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Test of a 10 x 10 Channel Photomultiplier based on Micro-Channel Plates for Scintillating Fiber Readout

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1 Introduction

The usage of scintillating fiber detectors is one of the promising techniques in particle physics. Because of their fast response, good spatial resolution, high radiation resistance and compactness they can be used as tracking detectors in modern experiments at high energy colliders [1–12].

A critical point is the choice of a suitable photo–detector which can efficiently read out a large number of fibers. Position–sensitive photomultipliers with up to a few hundred channels are of practical interest as photo–detectors. Different types of these devices are produced by industry and studied in detail by several groups [2–6,11,12]. The main goal of our investigations is the test of the 100–channel photomultiplier FEU–2MCP–100 [2] based on two micro–channel plates, as a readout device for scintillating fibers.

Our activities were initiated by plans to employ this kind of photomultiplier for an upgrade project of the H1 experiment at the HERA e–p collider [3]. Scintillating fiber detectors installed in Roman Pots are foreseen to measure forward scattered protons which escape the central detector at very small angles.

The general properties of this type of multi–channel photomultiplier (MCPM) were supplied by the producer [13,14]. We concentrated our measurements on those characteristics which are important for an application in the Roman Pots.

The description and general properties of the MCPM are given in section 2. Coupling light emitting diodes by light guide fibers to all channels of the MCPM the sensitivity for low light intensities, the cross talk, the frequency dependence and the long time behavior were studied. The results of these measurements are given in section 3. The MCPM was also tested in combination with a scintillating fiber detector. Cosmic particles (section 4) and beam dump muons (section 5) were used to measure the efficiency and the spatial resolution of this set–up. The main results and possible improvements of this type of MCPM are presented in the summary (section 6).

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Abstract

A 100–channel position–sensitive photomultiplier based on two micro–channel plates has been tested as readout device for scintillating fibers. The sensitivity of all channels, the cross talk, the frequency dependence and the long time behaviour have been studied using light emitting diodes. Exposing a scintillating fiber detector to cosmic particles and beam dump muons the detection efficiency and the spatial resolution have been measured.

2 Description of the multi–channel photomultiplier

The MCPM has a multi–alkaline (Sb–Na–K–Cs) photocathode which is sensitive in the spectral region from 350 nm to 850 nm with a maximum quantum efficiency of 10% at 500 nm. The producer quotes a luminous sensitivity of the photocathode of 120–150 μA/Lm. The entrance window of the MCPM is formed by a flat–concave optical plate with a sensitive area of 25 mm diameter.

The multiplying system is based on two micro–channel plates with a channel inclination angle of 7 degrees. The diameter of the micro–channels is 10 μm, the pitch is 15 μm.

Focusing and distortion electrodes are used to obtain an image with small cross talk and distortion. The anode matrix consists of 10×10 pixels of 1.5×1.5 mm^2 size with a pitch of 2.2 mm.

The maximum gain is 3×10^5 at a high voltage of 2.8 kV. The anode pulse time is about 5 ns. The maximum anode current for all channels together is 100 nA while the dark current is around 1 nA.

The MCPM housing has an outer diameter of 50 mm and a length of 80 mm. A schematic view of the MCPM and the high voltage divider is shown in fig. 1.

3 Single fiber measurements

3.1 Set–up and readout electronics

The scheme of the set–up including readout electronics for single fiber measurements is shown in fig. 2.

Green and blue light emitting diodes (LED) with a maximum intensity at 550 nm and 430 nm, correspondingly, were used in a pulse regime for the MCPM exposition. The light was transfered via green and blue light guide fibers of 1 mm diameter onto the photocathode.

Using a microscope mechanics as a x–y scanner allowed to rotate and move the fiber relative to the photocathode surface in x– and y– direction with a precision of about 10 μm.

The readout electronics consists of a 16–channel charge–sensitive preamplifier with a sensitivity of 450 mV/pC and a time response of about 50 μs, a 16–channel differential amplifier (CAMAC) with a gain factor of 20 and a pulse time of about 1 μs and a 10–bit ADC with a sensitivity of 6 mV/count.

For the measurement of the frequency dependence of the MCPM response we used a fast current preamplifier with a sensitivity of about 2.5 V/pC and a pulse time of about 20 ns [16], a fast amplifier (CAMAC) with a gain factor of 8 and a rise time of a few ns and a 10–bit ADC with a sensitivity of 0.25 pC/count. An IBM PC 386 computer was used for data recording.

3.2 Sensitivity and cross talk

To measure sensitivity and cross talk, the fiber was moved over the photocathode surface to find the position which corresponds to the maximum amplitude in the exposed channel and the lowest cross talk in the neighbouring channels. The cross talk was defined as the ratio of the average amplitude in the neighbouring channels to the average amplitude in the exposed channel.

The LEDs were calibrated using a photomultiplier FEU–130 [15] with a quantum efficiency of 4% and 13% in the green and blue light region, respectively.

The light intensity was chosen between 10 and 30 photons per LED pulse according to the expected amount of light from a minimum ionizing particle crossing a 1 mm scintillating fiber [12]. The frequency of the LED pulses was 1 kHz.

The high voltage of the MCPM was set to the maximum value of 2.8 kV to obtain the maximum amplification of light pulses.

The efficiency was defined as the ratio of the number of anode signals above the threshold of 20 ADC counts to the total number of light pulses. For three adjacent pixels the coordinate dependence of the efficiency in the LED regime of 20 green photons is shown in fig. 3. The efficiency distribution has a plateau of about 1 mm width in the exposed channel. The cross talk increases significantly for an exposition near to the pixel edge.

For all channels the average efficiency in the light regime of 20 green photons is shown in fig. 4. Most channels have values between 70% and 80% detection efficiency. Only the channels in the corners and two bad channels at the positions (2,6) and (2,7) have a lower efficiency around 50%.

The average efficiencies of all channels in dependence on the numbers of green and blue photons are given in table 1. As can be seen, the MCPM is more sensitive for blue than for green light. The cross talk in all channels is around 1.0–1.5%.

3.3 Frequency dependence

The frequency dependence up to 1 MHz in the light regime of 25 green photons per LED pulse was measured for several MCPM channels. For these measurements the high voltage of the MCPM was lowered to 2.7 kV. Also the amplitude threshold was slightly decreased to keep the cross talk on the level of 1.5%.

The frequency dependence of the amplitude and the efficiency for one typical channel is shown in fig.5. While the amplitude dramatically decreases for frequencies greater than 10 kHz the behavior of the efficiency is rather flat up to a few 100 kHz.

The steep fall of the amplitude at frequencies greater than 10 kHz is caused by saturation effects in the micro–channels. The low conductivity in the micro–channels and the formation of high space charge densities at the exit of these channels prevent an application at higher repetition rates [13–14].

The efficiency is not so strongly influenced by saturation effects since the signal amplitudes are still above the threshold. The frequency measurements were also performed at the lower MCPM voltage of 2.6 kV. The signal amplitudes were smaller but the fall off with increasing rate was more flat. At 1 MHz the signal amplitudes decreased only by a factor 3 at the high voltage of 2.6 kV instead of a factor 5 at 2.7 kV.

3.4 Long time behavior

We measured the life time of one MCPM channel at the high voltage of 2.8 kV. The LED was operated at 1 MHz in the light regime of 25 green photons per pulse. Under these conditions the exposed MCPM channel was in deep saturation. The value of the anode current was about 20 times larger than the maximum value of 1 nA/mm^2 recommended by the producer[13,14]. Measurements of signal amplitudes before and after the light exposition were made at a lower frequency of 10 kHz.

The average amplitudes of the LED pulses as a function of the exposition time are summarized in table 2. In the first 100 hours of exposition the signal amplitude decreased continuously. Then a plateau was reached at the level of 1/3 of the amplitude before the exposition. According to the producer such a behavior can be explained by the removal of the alkali layers from the inner walls of the micro–channels. Some hours after each exposition the signal value recovered slightly.

At the lower MCPM voltage of 2.6 kV the time behaviour of another channel was studied in the regime without current saturation. Using LED pulses with a frequency of 100 kHz the anode current decreased to 1 nA/mm^2. Under these conditions the amplitude did not show any decreasing behaviour after 70 hours of exposition.

As a general recommendation for a stable long time behavior, this type of MCPM should only be operated in the regime without current saturation in the micro–channels, i.e. at the lowest MCPM voltage which still gives sufficient signal amplitudes.

4 Cosmic ray measurements

4.1 The set–up and readout electronics

For cosmic ray measurements a scintillating fiber detector was built. It consists of four double layers of 1 mm blue/green scintillating fibers staggered by half of the diameter. Each double layer has 2 × 12 fibers of about 85 mm length coherently arranged with a pitch of 1.05 mm (see Fig.7). The third and fourth double layers are shifted by 0.25 mm relative to the first two double layers. The thickness of the double layer is 2.5 mm. One part of the detector consists of 96 blue fibers, the other one of 96 green fibers emitting light at 420 nm and 500 nm, respectively.

All 96 fibers of each part of the detector were glued into a special plastic mask which corresponds to the array of the 10 × 10 MCPM channels. The positions of the fibers in the regular mask have an average deviation of 100 μm from the position which corresponds to the amplitude maxima.

A special mechanics allowed the movement of the MCPM mask on the photocathode surface in x– and y–direction with a precision around 10 μm. With lower precision also rotations were possible.

Four green LEDs were used for calibration purposes and tuning of the mask position in respect to the photocathode. They were coupled via 1 mm light guide fibers to the mask positions (3,3), (3,8), (8,3) and (8,8). Maximum amplitudes in the exposed channels and symmetric cross talk in the surrounding channels were used as criteria for the optimum mask position.

A trigger signal from cosmic particles was formed by the coincidence of the signals from two scintillation counters. The trigger counters were arranged above and below the fiber detector and overlapped the sensitive detector area. The noise rate of each trigger counter was less than 100 pulses/s which gave a very low probability of accidental coincidences.

The readout electronics was based on two 128 channel MX–4 chips [11]. Each MX–4 chip was connected to 50 channels of the MCPM. The serial output of these boards was digitized by a SIROCCO–II 10–bit flash ADC using a VME–OS9 online data taking system with CAMAC interface. The sensitivity of the MX–4 preamplifiers was around 3 V/pC. The gains of all channels were measured and an overall gain spread less than a factor of 1.5 was observed.

4.2 Data taking and statistics

Cosmics data were taken for both parts of the detector with the blue and the green scintillating fibers. Two MCPMs of the type described were used for the readout. Since the gain of the MCPM increases considerably with increasing voltage, the measurements were carried out for three values of the high voltages: 2.6 kV, 2.7 kV and 2.8 kV. The raw data statistics of cosmic particles was between 3000 and 6000 events per data sample. Altogether, about 60000 events were recorded. The track of the cosmic particle passing all fiber layers could be reconstructed with a probability between 20% and 40%, depending on the high voltage .

4.3 Hit finding and track reconstruction

Before the data taking the mean pedestal amplitudes and the root–mean–square (RMS) of the pedestal fluctuations of all individual MCPM channels were measured. The average signal amplitude of cosmic particles corresponds to values of 15–20 times the pedestal RMS, depending on the high voltage. The mean pedestal amplitudes were subtracted from the raw amplitudes. All signals with amplitude above a threshold of 3 times the pedestal RMS of each individual channel were accepted as hits. The threshold cut was chosen as a compromise between the number of track hits and the contribution of background hits.

To reconstruct a track we required at least 3 hits inside a narrow corridor of ± 0.75 mm around the particle track. The final track was obtained by an iterative straight line fit of all hit candidates inside the track corridor.

The distribution of the residuals of all track hits is shown in fig. 6a. Most hits are inside a corridor of ± 0.5 mm which is one half of the fiber diameter. The hits at larger distances are caused by cross talk, MCPM noise and geometric inaccuracies of the fiber positions.

A typical hit pattern from a traversing cosmic particle is shown in fig. 7. To estimate the internal resolution of the fiber detector we calculated for each event the minimum overlapping corridor of all hit fibers which belong to the track. The size of the overlapping region divided by $\sqrt{12}$ defines the internal resolution of the fiber detector which is given in fig. 6b. The mean value of the distribution is about 100 μm, which can be considered as the internal resolution of the fiber detector.

4.4 Efficiency and cross talk

Due to the soft trigger conditions not all cosmic particles traversed all fiber layers of the detector. In the further analysis only tracks crossing all 8 fiber layers with at least 4 hits were accepted.

For the detector part with the blue fibers the average efficiency per layer corrected for background hits is presented in fig. 8. The values vary between 60% and 70%.

The contribution of background hits depends on the amplitude threshold, the geometrical cuts to select track hits and the accuracy of the fiber mask alignment on the photocathode. It was determined from the number of fiber hits outside the track corridor. The fraction of background hits per fiber layer normalized to the size of the track corridor is also shown in fig. 8. It is on the level of 5%.

The efficiency values of all fibers are distributed as shown in fig. 9. The distribution has a mean value of 64% and a spread of 10%. The lowest values of the efficiency correspond to the channels in the corners of the MCPM and the two bad channels.

The multiplicity distribution of track hits was fitted by a binomial function as indicated in fig. 10. This fit gives an estimation of the average detection efficiency per fiber layer which is 64% for the detector with the blue fibers.

In Fig. 11 the average values of the detection efficiency are compiled, as a function of the high voltage of the two MCPMs used to read out the two parts of the fiber detector. The efficiency increases significantly with increasing MCPM voltage. For the detector part made of blue scintillating fibers it is about 50% at 2.6 kV and increases to 65% at 2.8 kV. The efficiency values obtained from both MCPMs are very similar.

The average efficiency for blue fibers is about 10% higher than for green ones. This difference does not indicate a higher sensitivity of the photocathode in the blue region but is caused by a greater amount of photons produced in blue fibers.

The resulting efficiency per fiber layer is compatible with the single fiber measurements assuming an average of 15 photons per minimum ionizing particle. In this case one can expect on the average about 1.5 photoelectrons from the photocathode, but due to the ratio of holes and support material of the micro–channel plates the average number of photoelectrons hitting into a micro–channel is only 1.0.

5 Accelerator measurements with muons

5.1 Set–up and data acquisition

Further tests of the MCPM in combination with the blue fiber detector were performed at the Serpukhov accelerator using muons from a dump of the neutron beam 5N. The proportional chambers of the EXCHARM spectrometer [17] were used for track reconstruction and allowed an unbiased estimation of the efficiency. An advantage of the accelerator facility is the possibility to collect a higher statistics than with the cosmics data.

Another goal of these measurements was to test a more sensitive readout electronics. For this experiment an assembly of 50 current preamplifiers [16] was used in combination with a 12–bit ADC of 0.1 pC/count sensitivity.

The fiber detector was placed in front of the EXCHARM spectrometer as shown in fig. 12. The trigger signal was formed by a coincidence of signals from two scintillating counters arranged in front of and behind the fiber detector overlapping its sensitive area. An additional anticounter covered the light guide fibers between the detector and the MCPM to suppress signals from particles crossing this region.

As in the cosmics measurements, data were collected at the high voltages of 2.6 kV, 2.7 kV and 2.8 kV. The beam dump produced a flux of about 3000 muons per spill passing the sensitive area of the fiber detector. The data acquisition was based on the online program of the EXCHARM spectrometer which accepted about 700 events per spill. The statistics was above 50000 events per data sample.

5.2 Hit determination and results

With the more sensitive electronics the RMS of the pedestal fluctuations could be reduced to about 3 ADC counts for all MCPM channels. The average amplitude of the signals from muons corresponds to values between 50 and 150 times the pedestal RMS, depending on the high voltage. To find a hit in the fiber detector we used threshold cuts between 25 and 75 ADC counts, to achieve in each case the same background level.

The muon tracks were reconstructed using the information from 8 two–coordinate proportional chambers with a wire pitch of 2 mm. Only events with exactly one track candidate were selected for the further analysis.

The distribution of distances between fiber hits and the reconstructed track is shown in fig. 13. The Gaussian fit gives a standard deviation of 730 μm. This value is in agreement with the accuracy of the track reconstruction in the proportional chambers taking into account Coulomb scattering and the lever arm of the extrapolated track.

For an estimation of the fiber efficiency all hits inside a corridor of ±2.2 mm around the reconstructed track were accepted as track hits in the fiber detector. Again, the fraction of background hits per fiber layer was at the level of 5%.

Due to the limited number of preamplifiers only four fiber layers were read out. The multiplicity distribution of track hits is presented in fig. 14. A binomial fit yields an average value of 62% efficiency per fiber layer. This value is in good agreement with the results from the cosmics data.

The dependence of the efficiency on the high voltage is presented in fig. 11. The more sensitive electronics allows to operate the MCPM in more favourable conditions at lower voltage. In this way the efficiency was improved by about 10% compared with the former cosmics measurements, and also the life time of the MCPM will be significantly enlarged.

6 Summary and conclusions

We tested a 100–channel photomultiplier based on two micro–channel plates, as readout device for scintillating fibers. The basic properties of the MCPM were investigated with LED pulses which were calibrated to produce the same amount of light as a minimum ionising particle traversing a 1 mm scintillating fiber. Coupling a single fiber to each MCPM channel the following results were obtained:

- the mean detection efficiency in the light regime of 15 photons is 70% for the blue fibers and 60% for the green ones at a high voltage of 2.8 kV;

- the cross talk is between 1.0% and 1.5% for an optimum position of each fiber relative to the center of the corresponding MCPM channel;

- for pulse rates up to 10 kHz per MCPM channel the signal amplitude shows no significant degradation while above that rate a steep fall–off was observed; however the efficiency loss is only a few percent up to rates around 100 kHz per channel;

- the operation of the MCPM in the saturation regime leads to a continous fall of the signal amplitudes; an anode charge of about 2 mC lowers the amplitude to 1/3 of its initial value.

In a more realistic application the MCPM was used as readout device for a multi–layer fiber detector. The detector consisted of two parts of blue and green scintillating fibers of 1 mm diameter arranged in 8 layers. All 96 fibers of each part were coupled with a special mask to the 10 × 10 MCPM channels. Cosmic particles and muons from a neutron beam dump were used to investigate the tracking properties of the combined system fiber detector plus MCPM. The following results were obtained:

- the internal resolution of the fiber detector consisting of 8 layers of 1 mm fibers is about 100 μm;

- at the maximum MCPM voltage of 2.8 kV the mean value of the detection efficiency is 64% for the blue fibers and about 10% less for the green fibers;
- the efficiency of the blue fibers decreases to 50% at the voltage of 2.6 kV – again the corresponding value for the green fibers is slightly worse;
- using a more sensitive readout electronics the efficiency at lower MCPM voltages could be significantly improved.

For future tests some modifications of the MCPM are in preparation: the quantum efficiency of the photocathode in the region of blue light will be increased up to 15%, the degradation of the signals at higher frequencies will be improved by a different production technology, and the number of anode channels will be enlarged up to 150 by an optimum coverage of the whole sensitive area of the micro–channel plates.

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TABLES

Table 1: Average detection efficiency of MCPM channels exposed to different numbers of photons of green and blue light.

	Green light (550 nm)			Blue light (430 nm)		
Number of photons	10	15	20	15	22	30
Efficiency	0.46	0.60	0.73	0.70	0.86	0.91

Table 2: Long time behaviour of one MCPM channel. The average amplitude of anode pulses in dependence on the exposition time, the number of light pulses of 25 green photons and the total anode charge.

Exposition time (hours)	0	15	35	40	62	84	106	129	155	219
Light pulse number (10^{10})	0.	5.	13.	14.	22.	30.	38.	46.	56.	79.
Total anode charge (mC)	0.	0.8	1.5	1.7	2.3	2.9	3.4	3.9	4.5	5.8
Average amplitude (pC)	0.170	0.095	0.088	0.058	0.057	0.057	0.056	0.056	0.054	0.052

FIGURE CATPIONS

Fig. 1 A schematic view of the MCPM FEU–2MCP–100 with the voltage divider as recommended by the producer.

Fig. 2 Scheme of the set–up including read out electronics for single fiber measurements using light emitting diodes.

Fig. 3 The detection efficiencies of three adjacent MCPM channels in dependence on the fiber position on the photocathode surface. The LED was operated in the regime of 20 green photons per pulse and the high voltage was 2.8 kV.

Fig. 4 Average efficiency of all MCPM channels exposed in the light regime of 20 green photons.

Fig. 5 Dependence of the signal amplitude and the detection efficiency of one MCPM channel on the frequency of light pulses of 25 green photons.

Fig. 6 a) Residuals of fiber hits for reconstructed tracks of cosmic particles traversing the part of the detector consisting of blue fibers b) the internal spatial resolution of this fiber detector.

Fig. 7 A schematic view of the end face of the fiber detector indicating a typical hit pattern of cosmic particles traversing the blue fiber detector.

Fig. 8 Distributions of the average tracking efficiency and the fraction of accidental background per layer of the blue fiber detector.

Fig. 9 Distribution of the individual detection efficiencies of all blue fibers of the detector.

Fig. 10 Multiplicity distribution of track hits from cosmic particles crossing all 8 layers of the blue fiber detector. The fit of a binomial function yields an average efficiency per layer of 64%.

Fig. 11 The average values of the detection efficiency of the blue and the green fiber detectors in dependence on the high voltage of the MCPM. Two MCPMs were tested with cosmic particles and muons from a beam dump.

Fig. 12 Layout of the EXCHARM spectrometer at the Serpukhov accelerator. The fiber detector was located between beam dump and the proportional chambers which were used as external reference system.

Fig. 13 Deviation of fiber hits from the reconstructed tracks using the proportional chambers of the EXCHARM spectrometer.

Fig. 14 Multiplicity distribution of track hits from beam dump muons crossing 4 active layers of the blue fiber detector. The curve represents a binomial fit which yields an average efficiency of 62% per layer.

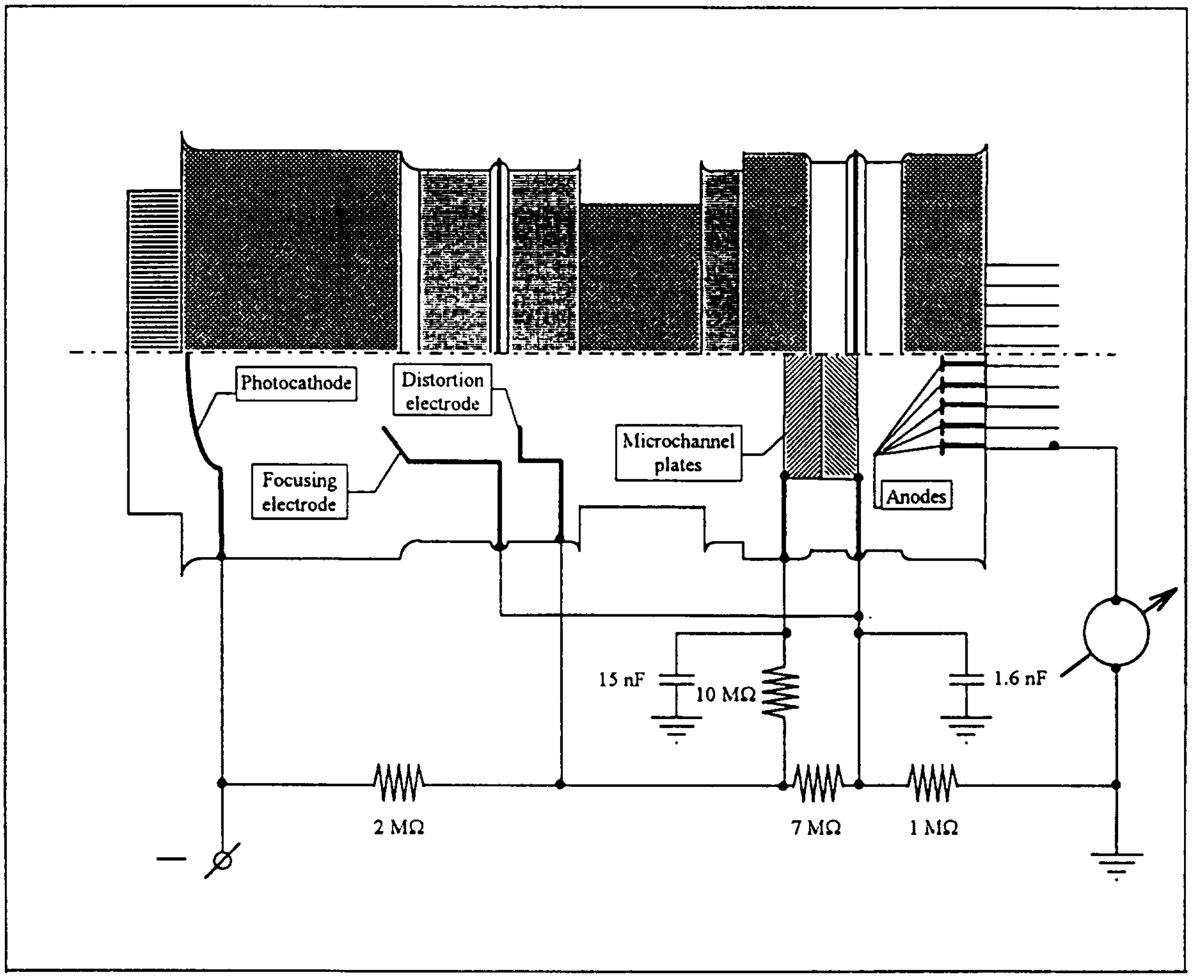
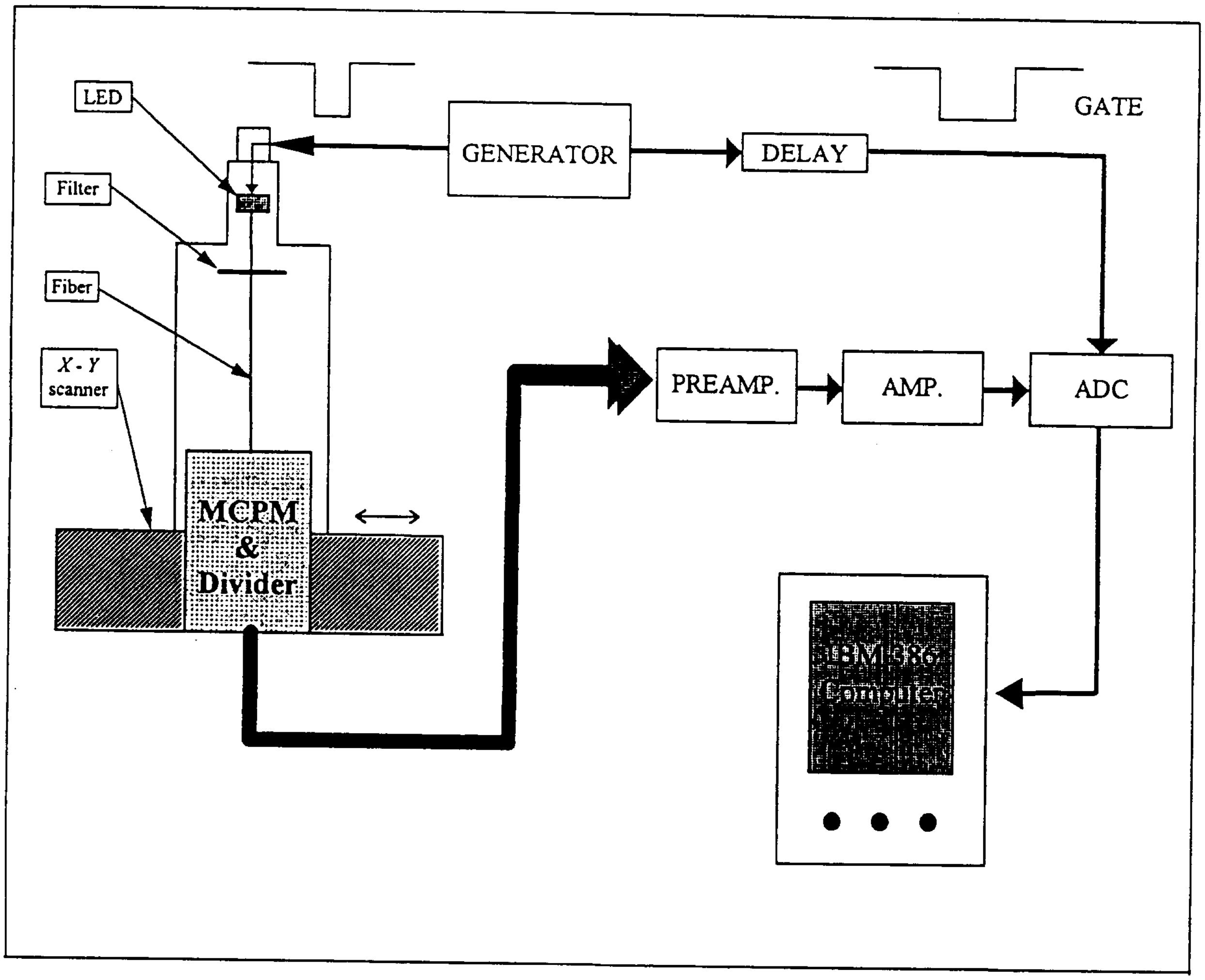

Photocathode
Distortion electrode
Focusing electrode
Microchannel plates
Anodes
15 nF
10 MΩ
1.6 nF
2 MΩ
7 MΩ
1 MΩ
−

Fig. 1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Filter
Fiber
X - Y scanner
MCPM & Divider
GENERATOR
DELAY
GATE
PREAMP.
AMP.
ADC
IBM 386 Computer

Fig. 2

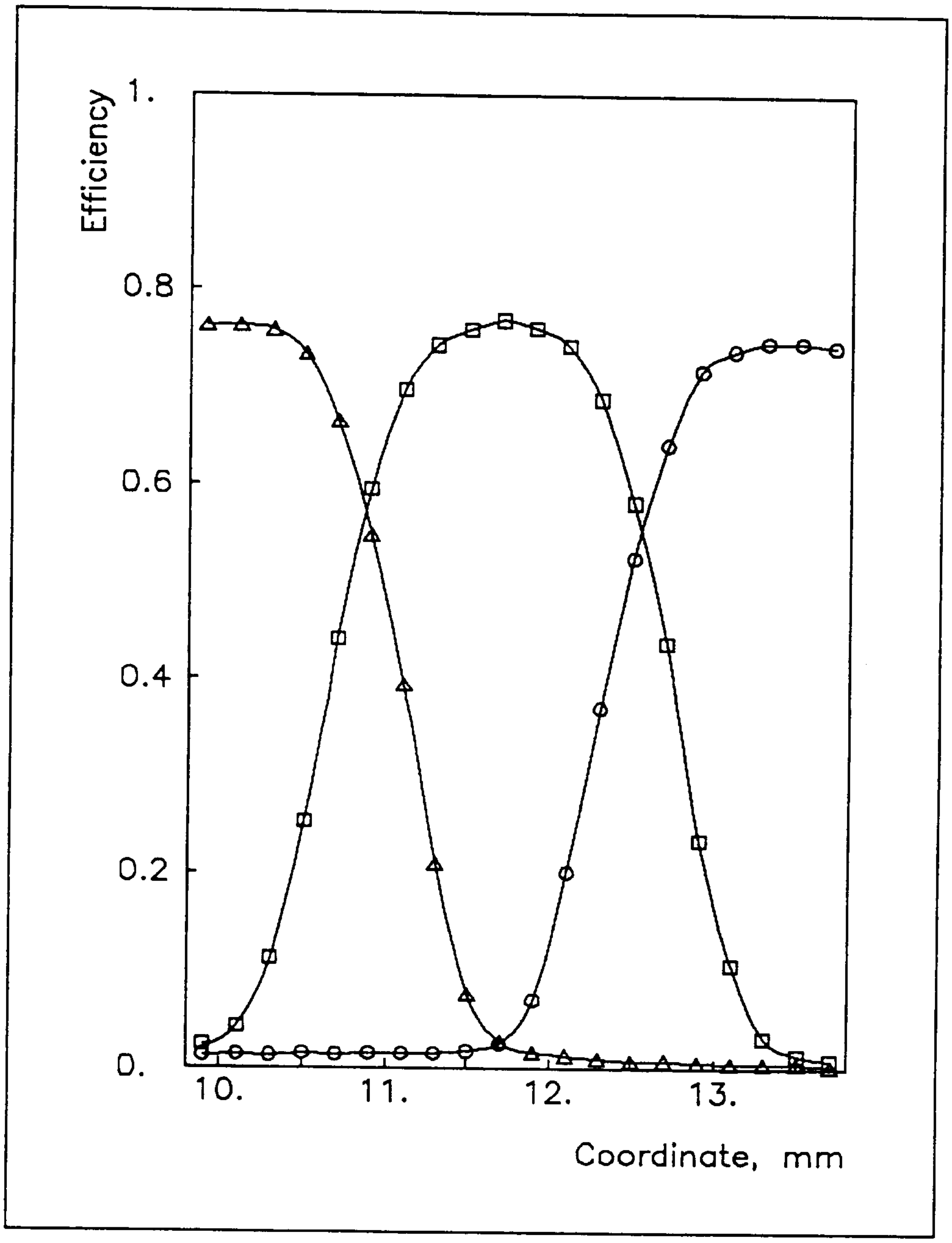


Fig. 3

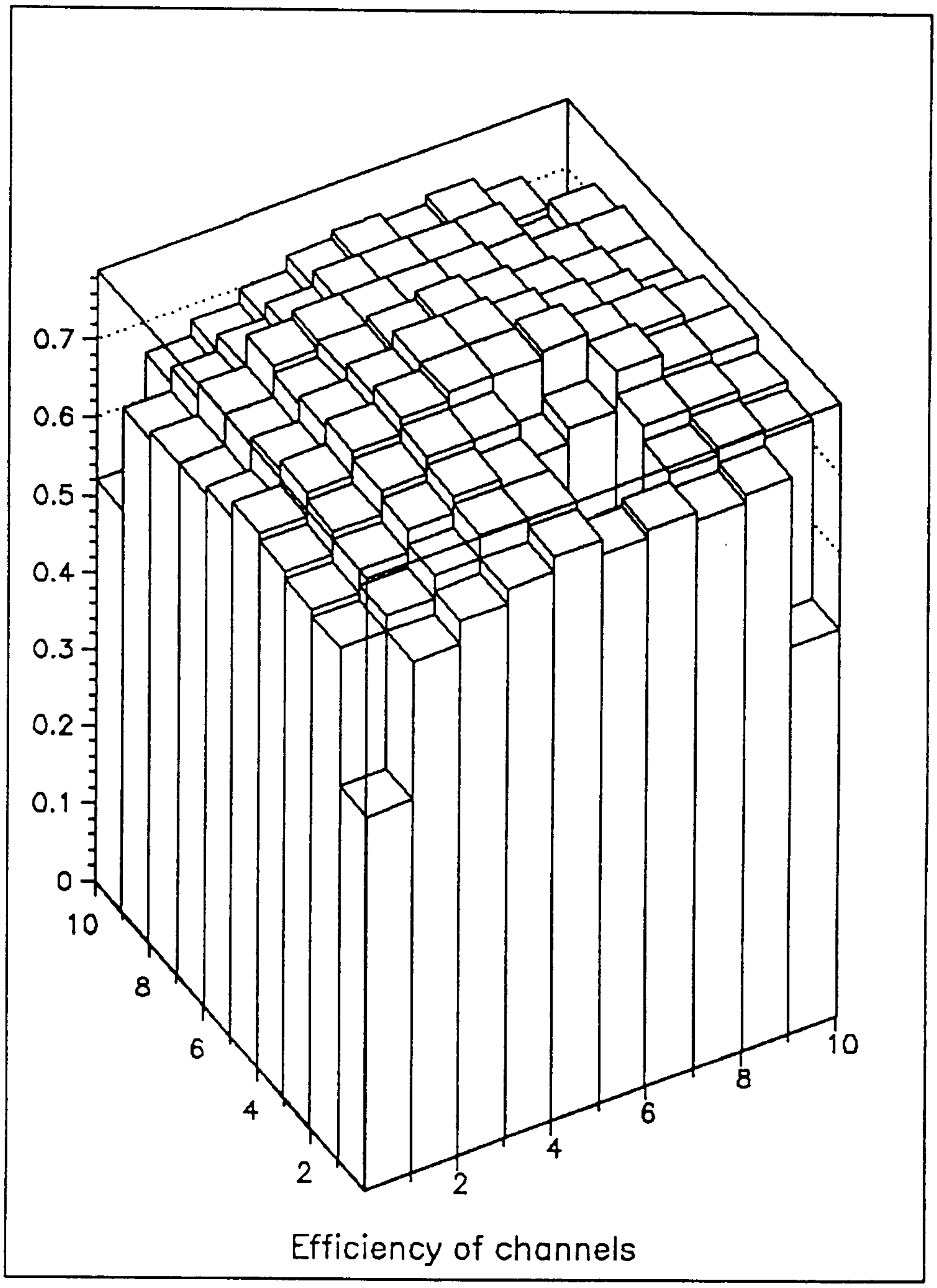


Fig. 4

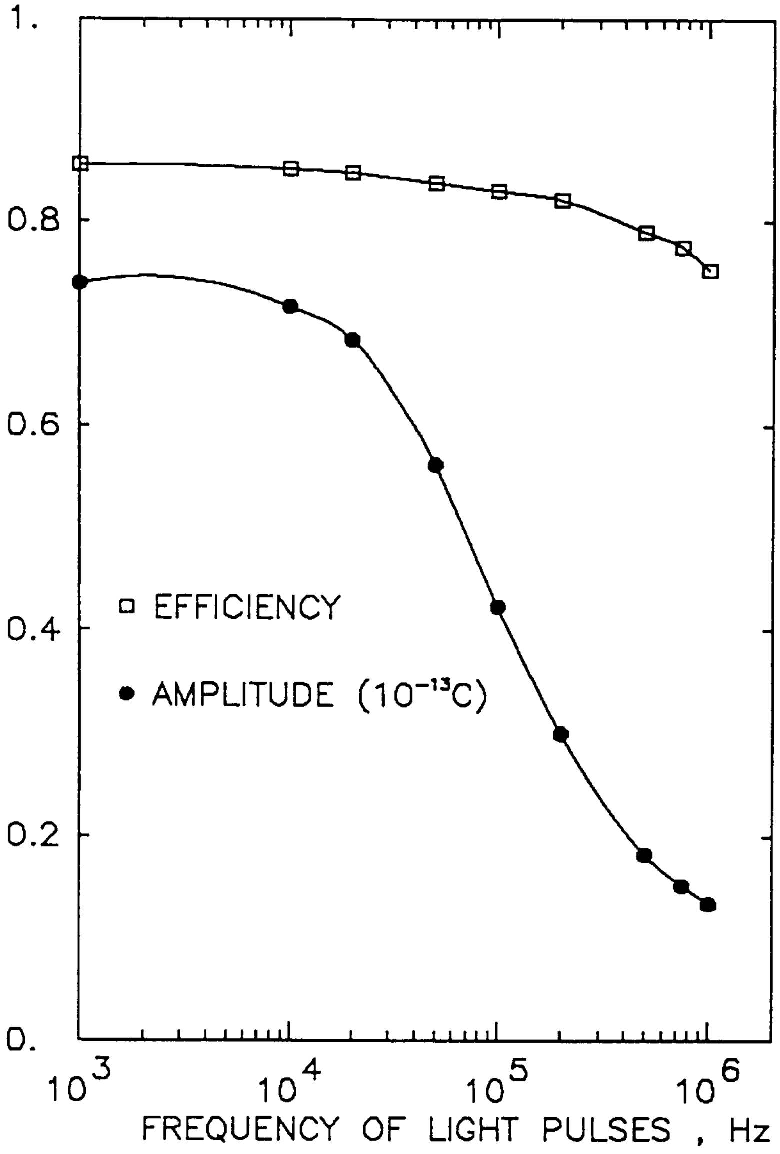

1.
0.8
0.6
0.4
0.2
0.
10^3
10^4
10^5
10^6
FREQUENCY OF LIGHT PULSES , Hz
□ EFFICIENCY
● AMPLITUDE (10^{-13}C)

Fig. 5

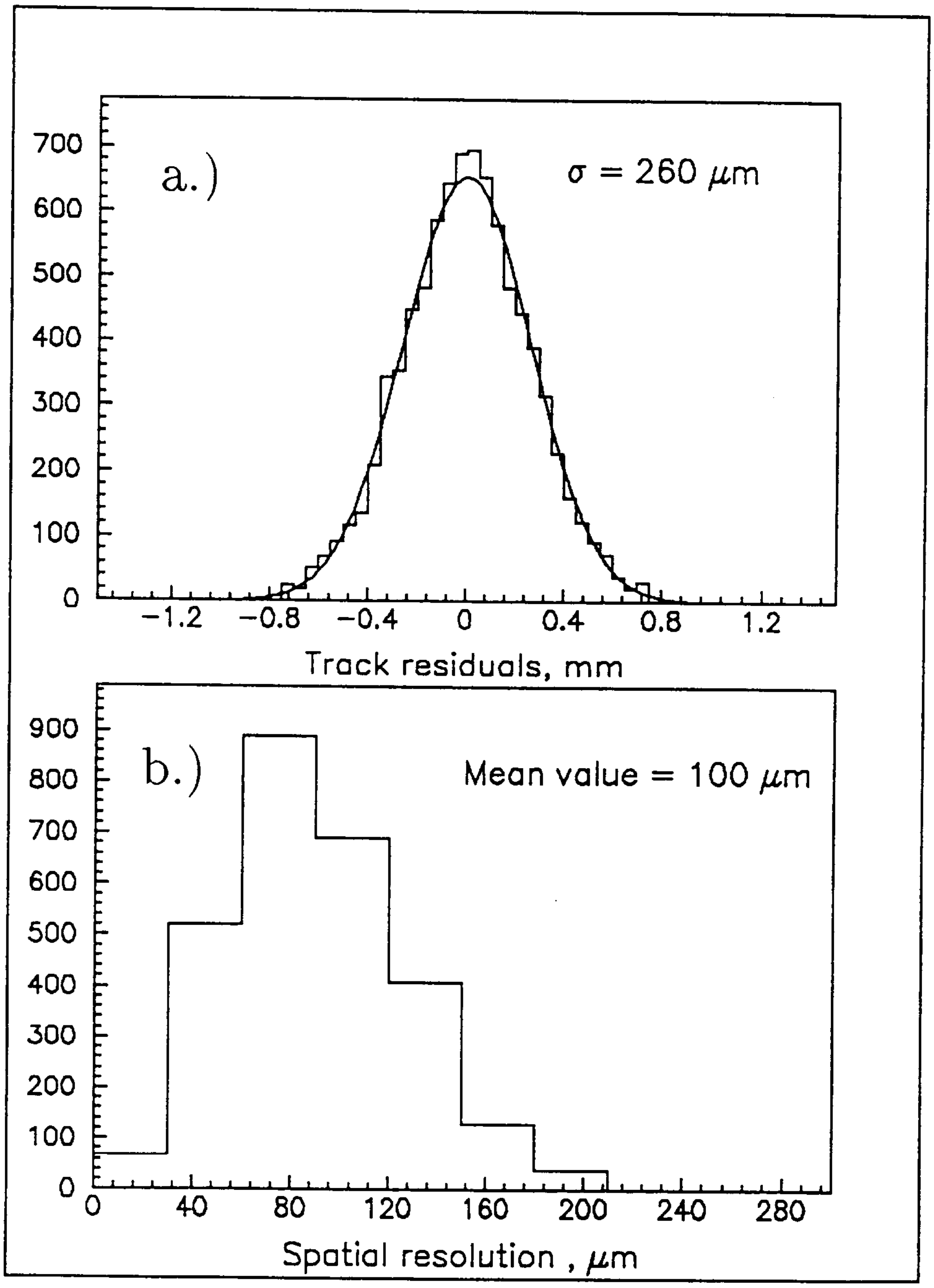

a.)
σ = 260 μm
700
600
500
400
300
200
100
0
−1.2
−0.8
−0.4
0
0.4
0.8
1.2
Track residuals, mm
b.)
Mean value = 100 μm
900
800
700
600
500
400
300
200
100
0
0
40
80
120
160
200
240
280
Spatial resolution , μm

Fig. 6

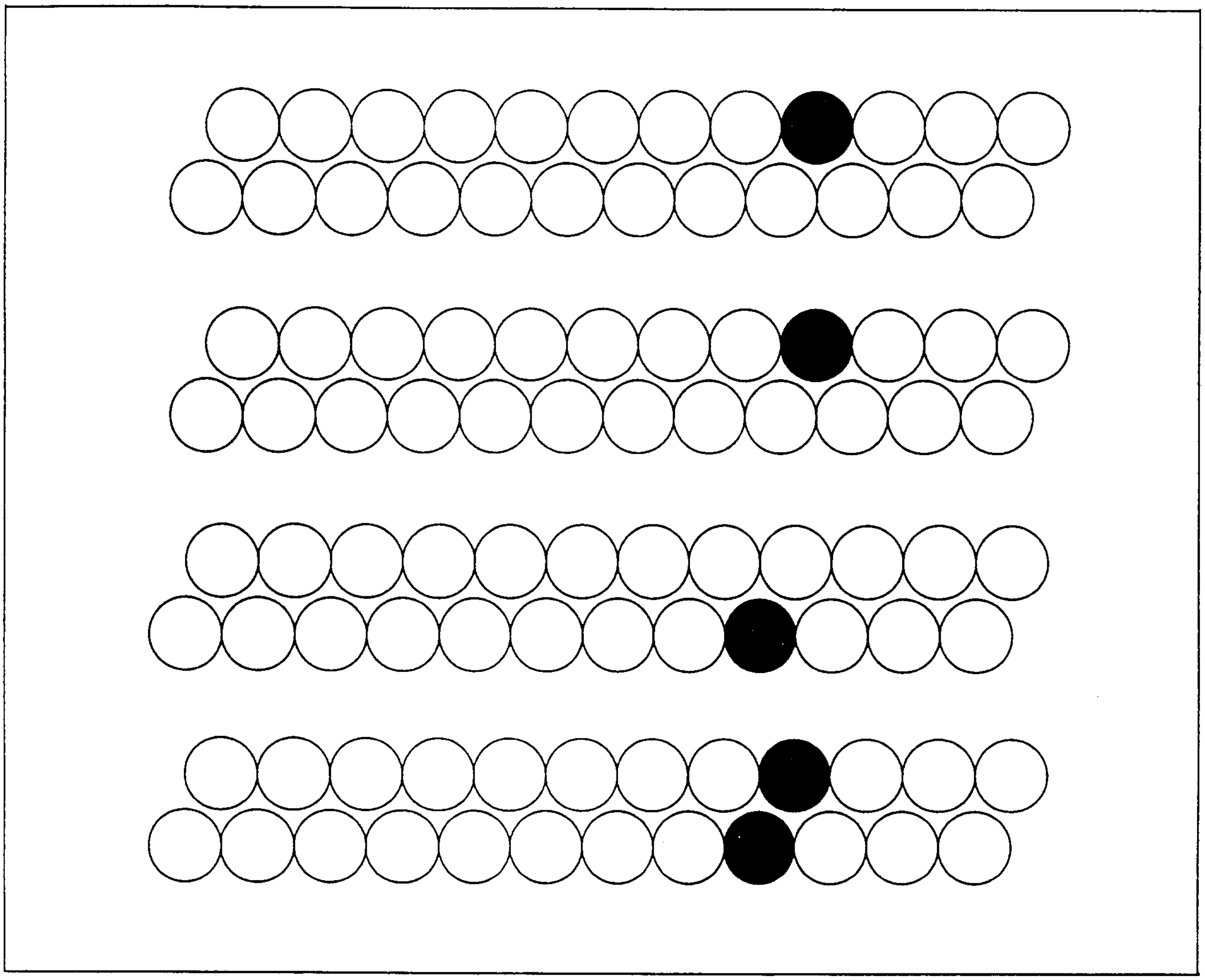


Fig. 7

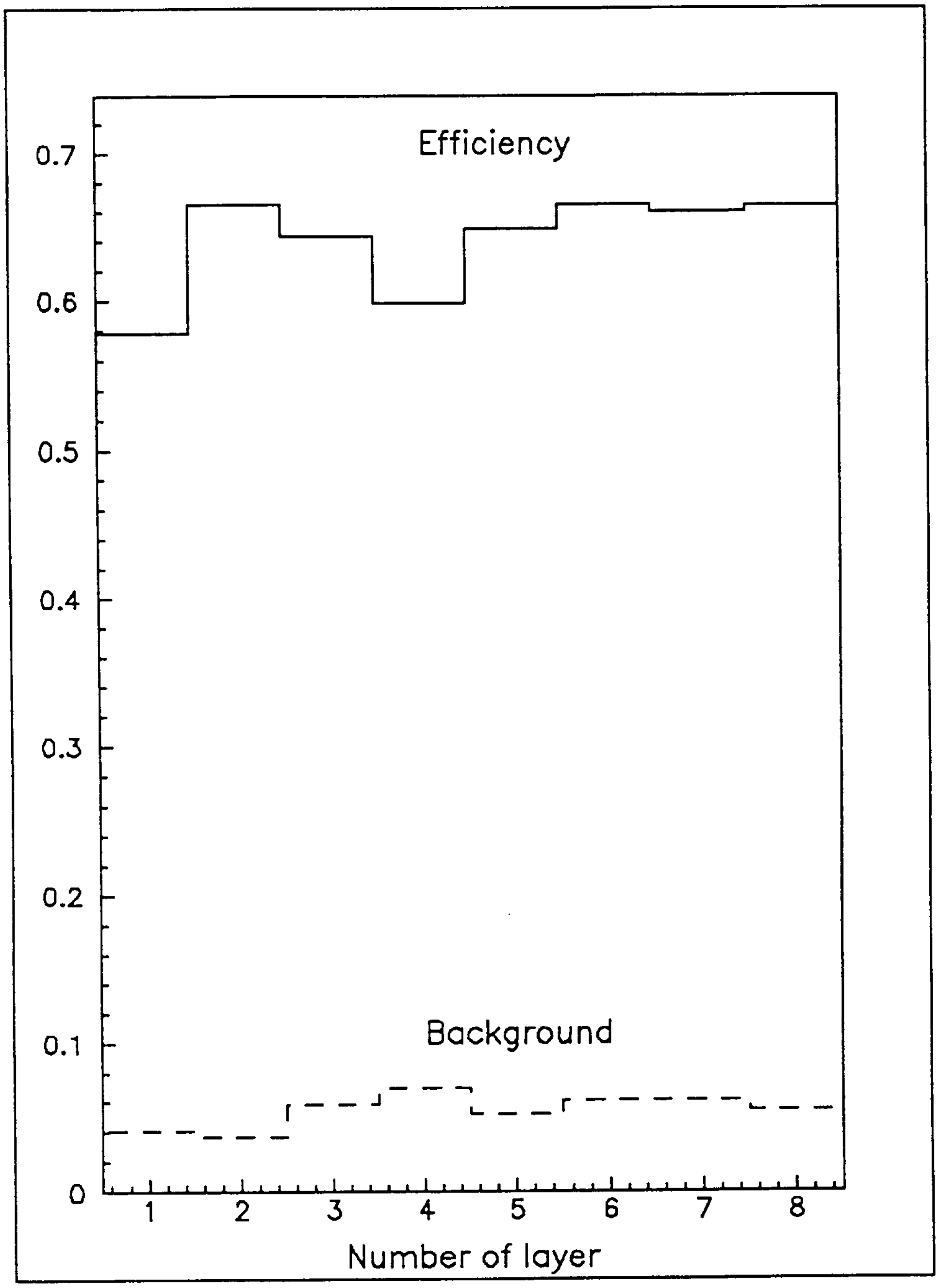
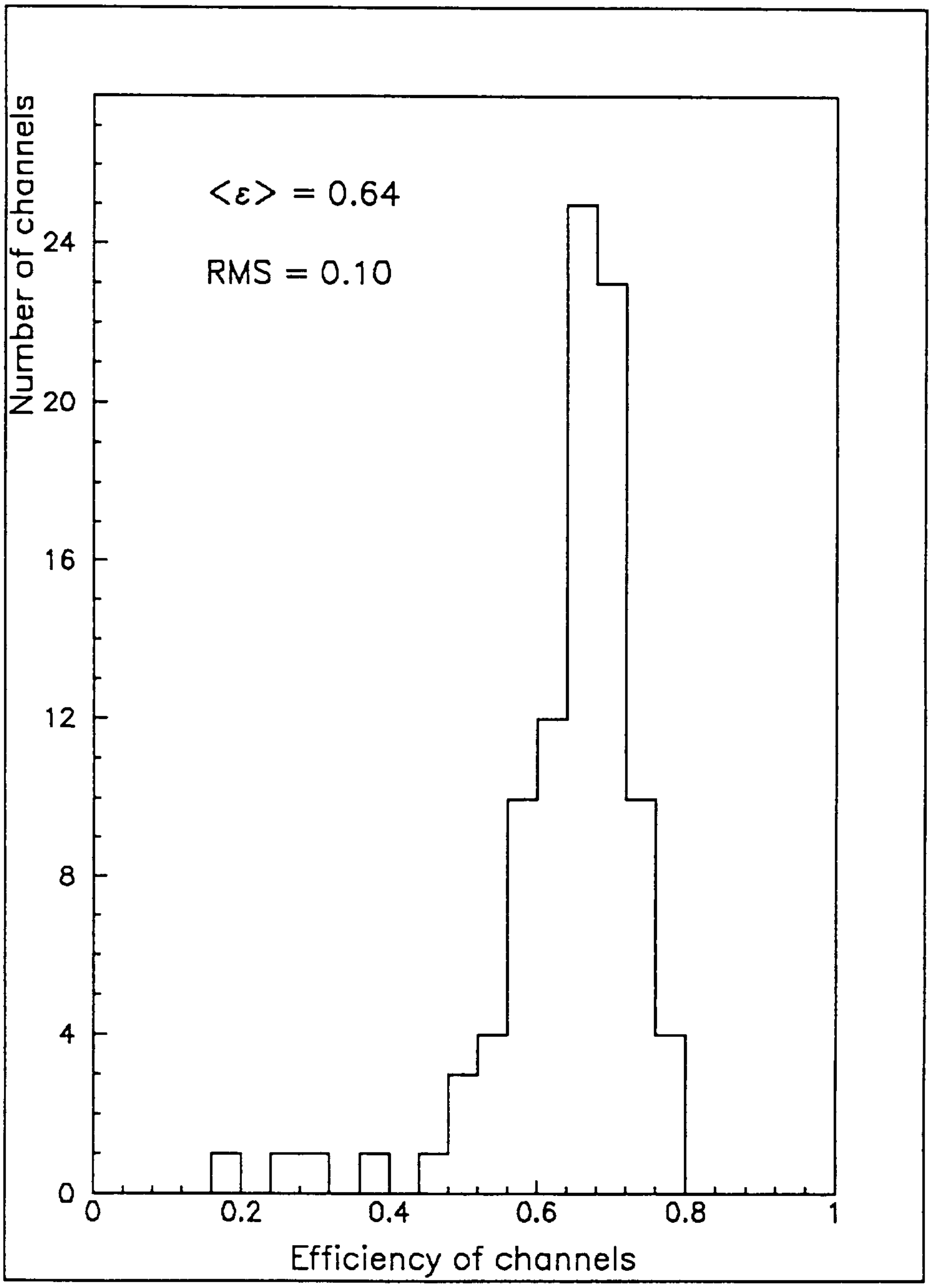

Efficiency
Background
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
Number of layer

Fig. 8



<ε> = 0.64
RMS = 0.10
Number of channels
0
4
8
12
16
20
24
0
0.2
0.4
0.6
0.8
1
Efficiency of channels

Fig. 9

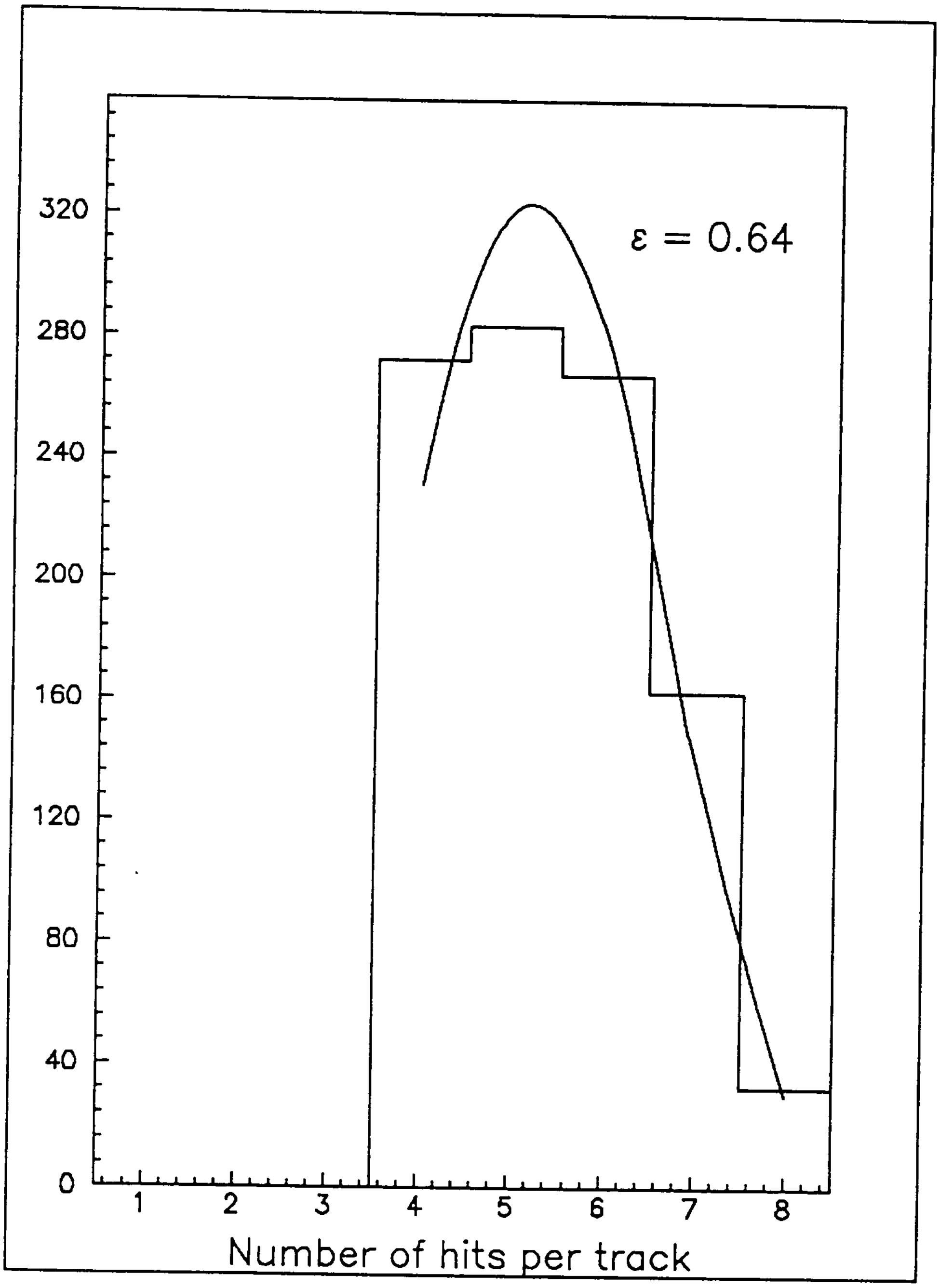

ε = 0.64
320
280
240
200
160
120
80
40
0
1
2
3
4
5
6
7
8
Number of hits per track

Fig. 10

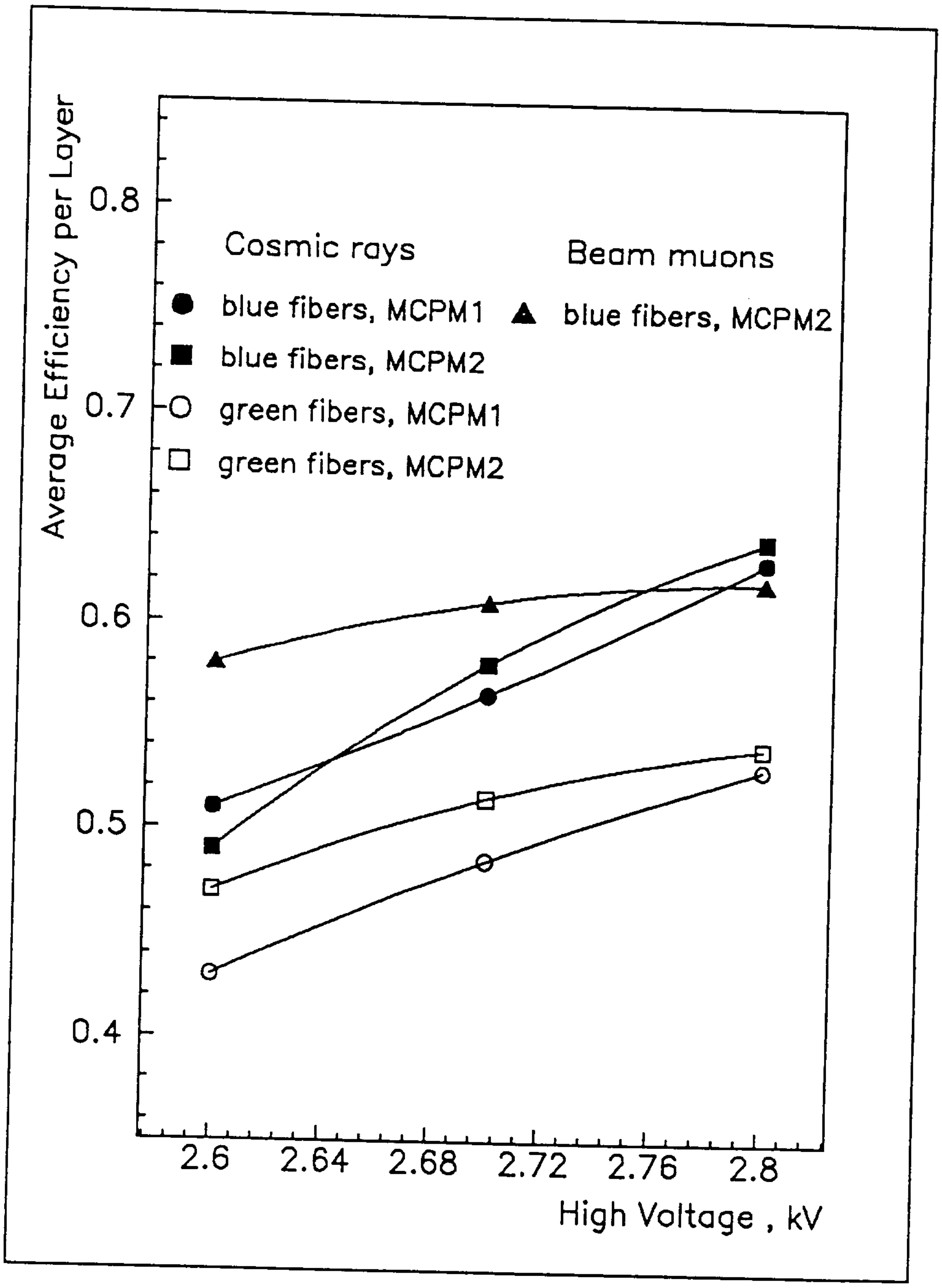

Average Efficiency per Layer
0.4
0.5
0.6
0.7
0.8
Cosmic rays
Beam muons
● blue fibers, MCPM1
■ blue fibers, MCPM2
○ green fibers, MCPM1
□ green fibers, MCPM2
▲ blue fibers, MCPM2
2.6
2.64
2.68
2.72
2.76
2.8
High Voltage , kV

Fig. 11

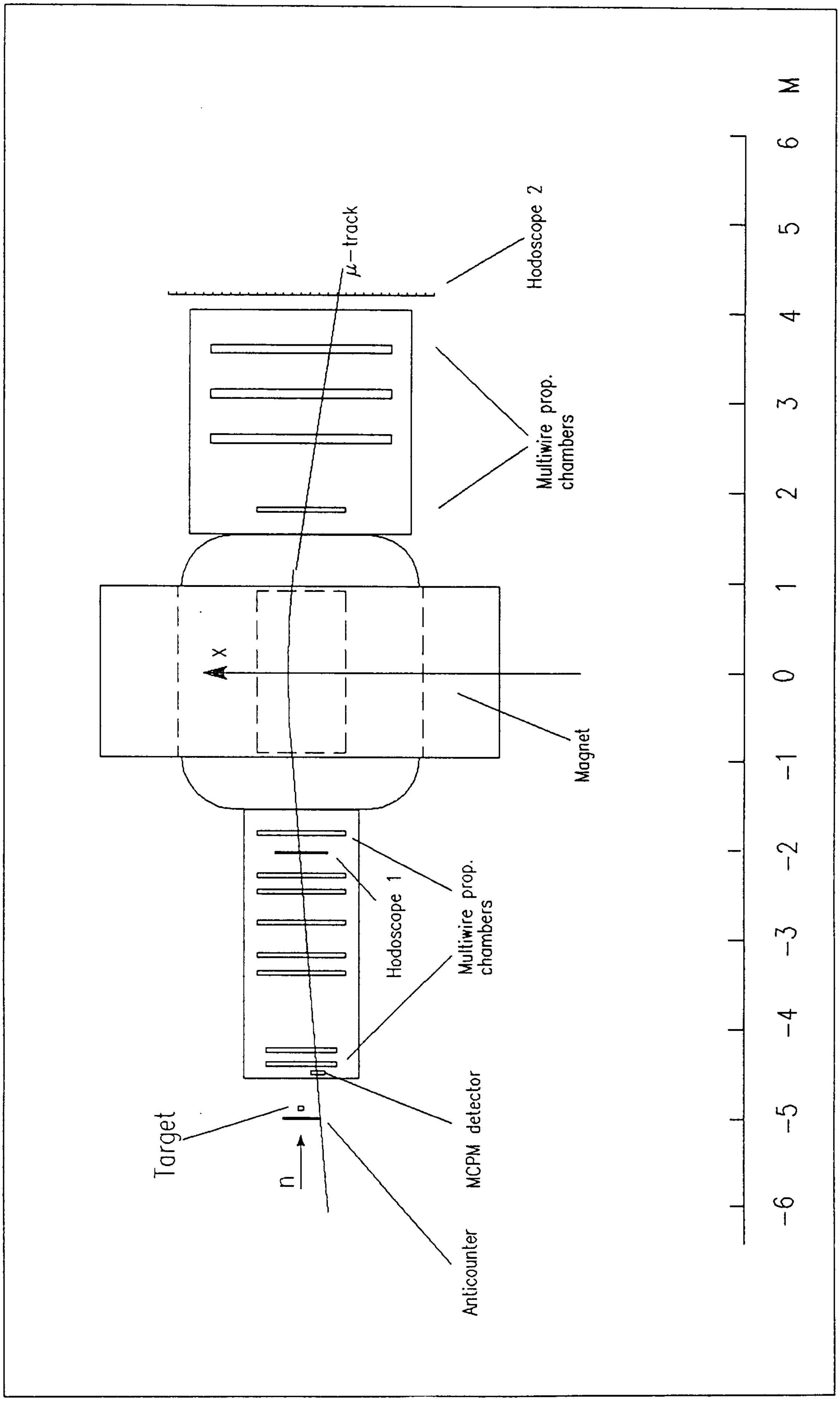

Target
n
Anticounter
MCPM detector
Multiwire prop. chambers
Hodoscope 1
Multiwire prop. chambers
Magnet
x
μ-track
Multiwire prop. chambers
Hodoscope 2
−6
−5
−4
−3
−2
−1
0
1
2
3
4
5
6
M

Fig. 12

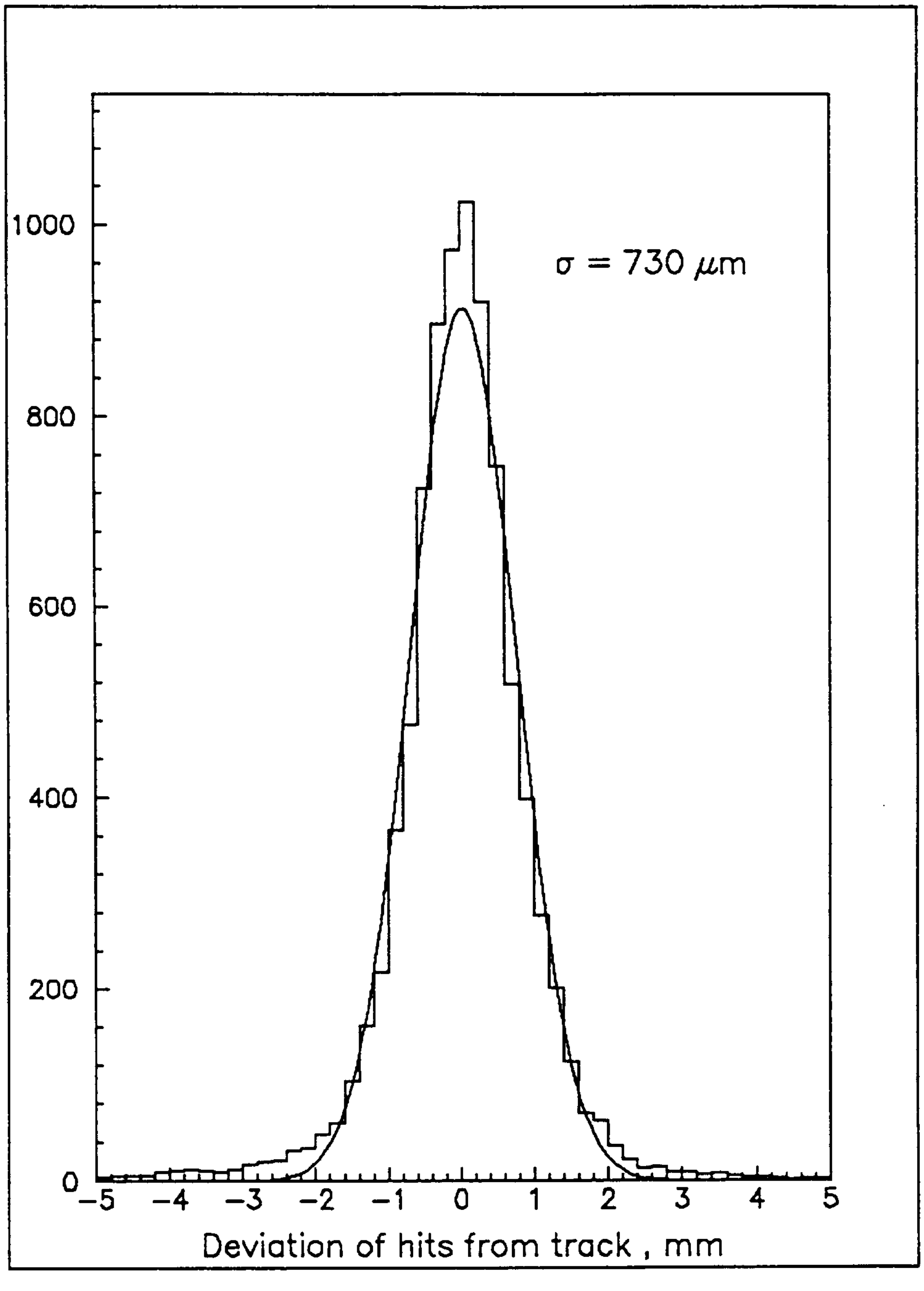

σ = 730 μm
1000
800
600
400
200
0
−5
−4
−3
−2
−1
0
1
2
3
4
5
Deviation of hits from track , mm

Fig. 13

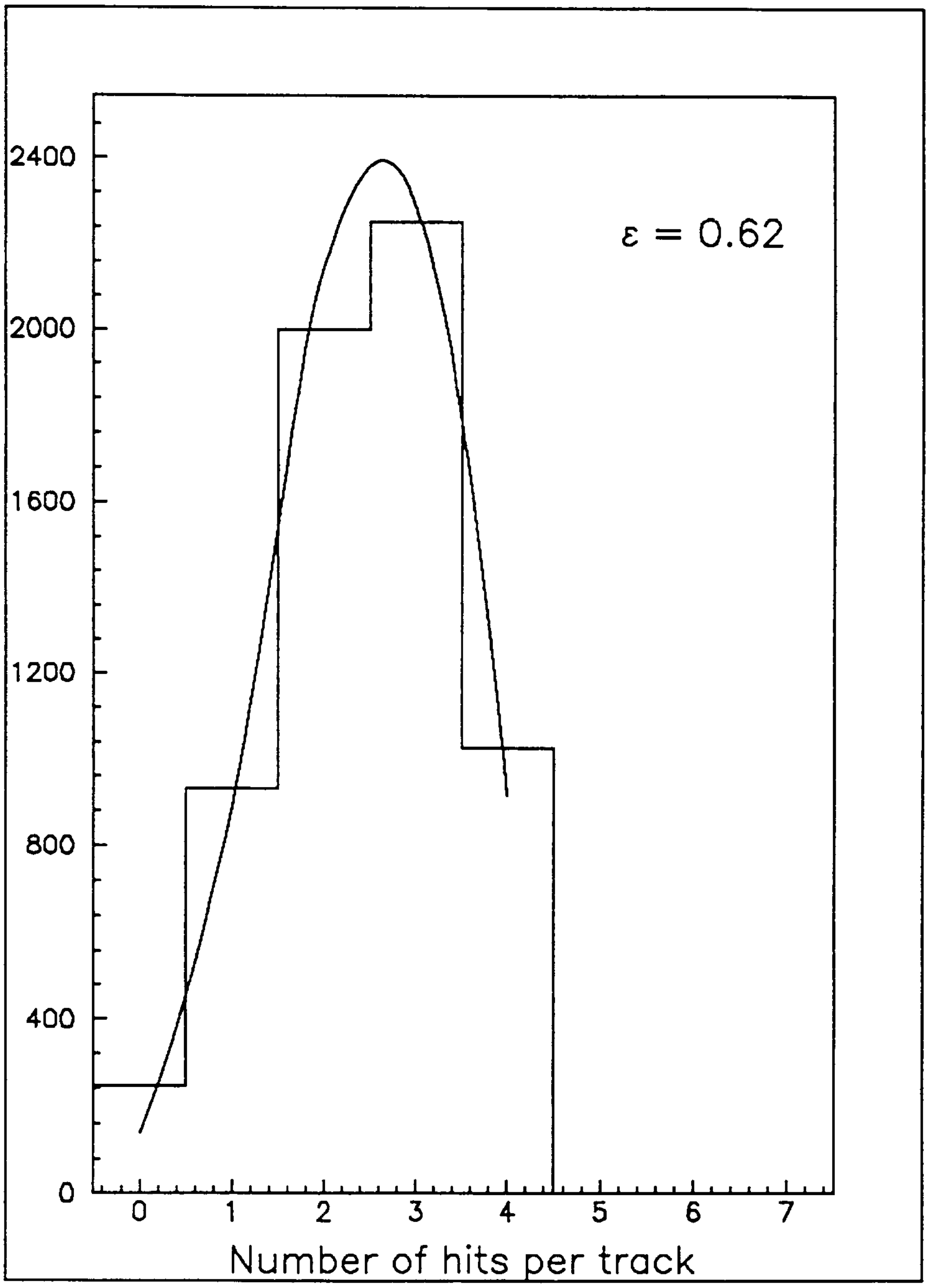

2400
2000
1600
1200
800
400
0
0
1
2
3
4
5
6
7
Number of hits per track
$\varepsilon = 0.62$

Fig. 14