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SOLENOIDAL DETECTOR NOTES

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ABSTRACT

The design of a hadron-photon calorimeter based on high pressure gas ionization tubes embedded in an energy absorber and nearly parallel to the incident particle direction is presented. The problems of energy resolution, electronic noise, time and position resolutions, as wel as radiation hardness of such a calorimeter are discussed. A cost estimate is worked out. All the resulting parameters are in good agreement with SDC forward calorimeter specifications.

1. Introduction

Work done thus far/1 -8/ has shown that high pressure gas ionization calorimetry has good energy, space and time resolution for particles with energy E > 20 GeV, is radiation hard and provides a stable and linear response to incident energy. Two different calorimeter designs were explored. The parallel plate sandwich design was sucsessfully used in small test calorimeters/1,6,7/. However, some problems, such as dead space and safety, may arise when one tries to construct a parallel plate high pressure gas calorimeter with a diameter of about three meters, as required for the forward SDC calorimeter (FCAL)/9/. Attempts /2,3,4/ have been made to use gas ionization tubes orthogonal to the incident particle direction. Unfortunately, such a design is dificult to endow with the tower structure favoured in present-day calorimeter technology.

In this paper we discuss the design of a high pressure gas ionization calorimeter built from stainless steel tubes, embedded in steel absorber and nearly parallel to the incident particle direction. A rod at the center of each tube is brought to positive high voltage to collect the charge produced by ionization. The main advantage of this design over the parallel plate one is safety. In addition there are excellent signal collection conditions in tubes, which are practically ideal waveguides, contrary to the multiplate structure where very intricate signal spreading leads to signal expansion/10/ and cross-talk between neighbouring calorimeter towers. However, the non-uniform transverse structure of the proposed calorimeter affects the energy resolution in a different way than the sampling of parralel plate calorimeters. The Monte Carlo simulations done for this work show that with some reasonable choice of calorimeter design parameters, its energy resolution complies well with FCAL specifications. The same is true of the calorimeter electronic noise, its position and time resolutions, its loading capability, and its radiation hardness. Design and technological studies of the proposed calorimeter show it to be highly cost efficient.

2. Calorimeter Design

The calorimeter consists of 10x10 cm^2 by 3 m long modules. A preliminary design of one such module is shown in Figs 1 and 2. It is made of 81 tubes closed at one end and welded to a one inch thick steel manifold at the other end. The absorber consists of steel laminations, similar to the ones used in magnet yokes, with a matrix of punched holes for the tubes to pass through. Charge collection rods run along the center of the tubes. The gap between the rod surface and the inner tube wall is 2 mm wide. The final inner tube diameter and rod thickness will be chosen, after extensive Monte Carlo simulations, to optimize the energy resolution. At this point our best estimate for these parameters is 7 mm and 3mm. Several ceramic spacers are placed along the rods to minimize sagging, and possibly to reduce the electromagnetic constant term in the calorimeter energy resolution function. A ceramic spacer is placed at one end of each rod to avoid electrical breakdown between the rod and the tube. The rods are all connected electrically with a wire or a copper clad G-10 board at the other end. A steel plate of a few mm thickness is welded to the manifold, as shown in Fig. 2. This plate, being on the side away from the incident particles, can be as thick as needed. It carries the gas and the high voltage/signal feedthroughs and a gas relief valve as shown in Fig. 1. The module will be filled with a gas mixture of 90% Ar + 10% CH_4 or 95% Ar + 5% CH4 at a pressure of 100 atm.

A FCAL can be built from about 600 such modules disposed almost parallelly to the proton beams (see Fig. 3). The exact number of modules depends on the FCAL geometry and on the distance between the calorimeter and the interaction point. Here, we have assumed this distance to be 12 m. Longitudinal segmentation, if it proves to be necessary, is possible. The proposed modular design can be implemented in both the "inverted cone" and the "back stop" geometries.

3. Energy Resolution

In this section we will discuss the results of the GEANT[11] Monte Carlo simulation of the tube calorimeter energy resolution in terms of the stochastic coefficient A and the constant term B of the calorimeter energy resolution function: $\sigma/E = \text{sqrt}\,[(A/\text{sqrt}E)^2 + B^2]$, where E is in GeV. The following calorimeter parameters were varied in the simulation (default values are given between parentheses): the tube inner radius (R = 3.5 mm), the rod radius (r = 1.5 mm), the absorber to active medium volume ratio (V = 3), the angle between the incident particle and the direction of the tubes ($\alpha = 5^{\circ}$), the absorber material (iron), the readout gas (90% argon + 10% methane), and the gas pressure (P = 100 atm).

It follows from our preliminary investigations[12] that the stochastic coefficient of the tube calorimeter energy resolution for hadrons depends rather weakly on calorimeter parameters and is about 70%, which is well within SDC forward calorimeter specifications[9]. The stochastic coefficient for electromagnetic (EM) particles is more sensitive to the calorimeter parameters and varies from 20% to 80%.

The real problem is with the constant term. It is especially large for EM particles because of the narrowness of EM showers, which leads to a strong dependence of the EM shower signal on the shower axis position between the tubes. As a result, the constant term for incident EM particles depends heavily on the calorimeter parameters and may reach a value as high as 40%. The hadron shower, being much wider than the EM one, should be insensitive to the calorimeter structure. However, since its energy has an electromagnetic component, the hadron energy resolution formula contains a constant term as well. But in this case it is significantly smaller and depends little on the calorimeter parameters.

The constant term depends not only on the geometrical parameters of the tube calorimeter but also on the absorber material. Using the same geometrical parameters, the EM constant term for an iron calorimeter is about two times smaller than for a lead one because the volume occupied by EM showers in iron is ~ 4 times larger than in lead. As a result, materials with low Z are preferable for calorimeters of this type.

The energy resolution of a calorimeter with the default parameters given above is shown in Fig.4 as a function of the angle α. One can see that the energy resolution of the most peripheral part of the FCAL ($2^{\circ} < \alpha < 5.7^{\circ}$) is reasonably good for hadrons, which comprise the main part of jets striking the FCAL.

There are two problems: large values of hadron constant term for the inner part of the FCAL and of the EM constant term for the whole calorimeter. We hope that both problems can be solved by using a few mm long ceramic spacers around the rods, frequently spaced along the tubes, to reduce the ionization signal produced by particles travelling along the tubes in the gas volume. This possibility is under investigation. We are also exploring the following options:

1. Modules with a denser tube arrangement in the inner part of the FCAL. As shown in Fig.5, reduction of absorber to active medium volume ratio to V = 2 decreases the hadron constant term to B ~ 5% for a tilting angle of $\alpha = 1^{\circ}$.

2. The installation of a passive lead preshower of several (4 - 6) radiation lengths thickness at a small distance in front of the FCAL. Such a preshower would disperse the energy of EM particles on the calorimeter surface, thereby reducing the constant term (see Fig.6). Energy losses in the preshower are not very large (Fig.7) and may even be useful because they partly compensate for the inequality of the calorimeter response to electrons and hadrons. (For our calorimeter the e/h ratio is about 1.10.)

Taking into account that the constant term for jets has to be somewhat smaller than for individual particles, we expect the overall FCAL energy resolution for jets to be:

$$\sigma/E = 0.6 / \mathrm{sqrt}(E) \oplus 0.05 . \qquad (1)$$

Some examples of the simulated tube calorimeter signal amplitude distributions are displayed in Fig.8.

4. Electronic Noise

From the point of view of signal propagation, each calorimeter tube is a perfect 3 m long waveguide with impedance $\rho_1 = 51\ \Omega$. To avoid signal reflection from the readout ends of these lines, the input impedance ρ of a preamplifier connected to the module (81 tubes connected in parallel) has to be equal to $0.63\ \Omega$. Calculations show that in this case the preamplifier noise is close to the thermal noise of a resistor with resistivity ρ:

$$Q_1 \approx \mathrm{sqrt}\,(kT\tau/\rho) \approx 20\ \mathrm{fC},$$

where k is the Boltzman constant, T the absolute temperature, and τ the signal gate width (~ 60 ns). Approximately 90% of a hadron shower occupies from 4 to 9 modules, resulting in an average noise Q ~ 50 fC. This value has to be compared with the simulated calorimeter response of 20 fC for 1 GeV of shower energy. Thus the electronic noise produces an uncertainty δE ~ 2.5 GeV in the energy measurement, and formula (1) has to be corrected as follows:

$$\sigma/E = 2.5 / E \oplus 0.6 / \mathrm{sqrt}(E) \oplus 0.05 . \qquad (2).$$

This dependence is illustrated in Fig.9.

5. Texas Towers

We calculated the Texas Tower (TT) rate in high pressure gas calorimetry with tubes and 100 atm argon with 5% methane, relative to the CDF forward calorimeter. The essential factors are the sampling fraction , the amount of energy loss in the active media (dE/dx), the proton density of the gas and the material the calorimeter is made of, and the energy of the shower producing the neutrons which eventually create the TT's by scattering the protons.

The sampling fraction scales the TT energy spectrum by a factor of 6 in high pressure gas calorimetry relative to the CDF forward calorimetry. From the dE/dx of minimum ionizing particles and of the heavily ionizing protons in 1 atm gas and 100 atm gas, we obtain a scaling factor of 25. Applying these scaling factors to the measured TT energy spectrum[13], we calculate a reduction factor of 10^8 for a 10 GeV (1 GeV E_t) cut on Texas Tower energy.

The proton density is approximately the same in high pressure gas calorimetry as in the CDF forward calorimetry. The higher multiplicities and energies at the SSC compared to the Tevatron are estimated to scale the TT rates by no more than a factor of 10. Therefore the overall reduction in TT rate in a SDC high pressure gas calorimeter is at least a factor of 10^7.

6. Time Resolution

The time resolution of a gas ionization calorimeter is determined by the time needed to collect electrons liberated in the gas. The electron drift velocity in argon with a small methane percentage at 100 atm pressure was measured by N.Giokaris et al[5]. Calculations made by G.Niculescu[14] agree very well with the measurements (fig.10), and demonstrate a rather high electron drift velocity for 10% methane concentration (fig. 11). Hence we expect ~ 30 ns collection time for tubes with a 2 mm wide gas gap. The full signal width at the amplifier output should not exceed 60 ns. Such a value was actually obtained in our recent parallel plate calorimeter beamtest[7].
It is perhaps possible to shorten the output signal down to 40 ns by very careful preamplifier pulse shaping. But a further decrease in signal width can only be achieved by reducing the gas gap. This possibility is to be investigated.

7. Position Resolution

The uncertainties in hadron shower position measurements due to lateral shower fluctuations could be smaller than 1 cm[15]. But for our non-projective calorimeter module disposition, the longitudinal shower center fluctuations cause an additional uncertainty in shower positioning, which can be as large as $\delta R = \lambda\alpha$, where R is the distance between the incident particle and the beam axis at the front of the FCAL, and $\lambda = 22$ cm is the nuclear interaction length. Because in our geometry the angle α depends on R as $\alpha = R/1200$ cm, the relative incident particle angle uncertainty would be:

$$\delta\Theta / \Theta = \delta R / R = 1.8\%.$$

Hence, the effect of $\delta\Theta / \Theta$ on the transverse momentum resolution is less than the contribution from energy resolution:

$$\delta P_t / P_t = \delta E / E \oplus \delta\Theta / \Theta.$$

8. Radiation Hardness and Space Charge Effect

The radiation hardness of a gas ionization calorimeter can be estimated by comparison with proportional chambers. By using a special gas mixture, proportional chambers usually preserve efficiency as long as the t otal charge having passed through the anode wire does not exceed 1 C/cm[16]. Such a charge will have passed through 1 cm of a calorimeter rod after absorbing ~ 50 Mrad of radiation. However, several factors tend to suppress the polymerisation phenomenon and its damaging influence on ionization chamber performance. First of all, molecular radicals are generated uniformly in the gas volume of an ionization chamber, so that their density is much smaller than in proportional chambers, where they appear mostly in small and dense electron avalanches. Secondly, the thickness of the polymer layer at the rod surface is two orders of magnitude less that on a proportional chamber anode wire because of the difference in diameters. And at last, the reduced electric field (E/P) at the cathode surface of an ionization chamber is about 10 times less than in a proportional chamber, which is crucial for the spark discharge formation. As a result, one can expect the radiation hardness of a gas ionization calorimeter to be as high as several hundred Mrad. However this problem needs to be experimentally investigated.

Radiation damage tests conducted by our group[8] showed that the characteristics of a high pressure ionization chamber were not affected by a 16 Mrad dose of radiation. This means that the calorimeter can work without changing gas at least up to this dose.

Both materials used in this calorimeter, steel and ceramic, are very radiation resistant.

Finally, regarding space charge effects, our calculations, in agreement with those of W.Wenzel[17], show that the field distortions are smaller than 10% as long as the radiation intensity does not exceed the 140 Mrad/year level. Even so, this amount of field distortion will not affect calorimeter performance because of the very large voltage plateau in the ionization chamber amplitude to voltage characteristic[7].

9. Cost

Estimations made by the company "Ability Engeneering Technology" result in the price per 0.1x0.1x3 m^3 calorimeter module, as described in section 2, to be about $3500 for large scale production (see Appendix I).

Approximately 1200 such modules are needed for two "back stop" calorimeters placed 12 m away from the interaction point. So the base cost of the forward calorimeters is K$4,200. Taking into account the "EDIA" (15%) and "contingency" (25%) additions[9], the full construction cost of the SDC forward calorimetry is estimated at K$6,000.

10. R&D Plans for FY92

We plan to carry out the following R&D work in FY92 in order to be ready to write a Technical Proposal for the SDC Forward Calorimeters.

1) Design and build the following four prototype high pressure modules:
   - one 10x10x10 cm^3 prototype for radiation damage studies (Feb. 20, 92)
   - one 10x10x60 cm^3 short version prototype (Feb. 25, 92)
   - two 10x10x10 cm3 full length prototypes (March 15, 92)

2) Perform radiation damage tests at a total dose of a few hundred Mrads with a ^{60}Co source on the radiation damage module (March 5, 92).

3) Perform electrical and electronic tests on the all prototype modules (March 20, 92).

4) Perform extensive Monte Carlo simulation studies to optimize the parameters of the tube calorimeter.

5) Develop a fast, low impedance preamplifier for the tube calorimeter.

6) Design and build a 16 module 40x40x300 cm^3 calorimeter.

7) Test this calorimeter in high energy electron and hadron beams.

The budget needed for items 1, 2, 3 and 6 is K$110.5; for items 4, 5 and 7, it is K$266.

11. Conclusion.

Table 1 lists the parameters of our proposed forward calorimeter design and shows the corresponding specifications provided in the SDC Letter of Intent[9] and the FCAL task force report of November 1, 1991.

In conclusion, we can state that the high pressure gas ionization tube calorimeter is a simple, radiation hard, safe, stable, easy to operate and cost effective device. Its parameters satisfy the specifications of the SDC forward calorimeter and could be modified if needed.

Parameter	Value in proposed design	SDC specification
1) Rapidity coverage	$3 < \|\eta\| < 6$	$3 < \|\eta\| < 6$
2) Distance from interaction point	12 m	12 m
3) Segmentation	10 x 10 cm	
	$\Delta\eta\ \Delta\phi < 0.2 \times 0.2$ for h<4	$\Delta\eta\ \Delta\phi = 0.2 \times 0.2$ for h=3
	$\Delta\eta\ \Delta\phi < 0.6 \times 0.6$ for h=5	$\Delta\eta\ \Delta\phi = 0.4 \times 0.4$ for h=5
4) Depth	15 λ, 3 m	14 λ
5) Radiation hardness	> 100 Mrad	0.07 Mrad/year for h=3
	(16 Mrad have been tested)	28 Mrad/year for h=5 (luminosity 10^{33} cm^{-2} c^{-1})
6) Signal duration	< 60 ns	(10 - 60) ns
7) Signal rise time	10 ns	< 16 ns
8) Energy resolution	10% for E > 100 GeV 5% for E > 1 TeV	10% for E > 1 TeV
9) Position resolution	$dR = 0.02\,R \oplus 1$ cm	
10) Electron identification	is possible	
11) Cost	$6.0 million	$20.6 million

Table 1: Forward calorimeter parameters in the proposed design, compared with SDC specifications.

References.

1. V.I. Baskakov et al., Nucl. Instr. and Meth. 159 (1979) 83.
2. Ts.A. Amatuni et al., Nucl. Instr. and Meth. 203 (1982) 179.
3. M. Barranco-Luque et al., BNL 31011, Brookhaven, 1982.
4. N.D. Giokaris et al., Proposal for Development of High Pressure Sampling Gas Ionization Calorimetry for the SSC, submitted to SSC-DOE in June 1989 (not published).
5. N.D. Giokaris et al., Nucl. Instr. and Meth. A291 (1990) 552.
6. D.M. Khazins et al., Nucl. Instr. and Meth. A300 (1991) 281.
7. L. Demortier et al., SDC-report, SDC-92-183, 1992.
8. L. Demortier et al., SDC-report, SDC-92-182, 1992.
9. Letter of Intent by the SOLENOIDAL DETECTOR COLLABORATION, november 1990.
10. R.N. Krasnokutsky et al., IHEP Preprint 91-16, Protvino, 1991.
11. R. Brun et al, CERN DD/EE/84-1, 1986.
12. N.D. Giokaris et al., Proposal for Development of High Pressure Sampling Gas Ionization Calorimetry for the SSC, 1991 (not published).
13. S. Cihangir et al., IEEE Trans. on Nucl. Science, vol. 36, No. 1, p 347 (1989).
14. G. Niculescu, diploma thesis, Bucharest University, 1991 (not published).
15. S. Iwata, DPNU-3-79, Nagoya, 1979.
16. J. Va'vra, Nucl. Instr. and Meth. 252 (1986) 547.
17. W.A. Wenzel, GIN-326, draft 8/14/91 (not published).

APPENDIX I

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October 21, 1991

Dr. Nikos Giokaris
Fermilab
P. O. Box 500
Batavia, IL 60510

REF: Quote #1472
Hadronic Detector Cell
Rockefeller University

Large quantity budgetary cost estimate of Hadronic Detector Cell - full production:

STAINLESS STEEL TUBE SHEET AND TUBES

Tube Sheet	$ 629
Caps	144
Wires	310
Insulators	126
Punch Set	25
Laminations	634
Relief Valve	28
Valve	40
Stack Lam.	90
Install Lam. Packs	140
Welding	416
Assy	342
Press Test	105
Weld Closed	90
Final Tests	125
Charging	240
	$3484

Price includes labor and material, but does not include final stacking and installation at site, or transportation costs to the site.

Very truly yours,
Ability Engineering Technology

Michael W. Morgan
President

MWM:jb

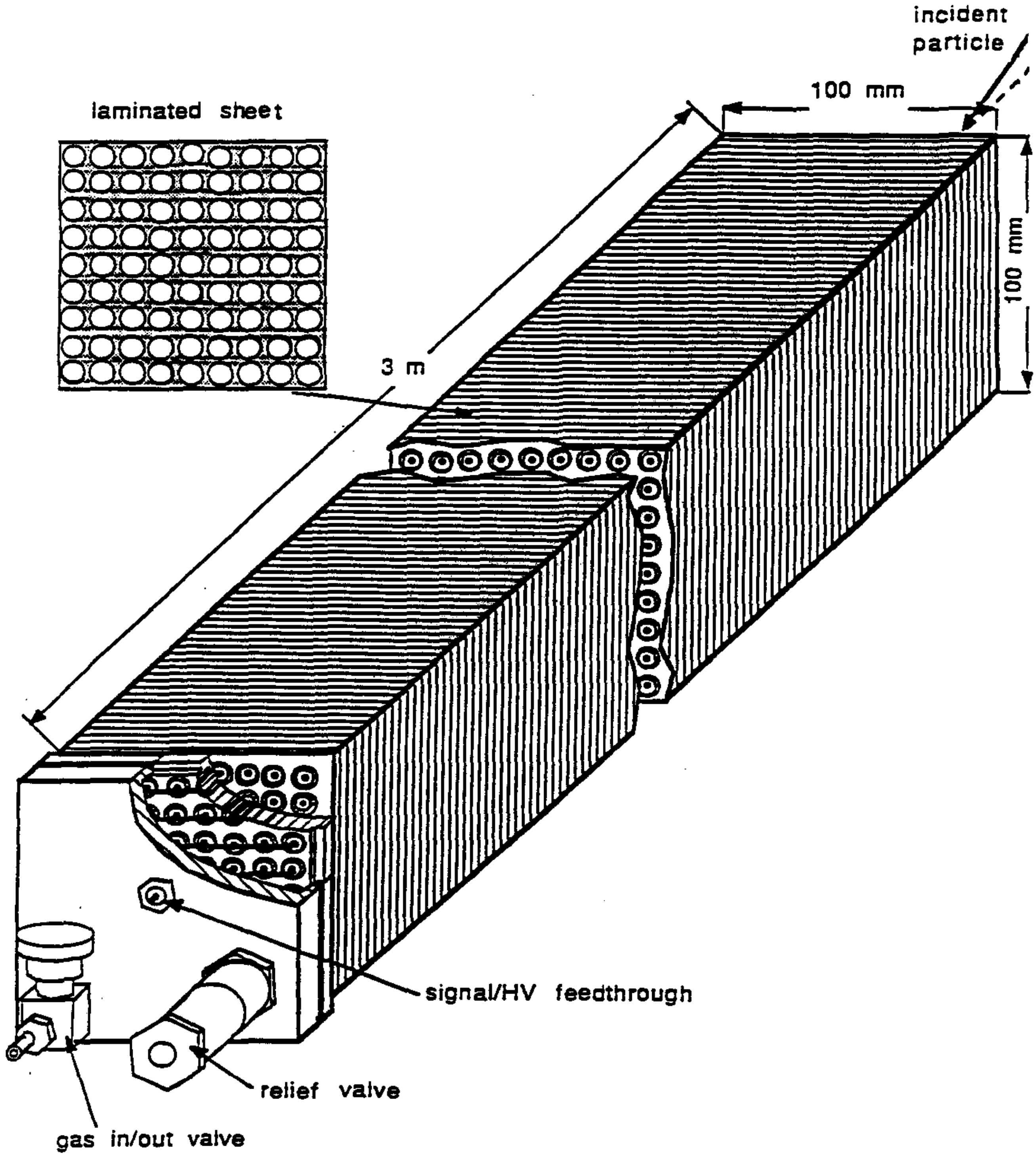


Fig.1. Schematic diagram of a high pressure tube calorimeter module.

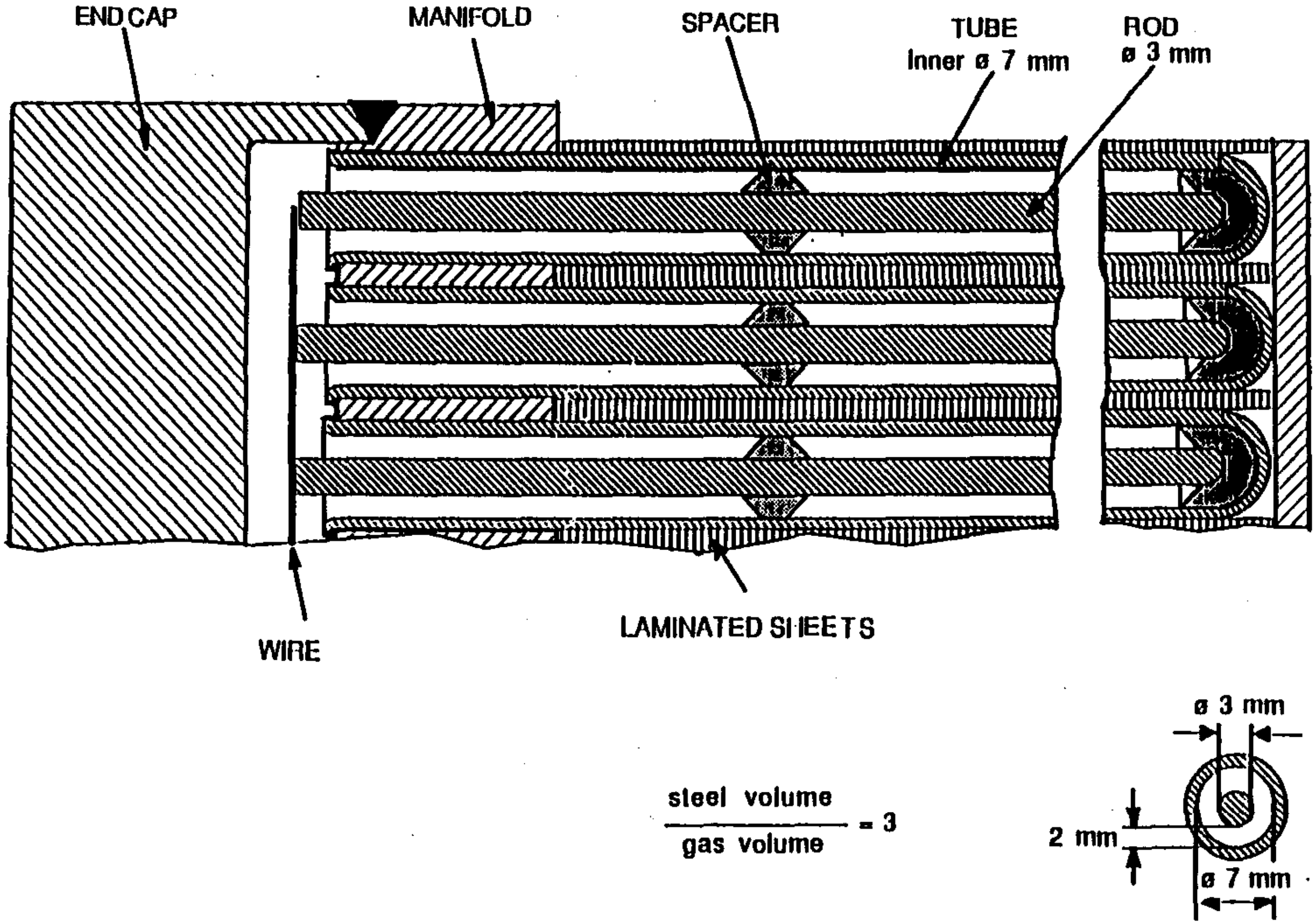


Fig.2. Longitudinal cross section of the module.

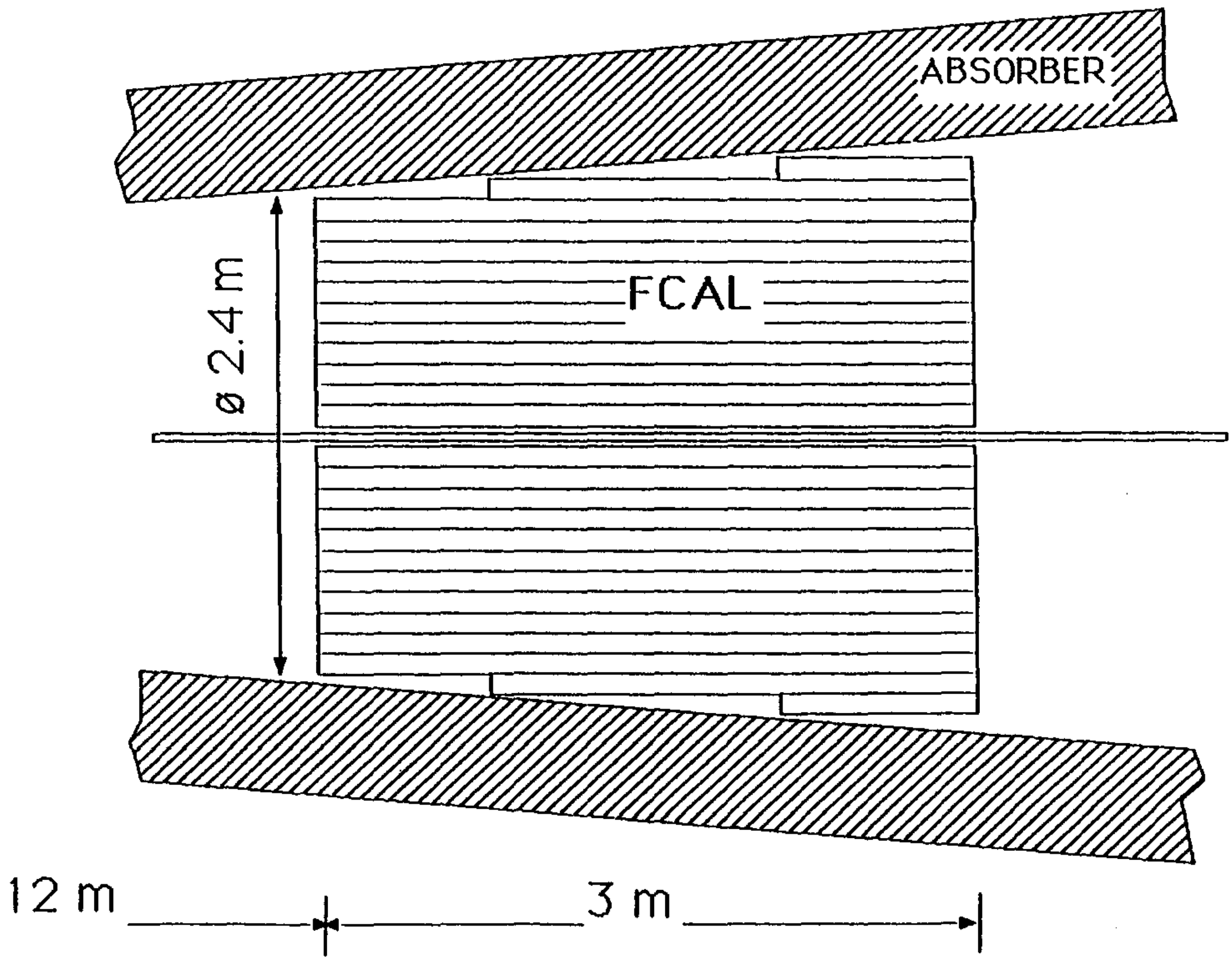
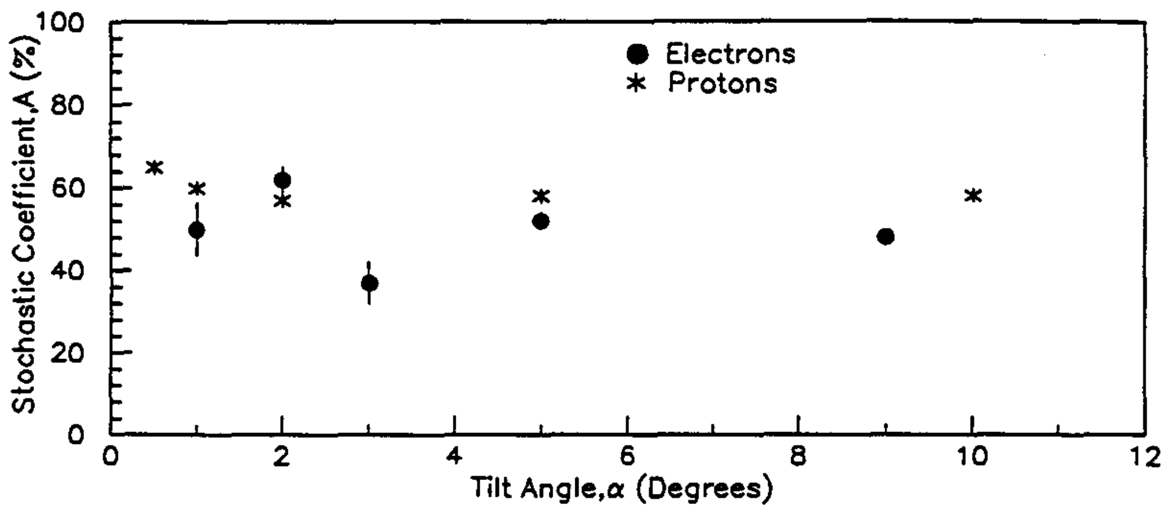


Fig.3. For tube calorimeter.



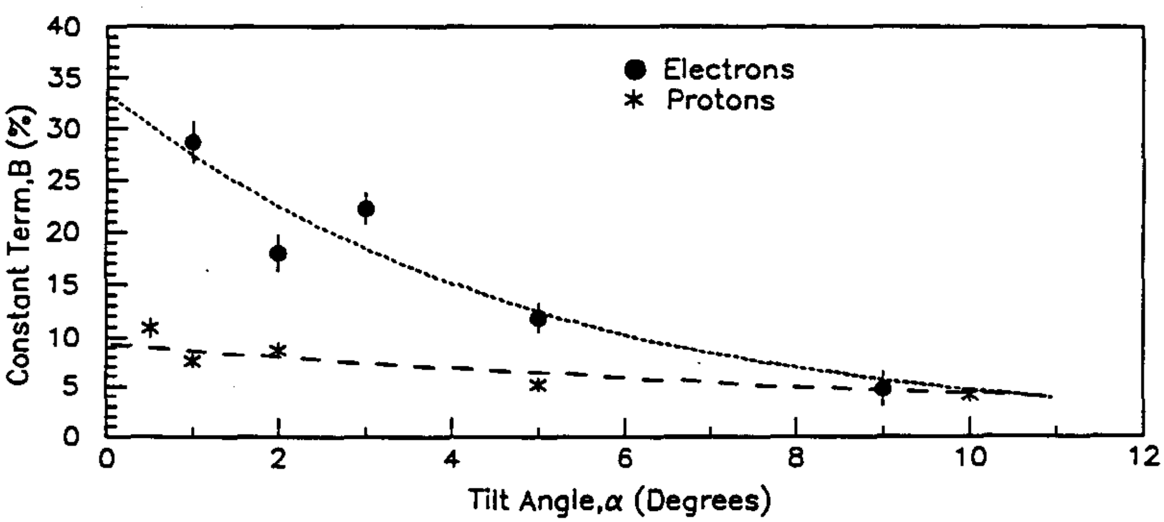


Fig.4. Dependence of the tube calorimeter energy resolution on the angle (α) between the incident particle and the direction of the tubes for protons and electrons.

The curves are polynoms for guiding the eye.

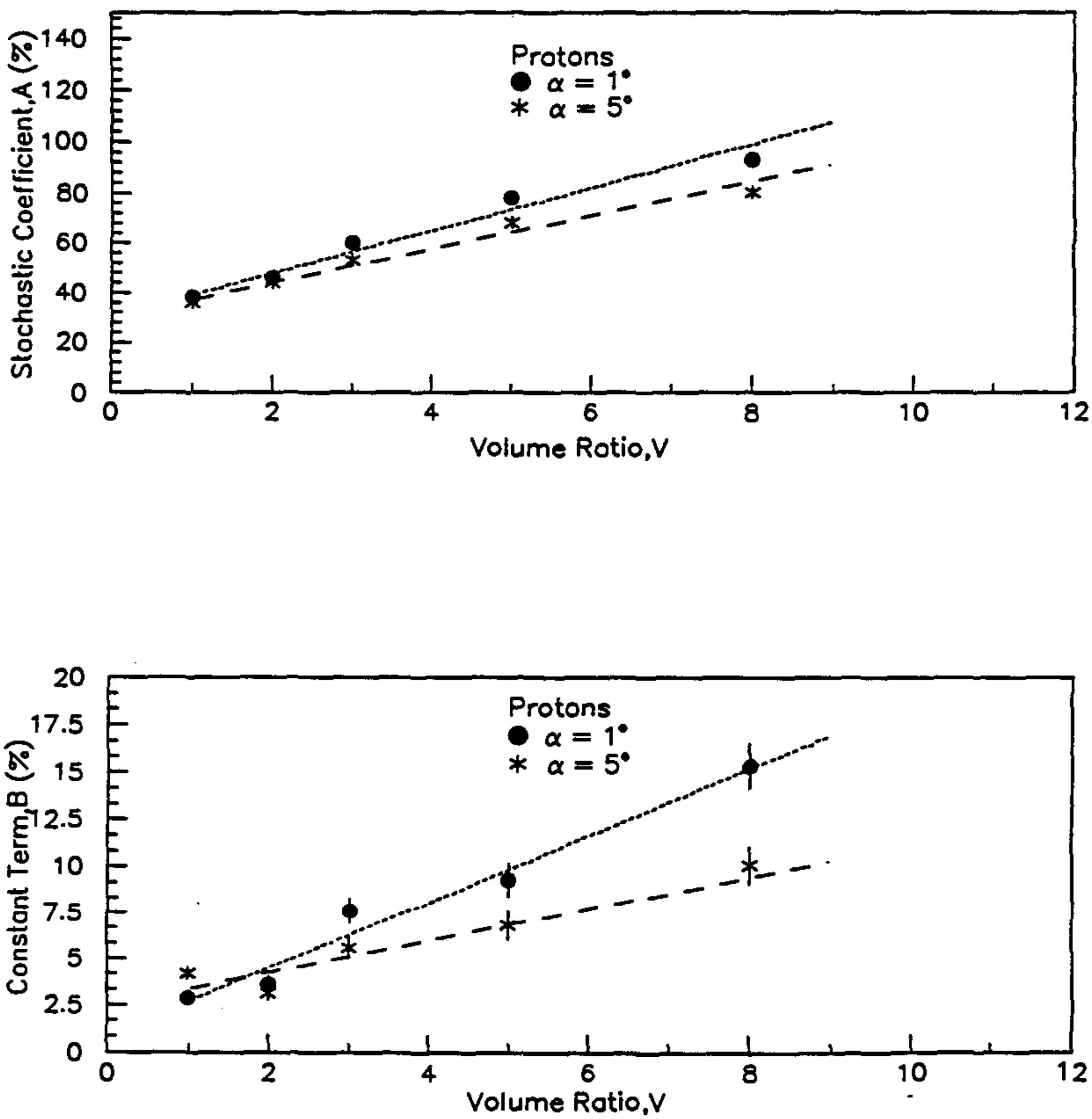


Fig.5. Dependence of the tube calorimeter hadron energy resolution on the volume ratio for two values of the tilt angle $\alpha = 5^{o}$ and $\alpha = 1^{o}$.

The curves are polynoms for guiding the eye.

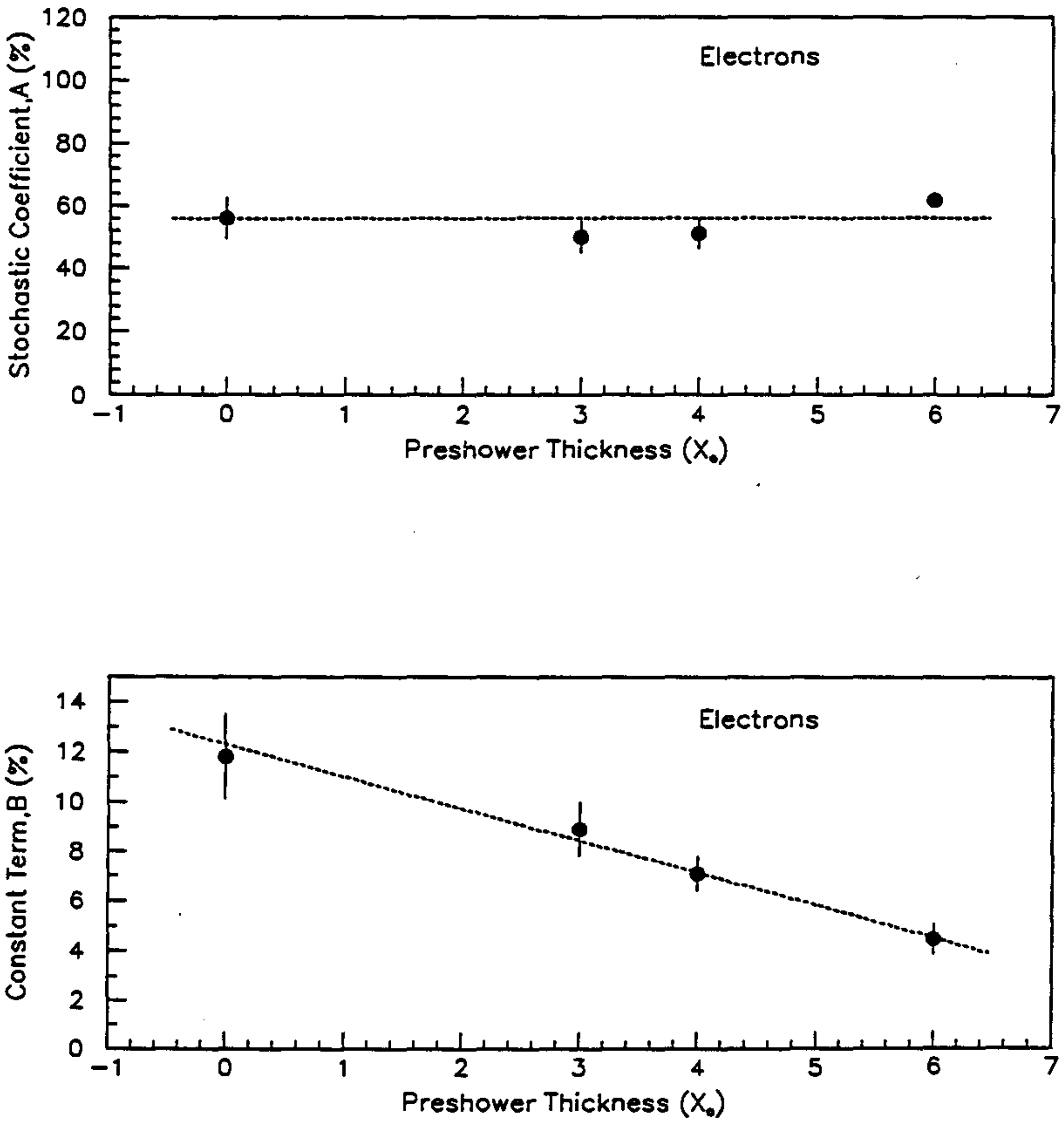


Fig.6. Preshower influence on the EM energy resolution of the tube calorimeter.

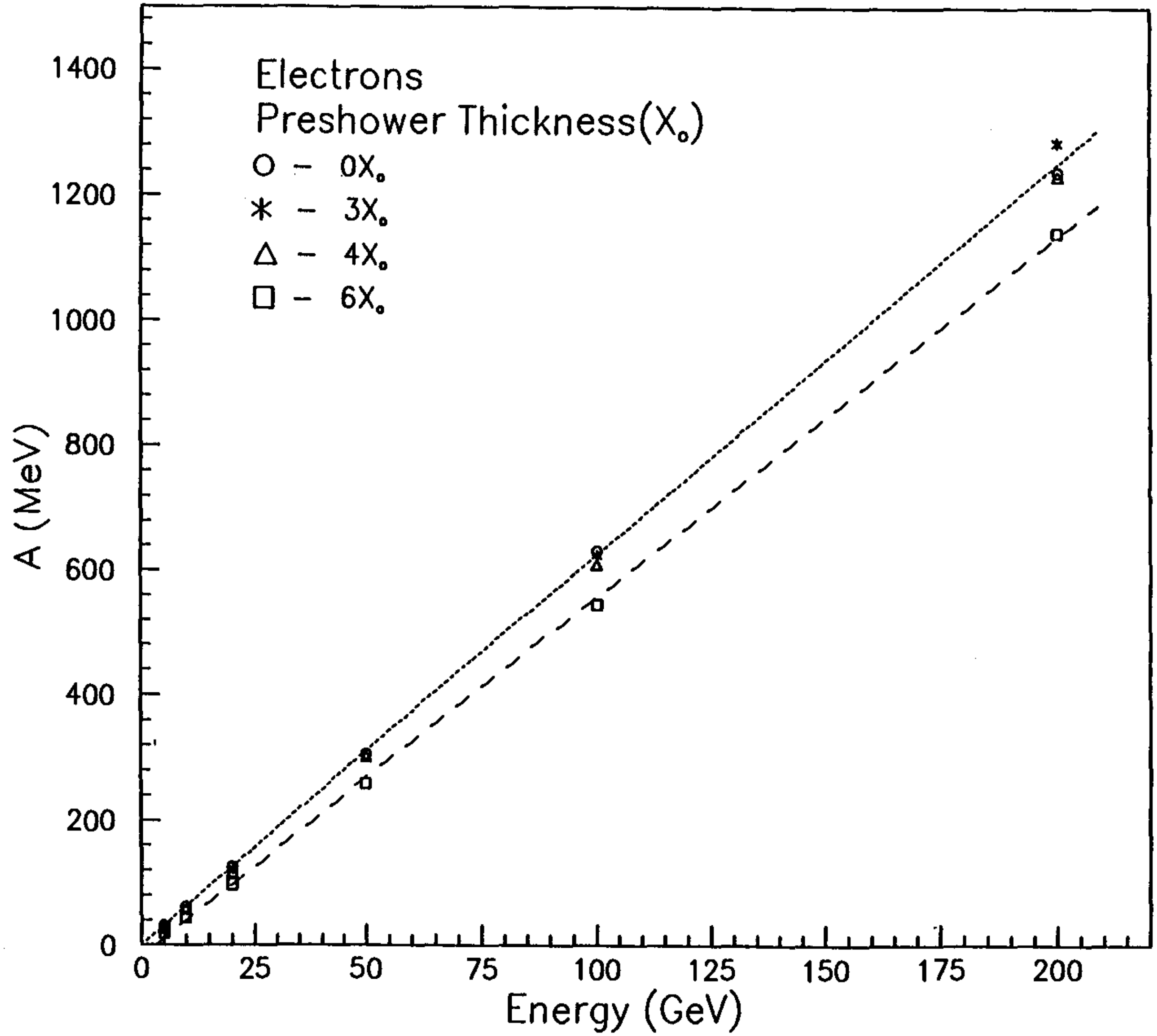


Fig.7. Preshower influence on the calorimeter response to the EM particles.

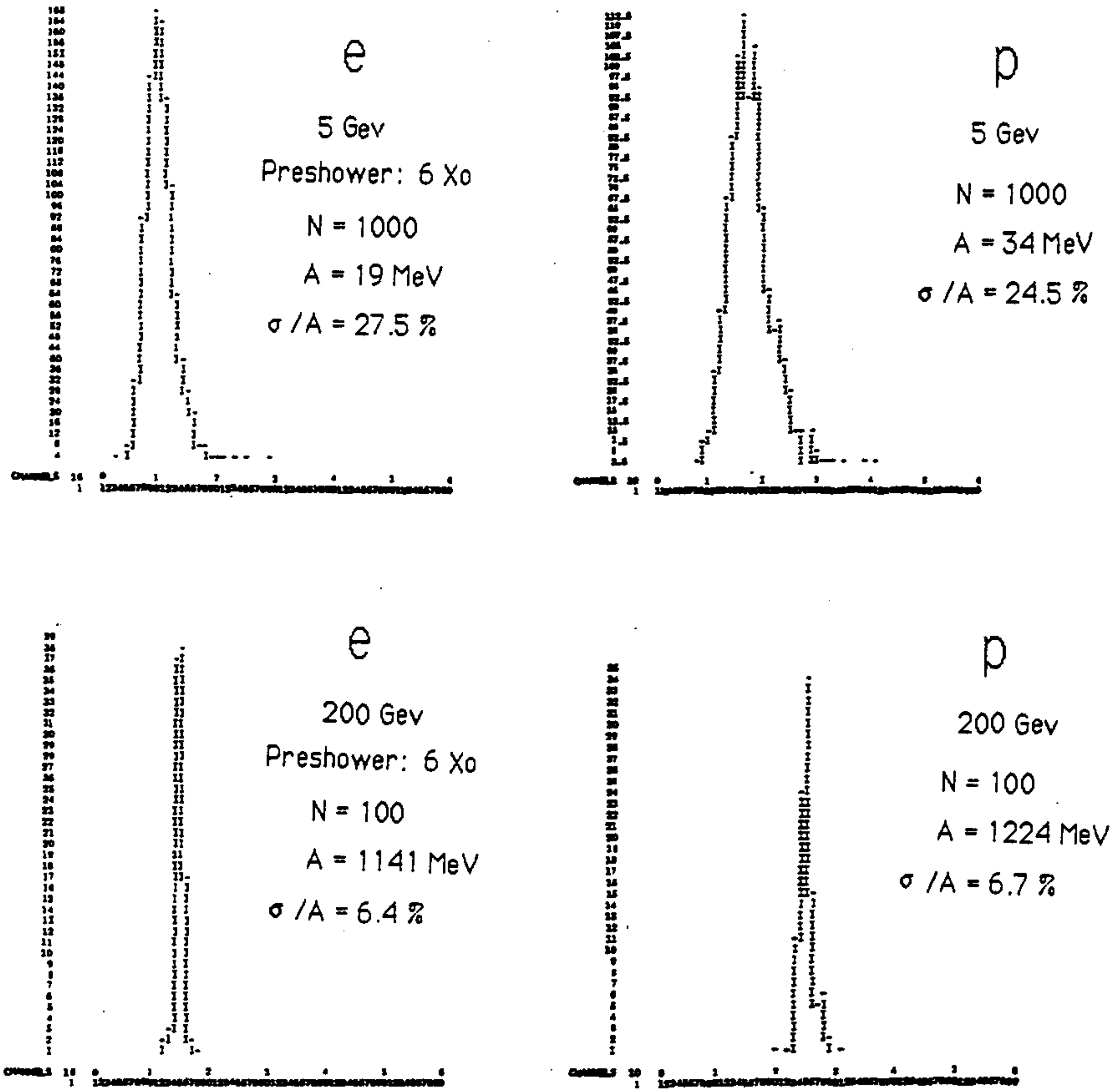


Fig.8. Examples of the simulated tube calorimeter signal amplitude distributions.

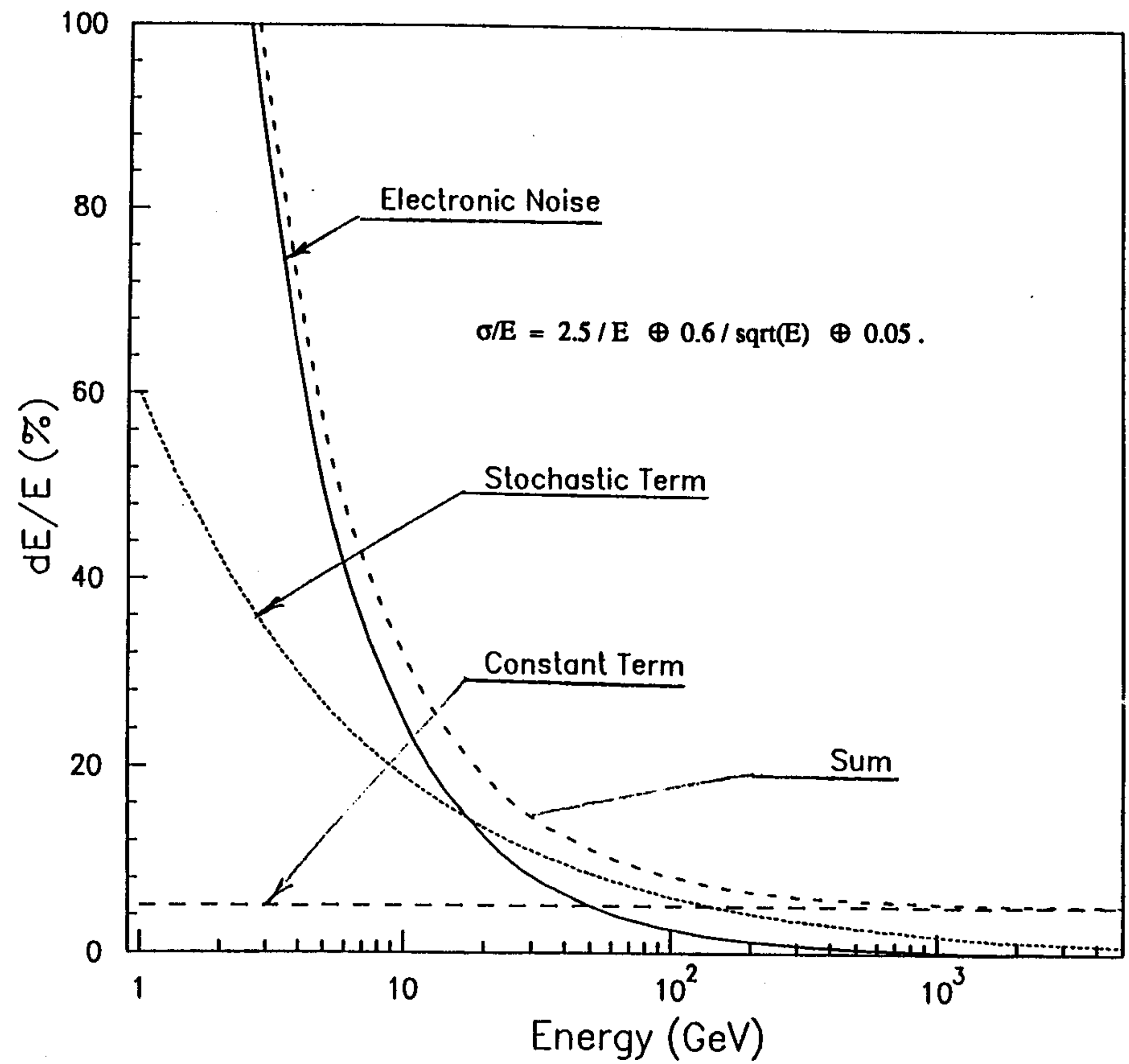


Fig.9. Resulting energy resolution of 'ube calorimeter.

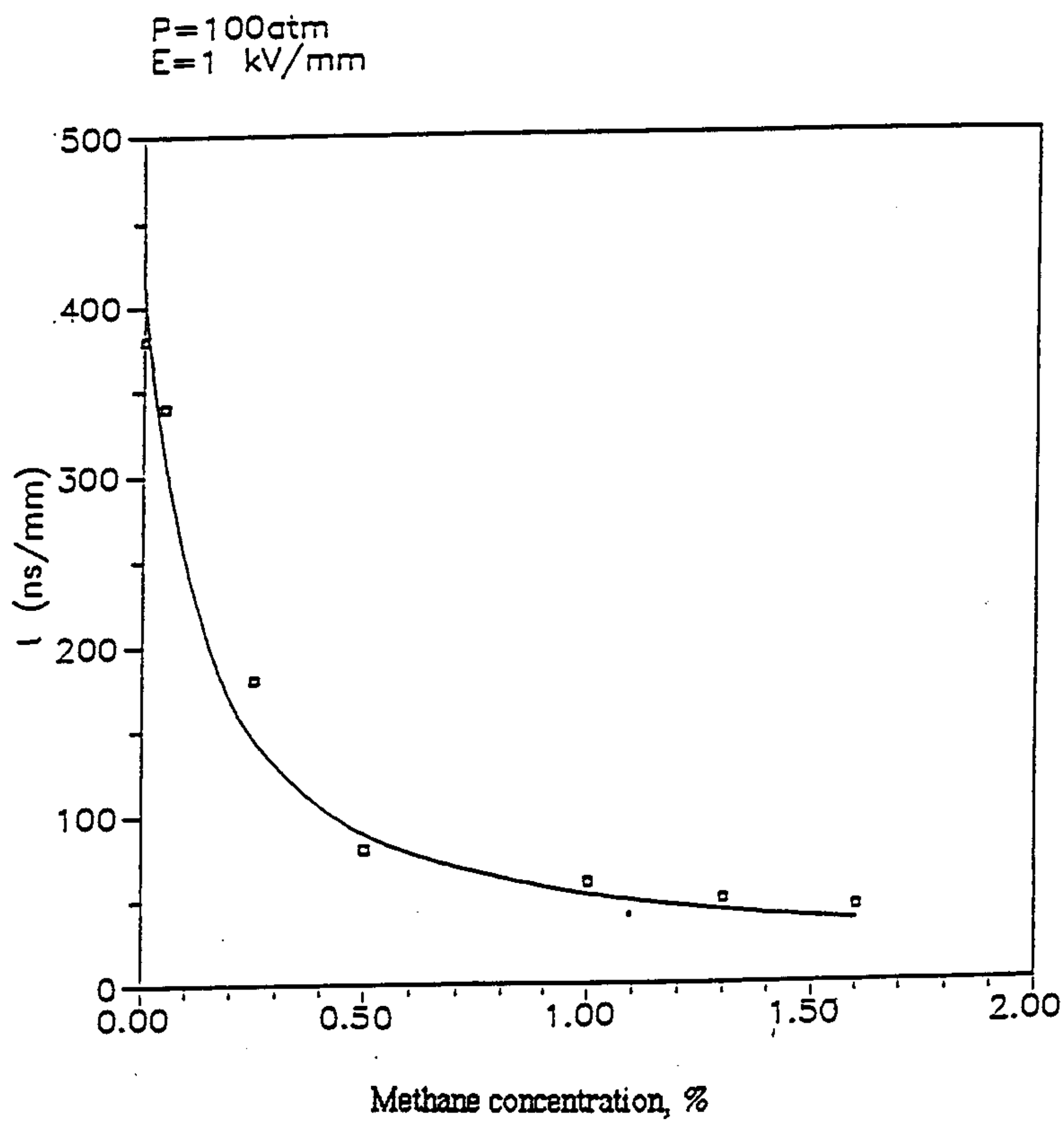


Fig.10.The inverse electron drift velocity in argon with different admixture of methane at 100 atm pressure. The points are the results of measurements[5], the curve is the result of calculations[13].

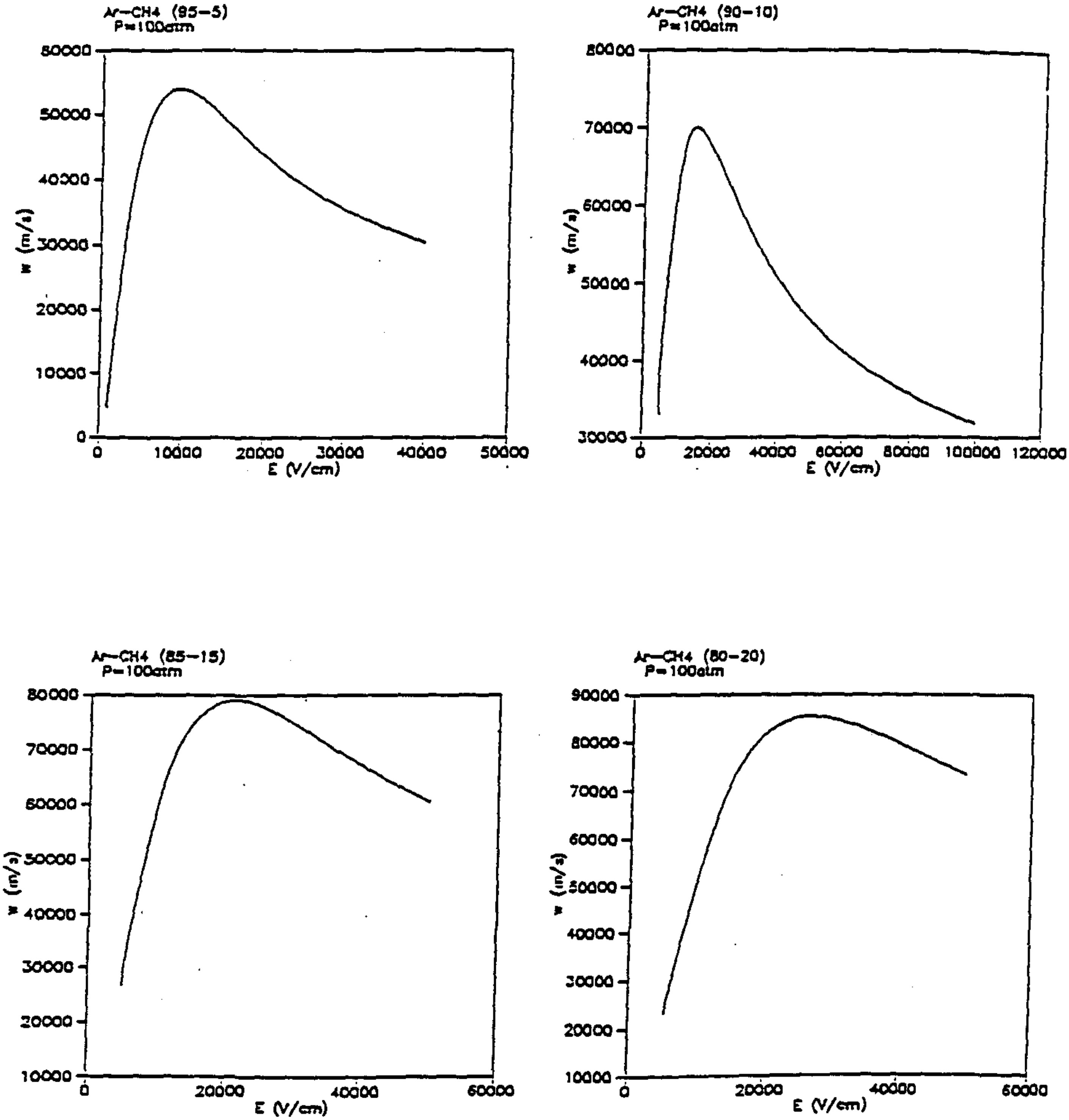


Fig.11.The electron drift velocity in argon vith different admixture of methane at 100 atm pressure, as calculated in/13/.