HERA: Lessons Learned from the HERA Upgrade

B.J. Holzer, DESY-HERA

Abstract

The HERA storage ring at the DESY institute in Hamburg was designed for the collision of proton and electron/positron beams. It came into operation in 1991 when the first beam collisions had been observed and routine data taking by the experiments H1 and ZEUS started in 1992. After a successfull operation during the period 1992-2000 a major upgrade has been performed to increase the luminosity of the machine. This article describes the modifications in the magnet lattice of both HERA storage rings, the layout of the new interaction regions and first of all the experience that we gained during the commissioning phase and routine operation of the new machine. Background sources, measurements and procedures in the upgraded HERA storage ring are discussed as well as the procedures that had been applied to overcome the problems that were encountered in the initial operation period of the new machine.

THE HERA STORAGE RING

The HERA machine [1] was constructed and operated as a double ring collider for the collision of protons and electrons/positrons at the DESY institute (Deutsches Elektronen Synchrotron) in Hamburg. The 920 GeV protons and the 27.5 GeV leptons were accelerated and stored in two independent rings, each of 6.3 km length, and brought into collision at the two interaction points "South & North" where the high energy detectors ZEUS and H1 were installed.

Figure 1: The HERA storage ring in Hamburg

Fig 2 shows the arrangement of the two storage rings in the tunnel: As both particles were basically travelling at the speed of light the two rings were located on top of each other to guarantee equal revolution frequencies of the two beams. In the run years 1992-2000 a steady increase of the delivered luminosity has been achieved by increasing the number of the stored bunches, the single bunch intensity and a moderate reduction of the beam size (i.e. a smaller beta function) at the collision points.

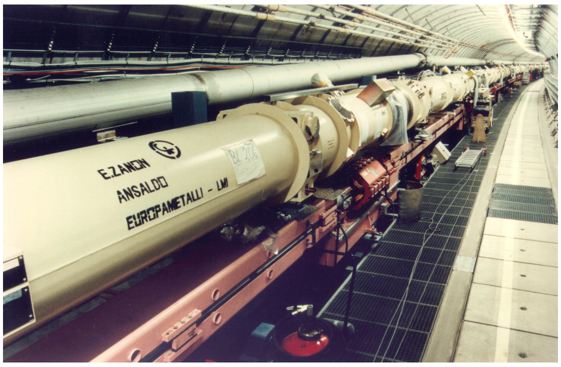


Figure 2: The regular lattice structure in the arcs of the two HERA storage rings

The integrated luminosity in this run period is presented in fig 3. In the run year 2000 the relevant machine parameters reached the performance limit and the luminosity that could be delivered by the machine was increasing basically linear with the run time of the storage ring. A further improvement of the machine performance therefore only could be achieved by a redesign of the interaction regions, allowing a stronger focusing and thus a smaller beta function at the interaction points.

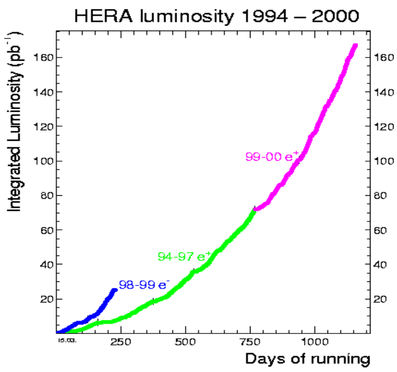
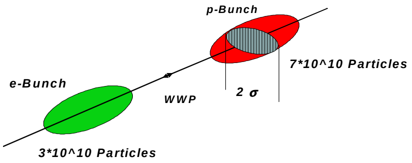


Figure 3: Integrated luminosity of HERA as a function of run time, as measured by the ZEA luminosity monitor

Given the luminosity formula for the collision of two independent particle beams, an upgrade of the HERA luminosity required a smaller size of the two beams at the interaction points in both transverse planes [2]. As immediate and unavoidable consequence the upgrade project was based on a faster beam separation: The low energetic electron beam had to be separated and guided in its own magnetic lattice before any focusing of the proton beam could take place.

The luminosity of a two ring collider is given by the well known formula



$$L = \frac{n_B * N_p * N_e * f_0}{2\pi * \sqrt{(\sigma_{x,p}^2 + \sigma_{x,e}^2)} * \sqrt{(\sigma_{y,p}^2 + \sigma_{y,e}^2)}}$$

For a given number of bunches n_b, single bunch intensities N_p, N_e of the two beams and the revolution frequency f_0, the luminosity depends only the transverse dimensions σ_x, σ_y of the two beams and any luminosity increase therefore is based on a reduction of the beta functions at the collision point.

The focusing structure of the new interaction regions was based on a doublet focusing in the case of the protons and a triplet for the electron beam. In both storage rings these new interaction regions were embedded as an insertion into the regular FoDo structure of the corresponding arcs (fig. 4).

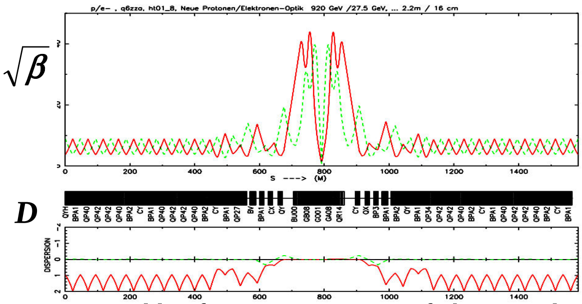


Figure 4: Doublet focusing structure of the mini beta insertion scheme for the proton beam optics of the HERA upgrade project

	HERA 2000	Upgrade
Energy	27.5 / 920 GeV	27.5 / 920 GeV
I	45 / 100	58 / 140 mA
N per Bunch	3.5 / 7.3 $*10^{10}$	4.0 / 10.3 $*10^{10}$
$n_{ae}s$ n_{coll}	189 / 180 174	189 / 180 174
β_x β_y ε_x	1.0 / 7.0 m 0.6 / 0.5 m 41 / 5.1 nm	0.63 / 2.45 m 0.26 / 0.18 m 20 / 5.1 nm
σ_x σ_y	190 μm 50 μm	112 μm 30 μm
L_0 L_{sp}	$1.7*10^{31}$ $6.7*10^{29}$	$7*10^{31}$ $1.8*10^{30}$

Table 1: Main parameters of the HERA storage ring, as achieved in the run year 2000 and foreseen in the upgrade project HERA 2

The main parameters of the machine are summarized in table 1 and refer to the values achieved in the run year 2000 and to the design values foreseen for the upgrade project.

LESSONS LEARNED FROM THE UPGRADE PROJECT

1.) The Hardware Installation:

For the installation of the new focusing structure of the upgrade project the hardware of the old lattice structure had to be removed completely. About 250 m on both sides of the interaction point had to be cleared before the new magnets, vacuum chambers and diagnostic tools could be installed. To protect the remaining part of the machine, the tunnel had to be sealed against dust and protected against damage from the machining tools like welding, soldering and cutting. Neither the normal conducting electron ring nor the super conducting proton structure showed any problem during the re-commissioning of the machine, proving that major work in the tunnel in close distance to the remaining hardware of the storage ring were not a worrying issue, if prepared carefully. Fig 5 shows the straight section of the HERA tunnel after the removal of the old magnets and before the hardware for the new interaction region had been installed.

Figure 5:HERA tunnel after removal of the old hardware in the interaction region N / S.

2.) The Upgrade Parameters:

As described in table 1 the upgrade project was mainly based on a smaller transverse size of the two colliding beams. A successful running of the machine therefore critically depended on the beam optics and according to that, measurement tools were applied to localise possible optics errors, and corrections to the beam optics were applied to guarantee the required precision of the beta functions. The result is qualitatively shown in fig 6: The integrated luminosity of HERA 1 (before the upgrade) and of HERA 2 (after the upgrade) are plotted as a function of the luminosity run time of the machine.

On the average an improvement factor of 3-4 in the delivered luminosity is achieved, in excellent agreement with the new machine parameters.

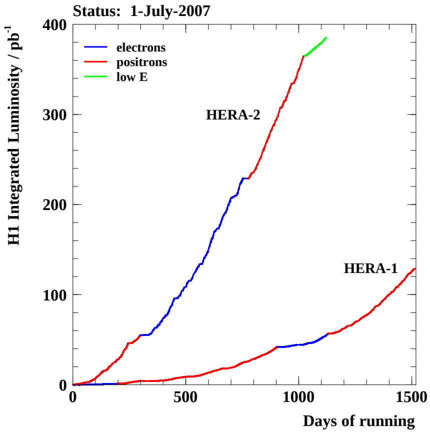


Figure 6: comparison of the intergrated luminosity of HERA 1 and the upgraded machine HERA 2, plotted as a function of running time.

3.) The New Magnets: Exotic Solutions are Feasible

The small beta functions of the two beams, required for the desired luminosity increase, led to a number of new developments to establish a fast beam separation and at the same time an early focusing of the beams. At a distance of only 11m from the interaction point (IP) the beam separation had to be big enough to localise the first proton quadrupole lens (fig. 7).

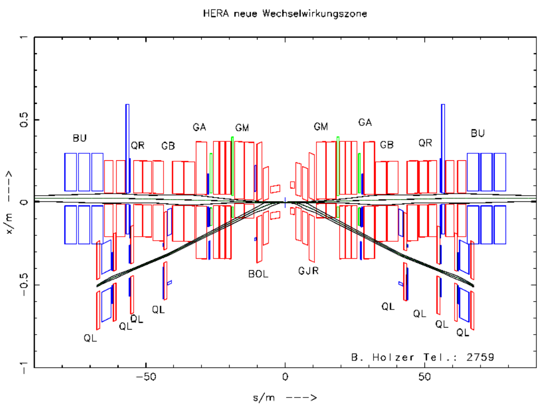


Figure 7: Separation scheme of the new interaction region: the first proton quadrupole lens is located at 11m from the IP.

For this magnet a special design has been worked out: It is built as half quadrupole, focusing the proton beam in the vertical plane, but leaving a field free space in the return yoke (i.e. the mirror plate) where the electron beam is passing (fig 8). To minimise the requirements on the beam separation the mirror plate even was cut out at the mid plane and only a small iron plate of 5mm transverse dimension was left for mechanical stability. Similar solutions had to be found for the down stream magnets of the proton lattice: These quadrupoles are built as full quadrupole magnets but again field free space had to be created inside the magnet for the electrons.

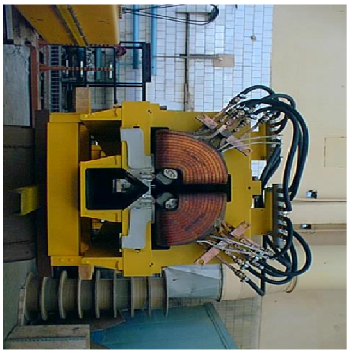


Figure 8: Half quadrupole GM of the proton ring: On the left hand side of the mirror plate a field free region for the passage of the electron bam is obtained.

Here the return yoke was cut out to leave the required space without affecting the field quality of the magnet. Fig. 9 shows a top view of the GN quadrupole after installation of the vacuum chambers and before closing the magnet yoke: In addition to the proton chamber two additional vacuum chambers are embedded into the iron yoke: on the right hand side (inner side of the ring) the electron beam pipe is seen, on the left hand side a special beam pipe for the synchrotron radiation photons that are generated during the beam separation is installed. This photon beam pipe leads further downstream to a water cooled synchrotron light absorber.

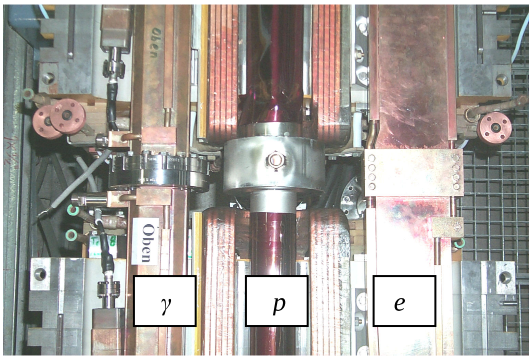


Figure 9: Three beam pipes embedded in the low beta quadrupole GN of the proton ring.

After the design and small improvements at the proto-type (mainly concerning the multipole contributions) these quite exotic magnets showed parameters well in the foreseen tolerance range and were running without problems in the HERA 2 machine.

In the case of the electron mini beta magnets a similar approach had to be found: Again an early focusing was required and for this purpose the first quadrupole magnet was built as a compact super conducting multiple coil, that could be integrated into the detector structure of the H1 and ZEUS experiment. The super conducting design here was chosen not to establish high fields but to deliver a very compact device containing for smallest outer diameter a vertical focusing quadru-pole lens, a sextupole magnet, a skew quadrupole, and horizontal and vertical dipole corrector windings (fig 10)

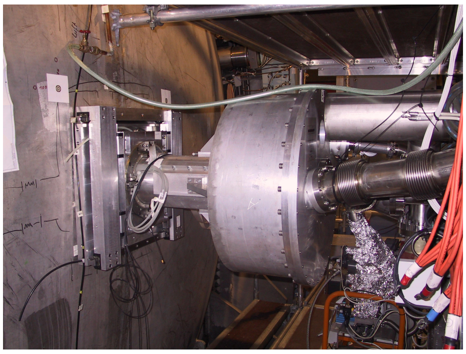


Figure 10: Compact super conducting mini beta magnet embedded into the H1 detector

4.) The Hardware: Running at theLlimit

Considering the compactness of the new interaction region and the strength of the magnets to achieve the required focusing, the hardware had to be pushed to its performance limit. While in the major part of the HERA machine a good rule was to run the magnets in the linear range of their excitation curve, the strong fields needed in the mini beta quadrupoles pushed the required gradients far into the nonlinear regime where saturation effects are considerably large. Dedicated field measurements and special magnet pre-cycles terefore had to be performed to guarantee small multipole effects and sufficient reproducibility of the fields also in this regime and to establish a precise magnet zransfer function up to saturation levels of 10%.
Again, preparing the hardware and the measurement tools in a decent manner, only slight corrections had to be applied afterwards to reach the required parameters. An example is shown in fig 11: The horizontal focusing quadrupole GA of the proron machine is powered on a level of nearly 10 % saturation. Still the magnet characteristics was reproducible, the beam optics needed only minor corrections for the saturation effects and the delivered luminosity corresponded to the expected values.

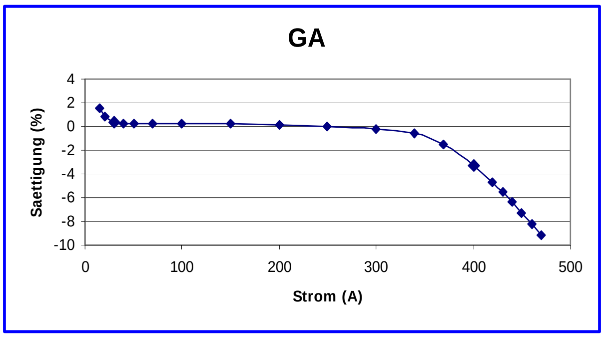


Figure 11: Excitation curve of the proton mini beta magnet GA: plotted is the deviation from the pure linear behaviour of the quadrupole excitation.

5.) Performance Limitations of HERA 2

It cannot be ignored that despite the hardware that had been carefully prepared and tested and despite measurement tools that had been established and tested already at the HERA 1 machine, a number of problems were en-countered during the commissioning phase and delayed the efficient data taking of the detectors.

Summarising briefly the main problems were:

- The installation and maintenance of the compact hardware in the new interaction regions was difficult and time consuming. Especially in case of technical failure an easy access to the densely packed components was not always possible.
- The magnet components installed close to the IP and mainly the magnets embedded inside the detectors were a source of orbit and optic errors. A decent alignment of these compo-nents turned out to be a difficult task and only a limited tolerance of the alignment of these quadrupoles could be achieved.
- The high power density in the new quadrupole magnets lead to several problems with the required cooling of the magnet coils. Several coils were affected and had to be exchanged.
- The synchrotron light power and mainly the stability of the light fan had been underestimated. The resulting high back-grounds, uncontrolled high radiation power at machine components and the radiation dose seen by several detector components turned out to be the most critical problem during the commissioning phase [3,4,5].

During the first two years after the hardware installation therefore the operation of HERA 2 was mainly determined by machine studies and improvements to overcome the problems and only a moderate integrated luminosity was delivered to the high energy physics experiments (fig. 12).

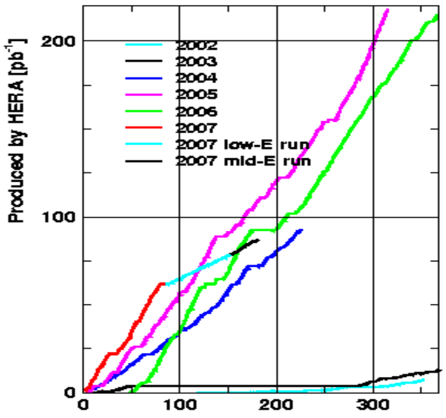


Figure 12: integrated luminosity of HERA 2, plotted as a function of run time for the years 2001 ...2007

6.) Alignment Tolerances:

The integration of the electron mini beta quadrupoles into the detector components lead to unforeseen difficulties for the alignment procedure of these magnets. Even though a special alignment system had been established, the control of the position and angle of the very first magnet - being embedded inside the H1 liquid argon cryostat - lead only to unsatisfactory results. To overcome this problem time consuming beam based measurements had to be performed like fitting the beam orbit under consideration of the local orbit corrector strengths as well as so called beam based alignment techniques to deduce a possible offset of the beam inside the quadrupole lenses. Fig 13 shows the result of such a measurement. The three curves correspond to the design values of the beam orbit in the quadriupole magnets, and the measured offsets before and after correction.

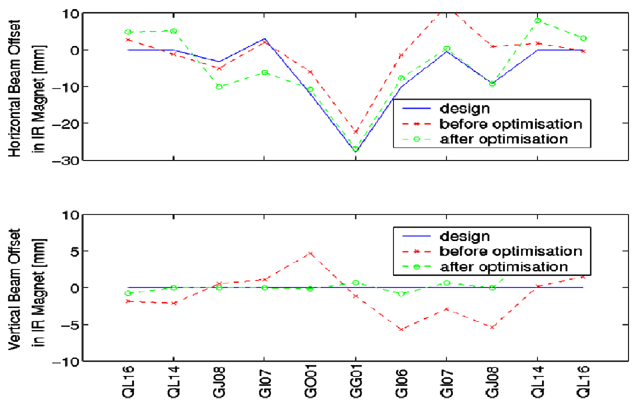


Figure 13: Beam based alignment for the HERA 2 interaction region quadrupoles: plotted are the design offsets of the quadrupole magnets and the measured values before and after correction in the horizontal and vertical plane

7.) External Fields and Orbit Stability:

While the stability of the beam orbit is an issue for a hadron machine that should not be neglected, it is of major importance in the presence of synchrotron light. Unfortunately the magnets of the electron storage ring were subject to the solenoid fields of the particle detectors. Mainly the first mini beta magnets that had been completely embedded inside the detector structure of the H1 and ZEUS experiments showed a strong effect during the ramp of the solenoid and/or the quadrupole field during the acceleration process. Beyond the direct influence via saturation of the magnet material a small transverse movement of the magnet was observed that lead to severe orbit distortions and to uncontrolled and irreproducible variations of the synchrotron light fan. Fig 14 shows a special example for this behaviour: During the closure of the calorimeter of the ZEUS detector the external iron structure of this detector part was moving and changed the strength and orientation of the solenoid field and the quadrupole stray field lines.

Figure 14: Orbit distortion during the closure of the ZEUS calorimeter. A local orbit correction algorithm had been installed to compensate the effect.

According to that, a distortion of the beam orbit was obtained and the background - mainly caused by the synchrotron light - reached easily intolerable levels.
To counteract these problems several procedures had been installed in the machine:

- An orbit feedback to compensate differences of the electron orbit with respect to a “golden orbit” that had been obtained during machine studies and luminosity test runs
- An alarm system for the detector part: in case of intolerable background situations, radiation monitors installed inside the high energy experiments could trigger the dump of the electron beam to avoid damage of detector components.
- An improved diagnostics and temperature system to protect the machine components (among these most of all the vacuum chambers) from damage
- improved shielding of the particle detectors against synchrotron light

8) The Human Factor:

It is just another way to express Murphy’s law: Experience shows that any improvement program on a running system will - with a high probability - lead in the first instance to a number of errors and unforeseen problems. The usual problems encountered in large machines like HERA are polarity errors in magnets, wrong allocations of power supplies and wrongly connected beam position monitors. Several techniques had to be established to measure the effect of possible errors in the new machine: Orbit response measurements to localise optics errors in both storage rings, beam based alignment techniques to centre the beam position monitors with respect to the quadrupole fields, tune controller loops that had to be installed or improved in both storage rings to compensate for the influence of nonlinearities, drifts and external fields. Finally in the case of the electron beam several orbit stabiliser systems were installed to control the orbit and the synchrotron light.

The effect on the data taking efficiency of the high energy experiments was drastic. A qualitative impression is given in fig 15: The background level inside the spacal detector of the H1 experiment is presented before and after optimisation of the electron beam parameters. The beam orbit and angle inside the interaction region, the tune of the machine and the position of the synchrotron radiation masks had a large inflence on the background seen by this detector component. It is not surprising that the control of the electron orbit upstream the detector turned out to be very critical but it was unexpected that corrections up to a distance of 200m from the IP had to be taken into account. Therefore in collaboration with the experiments special background signals were provided and techniques were established to optimise the machine parameters according to the background signals of H1 and ZEUS.

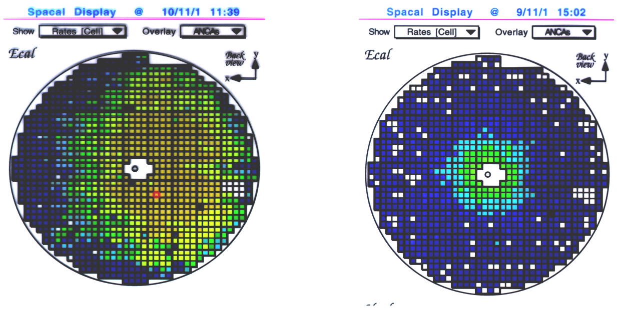


Figure 15: Background seen by the H1 SPACAL detector for a problematic beam orbit (left) and an optimised situation (right)

9.) The Good News: Lessons we Learned

In spite of the problems found during the machine commissioning phase and in spite the lengthy machine development program that was needed to study the problems the machine efficiency and mainly the data taking efficiency of the high energy detectors could be improved considerably.

After a challenging optimisation and improvement program the efficiency of the new machine reached finally values of 67% (fig. 16), a performance level that is considered to be excellent and that corresponds to the numbers that had been achieved in the run years 1999/ 2000 with the old machine HERA 1.

This value includes the time needed to cycle the machine, inject and accelerate the particle beams and prepare for luminosity. And it includes naturally hardware errors and the time for repair or replacement.

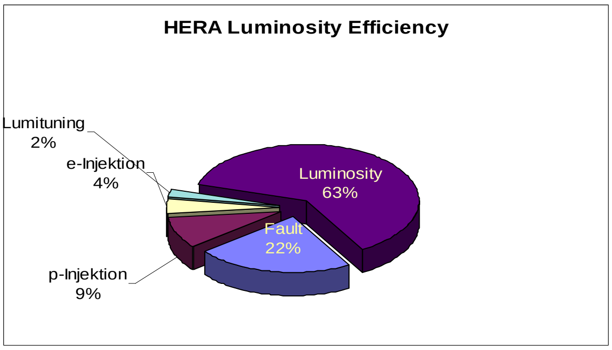


Figure 16: HERA 2 luminosity efficiency during the run year 2007

At the same time the specific luminosity - being determined by the effective cross section of the two beams and so being the most critical measure of the machine parameters - reached the design value. As mentioned in table 1 a value of

$$L_{spec} = 1.8 * 10^{30} \frac{1}{cm^2 s^2 mA^2}$$

was expected for the HERA 2 machine. The value of $L_{spec} = 1.77 * 10^{30}\ cm^{-2}s^{-1}mA^{-2}$ measured by the luminosity calorimeter of the H1 experiment is in excellent agreement with this expectation (fig 17).

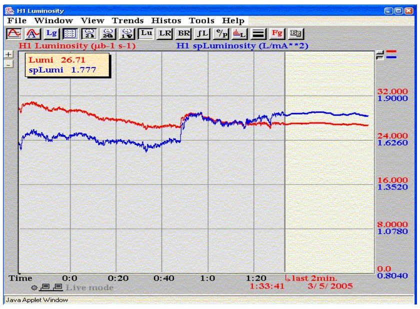


Figure 17: specific luminosity, measured by the H1 detector during a routine run in 2007:

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