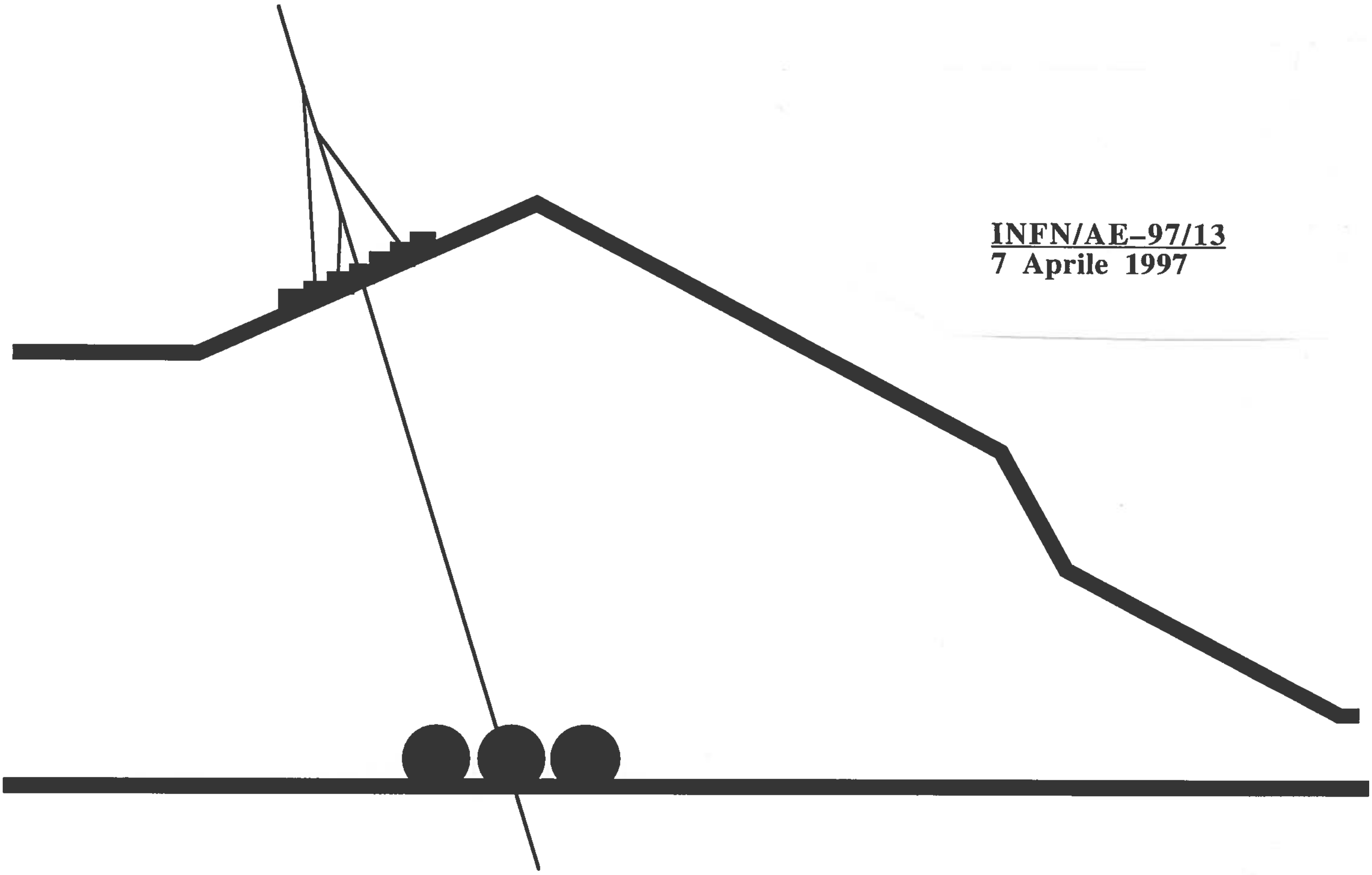

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Systematic study of the features of the streamer discharge by means of pulse shape analysis

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Abstract

Several measurements were performed with a streamer tube on a muon beam in different geometric and operational configurations. The use of a wave form digitizer in recording streamer pulses produced by minimum ionizing particles allowed the discrimination between single and multiple streamer discharges. The rate of occurrence of multi-streamer pulses as a function of different parameters has been measured. Also, the dependence of charge and pulse shape on the angle of the track with respect to the wire were studied. The analysis of pulse shape can be used to improve the comprehension of the phenomenology of the streamer discharge, putting constraints on the existing models.

1 Introduction

Gaseous detectors operated in the streamer mode are now in operation since many years[1]. However, a full understanding of the development of streamer multiplication has not yet been achieved. In order to help the phenomenological study of this process, more data, taken under well controlled conditions, concerning some distinctive features of the streamer discharge, can be useful in this respect. In particular, the study of the shape of the current pulse can give information on the radial distribution of space charge along the streamer. In this respect, it is interesting to investigate deviations from the typical triangular shape of single streamers, since these might be connected to more complex phenomena, as multiple radial elongations already reported in the literature[2]. Furthermore, a detailed knowledge of the spatial extension of the region of wire inhibited for further discharges by the streamer itself (dead region), is also useful for that, since it surely depends on the space charge distribution of the streamer.

The aim of this work is to measure the dependence of the streamer properties (e.g. pulse shape, charge, multiplicity, etc.) in a streamer tube device, as a function of different parameters. This was done on a beam in order to have a good track definition and well controlled conditions. In particular, measurements were done at different values of the anode to cathode voltage, for different gas mixture compositions and different angle of incidence of the track with respect to the wire. In order to have information on pulse shape, we used a 80 MHz waveform digitizer. Such a study is also important for practical applications, since the knowledge of the streamer tube response as a function of the angle between the particle track and the anode wire is found to be of relevance in the analysis performed by underground experiments for the search for fast moving magnetic monopoles using the streamer tube system[3]; furthermore, it is of substantial importance for all calorimetric applications of streamer tubes[4].

The experimental setup is described in section 2, while in section 3 we describe the identification and measurement of the parameters of the pulse shape, leading to the separation between single and multiple streamer pulses. In section 4 we summarize the properties of selected single streamer pulses and in section 5 we show the results concerning the dead region along the anode wire, having selected single streamer pulses. In section 6 we suggest, on the basis of the present data, a simple phenomenological description of the mechanism of pulse generation, with the aim to achieve a better understanding of streamer development.

2 The experimental setup

We have used 20 cm long streamer chambers with the same geometrical parameters as the ones used in the MACRO experiment[5]: 3×3 cm^2 cell size and Be-Cu anode wire with 100 μm of diameter.

The chambers were placed on the H8 beam extracted from CERN SPS, parasiting the test of the e.m. calorimeter of the ATLAS collaboration[6]. The equipment were placed downstream a beam dump, in order to select the muons contaminating the electron beam. Muon energy ranged from 100 GeV to 200 GeV. As can be seen in Fig. 1, the streamer chamber could be tilted with respect to the beam direction in order to allow measurements at different angles of incidence.

The trigger was provided by a fast coincidence of two plastic scintillators with an overlapping area of about 1 cm^2. A 80 MHz wave form digitizer was used to record the streamer pulse shape, charge and timing. Charge and time measurements were also independently performed by an ADC and a TDC. Both the WFD and the ADC response were calibrated and residual non linearity in the range of interest turned out to be less than 1% (see Fig. 2).

As gas mixtures we used argon + isobutane with different ratios: 50% − 50%, 60% − 40%, 70% − 30% and 75% − 25%. Those ratios, as established using the nominal calibration of massive flux meters, are directly connected to the time width of the current pulses of single streamer discharges. This width varies inversely with the fraction of quenching component[7]. We obtain widths ranging from about 100 ns for the nominal 50% of isobutane, to 400 ns for the nominal 25%. According to the simple phenomenological considerations about streamer discharge, reported in section 5, the different widths correspond to different radial extensions of the streamer process. For each of the quoted gas mixtures, we have collected a few thousands of events.

3 Analysis of the current pulse shape

The use of a wave form digitizer allowed us to select different classes of pulses and better understand the properties of the streamer itself. An example of the typical simplest shape, as obtained for muons crossing the chamber perpendicularly to the anode wire, is given in Fig. 3 (after the baseline subtraction), as detected for the gas mixture giving a base width of about 200 ns (argon 60%–isobutane 40%) at the operation point just above the knee of the singles rate plateau, which for this gas mixture corresponds to 4100 kV. As shown in the literature of streamer tubes, this operation point corresponds to the region where full transition from proportional to streamer discharge reaches about 100% of probability. This also correspond to full detection efficiency for fixed discrimination threshold. For each gas mixture we have determined the corresponding knee voltage and we have verified the detection efficiency on the beam with respect to the trigger counters. Unless differently stated, for each gas mixture we shall consider only high voltage values above such a knee.

We associate the typical shape of Fig. 3 to the occurrence a single streamer pulse. It appears extremely close to a triangular shape, but for the residual integrations due to the bandwidth of the equipment. We are therefore lead to the hypothesis that the streamer current pulse can be approximated by:

$$i(T) = I_0 \left[\left(1 - \frac{T}{T_{max}}\right) - \left(1 - \frac{T}{T_{max}}\right) \theta \left(T - T_{max}\right) \right] \qquad (1)$$

Where T_{max} is the base duration of the current pulse and I_0 is the peak current (I_0 ~1 mA at the operation point corresponding to the knee of the singles rate plateau). Of course, such an hypothesis neglects possible substructures whose time scale is smaller than the resolution of our waveform digitizer. In this approximation the front edge has zero rise time. In actual measurements that is a parameter of difficult evaluation, since it is dominated by the instrumental bandwidth. We know from the existing literature[8] that the development process can last only few ns, surely less than 5 ns, and maybe even less than 2 ns. However, longer rise times have been reported[9, 10], possibly depending on the gas mixture. A precise measurement of the rise time of the streamer pulse in different operation conditions would be extremely interesting, since its value depends on the mechanism of the sudden transition from the primary proportional avalanche to streamer. Our setup was not conceived for such a measurement, which will be the object of a future investigation.

However, a general expression for the resulting pulse shape $V(t)$ as measured across a resistance R, in the case in which the system introduces an integrating time constant τ, is given by:

$$\begin{aligned} V(t) = R I_0 \Bigg(1 - e^{-t/\tau} - \frac{1}{T_{max}} \times \\ \left[(t - \tau) + \tau e^{-t/\tau} \right] + \theta \left(t - T_{max}\right) \frac{1}{T_{max}} \left[(t - T_{max} - \tau) + \tau e^{-\frac{t - T_{max}}{\tau}} \right] \Bigg) \end{aligned} \qquad (2)$$

We have successfully applied eq.2 in fitting the observed pulse shape, leaving I_0, T_{max} and τ as free parameters. As already stated, for each gas mixture we have fitted the data taken at the operation voltage just above the knee of the singles rate plateau. For the typical pulse shape shown in Fig. 3, τ turns out to be practically a constant (of the order of 12 ns), thus reinforcing our belief that it is dominated by the integration of the electronic chain, and that the true rise time is indeed shorter. We also reproduce the known feature that I_0 is distributed closely to a gaussian with σ ~25–30%[1].

After the systematic application of the previous concepts to the fit of the pulse shape, we were able to observe a significative fraction of deviations from the typical shape of Fig. 3. However, these different shapes can be still grouped into distinct classes. A possible classification is proposed in the following, associating each class with some particular feature of the streamer multiplication.

1. "Double Streamer". It appears as the superposition of two distinct single pulses at different times, as the case of Fig. 4. We have to clarify at this point that the case of Fig. 4 is not a simple afterpulsing due to secondary electrons extracted from the cathode by photons emitted in the primary streamer multiplication.

For the geometry of our test tube and for the argon–isobutane gas mixtures, such afterpulses occur after about 600 ns from the first, primary, pulse. Here and in the following, we will consider only a time window of 500 ns, in order to reject real afterpulses. Coming back to the examination of Fig. 4, we have noticed that in most of the pulses belonging to this class, the second streamer has always a lower peak current. This suggest that the second streamer occurs at a distance along the wire not far from the location of the primary one, where the space charge effects are still not negligible.

2. A particular case is the "Double Contemporary Streamer", as shown in Fig. 5. This seems indistinguishable in shape from that of Fig. 3 but for the fact that the peak current is at least twice as that of the single streamer. This shape can be explained by the simultaneous occurrence of more than one streamer. There is a natural explanation of this occurrence for tracks at angle with respect to the wire, as reported later.

3. The "Double Slope Streamer", as that of Fig. 6. It looks like as the superposition of at least two triangles with different T_{max} values, or as a particular case of double streamer. We shall justify that as the possible simultaneous occurrence of at least two streamer discharges having different radial extensions from the wire, or the occurrence of a bifurcation of a first streamer development. Experimental evidence of the existence of such multiplications is given in [2]

4. "Multiple Streamer", as the example of Fig. 7, which are presumably given by the occurrence of many streamers at different times (part of them being also almost simultaneous).

By looking at the first and second derivative of the signal we were able to identify the various structures of the pulse. In particular, we could clearly distinguish single streamer pulses from multiple ones. This allowed us to measure the fraction of different classes, for a given gas mixture. We have performed a preliminary evaluation of the evolution of the fraction of the different classes of pulses as a function of high voltage, by means of visual scanning. We find that the fraction of multiple streamer pulses increases as a function of high voltage, with a correspondent decrease of single streamer pulses. We interpret this behaviour as an increase of probability that some photon escaping the multiplication region will initiate a new avalanche, nearby the primary streamer, which then develops in a new streamer. Such probability increases because the electric field near the wire increases, and the threshold value (see Section 5) can be easier achieved. This will be rediscussed later, showing the results of a search using an automatic pattern recognition algorithm.

Not only the fraction of multiple streamers increases, but also their complexity. This can be seen in Fig. 8, where the average number of distinct peaks in samples taken with different gas mixtures, is plotted as a function of high voltage.

4 Properties of Single Streamer Pulses

In this section we report the results of the study of the characteristics of single streamer pulses produced by muons crossing the chamber perpendicularly to the anode wire. This selection should allow a better understanding of the basic process. An automatic pattern recognition algorithm, based on the mentioned analysis of the first and second time–derivative of the pulse shape has been implemented for this purpose. Several gas mixtures were analysed for that purpose at different values of the high voltage ranging from a couple of hundreds volt before the knee of the efficiency curve up to the end of the plateau region.

In Figs. 9,10,11 we report the values of the total charge, of the amplitude of single streamers, together with its width at 10% of the amplitude, as a function of the anode voltage for all the four gas mixtures we used. From these plots we can see the exponential rise of the charge and the amplitude as a function of the High Voltage, while the width is only weakly increasing with this parameter. According to our preferred interpretation (see Sec. 5), this means that the time development of the streamer is essentially saturated and weakly dependent on the electric field strength in the cell. Also, the larger is the quencher fraction, the smaller are the time width and the total charge of the pulses.

Is is interesting to note that the increase of charge of single streamer pulses is dominated by the increase of peak current I_0, while the increase of the time duration at the base of the triangle is slowly changing. This can be seen in Fig. 12, where we plot the angle at the vertex of the triangular shape as a function of high voltage; data from different gas mixtures have been superimposed. The angle decreases as high voltage increases, *i.e.* the increase of charge can be obtained only by a faster increase of I_0 with respect to T_{max}. The base duration is not exactly constant, as can be seen in Fig. 11. According to the first order model that we discuss in Section 5, T_{max} is proportional to the radial elongation of the streamer and the present data imply that, for a given gas mixture, the radial elongation is almost constant for increasing electric field, while the charge density in the streamer has a more pronounced variation.

In Fig. 13 the fraction of single streamer pulses is shown to be smaller for higher values of the high voltage and for a smaller quantity of quencher in the gas mixtures. From that figure we can also see that this fraction is a universal function of the streamer charge, whatever the High Voltage and the gas composition are. We can also mention that the fraction of multiple, complex-shaped, streamer increases with high voltage, in a complementary way to that of single streamers, while the relative amount of double streamers is practically constant.

5 The Dead Region Along the Wire

For all the gas mixtures and at several values of the High Voltage, we measured the single streamer properties for different angles between the direction of the beam and that of the anode wire. This allows in principle a study of some space charge effects of the streamer multiplication. In fact we expect that the occurrence of one streamer multiplication will make a region of the wire unable to develop a new discharge for some time. Now, in case one has a track at some angle with respect to the wire, we expect that many streamers, at close times, are generated along the track projection along the wire L_p. The number of such streamers should be dominated by a sort of quantization depending on the extension of the dead region along the wire. Also, a departure from single streamer is expected only when L_p exceeds such a dead region. In principle, assuming the first order model proposed in Section 5, where the streamer multiplication is conceived to be composed by a rather uniform column of ion pairs, the extension of the dead region could be calculated, but this goes beyond the aim of the present paper.

To perform the proposed study we have defined L_p as the track–length in the sensitive volume projected along the direction of the wire. We assume the number of produced streamers to be proportional to the total charge in the pulse. Thus a larger charge pulse is expected for increasing L_p. The value of the charge as a function of L_p is shown in Fig. 14 for a given gas mixture and a couple of values of High Voltage.

Two different regions can be easily seen. In the first one, for $L_p \lesssim 1$ cm, the charge is shown to be constant: this is the so called *dead zone*. In this zone space charge effects due to the presence of the first streamer prevent the development of a second avalanche, thus forcing the charge to be constant. The second region is characterized by a linear increase of the charge with L_p. Here multi-streamer formation produces pulses with larger values of the charge.

It is important to stress that we did not observe any saturation of the charge at large values of L_p, even when the charge at L_p=0 is large (for instance when the anode voltage is large), that is under operation conditions such that a wide dead zone is expected.

In the same figure the slope S of the linear rise region is reported as a function of the value of the charge $Q_\circ$ at $L_p = 0$ for several gas composition and High Voltage. Both variables are normalized at their values at the knee of this curve. All the points lie on the same curve and are also in agreement with MACRO data[3] (obtained with a helium(73%)/n-pentane(27%) gas mixtures). This "universal" behaviour allows a parametrization of the streamer charge response as a function of $Q_\circ$ for different geometrical configurations. This can be exploited to discriminate between e.g. muons and heavily ionizing particles also for slanted tracks [11].

6 Suggestions for a Phenomenological Model of the Streamer Discharge

A fully quantitative model of the streamer development, at present, does not exist, at least in the case of non uniform electric fields. Some models have been developed in the past, limited to the case of a uniform external field[12]. More recent attempts can be found in ref.[9, 13, 14, 15]. We signal in particular the work of Gallimberti concerning spark development[16]. Most of the attention has been devoted so far to give a quantitative description of the sudden transition mechanism from the primary proportional avalanche to the streamer. Here instead, we intend to make use of the information coming from the observed pulse shape, in order to give some hints and constraints to models describing the distribution of charge and of the relevant electric field along the streamer. This of course refers to the situation in which the streamer has already completed its longitudinal development, but we think that such information can be useful as well for the models of the transition mechanism.

Let us start in any case to summarize the basic qualitative concepts of the streamer development. The general idea is the following: electrons extracted in the gas after some ionization process are accelerated by an external field $\vec{E}_0$ (in our case by the field generated by the wire at a given potential with respect to the cathode). As soon as these electrons gain enough energy to ionize themselves other atoms of the gas, a multiplication process develops (also called avalanche). Thinking to the case of a wire device, this stage, for the moment, fully corresponds to the development of a typical proportional discharge. This kind of avalanche is made of both electrons and positive ions drifting in opposite directions along the external field lines. Electrons have a much higher mobility with respect to ions, so that the two charge carriers are quickly separated. A relatively small displacement of the electron cloud with respect to the ions is sufficient to give rise to a dipolar field, $\vec{E}_d$. In Fig. 15 we pictorially describe such an evolution in the case of a uniform external field. In the region where electrons and positive ions are closely distributed, the local space charge shields the external field, and recombination phenomena occur. This is of particular relevance when the multiplication in the avalanche is very high, typically when more than a few 10^8 pairs have been produced. In these conditions, $|\vec{E}_d| \sim |\vec{E}_0|$ in the space region inside the avalanche. During recombination many UV photons are emitted, practically with an isotropic angular distribution. In the case of the $1/r$ field generated by a wire, we expect that the region of the avalanche far from the wire will be the one from which most of the photons are emitted.

These photons will photo-ionize other atoms of the gas mixture, so that other electrons can initiate a multiplication process. We have to notice how the simplest photoionization mechanisms cannot account for the observed phenomenology[15, 17, 18]. Now, the dipolar field produced by the electron-ion separation tends to enhance the external field in the direction of the axis of the primary avalanche, while, on the lateral sides, gives rise to a depletion effect. Therefore, as soon as the dipolar field is enough intense, the multiplication is favoured along the axis of the primary avalanche, while it is depressed in the space region around. Only the avalanches aligned with the direction of the primary multiplication, and near to the tips of it, have a chance to develop. These secondary avalanches merges with the primary one, giving rise to a propagating stream of ionized plasma: the "streamer".

The same field configuration prevents, at first order, the development of discharges all around the main streamer, thus originating the space limitation along the wire direction. However, as we have shown before, we expect that for increasing electric field, the probability of having secondary streamers near the first one increases (production of multi–streamers)

Let us use, for a numerical example, the case of wire devices. For an operating voltage of a few kV, at 0.5 mm from the wire the applied field reaches, typically, an intensity of the order of $\vec{E}_0$ ~15 kV/cm. If we naively approximate the field inside a sub-avalanche as that given by two opposite charges (representing respectively the centers of gravity of the electron and of the positive ion clouds) whose relative distance is of the order of 0.2 mm, then inside the droplet a counter-field of the same order of $|\vec{E}_0|$ is reached if the multiplication factor is of the order of 10^7. Historically, this was the consideration which brought to the so called "Raether's condition", which establishes that a multiplication process turns out in a breakdown when $\alpha \cdot x \sim 20$, where x is the longitudinal size of the avalanche and α is the First Townsend Coefficient (the inverse of the mean free path for an electron to produce one electron-ion pair; for a given gas mixture it is a function of the electric field intensity and of the pressure, usually in the "reduced" form $E(x)/p$[8].

The existence of a threshold behaviour can be evidentiated by the measurement of the multiplication factor as a function of high voltage (or electric field), for a given detector and gas mixture. As shown by many authors, after an almost saturated proportional regime, a new region appears where a new process develops, characterized by a sudden jump in the multiplication factor (see for instance ref.[19]). The region where the two curves are superposed one to the other has to be intended as a transition region in which a proportional avalanche has a non zero probability to turn into a streamer discharge. Such a probability increases with high voltage until eventually all discharges become streamer ones (full streamer efficiency). That corresponds to the region where a plateau in the singles counting rate is observed, for a given current threshold.

Now we have to notice how in a uniform external field the streamer shape must be almost symmetric, and must propagate in both directions with about the same speed, as was also verified by the experiments. This is clearly not the case for the wire fields. Here the primary avalanche is produced near or around the wire, and it already exhibits an asymmetric shape (pictorially a drop shape, due the diffusion process of the electrons as they drift). The only free way for the streamer to propagate is creating additional avalanches by photo-ionization in the direction from the wire to the cathode. The streamer process has to extinguish itself before reaching the cathode, otherwise a breakdown will occur (the plasma is a conductive medium: it will short circuit cathode and anode). The extinction is obtained in small part by the 1/r behaviour of the wire field, and by the UV photoabsorption by gas molecules. In fact, each new sub-avalanche initiated by a photo-ionization event will be located farther away from the wire than the previous one, therefore the accelerating field will be less and less intense, even considering the contribution of the additional dipolar field. However, this cannot be enough as a reduction factor, since the number of emitted UV photons is generally large and they may have a considerable mean free path. The extinction is therefore achieved making use of a gas component having consistent "quenching" properties. The most effective photo-absorbitive gases are those who can exhibit absorbtion bands, more than discrete levels[8]. This property is typical of complex molecules. Heavy hydrocarbons are among these. As an example, methane has an absorption continuum for wavelengths shorter than 145.0 nm, which usefully covers the energy of photons emitted by argon, whose principal emissions from the first excited states have a wavelength of 104.8 and 106.6 nm. This is the reason why a stable streamer mode has been observed in drift chambers: their gas mixture usually contains more quenching component than a mixture needed just for proportional operation. In fact, even if it is almost an accidental coincidence, complex molecules are also rich of roto-vibrational energy levels which contribute to the inelastic collisions of drifting electrons, thus allowing the possibility of reaching a saturated drift speed. According to the described mechanism we expect that the heavier the hydrocarbon, the higher will be the quenching capability and therefore the larger will be the operation stability.

The complete development of the streamer is a very fast process, of the order of very few nanoseconds, and this should correspond to the fast rise time of the streamer current pulse. This high speed is due to the fact that, as explained above, the necessary intensity of the dipolar field can be already reached when the electron cloud is slightly displaced with respect to the ions. Multiplication factors of the order of 10^8 or more can be easily reached, if we also consider the ion-electron pairs which are going to recombine. In these few nanoseconds, a stream of electrons extending from a few millimeters up to 1 cm, or more, according to the gas mixture, is ready to drift towards the cathode.

At this point the remaining part of the current pulse is generated, and here we focus our attention.

First, we remind how this situation is completely different to what is observed in the proportional discharge, where multiplication electrons are produced just in the region surrounding the wire. These differences bring to a substantially different pulse structure. The observed shape (triangular) strongly reminds the theoretical shape expected in ionization chambers with uniform electric field. The current pulse in any ionization detector in gas is determined by the displacement of charge carriers along the applied electric field. For any given charge-packet δQ moving with a drift speed v, at distance x from the sense electrode kept at potential V_0, simple energy conservation allows to write the expression for its current contribution:

$$\delta i(x) = \delta Q \cdot v \cdot \frac{|E(\vec{x})|}{V_0} \tag{3}$$

Such an expression, also known as Ramo's theorem[20], is valid whenever all radiative phenomena are negligible, or in other words, when the drift speed is much lower than the speed of light, as it is for electrons drifting in a gas. A part from energetic considerations, such an expression is also obtainable by a quasi-static description of the time variation of the induced charge on the sense wire as due to the charges drifting between anode and cathode. Both electrons and ions in principle contribute to the total current, however it is well known that $v^{-}_{drift} >> v^{+}_{drift}$, thanks to the mass difference. Therefore, whenever electrons have a chance to drift for a sufficiently long distance their contribution to the induced current is much larger than that of positive ions, for a similar external electric field. In particular, this does not happen in proportional devices, where multiplication electrons are so closely concentrated near the wire that in few nanoseconds they are completely collected, so that all the induced current is due to the motion of positive ions going away from the anode. In the case of streamer discharge instead, the plasma electrons are distributed almost uniformly along the streamer. The typical characteristic drift times of electrons in chamber gas mixtures is of the order of a few hundreds of nanoseconds/cm. Thus, since the streamer avalanche may extend itself for a radial length of the order of 1 cm, we are really in the condition in which the current from electrons is dominant with respect to that from positive ions, which in the following will be neglected.

Now, if we select the simplest class of streamer pulses, *i.e.* the single streamers, the observation of a triangular pulse shape can bring to some fundamental conclusions. In order to be more quantitative about the similarity to a triangle, we have measured the fluctuations of the time derivative of the trailing edge of the collected single streamer pulse. We find that such trailing edge is effectively described by a straight line, (namely having a constant derivative) with local deviation which do not exceed the 30% of the average derivative value. Therefore, this implies that at any distance from the wire, the following condition holds within 30% fluctuations:

$$\delta Q \cdot v \cdot |E(\vec{x})| \ \sim \ constant \tag{4}$$

although we expected a different behaviour in the region very close to the wire, where the intensity of the electric field rapidly increases. If we assume that the drift velocity of the electrons remains saturated around the typical value of 5 cm/μs, again within a 30% variation, then, in order to achieve the established condition, the space charge ρ along the streamer must be arranged in such a way to give, at any time:

$$\rho(x) \cdot |E(\vec{x})| \ \sim \ constant \tag{5}$$

So, if the streamer charge is Q_{total}, and the streamer length is h, neglecting the size of the wire radius, the total current at time T is given, similarly to what happens in ionization chambers for tracks crossing a full gap of extension h, by the expression:

$$i(T) = k\rho v \int_0^{l(T)} dX \tag{6}$$

where $\rho = Q/h$ is the linear charge density of the streamer electrons, having taken for $Q = \beta Q_{total}$ the charge actually participating to the drift, that is having considered only the charge fraction survived to the recombination processes; $k = |\vec{E}_{drift}|/V_0$ and $l(T)$ is the length of electrons stream moving at time T: $l(T) = h - vT$. This occurs up to $T_{max} = h/v$, which is the total time to drift along h. We arrive in this way to a triangular pulse shape, whose duration is proportional to the radial extension of the streamer discharge, as schematically plotted in Fig. 16. We stress that some recombination must occur even during the electron drift: this has to be considered in order to explain the observation of light at the same time and for the same duration as that of the current pulse [10, 9]. Another source of photons might come from energetic electron collisions[17]. We can define an effective charge participating to the current production, as $Q_{eff} = T_{max}\, k\beta\, Q_{total}\, v$. The effective time duration of the pulse has been demonstrated to depend on the fraction of quenching component[1]: the lower is that fraction, the larger will be the radial extension of the streamer, and consequently larger will be the time duration of the current pulse, in agreement with our simple model. Of course, we cannot expect that v or $|\vec{E}_{drift}|/V_0$ can be really constant along the whole drift, so that deviations from the perfect triangular shape must be observed. Furthermore, we may expect that the electrons complete their drift towards the wire moving in packets, introducing some discontinuity. This could explain some irregularities sometimes visible in the trailing edge of the triangular pulse. Also, we must not forget that there is also a small additive contribution, of the same sign, given by the drift of positive ions towards the cathode. Such a contribution will have a time shape very close to that calculable for proportional devices ($\sim 1/t$)[21].

The calculation of the k coefficient is hard, but we can estimate it making a numerical example close to the case of the streamer tubes of the MACRO experiment[3]. Let us assume a multiplication factor of 10^8, where the total ionization is made of 100 electron-ion pairs. Assuming also that only a fraction β of pairs survives after recombination in the streamer process, the final streamer charge will thus be $Q = \beta$ 1.6 nC. The typical drift speed is $v = 5$ cm/μs, and a reasonable radial extension of the streamer is $h = 0.5$ cm. Then $T_{max} = 100$ ns, and this will be the time duration (the base of the triangular pulse). The peak current will be $i_{peak} = k\beta\, Q\, v$. The experimental observation is that, for V_0 not too high (just after the "knee" of the efficiency plateau, see section 3), $i_{peak} \sim 1$ mA, so we obtain that $k\beta \sim 0.125$ cm^{-1}. The area under the pulse shape (electrode charge collected by the anode) is given by

$$Q_C^- = \frac{k\beta Q v T_{max}}{2} \tag{7}$$

and in our simplified numerical example we get $Q_C \sim 50$ pC. At long times (for instance when considering the average DC current drawn by an operating device) also the positive ion contribution of the same order of magnitude has to be added; a typical value for the DC current per unit counting rate is ~ 0.2 nA/Hz.

When, for a given gas mixture, the operating V_0 is increased, Q increases (although with a mush slower rate than in proportional mode), and the peak current has to change accordingly. We have not yet a detailed model to understand the dependence of $k\beta$ with V_0. We can also expect changes in h and v. The overall effect can be learned by the experience. For the moment we can state that when changing for instance gas mixture (corresponding to a change in both h and Q), if an operation voltage V_0 is chosen maintaining the same difference with respect to V_0^{thres}, then the product $k\beta$ assumes an almost universal value. Therefore, in these conditions, Q/T_{max} (*i.e.* the peak current) has to be a constant, and this seems to be almost true. The data shown here (See Figs. 9,10, 11 and 12) seem to point out that the increase of T_{max} as a function of high voltage is slower than that of the peak current.

In other cases we can expect to have the simultaneous occurrence of more than one streamer discharge, emerging from the same primary avalanche as reported in ref.[2]. As observed in this last quoted reference, the probability of this "bifurcation" to occur should depend on primary ionization, since we expect that the different streamer elongations would depart from distinct asymmetries in the primary avalanches. Such asymmetries can be originated, for instance, by the arrival of different clusters of secondary electrons. Such a shape has been effectively observed in streamer tubes. We find it more probable in particular conditions, such as the operation at a very high voltage, when the multi- streamer occurrence has a high probability. The two (or more) simultaneous streamer discharges may have different elongations and total charge due to local space-charge effects. If, for example, we have two streamer elongations, 1 and 2, characterized respectively by Q_1, h_1 and Q_2, h_2, our simple model predicts a composite current pulse shape having two distinct slopes for h_1 different from h_2 (Fig. 17).

7 Conclusions

We have analysed the shape of the current pulses from limited streamer tubes in different and controlled conditions. We have identified different classes of pulses, but all of them can be interpreted in terms of a basic shape: that of the single streamer pulse. It exhibits a characteristic triangular shape. On the basis of the present knowledge of the streamer mechanism, and following a similarity with the pulse generation mechanism of ionization chambers, we have been able to establish a quantitative relation between the drift velocity, space charge density and the resulting electric field inside a fully developed streamer discharge. Such a relation has to be considered by the models aiming to a quantitative description of the streamer generation and development.

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Figure Captions

Fig. 1 The experimental setup: the angle between the beam and the wire is also shown.

Fig. 2 Calibrations of the ADC and of the WFD.

Fig. 3 Typical single streamer pulse.

Fig. 4 Example of double streamer pulse.

Fig. 5 Example of pulse from two simultaneous single streamers.

Fig. 6 Example of streamer pulse with at least two different distinct slopes in the trailing edge.

Fig. 7 Example of multiple streamer pulse.

Fig. 8 Average number of distinct peaks in the pulse shape as a function of high voltage.

Fig. 9 Total charge of single streamers as a function of High Voltage. Only muon trajectories perpendicular to the wire are considered.

Fig. 10 Amplitude of single streamers as a function of High Voltage. Only muon trajectories perpendicular to the wire are considered.

Fig. 11 Pulse width of single streamers as a function of High Voltage. Only muon trajectories perpendicular to the wire are considered.

Fig. 12 Angle at the vertex of the triangular shape of selected streamer pulses as a function of high voltage. Only muon trajectories perpendicular to the wire are considered. The points relative to the gas mixture argon 75%–isobutane %25 seem to deviate from a general behaviour, but in that case the operation plateau of the streamer tube was much narrower than the other ones (only ~150 V wide), resulting in a more difficult establishment of an operation point comparable to that of the other cases.

Fig. 13 Fraction of single streamers as a function of pulse charge (above) and High Voltage (below). Only muon trajectories perpendicular to the wire are considered. As far as the irregularity exhibited for the case of the gas mixture argon 75%–isobutane %25 is concerned, see the comment to Fig. 12.

Fig. 14 Dependence of streamer charge on the muon pathlenght projected along the direction of the wire for a couple of High Voltage values (above). In the figure below, the slope of the linear part of this plot is reported as a function of the normal incidence charge in the figure. Data obtained from the streamer tubes of the MACRO experiment[3] are superimposed.

Fig. 15 Schematic development of the streamer discharge: a) electron-ion pair creation, b) growth of proportional avalanche, c) radiation of recombination photons, d) new avalanches develop, e) the avalanches grow and merge into a single streamer.

Fig. 16 The streamer current pulse according to the simplified model described in the text.

Fig. 17 Current pulse shape in the case of the simultaneous occurrence of two different streamers.

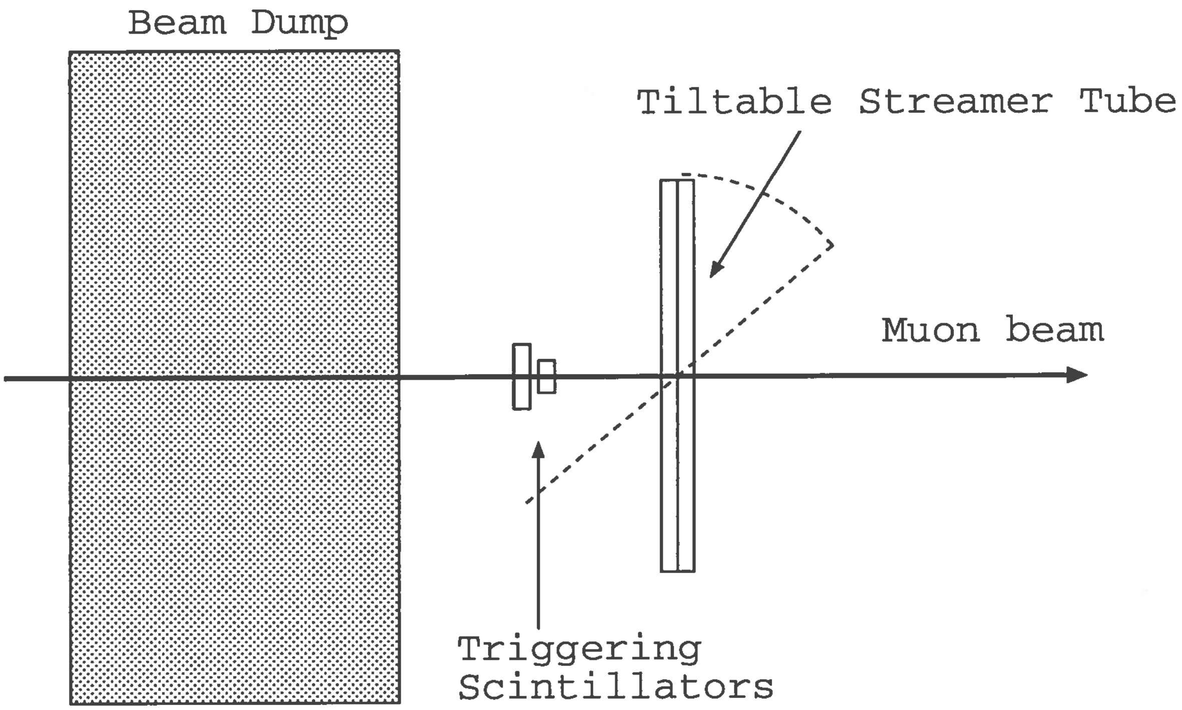

Beam Dump
Tiltable Streamer Tube
Muon beam
Triggering Scintillators

Figure 1:

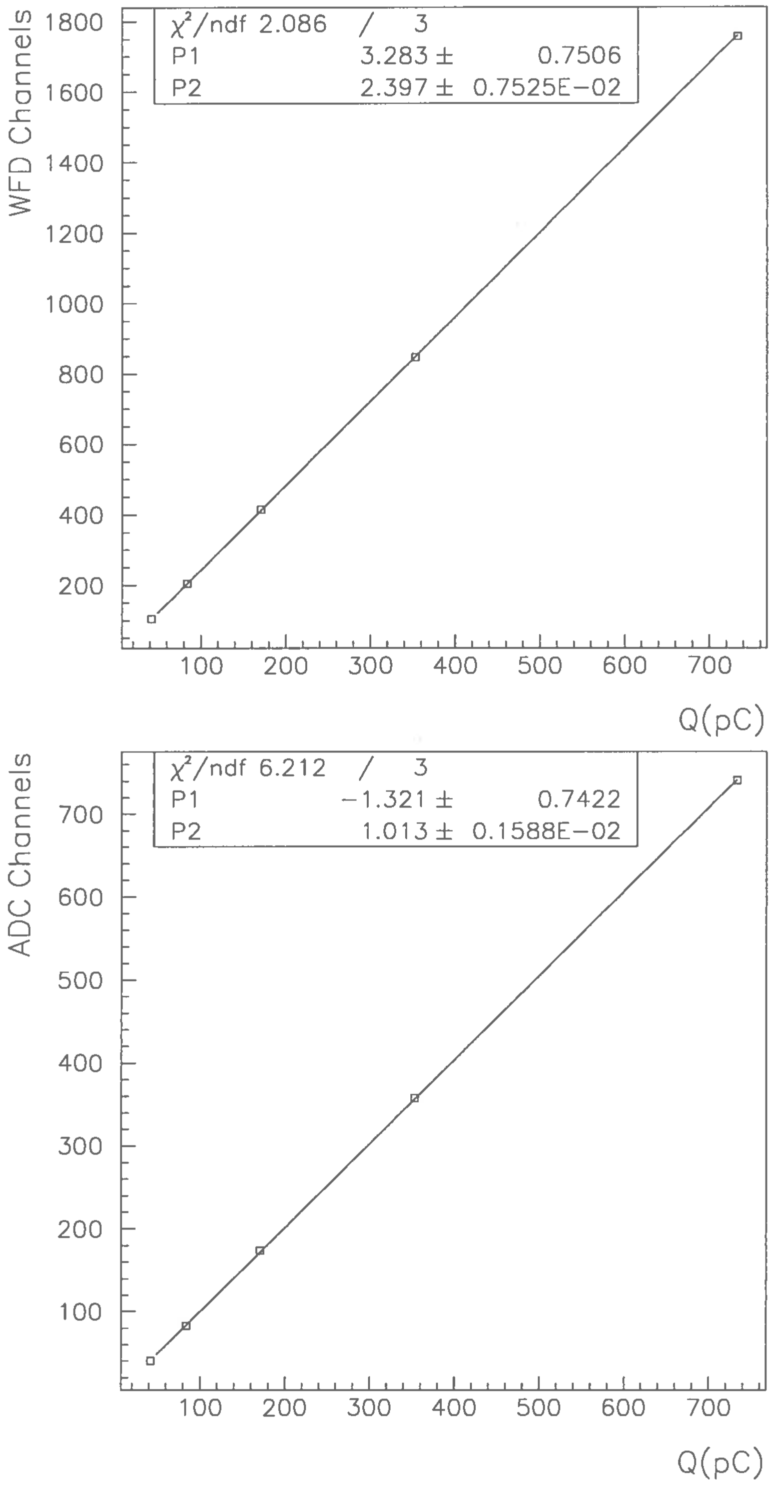

χ^2/ndf 2.086 / 3
P1 3.283 ± 0.7506
P2 2.397 ± 0.7525E−02
WFD Channels
1800
1600
1400
1200
1000
800
600
400
200
100
200
300
400
500
600
700
Q(pC)
χ^2/ndf 6.212 / 3
P1 −1.321 ± 0.7422
P2 1.013 ± 0.1588E−02
ADC Channels
700
600
500
400
300
200
100
100
200
300
400
500
600
700
Q(pC)

Figure 2:

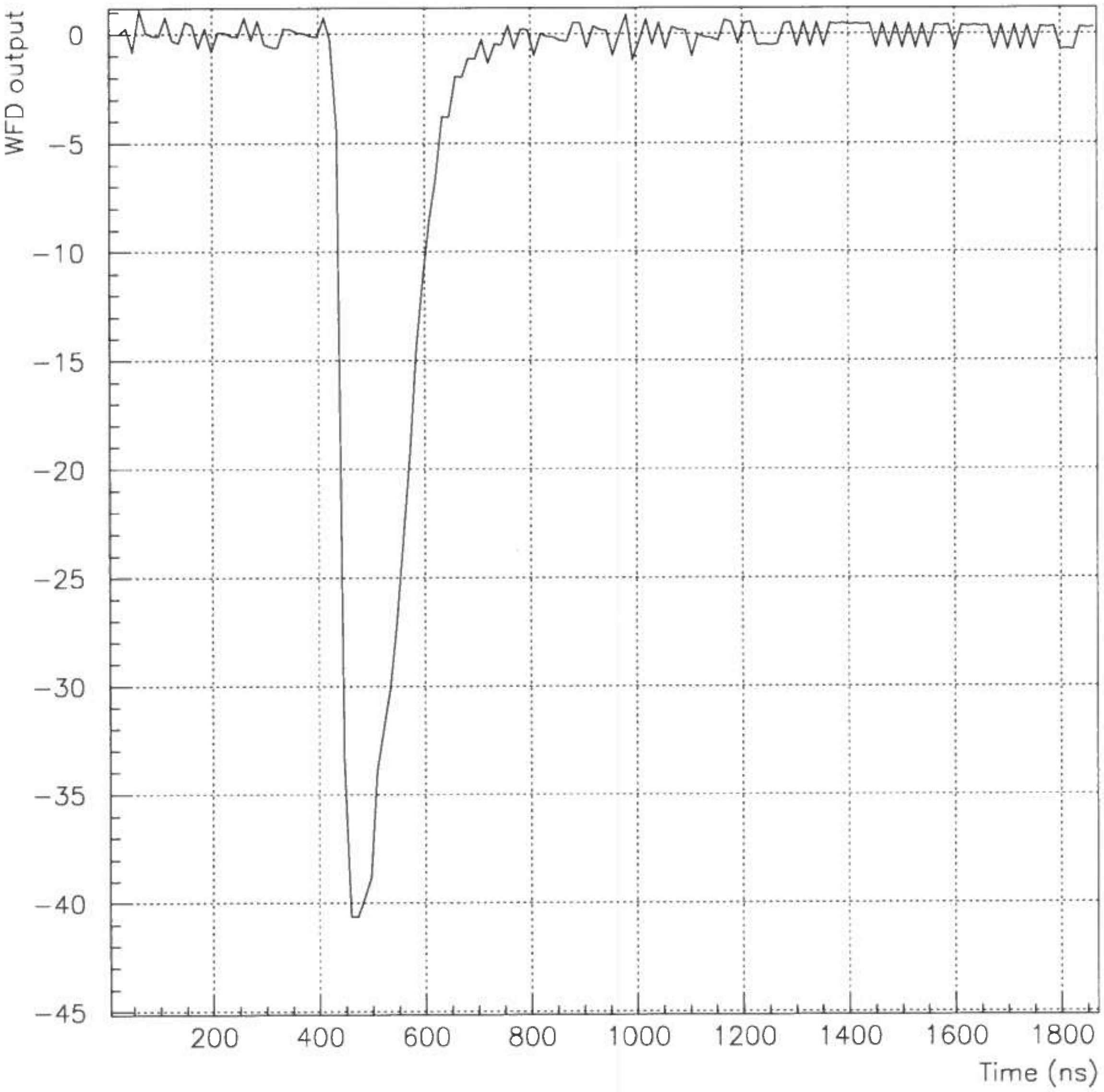

WFD output
0
−5
−10
−15
−20
−25
−30
−35
−40
−45
200
400
600
800
1000
1200
1400
1600
1800
Time (ns)

Figure 3:

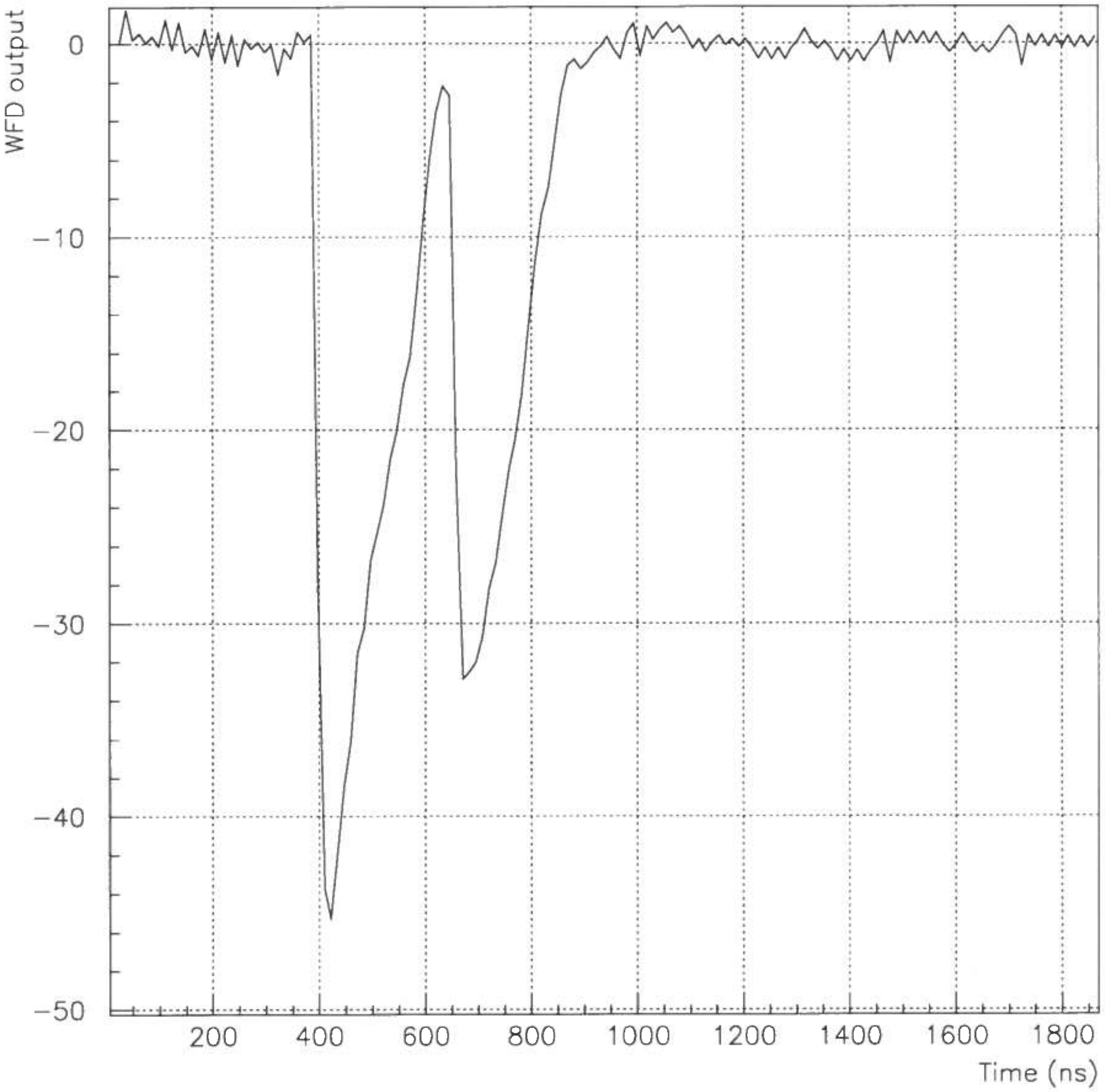

WFD output
0
−10
−20
−30
−40
−50
200
400
600
800
1000
1200
1400
1600
1800
Time (ns)

Figure 4:

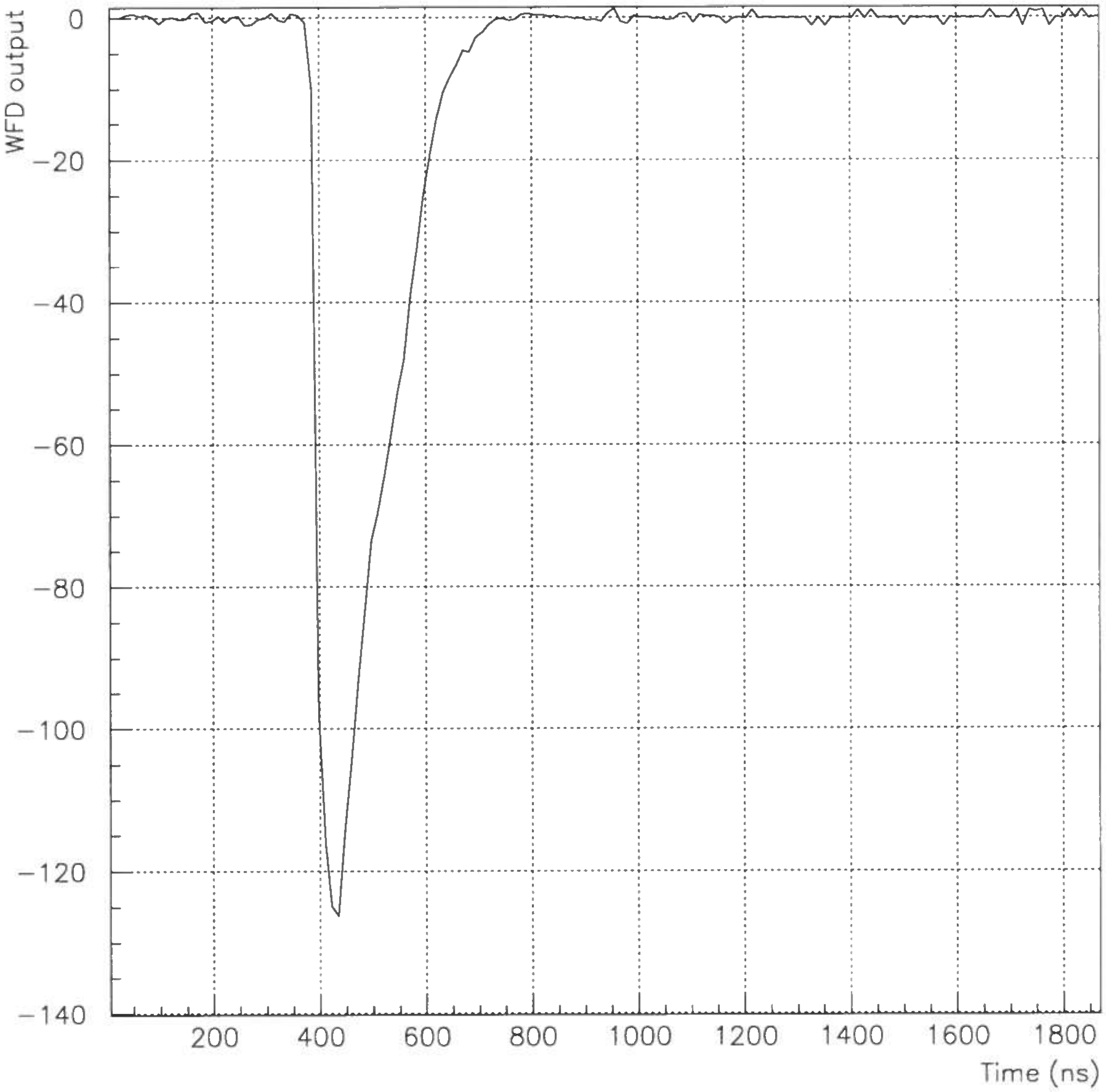

WFD output
0
−20
−40
−60
−80
−100
−120
−140
200
400
600
800
1000
1200
1400
1600
1800
Time (ns)

Figure 5:

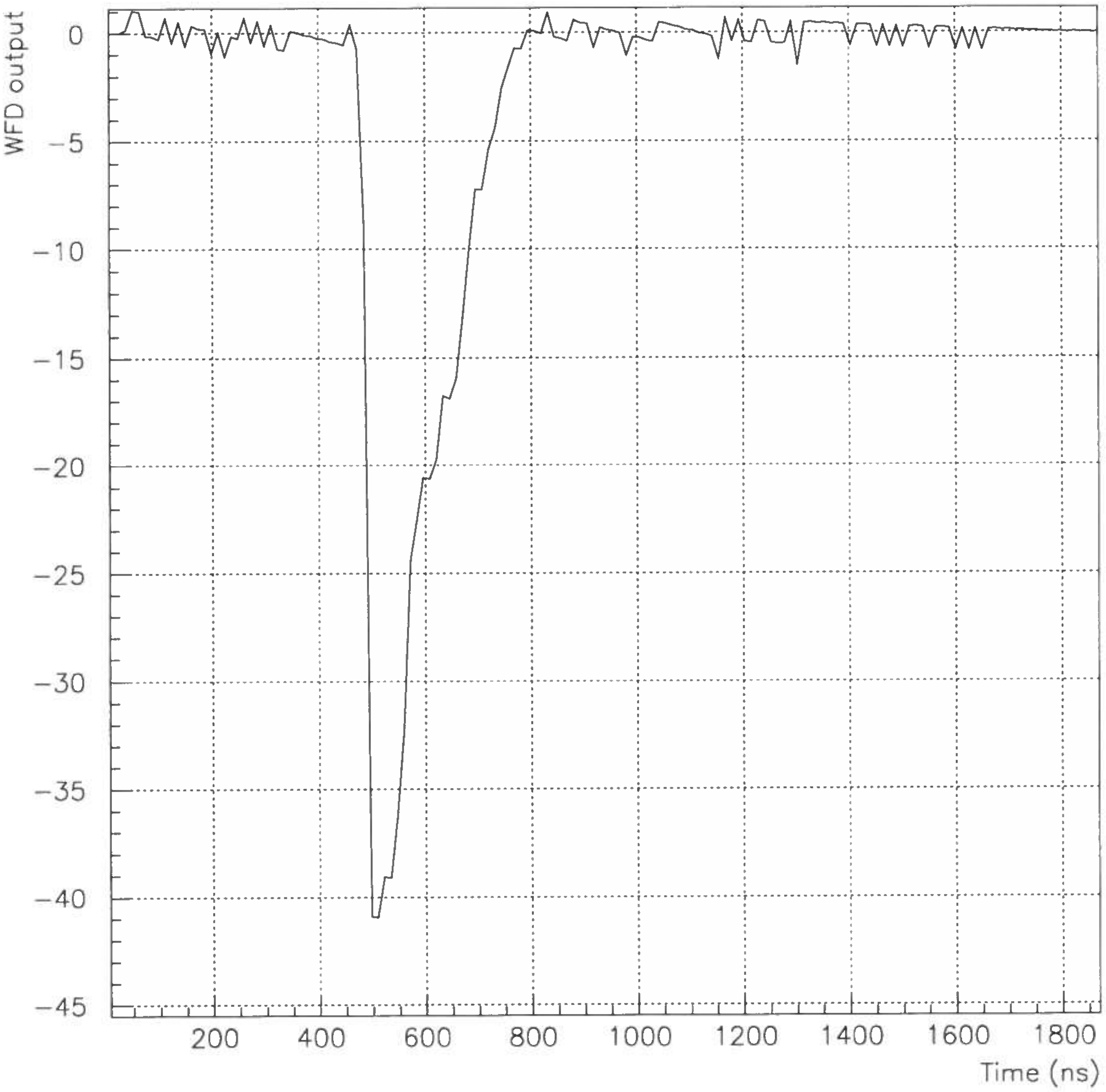

WFD output
0
−5
−10
−15
−20
−25
−30
−35
−40
−45
200
400
600
800
1000
1200
1400
1600
1800
Time (ns)

Figure 6:

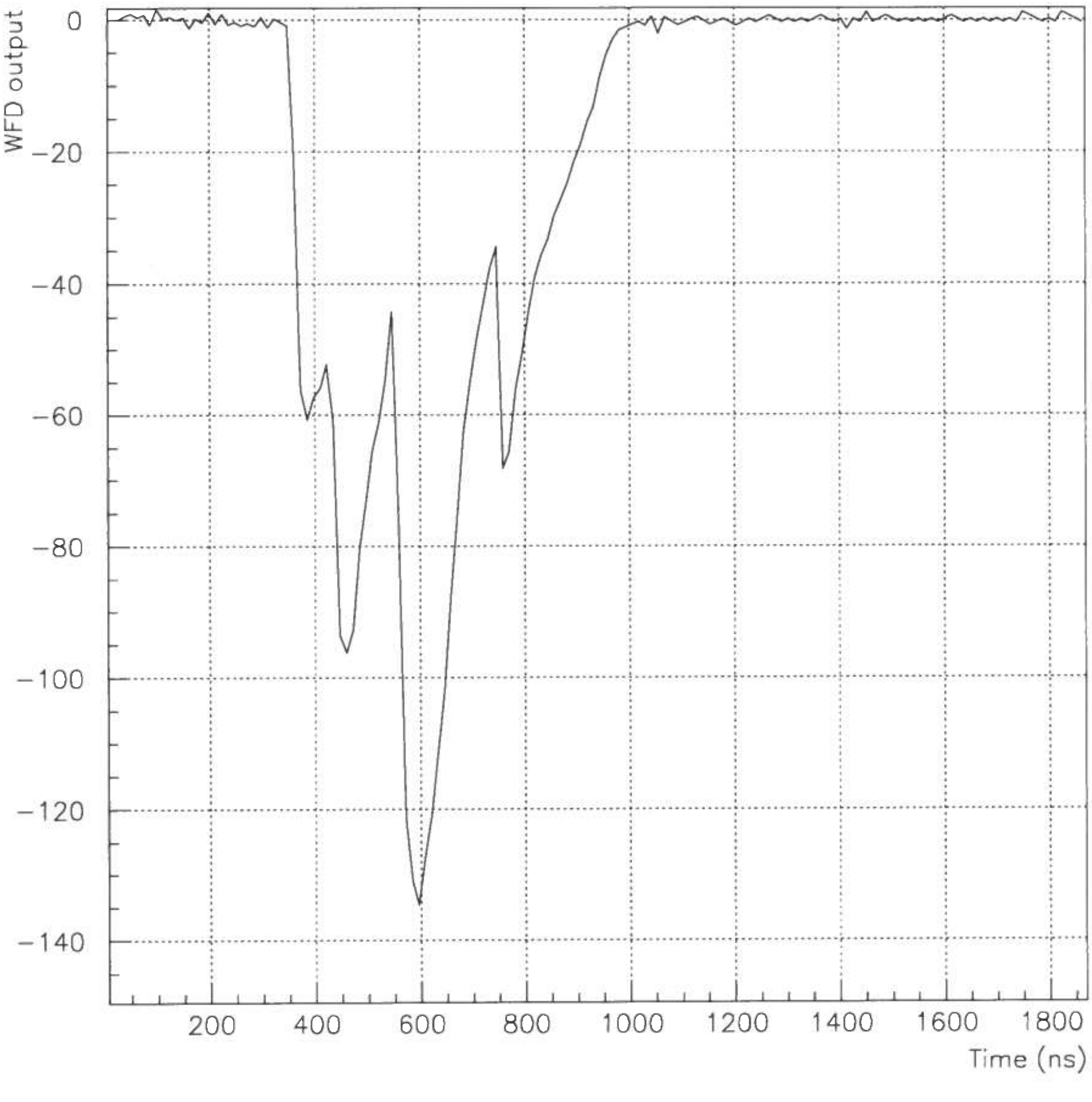

WFD output
0
−20
−40
−60
−80
−100
−120
−140
200
400
600
800
1000
1200
1400
1600
1800
Time (ns)

Figure 7:

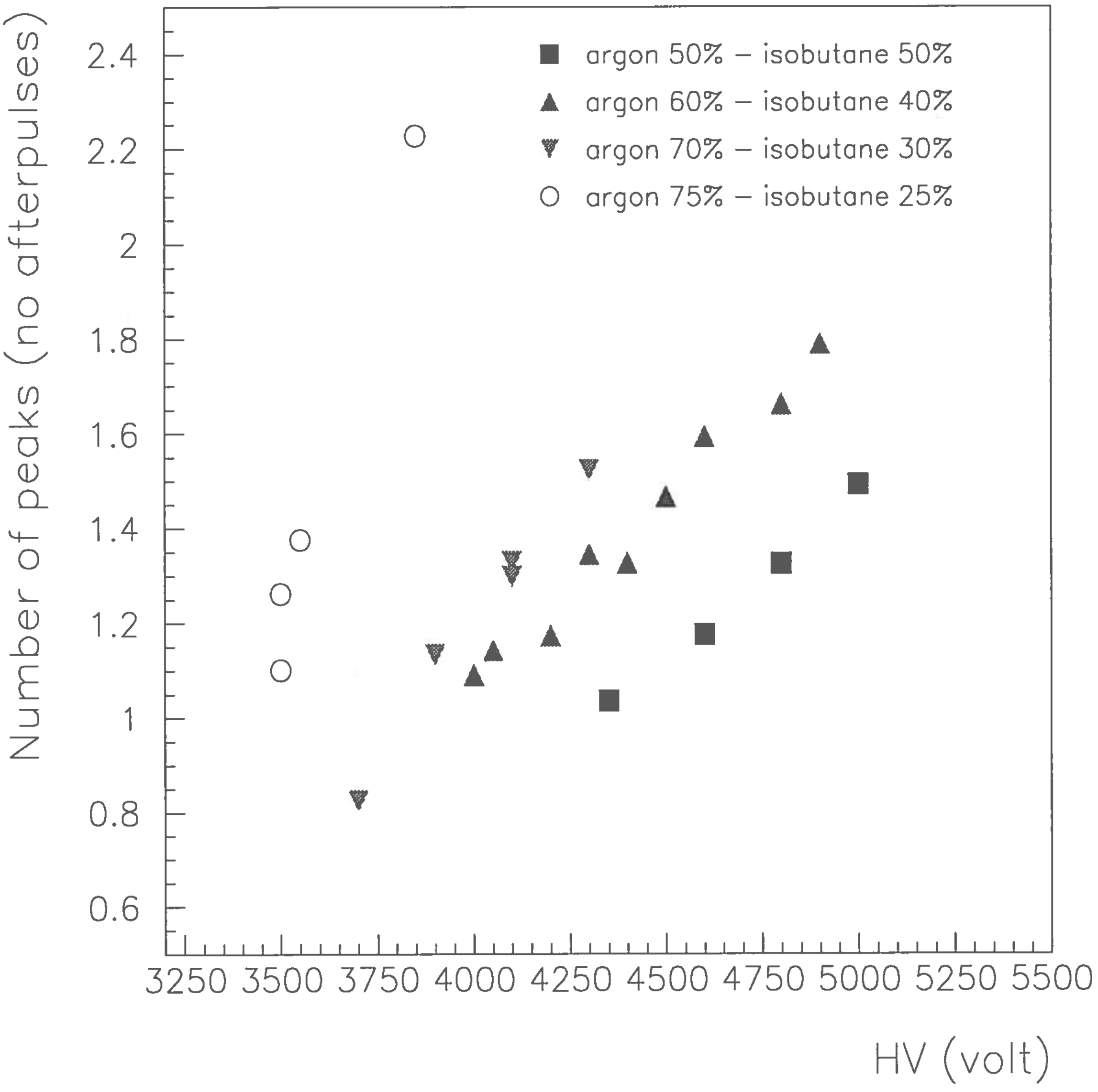
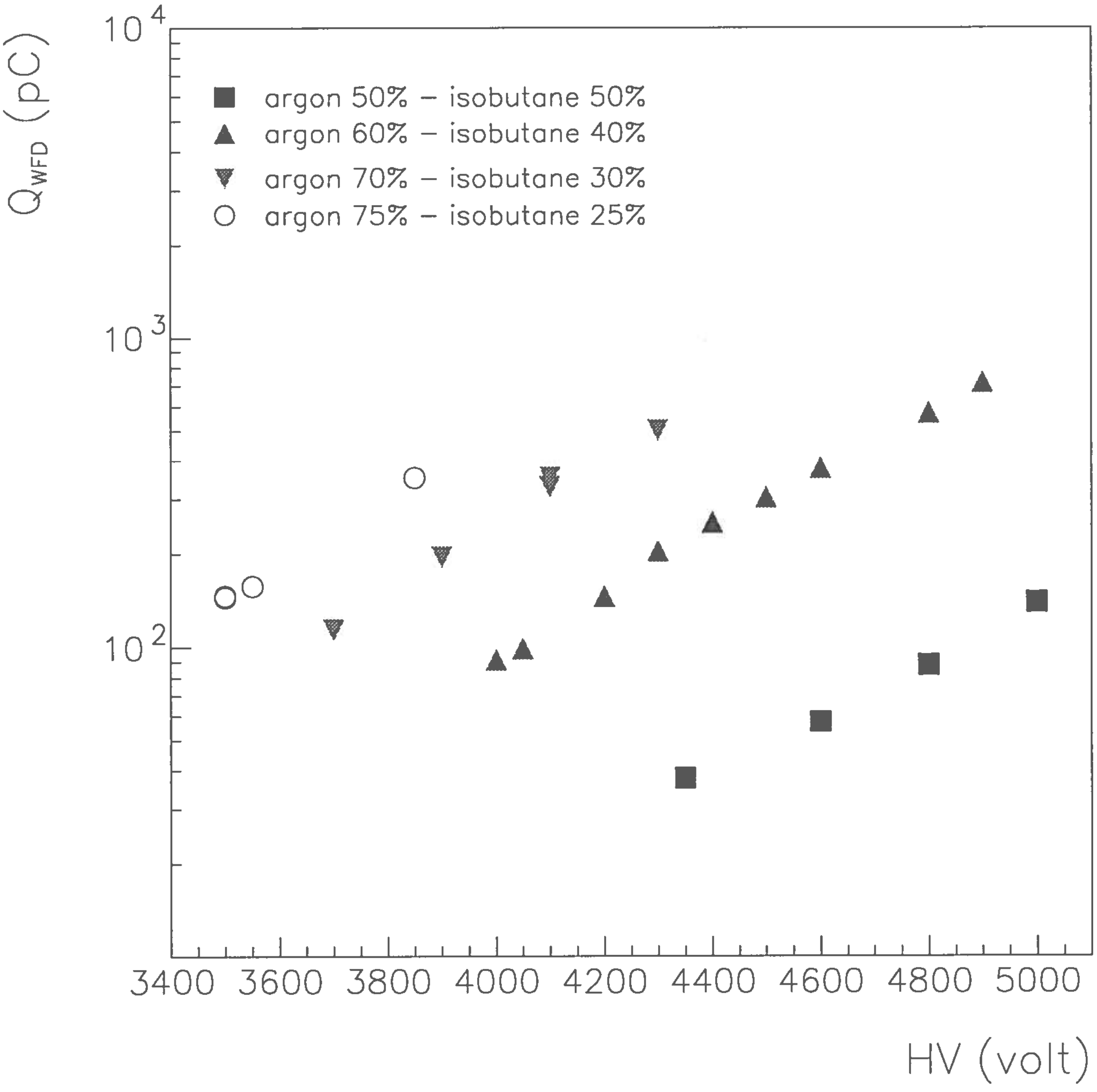

Number of peaks (no afterpulses)
HV (volt)
argon 50% – isobutane 50%
argon 60% – isobutane 40%
argon 70% – isobutane 30%
argon 75% – isobutane 25%
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
3250
3500
3750
4000
4250
4500
4750
5000
5250
5500

Figure 8:



Q_WFD (pC)
10^4
10^3
10^2
■ argon 50% – isobutane 50%
▲ argon 60% – isobutane 40%
▼ argon 70% – isobutane 30%
○ argon 75% – isobutane 25%
3400
3600
3800
4000
4200
4400
4600
4800
5000
HV (volt)

Figure 9:

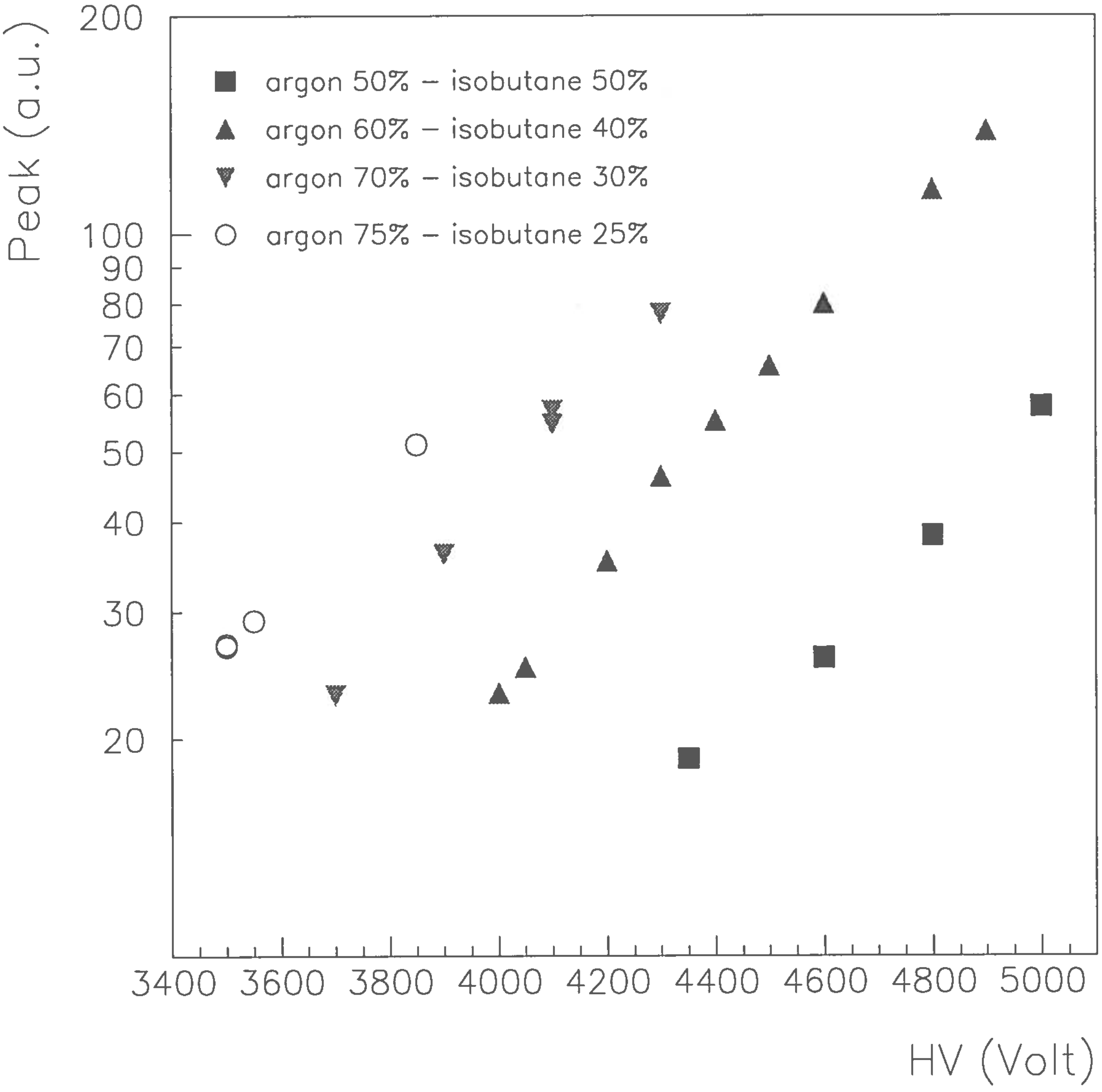

Peak (a.u.)
200
100
90
80
70
60
50
40
30
20
■ argon 50% – isobutane 50%
▲ argon 60% – isobutane 40%
▼ argon 70% – isobutane 30%
○ argon 75% – isobutane 25%
3400
3600
3800
4000
4200
4400
4600
4800
5000
HV (Volt)

Figure 10:

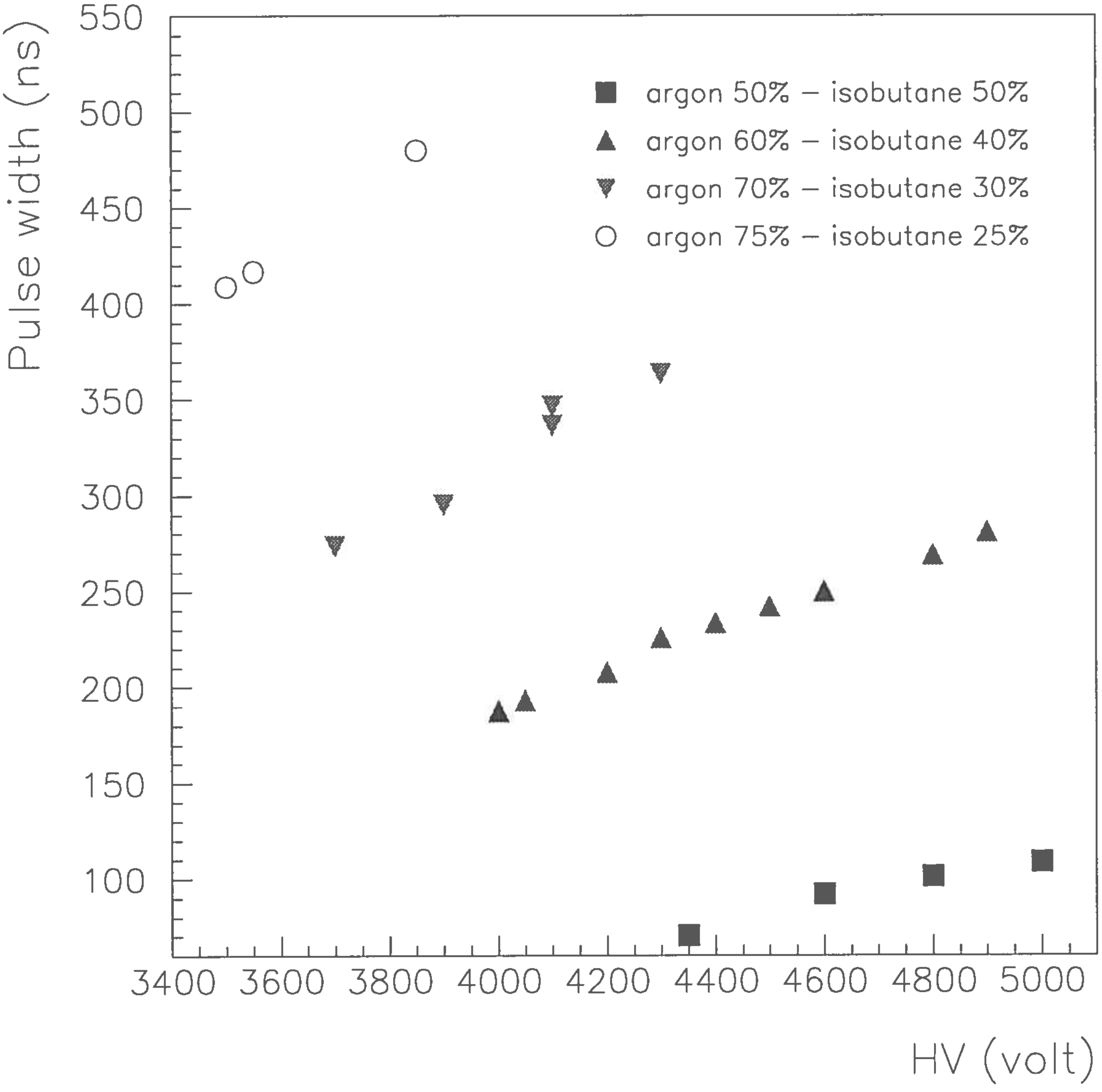
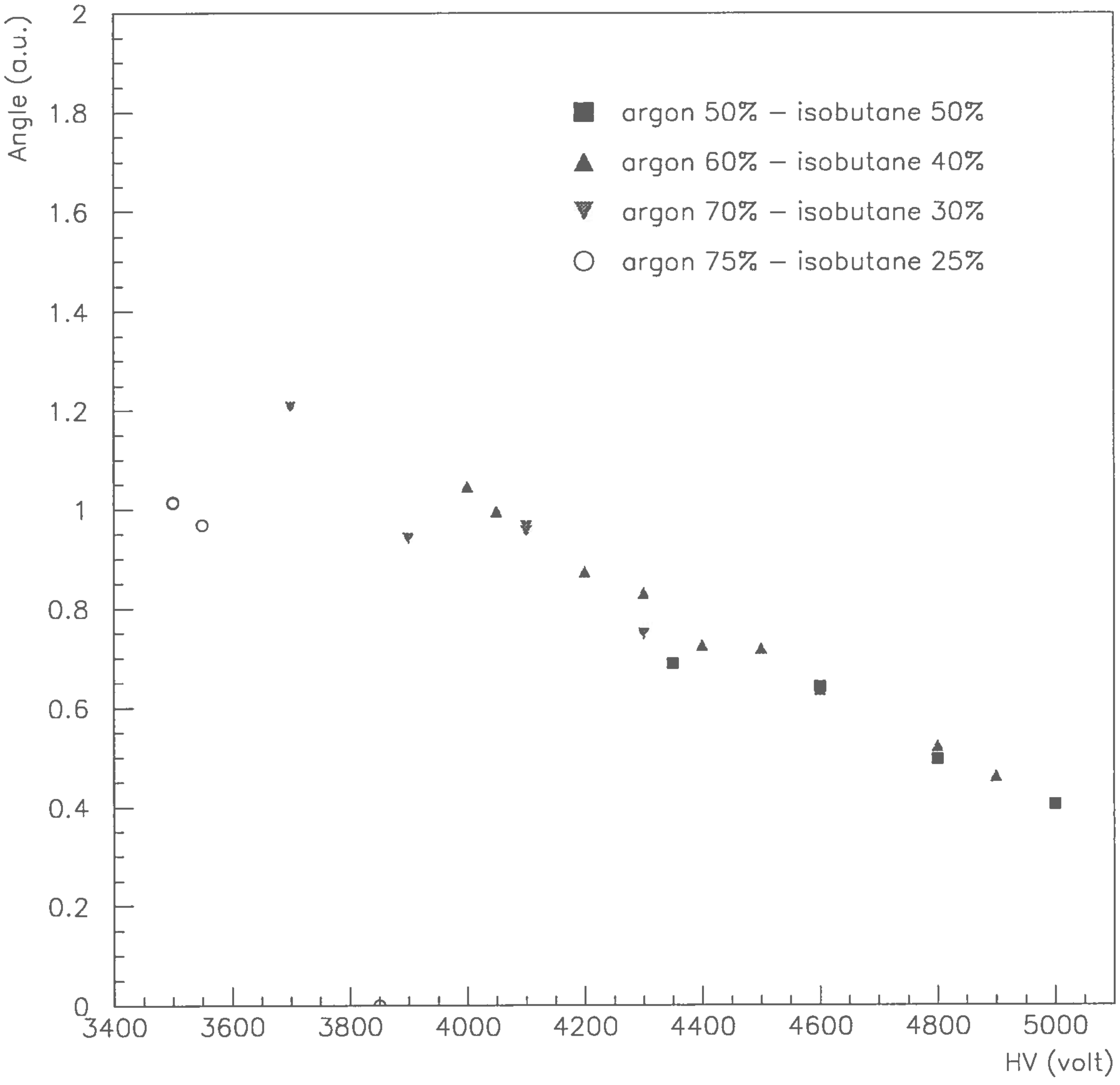
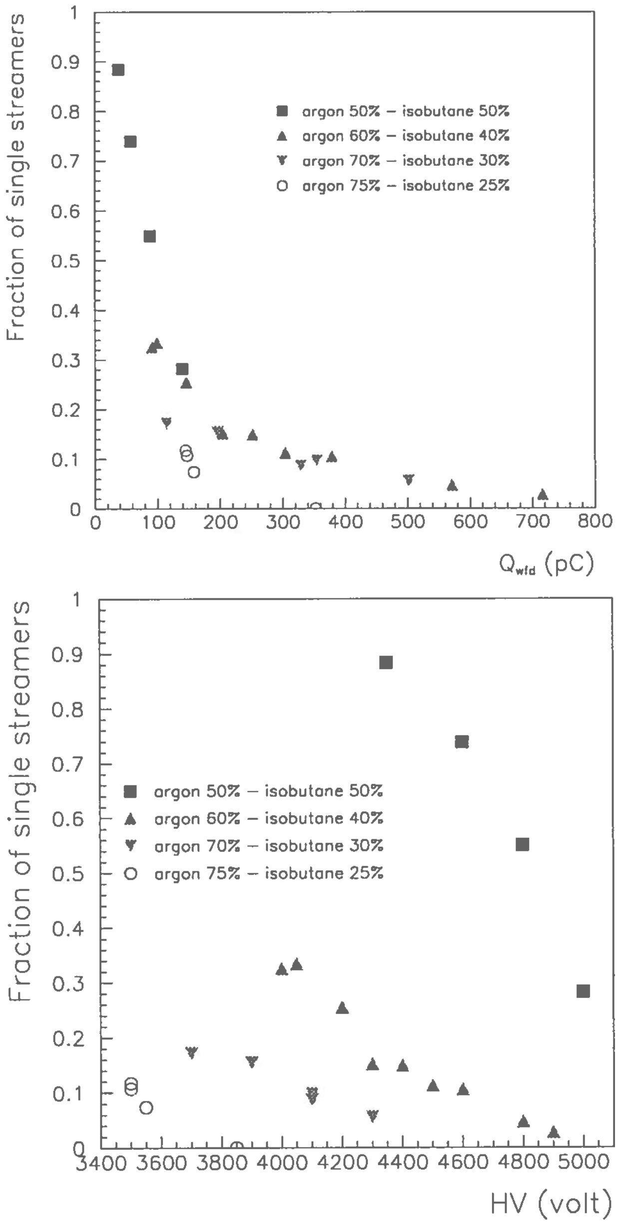

Pulse width (ns)
550
500
450
400
350
300
250
200
150
100
3400
3600
3800
4000
4200
4400
4600
4800
5000
HV (volt)
■ argon 50% – isobutane 50%
▲ argon 60% – isobutane 40%
▼ argon 70% – isobutane 30%
○ argon 75% – isobutane 25%

Figure 11:



Angle (a.u.)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
3400
3600
3800
4000
4200
4400
4600
4800
5000
HV (volt)
■ argon 50% – isobutane 50%
▲ argon 60% – isobutane 40%
▼ argon 70% – isobutane 30%
○ argon 75% – isobutane 25%

Figure 12:



Fraction of single streamers
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
600
700
800
Q_wfd (pC)
argon 50% – isobutane 50%
argon 60% – isobutane 40%
argon 70% – isobutane 30%
argon 75% – isobutane 25%
Fraction of single streamers
3400
3600
3800
4000
4200
4400
4600
4800
5000
HV (volt)

Figure 13:

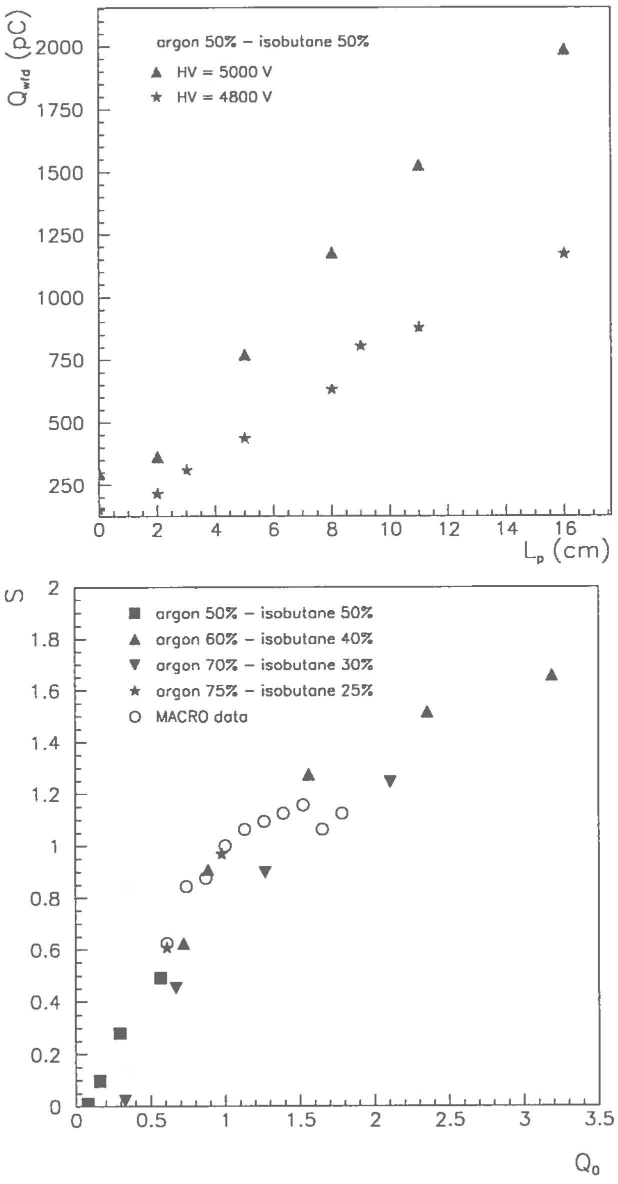

argon 50% – isobutane 50%
▲ HV = 5000 V
★ HV = 4800 V
Q_{wfd} (pC)
2000
1750
1500
1250
1000
750
500
250
0
2
4
6
8
10
12
14
16
L_p (cm)
■ argon 50% – isobutane 50%
▲ argon 60% – isobutane 40%
▼ argon 70% – isobutane 30%
★ argon 75% – isobutane 25%
○ MACRO data
S
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
3.5
Q_0

Figure 14:

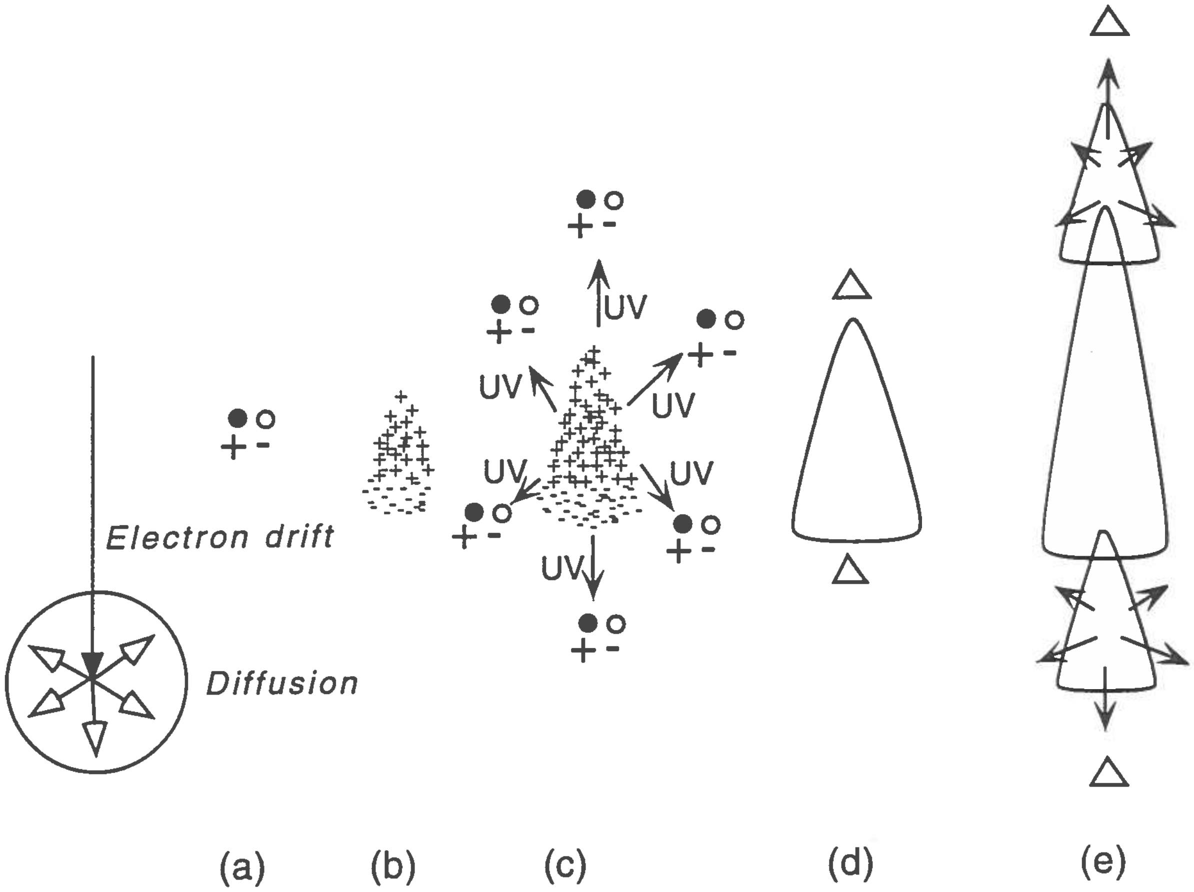


Figure 15:

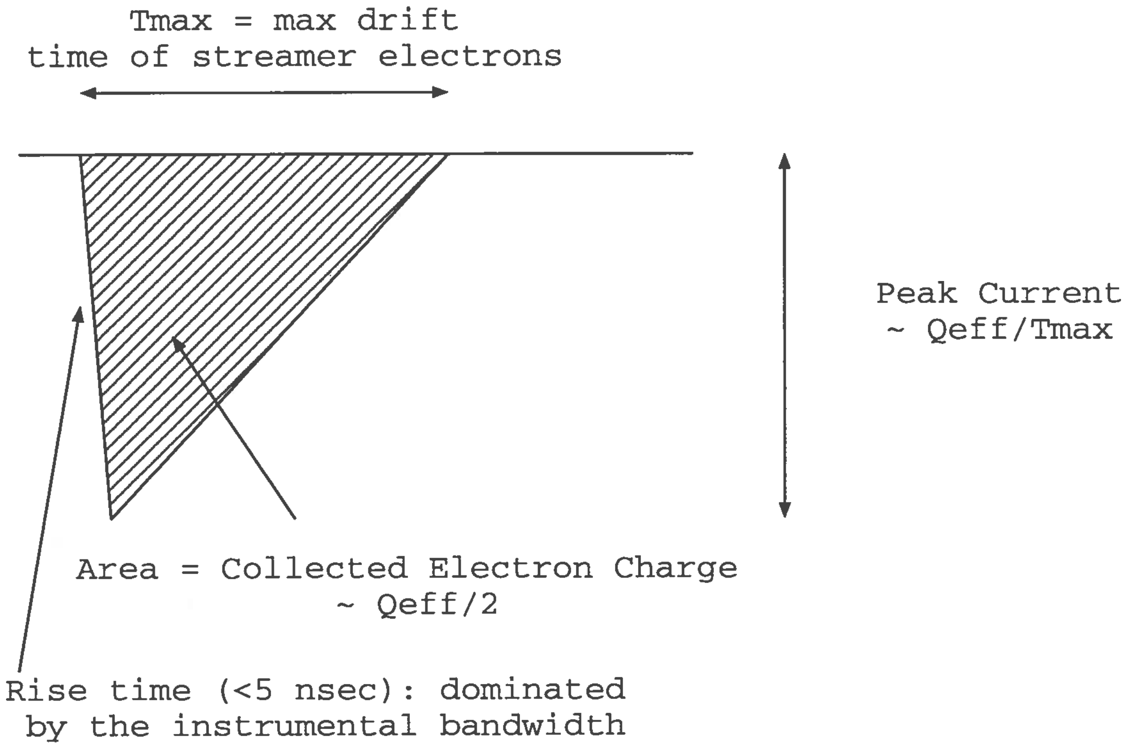
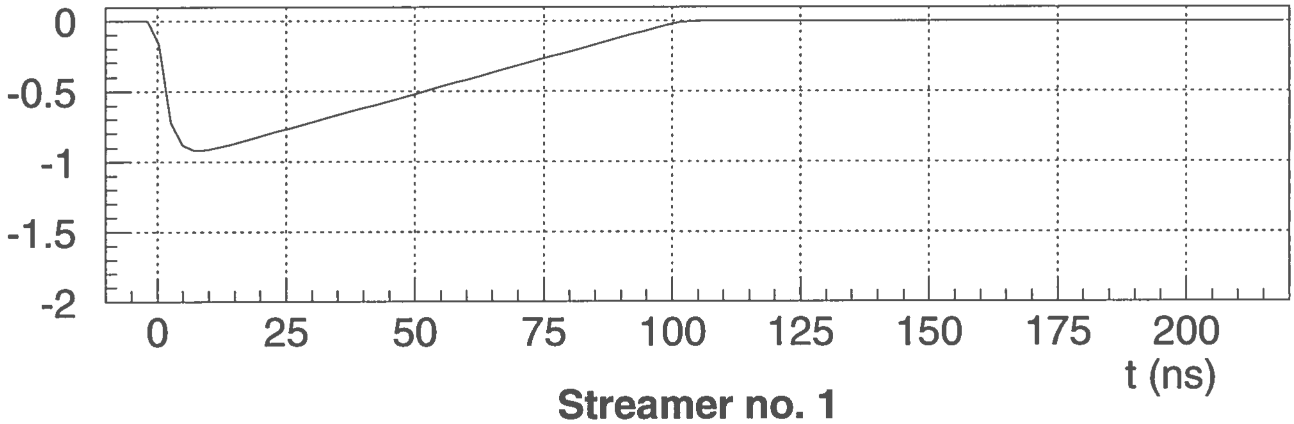
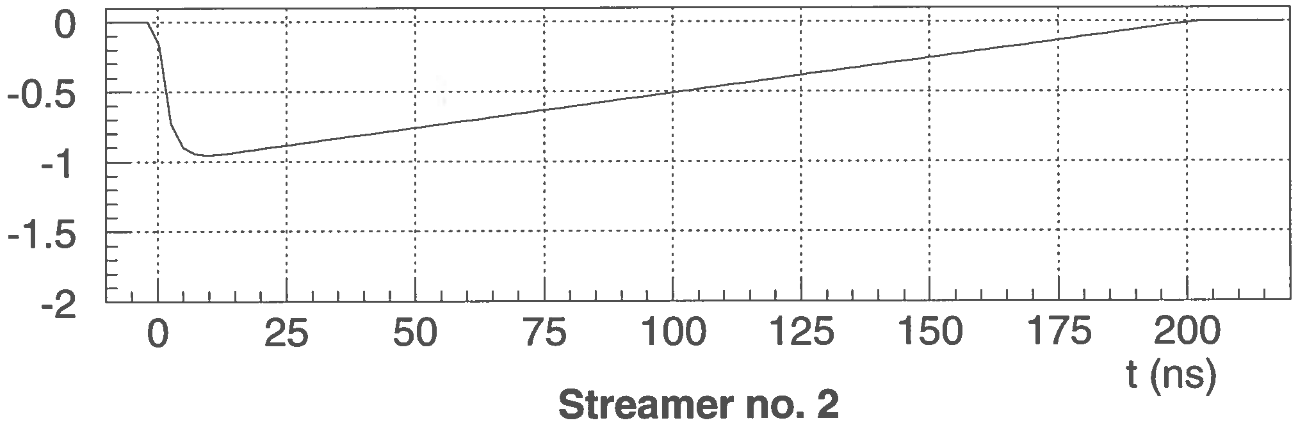

Tmax = max drift
time of streamer electrons
Peak Current
~ Qeff/Tmax
Area = Collected Electron Charge
~ Qeff/2
Rise time (<5 nsec): dominated
by the instrumental bandwidth

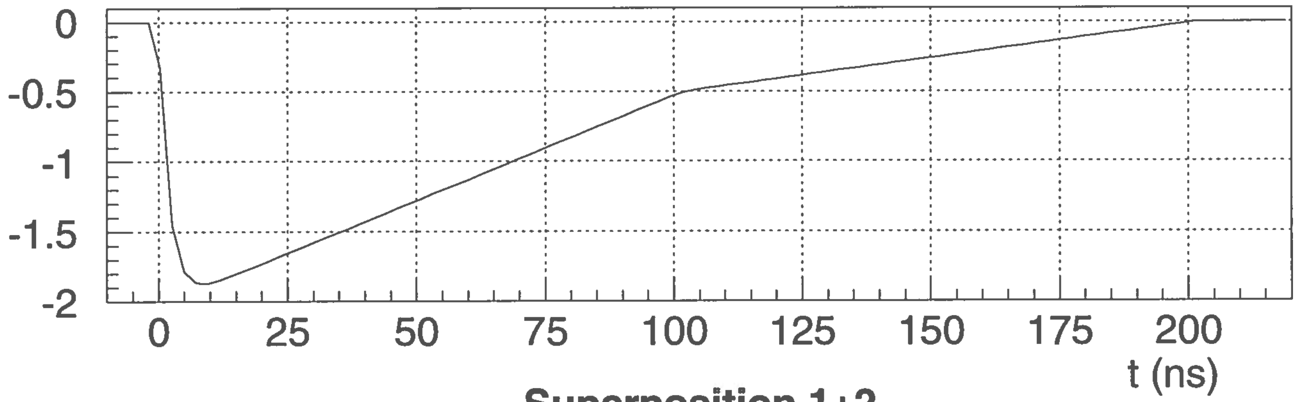
Figure 16:



Streamer no. 1



Streamer no. 2



Superposition 1+2

Figure 17: