CHAPTER III
THE ZEUS EXPERIMENT

3.1 HERA

Physics programs at colliding beam facilities are determined by square of the center of mass energy(s) and the species of the colliding particles. While multiple e^+e^- and $p\bar{p}$ colliders have been in use since 1970 and 1975 respectively, The Hadron Electron Ring Accelerator(HERA)[16],located at DESY laboratory(Deutsches Elektronen-Synchrotron) in Hamburg, is presently the only ep collider in the world. It provides ep collsions at $s = 98,400\text{GeV}^2$, which is $10^2 \sim 10^3$ times higher than what was available at previous fixed target lepton-nucleon scattering facilities. As a big science project, HERA facility is not limited to providing e^-p collisions. A complete structure function program requires electron deuteron data and polarized beams of e^-, e^+ and p. These will be available at HERA in the future.†

HERA was built between 1984 and 1990 by an international collaboration of 12 countries (Canada, China, CSFR, France, Germany,‡ Israel, Italy, the Netherlands, Poland, the U.K., and the USA). The first data-taking started in the summer of 1992.

The layout of HERA is shown in Figure 10. In the HERA tunnel are two separate synchrotron rings, one for the acceleration and storage of the proton beam and the other for the electron beam. The two counter-rotating beams are

† During part of the 1994 runs, HERA was successfully operated in e^+p collision mode. Polarizations of up to 70% have already been achieved at HERA.

‡ Germany was still two countries during that period.

Figure 10: The layout of HERA. Two independent synchrotron rings, for e and p respectively, are installed in the HERA tunnel which runs 10-25m underground in the city of Hamburg, Germany. The pre-accelerator systems(LINAC I, LINAC II, DESY II, DESY III, PETRA), are on the site of DESY laboratory. The ZEUS detector is located in the South Experimental Hall(underground).

brought into head-on(0° crossing angle) collisions at two interaction points at the North and South interaction regions for the experiments H1(Ref. 17) and ZEUS respectively.† Also shown in Figure 10 is the pre-accelerator complex which injects pre-accelerated bunches of electrons(at 14 GeV) and protons(at 40 GeV) into the HERA rings during refilling. Refilling of electron and proton beams are necessary because luminosity lifetime is finite, typically a few hours.

Table 1: Design parameters of HERA[18]

Parameter	e	p
beam energy	30GeV	820GeV
s	$9.84 \times 10^4\text{GeV}^2$	
Luminosity	$1.5 \times 10^{31}\text{cm}^{-2}\text{sec}^{-1}$	
injection energy	14GeV	40GeV
number of interaction points	3	
tunnel circumference	6336m	
no. of main dipoles	465	422
no. of main quadrupoles	605	224
main dipole field	0.164 T	4.68 T
time between crossings	96ns	
no. of buckets	220	220
max. no. of bunches	210	210
particles per bunch	3.5×10^{10}	10^{11}
beam current	60mA	160mA
bunch length(σ_z)	0.8cm	11-15cm
beam width σ_x at int. point	0.3mm	0.3mm
beam height σ_y at int.point	0.04mm	0.1mm
filling time	15min	20min

Some design parameters of HERA are listed in Table 1. The machine design and the physics objectives are closely related. A major physics topic at HERA is the measurement of proton structure functions through deep inelastic scattering(DIS). With an s of about 9×10^4 times of proton mass, HERA allows measurement of proton structure functions in kinematic region up to $Q^2 \sim 4 \times 10^4$

† The East interaction region is reserved for a fixed target experiment HERMES.

and down to $x < 10^{-4}$ where higher order perturbative QCD calculations can be tested or challenged.[19] The machine also serves for further testing of electroweak theory in kinematic region of Q^2 larger than M_Z^2 and M_W^2.[20] Searches for phenomena of new physics beyond the standard model, such as leptoquarks[21] and excited fermions,[22] have also been the motivation for the construction of HERA. Apart from these luminosity demanding topics, HERA also plays a major role in studies of photoproduction and diffractive scattering, making connections between perturbative QCD and the old physics of soft and semihard scatterings.[23]

While large s kinematically allows very hard scatterings to occur, actual observation of these hard processes demands correspondingly high luminosity, because the total cross section is smaller for harder scatterings(in the case of DIS, it is set by $\alpha_{em}^2 s/Q^4$). At the design luminosity of $1.5 \times 10^{31}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$(equivalent to $0.054\,\mathrm{pb}^{-1}\mathrm{hr}^{-1}$), 50-100 pb^{-1} of data may be accumulated per year. This is to be compared with $\alpha_{em}^2/s \approx 0.2$pb which sets the order of the cross section for the hardest electromagnetic scattering at HERA.

A feature of HERA contributing to its high luminosity, is its high bunch crossing frequency. In synchrotron rings, beam particles are driven by the RF(radio frequency) field into a number of equally spaced bunches during acceleration. At HERA, 220 bunch buckets circulate in the electron ring and an equal number in the proton ring, so that bunch bucket crosses at the interaction points every $96ns$. This bunch crossing time interval at HERA is much shorter than that in any other existing colliders (3.5 μs at Tevatron and 3.8 μs at S$p\bar{p}$S). This demands novel approaches in the detector readout and trigger designs.

As usual, it takes several years for a machine to reach its design capacity. HERA performed exceedingly well in 1993, the second year of its operation. An integrated luminosity of 1pb^{-1} was delivered, mostly between late July and October. The electron beam energy was 26.7 GeV, a little lower than the design value 30 GeV. Correspondingly, $\sqrt{s}$ is 296 GeV. Among 220 electron buckets and 220 proton buckets, 84 pairs of electron and proton buckets, 10 unpaired electron buckets and 6 unpaired proton buckets were filled. Unpaired electron(proton) bunches

Table 2: Performance of HERA in 1993

Parameter	1993	design
p beam	820 GeV	820 GeV
e beam	26.7 GeV	30 GeV
s	$8.76 \times 10^4 \mathrm{GeV}^2$	$9.84 \times 10^4 \mathrm{GeV}^2$
Luminosity	$1 \times 10^{29} \mathrm{cm}^{-2}\mathrm{sec}^{-1}$	$1.5 \times 10^{31} \mathrm{cm}^{-2}\mathrm{sec}^{-1}$
no. of colliding bunches	84	210
time between crossings	96 ns	96 ns
e current	12-15 mA	60 mA
p current	12-15 mA	160 mA
e bunch length(σ_z)	1cm	0.8 cm
p bunch length(σ_z)	20cm	11-15 cm
e beam lifetime	2-15 hr	$>$ 5hr
p beam life time	10-500 hr	$>$ 10 hr

are called "electron(proton) pilot bunches". Pilot bunches were used in studies of beam related background. ZEUS also triggered on 28 crossings of empty bucket pairs in each cycle to allow studies of background uncorrelated to the beams such as cosmic-ray background and false events from detector noise. The maximum luminosity reached during this period was about 10% of the design luminosity. The lifetime of the proton beam was longer than 100 hours and the lifetime of the electron beam(for good running conditions) was 7 to 10 hours. Stability of the beam crossing is reflected in the distribution of the event vertex centered at $6cm$ upstream of the proton beam from the nominal interaction point, with a Gaussian spread of $10cm$ due to the length (about $20cm$) of the proton bunch. Performance of HERA in 1993 is summarized in Table 2