The ZEUS experiment at the e-p collider HERA

Marco Schioppa
Universitá della Calabria

August, 1994

Abstract

Electron - proton interactions have been one of the most fruitful ways to explore the structure of matter. The storage ring HERA, which produces collissions between 820 GeV protons and 30 GeV electrons, allows us to test electron and quark substructures with an accuracy of about 10^{-16} cm. This is two orders of magnitude smaller than previous experiments.

Careful measurements of the structure functions will provide stronger test of QCD for Q^2 values as high as $40,000 GeV^2$.

1 Structure of the proton

According to the electro-weak theory, the e-p interaction is described by an exchange of a virtual boson $\gamma, Z^0, W^{\pm}$. The basic deep inelastic scattering (DIS) is illustrated in fig. 1. The transfered momentum from the electron to the hadron system represents the momentum of such boson. The accuracy Δr on which the virtual boson "explores" the proton structure is given by the Heisenberg's uncertainty principle:

$$\Delta r \cdot q \simeq 1.$$

It means that increasing q, the resolution becomes better and better and we can explore a proton structure at smaller distances.

2 Electro magnetic form factors

The differential elastic diffusion cross section for point-like particles of spin $\frac{1}{2}$ is described by:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 sin^4(\frac{\theta}{2})} \left(\frac{cos^2\frac{\theta}{2}}{1 + 2\frac{E}{M} sin^2\frac{\theta}{2}} \right) \left(1 + \frac{q^2}{2M^2} sin^2\frac{\theta}{2} \right)$$

Figure 1: Diagram for *ep* scattering.

where $q^2 = |\vec{k} - \vec{k}'|^2 - (E - E')^2$ represents the square momentum transfered from the lepton, of energy E and momentum k, to the target of mass M. The scattered lepton at the angle θ has energy E' and momentum k'.
Experimentally, we observe that by increasing q, the transfered momentum from the electron to the proton, the differential cross section becomes smaller than the theoretical prediction. This means that the target (the proton) has *finite dimensions.* The right formula that describes correctly the elastic scattering of electrons on protons is the Rosenbluth one:

$$\left.\frac{d\sigma}{d\Omega}\right)_R = \frac{d\sigma}{d\Omega}\left[A(q^2) + B(q^2)tg^2\frac{\theta}{2}\right]$$

where:

$$\begin{aligned} A(q^2) &= F_1(q^2) + \frac{q^2}{4M^2}F_2(q^2) \\ B(q^2) &= \frac{q^2}{4M^2}\left[F_1(q^2) + F_2(q^2)\right] \end{aligned}$$

The functions $F_1(q^2)$ and $F_2(q^2)$ are called *electromagnetic form factors* of the proton.

3 Structure functions

In $e - p$ experiments, besides the elastic scattering we meet reactions with production of particles. The *inclusive reactions*

$$ep \longrightarrow eX$$

Figure 2: Inclusive reaction in $e - p$ experiments.

are of particular importance to study the hadron structure. The diagram of such reactions is illustrated in fig. 2. The differential cross section for this kind of reactions is described by:

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{q^4}\left[cos^2\frac{\theta}{2}W_2(q^2,\nu) + 2sin^2\frac{\theta}{2}W_1(q^2,\nu)\right]$$

where $\nu = \frac{\vec{p}.\vec{q}}{M} = E - E'$ represents the transfered energy from the electron, of energy E, to the proton system, of mass M.

The functions W_1 and W_2 are called *structure functions.* They represent the analogous of the form factors in the inelastic interactions: their Fourier anti-transform describes the instantaneous spatial distribution of charge and current inside the target.

Experimentally, we find that for high transfered momentum q, the cross section does not change with q^2 and ν. In this case, we talk about *scale invariance.*

Bijorken has shown that:

$$\begin{aligned} \lim_{q^2,\nu\to\infty} MW_1(q^2,\nu) &\longrightarrow F_1(x) \\ \lim_{q^2,\nu\to\infty} \nu M_2(q^2,\nu) &\longrightarrow F_2(x) \end{aligned}$$

where $x = -q^2/2M\nu$.

To explain the scaling, Feynman, Bijorken et al. developed the theoretical model named *parton model.* According to this model, the nucleon consists of massive point-like particles non interacting between them. Then, for deep inelastic scattering, the boson interacts directly with the partons, and the cross section can be expressed as a function of usual form factor employed in elastic processes.

But it is not all. The QCD predicts, by means of Altarelli - Parisi equation,

Figure 3: The structure function F_2 for protons as measured by SLAC and BCDMS and as expected from HERA experiments.

that the parton distribution into the proton changes with increasing of q^2 (scaling violation). It means that the boson, if q is big enough, can test the parton and gluon distribution into the proton. In this case the structure function $F_1(x)$ and $F_2(x)$ become $F_1(x, q^2)$ and $F_2(x, q^2)$ respectively. The structure functions measured in previus experiments have been extrapolated by QCD evolution to the HERA regime (fig. 3).

Careful measurement of the structure functions at HERA can add important informations for our understanding on the gluon and parton distribution into the nucleon.

Figure 4: Diagram for DIS in lowest order.

4 DIS at HERA

For Q^2 much larger than the mass squared of the proton, the proton can be thought of as a group of quasifree constituents - quarks, gluons... - one of which interacts with the virtual boson while the rest of group (=proton remnant) moves on unperturbed. The basic $e-p$ process to test the structure of the proton is shown in fig. 4. The interaction can be described in terms of the usual kinematic variables which assume, for 30 GeV electrons and 820 Gev protons, the follower form:

e	$=$	$(0,0,-E_e,E_e)$	four momentum of incoming e
p	$=$	$(0,0,E_p,E_p)$	four momentum of incoming p
θ			angle of scattered electron e'
s	$=$	$\|e+p\|^2 = m_e^2 + m_p^2 + 2E_eE_p - 2\vec{e}\vec{p}$	square of total c.m. energy
	$\simeq$	$4E_eE_p$	
Q^2	$=$	$-q^2 = -\|\vec{e}-\vec{e'}\|^2$	square of four momentum transfer
	$=$	$-m_e^2 - m_{e'}^2 - 2E_eE_{e'} + 2\vec{e'}\vec{e}$	
	$\simeq$	$-2E_eE_l(1-cos\theta) = 4E_eE_l sin\frac{\theta}{2}$	
Q^2_{max}	$=$	s	maximum possible value
ν	$=$	$q \cdot p/m_p$	energy of current in p rest system
ν_{max}	$=$	$\frac{s}{m_p}$	maximum energy
y	$=$	$\frac{\vec{p}\vec{q}}{\vec{p}\vec{e}} = \frac{\nu}{\nu_{max}}$	fraction of energy transfer
x	$=$	$\frac{Q^2}{2\vec{p}\vec{q}} = \frac{Q^2}{y \cdot s}$	Bjorken scaling variable

where the electron and proton masses, m_e and m_p have been neglected. The square of four momentum transfer assumes its maximum value when the outcoming lepton is scattered at $\theta' = 180^o$ ($Q^2_{max} = 4E_eE_p = 98400 GeV^2$). The variables x and y define respectively the fraction of the proton momentum carried by the struck quark, and the fraction of energy transfered to the proton in its rest system.

For fixed c.m. energy, inclusive scattering is described completely by two variables for which e.g. x and Q^2 can be chosen. The same variables describe the lowest order process where the electron scatters elastically on a free constituent of the proton (see fig. 1).

Figure 5: NC event.

Figure 6: CC event.

In the process mediated by neutral bosons γ or Z^o (fig. 5) these variables can be determined either from the energy and angle of the scattered electron, or from the final state hadron system, or from a mixture of them. The variables which are mostly used in the neutral current process are:

$$\begin{aligned} Q^2 &= 2E_eE_{e'}(1+cos\theta) \\ y &= 1-\frac{E_{e'}}{2E_e}(1-cos\theta). \end{aligned}$$

In the process mediated by charged bosons $W^{\pm}$ (fig. 6) only the hadron shower X is accessible for measurement. In order to describe these process, the hadron variables can be determinated approximately by summing the energies (E_h) and transverse ($p_{\perp h}$) and longitudinal momentum (p_{zh}) of all finale state by using the method of Jacquet-Blondel (1979):

$$\begin{aligned} Q^2_{JB} &= |\sum_h p_{\perp h}|^2/(1-y_{JB}) \\ y_{JB} &= \sum_h (E_h - p^z_h)/2E_e. \end{aligned}$$

	HERA	pre-HERA
$s(GeV)$	10^5	10^3
maximum practical $Q^2(GeV^2)$	$4 \cdot 10^4$	$4 \cdot 10^4$
$\Delta(cm^{-1})$	$1 \cdot 10^{-16}$	$1 \cdot 10^{-15}$
$\nu_{max}(GeV)$	52 000	500
maximum x at $Q^2 = 10GeV^2$	$1 \cdot 10^{-4}$	$1 \cdot 10^{-2}$

Table 1: Kinematic region accessible at HERA ($E_e = 30GeV$, $E_p = 820GeV$).

5 Kinematic regime of HERA

In table 1 is shown the kinematic ranges accessible at HERA and in previous lepton-nucleon scattering experiments. The maximum energy transfer and the Q^2 domain over which lepton nucleon scattering can be measured is increased by two order of magnitude respect the previous experiments.

6 Cross section for DIS

Neutral and charged current cross section are related to the structure function F_i of the proton. For NC process ($ep \rightarrow eX$) we have:

$$\frac{d^2\sigma(\gamma + Z^o)}{dQ^2dx} = \frac{2\pi\alpha^2}{xQ^4}\left[y^2xF_1(x,q^2) + (1-y)F_2(x,Q^2) + \frac{y-y^2}{2}xF_3(x,Q^2)\right].$$

The F_3 term measures parity violating contributions which arise from Z^o exchange. It is significant only when Q is comparable to or larger than the Z^o mass.
For CC process ($ep \rightarrow \nu X$) we find:

$$\frac{d^2\sigma(W)}{dQ^2dx} = \frac{G_F^2}{\pi x}\frac{M_w^2}{Q^2} + M_W^2\left[y^2x\mathcal{F}_1(x,Q^2) + (1-y)\mathcal{F}_2(x,Q^2) + \frac{y-y^2}{2}x\mathcal{F}_3(x,Q^2)\right]$$

where G_F is the Fermi coupling constant, $G_F = 1.02 \cdot 10^{-5}/m_p^2$.
The main difference between the NC cross section from photon exchange and the CC cross section from W exchange is due to the different propagator terms:

$$\frac{d^2\sigma(W)}{d^2\sigma(\gamma)} \approx \left[\frac{Q^2}{Q^2 + M_w^2}\right]^2.$$

The structure function from NC and CC scattering are in principle indipendent. They can be related via quark-parton model (QPM). The QPM prediction for F_2 for the case of photon exchange is:

$$F_2^{ep\rightarrow eX}(x) = \sum_q e_q^2 xq(x) = x\left[\frac{4}{9}u(x) + \frac{4}{9}\overline{u}(x) + \frac{1}{9}d(x) + \cdots\right].$$

Since only pointlike spin $\frac{1}{2}$ constituents contribute the two structure function F_1 and F_2 are correlated by the Callan-Gross relation (1969): $F_2(x, Q^2) = 2xF_1(x, Q^2)$. Including Z^o exchange the QPM leads to the following expressions (see Ingelman and Rückl 1987):

$$\begin{aligned} F_2^{ep\to eX}(x) &= 2xF_1 = \sum_q x(q+\overline{q})A_q(Q^2) \\ xF_3^{ep\to eX}(x) &= \sum_q x(q-\overline{q})B_q(Q^2). \end{aligned}$$

At energies well above flavour thresholds, the corrisponding QPM expressions for CC case are (see Rückl 1987):

$$\begin{aligned} \mathcal{F}_2^{ep\to \nu X}(x) &= x\mathcal{F}_1 = x\left[u(x)+c(x)+\overline{d}(x)+\overline{s}(x)+\cdots\right] \\ x\mathcal{F}_3^{ep\to \nu X}(x) &= x\left[u(x)+c(x)-\overline{d}(x)-\overline{s}(x)+\cdots\right]. \end{aligned}$$

Structure function measurements at a given value of Q^2 can be extrapolated to other Q^2 values by QCD evolution with the help of the GLDAP formalism (Gribov-Lipatov-Dokshitze-Altarelli-Parise). In the derivation of the evolution equations $ln\frac{1}{x}$ terms are neglected over lnQ^2. While this is justified for the range $x > 10^{-2}$ covered by fixed target experiments it may not be so for x value small as 10^{-4} accessible at HERA. In fig. 7a,b are shown the number of events expected from NC and CC scattering at $Q^2 > 1000GeV^2$ for an integrate luminosity of $500pb^{-1}$.

In order to know the right parton and gluon distributions in a proton we need to take recourse to data. The average momentum fraction of the sea quarks is expected to be smaller than that of gluons and the latter to be smaller than that of valence quarks. The HERA's experiments can significantly improve our understending about the proton structure.

7 Heavy quark production at HERA

The quantum parton model predicts, for events with heavy quarks in the final state (fig. 8a), a cross section smaller than boson gluon fusion prediction (fig. 8b).

The answers that the study of heavy quarks at HERA should give us are mainly related with the following questions:

- the mechanism of the heavy quark production, which is not clear yet;
- the identification of the process with heavy quarks can allow us to measure the gluon structure functions in a kinematic region never investigated before.

Figure 7: Events numbers for NC and CC scattering at HERA calculated with LEPTO and EHLQ (Eichten et al. 1988) structure functions.

Figure 8: Diagrams for a) QPM process, b) BGF process.

Circumference of HERA tunnel	6336 m
Depth under ground	10 - 25 m
Nominal energy for p	820 GeV
Nominal energy for e	30 GeV
Center of mass energy	314 GeV
Magnetic bending field for e	0.164T
Magnetic bending field for p	4.682T
Circulating current I_e	60 mA
Circulating current I_p	160 mA
Beam size at IP for e	0.3x0.04x7.8 mm
Beam size at IP for p	0.32x0.1x150 mm
Nominal luminosity per IP	1.5 $10^{31} cm^{-2} s^{-1}$
Specific luminosity	3.3 $10^{29} cm^{-2} s^{-1} mA^{-2}$
Maximum number of e bunches	210
Maximum number of p bunches	210
Bunches distance	28.8 m (96 ns)
Cost of the HERA collider	$\sim$ 1000 million D.M.

Table 2: HERA main general parameters

8 Electron - Proton collider HERA

The layout of HERA is shown in fig. 9. Two separate magnet system guide the e and p beams around the 6.3 km long ring. The proton injection starts (see fig. 10) with negative hydrogen (H^-) from the 50 MeV Proton Linac, followed by acceleration in the proton synchrotron *DESY III* up to 7.5 GeV. From here, protons are transfered via *PETRA* at an energy of 40 GeV to the *HERA* proton storage ring.
The electrons are preaccelerated first in a Linac accelerator *Linac I* at 220 MeV and at *DESY II* up to 7.5 GeV. The particles are then accelerated in *PETRA* to an energy of 14 GeV and injected into HERA.
Table 2 shows some of the parameters of HERA collider. There are four experimental halls, two of which are accupied by H1 and ZEUS. The third has been allocated to HERMES.

9 ZEUS detector

HERA e-p collider produces a large variety of reaction with widely energy spectrum. This feature together with the require for detecting and identifying all particles that appear in e-p collision (such as electron, neutrino, photon, etc.) places different requirements on the detector. To accomplish all HERA physics

Figure 9: Layout of HERA electron-proton collider.

Figure 10: The injection system for HERA.

Figure 11: Schematic view of the central part of the ZEUS detector.

program the detector must be able to assure, over all solid angle, a very good charge particles momentum measurement, a precise and hermetic electromagnetic and hadronic calorimeter (with the calibration known at the 1-2% level) and the muon identification. Another big challenge comes from the background events produced for instance by beam proton on the beam pipe wall or in the residual gas. The high background rate (10-100 KHz) combined with the short bunch crossing interval forced the HERA experiments to develop novel concepts of electronic read out and triggering.

The ZEUS collaboration consists of about 400 physicists from 12 countries and 50 institutes.

A view of the central part of the ZEUS detector is shown in fig. 11. Charge particles are tracked by the inner tracking detector which operate in 1.43T magnetic field provided by a thin superconductive solenoide. The inner tracking detector consists of a very precise cylindrical drift chamber (VXD) surrounded by a central tracking detector (CTD), which consists of 72 cylindrical drift chambers layers. Using the combined data from both chambers the primary vertex position resolution is 0.6 cm in the z direction and 0.1 in the xy plane. The resolution in the transverse momentum for full length tracks is $\frac{\sigma(p_T)}{p_T} = \sqrt{(0.005 p_T)^2 + (0.016)^2}$. To improve the angular coverage in the forward and rear direction 4 planar drift chambers (FTD, RTD) are added to the CTD. A transition radiation detector (TRD) helps with electron identification in the forward region. The solenoid is surrounded by a high resolution uranium-scintillator calorimeter divided into three parts (BCAL, RCAL and FCAL). The iron yoke serves as the assorber for the backing calorimeter (BAC) and as a muon filter. Large area LST chambers measure the position and direction of muons in front and behind the iron yoke (BMUON, RMUON). In the forward direction a spectrometer of two iron toroids and drift chambers (FMUON) identifies muons and measures their momenta up to $150\frac{GeV}{c}$.

Very forward scattered protons ($P_T < 1\frac{GeV}{c}$) are measured in the leading proton spectrometer (LPS) which uses the proton ring magnet for momentum analysis and detects the scattered protons.

Particles produced by the proton beam upstream of the detector are detected in the VETO WALL.

10 Vertex Detector (VXD)

The purpose of the VXD is twofold: to detect short-live particles and to improve the relation σ_p/p. It is a high precision cylindrical drift chamber with wires running parallel to the beam. It works in a high background environment and has to be as transparent as possible to reduce multiple scattering.

The chamber is divided into 120 radial cells. Each one (see fig. 12) is defined by three radial planes:

Figure 12: Wire arrangement in a VXD cell.

Figure 13: VXD front view (half part).

Wire	Diameter (μm)	Mechanical tension (gr)	Electrical potential (V)
sense	20	50	0
field	50	200	-2150
drift	50	250	-1830/-2300

Table 3: VXD wires are made of gold plated tungsten.

Figure 14: VXD spatial resolution (CERN-PS test beam).

- central plane: 13 field wires alternated with 12 sense wires
- shielding planes: 25 equidistant drift wires each.

The VXD vessel (shown in fig. 13) consists of two carbon fiber (CF) cylinders. The inner one is 1.2 mm thick and 99 mm of radius. It is centered on the beam pipe axis and supports the compressive load (1134 kg) of the wires. The external CF tube is 0.72 mm thick and has a radius of 159 mm. It is centered on the beam axis with a displacement of 10 mm. This displacement is necessary to solve the left-right ambiguity. In table 3 are shown the main characteristics of VXD wire. The total amounts of wires is 6000.

The VXD is filled with a slow gas *dimethylether (DME)*. In this gas the drifting electrons are *thermal* also at high values of E (2kV/cm). The drift velocity is about 5μm/ns allowing us to achieve a spatial resolution of 35μm in the central drift region (see fig. 14). The efficiency measured at the test beam, as a function of gain voltage, shows a large plateau with a knee at about 2050 V.

Figure 15: VXD high voltage characteristic.

At the chosen working point $V_g = 2150V$ the efficiency is as high as 96% (see fig. 15).
The chamber has been tested up to one order of magnitude higher than expected at HERA and no appreciable variation on resolution and efficiency has been observed within the explored rate range.

11 Central tracking detector (CTD)

The purposes of the CTD are:

- separation and reconstruction of charged and neutral current events over a wide range of Q^2;
- reconstruction of hadron and electron tracks with momentum resolution better than $\sigma_p/p_t \overset{\sim}{<} 0.003p_z$ over a wide angular range;
- electron tagging by dE/dx;
- event triggering using vertex information.

The CTD is a vector drift chamber with maximum drift time of 500 ns, so that all information is avalaible for use in triggering. It consists of a cylindrical wire chamber using nine superlayers (see fig. 16). Five superlayers have wires parallel to the chamber axis; the other four have small angle in order to reconstruct the z-coordinate of tracks. Each superlayer has eight sense wire layers.
The CTD is designed to work in high magnetic fields (for precision momentum determination). As a consequence, the electron drift trajectories are rotated at

Figure 16: Layout of wires in a CTD octant.

Figure 17: Electric field trajectories with and without magnetic field.

Wire	Material	Diameter (μm)	Sagitta (μm)	Wire/cell
Sense	W	30	86	8
Ground	Cu - Be	70/100	86/95	11
Field	Cu - Be	150/200/300	300	19
Shaper	Cu - Be	100/200	300	4

Table 4: CTD has 576 cells with 4608 sense wires and 19584 field wires.

a Lorentz angle with respect to the electric field direction (see fig. 17). Like the CDF apparatus, the CTD is arranged in order to operate at a large Lorentz angle (45^o). This is an advantage in track finding out of time rejection. The electrons drift along straight parallel trajectories, set up to be tangent to the chamber azimuth at the cell center. This reduces the time-to-drift correction for inclined tracks respect to the drift trajectories. Moreover, it solves the left-right ambiguity.

The chamber is filled with $Ar/CO_2/C_2H_6$ at 85/13/2%. The drift velocity is about 50 $\mu m/ns$ and remains quite constant for a large range of electric field values. To maintain parallel drift trajectories in the magnetic field, the electric field should be uniform. The use of potential wires between the sense ones allows independent adjustment of gain and drift field.

The wire materials, diameters and mechanical tensions are shown in table 4. The trajectories are reconstructed in the CTD at polar angles from 15^o to 164^o (requiring hits in 12 or more layers). The measured spatial resolution per wire is about 150 μm (θ-dependent). The active volume of the chamber has inner radius of 18.2 cm and outer radius of 79.4 cm and a total length of 205 cm.

12 Forward and rear tracking detectors

Their purpose is to improve the angular coverage of the CTD by adding four planar drift chambers. Each chamber consists of three independent layers of drift cells with fixed wire orientations (see fig. 18). The three layers are glued together in a way that the wire direction is rotated by 120^o going from one layer to the adjacent one.

Each drift cell has six sense wires (see fig. 19). Thus, one chamber measures three projections (u, v, w) of a track element with up to six digits per projection. The inner dimensions of a drift cell are 48×24 mm^2. The six sense wires (30 μm in diameter) are spaced at 7 mm, and are alternated with seven field wires (121 μm in diameter). All wires are perpendicular to the chamber axis. In order to solve the left-right ambiguity the sense wires are staggered with respect to the median plane by $\pm 150 \mu m$ (see fig. 20).

Figure 18: Layout of a FTD/RTD planar drift chamber.

Figure 19: Cross section of FTD(RTD) drift cell in one layer.

Figure 20: FTD/RTD cell wire arrangement.

Five field shaping strips on either side of the drift cell (2 mm wide and spaced by 2 mm) allow us to produce homogeneous electric drift field even at the edges and to equalize the surface field (the gas gain) of the six sense wires (see fig. 21). The FTD (RTD) cells are operated with Ar/C_2H_6 at 50%/50% at atmospheric pressure. The potentials of wires, cathods and strips are chosen by calculations (simulation) and by experimental checks. With the set of voltages used for the latest test beam, the average drift field is about 1.2 kV/cm, and the gas gain is about5×10^4. The achieved single wire resolution is 120 - 130 μm depending on drift distance and track angle. RTD covers a polar angle of $10^o - 20^o$ and FTD a polar angle of $8^o - 27^o$.

13 Transition radiation detector (TRD)

Its purpose is identification of electrons in the range of 1 to $30\frac{GeV}{c}$ with a h/e rejection ratio of about 10^{-2}. It is a radiator in polypropylene fibers (fiber diameter $\cong 20\mu m$) followed by a planar drift chamber (see fig. 22). When a particle with charge ze cross the boundary between vacuum and a medium, as shown in fig. 23, it radiates energy with intensity proportional to the Lorentz factor γ. For particle with $\gamma = 10^3$ the radiate photons are in the soft x-ray range 2 to 20 eV. Since the emission probability of the soft X-ray is proportional to $\alpha = 1/137$ per boundary crossing, practical detectors use radiators with several hundred interfaces, e.g. foils of lithium or plastic in a gas. The ZEUS TRD radiators consist of polypropylene fibers (20μm in diameter) with a total depth of 70mm. Even if the results obtained for pion contamination are slightly

Figure 21: Electron drift trajectories. Left side shown the correct operative way; right side shown the wrong one.

Figure 22: TRD layout.

Figure 23: Charge particle cross a boundary between vacuum and a medium.

worse compared with the regular radiator consisting of polypropylene foils. The solution with the fibers has some advantages:

- The mechanical tension introduced by stretching the foils would require rigid frames.

- Due to the random orientation of the fibers the dependance on the track angle is less than when using foils.

During the process of production, the fibers were compressed to the desired density (0.101 g/cm^3, equivalent to 300 foils of PP), to form fleece layers of $\sim 2.2mm$ and then stacked in order to achieve a radiator thickness of $\sim 70mm$. The radiator is followed by a 22 mm depth drift chamber. The drift chamber is divided into a logitudinal drift gap of 16 mm and a gas amplification region of 6 mm. A wire plane of 50μm diameter wires, spaced by 1.5 mm, separates both regions. The 6mm amplification gap is formed by potential wires (120μm M_o plated gold) with sense wires (30μm W plated gold) centered between them with a spacing of 6 mm (see fig. 24).

The chamber is filled with Xe with 10% of added mixture of quench gas (8% CO_2 and 2% of iso-C_4H_{10}) at atmospheric pressure. The TRD covers the forward angular region from 7^o to 26^o.

The TRD consists of four modules. Two packages of two modules each are sandwiched between the three FDT chambers.

Figure 24: TRD drift cell.

14 Thin superconductive solenoid

In order to measure the momentum of charged particles we use an axial magnetic field produced by a thin superconductive solenoid located between the central tracking detector and the barrel calorimeter. The volume where the solenoid must operate is a cilynder of 1.85 m diameter and 2.46 m length. The main requirements for the thin solenoid are:

- to generate an axial magnetic field of about 1.5T in the region of the tracking devices (operating current of about 5 KA);
- to be almost transparent for electrons and photons in order to avoid their detection in the calorimeter ($\stackrel{\sim}{<}$ $0.9X_o$ at 90^o with respect to the beam direction);
- field inhomogenity must be less than 8% in the forward and rear region.

15 High resolution calorimeter

The main purposes of the ZEUS high resolution calorimeter are:

- to measure jet energy with a resolution of $\sigma(E)/E = 35\%/\sqrt{E}$;
- to achieve angular resolution for the jet better than 10 mrad and good jet;
- hadron-electron separation for both isolated electrons and electrons in jets.

Figure 25: High resolution calorimeter layout.

The calorimeter surrounds completely the solenoid and the tracking detectors (see fig. 25). The solid angle covered is $\sim$99.7%. The calorimeter is divided in three parts:

1. the forward calorimeter (FCAL) covering a polar angle from 2.2^o to 39.9^o;
2. the barrel calorimeter (BCAL) extending from 3.67^o to 129.1^o;
3. the rear calorimeter (RCAL) extending from 128.1^o to 176.5^o.

The structures of FCAL, BCAL and RCAL are similar. Trying to make the construction of the calorimeter easier, a modular approach has been adopted. FCAL and RCAL consist of 24 modules, whereas the BCAL consists of 36 modules. Each module is subdivided longitudinally in two parts. The inner part is the electromagnetic calorimeter (EMC) with a depth of $\sim 25\mathrm{X}_o$ ($\sim 1\ \lambda$). The outer part is called the hadronic calorimeter (HAC) and the depth varies from $\sim 6\lambda$ in the very forward direction to $\sim 3\lambda$ in the rear direction (see fig. 26).
The modules consist of depleted uranium plates (the sampling thickness chosen is $1\mathrm{X}_o$: 3.3mm thick at a density of 18.5 g/cm^3) between scintillator plates segmented in tiles. The scintillator thickness is 2.6 mm and was chosen in order to achieve $h/l = 1$.
The depleted uranium plates are fully encapsulated by a stainless steel foil of 0.2 mm thick in the EMC and 0.4 mm in the HAC. The steel foils serve to adjust the signal from the uranium radiactivity, which has to be low enough

Figure 26: FCAL module.

	Electromagnetic	Hadronic
FCAL	5x20 cm^2 non projective towers	20x20 cm^2 non projective towers
RCAL	10x20 cm^2 non projective towers	20x20 cm^2 non projective towers
BCAL	5x20 cm^2 projective towers	20x20 cm^2 non projective towers

Table 5: Dimension and arrangement of scintillator tiles.

to keep the photomultiplier dark currents small, yet enough for calibration. To obtain good granularity the scintillator plates are segmented in tiles as shown in table 5. The optical read-out of the scintillator in the calorimeter uses wavelength shifter plates to collect the light from each subtower of the calorimeter. The light emitted by the scintillator tile is transmitted across a small air gap to the WLS, where it excites fluorescense (see fig. 27). The shifted light travels along the WLS by total internal reflection into a light guide which directs it into a photomultiplier tube. The WLS and light guides are made of 2 mm sheets of polymethyl methacrylate dopped with a fluorescent dye Y-7 and UV absorbant ($\lambda > 360$nm). The main reason for this choice is that Y-7 absortion and emission spectra match well the emission spectrum of the scintillator and the spectral sensibility of the bi-alkaline photocathods.
In FCAL and BCAL the read out of hadron calorimeter is divided in two sections:

Figure 27: Optical readout of scintillators.

FCAL	2×3 absorbtion length
BCAL	2×2 absorbtion length

There is only one HAC section inside the RCAL with a depth of 3 absorbtion length.
The choice of scintillator and photomultiplier for read out offers the additional advantage that the pulses can be kept shorter than the bunch crossing time of 96 ns in order to avoid pile up effects and the supression of cosmic rays background (the rate of cosmic rays is ~ 5 kHz) and beam gas background (see fig. 28).

It has been shown through experiments that the DU scintillator calorimeter achieves equal response to electrons and hadrons (e/h = 1.00 ±0.05). The energy resolution for hadrons and jets is $\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E}}$.

16 Iron yoke

The yoke is shaped as an octagonal cylinder which is closed by an endcap on either side. In order to enable access to the detector components inside, the yoke splits in three parts: the two clam shells and the bottom yoke (see fig. 29). The total weight of the yoke, without detector components, is 1962 ton. The yoke is built with modules which are bolted together. There are ten octagonal modules, three bottom yoke modules and four modules for each cap. Each module is constructed with 73mm thick iron plates welded together with 37 mm thick space bars between them to avoid the instrumentation of the yoke with the proportional tube chambers of the BAC calorimeter. The number of plates is:

Figure 28: Background separation through calorimeter timing.

10	in octagon and bottom modules
11	in forward endcap modules
8	in rear endcap modules

The iron yoke can be magnetized by Cu coils up to 1.73 T. There are two coils for each endcap and four coils for the octagonal part (see fig. 30).

16.1 Hadron Electron Separator

The identification of electrons is very important in the separation between neutral and charged current events. The combined information from the calorimeter, the $\frac{dE}{dx}$ measurement of the central track detector and the transition radiation detector is insufficient to ensure the required hadron rejection for photon gluon fusion detection of charm and bottom quark production via their semi-electronic decay. The separation between hadrons and electrons is committed to a small area silicon diodes placed in the front part of calorimeter (see fig. 26). The separation is based on the fact that electron and hadron interactions behave differentely in the calorimeter: the hadronic interaction length is 20 times larger than the electromagnetic radiation length. As a consequence electron showers start early in the calorimeter and are narrow, while hadrons tends to interact later and produce wider shower.
It has been demonstrated that a hadron–electron separator HES built from $3x3cm^2$ silicon diodes ($300-400\mu m$ thick fully depletted) provides good hadron-electron separation, possesses sufficient radiation hardness and is technically feasible.

Figure 29: The iron yoke in open position.

Figure 30: Position of yoke coils.

Figure 31: Elements of a BAC proportional tube.

The HES detector covers the electromagnetic sections of the rear and barrel calorimeter by one layer and the forward calorimeter by two layers. The total number of diodes required is 20,000 in FCAL, 20,000 in BCAL and 10,000 in RCAL.

16.2 Backing Calorimeter

The BAC gaseous detector is an aluminium proportional chamber sampling calorimeter. It is assembled from 8 or 7-tube wide aluminium modules placed longitudinally the beam axis between the 73mm thick iron plates of the barrel iron yoke. In the two end caps of the iron yoke the modules are placed horizontally and orthogonal to the beam axis. The fig. 31 shows a sketch of a single aluminium proportional tube. Gold plated tungsten wires of $50 \mu m$ diameter are being streched inside the $15x11mm^2$ cells of an aluminium extrusion and soldered at the edges. The aluminium cathod pads 50 cm long are placed 1 mm above the extrusion comb. A gas mixture of Argon-CO_2 is used $(80 - 20\%)$. The operating voltage is about 2kV.

Energy in BAC is measured by summing the analog signals from the wires. The locations of the energy deposits along the wires are determined by means of non-projective pad towers.

Since there are no muon chambers underneath the ZEUS detector, layers 1, 5 and 9 of the bottom BAC chambers have special cathod pads to allow for the measurement of muon trajectories. The measured energy resolution of BAC is $\sigma(E)/E = 110\%/\sqrt{E}$. The spatial resolution for the μ chambers is about 1 mm.

Figure 32: Barrel and Rear Muon Detector.

16.3 Barrel and Rear Muon Detector

In fig. 32 is shown the disposition of the barrel and rear muon chambers. The main task of the barrel and rear muon detector is to identify pointing tracks penetrating the total calorimeter and iron thickness and re-measuring their momentum. Each barrel chamber consists of 2 double layers of limited streamer tubes (LST) placed longitudinally the beam axis and is equipped with external read-out strips (analog read-out) orthogonal to the LST wires. In the cross direction signals from the each LST wire are sent to TDC electronics to allow a precise coordinate measurement. The rear muon chambers are equipped with LST placed horizontally and orthogonal to the beam axis with the same read-out electronics as the barrel part.

Within each chamber (see fig. 33) the two double layers of LST are separated by a gap of 20 cm for the chambers inside the yoke (BMUI) and of 40 cm for the chambers placed arround the yoke (BMUO). In between the gap there is an aluminium honeycomb structure which ensures very rigid and almost perfectly planar support for the strips and LST. In total there are twenty chambers equipped with two double layers of LST. The dimensions of the chamber range from 16 to 41 m^2. The total sensitive area is $\approx 2000\ m^2$. There are 27000 digital channels with TDC read-out and 49000 analog channels. The gas composition is $CO_2 : Ar : C_4H_{10} \ = \ 88\% : 3\% : 9\%$.

The intrinsec spatial resolution is $\approx 150\mu$m via drift time and $\approx 700\mu$m via center of gravity of the collected charges on the strips.

Figure 33: Cross section of a BMUON chamber.

16.4 Forward Muon Detector

The forward muon spectrometer is shown in fig. 34. Two toroids of 6m diameter and 45cm wide provide an average magnetic field of 1.7 Tesla inside the toroid itself. Four planes of LST (LT1, LT2, LT3, LT4) with $\rho - \phi$ strip read-out are used to define a trigger on high energy muons, selecting both in direction and magnetic deflection. Four planes of drift chambers (DC1, DC2, DC3, DC4) give very precise position measurements for the momentum evaluation at small angle ($<$ 200 mrad) where CTD and FTD momentum resolution is very bad. LT1 and DC1 are placed inside the iron yoke between the FCAL and FBAC. All other detector planes are attached to the upper support structure of the toroids. Finally two WALLs of LST ensure a complete angular coverage up to the BMUON region.

Each plane of DC is formed by eight trapezoidal drift chambers. The fig. 35 shows the chamber layout and the drift cell. The chambers are filled with a gas mixture of $Ar : CO_2 : CH_4 \ = \ 90\% : 9\% : 1\%$. Latest spatial resolution measurement gives $300 \mu m$.

Each plane of LT is divided into 4 chambers. A quadrant (fig. 36) consists of two layers of LSTs placed horizontally and orthogonal to the beam axis. For each layer of a quadrant the read-out system consists of 64 ϕ strips 1.4^o wide and 256 ρ strips 2 cm wide.

Each WALL plane consists of eight rectangular chamber (see fig. 37). There is one layer of LST and the read-out system is performed by 64 ϕ strips 0.703^o wide and 196 $pseudo - \rho$ strips 1.8 cm wide.

Both LT and WALL detectors are filled with the same gas misture: $CO_2 : Ar : C_4H_{10} \ = \ 88\% : 3\% : 9\%$.

Figure 34: FMUON detector layout (side view).

Figure 35: Layout of (a) one drift chamber and (b) one elementary cell.

Figure 36: LT chamber layout.

Figure 37: LW chamber layout.

17 Leading Proton Spectrometer

In most $e-p$ interactions the debris of proton is emitted at very forward angles and escape undetected down the beam pipe. The processes expected to generate leading protons are diffractive photoproduction, photon gluon fusion and also neutral and charged current interaction. Low angle proton spectrometer makes use of six measuring stations in conjunction with the bending magnets of the HERA proton ring. Fig. 38 shown the position of the six measuring stations placed along the outgoing proton beam. Each of the six station is equipped with six large planes of $100\mu m$ wide Silicon microstrip detectors: two (U) positioned ad $+45^o$, two (V) at -45^o and two (Y) at 0^o relative to the strongest magnetic deflection.
In total there are about 52,000 read-out channels and it is possible to reach a spatial resolution of $25\mu m$ and a momentum resolution between 0.15% and 0.9% at $820\frac{GeV}{c}$.

18 Data acquisition

The ZEUS experiment consists of approximately 20 components divided in

- sub-detector components (detector, front-end electronics, read-out chain, calibration systems and slow control system for monitoring hardware);
- three trigger components to filter events;
- two data flow components responsible for event building.

The expected rates for various types of interaction (NC, CC, PGF, QCD-compton, VDM) for an istantaneous luminosity of $2 \cdot 10^{-5} pb^{-1} s^{-1}$, a part from $low - Q^2$ photoproduction, are below 1 Hz. The main types of backgrounds (proton beam-gas interactions, proton halo beam events and cosmic induced events) produce, on the contrary, a rate of about 50 KHz and a significant fraction of which cause signals in the detector. For this reason a three level-trigger system is required.
Since the interval between two consecutive beam crossing (96ns) is too small for a reasonable trigger decision all components make use of pipelined electronics. The overall architecture for ZEUS detector trigger and data acquisition system is shown in fig. 39. The First-Level-Trigger has the task to set a trigger rate of 1KHz by eliminating most of the beam-gas and beam-halo background. Results of the local processors are combined in the global first level trigger box (GFLTB). The GFLT box has the task to syncronize all component readout, to receive and elaborate ≈ 600 bits from local FLT's and to produce 64 pre-scalable different sub-triggers. It makes use of programmable gate arrays technology and runs in pipelined mode with 10 MHz clock.

Figure 38: Plan of the LPS spectrometer.

The Second-Level-Trigger analyze the digitized data of the components. Combining the results of the local processors in the global second level trigger box (GSLTB) results a reduction of the trigger rate to 100 Hz. The GSLT box receives and elaborates 10 - 300 bytes from local SLT's. It makes use of transputer technology and runs in asynchronous pipelined mode.
After a positive decision the data of all sub-detectors are gathered into the Event Builder processors and sent to a Third-Level-Trigger processor farm of Silicon Graphics stations.
The EVB system collects the event data from all components (100 Kbytes/event) and formats data in ZEBRA structures. It makes use of transputer technology. The TLT runs a (reduced) version of a full offline analysis code and passes an output rate of about 3-5 Hz. It consists of parallel processors (Silicon Graphics 4D/35, 30 Mips) and it controls direct link (1.6 MBytes/s) to IBM disks for data storage.

19 Results from ZEUS detector on e-p collision at HERA

19.1 Photoproduction

The high c.m. energy of HERA allows the study of photoproduction over a wide energy range. Like purely hadronic reaction, γp scattering is expected to have a soft component due to peripheral processes and a hard component arising from the scattering of a parton from the proton on a parton from a vector mesons (see fig. 40). In addition to its hadronic features, the photon can couple directly to quarks and the coupling is pointlike. This leads additional hard scattering processes which become prominent at high energies and which are not present in hadron-hadron interactions (see fig. 41):

- direct photon processes (photon-gluon fusion and QCD-Compton process);
- resolved photon processes (quark and gluon content of the photon interact with the hadron costituents).

The figure 42 shows total photoproduction cross section as a function of the photon–proton c.m. energy ($W = \sqrt{4(E_e - E_{e'})E_p}$) as measured in previous experiments up to 18 GeV and by H1 and ZEUS. The curves labelled DL and ALLM are Regge type fits to hadron-hadron and pre-HERA photon-proton cross section. The other curves are based on the assumption that the total cross section is a sum of soft part plus the contributions from direct and resolved photons.
In DIS a new class of events was found by ZEUS and confirmed by H1 which are caracterized by a large rapidity gap between the proton beam direction and

Figure 39: ZEUS trigger and data acquisition system.

Figure 40: Diagrams for photoproduction via Vector Dominance Model.

Figure 41: Diagrams for direct photon processes (a-b), and for resolved photon processes (c-f).

Figure 42: Total γp cross section as a function of W.

Figure 43: Tagged photoproduction. Points are data and histogram is a prediction for nondiffractive photoproduction.

the first significant energy deposition away from it. A search in photoproduction shows the presence of the same type of events. The analysis has been porformed in terms of pseudorapidity $\eta = -ln\ tan\frac{\theta}{2}$. In fig. 43 the distribution of η_{max} is shown (η_{max} is the pseudorapidity of the condensate closest to the proton direction. A condensate is a group of contiguous calorimeter cells with a total energy > 0.4 GeV.). The large peak at η_{max} between 3 to 6 corrisponds to data collected by FCAL. It consists mainly of nondiffractive events. The second peak near η_{max}=-2 arising from diffractive production comes from RCAL.

While the observed size and energy dependence of the total cross section $\sigma_{tot}(\gamma p)$ do not provide evidence for direct and resolved photon contribution, the analysis of the final states shows the presence of these terms very clearly in the hard scattering contributions. Both direct and resolved processes produce quarks and gluons in the final state. At sufficientely high energies the final state partons manifest themselves as jets of hadrons. The topology of hard scattering events from direct and resolved photon processes is shown in fig. 44.

The jet energies and momenta can be used to estimate the energies and momenta of the final state partons. Fig. 45 shown a two back-to-back jets with a proton remnant. Each jet has an energy of about 30 GeV. Since no energy is deposited in RCAL, where we expect the fragments of photon remnant in a resolved process, this is a candidate for a direct photon interaction. Clear evidence for resolved photon process can be seen in the characteristics of the two-jets sample. Requiring both jets to have $\eta_{jet} < 1.6$ the distribution of the photon momentum fraction x_γ^{meas} ($= \sum_{jets}(E - p_z)_{jet} / \sum_h (E - p_z)_h$), displayed in fig. 46, shows a rise at low x_γ^{meas} which can be explaned as resolved processes, and a rise at high x_γ^{meas} which can be explaned as direct processes.

Figure 44: Topology of hard photoproduction from (a) direct photon process and (b) resolved photon process.

Figure 45: A photoproduction event with 2 jets.

Figure 46: Distribution of x_{γ}^{meas} for events with two jets. The two superimposed histograms are the MonteCarlo distributions of the resolved and direct contribution.

Figure 47: The DIS events. The shared area shows the $x - Q^2$ region covered by fixed target experiments.

19.2 DIS and structure function

The structure function F_2 has been determinated on a integrated luminosity of $300 nb^1$ using $ep \rightarrow eX$ inclusive reaction. The kinematic properties of scattered electron and produced hadrons has been determinate by the calorimeter. The distribution of the events in the x, Q^2 plane is displayed in fig. 47. The highest Q^2 event detected by ZEUS has been $2.15 \cdot 10^4 GeV^2$ (x=0.28) for NC events. The results on F_2 are summarized in fig. 48. The HERA data extend the x-range for F_2 of two order of magnitude. The data show a significant rise in F_2 towards low x and it means that the parton density increase with decreasing x. The Q^2 dependance of F_2 for fixed x is in agreement with scaling violation expected from perturbative QCD.

The standard DIS event show energy deposition in the forward region. ZEUS

Figure 48: The structure function $F_2(x, Q^2)$ for different x intervals.

has observed a class of events which have different characteristics (see fig. 49). The special feature of these events is the absence of energy deposition in the proton direction. The distribution of the pseudorapity of the calorimeter cluster closest to the proton direction with the largest η for all DIS events shows two groups of events. The standard Monte Carlo simulation for DIS scattering is in good accord with experimantal data above $\eta = 2$. Events with $\eta_{max} < 1.5$ are denoted as events with a large rapidity gap.

Fig. 50 shown the hadronic system mass M_x as a function of $\gamma^* p$ c.m. energy for all DIS events. Large rapidity gap events have preferentially small M_x values. The events with large rapidity gap are expected if the virtual photon interacts with a colorless object like the Pomeron (fig. 51).

Figure 49: A DIS event at $Q^2 = 64 GeV^2$ with a large rapidity gap.

Figure 50: The hadronic system mass $M_x = sqrt(E_H^2 - p_H^2)$ as a function of $\gamma^* p$ c.m. energy for all DIS events.

Figure 51: Schematic diagram for difractive dissociation in DIS.