HERA Accelerator Studies 2000

G. H. Hoffstätter

Abstract

The HERA accelerator study periods during 2000 were mainly concerned with issues of the luminosity upgrade project. These studies have been described in detail in [1] and will be summarized in this report. The luminosity upgrade was already an important subjects during the accelerator studies of December 1998 [2] and during the year 1999 [3]. Part of these studies have also been reported in [4, 5, 6, 7].

It is planned to reduce the horizontal electron emittance from the current 41πnm to 22πnm during the luminosity upgrade by increasing the RF frequency by about 250Hz and by using a 72° optics. While the luminosity in such an optics was initially too small, luminosity scans indicated that a too large vertical electron beam size limited the luminosity. Decoupling by a vertical closed orbit bump through sextupoles and a minimization of the vertical dispersion then lead to improved luminosity scans and to a satisfactory luminosity for the 72° optics. To estimate the effect of the increased beam–beam forces on the electron beam after the luminosity upgrade, several optics with 72° degrees phase advance per FODO cell but with different beta functions at the interaction points were used to establish luminosity. These studies indicated that the beam–beam force will not diminish the luminosity for the luminosity upgrade parameters. While increasing the luminosity by the mentioned emittance reduction schemes, the electron beam polarization should not be reduced. Therefore the change of polarization with an RF shift was investigated and a spin matched 72° optics was used to store a polarized beam with up to 65% polarization.

1 Introduction

The HERA accelerator studies which were performed during the year 2000 were a joined work of many participants. The following persons described their studies in the sections which they contributed to the report [1]:

DESY: F. Brinker, W. Decking, K. Ehret,
M. Funcke, E. Gianfelice, S. Herb, G. H. Hoffstaetter,
U. Hurdelbrink, W. Kriens, C. Montag, F. Stulle,
E. Vogel, M. Werner, A. Xiao,
CERN: H. Burkhardt, F. Schmidt, R. Tomás,
BNL: W. Fischer

Besides the subjects mentioned in the abstract, beam steering in the new interaction regions is also a very important subject for the luminosity upgrade; a study related to bridge movements will however not be covered here since it is covered in detail in the accompanying paper [14]. For the first time a longitudinal bunched beam echo was detected at HERA-p by measurements of the longitudinal oscillation amplitude and of bunch length oscillations in the proton beam. These accelerator studies are covered in an accompanying paper [15] and are therefore not further described here. The interaction rates in the HERA–B wires strongly depends on the position of the wires. In order to reduce this sensitivity, it was investigated whether the tails of the proton beam could be populated without a reduction of the luminosity by applying tune modulations to HERA–p. The following other studies with HERA–p were performed in a collaboration with CERN: The dynamic aperture and the detuning of the proton ring was investigated since such a measurement can yield valuable insight for the LHC. In a realistic accelerator synchrotron radiation at low frequencies is suppressed due to shielding by the beam pipe. To study this shielding effect, the energy loss of a low energetic coasting proton beam was measured. Since these accelerator studies of HERA–p did not lead to final conclusions, they will not be covered here, but the interested reader can find a detailed description in [1].

The luminosity in HERA will be increased by a reduction of the beam sizes of the electron and the proton beams. This will be done by an installation of dipole magnets very close to the interaction point (IP) for early separation of the electrons from the proton beam. This then allows a focusing of the proton beam very close to the IP by newly installed magnets. These hardware changes are described in [8, 9, 10, 11, 12, 13]. The early separation of the beams is simplified by a small electron emittance.

The mechanisms responsible for the electron emittance and the means which will be used in the luminosity upgrade to reduce the electron emittance have been described in [7] in simple terms. These means are a combination of increasing the frequency of the 500MHz RF system by about 250Hz and of using a 72° FODO optics in HERA's arcs as compared to the current 60° optics. 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?
- Will the RF frequency shift cause a reduction in polarization?
- Will the RF frequency shift increase the luminosity as expected?

2 Investigation of Upgrade Concepts

2.1 Smaller Beam Spots at the IP

The beam spots at the IP will be reduced according to the following table

Year	σ_x^e	σ_y^e	σ_x^p	σ_y^p
2000	192 μm	50 μm	189 μm	50 μm
2001	112 μm	30 μm	112 μm	30 μm

This leads to the following change of the tune shift parameter for each of the two IPs:

Year	ξ_x^e	ξ_y^e	ξ_x^p	ξ_y^p
2000	0.012	0.031	0.0013	0.0004
2001	0.034	0.051	0.0015	0.0005

A stronger tune shift parameter goes along with stronger nonlinearities of the particle dynamics. The stronger proton beam–beam tune shift parameter could therefore lead to a reduced dynamic aperture for the proton beam and therefore to reduced proton lifetimes. The increased electron beam–beam tune shift parameter could lead to a blowup of the electron emittances and therefore to a reduction of the luminosity and of the electron lifetime.

2.1.1 Beam–Beam Force on the Proton Beam

The accelerator studies which have been performed to investigate the influence of an increased beam–beam force on HERA's protons have been described in detail in [5, 16]. For these studies a very irregular fill pattern of the electron ring was filled. 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 have to be between 16 mA and 73 mA. In these experiments proton beam–beam tune shift parameters have been reached which are larger than those expected for the design electron currents of 56 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 proton beam–beam tune shift parameter.

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.

2.1.2 Beam–Beam Force on the Electron Beam

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 [1]. 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 1. 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.

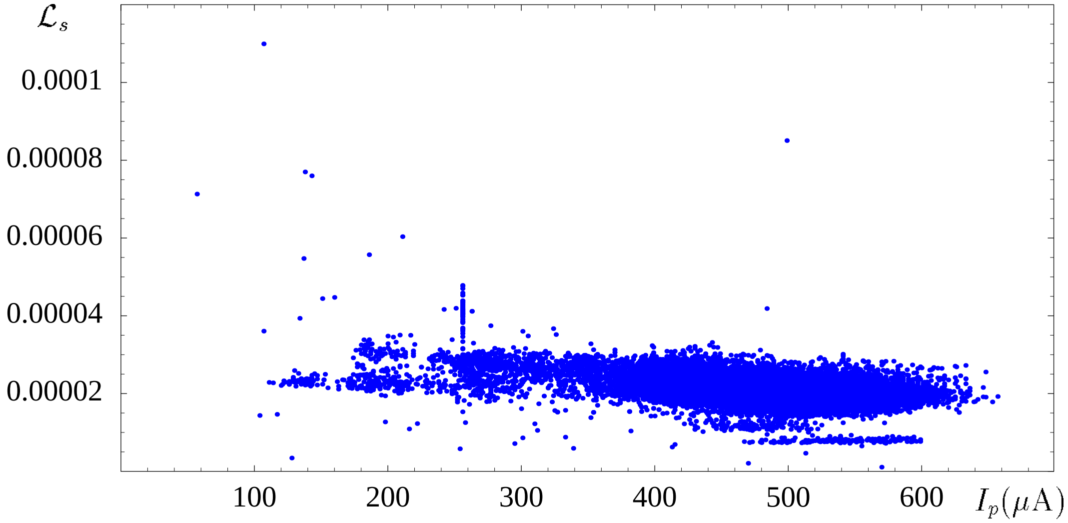

Figure 1: The specific luminosity $\mathcal{L}_s$ (arbitrary units) for each colliding bunch against the proton bunch current I_p (μA) as obtained by H1.

With two collision point 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. Therefore the ZEUS luminosity was measured while the beams were separated at H1 and then with collisions at the H1 IP. In fact a small increase of luminosity due to the collision at H1 was observed, which has been shown to be compatible with a beta beat due to the focusing strength of the proton beam at H1. 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 value of $\beta_x^e = 0.9$ m and $\beta_y^e = 0.6$ m. To investigate if this 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 $\beta_x^e = 2.2$ m and $\beta_y^e = 0.9$ m which lead to beam–beam tune shift parameters of $\xi_x^e = 0.026$ and $\xi_y = 0.047$. 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_y^e has been increased dramatically in 5 stages up to $\beta_y^e = 4$ m. Since bigger e^+ beta functions lead to an increased electron spot size at the IP, the proton beam sizes are no longer matched when the beam–beam tune shift is increased by increasing the beta functions. To diminish this mismatch, the optics with increased beta functions had 72° focusing in the arcs and nominal emittances of $\epsilon_x^e = 32$nm. The luminosity was optimized by varying the decoupling bump, 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 $\beta_x^e = 1$ m and $\beta_y^e = 0.7$ m. The proton emittance was not measured but $\epsilon_x^p = 15\pi$ mm mrad, $\epsilon_y^p = 12.5\pi$ mm mrad would lead to this luminosity. Then five different optics with $\beta_x^e = 2.5$ m, $\beta_x^e \in \{1, 1.5, 2, 3, 4\}$ 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 $\beta_x^e = 2.5$ m was chosen for each of these optics since the corresponding horizontal beam–beam tune shift of $2\Delta\nu_x^e = 0.082$ is slightly higher than expected for the design proton current of 140mA after the luminosity upgrade. Figure 2 shows the luminosity which was achieved at ZEUS for the different β_y^e. The fitted curve does not take into account the optics with $\beta_y^e = 0.7$ m since this optic has $\beta_x^e = 1$ m rather than $\beta_x^e = 2.5$ m as in the other cases. This figure shows also that the luminosity would be significantly larger than what was measured when the beam–beam force would not have influenced the electron beam.

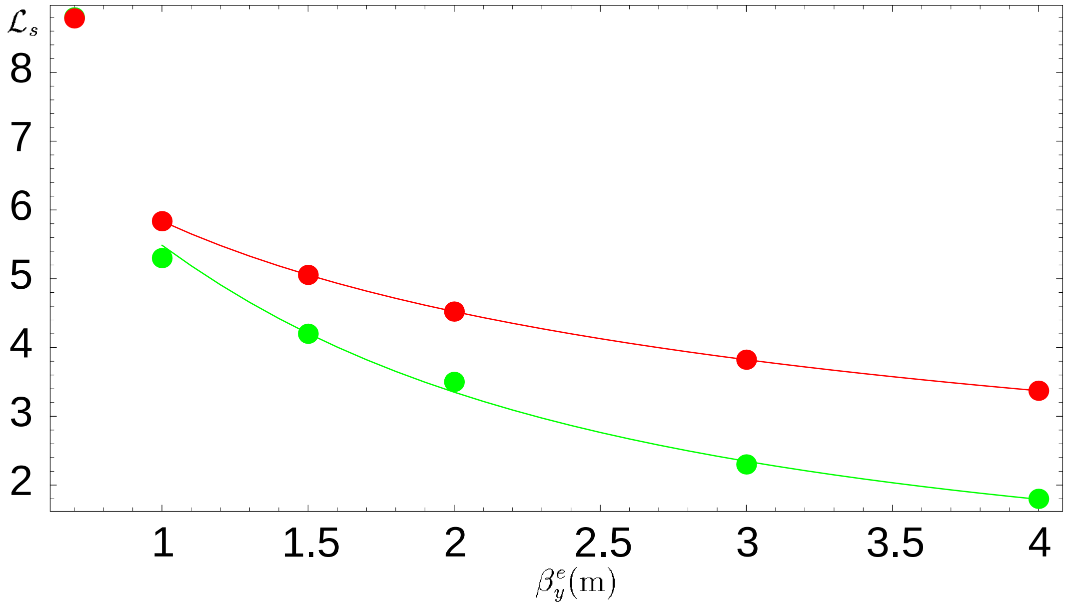

Figure 2: Bottom (green): The specific luminosity $\mathcal{L}_s$ in units of 10^{29} cm^{-2}mA^{-2}s^{-1} for six optics with different beta functions. Top (red): Computed specific luminosity when the beam–beam effect is not taken into account.

The emittances measured at H1 and ZEUS are shown in figure 3 and a fit to the average of the two measurements is also shown. It has been shown in [1] that the strong decrease of the luminosity in figure 2 is due to this blowup of the vertical emittance.

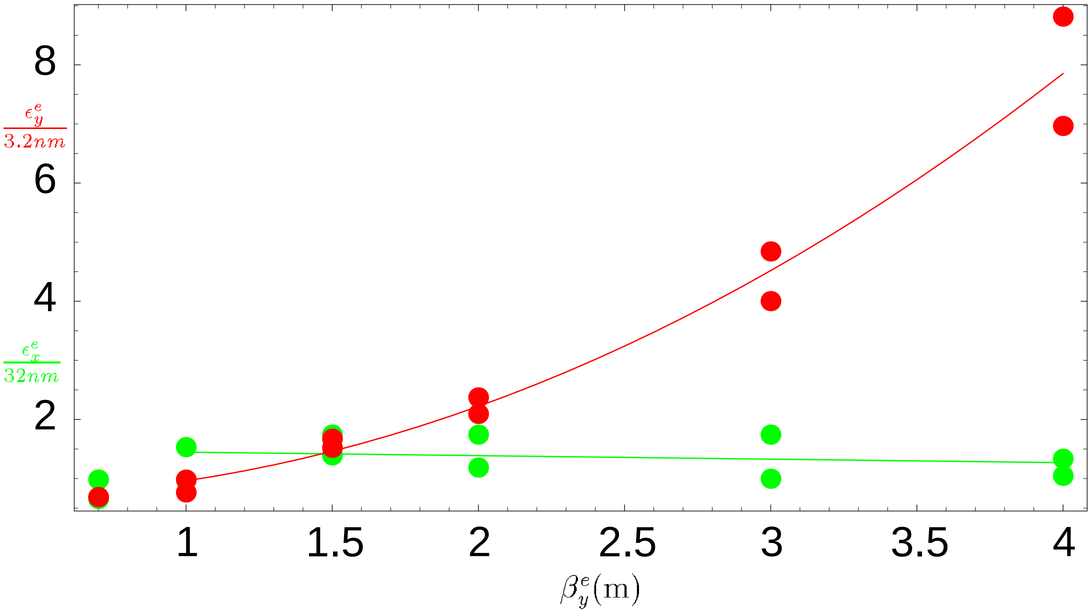

Figure 3: Top (red): The vertical emittance relative to the computed value of 3.2nm. Bottom (green): The horizontal emittance relative to the computed value of 32nm. While ϵ_x^e does not seem to change much, the vertical emittance is blown up by up to a factor of 8.

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 at for the electron beam–beam tune shift parameter which corresponds approximately to a vertical beta function of $\beta_y = 1$ m in the figures 2 and 3.

2.2 Stronger Focusing for Electrons

The change of the focusing strength in the arcs from 60° to 72° per FODO cell changes the electrons' dynamics. To test whether this will lead to problems, a spin matched HERA–e luminosity optics with 72° was computed. The dynamic aperture, polarization, and luminosity were then measured in this optics.

2.2.1 Dynamic Aperture

The 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 the dynamic aperture of HERA–e was measured several times by kicking the beam to an amplitude where half the beam current is lost [2]. The dynamic aperture was found to be slightly above 12 σ which allowed an unproblematic operation of the electron ring.

2.2.2 Polarization

Figure 4 shows the first polarization optimization with the spin matched 72° optics. First the vertical dispersion was minimized by an SVD procedure [17] 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.

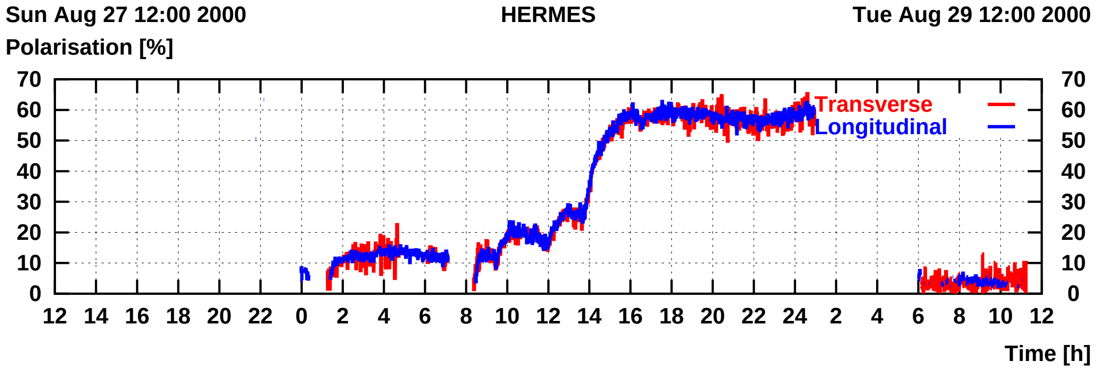

Figure 4: Polarization during optimization (energy and harmonic bumps scan). of the 72° spin matched optics

2.2.3 Luminosity

Finally we wanted to check whether the stronger focusing leads to the expected reduction of the electron emittances, or if it ultimately 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 $7.4{\cdot}10^{29}\ \mathrm{cm^{-2}mA^{-2}s^{-1}}$, the specific luminosity for the 72° optics was 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 the vertical decoupling bump through sextupoles and by an SVD based dispersion correction, the luminosity scan lead to $\epsilon_x \approx 28$ nm and $\epsilon_y \approx \epsilon_x \cdot 3.3\%$. The nominal emittance of the optics was 32 nm. The specific luminosity was up to $8.8 \cdot 10^{29}$. The luminosity scan data are depicted in figure 5.

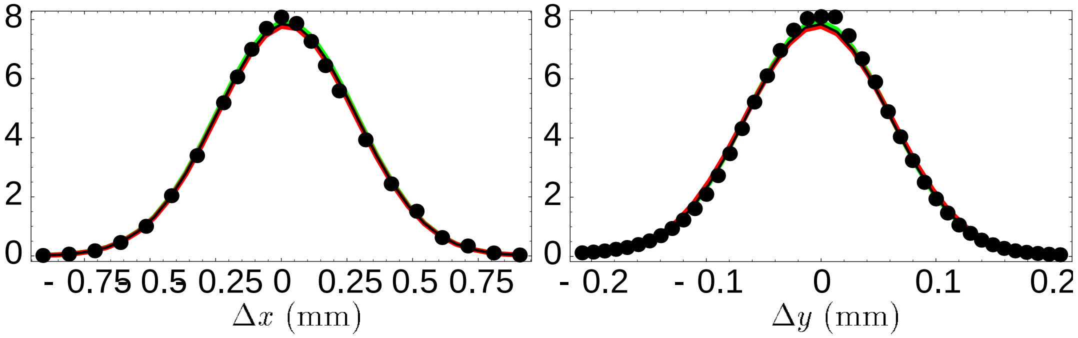

Figure 5: Luminosity scan at ZEUS. Left: The horizontal luminosity scan. Right: The vertical luminosity scan. The luminosity data (dots) and a bell curve fit (black) together with the expected luminosity (red and green) after correcting for the varying beam–beam kick and for the varying beam–beam lens.

2.3 RF Frequency Shift

An additional decrease of the emittance by shifting the RF frequency of the 500 MHz RF system by about 250 Hz is planed and therefore the effect of this frequency shift on the electron polarization and on the luminosity was analyzed.

2.3.1 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. As shown in table 2 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 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.

2.3.2 Luminosity

After luminosity 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 6. The agreement is remarkably good. The increase in luminosity verifies that the emittance reduction by increasing the RF frequency can be used. In fact the relative increase of the luminosity was initially stronger than expected and only resembled the theoretical curve in figure 6 after it was considered that the current

Table 1: August measurements

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 2: 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.

RF frequency seems to be 175 Hz below the center frequency of HERA–e. This frequency offset was measured by several independent measurements, which are described in [2, 3].

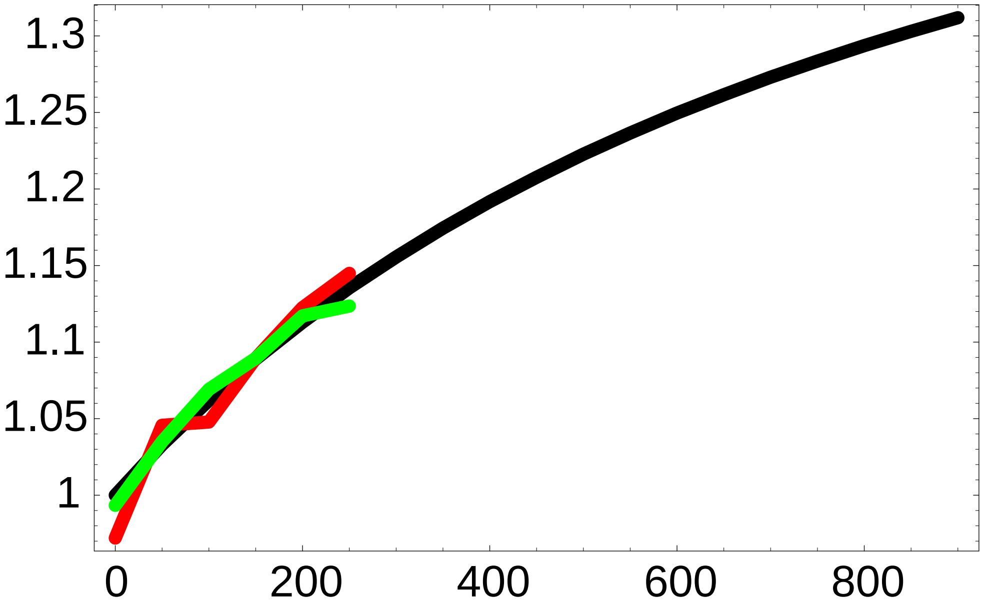

Figure 6: Relative increase of luminosity with increasing RF frequency in the 500 MHz electron RF system for ZEUS (red), H1 (green), and simulated (black).

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