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HERA PERFORMANCE AND PROSPECTS

FERDINAND J. WILLEKE
Deutsches Elektronen-Synchrotron
Notkestrasse 85, 22607 Hamburg, Germany
E-mail: Ferdinand.willeke@desy.de

With the design luminosity already surpassed in 1997, an ambitious upgrade of the HERA proton-lepton collider was installed in 2000/2001 to provide higher luminosity and longitudinally polarized lepton beams in the colliding beam experiments, H1 and ZEUS. Initially, experimental backgrounds limited the total beam currents. After completion of the HERA-B experiment in 2003, the number of colliding bunches was reduced while maintaining the same total beam currents to increase the single-bunch beam currents. With pre-upgrade bunch currents the specific luminosity was measured to be three times higher with the upgrade. Following modifications which helped to alleviate the detector backgrounds in 2003 and an extended period of steady operation, HERA is now operating with the design number of bunches while the total beam currents for protons and positrons I_p, I_e are being steadily increased. With less than 60% of the total design current, peak luminosities of $I_p \times I_e = 3.5 \times 10^{31} cm^{-2} s^{-1}$ have been demonstrated with a longitudinal polarization at the interaction points exceeding 50%. In this report, the experience with the luminosity upgrade and future prospects will be described.

1 Introduction

HERA [1], the only lepton-proton collider has now entered a new phase of operation. The 6.3 km double-ring collider accelerates at present about 100 mA of protons to an energy of 920 GeV for interactions with 27.5 GeV leptons with currents of about 50 mA using 174 colliding bunches.

HERA was built with substantial resources from outside Germany. It is the first accelerator built in this way and serves as a model for the LHC and possibly for future large accelerators physics.

The accelerator complex was proposed in 1981 and construction took place between 1984 and 1991. The proton ring has superconducting magnets with dipole fields of 5 Tesla, to beam energies of 920 GeV. The lepton ring requires high RF power to compensate for an 86 MeV energy loss of the leptons at 27.5GeV due to synchrotron radiation. A 500MHz RF voltage of $100MV$ is provided by 86 normal conducting 5-cell and 7-cell cavities and $40MV$ are generated by 16 superconducting 4-cell 500MHz cavities.

A most critical design choice was the use of the existing PETRA accelerator as an injector which limited the injection energy of the protons to 40GeV. The bending field in HERA at this energy is strongly distorted by eddy-current effects which reduces the dynamic aperture and leads to operational difficulties because of rapid changes in these field components at the onset of acceleration.

Other critical choices were the use of the old PETRA 500 MHz RF system in the lepton ring, small bending radii in the injection lines, which implies tight apertures, the use of the obsolete PETRA control system and the use of a refurbished power supply for the superconducting main power circuit of HERA.

Commissioning of the accelerators took place in 1991/92 with first collisions in 1991. Over the next few years the luminosity produced by HERA increased steadily [3] as experience was gained, for example, in controlling the effects of eddy currents in the super-conducting magnets [4] and in optimizing the parameters relevant for controlling the proton beam lifetime with beams in collision [5]. The design luminosity of $1.4 \times 10^{31} cm^{-2}s^{-1}$ was surpassed in 1997 [6].

The integrated luminosity was further increased following an extensive program for improving accelerator availability [7,8] in 1997/98. This effort included

- replacement of the integrated ion getter vacuum pumps by non-evaporating getter pumps (NEG) which do not require high voltage for operation and which helped to minimize the detrimental effects of trapped dust particles in the beam of the lepton ring, which is relevant for operation with electrons [9,10]

- the addition of more RF systems in the lepton accelerator to allow for higher beam currents

- improvements (i.e. addition of a bias voltage for the couplers of the superconducting cavities) and replacement of various elements (i.e. power supplies and low beta-quadrupole magnet coils) to enhance reliability

- aperture increases in the injection beam lines

- an upgrade of the HERA control system.

Having surpassed the design goal for peak luminosity with an integrated luminosity of $\simeq 185pb^{-1}$, an upgrade was deemed necessary to significantly increase the luminosity. The constraints on colliding beam performance prior to the upgrade may be seen using the following expression for the total luminosity assuming matched beam sizes, no variations in bunch parameters across the bunch trains, and head-on collision:

$$L = \frac{N_p \cdot I_e \cdot \gamma_p}{4\pi e \varepsilon_{Np} \sqrt{\beta_{xp}\beta_{yp}}} \tag{1}$$

where $\gamma_p = E_p/m$ and the variable parameters are the proton beam brightness N_p/ε_{Np} with N_p the number of protons per bunch and ε_{Np} the normalized proton beam emittance, I_e the total lepton current, and β_{xp}, β_{yp} respectively the horizontal and vertical proton beam β-functions at the interaction point (IP).

The proton beam brightness with $N_p/\epsilon_{Np} = 10^{11}/4\mu m$ was limited by space-charge effects in the pre-accelerators and in HERA potentially by the increase in lepton beam tune spreads or emittances as a function of single-bunch proton beam current. The total lepton beam current I_e was and still is by total available RF power and potentially by the tune spread imparted to the protons from the beam-beam interaction. The proton and lepton beta functions at the IP, $\beta_{xp} = 7m$ and $\beta_{yp} = 50cm$ were limited by the geometry of the interaction region.

2 The HERA Luminosity Upgrade

Given the limitations just described, the most cost-effective and minimum risk option for a substantial luminosity increase was considered to be modifications to the HERA interaction regions (IRs) [11] to achieve smaller β-functions for both beams at the collision points. This was decided upon after investigating alternative options such as extensive RF system upgrades or upgrades of the injector chain. The layout of the interaction region [12] which facilitates stronger focussing of the proton beam with $\beta_{xp} = 2.45m$ and $\beta_{yp} = 18cm$ and lepton beam $\beta_{xe} = 0.6m$ and $\beta_{ye} = 26cm$ is based on minimizing the distance of the lepton and proton low-β quadrupole magnets from the IP. This requires strong magnetic separation of the two beams since the leptons cannot be exposed to the strong focusing fields of the protons. The essential feature of the modifications include for this reason the superconducting combined-function magnets with separator dipole fields and the low-β-focusing fields for leptons placed inside the detectors. A new type of septum quadrupole magnet with a mirror plate which has a cut-out for the lepton beam allows placing the first focusing lens for protons as close as 11m from the IP.

The strong magnetic separation leads to a high power synchrotron radiation of about 28 kW emitted by the lepton beam. An essential feature of the IR upgrade is the complicated vacuum system. The keyhole-shaped beam pipes allow the radiation to pass through the entire interaction region to be absorbed far away at the downstream side of the detector at 26m from the IP. Special collimation and masking inside the detectors are included to shield from backscattered radiation from the far-away absorber and from 11m were the proton and lepton beam pipes separate[12]. A challenging issue is the displacement of the superconducting low-β quadrupoles under the influence of magnetic interaction with the detector solenoid by up to 1mm during acceleration due to the soft supports inside the H1 and ZEUS detectors.

With this geometry the proton horizontal and vertical RMS beam sizes at the interaction point were reduced from $\sigma_x \times \sigma_y = 190\mu m \times 50\mu m$ to $\sigma_x \times \sigma_y = 112\mu m \times 30\mu m$. To match the lepton beam sizes to those of the protons, in addition to the stronger focussing of the lepton beams in the interaction region, the emittance was reduced by a combination of an increased betatron phase advance (from 60 to 72 degrees per FODO cell) and a relative RF frequency shift of $\Delta f/f = 7 \times 10^{-7}$ [13].

Installation of the new interaction regions took place in 2000/2001. In total, over 250 m of new vacuum chambers were installed at each interaction region, which includes new 60m long spin rotators [29] on both sides of the H1 and ZEUS colliding-beam experiments to provide for longitudinally polarized leptons.

3 Experience with the Upgraded Accelerator

Accelerator commissioning with the upgraded interaction regions began in late 2001 and continued through the fall of 2002. The storage and acceleration of single beams and high single bunch luminosity was demonstrated quickly. New operational procedures were implemented to achieve good accelerator performance.

Essential improvements include beam based alignmentin the IR, beam orbit control using feedback. Until the beginning 2003, the essential design features of the luminosity upgrade were validated using reduced number of bunches and nominal (i.e. pre-upgrade) single-bunch beam currents. During dedicated studies, the design beam parameters and a three-fold increase in specific luminosity and longitudinally polarized lepton beams in collision were demonstrated.

However, the total beam currents were found to be limited by unexpectedly high background rates in the detectors.

During the 2002 and 2003 shutdowns, modifications were made to help mitigate certain background issues. Since then the total beam currents in HERA continue to be increased and both the integrated and peak luminosities delivered to the experiments are rising steadily. In the following we summarize the most important activities from commissioning of the luminosity upgrade.

3.1 Detector Backgrounds

Four sources of detector backgrounds have been identified, studied and cured. The direct synchrotron radiation generated in the magnetic fields upstream of the detector is avoided by the IR geometry with sufficiently large apertures inside the detector and by synchrotron radiation masks to shield the detector from radiation from far-away magnets. However in case of magnet misalignment, the radiation from particles in the tails of the transverse beam distribution can inpinge on the beam pipe inside the detector. This source of background could be brought quickly under control using beam-based alignment of the low beta quadruple magnets and by proper adjusting the collimators. One far-upstream collimator at 66m from the IP needed to be added.

A second source of background are leptons which scatter on the residual gas in the IR upstream of the detector, lose part of their energy by radiating bremsstrahlung and are likely to hit the beam pipe in the detector. A dedicated masking system can only partially shield the detector region from such particles. The corresponding background, however, has improved substantially by scrubbing the vacuum pipe with synchrotron radiation. A NEG pump was added inside a 6m long section without pumping during the 2002 shutdown. Since the fall 2003, this source of background is not important any more

A further source of background is the synchrotron radiation that is backscattered from the downstream absorbers into the detector. The downstream absorbers have been placed 23m away from the IP and the vacuum system provides sufficient aperture for the wide synchrotron radiation fan through the entire interaction region. At the location where the proton and lepton beam pipes separate at 11m from the IP, however, an additional absorber is unavoidable. This turned out to be a source of strong background in one of the detectors and required an improvement of the masks in 2003 which eventually eliminated this source of background.

The detectors also suffered from hadronic backgrounds from protons lost in the interaction region. The corresponding large leakage currents of the H1 central tracking chamber were found to be proportional to the product of the proton and lepton beam current, which suggested that protons were scattered on the residual desorbed from the beampipe due to synchrotron light emitted by the lepton beam. The sensitive region extends from $2m$ to $10m$ in the incoming-proton side of the IR as has been revealed by detailed background modelling [14,15] and by beam experiments with pressure bumps. The residual vacuum pressure was produced in part by heating of the synchrotron radiation masks inside the detector and the corresponding strong thermal desorption. An improved tapered design of the masks and local water cooling (in case of the H1 detector) helped to reduce the proton-induced backgrounds. The largest improvement however was achieved by operating the accelerator routinely with high intensity lepton beams. Backgrounds conditions for the H1 detector are now tolerable, however the safety margin is small and possible vacuum leaks still present a threat to the H1 experiments.

3.2 Operational improvements

Of the many improvements implemented, beam-based alignment (BBA) in the new compact IRs and feedback loops for orbit stabilization have proven particularly effective. A refined method of BBA of the combined function magnets in the IR was developed [16,17] to better control the beam trajectories in the IR thereby minimizing spurious synchrotron radiation generated by beams off–axis in the quadrupoles. Control of the closed orbit during the entire operation cycle to the level of 0.1mm RMS was found to be necessary for a number of reasons the most important ones being radiation damage of sensitive detectors by direct synchrotron radiation, heating of the beam pipe by synchrotron radiation, beam emittance control and control of detrimental nonlinear synchro-betatron resonances. Time-dependent orbit fluctuations, arising in part from magnet displacements due to magnetic forces, are therefore controlled using automated orbit steering [18] to reference orbits allowing superimposed closed-orbit bumps. Desired orbit changes by various closed orbit bumps are taken into account in the reference orbits which are continuously updated. This system is very valuable in avoiding irradiation of sensitive detectors during acceleration, undesired heating of the vacuum system by uncontrolled synchrotron radiation or creation of additional sychrotron radation due to large beam offsets in the low-β quadrupole magnets. This new algorithm allows independent luminosity and background tuning at each of the three IR without distortions by spurious non-closure of orbit bumps and allows polariztion tuning with harmonic closed orbit bumps. Experience with this sophisticated system is very good as evidenced by the increased operational stability.

3.3 Verification of the upgrade parameters and beam-beam effects

While still limited in total beam currents, accelerator studies were undertaken in 2002 and 2003 using about 2/3 of the nominal number of colliding bunches and single-bunch beam currents equal to those of prior to the upgrade. The experiments [19] validated the design beam parameters and a 3-fold increase in specific luminosity. Despite the reduced total beam currents, a total luminosity of $2.7 \times 10^{31} cm^{-2} s^{-1}$ was demonstrated in these dedicated experiments. The specific luminosity was optimized by careful control of the beam optics. Two pairs of skew quadrupoles around each of the two IPs were used to provide local compensation of the detector solenoids and to adjust the axis of the beam ellipse in the IP to obtain maximum overlap between the two beams. Beam optical errors are measured with an accuracy of about 5% using a fast algorithms based on the response of beam position measurements to dipole corrector changes [27]. This allowed to compensate optical errors and limit β-beating to approximately 10% in both planes for both beams. Three dimensional scans of the relative positions of the two beams using the luminosity measurements [28] as a figure of merit allow to obtain an optimum overlap of the beam centre in all three dimensions.

The small proton beam sizes at the collision points in the upgraded lattice give rise to significant beam-beam effects on the lepton beam. The linear beam-beam tune shift parameters of the leptons at each of the two interaction points are $\Delta\nu_x = 0.020$ horizontally and $\Delta\nu_y = 0.045$ vertically; With a horizontal tune of $Q_x = 54.12$ close to integer, the additional focusing of the leptons by the protons (the so-called dynamic beta effect) can be considerable and the resulting beam-beam induced β-beat is suppressed using a special optic to produce a phase advance of exactly $\pi/2$ between the two interaction points. The lepton beam tune spreads at nominal proton single-bunch currents are close to 0.1 in the vertical plane and close to 0.05 in the horizontal plane, which restricts the choice of possible betatron tunes whereby the influence of beam-beam and lattice nonlinearities are critical.

While many experiments were performed prior to the luminosity upgrade under special conditions created to simulate the expected conditions [21,22], confirmation of certain aspects of the beam-beam interaction could take place only following the upgrade of both the interaction regions and accelerator optics. In dedicated studies [23] several effects which resulted in decreased specific luminosity were identified: lepton and proton beam emittance growth arising from beam-beam resonances, the dependence of proton beam emittance on proton beam current, lepton beam emitttance growth from normal (and later, from synchro-betatron) resonances, and the effects arising from the presence of two interaction points. As predicted by simulations of the beam-beam interaction in the strong-strong model [24], the lepton bunches have occasionally been observed to perform coherent dipole oscillations. The proton bunches are then continuously excited by the leptons which leads to an increase of about $\simeq$ 10% of the proton transverse emittances. The effect is observed to depend strongly however on both lepton and proton betatron tunes. Under worst conditions, with the lepton tunes too close to a resonance (in this case $Q_x + 3Q_s$=0), the proton beam emittances have been observed to increase by factors of 2-4. Such emittance growth is now avoided by precisely controlling the betatron tunes of both beams and by bringing the beams into collision sequentially at the two interaction points.

3.4 Synchro-Betatron Resonances

The nominal operating point in the HERA lepton tune diagram is selected to allow for build-up of high lepton beam polarization. With this constraint, the choice of horizontal lepton beam tune is between the 2^{nd} and 3^{rd} order synchro-betatron resonances $Q_x + mQ_s$, (m=2,3, Q_x denotes the betatron tune, Q_s denotes the synchrotron tune). Resonant synchro-betatron coupling leads to a large increase in the transverse oscillation amplitudes and thus a strong increase in the effective beam emittance. The consequences are poor lifetime and reduced luminosity.

The new lattice for leptons after the upgrade has several disadvantages with respect to synchro-betatron coupling: The horizontal emittance is reduced from 40nm to 30nm which requires the stronger focusing of the beam in the arcs (72° instead of (60° per FODO cell). The corresponding smaller momentum compaction factor gives a smaller synchrotron frequency which reduces the space between synchro-betatron resonances. At the same time the increase of the RF frequency used for a further reduction of the horizontal emittance leads to an increase in the beam energy spread and thus leads to a larger longitudinal emittance which increases the width of synchro-betatron resonances. Furthermore the 72°-lattice does not provide favourable conditions for compensation of higher-order chromatic effects with multiple sextupole families. The analysis [20] showed that this leads to a strong enhancement of the 3^{rd} order synchro-betatron sideband resonance $Q_x + 3Q_s$ so that the tune is trapped between two detrimental strong synchro-betatron resonances. This difficulty was solved [20] using a new lattice with a betatron phase advance between experiments of precisely $\pi/2$, which provides intrinsic compensation of non-linear chromaticity. Closed orbit oscillations and antisymmetric orbits around the IP lead to a strong enhancement of the second synchro-betatron resonance $Q_x + 2Q_s$. However with precise control of the beam orbit with the orbit stabilizing feedback the strength of this resonance is sufficiently well controlled. With these measures, colliding beams with high luminosity and high polarization have been made possible.

4 Lepton beam polarization

An important feature of HERA are longitudinally spin-polarized lepton beams. Since 1994, a pair of spin rotator magnets [29] have been installed around the East interaction point and beams with up to 60% longitudinal polarization were made available since 1995 for the HERMES experiment [30].

The performance upgrade includes also longitudinally polarized lepton beams in the colliding beam experiments. To achieve this additional pairs of spin rotators were added on both sides of the IPs. A spin-matched optics was developed [25] taking into account the non-local compensation of the detector solenoidal fields and the increased betatron coupling required to match the vertical beam sizes at the IPs. Polarization in the upgraded HERA lattice is more difficult for the following reasons: there are three pairs of spin rotators instead of one which leads to a reduction of polarization due to the Sokolov-Ternov effect in the vertical bending magnets. Furthermore, the detector solenoid is not locally compensated and the beam orbit is non-parallel to the solenoid axis. The forces on the lepton spin imposed by the proton beam are increased by a factor of 1.8 in the horizontal direction and by a factor of 1.6 in the vertical direction. Despite these difficulties, longitudinally polarized lepton beams are provided simultaneously to the two colliding beam IPs and at the HERMES IP due to a spin matched optics in the straight sections, good orbit control especially in the IR and an extended scheme of harmonic bumps [25] to cancel depolarizing resonances due to imperfections. Polarization between

40% $-$ 50% are routinely achieved. The beam-beam effects on polarization are evidenced by the fact that the betatron tunes are quite critical for polarization and since a slow increase of polarization is observed during a 10h luminosity run while the proton beam emittance is slowly growing by a factor of $1.2 - 1.5$.

5 Present performance and future plans

With the detector leakage currents substantially reduced by improved masking at one of the two experiments and by rigorously enforcing routine operations, which evidenced the strong influence of vacuum conditioning, HERA is in 2004 no longer limited in total beam currents and is operating with currents comparable (or exceeding) those used prior to the luminosity upgrade. The peak luminosities as measured in the two colliding beam experiments have been increased during the year 2004 steadily to about twice the typical values achieved before the upgrade. By the end of June 2004, the maximum achieved peak luminosity amounts to $L_{peak} = 3.8 \times 10^{31} cm^{-2} sec^{-1}$ with about 100mA of protons in 180 bunches, and 48mA of positrons in 180 bunches of which 174 are colliding with protons. The corresponding maximum specific luminosity amounts to $L_{spec} = 1.5 \times 10^{30} mA^{-2} cm^{-2} sec^{-1}$. The measured luminosity and luminosity calculated from the beam parameters agree within 10% by taking into account the residual beam-beam β-beat.

Two effects substantially limited the integrated luminosity over first half of 2004. First, beam losses occasionally occurred, whereby the detected radiation level outside the tunnel proper reached the substantially reduced levels allowed for by new radiation safety rules. For about 2 months, the total proton beam current was administratively limited to 20 mA while the protection system was upgraded (fast dumps within $150\mu sec$ triggered by sudden changes in beam intensitypower supply currents beam loss signals and beam orbits). The second effect related to the production of dc proton beams, which caused spikes in the proton backgrounds at one of the experiments. The source was found to be a faulty cable which has since been replaced.

The maximum luminosity production rate which can be expected from the present level of peak performance amounts to $1.4 pb^{-1} day^{-1}$ while the actually achieved production rate amounts to only up to $0.8 pb^{-1} day^{-1}$. For this reason, present efforts aimed towards maximizing the integrated luminosity now focus on improving the accelerator availability and operational efficiency.

The availability of the complex system of HERA accelerator components has always been quite critical. In the past, as already mentioned, an agressive upgrade programme led to the good performance in 1999 and 2000.

The present, modest HERA improvement program includes upgrading the low-level controls of the proton RF systems, adding more vacuum pumps in the lepton RF systems, and upgrading the cryogenic system (compressors and controls). An aggressive program of preventive maintenance has been initiated and the benefit of this effort begins to show. The efficiency will further be increased by improved application software which supports operations, and improved beam diagnostics such as new beam position and profile monitors, modifications for the collimation systems, and the addition of longitudinal damping in the proton ring for suppression of longitudinal coupled bunch instabilities [26].

Further increase of luminosity is expected to be achieved by controlling the longitudinal instabilities of the proton beam which should allow for better bunch length control during the energy ramp and enable full exploitation of the luminosity upgrade by reducing the hour glass effect and enabling a further decrease of the beta-functions at the interaction points.

The near-term goal is to produce luminosity with a rate of $1pb^{-1}day^{-1}$. The HERA II run will continue from the fall of 2004 until summer of 2007 which comprises about 750 days of luminosity running. Taking into account the luminosity already delivered since 1992, it appears feasible, though it requires an optimistic extrapolation, to achieve a total HERA luminosity of $(\int L \cdot dt)_{HERA} = 1 \cdot fb^{-1}$.

Following a required shutdown for radiation interlock tests beginning in the middle of August 2004, it is planned to begin operation with electron beams. The present operations schedule calls for the end of the HERA physics program in year 2007. Longer term possibilities for HERA were presented in reference [8].

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