# Performance Limitations at HERA

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*Abstract*

After the completion of the electron proton collider, HERA, at DESY and the commissioning of the machine in 1991, HERA is running now in its third year of operation. In 1993 the electron and proton rings were running routinely at energies of 26.6 GeV and 820 GeV respectively. The 84 electron and proton bunches collided at the interaction points North and South, where the detectors H1 and ZEUS are located. A total integrated luminosity of $1000nb^{-1}$ could be delivered to both experiments. In 1994 the number of bunches has been increased to 170 and the protons are running with an increased bunch current of up to 300 $\mu$A. The machine performance will be summarized and the plans for a further increase of the integrated and peak luminosities will be discussed. The modification of HERA for future experiments with polarized electron beams and with internal targets in the proton machine will be presented.

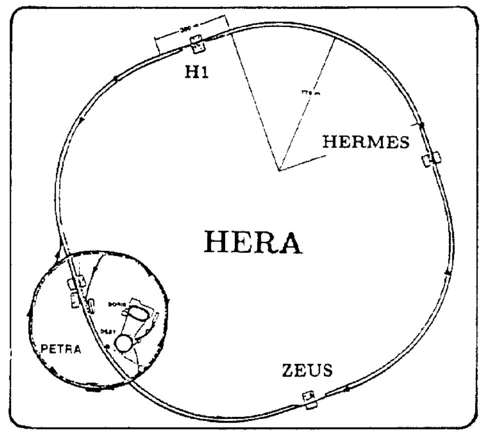


Figure 1: Geometry of the electron proton collider HERA. The bunches of the proton and electron machine collide at the interaction points "North" and "South" where the detectors of the experiments ZEUS and H1 are located. The straight section "East" is prepared for the third experiment Hermes which will be installed in winter 1994/95.

## 1 INTRODUCTION

The Hadron-Electron-Ring-Accelerator, **HERA**, is an accelerator facility for the investigation of electron–proton collisions [1], [2],[3],[4],[5].

It consists of two separate storage rings with a circumference of 6335 m each. They are located one upon another in a common tunnel 10–20 m underground. The proton beam is injected into HERA at an energy of 40 GeV and accelerated to the design energy of 820 GeV. It is guided in a superconducting magnet structure. For the electron ring a conventional magnet design was chosen whereas the normal conducting rf–system of the electron machine is supported by 16 superconducting resonators to reach the maximum energy of 30 GeV [6].

The geometry of the HERA–collider, as shown in fig. 1, is given by 4 straight sections where up to 4 experiments can be situated. They are connected by 4 arcs. In the straight section "North" and "South" the two counter-rotating beams are bent and focussed onto a common interaction point where the detectors of the experiments "H1" and "ZEUS" respectively are located to measure the e–p interactions.

The beam separation is designed for a head-on collison of both beams. In the straight section "East" – formally designed in full analogy to the interaction regions "N" and "S" – the lattice and the beam optics were modified during the last winter shut-down of HERA to prepare the installation of a third experiment "HERMES" where the interaction of the polarised electron beam with an internal gas target will be measured. The electron and proton beam will pass the experimental area of the new detector in separate vacuum chambers.

HERA was constructed by an international collaboration of more than 40 institutes and laboratories from 12 countries. Contributions were both in the form of construction and delivery of components for the facility as well as contribution to the manpower during the design and commissioning phase.

The construction of Hera started in 1984, and in 1990, after a period of 6 years both storage rings were technically completed. The commissioning phase, starting in 1991, was completed when luminosity was first achieved on 31st May 1992 with the collision of 10 counter-rotating bunches at both experiments H1 and ZEUS.

## 2 STATUS OF THE MACHINE

The main goal in 1993 was the optimisation of the luminosity in HERA. 90 bunches were stored in each beam and an overall integrated luminosity of more than 1000 $nb^{-1}$ could be achieved by the end of the year.

Fig 2 shows the integrated luminosity $\int \mathcal{L}dt$ collected during the run periods 1992, 1993 and the present state of the 1994 run. The main factor for the continuing increase

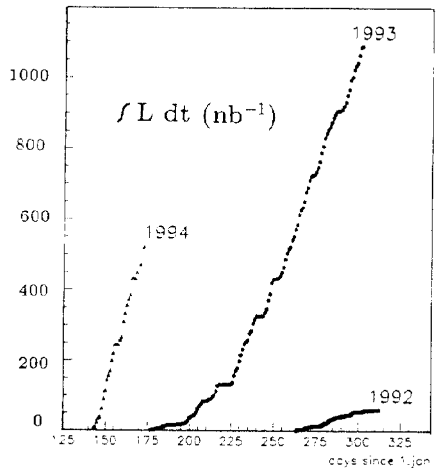


Figure 2: Intergated luminosity of Hera measure by the experiment Zeus during the run periods 1992,1993 and 1994

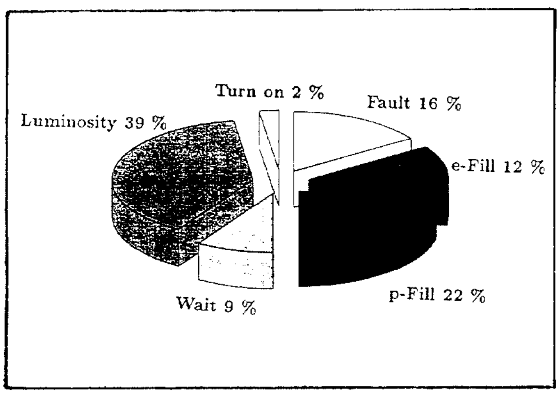


Figure 3: Run statistics of HERA for the dedicated run time in aug. 1993: nearly 40 % of the dedicated time was spent for luminosity operation

of the delivered luminosity is the number of bunches stored in the machine – corresponding to an increase in beam currents – and the technical reliability of the machine components.

Especially, in the case of the proton storage ring that is constructed as a superconducting machine [7], special care had to be taken to protect the magnets from beam induced quenches. The ring therefore is equipped with a quench protection system [8] to prevent damage from the superconducting magnets. The stability and performance of the magnets and the protection system are the basis for the technical reliability of the machine and must be emphasised.

The run statistics of the HERA collider is reflected in fig. 3. For the run period of August 1993 the time spent for luminosity operation, injection and ramping of both beams and the time spent due to faults is plotted.

On the average nearly 40 % of the dedicated run time could be used for luminosity operation. A large amount of time has to be spent for the optimisation of the proton injection: Due to persistent current effects in the superconducting magnets at injection energy and due to their time dependent behavior the proton injection into HERA has to be optimised carefully. In general several shots from the PETRA booster are needed to obtain adequate injection conditions.

## 3 PERFORMANCE OF THE ELECTRON RING

In the electron ring an average beam current of 15 mA was stored and accelerated to the luminosity energy of 26.6 GeV corresponding to a single bunch current of 0.17 mA.

Limitations due to the single bunch current were not expected and never observed, as, in machine studies, a particle intensity of $3.3 \times 10^{11}$ could be accumulated in one single bunch. This corresponds to a bunch current of 2.5 mA and surpasses the desired design value of 0.28 mA by a factor of 9.

For the multibunch operation in the electron storage ring current limitations were expected. The impedance of the rf-system in the machine gives rise to coupled bunch instabilities with a threshold of $I_{thr}$ = 3 mA. As a design current of I =58 mA is foreseen HERA was equipped with a multibunch damping system of 5 Mhz bandwidth in the electron machine to damp the multibunch instabilities [9]. A current of 40 mA could be stored at 12 GeV without any indications of instability problems.

An unexpected and completely different limitation of the stored beam current in the electron machine occurred by a sudden unpredictable reduction of the lifetime of the electron beam. Already in 1992 a breakdown of the electron lifetime in Hera was observed when the intensity of the stored beam reached about 3 mA. After a breakdown, the lifetime never recovered, not even for very small beam currents.

For the investigation of this problem the Hera beam loss monitoring system was used [10]. It was designed for superconducting proton storage ring to protect the magnets against beam loss induced quenches and could easily be extended to the electron ring. A typical result of the beam loss measurements is shown in fig 4 where the electron beam current is displayed together with the lifetime and the measured loss rate at a single beam loss monitor. As indicated in the figure, the $\tau_e$ breakdown correlates with with losses seen by a single loss monitor. In further investigations a correlation of the problem with the status of the integrated ion sputter pumps in the storage ring could be demonstrated.

Simulations were carried out to study the capture of micro particles that are created in the integrated ion sputter pumps and accelerated into the stored beam [11], [12]. They give a further indication for the correlation of the problem with the sputter pumps which is supported by the fact that the storage ring DORIS, serving now as a synchrotron light source and suffering from the same problem, is running without lifetime dominated intensity limitations since it has been operated with positrons.

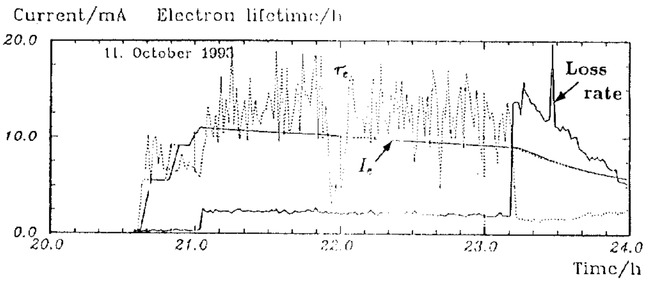


Figure 4: A typical observation during the breakdown of the electron lifetime: The dropping down of the lifetime occurs in coincidence with a raise of the lossrate at local positions in the ring, plotted as dashed line inthe figure

By replacing a small piece of beampipe with integrated pumps, the threshold for the lifetime break-down in Hera could be raised by a factor of 5 and a beam of 15 mA could be stored at 26.6 GeV with a lifetime of up to 10 hours.

In the present run, 1994, an overall current of more than 25 mA in 168 bunches has been achieved in the HERA electron ring by lowering the HV–supply for the integrated pump devices.

# 4 PERFORMANCE OF THE PROTON RING

The performance of the proton storage ring which is designed and constructed as a superconducting machine is subject to persistent current (p.c.) effects of its magnets. As the influence of these persistent currents is most critical at low energies it is the injection and the low energy ramp steps of the HERA proton ring where most optimisation and control of the field properties has to be applied.

The influence of p.c. effects on the field quality of the storage ring magnets has been extensively studied by field measurements [13]. For the most important contributions which turn out to be the dipole and sextupole fields automated procedures were developed and implemented to correct the time dependent behavior of the p.c. contributions to the chromaticity and energy of the ring [14]. In two reference magnets, one per production line, the dipole and sextupole fields are measured using NMR and hallprobes and rotating coils respectively. The correction currents are calculated and applied on-line to the correction magnets in the ring at injection energy and during the acceleration of the beam up to 150 GeV. For higher energies the influence of p.c. effects can be neglected.

The chromaticity $\xi = \Delta Q/\frac{\Delta p}{p}$ of the proton machine is dominated by the influence of the persistent currents. Their contribution amounts to ± 300 and surpasses the natural chromaticity of the ring by a factor of 5. In fig. 5 the time dependent behavior of $\xi$, given by the logarithmic decay of the p.c. contributions is shown. A rate of $\frac{\Delta\xi}{t} =$ 30 /h is measured. In the second part of the figure the

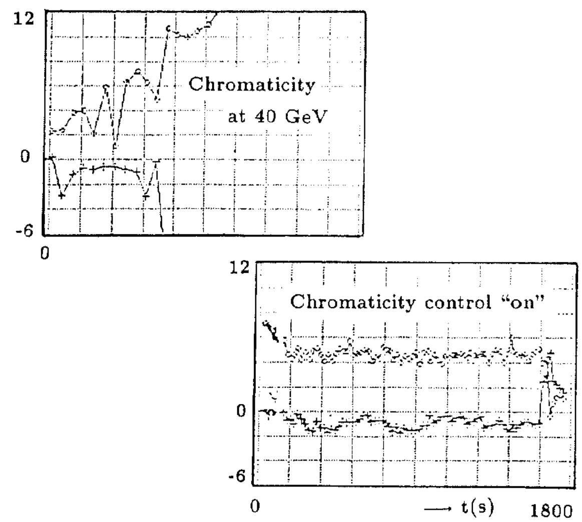


Figure 5: Time dependent behavior of the persistent current contribution to the chromaticity in the HERA proton storage ring. In the second part of the plot the effect of the persistent current decay is counteracted by an automated control of the chromaticity.

automated correction based on the field measurement is applied and the chromaticity is kept constant within $\Delta\xi = \pm 0.5$.

Nevertheless the parameters of the injected beam, i.e. tunes, chromaticity, energy and injection oscillations need careful optimisation after each magnet cycle to obtain the small beam emittances necessary to match the beam sizes of protons and electrons during luminosity conditions and to provide a sufficient lifetime during injection. This optimisation procedure, in combination with the small repetition rate of the booster PETRA, explain the contribution of the proton injection procedure to the dedicated run time in fig. 2.

**Current limitations:** In 1993 the proton ring was running with an average current of 15 mA distributed over 90 bunches. The increase of the number of bunches to 170 together with higher single bunch currents delivered by the synchrotron DESY III resulted in an increase of the stored beam currents to 50 mA in the 1994 run. The main limitation is still given by the single bunch currents delivered by PETRA, which amounts to 40% of the expected design value.

A performance limitation of a different kind that restricts the beam quality is observed in the proton machine: Occasionally a coherent transverse excitation of the beam occurs during the ramp at low energies, sometimes even at injection. It results in a blow up of the beam emittances – even leading to particle loss – and would create intolerable background conditions if such a beam were to be brought into collision with the electrons.

The effect was observed for the first time in 1992 and has been extensively investigated since then. It is observed as a single bunch effect depending on the bunch parameters such as bunch current and density and tune spread and does not depend on the total current stored in the machine. An external excitation can most probably be excluded.

A feedback test was performed using the narrow band detector of the Hera tune measurement system with one single bunch in the machine. The excitation could be damped successfully and after a period of tests for broadband multi-bunch feedback detectors it was decided to build a multi-bunch feedbacksystem to cure the problem. Major parts of the system are now available.

## 5 PERFORMANCE OF LUMINOSITY OPERATION

The continuing increase in the performance of the luminosity operation of HERA is already reflected in fig. 2 where the integrated luminosity of the machine is plotted.

More detailed information about the performance of the machine during luminosity operation can be deduced from the value of the specific luminosity. The specific luminosity is independent from the stored beam currents, and for a given collision frequency of the counter-rotating bunches it is only a function of the geometrical parameters of the beams at the interaction point. As in the HERA collider two beams of different particles are colliding, it is especially important to match the beam sizes of electron and protons to get a high specific luminosity and tolerable background conditions at the experiments.

By careful adjustment of the injection parameters correction of the persistent current effects described in section 4 and preservation of the emittances during the acceleration of the proton beam to 820 GeV, specific luminosities of more than $\mathcal{L}_{spec} = 5 \times 10^{29}$ cm $^{-2}$ s$^{-1}$ mA$^{-2}$ are being obtained routinely. They surpass the design value of $\mathcal{L}_{des} = 3.4 \times 10^{29}$ cm $^{-2}$ s$^{-1}$ mA$^{-2}$ by more than 60 % and lead to low background rates and stable conditions for the two experiments H1 and ZEUS.

As the two counter-rotating beams of HERA are stored in separate rings they have to be deliberately brought into collision at the interaction points. An optimal beam centering obviously turns out to be an essential issue during collisions to reach high luminosity values and to minimize the influence of nonlinear beam-beam forces of the electrons on the proton beam. Especially in the vertical direction where the dimension of the electron beam is small an increase of the proton emittance is obtained if the beam sizes are not well matched.

The stability of both beams during luminosity is surprisingly good. The head-on collisins of the electrons and the protons can be maintained for many hours without problems due to the stability of the collision orbits. After the cycling of the magnets, preparing new injection and acceleration of the beams the reproducibility of the collision orbits amounts to $(1-2)\sigma$ and the centering of the beams needs only small further correction.

By the increase of the number of stored bunches in both rings and higher single bunch currents the total luminosity of the machine could be enhanced and a value of $\mathcal{L} = 2.5 \times 10^{30}$cm$^{-2}$ s $^{-1}$ has been obtained up to now. This corresponds to 17 % of the design value.

**Beam beam effect:**
The most significant evidence for the beam beam interaction in the proton beam is the limitation of the proton lifetime. Lifetime values of more than $\tau = 1000$ h are obtained in the 820 GeV proton beam if the particles are stored without colliding electrons. Under luminosity conditions this high value is reduced to $\tau = 100 - 300$ h. At the same time an increase of the horizontal and vertical emittance of the protons is observed that amounts to $\frac{\Delta\epsilon}{t} = (1-2)\pi$ mm mrad/h. This is the reason for a small continous decrease of the specific luminosity during a proton fill and defines the ultimate availability of the proton beam for luminosity as the particle background increases in the detectors.

Nevertheless 2 - 3 electron fills on the average can be brought into collision with the same proton beam and a new proton injection is performed about once a day.

Compared to the lifetime of the proton beam of several hundred hours, the luminosity lifetime – determined by the emittance growth rate of the beam and the much smaller lifetime of the electrons – results in $\tau_{Lumi} = (5-10)$ h.

In the case of the electrons the beam-beam effect characterized by the linear beam-beam tuneshift parameter $\Delta\nu$ reached its design value of $\Delta\nu = 0.02$ in 1993. With the increase of the particle density in the proton ring obtained in 1994 the beam optics of the electrons had to be adjusted to counteract the higher proton intensity with a somewhat smaller beta function for the electrons at the interaction point.

## 6 POLARISATION

In the winter shut down 1993/94 the straight section "East" of Hera was modified to prepare the machine for the third experiment "HERMES". Electron and proton beams are passing now the former interaction region in separate vacuum chambers. The HERMES experiment will measure the spin dependent interactions of a polarised electron beam with an internal polarised gas target in HERA [15].

Therefore the polarisation of the electron beam in HERA was measured using the polarimeter installed in section "West" [16] and in the run period 1993 the transverse polarisation of the electrons was optimised. As a result a maximum value of $\mathcal{P}_\perp = 68\%$ was obtained in dedicated polarisation runs. During the routine luminosity operation of the machine a polarisation of $\mathcal{P}_\perp = 60\%$ has sofar been achieved.

The basis of this success is a well corrected orbit of the electrons in HERA and the developement of a harmonic correction bump procedure [17]. The influence of the solenoid fields of the detectors H1 and ZEUS turned out to be negligible if compensated by the correction solenoids in the experimental area.

An essential issue for the experiments using polarised electrons is the fact that longitudinal polarisation is needed at the interaction point. In the storage ring a longitudinal direction of the spin cannot be maintained because of the vertical fields of the main dipole magnets. In order to obtain a longitudinal spin at the interaction point a spin rotator for the Hera machine has been installed [18] to flip the spin of the electrons into the longitudinal direction as it passes the interaction region of Hermes. Afterwards before entering the regular structure of the arcs of the machine the spin is turned back into the vertical direction.

The spin rotator was installed in the Hera machine at the beginning of 1994 in the straight section East. After careful optmisation of transverse polarisation with the rotator switched off, a polarisation of almost the same degree could be observed after the rotator magnets had been switched on. The resulting measured longitudinal polarisation of the electron beam in Hera is shown in fig. 6. A value of $\mathcal{P}_{||} = 60\%$ was achieved without problems and the Hera machine is now running with longitudinally polarised electrons routinely.

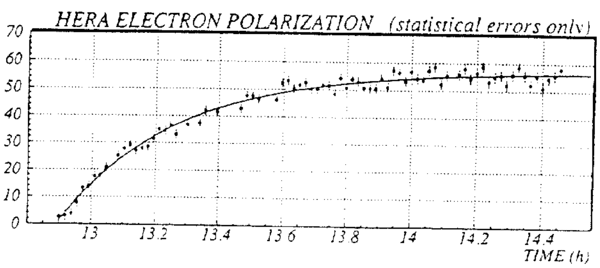


Figure 6: Longitudinal polarisation in the HERA electron ring. The vertical direction of the electron spin is turned into the logitudinal one during the passage of the experimental area.

## 7 CONCLUSION AND FUTURE PLANS

During the run periods 1992, 1993 and the beginning of 1994 the operation of HERA as a electron proton collider was characterised by increasingly stable and reliable conditions. The experience with two colliding beams of different kinds of particles is very positive. Limitations in the performance of the collider are at present given by the stored beam currents that did not yet reach their design values. A large improvement however was achieved in 1994 concerning the number of bunches and the bunch currents as well.

After the optimisation of the transverse polarisation of the HERA electron beam in 1993 the installation of the spin rotator in the winter shutdown 1993/1994 and its succesful operation, a longitudinal polarised electron beam is now available in HERA. This is the first time that longitudinal polarisation is achieved in a storage ring and it is the supposition for a third experiment "HERMES" that will be installed in HERA in 1995 to measure the interaction of the polarised electrons with an internal polarised target.

In addition a 4th experiment "HERA-B" in the HERA machine is proposed [19]. It will study CP-violating events in the interaction of the HERA proton beam with an internal wire target. At present the possible modifications of the HERA lattice and beam optics and the implications for the electron proton operation of such an experiment are investigated.

Beyond that the main concern of the studies will be the improvement of HERA with respect to a further approach of the design parameters.

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