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Space-charge effects of positive ions on the development of pulses in parallel-plate avalanche counters

M. Nakhostin *, M. Baba

Cyclotron and Radioisotope Center, Tohoku University, Sendai 980-8578, Japan

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ABSTRACT

The effects of the space-charge of positive ions on the development of α-particle induced pulses in a parallel-plate avalanche counter (PPAC) were studied by using pulse-shape analysis techniques. The analyses were separately carried out on the electron and the positive ion components of the pulses, reflecting the space-charge effects during and after the multiplication of charges in an external uniform electric field. Some calculations of the space-charge electric field and the first Townsend coefficient were carried out to explain the experimental waveforms. The dependence of the shape of the pulses to the amount of primary ionization is particularly discussed.

1. Introduction

The multiplication of charges through building up electron avalanches in a gaseous medium and in the presence of an external uniform electric filed has been long used for radiation detection applications [1–3]. A strong uniform electric field is produced between two thin parallel-plate electrodes and the space between the electrodes (generally a few millimeters) is filled with a suitable gas. When primary electrons are created in the space between the electrodes, the drift and multiplication of charges in the strong electric field induces a detectable signal on the electrodes of the detector. The most common application of gaseous detectors with parallel-plate geometry, or the so-called parallel-plate avalanche counters (PPACs), is in the nuclear physics experiments involving heavily ionizing particles. In such applications, PPACs are operated at low gas pressures (normally below 10 Torr) and serve as a transmission detector, providing information on the attributes of charged particle beams such as intensity, timing and spatial distribution. Some examples of the current applications of PPACs in nuclear physics experiments can be found in Refs. [4–6]. PPACs have been also used at normal pressure forx-ray detection [7,8] and for building hybrid gaseous detectors in combination with multiwire or microstrip gas chambers [9,10]. Another application of PPACs is in the measurements of the parameters of gas amplification process in uniform electric fields [11–13].

The development with time of pulses in PPACs has been reported by Schmidt [14] and Draper [15] and in great details, in the comprehensive study of Sauli [16]. In these studies, the shape of pulses was calculated based on the existence of a uniform electric field in a detector's gap. However, when the amount of charge generated in the detector becomes significant, the electric field is not uniform anymore because it is distorted by the space-charges of positive ions and electrons. The space-charges cause a dynamic deformation of the electric field distribution in the detector's gap which strongly affects the drift and multiplication of charges in the detector. The space-charge effect was recognized in PPACs operating under high gas amplifications as a slowdown in the rise of the amplitude of the pulses with the bias voltage [17] and also as a deviation from the linear dependence between the amount of primary ionization and the pulse amplitude [18,19]. The space-charge effects have been widely studied in the field of the investigation of electrical discharge (e.g. Refs. [20–22]), and in the field of gaseous radiation detectors (e.g. Refs. [23,24]). However, with the development of fast waveform digitizers and the availability of low noise and wide bandwidth current-sensitive preamplifiers, it is now possible to study the gas amplification process through an event-by-event analysis of the shape of output pulses. By using digital techniques, it has been recently shown that, under the space-charge effect condition, the shape of current pulses from PPACs is correlated with the amount of primary ionization, leading to a pulse-shape discrimination property [25]. In this paper, we further study the reflection of the space-charge effect on the shape of current pulses from a PPAC by using digital techniques. The pulse-shape analysis is separately performed on the electron and the positive ion components of the pulses and some calculations

* Corresponding author. Current address: Department of Physics, University of Surrey, Guildford, UK. Tel.: +44 1483 686113; fax: +44 1483 686781.
E-mail address: Nakhostin.m@gmail.com (M. Nakhostin).

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based on the basic relations governing the gas amplification process are performed to explain the waveforms. The dependence of the temporal shape of the pulses to the amount of primary ionization is particularly discussed.

2. Experimental setup

The results presented in this work were obtained with an avalanche counter of 5×5 cm^2. The electrodes of the counter were made of 6 μm aluminized Mylar foil, well stretched over glass-epoxy frames. The gap between the electrodes of the detector is 3 mm. The detector is enclosed by a vacuum chamber and the chamber is flushed with an isobutane (i-C_4H_{10}) gas at 6.9 Torr of pressure. The pulses initiated by α-particles from ^{241}Am are read out with a fast current-sensitive preamplifier with a rise-time of 1 ns. The detector and the preamplifier are connected together with a 50 Ω cable (10 cm long). The preamplifier pulses are digitized by means of a fast digital oscilloscope at a sampling interval of 100 ps and with 8 bit resolution. The oscilloscope has 1 GHz of bandwidth. The digitized pulses are then analyzed by using a program written in MATLAB.

3. Pulse-shape analysis

A current pulse from a PPAC consists of a fast electron component followed by a slow component induced by the drift of positive ions. The different durations of the two components of the pulses is due to the fact that, in low gas pressure PPACs, the drift velocity of electrons is at least one order of magnitude larger than that of positive ions (see following sections). The significant difference in the time scale of the electron and the positive ion components of current pulses enables one to separate the electron component by passing a digitized pulse through a digital pulse differentiator whose time constant is small enough to only pass the fast electron component. The positive ion component of the pulse can be then obtained by subtracting the electron component from the whole signal. The separated electron and the positive ion components of a typical current pulse are shown in Fig. 1. By separating the electron and the positive ion components of the pulses, the reflection of the space-charge effects on each component can be conveniently studied. In the following sections, the shape of pulses acquired from a bias voltage of 510 V at which current pulses appear at the output of the preamplifier to the maximum safe voltage of 640 V are analyzed.

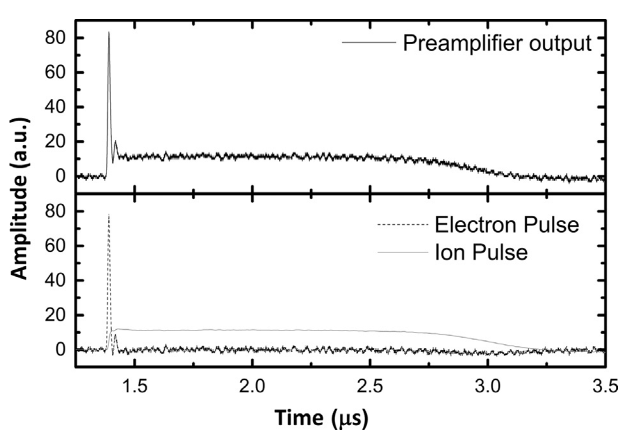

Fig. 1. Separation of the electron and the positive ion components of a current pulse by passing the pulse through a digital high-pass filter with a time constant of 80 ns. (Top) A current pulse at the output of the preamplifier. (Bottom) The separated electron and the positive ion components of the pulse. The small peak after the electron pulse is a pulse reflection due to an impedance mismatch. As a result of the high-pass filtration, the high-frequency noise on the positive ion pulse is significantly suppressed.

3.1. Analysis of electron pulses

The temporal shape of the pulses is analyzed by using the Shokley–Ramo theorem [26,27]. According to the Shockley–Ramo theorem, an electron current pulse can be described as

$$i_e(t) = e n_e(t) E_w v_e(t), \tag{1}$$

with i_e being the induced current, e the electron charge, $n_e(t)$ the number of electrons in the detector, E_w the weighting field, and v_e the electrons drift velocity. E_w only describes the coupling of the charge carriers movement to the readout electrode and is not to be confused with the electric field which determines the drift and multiplication of electrons inside the detector. In the case of a PPAC with an inter-electrode distance of d, the weighting field is simply given by $1/d$. On the other hand, the number of electrons $n_e(t)$ and the drift velocity of electrons v_e depend on the actual electric field intensity inside the detector. The instantaneous number of electrons is determined by the number of primary electrons, the rate of the multiplication of electrons across the detector's gap and the rate of the collection of electrons on the anode. The multiplication of electrons in uniform electric fields is described by the equation

$$n(t) = n_o e^{\alpha v_e t} \tag{2}$$

where $n(t)$ is the average number of electrons in an avalanche at a time t after its start, n_o is the number of primary electrons, and α denotes the first Townsend coefficient. The first Townsend coefficient is a function of the electric field and the type and the pressure of the filling gas and can be described by [28]

$$\alpha = APe^{-BP/E}, \tag{3}$$

where A and B are the gas constants, P is the gas pressure and E is the electric field. By assuming that in a thin gap of a low pressure gas the ionization density function of charged particles is constant and the electric field is uniform, the instantaneous number of electrons $n_e(t)$ is calculated as

$$n_e(t) = n_o e^{\alpha v_e t} - n_o \frac{v_e t}{d} e^{\alpha v_e t} = n_o \left(1 - \frac{v_e t}{d}\right) e^{\alpha v_e t}, \tag{4}$$

where the first term describes the multiplication and the second term describes the collection of the electrons. While Eq. (4) combined with Eq. (1) satisfactorily describes the shape of electron pulses at low voltages, at higher voltages the uniformity of the electric field is distorted by the space-charge effects and thus deviations from Eq. (4) are anticipated. Fig. 2 shows the electron pulses acquired at different voltages. The pulses were obtained by passing the digitized preamplifier pulses through a digital differentiator with a time constant of 80 ns. The time constant of the filter was chosen to be just greater than the maximum duration of the electron pulses at 640 V. The electron pulses exhibit a large spread in amplitude caused by the fluctuations in the energy-loss of α-particles, as well as, fluctuations in the gas amplification process. However, in spite of the large fluctuations in the amplitude of the pulses, in the voltage range of 510–580 V, the duration of the pulses remains independent from the amplitude of the pulses (Fig. 2A and B). The pulses quickly reach to their maximum value, leading to a fast rise-time of ~8 ns (10–90% of the pulses amplitude). The trailing-edge of a pulse happens when the rate of the collection of electrons on the anode exceeds the rate of the multiplication of electrons in the detector's gap. In our measurements, the trailing-edge of the pulses is affected with the decay-time constant of the preamplifier and thus is not used for pulse-shape analysis. It is worth mentioning that the most probable