A TPC DETECTOR FOR STUDYING PHOTO-NUCLEAR REACTIONS AT ASTROPHYSICAL ENERGIES WITH GAMMA-RAY BEAMS AT ELI–NP*

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An active-target Time Projection Chamber (ELITPC) is being developed at the University of Warsaw to investigate the photo-disintegration reaction ^{16}O(γ,α)^{12}C at energies relevant for nuclear astrophysics (down to $\sim$ 1 MeV in the centre of mass). Selected results from ongoing R&D activities are presented in this paper.

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1. Introduction

The investigation of those nuclear reactions that are important for nucleosynthesis is essential in order to provide input for stellar evolution calculations and theory validation, but their measurement at the relevant energies is often extremely difficult. In particular, the study of the ^{12}C(α,γ)^{16}O reaction, which regulates the production of oxygen and carbon at energies close to the Gamow peak is not an easy task. Since it is not possible with present day experimental conditions to measure its cross section at the Gamow peak

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energies, it is mandatory to obtain precise experimental data on the cross section for energies as close as possible to the Gamow peak. In order to overcome the problem of the Coulomb barrier when measuring the reaction probability at such low energies, the time-reversal reaction can be investigated instead. Such approach is possible thanks to the advent of intense monochromatic γ-ray beams. The time-reversal (photo-disintegration) reaction $^{16}O(\gamma,\alpha)^{12}C$ will be investigated when the ELI–NP facility, under construction at Bucharest-Măgurele, Romania, will come into operation. For this purpose, an active target Time-Projection Chamber (ELITPC) is under development at the University of Warsaw, with the flagship experiment being the measurement of the cross section for its E1 and E2 components down to energies of about 1 MeV in the centre of mass (E_{CM}) [1]. For the lowest E_{CM} values, the reaction products will have only a few hundred keV energy and short ranges. In order for their tracks to be at least 1 cm long in the active volume, a low-density gas mixture is needed. In this respect, the optimum gaseous target at the lowest energy foreseen (*i.e.* $E_{CM} = 1.0$–1.1 MeV) will be pure CO_2 at ~ 100 mbar.

The ELITPC detector will employ Gas Electron Multiplier (GEM) foils [2, 3] for electron charge amplification. Feasibility studies of 3D track reconstruction using a small-scale prototype filled with He/CO_2 gas mixtures at atmospheric pressure are discussed in our previous works [4, 5]. In this paper, we report on selected results from the ongoing R&D on GEM structures operated at low-pressure in pure CO_2.

Over the past 20 years, several experimental groups studied the operation of GEM-like structures at low gas pressures. Apart from standard chemically etched 50-μm-thick polyimide GEM foils [6, 7], different thick-GEM structures (100 μm–3.2 mm) made of PCBs, liquid crystal polymers and ceramics were tested [8–15]. Still, with exception of Ref. [15], none of the previous works focused on operation in pure CO_2 at pressure regimes around 100 mbar.

2. Low-pressure test bench

In order to optimize the GEM amplification structure for ELITPC project needs, a cylindrical vacuum vessel with scaled-down model GEM detector is employed. The test chamber consists of two aluminium endcaps and a stainless steel barrel. Endcaps are equipped with several ports for high voltage distribution, signal extraction, pressure measurements, gas exchange and X-ray window. The internal detector structure, comprising of drift cage, triple-GEM stack under test and segmented anode, is fixed to one of the endcaps by four insulating pillars (see Fig. 1).

The drift cage is formed by nine equidistant copper rings (100 mm internal diameter) closed by a stainless steel wire-mesh electrode. Adjacent field-shaping electrodes are interconnected by 10 MΩ resistors. The height of the active volume is 100 mm. The GEM stack is formed by identical circular GEM foils glued onto 3 mm-thick insulating frames (active area $\phi = 50$ mm, total copper area $\phi = 110$ mm). Two types of GEM foils are envisaged in the tests: "standard" ones (50 μm-thick, 140 μm staggered hole pitch, 50-μm/70 μm internal/external hole diameter) and "thick" ones (125 − μm-thick, 200 μm staggered hole pitch, 80 μm/120 μm internal/external hole diameter). In this paper, our first results for the "standard" structures are presented. The circular PCB anode is segmented into three concentric pads: central signal pad ($\phi = 40$ mm), middle veto ring ($40 < \phi < 60$ mm) and outer grounded ring ($60 < \phi < 112$ mm).

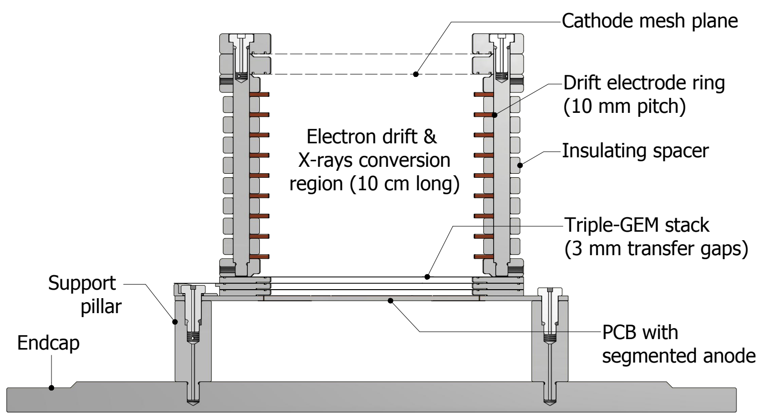

Fig. 1. Cross section of the triple-GEM model detector for gas gain studies.

Only relatively-low outgassing materials were employed: stainless steel, copper, PEEK, polyimide and ceramics. However, limited outgassing is still expected from the readout PCB made of FR4, soldered SMD resistors and epoxy adhesive used to fix GEMs and wire-mesh electrodes. The measured combined effect of leak and outgassing rates is below 2×10^{-5} mbar L/s at room temperature, which allows one to obtain stable gas gains for at least 8-hour period without exchanging the gas.

At first, the vacuum vessel and the whole gas system are evacuated to a vacuum level of about 5×10^{-5} mbar. The desired pressure of the gas is then set by injecting pure CO_2 from a compressed gas bottle (purity 5.3) via a dual-stage pressure regulator and a precise multi-turn dosing valve. Finally, the chamber is isolated from the gas system using a set of vacuum valves.

In order to study the gas gain at different pressures and electric fields, an X-ray tube was placed in front of the X-ray window located above the cathode wire-mesh plane. The energy spectrum of XRF photons generated by the X-ray tube operated at 10 kV and filtered through Ti foil (110 μm) and Kapton window (50 μm) is quasi-monochromatic with a dominant energy peak at about 4.9 keV (9% FWHM). The X-ray beam profile in the conversion region is smaller than the area covered by the central pad and by the active area of the triple-GEM stack.

The primary ionization electrons from photo-absorption taking place in the drift volume are amplified by GEM structures and the fast electron component of the induced signal is collected by two signal pads of the anode. For each high voltage working point, the pulse-height spectra from the central pad and event-by-event waveforms from central and veto pads were recorded using a multi-channel analyzer and a 4-channel digital oscilloscope, respectively.

3. Preliminary results

For a given gas mixture, pressure, electric drift field, geometry of GEM foils and transfer gaps, the effective gain[1] depends on gain sharing between subsequent GEMs and on their respective transparencies for electrons and positive ions. By combining several GEM planes, one can achieve same effective gain as for single GEM structure but at lower (safer) electric fields applied to GEM holes (*e.g.* away from the Raether limit). The optimal TPC working point is a compromise between maximisation of the gas gain (signal-to-noise ratio), maintaining good energy resolution and avoiding parasitic effects such as sparks, photon feedback or positive ion feedback.

We have tested several combinations of GEM voltage ratios and transfer gap voltage ratios for the triple-GEM stack made of standard 50 μm CERN-made foils operated in pure CO_2 at 100 mbar. Satisfactory results in terms of the maximal gain were obtained for asymmetric gain sharing between GEMs ($\Delta V_{\mathrm{GEM}_\mathrm{j}}$ ratio $= 1.2/1/0.8$) and for reduced transparency of the middle transfer gap ($E_{\mathrm{Transfer}_\mathrm{j}}$ ratio $= 3/1/3$). The position of the main peak in the measured pulse-height spectra was used to estimate the effective gain of the triple-GEM stack. The average energy needed to create a single electron–ion pair in CO_2 gas ($W_I = 33$ eV) was taken from Ref. [16]. In Fig. 2, the resulting gas gain curve is shown, for fixed transfer and drift electric fields, as a function of the average ΔV_{GEM} voltage.

The pulse-height distribution corresponding to effective gain of about 4×10^3 is shown in Fig. 3 (left). The FWHM of the main peak is about 25%. The maximal gain was limited by positive ion feedback phenomenon [3, 17] due to ion transport from the GEM plane closest to the signal anode (GEM_1) to the GEM plane facing the drift region (GEM_3). The ion feedback due to primary ionization losses in the drift region was negligible at counting rates of 10–70 Hz, which are comparable to the γ-ray beam repetition rate of 100 Hz foreseen at the ELI–NP facility.

[1] Ratio of the number of electrons collected by the anode to the number of primary electron–ion pairs.

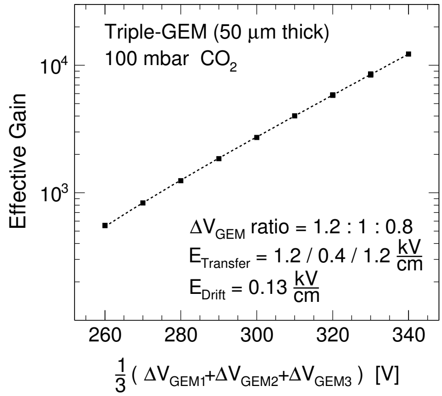

Fig. 2. Effective gas gain of triple-GEM stack as a function of the average $\Delta V_{\rm GEM}$.

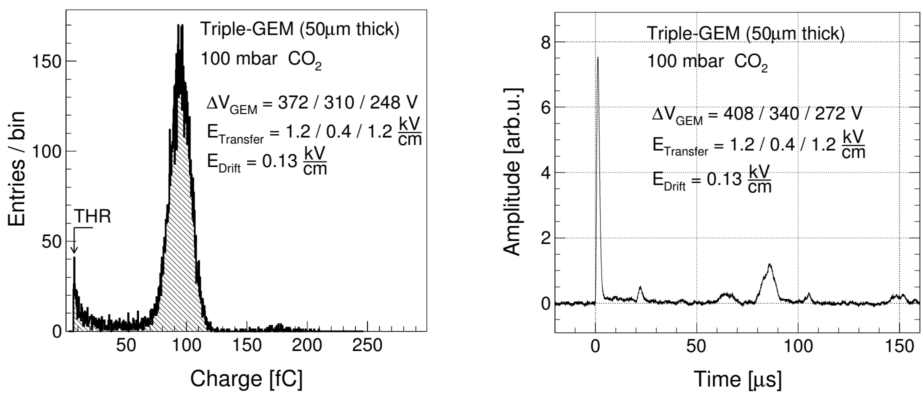

Fig. 3. Left panel: Pulse-height spectrum corresponding to effective gain of 4×10^3. Right panel: Signal shape corresponding to effective gain of 1.2×10^4.

An example of signal shape corresponding to the highest achievable gain ($\sim 1.2\times10^4$) is depicted in Fig. 3 (right). A secondary peak delayed by about 85 μs is clearly visible. The measured delay for given applied electric fields and total drift distance of positive ions in the transfer gaps is compatible with mobility of CO_2^+ ions in their parent gas ($\mu = 1.09$ cm^2 V^{-1} s^{-1}) [18].

4. Summary

We have investigated possibility of using a triple-GEM structure made of the standard 50-μm-thick GEMs for an active-target TPC filled with pure CO_2 at 100 mbar. The positive ion feedback limits the maximal effective gain to about 10^4. Comfortable operation free of ion feedback is possible up to effective gains of about 5×10^3. Similar tests will be performed with thicker

125 μm GEM foils in view of extending the maximal effective gain while keeping reasonable signal-to-noise ratio. These tests will allow to optimize the read-out structure for the final design of the detector. The next step will be to run tests with low-energy charged particles and the small-scale prototype filled with CO_2 at low pressure to validate reconstruction procedures.

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