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Performance of proportional counters filled with Xe + 5% TMA under high count rate-pressure scaling

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Abstract: The total space charge effect includes the cumulative effect of positive ions created from many different avalanches. The presence of positive ions in the avalanche multiplication region reduces the gas amplification factor. The gas gain has been measured for a low and high count rate by means of the current method for sealed cylindrical proportional counters of radius b = 12.5 mm with an axially placed anode of radius a = 50 µm. The gas gain curves covered the whole gas gain region from the ionisation chamber to that close to continuous discharge. The gas gain was determined for 5,9 keV X-rays of varying intensity and of constant high radiation intensity. For any count rate there is always a critical voltage, which divides the operation range of the counter into two regions, i.e. the region in which no changes in the gas gain with a count rate are observed and the region in which the space charge of positive ions reduces the gas gain. The values of current over which a 5% reduction in gas gain is observed have been determined. The measurements were made for a mixture pressure range from 294 hPa to 1800 hPa. The obtained results, which are presented here, can be favourable for micromegas-TPC operating in an Xe-TMA mixture.

Keywords: Gaseous detectors; Charge transport and multiplication in gas

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Contents

1 Introduction

The difficult operating conditions of radiation detectors impose strong restrictions on the choice of the working gas. The gas must guarantee the stable operation of the detector over a sufficiently high gas gain range, for a large integrated charge per centimeter of the anode wire and for a high intensity of the measured radiation. Counters filled with xenon-based mixtures are often used for X-ray astronomy [1] or in high energy physics experiments [2] due to a high absorption efficiency of Xe for hard X-rays. For the stable counter operation at high gas gains quenching agent have to be added to the main gas. Kr + H_2 [3], CO_2 [4], CH_4 [5] and CO_2-O_2 [6] are very good admixture to Xe thanks to which a very good energy resolution and high gas gain are obtained. However, the best quench gas for xenon is TMA (Trimethylamine, $N(CH_3)_3$) [7, 8] having an ionization potential of $\sim 7,75$ eV that lies just below the 8,32 eV metastable state of Xe. In this mixture, excitation energy of Xe atom can be used to ionize TMA molecule by the mechanisms called Penning transfers [9, 10]. Both the amplified charge and scintillation can be measured in this mixture [11]. The use of this mixture as the working gas in detectors in high energy physics experiments requires their work at high radiation fluxes. The increase of radiation intensity measured by a proportional counter leads to undesirable changes of its parameters, such as pulse height and energy resolution. It has been found that the pulse height significantly decreases with increasing radiation intensity. This change is called "count rate effect". The count rate effect known also as the total space charge effect includes the cumulative effect of positive ions created from many different avalanches [12–14]. The continuous decrease in the gas amplification factor results from the presence of slowly moving positive ions in the avalanche multiplication region. Very preliminary results of the measurements of detectors performance under high count rate filled with this mixture are included in ref. [15]. In this paper the performance of counters filled with Xe + 5% TMA at a mixture pressures, p, from 294 hPa to 1800 hPa under high count rate conditions is presented. The upper limit of the particle flux (to avoid the electric field deformation) is determined.

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2 Measurements

The measurements were carried out not only for single anode and side window but for cylindrical proportional counter as well. This counter was filled with Xe + 5% TMA mixture with a total pressure from 294 hPa to 1800 hPa. The counter possessed W(Au coated) anode 100 µm in diameter, and a brass cathode 25 mm in diameter. The gas gain has been measured as a function of the applied anode voltage for a low (figure 1) count rate by means of the current method. Figure 2 clearly shows the effect of rate. The gas gain curves are measured in a wide range from the ionization chamber regime up to that close to breakdown limit. Gas gain was determined for 5,9 keV X-rays (^{55}Fe radiation source) of varying intensity, the current flowing through the counter was always below 400 pA, (figure 1) and of constant high radiation intensity, (figure 2). The irradiated area was 1 cm of the anode length. Details on the gas gain measurements are given in appendix A. The arrow in figure 2 shows the anode voltage at which the gas gain curves measured for a low and for a high flux of radiation start to separate [16, 17]. In the region below the arrow no changes in the gas gain with a count rate are observed. Above the arrow there is already an influence of the space charge of positive ions in the avalanche multiplication region, which reduces the gas gain.

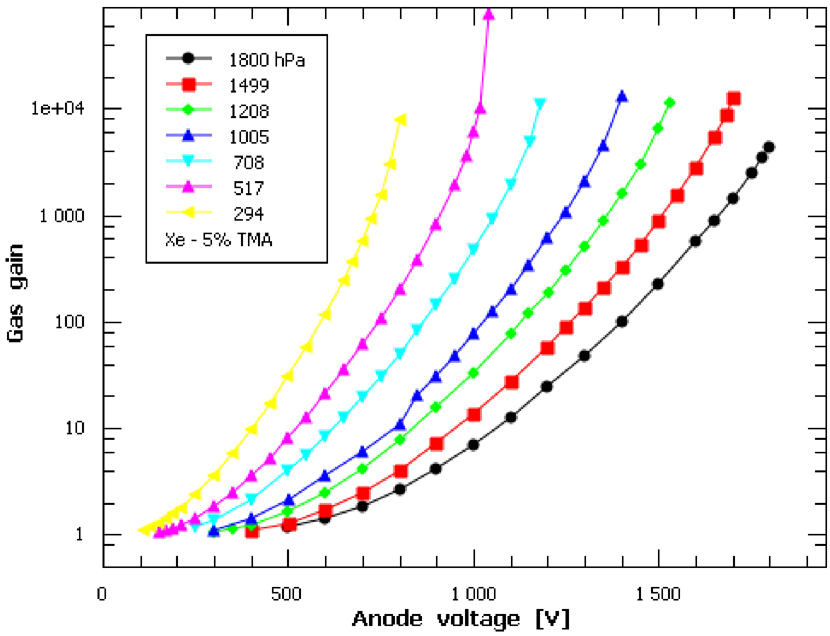

Figure 1. Gas gain as a function of applied anode voltage. To eliminate the space charge effect, the current flowing through the counter was always below 400 pA.

3 Data analysis

The value of the current, for the voltage indicated by the arrow in figure 2, at which these curves separate is named I_{cr} (critical current) and depends on mixture pressure. The 5% reduction of gas gain was assumed as the criterion for the I_{cr} determination. Determined in this way I_{cr} as the function of mixture pressure is shown in figure 3. I_{cr} increases with decreasing mixture pressures,

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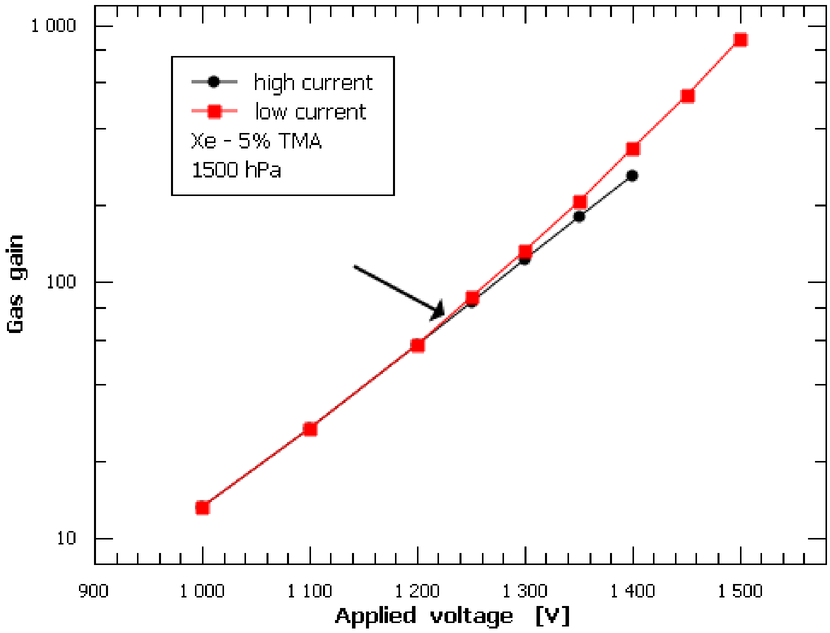

Figure 2. Gas gain as a function of the anode voltage for a low and high count rate (example). The arrow indicates the start of the gas gain curves separation and the start of the total space charge effect manifestation.

especially for a mixture pressures below 1000 hPa. It is associated both with an increase in the electron avalanche radius and with an increase in ion drift velocity [18]. The radiuses of the electron avalanche zone are determined from the Diethorn equation (details are given in [19]) and are displayed as the function of the gas gain in figure 4. It is clearly seen that the curves for the mixture pressures higher than 1000 hPa lie very close together, while the curves for the lower mixture pressures separately, distinctly above them. For the lower mixture pressures the density of the space charge around the anode is reduced. Lower charge density means both the less deformation and the less degradation of the electric field in the electron multiplication region.

The current, I, flowing through the counter can be expressed by the following expression [16]:

$$I = \frac{\Delta E}{W} \times A \times R \times e, \tag{3.1}$$

where ΔE is the deposited energy by a single registered particle, W is the energy required to produce an ion-electron pair, R is the count rate in cps, e is the elementary charge and A is the gas gain. Thus, R can be calculated from equation (3.1)

$$R = \frac{I \times W}{A \times \Delta E \times e}, \tag{3.2}$$

and

$$R_{\max} = \frac{I_{\text{cr}} \times W}{A \times \Delta E \times e}, \tag{3.3}$$

where $R_{\max}$ is the maximal intensity of the counted particles (in cps) and I_{cr} is the highest current that can flow through the detector without deforming the electric field (the current corresponding

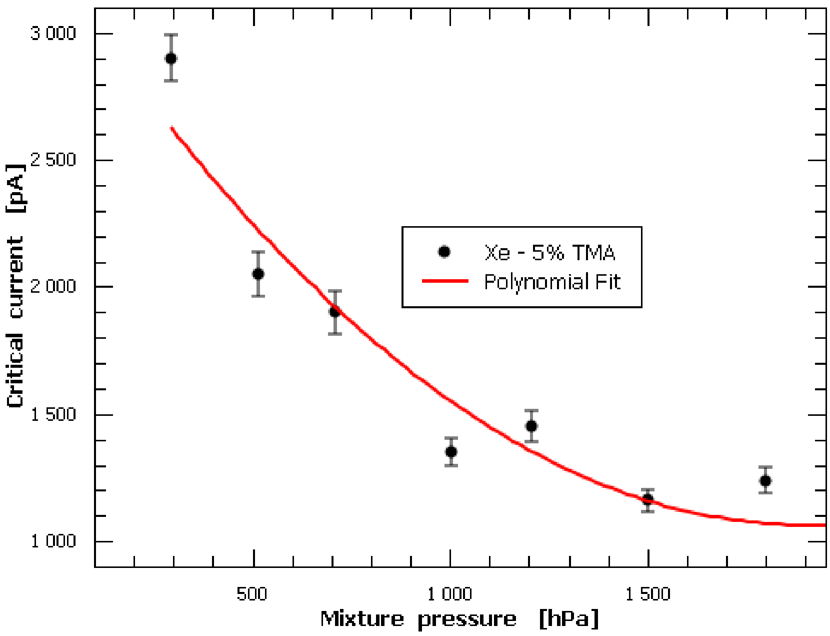

Figure 3. Values of critical currents over which 5% reduction in the gas gains are observed as the function of the mixture pressure. The Polynomial Fit is given only to guide the eyes.

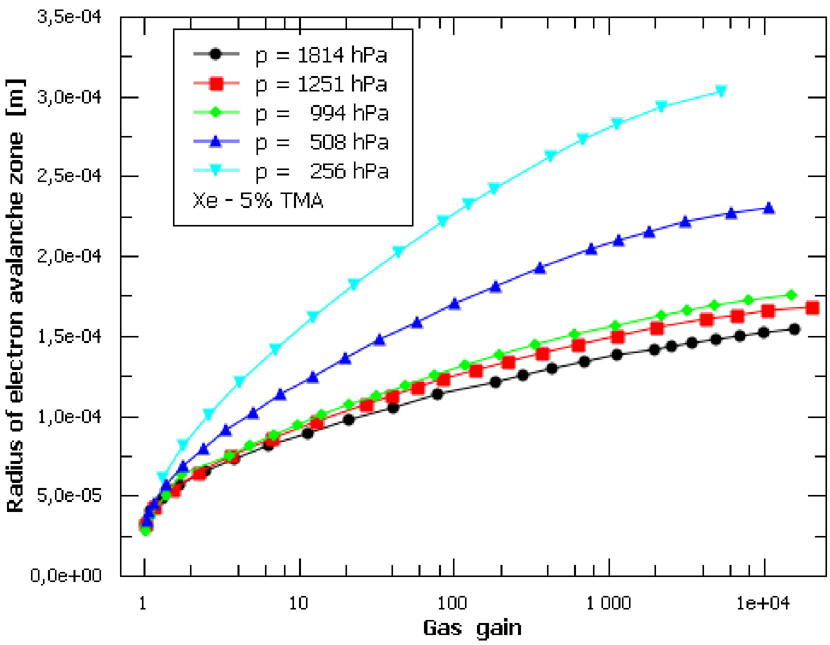

Figure 4. The radius of the electron avalanche zone as the function of gas gain for different mixture pressures. The values of the radiuses of the electron avalanches are calculated from the Diethorn formula.

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to anode voltage shown by the arrow in figure 2, for which the gas gain is reduced by 5%). For the point indicated by the arrow in figure 2 the $R_{\max}$ is $\sim 10^5$ cps for a deposited energy of 5,9 keV (^{55}Fe radiation source) and for the gas gain $A \sim 100$.

4 Short summary

The gas gain has been measured as a function of the applied voltage by means of the current method for sealed cylindrical proportional counters of radius b = 12, 5 mm with an axially placed anode of radius 50 µm, from the ionisation chamber to that close to continuous discharge for Xe + 5% TMA mixture, for the mixture pressures from 294 hPa to 1800 hPa, for the low and high rate of the incoming photons. Measured gaseous gain are as high as 10^4. The critical current, I_{rc}, over which the 5% reduction in the gas gain caused by the space charge around the anode was determined experimentally for each mixture pressure. The value of I_{cr} for the mixture pressures closed to 0,1 MPa is on the level of $\sim 1,5$ nA and is much lower than those presented in [20]. It was found that I_{cr} strongly depends on the mixture pressure and increases with decreasing pressure. It is connected with the decreasing of the charge density. Two effects are responsible for the decrease in charge density:

(1) increase in the radius of the electron avalanche zone,

(2) increase in the ion drift.

Having the value of I_{cr} one can calculate the maximum flux of radiation that can be counted properly by the detector.

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A Details on the gas gain measurements

The determination of the gas gain coefficient using the current method depends on measuring the anode current at a changing anode voltage. In the first step, the saturation current (current with ionization and without multiplication), I_0, in the ionization chamber mode is determined, and then the current, I, for higher anode voltage, where there is already an avalanche multiplication of electrons. Dividing I/I_0, we calculate the gas gain, A. The advantage of this method is the ability to measure A in the full range of gas gains ($1 \leq A \leq 10^6$) using a source of soft X-rays. The difficulty of the method is to accurately determine the current I_0, mostly on the level of pA, and to eliminate the influence of the space charge at a gas gain higher than 100. The current in the ionization chamber mode is about 100 times greater than the dark current. The effect of the space charge can be eliminated by decreasing the intensity of the radiation so that the current measured by the electrometer does not exceed a certain critical value. Practically, this means that the measurement of the gas gain is performed in several stages, in the range of the gas gain from 1 to 100, then of up to 10^4 and next for higher values. In each of these ranges, a different intensity of radiation is used.

The multiplication of electrons in cylindrical electric field is described by the following relationship:

$$dN = \alpha(r) N dr \tag{A.1}$$

where: dN is the increase in the number of electrons formed in the collision ionization process on the path dr in the direction of the electric field lines from the point distant by $r + dr$ to the point distant by r, N is the number of electrons in the distance $r + dr$, and α(r) is the first Townsend ionisation coefficient.

In the counters working in the proportional mode, the anode is made of thin wire with a radius of several dozen µm, which causes a high non uniformity of the electric field. The research and computer simulations have shown that the avalanche multiplication of electrons begins at a distance of a few

radii of the anode wire from its surface. So, the multiplication of electrons occurs in a highly non uniform electric field. Equation (A.1) for cylindrical geometry can be written in the form:

$$\int_{N_0}^{N} \frac{dN}{N} = -\int_{c}^{a} \alpha(r)\, dr \tag{A.2}$$

where: N_0 is the numbers of electrons of the total primary ionization, N is the final number of electrons after avalanche multiplication and c is the distance from the centre of the anode wire at which the multiplication starts.

By integrating the left side of the equation (A.2) one obtains:

$$\ln \frac{N}{N_0} = \ln A = -\int_{c}^{a} \alpha(r)\, dr \tag{A.3}$$

where A is the gas gain factor. There is no fundamental expression for the Townsend coefficient α(r), it has to be measured for every gas mixture.

Diethorn [21] derived a linear relation for the Townsend coefficient:

$$\frac{\alpha}{p} = CS \tag{A.4}$$

and calculated:

$$\frac{\ln A}{paS(a)} = C \ln S(a) - K, \tag{A.5}$$

and

$$\frac{\Delta \ln A}{\Delta U} = D \ln U + B, \tag{A.6}$$

here C and K are characteristic constants for the mixture, D and B-constants which depends on the mixture type and counter geometry, $S(a)$-reduced electrical field at the anode surface, U-anode voltage, p-mixture pressure. Due to equation (A.6) the $\frac{\Delta \ln A}{\Delta U}$ is monotonic function of $\ln U$ without any jump.

Figures 5 and 6 show the tangent of the angle of inclination of the gas amplification curve, i.e. the expression $\Delta \ln A/\Delta U$ as a function of the voltage between the anode and the cathode. Characteristic is a strong increase in the slope of the gas amplification curve above the $U = 1100$ V, which is associated with the occurrence of secondary effects described by the second Townsend ionization coefficient, β, [22, 23]. The slope of the gas gain curve corrected due to the β coefficient

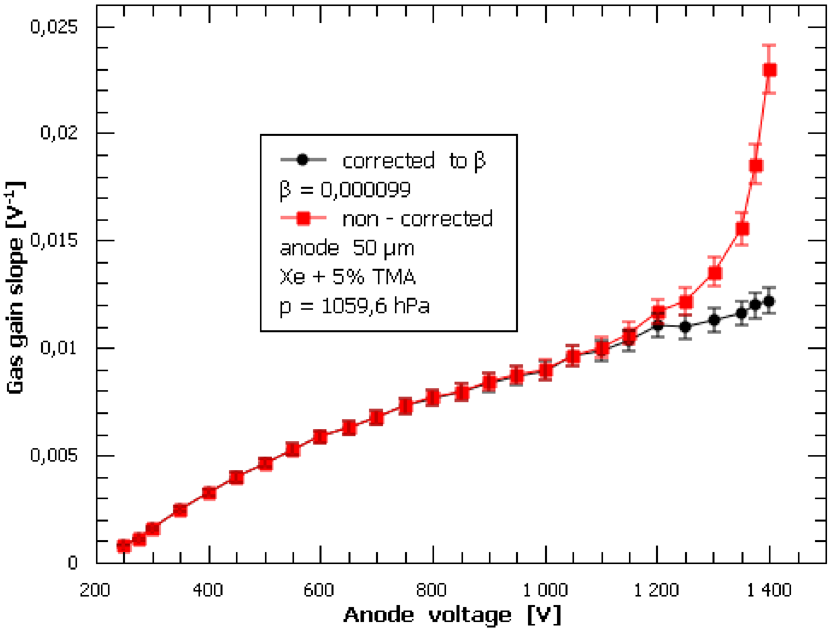

Figure 5. The slope of the properly measured gas gain curve, the raw data and that corrected to the β coefficient, versus the anode voltage.

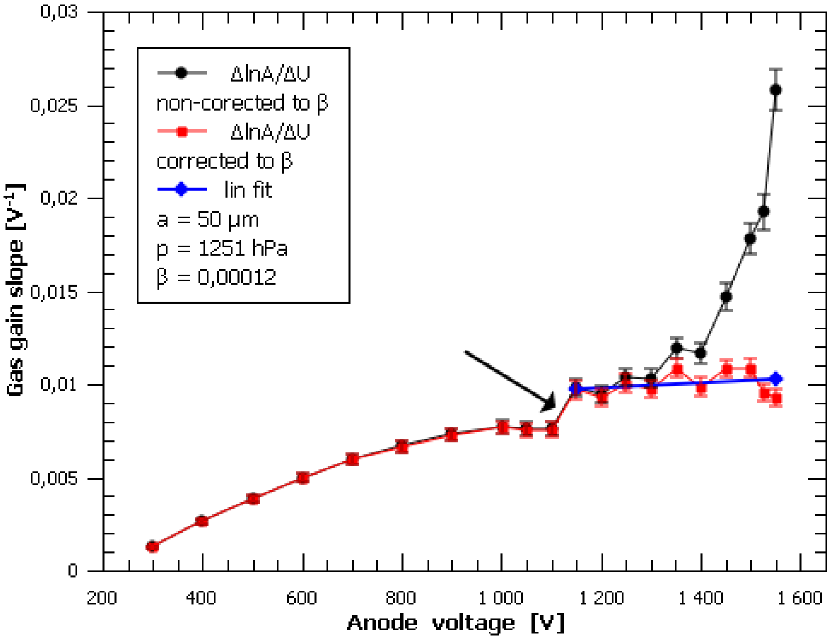

Figure 6. The slope of the improperly measured gas gain curve, the raw data and that corrected to β coefficient, versus the anode voltage. The arrow indicates the rapid change in the slope due to the space charge deforming the electric field close to the anode surface.

is also shown. Figure 5 shows the slope of the properly measured gas gain curve. In figure 5, the arrow indicates the voltage at which the reduction in the radiation source intensity was made. A jump on the slope of the gas gain curve is observed. To the left of the arrow, the slope of the gas gain curve is too low, what is due to the space charge deforming the electric field around the anode. The current flowing through the counter at this voltage before the reduction of the radiation intensity was 1.46 nA. Summing up, the calculation of the slope of the gas amplification curve can be an indicator of the correctness of the gas gain measurements.

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