Implementation of a compensating calorimeter in the Zeus detector
Aims of the Zeus detector:

- High precision measurement of the nucleon structure functions
- Investigation of the scale breaking effects in $F_2(x, q^2)$

Resulting requirements for the calorimeters:

- Large area in the $(q^2, x)$ space has to be accessible
- Access to the very low $x$ region
Neutral current events:

Kinematic properties can be derived from lepton and jet characteristics
→ Redundancy and increased precision due to measurements of the electron

In order to achieve maximal resolution for hadronic jets a compensating calorimeter is required

Charged current events:

Information about kinematics only available from jet measurements
→ Hadronic jet measurements have to be as precise as possible
Design summary of the Zeus calorimeters:

- Compensating calorimeter with $\frac{e}{h} = 1$ within 1%
- High resolution for em and hadronic calorimeter
- Precise direction measurement of the fragmenting quark
  $\rightarrow$ High angular resolution for jets
- Hermetic over the $4\pi$ solid angle
- Good calibration to 1% level
- Uniform response
Realization of these design parameters
The correct thickness ratio between Uranium absorber plate and scintillating plate to achieve compensation was determined by Monte Carlo studies and prototype testing:
Results of measurements with test modules:

<table>
<thead>
<tr>
<th>Setup</th>
<th>Energy [GeV]</th>
<th>EM Resolution</th>
<th>Had Resolution</th>
<th>e/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>5mm lead, 5mm scintillator</td>
<td>5</td>
<td>0.136</td>
<td>0.534</td>
<td>1.35±0.06</td>
</tr>
<tr>
<td>3.2mm Uranium, 5mm scintillator</td>
<td>5</td>
<td>0.155</td>
<td>0.416</td>
<td>1.12±0.05</td>
</tr>
<tr>
<td>3.2mm Uranium, 3mm scintillator</td>
<td>30</td>
<td>0.186</td>
<td>0.391</td>
<td>1.00±0.05</td>
</tr>
<tr>
<td>3.2mm Uranium, 3mm scintillator, attenuation correction</td>
<td>30</td>
<td>0.181</td>
<td>0.353</td>
<td>1.01±0.05</td>
</tr>
<tr>
<td>3.2mm Uranium in steel foil, 3mm scintillator, attenuation correction</td>
<td>30</td>
<td>0.179</td>
<td>0.342</td>
<td>0.96±0.05</td>
</tr>
</tbody>
</table>
A closer look on the calorimeter modules of the FCAL

- Depleted uranium (DU) plates interleaved with plastic scintillator tiles
- Uranium plates were clad in stainless steel for safety reasons
- Thickness ratio of 3.3mm (Uranium) to 2.6mm (scintillating plates) achieves compensation
- Two PMTs for each scintillating plate
Sources of non uniformities:

- Light attenuation in the scintillating tiles
  → Resolved by using the signal of both PMTs and adding a correction pattern around the plates
- Light attenuation in the WLS
  → Additional reflecting foils to correct for the attenuation
- Cerenkov light in the WLS bars
  → 2mm thick lead foils between adjacent calorimeter modules
Calibration of the calorimeter system

Several methods were implemented for calibration purposes:

- Natural radioactivity from the uranium plates
- $^{60}$Co-sources which can be moved along the WLS bars
- Laser system for calibration of the PMTs and measurement of the timing resolution
Signals from the uranium radioactivity (UNO signals) can be used to calibrate the entire optical readout system.

The current \( I_{UNO} \) is directly proportional to the gain of the measured uranium signal.

Uranium signal
Integration Time 10 \( \mu \text{s} \)

[Graph showing pulse height vs. number of events with a peak around 200 ADC counts]
Measurements of the ratio $\frac{e^-}{UNO}$ and $\frac{\mu^-}{UNO}$ over time show that the UNO signals can be used to monitor changes in PMT gains at the level of 1%. The spread in the mean values from the electron and muon signals was as large as 5%.
Noise in the RCAL measured by empty triggers:
Test beams with electrons, pions and muons

Response to electrons and hadrons
Linearity and energy resolution:

- Response to electrons linear within 1% over the entire energy range
  
  Energy resolution for electrons: \( \frac{\sigma}{E} = \frac{18\%}{\sqrt{E}} \)

- Linearity of the response to hadrons can be derived from the \( e/\pi \) signal ratio

  Energy resolution for hadrons: \( \frac{\sigma}{E} = \frac{35\%}{\sqrt{E}} \)
The resulting $e/h$ signal ratio:

The ratio equals 1 within 1% for kinetic energies $E_{kin} > 3\text{GeV}$
Summary

The calorimeters of the Zeus project achieved compensation for energies above 3\text GeV.

The high energy resolution of \(\frac{35\%}{\sqrt{E}}\) for hadrons and \(\frac{18\%}{\sqrt{E}}\) for electrons was reached.

The required calibration levels for high precision measurements were achieved using natural radiation of the depleted uranium tiles.
Backup Slides

Correction of light attenuation in the scintillating tiles:

Correction of light attenuation in the wavelength shifter bars:
Effect of lead foil between the modules on the produced Cerenkov light: