HERA STATUS AND PERSPECTIVES OF FUTURE LEPTON-HADRON COLLIDERS

F. Willeke, DESY, Hamburg, Germany

Abstract

HERA, the only lepton-hadron-collider is entering a 2nd phase of operation. The commissioning of the accelerator with new interaction regions built for increasing the luminosity by a factor of 3.5 to $7\times10^{31}cm^{-2}sec^{-1}$ is in progress while new ideas are being discussed for the next generation of Lepton-Hadron colliders, which go beyond the kinematics and luminosity limitations of HERA. These are presented and discussed briefly.

1 INTRODUCTION

HERA, the first Lepton Hadron Collider surpassed its design performance in 1997 and has accumulated a luminosity of $185pb^{-1}$ by the year 2000. This has resulted in a number of fundamental physics observations. The kinematics range of lepton proton collisions in HERA made a large fraction of phase space accessible for measurements and has provided a new understanding of strong interactions and the nature of the proton. In particular it confirmed the point-like nature of the constituents of the proton on a scale of 10^{-18}m [1].

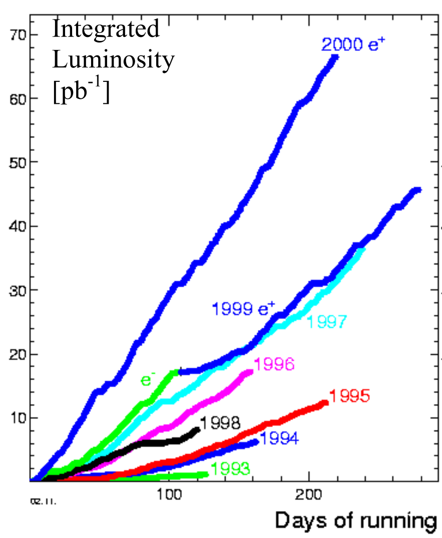

Figure 1: HERA Luminosity production as detected by the ZEUS luminosity monitor.

However, despite the good performance of HERA the achievable interaction rate has precluded detailed investigation of the underlying physics of extremely hard collisions with extremely large transverse momentum transfer. With the increase of luminosity after the HERA upgrade, one is expecting to collect up to $1fb^{-1}$ by 2007. This will considerably improve the precision of measurements in the interesting regions of phase space [1].

The phase space region of large transverse momentum (high Q^2) transfer with very small parton initial momentum (low x) in e-p collisions revealed an unexpected high density of virtual partons. The extension of these parameters to extreme values is expected to reveal further information on strong interactions and confinement. However, HERA´s kinematic range is limited. There is thus considerable interest the next generation of lepton-hadron colliders, which push the kinematics limits or alternatively provide a much larger luminosity and use light and heavy ions instead of protons as targets.

2 LEPTON-HADRON COLLIDER LUMINOSITY LIMITATIONS

The luminosity L of lepton proton colliders in the HERA energy regime may be written as

$$L = \frac{N_p \cdot I_e \cdot \gamma_p}{2\pi \cdot e \cdot \varepsilon_N \sqrt{\beta_{xp}\beta_{yp}}} \qquad \textbf{(1)}$$

N_p is the number of protons per bunch. I_e is the total electron beam current. ε_N is the normalized emittance of the proton beam. β_{xp}, β_{yp} are the beta functions of the proton beam at the interaction point, γ_p is the Lorentz factor of the protons and e is the elementary charge. The following boundary conditions have been obeyed to write the luminosity in this from. Single particle stability of the protons requires the crossing angle to be smaller than 1 mrad [2]. Furthermore, HERA experience has taught that matched beam cross sections at the interaction point are crucial for good lifetime and tolerable experimental backgrounds [3]. Finally, equation (1) assumes that the beam-beam tune shift for the lepton beam has not yet been reached. The luminosity is limited by the total lepton beam current, which depends on the available RF power necessary to balance the power loss due to synchrotron radiation. Because of the γ_e^4-dependence of this loss, there is a trade-off between energy and luminosity. For HERA the choice was made for the highest achievable beam energy for physics reasons. The second factor, which limits luminosity, is the hadron-beam brightness N_p/ε_N. It is typically limited by space charge effects in the low energy end of the injector chain. However, at high beam energy, dense beams are subject to Coulomb scattering of protons within the bunch, the so-called intra-beam scattering (IBS) [15], which leads to a significant growth of the beam emittances. For HERA, parameters the growth in the longitudinal phase plane are dominant. This effect also leads to a limitation of the third factor in the luminosity formula, the beta function at the IP. The beta function averaged for all collision points along the bunch is limited for given bunch length (hourglass effect). Beta functions may also be limited by the constraints of the interaction region layout, which may become quite restricting due to the need to handle the synchrotron radiation generated in the beam separation magnets. The most fundamental limitation in lepton proton luminosity thus arises from IBS. Stronger longitudinal focusing by a larger cavity voltage U_{RF} can reduce IBS. However, the growth time scales only with $(U_{RF})^{1/2}$ and a larger U_{RF} will increase the momentum spread of the hadron beam which should be small for good background conditions. Studies have been performed for cooling the high-energy hadron beam. However this appears to be very difficult [17].

The other fundamental limit on hadron beam brightness is the beam-beam effect on the lepton beam. Beam-beam tune shift limits for lepton colliders [4,5] are found in the range of $\Delta\nu$ =0.02-0.06. In a Lepton-Hadron collider, where the beam-beam tune shift may by written

$$\Delta\nu_{ye} = \frac{r_e}{2\pi}\frac{\gamma_p}{\gamma_e}\frac{N_p}{\varepsilon_N}\frac{\beta_{ye}}{\beta_{yp}\left(1+\sqrt{\beta_{xp}/\beta_{yp}}\right)} \qquad \textbf{(2)}$$

(r_e is the classical electron radius, γ_e is the relativistic factor and β_{ye} is the vertical beta function of positrons at the IP), one has to stay below this limit slightly in order to avoid spoiling of the hadron beam quality by coherent oscillations of the lepton beam. In HERA, beam-beam tune shifts of $\Delta\nu$ =0.036 [6] have been reached routinely under stable operating conditions. It is difficult to mitigate the beam-beam effect in lepton hadron colliders. The natural way is reducing the beta lepton function β^* (thereby increasing the emittance) which however is also limited by the hadron bunch length. An optimum layout for a lepton hadron collider should thus reach both the hadron beam brightness limitations given by IBS and the beam-beam effect on the leptons.

If beam energies much lower than the ones in HERA are considered, the RF power is no longer a limiting factor. The lepton beam intensity can be raised by filling more bunches. The bunch distance can be more easily reduced since the synchrotron radiation issues, which result from the beam separation scheme, are less severe. Furthermore, for smaller hadron beam momentum, electron cooling may become feasible [21] and the beam brightness limitations can be overcome. Assuming that there are no further beam current limitations, the luminosity depends essentially on the beam-beam limits for leptons and hadrons and the achievable beam divergence as limited by the IR optics and aperture [20]

$$L = \frac{4\pi\cdot f_{rev}\cdot n_b\cdot\Delta\nu_p\cdot\Delta\nu_e\cdot\sigma_e^{'*}\cdot\sigma_p^{'*}\cdot\gamma_e\gamma_p}{r_e r_p} \qquad \textbf{(3)}$$

(σ' are the rms beam divergences around the IP, $f_{rev}n_b$ is the bunch frequency). Using optimistic values for the beam-beam tuneshift limitations, luminosities in the order of $L=10^{33}cm^{-2}s^{-1}$ result from this formula.

3 HERA LUMINOSITY UPGRADE

In the fall of 2000, the HERA interaction regions around the colliding beam experiments H1 and ZEUS have been dismantled over a length of 240m and in the spring of 2001, new interaction regions have been installed. The low beta quadrupoles are now much closer to the IP. This allows reducing the beta functions at the IP of the two beams significantly in both planes. The beam cross section is now 112μm x 30μm which is five times smaller than the design beam cross section with the same aperture margin (12 σ) or 3 times smaller than the cross section in the year 2000 with reduced aperture margins. This is achieved by a combination of superconducting magnets inside the colliding beam detectors (see Figure 2), new half-quadrupoles with a cutout mirror plate and stronger focusing in the arcs of the lepton ring. The synchrotron radiation from the magnetic beam separation is generated inside the detectors, transported to a keyhole shaped beam pipe between the coils of the downstream low beta magnets and is absorbed on the far downstream end of the IP. The design is described in detail in references [7,8,9].

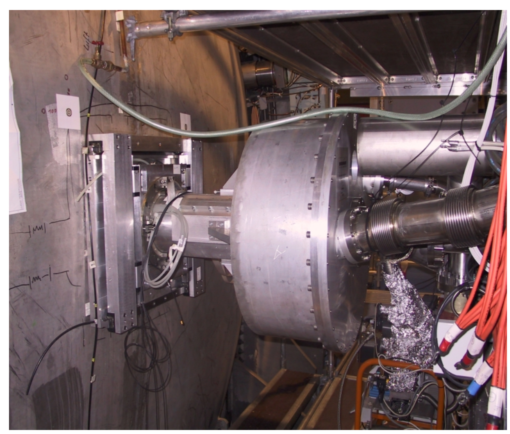

Figure 2 Superconducting low-β quadrupole-separator dipole in the Detectors: Visible is the end can of the 3.2 m long GO magnet in the H1 liquid Ar calorimeter.

The design parameters are in Table 1.

Parameter	up to 2000		after the upgrade	
	HERA-e	HERA-p	HERA-e	HERA-p
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}/n_{col}	189/174	180/174	189/174	180/174
$\beta_x^\star/\beta_y^\star$(m)	0.90/0.60	7.0/0.5	0.63/0.26	2.45/0.18
ϵ_x(nm)	41	$\frac{5000}{\beta\gamma}$	20	$\frac{5000}{\beta\gamma}$
ϵ_y/ϵ_x	10%	1	17%	1
$\sigma_x/\sigma_y(\mu m)$	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
$2\Delta\nu_y$	0.061	0.0007	0.103	0.0009
$\mathcal{L}(cm^{-2}s^{-1})$	$16.9\cdot10^{30}$		$75.7\cdot10^{30}$	
$\mathcal{L}_s(cm^{-2}s^{-1}mA^{-2})$	$0.66\cdot10^{30}$		$1.82\cdot10^{30}$	

Table 1. HERA main Operation Parameters before and after the upgrade

All critical design issues such as beam-beam tune shifts, the dynamic aperture of the lepton beam, the electron spin polarization in the new electron lattice were tested successfully in 2000 in the old lattice to the extent possible [10]. The overall conclusion of these experiments was that the parameters of the HERA luminosity upgrade as referenced in table 1 are well within the limitations and that the upgrade should be feasible.

4 HERA STATUS

The installation of the HERA luminosity upgrade component progressed without unpleasant surprises. The recommissioning of the two HERA rings started in August 2001 with protons and positrons. A number of challenging operational difficulties had to be solved. There are movements of low beta quadrupoles under the influence of magnetic forces due to unavoidably weak supports inside and around the colliding beam detectors, moving detector parts containing magnetic material in the vicinity of iron free superconducting magnets, strong coupling effects by uncompensated solenoid fields. At the same time, the sensitivity of the beam orbit and beam optics to distortion is enhanced due to aggressive focussing parameters. All these problems could be solved by making use of the very flexible HERA operating system and by making use of beam orbit feedback.

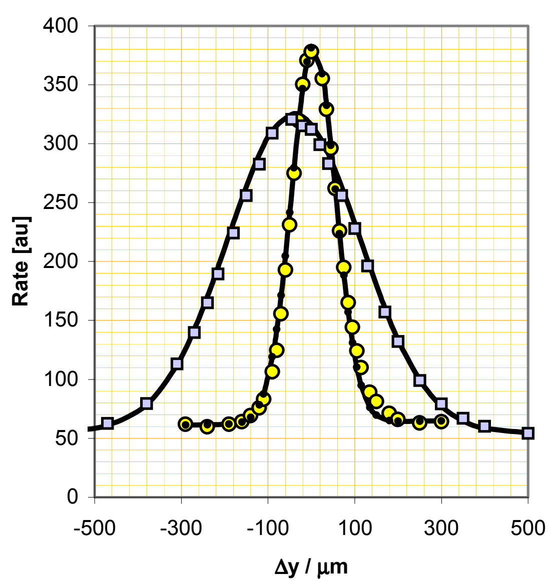

Figure 3: HERA Luminosity Scan using ZEUS luminosity rates. The luminosity rate is plotted versus horizontal and vertical beam separation Δy at the IP. The rms width of the vertical (circles) and the horizontal (squares) curves are Σ_y=51µm and Σ_x=153 µm corresponding to the effective beam sizes. The specific luminosity derived from these measurements $L_{spec}=1.68\cdot10^{30}cm^{-2}s^{-1}mA^{-2}$ is close to the design value $1.82\cdot10^{30}cm^{-2}s^{-1}mA^{-2}$.

Once both rings had been re-commissioned and the beam optics had been verified, the proton and the positron beam could be brought into collisions without much difficulty. The specific luminosity was measured by transversely scanning the relative beam positions of the two beams at the interaction point. This procedure provides a direct measurement of the effective beam cross-section at the IP. The specific luminosity (see figure 2) is found within 80% of the design value. The positioning of the positron beam in the low-β quadrupoles turned out to be very critical for the synchrotron radiation backgrounds as expected. For this reason a large effort has been made to align the low-β quadrupoles with the beam (beam based alignment). Beam based alignment in long combined function magnets with design offsets of the beam with respect to the quadrupole axis and aggressive beam optics in the interaction region turned out to be quite difficult and required a thorough analysis [11]. The vertical beam offset in the low beta quadrupole could be reduced this way to values around 100 µm. (See figure 4).

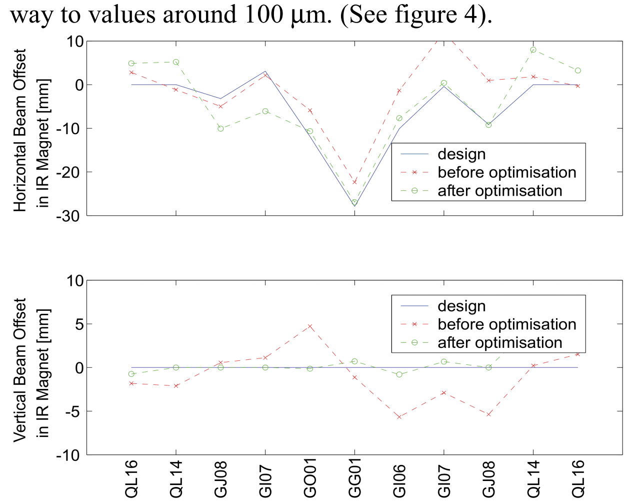

Figure 4 Results of Beam Based Alignment in HERA IR South: Beam Orbit with respect to axis of the low beta quadrupoles before and after alignment.

Based on this success, the synchrotron radiation background levels in the H1 detector could be reduced to values below the values obtained in the year 2000 run. Possible synchrotron radiation and charged particles however still represent a considerable hazard for detector components close to the beam pipe. This imposes a large operational problem. The beam orbit has to be stabilized to sub-millimetre level during ramping and the low beta squeeze. This can only be accomplished by additional orbit feedback that is being prepared.

5 HERA FUTURE PLANS

The HERA physics program requires an integrated luminosity of 1 fb^{-1} [1]. It is expected that this luminosity, equality split between electron–proton and positron-proton collisions, will be delivered by the end of 2006.

The HERA physics program also requires a polarized lepton beam. Successful polarization tests with the new e-ring lattice with 72° betatron phase advance in the arcs were performed in the year 2000[10]. Polarized beams with uncompensated solenoids and two additional pairs of spin rotators installed around H1 and ZEUS however require improved orbit control supported by beam based alignment and more sophisticated harmonic bump tuning to achieve polarization values close to the 60% achieved in 2000 [12].

At present, there are no plans to continue HERA operations after 2006. Moreover, there are plans to transform the PETRA injector ring into a 3rd generation light source [13] starting in 2007. Proton injection into HERA would then require a new 40GeV proton booster.

6 THE THERA ELECTRON PROTON COLLIDER

TESLA, the 500GeV c.m. e^+e^- Linear collider, presently under study [14], will provide electron beams up to a beam energy of 800GeV. The TESLA tunnel has been aligned to allow collisions between the electrons and protons stored in the HERA proton ring. This constitutes THERA, the TESLA-HERA-Electron-Proton-Collider.

The achievable THERA luminosity is constrained by the electron beam power, which limits the electron intensity for a given beam energy, the intra-beam scattering which limits the brightness N_p/ε_N of the proton beam, and the β–function of the protons at the IP achievable within the practical limits of focusing at the interaction point (IP). In the limit of ultra-short bunches and assuming head-on collisions, round beams, and equal transverse beam sizes for electrons and protons at the IP, the luminosity can be written in the following form

$$L = 4.8\cdot 10^{30} cm^{-2}\sec^{-1}\frac{N_p}{10^{11}}\frac{10^{-6}m}{\varepsilon_N}\frac{\gamma_p}{1066}\frac{10cm}{\beta^*}\frac{P_e}{22.6MW}\frac{250GeV}{E_e} \quad \textbf{(4)}.$$

($\beta^*=\beta_{yp}=\beta_{xp}$ is the proton beta function at the IP, P_e is the lepton beam power and E_e is the lepton beam energy)

Taking the general limitations on proton beam brightness into account, an IBS growth time of 2.9 hours is calculated for a 1 TeV proton beam with an initial transverse normalized emittance of $\varepsilon_p = 1\cdot 10^{-6}$ *m*, an initial bunch length of σ_p = 10 cm, and an initial relative energy spread of $\sigma_{pe} = 1.1\ 10^{-4}$. The transverse growth time is just 2 hours. This determines the luminosity lifetime and must be considered as an upper limit for the proton density. In order to achieve smaller proton beam emittance, cooling is required. For example, to reduce the emittance by a factor of five, cooling times of 12 min must be achieved to balance the IBS emittance growth. Up to this point, no such powerful cooling systems are available. This leads to the conclusion, that a normalized emittance in the order of $\varepsilon_p = 1\cdot 10^{-6}$ *m* with $N_p = 10^{11}$ has to be considered as a minimum for THERA. It represents quite a challenge to achieve the corresponding beam brightness in the injector chain. At present, the best beam brightness values achieved in the DESY III synchrotron are in the range of $N_p / \varepsilon_p = 1.3\cdot 10^{11}$ /$3\cdot 10^{-6}$ m [16] which falls short by a factor of 2.3 to the target value of $10^{11}/10^{-6}$ *m*. Electron cooling in the lower energy stages [17] may be necessary to achieve the target value. Active feedback to damp injection oscillations might be needed in the higher energy stages. The conclusion is that the TESLA beam brightness target values constitute an ambitious but maybe not unrealistic goal for THERA.

Small values of the β-function at the IP are essential for high luminosity. β^* is limited by the chromaticity of the protons, which is generated in the low-β quadrupole magnets, by aperture limitations in connection with a maximum achievable field gradient in the quadrupole magnets and by the proton bunch length. As chromaticity and maximum beam size grow linearly with the final focus quadrupole distance from the IP, it is desirable for fixed β* to focus electrons and protons simultaneously, thereby minimizing the distance of the quadrupole magnets to the IP. At 1 TeV proton energy, the bunch length should be 10 cm or longer for adequate IBS life times. In addition, in order to avoid the excitation of synchro-betatron resonances of the protons by the electrons, the crossing angle must be limited to a few mrad.

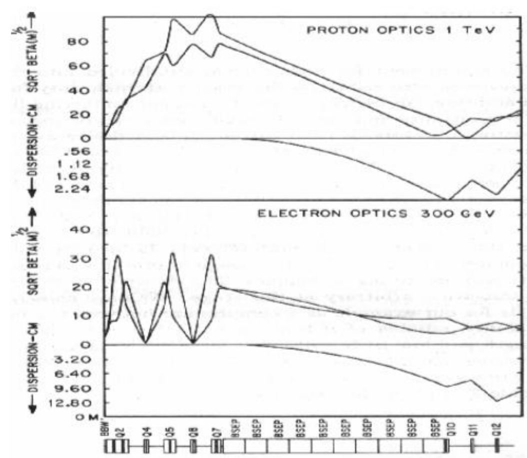

Figure 5 Possible layout for the THERA IR for e/p energy ratios between 1-4 and. The case for 1TeV protons and 300 GeV electrons as is shown. A triplet and two doublets focus the electron beam strongly. At the beam envelop waists in-between these lenses, strong quadrupole magnets are placed which primarily focus the protons. After the two beams are properly focused, at 70 m from the IP, a long soft quadrupole magnet, which is aligned along the electron beam orbit, smoothly bends the protons away. This arrangement avoids any extra upstream synchrotron radiation generated by the beam separation.

Additional beam separation techniques are thus required, possibly using soft magnetic separation. Figure 5 shows the conceptual layout and the resulting envelope functions that meet the requirements. The layout has been designed for a ratio of proton to electron energies of 1TeV/300

GeV [18]. The electron beam is focused by a superconducting quadrupole triplet which is placed at 5 m from the IP and two doublets which give 50 cm at the IP and also low β at 25 m and 50 m from the IP. At these latter positions strong quadrupoles for the protons are placed which, because of the low electron β there, have minimum influence on the electrons while effecting a β* of 10 cm for the protons. The quadrupole gradients are 150 T/m; the lengths of the quadrupoles vary between 2 and 4 m to achieve a good optical match. An aperture of 30mm appears to be technically feasible but very challenging since it requires peak fields of 9 T. The beta functions of the protons reach maximum values of 1000 m in the low-beta quadrupoles. This corresponds to ten standard deviations of the proton beam size and appears to be acceptable based on HERA operational experience. A 100 m long separator magnet, which is placed at 60 m distance from the IP, acts to separate the two beams. It is a soft, defocusing quadrupole (G = 10 T/m), which is aligned along the electron orbit while the protons pass off-centre and receive a deflection. A tiny crossing angle of 0.05 mrad avoids the first parasitic crossing at 65 m and provides the required small initial pre-separation of the two beams. This arrangement avoids any extra up-stream synchrotron radiation by the beam separation magnets. It is remarkable, that this scheme is very flexible as far as the energy ratio of the beams is concerned. It allows to separate beams with a ratio of beam energies between one and four. The electron beam is focused by the beam-beam interaction at the IP as well as the outgoing lenses. Inclusion of the beam-beam interaction in the linear optics shows that the e-beam is still well behaved as it exits the IP region. Full separation is achieved at 50 m from the IP. In Table 2, the THERA parameters are summarized.

Electron Beam Parameters			
Energy	250GeV	Acc. Grad.	23.4MV
Electr./bunch	2 x 10^{10}	Beam Puls	1.19ms
Inv.emittance	100 μm	Bunches	56x(9+6Emp.)
$\beta^*_{x,y}$	50cm	Bunch Spac.	211.37ns
Bb tune shift	0.228	Duty cycle	0.5%
disruption	0.02	Rep.Rate	5Hz
RF Freq	1301MHz	Beam Power	22.6MW
Proton Beam Parameters			
Energy	1TeV	$\beta^*_{x,y}$	10cm
Proton/Bunch	10^{11}	Norm. Emitt.	1μm
Beam Current	71mA	IBS GrowthTime	2.88h (long.)
Bunch Length	10cm		
Collider Parameters			
Hourglass Reduction	90%		
Crossing Angle	0.05mrad		
Luminosity	4.1 x 10^{30} $cm^{-2}sec^{-1}$		

7 CONCLUSIONS

Physics of lepton hadron colliders has developed a completely new view of the proton in the last decade. At present all efforts are being made to turn the HERA luminosity upgrade into a success and to collect $1fb^{-1}$ by 2007. This will be the maximum luminosity, which can be achieved in HERA in a reasonable time. There has been studies for colliding the TESLA electron beams with protons stored in HERA which allows to investigate ep collisions at 500GeV c.m. The achievable luminosity is limited be power considerations and intra beam scattering. Powerful electron cooling systems are necessary to overcome IBS limitations. However such cooling systems are very expensive and there are many unsolved questions. Another approach has been pursued with vigor in the recent few years [19]. If the lepton energy is lowered significantly, then the beam power limitations have been removed and the beam intensity are ultimately limited by the beam-beam effect and the achievable collision frequency. In this case luminosities in the range of $L=10^{33}cm^{-2}s^{-1}$ appear to be possible. However these considerations are still at a preliminary stage and it will be interesting to see the results of the work planned for the future.

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