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Live event reconstruction in an optically read out GEM-based TPC

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ABSTRACT

Combining strong signal amplification made possible by Gaseous Electron Multipliers (GEMs) with the high spatial resolution provided by optical readout, highly performing radiation detectors can be realized. An optically read out GEM-based Time Projection Chamber (TPC) is presented. The device permits 3D track reconstruction by combining the 2D projections obtained with a CCD camera with timing information from a photomultiplier tube. Owing to the intuitive 2D representation of the tracks in the images and to automated control, data acquisition and event reconstruction algorithms, the optically read out TPC permits live display of reconstructed tracks in three dimensions. An Ar/CF_4 (80/20%) gas mixture was used to maximize scintillation yield in the visible wavelength region matching the quantum efficiency of the camera. The device is integrated in a UHV-grade vessel allowing for precise control of the gas composition and purity. Long term studies in sealed mode operation revealed a minor decrease in the scintillation light intensity.

1. Introduction

The universality of Time Projection Chambers (TPCs) [1] makes them an attractive detector concept for a wide range of applications. To permit an accurate 3D reconstruction of particle tracks, the 2D projection on the endcap of a TPC must be recorded with possibly high spatial resolution. Additionally, the drift time information used to calculate the Z-coordinate of a particle track must be obtained with possibly high time resolution.

To enable the detection of various types of radiation from low-energy X-rays to highly ionizing alpha particles, robust signal amplification technologies such as Gaseous Electron Multipliers (GEMs) can be employed [2]. This variety of MicroPattern Gaseous Detectors (MPGDs) is composed of thin perforated foils with a conductor–insulator–conductor structure and allows for high electron multiplication factors by avalanche amplification in high electric field regions in the GEM holes with typical diameters of tens of micrometers. Employing multiple GEMs as consecutive amplification stages allows high effective charge gain factors [3] while still operating the detector in a stable regime. MPGD amplification stages such as triple-GEMs are therefore a high potential technology for TPC endcaps [4] providing high signal amplification and detection of weakly ionizing particles in the active volume. MPGDs are at the core of multiple ongoing detector upgrades and developments. The TPC of the ALICE experiment is currently undergoing an upgrade to employ a GEM-based readout [5], while the ATLAS collaboration is developing a muon spectrometer readout based on Micromegas, which can sustain high particle fluxes and is capable of achieving high spatial resolution [6]. In view of directional dark matter search experiments, optically read out GEM-based TPCs have been suggested and investigated as a candidate technology for providing accurate information about electron and nuclear recoil tracks [7].

Aiming at high spatial resolution in the readout of the endcaps of a TPC, optical readout is an attractive alternative to commonly used electronic readout concepts. Optical readout is based on the recording of scintillation light emitted in the gas in the active volume and has previously been shown to allow for high spatial resolution [8]. The optical readout concept provides a good track recognition capability as already demonstrated in imaging chambers based on parallel-grid chambers [9]. Coupling MPGDs such as GEMs with optical readout allows for high signal amplification as well as good position resolution and comes with the additional advantage of high signal-to-noise ratios and the inherent insensitivity to electric noise.

Optically read out TPCs employing combined readout with cameras and Photomultiplier Tubes (PMTs) have previously been developed

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for the study of rare decay modes and proton spectroscopy [10–12]. Using multistep avalanche chambers or GEMs as amplification and scintillation stages and operating in Ar–He gas mixtures with small additives of triethylamine or N_2, these previous works successfully demonstrated the applicability of optical TPCs for imaging of two-proton decays of ^{45}Fe nuclei [12] or proton spectroscopy of ^{48}Ni, ^{46}Fe and ^{44}Cr [11]. A similar readout concept has also been implemented by the DMTPC project, which aims at observing dark matter interactions by determining the energy and direction of nuclear recoils [13]. Optically read out TPCs have also been used in nuclear astrophysics experiments such as studies with gamma-ray beams [14,15].

We present a TPC based on a triple-GEM amplification stage optically read out by a high-resolution CCD camera, which provides an image of the 2D projection of alpha tracks, and a PMT, which simultaneously provides timing information to perform 3D track reconstruction. Using an Ar/CF_4 gas mixture with scintillation light emission in the visible wavelength regime, emitted light can be recorded without the need for wavelength shifters. The operation of the presented device is fully automated and allows for live 3D reconstruction and display of alpha particle tracks. Additionally, the described detector is built to highest purity requirements and demonstrates the possibility to realize a sealed TPC based on optically read out MPGDs.

2. Experimental methods

The drift volume of the presented optically read out GEM-based TPC is formed by a circular field shaper with a length of 10 cm and a diameter of 10 cm, which is coupled to a triple-GEM with an active region of 10×10 cm^2. These two elements are placed in a UHV-grade vessel to allow for a highly controlled environment and a pure gas filling. All components of the detector vessel are sealed by Cu gaskets. Inside the gas volume, the usage of low-outgassing materials such as oxygen-free Cu for the field shaper electrodes, ceramic for the GEM frames and polyether ether ketone (PEEK) for a holder for the triple-GEM stack ensures high gas purity and permits the operation of the TPC in flushed as well as sealed modes. Electrical connections are made by clamping to avoid the use of solder in the gas volume and all-metal valves and pressure transducers were used. Two borosilicate viewports 63 mm in diameter on opposite sides of the vessel allow the optical readout of scintillation light in the visible wavelength regime produced in the gas volume. Behind these viewports, a CCD camera (QImaging Retiga R6) facing the last GEM of the triple-GEM stack and a PMT (Hamamatsu R375) facing the cathode mesh used to define the drift field are placed as shown in Fig. 1.

The 6-megapixel CCD camera with bulb-mode triggering capabilities features a 12.5×10 mm^2 imaging sensor with pixels of 4.54×4.54 μm^2. The imaging sensor is cooled to −20 °C to achieve a low read noise of 5.7 electrons (RMS) and a dark current rate of 0.00017 electrons/pixel/second. Imaging the full active area of the detector, a magnification factor of approximately 10 results in an effective pixel size of about 45×45 μm^2 on the imaging plane. The PMT was operated at a gain of approximately 2×10^6 in order to be sensitive to primary scintillation signals.

The employed GEM foils feature holes with a diameter of 70 μm and a hole pitch of 140 μm, which are chemically etched into the Cu-polyimide-Cu composite material by a double-mask etching technique. For highly ionizing alpha particles, the triple-GEM was operated at moderate gains of several 10^3. A stainless steel mesh-cathode is used together with the field shaper composed of multiple ring-shaped Cu electrodes connected with high-voltage resistors to define the electric drift field in the active volume of the TPC. The presented setup permits drift fields of up to 500 V/cm and can also be used with significantly lower drift fields of tens of V/cm due to the low level of outgassing and the resulting high gas quality in the detector vessel minimizing the significance of attachment and loss of primary electrons.

The PMT facing the cathode is used to record both the primary scintillation signal as well as the secondary scintillation light emitted after primary electrons have drifted towards and reached the triple-GEM and have been amplified in the high electric field regions inside the GEM holes. Due to the optical transparency of the GEM foils of about 20%, the PMT may record scintillation light emitted from all three GEMs in the multiplication stage with the majority of the detected photons originating from the third GEM. The acceptance factor for the detection of secondary scintillation photons by the PMT was determined to be approximately 6.4×10^{-4} by ray tracing simulations and by taking into account the emission spectrum of the Ar/CF_4 gas mixture, the wavelength-dependent transmission of the borosilicate viewport and the quantum efficiency of the PMT.

As signal amplification in the GEM stack happens fast due to high electric fields inside the GEM holes and transfer fields of about 2 kV/cm between GEM foils, this impacts the timing characteristics of the signals observed by the PMT only minimally. The CCD camera facing the bottom of the triple-GEM records integrated images of the 2D projection of the particle track on the GEM stack, which acts as the endcap of the TPC. Due to state-of-the-art imaging sensors not being sensitive to a level where single photon detection is feasible and the low optical transparency of the triple-GEM stack, the CCD camera is not capable of recording primary scintillation signals and only records the much stronger secondary scintillation light emitted during avalanche amplification in the GEM holes.

To maximize the signal-to-noise ratio both in the images recorded with the CCD as well as in the PMT response, an Ar/CF_4 gas mixture with a composition of 80/20% (by volume) was used. The maximum achieved light yield with this mixture was 0.3 photons per secondary electron produced during electron avalanche multiplication. The emission spectrum of the scintillation light of this mixture features a pronounced intensity peak at 630 nm in the visible wavelength regime. Therefore, it can be efficiently recorded by the CCD camera, which has a quantum efficiency peaking at 75% for 600 nm. The quantum efficiency of the CCD and the PMT at 630 nm were 73% and 11%, respectively. This match between the scintillation light emission spectrum and the wavelength-dependent quantum efficiency of the CCD permits high light sensitivity.

Before the initial gas filling, the detector vessel is pumped to a pressure of about 10^{-6} mbar with a turbomolecular pump. Extended pumping for 48 h is used to minimize the residual outgassing from the detector elements inside the chamber. Subsequently, the detector vessel is sealed off with an all-metal valve. Only after extensive purging of all gas lines is the detector filled with the desired gas mixture to a pressure of 1 bar.

To permit live 3D reconstruction of alpha particle tracks in the TPC, a triggering, data acquisition and reconstruction algorithm was developed and implemented both in hardware as well as software. PMT signals are recorded by a digital storage oscilloscope (DSO) (LeCroy WaveRunner 625Zi, 2.5 GHz, 40 GS/s) and the intense and unambiguous secondary scintillation signals are used as a trigger to identify the occurrence of a new event. These trigger signals are used to stop the exposure of the CCD camera as well as to trigger the data acquisition of the PMT waveform from the DSO and the recorded image from the CCD camera via a microcontroller coupled to a control script executed on a standard desktop computer. Once a PMT waveform and the matching CCD image have been transferred to the computer, a reconstruction algorithm automatically performs a 3D reconstruction of the particle track, stores the data for later offline analysis and displays a 3D representation of the event on-screen.

The exposure time of the recorded CCD images depends on the time between subsequent events and varies from image to image due to the employed bulb mode triggering. Therefore, the noise level due to the dark current of the pixels of the CCD camera, which depends on the exposure time, is different for each image. For the used imaging sensor, the read noise of 5.7 electrons (RMS) is much more significant than the dark current rate of 0.00017 electrons/pixel/second for typical exposure times of less than 1 s.

Alpha particles originating from the decay of ^{220}Rn were used for the demonstration of the track reconstruction capabilities of the presented