EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/87-130
July 27th,1987

SILICON SAMPLING CALORIMETRY

S.Pensotti°[1], P.G.Rancoita[1], L.Vismara[1],
A.Seidman[2],

Geneva, July 11, 1987

Abstract:

A review of experimental studies, carried out by the SICAPO collaboration at CERN, on Si/W and Si/U sandwich calorimeters is presented. Results on the response of sensed energy versus incoming electron energy and depleted layer width, of the longitudinal and lateral development of electromagnetic showers and of the energy resolution, are given and compared with data from Hamburg (Si/Pb) and Tokyo (Si/Pb and Si/W) calorimeters. The performance of the electromagnetic section of a large Si/U hadronic calorimeter is also described.

presented at the International Conference on
Advances in Experimental Methods for Colliding Beam Physics
SLAC, 9-13 March 1987

1) INFN, Milan, Italy
2) Tel-Aviv University, Tel-Aviv, Israel
o) also University of Milan, Italy

1. Introduction

Recently, investigations of the usage of large ion-implanted silicon detectors in high-energy physics (especially in calorimetry) have been started. Also studies on the possible, not fully depleted use of relatively inexpensive, low-resistivity detectors were performed.

The SICAPO (SIlicon CAlorimeter and POlarimeter) collaboration at CERN, developed Si/W and Si/U sandwich calorimeters. After preliminary studies in 1983, the experimental tests were carried out at the CERN-PS and SPS on both the calorimeters and silicon detectors, fully and not fully depleted.

In this paper, the energy resolution, the response of sensed energy versus incoming electron energy and depleted layer width, and the longitudinal and lateral development of electromagnetic showers are presented. The results are also compared with data from the Si/Pb calorimeters of the Hamburg group and from both Si/Pb and Si/W calorimeters of the Tokyo group.

Mosaic silicon modules of 504 cm² active area enable the construction of a silicon sampling hadronic calorimeter. The usage of the serial coupling of 5 silicon detectors of 28 cm² area allows to employ fast electronics (about 100 ns base-time signals) with a wide dynamic range. The results from the experimental test of the Si/U calorimeter electromagnetic section are also presented.

2. Si detectors and electronics of SICAPO e.m. calorimeters

The detectors employed by the SICAPO collaboration had physical thicknesses between 250 and 300 μm and an active area of 5 x 5 cm². They were operated not fully depleted [1]. The stability of the depleted layer width X_d (normally 200 μm), was found to be about 0.5 %. The variationof X_d as a function of the position, was measured by studying the most probable energy-loss of 80 GeV protons traversing the silicon detectors depleted at 200 μm. The variation was found to be not systematic and ±6(±3) μm on average.

The energy scale calibration was performed by exposing each individual device to single relativistic particles (100 GeV protons) without inserting any absorber plate (Fig. 1). The standard deviation of the Gaussian noise distribution was 26.7 keV on average [1]. This value takes into account the contribution due to electronics, detector and cable.

The shaping time of the ssociated electronics was about 1 μs.

3. Experimental results from electromagnetic Si-calorimeters

The first calorimeter investigated by SICAPO collaboration [2] was an electromagnetic calorimeter consisting of 24 radiation lengths (X_0) of tungsten, in which a silicon detector (depleted up to 200 μm) was located every two radiation lengths. The overall length of the calorimeter was 12 cm. The experiment was carried out in the X7 beam at CERN-SPS. The energies of the incoming electrons was between 4 and 49 GeV and the intensity roughly 10^2 to 10^3 electrons per burst (with duration of 2 s).

Another SICAPO calorimeter [3] contained 24 radiation lengths of either uranium or tungsten, with a silicon detector located after each two radiation lengths of absorber. The silicon detectors were operated with depletion layers of 200 and 70 μm. The experiment was performed at the t_9 beam at CERN-PS, with E being 2, 4 and 6 GeV.

The same calorimeter configuration [4] with tungsten absorbers, but with detectors operated at depletion depths of 40, 70, 100, 125, 150 and 200 μm (by adjusting the reverse bias voltage), was investigated at the same beam. This enabled us to study the calorimeter performance as a function of X_d for incoming electrons of 4 GeV.

3.1. Energy response vs incoming electron energy and depleted layer width

The energy response (ε) of a Si/W calorimeter was found to be linear to better than 1% for energies (E) of incoming electrons between 4 and 49 GeV [2]. The least square fit to the mean energy deposited in the calorimeter as a function of E (in GeV), gives

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

Fig. 2 presents the energy response of Si/U and Si/W calorimeters for incoming electron energies between 2 and 4 GeV [3]. The data show the linear response of the sensed energy versus E, seen at high energies [2]. The linearity is observed for the detectors operated at X_d of 200 and 70 μm and employing both uranium and tungsten as showering media. However, independently of the X_d values, the mean sensed energy is about 11% higher when uranium absorbers are used. This is also related to the difference of critical energies between U and W [5].

Fig. 3 shows the overall energy response of a Si/W calorimeter as a function of the silicon detector depletion depth. The incoming electron energy is 4 GeV [4]. Noteworthy is the positive energy intercept of the line, caused by charged diffusion in the silicon (the migration effect [6].

Part of the carriers, generated closest to the junction is always being collected from the field-free region, even for no externally applied bias voltage. From the fitted slope and intercept (Fig. 3), we found an average effective contribution from the field-free region, X_{FF}, of (23 ± 2) μm at zero depletion depth. This value has to be compared with that of 25 μm [6], found with similar shaping time-constant of electronics, but under non-showering conditions with relativistic β^- particles.

The energy response of the individual silicon devices (up to depths of 16 - 18 radiation lengths) is quite similar to the overall response, i.e., a linear dependence of the deposited energy versus the depleted layer width. Furthermore, it was observed that, as expected, since the slopes are proportional to the number of equivalent minimum ionizing particles traversing the detectors, they increase monotonically afterwards.

The response of the last four detectors (Fig. 4) is highly non linear and shows a rapid growth in the deposited energy at large values of depletion depth. This effect is expected (and observed [2] - [4] when the detectors are operated not fully depleted (for fully depleted detectors see [7] - [10]). Electrons and photons with energies near and below the critical energy might be responsable for the observed behavior. Early in the shower, when the average particle energy is large compared with the critical energies, the shower development shape is approximately independent of absorber and depletion width. Later, low energy phenomena contribute to the shower development. These include the non-linear relationship between total electron range and kinetic energy, the high sensitivity of silicon as a low energy photon detector. As a result, one expects, late in the shower development, a complicated dependence of the deposited energy on absorber material and depletion width X_d In particular in the field-free region soft electrons are generated by low energy photons and diffused in the space-charge region.

However, the deposited energy in these detectors is small compared to the overall deposited energy in the calorimeter and does not prevent in the linear calorimeter response versus the depleted layer width.

3.2. Energy resolution

The energy resolution measured by SICAPO collaboration [2], of Si/W calorimeter with detectors depleted at 200 μm was

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

where τ is the sampling frequency (namely the number of radiation lengths of passive material interspaced between active samplers). The energy resolution of Si/W and Si/U calorimeters was found to be degraded by no more than 10 - 15% by operating the detectors at 70 μm of depletion depth [3].

The Tokyo group obtained $\sigma(E)/E \approx 17.5\%\sqrt{(\tau/E)}$ with a Si/Pb calorimeter (with 10 X_0 depth and an active sampler every 5 mm of Pb) for electron between 0.25 and 0.75 GeV [7] and $\sigma(E)/E \approx 17\%\sqrt{(\tau/E)}$ with a Si/W calorimeter (with non homogeneous sampling and 18 X_0 depth) for electron energies between 0.5 and 4.5 GeV [8]. The 1 mm thick devices were fully depleted.

The Hamburg group measured $\sigma(E)/E \approx 18.3\%\sqrt{(\tau/E)}$ with a Si/Pb calorimeter of 25 X_0 depth and an active sampler (fully depleted silicon detectors) every 6 mm of Pb for electron energies between 2 and 6 GeV [11].

3.3. Longitudinal shower development

The longitudinal shower transition curve has been investigated as a function of both the incoming electron energy and the silicon depleted layer width by the SICAPO coiiaboration [2] - [4]. Fig. 6 presents the longitudinal shower transition curves measured at six depletion depth from 40 to 200 μm for incoming electron energy of 4 GeV in a Si/W calorimeter [4]. The longitudinal shower development shows a two component tail structure for X_d larger than 125 μm. This is in agreement with the observed behavior of Si/W and Si/U calorimeters for incoming electron energies between 4 and 49 GeV [2] and between 2 and 6 GeV [3] when the detectors are operated at 200 μm of depletion depth.

The second tail component is related to the non linear energy deposited in the undepleted detectors at depths greater than or equall to 18 X_0. As discussed in section 3.2, this "volume effect" is possibly due to soft electrons depositing a large amount of energy near the end of their range.

A single tail component is observed (data from Tokyo and Hamburg calorimeters [7] - [11]) when fully depleted silicon detectors are employed.

3.4. Lateral shower development

The lateral electromagnetic shower development was studied for 2, 4 and 6 GeV electrons [12] in a silicon sampling calorimeter with tungsten and uranium as absorbers, at various depths of radiation lengths, up to 16 by SICAPO collaboration. The measurements were performed with a HAMAMATSU 1 mm pitch silicon strip detector, 28 x 28 mm^2 area and 190 μm thick.

The full width at half maximum (FWHM) of the summed distribution along X_0 is 6 mm at 2 GeV and 5 mm at 6 GeV for both uranium and tungsten. At 4 GeV it is 6 mm for uranium and 5 mm for tungsten.

The Tokyo group [8] has shown the lateral shower development (summed along X_0) for electromagnetic showers in a Si/W calorimeter, having 5 mm resolution at 4.5 GeV of incoming electron energy. The FWHM of the distribution was about 13.3 mm. This is about twice the value of that expected from the Monte Carlo calculations [8] and actually found in the above described experiment.

4. Large area Si-mosaic and readout electronics for hadronic calorimetry

In calorimetry, large area silicon detectors are required, but since the active volume may be small, relatively low resistivity, not fully depleted devices can be used [13].

It is planned by the SICAPO collaboration (Genoa, Florence, Hamburg, McGill, Milan, Pavia, Tel-Aviv and Trieste) at CERN, to develop a full Si/U hadronic calorimeter, consisting of 130 silicon sampling planes (about 6.5 m^2) by the end of 1987, with silicon mosaic modules located every 5 mm of uranium (which is about 4.8% of an interaction length).

4.1. Silicon sampling unit

A silicon sampling unit (whose active area is 504 cm^2) is made of 18 trapezoidal silicon detectors, each of about 28 cm^2 area and 400 µm thickness. They are being processed, using 100 mm diameter silicon wafers. They are p-i-n diodes, operated usually at depleted layer width of 200 µm. So far, floating zone silicon, with typical resistivity of 1 - 2kΩcm, seems to be suitable for large area detectors in calorimetric applications. The active area of a silicon detector is extended laterally beyond the junction region, A_j, by electrical field lines. This extended active area, A_E, is to a first approximation, proportional to the depleted region X_d [cm]:

$$A_E = \lambda X_d P \qquad [cm^2]$$

where P is the junction perimeter in cm and λ (whose fitted value was found to be 0.10 ± 0.06 [13]) is the ratio between the lateral extension of the active area and the depleted layer width. Thus, the total active area of a device is given by the sum of A_j and A_E

For the case of trapezoidal detectors, a laser cutting method was developed, using a CO_2 laser. By assembling a silicon detector mosaic, dead areas are necessarily introduced, since the supporting wafer is larger than the junction region. In order to minimize these losses in the active area, the laser cut should be performed as close as possible to the junction edge. It was shown [13] that with this technique, a negligible variation of leakage current occurs when the cut is made as close as 175 µm to the metallized region of the detector. In this way the mosaic dead area could be reduced to a few percent of the total active area.

For detector modules, two fiberglass sheets were used to bring the electrical connections to both junction and rear side of the detectors. They are attached to the fiberglass by silicon rubber and electrically connected to the metal paths by conductive epoxy resin. The contacts are brought to an external flat cable. To define and monitor the energy scale of the device, radioactive α-sources (usually U^{233}) can be deposited on the detector surface by a technique similar, in most respects, to vacuum evaporation or sputtering. This technique is highly reliable and provides in-situ calibration of silicon detectors, placed in experimental apparatus.

4.2. Readout electronics and leakage current monitoring system

In order to reduce the number of electronic channels and the overall detector capacitance, a serial coupling of silicon devices has been studied (as suggested by C.Rubbia). Along the beam direction, five successive sampling mosaics are connected to a readout unit (Fig. 6). A hybrid network circuit realizes the serial coupling of detectors located at the same position in these five mosaic planes and provides the output connections for the leakage current monitoring system.This system, based on a microprocessor, may monitor every two seconds the detectors (about 2000) of the full hadronic Si/U calorimeter.

The silicon detectors of a sampling plane require the same bias voltage in order to be depleted at 200 µm. Due to the serial coupling the overall capacitance of 5 detectors of 28 cm^2 area and 200 µm depletion depth is about 290 pF.

The charge sensitive preamplifier (Fig. 6) was designed to give a linear response (for about three and a half order of magnitudes) up to 80 - 90 MeV of energy deposited in the associated detectors [14]. In the input stage, it employs four bipolar transistors NEC NE856. The output signals have a rise-time of about 25 ns and a fall-time of about 60 ns. The standard deviation of the Gaussian noise distribution is about 15 keV for an input capacitance of 330 pF. This value takes into account both the overall detector capacitance and the stray capacitance.

5. Test of the electromagnetic section of Si/U hadronic calorimeter

The electromagnetic section of the SICAPO Si/U hadronic calorimeter [14] contained 15.6 radiation lengths of uranium. Two readout units were required by the silicon mosaics (Fig. 7) which are located next to a 5 mm thick (1.56 X_0) and 50 x 50 cm^2 area uranium plate. The silicon detectors were depleted at 200 μm and had leakage currents between 0.3 and 2.0 μA. The total silicon active area was about 0.25 m^2.

The test was carried out at the t_9 beam at CERN-PS [14]. The incoming electron energies were 2, 4 and 6 GeV. A gas Cherenkov counter filled with helium at 1.4 bar, was used to select electrons. A beam scanner, consisting of a scintillator counter of 0.5 x 0.5 cm^2 area, ensured that only those electrons impinging on the middle of the calorimeter, triggered.

Fig. 8 shows the mean energy deposited in the calorimeter, which is a linear function of the incoming electron energy. The mean energy deposited in the calorimeter is

$$\varepsilon = (3.56 \pm 0.14)\ E + (-0.18 \pm 0.41) \quad [\mathrm{MeV}]$$

where E is the incoming electron emergy in GeV. The reduction of the energy response, compared to the one measured in [3] is mainly due to the fiberglass supports, used to bring the electrical connection to both the junction and the rear side of the detectors. The fiberglass absorbs soft electrons, thus, reducing the total energy sensed. A low Z absorber can be used to reduce the response of the electromagnetic component in a hadronic shower, while the pure hadron (most of them relativistic or quasi-relativistic) component is practically not affected. In this way, e/h=1 can be obtained without exploiting the neutrons generated in the nuclear collisions.

The energy resolution was found to be given by $\sigma(E) = k\sqrt{(\tau/E)}$. In fig. 9 the measured values of k are shown. The weighted mean of k is (19.8 ± 1.3)%. In a previous measurement [2] k = (17.6 ± 0.3)% was found with a Si/W calorimeter containing 24 X_0. However the longitudinal energy loss affects the energy resolution. In fig.10 the parameter k (for incoming electron energy of 4 GeV) is shown for four values of the Si/W calorimeter total depths: 18, 20, 22 and 24 X_0. Thus, the actually found value of k is in agreement with that observed in the Si/W calorimeter data [2].

6. Conclusions

A silicon sampling calorimeter fulfils the requirements of compactness, granularity, long-time stability and reliability needed in colliding beam machine experiments.

The energy resolution for electromagnetic shower is about $17\%[\sqrt{(\tau/E)}]$, for a calorimeter depth of 24 X_0 and with silicon sam samplers depleted at 200 µm. It is degraded by about 10 - 15% when the detectors have a depleted layer width of 70 µm or the calorimeter depth is about 16 X_0.

The observed reduction of the energy sensed in electromagnetic showers, due to the fiberglass supports in front of the silicon mosaic, can be exploited to equalize the response of a Si/U hadronic calorimeter to incoming electrons and hadrons.

Mosaic modules of silicon detectors, whose dead area is less than a few percent, enable the construction of silicon sampling calorimeters.

Experimental measurements on the performance of hadronic sampling calorimeters with uranium, lead and iron absorbers, will be carried out by the SICAPO collaboration by the end of 1987.

References

[1] G.Barbiellini, P.Buksh, G.Cecchet, J.Y.Hemery, F.Lemeilleur, P.G.Rancoita, G.Vismara and A.Seidman, Nucl.Inst.Meth.Phys.Res. A235 (1985)216.

[2] G.Barbiellini, G.Cecchet, J.Y.Hemery, F.Lemeilleur, C.Leroy, G.Levman, P.G.Rancoita and A.Seidman, Nucl.Inst.Meth.Phys.Res. A235(1985)55.

[3] G.Barbiellini, G.Cecchet, J.Y.Hemery, F.Lemeilleur, C.Leroy, G.Levman, P.G.Rancoita and A.Seidman, Nucl.Inst.Meth.Phys.Res. A236(1985)316.

[4] G.Barbiellini, G.Cecchet, J.Y.Hemery, F.Lemeilleur, C.Leroy, G.Levman, P.G.Rancoita and A.Seidman, Nucl.Inst.Meth.Phys.Res. A240(1985)289.

[5] F.Lemeilleur, C.Leroy, P.G.Rancoita and A.Seidman, Nucl.Inst.Meth.Phys. Res. A241(1985)600.

[6] N.Croitoru, P.G.Rancoita and A.Seidman, Nucl.Inst.Meth.Phys.Res. A234 (1985)443.

[7] A.Nakamoto, H.Murakami, T.Doke, J.Kikuchi, K.Masuda, K.Kasahara, M.Mitsui, K.Muraki and T.Yuda, Nucl.Inst.Meth.Phys.Res. A238(1985)53.

[8] A.Nakamoto, H.Murakami, T.Doke, T.Kashiwagi, J.Kikuchi, K.Masuda, K.Kasahara, K.Muraki, T.Yuda and Y.Watanabe, Nucl.Inst.Meth.Phys.Res. A251(1986)275.

[9] M.Bormann, E.Fretwurst, G.Lindstroem, U.Pein and H.-Ch.Schleyer, Nucl. Inst.Meth.Phys.Res. A240(1985)63.

[10] M.Bormann, E.Fretwurst, G.Lindstroem, U.Pein, V.Riech, H.-Ch.Schleyer and H.Weiss, Beam tests with large-area silicon-sandwich calorimeters for electron energies between 1 and 6 GeV, presented at the 2nd Topical Seminar on Perspectives for Experimental Apparatus at Future High Energy Machines, San Miniato 5-9 May, 1986.

[11] M.Bormann, E.Fretwurst, G.Lindstroem, U.Pein, V.Riech, H.-Ch.Schleyer and H.Weiss, Private Communication (Feb.1987).

[12] F.Lemeilleur, P.G.Rancoita and A.Seidman, Lateral electromagnetic shower development in Si/W and Si/U sandwich calorimeter, to appear in IEEE Trans.Nucl.Sci.(1987).

[13] S.Pensotti, P.G.Rancoita, A.Seidman, L.Vismara and M.Zambelli, Large area silicon detection in hadronic calorimetry, presented at the 2nd Topical Seminar on Experimental Apparatus at Future High Energy Machines, S.Miniato 5-9 May 1986, CERN-EP/86-103, August 1986.

[14] G.Barbiellini, C.Furetta, S.Pensotti, P.Rancoita, A.Seidman and L.Vismara, Private Communication (Feb.1987).

FIGURE CAPTIONS

Fig. 1 : Energy-loss spectrum of a relativistic proton traversing a 5 x 5 cm² silicon detector depleted at 200 μm. The most probable energy-loss is 56 keV and the standard deviation of the Gaussian noise contribution is 20.8 keV.

Fig. 2 : Mean energy detected by the calorimeter vs the incoming electron energy for uranium with a silicon depletion layer of 200 μm (■); for uranium with a silicon depletion layer of 70 μm (□); for tungsten with a silicon depletion layer of 200 μm (●); for tungsten with a depletion layer of 70 μm (○). The full lines are the least squares fits to the data. The incoming electron enetgy is 4 GeV.

Fig. 3 : The energy response of the calorimeter as a function of the silicon detector depletion depths X_d The line shown is a least squares fit of the data.

Fig. 4 : The energy response of the last four silicon detectors located at 18, 20, 22 and 24 radiation lengths into the calorimeter, as a function of depletion depth [4].

Fig. 5 : The longitudinal shower development in the silicon/tungsten sampling calorimeter for depletion depths, X_{d}, of 40, 70, 100, 125, 150 and 200 μm. The incoming electron energy is 4 GeV. The curves superimposed on the figure, show the results of a linearized least squares fit to the data.

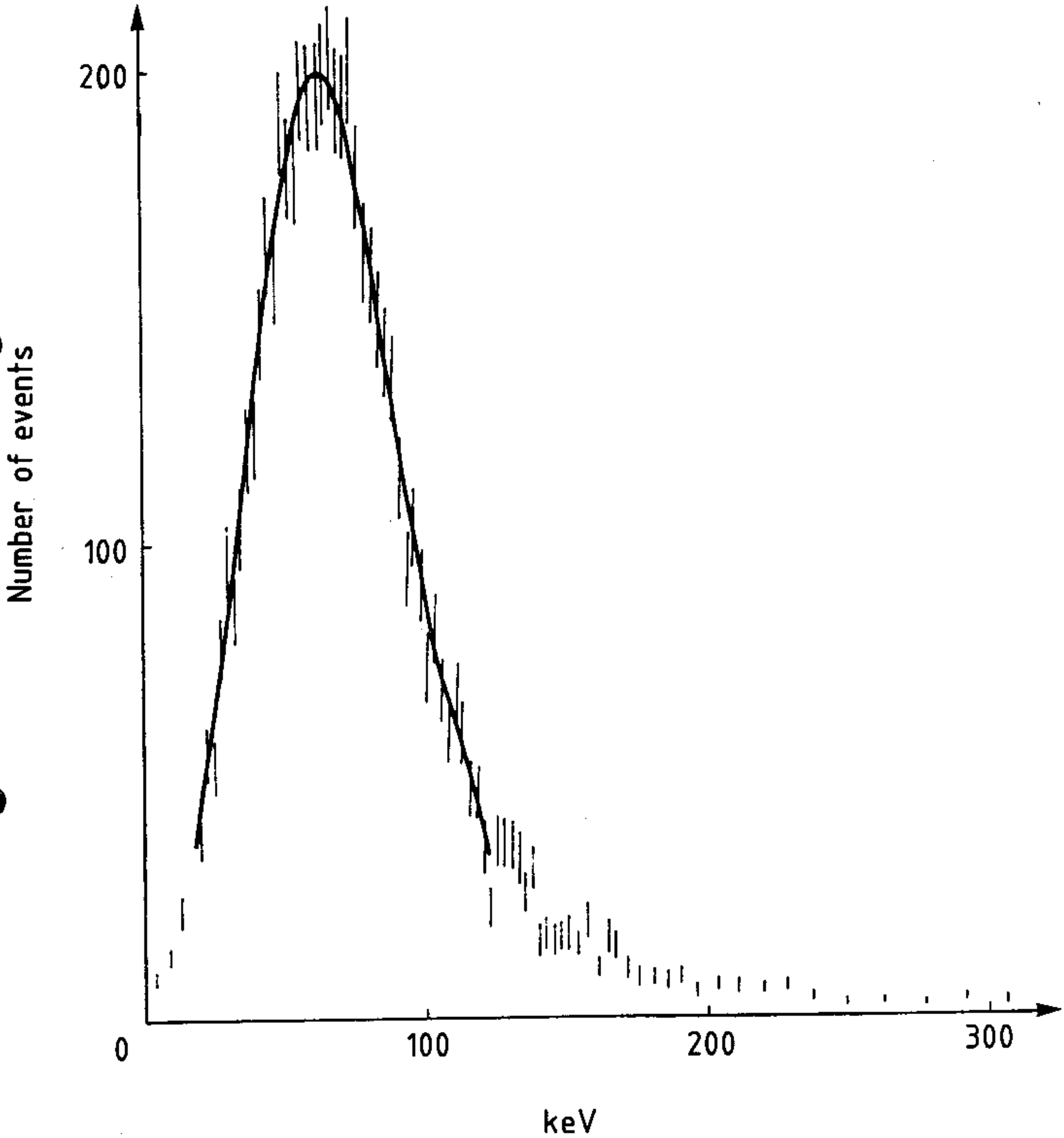
Fig. 6 : Readout unit for five sampling mosaic planes. The flet cables on the left, transfer signals from the mosaic planes. In the middle of the readout unit, there 18 hybrid network circuits for the serial coupling of detectors and to the right the hybrid preamplifiers. The output pins next to the preamplifiers, allow to monitor via microprocessor the leakage current of the 90 Si-detectors coupled to the readout unit

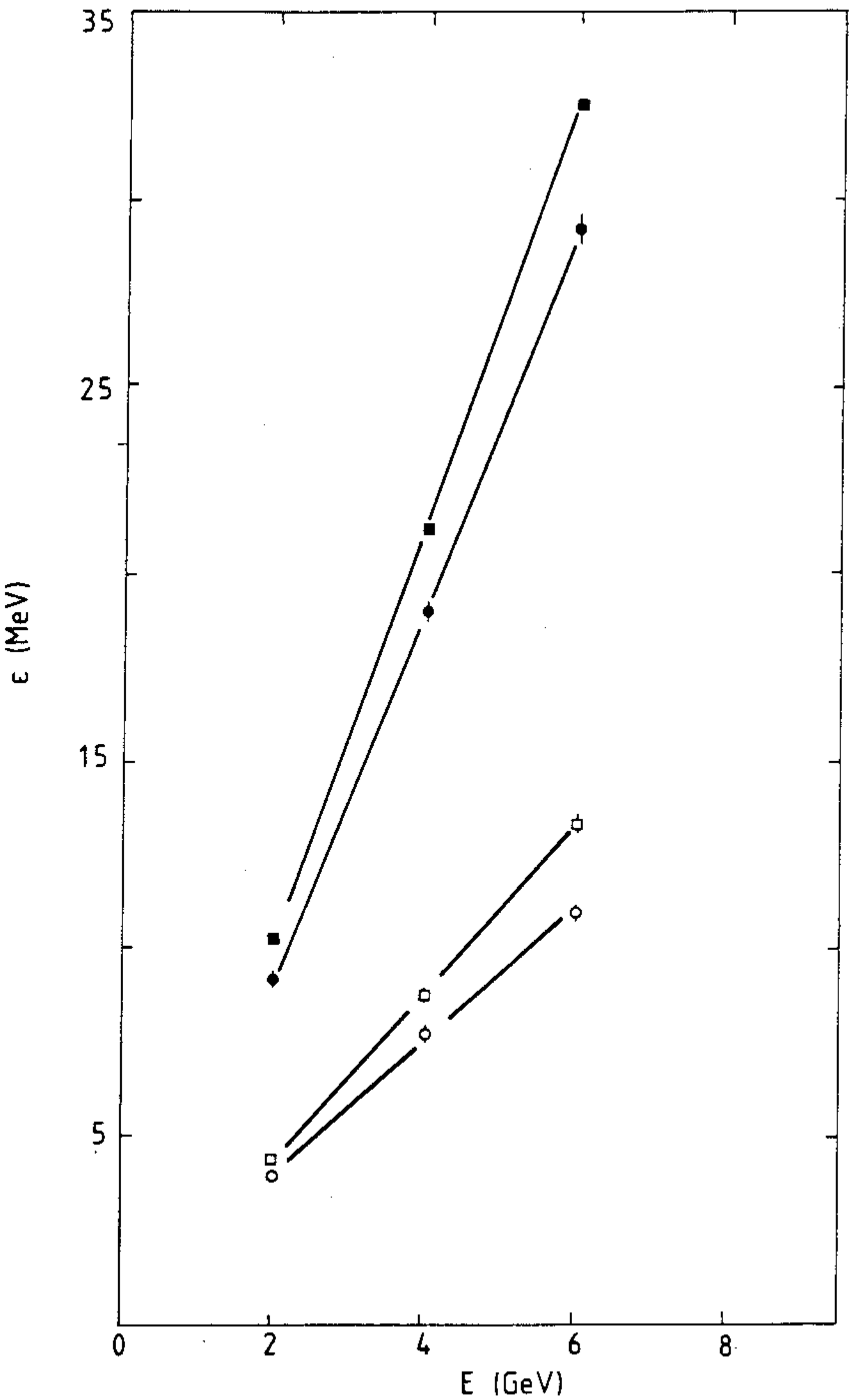
Fig. 7 : Silicon plane and electronics (top part of the calorimeter container) used in the test of the electromagnetic section of Si/U SICAPO calorimeter.

Fig. 8 : Mean energy deposited in the calorimeter as a function of the incoming electron energy.

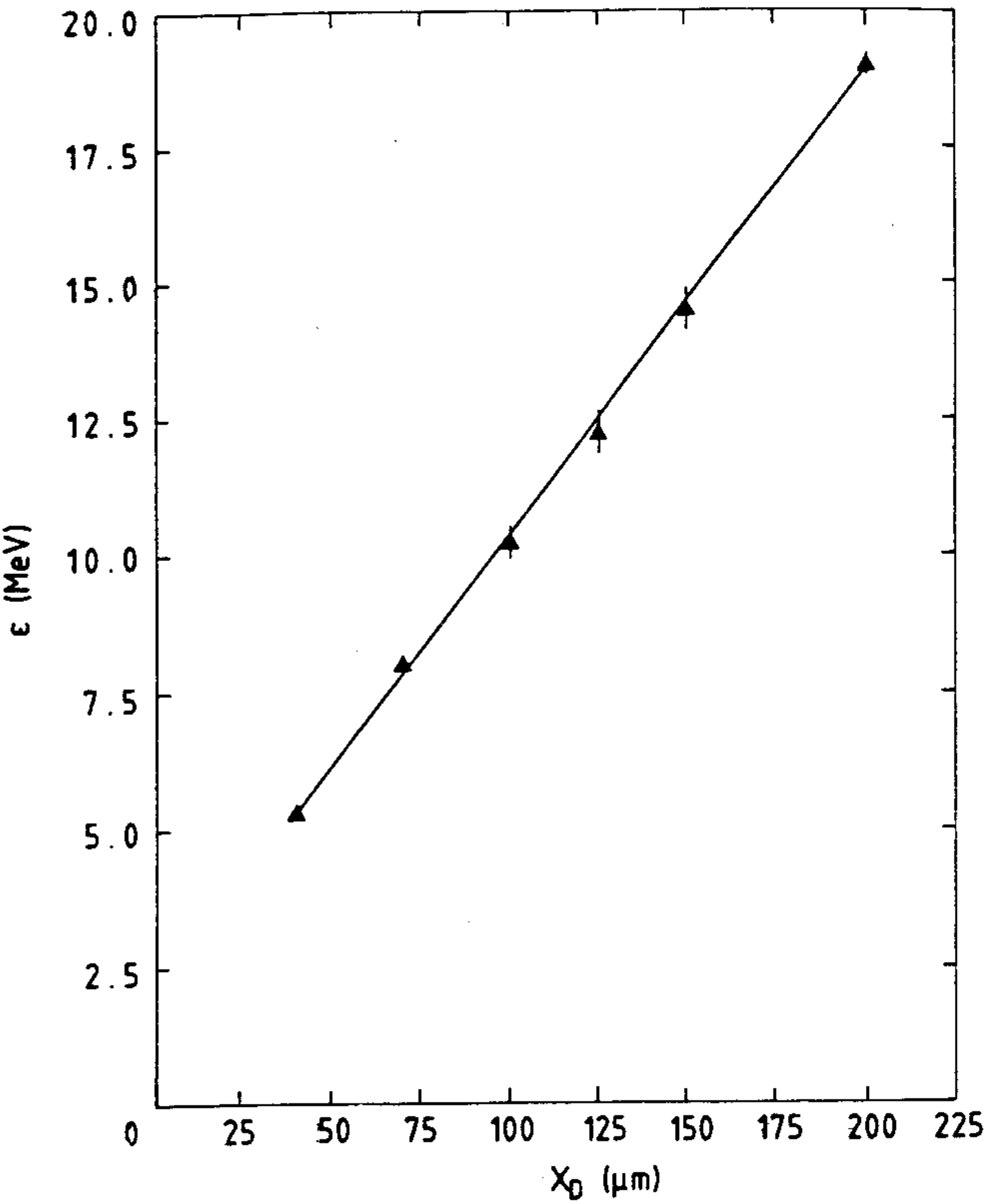
Fig. 9 : k values in % versus incoming electron energy.

Fig. 10 : k values in % for different total depth of Si/W calorimeter.

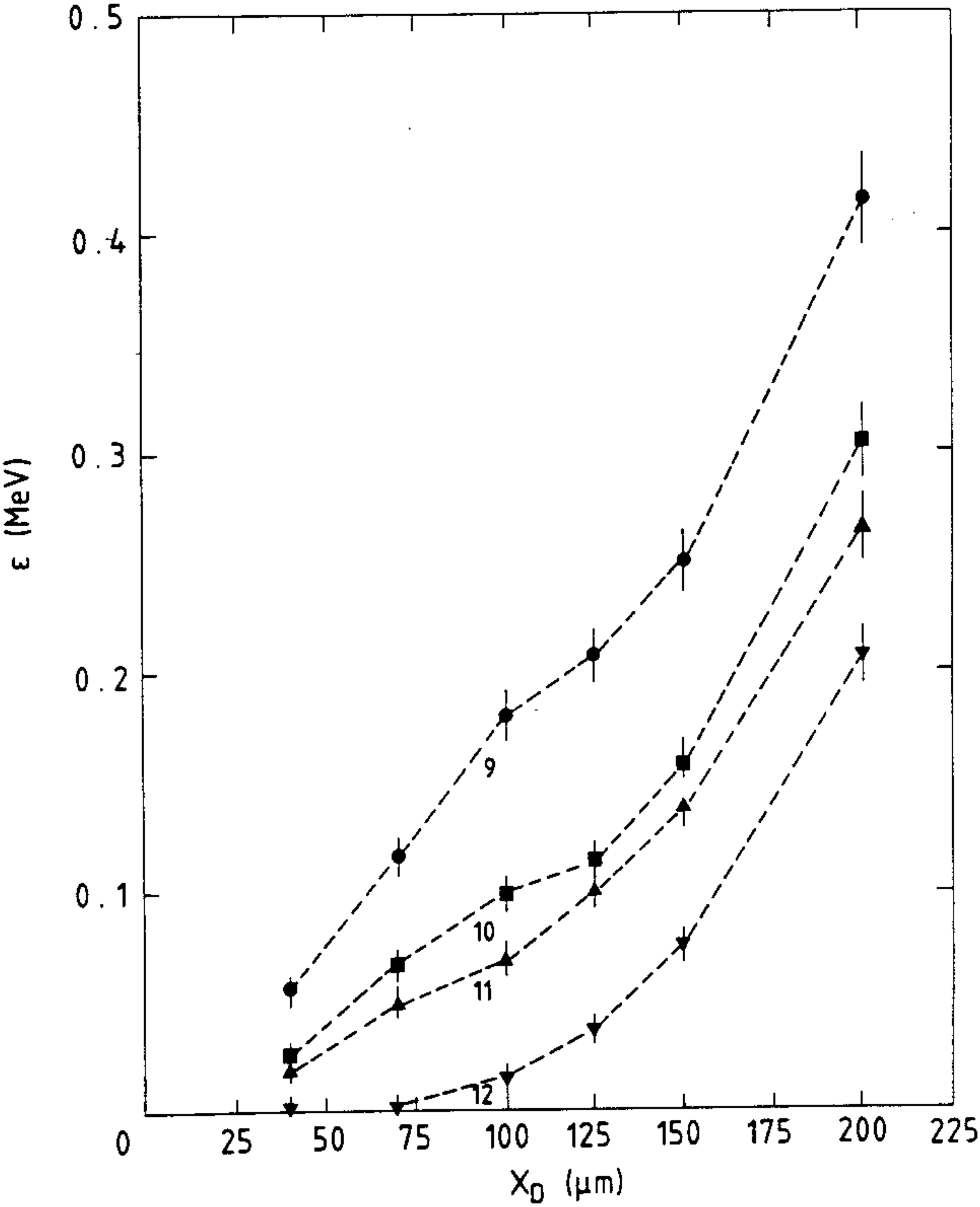

200
100
0
100
200
300
Number of events
keV

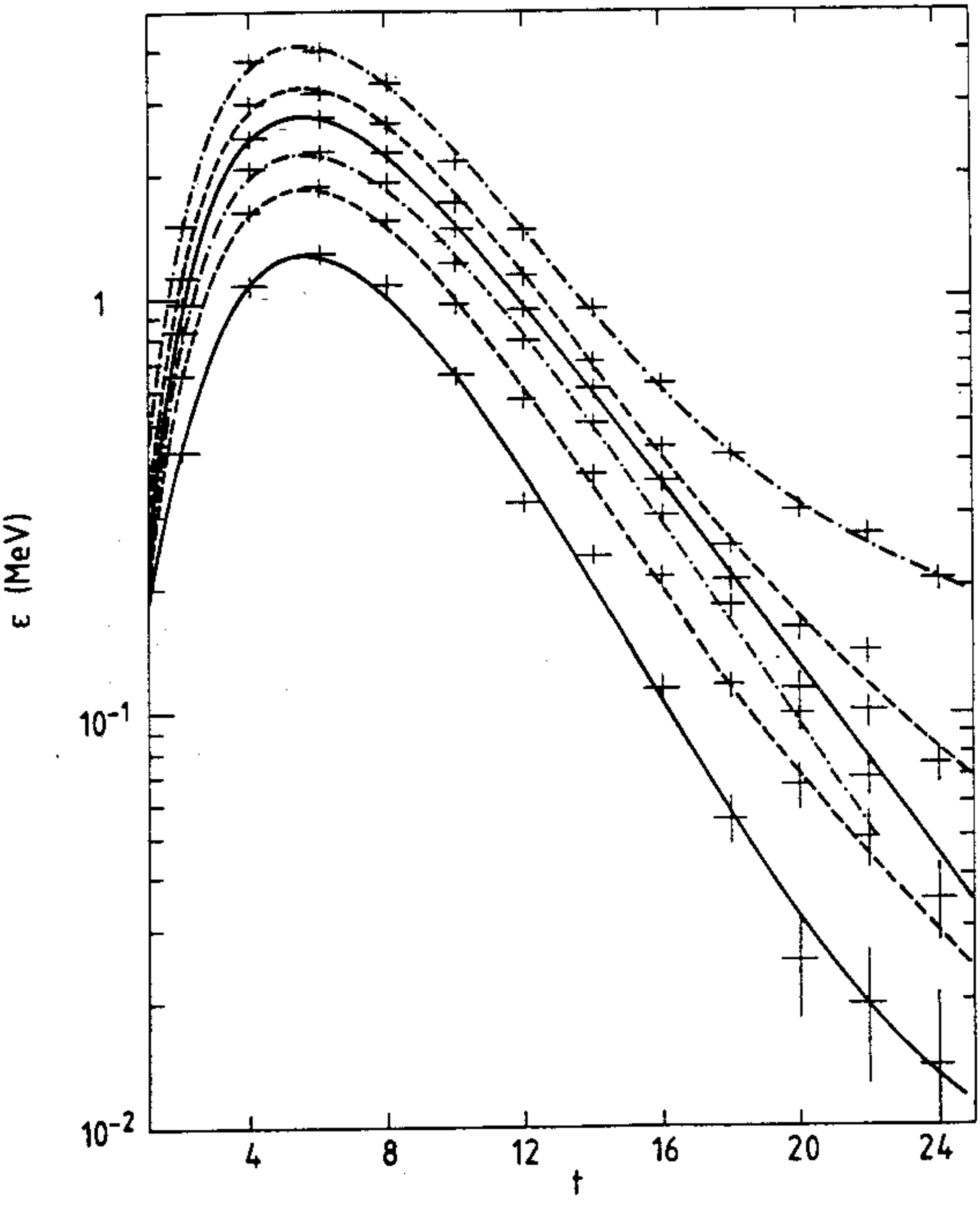


35
25
15
5
ε (MeV)
0
2
4
6
8
E (GeV)



20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0
25
50
75
100
125
150
175
200
225
ε (MeV)
X_D (μm)


0.5
0.4
0.3
0.2
0.1
0
ε (MeV)
25
50
75
100
125
150
175
200
225
X_D (μm)
9
10
11
12



ε (MeV)
1
10^{-1}
10^{-2}
4
8
12
16
20
24
t

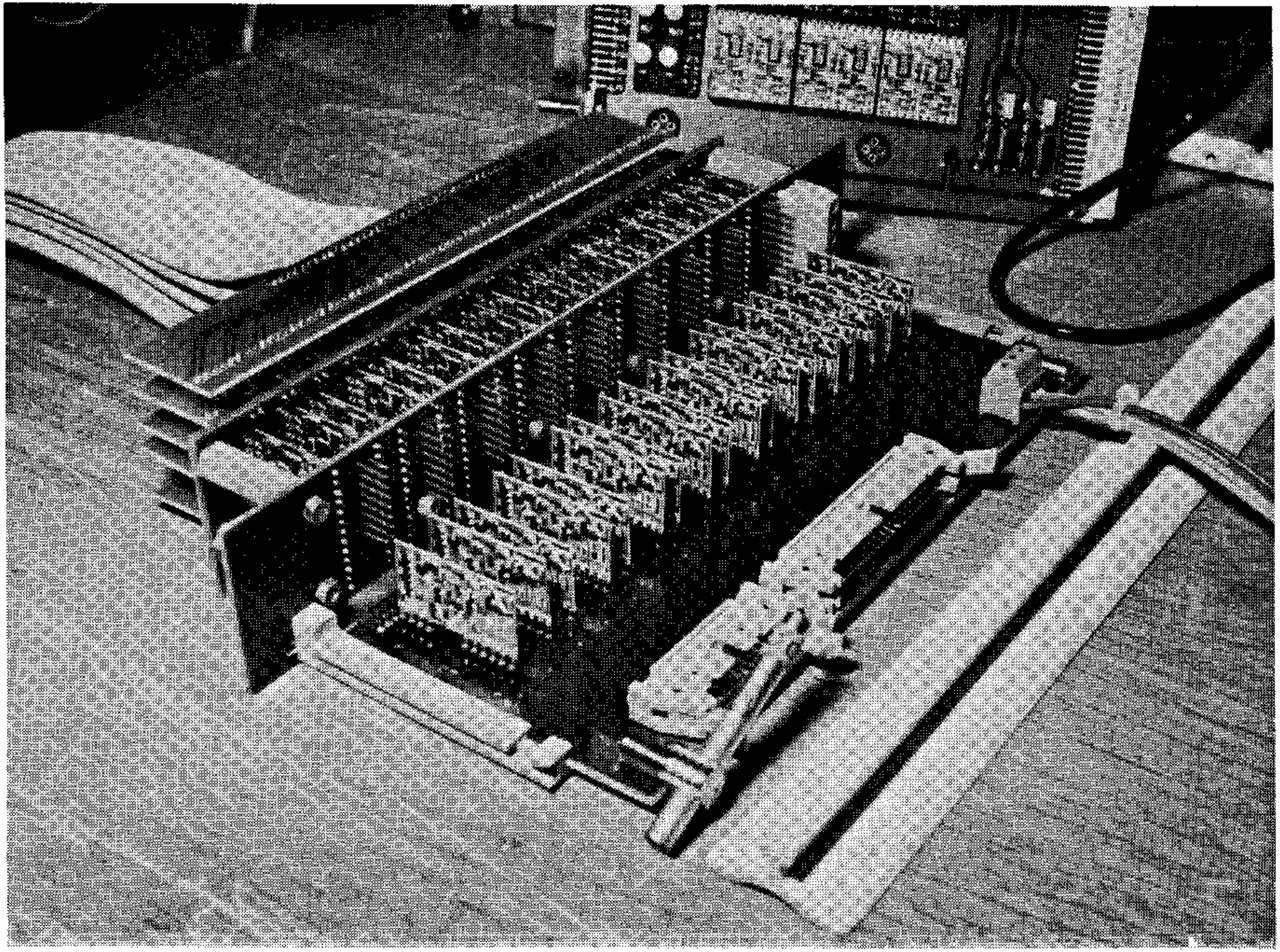


Fig.6

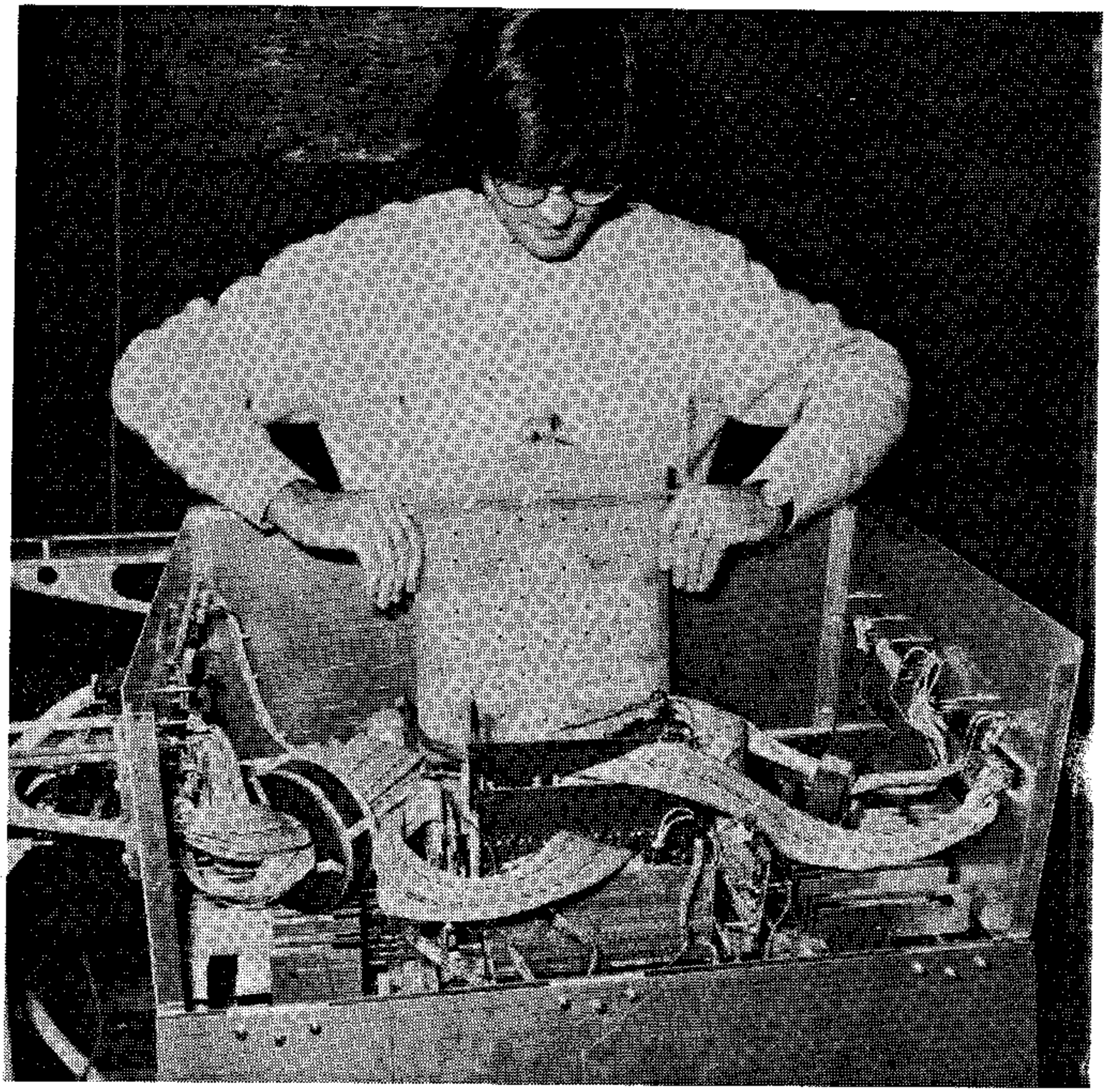
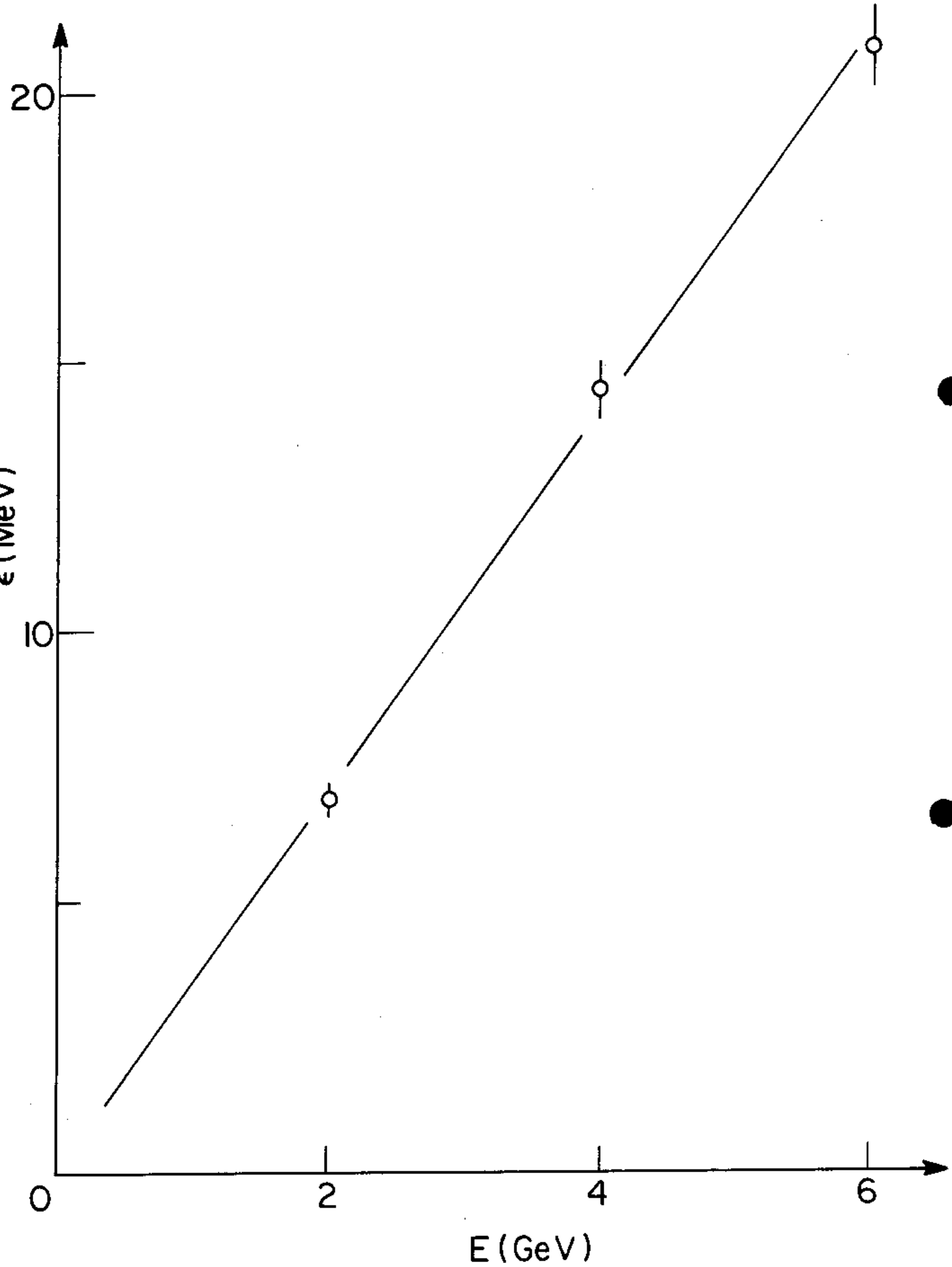
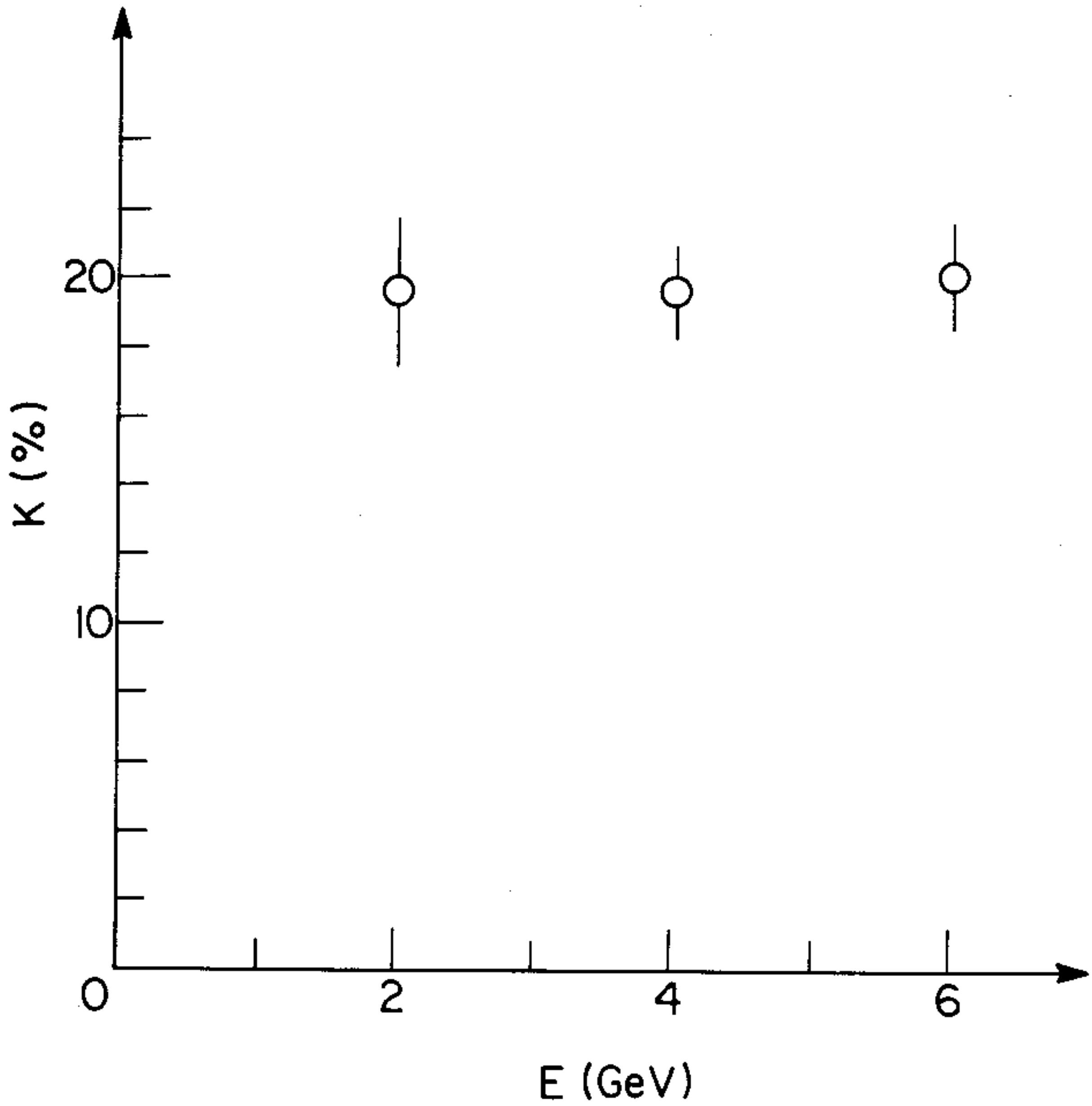


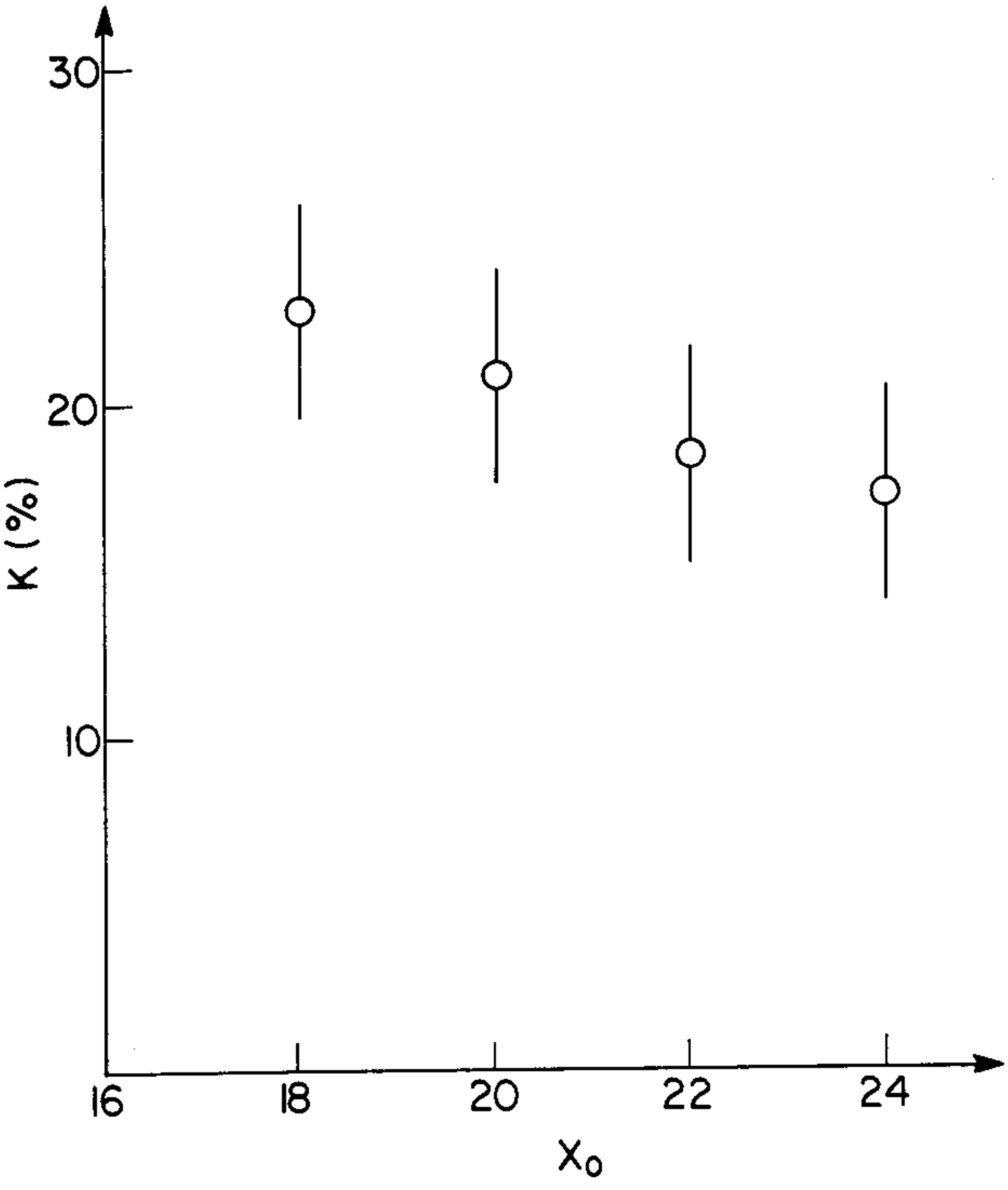
Fig.7



20
10
ε (MeV)
0
2
4
6
E (GeV)



20
K (%)
10
0
2
4
6
E (GeV)



30
20
10
K (%)
16
18
20
22
24
X_0