OPERATIONAL EXPERIENCE WITH HERA

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Abstract

The electron-proton collider HERA (Hadron Electron Ring Accelerator) at DESY will conclude operations at the end of June 2007 after 16 successful years. An upgrade of the interaction regions in the year 2001 increased the luminosity of HERA by a factor of 2.7 resulting in a peak value of $5.1 \cdot 10^{31}$ cm^{-2} s^{-1}. For a special experiment, HERA has been operated for the last two months of operation with a reduced proton energy of 460 GeV and 575 GeV. An overview of the accelerator physics and operational challenges, the performance over the last years, the continuous efforts to upgrade and improve the accelerator and an assessment of reliability and availability issues of HERA will be presented.

INTRODUCTION

HERA, the only e/p collider in the world, provides collisions between protons of an energy of 920 GeV and polarized electrons (or positrons) of 27.5 GeV. HERA consists of two independent storage rings with a circumference of 6.3 km. In the two interaction regions (IRs) in the north and south the experiments H1 and ZEUS are installed. They measure the properties of the sub-structure of the proton by deep inelastic scattering. In addition the HERMES experiment investigates the polarized quark-gluon structure of the nucleons using collisions between the polarized lepton beam and an internal polarized gas target.

The proton ring HERA-p uses superconducting magnets in the arcs and normal conducting magnets in the straight sections. The field of the dipole magnets at 920 GeV is 5.1 T. The electron ring HERA-e is operated with an energy of 27.5 GeV and uses superconducting magnets only in the IRs. All other magnets in HERA-e are normal conducting.

HERA OPERATION

HERA was approved in the year 1984 and commissioned in 1991. Luminosity operation started in 1992 for the two colliding beam experiments H1 and ZEUS. In 1994 the experiment HERMES was installed in the east hall of HERA.

During the years 1992–2000 the experiments H1 and ZEUS collected an integrated luminosity of about 200 pb^{-1} of data (Fig. 1). In 1997 it became clear that a considerable increase of the integrated luminosity required an upgrade of the machine. In 2000/2001 the IRs of H1 and ZEUS were modified to provide a factor of 2.7 more specific luminosity by reducing β^* [1]. The detectors of H1 and ZEUS were upgraded as well.

One of the central issues of the ambitious luminosity upgrade of HERA was the installation of superconducting magnets inside the H1 and ZEUS detectors [2]. They provide an early separation for the proton and lepton beam and allow the first proton magnets to be moved closer to the interaction points (IPs). In addition pairs of spin rotators at H1 and ZEUS were installed to turn the polarization direction of the lepton beam in the longitudinal direction at the IPs [7].

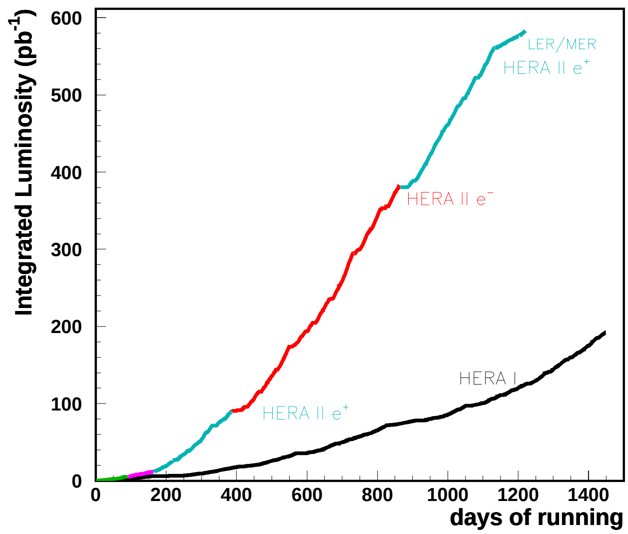

Figure 1: Delivered luminosity of HERA I and II.

High Energy Run

Although the design value of the specific luminosity of $1.82 \cdot 10^{30}$ mA^{-2}cm^{-2}s^{-1} was achieved soon after the commissioning of HERA II, the understanding and cure of background problems delayed the start of HERA II data taking to 10/2003.

Until 3/2007 HERA was running with protons of 920 GeV and polarized leptons of 27.5 GeV, equally split between e$^+$p and e$^-$p operation. The peak luminosity achieved was $L = 5.1 \cdot 10^{31}$ cm^{-2}s^{-1} and the mean luminosity production reached 1 pb^{-1}/day. Proton currents up to 110 mA (limited by the performance of the pre-accelerators) and positron currents of 45 mA (limited by RF-power and vacuum conditions) have been achieved. The upgrade increased the total integrated luminosity delivered by HERA to 800 pb^{-1}.

Low and Medium Energy Run

At the request of the experiments HERA has been operated in 2007 for two months with a reduced proton energy

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of 460 GeV and for one month with 575 GeV. The purpose of the experiment is to measure the structure function F_L using different center-of-mass energies. Due to the scaling law of the specific luminosity $L_s \propto 1/\gamma^2$ the luminosity production was only one fourth at 460 GeV compared to 920 GeV.

An integrated luminosity of 12 pb^{-1} was requested by the experiments. Due to the good performance of HERA this goal was already achieved at the end of May 2007, which gave us the opportunity to establish another optic with an intermediate proton energy of 575 GeV. It will be used until the end of HERA operation.

ACCELERATOR PHYSICS CHALLENGES

Persistent Current Effects

Due to strong persistent currents in the superconducting magnets of HERA-p, field distortions reduce the dynamic aperture at the injection energy of 40 GeV [3]. Careful adjustment of betatron tunes, coupling and chromaticities is required to achieve a sufficient lifetime during injection and the first part of the energy ramp. To avoid emittance dilution effects due to injection mismatch the energy and the trajectory of the injected beam has to be corrected very exactly at every beam injection ($\Delta p/p \leq 4 \cdot 10^{-4}$ and $\Delta x, y \leq 1$ mm). Dipole field variations at 40 GeV are controlled by measuring the magnetic field using NMR probes in two reference magnets.

The tunes and the chromaticity have also to be controlled very well during acceleration. Otherwise the beam is either lost due to low lifetime or the emittance can grow due to the head-tail instability if the chromaticity becomes negative. The effect of the persistent currents was controlled using the measurement of the sextupole field distortions in reference magnets, by means of a lookup table and using the spectrum of a sensitive BPM and manual adjustments by the operators. An active damping of the head-tail instability has been implemented but was not used, because the rate of emittance growth due to feedback noise of the necessary tune feedback control loop was too big.

Synchro-Betatron Resonances

The range of possible working points of HERA-e is limited by strong 2nd and 3rd order synchro-betatron resonances (SBR). They are excited by accumulated orbit and dispersion distortions around the ring of HERA-e [4].

Carefully corrected distortions of the orbit and the dispersion function, empirical tuning of dispersions corrections and the tuning of the horizontal slope at the IPs are necessary to keep the strength of the SBRs small and to guarantee good beam lifetime. Otherwise the electron beam emittance will increase and the experiments suffer from e-background.

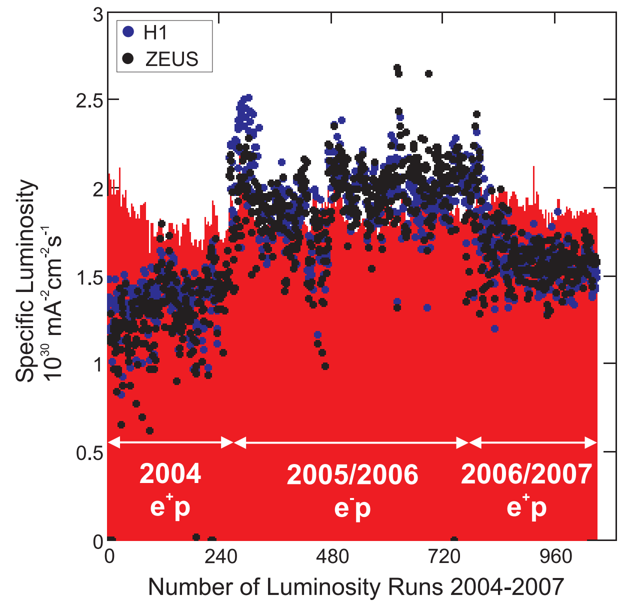

Figure 2: Measured specific luminosity of H1 and ZEUS (•) and theoretical prediction based on beam parameters (bars).

Beam Size Matching

During the first operational phase of HERA it was found, that equal beam sizes of proton and electron beam at the IPs and a careful centering of beams are necessary to get sufficient proton lifetime [5]. To achieve matched beams, optics measurements using the response matrix method have been regularly carried out in both machines and empirical optics corrections have been computed and applied.

Specific Luminosity

Due to the collision of different particles and the restriction of the betatron tune to get polarization, HERA can't use the effect of dynamic beta beating to increase the specific luminosity.

It has been observed, that the specific luminosity L_s is different for electron and positron operation due to the focusing/defocusing effect of the beam-beam force (Fig 2). For operation with electrons a specific luminosity of $L_s = 2.0 \cdot 10^{30}\,\mathrm{cm^{-2}mA^{-2}s^{-1}}$ and for positrons $L_s = 1.5 \cdot 10^{30}\,\mathrm{cm^{-2}mA^{-2}s^{-1}}$ has been achieved.

To take advantage of this effect, tunes for e$^+$-operation were chosen in 06/07 below the integer resonance (mirror tunes). That increased the specific luminosity to $L_s = 1.7 \cdot 10^{30}\,\mathrm{cm^{-2}mA^{-2}s^{-1}}$. The tunes of HERA-p have been moved also to mirror tunes to avoid e/p orbit instabilities.

Polarization

A unique feature of HERA is the polarized electron beam. Electrons circulating in the vertical guide field emit synchrotron radiation and can become polarized by radia-

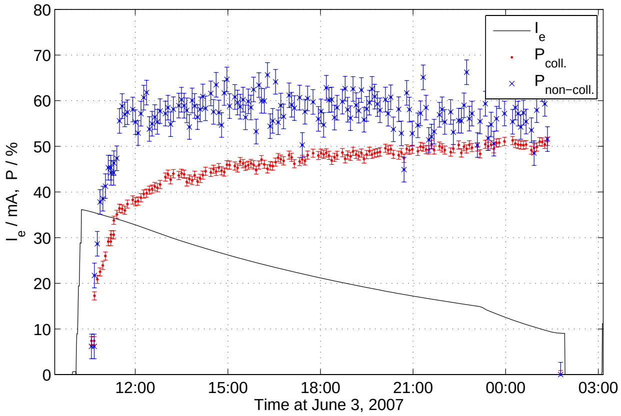

Figure 3: Positron current (−), polarization of colliding bunches (•) and non-colliding bunches (×) during a run.

tive self-polarization [6]. A stationary state is reached due to spin-diffusion of the beam. Pairs of rotators turn the vertical direction of the spin in the arcs into the longitudinal direction at all three IPs.

The beam-beam interaction has a strong influence on the polarization (Fig. 3): During a run the polarization of the colliding bunches P_c approaches the polarization of the non-colliding bunches P_{nc} (some non-colliding bunches are filled for the background calculation of the luminosity monitors). The reason for that is the tune change of the colliding bunches due to the decrease of the beam-beam interaction, when the proton emittance grows.

A spin-matched optics, carefully corrected closed orbit and dispersion distortions, energy scans and harmonic bump scans were required to achieve good polarization [7]. Polarizations of $P_c = 45$ % for e^+ and $P_c = 40$ % for e^- have been obtained for the high energy run. Because of the weaker beam-beam effect for the low and medium energy run $P_c = 50$ % and $P_{nc} = 60$ % has been reached.

IMPROVEMENT PROGRAM

Until the end of HERA operation several projects to improve the beam quality have been carried out. The last two projects were a feedback to damp longitudinal coupled bunch oscillations of the proton beam and a local IP orbit feedback for the lepton beam.

During proton acceleration longitudinal emittance dilution due to coupled-bunch instabilities are observed. This bunch lengthening reduces the luminosity for low β^*-optics (hourglass effect). A feedback system to suppress this instability has been installed successfully [8].

Due to ground motion the closed orbit of the electron beam moves in the frequency range of 0–20 Hz by $\approx$100 μm in the arcs. These oscillations couple at the IPs to the proton beam and can increase the proton background production and can enhance the emittance growth of the proton beam. Four feedback loops using 8 dedicated BPM electronics and 16 air coils have been installed for a local IP orbit feedback system [9]. The feedback has a sampling frequency of 800 Hz, a bandwidth of 30 Hz and can damp the oscillations by a factor of 10.

OPERATIONAL EXPERIENCE

One of the challenges of the luminosity upgrade was the handling of 30 kW synchrotron radiation (SR) power generated by the superconducting separation magnets in the IRs [2]. Movement of these magnets during energy ramping of the electrons and during the luminosity run made the implementation of a sophisticated global orbit correction feedback necessary.

The reliability of the technical components of HERA is a major issue. Since a reliability upgrade in 1997/98 the availability of the machine has been increased constantly. Very useful to improve the availability of HERA were preventive maintenance, more fault diagnostics, improved controls and organizational measures. An availability of 80 % has been achieved in 2006/07.

CONCLUSION

The operation of the e/p collider HERA will come to an end at June 30th, 2007 after 16 years. HERA has accumulated 800 pb^{-1} during this time and reached a luminosity production of about 1 pb^{-1}/day. The luminosity achieved at HERA after the luminosity upgrade has exceeded the design luminosity by a factor of 3.4. The rich physics program of HERA gave deep insight into the low-x proton structure, the QCD-structure of the proton and the polarized gluon contents of the proton.

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