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Operation of gas electron multiplier (GEM) with propane gas at low pressure and comparison with tissue-equivalent gas mixtures

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ABSTRACT

A Tissue-Equivalent Proportional Counter (TEPC), based on a single GEM foil of standard geometry, has been tested with pure propane gas at low pressure, in order to simulate a tissue site of about 1 μm equivalent size. In this work, the performance of GEM with propane gas at a pressure of 21 and 28 kPa will be presented. The effective gas gain was measured in various conditions using a ^{244}Cm alpha source. The dependence of effective gain on the electric field strength along the GEM channel and in the drift and induction region was investigated. A maximum effective gain of about 5×10^3 has been reached. Results obtained in pure propane gas are compared with gas gain measurements in gas mixtures commonly employed in microdosimetry, that is propane and methane based Tissue-Equivalent gas mixtures.

1. Introduction

In microdosimetry [1] the effects of ionising radiation on biological targets can be experimentally investigated by measuring the statistical distribution of energy-deposition events at a microscopic level.

The reference instrument to carry on this investigation is the Tissue-Equivalent Proportional Counter (TEPC). A traditional TEPC is a proportional counter with a central anode wire operated with a tissue-equivalent (TE) gas mixture. For hadrontherapy application, commercial TEPC cannot be employed, because their large size does not allow to attain a good spatial resolution and because of pile-up of the electronic signals occurring in such high dose-rate radiation fields [2]. To reduce the effects of dead time and spectrum distortion due to pulse pile-up, the physical dimension of a TEPC must be reduced. In the last two decades, several groups have developed various types of mini TEPCs [3–6], by miniaturising the dimensions of all components of a conventional TEPC and employing a cylindrical geometry rather than the usual spherical one, otherwise preferred because it guarantees an isotropic response and because of the lowest relative variance of the chord length distribution [7]. A few attempts to develop a different kind of TEPC, based on a Gas Electron Multiplier (GEM) or Thick Gas Electron Multiplier (THGEM) are also reported in the literature, both for radiotherapy and radioprotection application [8–10]. The Gas Electron Multiplier (GEM) [11] is a two-side copper-clad Kapton foil, perforated with a high density of holes. These holes are commonly etched using a photolithographic process with a pitch of usually 140 μm and diameter of about 70 μm (so-called standard geometry). Application of a potential difference between upper and lower electrode creates a high electric field inside the holes. Inserted in the drift gap of a gas detector, nearly all drifting electrons are guided into these holes where they undergo proportional gas amplification. The big advantage of this detector type is the separation of drift gap, gas amplification and readout stage, resulting in the fact that the readout signal is only due to motion and collection of the electrons. This separation provides not only a margin of safety in case of discharges occurring in the GEM foils, it also allows high flexibility in the geometry of the readout structure. Besides, for microdosimetric applications, the separation between drift and amplification stage allows to measure spectra of energy deposition in small simulated site sizes, which are believed to be important for an improved understanding of the biological effects of densely ionising radiation [12]. In fact, while with single wire TEPCs the energy resolution becomes unacceptably poor when operating at pressures low enough to simulate diameters lower than some hundreds of nanometres, due to the enlargement

Abbreviations: GEM, Gas Electron Multiplier; THGEM, Thick Gas Electron Multiplier; TE, Tissue-Equivalent; TEPC, Tissue-Equivalent proportional Counter; TE-CH_4, methane-based Tissue-Equivalent gas mixture; TE-C_3H_8, propane-based Tissue-Equivalent gas mixture; SV, sensitive volume; PCB, printed circuit board; cps, count per second; FWHM, Full Width at Half Maximum; ENC, equivalent noise charge

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of the electronic avalanche region [13], the separation between drift volume and charge multiplication region obtained with a TEPC based on GEM allows measurements simulating some tens of nanometres with good energy resolution [14].

The application of a GEM for the design of a microdosimetric detector simplifies the construction of a miniature counter with a small sensitive volume to reduce pile-up effects [8] and the design of multi-element counter configurations to increase the sensitivity of the TEPC to measure very low radiation field [9]. In both the detector design of Farahmand et al. [8] and that of Orchard et al. [10], a solid TE structure host a cylindrical gas cavity in which the energy deposition occur and the released charge is then extracted and amplified by the GEM and finally collected at the readout anode. Differently, in the design of Dubeau and Waker [9] the TEPC is without side-walls, being delimited at the top by a TE drift electrode and at the bottom by the GEM, while the collection volume is defined by the size of the collecting anode strips. Strips are connected to a single readout channel, to acquire collectively the response of a large number of miniature individual sensing volumes.

The authors of this work have recently constructed a multi-element TEPC based on a single GEM foil as multiplying element, for hadrontherapy application. Similarly to the design of Dubeau and Waker [9], the collection volumes are without side-walls and are defined by the size of the collecting anode pads. In this detector yet the charge collected on different pads can be acquired independently, opening the experimental way to a two dimensional microdosimetric mapping of a radiation field.

In experimental microdosimetry, microscopic tissue sites of size D' are simulated by filling a cavity of geometrical size D with TE gases at low pressure: $D' = D\rho_{gas}/\rho_{tissue}$, where ρ_{gas} is the density of the gas and ρ_{tissue} is the density of the tissue, assumed to be equal to 1 g cm^{-3}.

The counting gases commonly used in microdosimetry are methane-based or propane-based TE gases, referred to as TE-CH_4 and TE-C_3H_8, respectively [15]. The components (percentage by partial pressure) of the former are 64.4% CH_4, 32.5% CO_2, and 3.1% N_2 and those of TE-C_3H_8 are 55% C_3H_8, 39.6% CO_2, and 5.4% N_2. The operation of GEM in these gas mixtures has been investigated by Farahmand et al. [14]: they found that the maximum safe gain is higher in TE-C_3H_8 gas rather than in TE-CH_4 gas and that this maximum occur for a gas pressure between 20–30 kPa, depending on the GEM geometries. GEM operation in TE-CH_4 was also investigated by Morimoto in a double GEM configuration [16]. Pure propane gas is also employed in microdosimetry, especially for space application, due to more stable behaviour on long-time operation and to higher gas gain with respect to TE-C_3H_8. The equivalence of microdosimetric spectra measured in TE-C_3H_8 and pure C_3H_8 has been proven when the gas density of pure C_3H_8 is reduced of a factor 0.75 as compared to TE-C_3H_8 in order to get the same equivalent site size [17]. The disadvantage of using pure C_3H_8 gas instead of TE-C_3H_8 gas is related to the different atomic composition of C_3H_8 (mass fractions: 18.3% H, 81.7% C) as compared with that of the commonly accepted TE-C_3H_8 gas mixture (mass fractions: 10.3% H, 56.9% C, 3.5% N, 29.3% O). As the properties of GEM in low pressure C_3H_8 are currently undocumented, in this work the effective gas gain of GEM has been investigated at 21 and 28 kPa of C_3H_8 gas by using a ^{244}Cm alpha source. Results obtained in C_3H_8 will be compared with those obtained by Farahmand et al. [14] in TE gas mixtures.

2. Materials and methods

A prototype multi-element proportional counter, based on the GEM, has been designed and constructed, with 16 cylindrical sensitive volumes (SVs) of 2 mm height and diameter. The TEPC-GEM elements are a cathode, made of conductive A-150 plastic, a GEM foil, with a sensitive area of 5×5 cm^2, and a readout printed circuit board (PCB), with 16 circular pads of 2 mm diameter, disposed in a 4×4 matrix (pitch of 4 mm). Fig. 1 provides a schematic view of the set-up. At 21 and 28 kPa of C_3H_8 gas the equivalent diameter of each SV is 75 μg cm^{-2} and 100 μg cm^{-2}, respectively at 20 °C (corresponding to 0.75 and 1.0 μm when scaled at density 1 g cm^{-3}).

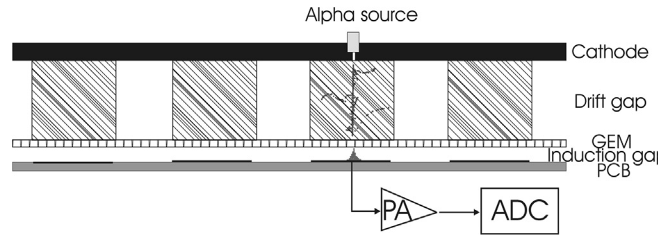

Fig. 1. Cross section of the GEM-TEPC. The shadow areas represent four of the sixteen SVs of the detector. One SV is crossed by the alpha particle track.

The GEM structure used in this work is the so called standard GEM, that is a Kapton foil of 50 μm thickness, with a 5 μm-thick copper coating on each side, perforated on a triangular pattern with a high density of holes with a double conical shape. The diameter in the copper surfaces, d_{Cu}, is 70 μm, the diameter in the Kapton, d_{Kapton}, is 50 μm. The holes have a distance, p, between the centres of 140 μm. The GEM foil is glued between two fibreglass frames, each one of 0.5 mm thickness. In the following text this geometry will be indicated as 140/70 GEM. The GEM and the PCB were produced at the CERN printed circuits workshop. The drift region (space between cathode and GEM) and the induction region (space between GEM and PCB) have a height of 2 mm and 0.5 mm, respectively and are filled with C_3H_8 gas.

The gain measurements were made in pulse mode employing a ^{244}Cm alpha source. On the cathode, 4 holes have been made, to insert the alpha source and to let alpha particles entering the detector through a 0.5 mm diameter, 2.6 mm long collimator. With the application of suitable potentials to the cathode and the two sides of the GEM, electrons released by ionisation in the drift region move towards the open channels of the GEM (amplification region), where they multiply in an avalanche in the high field and transfer to the second gap (induction region). Drift and induction electric fields are quite high to have a good match between large gains and high transparency of the GEM and a fast electron transfer to the readout. These fields are obtained with the readout board grounded and three high voltage power supplies, with negative polarity, for the two faces of the GEM and the cathode. This configuration has the advantage of eliminating the signal resistor and blocking capacitor and produce a reduction of the detector capacitance. It also eliminates high voltage on the anode feedthrough which may cause noise [18]. High voltages were supplied directly to the drift electrode and the two sides of the GEM through independent outputs of a ORTEC 710 bias supply through 2 MΩ protection resistors connected in series with each electrode. This method has been preferred to the use of a single power supply with an external resistive partition network for powering the two sides of the GEM [19] because it allows independent control of the drift, amplification and induction fields. Signals are induced on the pick-up pad with an amplitude corresponding to the total collected charge. The charge produced on the readout pad was fed into a charge preamplifier and pulses were then directly sent to a CAEN DT5724 Digitizer (4 Channel 14 bit 100 MS/s) equipped with DPP-PHA Firmware (Digital Pulse Processing for the Pulse Height Analysis) controlled by a PC. This