HERA Operations and Physics

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Abstract

HERA is designed to collide 820 GeV protons with 30 GeV electrons in 4 interaction regions spaced equidistant around its 6.3 km circumference. The initial commissioning of the HERA collider was successfully completed in the summer of 1992 with the start up of the experimental programme. In the talk I'll first focus on the performance of the accelerator and on the operational experience. At present two general pupose detectors H1 and ZEUS have been installed in two of the four interaction regions of HERA. I'll briefly review the layout and the performance of these detectors and then report on the first physics results. At the end I'll comment on a possible fixed target programme at HERA using targets installed in the circulating electron and proton beams.

I. INTRODUCTION

Last year the electron-proton collider HERA [1] and its large multipurpose detectors H1 [2] and ZEUS [3] made the transition from a virtual to a real source of data on electron-proton interactions in a new, greatly expanded kinematic region.

The HERA project is a truly international effort. It was built within the framework of a collaboration where institutions in 10 countries contributed either components built at home or delegated skilled manpower to work on the project at DESY. Also the large detectors H1 and ZEUS have been built and are exploited by international collaborations. Only some 25% of the 750 physicists presently involved in the programme are from German institutions while the remainder comes from 69 institutions in 15 countries.

Data taking by H1 and ZEUS started at the end of May 1992 and continued to November 8, with a 7 weeks shutdown in August and September. The remaining time until early December was used for machine studies.

During this period a total, integrated luminosity of 58 nb^{-1} was delivered to each of the experiments and data corresponding to some 30 nb^{-1} were recorded.

Both experiments functioned from the outset and they have already analyzed and published a series of papers on deep inelastic scattering at low x [4,5], on photo production [6,7] and on the search for new particles [8,9].

The winter shutdown 92/93 has been used to upgrade the control system and to prepare HERA for multibunch operation. Improvements to the detectors and to the data acquisition system have also been made.

II. HERA

2.1 Overview

HERA is made of two independent accelerators designed to store respectively 820 GeV protons and 30 GeV electrons and to collide the two counterrotating beams head on in four interaction regions spaced equidistant around its 6.5 km long circumference.

The layout of the accelerator complex is shown in Fig. 1.

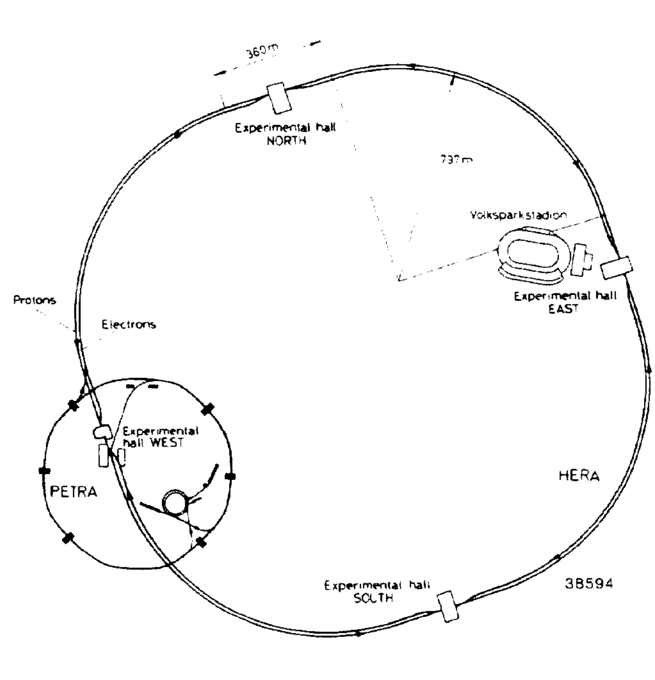

Fig. 1.
The layout of the HERA accelerator complex.

The general purpose detectors H1 and ZEUS are installed in straight section North, respectively South. In straight section East the HERMES experiment, designed to scatter longitudinally polarized electrons on polarized H, D and He^3 targets installed in the internal electron beam, will be installed. An experiment, designed to measure the CP violation in the $b\bar{b}$ system, using an internal wire target in the halo of the proton beam, is being considered. If approved, this experiment will be installed in straight section West.

2.2 The HERA Electron Ring

The injection into the electron ring works well with an efficiency of roughly 80%.

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The design energy of 30 GeV was reached using the normal and the superconducting RF system [10] in parallel. However, to have sufficient safety margin in the case an RF station is lost, the HERA operating energy was chosen to be 26.7 GeV.

The superconducting RF system is made of 16 four cell superconducting 500 MHz cavities assembled pairwise into 8 cryostats. The S.C. RF system has now been in operation for some 10000hrs. It has been very reliable and it provides nearly a third of the total circumferential voltage of 160 MV.

During the 1992 run the maximum current which could be stored with lifetimes on the order of a few hours was limited to roughly 3 mA at 26.7 GeV. This limit may have been due to dust particles trapped in the strong field of the circulating electron beam. Using the proton loss monitors, the beam loss was traced back to two vacuum chambers hit by synchrotron radiation from a reverse bend magnet. Replacing these vacuum chambers seems to have solved the problems. A total of 27 mA have now been stored in 100 bunches compared to the design value of 60 mA in 210 bunches.

A 5 MHz bandwidth multibunch feedback system needed to control coupled bunch instabilities, has been installed and successfully commissioned.

The observed transverse beam polarization [11] is shown in Fig. 2 as a function of synchrotron tune and beam energy. The buildup time of 25.8 min is consistent with the measured masimum beam polarization of 58 ± 5%. A high polarization can be achieved routinely.

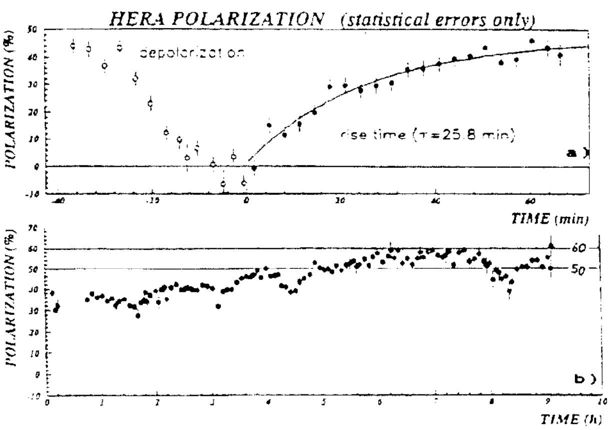

Fig. 2.
a) The transverse electron beam polarization as a function of time. The build up of transverse polarization is easily seen.
b) Beam polarization during a long storage.

2.3 The HERA Proton Ring

The operation of the HERA proton ring has been greatly eased by the reliability and the stability of the accelerator. In particular the refrigerator and the superconducting magnet system have been extremely reliable.

A total of 2156 superconducting magnets and correction coils are installed in the HERA proton ring. None of the magnets in the ring had to be removed during 2½ years of operation. Only a few beam induced and no spurious quenches have been observed.

The field quality of the superconducting magnets is seriously affected by persistent magnetization currents. However, the strength of persistent current multipoles vary little from magnet to magnet and are well reproducible and can hence be compensated by correction coils wound directly on the dipole and quadrupole beam pipes.

In order to determine the required strength of the correction elements at injection and during acceleration, the dipole and sextupole fields are measured continously in two superconducting reference magnets, powered in series with the ring magnets.

The proton beam lifetime at injection is on the order of 10hrs after a careful cycling of the magnets and after correction of persistent current multipoles using the scheme outlined above.

The geometric acceptance is larger than 2 π mm mrad and the dynamic acceptance is of order 1 π mm mrad. The design value of the unnormalized 2σ transverse emittance is 0.5 π mm mrad at injection. Including magnet cycling the proton filling time is roughly 1 hour.

The proton injection efficiency is of order 95%.

Only small beam losses occur during the acceleration cycle from 40 GeV by 820 GeV. The single bunch current is limited to $4 \cdot 10^{10}$ protons/bunch compared to the design value of 10^{11} protons/bunch. So far at most 160 proton bunches with low currents have been stored. With 90 bunches a total of 17 mA have been stored compared to the design value of 160 mA in 210 bunches.

The measured proton lifetime at 820 GeV for 10 bunches each with 25% of its design intensity is several weeks. The measured normalized 2σ emittance is on the order of 25 π mm mrad in agreement with the design value.

2.4 Colliding Beams

The luminosity is measured using the bremsstrahlungs reaction e+p=e+γ+p with the electron and the photon detected in coincidence. A maximum luminosity of $2.5 \cdot 10^{29}$ cm^{-2}s^{-1} with 9 bunches in each beam has been observed corresponding to 25% of the design luminosity per bunch crossing. The observed proton tune shifts are close to their design values of 0.001, wheras the electron tune shifts are a factor of two below design.

During the 1992 run the number of electron bunches was limited to 10 by the maximum electron current which could be stored in the ring. This limit has now been raised to 27 mA corresponding to 100 bunches at design current. A total of 160 proton bunches has been stored in HERA. The number of protons per bunch has so far been limited by the proton injectors and by losses during beam transfers to 25% of the design value.

In the 1993 run we thus expect to be able to raise the number of colliding bunches to 100 in each ring with the same bunch currents as in 1992. This would yield a peak luminosity of order $2 \cdot 10^{30} cm^{-2} s^{-1}$.

The proton beam lifetime is strongly dependent on the transverse dimensions of the electron beam and is maximized when the cross sections of the two beams match at the interaction point and the beams are well centered. The values of the β-functions at the interaction point has been adjusted to match the transverse size of the two beams. Under these conditions the proton beam lifetime is of order 50 hours compared to a typical 4 hour lifetime of the electron beam. Thus in general protons are filled once every 24 hours wheras electrons are dumped and reinjected every 4 to 5 hours.

The stored currents, luminosity and the specific luminosity as measured using the H1 luminosity detector is plotted in Fig. 3.

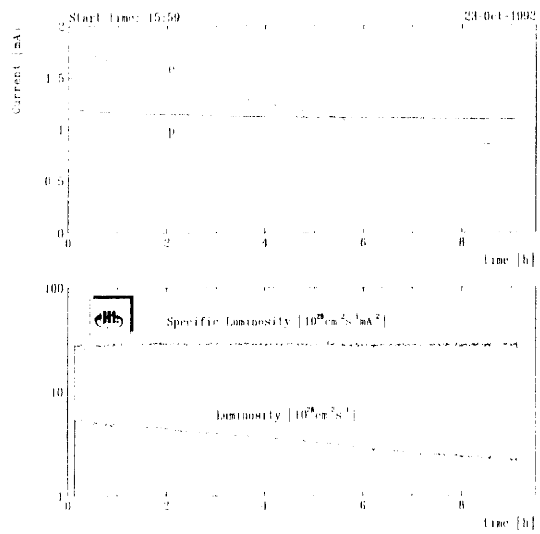

Fig. 3.
The stored currents, the luminosity and the specific luminosity as measured by the H1 detector as a function of storage time.

The specific luminosity, defined as $L / I_p \cdot I_e$ is a measure of beam overlap and transverse beam dimensions. Wheras the luminosity drops by a factor of 2 during the 9 hours storage time the specific luminosity remains nearly constant. This demonstrates the stability of the two rings and that the proton beam emittance remains constant over the fill. It also demonstrates that the proton beam emittance is not strongly influenced by noise in the electron beam - i. e. there is negligible cross talk between the two beams.

III. THE PHYSICS

3.1 Introduction

In a deep inelastic electron-proton collision the incoming electron interacts directly with one of the quarks in the proton by means of a spacelike current, charged or neutral. This results in a very simple final state topology. The struck quark will materialize as one or several jets of hadrons whose momentum components transverse to the beam axis are balanced by the transverse momentum of the final state electron (or neutrino). The remainder of the proton will appear as a sharply collimated jet of hadrons travelling along the initial proton direction.

This event topology is indeed observed at HERA as shown for a neutral current event $e+p \rightarrow e+X$ in Fig. 4.

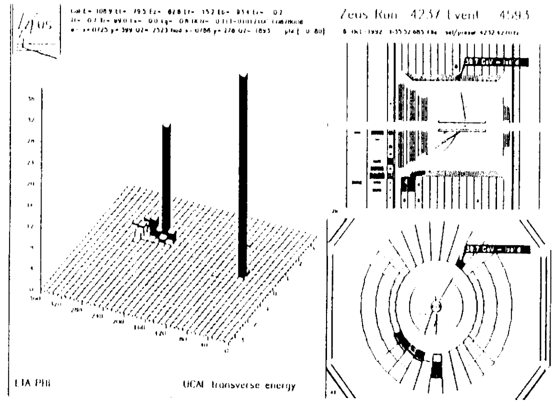

Fig. 4.
Deep inelastic neutral current event observed by the ZEUS detector at HERA.

A deep inelastic process is described in terms of

$$-Q^2 = (k - k') \quad \text{and} \quad \nu = {}^{pQ}\!/_{mp}$$

where the fourmomenta of the incident lepton, the final state lepton and the incident proton are denoted by k, k′ and p. Often the scaled variables $x=Q^2/2m\nu$ and $y={}^{\nu}\!/_{\nu_{max}}$ are used. With HERA, present maximum values of Q^2 = 600 GeV^2 and ν = 400 GeV which are available in fixed target experiments can be extended by nearly two orders of magnitude to Q^2 and ν values of order 30000 GeV^2 and 40000 GeV.

A complete up-to-date discussion on HERA physics can be found in reference 12.

3.2 Physics Results

3.2.1 Deep inelastic neutral current events

The kinematic region in 1/x and Q^2 available to HERA and to a 600 GeV muon beam incident on a proton at rest is plotted in Fig. 5.

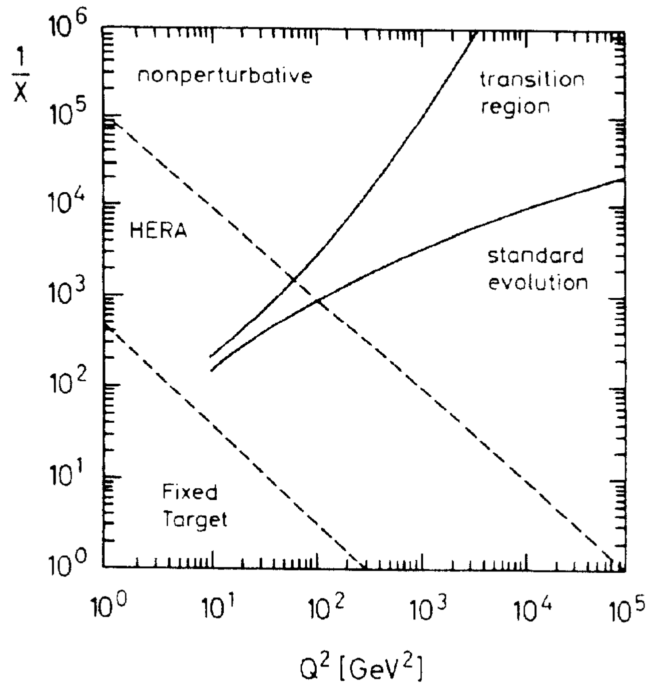

Fig. 5.
The kinematic region in 1/x and Q^2 available at HERA and with a 600 GeV muon beam incident on protons at rest. The perturbative and non-perturbative domains are separated by a transition region.

The kinematic region can be divided into three main areas: a QCD perturbative region located in the lower right hand corner at moderate x and large Q^2, a non-perturbative region in the left hand upper corner and a transition region in between.

At low x-values the structure functions are dominated by the gluon distribution function $xG(x,Q^2)$. Extrapolating $xG(x,Q^2)$, as determined in the perturbative region, towards small x for constant Q^2 leads to a steeply increasing function that violates unitarity. Since the gluon density increases with 1/x, the gluon-gluon interaction can no longer be neglected although the gluon-gluon coupling $\alpha_s(Q^2)$ is still small. In this transition region one may be able to use the parton language and the behaviour of the structure functions may be described by adding a recombination term to the perturbative evolution equations.

A further extrapolation in 1/x yields a very dense partonic system. Although the coupling constant is still small the effective interactions are strong due to the high parton densities. In this region the perturbative approach breaks down and the parton picture may not be applicable.

At HERA the structure functions can be explored down to x-values of 10^{-4}, a factor of 100 below the region available in fixed target experiments. Both experiments reports data on $e+p \rightarrow e+X$. The details of the experiments and the data reduction can be found elsewhere [4,5]. The formfactor $F_2(x_1Q^2)$ measured by the H1 collaboration is plotted in Fig. 6 versus x for Q^2 = 15 GeV^2 and Q^2 = 30 GeV^2. Note the rise in the formfactors towards lower values of x, reflecting the increase in gluon density.

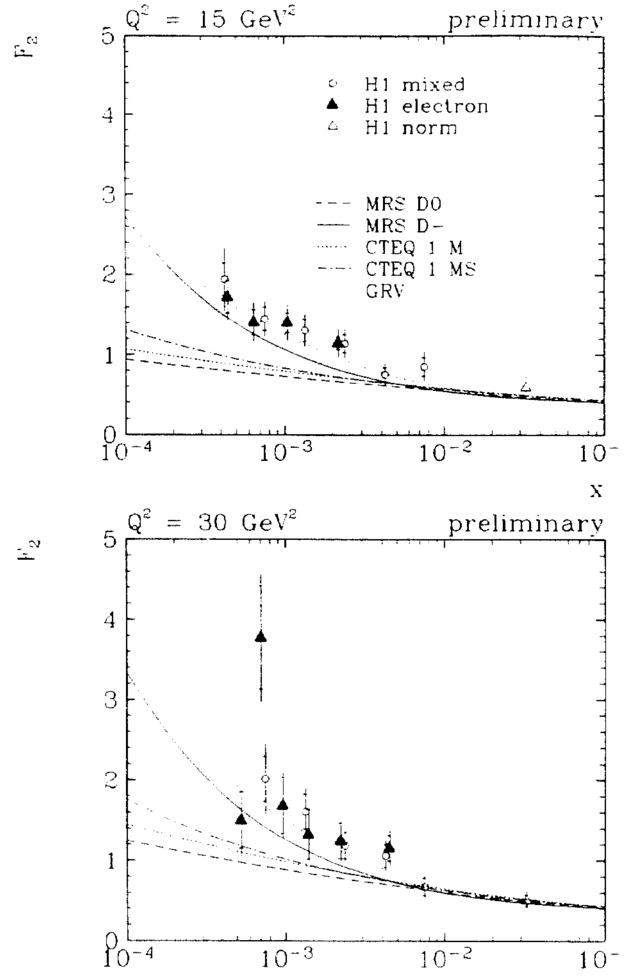

Fig. 6.

The formfactor $F_2(x_1Q^2)$ plotted versus x for Q^2 = 15 GeV^2 and Q^2 = 30 GeV^2. The data are from the H1 collaboration.

3.2.2 Photoproduction

The photon is a particle with unique properties. On the one hand it is a fundamental gauge boson with well defined couplings to basic fermions and gauge bosons, on the other hand, part of the time the photon behaves like a strongly interacting vector boson. For larger values of $p_\perp$, the photon interacts indeed dominantly via its hadronic constituents, quarks and gluons, yielding resolved photon events. The total photon-photon section has previously been studied for center of mass energies up to 18 GeV. Both experiments reports [6,7] data on the total photoproduction cross section:
H1 quotes at a c. m. of 200 GeV:

$$\sigma_T(\gamma p) = (150 \pm 15(stat.) \pm 19(syst.))\mu b$$

ZEUS reports at a c. m. of 210 GeV:

$$\sigma_T(\gamma p) = (154 \pm 16(stat.) \pm 32(syst.))\mu b.$$

The data are in good agreement with predictions based on Regge models and show an increase with energy similar to that observed in the p-p total cross section.

The hadronic character of the photon can also be observed directly in the final state. A pointlike interaction between the quark and the photon will in general yield two jets of hadrons from quark fragmentation. If the photon interacts via one of its hadronic constituents then we will observe, in addition to the two hadron jets at large angles also a jet along the incident electron direction resulting from the fragmentation of the remains of the photon. Lego plots, showing the two classes of events, are depicted in Fig. 7.

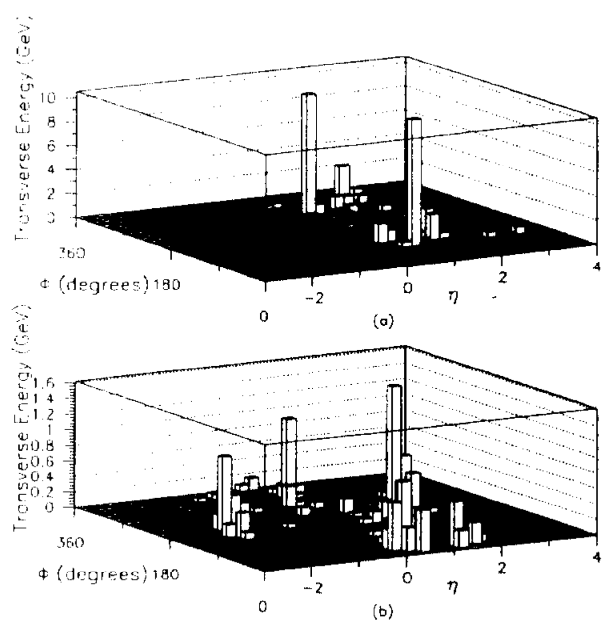

Fig. 7.
Deposited energy in photoproduction events as a function of q and $\eta = -\ln\tan\theta/2$ measured by the ZEUS collaboration.

The occurance of resolved photon events have been confirmed by a detailed analysis [6,7].

3.2.3 Search for new particles

HERA is ideally suited to search for leptoquarks, exotic particles with mixed electron baryon quantum numbers. Leptoquarks occur naturally in composite models in which leptons and quarks are made of common building blocks and in various technicolour models. Particles with mixed baryon-lepton quantum numbers also occur in certain classes of supersymmetric models. The favoured leptoquark decay mode is into an electron and a quark jet.

Leptoquark production will thus lead to a neutral-current type final state and will show up in the x-distribution of neutral-current events as a bump at
x=(Mass of Leptoquark)^2/(Center of Mass energy)^2.

Both groups quote mass limits [8,9] as a function of the electron-quark coupling constant. Assuming this coupling strength to be of order $e = \sqrt{4\pi\alpha}$, the experiments find that the mass of an (eu)-bound state must be above roughly 170 GeV depending somewhat on the helicity structure of the eu coupling.

3.3 Fixed target experiments

HERA offers the intriquing possibility of carrying out high luminosity, high duty cycle experiments by using internal targets in both the electron and the proton beam.

The aproved HERMES experiment plans to use the longitudinally polarized electron beam incident on a polarized H, D or He^3 gas jet target to investigate the nucleon spin structure. Given the good duty cycle the experiments can measure the scattered electron in coincidence with the hadronic final state.

The ARGUS collaboration are investigating the possibility of doing fixed target b-physics at HERA by positioning a thin wire target in the halo of the proton beam. Indeed, early studies using an internal target at HERA have given promising results. Although the primary goal is to measure the CP-violating parameters in $B^0 \rightarrow J/\psi K^0_s$ channel a series of other experiments on B physics can also be carried out.

IV. REFERENCES

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