficient proton beam lifetime ($>$ 10 hours) can be found under these circumstances. If it turns out that the vertical electron emittance cannot be increased without reducing the degree of polarization, decreasing the vertical β^* for the protons at the interaction point would probably be the most effective way of reducing the proton emittance growth rate (keeping the luminosity constant, the electron beam current could be reduced such that approximately $\Delta Q_z \approx \beta_z^{*3/2}$, and the beam size mismatch would be reduced at the same time). From the point of view of chromaticity this should not be a problem, but the relatively small aperture in the low β quadrupoles could present a more severe limitation (increased background in the experiments due to particle losses at the aperture limit [9]). Experience will show whether the proton collimator system [10] can be effective enough to suppress the background. In addition, a compensation of the time-dependent transverse beam separation with an orbit feedback system could help to increase the space available in the tune diagram for a "good" working point by suppressing the odd-order resonances.

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