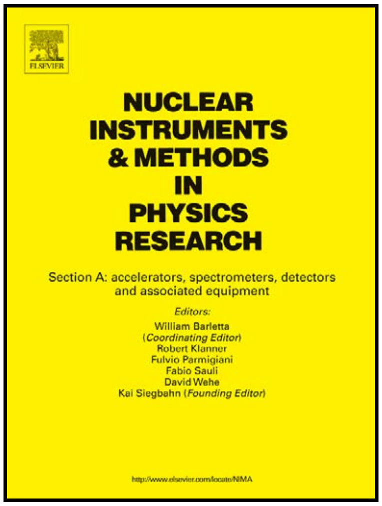

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

Section A: accelerators, spectrometers, detectors and associated equipment

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M. Nakhostin, P.M. Walker

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Determination of gas amplification factor by digital waveform analysis of avalanche counter signals

M. Nakhostin[*] and P. M. Walker

Department of Physics, University of Surrey, Guildford GU2 7XH, UK

Abstract.

A novel method for event-by-event determination of the gas amplification factor in a uniform electric field has been developed. The method is based on the digital waveform analysis of signals from an avalanche counter and offers several advantages such as independence from determination of the primary ionization and total charge, and it is immune to the space charge effect that can seriously affect the gas amplification process.

Keywords: Townsend coefficient, Avalanche counters, Isobutane

[*]Corresponding Author:

E-mail address: M.nakhostin@surrey.ac.uk (M. Nakhostin),

Tel.:+44 1483 686113

Fax: +44 1483 686781

1. Introduction

In a detector operating under gas amplification, the primary electrons produced by the radiation gain energy from the electric field to ionize the gas molecules that they hit. The average distance an electron travels between the ionizing collisions is called the mean free path for ionization and its inverse, the number of ionizing collisions per cm, is called the first Townsend coefficient, α. This coefficient is a fundamental parameter for determination of detector gas gain. Precise measurement of the α-coefficient is required for practical use as well as evaluation and adjustment of the proposed theoretical models. The most common method for determination of the α coefficient is based on the comparison of the initial charge deposited by the radiation and the total charge generated by the gas amplification process (see for example ref. [1-3]). However, the accuracy of this method is limited by the inaccuracies in the determination of the amount of primary and total charges. The measurement is further complicated by the space charge effect that can seriously affect the gas amplification process.

In this paper, we present a novel method for event-by-event determination of the Townsend coefficient in a uniform electric field. The method is based on digital waveform analysis of the signals from an avalanche counter. The method avoids determination of the primary ionization and total charge and offers a high degree of immunity to the space charge effect.

2. Theoretical considerations

Avalanche counters are simple and effective transmission detectors in nuclear physics. A detector consists of two parallel electrodes with a few mm gap between them which is filled with a suitable gas. When a charged particle passes through the detector, the amplification of primary charges leads to a detectable signal, which is due to the motion of electrons and positive ions in the detector gap. The development with time of the current in the external circuit of a parallel plate avalanche counter is very well understood and theoretical analyses have been presented by Schmidt [4] and Draper [5] and in detail, in a comprehensive study of Raether [6]. The use of an avalanche counter as a timing detector is based on the electron current signal which leads to a time resolution of a few hundreds of ps. In the case of uniform deposition of primary ionization in the detector gap, the electron current is given by:

$$i_e = \frac{Q_0 \cdot v}{d} \cdot (1 - \frac{v \cdot t}{d}) \cdot e^{\alpha \cdot v \cdot t} \qquad (1)$$

In this relation, Q_0 is the amount of primary ionization, d is the detector gap thickness, α is the first Townsend coefficient and v is electron drift velocity. When the avalanche counter signal is readout by a charge sensitive or integrating preamplifier, the contributions of electrons and ions in the voltage pulse are given by [5]:

Electron signal:

$$V_e = \frac{Q_0}{C} \cdot \left(\frac{e^{\alpha \cdot d} - \alpha \cdot d - 1}{(\alpha \cdot d)^2}\right) , \qquad (2)$$

Ion signal:

$$V_{ion} = \frac{Q_0}{C} \cdot \left(\frac{e^{\alpha \cdot d}}{\alpha \cdot d}\right) , \qquad (3)$$

where C is the detector capacitance. From the equations (2) and (3) it follows that the ratio of V_{ion}/V_e is an explicit function of the Townsend coefficient as:

$$\frac{V_{ion}}{V_e} = \alpha \cdot d \qquad (4)$$

Our method for measuring the Townsend coefficient is based on a precise determination of this ratio by a careful analysis of the detector waveforms.

3. Experimental setup

The experimental arrangement used in this work is shown in Fig.1. It consists of an avalanche counter of 5×5 cm^2 whose electrodes are made of 6-μm aluminized Mylar foil, well stretched over glass-epoxy frames. The gap between the electrodes of the detector is 3-mm and is maintained by means of a highly machined spacer. The tests are performed using a ^{241}Am α-source. A collimator with an opening of 5 mm diameter is placed in front of the counter to ensure that the α-particles` flight path is normal to the detector electrodes. The counter together with the ^{241}Am α-source and collimator are enclosed in a vacuum chamber and the chamber is flushed with isobutane (i-C_4H_{10}) gas at 6.927 Torr of pressure.

The signals initiated by the passage of α-particles through the detector are read out with a fast current-sensitive preamplifier (rise-time≤ 1 ns) which delivers the signals with minimal degradation of signal waveforms. The preamplifier output is digitized by means of the Lecroy WavePro7000 digital storage oscilloscope with a sampling rate of 10 GS/s and 8-bit resolution. The tests are done at several operating voltages from 500 to 620 V and at each voltage thousands of pulses are acquired for analysis.

4. Results and discussion

An example of a digitized pulse from the avalanche counter is shown in Fig. 2.A. The signal seen by the current-sensitive preamplifier is composed of two components. There is an initial very fast pulse from the electrons arriving at the anode that is then followed by a much longer induced signal, typically of several microseconds duration, as the ions librated in the avalanche drift away from the anode to be neutralized on the cathode electrode. Fig.2.B shows the voltage pulse which has been obtained by numerical integration of the current signal. One can see that the contribution of electrons and ions is clearly distinguishable. The reason that the voltage pulse is obtained by numerical integration of the current signal rather than direct measurement by a charge-sensitive preamplifier is that the current-sensitive preamplifier gives minimal degradation of signal waveform, while for a charge-sensitive preamplifier the shape of the electron component can be seriously affected by the frequency response of the preamplifier. To measure the contribution of electrons and ions to the voltage pulse, the challenge is to precisely determine the border between the two components of the signal. The algorithm employed for this task is illustrated in Fig.2. By using the current signal, the duration of the electron current is determined, and the voltage corresponding to the end of the electron current is taken as the voltage signal due to electrons.

One parameter that can seriously affect the accuracy of the Townsend coefficient measurement is the space charge effect. The space charge effect results from the fact that at high values of gas amplification, the electric field due to the charge generated by the process of electron avalanche becomes comparable with the external electric field and consequently it can modify the electric field in the detector gap. This leads to a significant error in the obtained α value as the actual electric field is smaller than the nominal value. The space charge effect manifests itself in different ways. We have developed a digital method that can detect the onset of the space charge effect very precisely. Fig.3 shows the rise-time of the electron current signal against the signal amplitude for several different supply voltages. It is seen that at low voltages the rise-time of the signals fluctuates around an average value which is mainly due to the electronic noise and fluctuations in the Townsend coefficient (see eq.1). As the supply voltage increases, a sharp increase in the rise-time of the signals is observed, which is a clear sign of the space charge effect. In fact, space charge reduces the electric field which consequently increases the rise-time of signals. From the Fig.3, one can see that the onset of the space charge effect is at 590 V and hence the signals at lower voltages are used for the α coefficient measurement.

The distribution of the α-coefficient, calculated for some typical operating voltages are shown in Fig. 4. It is seen that as the voltage increases a clear shift in the most probable value of the α coefficient is observed. The large variations in the α value at low voltages is due to the poor signal-to-noise ratio of the electron signals. The most probable value of the α-coefficient as an inverse function of the reduced electric field (E/P, where E is the electric field and P is the gas pressure) is shown in Fig.5. Since the distributions are accompanied with a tail in the left side, the most probable values were determined by fitting a Gaussian function to the part of the spectra, associated with the events above the full-width-at-half-maximum (FWHM) of the distributions (see Fig.4). In a uniform electric field, the α coefficient is well described by the Townsend classic formula:

$$\alpha = A \cdot P \cdot \exp\left(\frac{-B \cdot P}{E}\right) \qquad (5)$$

where A and B are the gas constants. By fitting the experimental data with the Townsend formula, the A and B values were obtained as: A= 27±5 cm^{-1} Torr^{-1} and B= 408±50 V cm^{-1} Torr^{-1}. These gas constants are in a good agreement with existing data for isobutane gas as A= 27 cm^{-1} Torr^{-1} and B=392 V cm^{-1} Torr^{-1} [7] and A=24 cm^{-1} Torr^{-1} and B= 442 V cm^{-1} Torr^{-1} [8].

In the determination of the α value by digital waveform analysis, the accuracy of measurement may be affected by several parameters such as signal digitization accuracy, the preamplifier response function, electronic noise and the statistical error in the determination of the most probable value of the α-coefficient. Considering that our preamplifier has a very fast rise time of less than 1 ns and signal sampling is done at very high sampling rate of 10 GS/s, corresponding to one sample every 100 ps, the error due to the first two parameters is negligible and the major sources of error would be the electronic noise and statistical error in the localization of the most probable value. The signal-to-noise ratio (root-mean-square noise) of the smallest electron voltage pulses, corresponding to 500 V supply voltage, for the events associated to the most probable value was measured to be 12. Since the largest noise error is associated with the smallest signals, the maximum error due to electronic noise is 8%. The maximum error in the most probable value due to statistical error was measured to be 1.2%. Therefore, the total maximum error of our measurement, which is associated with the lowest voltage, is estimated to be 8.09 %.

5. Summary

For the first time, a method for an event-by-event determination of the Townsend coefficient has been developed. The method avoids the determination of primary charge and total ionization and offers a high degree of immunity to the space charge effect. With the minimization of electronic noise, the event-by-event determination of the gas amplification factor opens the way for quantifying the fluctuations in the gas amplification process which could be used to improve the energy resolution through a digital analysis of the detector signals. Such studies are underway in our laboratory.

Acknowledgment

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Figures captions

Figure 1. Schematic diagram of the setup used for the measurements.

Figure 2. (A) A typical current signal from an avalanche counter and (B) charge signal obtained by numerical integration of the current signal. The electron voltage is determined by picking the voltage at the time corresponding to the end of electron current. The border between the two components is shown by the arrow in the inset of

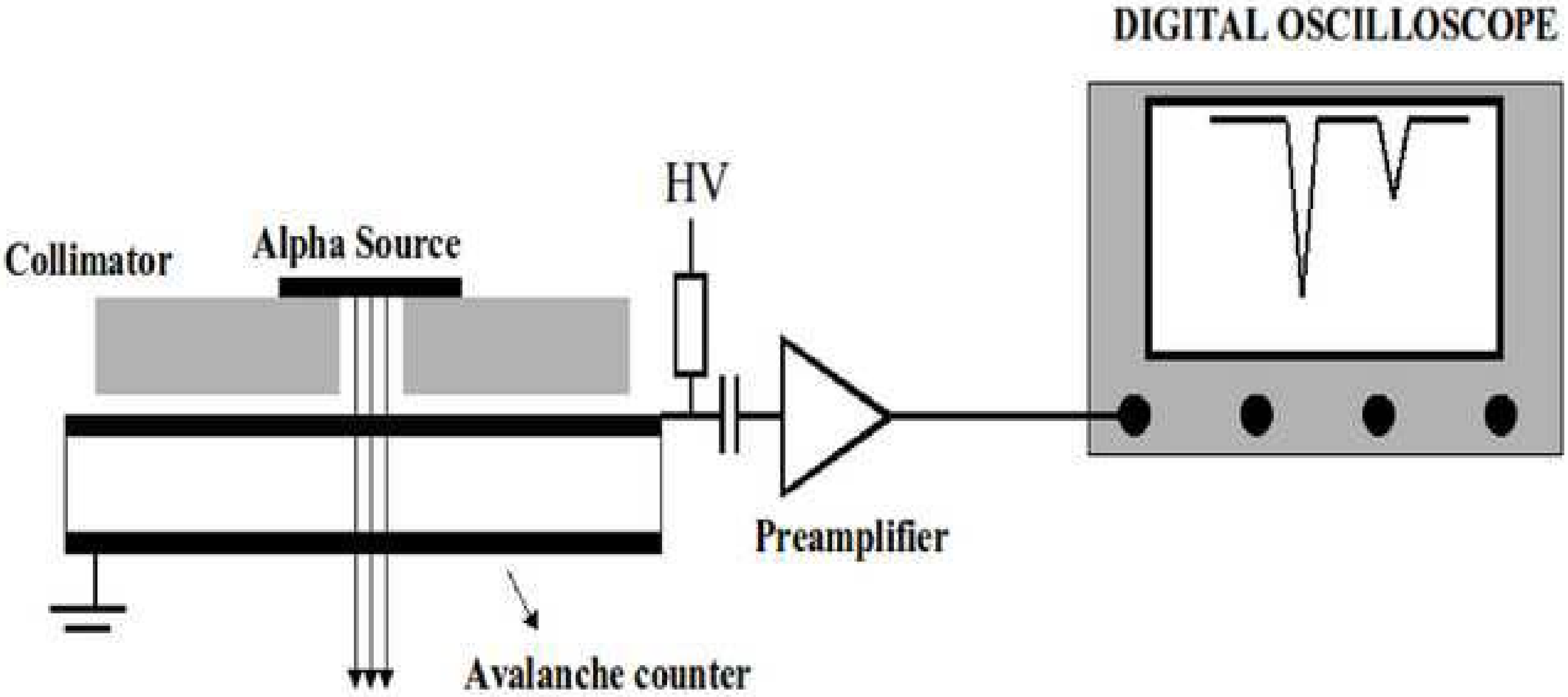
Fig. 2.A.

Figure 3. Determination of the onset of the space charge effect. While in the absence of the space charge effect the rise-time of the signal fluctuates around an average value, a drastic increase in the rise-time of the signals is caused by the space charge effect. The onset of the space charge effect is at 590 V. It is seen that the signals with large amplitude are most strongly affected by the space charge. The variation in the signal amplitude comes mainly from the fluctuations in the energy-loss of α-particles and the gas amplification factor [9, 10].

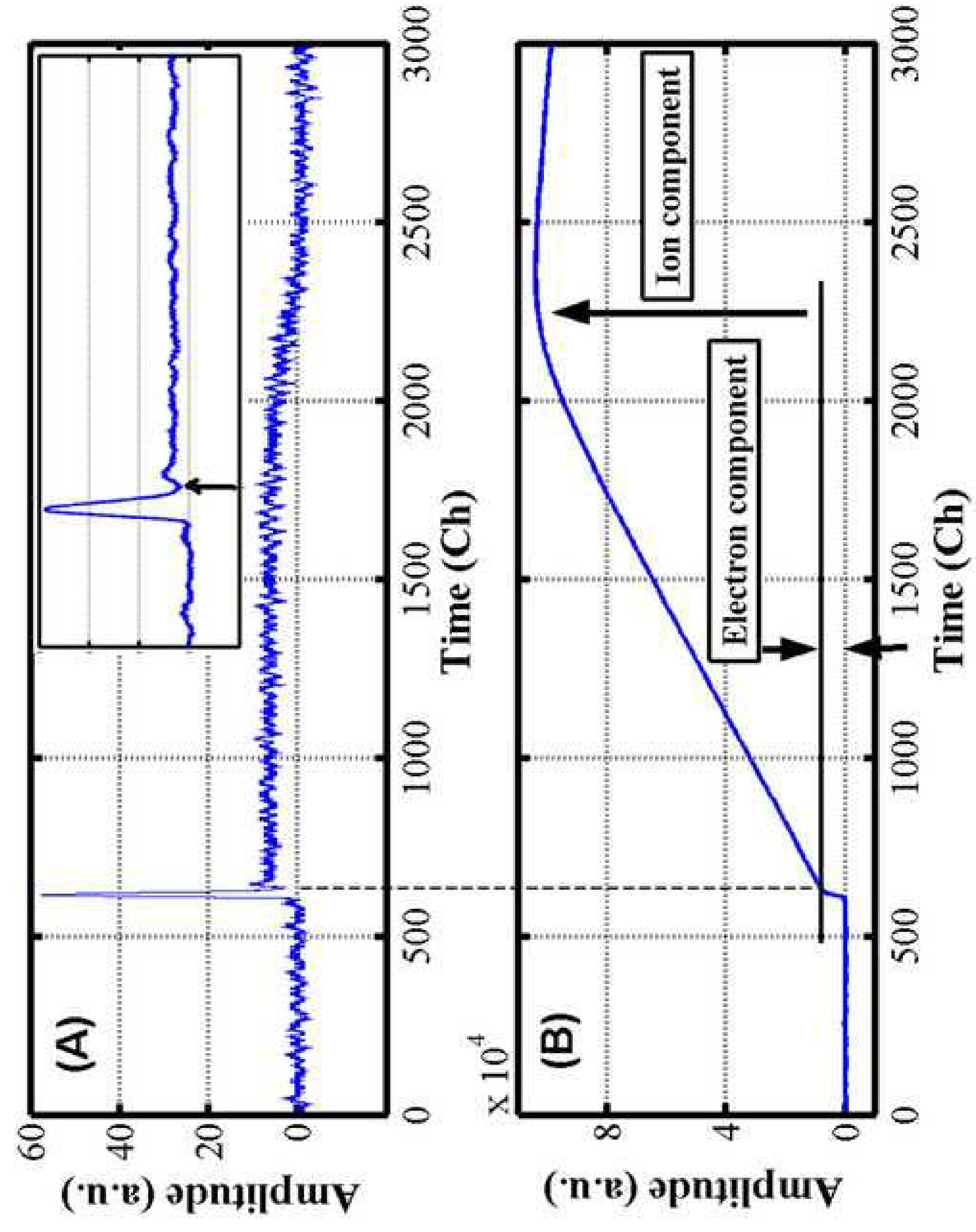
Figure 4. Distribution of the Townsend coefficient in isobutane for several operating voltages.

Figure 5. Townsend coefficient vs inverse of the reduced electric field (P/E). By fitting the Townsend formula to the experimental data, the isobutane gas constants are obtained as A= 27 cm^{-1} $Torr^{-1}$ and B= 408 V cm^{-1} $Torr^{-1}$.

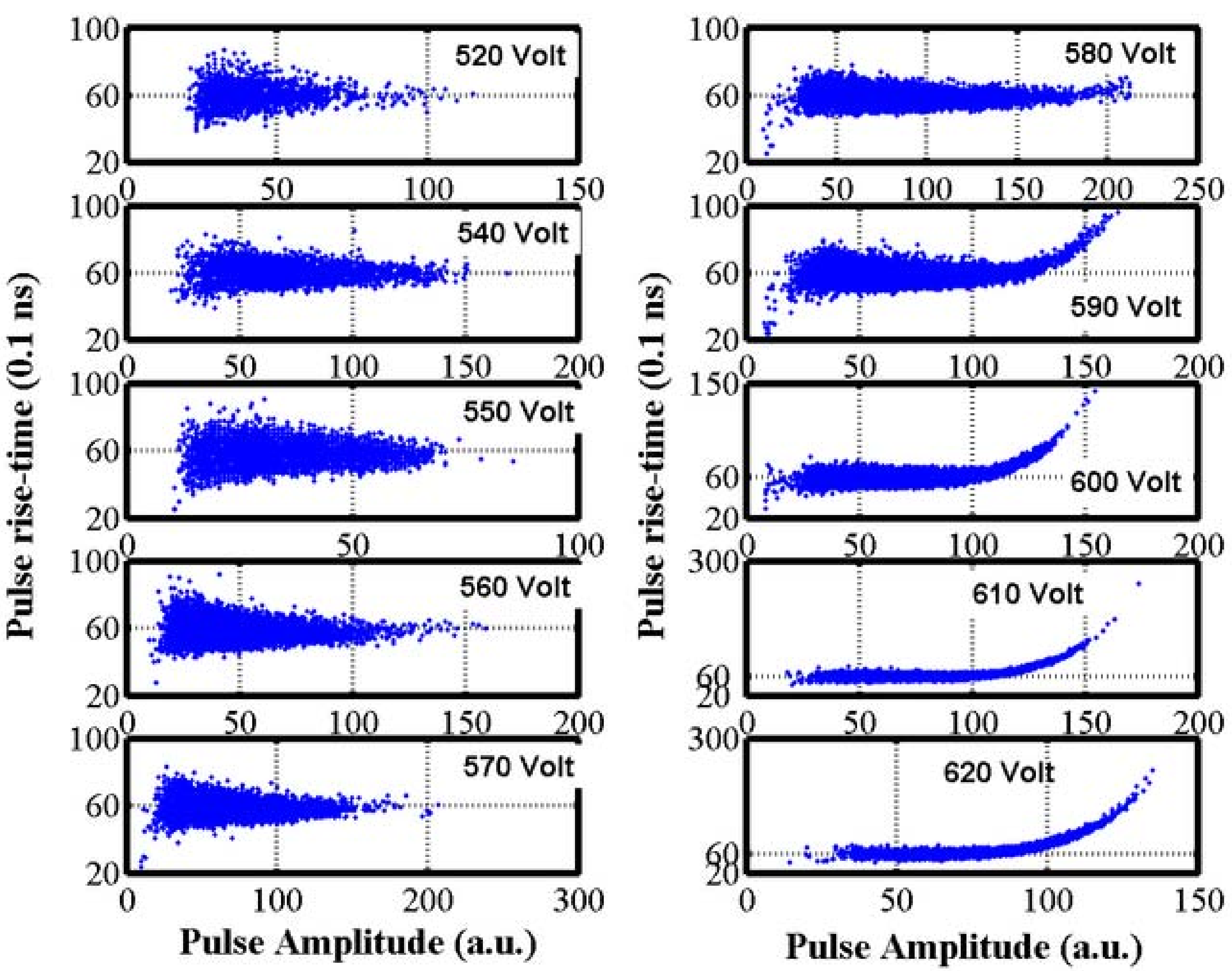
Figure(1)


DIGITAL OSCILLOSCOPE
HV
Collimator
Alpha Source
Preamplifier
Avalanche counter

Figure(2)

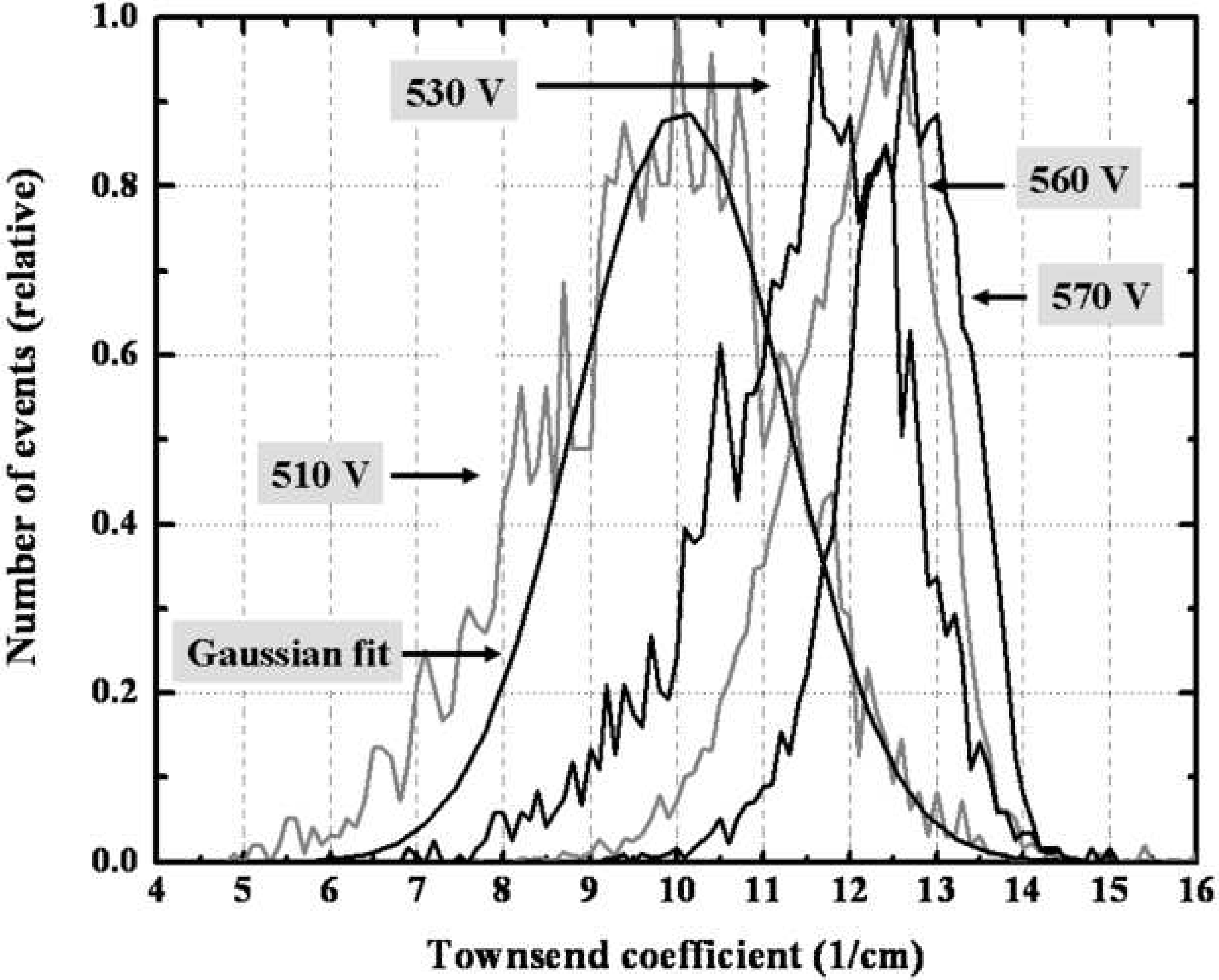

(A)
Amplitude (a.u.)
60
40
20
0
0
500
1000
1500
2000
2500
3000
Time (Ch)
(B)
x 10^4
Amplitude (a.u.)
8
4
0
Electron component
Ion component
0
500
1000
1500
2000
2500
3000
Time (Ch)

Figure(3)



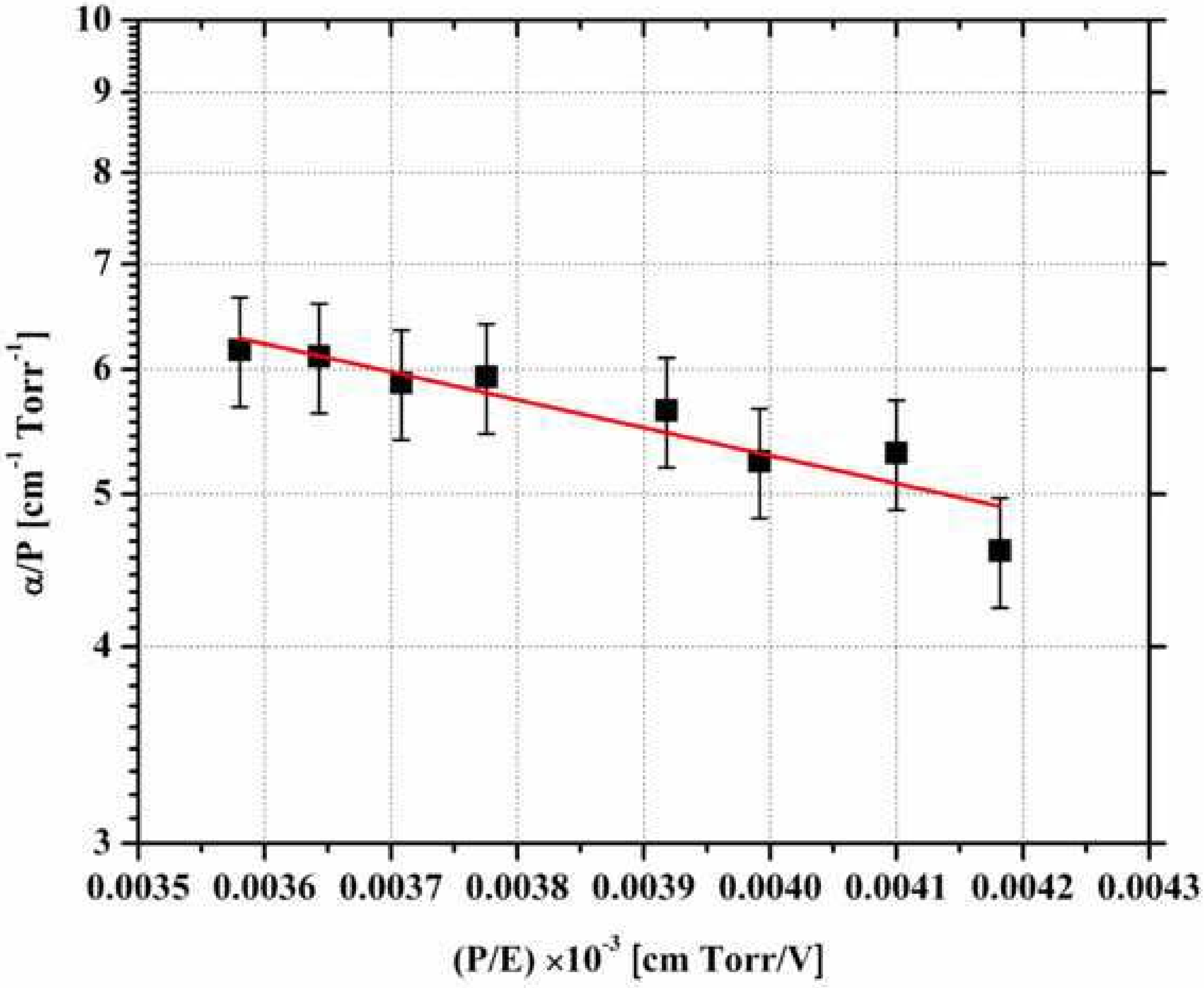
520 Volt
540 Volt
550 Volt
560 Volt
570 Volt
580 Volt
590 Volt
600 Volt
610 Volt
620 Volt
Pulse rise-time (0.1 ns)
Pulse Amplitude (a.u.)

Figure(4)



1.0
0.8
0.6
0.4
0.2
0.0
Number of events (relative)
4
5
6
7
8
9
10
11
12
13
14
15
16
Townsend coefficient (1/cm)
530 V
560 V
570 V
510 V
Gaussian fit

Figure(5)


α/P [cm⁻¹ Torr⁻¹]
10
9
8
7
6
5
4
3
0.0035
0.0036
0.0037
0.0038
0.0039
0.0040
0.0041
0.0042
0.0043
(P/E) ×10⁻³ [cm Torr/V]