HERA Luminosity Upgrade
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Abstract

A proposal to increase the electron-proton luminosity potential of HERA has been worked out. The design of HERA foresaw β-functions of $\beta_x^* = 10\,m$ and $\beta_y^* = 1\,m$ for protons at the IP. The corresponding luminosity is $L = 1.5 \cdot 10^{31}\,cm^{-2}sec^{-1}$ assuming a proton bunch population of 10^{11}, a normalized transverse proton beam emittance of $5\pi\,mrad\;mm$ and a total electron beam current of $58\,mA$. In the present HERA lattice the amplitude functions have been successfully decreased already substantially to $\beta_x^* = 7\,m$ and $\beta_y^* = 0.5\,m$ which allows a luminosity of $L = 2.3 \cdot 10^{31}\,cm^{-2}sec^{-1}$ assuming design intensities and emittances. The new proposed lattice with machine magnets inside the colliding beam detectors and new types of septum magnets allows to squeeze the β-functions of the protons down to $\beta_x^* = 2.45\,m$ and $\beta_y^* = 0.18\,m$ which allows for a luminosity of $L = 7.4 \cdot 10^{31}\,cm^{-2}sec^{-1}$.

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1 How to read this report

The present report is not a complete description of a consistent design of the new HERA interaction regions, though this would have been desirable. But it has to be understood as a snapshot of the present stage of the design.

The design has evolved from a very ambitious parameter set based on normal conducting separator and focusing magnets inside the colliding beam detectors. It is called **"REV 0"**. This design with a luminosity above $L = 9 \cdot 10^{31}\, cm^{-2} sec^{-1}$ had to be revised because some assumptions turned out to be too optimistic. Nevertheless, many investigations have been done based on these design parameters. Not all of them are completely invalid, since many investigations are rather insensitive to a change in parameters such as beam size at the IP. Whenever this is the case, it has been decided to include the results in this report. The corresponding sections are marked as REV0 design and they will be replaced by more up-to-date in a later version of this report.

The next stage in the design procedure is called **"REV 1"**. It is based on a realistic engineering design of the magnets inside the detectors. But it leads to larger chromatic effects in the electron ring. The lattice in the proton machine was re-iterated according to the results from the magnet development procedure. The luminosity in this lattice is reduced to $L = 7.4 \cdot 10^{31}\, cm^{-2} sec^{-1}$.

In order to relax some of the problems discovered when REV1 was investigated, a new version of the magnets inside the detector based on superconducting technology has been worked out. The design offers increased apertures for the beam inside the detector, less material installed in the detector and a strong reduction of chromatic effects for the e-beam providing the same luminosity as REV1. This design which is rather new is called **REV 2**. It is at a rather early stage and not all of the investigations done previously have been repeated for the new design.

Some of the important chapters of this report are still missing. This is partly because the work could not be completed up to now or the work has not yet been written up. Among the critical components missing from this report is the vacuum system for which the work has just started.

Despite the missing parts, the report will provide an overview on the work which has been performed for the time being.

2 Introduction

The HERA electron-proton collider started operating in June 1992. Since then the delivered luminosity has been steadily increasing: The integrated luminosities were $1\,pb^{-1}$ in 1993, $6\,pb^{-1}$ in 1994, $12\,pb^{-1}$ in 1995 and $17\,pb^{-1}$ in 1996 (see also Fig. 3). In 1997 a peak luminosity of $10^{31}\,cm^{-2}\cdot s^{-1}$ has been frequently surpassed, so that the machine is now running close to its design luminosity of $1.5\cdot 10^{31}\,cm^{-2}\cdot s^{-1}$.

So far the data have mainly been used to explore the structure of the proton and to make new and accurate tests of QCD. These results have attracted wide attention. It must however be noted that this is 'low Q^2 -physics' compared with the electroweak scale of $Q^2 = {M_W}^2$. The physics on the electroweak scale has so far been barely touched. This is the region HERA was built to explore. The unique features of HERA, like electron polarization and the capability to compare electron and positron running, are relevant only in the electro-weak regime. New important tests of EW interactions will have to be done; in addition new phenomena outside the standard model are more likely to appear. The observation of an excess of deep inelastic scattering events by H1 and ZEUS is a case in point [1] [2]. Even though the observation is not statistically convincing, it shows the discovery potential of the machine in the largely unexplored mass region above 200 GeV.

The need of a luminosity upgrade can be easily seen by this example. If the effect turns out to be real, it signals new physics beyond the standard model. With the present luminosity each of the two experiments would collect less than a dozen events/year. This number is by far not enough to explore an entirely new field of physics.

Increasing the luminosity $\mathcal{L}$ will increase the effective center of mass energy and therefore the effective mass range approximately like $(\mathcal{L})^{1/4}$. For example, a luminosity increase by a factor 4 is roughly equivalent to an increase of the proton beam energy from 820 GeV to 1160 GeV. Therefore a luminosity increase is a better way to improve the capabilities of HERA in the short/middle term than an energy increase. This can be worked out in some more detail.

First a change of the electron (positron) energy is considered. The luminosity is given by:

$$L = \frac{I_e \cdot N_p}{2\pi \cdot e \cdot \sigma_x \sigma_y}.$$

The electron current I_e depends on the energy E of the electron beam for the present RF power like

$$I_e = I_0 \cdot \left(2\left(\frac{E_0}{E}\right)^4 - \left(\frac{E}{E_0}\right)^4 \right),$$

where $E_0 = 27.5\,\mathrm{GeV}$, I_0 is the current at 27.5 GeV. The formula yields $L = 0$ for $E = 30\,\mathrm{GeV}$. The second constraint for the luminosity is $N_p/E =$ constant from the $\Delta\nu_e$ tune shift condition. The event rate for a given reaction is then

$$R = L \cdot \sigma,$$

where σ is the cross section and L is the luminosity as a function of E, with proper consideration of the constraints from the RF power and from $\Delta\nu$.
For the example of leptoquark production the cross section is approximately given by

$$\sigma = \frac{\pi}{4s} \cdot g^2 \cdot q\left(\frac{m_{LQ}^2}{s}\right)$$

where s is the cm energy squared and the quark density q(x) is approximated, at large Q^2 , by

$$q(x) \approx (1-x)^{4.9}$$

with $x = {m_{LQ}}^2/s$, where m_{LQ} is the mass of the leptoquark. Fig. 1 shows the rate as a function of the electron energy for the two values of the leptoquark mass of 200 and 240 GeV. Changing the electron energy within reasonable limits does not result in a worthwhile increase of the production rate. Of course, an increase of the RF power would lead to an increase of the counting rate and particularly the rate of very heavy leptoquarks would profit from it.

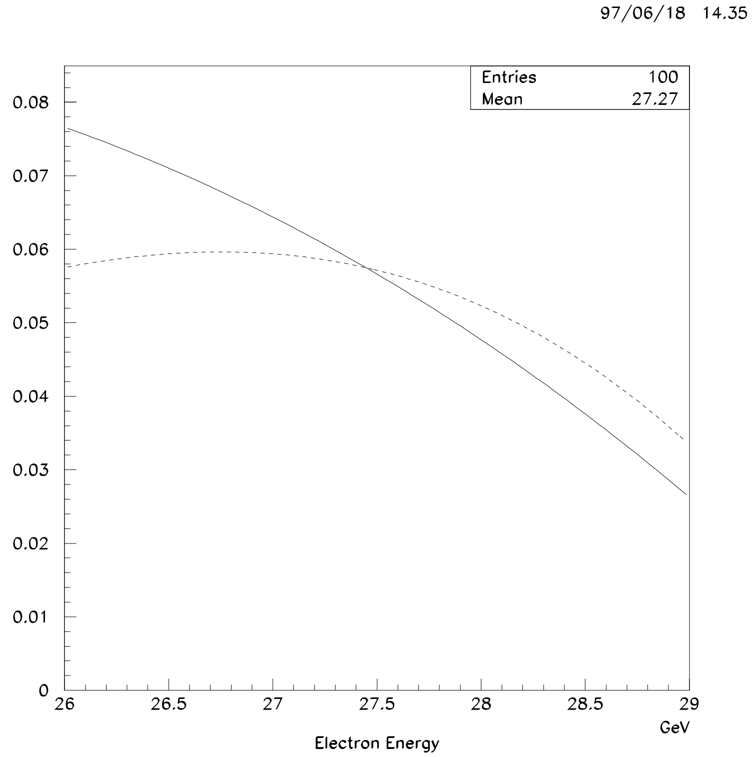

Figure 1: Production rate of a leptoquark as a function of the electron energy for two values of the leptoquark mass of 200 (solid line) and 240 GeV (dotted line).

As a second example a change of the energy E_p of the proton beam is considered. Since only a relatively small energy increase appears practical, one can set the luminosity approximately constant as a function of E_p. Fig. 2 shows the production rate of leptoquarks as a function of E_p, for the two values of the leptoquark mass of 200 and 240 GeV. An energy increase from 820 GeV to 900 GeV has relatively little effect for the production of a 200 GeV leptoquark, whereas the rate increases by a factor 2 for a 240 GeV leptoquark. This is still less than the increase expected from the luminosity upgrade scheme.

In the proceedings of the 1995/96 Workshop 'Future Physics at HERA' [3] (ed.Ingelman,De Roeck and Klanner), the consequences for physics of a luminosity upgrade have been investigated in great detail. It is shown, that the upgrade would improve the research opportunities

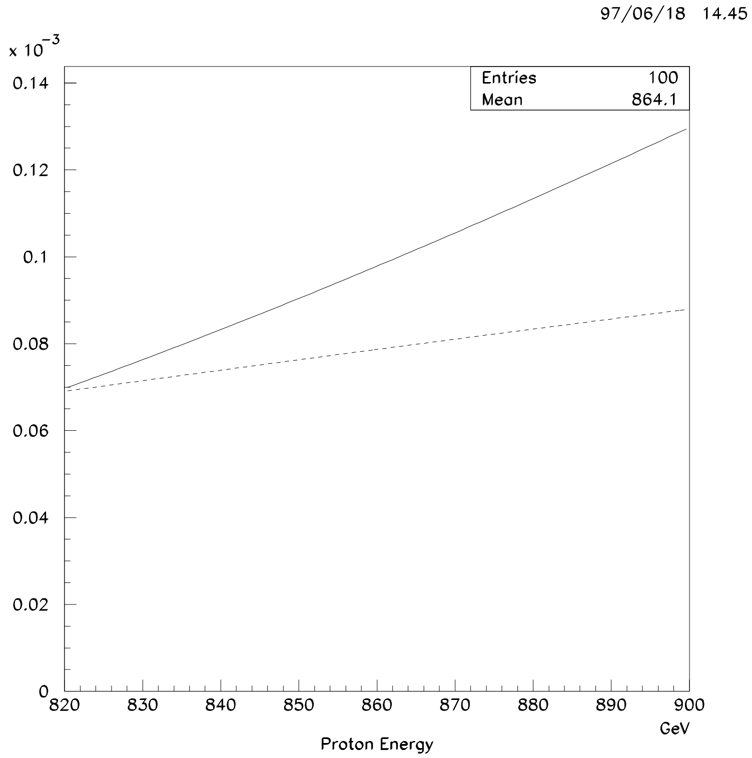

Figure 2: Production rate of a leptoquark as a function of the proton energy for two values of the leptoquark mass of 200 (dotted line) and 240 GeV (solid line).

of the machine tremendously, and thereby provide a strong motivation to operate HERA at the largest possible luminosity. A new generation of experiments would become feasible and the potential for discoveries and their investigation would increase very significantly.

In the meantime work has mainly concentrated on looking carefully and in detail on the realisation of the upgrade scheme. More careful considerations of the optics and of a number of other details have led to important changes of the original concept described in the Workshop Proceedings. Nevertheless it was possible to maintain the original goal for the luminosity improvement.

References

[1] H1 Collab., C. Adloff et al., Z.Ph. C74 (1997) 191.

[2] ZEUS Collab., J. Breitweg et al., Z.Ph. C74 (1997) 207.

[3] Proceedings of the 1995/96 Workshop 'Future Physics at HERA', ed. G. Ingelman, A. De Roeck and R. Klanner (1996)

3 Luminosity Prospects of HERA

3.1 HERA Operational Experience

The HERA electron proton collider is the first accelerator of its kind. Two species of charged particles which are stored in two different accelerator rings are brought into collisions. The accelerator was designed for the collisions of $30GeV$ electrons or positrons with $820GeV$ protons. The design goals correspond to maximum beam currents of $58mA$ electron/positrons and $160mA$ protons respectively. After commissioning in 1991, HERA started to deliver e-p luminosity to the colliding beam experiments H1 and ZEUS in 1992. Since its first year of running, the performance of HERA was steadily improved and the integrated luminosity could be increased by large factors from year to year. This is reflected in Fig. 3 which shows the integrated luminosity of HERA in the years 1992-1997.

At present, the maximum bunch intensity of the proton beam is limited by the performance of the whole HERA acceleration chain. The DESYIII booster synchrotron, where the intensity and the brightness of the proton beam is limited by space charge effects at injection energy, operates at design parameters of 10^{11} protons per bunch or even slightly above normalized beam emittances of $\varepsilon \cdot \gamma = 8\pi mradmm$ (90% of the beam). The apertures at extraction from DESYIII and injection into PETRA are extremely tight. There are unavoidable beam losses and only $8.5 \cdot 10^{10}$ protons per bunch are injected into PETRA. PETRA acceleration has been steadily improved and one is now able to deliver routinely a proton beam of $90mA$ which corresponds to $7.1 \cdot 10^{10}$ protons per bunch, 71% of the design value. The transfer between HERA and PETRA suffers from the small aperture available in the $40GeV$ proton beam line with a transfer efficiency of at most 95%. About 5% of the beam loss occurs during injection into HERA. From the remaining intensity another 5% is lost due to a beam lifetime of about $3h$ while HERA is waiting during the 15min filling procedure. The losses during acceleration are usually small. As a result, presently $80mA$ which is $6 \cdot 10^{10}$ protons per bunch (180 bunches) can be made available for e-p collisions routinely which is about 60% of the design value.

The intensity of the lepton beam suffered in the case of electrons from a breakdown of the beam lifetime due to interactions of the beam with the ion pumps. This problem disappeared when operation was switched to positrons. The beam intensity at this point is limited at about $45mA$ by rf power and reliability constraints. Thus the HERA intensity limitations are well understood. They are not of fundamental nature and measures are being taken for a step-by-step improvement programme.

The beam dimensions at the interaction points of both proton and electron beams are smaller than the design values. In both accelerators it was possible to give up safety margins of the apertures which allowed for stronger focusing and smaller β-functions at the IP. The β-functions achieved so far are $\beta^*_{xp} = 7m$; $\beta^*_{yp} = 0.5m$; $\beta^*_{xe} = 1m$; $\beta^*_{ye} = 0.7m$ which reduces the effective cross-section $\sqrt{(\varepsilon_p \beta^*_{xp} + \varepsilon_{xe}\beta^*_{xe}) \cdot (\varepsilon_p \beta^*_{yp} + \varepsilon_{ye}\beta^*_{ye})}$ by a factor of 0.6 with respect to the design value. The fact, that the proton beam intensity is still below design has the side effect, that the proton beam emittance is also below design. Usually emittances somewhat smaller than $\varepsilon_N = 20\pi mrad\ mm$ can be achieved in HERA luminosity operation. This is the reason why the specific luminosity is in excess of the design value by almost a factor of two and it gives luminosity peak values of $L_{peak} = 1.2 \cdot 10^{31} cm^{-2} sec^{-1}$, which is 80% of the design values despite the low beam intensities.

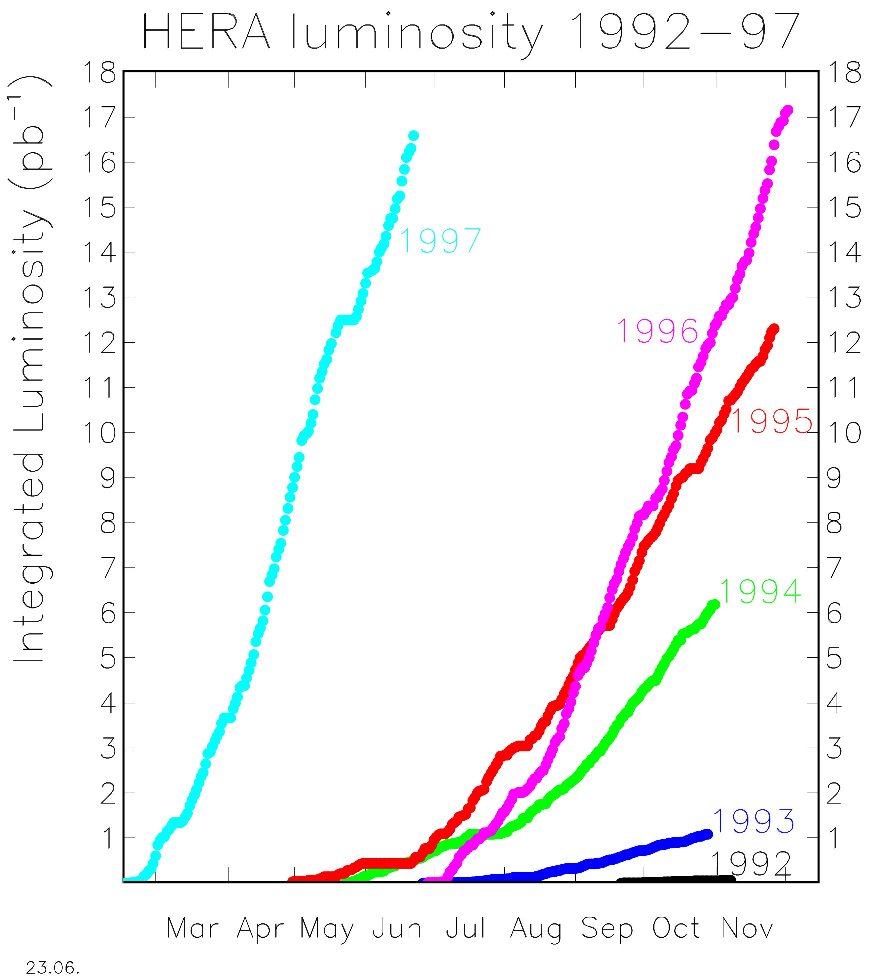

Figure 3: HERA Integrated Luminosity as Measured by the ZEUS Luminosity Monitor as a Function of Time for the years 1992-1997

The stability of both beams in collision is very good. This is true in particular for the protons where the beam lifetime during luminosity operation is in the order of several hundreds of hours and there is very little emittance growth ($\dot{\varepsilon}_N/\varepsilon_N = 0.03/hour$). This however requires well matched beam cross sections at the IP in order to avoid an enhancement of the nonlinearity of the beam-beam interaction. Under these conditions and with beam-beam tune shifts in the order of $\Delta\nu = 10^{-3}$, the proton beam seems to be not too close to the beam-beam limit.

The stability of the positron beam is very good as well. Its lifetime is given by beam gas bremsstrahlung due to desorbed gas from the walls of the vacuum pipe. Due to unavoidable dispersion in the rf regions which are located in each of the straight sections next to the IP, synchro-betatron resonances, $nQ_x + mQ_s = p$, are quite strong. Resonant tunes must be avoided which limits the available tune space. Good electron spin polarization requires a working point in between the resonances $Q_x + 2Q_s = 0$ and $Q_x + 3Q_s = 0$ which causes the beam to blow up somewhat in collisions which causes a loss of luminosity of 10%.

The bright HERA proton beam leads to strong beam-beam forces experienced by the lepton beam. The maximum beam-beam tune shift values in 1996 were around $\Delta\nu_y = 0.035$ and reaching up to 0.04 on a few occasions. These corresponds to record values observed at PETRA operated in e^+e^- mode and at LEP[2, 3]. If the working points are controlled well, the stability of the positron beam is satisfactory. There is no correlation between proton intensity and specific luminosity.

An important feature of HERA are the spin polarized lepton beams. Since 1995 HERA is operated with one spin rotators pair in the East straight section for longitudinally polarized beam for the HERMES experiments. There are some indications that it is more difficult to obtain maximum electron spin polarization values of 60% with high proton intensity.

The biggest challenge in HERA luminosity operation is to achieve reasonable reliability and availability of the whole accelerator complex. On average, the time spent in luminosity operation in 1996 was 43% of the scheduled time. The rest of the time was needed for injection, ramping, tuning, recovery from technical faults and trouble shooting. The 1996/1997 efficiencies reflect a good progress in HERA reliability. This progress is the result of efforts invested into the power supply and rf systems, the result of improved organization and operator training. Nevertheless, there is room for improvement in reliability and efficiency since these results have to be compared to a maximum possible efficiency of the order of 80%.

The integrated luminosity yield could be increased by a big step every year. In 1993, the luminosity amounted to $1pb^{-1}$, in 1994, the result was $6pb^{-1}$, in 1995 $12.3pb^{-1}$ and in 1997 $17.2pb^{-1}$ has been achieved. In 1997, luminosity is produced with a monthly rate of $4.5pb^{-1}$.

This steady progress gives confidence, that the design luminosity of HERA can be reached in the near future and integrated luminosities of $35pb^{-1}$ per year appear to be possible in the next few years of operation. Improvements much beyond these prospects require an upgrade programme such improvements on the accelerator chain [8, 9] and rebuilding the HERA interaction region.

3.2 HERA Luminosity Limitations and Constraints

The luminosity of the HERA e-p collider may be written as

$$L = \frac{N_e N_p N_B f_{rev}}{2\pi\sqrt{\sigma_{xp}^2 + \sigma_{xe}^2}\sqrt{\sigma_{yp}^2 + \sigma_{ye}^2}} \tag{1}$$

(N_p is the number of protons per bunch, N_e is the number of leptons per bunch, N_B is the number of bunches, f_{rev} is the revolution frequency, $\sigma_{x,y,e,p}$ are the rms beam sizes at the IP for protons and leptons respectively). To show how the luminosity is limited, the expression may be rewritten in terms of limited quantities and taking into account additional constraints.

An important restriction is that the beam cross section of protons and leptons have to match to limit the effects of the nonlinearity of the beam-beam interaction. This is particularly important for the proton beam to avoid emittance blow-up, bad lifetime and large backgrounds. Thus one has $\sigma_{zp}^* = \sigma_{ze}^* = \sigma_z^*$ (z denotes horizontal or vertical, p and e denote protons or leptons respectively).

Without a substantial and very expensive upgrade of the rf system, the total beam current of the lepton beam I_e, $N_e = I_e/(e \cdot N_B \cdot f_{rev})$, will be always limited by the available rf power. This limitation can be overcome by reducing the beam energy. However, the necessity of longitudinally polarized beams set a lower limit on beam energy. The so called HERA "mini-spin-rotator" [7] works only down to energies of about $26.5 GeV$. This limits the beam energy to a rather small range and no substantial increase in luminosity can be gained.

The number of protons per bunch will be ultimately limited by space charge effects in the injector chain. The maximum number of protons per bunch N_p is therefore related to a maximum beam brightness N_p/ε_N, where ε_N is the normalized proton emittance.

Since the two beams have to be separated after collisions before focusing elements for the proton beam can be placed, the beam size at the IP is expected to be limited by the maximum β-function of the protons at the IR low β quadrupole magnets.

Taking these considerations into account, the luminosity may be rewritten as

$$L = \frac{I_e \cdot N_p \cdot \gamma_p}{4\pi e\sqrt{\beta_{xp}^* \beta_{yp}^*}\varepsilon_N}. \tag{2}$$

One can see that the luminosity is independent of the number of bunches as long as the beam-beam tuneshift limitation of the proton beam is not reached

$$\Delta\nu_{x,y}^p = \frac{r_p I_e \sqrt{\beta_{x,y}^p}}{2\pi e f_{rev} N_B \varepsilon_N (\sqrt{\beta_x^p} + \sqrt{\beta_y^p})}. \tag{3}$$

(r_p is the classical proton radius). As long as one is not limited in the β-function of the lepton-beam, thus $\beta_{x,y}^e = \beta_{x,y}^p \varepsilon_{x,y}^p / \varepsilon_{x,y}^e$, the e-beam-beam tuneshift can be always controlled by an appropriate choice of the lepton beam emittance. Fortunately HERA has a big built-in flexibility of focusing in the arcs.

$$\Delta\nu_{x,y}^e = \frac{r_e N_p \sqrt{\beta_{x,y}^p}}{2\pi \gamma_e \varepsilon_{x,y}^e (\sqrt{\beta_x^p} + \sqrt{\beta_y^p})}. \tag{4}$$

(r_e is the classical electron radius.)

These considerations lead to the conclusions that the most promising way to increase the HERA luminosity is to reduce the β-functions at the IP by a new IR geometry with the proton low-β quadrupoles closer to the IP. Improvement factors of up to five compared to the design value and up to three compared to the 1997 running conditions can be reached. Further reduction of the β-functions of the protons is limited by the proton bunch length.

3.3 Design Considerations for the Present and for the Upgraded Interaction Region

Since there was no experience on electron proton collisions available, the HERA designers were conservative in the choice of the basic beam parameters and in the layout of the accelerator lattice. This was necessary to provide flexibility in case of unexpected difficulties with the collisions of unequal species.

The layout of the interaction point was a particular concern of the HERA designers since many difficulties had to be overcome and many constraints had to be taken into account. First, the luminosity depends on the beam size at the interaction point (IP). This is limited by aperture and by chromatic effects of the low β-quadrupole magnets. To reduce these constraints on small beam size, the low-β-quadrupoles should be placed as close as possible to the interaction point.

Before the strong low-β quadrupoles for the high energy proton beam can be placed, the beams must be sufficiently separated. This can be accomplished by a crossing angle or by a separator magnet.

A crossing angle implies a complicated antisymmetric geometry and requires very short proton beam sizes which implies a large rf voltage. The latter one has also implications on beam stability and limits the beam currents of the protons. Furthermore, beam collisions under a crossing angle generate synchro-betatron coupling which is also detrimental for the beam stability. It is expected to lead to strong intensity limitations of the two beams. For all these reasons, a crossing angle geometry has been abandoned and head-on collisions have been considered only. Recent investigation of proton beam stability [1] confirm that a crossing angle in HERA has to be limited to a maximum of 3 $mrad$ in order to avoid problems with proton beam stability in collisions. Therefore separation by magnetic field has been considered. This conclusions also remains valid for the new HERA interaction region.

A quick beam separation is important for high luminosity. But quick separation requires considerable magnetic fields which lead to strong synchrotron radiation from the lepton beam. This is a potential source of large backgrounds for the colliding beam detectors. A number of additional constraints had to be taken into account. The unavoidable dispersion generated in the separators had to be kept to a minimum to avoid strong synchro-betatron coupling by dispersion in the close-by rf cavities. Furthermore, the IR-straight section had to be made spin-transparent to allow for longitudinally polarized lepton beams.

To achieve small proton beam sizes at the IP is thus difficult. As already mentioned, the beam sizes of the two beams have to be matched at the IP in order to limit the non-linearity of the beam-beam interaction seen by the proton beam. Given the rather small HERA lepton beam emittance, it turns out to be rather easy to adapt the lepton beam to whatever can be achieved by the protons. The HERA luminosity in the present is thus limited by the ability to focus the proton beam at the IP. To overcome this limitation is the target of the upgraded interaction point.

The compromise found between the various constraints to place the first focusing elements of the proton beam at a distance of $27m$ from the IP which allowed for β-functions of $\beta_x^* = 10m$ and $\beta_y^* = 1m$ at the IP. With the normalized beam emittance of $\varepsilon\gamma = 5\pi mrad mm$ and the beam intensity of 10^{11} protons per bunch which was expected from the proton injector chain and the maximum lepton current of $I_e = 58mA$ which is limited by the installed rf power of $10.5MW$, a peak luminosity of

$$L_{peak} = 1.5 \cdot 10^{31} cm^{-2} sec^{-1} \tag{5}$$

was expected for HERA.

Experience of four years of colliding beam operation of HERA led to the following conclusions: The synchrotron radiation background in HERA is well tolerable if the beams and collimator positions are well optimized. The main source of residual synchrotron radiation background comes from tip-scattering from the upstream synchrotron radiation masks. Thus if the upstream synchrotron radiation masks could be avoided, a considerably larger amount of synchrotron radiation generated in the interaction region could be tolerated. This means that the beams could be separated more quickly, low β-quadrupoles for the protons could be placed closer to the IP and the luminosity could be increased by smaller β-functions of the protons at the IP. This is accomplished by separator magnets which are twice as strong as the present ones but which are placed inside the detector close to the IP. Then, the synchrotron radiation will pass through the IR and can be absorbed further downstream. No upstream masks need to be placed which absorb the high power synchrotron radiation and one only has to worry about backscattering from the downstream masks.

A second conclusion may be derived from recent HERA experience. The maximum tolerable beam-beam tuneshift levels assumed for the e-p collider in the original design are probably too conservative. As long as the proton beam size is well matched to the size of the lepton beam, the proton beam lifetime in collision is more than $100 hours$ and the background from lost protons in the IR is low. The beam-beam tuneshift of the lepton beam however has reached values by now which are close to the limits. This means that one can only profit from a brighter proton beam if the β-functions of the electron beam can be reduced sufficiently to match the proton beam cross section.

A new lattice for the HERA interaction regions must therefore provide better focusing for the protons and also provide smaller β-functions for the lepton beam. This requires focusing fields to be included in the separator magnets.

4 General Description

The new HERA interaction region allows to reduce the β- or amplitude functions for both beams at the interaction point in order to reduce the beam cross section to increase the luminosity.

The β-functions of both protons and electrons are limited by the following effects:

- Aperture limitations (mechanical or magnetic field) in the low-β quadrupole magnets.
- Large chromaticity requires stronger sextupole strength which reduces the dynamic aperture
- The beam cross sections must be matched to limit the nonlinearity of the beam-beam interaction
- The β-functions of leptons and protons can not be smaller than the proton rms bunch length which is in the order of $16cm$

These limitations are reduced by installing the low-β quadrupole magnets closer to the interaction point (IP) since the beam size and the chromaticity increases about linearly with the distance of these elements from the IP.

The leptons can not be exposed to the strong focusing fields of the protons and the beams must first be separated by a dipole field. The separating field will be generated by magnets inside the detector. In the latest version of the lattice (Rev2), these magnets will be superconducting. The bending radius is reduced by almost a factor of three compared to the present design. It is $438m$ on average which corresponds to a magnetic field of $0.25T$. Within a length of $3.5m$, the leptons are deflected by $8mrad$. This provides a separation of $56mm$ at $11m$ from the IP which is sufficient to place a septum quadrupole to focus the proton beam. Strong synchrotron radiation is generated in these separator magnets with a power of $25kW$. Since the radiation is generated inside the detector and is confined within a radiation fan of $2 \times 8mrad$, this radiation will be absorbed by absorbers which are located downstream of the experiment at a distance of $25\,m$ from the IP.

The proton low-β-quadrupoles start at $11m$ from the IP. They are designed as septum quadrupoles. They form a focusing doublet with a vertically and a horizontally focusing lens (in this order looking from the IP). The proton β functions can be strongly reduced from presently $\beta_x^* = 7m$ and $\beta_y^* = 0.5m$ to values of $\beta_x^* = 2.45m$ and $\beta_y^* = 0.18m$. The vertical β-function of the protons is then close to the bunch length limit. Unless the present beam optics which provides only a half aperture of 10 rms beam sizes, the new lattice designs provides room from 12.5 rms beam sizes in the low β quadrupoles and thus provides the same margin as the 1994 beam optics.

The separator magnets inside the detector also provide focusing of the positron beam in the vertical plane. This is necessary to match the beam cross section at the IP without excessive lepton beam chromaticity or beam-beam tuneshift. Outside the detector, there are two further low β quadrupoles. The first one provides focusing in the horizontal plane and the second one completes the low-β-triplet by focusing the vertical plane. This triplet focusing allows to balance the peak values of the vertical and horizontal β function of the lepton beam and provides a sufficiently small horizontal beam size at the point where the vacuum systems of the two beams separate. These two quadrupoles are aligned on the lepton beam orbit to minimize the synchrotron radiation generated inside these elements.

At 11 m from the IP, the two beams are separated by $56mm$. This is sufficient to place a septum quadrupole which provides focusing for the proton beam in the vertical plane. These septa are half quadrupoles with a cut-out mirror plate. The vertical focusing of the protons is completed by a septum-coil quadrupole. The lepton beam passes through the field free gap between the coil and the return yoke. At $30m$from the IP, the two beam are separated by about $210mm$. This is sufficient for a conventional quadrupole for horizontal focusing of the protons (HERA QR-type).

Figure 4 shows a schematic top view of the interaction region with the beam envelopes of proton and lepton beam.

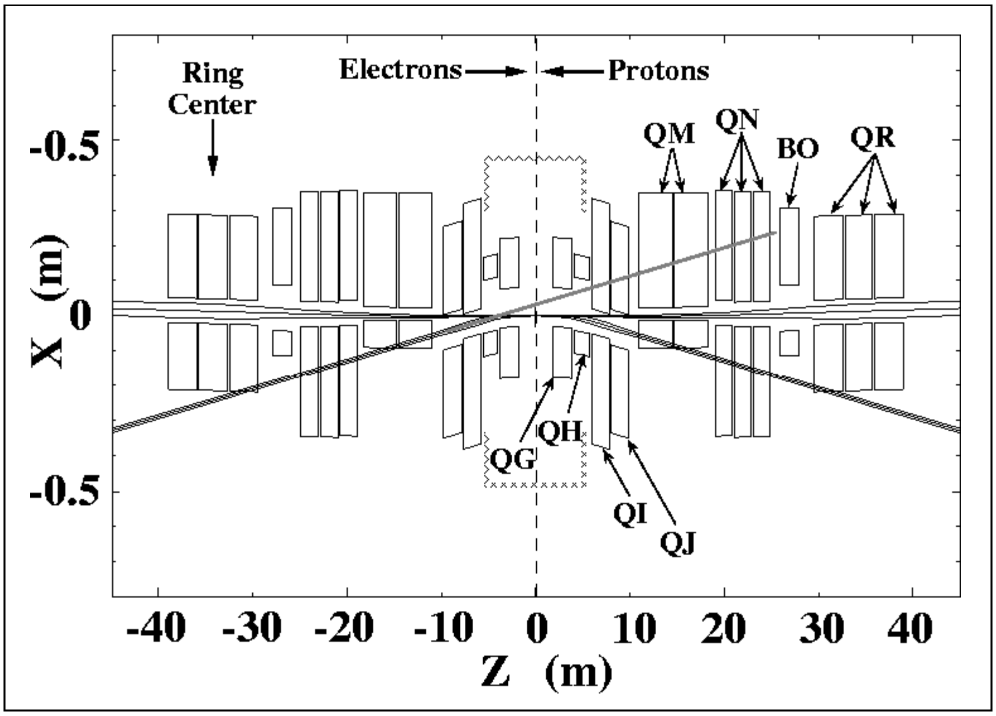

Figure 4: Schematical Top View of the New HERA Interaction Region (Rev2 Lattice): The interaction point (IP) in the middle of the drawing is surrounded by superconducting combined function magnets which separate the two beams by an 8 mr kick and which provide vertical focusing to the lepton beam. The strong synchrotron radiation generated by these magnets is passing the detector region and the downstream magnets and is absorbed at 11 m, 19 m and 25 m downstream of the IP. The next elements are two low β-quadrupoles which are aligned on the design orbit of the lepton beam. Behind these magnets, at 11 m from the IP, the two beams are sufficiently separated, to place a strong septum quadrupoles which provides focusing in the vertical plane for the proton beam. These are half quadrupoles with a cut-out mirror plate. The lepton beam is not affected by these magnets. Current septum quadrupoles complete the vertical focusing of the proton beam. Horizontal focusing starts at $30\,m$ from the IP using conventional quadrupoles.

In order to match the transverse dimensions of the two beams at the IP, the emittance of the electron-beam has to be reduced. This accomplished by changing the betatron phase advance in the arc from at present $60degr$ per FODO cell to ninety degree in the horizontal plane and sixty degree in the vertical plane. This choice compromises between small emittance and sufficient dynamic aperture which becomes a problem for strong focusing in the arcs. Dynamic aperture considerations limit the vertical β-function at the IP.

A consequence of installing machine magnets inside the detector is that the compensation solenoids must be removed and the cross coupling generated by the detector solenoid field must be compensated by rotating the low beta quadrupoles by a few milliradian.

The lattice of the proton ring outside the interaction region remains almost unaffected by the luminosity upgrade. The strength of the sextupoles must increase somewhat due to slightly increased chromaticity.

5 Parameters for Upgraded HERA Luminosity Operation

Beam Energies:
The upgraded lattice is designed to allow collisions between protons and leptons at the nominal HERA beam energies, namely $30GeV$ for leptons and $820GeV$ for protons.

Since it will be very expensive and difficult to reach high positron or electron intensities at the maximum energy, the operating energy for maximum luminosity and reliable operation will be most likely less than $30GeV$. On the other hand, the rate of high Q^2 DIS-events in e-p collisions is expected to drop drastically with energy which is an important reason for keep the energy as high as possible. The lower limit of the lepton beam is given by the demand for longitudinally polarized lepton spin at the IP. The tunability of the HERA mini spin rotator taking into account space restrictions in the HERA tunnel gives a lower limit of about $26GeV$ [7]

The maximum energy of the protons could be increased up to $1TeV$ if sufficient safety could be provided for the superconducting magnet system. This is not the case with the present quench protection system and present cryogenics parameters. Because of the uncertainty whether it will be possible to operate with a higher proton energy, the parameters and the lattice will be optimized for $820GeV$ operation. Additional quadrupoles for the proton beam are foreseen to reach $1TeV$ with somewhat less (-20%) luminosity.

The conclusion from this consideration is that for optimization of the lattice, energies of $30GeV$ and $820GeV$ are going to be chosen though the operating energy of the leptons will be somewhat lower.

β-Functions:
The parameters for luminosity operation for an upgraded HERA are optimized around the smallest achievable values of β-functions namely

$$\beta^*_{xp} = 2.45m;\ \beta^*_{yp} = 0.18m;\ \beta^*_{xe} = 0.63m;\ \beta^*_{ye} = 0.26m \tag{6}$$

The limitations of the β-functions are as follows:
The vertical β-functions of the proton beam
The new interaction region design allows to reduce the value of the vertical β-functions of the protons at the IP to values of down to $13cm$ without touching aperture or chromaticity limitations. The value of the vertical β-function of the protons is however limited by the proton bunch length. The proton bunch length in HERA in $820GeVc^{-1}$ storage operation is determined by intra-beam scattering. The longitudinal beam emittance in HERA at injection is about $0.05eVsec$ which would allow for a bunch length of 11cm. For the full proton intensity of $N_p = 10^{11}$ per bunch, and an rf voltage of $U = 320kV$ (208MHz system), an intra-beam scattering growth time of about 3 hours is calculated using the theory of Piwinski [6]. Using the full available voltage of $U = 2.4MV$, this growth can be reduced and growth times of about 5 hours are achieved. However under these conditions, the rms energy spread of the beam changes from $5 \cdot 10^{-5}$ to $8 \cdot 10^{-5}$. This causes a reduction of proton beam life time and presumably an increase of background due to lost protons. It is unclear whether a modest suppression of intra-beam scattering justifies a substantial increase in energy spread. It is therefore assumed that the achievable bunch length of the HERA proton beam will be around 16cm which corresponds to an emittance of $0.1eVsec$. In this case, the intra-beam scattering growth time is about 8

hours with $U = 320kV$. This more realistic set of parameters is assumed to determine the proton bunch length and thus the minimum β_y-value at the IP.

The horizontal β-function of the proton beam

Even with the new separation and focusing scheme, the horizontal β-function of the proton-beam is still limited by apertures and chromaticity. The layout described below allows for peak values of the β-function of about 1900m which is slightly less than the 1997 values. However, the aperture in units of rms beam sizes is larger compared to 1997 and corresponds with $12.5\sigma_x$ to the 1995 operating conditions. This increased safety margin is considered necessary because the 1997 operating intensity is only 60% of the final goal. The quadrupole strengths increase by about a factor of two. Therefore, the contribution of the IRs to the horizontal chromaticity roughly doubles its value and the total horizontal chromaticity increases from -69 to -76. This reduces the dynamic aperture according to the scaling law in reference [5] by about 10%. Since the dynamic aperture of the protons is expected to be very important for background and collimation, and since these have always been critical issues in HERA operation, the chromaticity should not be increased further. The resulting minimum horizontal β-function is about $2.0m$. The design is optimized for $2.45m$.

The horizontal β-function of the Electron/Positron beam

While in the present lattice the focusing properties of the lepton beam is far from limitations, this is not true any more for the new lattice. Since the focusing elements of the proton beam are placed to start a $11m$ from the IP, the horizontal beam size of the electron at the septum quadrupole is critical. In order to maintain an aperture of $20\sigma_x$ as in the present lattice the beta-function at the septum must be below 100m. To match at the same time the horizontal beam size of the protons at the IP, the beam emittance of the positrons must be reduced by changing the horizontal focusing in the arcs to 90 *degree* per FODO cell. Under these conditions, a horizontal β-function of about $60cm$ can be achieved.

The vertical β-functions of the Electron/Positron beam

Vertical focusing combined function separators inside the colliding beam detectors help to achieve small vertical β-functions of the electron beam. In order to control the horizontal beam size at the septum however, the vertical β-function in the low-β quadrupoles becomes rather large with values above $300m$ (in Rev1; in Rev2, the values are below $200m$). This increases the chromaticity by about 50%. Since the small horizontal emittance comes along with small horizontal dispersion and thus with strong sextupoles to compensate the chromaticity, dynamic aperture becomes an issue. This limits the value of the vertical β-function at the IP to about 27cm. On the other hand, larger values of β_y^* increase the vertical beam-beam tuneshift of the leptons to values above 0.04. Since values around 0.04 are considered to be close to the beam-beam limit, there is only a small window for the choice of the vertical β-function around 27cm.

Electron/Positron Beam Intensity: The beam intensity in HERAe will be always limited by the available rf power. It is closely related to the lepton beam energy. The presently installed rf power does not allow to store the design current of $58mA$ at a beam energy of $30GeV$. Therefore there are plans for a 8th rf station with 14 5-cell room temperature cavities which will provide additional $1.5MW$ of rf power. Even with this new station and operating the system at full power and, in addition, assuming a voltage of $40MV$ contributed by the superconducting cavity system, the design beam current of $58mA$ can only be stored up to a beam energy of $29.7GeV$. At $30GeV$ only about $51mA$ can be reached. Since we know that the rf system only works reliable up about $80\% - 90\%$ of the nominal maximum power, the beam current at $30GeV$ will be more likely only about $40mA$. The maximum energy which will allow the design beam current of $58mA$ will be about $28.5GeV$ assuming full power operation and $27.5GeV$ for realistic rf parameters (Each room temperature rf system delivers $1.25MW$, and superconducting rf is powered with only $1MW$, perfect rf matching is assumed so that there is no noticeable reflected power). In case, the operating energy (E) would be chosen even at a lower value, the available rf power would allow a drastic increase in beam current which scales with E^4. However, there are a number of additional limitations which make it difficult to reach larger beam current. The multi-bunch damper system is designed for $4 \cdot 10^{10}$ particles per bunch and is not expected to allow for a substantial increase in beam current [4]. Some of the bellows in the straight sections have long rf finger contacts. Some of these fingers have been found to be molten though the machine was then operated with only $30mA$ positrons. Before the beam intensity can be considerably increased, all these bellows need most likely to be reoptimized and replaced. The experimental beam pipe shows some heating at injection energy which is close to tolerable limits. With some improvement in cooling it might be possible to accommodate design intensities. A substantial increase of beam current requires, however, compromises to be made in the design of the experimental beam pipe. For this reasons, the parameters of the new lattice are optimized for the design current of $58mA$. Further increase of this intensity would increase the beam-beam tuneshift of the protons. With present parameters of $\Delta\nu = 0.0015$ they should be below the limit so that there is room for improvement on e-beam currents.

Number of bunches and bunch spacing:

The design bunch spacing in HERA is $96ns$. This number can only be changed by a new rf acceleration in DESYIII and PETRA or by very fast and strong kicker magnets. On the other hand, as long as the beam-beam tune shift limit of the proton beam is not reached, the luminosity is independent of the number of bunches. In the upgraded lattice, the beam-beam tuneshift values of the protons are expected to be below the limits assuming the standard bunch spacing of $96ns$. No substantial increase in luminosity can therefore be expected from an increased number of bunches. No efforts will be made to reduce the bunch spacing and no efforts will be made to produce more bunches in HERA. Thus we assume, that we will fill the machine with 180 bunches as in present operation. Some 174 will be colliding bunches. Six non-colliding bunches are going to be used for background discrimination. Under these circumstances the number of positrons/electrons per bunch will be $N_e = 4.25 \cdot 10^{10}$.

Proton Beam Intensity: The DESYIII booster synchrotron is presently able to deliver a proton bunch intensity of up to $1.25 \cdot 10^{11}$ protons per bunch. The beam intensity in HERA is limited by small beam loss due to limited aperture in beam transfer elements, injection losses due to poor life time and acceleration losses. At present, the proton intensity per bunch at HERA can be as large as $6.6 \cdot 10^{10}$. The particle losses are no principle problem. A programme is underway to improve the proton acceleration chain. It is reasonable to assume, that the design bunch intensity of 10^{11} protons per bunch will be reached in the HERA proton ring eventually.

Proton Beam Emittance: The beam brightness N_p/ε_N is ultimately limited in DESYIII by space charge effects. The emittance which is presently achieved in HERA with $6.6 \cdot 10^{10}$ protons per bunch is as small as about $3.5 - 4.5\pi mradmm$. This value of the HERA emittance is not much different from the 1995 values, where the beam intensity was only about $4.5 \cdot 10^{10}$ protons per bunch. This is not surprising since the emittance is defined by apertures in transfer lines and by the dynamic aperture of HERA. We therefore think it is not too optimistic to count on further progress in the accelerator chain and to assume the design emittance of $\varepsilon_{xN} = \varepsilon yN = 5\pi mradmm$ for future HERA operation with full intensity.

Electron/Positron Beam Emittance: At present, the limitation of the beam sizes at the

	e-beam	p-beam
energy	$30GeV$	$820GeV$
number of bunches total/colliding	180/174	180/174
bunch charge N	$4.18 \cdot 10^{10}$	$10 \cdot 10^{10}$
Beam Current	$58mA$	$140mA$
normalized emittance ε_N	$2.44 \cdot 10^{-11} mGeV^{-2}$	$5\pi mradmm$
horizontal emittance	$22nmrad$	$5.7nmrad$
emittance ratio	0.18	1
horizontal β at IP β_x^*	$0.63m$	$2.45m$
vertical β at IP β_y^*	$0.26m$	$0.18m$
beam size $\sigma_x \times \sigma_y$	$118\mu m \times 32\mu m$	$118\mu m \times 32\mu m$
beam-beam tune shift/IP $\Delta\nu_{x,y}$	0.027, 0.041	0.0017, 0.00046
luminosity	$7.36 \cdot 10^{31} cm^{-2} s^{-1}$	
specific luminosity	$1.64 \cdot 10^{30} cm^{-2} s^{-1} mA^{-2}$	
Improvement Compared to Design	4.9	

Table 1: Parameters for which the Upgraded IR Lattice is optimized

IP is given by the limited ability to squeeze the proton beam at the IP. In order to match the beam sizes of protons and electrons it is necessary to reduce the the beam emittance from presently $\varepsilon_e = 40nm$ to values of about half this size. Values of $\varepsilon_e = 22nm$ can be achieved by changing the horizontal focusing in the arcs to $90degree$ β-tron phase advance per FODO cell. An emittance ratio of $\varepsilon_{ey}/\varepsilon_{ex} = 0.18$ is necessary to match the sizes of proton and lepton beams at the IP in the vertical plane.
Beam-Beam Tune Shift: Based on the parameters discussed above, the beam-beam tune shift per IP of the protons does not exceed $\Delta\nu_{xp} = 0.002$. This is considered below the limits. The vertical tune shift for protons is still quite small. The necessity to reduce the lepton beam emittance however pushes the lepton beam-beam tune shift slightly above $\Delta\nu_{xe} = 0.04$. This must be considered close to the limit taking into account the available HERA operational experience and taking into accounts the experience made at PETRA and LEP.

With these parameters, a luminosity of $L = 7.36 \cdot 10^{31} cm^{-2} sec^{-1}$ can be achieved. The parameters described in this section are summarized in table 1.

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