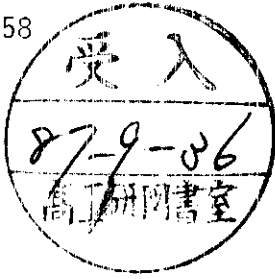


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TEST PROGRAM FOR THE ZEUS CALORIMETER

by

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Test Program for the ZEUS Calorimeter

Robert Klanner
D E S Y

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Abstract

This talk covers some of the experimental studies, which have led to the design of the ZEUS uranium scintillator calorimeter. It is shown how, by varying the scintillator to uranium ratio, equal response for electrons and hadrons and optimum hadronic energy resolution ($\sigma_E/E \sim 35\%/\sqrt{E}$) over a wide energy range can be achieved. A similar optimisation has been done for a lead scintillator calorimeter, and almost equal response for hadrons and electrons together with a hadronic energy resolution of $\sim 44\%/\sqrt{E}$ up to ~ 75 GeV has been achieved. Various practical aspects of calorimetry using scintillator as detector material will also be discussed. The work described in this talk has been done by many members of the ZEUS collaboration.

1. Introduction

The electron collider HERA, presently under construction at DESY, Hamburg, will collide 30 GeV electrons with 820 GeV protons in 1990. Two multipurpose detectors, H1 and ZEUS are in preparation to exploit the physics of HERA.

Figure 1 shows a schematic view of the ZEUS detector [1]. The topic of this paper is the ZEUS high resolution calorimeter CAL, which attempts to achieve the following performance:

- (i) hermeticity for energy measurement over the entire solid angle, excluding only a small region around the beam pipe,
- (ii) best achievable energy resolution for hadrons and hadron jets independent of the jet fragmentation,
- (iii) absolute calibration of the energy scale as well as long term stability and uniformity of the energy scale to better than 2%,
- (iv) angular resolution for jets of ~ 10 mrad,
- (v) energy resolution for electrons of about $\sim 15\%/\sqrt{E[\text{GeV}]}$ and good electron hadron separation,
- (vi) signals shorter than the HERA bunch crossing time of 96 nsec.

The technical solution chosen by the ZEUS collaboration is a sampling calorimeter using plates of depleted uranium as absorber and plastic scintillator, read out via plastic wave length shifter bars, as detector. This talk describes the main features of the proposed calorimeter and the present status of its design.

The sampling structure has been chosen after detailed experimental and theoretical studies of the response of calorimeters with different uranium and scintillator thicknesses, to hadrons, electrons and muons for energies between 3 and ~ 100 GeV. These measurements confirm the recent calculations by H. Brückmann et al. [2] and R. Wigmans [3]. They show how the proper detection of the slow

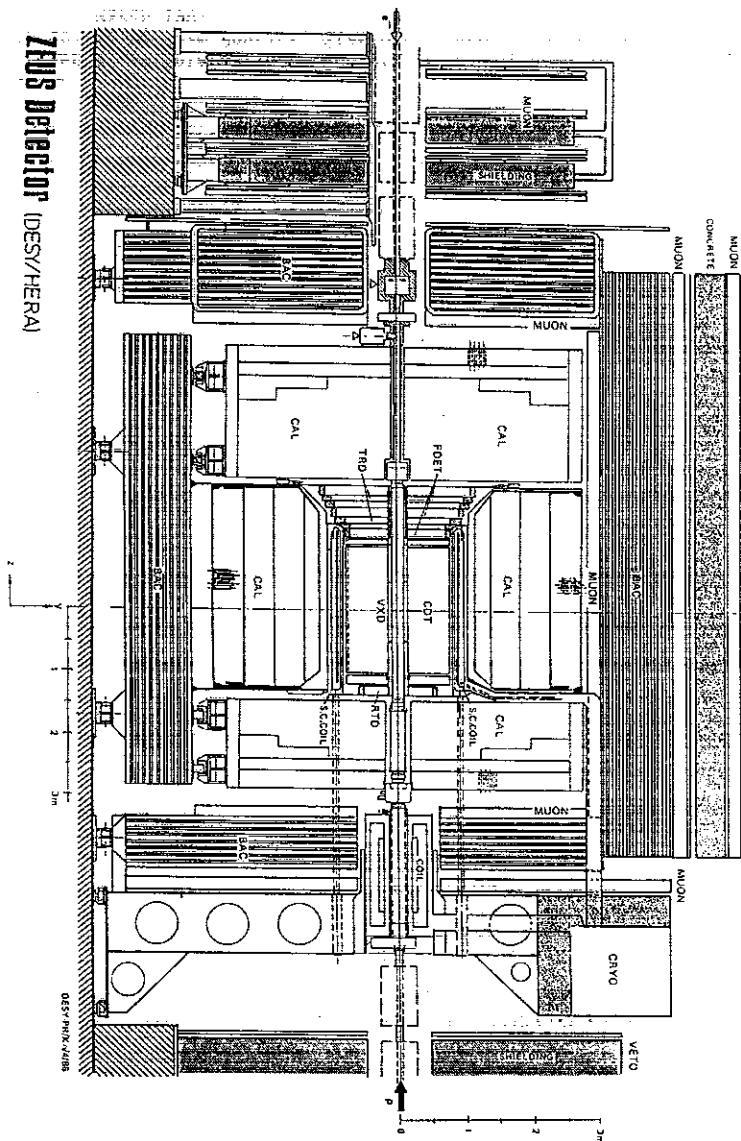


Figure 1: Layout of the ZEUS detector - cut along the beam

neutron component of hadronic showers can be used to optimise the response of hadronic calorimeters. As an extension of this work, a lead scintillator calorimeter has been built, which confirms the prediction, that equal average response for electrons and hadrons, and good hadron resolution can also be achieved for other absorbers than depleted uranium.

The second part of the talk discusses more practical aspects of calorimetry using scintillator as readout material, in particular the question of non-uniformity of response at the boundary between calorimeter modules due to wave length shifters, and finally the sensitivity to radiation damage of plastic scintillator and wave length shifter bars.

2. Layout and Design of the ZEUS Calorimeter

The layout of the ZEUS detector (figure 1) shows that the high resolution calorimeter "CAL" consists of the forward (FCAL), the barrel (BCAL) and the rear section (RCAL). Table 1 gives information on the angular coverage, the depth of the different sections, and number of read out channels.

Table 1: Parameters of the ZEUS High Resolution Calorimeter

Name	FCAL	BCAL	RCAL
range in polar angle	2.3° - 36.4°	36.4° - 130.4°	130.4° - 172°
depth in int. length	7λ	5λ	4λ
# long. readout segments	3	3	2
# readout channels	4096	5440	3212
total absorber weight	200 t	250 t	115 t
total scintillator weight	8 t	16 t	4.5 t

The BCAL consists of 32 identical segments forming a barrel concentric around the HERA beams. FCAL and RCAL consist of rectangular boxes, which build up two walls perpendicular to the beam pipe. The sampling structures in all sections and along the entire depth of the calorimeter are identical: 3.3 mm thick plates of depleted uranium "DU" with ~ 1.7% Nb (density ~ 18.5g/cm³), clad in stainless steel (0.2 mm for the first 25 plates and 0.4 mm for the remainder) alternate with 2.6 mm thick sheets of plastic scintillator "SCI" (SCSN-38 from Kyowa). The longitudinal and transverse segmentations are achieved by wave length shifter bars "WLS". All scintillator tiles are read out from two sides for good uniformity and additional spatial information through "light-division".

The first 25 DU-plates constitute the electromagnetic sections. They are read out by scintillator tiles of about 5 cm x 20 cm area. In the BCAL, whose electromagnetic section is projective in both θ and φ , the dimensions of the scintillators increase with depth. FCAL and RCAL are non-projective. The electromagnetic section is followed by the hadronic sections: one in the RCAL and two in the BCAL and in the FCAL, with depths as given in table 1. The transverse segmentation is 20 cm x 20 cm for FCAL and RCAL. These sections of the BCAL are projective in φ but non-projective in θ ; the dimension of the scintillator tiles is 20 cm x 20 cm, when projected onto the front face of the calorimeter. This segmentation results in a total of 7964 photomultipliers for the electromagnetic sections and 4784 for the hadronic sections for all of the calorimeter sections.

Figure 2 shows a simplified drawing of one of the modules of the FCAL. The module has a sensitive area of 20 cm x 460 cm (width x height). The mechanical elements are a C-frame, the DU plates, an Al front plate and spacers separating the plates. The DU plates are connected via profiles to the upper and the lower legs of the C-frame. Highly tensioned steel straps connect the front plate to the back beam thus clamping the DU-plates. They apply enough force through the spacers, so that the module can resist accelerations during transport and installation. The figure also shows the scintillator tiles as well as the wave length shifter plates and light guides, which transport the light to

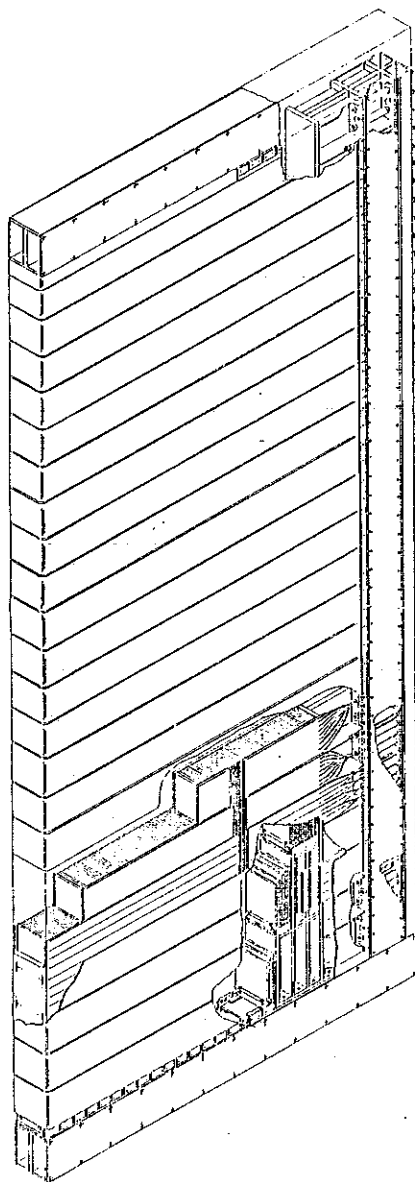


Figure 2: Layout of a ZEUS FCAL module

the photomultipliers located at the back of the modules. The gap between the edges of the uranium plates of adjacent modules, which contains the wave shifters, mechanical structures and enclosure for gas and light sealing, is 1 cm at the electromagnetic section. It increases to 2 cm at the end of the calorimeter. The design of the BCAL modules are similar and we refer to [1] for details. The depth of the high resolution calorimeter has been determined from the requirement, that for 90% of the jets with the maximum jet energy expected in any particular region of the calorimeter, the energy containment is 95%. In this way a high resolution sample of events can be selected in the physics analysis with 90% efficiency using the backing calorimeter (BAC in figure 1) as off-line veto. This optimisation was done using the measured longitudinal shower distributions of hadrons and electrons in a uranium scintillator calorimeter [4] as input into the Lund Monte Carlo code for simulating jets [5].

3. Energy Resolution and the e/h-Ratio

This section investigates the following questions for calorimeters using scintillator as detector and depleted uranium or lead as absorber:

- (i) how does the energy resolution depend on the thickness of the materials (d_{SCI} , d_{ABS})?
- (ii) under which conditions can equal response for the hadronic and the electromagnetic component be achieved?

For our study we have been guided by the present understanding of calorimetry [2,3], which we sketch in a simplified way:

- the energy of the incident hadron is deposited in the calorimeter in form of:

- (i) the electromagnetic component (γ , e),
- (ii) ionising charged hadrons (π , p , etc.),
- (iii) nuclear binding energy,
- (iv) low energy (20 MeV) neutrons from nuclear evaporation and the low energy tail of the intranuclear cascade; neutrons coming from nuclear reactions introduced by secondary neutrons are of less importance,
- (v) low energy γ 's from nuclear deexcitation.

- the hadronic energy resolution σ_h/E_h has contributions from sampling fluctuations, which get reduced if the sampling frequency is increased and which decrease with increasing energy as $\sigma_h/E_h \propto 1/\sqrt{E_h}$.

- additional contributions to σ_h/E_h come from the fluctuations in the way the energy is deposited and the corresponding detection efficiencies. This term decreases slower than $1/\sqrt{E_h}$ with increasing energy, and therefore frequently dominates the energy resolution at high energies. It is minimal if electrons and hadrons give the same response abbreviated as $e/h = 1$. In first approximation e/h depends for a given choice of materials on d_{ABS}/d_{SCI} in the following way:

The response of the contributions (i) and (ii) just depends on the ratio d_{SCI}/d_{ABS} . The term (iii) is not detected at all. The total energy lost in nuclear binding energy however is strongly correlated with the energy given to low energy neutrons (iv). The detection efficiency for the slow neutrons is approximately independent of d_{SCI} . Neutrons lose most of their energy by scattering elastically off the free protons of the scintillator, and hardly via scattering off the heavy uranium nuclei. Since the interaction length of slow neutrons in a typical calorimeter is large compared to the dimensions of the layer structure, decreasing d_{SCI} just results in an energy deposition further away from the interaction point where the neutrons have been produced. The energy deposited in the scintillator however is hardly reduced, if the calorimeter is of sufficient size. We thus expect that e/h decreases with increasing d_{ABS}/d_{SCI} . As the neutrons take a finite time until they lose their energy in the

scintillator we expect e/h to decrease with increased integration time. This has actually been observed experimentally[4].

The contribution (ν) is detected only with low efficiency, if scintillator is used as detector, and can be neglected in the qualitative discussion.

Quantitative predictions for e/h and energy resolutions can be found in [2,3]. For a scintillator thickness $d_{SCI} = 2.5$ mm $e/h = 1$ is predicted for $d_{DU} = 3.2$ mm and $d_{Pb} = 10.0$ mm. This difference in d_{ABS} is due to the reduced production ($\sim 2/3$) of slow primary neutrons in lead compared to uranium.

Table 2 and 3 give an overview of the different hadron calorimeter configurations studied by members of the ZEUS collaboration, as well as the references for a more detailed description.

Table 2: Uranium Scintillator Test Calorimeters

Name	WA 78/HERA	T35	T60A	T60B
d(DU)	10 mm	3 mm	3.2 mm	3.2 mm
d(SCI)	5 mm Ne 110	2.5 mm SCSN-38	5 mm SCSN-38	3 mm SCSN-38
depth	$5.5\lambda + \text{back}$	4.2λ	4.4λ	$6.0\lambda + \text{back}$
area	$60 \times 60 \text{cm}^2$	$60 \times 60 \text{cm}^2$	$60 \times 60 \text{cm}^2$	$60 \times 60 \text{cm}^2$
effective λ	19.1 cm	18.2 cm	33.3 cm	25.7 cm
trans. segmentation	$60 \times 60 \text{cm}^2$	$20 \times 20 \text{cm}^2$	$5 \times 60 \text{cm}^2$	$5 \times 60 \text{cm}^2$
long. segmentation	0.45 λ	4.2λ	1.1 λ	1.5 λ
energy range	5-210 GeV	3-9 GeV	3-9 GeV	10-100 GeV
reference	[4]	[6]	[7]	[7]

Table 3: Lead Scintillator Test Calorimeters

Name	T60C	T36
d(Pb)	5 mm	10 mm
d(SCI)	5 mm SCSN-38	2.5 mm SCSN-38
depth	4λ	$5\lambda + \text{back}$
area	$60 \times 60 \text{cm}^2$	$68.4 \times 66 \text{cm}^2$
effective interaction length	37.1 cm	22.1 cm
transverse readout segmentation	$5 \times 60 \text{cm}^2$	$22.8 \times 22 \text{cm}^2$
longitudinal readout segmentation	1λ	$1\lambda + 4\lambda$
energy range	3-9 GeV	3-75 GeV
reference	[7]	[8]

For the relative calibration of the individual photomultipliers the photocurrent from the uranium radioactivity has been used for the uranium calorimeters. This calibration has been cross-checked using electrons, muons and γ -sources. The calibration of the lead calorimeters has been done with electrons, muons and γ -sources.

As an illustration of the performance of these calorimeters, figure 3 shows the pulse height distribution for electrons, hadrons of different energies and muons of 10 GeV for the experiment T60B. The distributions for hadrons and electrons are well described by gaussian functions for several standard deviations around the most probable value. At higher energies deviations from gaussian distributions are observed for lower pulse heights. They are ascribed to longitudinal energy leakage, and can be removed by eliminating events which have energy deposited in backing calorimeters which follow some of the test calorimeters. Mean values and standard deviations are obtained by fitting gaussian functions in the region ± 3 standard deviations around the mean value.

Figure 4a shows the energy resolution $\sigma_h/\sqrt{E_h}$, and figure 4b the ratio of electron to hadron response e/h for the uranium scintillator calorimeters. Figure 5 shows a comparison of the measured e/h ratio at 10 GeV with the prediction by H. Brückmann et al. [2]. We should notice that in

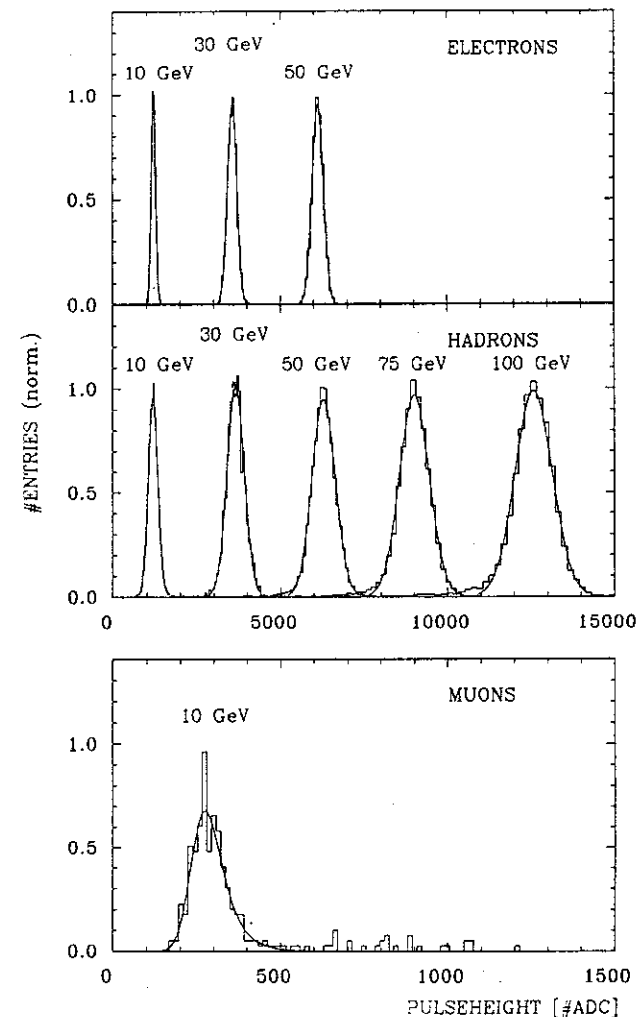


Figure 3: Response of the test setup T60B for:
a) Electrons,
b) Hadrons,
c) Muons.

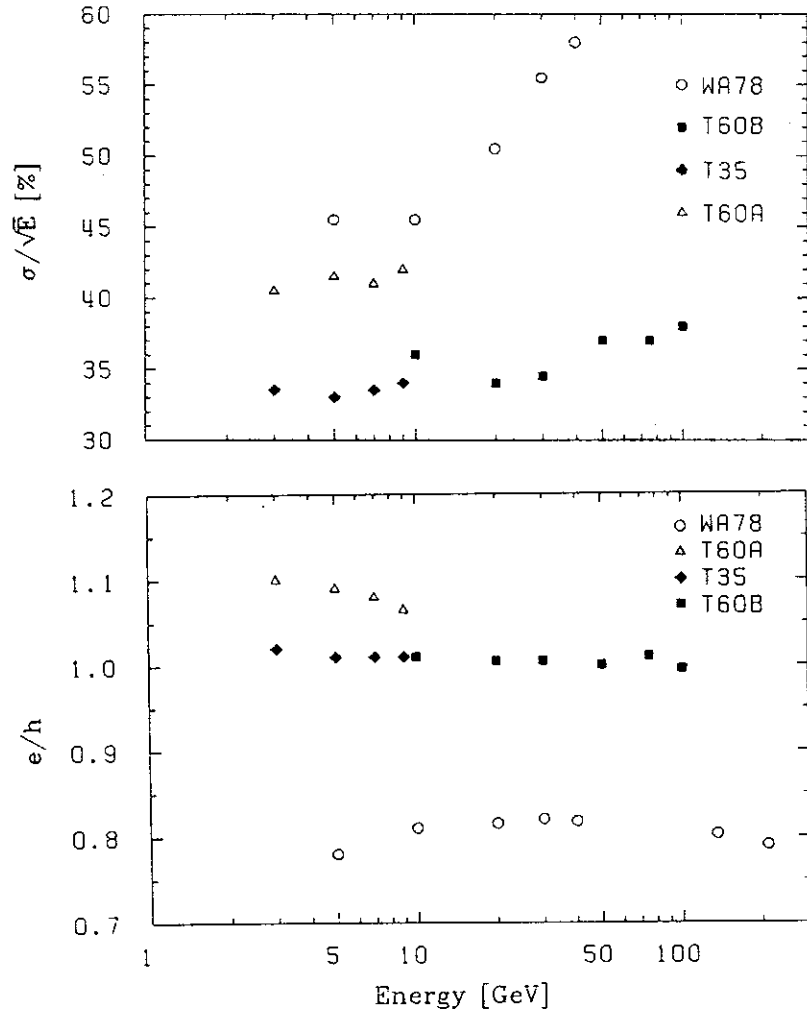


Figure 4: Response of the uranium scintillator test calorimeters as function energy. The data are corrected for transverse leakage and longitudinal readout uniformity.
a) Standard deviation of the hadronic energy distribution $\sigma_h/\sqrt{E_h}$,
b) Ratio of mean electron to hadron response.

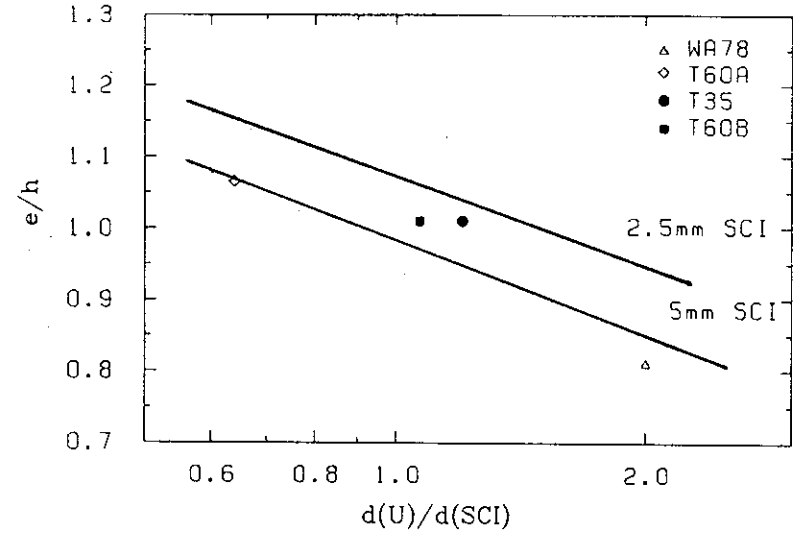


Figure 5: Comparison of the measured electron to hadron ratio at 10 GeV to the predictions of H. Brückmann et al. [2].

particular the e/h ratios are very difficult to measure, as they critically depend on the uniformity of response achieved for the readout. For the data shown, an attempt has been made to correct for these effects to the best of the author's knowledge. For the data of [6], the leakage correction as estimated in the publication has been used.

We note that T35 has achieved an energy resolution of $\sim 34\%/\sqrt{E}$ in the range of 3-9 GeV and T60B a similar resolution at low energies, worsening to about $38\%/\sqrt{E}$ at 100 GeV. These two calorimeters have a ratio of $d_{ABS}/d_{SCI} \cong 1.2$ and both have e/h compatible with 1. The other two tests T60A and WA78/HERA have significantly different d_{ABS}/d_{SCI} ratios. Their e/h ratios are significantly different from one and the energy resolutions are significantly worse, already at beam energies below 10 GeV and even more at higher energies. The data confirm the prediction that the best energy resolution, and the scaling of the resolution as $1/\sqrt{E}$ is achieved only for $e/h \sim 1$.

Figure 6a and 6b show the energy resolutions $\sigma_h/\sqrt{E_h}$ and e/h -ratios for the two lead tests. The data are corrected for nonuniformities and leakage. The response of the T36 calorimeter to electrons and hadrons of different energies, and to muons at 10 GeV is shown in Figure 7.

Like for the uranium calorimeters the response can be well described by Gaussian functions, except for a low energy tail, which is ascribed to leakage, and which can be removed by cuts. For details we refer to the original paper [7,8]. Qualitatively the results are like for the uranium calorimeters. The energy resolution improves with e/h approaching one. For an absorber to detector ratio d_{Pb}/d_{SCI} of about four an e/h -ratio of 1.05 with an estimated uncertainty of 0.05, and an energy resolution of $\sigma_h/\sqrt{E_h} \sim 44\%$ is achieved. For the readout method chosen (plates of scintillator readout via wave length shifter) the chosen 2.5 mm thickness of scintillator represents a practical lower limit. Thus 10 mm Pb plates had to be chosen, which resulted in the poor electromagnetic energy resolution of $\sigma_e/\sqrt{E_e} \sim 24\%$ and possibly in a significant contribution of sampling fluctuations to the hadronic energy resolution.

On the basis of these measurements, detailed Monte Carlo studies and the possibility of using

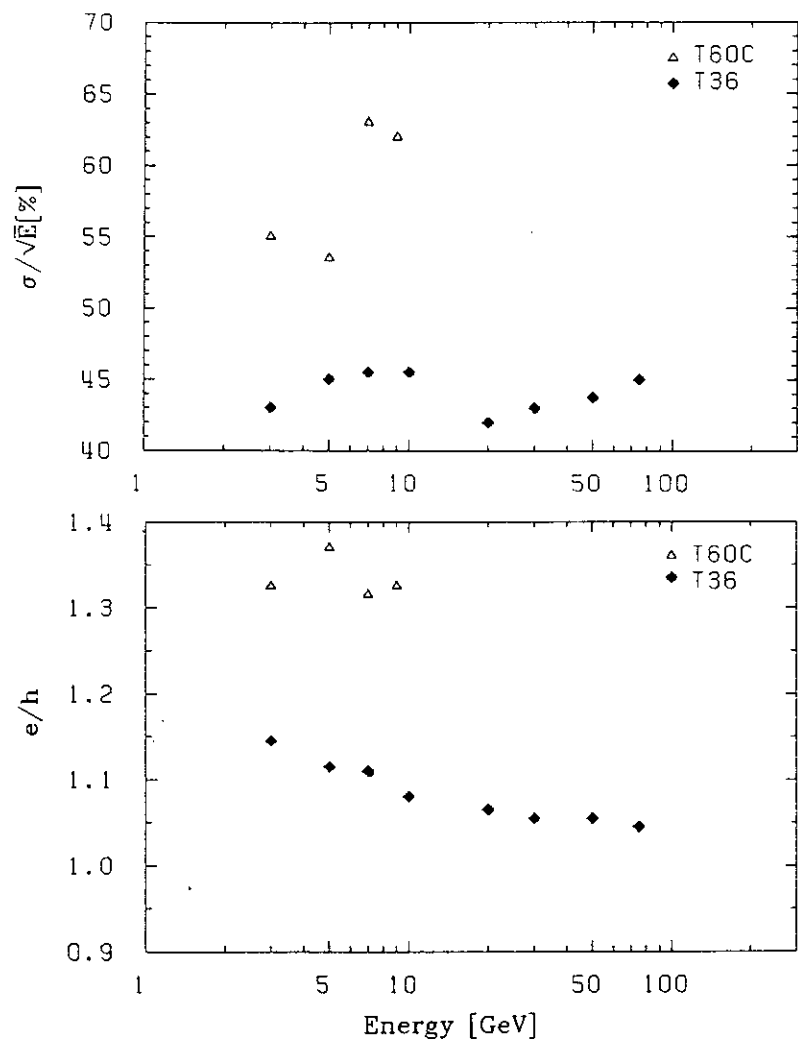


Figure 6: Response of the lead scintillator test calorimeter as function of energy.
 a) Standard deviation of the hadronic energy distribution $\sigma_h/\sqrt{E_h}$,
 b) Ratio of mean electron to hadron response, corrected for transverse energy leakage.

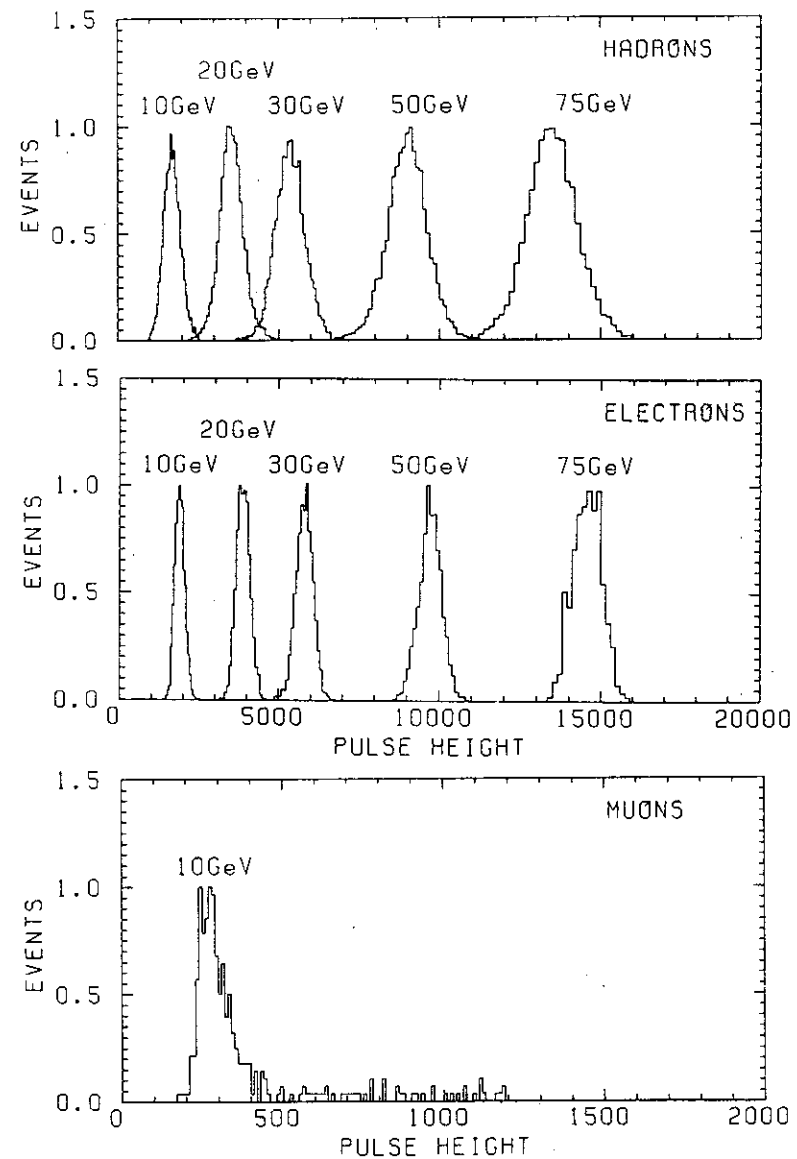


Figure 7: Response of the test setup T36 for:
 a) Electrons,
 b) Hadrons,
 c) Muons.

the natural radioactivity of uranium for calibration, the ZEUS collaboration has chosen a sampling structure of 3.3 mm depleted uranium, clad with thin (0.2 to 0.4 mm) steel sheets, and 2.6 mm of plastic scintillator SCSN-38 for the high resolution calorimeter.

4. Influence of Readout Uniformity

The ZEUS collaboration has set as his goal for the performance of the calorimeter an electromagnetic energy resolution of $15\%/\sqrt{E}$ with a constant term of about 2%, and a hadronic energy resolution of $35\%/\sqrt{E}$ with a constant term below 2%. This can only be achieved via excellent uniformity of response, low noise and precise cell to cell calibration.

Detailed experimental and Monte Carlo studies of the influence of nonuniformity of readout and inhomogeneities of the calorimeter on e/h ratios and energy resolutions have been performed. Here we present measurements, which convince us that the effect of the wave length shifter gap between adjacent modules does not result in an unacceptable calorimeter performance. First we note that in the ZEUS calorimeter, there are no gaps which directly project to the interaction point. As a result all particles will sooner or later traverse absorber material. By choosing the proper response of the wave shifting material to charged particles, via doping with UV-absorbant, the ratio of light yield to energy loss in the wave shifter matches approximately the corresponding ratio in the uranium scintillator calorimeter. In this case the wave length shifter gaps do not worsen the energy resolution, but only change the longitudinal shower distributions. This has been demonstrated by a setup of 3 electromagnetic calorimeters as shown in figure 8a [9]. The sampling structure of the calorimeters were 6 mm of lead and 5 mm of SCSN-38 plastic scintillator. Figure 8b shows the mean response and figure 8c the standard deviation of the energy response for 3 GeV electrons, when scanning the beam over the gap between the calorimeters. The maximum change in response is $\pm 2\%$ in a small region around the gap, and there is hardly any change in the energy resolution. In particular deviations from the gaussian response function are absent. Using the data as input to estimate the energy resolution for hadron jets, indicates negligible effects. These measurements will be repeated with a calorimeter of the final geometry and sampling structure.

5. Radiation Stability of Plastic Scintillator and Wave Length Shifter

Radiation damage of the optical components is one of the major worries if one uses scintillator to read out a calorimeter at a high luminosity storage ring. There are many reports of performance degrading with time, due to the radiation damage or scintillator aging.

The systematic investigation of radiation damage is difficult due to the many parameters on which it depends like:

- production technology of the material,
- purity of the base materials,
- type of ionising radiation,
- radiation dose and dose rate,
- environmental conditions (gas, temperature, humidity ...).

Members of the ZEUS collaboration [10] have started systematic studies for the materials to be used in the ZEUS calorimeter: SCSN-38 for plastic scintillator, plexiglass doped with K-27 or Y7 for wave length shifting, and plexiglass doped with UV-absorbant as light guide. Irradiations have been done with 25 MeV protons, γ 's from ^{60}Co and low energy electrons for different doses, dose rates,

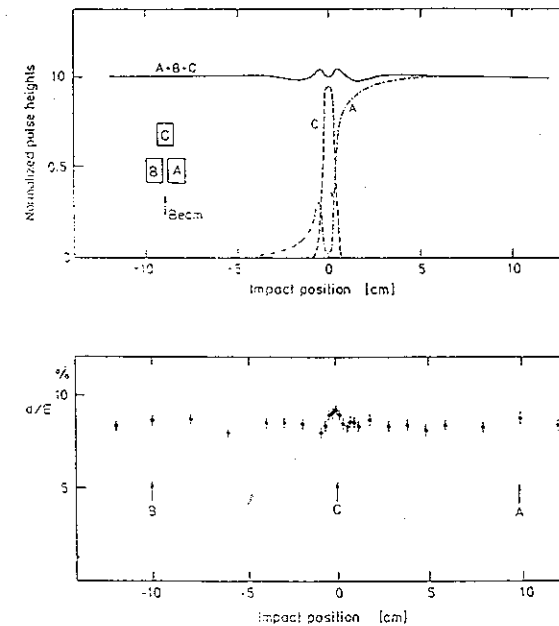
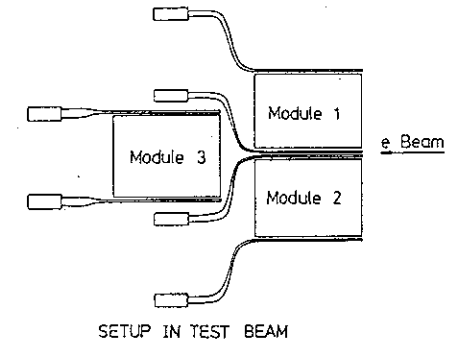


Figure 8: Three calorimeter test to measure the influence of the wave length shifter gap on the response of a lead scintillator calorimeter.

- a) Experimental Setup,
- b) Mean energy ($\langle E \rangle$) as function of impact point of the beam for 3 GeV electrons,
- c) Standard deviation of the energy distribution as function of the impact point of the beam for 3 GeV electrons.

in air, nitrogen and argon. The investigations include light transmission measurements as function of wave length using a spectral photometer for thin samples (typically few mm). For longer samples light yield and light transmission over longer distances are measured by scanning the scintillator with light from a pulsed UV lamp appropriately filtered, or electrons from radioactive sources. The pulse heights of individual events are measured and accuracies below $\sim 1\%$ are achieved.

Figure 9 shows a typical result. A SCSN-38 bar of dimensions 0.3 cm x 2 cm x 26 cm has been irradiated with protons of 25 MeV to a total dose of 1 kGy, leaving 3 narrow regions at the beginning, middle and end of the strip non-irradiated. The atmosphere was either air or nitrogen. For the measurement one edge of the scintillator was covered with black velvet, the other edge coupled via a wave length shifter to a photomultiplier. The light was excited via a Xenon flashlamp filtered to a wave length of ~ 340 nm. Figure 9 shows the ratios of light yields after irradiation to before irradiation as function of the distance from the wave length shifter. The measurements were done 2 days and 9 days after irradiation and storage in the indicated gases. A comparison of light yield ratios in the non-irradiated region in the center to the close-by irradiated regions measures the change in light yield. The dependence of the decrease of the ratio on the distance from the wave length shifter measures the attenuation of the light. In both air and nitrogen, we find a small (few percent) decrease of the produced light, whereas there is a significant increase in light attenuation in particular for the exposure in nitrogen.

Figure 10 shows for irradiation with 1 kGy and 10 kGy the change in light yield, as defined above, and the change in light attenuation, defined as:

$$\frac{\text{Light}(x = 18.8\text{cm})/\text{Light}(x = 2.8\text{cm})_{\text{irradiated}}}{\text{Light}(x = 18.8\text{cm})/\text{Light}(x = 2.8\text{cm})_{\text{non irradiated}}}$$

as a function of the days between irradiation and measurement. It can be concluded that at 10 kGy there is about a 5% reduction in light yield, possibly slowly recovering with a time constant of more than 100 days, quite independent of the gas. The light transmission is strongly reduced, in particular in nitrogen; it however recovers with time constants of the order of hundred days. These observations have been confirmed by measurements with low energy electrons and the spectral photometer. We should also note that in the region of highest radiation dose in the ZEUS experiment, the maximum scintillator dimensions are ~ 20 cm.

For a wave length shifter made from plexiglas with 120 mg/l K-27 doping, irradiated to 10 kGy via 25 MeV protons, the measurements are shown in figure 11. There is a strong radiation damage in air and in nitrogen. Whereas the damage completely recovers in air after about 100 days, it is permanent or even worsening in nitrogen. For the ZEUS calorimeter the maximum length of wave length shifters is about 70 cm.

The maximum radiation dose to which the optical components of the ZEUS calorimeter will be exposed have been estimated to be:

- 6 Gy per year from uranium with 0.2 mm cladding
- 2.2 Gy per year from uranium with 0.4 mm cladding
- 300 Gy per year from HERA, close to the beams
- 10 Gy per year from HERA, about 1.2 m away from the beam.

The studies of radiation damage are continuing, but presently we think that with the chosen materials for scintillator, wave length shifters and light guides and special care in particular at the early stages of HERA (e.g. move front and rear calorimeters 40 cm away from the beam during injection) we shall be able to cope with the problems of radiation damage.

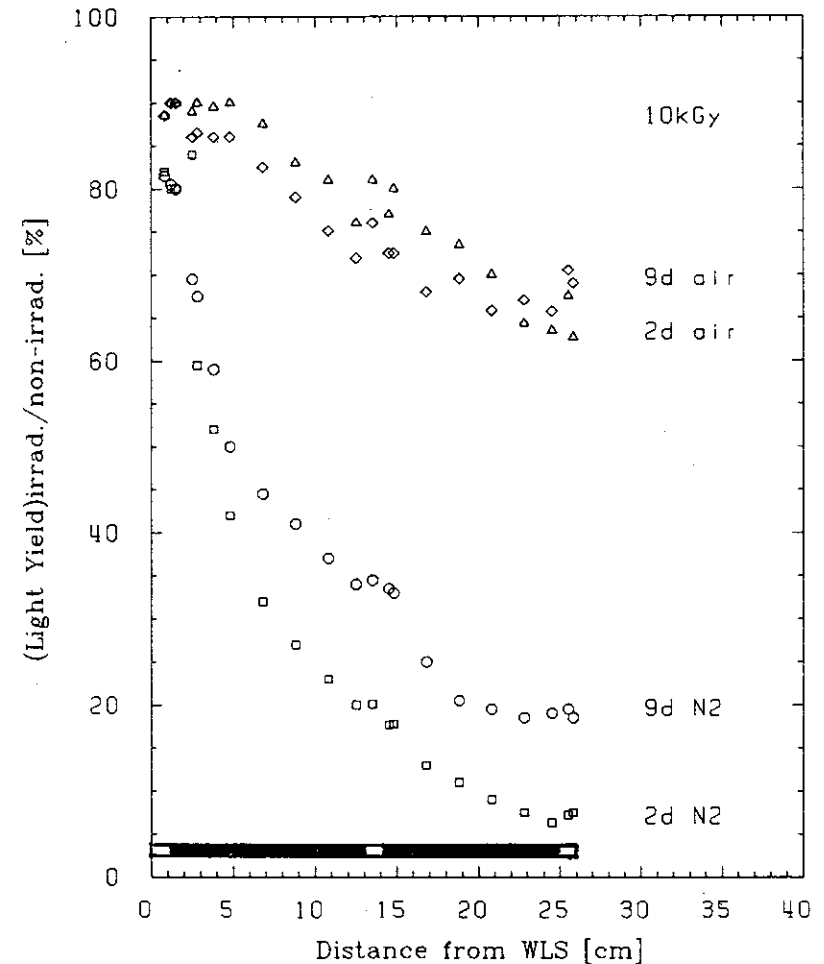


Figure 9: Radiation damage studies for 2.5 mm thick plastic scintillator SCSN-38. Shown is the pattern of irradiation and the ratio of pulse height measured by excitation with light from a Xenon lamp after and before irradiation. Data presented for irradiation with 10 KGy of 25 MeV protons for material stored in air and nitrogen. Measurements have been done 2 days and 9 days after irradiation.

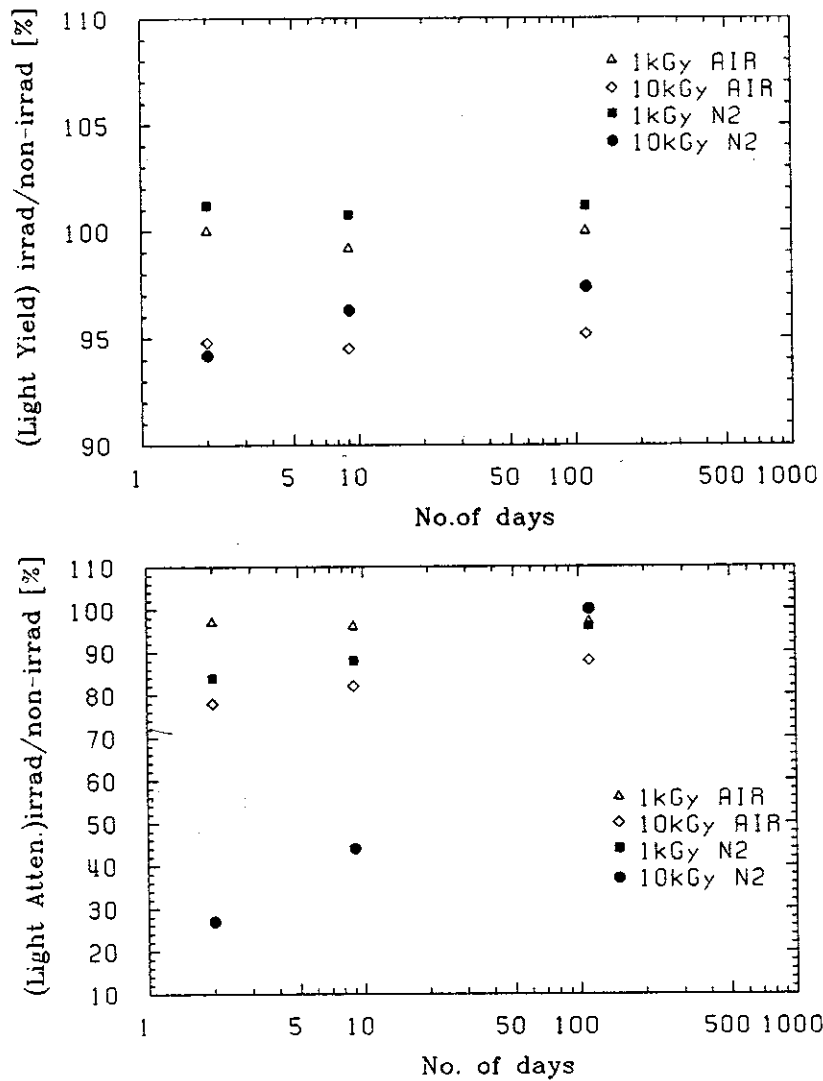


Figure 10: Measurement of light yield and light attenuation for 2.5 mm thick scintillator SCSN-38 for 1 kGy and 10 kGy irradiation with 25 MeV protons. Measurements are done for material stored in air or nitrogen and have been performed 2, 9 and 111 days after the irradiation. For the exact definition of the quantities measured see text.

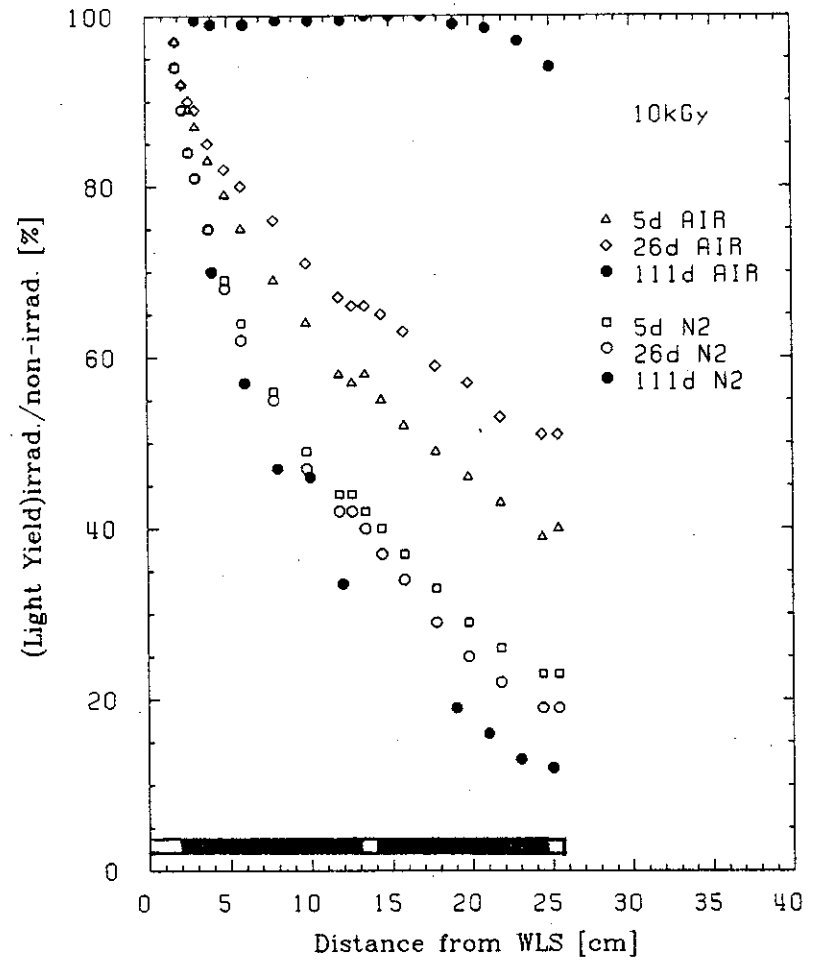


Figure 11: Radiation damage studies for 2 mm thick plexiglass doped with 120 mg/l K-27. Shown is the pattern of irradiation and the ratio of pulse height measured by excitation with light from an SCSN-38 scintillator after and before irradiation. Data are shown for irradiation with 10 kGy of 25 MeV protons for materials stored in air and nitrogen. Measurements have been done 5, 26 and 111 days after irradiation.

6. Conclusions

This talk gives a short review of some of the research and development work done by the ZEUS collaboration towards a high resolution calorimeter for the HERA storage rings. The most important results are:

- the technique of achieving equal response for electrons and hadrons and an energy resolution of $\sigma/E \sim 35\%/\sqrt{E}$ for hadrons using uranium as absorber and plastic scintillator as pioneered by Fabjan and Willis [11] has been confirmed. The measurements quantitatively follow the recent predictions. In particular they confirm the important role of the proper detection of the signal from low energy neutrons,
- it has been shown for the first time that compensation can also be achieved using lead and scintillator,
- various problems related to nonuniformities in a calorimeter using scintillator and wave length shifter have been studied and partially solved,
- studies of radiation damage indicate that by proper choice of materials and gases this problem can be overcome

During 1987 ZEUS will build prototype calorimeters with the final geometries to confirm the optimisation which has led to the present design. The start of the construction of the final calorimeter modules is planned for the first half of 1988.

Acknowledgement

The author would like to thank his many colleagues working on the calorimeter of the ZEUS detector for their collaboration, and the permission to present some of their work. The measurement would not have been possible without the excellent technical help from our home institutes, in particular from NIKHEF-H at Amsterdam, DESY at Hamburg, and the Universities of Hamburg and Rome. Most of the beam tests have been performed at CERN, and we should like to thank for the hospitality and the technical support.

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Table Captions

Table 1: Parameters of the ZEUS High Resolution Calorimeter.

Table 2: Uranium Scintillator Test Calorimeters.

Table 3: Lead Scintillator Test Calorimeters.

Figure Captions

Fig. 1 : Layout of the ZEUS detector - cut along the beam

Fig. 2 : Layout of a ZEUS FCAL module

Fig. 3 : Response of the test setup T60B for:

- a) Electrons,
- b) Hadrons,
- c) Muons.

Fig. 4 : Response of the uranium scintillator test calorimeters as function energy.

The data are corrected for transverse leakage and longitudinal readout uniformity.

- a) Standard deviation of the hadronic energy distribution $\sigma_h/\sqrt{E_h}$,
- b) Ratio of mean electron to hadron response.

Fig. 5 : Comparison of the measured electron to hadron ratio at 10 GeV to the predictions of H. Brückmann et al. [2].

Fig. 6 : Response of the lead scintillator test calorimeter as function of energy.

- a) Standard deviation of the hadronic energy distribution $\sigma_h/\sqrt{E_h}$,
- b) Ratio of mean electron to hadron response, corrected for transverse energy leakage.

Fig. 7 : Response of the lead scintillator calorimeter T36 for:

- a) Electrons,
- b) Hadrons,
- c) Muons.

Fig. 8 : Three calorimeter test to measure the influence of the wave length shifter gap on the response of a lead scintillator calorimeter.

- a) Experimental Setup,
- b) Mean energy $\langle E \rangle$ as function of impact point of the beam for 3 GeV electrons,
- c) Standard deviation of the energy distribution as function of the impact point of the beam for 3 GeV electrons.

Fig. 9 : Radiation damage studies for 2.5 mm thick plastic scintillator SCSN-38. Shown is the pattern of irradiation and the ratio of pulse height measured by excitation with light from a Xenon lamp after and before irradiation. Data presented for irradiation with 10 KGy of 25 MeV protons for material stored in air and nitrogen. Measurements have been done 2 days and 9 days after irradiation.

Fig. 10 : Measurement of light yield and light attenuation for 2.5 mm thick scintillator SCSN-38 for 1 kGy and 10 kGy irradiation with 25 MeV protons. Measurements are done for material stored in air or nitrogen and have been performed 2, 9 and 111 days after the irradiation. For the exact definition of the quantities measured see text.

Fig. 11 : Radiation damage studies for 2 mm thick plexiglass doped with 120 mg/l K-27. Shown is the pattern of irradiation and the ratio of pulse height measured by excitation with light from an SCSN-38 scintillator after and before irradiation. Data are shown for irradiation with 10 kGy of 25 MeV protons for materials stored in air and nitrogen. Measurements have been done 5, 26 and 111 days after irradiation.