Fermi National Accelerator Laboratory

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Abstract

Calorimeters using high pressure gas as active medium are now being considered as candidates for the forward region of detectors at high luminosity colliders. A parallel plate electromagnetic calorimeter and a high pressure test vessel have been used to study and compare the response of $Ar+CH_4$, $Ar+CF_4$, $Ar+C_2H_6$, $Xe+CH_4$ and $Xe+CF_4$ gas mixtures to 50 GeV electrons and to alpha particles from an ^{241}Am source. Results on the energy resolution, the electron drift velocity, and the collected charge as a function of electric field and gas pressure for the different gas mixtures are compared.

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1. Introduction

Calorimeters at small angles at the new high-energy, high-luminosity, hadron colliders such as SSC and LHC, have to be very fast, stable and extremely radiation hard. A technique with great potential to satisfy these stringent demands is the one that uses noble gases at high pressure as sampling medium. The proof of principle of this technique at pressures up to 100 atm has been provided by work done in the USA and in Russia [1-5]. From these studies it has become clear that a small fraction of electron cooling additive must be mixed with the noble gas in order to produce signals of a few tens of nanosecond duration. (The time between beam crossings at the SSC is 16 nsec.) However the additive may have adverse effects on other important properties of the calorimeter such as collected charge, stability, energy resolution and radiation hardness. In this paper we report results from a first study of CH_4, C_2H_6 and CF_4 as additives in argon and xenon gases at high pressure. The effect of the additives on collected charge, stability, energy resolution, and electron drift velocity were studied. The effect of these additives on the radiation hardness is presently being investigated by our group and the results will be reported in a forthcoming publication.

2. Experimental Setup and Data Acquisition

The study of the signal size and electromagnetic energy resolution with different gases was performed with a prototype parallel-plate, high-pressure gas electromagnetic calorimeter. The drift velocity was measured with a high-pressure test vessel. Both devices were also used for signal stability studies. For detailed descriptions of the calorimeter and the vessel see ref. 4 and 2, respectively. For completeness, their main features are summarized here.

2.1 Prototype Calorimeter

The prototype calorimeter consists of ten sampling layers, each of which is a high pressure vessel made up of two parallel steel disks bolted together. The disks have an outside diameter of 28.6 cm and are approximately 3.0 cm thick, making the assembled calorimeter about 30 radiation lengths long. A 21.2 cm diameter, 5.5 mm deep recess is milled in one of the two disks that constitute a vessel. In the middle of this recess, a 1.5 mm thick G10 readout board is supported with ceramic spacers. High pressure gas occupies the 2 mm gap on each side of the G10 board.

The calorimeter was tested in the Fermilab NT beam line. Fast preamplifiers with 5 ns rise-time, 214 Ω input impedance, and 32 mV/μA sensitivity were used. No signal shaping was done.

A set of scintillation counters and a transition radiation detector were used for

defining the beam and triggering the readout system. This trigger resulted in a reasonably clean electron sample at 50 GeV.

Pedestal events were collected during each data-taking run between consecutive beam spills. Electronic calibration was performed by injecting a pulse of known current, and with a width similar to that observed from beam particles, at the input of each preamplifier. These data provide the absolute charge calibration and the relative channel-to-channel calibration.

2.2 High-Pressure Test Vessel

The high-pressure test vessel contained a gas volume of about one liter. The vessel was evacuated to 10 to 20 mTorr before it was filled with gas. The argon gas used was Matheson grade with 99.9995% minimum purity in the tank.

An ^{241}Am alpha-particle source was implanted at the center of a 2 cm diameter cathode. A positive high voltage was applied to an equal size metallic plate opposite the cathode. The gap between the two plates could be varied from 2 to 10 mm. All the measurements reported in this paper were done with a 4 mm gap.

The readout electronics were different from those used in our original studies[2]. Here we used the same fast preamplifier as described in section 2.1. The alpha particles have a short range in high pressure gas and produce electrons very close to the cathode. Movement of these electrons towards the anode induces a rectangular current pulse at the preamplifier input. We measured the width of this pulse with an oscilloscope to determine the electron drift velocity in the gas. The challenge was to trigger the oscilloscope. The amplitude of the signal from the alpha source was too close to the preamplifier noise level to use to self-trigger the oscilloscope. To overcome this problem, we processed the signal into two parallel channels. In the first channel, we suppressed the high frequency noise components with a low frequency amplifier and discriminated the signal. However, the discriminator output signal after the slow amplifier had a large time jitter. To minimize the jitter, a fast amplifier was used in the second channel and the discriminator in this channel was adjusted to half of the original pulse amplitude. Then the coincidence of these two channels was used to trigger the oscilloscope. In fig. 1 we show the pulse observed on the oscilloscope for 95%Ar+5%CH_4 gas at 100 atm and at 600 V/mm.

3. Data Analysis

For the beam test the data analysis was done as follows. For a given run, the channel pedestals were computed by averaging the channel pulse heights over all the pedestal events in the run. For each beam event in the same run, these pedestals were subtracted from the corresponding channel pulse heights. The results were then multiplied by individual channel calibration factors which convert the ADC counts into charges.

Finally, a small correction factor was applied to compensate for the loss of pressure due to gas leakage during a run. This correction is typically of the order of a few percent, and was computed by linear interpolation between gas pressure measurements performed before and after each run. Since we recorded the time of occurrence of each event, it was possible to apply the pressure correction on an event-by-event basis. The sum of the ten electron channels was then formed, and the mean and the width of the corresponding distribution were extracted by fitting with a Gaussian. Since we did not measure the incident electron momentum for each event, we corrected the width of the electron peak by subtracting the beam momentum bite in quadrature. This bite was estimated to be $(2.5 \pm 0.5)\%$. We similarly corrected the width of the electron peak for electronic noise by subtracting the pedestal width in quadrature. This reduced the width by less than 5% at 50 GeV.

The drift velocity for each gas mixture was obtained by dividing the 4 mm drift gap of the test vessel by the FWHM pulse duration observed on the oscilloscope . The error on the drift velocity is dominated by the accuracy of the drift time measurement and is estimated to be $\pm 5\%$.

4. Results

The test beam results pertaining to the performance of the prototype calorimeter with Ar+ CH_4 gas mixtures at various pressures have been published in ref. 4. Here we will focus on the performance of the tested gas mixtures with 50 GeV electrons.

4.1 Prototype Calorimeter

The charge collected for 50 GeV electrons as a function of the voltage across the 2 mm gap is shown in fig. 2 for three argon gas mixtures at 100 atm. For all three mixtures the plateau is reached below 1500 V, which corresponds to an electric field of less than 750 V/mm.

Fig. 3 shows the charge collected as a function of voltage for a 97%Xe+3%CH_4 gas mixture at 52.7 atm and a 96%Xe+4%CH_4 gas mixture at 27.7 atm. Whereas at 27.7 atm the plateau is reached at an electric field of 650 V/mm, at 52.7 atm the signal does not saturate within the measured voltage range. This is due to much larger electron-ion recombination at the higher pressure.

The pulse-height spectra for the three argon gas mixtures at 100 atm are shown in figs. 4a-c for an electric field of 750 V/mm. The Xe+CH_4 pulse-height spectrum at 52.7 atm is shown in fig. 4d for two values of the electric field. The collected charge per GeV electron energy and the energy resolutions (σ/E) calculated from the means and the widths of these distributions are listed in Table 1.

Table 1: Energy Resolution and Collected Charge/GeV Measured at 750V/mm and 100 atm of Various Gas Mixtures

Gas	Resolution at 50 GeV(%)	Collected Charge (fC/GeV)
95%Ar+5%CH_4	6.15 ± 0.14	3.84 ± 0.12
95%Ar+5%CF_4	6.07 ± 0.24	4.25 ± 0.14
95%Ar+5%C_2H_6	6.45 ± 0.28	4.18 ± 0.13
96%Xe+4%CH_4†	5.5 ± 0.3	4.54 ± 0.20
97%Xe+3%CH_4‡	4.4 ± 0.2	5.57 ± 0.18*

† at 27.7 atm
‡ at 52.7 atm
* at 1500 V/mm

The calculated values for the collected charge are (4.5 ± 0.5) fC/GeV for the argon mixtures[4] and (4.5 ± 0.6) fC/GeV and (13 ± 3) fC/GeV for the Xe+CH_4 mixtures at 27.7 atm and 52.7 atm, respectively. The difference between the measured and the calculated values at 52.7 atm can be explained by the fact that total charge collection was not achieved at this pressure during the beam test (see fig. 3). We showed in ref. 4 that the energy resolution can be parameterized as:

$$\sigma(E)/E = \mathrm{A}/\sqrt{E}. \qquad (1)$$

Using the measured widths from Table 1 we get an average value for A of (43.7 ± 0.8)% for the argon mixtures, and of (31 ± 1)% and (39 ± 2)% for the Xe+CH_4 gas mixture at 52.7 atm and 27.7 atm, respectively. The EGS4[6] prediction for the argon mixtures, which is (45 ± 1)%, agrees well with the measured resolution. The predictions for xenon mixtures are (35 ± 1)% at 52.7 atm and (44 ± 1)% at 27.7 atm. The energy resolution is much better with the xenon gas mixture at 52.7 atm than with the argon gas mixtures, which have lower density. The energy resolution is expected to improve with increasing density, since the total track length of soft particles in the gas regions of the calorimeter, and hence the fluctuations in energy, diminishes as the gas becomes denser. This idea is supported by fig. 5 where we show the energy resolution as a function of gas density as predicted by EGS4. A kinetic energy cutoff of 200 keV for both electrons and photons was used. The smooth curve is an exponential fit to all points. This Monte Carlo curve is compared with the data in fig. 6.

4.2 High-Pressure Test Vessel

As indicated earlier, the electron drift velocity (V_d) measurements were performed with the high pressure vessel described above. The dependence of V_d on the ratio of the

electric field to pressure (E/P) for the gas mixtures we studied at various pressures is shown in figs. 7-11. For each gas, we observe that the maximum velocity is reached at an E/P value approximately independent of the pressure. The observed variation in V_d at the maximum is not more than 15% in the range of pressures where we took measurements. The maximum V_d and the corresponding E/P values are listed in Table 2. These values agree with the ones measured at lower pressures (see ref. 7 and the references therein).

Table 2: Maximum Drift Velocity and Associated E/P for Various Gas Mixtures

Gas	Maximum Drift Velocity(cm/μs)	Associated E/P (V/cm.atm)
95%Ar+5%CH_4	5.0	~100
95%Ar+5%CF_4	11.5	~400
95%Ar+5%C_2H_6	4.2	~150
97.1%Xe+2.9%CH_4	1.7	~300
97.1%Xe+2.9%CF_4	4.2	~900

We also observe that the argon mixtures are much faster than the xenon mixtures, and that for both the argon and xenon mixtures the drift velocities with CF_4 are more than a factor of two higher than with CH_4 or C_2H_6. At the same time, the E/P values required to reach the maximum V_d are larger for CF_4 by a factor of about 3. The dependence of the maximum V_d and of the corresponding E/P value on the CF_4 concentration in Ar+CF_4 is shown in fig. 12. We see that even 1.5% CF_4 in argon results in a maximum V_d twice as large as that obtained by adding 5% CH_4 or C_2H_6 at a similar E/P setting.

Table 3: Maximum Collected Charge for Alpha Particles in Various Gas Mixtures

Gas	Collected Charge at Saturation(fC)	E/P (V/cm.atm)
95%Ar+5%CH_4	34	300
95%Ar+5%CF_4	33	400
95%Ar+5%C_2H_6	33	200
97.1%Xe+2.9%CH_4	40	500
97.1%Xe+2.9%CF_4	40	1000

The charge produced by the alpha particles and collected by the anode of the pressure vessel with 95%Ar+5%CH_4 is plotted as a function of the reduced field E/P in fig.

13, for a pressure range of 10 to 100 atm. At a fixed value of the electric field the recombination increases strongly with pressure. In order to compare the gas mixtures we studied, we list in Table 3 the saturation charge at 10 atm and the E/P value where the saturation starts for these mixtures. The average saturation charges for argon and xenon (34 fC and 40 fC, respectively) are inversely proportional to the mean energy per ion pair for the argon and xenon gases (26.4 $\pm$ 0.5 eV[8] and 21.9 $\pm$ 0.3 eV[9], respectively).

4.3 Stability

As mentioned above, the Ar+CH_4, Ar+C_2H_6, Ar+CF_4 and Xe+CH_4 mixtures were studied in the test beam. As already reported in ref. 4, Ar+CH_4 was very stable, i.e. the change in signal size could be accounted for in terms of variances in gas pressure, amplifier gains and pedestals. Similarly, no instability was observed with the Ar+C_2H_6 and Xe+CH_4 mixtures. However the 95% Ar+5% CF_4 mixture showed a large instability in the form of 10% to 20% reduction in signal size a few hours after the gas was injected into the calorimeter. The radiation dose produced by the beam interactions in the calorimeter, estimated to be much less than 1 $\sim$ krad, is too small to explain such behavior. On the other hand, a two week long stability study performed with our high pressure test vessel with 95% Ar+5% CF_4 did not reproduce this behavior. The radiation dose in the test vessel due to the alpha particles is equivalent to the dose received by the calorimeter in the beam. However the materials in contact with the gas are different in the two setups. For example, CF_4 could react with the G-10 boards in the prototype calorimeter and produce a very electronegative product. Since the 95%Ar+5%CF_4 gas mixture has a very large drift velocity, it is very important to understand the cause of the instability observed in the test beam. Our group intends to carry out radiation damage and other studies to determine the conditions for which the Ar+CF_4 mixture is stable.

5. Summary

We have compared the collected charge, the energy resolution, the signal speed and the stability of the Ar+CH_4, Ar+C_2H_6, Ar+CF_4, Xe+CH_4 and Xe+CF_4 gas mixtures. We observed for all mixtures that the maximum signal speed was reached at E/P settings independent of the pressure of the mixture. We also observed that the energy resolution improved with increasing density of the gas mixture. In particular, our results show that the argon mixtures are much faster than the xenon mixtures, but the latter give better energy resolution, even at considerably lower pressures. Therefore the argon mixtures are more attractive for calorimeters at the new high energy, high luminosity colliders where speed is more important. The xenon mixtures could be used in fixed target experiments where energy resolution takes precedence over speed and a lower pressure is preferable for practical reasons.

The $Ar+CF_4$ mixture has been proven to be excellent in signal speed. However, its instability observed in the test beam is worrisome and it should be studied further.

Acknowledgements

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[2] N.D. Giokaris et al., Nucl. Instr. and Methods A291 (1990) 552.
[3] D.M. Khazins et al., Nucl. Instr. and Methods A300 (1991) 281.
[4] L. Demortier et al., Nucl. Instr. and Methods A324 (1993) 77.
[5] S. Denisov et al., to be published in the Proceedings of the 3rd International Conference on Calorimetry in High Energy Physics, September 29-October 2, 1992, Corpus Christi, Texas.
[6] W. R. Nelson, H. Hirayama, D. W. O. Rogers, SLAC-Report-265 (1985).
[7] Anna Peisert and Fabio Sauli, CERN 84-80 (13 July 1984).
[8] International Commission on Radiation Units and Measurements Report No.31 (ICRU, Bethesda, MD, 1979).
[9] N. Ishida at al., Physical Review A46 (1992) 1676.

Figure Captions

Figure 1: Oscilloscope trace due to alpha particles ionizing a 95%Ar+5%CH_4 gas mixture. The gap is 4 mm, the pressure is 100 atm, and the field is 600 V/mm.

Figure 2: Charge collected by the prototype calorimeter in a 50 GeV electron beam as a function of high voltage for various argon gas mixtures at 100 atm. The lines are for guiding the eye.

Figure 3: Charge collected by the prototype calorimeter in a 50 GeV electron beam as a function of high voltage for two xenon gas mixtures. The lines are for guiding the eye.

Figure 4: The pulse height spectra of a 50 GeV electron beam when the prototype calorimeter is operated with various gas mixtures. a-c) Argon mixtures at 100 atm and at 750 V/mm, d) xenon mixture at 52.7 atm and, at 750 V/mm and 1500 V/mm.

Figure 5: Electromagnetic energy resolution as a function of gas density as predicted by EGS4. The curve is a fit to all points.

Figure 6: Electromagnetic energy resolution as a function of gas density as measured in the beam test. The curve is the EGS4 prediction presented in fig. 5.

Figure 7: Electron drift velocity as a function of E/P for 95%Ar+5%CH_4 at various pressures.

Figure 8: Electron drift velocity as a function of E/P for 95%Ar+5%C_2H_6 at various pressures.

Figure 9a: Electron drift velocity as a function of E/P for 98.5%Ar+1.5%CF_4 at various pressures.

Figure 9b: Electron drift velocity as a function of E/P for 97%Ar+3%CF_4 at various pressures.

Figure 9c: Electron drift velocity as a function of E/P for 95%Ar+5%CF_4 at various pressures.

Figure 10: Electron drift velocity as a function of E/P for 97.1%Xe+2.9%CH_4 at various pressures.

Figure 11: Electron drift velocity as a function of E/P for 97.1%Xe+2.9%CF_4 at various pressures.

Figure 12: Maximum electron drift velocity (left scale) and the corresponding E/P value (right scale) as a function of CF_4 concentration in argon. The lines are for guiding the eye.

Figure 13: Charge collected by the high pressure vessel due to alpha particles as a function of E/P for 95%Ar+5%CH_4 gas mixtures at various pressures.

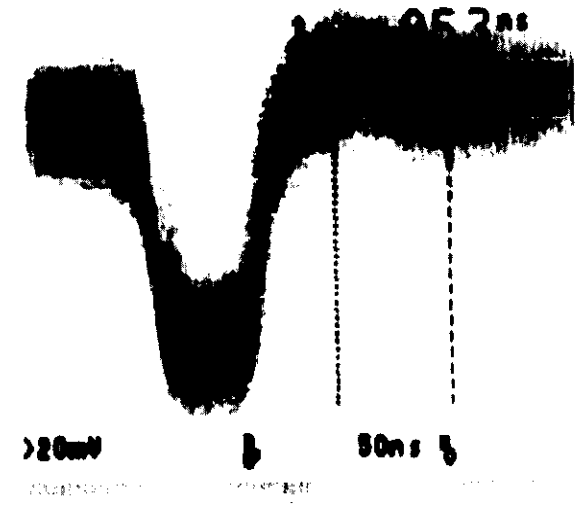


Figure 1

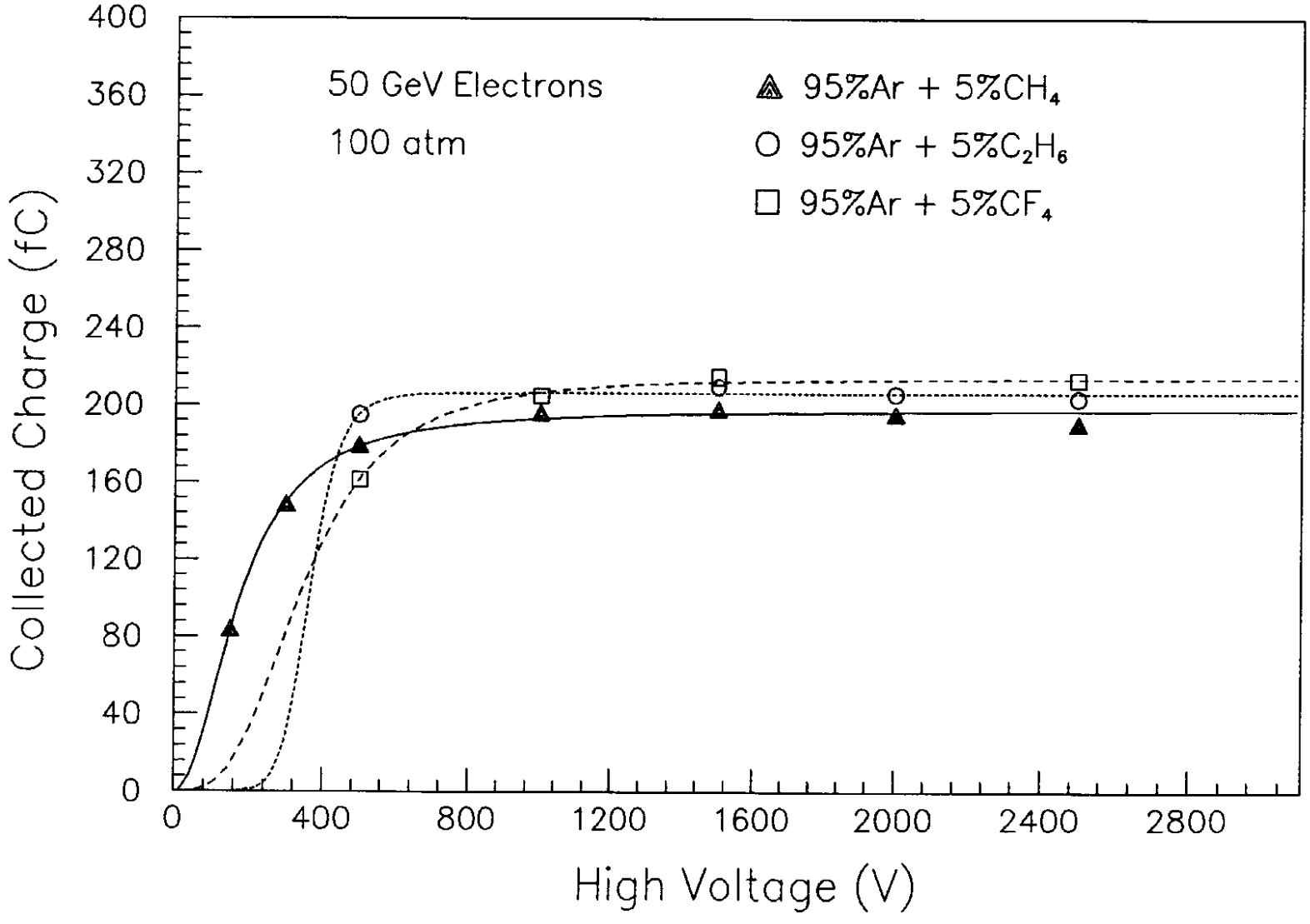

50 GeV Electrons
100 atm
95%Ar + 5%CH4
95%Ar + 5%C2H6
95%Ar + 5%CF4
Collected Charge (fC)
High Voltage (V)
0
40
80
120
160
200
240
280
320
360
400
0
400
800
1200
1600
2000
2400
2800

Figure 2

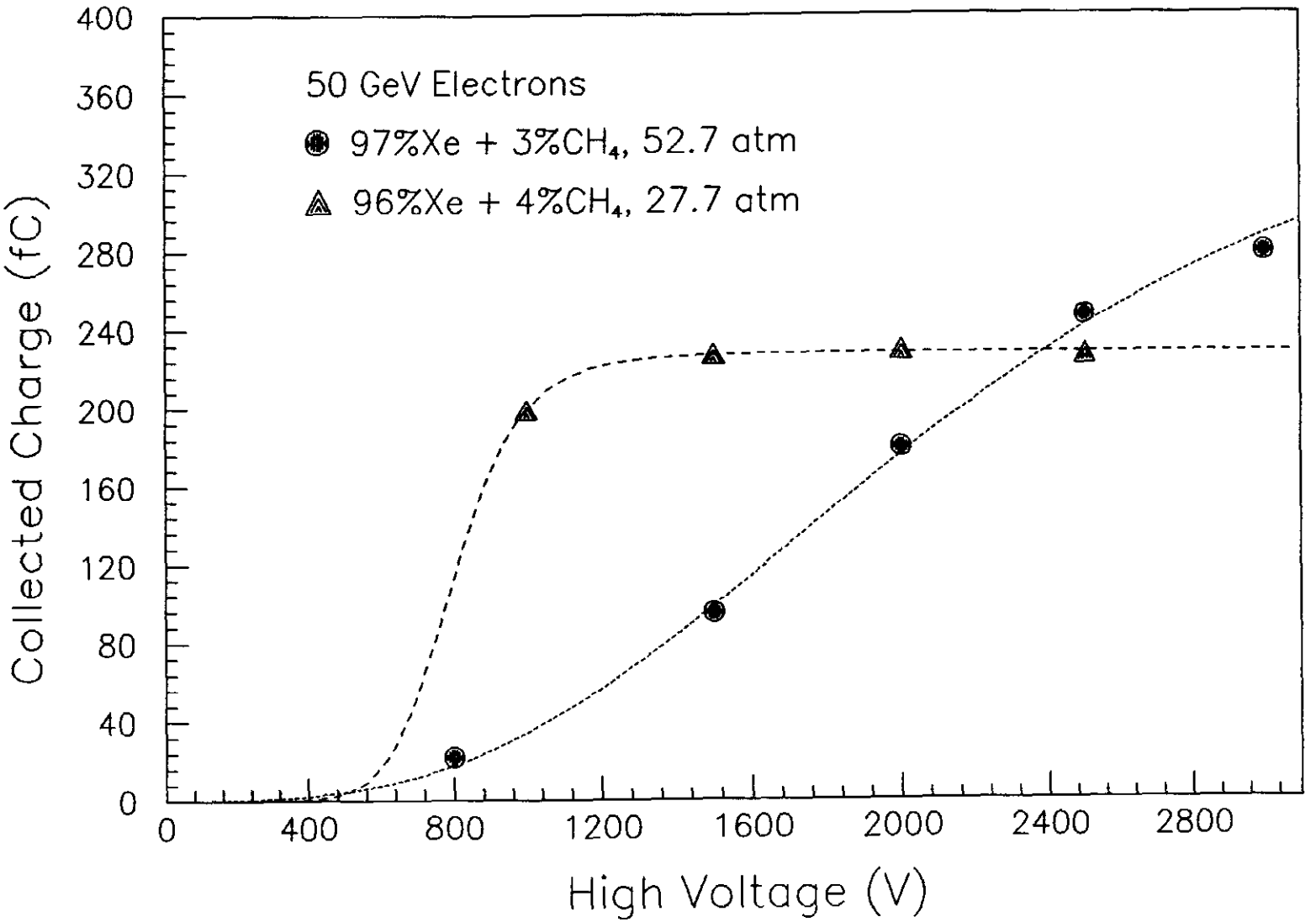

50 GeV Electrons
97%Xe + 3%CH4, 52.7 atm
96%Xe + 4%CH4, 27.7 atm
Collected Charge (fC)
High Voltage (V)
0
40
80
120
160
200
240
280
320
360
400
0
400
800
1200
1600
2000
2400
2800

Figure 3

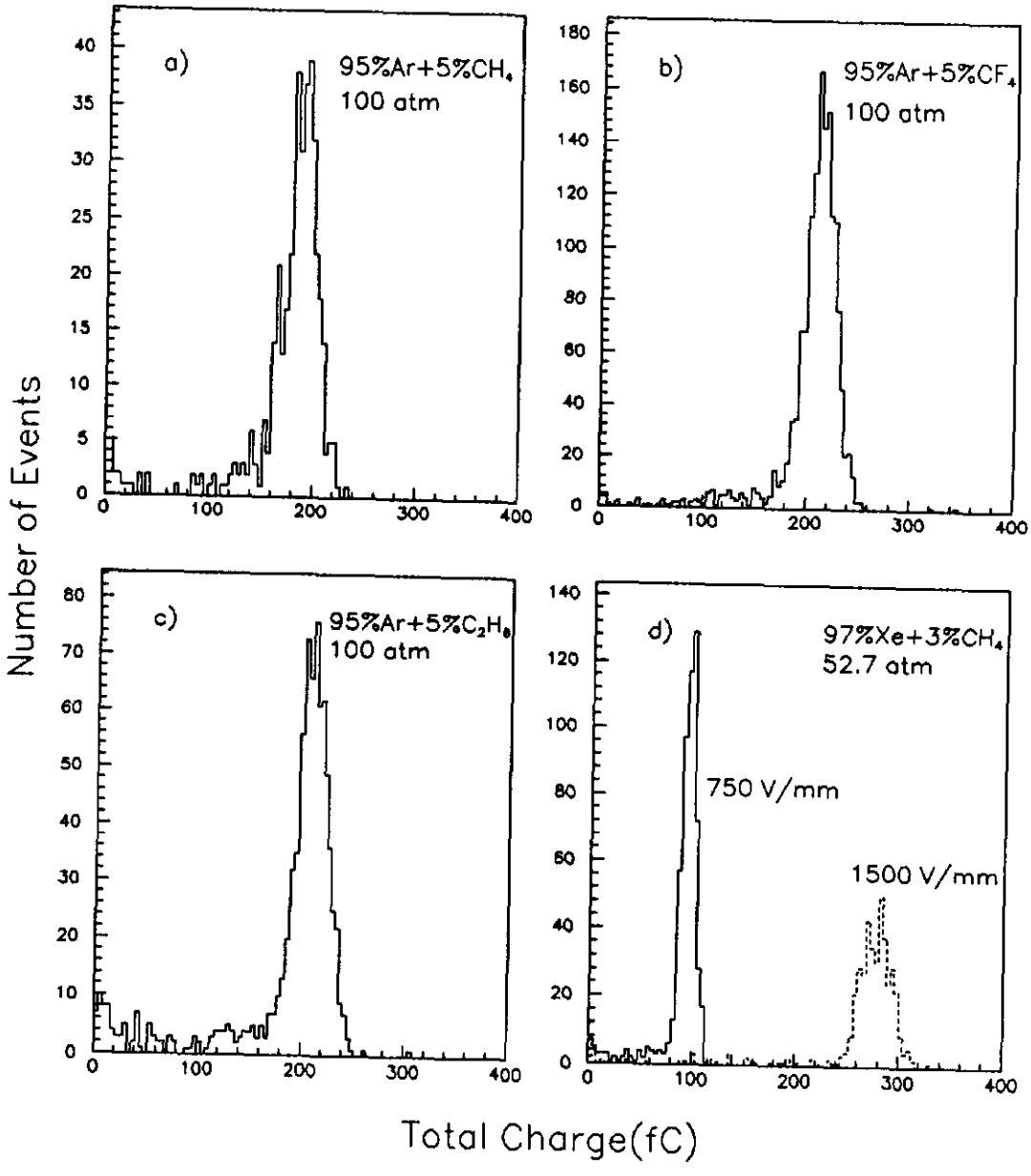

a)
95%Ar+5%CH4
100 atm
b)
95%Ar+5%CF4
100 atm
c)
95%Ar+5%C2H6
100 atm
d)
97%Xe+3%CH4
52.7 atm
750 V/mm
1500 V/mm
Number of Events
Total Charge(fC)

Figure 4

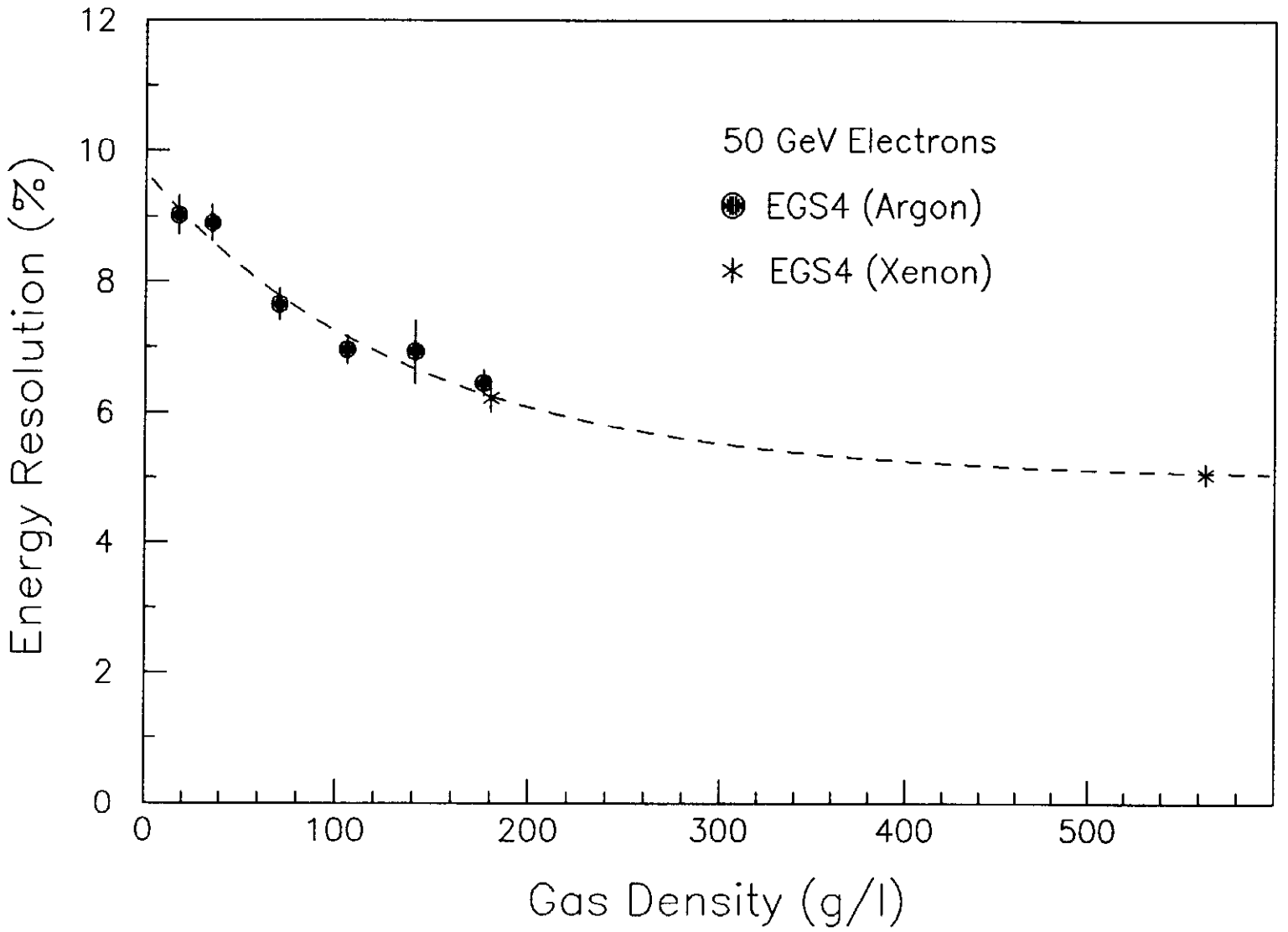

12
10
8
6
4
2
0
Energy Resolution (%)
0
100
200
300
400
500
Gas Density (g/l)
50 GeV Electrons
EGS4 (Argon)
EGS4 (Xenon)

Figure 5

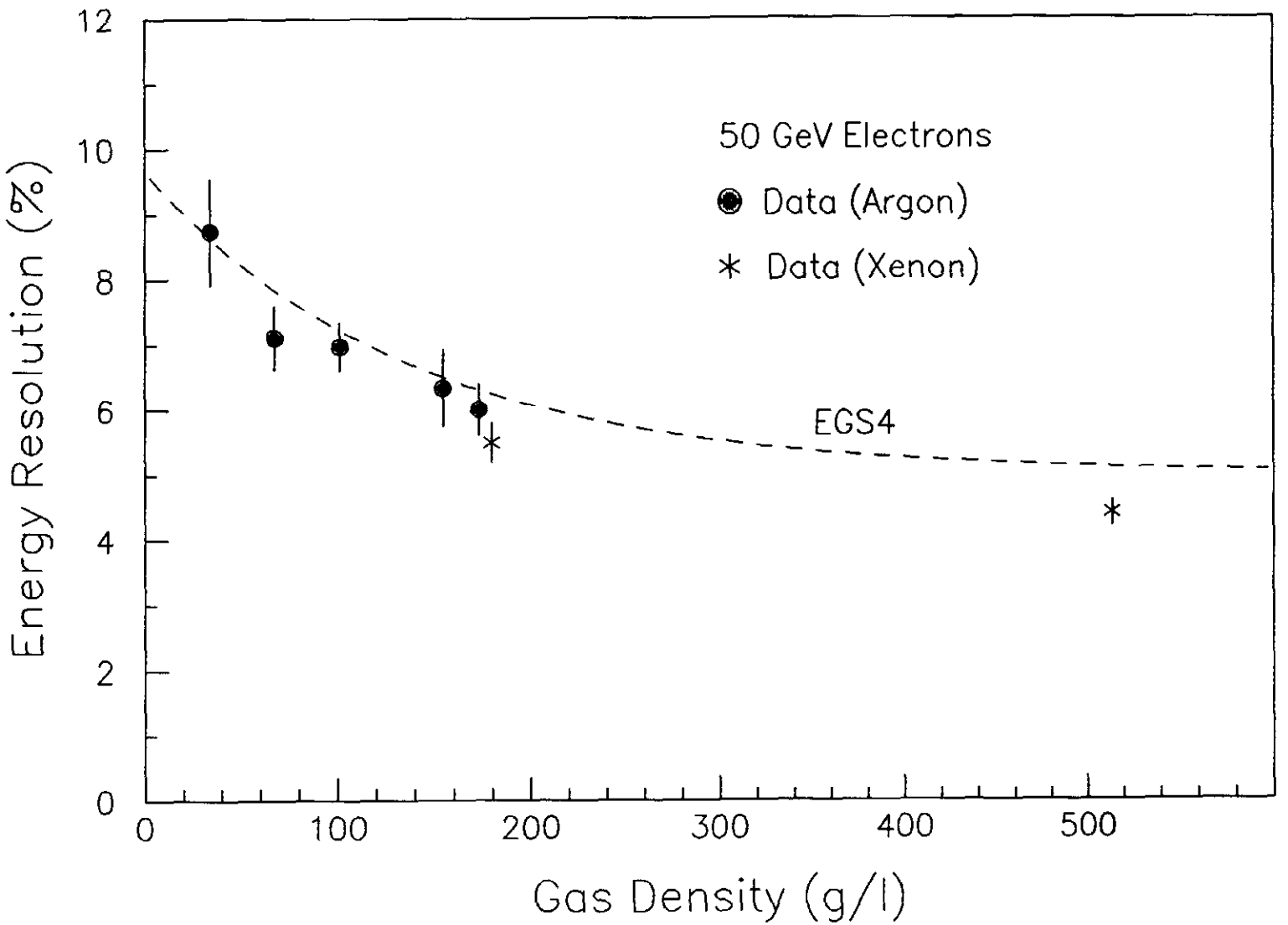

12
10
8
6
4
2
0
Energy Resolution (%)
0
100
200
300
400
500
Gas Density (g/l)
50 GeV Electrons
Data (Argon)
Data (Xenon)
EGS4

Figure 6

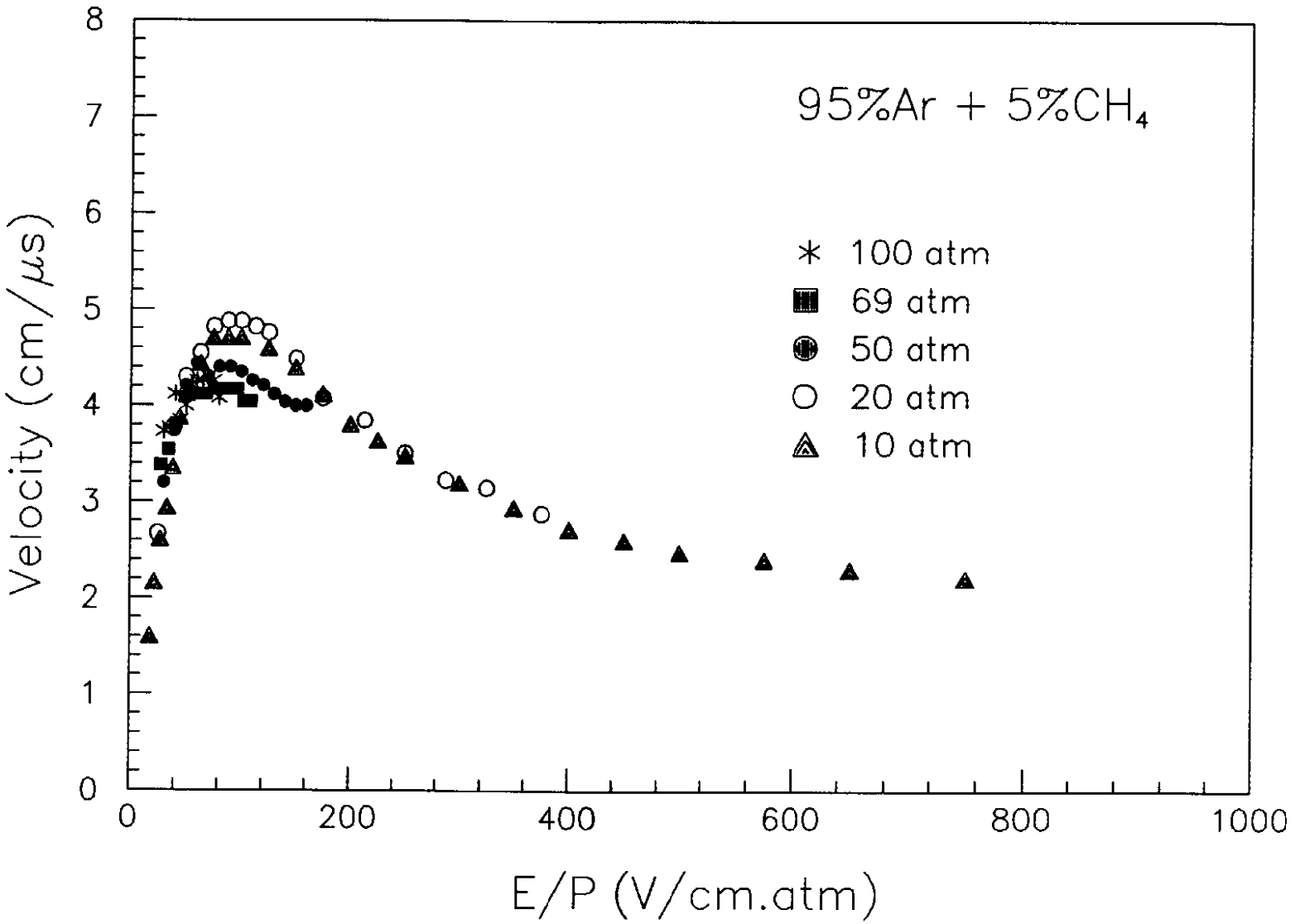
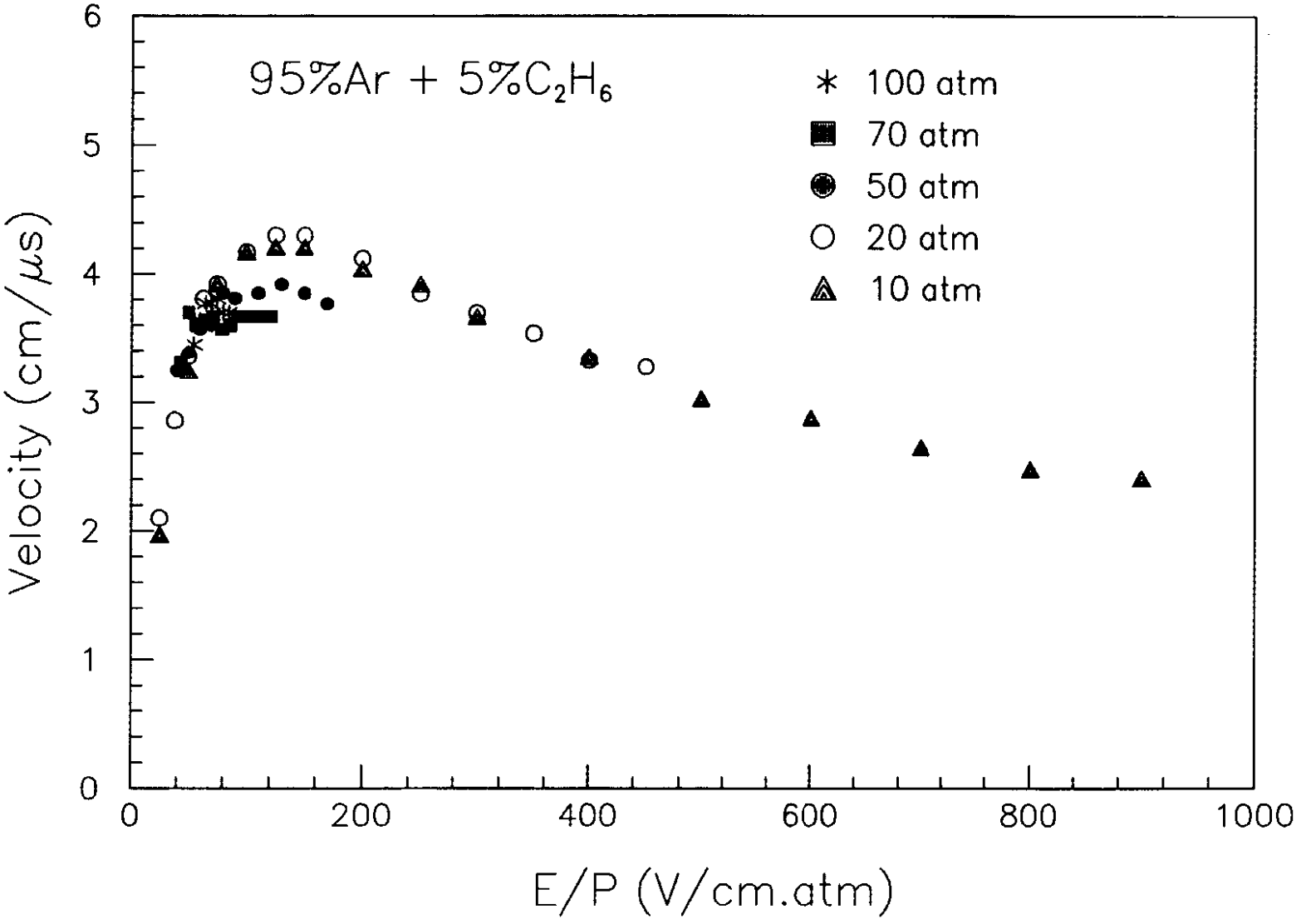

95%Ar + 5%CH4
100 atm
69 atm
50 atm
20 atm
10 atm
Velocity (cm/μs)
E/P (V/cm.atm)
0
1
2
3
4
5
6
7
8
0
200
400
600
800
1000

Figure 7


95%Ar + 5%C2H6
100 atm
70 atm
50 atm
20 atm
10 atm
Velocity (cm/μs)
E/P (V/cm.atm)
0
1
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200
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800
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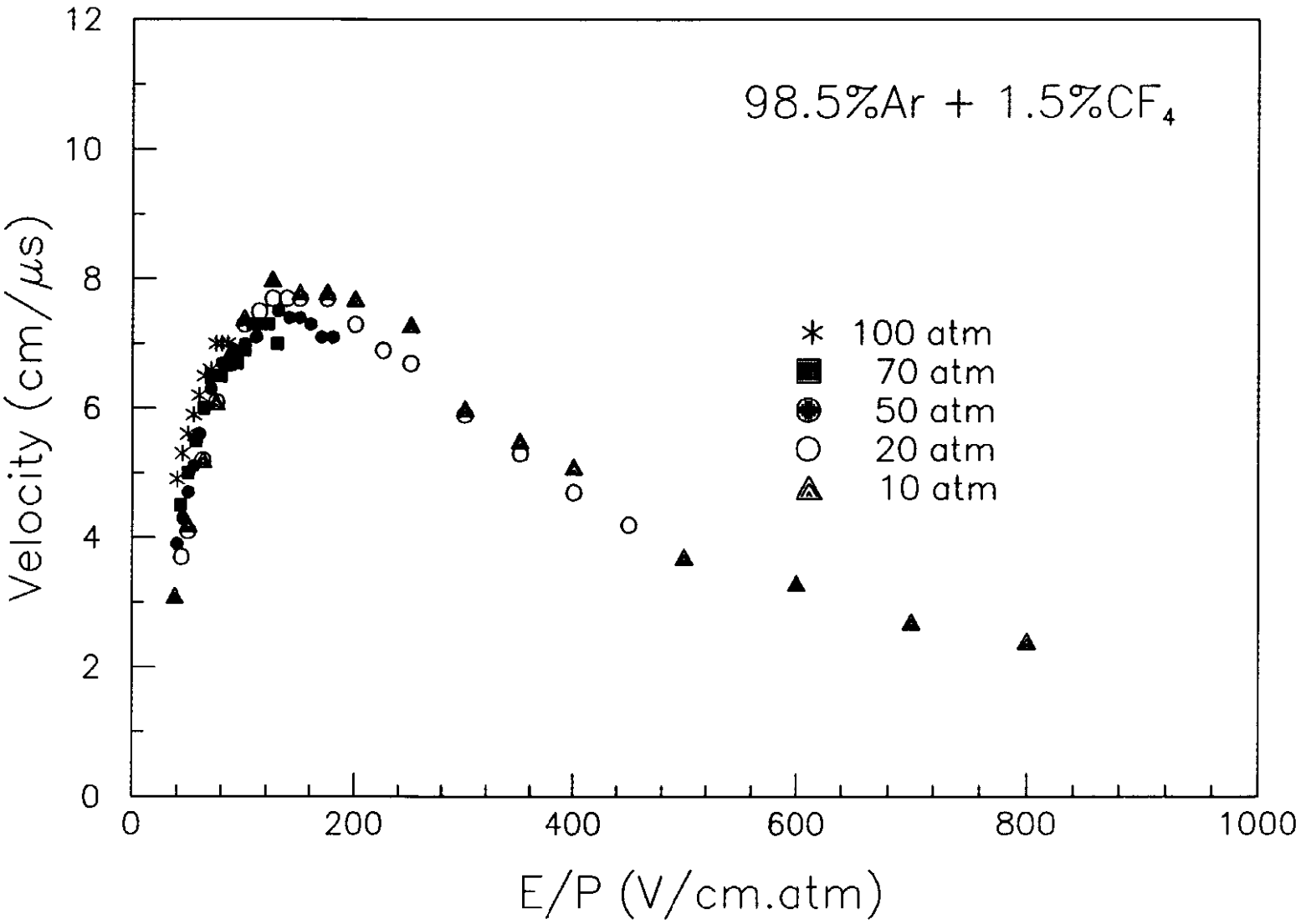
Figure 8


98.5%Ar + 1.5%CF4
100 atm
70 atm
50 atm
20 atm
10 atm
Velocity (cm/μs)
E/P (V/cm.atm)
0
2
4
6
8
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12
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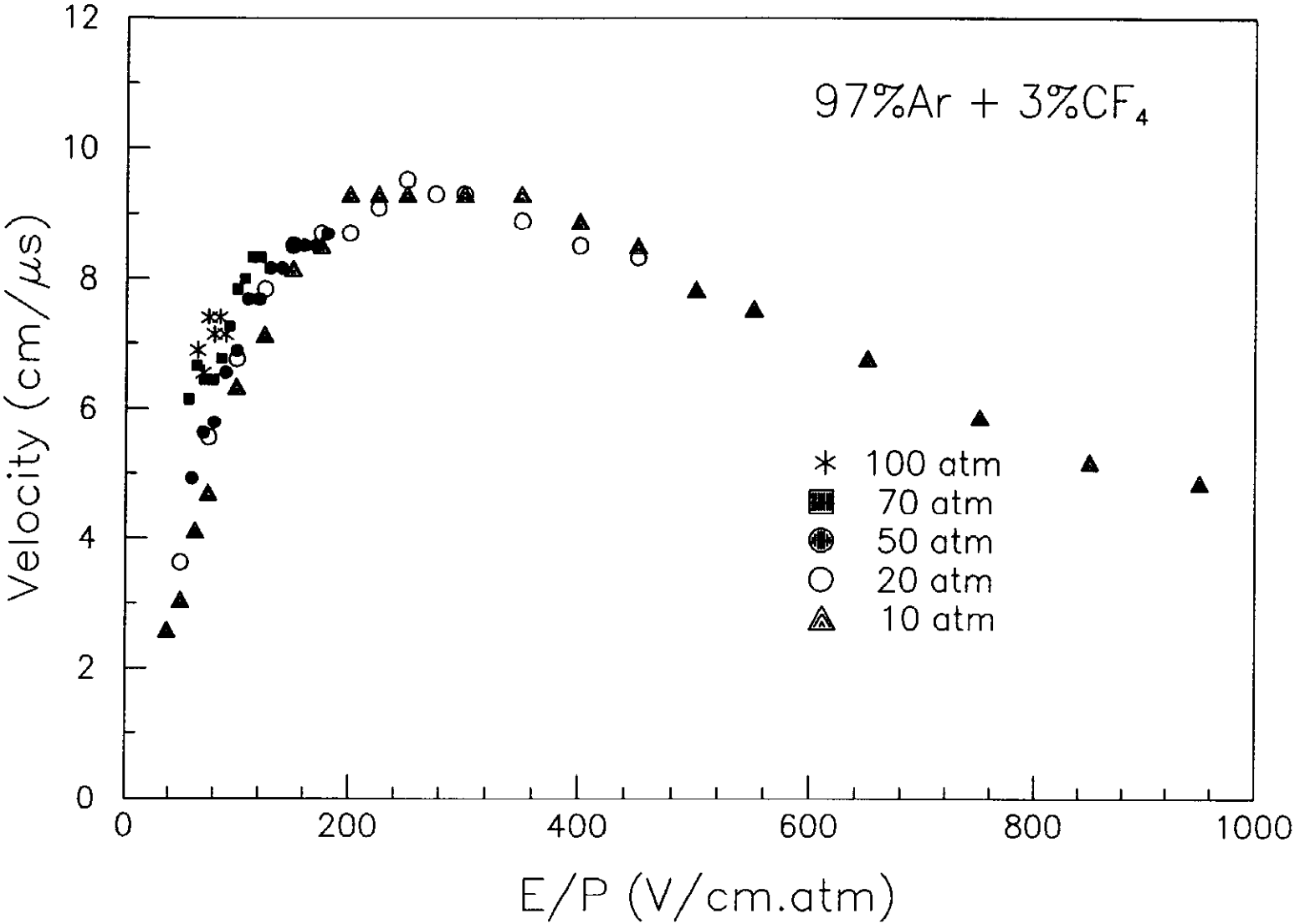
200
400
600
800
1000

Figure 9a


97%Ar + 3%CF4
100 atm
70 atm
50 atm
20 atm
10 atm
Velocity (cm/μs)
E/P (V/cm.atm)
0
2
4
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12
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200
400
600
800
1000

Figure 9b

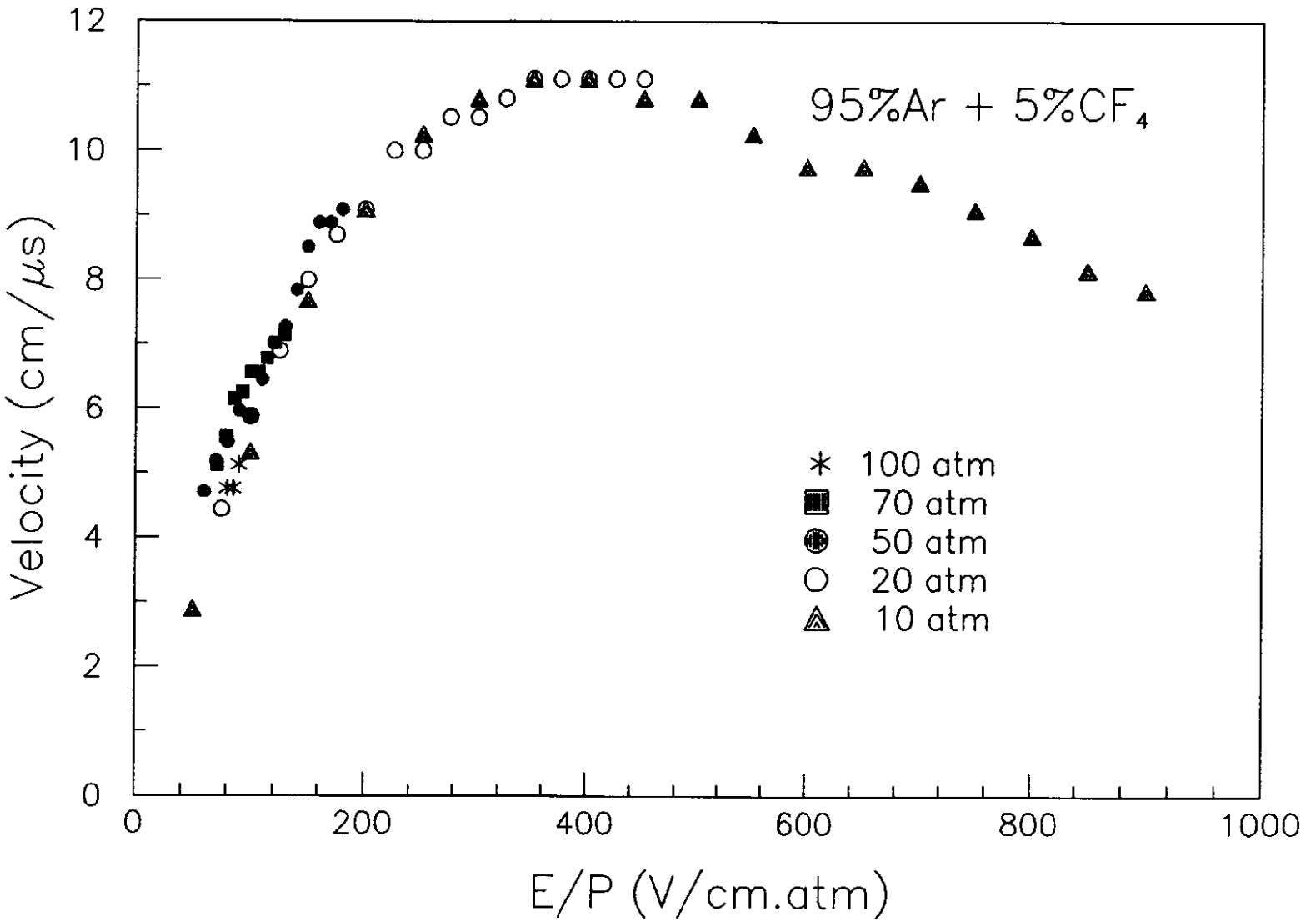
95%Ar + 5%CF4
100 atm
70 atm
50 atm
20 atm
10 atm
Velocity (cm/μs)
E/P (V/cm.atm)
0
2
4
6
8
10
12
0
200
400
600
800
1000

Figure 9c

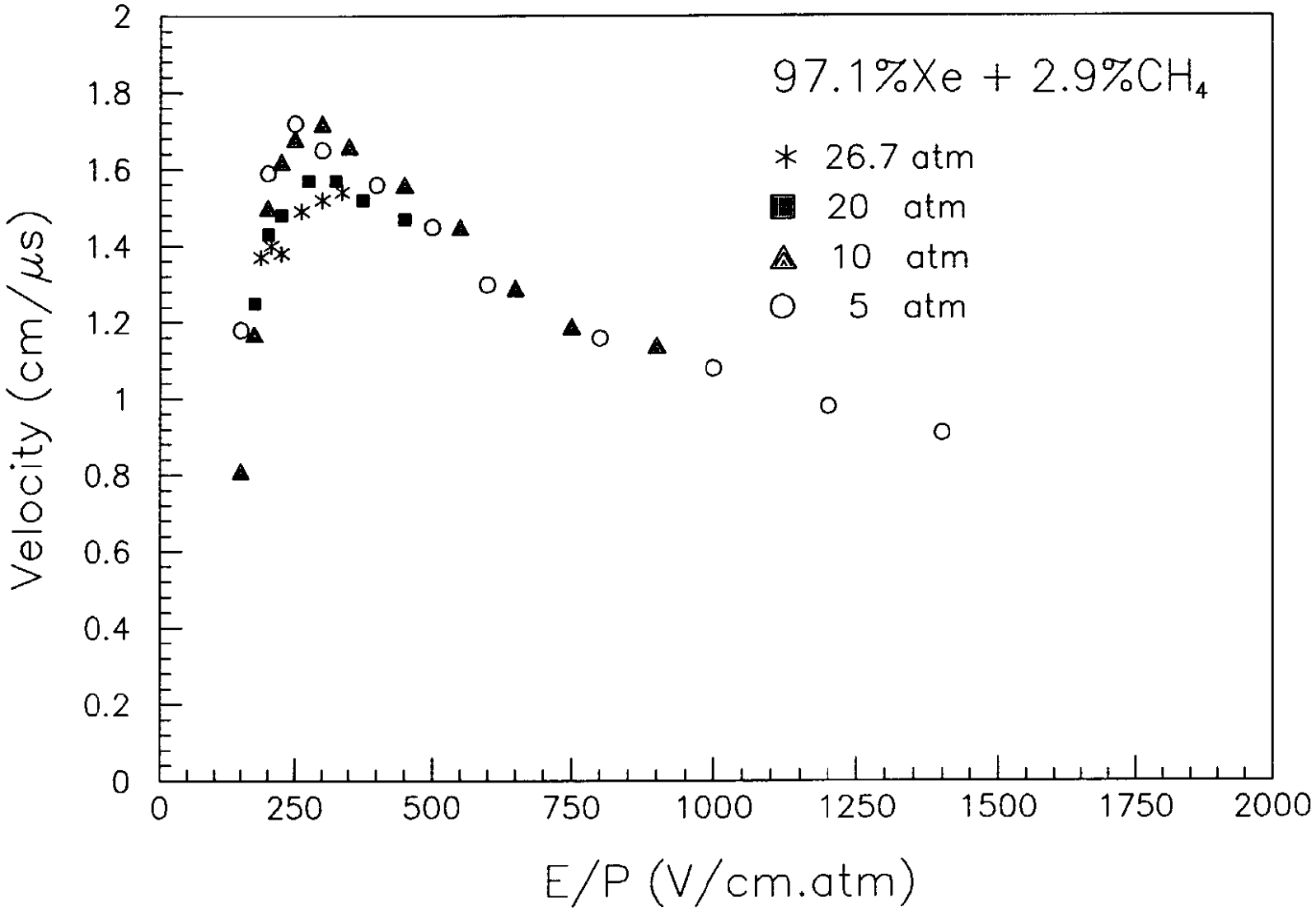
97.1%Xe + 2.9%CH4
* 26.7 atm
20 atm
10 atm
5 atm
Velocity (cm/μs)
E/P (V/cm.atm)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
250
500
750
1000
1250
1500
1750
2000

Figure 10

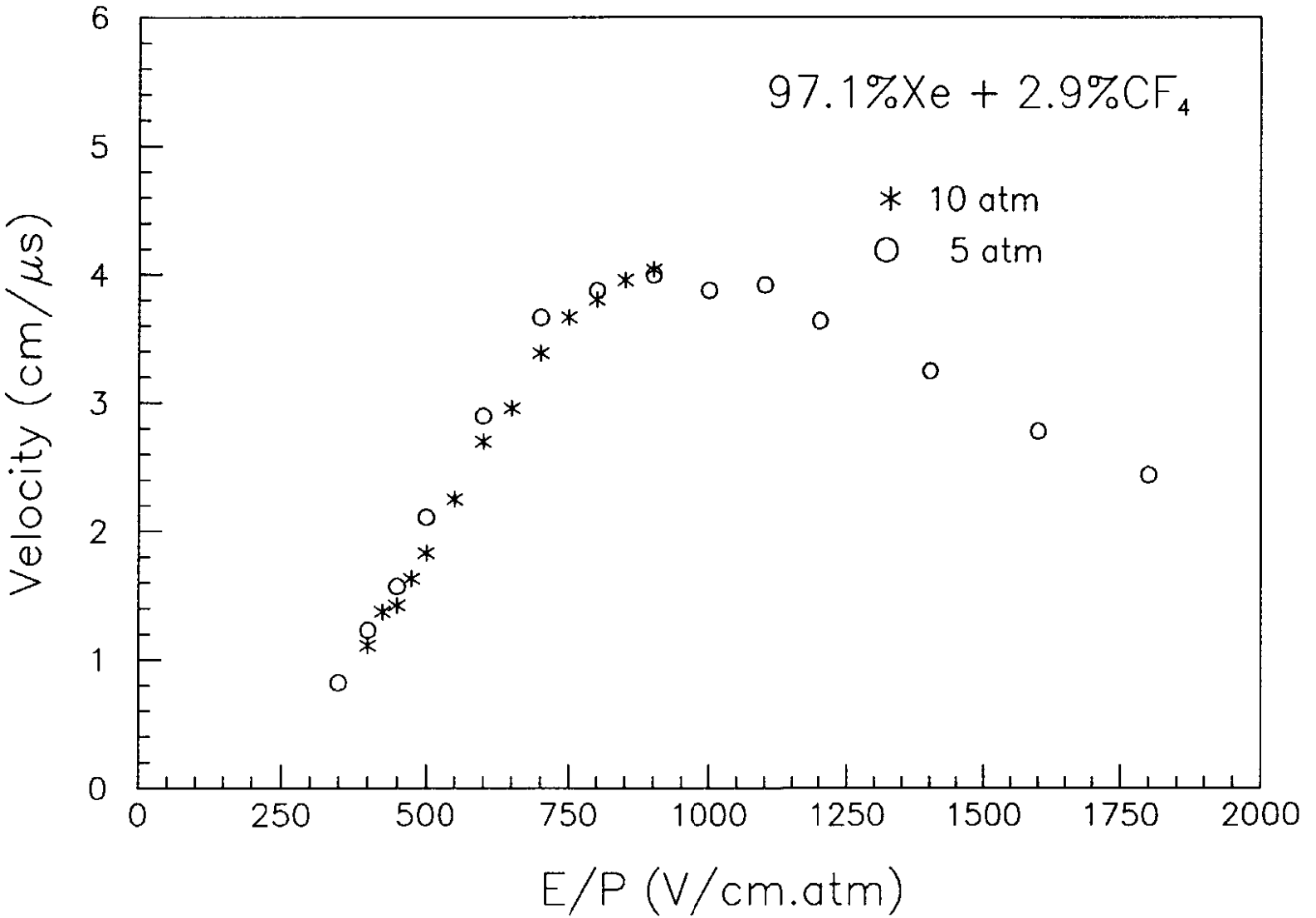
97.1%Xe + 2.9%CF4
* 10 atm
O 5 atm
Velocity (cm/μs)
E/P (V/cm.atm)
0
1
2
3
4
5
6
0
250
500
750
1000
1250
1500
1750
2000

Figure 11

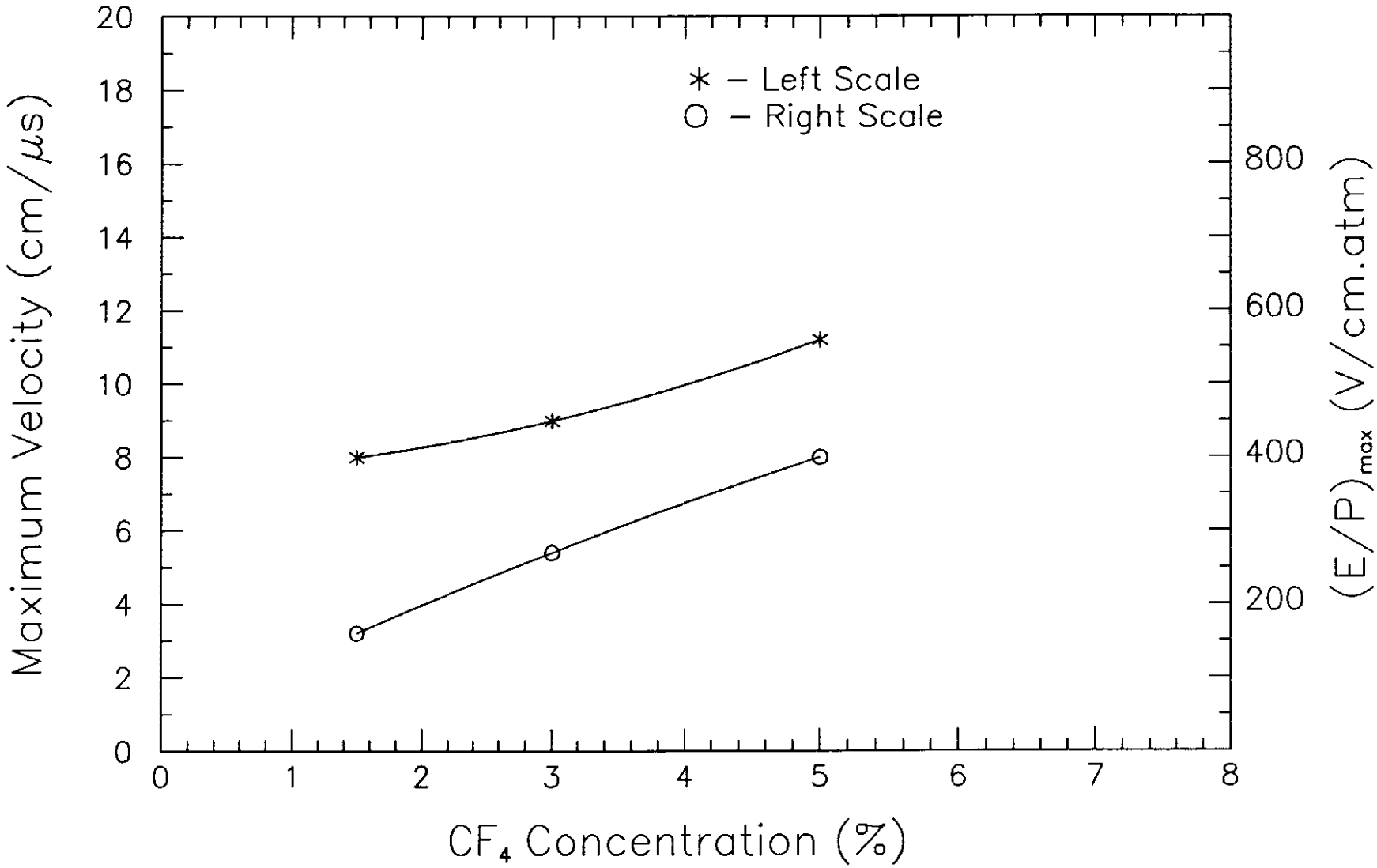
* – Left Scale
O – Right Scale
Maximum Velocity (cm/μs)
(E/P)max (V/cm.atm)
CF4 Concentration (%)
0
2
4
6
8
10
12
14
16
18
20
200
400
600
800
1
3
5
7

Figure 12

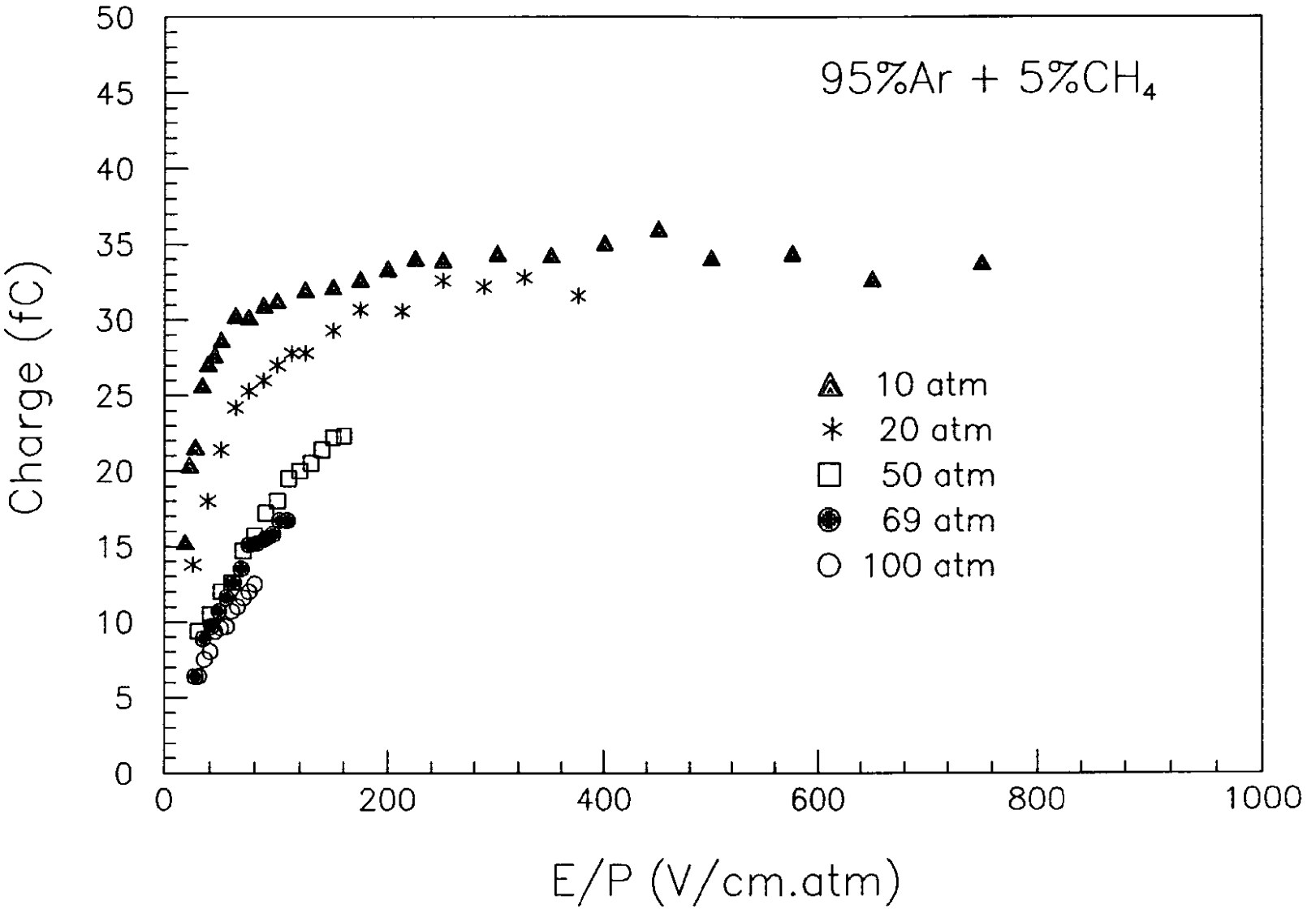
95%Ar + 5%CH4
10 atm
20 atm
50 atm
69 atm
100 atm
Charge (fC)
E/P (V/cm.atm)
0
5
10
15
20
25
30
35
40
45
50
0
200
400
600
800
1000

Figure 13