Micro Pattern Gas Detector Optical Readout for Directional Dark Matter Searches

G.Cavoto[a,c], I.Abritta[a,c], E.Baracchini[b], M.Angelone[f], F.Bellini[a,c], L.Benussi[e], S.Bianco[e], E.Di Marco[c], S.Fiore[f], S.Loreti[f], G.Maccarone[e], M.Marafini[c,d], G.Mazzitelli[e], A.Messina[a,c], D.Piccolo[e], M.Pillon[f], D.Pinci[c], F.Renga[c], F.Rosatelli[e], T.Thorpe[b], S.Tomassini[e], C.Voena[c]

[a]*Sapienza Università di Roma, Dipartimento di Fisica, Roma, Italy*
[b] *Gran Sasso Science Institute, L'Aquila, Italy*
[c]*INFN Sezione di Roma, Roma, Italy*
[d]*Centro Fermi, Roma Italy*
[e]*INFN Laboratori Nazionali di Frascati, Frascati (Roma), Italy*
[f]*ENEA, Department of Fusion and Technology for Nuclear Safety and Security, Frascati (Roma), Italy*

Abstract

The Time Projection method is ideal to track low kinetic energy charged particles, in particular for the study for Dark Matter interactions. With this technique we aim to readout large volumes with a moderate number of channels providing a complete 3D reconstruction of the tracks within the sensitive region. The total released energy and the energy density along the tracks can be both measured allowing for particle identification and to solve the head-tail ambiguity of the track. Moreover, in gas, nuclear recoils induced by a Dark Matter particle scattering can yield tracks long enough for its direction to be inferred. We describe here a prototype TPC with a GEM amplification stage. The readout is based on the detection of the light produced in the GEM with a high granularity sCMOS sensor in conjunction with a photomultiplier. The prototype was exposed to γ and neutron source and to minimum ionizing particles, obtaining very promising results in terms of detection efficiency, energy resolution and particle identification.

Keywords: Micro-pattern gas detectors, GEM, dark matter

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1. Introduction

One of the most intriguing and long-standing problem in contemporary physics is the investigation of the nature of Dark Matter (DM). Evidence for the existence of DM is coming from different astrophysical and cosmological observation, but no uncontroversial direct detection of the constituents of DM in the form of particles has been made. From the measurements of the star velocities in various galaxies, the presence of a halo of dark matter particles has been inferred. The planet Earth would therefore be immersed in a almost uniform halo of particles (with a density of 0.3 GeV/cm^3). Since the Earth is moving with the Sun towards the Cygnus constellation, an apparent *wind* of DM particles (with a velocity of 10^{-3} c) would hit any terrestrial experiment. Given the unknown nature of DM, there is little consensus on how DM particle would interact with ordinary matter. The most general assumption is such that the detection mechanism is based on the elastic scattering of a DM particle with either a nucleus or an electron that are then recoiling. The expected cross sections for this interaction are in fact very low, leading to few possibile events detectable per year per kg of mass target. Moreover, especially in the range of possibile mass values below 10 GeV the kinetic energy of the recoiling nuclei is tiny, as low as a few keV. We are therefore proposing to use a Time Projection gas Chamber (TPC) technique to *image* the nuclear recoil. The ionization electrons created in the gas mixture are drifted to the anode in a uniform drift field. A very low energy threshold could be attainable and a determination of the topology of the recoil would be possible, offering a new tool for the background rejection. Eventually, such detector could be used to measure also the direction of the recoil and therefore be sensitive to the existence of a DM wind - that would represent a distinctive signature for DM particles [1, 2, 3, 4, 5] and also [6, 7, 8].

2. TPC Prototypes and light readout

A very promising amplification system at the anode of a TPC can be a series of Gas Electron Multiplier (GEM), given their relatively high gain and fine granularity. In the charge multiplication process taking place within the GEMs, light is copiously produced due to the de-excitation of the gas molecules.. We therefore propose to read-out this light with high granularity sensors, featuring a very low noise. Such readout avoids to be electrically coupled to the high voltage of the GEMs by placing sensors out of the sensitive volumes (and therefore reducing the possible contamination of the gas itself). A system of lenses and mirrors can then be used to project large surfaces to small area sensors[9, 10]. A number of prototypes were developed all featuring a triple GEM system and routinely operated with a He/CF_4 60:40 gas mixture at atmospheric pressure. A sCMOS sensor [1] with 4M pixels and less than 2 photon noise per pixel is sensitive to the light spectrum emitted by the He/CF_4 gas mixture. A prototype (ORANGE) with a 1 cm drift region gap and 10 x 10 cm^2 GEMs was exposed to a 450 MeV electron beam (at the INFN Frascati Beam Test Facility). By activating the sensor for 10-100 ms long intervals, detailed images of the ionization trail produced in the gas by the electrons of the beam are obtained. The light profile is so accurate that the ionization cluster structure is visibile. With this prototype a combined readout was attempted by using a fast light detector (PMT) in conjunction with the sCMOS sensor. The PMT signal can in fact be interpreted as the superimposition of light flashes due to different ionization clusters. Given a drift velocity of about 7 cm/μs a 150 ns long PMT signal is acquired when the ionization cluster are covering the whole drift gap. The time structure of the PMT signal waveform and the spatial distribution of the recorded light by the sCMOS camera can be correlated to obtain a 3D reconstruction of the image (see [11] for more details). Larger volume prototypes (LEMON, 7 liters) were then studied in a path towards a 1 m^3 DM detector

[1] ORCA Flash 4.0 sCMOS sensor from Hamamatsu.

demonstrator. The LEMON prototype is featuring an elliptical field cage hosting a 20 cm long gap to make electron drift to a 24x20 cm^2 triple GEM system. A movable bellow is used to place the sCMOS camera at a suitable distance to image the entire surface of the GEMs. LEMON was exposed to the 450 MeV electron beam and images of electron tracks 20 cm long at different distance from the GEM were obtained. The energy resolution was inferred by assuming a uniform ionization ($\frac{dE}{dx}$) and by counting the ionization clusters along the beam electron tracks: it results to be about 25% for an energy release of 2-5 keV. The diffusion of drifting electron in gas was also observed as a broadening of the ionization cluster images: this might exploited to infer the longitudinal coordinate along the drift direction, with a measured resolution of about 2 cm at a 20 cm distance from the GEMs.

3. Results

The TPC prototypes were exposed to radioactive sources (either ^{55}Fe X-ray source or AmBe sources, emitting few MeV neutrons along with 60 keV and 4 MeV photons). The ^{55}Fe source study was particularly important to assess the LEMON detector performances in terms of the lowest possible energy threshold and electron transport properties. The source was installed within the gas volume and collimated by the field cage structure to a relatively small point about 20 cm far from the GEMs. A simple clustering algorithm was used to find connected region of pixels with a number of counts above the noise level.

In Fig.1 two light spots due to two ^{55}Fe X-ray absorptions in the gas are clearly visible. No further analysis of the spot topology was attempted at this stage.

Nevertheless, this allowed to infer an energy calibration of the LEMON prototype by recording the total amount of light detected in a single spot. The distribution for several spots of the recorded light is shown in Fig.2. From a fit to the distribution the ^{55}Fe signal can be separated by the background assuming a Polya function to describe the signal and an exponential for the background.

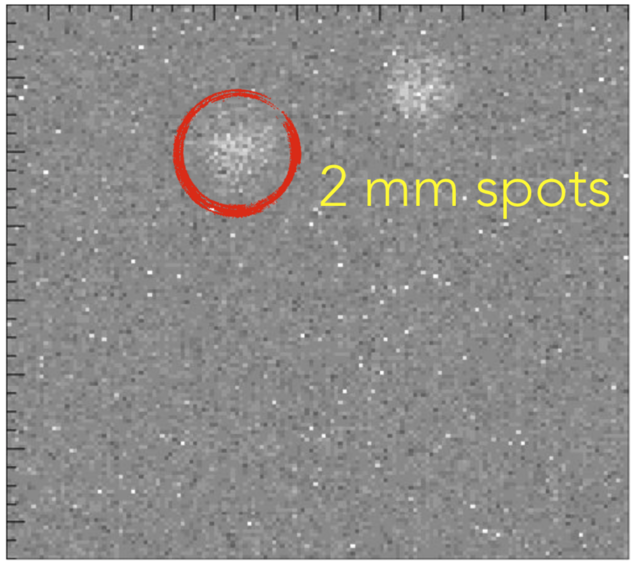

Figure 1: Light spots originated by ^{55}Fe 5.9 keV photon absorption in the gas.

This background is likely to be largely dominated by the detector material radioactivity and by cosmic rays, while the intrinsic noise of the sensor would yield only few fake events per year. Since no spot topological information has been used, there is room for further background suppression.

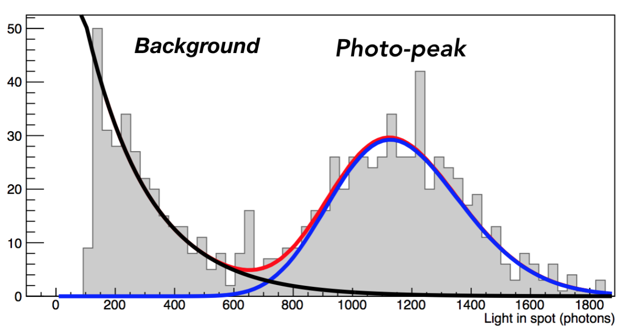

Figure 2: Distribution of the light recorded in the reconstructed spot in presence of a ^{55}Fe source. The photo-peak allows to determine the energy calibration and energy resolution at few keV. The background is largely due to radioactivity of the materials and cosmic rays.

From this same sample of data, information on the performance as a function of the TPC operational parameters (drift field, GEM gain, etc.) were obtained. The LEMON prototype is found to be fully efficient with a drift field of about 300 V/cm. From the RMS of the ^{55}Fe signal distribution a 20% energy resolution is deduced. Moreover, a 2 keV threshold would remove all the intrinsic sensor noise.

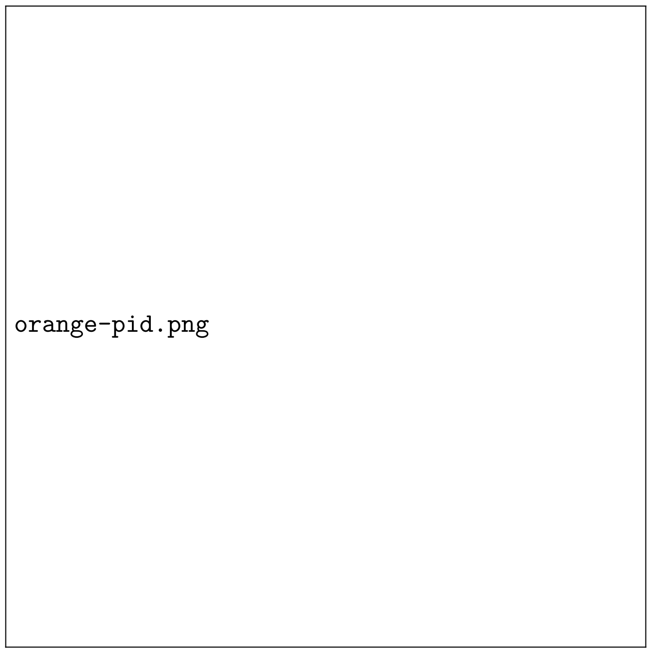

Figure 3: Image of nuclear and electronic recoils due to neutron and photon originated by AmBe source obtained with the ORANGE prototype. A magnetic field parallel to the electron drift direction is present. Nuclear and electronic recoils are clearly discriminated by the recorde light per unit length.

For the development of a DM detector, the response of the prototypes to nuclear recoils must be studied. Neutrons are commonly used to induce nuclear recoils which are similar to those believed to be a signature for DM. We then exposed the ORANGE prototypes to a Am-Be source that is emitting neutrons with a kinetic energy in the range 1-10 MeV along with 4 MeV and 60 keV photons. For this measurement ORANGE was exposed to a 0.2 T magnetic field with the field lines parallel to the electron drift velocity direction. In Fig.

3 three topologies are visible, electrons with a kinetic energy of about 60 keV, MeV electrons and nuclear recoils. They can easily be distinguished by the light density along the track, with the MeV nuclear recoils producing the brightest tracks since they yield the largest ionization density ($\frac{dE}{dx}$) in the gas.

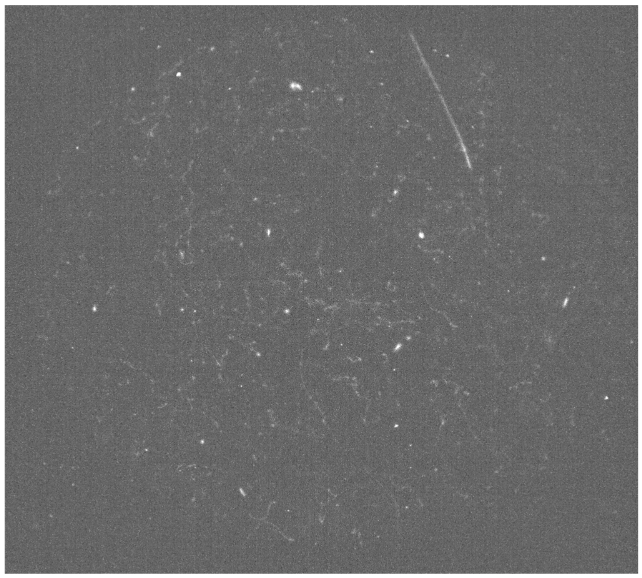

Figure 4: LEMON prototype exposed to a 2.45 MeV neutron beam. A long nuclear recoil track is well visibile on the top right.

Moreover, the larger prototype LEMON was exposed to a beam of monochromatic and parallel neutron (2.45 MeV energy, available at the Frascati Neutron Gun facility (FNG - ENEA). In Fig. 4 a typical image recorded during this data-taking is shown. A diffuse background caused by relatively low energy photons is present, but a candidate nuclear recoil is well visible - compatible with a proton scattered off the plastic support of the field cage by a neutron.

The high accuracy of the image reconstruction (about 150 μm pixel size) allows to evaluate the specific ionization $\frac{dE}{dx}$ of the recoiling particles and even to appreciate differences in the $\frac{dE}{dx}$ values along the reconstructed track direction. In the sample of events recorded at the FNG, we isolated few low energy recoil candidates by measuring the observed light and converting it into energy by

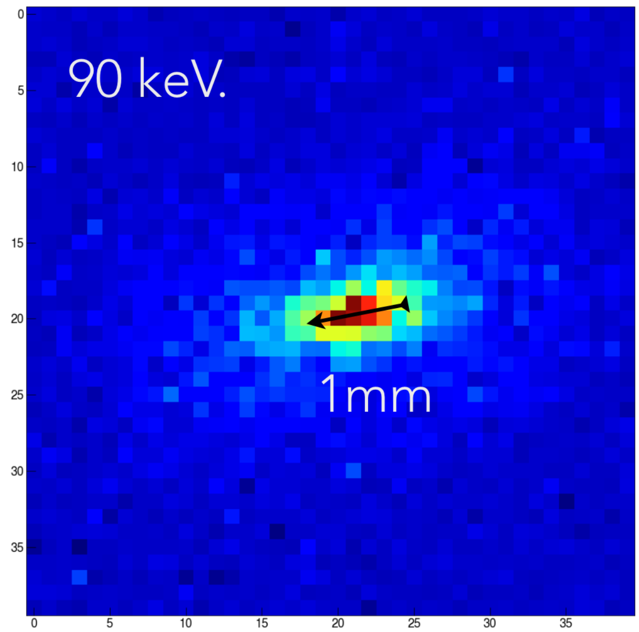

Figure 5: LEMON prototype, candidate He recoil from 2.45 MeV neutron. The recoil particle energy is measured by the recored light. The arrow represents the candidate direction expected from the initial neutron direction.

using the ^{55}Fe calibration line. In Fig. 5 and Fig,6) two examples of recoil candidates are shown with their directions compatible with those of the incoming neutrons.

4. Outlook

An R&D towards a ton-scale DM detector based on the gas TPC technology has recently started, exploring a slow optical readout (based on sCMOS cameras) of the light emitted from the GEMs during the avalanche coupled to a fast readout (via a PMT os SiPM) of the same light. In particular, the focus of this development is on the low energy deposit regime (down to few keV) and on the pattern recognition of the charged particles tracks with the goal to discriminated electronic recoils from the nuclear recoils. This would also determine the capability of such detector to infer the initial direction of a DM particles

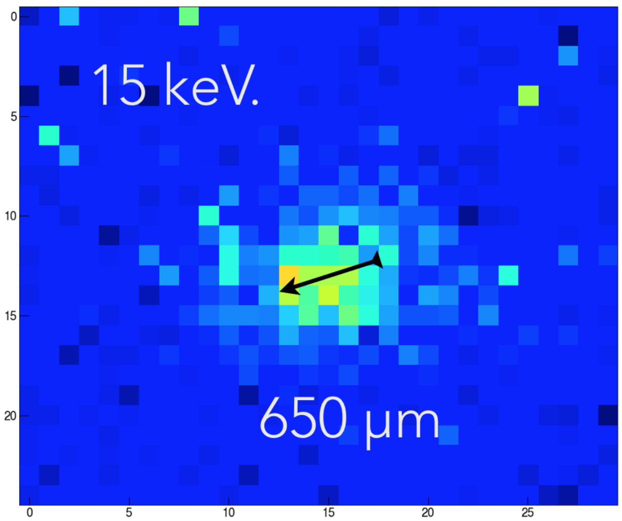

Figure 6: LEMON prototype, low energy candidate He recoil from 2.45 MeV neutron. The recoil particle direction is inferred by the direction of the incoming neutrons. The arrow represents the candidate direction expected from the initial neutron direction.

present in the Galactic halo. A 1 m^3 demonstrator (named $CYGNO$) hosting two 50 cm long drift regions each separately instrumented with a 3x3 triple GEM matrix at the anodes is going to be built in the next years with the aim of clarifying various issues, namely the background level, the stability, scalability ad reliability of such approach toward a large volume (100 - 1000 m^3) detector.

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References

References

[1] J. B. R. Battat, et al., Low Threshold Results and Limits from the DRIFT Directional Dark Matter Detector, Astropart. Phys. 91 (2017) 65–74. arXiv:1701.00171, doi:10.1016/j.astropartphys.2017.03.007.

[2] J. B. R. Battat, et al., Readout technologies for directional WIMP Dark Matter detection, Phys. Rept. 662 (2016) 1–46. arXiv:1610.02396, doi:10.1016/j.physrep.2016.10.001.

[3] J. B. R. Battat, et al., First measurement of nuclear recoil head-tail sense in a fiducialised WIMP dark matter detector, JINST 11 (10) (2016) P10019. arXiv:1606.05364, doi:10.1088/1748-0221/11/10/P10019.

[4] C. Deaconu, M. Leyton, R. Corliss, G. Druitt, R. Eggleston, N. Guerrero, S. Henderson, J. Lopez, J. Monroe, P. Fisher, Measurement of the directional sensitivity of Dark Matter Time Projection Chamber detectors, Phys. Rev. D95 (12) (2017) 122002. arXiv:1705.05965, doi:10.1103/PhysRevD.95.122002.

[5] E. Baracchini, G. Cavoto, G. Mazzitelli, F. Murtas, F. Renga, S. Tomassini, Negative Ion Time Projection Chamber operation with SF_6 at nearly atmospheric pressure, JINST 13 (04) (2018) P04022. arXiv:1710.01994, doi:10.1088/1748-0221/13/04/P04022.

[6] J. B. R. Battat, et al., Measurement of directional range components of nuclear recoil tracks in a fiducialised dark matter detector, JINST 12 (10) (2017) P10009. arXiv:1707.09431, doi:10.1088/1748-0221/12/10/P10009.

[7] G. Cavoto, E. N. M. Cirillo, F. Cocina, J. Ferretti, A. D. Polosa, WIMP detection and slow ion dynamics in carbon nanotube arrays, Eur. Phys. J. C76 (6) (2016) 349. arXiv:1602.03216, doi:10.1140/epjc/s10052-016-4193-7.

[8] L. M. Capparelli, G. Cavoto, D. Mazzilli, A. D. Polosa, Directional Dark Matter Searches with Carbon Nanotubes, Phys. Dark Univ. 9-10 (2015) 24–30, [Erratum: Phys. Dark Univ.11,79(2016)]. arXiv:1412.8213, doi:10.1016/j.dark.2015.12.004, 10.1016/j.dark.2015.08.002.

[9] M. Marafini, V. Patera, D. Pinci, A. Sarti, A. Sciubba, E. Spiriti, ORANGE: A high sensitivity particle tracker based on optically read out GEM, Nucl. Instrum. Meth. A845 (2017) 285–288. doi:10.1016/j.nima.2016.04.014.

[10] M. Marafini, V. Patera, D. Pinci, A. Sarti, A. Sciubba, E. Spiriti, High granularity tracker based on a Triple-GEM optically read by a CMOS-based camera, JINST 10 (12) (2015) P12010. arXiv:1508.07143, doi:10.1088/1748-0221/10/12/P12010.

[11] V. C. Antochi, E. Baracchini, G. Cavoto, E. D. Marco, M. Marafini, G. Mazzitelli, D. Pinci, F. Renga, S. Tomassini, C. Voena, Combined readout of a triple-GEM detector, JINST 13 (05) (2018) P05001. arXiv:1803.06860, doi:10.1088/1748-0221/13/05/P05001.