STATUS OF HERA

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Abstract

HERA is a double ring accelerator complex at DESY in Hamburg built for electron-proton collisions. Two of the four interaction regions are laid-out for colliding beam detectors. The high energy physics experiment H1 is located in the hall North, and the experiment ZEUS in the hall South. During 1995, HERA was operated with 27.5 GeV positrons and 820 GeV protons for luminosity production. It produced a total integrated luminosity of more than 12 pb^{-1} for the collider experiments. The HERA electron ring was operated with positron currents of up to 40 mA in 189 bunches. The maximum total proton current was 76 mA in 180 bunches. Recently, both HERA rings have been modified to accommodate internal target experiments. In 1995, the HERMES detector in the East hall came into operation. It is used to study the collisions of longitudinally polarized positrons with an internal polarized gas target. The first pair of spin rotators has been installed in 1994 to provide longitudinal polarization in the East straight section of the electron ring. HERA routinely provided positron beams with more than 60 % spin polarization. Starting in 1996 a fourth experiment HERA-B is being installed in the HERA proton ring. It will be used to study B-mesons produced in the collisions of halo protons with a wire target. Parts of the detector will be commissioned during the 1996 colliding beam operation.

1 INTRODUCTION

The **H**adron **E**lectron **R**ing **A**ccelerator HERA is a double ring accelerator complex at DESY in Hamburg. Electron and proton storage rings have been built in a common tunnel fifteen to twenty meters under ground. The tunnel consists of four straight sections connected by four arcs. Underground experimental halls are located in the middle of each straight section. A simplified overview of the complex including the pre-accelerators is shown in Figure 1. In the arcs the proton machine is mounted above the electron machine. HERA was conceived as an electron-proton collider [1]. Two of the four interaction regions are laid-out for colliding beam detectors. The high energy physics experiment H1 is located in the hall North, and the experiment ZEUS in the hall South. In these straight sections the counter rotating beams can collide head-on. Therefore the protons must be bent into the electron plane and the electrons must be steered into the direction of the protons.

Recently, the two other straight sections have been modified to accommodate internal target experiments.

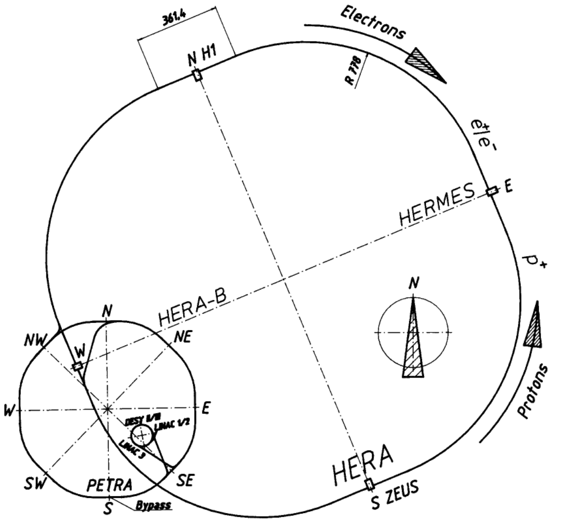

Figure 1: Layout of the electron proton collider HERA.

Originally the straight section East was designed for electron-proton collisions. The two beam pipes were separated horizontally by 71.4 cm in the year 1994. An internal gas target and a pair of spin rotators were then built for the experiment HERMES into the electron machine. The first rotator of the pair rotates the vertical spin polarization into the longitudinal direction, the second rotates the spin back. The HERMES experiment is designed to study the spin structure of protons and neutrons. For this purpose the longitudinally polarized electron beam is scattered on a polarized internal gas target of hydrogen, deuterium or helium [2].

The West hall was originally laid-out exclusively for machine utilities, including the proton dump system. The two vacuum chambers are separated horizontally and vertically. During the winter shutdown 1995/96 this straight section was extensively modified for the installation of the fourth detector, HERA-B. This experiment will study B-mesons produced in the collisions of halo protons with wire targets [3]. For this purpose an asymmetric low beta insertion was installed in the proton storage ring to focus the proton beam on the internal targets. Parts of the detector will be commissioned during the 1996 colliding beam operation.

HERA storage rings are designed for 820 GeV protons and 30 GeV electrons or positrons. The main design parameters of HERA are listed in Table 1. The storage rings have a circumference of approximately 6336 m. Protons are transferred from PETRA at a momentum of 40 GeV / c after having been accelerated from

	e^+ / e^-	p^+
Circumference L	6335.82 m	
Injection momentum p_0c	12 GeV	40 GeV
Design momentum p_Nc	30 GeV	820 GeV
Center of mass energy E_{cm}	314 GeV	
Number of bunches N	210	
Number of buckets N_B	220	
Average beam current I	58 mA	163 mA
Luminosity per IP $\mathcal{L}$	$1.5\ 10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	
Specific luminosity $\mathcal{L}_{sp}$	$3.3\ 10^{29}\ \mathrm{mA}^{-2}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	
Length of straight sections	4×361.4 m	

Table 1: Main design parameters of HERA.

$7.5\ \mathrm{GeV} / c$. The complete injection chains are listed in Table 2. The ratio of the circumferences of HERA and PETRA is 11 to 4. Thus to produce a complete HERA proton fill requires three PETRA fills of up to 70 bunches to be injected, ramped and ejected into HERA. The proton machine has a superconducting magnet structure in the arcs. The bending magnets and the main quadrupoles are excited by a current of 5024 A at 820 GeV, achieving a field strength in the dipole magnets of 4.65 T.

Electrons are transferred from PETRA at an energy of 12 GeV after having been accelerated from 7 GeV. Fifty five-cell and 32 seven-cell normal conducting 500 MHz cavities and 16 four-cell superconducting cavities are installed in the electron machine. Due to this high total shunt impedance it is not possible to transfer the total charge from PETRA to HERA at once [4]. Instead an injection scheme was chosen in which three consecutive electron bunches are transferred fourteen times. In this scheme five PETRA fills are needed to produce a complete HERA luminosity filling. The beams are synchronized in luminosity operation. This is achieved by making the revolution frequencies of the protons and of the electrons equal and by phase-locking the two rf frequencies. In this way it is ensured that the collision points are centered in the interaction regions.

On October 19, 1991 the H1 luminosity monitor detected the first proton-electron collisions in HERA. In June 1992 the two colliding beam detectors H1 and ZEUS started data taking. This concluded an eight year construction period which began with the authorization in 1984.

	Momentum pc / GeV		Velocity β
	e^+ / e^-	p^+	
LINAC 2/PIA	0.45		
DESY II	7.0		
PETRA	12		
HERA^e	30		
LINAC 3		0.31	0.3137152
DESY III		7.5	0.9922652
PETRA		40	0.9997250
HERA^p		820	0.9999993

Table 2: The injection systems for HERA.

2 CURRENT STATUS

In the year 1995 HERA operated routinely for the collider experiments and for the fixed target experiment HERMES. 180 proton bunches and 189 positron bunches were stored in the machines. 174 bunches in both beams collide at the two interaction regions. The remaining six proton pilot bunches were used for background discrimination of the proton-gas scattering. The luminosity monitors measure the bremsstrahlung produced in electron-proton scattering ($ep \rightarrow e'\gamma p$). Because the electrons are also decelerated by the residual gas, the remaining 15 electron pilot bunches are used to measure this unavoidable background. A total integrated luminosity of more than $12\ \mathrm{pb}^{-1}$ was achieved during last year. Figure 2 shows the integrated luminosity produced in each year since the first data taking. The values were measured with the luminosity monitor of the ZEUS experiment. The luminosity monitor of the H1 experiment has indicated systematically lower on-line luminosity. In order to understand this systematic difference the effective beam sizes were measured [5]. The effective cross sections of the beams were determined by measuring the specific luminosity as a function of the transverse beam separation, since the specific luminosity itself depends only on these effective sizes. Within the precision of this measurement the effective beam sizes at both interaction points are equal. The difference in the luminosity measurements can be explained by the difference in the

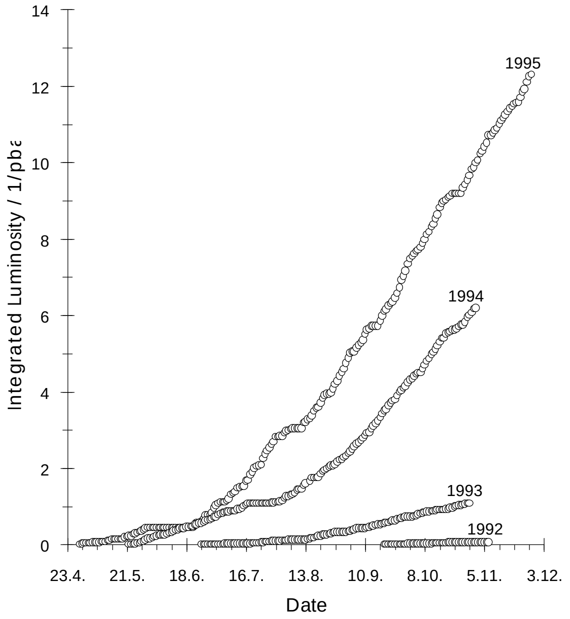

Figure 2: The total integrated luminosity per year.

	Design	1992	1993	1994	1995	1996
Number of p bunches	210	10	90	170	180	180
Number of e bunches	210	12	94	168	189	189
Number of colliding bunches	210	10	84	153	174	174
p momentum p_0 / GeV / c	820	820	820	820	820	820
p current I_0 / mA	163	2		54	73	80
e momentum p_0 / GeV / c	30	26.67	26.67	27.52	27.52	27.52
e current I_0 / mA	58	3.4		36	37	40
Specific luminosity $\mathcal{L}_{sp} / 10^{29}\,\mathrm{mA}^{-2}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	3.33			4.0	5.0	6.0
Luminosity $\mathcal{L} / 10^{31}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.5			0.4	0.7	0.8
Delivered integrated luminosity $\int \mathcal{L}\,dt$ / pbarn^{-1}	(50)	0.06	1.1	6.2	12.3	15
Long. polarization P_0 / %				65	70	70

Table 3: Development of the main machine parameters since the first data taking in 1992.

on-line evaluation of the photon and electron counting rates. ZEUS uses only the photon rate for the luminosity measurement while H1 measures the coincidence rate of the bremsstrahlung photons and the decelerated electrons. The slope of the electron beam in the interaction point must be well adjusted in both planes for the photons to hit the photon detector. The acceptance of the electron detector depends on the beam position and on its slope, especially in the horizontal plane. With an optimal adjustment both monitors have measured the same luminosity. It is extremely difficult during luminosity operation to adjust the conditions for the coincidence measurement and to keep them constant over long periods of time.

Up to July 1994 data have been taken with electrons. Afterwards, due to an electron beam lifetime problem, luminosity operation was continued with positrons. The break in the slope of the 1994 curve in Figure 2 indicates the change from electrons to positrons. The slope of the integrated luminosity curve is much higher with positrons than with electrons. This is explained by the difference in the beam lifetimes. In Table 3 the development of the main machine parameters are listed. The delivered luminosity has been steadily increasing. The main factors are improved technical reliability of the machine and the increase in the number of bunches. In Figure 2 one can recognize that the time periods with continuous luminosity operation have become longer every year. Nevertheless a large potential for increasing the integrated luminosity up to the design value is in further improvements in the technical stability of the machine in addition to increasing the beam currents. In the last year HERA was running in luminosity operation one third of the time scheduled for electron-proton collisions. This time can be doubled and is limited by the magnet cycle, beam filling and energy ramping times. Figure 3 shows the distribution of the initial proton and positron currents over the last year. One can recognize that both machines have run reproducibly after overcoming the initial start-up problems. At the beginning of the year the major problems included a broken connection of a superconducting correction quadrupole, a destroyed cold quench protection diode and a short in the windings of a normal conducting low beta quadrupole of the proton ring. In order to repair the cold diode one octant was warmed up and cooled down again. This is the reason for the three week break in June. During 1995 the proton machine was running with an average initial current of 55 mA distributed in 180 buckets. The maximum current was 73 mA. The limitations were given by the maximum current of PETRA and by the transmission efficiency. PETRA was running with an average current of 75 mA at 40 GeV distributed in 60 buckets. The maximum value was 100 mA. The design current of PETRA is 150 mA in 70 bunches. 52 MHz and 208 MHz rf systems are installed in HERA. The proton bunches are transferred into the 52 MHz buckets and are compressed into the 208 MHz buckets during acceleration. At 820 GeV the bunch length was typically $\sigma_s = 20$ cm. A continuing problem is the population of the buckets

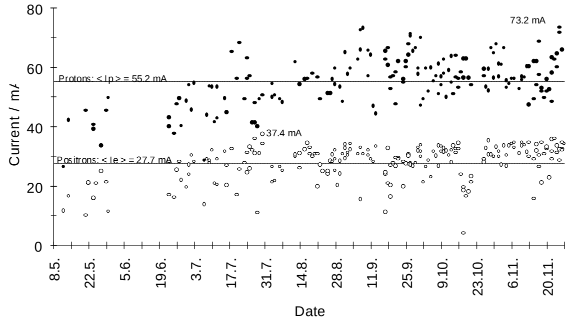

Figure 3: Proton and positron beam currents in 1995.

adjacent to the main bunches. Because the bucket sizes of PETRA and HERA are not well matched. the tails of the longitudinal distribution populate the satellite buckets in HERA. During luminosity operation these satellite bunches are one source of background. The background conditions were without exception clearly worse at a second positron fill. There are indications from the two high energy physics experiments that the satellite buckets are further filled during the preparation of a new positron filling, while the beams are still separated. This could be one explanation why the background is increased. Therefore one has run with only one luminosity run per proton filling. The injection optimization and the ramp procedure were improved last year. The dipole and sextupole fields change during flat bottom by the decay of the persistent currents in the superconducting cables. The drift is corrected automatically. The non-linear behavior of the sextupole component of the superconducting dipole field is corrected during the first step of ramp. During the acceleration the tune of the machine is corrected by tables. As a result of these improvements, ramps with negligible losses were routinely possible.

At the beginning of luminosity operation the HERA electron machine was running with an average positron current of nearly 28 mA distributed in 189 buckets. The maximum current was 37 mA. The limitation was given by the rf power. Seven 500 MHz double klystrons for six normal conducting and one superconducting cavity section are installed. The maximum power is 1500 kW per transmitter. Stable operation was possible only at lower values. The superconducting cavities were limited to a total power of 800 kW. The limit for the normal conducting cavities was between 1200 kW and 1400 kW. In 1995 the HERA electron machine accumulated a circulating charge $\int idt$ of 43 Ah. In the straight section West the transverse polarization was measured by observing the vertical asymmetry of Compton-scattered, circularly polarized light. In luminosity operation the average saturation polarization reached a value of 60 %. After luminosity tuning the experiment HERMES could open the gas valve and start data taking in parallel with the colliding beam operation. One can see in Figure 4 the change in the positron beam lifetime due to the HERMES internal gas target. The effect on the positron beam lifetime was between 30 and 50 hours. The beam lifetime without gas inlet was between 10 and 15 hours. Except for the reduction of the beam lifetime by about 15% no other disturbances were observed by the collider experiments. During the winter shutdown 1995/96 a longitudinal polarimeter was installed additionally in the straight section East.

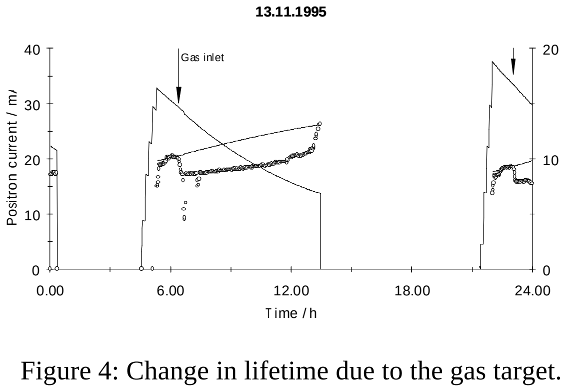

Figure 4: Change in lifetime due to the gas target.

In 1995 the average luminosity at the beginning of a fill reached $\mathcal{L} = 3.8\ 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ per interaction point. The maximum luminosity was $7.0\ 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, roughly half of the design value. The main limitation was the proton and positron beam intensities. Figure 5 shows the specific luminosity at the beginning of each luminosity run during the last year. The mean value was $\mathcal{L}_{sp} = 4.9\ 10^{29}\,\mathrm{mA}^{-2}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The specific luminosity is defined as the luminosity divided by the product of the beam currents. The specific luminosity depends only on the proton and electron beam sizes at the interaction point. In the last year the specific luminosity was higher than the design value. This is a result of a stronger focusing of both beams and of a smaller proton beam emittance. The luminosity lifetime was mainly determined by the positron beam lifetime. The proton beam lifetime was typically of the order of several 100 hours and in many luminosity runs the emittance of the proton beam showed no deterioration. This is a result of the optimally matched beam sizes at the interaction points which minimizes the non-linear beam-beam interaction.

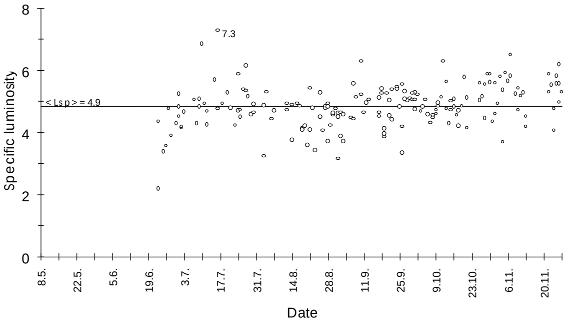

Figure 5: Specific luminosity $\mathcal{L}_{sp}$ / $10^{29}\,\mathrm{mA}^{-2}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

2 ELECTRON BEAM LIFETIME

HERA is designed for the collision of protons with electrons and positrons. For the physics program it is essential that the collider experiments can take data with both sorts of leptons. In HERA the operation with electrons is much different from the operation with positrons [6,7]. Figure 6 shows the electron beam lifetime versus current. At high intensities the lifetime drops to several hours during or shortly after the energy is ramped from 12 to 27 GeV. Figure 4 shows the beam lifetime versus current during a positron fill. One can see that the

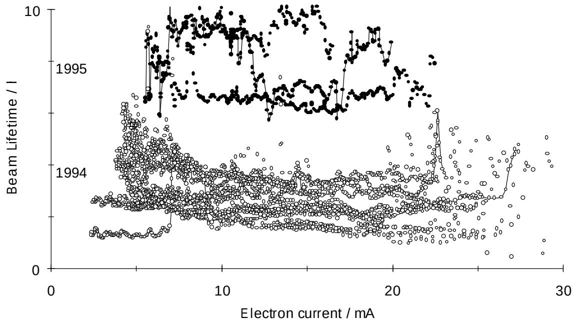

Figure 6: Beam life time versus electron current.

lifetime without gas inlet is dominated by the synchrotron light gas desorption. In this case the lifetime τ depends on the current i as:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \frac{i}{\lambda},$$

where τ_0 is the beam lifetime for small currents and the parameter λ takes the synchrotron light desorption into account. Due to a cleaning effect this parameter decreases with increasing circulating charge (dose). At the end of last year we reached following typical values:

$$\tau_0 = 17\,\mathrm{h}$$

$$\lambda = 700\,\mathrm{mA\,h}.$$

The current understanding of the lifetime problem with electrons is as follows: During operation the integrated ion sputter pumps in the main dipoles release micro particles that are ionized by the circulating beam. The negative potential of the electron beam traps the particles and the beam lifetime is reduce by bremstrahlung. An additional hint for this model is that breakdowns can be triggered by switching the high voltage of the pumps. The problem should be solved by installing passive NEG-pumps. Loss measurements [8] were performed with electrons in 1995, during which an active problematic section was found. The high voltage of the dipole pumps in this section was switched off, and afterwards, runs with electron currents up to 20 mA with improved lifetime were observed, Figure 6. During this winter shut-down this vacuum section was equipped with NEG strips. Figure 7 shows a cut through a dipole vacuum chamber with an integrated NEG-pump.

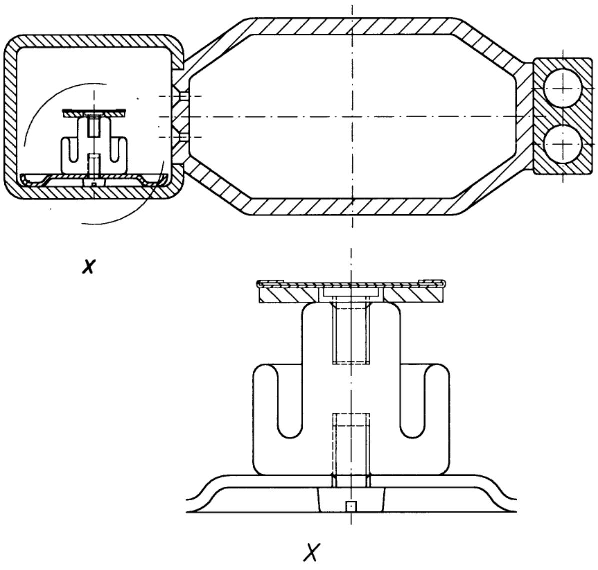

Figure 7: A cross section of a HERA dipole chamber with a NEG pump.

3 OUTLOOK

The most important aim in the near future is to reach the design integrated luminosity with HERA. For 1996 an integrated luminosity of $15\,\mathrm{pb}^{-1}$ per interaction point is planned. Due to the installation of the new interaction region in hall West this year's run period starts only in July and will end in November. Further machine studies are scheduled for the investigation of the electron beam lifetime problem. In the next shut down an exchange of the integrated dipole ion sputter pumps by passive NEG-pumps is planned.

REFERENCES

[1] ‘HERA, A Proposal for a Large Electron-Proton Colliding Beam Facility at DESY’, edited by B. H. Wiik, DESY HERA 81/10 July 1981.

[2] ‘HERMES, A Proposal to Measure the Spin-Dependent Structure Functions of the Neutron and the Proton at HERA’, by the HERMES Collaboration, DESY PRC 90/01.

[3] ‘HERA-B, An Experiment to Study CP Violation in the B System Using an Internal Target at the HERA Proton Ring’, by the HERA-B Collaboration, DESY PRC 95/01, January 1995.

[4] ‘Compensation of the Multi Bunch Instabilities with Feedback Systems’, by M. Ebert et al, Proceedings of the XVth International Conference on High Energy Accelerators, Hamburg, 1992, Volume I, Page 421.

[5] ‘Determination of HERA Specific Luminosity from Beam Separation Scans’, by R. Brinkmann, DESY HERA, Technical Note 94-03, August 1994.

[6] ‘The Electron Beam Lifetime Problem in HERA’, by D. R. C. Kelly et al., Proceedings of the Particle Accelerator Conference, Dallas, 1995.

[7] ‘HERA Electron Beam Lifetime Disruption Machine Studies and Observations’, by D. R. C. Kelly, W. Bialowons and K. Wittenburg, Proceedings of this conference.

[8] ‘Electron Beam Loss Monitors for HERA’, by W. Bialowons, F. Ridoutt and K. Wittenburg, Proceedings of the Fourth European Particle Accelerator Conference, London, 1994, Volume 2, Page 1628.