3: Activity Reports

3.1 The Luminosity Upgrade of HERA

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After the design luminosity has been exceeded [1, 2] in the electron–proton collider HERA, the interaction regions are being rebuilt to obtain smaller β^* at the two interaction points (IPs) [10, 11, 12]. This should increase the luminosity by about a factor of 4 yielding $\mathcal{L} = 0.74 \cdot 10^{32}$ cm^{-2}s^{-1}. To achieve this, it can not be avoided that the beam–beam tune shift of the e–beam is increased and that the vertical β^*_{py} of the protons becomes comparable to the proton bunch length. This implies new beam dynamical conditions. In accelerator studies, the beam–beam effects of the two HERA beams have been explored and the new low emittance optics has been implemented and tested with a polarized positron beam. These studies have been described in detail in [3, 4, 5] and will be summarized in this report. Part of these studies have also been reported in [6, 7, 8, 9, 2].

3.1.1 Introduction

With a length of 6336m, HERA is the largest accelerator at DESY in Hamburg. It provides collisions between a 920GeV proton beam and a 27.5GeV polarized electron beam and supplies four high energy physics experiments. H1 and ZEUS are the world's only high energy e/p collider experiments; HERMES and HERA–B have a fixed target. HERA–B scrapes the proton halo with wires, and HERMES has a polarized gas storage cell target in the polarized electron beam to analyze the polarized quark–gluon–structure of the nucleons. HERMES is currently the only experiment which takes advantage of the typically 60% polarization of the electron beam, since only around this experiment spin rotators bring the spins in a longitudinal direction.

Altogether there are 10 accelerators at DESY, 8 of which are required for providing HERA's high energy collisions. The other two are the 2nd generation light source DORIS and the TESLA Test Facility (TTF) with its integrated SASE FEL which produces the world's highest energy FEL x-ray beams with wavelengths between 180 nm and 80 nm. This facility will be upgraded to 6 nm wavelength by 2003 and is a test bed for the 33 km long TESLA linear collider.

Figure 3.1 shows how the integrated luminosity of HERA increased over the years in an exponential way to a total of around 180pb^{-1}. In the year 2000 HEAR exceeded its design goals with a luminosity of $\mathcal{L} = 0.2 \cdot 10^{32}$ cm^{-2}s^{-1} and an integrated luminosity of 67 pb^{-1}. But now a regime has been reached for which the curve is linear with time. To obtain a faster collection of integrated luminosity, a luminosity upgrade project is required. But this is not only a natural accelerator development, it is also strongly requested by the high energy physics community. HERA has been switched off in September 2000 to rebuild the interaction regions, and first beams are expected for the middle of July 2001.

For equal proton emittances $\epsilon_{px} = \epsilon_{py}$ and assuming that the proton beam size at the interaction point can always be matched by the electron beam ($\sigma_{ex} = \sigma_{px}$, $\sigma_{ey} = \sigma_{py}$), equation (3.1) shows that the luminosity can be increased by boosting the brightness N^p_{ppb}/ϵ_{px} of the p beam, by increasing the e current I_e, or by a decrease of the proton beta functions β^*_{px} and β^*_{py} at the collision

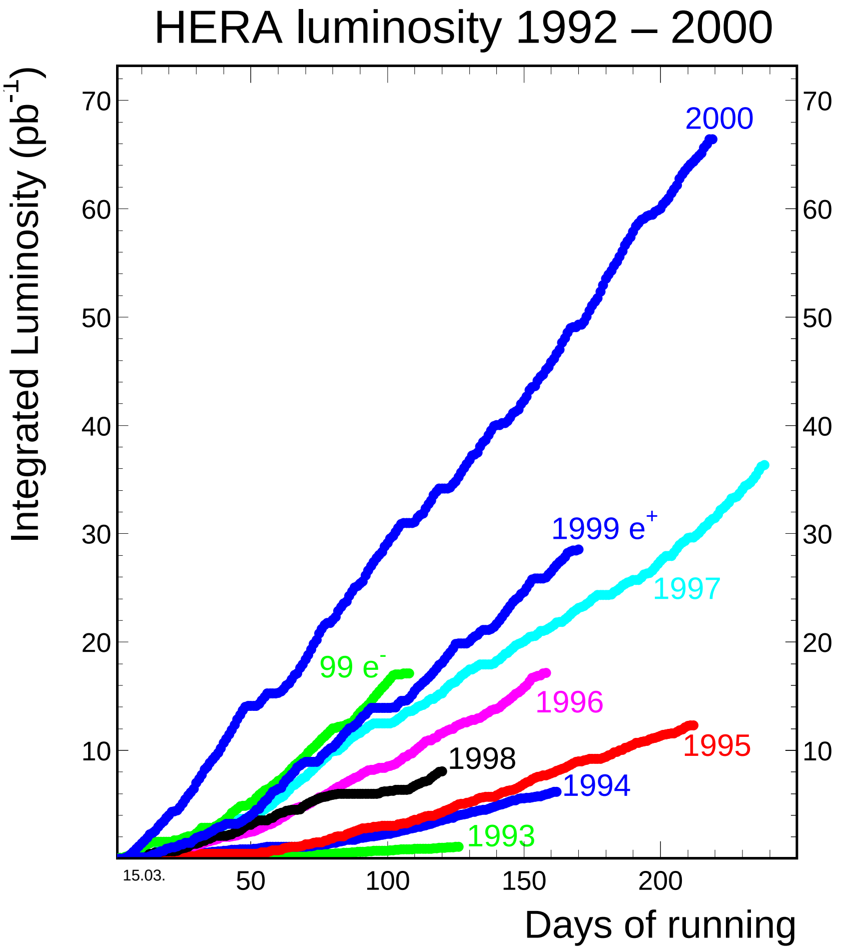

Figure 3.1: Integrated luminosity for each year of HERA running.

points,

$$\mathcal{L} = \frac{N_{ppb}^{p}}{\epsilon_{px}} \frac{I_e}{4\pi e} \frac{1}{\sqrt{\beta_{px}^{*}\beta_{py}^{*}}} \,. \tag{3.1}$$

These three measures have been found to be about equally expensive, but modifying the interaction region for obtaining smaller beta functions was found to be the safest method.

In order to focus the proton beam stronger in the experimental region, the electron beam has to be separated from the proton beam as early as possible [10, 11, 12, 6]. Whereas the first proton quadrupole is currently 26 m after the IP this distance will be only 10 m after the luminosity upgrade. Additionally the upgrade project includes 60 m long spin rotators at both sides of the H1 and ZEUS detectors. The complete upgrade involves 448 m of new vacuum pipes, 4 superconducting magnets for early separation of the e and p beams inside the detectors with a distance of only 2 m from the IP, and 54 normal conducting magnets. The superconducting magnets have been built by BNL and the normal conducting magnets have been built by the Efremov Institute in St. Petersburg.

Whereas the magnet arrangement around the detectors is currently symmetric, it will no longer be symmetric after the upgrade as shown in figure 3.2. Due to the bends inside the detectors the synchrotron radiation can no longer be collimated upstream of the experiment but has to be guided through the beam pipe. Starting at 11 m after the IP, the radiation fan has its own beam pipe leading to a radiation absorber. Scattered electrons are collimated upstream of the detector by a bend section and gas scattering close to the detector is minimized by the installation of many NEG pumps.

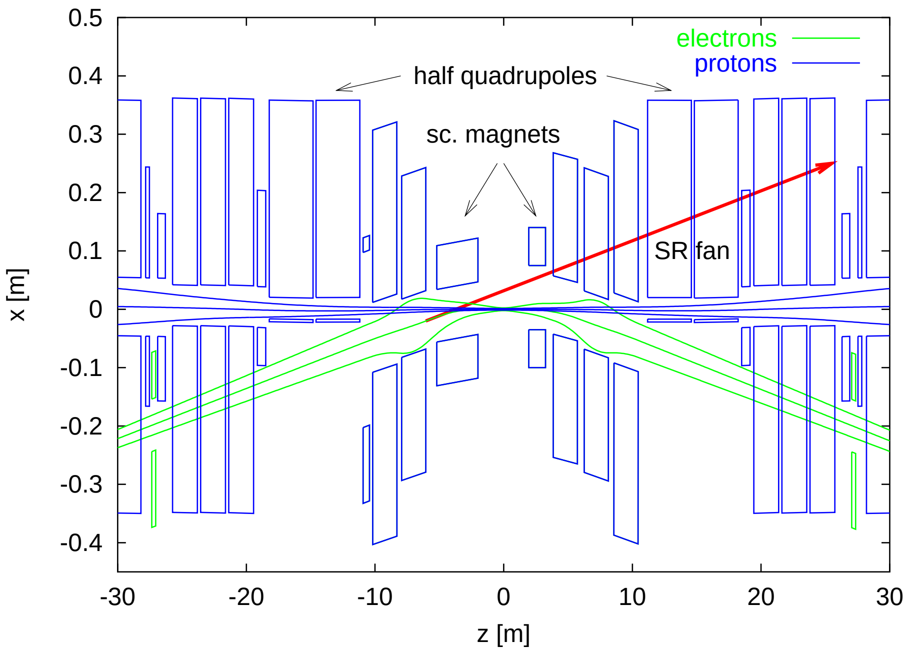

Figure 3.2: Layout of the interaction region after the luminosity upgrade.

Owing to the simultaneous presence of the proton beam, the electron beam, and the synchrotron radiation beam, some of the vacuum components are quite complicated. An example is shown in figure 3.3.

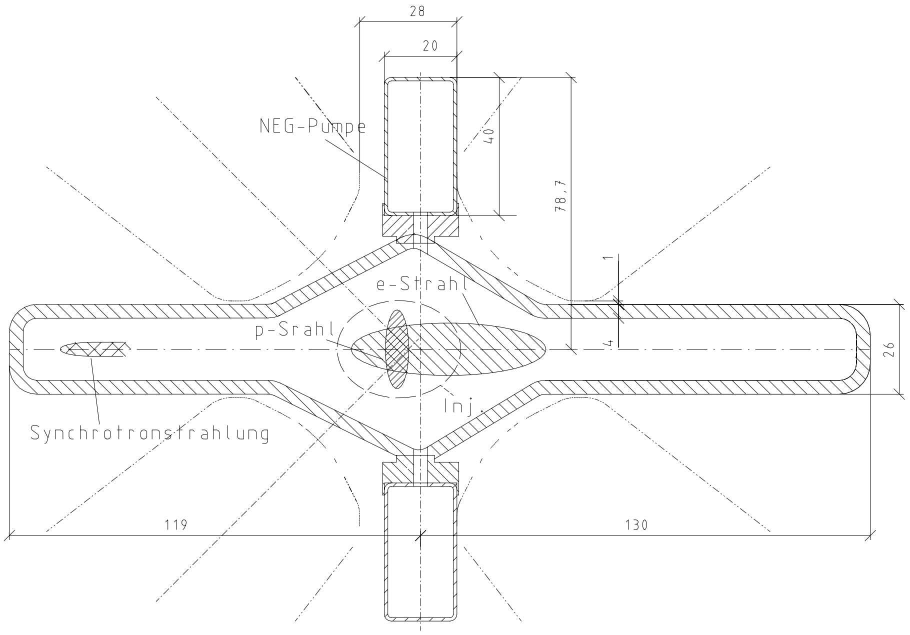

Figure 3.3: Custom designed vacuum chamber for the e beam, the p beam, and for the synchrotron radiation beam.

Also the detectors themselves will experience a major rebuild. Currently there are no magnets

Parameters	currently		after the Upgrade	
	e-ring	**p-ring**	**e-ring**	**p-ring**
E(GeV)	27.5	920	27.5	920
I(mA)	50	100	58	140
N_{ppb}(10^{10})	3.5	7.3	4.0	10.3
n_{tot}	189	180	189	180
n_{col}	174	174	174	174
β_x^*(m)	0.90	7.0	0.63	2.45
β_y^*(m)	0.60	0.5	0.26	0.18
ϵ_x(nm)	41	$\frac{5000}{\beta\gamma}$	20	$\frac{5000}{\beta\gamma}$
ϵ_y/ϵ_x	10%	1	17%	1
σ_x/σ_y(μm)	192/50	189/50	112/30	112/30
σ_z(mm)	11.2	191	10.3	191
$2\Delta\nu_x$	0.024	0.0026	0.068	0.0031
$2\Delta\nu_y$	0.060	0.0007	0.103	0.0009
Polarization	60%	0%	45%	0%
$\mathcal{L}$	$0.172\cdot10^{32}$		$0.744\cdot10^{32}$	
$\mathcal{L}_s$	$6.70\cdot10^{29}$		$17.9\cdot10^{29}$	

Table 3.1: Parameters of HERA before and after the luminosity upgrade.

inside the detector except of its huge solenoid for particle identification and the corresponding compensation solenoid. After the luminosity upgrade there will be two combined function magnets inside each detector. They are superconducting, to allow for a small diameter which can be fitted inside the detectors. The compensation solenoid will be eliminated and coupling will be compensated by skew quadrupole windings in these superconducting magnets and by 4 additional dedicated skew quadrupoles, 2 on each side of the interaction region. Together with the asymmetry of the interaction region, this will make spin matching more difficult and providing longitudinal electron polarization in the experiment will become quite challenging.

Important parameters of the luminosity upgrade project are shown in table 3.1. One of the critical points will be the exceptionally large vertical electron beam–beam tune shift $2\Delta\nu_{ey}$ due to the 2 collider experiments. The luminosity $\mathcal{L}$ is given in units of cm^{-2}s^{-1} and the specific luminosity in units of cm^{-2}s^{-1}mA^{-2}. The polarization has not been accurately simulated yet and 45% is only a rough estimate.

To reduce the electron spot size and to simplify the early separation of the beams, the electron emittance will be reduced from currently 41 to 20 nm by using 72° phase advance per FODO cell rather than the current 60°, furthermore the frequency of the 500 MHz rf system will be shifted by about 250 Hz. The smaller beam sizes at the IPs and these emittance reduction schemes lead to changes in the beam dynamics which could lead to problems after the luminosity upgrade. Therefore potential problems have been identified and analyzed in accelerator physics studies. The following questions were analyzed:

- Will the reduced electron spot size cause too strong beam–beam forces on the protons?
- Will the reduced proton spot size cause too strong beam–beam forces on the electrons?
- Will the 72° focusing cause a too small dynamic aperture of HERA–e?
- Will the 72° focusing cause a reduction in polarization?

- Will the 72° focusing increase the luminosity as expected?
- Does the current rf frequency allow for the required frequency shift?
- Will the rf frequency shift cause a reduction in polarization?
- Will the rf frequency shift increase the luminosity as expected?

3.1.2 Investigation of Upgrade Concepts

3.1.2.1 Beam–Beam Force on the Proton Beam

The stronger beam–beam tune shift parameters shown in table 3.1 go along with stronger nonlinearities of the particle dynamics and could lead to a reduced dynamic aperture for the proton beam and therefore to reduced proton lifetimes.

To study these effects, a very irregular fill pattern of the electron ring was used [7, 13]. In this fill pattern some electron bunches were filled with only about 100 μA and others with up to 450 μA. These different electron intensities lead to different beam–beam forces for different proton bunches and therefore to different beam–beam tune shift parameters. For luminosity upgrade conditions, the total electron currents in HERA which would produce these beam–beam parameters would vary between 16 mA and 73 mA. But the design electron current is only 58 mA.

An investigation of the bunch by bunch specific luminosity showed that the specific luminosity was not smaller for the bunch pairs with large electron bunch current and also the luminosity lifetime did not diminish with a stronger beam–beam force for the protons.

It has however been observed that the proton lifetime diminished from about 200 h to 50 h for the bunches which collided with high current electron bunches. Furthermore the proton tail population was measured with the HERA–B target wire and could be shown to increase due to collisions with high current electron bunches.

The proton dynamics will therefore be significantly influenced by the stronger beam–beam forces after the luminosity upgrade but the achievable luminosity will not be limited by this effect.

3.1.2.2 Beam–Beam Force on the Electron Beam

The increased electron beam–beam tune shift parameters could lead to a blowup of the electron emittances and therefore to a reduction of the luminosity and of the electron lifetime.

The accelerator studies which have been performed to investigate the influence of an increased beam–beam force on HERA's electrons have been described in detail in [3]. The beam–beam force on the electrons can currently not be increased to the force expected for the luminosity upgrade since the proton currents are currently limited to about 110 mA and the proton beam can not be focused to a smaller spot at the IP before the upgrade magnets are installed specifically for that purpose. But a significant dependence of the specific luminosity on the proton current for today's HERA might hint at a beam–beam force induced increase of the e^+ emittance after the luminosity upgrade. To test whether such a dependence exists for today's HERA parameters, the specific luminosity at H1 for each bunch pair was plotted against the proton bunch current in figure 3.4. The bunch by bunch specific luminosity is displayed for each luminosity run of the first four months of the year 2000, where for each run the data were taken shortly after the start of the run. To establish that a beam–beam force induced blowup of the electron beam diminishes the luminosity, a noticeable drop of the luminosity at high proton currents would have to be visible, which is not the case.

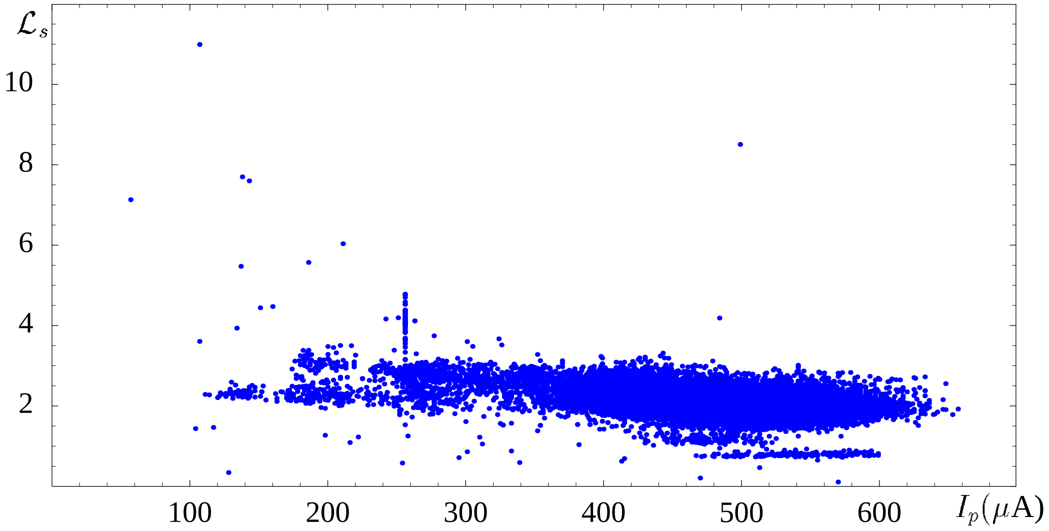

Figure 3.4: The specific luminosity $\mathcal{L}_s$ (arbitrary units) for each colliding bunch against the proton bunch current I_p (μA) as obtained by H1.

With two collision points the beam–beam tune shift is larger than with one IP and a reduction of the specific luminosity due to a second IP in HERA could indicate a beam–beam induced blowup of an electron emittance. But it was observed that the luminosity with two IPs was slightly higher than with only one IP, which has been shown to be compatible with the creation of a beta beat in one experiment which changes the luminosity in the other experiment. But no indication of an increased electron emittance has been found.

For a given proton current and spot size, the electron beam–beam tune shift can be increased by increasing the electron's beta functions at the IP above the luminosity values of $\beta^*_{ex} = 0.9$ m and $\beta^*_{ey} = 0.6$ m. To investigate if an increased electron beam–beam tune shift leads to an emittance blowup, e/p collisions were established for the electron injection optics with the current $60°$ focusing scheme in the arcs. This injection optics has beta functions of $\beta^*_{ex} = 2.2$ m and $\beta^*_{ey} = 0.9$ m which lead to beam–beam tune shift parameters of $\xi_{ex} = 0.026$ and $\xi_{ey} = 0.047$. For these parameters, which are similar to those expected for the luminosity upgrade conditions, no unexpected reduction in luminosity has been observed.

Since no beam–beam limitation has been observed under these simulated luminosity upgrade conditions, β^*_{ey} has been increased dramatically in 5 stages up to $\beta^*_{ey} = 4$ m. For these beta functions, the proton beam sizes were no longer matched to the electron beam sizes. To diminish this mismatch, the optics with increased beta functions had $72°$ focusing in the arcs and nominal emittances of $\epsilon_{ex} = 32$ nm. The luminosity was optimized by varying a vertical decoupling bump through sextupoles, which lead to an emittance coupling of less than 10%.

With a proton current of 90mA, a specific luminosity of $\mathcal{L}_s = 8.8 \cdot 10^{29}$ cm^{-2}mA^{-2}s^{-1} was reached for a spin matched $72°$ optics with $\beta^*_{ex} = 1$ m and $\beta^*_{ey} = 0.7$ m. The proton emittance was not measured but $\epsilon_{px} = 15\pi$ mm mrad, $\epsilon_{py} = 12.5\pi$ mm mrad would lead to this luminosity. Then five different optics with $\beta^*_{ex} = 2.5$ m, $\beta^*_{ey} \in \{1, 1.5, 2, 3, 4\}$ m were installed with separated beams at the interaction points and then luminosity was established and optimized for each of these optics. The value of $\beta^*_{ex} = 2.5$ m was chosen for each of these optics since the corresponding horizontal beam–beam tune shift of $2\Delta\nu_{ex} = 0.082$ is slightly higher than expected for the design proton current of 140mA after the luminosity upgrade. Figure 3.5 shows the luminosity which was achieved at ZEUS for the different β^*_{ey}. The fitted curve does not take into account the optics with

$\beta^*_{ey} = 0.7$ m since this optic has $\beta^*_{ex} = 1$ m rather than $\beta^*_{ex} = 2.5$ m as in the other cases. This figure shows that the luminosity would be significantly larger than what was measured when the beam–beam force would not have influenced the electron beam.

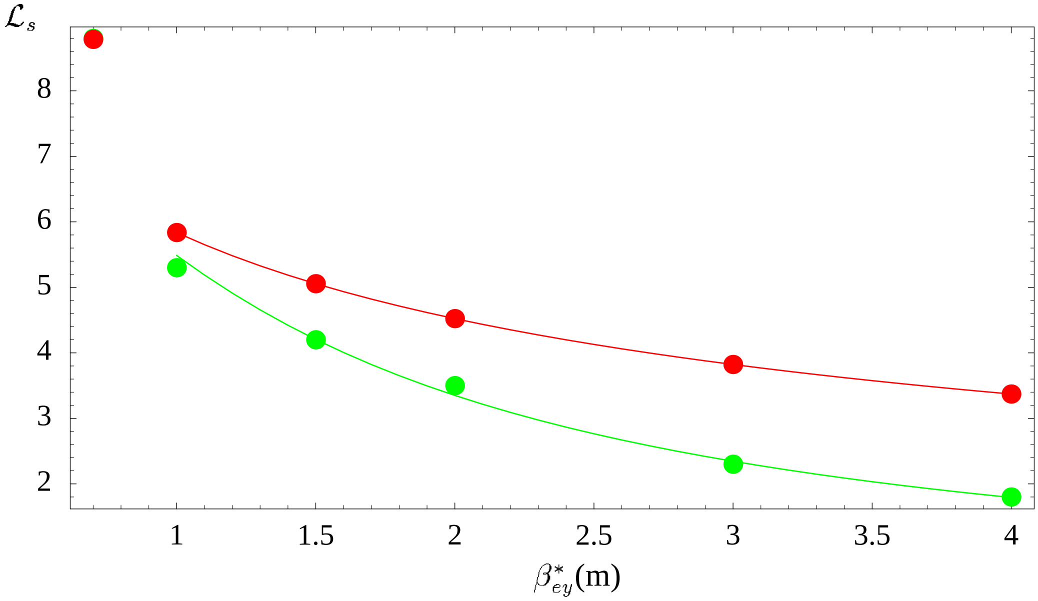

Figure 3.5: Bottom (green): The specific luminosity $\mathcal{L}_s$ in units of 10^{29} cm^{-2}mA^{-2}s^{-1} for six optics with different beta functions. Top (red): Computed specific luminosity when the beam–beam effect is not taken into account.

The emittances measured at H1 and ZEUS are shown in figure 3.6 and a fit to the average of the two measurements is also shown. It has been shown in [3] that the strong decrease of the luminosity in figure 3.5 is due to this blowup of the vertical emittance.

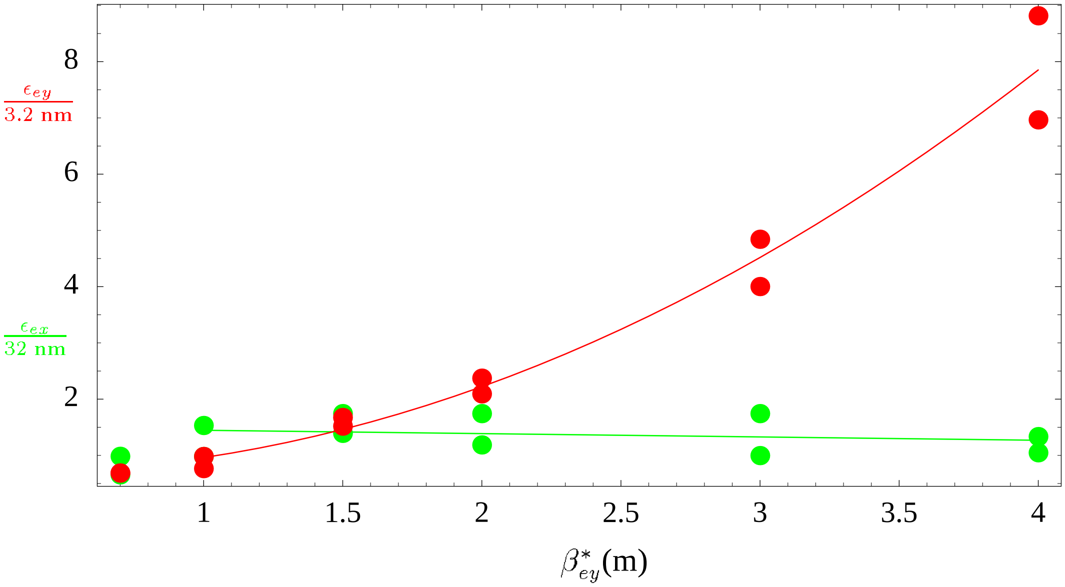

Figure 3.6: Top (red): The vertical emittance relative to the computed value of 3.2 nm. Bottom (green): The horizontal emittance relative to the computed value of 32 nm. While ϵ_{ex} does not seem to change much, the vertical emittance is blown up by up to a factor of 8.

While these studies show that the beam–beam tune shift parameter at HERA can lead to a very large blowup of the emittance, it is encouraging that such a blowup does not limit the luminosity for the vertical electron beam–beam tune shift parameter of the upgrade project which corresponds approximately to a vertical beta function of $\beta^*_{ey} = 1$ m in the figures 3.5 and 3.6. It is remarkable that HERA could be operated in stable luminosity condition with good lifetime for a vertical emittance blowup of 8 and with a beam–beam tune shift parameter of 0.5, corresponding to $\beta^*_{ey} = 4$ m.

3.1.2.3 Dynamic Aperture

Changing from $60°$ to $72°$ focusing per FODO cell decreases the electron emittance, but it also increases the natural chromaticity. The chromaticity correction therefore requires stronger sextupoles which in turn reduces the dynamic aperture. Therefore a spin matched HERA–e luminosity optics with $72°$ was computed and the dynamic aperture for this optics was measured several times by kicking the beam to an amplitude where half the beam current is lost [5]. The dynamic aperture was found to be slightly above 12 σ which allowed an unproblematic operation of the electron ring.

3.1.2.4 Polarization

Figure 3.7 shows the first polarization optimization with the spin matched $72°$ optics [14]. First the vertical dispersion was minimized by an SVD procedure [15] and the vertical emittance was minimized by decoupling the linear optics with vertical bumps through sextupoles. Then energy scans and the harmonic spin matching bumps, which were computed for this $72°$ optics, were used very successfully to find a maximum polarization of 65% in only a few hours. Due to this extraordinary fast polarization optimization we trust that the stronger focusing after the luminosity upgrade will not cause a problem for the electron polarization.

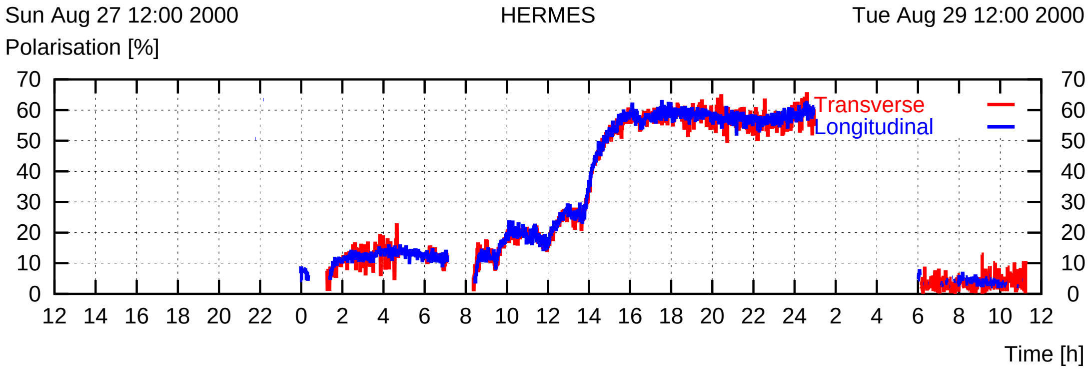

Figure 3.7: Polarization during optimization of the energy and the harmonic bumps of the $72°$ spin matched optics.

3.1.2.5 Luminosity

Finally we wanted to check whether the stronger focusing leads to the expected increase in luminosity. To check this, luminosity scans were performed as follows: The spin matched $72°$ optic was installed in the current ring and the e^+ and proton beams were brought into luminosity condition.

Then the proton beam was shifted with respect to the e^+ beam and the luminosity was recorded as a function of the amplitude of the symmetric bump which shifted the proton beam. While a wire scanner was used to determine the proton beam size, this luminosity scan was used to determine the e^+ emittances. As a reference, a luminosity scan was also produced for the current optics of HERA-e with $60°$ phase advance per FODO cell.

The beam–beam force acting on the e^+ beam is changed during the luminosity scan. This leads to a varying kick on the e^+ beam and to a varying disturbance to the beta function. These two effects were taken into account when determining the emittances of the e^+ beam. The first of these effects turned out to be very important. The HERA proton beam was assumed to be unaffected by the beam–beam force during the luminosity scan.

While the specific luminosity in the $60°$ optics was around $7.4 \cdot 10^{29}\ \mathrm{cm}^{-2}\mathrm{mA}^{-2}\mathrm{s}^{-1}$, the specific luminosity for the $72°$ optics was initially only about $5.4 \cdot 10^{29}$. A detailed analysis of the vertical and horizontal luminosity scans was used to show that the electron motion had a strong coupling between the horizontal and the vertical plane. After this coupling was eliminated by vertical decoupling bumps through sextupoles and by an SVD based dispersion correction, the luminosity scan lead to $\epsilon_{ex} \approx 28$ nm and $\epsilon_{ey} \approx \epsilon_{ex} \cdot 3.3\%$, and a specific luminosity of up to $8.8 \cdot 10^{29}$ cm^{-2}s^{-1}mA^{-2} was obtained. The luminosity scan data are depicted in figure 3.8.

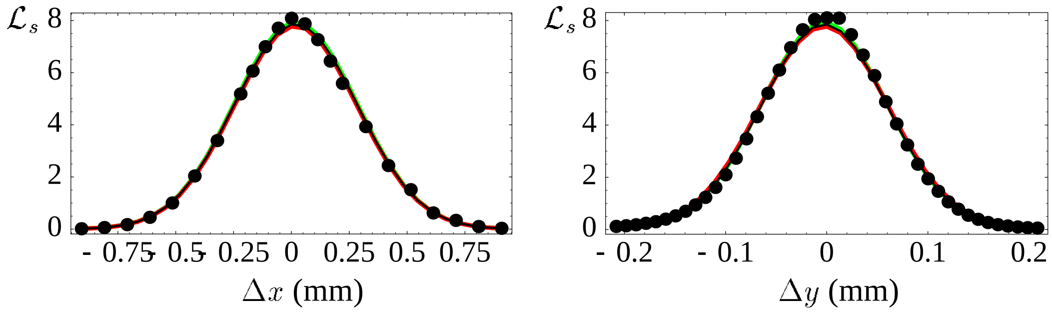

Figure 3.8: Luminosity scan at ZEUS. Left: The horizontal luminosity scan. Right: The vertical luminosity scan. The luminosity data (dots) and a bell curve fit (black) together with the expected luminosity (red and green) after correcting for the varying beam–beam kick and for the varying beam–beam lens.

3.1.2.6 RF frequency shift

An additional decrease of the emittance by shifting the frequency of the 500 MHz rf system by about 250 Hz is planed and therefore the deviation of the rf frequency from the center frequency was measured to find out whether there is sufficient margin for increasing the rf frequency. Table 3.2 shows the 6 different methods used to determine the current distance from the center frequency [5, 4]. The fact that HERA has so far been operated about 175 Hz below the center frequency shows that there is a comfortable margin for increasing the rf frequency for the luminosity upgrade.

3.1.2.7 Polarization

To check whether the electron polarization after the luminosity upgrade could suffer from the shifted rf frequency, the polarization was optimized in the $72°$ optics and then the rf frequency was increased by up to 500 Hz [14]. As shown in table 3.3 no significant decrease of the polarization has to be expected at frequency shifts of up to 400 Hz. This is an encouraging result since the

Beam loss at damping poles	$\Delta f_{rf} = -163\text{Hz} \pm 20\text{Hz}$
Change in damping times	$\Delta f_{RF} = -250\text{Hz} \pm 150\text{Hz}$
Horizontal sextupole center of the ring	$\Delta f_{RF} = +130\text{Hz} \pm 25\text{Hz}$
Vertical sextupole center of the ring	$\Delta f_{RF} = -70\text{Hz} \pm 50\text{Hz}$
Change of the synchrotron light spot with Δf_{RF}	$\Delta f_{RF} = -175\text{Hz} \pm 70\text{Hz}$
Electron emittance from beam scraping	$\Delta f_{RF} = -160\text{Hz} \pm 60\text{Hz}$

Table 3.2: Different measurements for obtaining the center frequency of HERA.

envisioned frequency shifts are below 300 Hz. For each setting of the rf frequency, the magnetic field was suitably changed to keep the electron energy constant. If this had not been done, the frequency shift of 500 Hz would have produced an energy change of about -50 MeV, which would have greatly influenced the polarization.

Δf_{rf}(Hz)	$< x >$(mm)	P (%)
200	-0.28	59.7 ±0.7
300	-0.43	61.1±0.6
350	-0.50	61.3±0.5
400	-0.57	59.6±0.5
500	-0.71	58.3±0.5

Table 3.3: Polarization for different frequency shifts. The rms closed orbit $< x >$ produced by changing the circulation time is also shown. For each setting of the rf frequency, the magnetic field was suitably changed to keep the electron energy constant.

3.1.2.8 Luminosity

After luminosity conditions had been established with the 72° optics, the frequency of the 500 MHz system was slowly increased by 250 Hz while the luminosity was recorded. The resulting relative increase in luminosity at H1 and ZEUS is shown in figure 3.9. The relative increase of the luminosity was stronger than initially expected but resembles the theoretical curve in figure 3.9 remarkably well after it was considered that the current rf frequency is about 175 Hz below the center frequency of HERA–e.

3.1.3 Conclusions

We conclude that the performance goal of the HERA luminosity upgrade of $\mathcal{L} = 0.74 \cdot 10^{32}$ cm^{-2}s^{-1} is not unrealistic and we are confident that it will be achieved. In [2] it has been described that the available aperture margins and proton emittances which can be smaller than designed will be helpful to compensate a possible shortfall of beam intensity in the short term.

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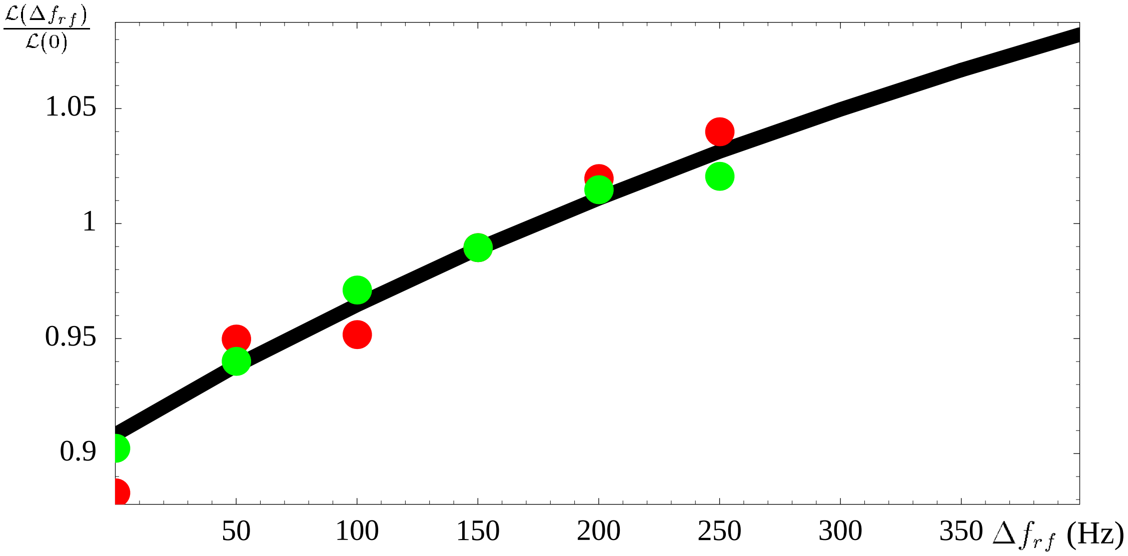

Figure 3.9: Relative increase of luminosity with increasing frequency in the 500 MHz electron rf system for ZEUS (red), H1 (green), and simulated (black).

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