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G.Barbiellini, G.Cecchet, J.Y.Hemery, F.Lemeilleur, C.Leroy, G. Levman, P.G.Rancoita and A.Seidman : ENERGY RESOLUTION AND LONGITUDINAL SHOWER DEVELOPMENT IN A Si/W ELECTRO-MAGNETIC CALORIMETER

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Energy resolution and longitudinal shower development in a Si/W electromagnetic calorimeter

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Abstract: The performance of a silicon/tungsten sandwich calorimeter has been investigated for incoming electron energies between 4 and 49 GeV. The calorimeter has an energy response which is linear to better than 1%, and an energy resolution of $\sigma(E)/E = (17.6 \pm 0.3)\% \sqrt{\tau/E}$, where τ is the number of radiation lengths of passive material interspaced between two active samplers. The longitudinal shower development has been fitted to a two exponential component fall-off beyond the shower maximum.

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1. Introduction

In the last years, silicon detectors have evolved as major devices in high-energy physics experiments [1]-[3], thanks to their high resolution, fast transit time, and their ability to operate in strong magnetic fields, in vacuum, and under geometric constraints.

In calorimetry large area detectors are usually needed but compact active elements sampling high Z materials are a substantial advantage for detectors used in collider experiments, thus relatively low resistivity, not fully depleted (undepleted) silicon devices can be used [4]-[6]. Silicon detectors and associated electronics have been developed in the last two years [6] and experimentally applied in electromagnetic calorimetry since they allow the construction of compact and stable calorimeters. Their leakage current is low (about 0.5-1.0 μA), their active area is large ($25 cm^2$), and they are operated undepleted [6]. The mean depleted layer has been set to 200 μm, although the physical thickness is between 220-300 μm.

This paper presents experimental results concerning the performance of a Si/W sandwich calorimeter: energy response, energy resolution, and longitudinal shower development as functions of the incoming electron energy.

2. Performance of silicon detectors and electronics

A study of the silicon detector capacitance, C_d, as a function of applied reverse bias voltage, V, has shown a good agreement (at better than 0.3%) with a step junction behaviour ($1/C_d \propto \sqrt{(V+V_B)}$), a built-in voltage of $V_B \approx 0.5$ V and no systematic resistivity variation across the detector. Furthermore, a systematic study of the depleted layer width variation across the detectors was carried out by exposing the devices to a 100 GeV/c proton beam at CERN-SPS. The energy-loss spectra, sensed by the devices, were recorded as a function of the proton impact position. From the measurement of the most probable energy loss, which is proportional to the depleted layer width, the variation of the depleted region width, ΔX_d, across the detector was determined to be $\Delta X_d = (5.8 \pm 2.6)$ μm for $X_d = 200$ μm.

The reverse bias voltage was applied via a 1MΩ series resistance. The leakage current variation followed the room temperature and affected the voltage by no more than a fraction of a volt. Thus the mean depleted layer width was stable at better than 0.3% [6].

The performance of the associated electronics was good both in calibration conditions (when minimum ionizing particles (m.i.p.) are traversing the devices) and in showering conditions. The standard deviation of the Gaussian noise distribution of each detector was 26.7 keV on average (equivalent to about 0.4 m.i.p.), taking into account the contributions due to electronics, detector and cabling.

To determine whether the detectors had any loss in charge collection, they were coupled to the same electronic channel, and exposed to m.i.p. The detectors were operated at a depleted layer width of 200 µm (detector capacitance of 1.3 nF). The peak positions of the pulse height distributions had the same value within measurement errors of a few percent. During the operational period of the calorimeter (a few months), constancy of the energy response was provided by setting the applied reverse bias to the value necessary to deplete 200 µm.

The energy calibration of the individual active sampler (a silicon detector and its associated electronics) was determined by exposing the devices to an Am^{241} alpha source. The distance between the junction surface and the radioactive source was (4.5±0.1) mm and the average alpha energy (5.08±0.11)MeV [7] (equivalent to 85 m.i.p.). The total range of the alpha particles in silicon is less than 40 µm, well within the 200 µm of the depleted layer width. In this way the energy calibration was defined by operating the electronics under showering conditions. Thus systematic errors in the energy calibration, due to the extrapolation from the energy loss of m.i.p., were avoided. However, no disagreement was observed between the two energy calibrations.

Variation in depleted layer width, which is quite constant, does not introduce fluctuations in the silicon detector responses to the deposited energy in a showering event. The gain variation of the associated electronics, described above, is not greater than 0.5%. Thus the calorimeter itself is highly stable and reliable.

3. Experimental set-up

The experiment was carried out in the X7 beam at CERN-SPS. The energies of the incoming electrons were between 4 and 49 GeV and the intensity roughly 10^2 - 10^3 e^- per burst (2s).

To determine the momentum profile of the beam we used the X7 beam-line spectrometer which consists of a horizontal bending magnet and four multi-wire proportional chambers, two in front of the magnet and two behind. The chambers in each set are separated by approximately 5.7 m and contain vertical wires with 1 mm wire spacing. This gives an angular resolution on beam particles of 0.2 mr. To select particles of a given momentum the spectrometer magnet is adjusted so that the desired particles are bend through 32 mr. The deviation of a particle's bending from the nominal value gives its deviation from the nominal momentum by

$$\Delta p/p = -\Delta\theta/\theta$$

Thus the spectrometer has a momentum resolution of about 0.6%. During our data taking the momentum spread of the beam varied from 3% at 49 GeV to 1% at the lower energies.

The position of the beam at the calorimeter was monitored by an additional two MWPC planes. These planes form a horizontal-vertical pair also with 1 mm wire spacing. They allowed us to select only those events with the showering particle well-centered in the calorimeter and to study the effect of the lateral containement on the calorimeter detected energy.

To trigger the calorimeter we used a paddle of scintillator P, and two threshold Cherenkov counters, whose signals were sent into a coincidence, C, and gave a π/e ratio of less than 1%. In addition, a beam scanner, B, consisting of a 0.5x0.5 cm^2 scintillator was placed immediately in front of the calorimeter. Each data run was taken with one of two triggers:

$$T_1 = P \cdot C$$

$$T_2 = P \cdot C \cdot B$$

A small silicon detector with only 0.25 cm^2 of active area was positioned in front of the first tungsten layer of the calorimeter. Its main use was to help identify events with more than one particle entering the calorimeter. These events, not more than a few percent, were rejected in the off-line analysis.

The calorimeter contained 24 radiation lengths of tungsten. A silicon detector with 25 cm^2 of active area was located after every two radiation lengths. The overall length of the calorimeter was 12 cm.

4. Experimental results

The lateral containment of the calorimeter was investigated by studying the mean energy deposited at 9, 25 and 49 GeV of incoming electron energies as a function of the impact position of the electron on the calorimeter. In the off-line analysis, the two MWPCs located in front of the calorimeter enabled to define impact annuli on the calorimeter face. In this way, electrons impinging in radial regions of 0.-0.5, 0.5-1.0, 1.0-1.5, 1.5-2.0, and 2.0-2.5 cm were selected.

The mean energy deposited was quite constant for electrons with impact positions in the central region with a radius of about 1 cm.

In order to study the resolution, energy response and longitudinal development only electrons entering the central 0.25 cm^2 region were selected. Showers possibly induced by more than one electron were eliminated using the MWPCs and the small silicon detector.

4.1. Energy response and resolution

Fig 1 shows the mean energy deposited in the calorimeter as a function of the incoming electron energy. The full line is a least square fit to the data

$$\varepsilon = (5.558 \pm 0.004)E + (-1.3 \pm 1.5) \qquad [\mathrm{MeV}]$$

where ε is the detected energy in MeV and E is the incoming electron energy in GeV. The small error in the computed slope shows the high degree of linearity of the calorimeter energy response.

To compute the energy resolution , $\sigma(E)/E$, Gaussian functions were fitted to the data. The energy distributions were measured, for each data

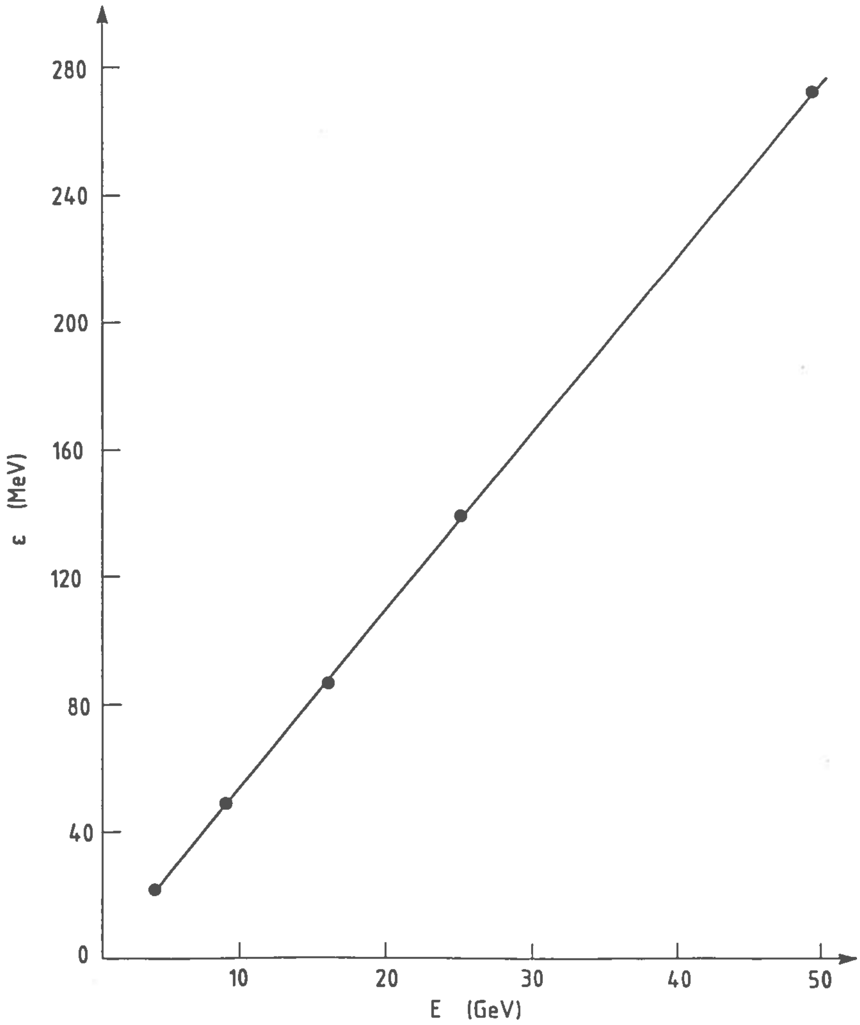

Fig. 1 - Mean energy detected by the calorimeter vs the incoming electron energy.

sample, in two independent ways: by adding up the energy sensed by the individual detectors in the off-line analysis (each detector had its own ADC channel), and by making a hardware sum (using a 127EW LeCroy linear Fan in). The two methods have different specific errors; the former requires a knowledge of every ADC channel's conversion scale (the 2259 LeCroy ADCs have a dispersion of ±7%), and the latter requires good gain equalization of the active samplers. For this purpose, adjustable commercial amplifiers[1] were introduced between the ADC channels and the elec-

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[1] 612AM LeCroy adjustable amplifier.

tronics associated with the detectors. Gain equalization to about 0.9% was achieved. Although the preamplifiers and amplifiers associated with the detectors were very stable, the gain stability of the commercial amplifiers was not better than 1-1.5% during tha data taking.

At the lowest energies, 4 and 9 GeV, the ADC resolution and the ADC pedestal variation contribute substantially to the errors on the energy resolution.

The energy difference distribution of even minus odd detectors is Gaussian with a width compatible, within the errors, to the width of the detected energy distribution. This indicates that the energy resolution is dominated by sampling fluctuations and can be given by, to a first approximation [8],[9],

$$\sigma(E)/E = k \sqrt{(\tau/E)}$$

where $\sigma(E)/E$ is the energy resolution of the calorimeter corrected for the broadening effect due to the beam momentum dispersion and detector equalization, τ is the number of radiation lengths of passive material interspaced between two active samplers. In this experiment we used $\tau=2$. In fig 2, the measured values of k are shown for both the off-line sum and the hardware sum. They are in good agreement. The weighted mean of k is

$$k = (\ 17.6 \pm 0.3\ )\%$$

In fig 3, the values of $\sigma(E)/E$ are shown as a function of the electron energy. The curve is $\sigma(E)/E = 17.6\% \sqrt{(\tau/E)}$

4.2. Longitudinal development

The study of the longitudinal shower development was made possible by the individual readout of every sampler. Fig 4 shows the average energy deposited as a function of the depth, expressed in radiation lengths, t, in the calorimeter. For large deposited energies the stability of our adjustable amplifiers dominates the error. For smaller energies the error in the pedestal determination also becomes important. We estimated a calibration error, due to a gain variation of the commercial adjustable amplifiers, of between 3 and 5 percent, and an error from the pedestal determination of ±0.1 MeV.

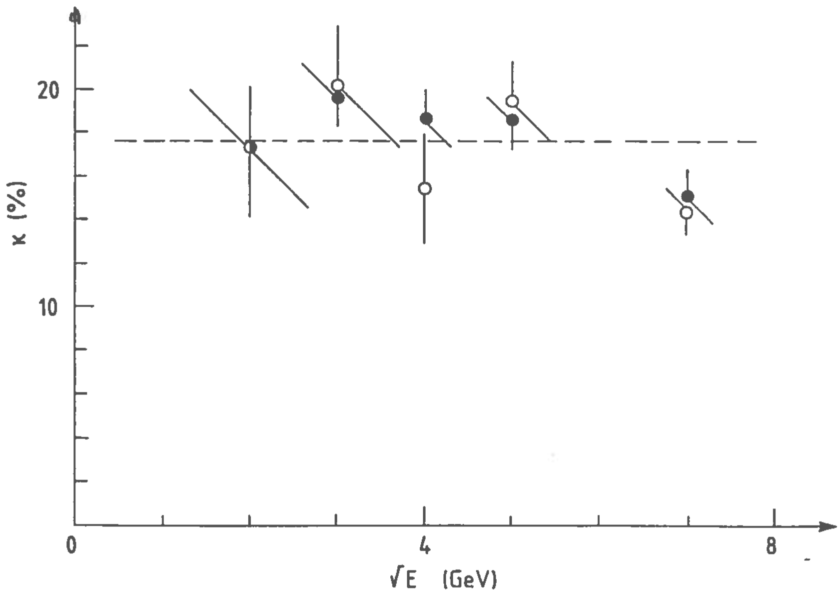

Fig. 2 - k values in %, the (o) data are for the off-line sum, the (o) data are for the hardware sum.

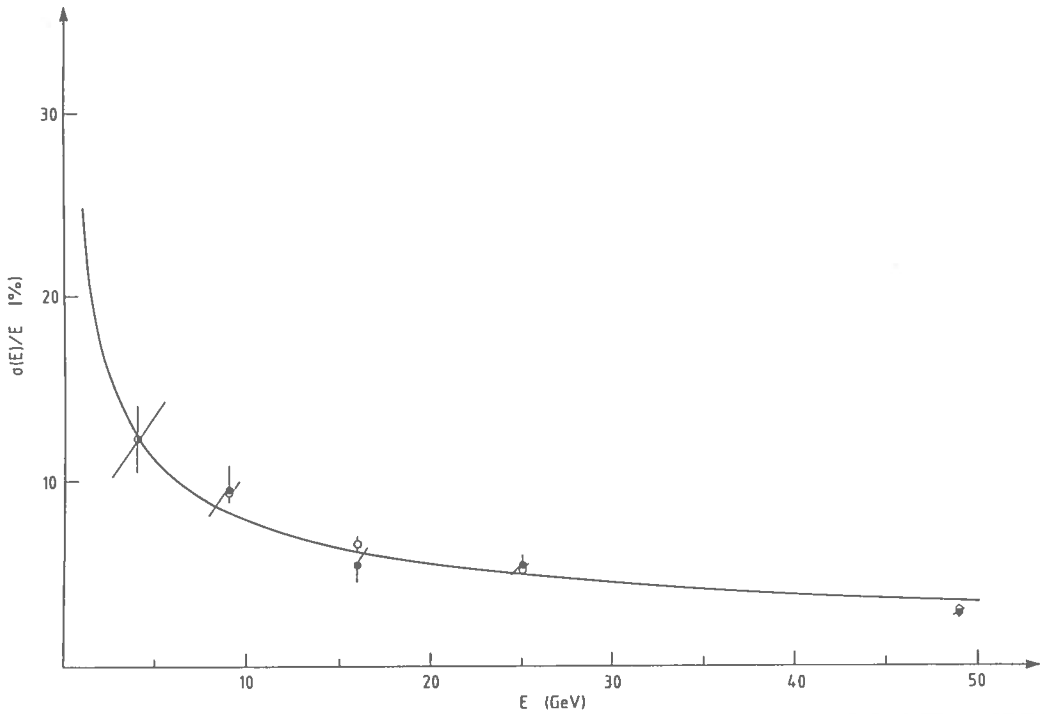

Fig. 3 - Values of $\sigma(E)/E$ vs the incoming electron energy. The full line is $\sigma(E)/E = (17.6\%)\sqrt{(\tau/E)}$, $\tau = 2$.

The energy deposited exhibits a steep rise with longitudinal depth followed by a slow decrease. The fall-off beyond shower maximum displays a two component structure, each component being approximately exponential. This structure is better seen at low electron energies (fig 4).

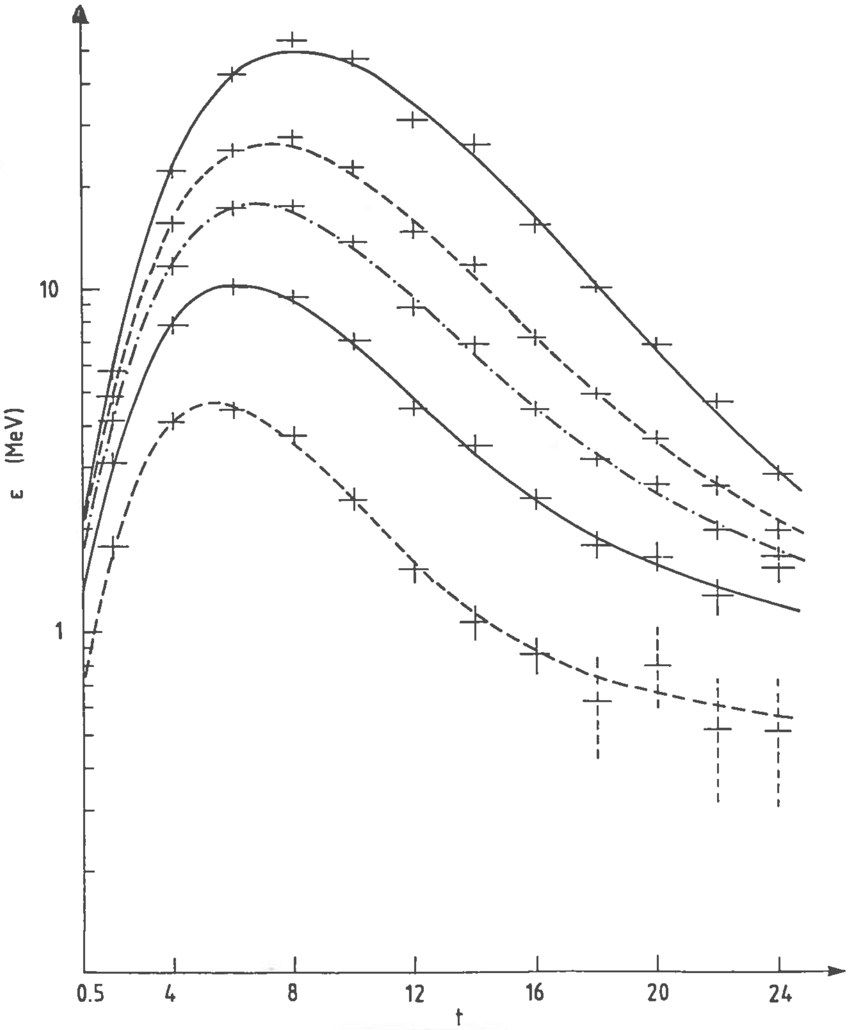

Fig. 4 - Longitudinal shower development vs the depth t in number of radiation lengths for 4, 9, 26, 25 and 49 GeV. The lines are the fitted curves.

The shape of the longitudinal development of an electromagnetic shower has often been parametrized by the empirical equation[10]

$$\varepsilon = \varepsilon_0 t^a \exp(-bt) \qquad (1)$$

where t is the shower depth in radiation lengths, and a and b are dimensionless functions of the incident electron or photon energy and ε_0 is a normalization constant in MeV. This equation is in good agreement with the Monte Carlo calculations of Longo and Sestili [11] who studied photon showers in lead glass; and with the well known computer code EGS [12]. It was found that a and b vary only slightly with energy, and that their variation may be taken to be logarithmic. The equation also agrees satisfactorily with some experimental results [13]-[15].

The experimental data show that the longitudinal shower development in the first half of the calorimeter roughly follows eq 1. Using a modified linearized least-squares gradient search [16], we fitted the data up to 12 radiation lengths. We found

$$a = (1.77 \pm 0.09) + (0.46 \pm 0.02)\ \ln(E)$$
$$b = 0.45 \pm 0.01$$

with $\chi^2 = 39$ for 22 degrees of freedom. This should be compared with the Monte Carlo predictions of [11]

$$a = 1.78 + 0.46\ \ln(E)$$
$$b = 0.48$$

A better parametrization of the data for all depths is obtained by adding a second term

$$\varepsilon = \varepsilon_0 (t/2)^a \exp(-bt) + \varepsilon_1 (t/2)^c \exp(-m(t-x_1)-y_1) \quad [\mathrm{MeV}] \quad (2)$$

where c, m, x_1, and y_1 are dimensionless constants varying at most logarithmically with incident energy and ε_1 is 1 MeV. When we fit by the same procedure as before we obtain the curves shown superimposed on the data in fig 4. The fit is excellent with $\chi^2 = 48$ for 49 degrees of freedom and

$$a = (3.2 \pm 0.5) + (0.3 \pm 0.2)\ \ln(E)$$
$$b = (0.75 \pm 0.10) + (-0.05 \pm 0.04)\ \ln(E)$$
$$c = (0.26 \pm 0.10)\ \ln(E)$$
$$m = (0.04 \pm 0.02)\ \ln(E)$$
$$x_1 = (-6.8 \pm 3.5) + (55.9 \pm 20.3)\ \ln(E)$$
$$y_1 = 2.5 \pm 0.4$$
$$\varepsilon_0 = (2.2 \pm 1.2) + (1.5 \pm 0.6)\ \ln(E) \quad [\mathrm{MeV}]$$

For this fit the normalization constant ε_0 is also given a logarithmic energy dependence.

The fit results can now be used to determine the position of the shower maximum t_{max}. This is shown plotted in fig 5. The position of the shower maximum increases with the logarithm of the incident energy according to

$$t_{max} = (3.97 \pm 0.24) + (1.02 \pm 0.11) \ln(E)$$

This is in good agreement with other experiments [17] and with the analytic approximation B of Rossi and Greisen [18]. The centre of gravity of the shower, t_{cg}, is given by

$$t_{cg} = (8.4 \pm 0.5) + (0.45 \pm 0.17) \ln(E)$$

These results are also shown in fig 5.

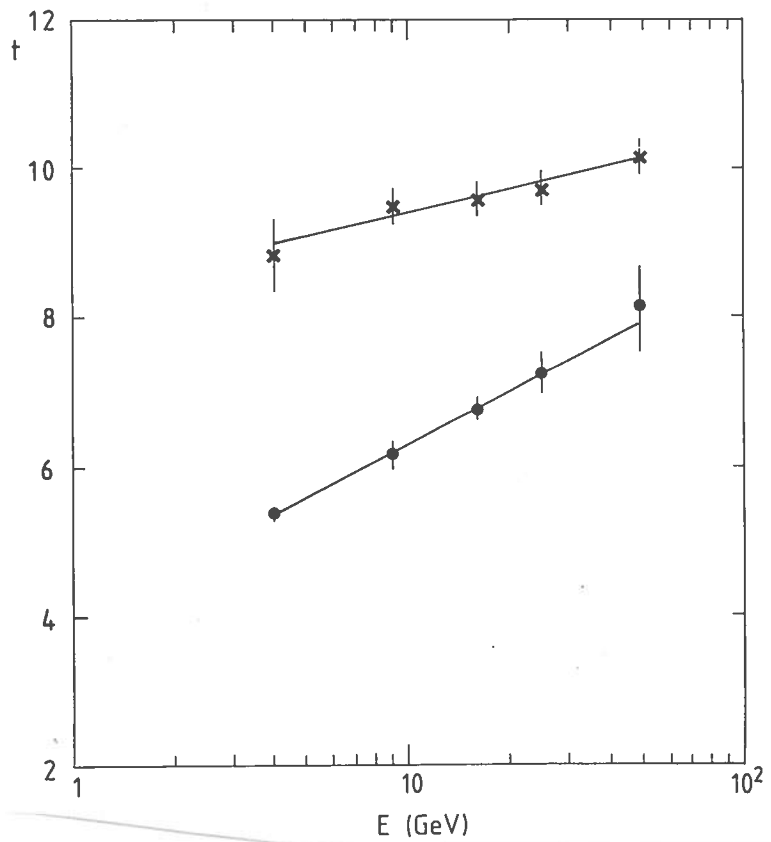

Fig. 5 - Shower maximum, t_{max}, and shower centre of gravity, t_{cg}, in unit radiation lengths vs incoming electron energy, bottom and top data respectively.

5. Conclusion

The Si/W sandwich calorimeter has a linear response (at better than 1%) to incoming electrons with energies between 4 and 49 GeV.

The energy resolution obtained is

$$\sigma(E)/E = (\ 17.6 \pm 0.3\ )\% \sqrt{(\tau/E)}$$

when the detectors were operated with a depleted layer width of 200 μm.

The longitudinal shower development shows a two component fall-off beyond the shower maximum. The decay rate suggests that, for electron energies as high as 49 GeV, a longitudinal shower containment of better than 96-98% can be achieved with 28-30 radiation lengths.

The shower maximum and center of gravity are in good agreement with other experiments and approximation B of Rossi and Greisen.

The absolute energy calibration is stable and the device itself is particularly reliable. The stability of the depleted layer width has been found to be about 0.3% over a period of few months.

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