EE

DESY HERA 95-10
December 1995

HERA-B Interaction Rate versus Luminosity at ZEUS and H1

M. Seidel

Deutsches Elektronen Synchrotron DESY
Hamburg, Germany

HERA-B Interaction Rate versus Luminosity at ZEUS and H1

M. Seidel

December 18, 1995

1 Introduction

Originally the HERA-B experiment was intended to run "parasitically". It was planned to make use of halo-protons which are going to be lost anyway and which would not contribute anymore to the ep luminosity at the detectors ZEUS and H1. However, in the meantime it turned out that very large lifetimes can be achieved in the proton machine and consequently the natural diffusion rate in the beam is often much to small for a sufficient interaction rate at HERA-B. This has two consequences – firstly the beam has to be scraped with the HERA-B wires continuously to keep the desired interaction rate and secondly the interaction rate on the wires tends to becomes very sensitive to small beam oscillations in the range of micrometers. This is due to the the sharp edge in the beam distribution which is produced by the scraping process and which stays sharp due to the often low diffusion rate.

In this note the effective luminosity reduction for the ep experiments due to HERA-B is estimated and possibilities to stabilize the HERA-B rate are considered. It will turn out that the integrated luminosity for a typical HERA run with one proton fill will not be reduced considerably, although HERA-B eats up a relatively large part of the proton beam during the run. Furthermore it seems to be possible to stabilize the interaction rate already with a small white noise excitation of the proton beam which would not disturb the beam core.

2 Proton Beam Scraping and Luminosity

As a basis for a typical future run of HERA we use the parameters given in table 1. For simplicity, but also in the spirit of a worst case estimate, the natural diffusion in the proton beam is assumed to be negligible, i.e. infinite lifetime. The initial proton and electron beam distributions are Gaussian. In order to achieve and maintain the desired interaction rate HERA-B will move the wire

proton current	$I_p = 100$ mA
HERA-B interaction rate	$\nu_{int} = 40$ Mhz
HERA-B efficiency	$\eta_{HB} = 70\%$
inititial e^+ current	$I_e = 35$ mA
initial e^+ beam lifetime	$\tau_e = 7.8$ h
run duration	$T_R = 12$ h

Table 1: Selected parameters for a typical future run. It is assumed that both beams are refilled after a run. The HERA-B efficiency is the ratio of the inelastic interaction rate on the wires to the total proton loss rate caused by scattering in the wires.

targets continuously inwards in both planes. We consider here the proton beam distribution in terms of the action variables $I_{x,y}$. The particle action I is a constant of motion in Hamilton treatment and is connected with the Betatron oscillations in the following way: $x(s) = \sqrt{2I\beta(s)}\cos(\phi(s) - \phi_0)$. Here s is the longitudinal path length, $\phi(s)$ the particle phase, $\beta(s)$ is the so called beta-function which can be interpreted as local wave length of the oscillation and ϕ_0 is the second constant of motion. All particles with actions $I_{x,y}$ beyond the amplitudes defined by the wires $I^{max}_{x,y} = d^2_{x,y}/(2\beta_{x,y})$ will be removed from the beam within a few thousand turns, i.e. in a time which is short compared to the beam lifetime. Here it is convenient to express the distances of the wires to the closed orbit in units of beam sigma: $d_{x,y} = n_{x,y}\sigma_{x,y}$.

The resulting beam distribution in action as a function of the wire positions is then:

$$f(I_x, I_y) = \frac{\beta_x\beta_y}{\sigma_x^2\sigma_y^2} e^{-\left(\frac{I_x\beta_x}{\sigma_x^2} + \frac{I_y\beta_y}{\sigma_y^2}\right)} \; \Theta\left(\frac{n_x^2\sigma_x^2}{2\beta_x} - I_x\right) \; \Theta\left(\frac{n_y^2\sigma_y^2}{2\beta_y} - I_y\right). \qquad (1)$$

where the stepfunctions $\Theta(\ldots)$ account for the fact that the particle density is zero beyond the wire-defined amplitudes $\beta_{x,y}$ and $\sigma_{x,y}$ are beta-functions and beam sizes at the location of HERA-B. The projection on the xy-plane can be derived by integration and yields:

$$\begin{aligned} f(x,y) &= \int\int f(x,x',y,y')dx'dy' \\ &= \frac{4\beta_x\beta_y}{\sigma_x^2\sigma_y^2}\int_{x'=0}^{x'_{max}}\int_{y'=0}^{y'_{max}} e^{-\left(\frac{x^2+x'^2\beta_x^2}{\sigma_x^2}+\frac{y^2+y'^2\beta_y^2}{\sigma_y^2}\right)}dx'dy' \qquad (2) \\ \text{with} \quad (x',y')_{max} &= \frac{\sqrt{n_{x,y}^2\sigma_{x,y}^2 - (x,y)^2}}{\beta_{x,y}} \end{aligned}$$

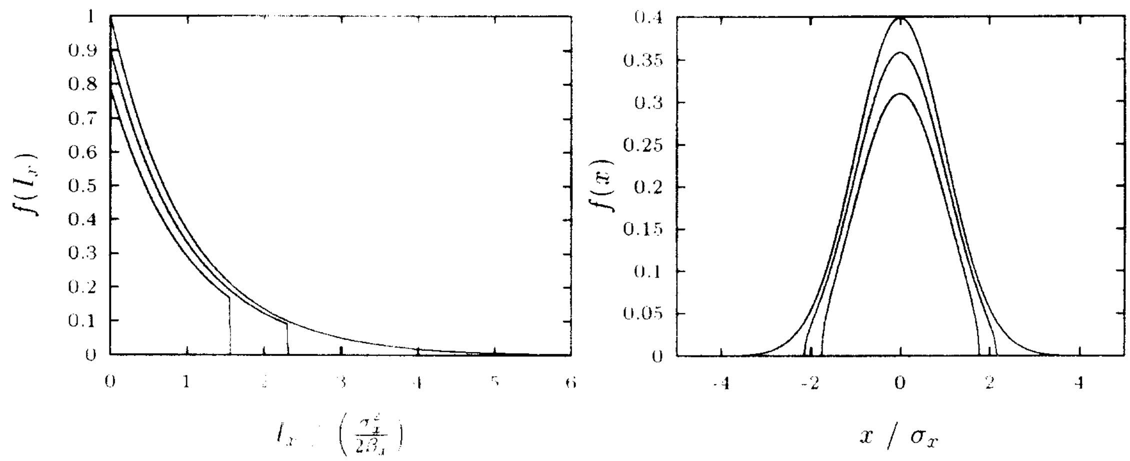

Figure 1: Examples for beam distributions after 0.05, 12, 24 hours, left side action dependent and projected on I_x, right side projected on x-axis. The decay in the core of the I_x dependent distribution is due to the simultaneous scraping in I_y.

$$f(x,y) \quad = \quad \frac{1}{2\pi\sigma_x\sigma_y}\,\mathrm{erf}\left(\sqrt{\frac{n_x^2 - x^2/\sigma_x^2}{2}}\right)\mathrm{erf}\left(\sqrt{\frac{n_y^2 - y^2/\sigma_y^2}{2}}\right)\,e^{-\left(\frac{x^2}{2\sigma_x^2}+\frac{y^2}{2\sigma_y^2}\right)} \tag{3}$$

Examples for distributions in I_x and x are shown in Fig. 1. From (1) the number of remaining particles as well as the loss rates in x and y can be calculated by integration of the distribution up to $I_{x,y}^{max}$:

$$\begin{aligned} N(t) &= N_0\left(1 - e^{-n_x^2(t)/2}\right)\left(1 - e^{-n_y^2(t)/2}\right) \\ \dot{N}_{x,y}(t) &= N_0\,\dot{n}_{x,y}(t)n_{x,y}(t)e^{-n_{x,y}^2(t)/2}\left(1 - e^{-n_{y,x}^2(t)/2}\right). \end{aligned} \tag{4}$$

If one demands equal and constant rates in both planes the wires have to be moved inwards according to:

$$n_x(t) = n_y(t) = \sqrt{-2\ln\left(1 - \sqrt{1 - \frac{\nu_{loss}}{N_0}t}\right)}. \tag{5}$$

Here $\nu_{loss} = \nu_{int}/\eta_{HB}$ is the total necessary loss rate in both planes. The corresponding position curve is shown in Fig. 2 for the parameters of table 1. After a running time of 12 hours 19 % of the beam are scraped away. Now we investigate the consequences of these scraping losses on the luminosity at ZEUS and H1, compared to the case without HERA-B. The luminosity for two beams with arbitrary transverse distributions is given by:

$$L = f_{rep}N_1N_2\int\int dx\,dy\,f_1(x,y)f_2(x,y). \tag{6}$$

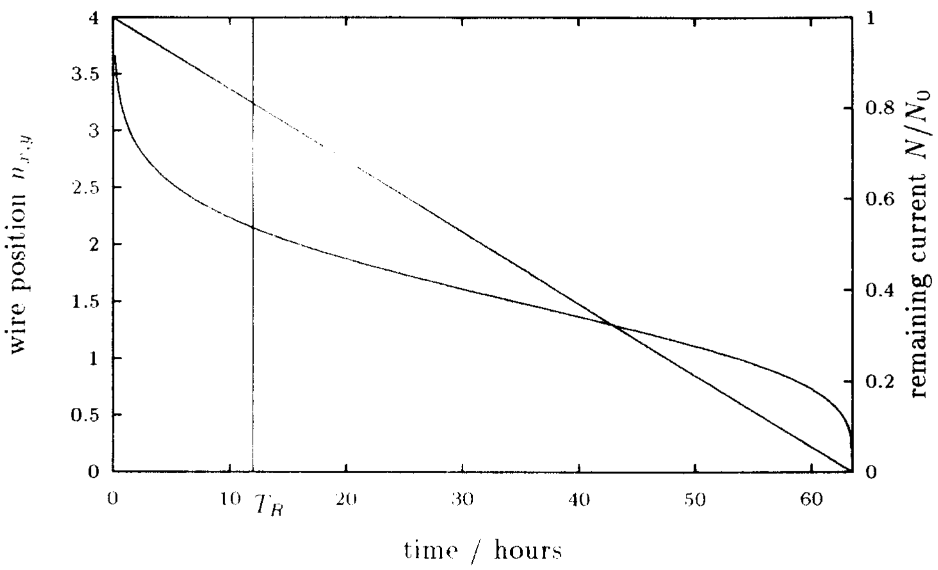

Figure 2: Wire position in units of beam-sigma (left scale) and relative beam loss (right scale, straight curve) as function of time. The endpoint of a typical run is marked.

If we insert now a Gaussian distribution for the electrons and the distribution (3) for the protons we obtain [1] :

$$L(t) \approx \frac{f_{rep} N_e(t) N_p(t=0)}{2\pi\sigma_x^e\sigma_y^e} \; \frac{\left(1 - e^{-\sqrt{1+a_x^2}\frac{n_x^2(t)}{2}}\right)\left(1 - e^{-\sqrt{1+a_y^2}\frac{n_y^2(t)}{2}}\right)}{\sqrt{(1+a_x^2)(1+a_y^2)}}. \qquad (7)$$

Here $\sigma^e_{x,y}$ are the dimensions of the electron beam and $a_{x,y} = \sigma^p_{x,y}/\sigma^e_{x,y}$ the matching ratios of proton- and electron beam sizes. The more general case of equation (7) is simplified if we assume matched beams $a_x = a_y = 1$ and $n_x = n_y = n(t)$. By insertion of (5) we obtain an explicit expression for the time dependence of the relative luminosity reduction ($L_0(t)$ is the corresponding luminosity without HERA-B):

$$\frac{L(t)}{L_0(t)} = \left(1 - \left(1 - \sqrt{1 - \frac{\nu_{loss}}{N_0}t}\right)^{\sqrt{2}}\right)^2. \qquad (8)$$

So far we did not take into account the decay of the positron beam due to it's limited lifetime. As a result of synchrotron radiation the positron beam lifetime

[1]We use the approximation $\int_0^n ds \;\; \mathrm{erf}\left(\sqrt{(n^2 - s^2)/2}\right) e^{-\alpha s^2} \approx \sqrt{\frac{\pi}{4\alpha}}\left(1 - e^{-\sqrt{\alpha/2}n^2}\right)$ for the evaluation of the integral.

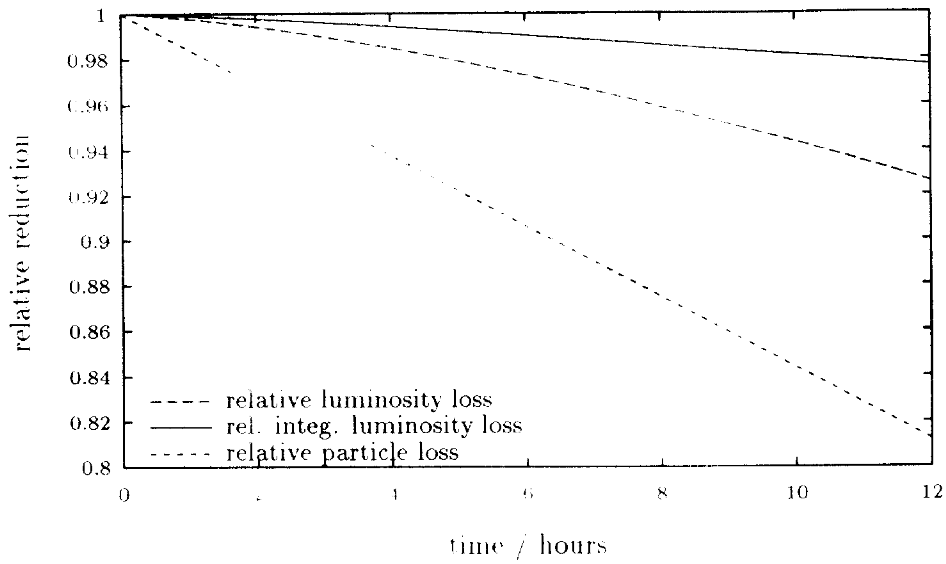

Figure 3: Relative and integrated luminosity reduction together with relative remaining beam current as function of time.

is current dependent and can be parametrized as follows [1]:

$$\frac{1}{\tau} = -\frac{\dot{I}_e}{I_e} = \frac{1}{\tau_1} + \lambda I_e. \qquad (9)$$

where $1/\tau_1 = 1/\tau_0 + 1/\tau_{Hermes}$, $\tau_{Hermes} \approx 50$ h (contribution from Hermes gas target), $\tau_0 \approx 20$ h (lifetime limit for vanishing positron current) and $\lambda \approx 1/(600\mathrm{mAh})$. The solution of the differential equation (9) yields for the number of particles in the positron beam as function of time:

$$N_e(t) = N_e(t=0)\frac{e^{-\frac{t}{\tau_1}}}{1 + \tau_1 \lambda I_e(t=0)\left(1 - e^{-\frac{t}{\tau_1}}\right)}. \qquad (10)$$

The reduction ratio κ of the integrated luminosity as a function of running time T_R is then given by:

$$\kappa(T_R) = \frac{\int_{t=0}^{T_R} L(t)dt}{\int_{t=0}^{T_R} L_0(t)dt}. \qquad (11)$$

In Fig. 3 the relative luminosity reduction is shown together with the reduction of the integrated luminosity and the relative proton current loss. It is remarkable that in a 12 h run one loses only 2.3 % of the integrated luminosity whereas 19 % of the proton beam current are scraped.

Of course the real proton beam distribution will not exhibit an exactly Gaussian shape, especially in the tails. However, since a large part of the beam has to

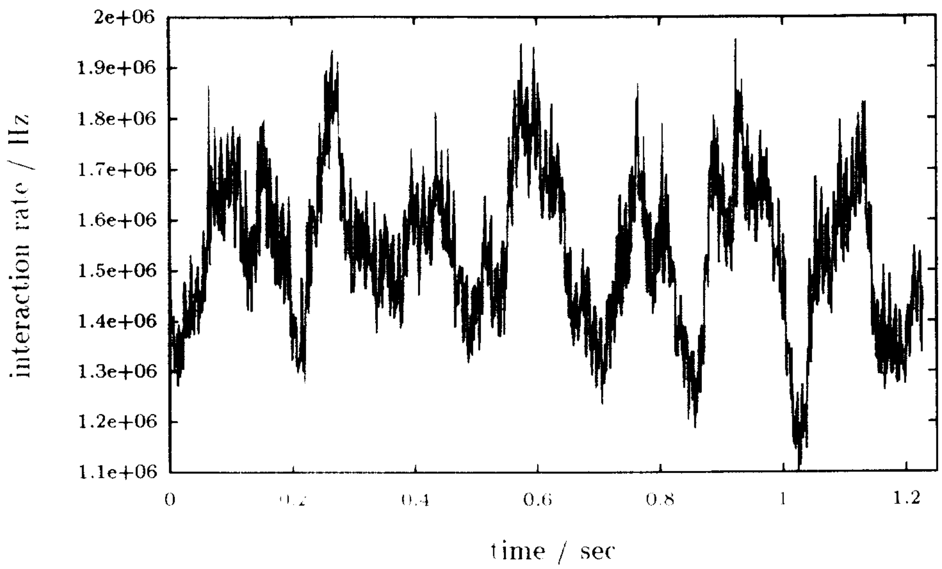

Figure 4: A rate sample measured at one of the HERA-B wires which touches the beam.

be scraped the Gaussian distribution is a reasonable estimate and slightly different shapes will not alter our result very much. Furthermore one should not forget that the above estimate neglects all diffusion processes in the proton beam during a run period and is therefore pessimistic in view of the luminosity reduction.

3 Rate Stabilization for HERA-B

If the proton beam exhibits small diffusion rates, scraping with the HERA-B wires will produce sharp edges in the beam distribution at the wire positions. The large slope of the particle distribution at the boundary results in a high sensitivity of the loss rate with respect to the beam position. On the other hand the beam will always move around on a μm scale within a wide frequency band. It ranges from slow drifts in the sub-Hz region, caused by ground motion, over the 10 Hz region which is dominated by mechanical vibrations of machine components up to single lines at 300/600 Hz originating from magnet power suppy ripple. Of course variations of the interaction rate will decrease the efficiency of the HERA-B detector. An example for rate variations is shown in Fig. 4 and a power spectrum in Fig. 5. Slow beam motions below $\approx$0.5 Hz can in principle be compensated by an intelligent control mechanism and by following the beam with the wires. However, at higher frequencies that becomes extremely difficult or impossible. Concerning the power supply ripple it seems possible to stabilize the beam itself by an active feed-forward system since these beam motions are in phase with the power net.

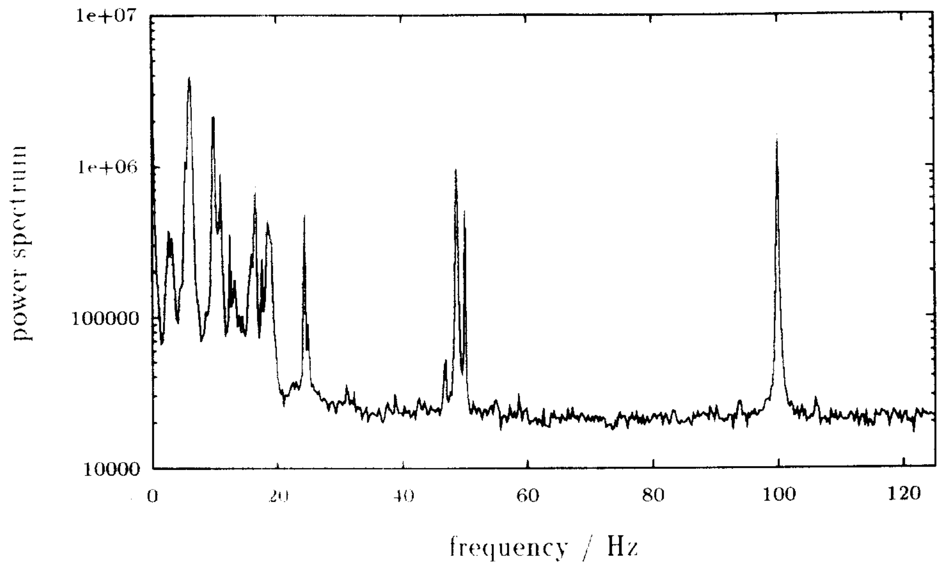

Figure 5: Power spectrum of the interaction rate at one of the HERA-B wires. The spectrum shows typical lines from power supply ripple at 50 and 100 Hz but also lines from vibrations of machine elements.

Eventually a better approach to overcome this problem is to make the loss rate less sensitive to beam motions by decreasing the slope of the beam distribution at the boundary. This can be achieved by introducing a small amount of artificial diffusion to the beam. Any diffusion process tends to smear out discontinuities in a distribution, as in our case the sharply defined edge with a large slope. It should be emphasized that the artificial diffusion is not primarily intended to transport particles to the wires, but only to reduce the slope of the beam distribution at the edge.

A typical (and analytically calculable) diffusion process is beam gas scattering where the particles receive independent, Gaussianly distributed kicks due to interactions with residual gas atoms. In practice this can be simulated by applying a white noise signal to a kicker magnet which acts on the beam. Such a scheme has been successfully used at the SPS accelerator with a coasting beam for crystal extraction experiments [4]. The main difference to our case is that HERA operates with a bunched beam and even a fast kicker would hardly be able to deflect individual particles within one bunch differently. So at each passage the whole bunch will be deflected by a random (from turn to turn) kick angle. However, since there is always an amplitude dependence of the tunes present the bunch will continuously filament and will exhibit a similar behaviour as for independent kicks of the particles. Since the necessary kicks are extremely small we make the ansatz to describe the time development of the distribution by the diffusion equation for incoherent kicks (see [2] or [3] for the two dimensional case including coupling). There is also some evidence from numerical simulations that this approach gives approximately correct results for the introduced emittance growth. The diffusion equation reads:

$$\frac{\partial}{\partial t} f(I,t) = \frac{\partial}{\partial I}\left(I \cdot D \frac{\partial}{\partial I} f(I,t)\right) . \tag{12}$$

where $D = \frac{1}{2I}\frac{\langle \Delta I^2 \rangle}{\Delta t} = \frac{1}{2}\beta_k \theta_{rms}^2 \nu_{rev}$. Here β_k is the beta-function at the kicker position, θ_{rms} the rms kick angle and ν_{rev} the revolution frequency. The solution of (12) can be expressed by a series of zero'th order Bessel functions:

$$f(I,t) = \sum_k c_k\, J_0\left(\lambda_k \sqrt{\frac{2I}{n^2\varepsilon}}\right)\, \exp\left(-\frac{\lambda_k^2}{4}\frac{D}{n^2\varepsilon} t\right) . \tag{13}$$

with n the aperture in units of beam sigma and ε the initial one-sigma beam emittance. The λ_k are the k'th zeros of the J_0 Besselfunction. For large k they behave approximately as $\lambda_k \approx \pi(\frac{1}{2}+k)$. The coefficients c_k are determined from the initial beam distribution:

$$c_k = \frac{1}{J_1^2(\lambda_k)} \int_{I=0}^{I=\frac{n^2}{2}\varepsilon} f_0(I) J_0\left(\lambda_k \sqrt{\frac{2I}{n^2\varepsilon}}\right) dI . \tag{14}$$

For $t = 0$ equation (13) represents an expansion of the initial distribution in terms of Bessel functions. For times $t > 0$ the individual terms of the series decay with individual lifetimes. In particular terms with high order have a short lifetime, even for a small diffusion coefficient D, since their lifetime scales with k^{-2}. On the other hand, if the initial beam distribution exhibits sharp features, these are represented by high order terms in (13). Therefore we find that applying white noise kicks to the beam will preferentially smear out the tails of the beam distribution and will leave the beam core undisturbed. Quantitatively this is demonstrated in Fig. 6 where an action dependent Gaussian distribution of type (1), scraped down to 3σ is shown. A small white noise excitation is applied and the decaying distribution is plotted every hour. One recognizes clearly that the large slope disappears rather fast whereas at some distance from the wire the distribution stays undisturbed. The asymptotic lifetime for this beam, which is limited at 3σ, is given by the lifetime of the first term in the series (13) and amounts still to 500 hours.

4 Conclusions

During a 12 h run HERA-B needs 20 % of initially 100 mA proton beam current to reach the desired interaction rate of 40 MHz. Though that seems to be a large fraction of the beam, the integrated luminosity for the ep detectors will decrease by less than 3%. This is due to the fact that HERA-B cuts into the tails of the

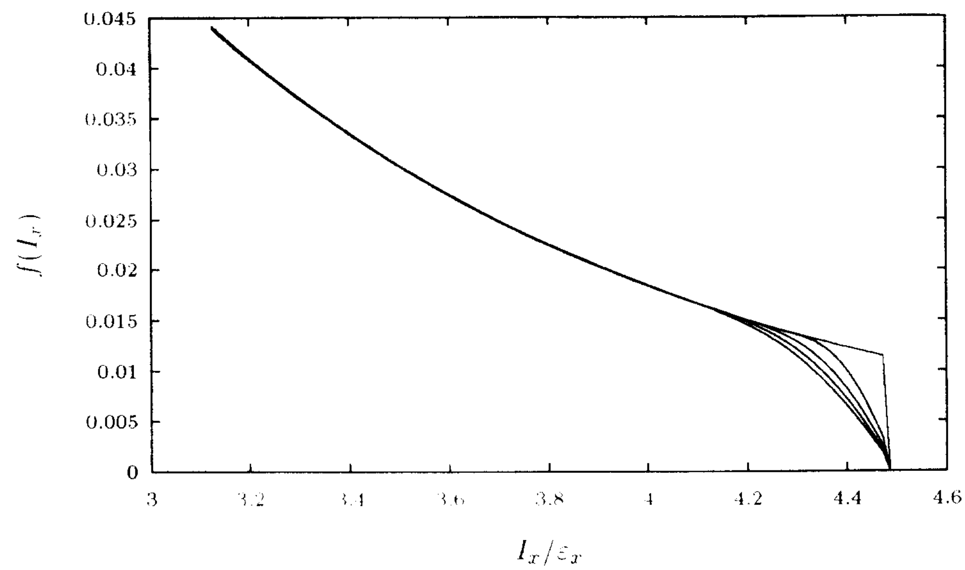

Figure 6: Time evolution of a scraped distribution under white noise excitation. The curves are taken every hour. The asymptotic lifetime due to the diffusion process is still 500 hours in this example.

beam which contribute less to the ep luminosity. Furthermore the decay of the e^+ beam gives the first part of the run a higher weight. It should be pointed out that these estimates are pessimistic since they are based on the assumption that the proton beam emittance does not grow during the luminosity run. If there is some emittance growth this would reduce the "natural" luminosity on which the derived reduction factors are normalized. Furthermore HERA-B would not be forced to scrape the beam so deeply.

A drawback of the scraping process is the sharp edge of the transverse particle distribution which develops after a while. It causes a high sensitivity of the HERA-B interaction rate with respect to small beam position jitter. Rate fluctuations, on the other hand, will reduce the efficiency of HERA-B and will cause longer running times. It has been demonstrated that a small white noise excitation of the beam can smear out the beam edges without influencing the beam core. It can be expected that this makes the loss rate less sensitive to beam jitter. However, a quantitative estimate is difficult and it is strongly preferable to test this experimentally in the machine.

Finally it should be stated that the HERA-B experiment is not necessarily in conflict with the ep experiments. This holds also with respect to proton induced background problems. Of course there will be larger losses due to the lifetime reduction and especially elastic nuclear scattering events in the targets are dangerous for the ep experiments since they produce large kick angles [5] and may cause background at the detectors. So careful beam collimation will be essential for a nonproblematic coexistence of HERA-B and the ep experiments. On the other hand one expects (and there is also experimental evidence) that scattering at the HERA-B wires spreads the impact parameter distribution of halo protons on any collimator by a large amount. This will strongly enhance the efficiency of beam collimation. In fact a similar collimation scheme with a thin pre-scattering target was proposed for the SSC collider [6]. A further argument is that HERA-B will scrape the beam down to rather small amplitudes. This will allow to close the collimators much tighter than natural aperture restrictions which will increase the collimation efficiency as well.

References

[1] W.Bialowons, private communication on positron beam lifetimes in HERA (1995)

[2] D.A.Edwards, M.J.Syphers, An Introduction to the Physics of High Energy Accelerators, John Wiley & Sons (1993)

[3] F.Zimmermann, F.Willeke, Residual Gas Scattering and Beam Lifetime in the HERA Proton Ring, Proceedings HEACC'92 (1992) 415

[4] W.Herr, Diffusion of Particles Induced by Transverse Noise and its Application to Crystal Extraction Experiments, CERN SL/92-53 (1992)

[5] E.Lohrmann, M.Seidel, Study of Background Caused by Scattering at the HERA-B Wire Target, DESY-HERA 95-04 (1995)

[6] M.Maslov, N.Mokhov, L.Yazynin, The SSC Beam Scraper System, SSCL-484 (199[illegible])