LOW-PRESSURE MULTISTEP DETECTORS – APPLICATIONS TO HIGH ENERGY PARTICLE IDENTIFICATION *

A. BRESKIN and R. CHECHIK **

Physics Department, Weizmann Institute of Science, Rehovot 76100, Israel

Multistep avalanche chambers operating at low gas pressures (10−40 Torr) can efficiently detect and localize single electrons, due to attainable amplification factors of the order of $10^8$. When filled with TMAE vapors such devices present several advantages for UV photons detection, and are presently applied for Cherenkov ring imaging. A new application for particle identification by $dE/dx$ measurements via low density cluster counting is discussed. Several parameters such as gain, diffusion and drift velocity of single electrons as well as a study of secondary effects are summarized for pure hydrocarbons and hydrocarbons + TMAE mixtures.

1. Introduction

Multistep detectors operating at low gas pressures [1] (2−40 Torr) are widely used for the detection of low ionization radiation [2]. The considerable increase in gaseous amplification, as compared to parallel plate avalanche counters or MWPCs [3], and their good timing and localization properties, make them an attractive tool for the detection of very low energy heavy ions, like evaporation residues in fusion processes [4,5], or low energy light ions as in the study of the Coulomb explosion of molecular ions [6]. These detectors have also been recently applied to the detection of slow neutrons [7], using appropriate converters, and of $\gamma$ photons using BaF$_2$ scintillation crystals [8]. One of the most attractive applications of low-pressure multistep chambers (LPMSCs) is, however, in the detection and localization of single electrons [9]. Typical gaseous amplification factors of the order of $10^8$ ensure detection efficiencies close to 100%. Single electrons can be localized with high accuracies as shown in fig. 1, limited mainly by the diffusion in the gas. The detection can be done at high counting rates due to the low charge densities of the avalanches and the fast removal of positive ions.

An idea to use this technique for UV photon localization with TMAE [Tetrakis(dimethylamine) ethylene]-filled devices [10] gave rise to a new photosensitive detector for Cherenkov ring imaging [11,12]. Its properties will be discussed below.

We are presently investigating the idea of using LPMSCs for particle identification by $dE/dx$ measurements via cluster counting, taking advantage of the low ionization (cluster) densities and the enhanced relativistic rise at low gas pressures. The method will be discussed in the present work.

We have studied intensively the properties of LPMSCs, operated with single electrons, using pure hydrocarbons and hydrocarbon−TMAE mixtures [12]. The results such as gain, transport coefficients of single

![Fig. 1](image)

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electrons and secondary effects will be summarized here.

2. Mechanism of operation of LPMSCs

The operation mechanism of the multistep chamber (see fig. 2) is based on dividing the amplification process into two steps [13]: an initial avalanche in a preamplification gap, limited by parallel grids, and further amplification in a second element, a parallel grid or a multiwire proportional chamber. The two steps are separated by an intermediate transfer region. Its function is to absorb UV photons produced in the gas during the avalanche process and to trap part of the back-drifting positive ions. This gap may also be used for gating purposes [13]. In the present application the preamplifying element is preceded by a conversion region from which ionization or photo produced electrons drift to the preamplifying element. The total amplification factor of such a detector is equal to the product of the individual gains of each element multiplied by the transfer efficiency of the preamplified charge (roughly equal to the field ratio of the transfer to the preamplifying element) [13]. An efficient transfer of the preamplified charge can take place only if the initial avalanche has a substantial lateral spread. This is the case in low pressure hydrocarbons where the electron diffusion in the course of the amplification process leads to a broad avalanche of 1–2 mm (fwhm) [3].

3. Properties of LPMSCs with single electrons

3.1. Experimental setup

In view of the application of LPMSCs to particle identification we have built a prototype detector to study the physical properties of single electrons at various operation conditions [12]. The circular detector, shown in fig. 2, has a 30 mm conversion region followed by a parallel-grid preamplification stage (3 mm gap). The preamplified charge is transferred over a distance of 30 mm to a MWPC. The position readout is done, for the purpose of the study, by tapped delay-lines coupled to the cathode wires that run in orthogonal directions. The UV source is a discharge H₂ lamp having a MgF₂ window. UV photons enter the detector through 100 μm × 10 mm slits and a Tetrasil quartz window coated with a 50 Å NiCr layer. Photoelectrons created at various depths of the absorption region, on the window electrode and on the cathode of the preamplifying element, reach the MWPC at different times with respect to the time zero signal provided by the UV lamp.

The detector operates in a flow mode, to avoid...
outgassing problems, with pure gases or with gases flowing through a TMAE-filled bubbler immersed in a temperature-controlled bath. The commercial TMAE was washed with distilled water and dried with normal silica gel. The achieved purity was sufficient for a stable detector operation. A more sophisticated purification method can be found elsewhere [14]. The detector is mounted in a stainless steel vessel, evacuated before gas filling to a vacuum of $10^{-5}$ Torr. The vessel temperature is maintained at a few degrees above the TMAE-bubbler temperature to avoid condensation.

### 3.2. Properties

We have studied pure ethane and isobutane or each of them mixed with a few per cent of TMAE. Methane was also tested but not systematically studied because of its relatively poor gain ($\sim 10^8$). The detector pressure was kept at 20 or 40 Torr and the liquid TMAE temperature was 27°C or 40°C, $p = 0.6$ or 1.5 Torr, respectively [15]. (In the case of the higher temperature we could not efficiently control the TMAE vapour pressure inside the detector. Due to condensation effects this pressure might have been lower than that expected for the vapour in equilibrium with the liquid in the bubbler.)

The following properties were studied:
- Total amplification factor.
- Longitudinal and transverse diffusion.
- Electron drift velocity.
- Secondary effects.

During all measurements particular care was taken to ensure that only single photoelectrons are detected. The properties are summarized here; a more detailed description is given elsewhere [12].

#### 3.2.1. Amplification

Amplification curves are shown in fig. 3 as a function of the potential applied to the MWPC final step. The parallel grid gain was kept constant at about $5 \times 10^4$. For the various operation conditions such as gas pressure, parallel grid preamplification or transfer fields (3–8 V/cm Torr), we have found about the same total amplification limit of $\sim 10^8$ (detected charge of $\sim 15$ pC). Typical current pulses of single and multiple photon events are shown in fig. 4.

#### 3.2.2. Transport coefficients

Electrons are photoproduced by the UV source in the following parts of the detector: the entrance window NiCr surface, the various electrodes and the gas itself (if TMAE is added). Only electrons submitted to the full double-step amplification can be detected, namely those that are produced within the conversion volume.

Taking the time pickup from the UV-source as a reference, longitudinal diffusion could be measured in pure gases by recording the fluctuations in the arrival time of electrons photoproduced on the window electrode and the parallel grid cathode. The results are summarized in fig. 5 as a function of the reduced electric field $(E/p)$ in the conversion gap. The drift velocity could be accurately measured from the arrival time of electrons produced on the two electrodes, 30 mm apart. The data are presented in fig. 6. The transverse diffusion was measured by recording the fluctuations in the localization of photons traversing the collimation slits. These fluctuations could be measured in pure gases for electrons produced on the two electrodes,
and in gas + TMAE mixtures for electrons produced all along the conversion region. Dividing the conversion region into several time-slices, we could record position spectra of photons absorbed at various depths. The transverse diffusion data are shown in fig. 5. From the transport coefficients data we can learn the following:
- Drift velocity in isobutane-TMAE is a slightly increased in comparison to pure isobutane. It seems that the increase is higher in ethane (two measured points only).
- Longitudinal diffusion is lower in ethane while the transverse diffusion is higher as compared to isobutane.
- Adding TMAE to isobutane does not change the transverse diffusion while that of ethane decreases (two measured points only).

The measured diffusion values are in agreement with calculated data [16,17].

### 3.2.3. Secondary effects

Secondary effects in gaseous detectors are major factors limiting the amplification. Secondary avalanches in photosensitive mixtures mainly arise from avalanche photons photoionizing the gas or producing photoelectrons on the various electrodes. We have quantitatively studied this effect, clearly shown in fig. 7. We have measured the ratio between the number of secondary and primary avalanches in various conditions as shown in fig. 8. This ratio is geometry dependent; in our particular case, the secondary avalanches are produced in an average solid angle of 2–3 sr. The measured secondaries could be produced on the preamplifier grid.

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**Fig. 4.** Current pulses from the LPMSC of fig. 2 (anode of the MWPC) obtained with a fast current preamplifier (gain of 200). Operation conditions: \( p = 20 \) Torr isobutane+TMAE (40°C), \( \text{HV1} = -1280 \), \( \text{HV2} = -1220 \), \( \text{HV3} = -260 \), \( \text{HV4} = +790 \) V. (a) Pulses of single photon events, 20 ns and 50 mv/div. (b) A multiphoton event, 50 ns and 50 mv/div.

**Fig. 5.** Transverse and longitudinal diffusion of single electrons for 1 cm drift. The diffusion coefficients were measured, and are given, for a pressure of 20 Torr (left scale), and are also extrapolated for atmospheric pressure (right scale). Calculated data – refs. [16,17].

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or in the conversion gas. It is shown, for example, that an effect of 0.5% is measured in pure isobutane at a gain of $10^8$ and that ethane, having worse photon-quenching properties, yields a 3% effect. Adding TMAE increases dramatically the secondary to primary ratio to values above 30%. However, one should note that the detector operation is not affected by this phenomenon. In fact, the secondary electrons arrive at the MWPC only after a time delay equal to their drift time along the transfer region (see fig. 7). If the transfer time is longer than the maximum drift time along the conversion region, the secondary effects could be discarded by inhibiting the electronics after the arrival of the last "real" electron to the MWPC element. This is a unique feature of the multistep amplification structure.

Fig. 6. Drift velocity of single electrons as a function of the reduced electric field in the conversion region.

Fig. 7. Current signals measured with the LPMSC of fig. 2, irradiated with UV photons. Gas = C$_2$H$_6$ + TMAE(40°C), $p = 20$ Torr. (a) Gain of $5 \times 10^7$, (b) $5 \times 10^8$. The main avalanche pulse is followed by a train of secondary pulses. The delay time of ~ 600 ns between the main and secondary pulses, due to the drift time in the transfer gap, is clearly seen.

Fig. 8. Fraction of secondary avalanches as a function of total gain in the LPMSC, for various gases and pressures. The effects of secondary avalanches originating from the preamplifier cathode grid and from the conversion gap gas volume are shown.
4. UV photon detection

4.1. General considerations

The imaging of UV photons is of great importance mainly in the domain of high energy physics and astronomy. It is usually achieved by means of wire chambers in which one detects secondary electrons photo-produced in photosensitive gas media [18]. The method is widely applied to particle identification by means of Cherenkov ring imaging [19] and recently to high energy calorimetry using photosensitive wire chambers coupled to BaF₂ scintillators [20].

These applications require high quantum efficiency for the photoelectric effect, high amplification capability to ensure an efficient single electron detection and good localization properties. The most efficient photosensitive vapor used for the UV photoconversion is TMAE having a photoionization threshold as low as 5.4 eV, a vapor pressure of 0.3 Torr at room temperature [15], and a quantum efficiency reaching about 60% at λ ~ 150 nm [21]. The techniques presently being used for UV-photon sensing in Cherenkov ring imaging are drift chambers [22] and multistep avalanche counters [23], both operating at normal gas pressures. Their properties are summarized by Seguinot in the current proceedings [21]. Both types of detectors suffer from limited amplification due to the high avalanche density and to secondary parasitic avalanches. This problem is particularly crucial in drift chambers, where special care has to be taken in the design of the sensing elements [21]. In the multistep chambers most of the parasitic photons are reabsorbed in the transfer region; however, the gain is still limited due to electrostatic grid deformation at high applied potentials. Other limitations in normal pressure operation come from the sensitivity to background ionizing particles, which sometimes create more primary charges than the Cherenkov photons themselves. Photosensitive LPMSCs filled with TMAE vapors can provide an efficient solution to Cherenkov ring imaging and will benefit from the following characteristics:

- very high gaseous gain (10⁵) and therefore high detection efficiency for single photoelectrons and cheaper electronics;
- low sensitivity to ionizing particles and thus more convenient operation in high background experimental environment, leading to less ambiguous image reconstruction;
- fast signals, allowing an efficient use of multihit electronics to obtain depth information by a “time-sliced” readout of the conversion region [24];
- non-sensitivity to secondary effects;
- lower self-absorption of UV photons in the carrier gas;
- high rate capability due to low charge density and fast removal of positive ions;
- low operating potentials.

4.2. Application to RICH

The LPMSC technique is presently being applied to Cherenkov ring imaging in the NA34 (HELIOS) relativistic heavy ion experiment at the CERN SPS [25]. The RICH is a part of an electron pair spectrometer designed to provide a signature to the existence of a deconfined state of quarks and gluons. It operates in a threshold mode, having the role of identifying electrons and rejecting a high hadron background (the ratio of hadrons/electrons is about 40:1). It consists of a 70 cm long CH₄ (atmospheric pressure) radiator coupled to a LPMSC photon detector through a CaF₂ window. The photon detector is of an annular geometry having an external diameter of about 1.4 m. Photoelectrons converted at various depths are preamplified in a parallel grid element and transferred to a MWPC (same scheme as shown in fig. 2).

The optimization of the various detector parameters, such as its geometry (conversion and transfer depth), the operating conditions (gas mixture, gas pressure, TMAE temperature) and the read-out method, has to take into consideration the number of photons to be detected and the expected particle background. Most often there are contradictions between the optimal choice of each of the parameters. In order to achieve the best localization resolution for a single photoelectron, a narrow conversion gap and a high operation pressure would be the best choice (diffusion is a function of \( \sqrt{X/p} \)). However, this would require operation with high TMAE concentration (i.e. uncomfortably high temperature), necessary in order to maintain high conversion efficiency (a depth of 3λ is needed for 95% conversion efficiency, λ being the photon conversion length). A narrow gap is also incompatible with multihit readout electronics. A rather wide gap has to be used to allow the efficient detection of multiple photons. In cases of high background, a gas having a low ionization density has to be chosen and the pressure has to be reduced to values compatible with the worst tolerable localization resolution.

In the present application we expect to record about 10 Cherenkov rings per event. Each ring, of ~ 7 cm diameter, is composed on the average of 12–15 photoelectrons. The expected background is rather high: about 30 ionizing particles, on the average, will traverse the sensitive volume. Aiming for the highest possible photodetection efficiency the following operation parameters are chosen:

- A conversion gap of 30 mm;
- TMAE temperature of 30°C (λ ≈ 10 mm) [15];
- \( \text{C}_2\text{H}_₆ \) at 40 Torr (~ 1.5 ion pairs/cm are deposited by a minimum ionizing particle).

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With these conditions the transverse diffusion is \( \sigma_t = 1.1 \text{ mm} \) (for an average electron drift distance of 20 mm). This number meets the present experimental requirements [25]. The particle background will yield about 150 primary charges, a number equivalent to that of the photoelectrons. We would like to emphasize here the importance of the low gas density, which is indispensable in the present application. Monte Carlo simulations [26] have shown that the cathode wire read-out is by far superior as compared to the wedge-and-strip method [11] from the point-of-view of pileup-effects. 2 mm-spaced cathode wires (groups of 2 wires, 1 mm apart) yield, in the present case, a photomultiplier detection efficiency close to 95% while the wedge-and-strip method would yield about 60% efficiency with 50 × 50 mm² elements [26].

A prototype of the RICH detector is being actively investigated by the Heidelberg–Weizmann groups [25].

5. Particle Identification via Ionization-Cluster Counting

5.1. Overview

Particle identification in the relativistic rise region, by measurements of energy losses through ionizing collisions in thin gas samples, is a widespread method in high-energy physics. It is an indirect method, in which charges composed of several primary and secondary ionization clusters, produced in a gas sample, are collected and multiplied to provide a pulse proportional to the energy loss in the given sample. Many samples \( (N > 100) \) are needed to provide reasonable pulse-height resolution, due to the Landau fluctuations in the primary ionization process (ejection of energetic \( \delta \) electrons). The phenomenology of energy loss by ionizing collisions is well described in the literature [27,28].

A direct measurement of the number of primary ionization clusters can provide a more precise tool for the determination of \( dE/dx \). The statistics of counting \( n \) individual clusters follows a simple poissonian low with a dispersion proportional to \( \sqrt{n} \), considerably inferior to the Landau fluctuation. In addition, fluctuations in the amplification process have no influence on the resolution. The main problem related to counting individual clusters is their high density in normal counting gases, at atmospheric pressure \( (N_p = 20–50 \text{ clusters/cm}) \). Due to electron diffusion, clusters mix during the drift process. Furthermore, small cluster pulses are lost due to gain limitations.

Properties of cluster counting have been theoretically studied by Lapique and Piz [29]. Attempts to resolve individual clusters in low electric fields were made by Walenta et al. in the time expansion chamber [30,31]. The method was shown to suffer a considerable loss of clusters for the reasons described above.

We propose a technique of cluster counting at low gas pressures, using LPMSCs. The advantages are numerous:

- low gas density and therefore well-separated clusters (~ 2.4 per cm at 40 Torr of isobutane).
- High amplification and thus high single cluster counting efficiency.
- Increased relativistic rise, which extends over a wider momentum range, due to smaller polarization effects in the lower density media [32] (see experimental data in ref. [33]).
- Lower probability to produce energetic \( \delta \) electrons per detector length.
- \( \delta \) electrons can be rejected due to their long range in the low density gas.

5.2. Experimental set-up

To study low-pressure cluster counting we have built a LPMSC detector schematically shown in fig. 9. It can operate in two modes:

1. Active wire method

   Particles enter in a direction parallel to the sensing element. Electron clusters drift across the conversion region into the sensing element. The signals are processed by amplifier and discriminator circuits [34]. The number of activated anode wires is proportional to \( dE/dx \). In addition to the cluster counting, the measure of the time of arrival of charges to successive wires and the localization of the avalanches along each wire provide the track direction. The contribution of the diffusion of each single electron is averaged as the tracking is done by a multitude of measuring wires. Due to the tracking facility, an important fraction of energetic \( \delta \) electrons can be rejected by introducing proper time gate intervals.

2. Longitudinal drift

   Particles enter in parallel to the electric field in the conversion region. Single wires or groups of several wires record successive electron avalanches, as in the longitudinal drift sampling [35]. Due to the high gain, low impedance fast current amplifiers, having 10 ns shaping times, can be used. Fast discriminators provide the number of primary clusters.

Our detector has a total sensitive length of 500 mm and a conversion depth of 60 mm. The preamplifying element has a 3 mm gap followed by a 10 mm transfer region. The final element is a MWPC with 10 \( \mu \text{m} \) anode wires, 1 mm apart. A structure with an anode plane having alternating sense and field wires will also be studied. The detector was operated with pure isobutane at a pressure of 20 Torr, in the longitudinal drift mode. Fig. 10 shows pulses recorded with \( \beta \)-electrons from a \( ^{89} \text{Sr} \) source, at various electric field strengths in the
conversion region. Individual clusters are well separated.

A pulsed N₂ laser (MOPA 600 S) is presently being mounted to perform systematic resolution measurements of both operation modes.

5.3. Resolution considerations

The factors governing the cluster counting resolution are the following: cluster density, gaseous amplification, diffusion, attachment, detector length and depth, δ-ray density and their suppression capability and, for the particle separation, the relativistic rise behaviour. The relativistic rise and δ-ray suppression will be part of our future beam studies. Assuming the case of full detection efficiency of single clusters and no attachment in the gas, the remaining parameters are the gas density, diffusion and total track length.

Let us assume the case of the “active wire” method. We can define a certain quality factor Q for the resolution of individual clusters. Q is defined as the ratio between the average distance between neighbouring clusters (density effect) and the transverse diffusion parameter σₓ, for a given detector depth and gas pressure (see σₓ values in fig. 6). As an example let us take the case of isobutane (N₄ at atmospheric pressure is 46 i.p./cm), and a required quality factor of 3 (distance of 3σ between clusters). The detector can operate at a pressure of 50 Torr if its conversion region depth is of 20 cm [σₓ(10 cm) = 1.1 mm]. In this case, a detector having 2 m length will theoretically yield a resolution of √n/n = 4%. A detector having a 60 cm depth [σₓ(30 cm) = 1.9 mm] will have to operate at a pressure of 17
Torr for the same $Q$ value and a dispersion of $\sqrt{n} / n \approx 7\%$ is expected for a 2 m track length.

Using multihit electronics and also taking into account the longitudinal diffusion, clusters would also be resolved along the drift path, resulting in less severe density requirements and therefore in a better resolution for a given detector length. About 80% of the clusters are single electron clusters. Multiple electron clusters may increase the number of counts and their contribution has to be studied. A practical detector scheme may consist of a stack of several, short drift elements operating in one of the proposed modes.

6. Summary

In this paper we present two methods for high energy particle identification, based on low pressure multistep counter technique: UV-photon detection for Cherenkov ring imaging and $dE/dx$ measurements via cluster counting. The LPMSC is an efficient and flexible tool for the detection and imaging of single electrons, and is characterized by high gain, fast signals, high counting rate capability and low sensitivity to background radiation. The performances of the LPMSC and the physical properties of single electrons in pure and TMAE-mixed hydrocarbons are presented. An immediate application of this technique as a photon detector for RICH is described. In this particular application highly efficient ring imaging is required under a high hadronic background. The low-pressure operation presents a unique solution in this case. The method of $dE/dx$ measurement by primary-cluster counting using a LPMSC is discussed, and is presently being developed. This method takes advantage of the increase in the relativistic rise, at low gas pressures, and its extension over a wider range of momenta. It presents a powerful tool for high energy particle identification by combining an efficient cluster counting, tracking and good 8 electron rejection capability.

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