Figure 12 shows the layout of the ZEUS luminosity monitor(LUMI).[28] LUMI consists of an electron detector(EDET) and a photon detector(GDET). Bremsstrahlung photons exit the beampipe through a window and enter the GDET. Similarly, bremsstrahlung electrons are deflected by the beam bending magnetic field, exit the beampipe through a window, and reach the EDET if E_e' is within appropriate energy range. Energies of bremsstrahlung photons and electrons are measured by a radiation hard lead-scintillator calorimeter in the GDET and EDET, with a resolution $\sigma_E/E_\gamma = 0.18/\sqrt{E_\gamma(GeV)}$.

The residual gas in the beampipe may also cause beam electron to bremsstrahlung. Additional event rate due to these background bremsstrahlung can be subtracted by measuring the event rate from e pilot bunches.[29]

3.2.3 Calorimeter

The calorimeter measures energy, position and arrival time of both neutral and charged particles without using magnetic field. Its energy resolution σ_E/E improves with increasing energy as $1/\sqrt{E(GeV)}$. It discriminates between electrons and hadrons. It is a fast device with response time $\sim 100ns$. It measures the time the particles reach the calorimeter with good resolution(less than $1ns$ at ZEUS). These features of calorimetry well match the needs of physics programs at HERA. Many QCD related topics at HERA rely on measurement of jets of neutral and charged particles, because a jet is kind of a "trace" left by a quark or a gluon. The measurement of proton structure functions, a major task at HERA, requires high precision measurements of energy and position for electrons and jets with energy up to a few hundred GeV. The high background rate at HERA requires rather sophisticated trigger algorithms based on features of global energy distributions which must be provided by the detector at every bunch crossing i.e. at every $96ns$, to avoid event pile-up.

The ZEUS calorimeter is a compensating sampling calorimeter of sandwich structure.[30] It consists of layers of dense absorber material(depleted uranium) interleaved with scintillator tiles. Showers of secondary particles produced in the absorber layers by the incident electron, photon or hadron are detected in the scintillator layers.

□ *Calorimetry*

In the case of $e^{\pm}$ and γ, the mechanism of calorimetry is well understood.[31] Radiative energy loss via bremsstrahlung($e \to e\gamma$) and pair production ($\gamma \to e^+e^-$) dominates at energies higher than a critical energy E_c, and dissipative energy loss via ionization, Compton scattering and photoelectric effect dominates at lower energy. The critical energy is approximately given by $E_c \approx 500\text{MeV}/Z$, where Z is the atomic number of the absorber, which yields about 6MeV for uranium. In describing radiative processes, material length is measured in units of the radiation length X_0, which is the mean distance within which an energetic electron radiates off 63.2% $(1 - 1/e)$ of its energy. X_0 can be calculated[31] and approximately expressed by[32]

$$\rho X_0 \approx 180\frac{A}{Z^2}\left[\frac{g}{cm^2}\right] \tag{47}$$

where ρ is the density of the material in gcm^{-3}. Roughly speaking, secondary particles with energy above E_c are detected with a finite probability(or sampled) by the scintillator layers, and particles with energy below E_c are absorbed in the absorber layers. Since the number of radiated particles with energy above E_c is proportional to E/E_c(if E is completely contained in the calorimeter), light in the scintillator layers is a measure of E, energy of the incident particle, with statistical fluctuation proportional to $\sqrt{E/E_c}$. $\sigma_E/E \propto 1/\sqrt{E(GeV)}$ is a general feature of sampling calorimeters. Number of generations of particles in a cascade is proportional to $\log(E/E_c)$. Therefore the penetration depth increases only logarithmically with incident particle's energy. The electromagnetic shower process can be well simulated in Monte Carlo programs. It is found that a depth of 25 X_0 is required to contain 98% of electromagnetic shower. The lateral size of an electromagnetic shower, due to multiple Coulomb scattering, is characterized by the Molière radius $R_M = X_0E_s/E_c$, where $E_s = 21.2\text{MeV}$. About 95% of electron energy is contained within a cylinder of radius $2R_M$.

For hadrons, the process of shower development and energy dissipation is much more complicated because a multitude of nuclear interactions are involved. In the course of secondary particle creation through inelastic nuclear reactions, much of the incident hadron's energy is dissipated into the medium in the form of nuclear binding energy and nuclear recoil energy. Some neutral and slow particles in the shower may not be detected by the scintillators. For all these reasons, hadronic energy is less visible in most calorimeters. A calorimeter's response to e and h(hadron) of the same energy is described by the e/h ratio. For a noncompensating calorimeter, the e/h ratio can be as as large as 1.5. Another complication arises from the fact that a hadronic shower actually contains a large electromagnetic fraction(30-50%) due to photons from π^0 and η decays. This fraction, called f_{π^0}, depends on the energy of the incident hadron and has a large fluctuation from shower to shower. For a jet of particles, the composition of the jet itself is an undetermined statistical quantity. Noncompensation($e/h > 1$), combined with undetermined f_{π^0}, severely degrades several aspects of the performance of a calorimeter.[33,34]

For uranium scintillator calorimeters, $e/h = 1$ can be achieved by a proper choice of the thickness ratio of the uranium and scintillator layers.[35] Response to electromagnetic showers is low in uranium, about 0.6 that of minimum ionizing particles(Mips). Hadronic response is enhanced by the large number of neutrons produced in uranium in the nuclear reactions. These neutrons interact with hydrogens in the plastic scintillators to produce visible signals.

The characteristic length for hadronic shower development is the nuclear interaction length λ. The depth required for containment of a fixed fraction of energy increases logarithmically with energy of the incident hadron. For ZEUS calorimeter, $\lambda \approx 25X_0$. It takes only one λ to confine an electromagnetic shower, but several(5-10) λ to confine a hadronic shower. Lateral spread of hadronic showers is also much wider than that of electromagnetic showers. These serve to discriminate electrons from hadrons.

The muon, with its mass about 200 times that of the electron, is very unlikely to bremsstrahlung(the critical energy E_c for a muon is several hundred GeV). It dissipates energy in the medium through ionization. In the ZEUS calorimeter, muons deposit only 0.3 GeV per λ on average.

□ *ZEUS Calorimeter*

The basic structure of the ZEUS calorimeter(CAL) is stacks of depleted uranium(DU) plates, clad in stainless steel foil, interleaved with plastic scintillator tiles(SCI). Each layer(DU+steel+SCI) is about $1X_0$ thick, mostly due to the DU plates of thickness $3.3mm$. SCI tile of thickness $2.6mm$ was chosen to achieve $e/h = 1$. The steel foil serves to attenuate the background from DU radioactivity.

Figure 14: Modular structure of the ZEUS calorimeter.

Mechanically, the CAL is divided into three components, FCAL, BCAL and RCAL (Figure 13), each made of a number of modules(Figure 14). The solid angle

Figure 13: Division and segmentation of the ZEUS calorimeter. (a) yz view of the calorimeter. (b) Readout segmentation of FCAL viewed from the interaction point. (c) Readout segmentation of RCAL viewed from the interaction point.

coverage is 99.8% in the forward hemisphere and 99.5% in the rear hemisphere. The only uncovered regions are the square beam holes of size $20cm \times 20cm$ in the center of FCAL and RCAL. Each module is further segmented lengthwise into

Figure 15: Isometric view of a BCAL module.

towers of transverse size typically $20cm \times 20cm$ (the width of a module is $20cm$) to achieve good angular resolution, and is divided in depth into an EMC section and one(in RCAL) or two(in FCAL and BCAL) HAC sections to achieve electron hadron separation.[†] The EMC sections are further segmented into cells of width $5cm$(in FCAL and BCAL) and $10cm$(in RCAL) to achieve better angular resolution in θ, which is in most cases more important in kinematic variable reconstruction due to a rotational symmetry in ϕ. The EMC section is $25X_0$ thick to contain 98% of electromagnetic shower. The depth needed to contain a hadronic shower depends on its energy. More particles with higher energy are expected in the forward hemisphere, since the ep center of mass frame is boosted toward the

[†] Most towers are nonprojective to reduce cost in mechanical construction. The EMC cells in BCAL are projective, the HAC cells in BCAL are projective in ϕ only, and towers in FCAL and RCAL are non-projective.

proton beam direction. The tower depth is 7λ in FCAL, 5λ in BCAL and 4λ in RCAL, to ensure proper energy containment in all directions. The segmentation scheme is shown in Figure 13. Towers in the outermost two rings of FCAL and RCAL do not contain finer segmented EMC cells because these towers are behind the BCAL when viewed from the interaction point.

There are nearly 6000 cells in the ZEUS calorimeter. Each cell is optically read out by two photomultiplier tubes(PMT). The blue light in all scintillator tiles of the same cell is collected from both sides of the module by wave-length shifter(WLS) sheets.[36] The light is absorbed by the WLS and emitted at a longer wave-length(green light) that matches the PMT gain curve. The light from both sides of a cell is guided to two separate PMTs to provide redundancy(to handle single PMT failure and malfunction) and enhance position measurement.

PMT signals are processed by the calorimeter electronics to determine the energy and arrival time of the particles. Precise(down to $1ns$) timing information provided by the ZEUS calorimeter is used by the online trigger to reject the beam gas and cosmic-ray background.

□ *Calibration and performance*

Calibration is an important part of the design, construction and operation of the ZEUS calorimeter. This involves readout calibration and absolute energy scale calibration. The electronic and optical readout systems(of nearly 12000 channels) were calibrated with several tools(partly built-in in the calorimeter) including the charge injection(to the front end electronics) system and the laser light flashing(emulating the scintillator light) system. The energy scale was calibrated by exposing the modules to test beam particles and cosmic muons. Signal from DU radioactivity(integrated over $20ms$) can serve as a very stable and convenient calibration tool as found in test beam results. Calibration constants of energy scale and readout systems must be monitored and updated continuously because of gradual changes or failures in scintillators, PMTs and electronics in the high radiation environment. These are routinely done on a daily or more frequent basis using the same calibration tools.

Results from the calibration work in test beams and in the first two years of data taking show that the ZEUS CAL possesses the following qualities:[18,37,38]

- Equal response to electrons and hadrons $e/h = 1 \pm 0.03$, in energy above 5-10 GeV.
- $\sigma_E/E = 18\%/\sqrt{E(GeV)} \oplus 1\%$ for electrons.
- Good $\sigma_E/E = 35\%/\sqrt{E(GeV)} \oplus 1\%$ for hadrons.
- Excellent time resolution of $0.3ns$(for cell energy above a few GeV) as measured by the laser calibration system(this is the intrinsic resolution), and $1.5ns/\sqrt{E(GeV)} \oplus 0.5ns$ in practical situations with an average proton bunch length of $60cm$ and other systematic effects.
- Uniform response as shown by better than 1% intercalibration among all cells.
- DU radioactivity, the dominant source of noise, is about 8-12 MeV per readout channel for EMC cells, and 14-32 MeV per channel for HAC cells.

However, it should be kept in mind that the above cited values of the CAL performance are mostly for single particles with energy above 5-10 GeV. For single particles with energy below 5 GeV or jets with moderate energy, these performance values may not apply. A major use of the CAL in $J/\psi \to e^+e^-$ measurement is in electron identification. For this purpose it is important to understand how the CAL responds to electrons and hadrons in the energy range of 1-3 GeV. Since the critical energy E_c is only about 0.01 GeV, the CAL responds to 1-3 GeV electrons quite the same way as it responds to 10GeV electrons. However, for hadrons with energy between 1-3 GeV, the CAL response can be significantly different from its response to higher energy hadrons, since ionization energy loss is about 0.3 GeV per λ for mips (minimum ionizing particles). In the FCAL prototype test beam, response to $e^{\pm}$, $\pi^{\pm}$ and p in the momentum range 0.5-10 GeV had been measured.[37] Figure 16(a) and (b) show the energy resolution and the e/h ratio as a function of E_k(kinetic energy). Compensation ($e/h \approx 1$) is achieved at energies greater than 3 GeV. At lower kinetic energy, pions and protons behave more like

Figure 16: (a) Energy resolution(a) and (b) the e/h ratio as a function of the kinetic energy of the indicated particles.

minimum ionizing particles, losing more energy through ionization. Given this unequal response to e and h, comparison between Monte Carlo and real data should be made with care.

One of the detector effects that is not covered by calibrations is dead material(coils, pipes, cables) in front of the CAL. These dead materials(with thickness up to a few radiation lengths depending on direction) absorb some energy of a particle or a jet before it reaches the CAL. This effect may be more significant for low energy particles. Noise suppression(removal of low energy cells) performed in the CAL reconstruction may also affect energy measurement of low energy particles. These will be discussed in more detail later.

3.2.4 CTD and VXD

J/ψ reconstruction relies on precise momentum measurements made by the tracking chambers. Tracking for charged particles was provided by the CTD(central tracking detector) and the VXD(vertex detector) during the 1993 runs.

Table 4: CTD superlayer parameters

superlayer	no. cells	stereo angle			radius	θ range
		mean	min	max	of cell	
1	32	$0°$			20.97cm	$11.3° - 168.2°$
2	40	$4.98°$	$4.64°$	$5.32°$	27.23cm	$14.5° - 164.8°$
3	38	$0°$			35.00cm	$18.4° - 160.7°$
4	56	$-5.31°$	$-5.06°$	$-5.55°$	41.30cm	$21.5° - 157.3°$
5	64	$0°$			48.73cm	$24.9° - 154.0°$
6	72	$-5.51°$	$-5.31°$	$-5.69°$	55.52cm	$27.9° - 151.0°$
7	80	$0°$			62.74cm	$30.9° - 147.9°$
8	88	$5.62°$	$5.46°$	$5.77°$	69.46cm	$33.5° - 145.2°$
9	96	$0°$			76.54cm	$36.1° - 142.6°$

The CTD is a cylindrical drift chamber,[39] bounded by two coaxial cylindrical shells of radius $18.2cm$ and $79.4cm$ and two end plates at $z = -105cm$ and $100cm$(all these numbers are for the active volume). A total of 24192 wires are stretched between the two end plates. These wires are organized into 576 drift