Nuclear Instruments and Methods in Physics Research A 788 (2015) 95–105

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

3-D tracking in a miniature time projection chamber

S.E. Vahsen [a,*], M.T. Hedges [a], I. Jaegle [a], S.J. Ross [a], I.S. Seong [a], T.N. Thorpe [a], J. Yamaoka [a], J.A. Kadyk [b], M. Garcia-Sciveres [b]

[a] *University of Hawaii, 2505 Correa Road, Honolulu, HI 96822, USA*
[b] *Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA*

ARTICLE INFO

Article history:
Received 24 July 2014
Received in revised form
3 February 2015
Accepted 2 March 2015
Available online 10 March 2015

Keywords:
TPC
GEM
Pixel
Directional
Neutron
Dark matter

ABSTRACT

The three-dimensional (3-D) detection of millimeter-scale ionization trails is of interest for detecting nuclear recoils in directional fast neutron detectors and in direction-sensitive searches for weakly interacting massive particles (WIMPs), which may constitute the Dark Matter of the universe. We report on performance characterization of a miniature gas target Time Projection Chamber (TPC) where the drift charge is avalanche-multiplied with Gas Electron Multipliers (GEMs) and detected with the ATLAS FE-I3 Pixel Application Specific Integrated Circuit (ASIC). We report on measurements of gain, gain resolution, point resolution, diffusion, angular resolution, and energy resolution with low-energy X-rays, cosmic rays, and alpha particles, using the gases Ar:CO_2 (70:30) and He:CO_2 (70:30) at atmospheric pressure. We discuss the implications for future, larger directional neutron and Dark Matter detectors. With an eye to designing and selecting components for these, we generalize our results into analytical expressions for detector performance whenever possible. We conclude by demonstrating the 3-D directional detection of a fast neutron source.

1. Introduction

Time Projection Chambers [1] with charge readout via micro-pattern gaseous detectors are the digital analog to bubble chambers, allowing 3-D reconstruction of ionization with many space points and great precision. Over the last decade, a number of studies have demonstrated impressive performance when reconstructing ionizing primary particles with such detectors [2–4]. Our group is investigating [6–10] the detection of nuclear recoils resulting from the scattering of neutral primary particles, such as neutrons and, potentially, WIMPs. Neutron detectors with improved directional sensitivity are likely to find applications in particle physics, nuclear physics, homeland security, and neutron imaging. Directional searches for WIMP Dark Matter are sensitive to a unique signature, a 24-h directional oscillation of the WIMP recoil distribution, due to the rotation of the earth [11]. Observation of this signature would constitute a convincing detection of WIMPs by demonstrating the galactic origin of the signal, and may be required to distinguish WIMP scattering from coherent neutrino scattering [12]. A number of technological approaches are being explored [13–21]. An ideal directional WIMP detector, capable of excluding the isotropy of nuclear recoils in galactic coordinates with order ten signal events, would track nuclear recoils in 3-D, with low energy threshold, and with the ability to detect which of the two possible directions along an observed track the recoiling nucleus moved [22]. The latter is also sometimes referred to as vector tracking, sense recognition, or head/tail recognition. The technology under study is a candidate for building such a detector. One obvious challenge for gas-based WIMP searches is low target mass per unit volume. However, the proper metric for comparing technologies is sensitivity per unit of cost. For high-resolution gas TPCs, the cost drivers are typically the readout plane and electronics. If the cost of these can be minimized, for instance by focusing the drift charge onto the detection plane [7], large gas TPCs will be more competitive.

We report here on the performance of a miniature prototype, D^3-Micro (Directional Dark Matter Detector – Micro), constructed at the University of Hawaii in 2010. In that detector the TPC drift charge is multiplied with a double layer of Gas Electron Multipliers (GEMs) [23] and detected with the ATLAS FE-I3 Pixel Application Specific Integrated Circuit (ASIC) [24]. The high double GEM gain (of order 10^4), low pixel threshold (typically 2000–4000e^-), and low pixel noise (typically 100–200e^-) result in several attractive features, such as stable operation with single electron efficiency near unity, self-triggered readout, and negligible rates of noise hits. In practical terms, this means that at high gain, essentially all primary ionization can be detected, so that the energy threshold is equal to the work function of the gas, typically about 30 eV. Therefore one can expect a large number of hits even for keV-scale tracks. It seems likely that these outstanding capabilities will enable reconstruction of tracks

* Corresponding author. Tel.: +1 808 956 2985.
E-mail address: sevahsen@hawaii.edu (S.E. Vahsen).

http://dx.doi.org/10.1016/j.nima.2015.03.009
0168-9002/

with the lowest energy threshold possible in any detector of ionization. Due to the self-triggering capability of the pixel chip, the detector produces no data in the absence of ionization in the drift gap, greatly reducing the requirements on DAQ electronics. This is important in the context of scaling to larger detectors.

All measurements presented here were carried out at atmospheric pressure (760 Torr). Initial measurements employed Ar:CO_2 (70:30), which is a commonly used detector gas, and allows a comparison with work by others [25]. Later measurements were performed with He:CO_2 (70:30), which is more suitable for reconstructing fast neutron recoils. Helium is a good neutron target, since up to 64% of the neutron energy can be transferred to a helium nucleus. Helium is also a good detection medium, since the low electron density results in small specific ionization, yielding longer recoil tracks. The CO_2 component improves detector performance and stability by reducing diffusion, by re-absorbing UV-photons emitted during the avalanche process (commonly referred to as quenching), and by raising the electric field strength threshold for sparking.

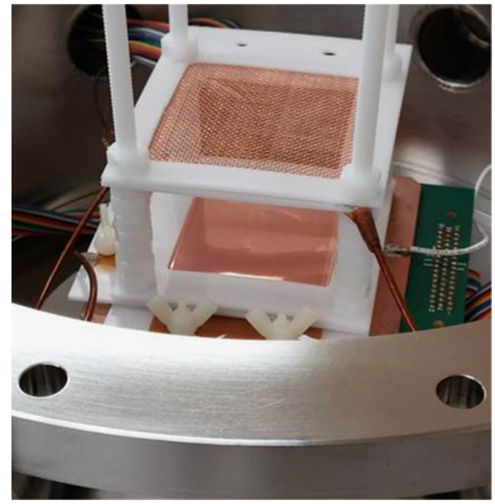

Fig. 2. D^3-Micro prototype in the test vessel, after the drift gap was increased to 45 mm, and the thickness of nearby Delrin (acetal) parts was reduced. These modifications were crucial for achieving a significant directional neutron signal.

2. Detector and principle of operation

The D^3-Microprototype consists of a Delrin (acetal) support structure, visible as white parts in Figs. 1 and 2 on which the different electrical components are mounted. The support structure resides inside a 25-l stainless steel test vessel. Much of the detector design, shown schematically in Fig. 3, is based on a previous prototype constructed at LBNL [4]. The sensitive volume of the detector consists of a drift gap situated between a copper mesh and the upper surface of GEM1. For most measurements the drift gap was 9.2 mm. For the demonstration of neutron detection, higher detection efficiency was required, and the drift gap was increased to 45 mm, as shown in Fig. 2. Ionizing radiation produces free electrons in this gap. These electrons then drift in a uniform electric field to a double GEM layer, where the electrons are avalanche multiplied, and finally the resulting avalanche charge is detected with an ATLAS FE-I3 pixel chip [24] operating in self-trigger mode (described below) and sampling at 40 MHz. The GEMs used are the standard CERN design with an active area of 5×5 cm and 140 μm hole spacing [23]. The transfer gap, defined as the distance between the lower surface of GEM1 and the upper surface of GEM2, is 2.8 mm. The collection gap, defined as the distance between the bottom surface of GEM2 and the upper surface of the pixel chip, is 2.2 mm. The pixel chip has an active area of $7.2 \times 8.0\ \mathrm{mm}^2$, divided into 2880 pixels. Each individual $50 \times 400\ \mu\mathrm{m}^2$ pixel contains an integrating amplifier, a discriminator, a shaper, and associated digital controls. A pixelized metal layer was deposited [4] onto the chip to increase the charge collection efficiency, but this led to a non-uniform efficiency, see Section 3.

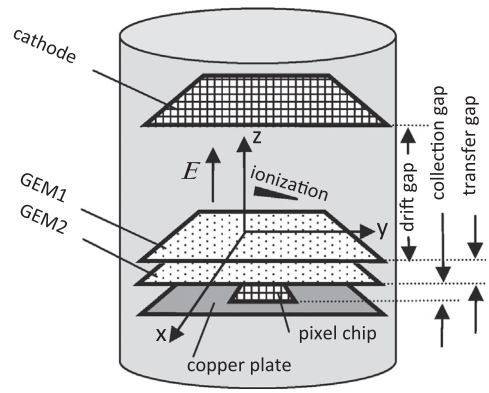

Fig. 3. Schematic representation of the D^3-Microprototype and definition of coordinate system. The origin is chosen so that $x=0$, $y=0$ coincides with one corner of the pixel chip and $z=0$ is at the bottom of the drift gap. The x- and y-axes are parallel to the 7.2-mm and 8.0-mm sides of the pixel chip, respectively. The z-axis points in the direction of the drift field, i.e. opposite to the direction of electron drift. The rectangular pixels measure 400 μm × 50 μm in $x \times y$. For fitted tracks, we use the spherical coordinate convention most common in physics: the polar angle, θ, is the angle between the z-axis and the track's direction vector. The azimuthal angle, ϕ, is the angle between the x-axis and the projection of the direction vector onto the x–y plane.

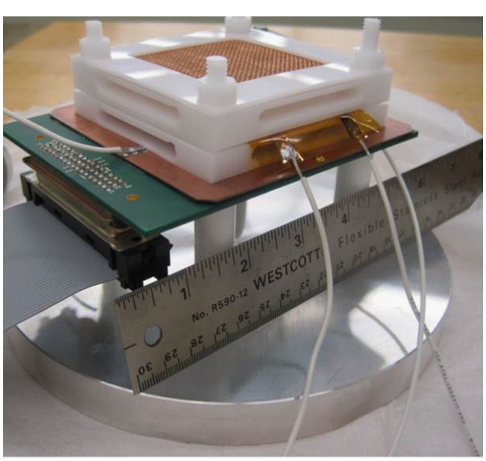

Fig. 1. D^3-Micro prototype n the original configuration used for most studies presented here. The sensitive volume consists of a 9.2-mm vertical drift gap between the copper cathode (mesh visible on the top of the detector) and the top GEM (foil protruding on the right).

When charge is detected in the chip (at least one pixel detects charge above threshold), the self-trigger results in the output of a zero-suppressed digital serial stream that encodes the 2-D position, arrival time, and amount of charge collected, for each pixel above threshold within the next sixteen cycles of 25 ns each. The charge collected in each pixel is deduced from the time above threshold (ToT), which is measured with 7-bit precision. By using the known drift velocity in the drift gap, the timing information is converted into a (relative) third spatial coordinate, so that a 3-D image of ionization in the drift gap is obtained, as shown in Figs. 10, 12 and 17. The pixel chip is glued to a circuit board and electrically connected with wirebonds, which are shielded against the electric field with a small metal overhang, as described in [4]. In addition to the digital charge readout via the pixel chip, the area surrounding the chip is covered with a copper plate which is connected via a capacitor to an Endicott eV-5093 charge sensitive preamplifier. The amplifier output is fed through a Canberra