EXPERIENCE WITH THE HERA LEPTON-PROTON COLLIDER

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Abstract

A review of the experience of operating the HERA lepton proton collider with a high luminosity of up to $5 \cdot 10^{31}$cm^{-2}s^{-1}, a discussion of the important accelerator physics issues and a summary of the most important physics results of the lepton-hadron (ep) collider HERA is presented.

INTRODUCTION

Collisions of high energy leptons with hadrons reveal the structure and dynamics and the nature of the forces between the constituents of hadrons. Electron scattering experiments on protons were performed already fifty years ago when R. Hofstadter and co-workers measured the nuclear form factor by analysis of (200-600) MeV electrons scattered on protons [1]. As leptons with energies of several GeV became available, a series of lepton nucleon scattering experiment revealed an inner structure of the proton with point-like constituents [2, 3]. This discovery was followed by many experiments yielding a better understanding of the proton structure. The experiments E49-89 at SLAC [4] observed that the cross section for small x[†] remained constant in the range of $x \approx 1/3$-0.01. This result (among others) suggested that additional quarks-antiquark pairs are produced inside the proton by the strong force between the valence quarks and the gluons. A lepton-hadron collider with large centre of mass energy (E_{cm}) was expected to provide the ultimate experimental evidence for this model because it would provide access to small x with sufficient spatial resolution or high Q^2. At that time, the HERA ep collider with E_{cm} = 318 GeV was proposed [5]. HERA was expected to provide precision measurements of the proton dynamic structure function F_2, of electro-weak and strong interactions, and to provide experimental evidence of lepton quark resonances. HERA was approved in 1984 and the physics program was started in 1992.

HERA OVERVIEW

HERA consists of two 6.4 km long storage rings, one with 5T superconducting magnets for the 920 GeV protons and another with normal conducting magnets for the 27.5GeV electrons or positrons. The beams collide at two collision points (IP) denoted by North and South, where the detectors H1 and ZEUS are located. The interaction regions (IR) were upgraded for a high luminosity of L > $5 \cdot 10^{31}$cm^{-2}s^{-1} in 2001 [6]. The HERA lepton beam is spin polarized by the Sokolov-Ternov [7] effect. Three pairs of ppin rotator magnets [8] around each of the three experiments provide longitudinally polarized leptons for collisions with protons.

HERA ACCELERATOR PHYSICS ISSUES

The HERA injection energy for protons is only 40 GeV, 0.043 times the operation energy of 920 GeV. The corresponding large persistent current field errors of the superconducting magnets at injection [9] are the cause for a small dynamic aperture of only 3.8 RMS times the beam sizes $\sigma_{x,y}$ [10]. This serious issue is solved by strictly controlling the beam parameters. Emittance dilution at injection is avoided by correcting injection errors to < 1mm transversely and to < $4 \cdot 10^{-4}$ in relative energy at each proton injection. The tunes during injection and the first part of acceleration must be kept to within a small window of $\Delta Q_{x,y} \leq 0.002$. They are controlled by a software-based feedback [11] with a non-destructive tune measurement [12]. Persistent and eddy current sextupole components of the guide fields must be suppressed dynamically to a level of 0.3% which is accomplished by a combination of continuous monitoring and correction via a reference magnet system, by look-up tables for correction of systematic errors and by manual fine tuning the chromaticity on analysis of the tune spectra. As a result, the chromaticities $\xi_{xy} = \Delta Q_{xy} ({}^{\Delta p}/{}_{p})^{-1}$ are controlled to about one unit. The betatron-oscillations must be decoupled to levels of < 0.005 in the coupling strength. Failure to meet these requirements leads either to beam loss > 1% due to poor dynamic aperture, or multi-mode head tail instabilities. The head tail instability is driven by a conspiracy of coupling and small values of chromaticity [13]. Attempts to control the instabilities during acceleration by broadband dampers [14] have been abandoned because of significant emittance growth due to feedback noise and the then required PLL-type tune measurement, and, more importantly, due to the loss of information necessary to fine-tune the chromaticities based on analysis of the tune spectra for maintaining good lifetime. This part of HERA experience may be relevant for the LHC. High precision, non-destructive tune and chromaticity measurements in conjunction with low-noise damper systems are deemed necessary for the LHC.

The lepton beam tune working space is limited by strong 2nd and 3rd order synchro-betatron resonances. In the vicinity of these resonances the emittance of the leptons growth dramatically and the lifetime becomes very poor. These resonances are excited by accumulative effects around the long circumference of HERA. The widths of

[†]The parameter x is the fractional momentum of the interacting proton-constituent. It is related to the transfer of energy $\nu = E - E'$ and the transfer of 4-momentum $Q^2 = (k-k')^2$ from the projectile to the target by basic kinematics (neglecting terms with the proton rest mass M) by $x = Q^2 \cdot (2M\nu)^{-1}$ and is thus determined from the directly measured quantities Q^2 and ν. While Q^2 constitutes the parameter which controls the spatial resolution, x controls the dynamics of the proton structure.

the 2nd order resonances can be controlled by careful measurement and compensation of dispersion errors, by suppressing orbit oscillations to a level of 0.1 mm with a slow orbit feedback [18], by careful control of the angle of the beam orbit in the interaction point and by empirically optimized dispersion bumps. The 3rd order synchro-betatron resonances are generated as interference between synchrotron side bands of the integer and the half-integer resonance. They are controlled by compensation of higher-order chromatic effects by proper betatron-phasing of the high chromaticity interaction regions [19].

HERA is unique in colliding very different species of particles. In order to establish stable beam-beam operation, matching of the beam cross sections at the IP to ≤20% of the relative beam size is required. The bunch intensity of both beams is limited by the beam-beam effect suffered by the opposite beam. The vertical beam-beam tune shift parameters at two collision points reach levels of $\Delta\nu_{ye}$= 0.05 for leptons and around $\Delta\nu_{yp}$= 0.001 for protons. The proton beam-beam effect is a soft limit. Increasing beam-beam forces produce a gradual increase in experimental background by increased diffusion of protons into the beam halo. Orbit stability is therefore most critical. If the beam retracts from the collimators, diffusing particles fill the gap between beam edge and collimators and are lost on the subsequent approaches to the collimators [15]. The collimation system has a leakage of about 1% [16]. This causes a sudden increase in background which is not tolerable. Power supply ripple, magnet defects or mechanical vibrations enhance the diffusion. Mechanical vibrations of the IR magnets of more than a few μm are not tolerable. Cultural noise has been observed to have an impact on backgrounds.

The beam-beam limit for the lepton beam occurs at values of the vertical beam-beam tune shift of $\Delta Q_y \leq 0.1$. These are values which are typically achieved at conventional electron-positron colliders. However, the mechanism of limitation is quite different at HERA. The choice of betatron tunes is restricted to values close to the integer resonance in order achieve a high polarization of the lepton beam (see below). This region in tune space is governed by strong synchro-betatron resonances. The beam-beam limit of HERA thus occurs if the lepton beam tune spread overlaps with these resonances. The corresponding coherent motion leads to dramatic emittance growth of the proton beam emittance. This kind of indirect impact on the proton beam into itself has been predicted by simulations [17]. Due to the collision of different species and the restriction in choosing the betatron tunes of the leptons, HERA cannot exploit the focusing effects of the beam-beam force (dynamic beta) as in modern electron-positron colliders. A significant difference in specific luminosity is observed in HERA for positrons, $L_{sp}=1.5\cdot10^{30}\mathrm{mA^{-2}cm^{-2}s^{-1}}$ and electrons, $L_{sp}>2\cdot10^{30}\mathrm{mA^{-2}cm^{-2}s^{-1}}$ which is attributed to the fact the beam-beam force is focusing for electrons and defocusing for positrons. In order to mitigate this effect, the tunes for positron operation are chosen below the integer resonance (mirror tunes). In order to avoid lepton-proton orbital instabilities, the tunes for protons must be chosen below the integer resonance as well in this case. This way the luminosity with positrons can be improved significantly, but is still lower than with electrons (see Figure 1).

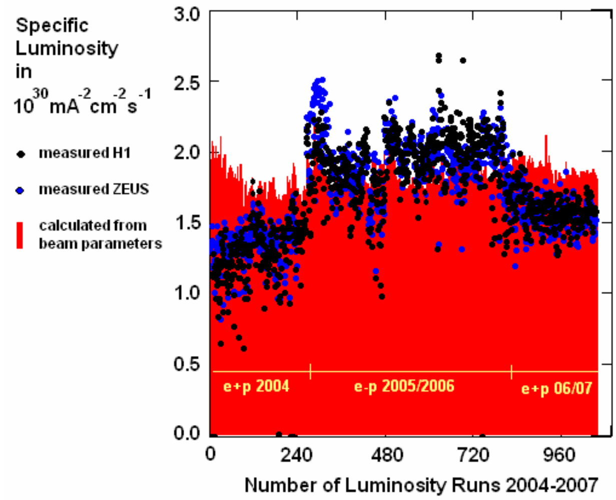

Figure 1: Specific Luminosity for HERA lepton proton collisions since 2004. The specific luminosity is significantly larger with electrons. Specific luminosity with positrons is recovered partly with tunes below the integer resonance in 2006/7.

Longitudinal spin polarization of the lepton beam is obtained by spin rotator magnets around the IRs, by spin transparent optics [20], by careful adjustment of the beam energy and by cancellation of detrimental harmonic content of spurious dipole errors [21] and by placing the betatron tunes as far as possible away from the half integer resonance. The polarization with three pairs of spin rotators reaches (50-60) % [22]. Colliding particles suffer a loss of (10-20) % of polarization. Optimum tunes for high luminosity conflict with high polarization and vice versa.

HERA OPERATIONAL ISSUES

Strong synchrotron radiation (30kW) in each interaction region, which is due to the magnetic separation of lepton and proton beams, generates considerable gas desorption and critical vacuum conditions. The desorbed gas particles become targets for the protons in the IR which causes critical background conditions. This is overcome by beam cleaning of the IR vacuum system, and good pumping in the IR, in particular also for high Z molecules such as Argon. Sufficient pumping is achieved by a combination of ion pumps, NEG pumps, Ti sublimation pumps, and pumping provided by the cold beam pipe of the superconducting separator magnets.

In order to control the high power synchrotron radiation beams of power, the beam orbits must be kept constant to sub-millimetre level during the entire operation cycle. The present HERA low beta quadrupole magnets, added during the 2001 upgrade are located inside the detector solenoid field and move by up to 1mm during the acceleration process. For this reason, a sophisticated orbit feedback has been implemented [30] that keeps the orbit within 0.1mm of a reference state which is interpolated between two reference states during acceleration and low beta squeezing and which recognizes and accommodates deliberate orbit changes for the sake of tuning. This sophisticated system is fully integrated in the automatic machine file handling system.

The availability of the large HERA accelerator complex was an important issue. In the last years HERA reached an availability of 72% of the scheduled time. The complicated injection, the slow acceleration and luminosity set up procedure required about 16% of the scheduled time so that the accelerator delivered luminosity for 56% of the time. These efficiencies have been achieved after high level of automatization of operations, and, more important, provisions of transient recording and long term archiving for all control points. This helps with quick trouble shooting and provides the base for error and performance analysis of the hardware components and for effective preventive maintenance. Preventive maintenance turned out to be particularly useful for increasing the availability of the more than 1200 power converters of HERA.

HERA STATUS AND PLANS

The HERA ep collider is presently operated with 920 GeV protons and 27.5 GeV positrons. The record peak luminosity with electron-proton operation is $L_{peak} = 5.1\cdot10^{31}cm^{-2}s^{-1}$ and the average luminosity production is $\approx 1\cdot pb^{-1}d^{-1}$. The peak luminosity in positron-proton operation is only 80% of the electron-proton operation, but the daily luminosity yield is about the same due to very stable conditions with positron running. Recent improvements include successful implementation and test of a broadband longitudinal damper system for the protons which provides proton bunch lengths of 12cm by suppressing coupled bunch instabilities [23]. A fast orbit feedback for the leptons has been implemented recently which is designed to reduce orbit oscillations with frequencies of up to 100 Hz to the 1 μm level at the IPs. The most important operating parameters are presented in Table 1. Figure 2 shows the HERA luminosity production in 2004-2006. After running with electrons since November 2004, positron-proton operation resumed in July 2006.

Before the end of HERA operation in June 2007, it is planned to operate HERA for three months with lower proton energy of 460 GeV for a luminosity of 10 pb^{-1}. In order to mitigate the stronger influence of the electron magnets on the proton beam and in order to achieve minimum beam-cross sections at the IP, the increased flexibility of the magnets for low energy operation has been fully exploited. As a result, low energy proton operation is possible without changing any magnet positions. A peak luminosity of $L = 1.47\cdot10^{31}cm^{-2}s^{-1}$ is expected for this mode of operation.

SELECTED HERA PHYSICS RESULTS

The HERA physics program started with a spectacular success. With a delivered luminosity of only 60 nb^{-1} in 1992, the total cross section of inelastically scattered 27.5 GeV electrons on 820 GeV protons plotted versus x revealed a dramatic increase of the density of proton constituents for x below 0.01 as shown in Figure 3 together with the data obtained by fixed target experiments ($x > 0.01$) for comparison. These results form the basis of our present understanding of the structure of the proton with a very large density of sea quarks and gluons which make up the 99% of the proton mass. Figure 4 summarizes the HERA measurements of the proton structure function F_2 versus Q^2 for fixed values of x.

Table 1: HERA Parameters in 2007

Parameter [Unit]	**Electro**	**Protons**
Beam Energy [GeV]	27.5	920 (460)
Particles per bunch [10^{10}]	≤ 3.68	≤ 8.75
Number of Bunches	184	180
Horiz./vert. Emittance [nm]	20 / 3	3.8 / 3.8
Bunch length [cm]	0.9	12
Vert./Hor. β at IP[cm]	26/62	18/245(36/490)
Beam Lifetime in collision	10-15	200
Longitudinal Polarization [%]	30-45	-
Peak Luminosity	$5\ (1.5)\cdot 10^{31}cm^{-2}s^{-1}$	
Average Luminosity	$1\ (0.25)\cdot pb^{-1}d^{-1}$	

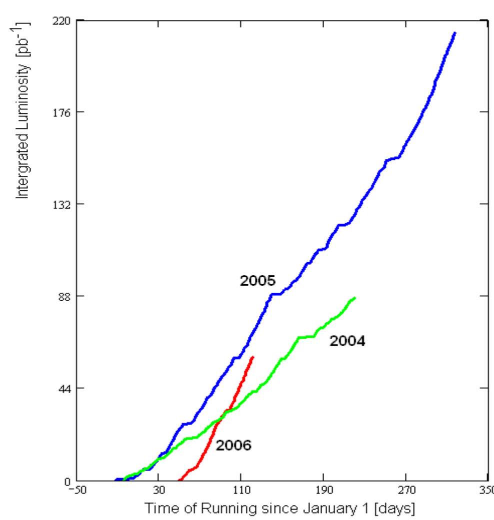

Figure 2: HERA luminosity accumulation 2004-2006

These measurements constitute the synopsis of the present understanding of the proton structure. The data reveal the spatial densities and the momentum distribution of quarks and gluons in the proton. The strong dependence on Q^2 (scaling violation) for small x is a consequence of short range quantum fluctuations of gluons into quark being resolved as the spatial resolution is increased.

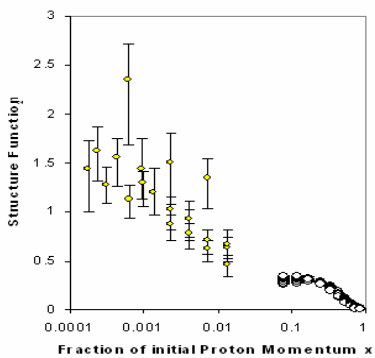

Figure 3: First measurement of ep scattering cross section versus x at HERA [24] including results of ref [4].

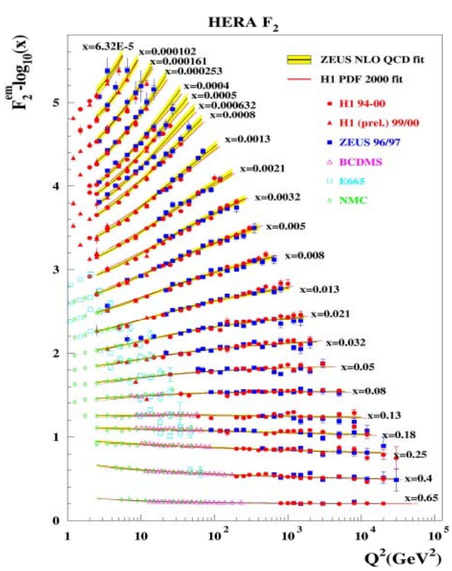

Figure 4: Proton structure function F_2 versus Q^2 in the range of $(1\text{-}10^5)$ GeV^2 for fixed values of x in the range of $0.65\text{-}6{\cdot}10^{-5}$ [25].

Another important part of the HERA physics program is measurements of the electro-weak interaction. According to electro-weak theory, electrons interact with quarks by exchanging either a photon, a neutral Z-boson or a charged W-boson. In ep scattering experiments, an electron is observed in the detector in the first two cases, also called neutral current events. The case of interaction via a W-boson, also called charged currents is characterized by the absence of an electromagnetic shower in the detector and missing transverse momentum because of an escaping neutrino. The scattering cross sections for Z and W exchange are proportional to $(Q^2+M_{W,Z}^2c^4)^{-2}$ thus are strongly suppressed by the large Z and W masses compared to electromagnetic exchange with a cross section proportional to Q^{-4}. HERA results on this topic are summarised in Figure 5. Plotted are the neutral and charged current cross sections versus Q^2 for proton electron and proton-positron scattering. All cross sections become comparable at $Q^2 \geq M_{W,Z}^2c^4$. Electron and positron cross sections for charged currents differ by a factor of two which is related to the u-d quark ratio of 2 and the helicity structure of the proton. Interfering γ and Z exchange reduces the cross section for proton-positron neutral current events as compared the proton-electron case. The measurements constitute a direct experimental verification of electro-weak theory.

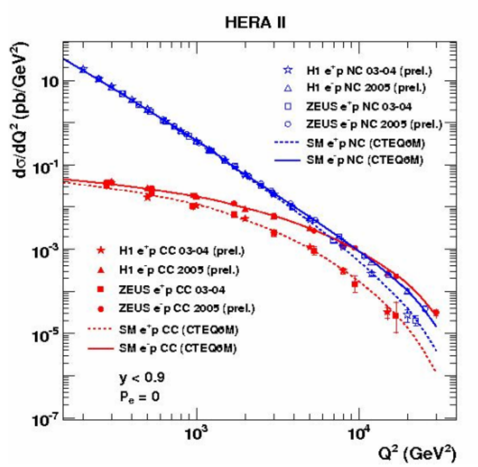

Figure 5: Charged (red) and neutral (blue) current cross sections of ep scattering at HERA [26] versus Q^2

At HERA, the coupling constant of the strong interaction α_s was measured with high precision. It can be extracted in numerous ways from ep scattering data, for example by detecting the relative cross section of ep scattering with one or two hadronic showers. The second hadronic shower arises from a decaying gluon emitted by the struck quark which has a probability proportional to α_s. The combination of all HERA data on α_s has yielded an error of less than 1% which is a significant improvement. Figure 6 shows a plot of α_s versus the energy $\mu = 1 / Q$. These data confirm the theory of asymptotic freedom, for which the Nobel Prize was awarded in 2004 [29] to David Gross, David Politzer and Frank Wilczek.

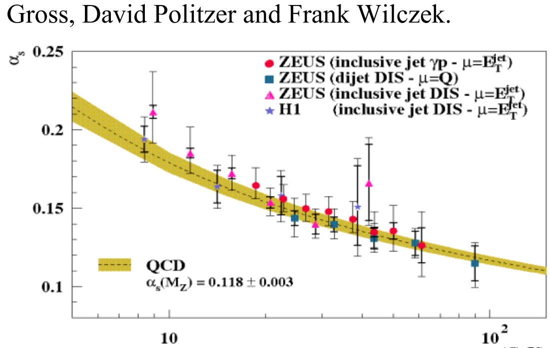

Figure 6: Measurements of α_s versus μ, the energy in the system of interacting quarks from HERA [27]

Electro-weak theory and the standard model predict that a W-boson will couple only to a left-handed electron. The polarization dependence of the charged current cross section for positrons has the opposite sign. Recent HERA data confirm these predictions with very high accuracy as shown in Figure 7 which depicts the charged current cross section for electron-proton and positron proton collisions as a function of polarization.

The examples given above represent only parts of the physics investigated at HERA. Note that the important results from the non-collider, fixed target experiments HERMES and HERA-B are omitted.

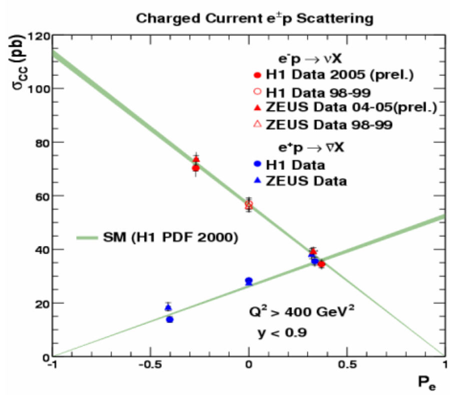

Figure 7: Measurements of the charged current cross section in HERA versus lepton beam polarization [28]

CONCLUSIONS

The HERA lepton proton collider which is being successfully operated since 1992 is soon coming to a conclusion. The achieved peak luminosity which was reached after an upgrade program exceeded the design luminosity by a factor of 3.4 and the luminosity production reached about 1 pb^{-1} per day. HERA is expected to produce a total luminosity of 850 pb^{-1} until July 2007. Most of the physics experiments which motivated the construction of this complicated machine were successfully addressed in the physics program. Some of the results obtained at HERA raised new questions which are considered to be investigated at a possible future lepton proton collider which needs a larger centre of mass energy such as the recently discussed lepton-hadron collider in the LHC tunnel [31].

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