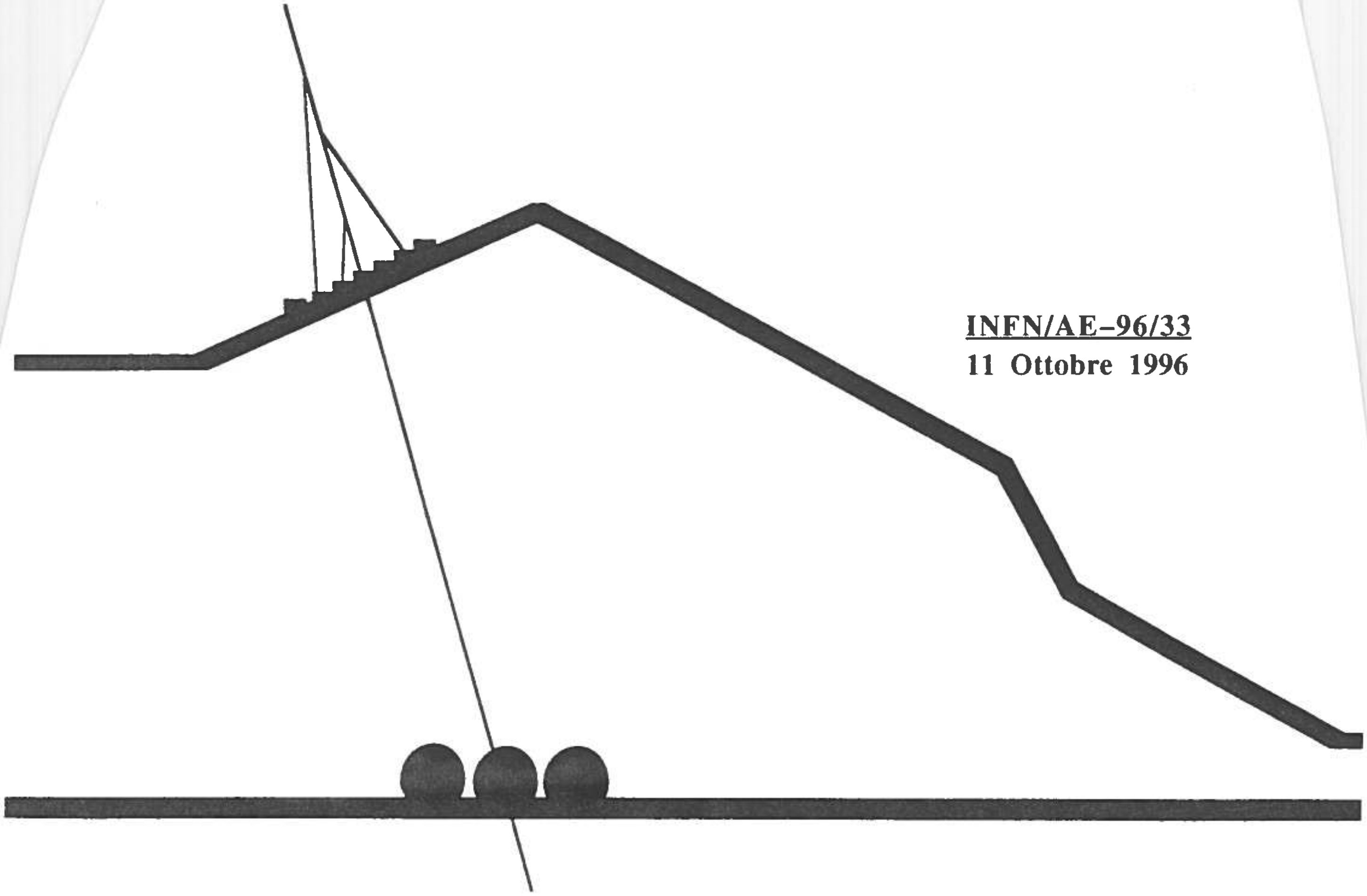

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STUDY OF LASER INDUCED IONIZATION IN PROPORTIONAL AND STREAMER TUBES FILLED WITH HELIUM BASED GAS MIXTURES

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Abstract

The use of an intense XeCl laser provided a unique way to produce large primary ionization in a streamer tube. The response of a proportional tube was also studied as a function of the laser intensity for calibration purposes and to to better understand the physical processes involved in the excitation-ionization mechanisms in the gas mixtures. Up to ionization powers as large as hundreds of m.i.p. the streamer tube response was shown to be logarithmic.

1 Introduction

The purpose of this investigation was to study the response of streamer and proportional tubes to large primary ionization produced in a helium based mixture by an intense ultraviolet laser. The study was stimulated by the interest in the streamer tube response to highly ionizing particles. The not complete saturation of the streamer tube response allows the discrimination between minimum ionizing particles and high Z ions or exotic objects like fast ($\beta > 5 \cdot 10^{-3}$) magnetic monopoles. This can be done if the dependence of the streamer charge on large ionizations in the sensitive volume is well known.

Large primary ionization in the gas volume can be obtained by using a beam of high Z ions [1]. However, in such a measurement, it is difficult to disentangle the effects produced by the δ-ray background.

The use of an intense XeCl laser provided a unique way to produce large primary ionization without this kind of background. Also, the large amount of energy emitted and the shorter photon wavelenght with respect to a N_2 laser, which was shown to cause an increase of the ionization cross section [2], allowed us to produce primary ionizations at the levels of hundreds of m.i.p. (minimum ionizing particle).

The response of a proportional tube was also studied as a function of the laser intensity. This was done not only to have a measure of the charge initially produced by the laser at a given intensity, but also to better understand the physical processes involved in the excitation-ionization mechanisms in the gas mixtures initiated by the ultraviolet photon beam.

In the following we will give a brief discussion of theoretical aspects involved in the laser induced ionization process. Then the experimental setup and the measurement procedure will be discribed. The conclusions of this work will be then given.

2 Theoretical aspects

The energy of the UV photons used to produce ionizing tracks in gas detectors is smaller than the ionizing potential of the main compounds of the mixture. As reported for example in [2],[3] and references therein, ion pairs are produced in the sensitive volume by means of a double step process on some impurities present in the gas mixture at a very low concentration. The first step is an excitation of a molecule to a metastable energy level, then a second photon can ionize it. Such kind of impurities are composite molecules with a variety of vibrational and rotational levels which are pratically omnipresent in the mixture in very small quantity (e.g. outgassing from the chamber system). Those impurities can also be added to the gas mixture in order to have larger signals. A deep study of these effects is reported in [4].

A simple model can be envisaged in order to have a mathematical treatement of this physical process. Let n be the number of ionizable molecules per unit volume present in the gas mixture and n_ϵ and n_I the number density of the molecules in the excited and ionized state respectively. Let σ_ϵ, τ_ϵ and σ_I^* be the excitation cross section, the lifetime of the excited state and its ionization cross section respectively. If this gas is reached by a laser pulse consisting of N_γ photons uniformly distributed on a surface s and a time interval τ_L, the following coupled differential equations can be written:

$$\begin{aligned} \frac{dn_\epsilon}{dt} &= -\frac{n_\epsilon}{\tau_\epsilon} + \sigma_\epsilon \frac{N_\gamma}{s\tau_L}(n - n_\epsilon - n_I) - \sigma_I^* \frac{N_\gamma}{s\tau_L} n_\epsilon \\ \frac{dn_I}{dt} &= \sigma_I^* \frac{N_\gamma}{s\tau_L} n_\epsilon \end{aligned} \tag{1}$$

An approximate solution of these equations, valid in the limit $n >> n_I$, is useful to directly see what is the dependence of $n_I(\tau_L)$ on the energy density radiated from the laser. Under this approximation, the solution can be easily shown to be

$$\frac{n_I(\tau_L)}{n} = \frac{1}{4} f(\xi) \frac{(y - \tau_L/\tau_\epsilon)^2}{y} \left[1 - \frac{1 - e^{-y}}{y} \right] \tag{2}$$

where ξ is the ratio of the cross sections and

$$f(\xi) = \frac{4}{\xi + \frac{1}{\xi} + 2} \tag{3}$$

$$y = (\sigma_\epsilon + \sigma_I^*)\rho_\gamma + \left(\frac{\tau_L}{\tau_\epsilon} \right) \tag{4}$$

with $\rho_\gamma = N_\gamma / s$, the photon density.
Let us consider the two different cases
1) $y \lesssim 1$
In this case the term in square brackets is $\sim y/2$, at the second order of an expansion in powers of y, and we have

$$\frac{n_I}{n}(\tau_L) \sim \frac{1}{8} f(\xi) \Big[(\sigma_\epsilon + \sigma_I^*)\rho_\gamma \Big]^2 \tag{5}$$

Therefore there is a quadratic dependence on the photon density (i.e. energy density). Let us notice that this regime is possible only for short enough laser pulses, namely $\tau_L \lesssim \tau_\epsilon$.
2) $y \gtrsim 10$
In this case the term in square brackets is ~ 1 and

$$\begin{aligned} &\tfrac{n_I}{n}(\tau_L) \sim \tfrac{1}{4} f(\xi) \Big[(\sigma_\epsilon + \sigma_I^*)\rho_\gamma \Big]^2 \left(\tfrac{\tau_L}{\tau_\epsilon} \right)^{-1} &&\text{if } \rho_\gamma << \tfrac{1}{(\sigma_\epsilon + \sigma_I^*)} \left(\tfrac{\tau_L}{\tau_\epsilon} \right) \\ &\tfrac{n_I}{n}(\tau_L) \sim \tfrac{1}{4} f(\xi) \Big[(\sigma_\epsilon + \sigma_I^*)\rho_\gamma \Big] &&\text{if } \rho_\gamma >> \tfrac{1}{(\sigma_\epsilon + \sigma_I^*)} \left(\tfrac{\tau_L}{\tau_\epsilon} \right) \end{aligned} \tag{6}$$

Therefore, we see that the dependence is quadratic for small ρ_γ and then becomes linear at larger photon density values. The quadratic dependence is a consequence of the two step process. It becomes linear when practically all the molecules are in the excited state. These formulae can not be applied for large enough cross sections and photon densities, where they fail by predicting $n_I \gtrsim n$.

Therefore the exact exact solution of the system must be found. It can be seen to be given by

$$\frac{n_I(\tau_L)}{n} = 1 - \frac{\beta_1 e^{\beta_2} - \beta_2 e^{\beta_1}}{\beta_1 - \beta_2} \tag{7}$$

where

$$\beta_{1/2} = \frac{y}{2}\left[-1 \pm \sqrt{1 - f(\xi)\left(\frac{y - \tau_L/\tau_\epsilon}{y}\right)^2}\,\right] \tag{8}$$

In this case, in the region corresponding to very high energy densities the saturation of the ionization yield of the laser pulse is possible. This correspond to an ionization of almost all the molecules which can undergo the double photon ionization process. In Fig.1 we show n_I/n as a function of $(\sigma_\epsilon + \sigma_I^*)\rho_\gamma$ for a variety of values of ξ and τ_L/τ_ϵ. It is also reported $f(\xi)$ as a function of ξ. The linear and quadratic behaviours are clearly visible. It can also be seen that the complete saturation occurs at larger photon densities for longer laser pulses (once the total number of photons is fixed).

A comparison of this model with the experimental results is given in the following.

3 The experimental setup

We have used 20 cm long gas chambers with the same geometrical parameters as the ones used in the MACRO experiment [5]: $3 \times 3\,\text{cm}^2$ cell size and Be-Cu anode wire. Two different active cells were used for the streamer and proportional tube respectively. This was done in order to allow the use of different diameter wire in the two cases. The diameter of the wire operating in the streamer regime was $100\,\mu$m, while a $30\,\mu$m wire was used for the proportional counter. For both cells two holes of 0.5 cm diameter were done to allow the laser beam to enter and exit the detector throught a couple of quartz windows.

An XeCl excimer laser ($\lambda_\gamma \simeq 308\,\text{nm}$ - $E_\gamma \simeq 4.1\,\text{eV}$) was used to ionize the gas. The laser pulse was long 10-20 ns, while the total energy radiated was of the order of 100 mJ/pulse.

The laser was focused on the gas detector using a lens with 70 cm of focal distance and a couple of diaphragms on the beam line. A convergent lens with large focal distance was chosen in order to have a region, of $\sim 5cm$ along the beam line, where the spot size and the energy density were uniform. This provided a good simulation of an inonizing track. The spot size was reduced to a rectangle of $2 \times 1\,\mathrm{mm}^2$ area and having a total energy of $\sim 5\,\mathrm{mJ/pulse}$. The intensity of the laser pulse reaching the chamber was varied using some optical filters on the beam line (see Fig.2) and monitored using a joulemeter. The beam was splitted by using a quartz window, placed before the lens, in order to send a small fraction of the light pulse to a phodiode used as both trigger and total energy monitor.

The streamer signal was picked-up on a $10\,\mathrm{k}\Omega$ resistor after a 680 pF capacitor, without the need of any amplification. A current amplifier was used for the signal coming from the proportional tube. It provided an output of 34 mV signal on a $50\,\Omega$ resistor for each μA of current in input. The linearity of the response of such amplifier was checked in the region of the measured signals and is shown in Fig.3.

A He 70% - isobutane 30% gas mixture was used. This allowed us to have a streamer signal with similar properties of the MACRO tubes. For a cosmic ray induced signal, we had a charge of $\sim$ 100-200 pC and a signal width (at 10% of the amplitude) of $\sim$150 ns, while the single counting rate plateau region (4100-4500 volt) was also very similar. Therefore the results obtained in this work could be directly applied in the search for highly ionizing particles (e.g. fast magnetic monopoles) with the MACRO detector.

The signals were analyzed using a digital Textronix TDS 620A oscilloscope with a sampling frequency of 500 MHz.

Particular care was taken in screening of detector and the electronics from the large electromagnetic noise produced by the discharge in the laser cavity.

4 The proportional tube response

As mentioned before, for the proportional tube we used a $30\,\mu$m diameter wire, in order to collect a larger amount of electrons and produce a larger signal. The response of such a tube to cosmic rays and laser radiation was studied at different values of the anode voltage ranging from 800 V to 2800 V.

In Fig.4 the pulse charge is shown as a function of the anode voltage for cosmic rays and for laser induced signals. Several curves are shown corresponding to different values of the laser intensity. In taking these data a transition from the proportional to the streamer regime was observed at higher voltages for a given laser intensity. This was also observed in a previous work using different gas mixtures and a nitrogen laser [6]. For the purpose of this work only the proportional signals where taken into account. The data have been taken in several intervals of HV, depending on the ionizing power of the laser. In particular, for each value of the laser energy density, the upper HV limit was fixed by the transition to the streamer regime (and the non linear response of the current amplifier for large input currents) while measurements at lowest HV were limited by the electromagnetic noise induced by the discharge in the laser cavity.

The evidence that all these curves, but the last two, are parallel (within the experimental errors) to the one obtained with cosmic rays is a check that the detector response is still proportional, in the proper HV range, to the primary ionization at least up to an energy density of $\sim 1\,\mathrm{mJ/mm^2}$. Therefore, up to this value of the energy density, we can correctly measure the primary ionization in m.i.p. by normalizing, at a given HV, each of the iso-density curves to the one obtained with cosmic rays.

The results of such procedure is shown in Fig.5, where the primary ionization (in m.i.p.'s) is given as a function of the laser energy density. Superimposed is another data set obtained, with the same method, after a re-filling of the chamber and a re-arrangement of the optics. The small difference in between the behaviours of the two data sets is a check for all systematic effects to be under control.

The behaviour of these data is such that the primary ionization produced by the laser is almost linear with the energy density, in the range under investigation. In particular the data are well fitted by a power law with an exponent of (1.13±0.06) [1].

A comparison of these data with our theroretical predictions can give us some very rough estimates of the parameters of the ionization process. Because of $\tau_L \simeq 10-20\,\mathrm{ns}$, we expect τ_L/τ_ϵ to be in the range of values shown in Fig.1 [3]. Therefore we can expect that we are in a situation in which $(\sigma_\epsilon + \sigma_I^*)\rho_\gamma \sim 10^{2\pm1}$ and $\xi \sim 10^{3\pm1}$, when the energy density is $\sim 10^2\,\mu\mathrm{J/mm^2}$. This means that

$$\begin{array}{lll} \sigma_\epsilon & \sim 10^{-14\pm1}\,cm^2 & \\ \sigma_I^* & \sim 10^{-17\pm2}\,cm^2 & \\ n & \sim 10^{7\pm2}\,cm^{-3} & \Rightarrow \quad \epsilon \sim 10^{-12\pm2} \end{array} \qquad (9)$$

which are compatible with previous works. In fact, excitation cross sections as large as $10^{-13}\,\mathrm{cm^2}$ have been reported for $\lambda \simeq 308\,\mathrm{nm}$ [2], while impurity concentrations, ϵ, as small as 10^{-15} have been shown to give detectable signals [8].

5 The streamer tube response

The streamer properties were studied as a function of the laser intensity, using the proportional tube response as a measure of the primary ionization produced in the sensitive volume. The high voltage at the anode wire of the streamer tube was set at 4200 V.

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[1] We fitted the data for energy densities greater than $5\,\mu\mathrm{J/mm^2}$. This was done because the e.m. background, induced by the discharge in the laser cavity, could affect the low energy density data.

A logarithmic dependence of the streamer charge on the ionizing power was measured. For laser pulses which produced an ionization as large as ~ 500 m.i.p., a streamer charge of about 5 times the cosmic ray induced charge was observed (see Fig.6). Such a result is in agreement with a previous work [1] in which the ionization was produced by the passage of high Z ions throught the sensitive volume.

This is of great importance for the identification of strongly ionizing particles like heavy ions or fast magnetic monopoles with this kind of detector [5].

It has to be noticed that, for large laser intensities, the pulses lost their triangular shape by showing a number of structures and peaks. This suggests that, for large primary ionizations, the formation of the avalanche might significantly change.

6 Discussion and conclusions

In this work we reported the results of a study of the response of He filled streamer tubes to large primary ionizations.

Ionizations as large as hundreds of m.i.p. were obtained by using an intense XeCl pulsed laser. The link between the energy density of the laser spot impinging the detector and the primary ionization was obtained by using a gas chamber operating in the proportional regime. A simple phenomenological model of the ionization process is in agreement with the observed behaviour of the proportional tube.

A logarithmic dependence of the streamer charge was obtained as a function of the primary ionization. This is in agreement with a previous work in which heavy ion beams were used for this purpose and allows the use of streamer tube in the search for heavily ioniziong particles like fast grand unified magnetic monopoles.

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References

[1] G. Battistoni et al., Nucl. Instr. & Meth. in Phys. Res., **A270**, 185 (1988)

[2] H.J Hilke, Nucl. Instr. & Meth. in Phys. Res., **A252**, 169, (1986)

[3] E.M. Gushchin, A.N. Lebedev and S.V. Somov, Nucl. Instr. & Meth., **228**, 94, (1984)

[4] A. Bamberger et al., Nucl. Instr. & Meth. in Phys. Res., **A251**, 67, (1986)

[5] M. Ambrosio et al., Astroparticle Phys., **4**, 33 (1995)

[6] W. Ji-Gang et al., Nucl. Instr. & Meth. in Phys. Res., **A267**, 396, (1988)

[7] J. Bourotte and B. Sadoulet, Nucl. Instr. & Meth., **173**, 463, (1980)

[8] M. De Salvo and R. De Salvo, Nucl. Instr. & Meth., **201**, 357, (1982)

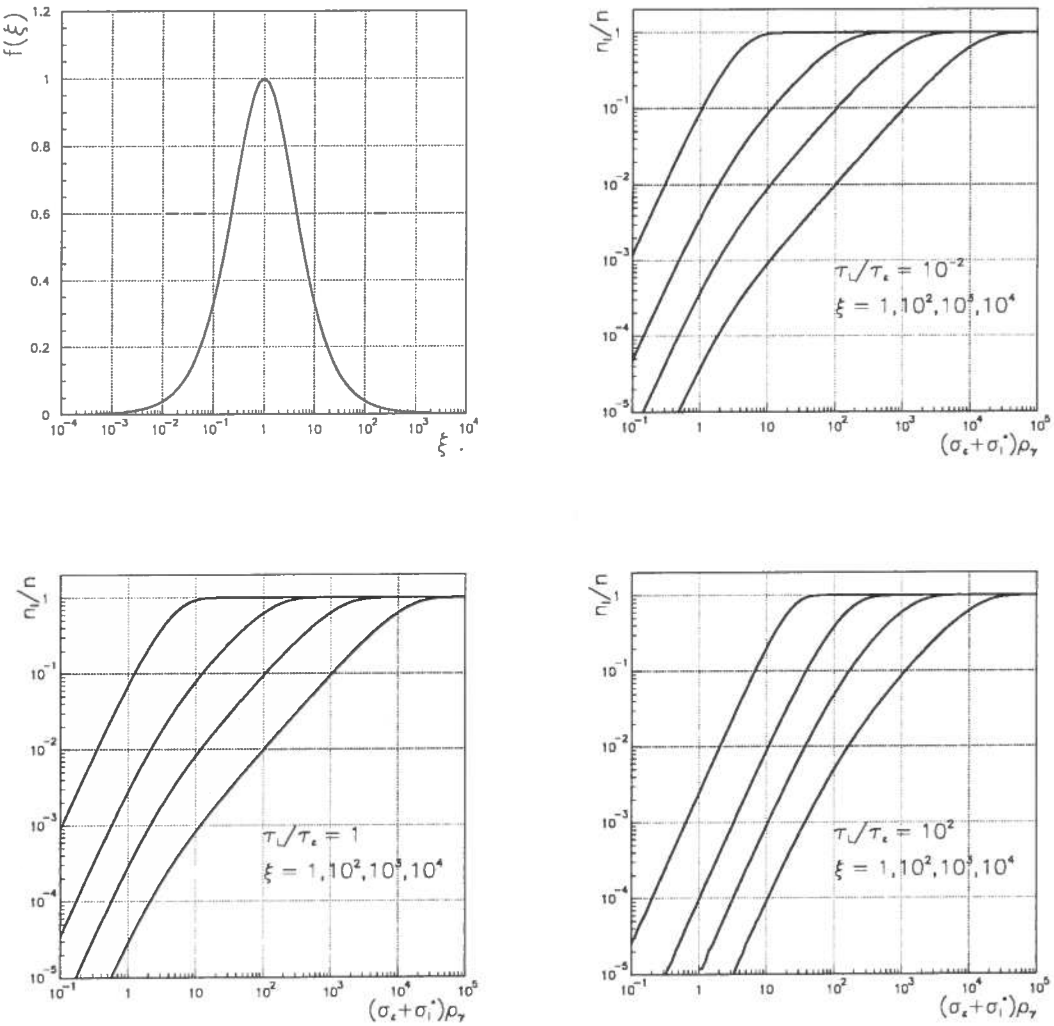

Figure 1: Theoretical predictions as given in Par.2. In (a) the behaviour of $f(\xi)$ as a function of ξ is reported. In (b),(c) and (d) n_I/n is shown as a function of $(\sigma_\epsilon + \sigma_I^*)\rho_\gamma$ for a variety of values of τ_L/τ_ϵ and ξ. The linear and quadratic behaviours are clearly visible before the complete saturation.

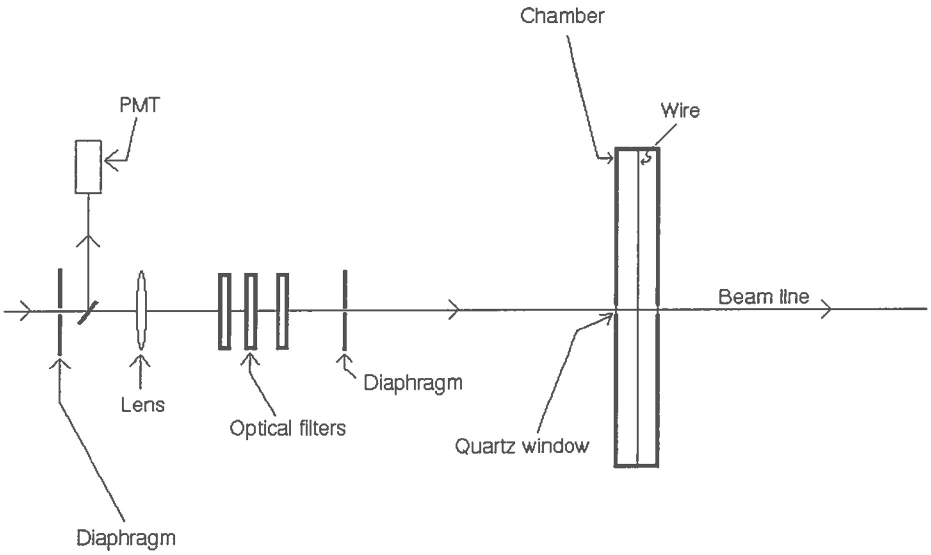

Figure 2: The experimental setup.

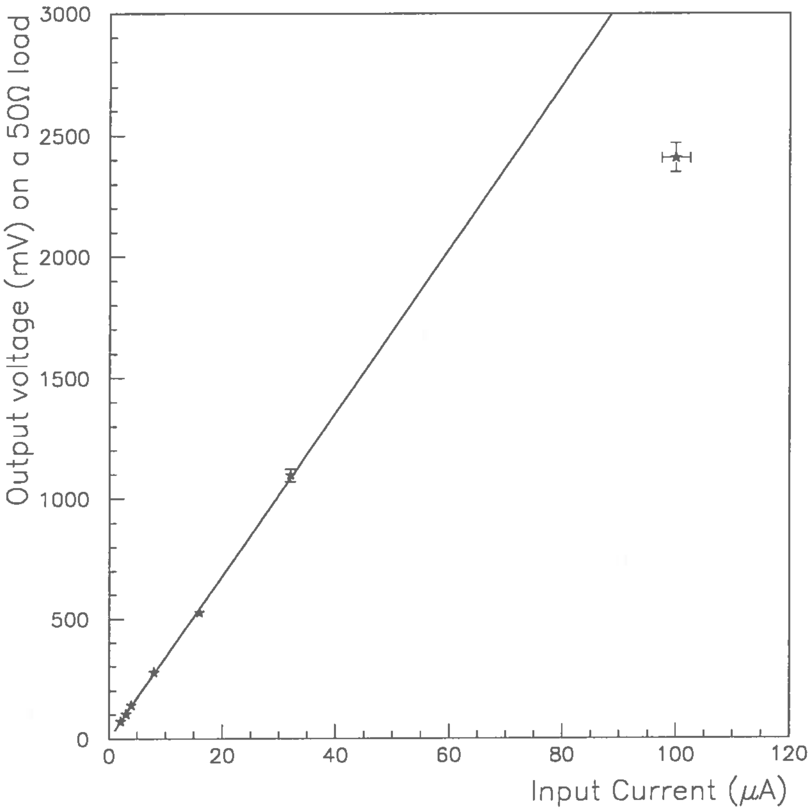

Figure 3: Calibration curve of the current amplifier used for the signal coming from the proportional tube. This device saturates the amplitude of the output signal at about 2V/50 Ω.

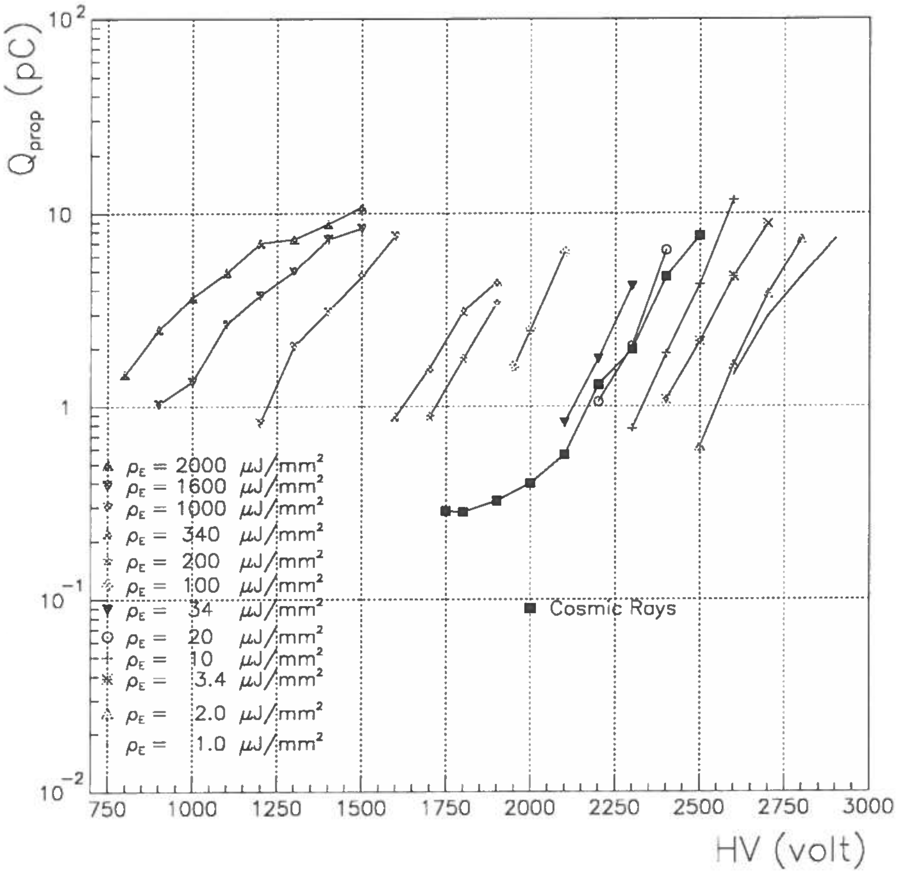

Figure 4: Pulse charge of the proportional tube as a function of HV for several laser intensities. The charge produced by cosmic rays is also shown (see text).

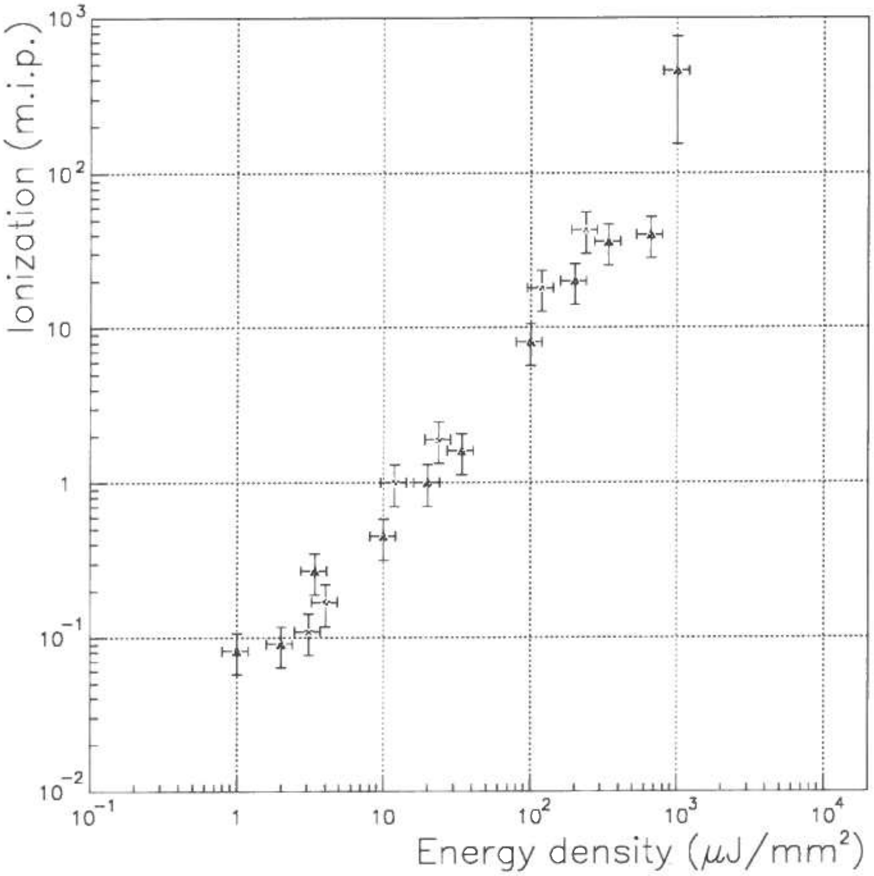

Figure 5: Ionization produced in the sensitive volume as a function of the energy density of the laser pulse. The stars and the triangles refers to two different data sets (see text).

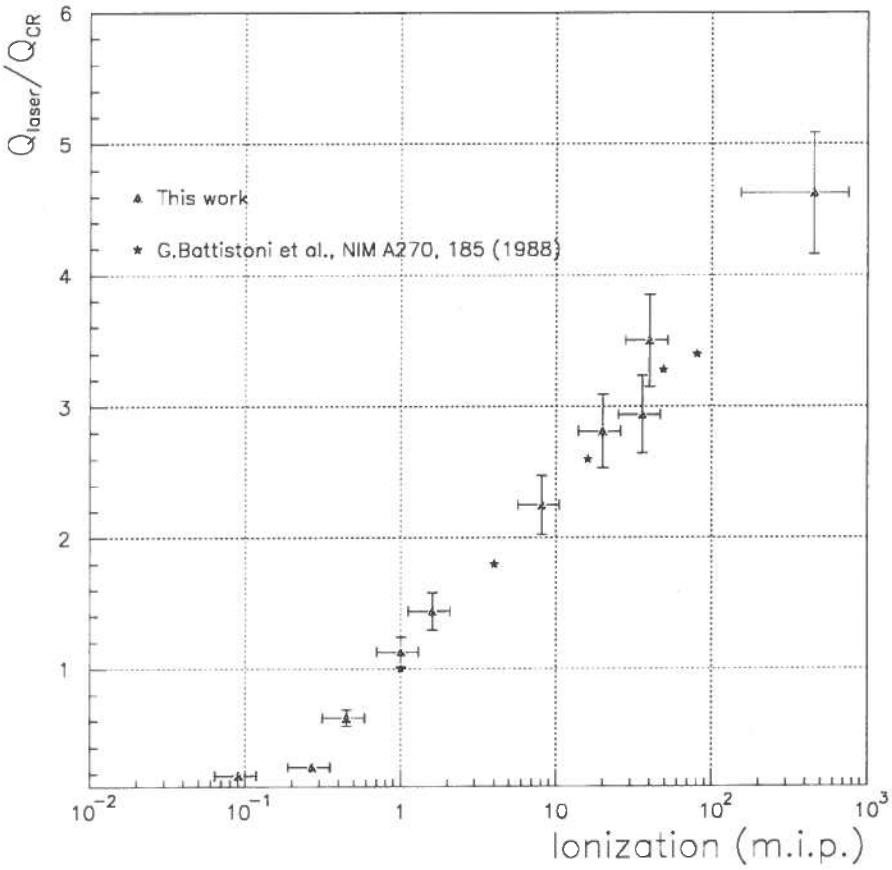

Figure 6: Streamer tube charge, HV=4200 V, divided by the charge produced by a cosmic ray, as a function of the primary ionization as measured by the proportional tube. Also shown, without the error bars, are the data obtained with high Z ion beams in [1].