RECENT AND PAST EXPERIENCES WITH BEAM-BEAM EFFECTS AT HERA

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Abstract

Proton beam stability when in collision with high current electron bunches was of foremost concern during the design stages of the HERA collider[1]. In initial commissioning the beam-beam interaction proved to be a key factor in determining the lifetime of the proton beam. It was quickly ascertained[2] that the proton beam lifetime in collision could be substantially increased by both matching the electron and proton beam sizes (σ) at the interaction points (IPs) and by carefully centering the beams. Presently, proton beam life times of hundreds of hours are routinely observed. In the near future, the accelerators will be upgraded[3] to include new low-β insertions and to allow for yet higher beam currents. Key factors affecting the stability of colliding proton beams will be described as well as recent experiments performed to explore at high electron beam currents new regimes of the proton beam-beam limit at HERA.

1 INTRODUCTION

An overview of the HERA injectors is shown in Fig. 1. The electrons from linac 2 are injected into DESY2 where they are accelerated to 7 GeV. After multiple single-bunch transfers into PETRA the beam is accelerated to 12 GeV. About 4.5 PETRA fill cycles are required to fill HERA with 189 bunches. The resulting current distribution consists of 3 groups of 63 bunches as shown for a representative fill in Fig. 2. The proton beam, produced in linac 3 at a final kinetic energy of about 50 MeV is transferred to DESY3 and accelerated to 7.5 GeV/c. 60 proton bunches are stored in PETRA after 6 cycles at DESY3. After acceleration, these 60 bunches are injected into HERA. After 3 such cycles, the HERA ring is filled with 180 proton bunches at 40 GeV(see Fig. 2). The resultant current distribution contains 15 non-colliding e^- bunches and 6 non-colliding proton bunches. The electron 'pilot' bunches are used to correct the online luminosity estimate for residual beam-gas scattering events.

With a head-on collision geometry at each of the two (symmetric) HERA interaction points, parasitic crossings and bunch scheduling issues are fortunately of no concern. The bunches are spaced by 96 ns which corresponds to 20

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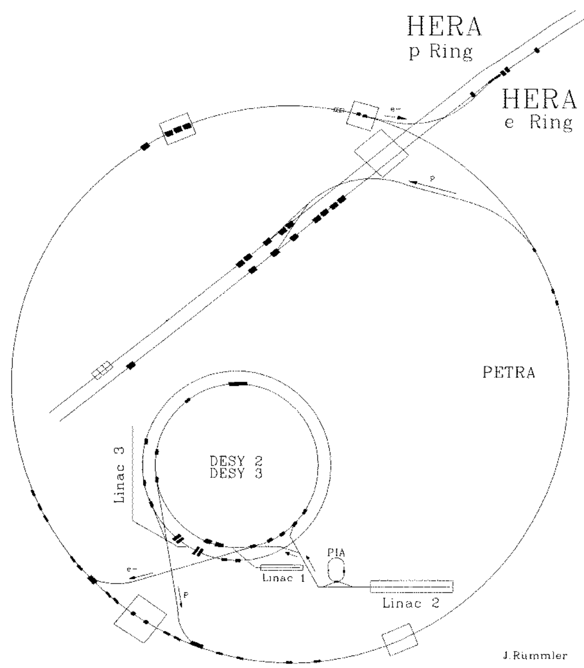

Figure 1: Map of HERA injector complex.

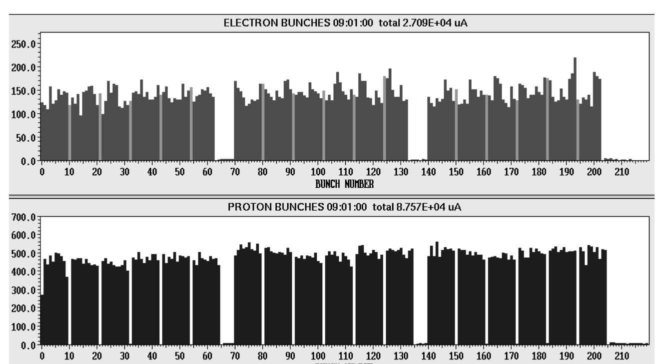

Figure 2: Electron (top) and proton (bottom) current distributions for a typical fill in HERA.

buckets of the 208 MHz proton rf system and 48 buckets of the 500 MHz electron rf system. The 11.6 m common orbit at the HERA IPs is less than half the 28.8 m bunch spacing.

The proton beam is always injected first into HERA. After verification of the proton beam orbits, tunes, and chromaticities, the beam is ramped to full energy at 920 GeV. Then the electrons can be injected, the beam orbits and tunes checked, and ramped to full energy. During the ramp, the proton beam is partially collimated to protect the high energy physics detectors. At the top of the ramp, the separation of the beams at the IPs is about 40σ vertically. The beams are then brought into collision by introduction of the `lumi optics' (to `squeeze' the beam by reducing the IP beta functions) and by bringing the beams transversely into collision. Usually the electron beam lumi optics are installed first, then the proton beam lumi optics are introduced. Towards the end of the proton beam squeeze, the orbits are centered vertically. The time scale is about 10 seconds for the last 3σ of the relative beam alignment. At HERA the beams are not intentionally displaced longitudinally, however once in collision, the relative phase of the beams at the IP is closely monitored using peak current detectors and, if necessary, corrected.

A selection of beam parameters is given in Table 1. The luminosity, given by

$$L = \frac{1}{2\pi}\frac{N_e N_p f_r}{\Sigma_x \Sigma_y} \quad (1)$$

with $\Sigma_{x/y} = \sqrt{\sigma^2_{x/y,e} + \sigma^2_{x/y,p}}$ and an interaction frequency of $f_r = 174 \times 47.273$ kHz, is typically $L = (8-10) \times 10^{30}$ cm^{-2}s^{-1}. The corresponding specific luminosity is $L_{sp} = 6.6 \times 10^{29}$ cm^{-2}s^{-1} mA^{-2} which is 75% greater than design[4] due primarily to the reduced β^* at the interaction points.

Parameter	proton	electron
E (GeV)	920	27.5
I_{tot} (mA)	80	30
N (total/colliding)	180/174	189/174
N_{ppb}	5.9×10^{10}	2.1×10^{10}
I_b (μA)	445	160
$\beta_x{}^*, \beta_y{}^*$ (m)	7,0.5	1,0.7
$\epsilon_{x,y}$ (nm-r)	5.1/5.1	40/4.0
σ_x, σ_y (μm)	190,50	200,53
ν_x, ν_y	0.291, 0.298	0.140, 0.194
ν_s	0.0011	0.0525
τ_x, τ_y (ms)	-	14, 14
τ_s (ms)	-	7
ξ_x, ξ_y	0.0007,0.00019	0.0108, 0.0287

Table 1: HERA parameters of the 1998/1999 physics run to date including the beam energy E, the total current I_{tot}, the number of bunches N, the number of particles per bunch N_{ppb}, the current per bunch I_b, the IP beta functions β^*, the beam emittances ϵ, the IP spot sizes σ, the betatron and synchrotron tunes ν_x, ν_y, ν_s, the damping times τ, and the incoherent beam-beam parameters ξ per crossing.

This report is organized as follows. First we discuss general observations and measurements related to beam-beam effects at HERA; we will summarize the knowledge gained since the time when beams were first collided at HERA. In addition, we will report on the observed impact of the beam-beam-effect on spin polarisation in HERA. Next we present recent measurements performed to determine if a beam-beam limit might be encountered at higher beam currents and or smaller beam emittances. The measurement results are categorized in terms of the effect of the beam-beam interaction on the beam core and the beam tails. We conclude with a brief outlook for future high luminosity operation to be achieved as specified in the report of the HERA luminosity upgrade[3].

2 GENERAL OBSERVATIONS

The most important factors[2] leading to successful colliding beam operation at HERA include optimization of the working point in the tune diagram and matching the beam cross sections at the IPs. These topics are discussed further below. It was found necessary[2] to maintain small relative separation of the beams at the IPs in order not to adversely affect the proton beam lifetime via a nearby nonlinear resonance. With head-on collisions, the relative separation between the beams is routinely maintained at a level of less than 0.1σ in both transverse planes.

2.1 Betatron Tune Windows

At HERA the betatron tunes of both beams are carefully monitored and controlled. For the proton beam, the tunes are selected[2][5] to be near the main coupling resonance between the 7th and 10th order nonlinear resonances; this working point avoids unstable low-order resonances. For the electrons, synchrobetatron resonances must be avoided to preserve polarization. For a time-independent specific luminisity, it has been determined[6] that the betatron tune must satisfy

$$\begin{array}{lll} Q^e{}_x = 47.147 \pm 0.002 & , & Q^e{}_y = 47.215 \pm 0.005 \\ Q^p{}_x = 31.293 \pm 0.002 & , & Q^e{}_y = 32.297 \pm 0.002 \end{array} \quad (2)$$

For comparison, the tune spread with beams in collision is about equal to the beam-beam parameters ξ. To minimize the sensitivity to orbit and energy deviations, it is necessary[6] to correct the beam trajectories and to maintain a chromaticity $\Delta\nu(\frac{\Delta p}{p})^{-1}$ to within ± 1 unit. In addition, for the protons with betatron tunes near the coupling resonance, the width of this resonance must be corrected to $\kappa \leq 0.005$. The regulation of the quadrupole power supplies controling the tunes is typically within a few times 10^{-5} for both beams.

2.2 Beam Cross Section Matching

Variations in the ratio of the proton to electron beam sizes was observed[2] to strongly affect the proton beam lifetime with beams in collision. This is demonstrated clearly in

Fig. 3 which shows the beam cross sections and lifetimes for different beam overlap ratios. The beam sizes and lifetimes from these measurements are shown, in the plotting order, in Table 2 along with present parameters (last row). Without collisions, the proton beam lifetime is about 5000 hours.

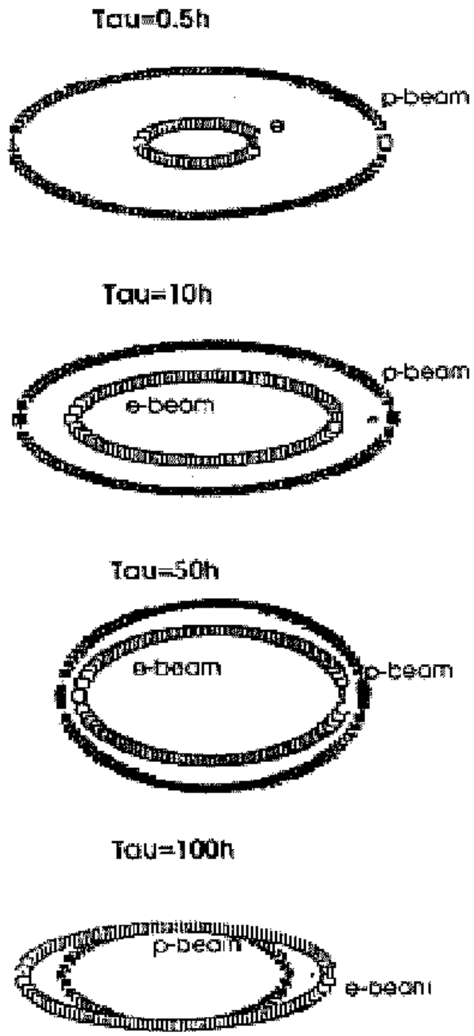

Figure 3: Proton beam lifetime for different ratios of electron and proton beam cross sections from reference [2]. The proton beam-beam tune shifts in all cases are about 0.0015.

To increase the proton beam lifetime during collisions, early in HERA history the electron β^*s at the IP were increased by about a factor of 2 while the protron beam β^*s were decreased by about 30%. Anticipated complications associated with maintaining matched beam cross sections were a reduction in available aperture, a stricter chromaticity margin, and an increased beam-beam tune shift of the electron beam. Fortunately, present day colliding beam operation does not seem impacted by any of these concerns.

$\sigma^p{}_x$ [μm]	$\sigma^p{}_y$ [μm]	$\sigma^e{}_x$ [μm]	$\sigma^e{}_y$ [μm]	τ_p [hrs]
410	120	130	33	0.5
410	120	290	70	10
330	100	290	70	50
210	50	290	53	100
190	50	200	53	

Table 2: Tabulated IP electron and protron cross sections corresponding to Fig. 3 from reference [2]. The last row corresponds to the 1998/1999 data taking period where the measured lifetime was typically 300 hours.

2.3 Beam Polarization

Running HERA in the last years we observe an average reduction of spin polarization of the electron/positron beam and an increased sensitivity to the choice of betatron and synchrotron tunes. We have different indications that tighly focussed and/or high current beams have had to less polarization[6]. With large tune shifts from the beam-beam interaction, sometimes the polarization approached only 50%. Since the time of these observations, the electron beam tune shift was decreased by reducing the β_e^* at the IP and now 55-65% electron polarization routinely is reached[4].

This is supported by the following observation. In routine operation, given the long proton beam lifetime of several hundreds of hours, typically two electron injection cycles per proton fill are employed. From the time history shown in Fig. 4, the electron polarization is often higher for those electron fills corresponding to the older and less focusing proton beams.

An additional indication is shown in Fig. 5. The measured spin polarization is plotted vs. the luminosity over a period of two weeks. The Polarization level reached after the build-up time is given by the uppermost points forming an edge sloping down towards higher luminosity. Initial electron currents were kept rather constant during this time, so luminosity on that line can be taken as a measure of the proton currents and thus the electron tune shift. The maximum is reached for zero luminosity, meaning electrons only, without beam-beam effect. Towards higher proton currents and electron tune shifts the polarisation drops by about 5-10%. Fig. 10 suggests that the vertical electron tune shift difference within the range of our proton intensities is about 0.008. Fig. 6 shows a spin tracking calculation using the code SITROS where for such an increase in vertical tune shift a reduction of spin polarization of about 5% was predicted in 1995.

As for the observed sensitivity to the tunes Fig. 7 and 8 show spin polarization level vs. spin tune calculated by SITROS with and without beam-beam-effect. In the presence of the beam-beam-effect additional resonances appear which change the former plateau in the midst between the integer resonances to a series of peaks which of course requires a very careful adjustment of all tunes to optimise polarisation. In addition, the average level is lowered. The calculation shown here is done for HERA design currents, i.e. a vertical electron tune shift of 0.04 and serves as a qualitative argument.

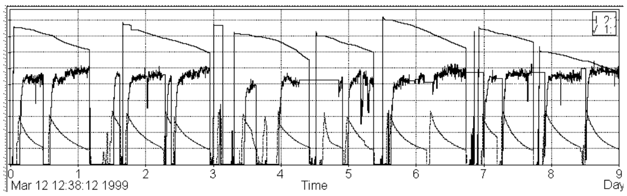

Figure 4: Time history of HERA proton (top) and electron (bottom) currents and the electron polarization (middle).

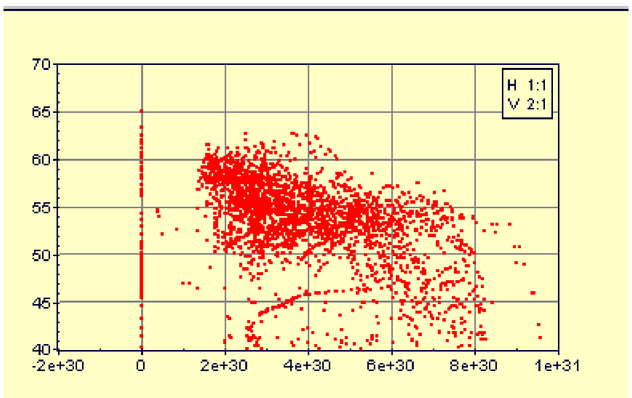

Figure 5: Polarisation vs. luminosity over a period of two weeks (starting March 11, 1999).

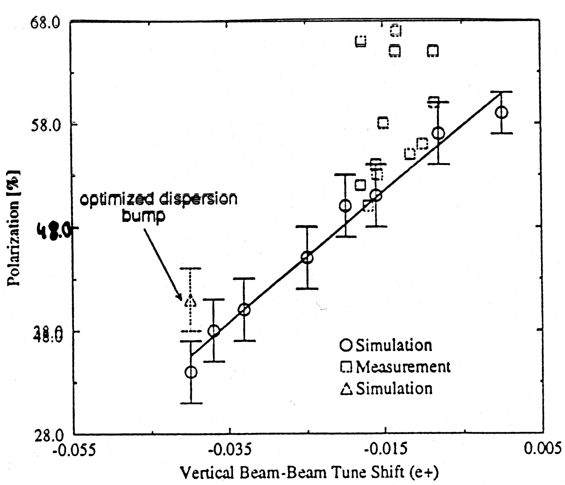

Figure 6: Polarisation vs. electron tune shift as predicted by the spin tracking code SITROS.

3 RECENT BEAM-BEAM MEASUREMENTS

The remainder of this report will focus on measurements made recently to explore the parameter space called for in

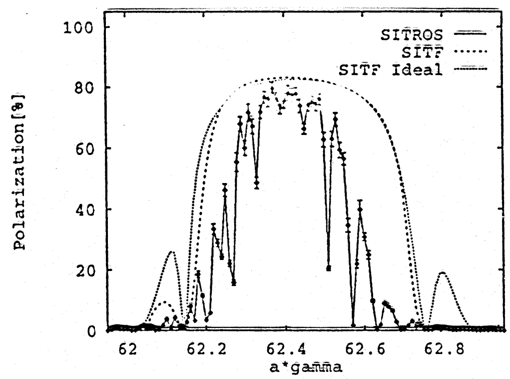

Figure 7: Polarisation vs. spin tune (proportional to beam energy) without beam-beam effect calculated with the spin tracking code SITROS. The dotted lineis a linear theory matrix calculation, the drawn line the result of a tracking calculation taking into account nonlinear effects. The beam energy window shown has a width of 440 MeV and is centered around the HERA operating energy.

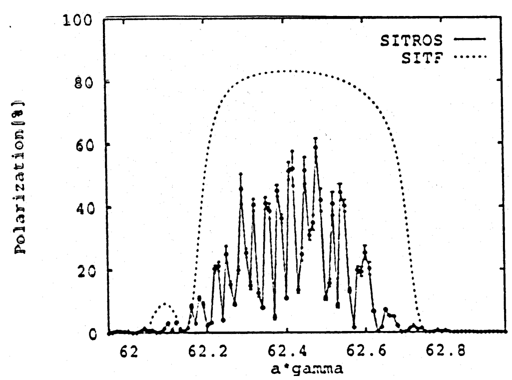

Figure 8: Polarisation vs. spin tune (proportional to beam energy) taking into account the beam-beam-effect (electron vertical tune shift = 0.04) calculated with the spin tracking code SITROS. For the meaning of the curves see caption Fig. 7.

the HERA luminosity upgrade[3]. The focus of the experiments was to explore the proximity to the proton beam beam-beam limit. Of particular interest was determining if we could, based on measurement results, extrapolate to predict with confidence the expected luminosity with the luminosity upgrade parameters realized.

3.1 BEAM-BEAM TUNE SHIFTS

The incoherent tune shift per IP of the electrons, is

$$\xi_{x,y} = (\frac{r_e}{2\pi}) \frac{N_{\rm ppb} \beta^*{}_{x,y}}{\gamma \sigma^p_{x,y}(\sigma^p_x + \sigma^p_y)} \qquad (3)$$

with $r_e = 2.82 \times 10^{-15}$ m, the proton rms beam size at the IP $\sigma^p_{x,y}$, and with the proton bunch population $N_{\rm ppb}$. For the electrons, a single bunch within a given bunch train may be externally excited and its betatron tunes measured[7].

This independent gating feature allows for comparison of the betatron tunes for colliding and non-colliding (pilot) bunches. An example is given in Fig. 9.

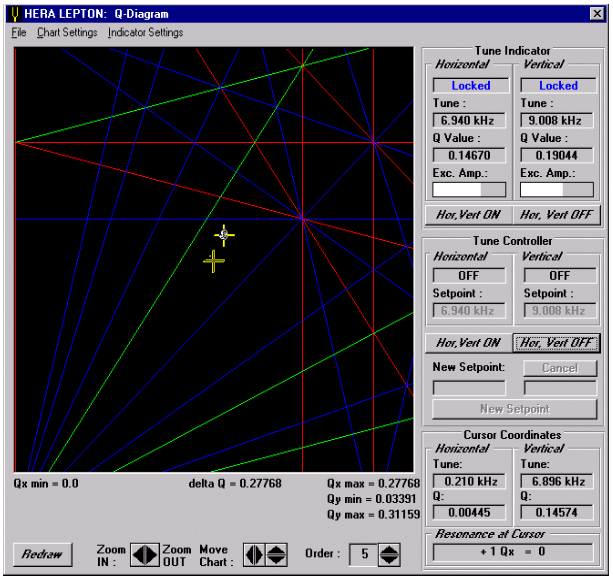

Figure 9: Tune diagram showing measured beam-beam tune shifts of an electron bunch in collision with protons (upper cross) and for a pilot bunch (lower cross).

Using this technique the electron beam-beam tune shift was measured over a small range of proton single bunch beam currents by taking the difference of the measured tunes for colliding and non-colliding bunches. The result is shown in Fig. 10. The horizontal and vertical tune shifts

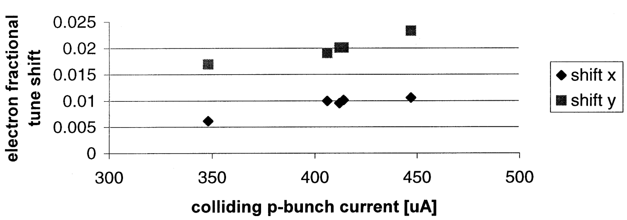

Figure 10: Fractional electron tune shifts vs. colliding p-bunch current.

were systematically less than expected. For example, the measurements at the beam currents of Table 1 were

$$\Xi_x^e = 0.010 \;\text{ and }\; \Xi_y^e = 0.024. \tag{4}$$

Here Ξ^e denotes the measured coherent tune shift. In order to compare with the incoherent tuneshift, we divide by a factor of two for the two HERA IPs. In addition we take into account that the tuneshift for the single particles with different oscillation amplitudes differs. The amplitude dependence must be averaged appropriately over all particles in the beam. The tune is measured by driving the beam in a phase locked loop. Assuming the oscillation amplitude is not small compared to σ_{ye}, the distorted distribution of the oscillating e-beam must be used for averaging the response to external excitation. For a Gaussian distributed e- and p-beams of rms beam sizes of $53\mu m$ and $50\mu m$ respectively and using an estimate for the coherent ocillation amplitude of $150\mu m$ we find a reduction factor for the measured tune with respect to the incoherent tuneshift of $r = 0.58$ (we have used the beam-beam potential for round beams to calculate this result). Thus we expect the measured tuneshift Ξ_y to be $2 \cdot 0.58 \simeq 1.2$ times larger than the calculated incoherent tuneshift of $\xi = 0.028$. This discrepancy is reduced by taking into account the additional focussing of the beam at each IP by the beam-beam interaction which in turn introduces a modulation of the beta function. The difference due to the perturbation from the unperturbed condition is

$$\frac{\Delta\beta}{\beta} = \frac{-1}{2\sin 2\pi Q} \oint k\beta \cos(2|\phi - \phi'| + 2\pi Q) ds', \tag{5}$$

where the beam-beam interaction is approximated as producing a perturbation of the form

$$kl\beta = 4\pi\xi. \tag{6}$$

Summing over the contributions from the two IPs we obtain

$$\Delta\beta = \frac{-4\pi\xi(\frac{\beta}{2})}{\sin 2\pi Q}\left[\cos(2\Delta\phi - 2\pi Q) + \cos(2\pi Q)\right], \tag{7}$$

where $\Delta\phi$ is the relative difference between IPs in the vertical betatron phase advance modulo 2π.

The influence of the dynamic beta also may explain (see below)the observation that the measured specific luminosity is routinely higher than expected. Solving self-consistently (that is, for a reduced β^* and hence reduced IP beam sizes Σ_y) we find that for $\Delta\phi$=0.074 the calculated specific luminosity now corresponds closely to the measurement and the calculated beam-beam tune shifts are somewhat closer to the measurements $\Delta\nu_{y-meas} = 0.024$, $\Delta\nu_{y-calc} = 0.04$. The corresponding reduction in ${\beta_y}^*$ is -0.18 m, which is a 25% effect. Both effects together, coherent oscillation and dynamic beta, could bring measured and expected tune shifts into reasonable agreement. It should be mentioned however, that the result depends very sensitively on the size of the coherent β-tron oscillation which we unfortunately do not know precisely.

3.2 *EFFECT ON BEAM LIFETIME*

For a number of bunch pairs, bunch current and life times were measured over a few hours. The proton lifetime correlates nicely with the intensity of the colliding electron bunch (Fig. 11). The electron lifetime is not correlated with proton bunch current.

3.3 *EFFECT ON BEAM CORE*

The luminosity versus beam current was measured by varying the current per bunch and measuring the luminosity per crossing for the bunch(es) of interest. For these measurements, the proton bunch currents were roughly constant

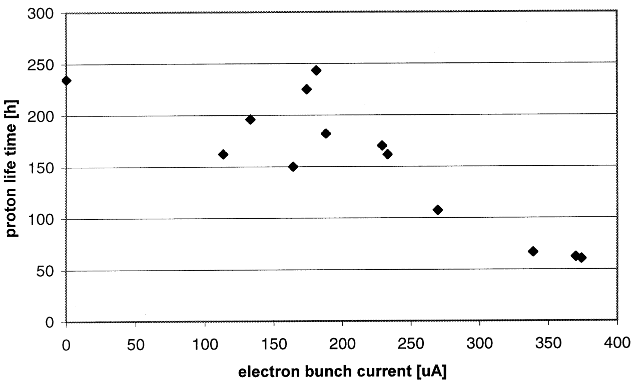

Figure 11: Proton bunch lifetime vs. colliding e-bunch current.

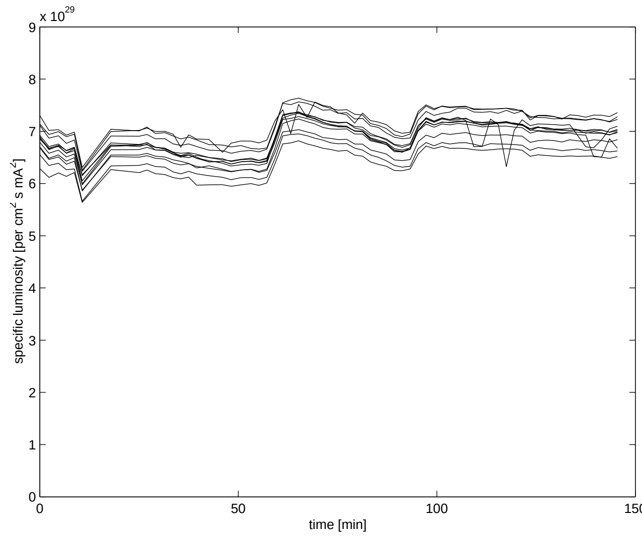

Figure 13: Specific luminosity measured by the H1 detector versus time for electron beam currents ranging from 75 to 450 μA in 25 μA steps. The proton bunch currents were on average 400 μA.

and a special fill with varying electron bunch currents was injected as shown in Fig. 12. The maximum single bunch electron current of about 450 μA is about 1.7 times the nominal (design)electron bunch current [10].

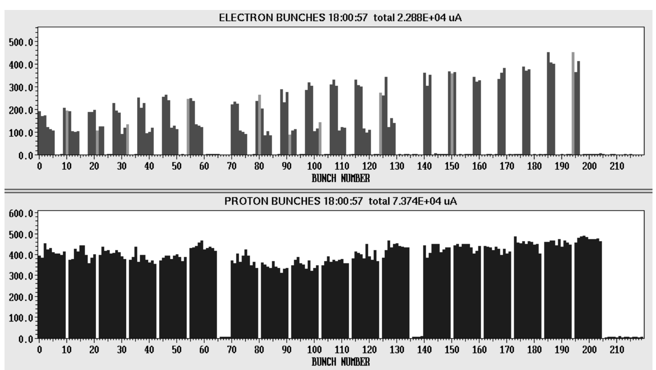

Figure 12: Current distributions used in beam-beam studies with highly irregular electron fill pattern.

Shown in Fig. 13 is the specific luminosity measured bunch by bunch by the H1 detector versus time for the electron bunch currents of Fig. 12. Each curve shows the average luminosity where the average is taken over all bunches with current in a window of 25 μA over the range of 75 to 450 μA. The gradual loss of specific luminosity during the measurements was recovered with tuning optimization as evidenced by the two step increases. There are two positive outcomes of this experiment. Firstly, there is no correlation between the luminosity at any given time with electron beam current (while not shown, the current is not increasing from bottom to top, for example). Secondly, the 10% variation between the curves remained unchanged over the duration of the experiment. Taken together this indicates that the beam-beam interaction at high beam currents, as in this measurement, should not contribute any time-dependent degradation of luminosity.

Two features of these data are not explained quantitatively. First the variation between the curves, being e-beam current independent, may or may not be a result of emittance degradations within HERA. Most likely, the injected beam emittance already varies. However, there is evidence of longitudinal beam instabilities measured at the top of the energy ramp and persisting for one to two hours[8]. Whether these observations are related has not been confirmed.

Taking as a measure of the time-dependence of the measured specific luminosity the values after optimization at 61.2 and 99.3 minutes, we find a change of 1.6$\%$ or about 2.6$\%$ per hour. This level of change is consistent with proton beam emittance dilutions arising via the beam-beam interaction with an accelerating voltage phase modulation on electron beam of much less than 1 mrad [11].

As mentioned previously, the measured specific luminosity exceeds the luminosity calculated with unperturbed beam optics. In this case, taking the maximum observed specific luminosity from Fig. 13, the apparent discrepancy is about 12.5$\%$ not taking into account the optics modification from the beam-beam interaction.

4 EFFECT ON BEAM TAILS

The population of the beam tails generated by the beam-beam interaction was studied with the current distribution shown in Fig. 12 using the data acquisition systems of HERA-B. During standard operation a 50μm wire, whose position is controlled by feedback to maintain a constant data rate, is moved into the beam. The wire intercepts the tails of the beam distribution and the interaction rates are recorded versus bunch number.

In this experiment, after ramping to full energy before colliding the beams, collimators in high dispersion regions were used to scrape the proton beam tails. Using the HERA-B data acquisition system, the tail population was observed to be uniform from bunch to bunch. After two hours of colliding beams, HERA-B was again used to measure the rate versus electron bunch number as shown in Fig. 14. The event rate is observed to mimic the population of the electron beam with which the proton collides (see Fig. 12); the proton event rate for collisions with high current electrons was clearly higher than that of lower current electron bunches. A possible explanation is that the higher current collisions with correspondingly large beam-beam tune shifts, have larger beam tails arising possibly from nearby nonlinear optical resonances.

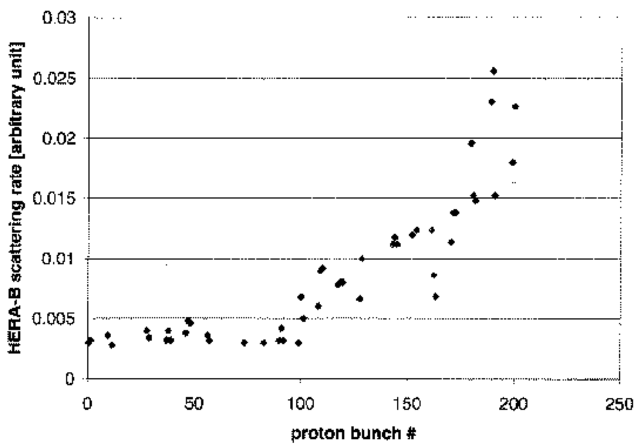

Figure 14: Beam tail scattering rate versus proton bunch number as measured by HERA-B with the scattering target just intercepting the beam halo.

The uniformity of the proton beam tails was next investigated by moving the HERA-B wire into the beam. The wire was stepped in 5 μm steps and the measured rates were recorded. Shown in Fig. 15 is the rate averaged over all bunches obtained with a high sampling frequency. In this experiment, the feedback loop used nominally to maintain a constant interaction rate was turned off; the step increases in measured rate correspond to the insertion of the wire and the exponential decay of the rate shows the removal of particles from the proton beam tail.

After collimating out the largest amplitude particles, the scattering rate versus bunch number was again measured as shown in Fig. 16. Comparison with Fig. 14 shows that the rate over the particle distribution became smoother; that is, the beam-beam interaction with the highest current electron bunches contributed to large amplitude particles while leaving the core of the beam distribution unchanged.

5 SUMMARY

The key factors leading to high luminosity at HERA include optimum choice of betatron tunes, maintaining the relative beam positions in the head-on collision geometry, and matching the beam cross sections at the interaction points. With these conditions satisfied, we have recently found that the measured specific luminosity actually ex-

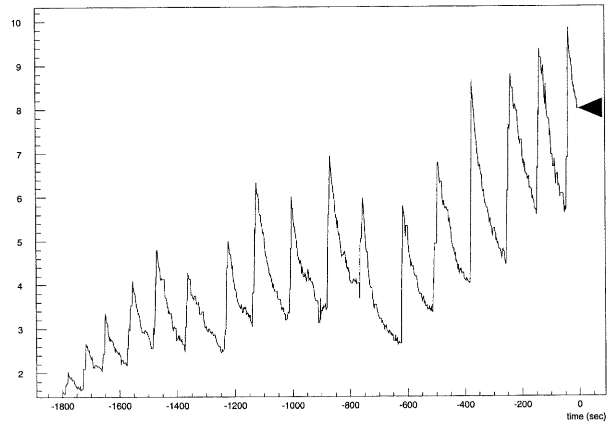

Figure 15: Beam tail scattering rate as measured by HERA-B versus time. The target was inserted in 5μm steps as indicated by the spikes. Time increases from left to right in this figure.

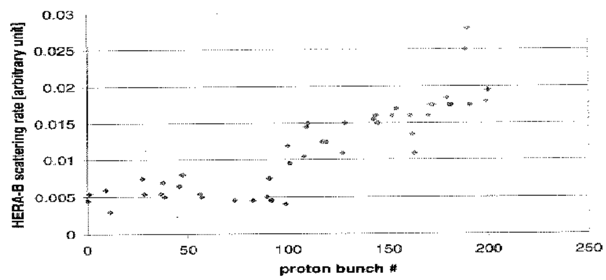

Figure 16: Beam tail scattering rate versus electron bunch current as measured by HERA-B with the wire about 100 μm closer to the core of the beam.

ceeds estimation based on standard formulas. Taking into account the additional focussing of the beam-beam interaction and coherent oscillations of the electron beam, calculations and measurement of the beam-beam tune shifts and specific luminosity can be brought into agreement. Recent high current experiments performed to confirm the feasibility of the HERA upgrade proposal yielded further measurements extending the parameter regime to higher beam currents. In particular, the measured beam-beam tune shifts and apparent luminosity excess could be explained by a 15% reduction of the IP beta function arising from the beam-beam interaction.

Even at electron beam currents almost a factor of 3 times nominal, there was no evidence of a proton beam-beam limit. Nor was there observed any correlation between the electron current and specific luminosity. This suggests strongly that the core of either beam is not degraded by the beam-beam interaction. The lack of variation with time in this experiment is very encouraging. Tail-scraping measurements also seem to indicate that the core of the beam distribution is left intact even at very high beam currents. Consistency between observations both old and new gives confidence that subtle nonlinearities in the beam-beam interaction should not limit accelerator performance with the parameters to be used in the HERA upgrade[3].

Acknowledgements

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