LENGTH OF CALORIMETERS
AND
EFFECT OF ABSORBERS IN FRONT OF CALORIMETERS

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ABSTRACT
A detailed analysis of the longitudinal hadron shower development was
performed with the longitudinally finely segmented WA78 calorimeter
at CERN (5–210GeV). The shower containment studies allow an optimi-
zation of the depth of hadron calorimeters and a reasonable extra-
polation for particles and jets to very high energies (∼1TeV).
The effect of absorbers in front of calorimeters on hadrons, electrons
and jets was studied systematically with the FCAL calorimeter proto-
type at CERN (0.5–100GeV).

1. LENGTH OF CALORIMETERS
1.1 INTRODUCTION
The optimum length of a hadron calorimeter is directly related to the longitu-
dinal development of hadron showers.

Longitudinal shower profiles have been measured for single particles and jets
with the WA78 hadron calorimeter at CERN in the energy range from 5GeV to
210GeV [1],[2].

A detailed analysis on the shower containment and the influence of dead ma-
terial (PM-boxes) inside the calorimeter was performed in particular with respect
to the optimization of the depth of the high resolution ZEUS uranium scintillator
calorimeter (σn/E ∼ 35%/√E) and extrapolations to higher energies.

1.2 THE WA78–H1–ZEUS CALORIMETER TEST
The WA78 hadron calorimeter (Fig. 1) consists of two parts with different
absorber material, upstream uranium layers (60 x 60 x 1 cm³) and down-
stream iron layers (60 x 60 x 2.5 cm³). The 1. part (5.4λ) was operated with 12 modules
of depleted uranium (10mm)/scintillator (5mm), 4 elements per module (0.45λ)
and the 2. part (8λ) with 13 modules of iron (25mm)/scintillator (5mm), also 4
elements per module (0.62λ).

Fig. 1 The Experimental Set Up of the WA78–H1–ZEUS Test
1.3 LONGITUDINAL HADRON SHOWER DEVELOPMENT AND SHOWER CONTAINMENT

The WA78 calorimeter has the advantage of a fine longitudinal segmentation and in addition the measurements allow a reasonable extrapolation to higher energies ($\approx 1$ TeV).

![Energy Deposit Graphs](image)

**Fig. 2** Longitudinal Shower Profiles for Hadrons between 5 to 210 GeV for all Events

**Fig. 3** Longitudinal Shower Profiles for Hadrons between 5 to 210 GeV for Events with Shower Vertices in the First Module

Figure 2 shows the longitudinal hadron shower profiles from 5 to 210 GeV for all hadrons (= single hadrons) as function of the calorimeter depth in units of nominal interaction lengths $\lambda$. Figure 3 is similar to Fig. 2, but for events with shower vertices in the first module ($0.45\lambda$) of the calorimeter. These events are considered to behave like jet-like objects and are also called jets in the following.

A phenomenological function has been fitted to the data. The curves are overlayed and in good agreement with the data for energies above 10 GeV.

The parametrization of the energy deposit $dE/dx(x)$ (Fig. 3) as function of the distance $x$ in interaction lengths from the shower vertex is:

$$\frac{dE}{dx}(x) = E_0 \left\{ \alpha \frac{b^{a+1}}{\Gamma(a+1)} x^a e^{-bx} + (1 - \alpha) c e^{-cx} \right\}$$

where $E_0$ is the incident energy, $a=3$, $b/(\lambda^{-1})=19.5$, $\alpha=0.13\pm0.02$ and $c/(\lambda^{-1})=(0.67\pm0.03)-(0.166\pm0.003) \ln(E_0[\text{GeV}]/50)$.

The shower distributions measured from the front end of the calorimeter ($t$) for all hadrons are given by the convolution of $dE/dx(x)$ with the shower vertices:

$$\frac{dE}{dt} = \frac{1}{\lambda_s} \int_0^t e^{-\frac{x}{\lambda_s}} \frac{dE}{dx} \left( t - x \right) dx$$

where $\lambda_s = 1.11$ represents the interaction length of the incoming hadrons.

In order to determine the optimum length of a calorimeter the fraction of events with a certain shower containment has to be known. The fractions of all hadrons and jets with a shower containment of 95% in the calorimeter as function of the calorimeter depth are presented in Fig. 4 and 5. The criterium for the depth of the ZEUS calorimeter was for example that 90% of the jets are contained in the uranium scintillator calorimeter with 95% of their energy [3].
1.4 Leakage Due to Dead Areas

The data offers also the possibility to investigate the influence of dead material, such as PM boxes, at various places inside the calorimeter [1].

The influence on the resolution due to the shower energy lost in the dead material of 0.6λ behind 5.4λ has been studied for 40GeV jets and behind 7.2λ for 135GeV jets. The chosen calorimeter configuration is presented in Fig. 6. It consists of a high resolution hadron calorimeter (a) plus (veto readout section (necessary only for very high energies) (b),) dead material (PM boxes) (c) and a coarser backing calorimeter (d).

The fraction of events contributing to nongaussian tails due to the energy lost in the dead material (PM boxes) is measured in units of the calorimeter resolution for hadrons ($\sigma_h/E=35%/\sqrt{E}=\sigma_{35}$) as function of the calorimeter depth. This is shown for jets in Fig. 7 and 8 if less than 2% of the shower energy is deposited in the backing calorimeter ($E_{BAC}$ < 2%, valid for about 90% of the events).

With a calorimeter depth of 5.4λ about 2.6% of the 40GeV jets are shifted additionally outside $1\sigma_{35}$ and 0.6% outside $2\sigma_{35}$.

For a corresponding investigation with a calorimeter depth of 7.2λ and 135GeV jets about 3% are additionally outside $1\sigma_{35}$ and 0.6% outside $2\sigma_{35}$.
1.5 EXTRAPOLATION TO 1 TEV PARTICLES AND JETS

As already mentioned a reasonable extrapolation to higher energies is also possible with these data [4].

The calorimeter depth needed for a certain shower containment (90%, 92.5%, 95%, 97.5%) as function of the energy is presented for 95% of single hadrons in Fig. 9 and for 95% of jets in Fig. 10. An extrapolation to 1 TeV is also indicated.
Figure 11 and 12 show the calorimeter depth necessary for 1 TeV single hadrons and jets (extrapolations) with a certain shower containment as function of the fraction of single hadrons and jets.

For 85% - 90% of the 1 TeV jets with a shower containment of 98.75% a calorimeter depth of about 10\(\lambda\) is needed or correspondingly for 95% of the 1 TeV jets with a shower containment of 95% also a calorimeter depth of about 10\(\lambda\) is necessary.

At 1 TeV the relative energy resolution of a high resolution hadron calorimeter with \(\sigma_{\text{h}}/E \approx 35%/\sqrt{E}\) approaches 1%.

In order not to lose this excellent energy resolution at very high energies due to energy lost in the dead material of the PM boxes a very promising solution is to install an additional readout section in front of the dead material as veto counter to select events fully contained in the high resolution calorimeter as indicated in Fig. 6.

2. EFFECT OF ABSORBERS IN FRONT OF CALORIMETERS
2.1 INTRODUCTION

Very often tracking chambers, a magnet coil and various mechanical constructions are installed in front of a calorimeter. For example the material in front of the high resolution ZEUS uranium scintillator calorimeter is over a wide range about 1-1.5 radiation lengths \(X_0\). But there are also narrow peaks up to 4 \(X_0\) at a few small regions where mechanical constructions are necessary. This material degrades the measured signal and the energy resolution of the calorimeter.

2.2 MEASUREMENT PROGRAM WITH THE FCAL PROTOTYPE

Systematic measurements with various thicknesses of absorber (Al) in front of the ZEUS forward calorimeter (FCAL) prototype [5] have been performed at CERN in the energy range from 0.5 to 100 GeV to determine quantitatively the effect of absorbers [6],[4].

The FCAL prototype (Fig. 13) consists of four modules with a front area of 80cm x 80cm (4 x (20cm x 80cm)), a depth of 2m (7\(\lambda\)) and 192 PMs [8].

![Fig. 13 The Module, Tower and Longitudinal Structure of the FCAL Prototype](image)

The experimental set up used at CERN consisted of the scintillation beam counters B1, B2, B3 and B4 defining the beam, two Cherenkov counters C1 and C2 and the FCAL prototype calorimeter itself (Fig. 14).
Fig. 14  The Experimental Set Up with the FCAL Prototype at CERN

Without material in front of the prototype the energy resolution is \( \sigma_h/E = 35\% / \sqrt{E} \) for hadrons and \( \sigma_e/E = 18\% / \sqrt{E} \) for electrons.

The main points of the measurement program are listed in the following:

**Hadrons and Electrons**
- Absorber in front: Aluminium 0cm, 9cm, 18cm, 27cm (= 0, 1, 2, 3 \( \times_0 \))
- Energy:
  - at CERN PS: 0.5, 1, 2, 3, 5 GeV
  - at CERN SPS: 10, 20, 30, 75 GeV

**Hadrons and Interaction Trigger – Jets**
- Absorber in front: Aluminium 0cm, 4cm, 10cm
- Energy: at CERN SPS: 50, 100 GeV

2.3 EXPERIMENTAL RESULTS

Fig. 15 Pulse Height Spectra for 30GeV Electrons without and with 27cm Al in Front of the Calorimeter

Fig. 16 Pulse Height Spectra for 30GeV Pions without and with 27cm Al in Front of the Calorimeter

Figure 15 and 16 show the pulse height spectra for electrons and pions at 30GeV without and with 27cm Aluminium absorber (3\( \times_0 \)) directly in front of the prototype. With absorber in front the mean values of the spectra are shifted significantly to lower values and the widths of the distributions increase.
Figure 17 and 18 show for electrons and hadrons at 30 GeV the ratio of the mean signal height and the standard deviation with material ($<Q>$, $<\sigma>$) and without material ($<Q_0>$, $<\sigma_0>$) as function of the absorber thickness in front of the calorimeter. For 1 $X_0$ material in front the mean value is reduced by about 1% for hadrons and 2% for electrons and decreases significantly in particular for electrons with increasing absorber thickness. The widths increase with absorber material in front and are for 1 $X_0$ by about 3% larger for electrons and 9% for hadrons.

Figure 19 shows the ratio $<Q>/<Q_0>$ for 9 cm, 18 cm and 27 cm Aluminium absorber as function of the particle momentum. The deviation from 1 is large at low momenta and is decreasing with increasing momentum. Monte Carlo simulations have been performed and a similar behaviour has been found [7].
Fig. 20  $e/h$ as Function of the Kinetic Energy $E_{KIN}$ for $p, \pi^+, \pi^-$

Figure 20 shows the $e/h$ ratios at equal kinetic energies $E_{KIN}$ for $\pi^+, \pi^-$ and $p$ [5]. $e/h$ is the same for $\pi^+, \pi^-$ and $p$ and depends in first approximation only on the kinetic energy $E_{KIN}$, the energy available for particle production and energy deposit in the calorimeter. At low energies hadrons lose more and more of their energy via $dE/dx$ and give the sampling fraction of a minimum ionizing particle (mip). Thus $e/h$ approaches $e/mip$, which is 0.62 in the present calorimeter. Due to the fact that the electron response $e$ corresponds essentially to the kinetic energy the ratio $<Q>/E_{KIN}$ shows with absorber in front less deviations from 1.

$$<Q>/E_{KIN}$$

Fig. 21  Ratio of the Mean Signal Height ($<Q>$) and the Kinetic Energy $E_{KIN}$ as Function of the Momentum

The normalized ratio $<Q>/E_{KIN}$ is shown in Fig. 21 for hadrons as function of the momentum. The different curves show the dependence of the absorber thickness. The deviation from $<Q>/E_{KIN} = 1$ is significantly reduced compared to $<Q>/<Q_0>$.

The analysis of the data taken with the interaction trigger in front of the FCAL prototype is in progress [8].
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