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Performance of a 3D optical readout TPC for the Cygno experiment

F.D. Amaro,[a] E. Baracchini,[b,c] L. Benussi,[d] S. Bianco,[d] C. Capoccia,[d] M. Caponero,[e,d] D.S. Cardoso,[f] G. Cavoto,[g,h] A. Cortez,[b,c] I.A. Costa,[i,h] E. Dané,[d] G. Dho,[b,c] F. Di Giambattista,[b,c] E. Di Marco,[h] G. D'Imperio,[h] F. Iacoangeli,[h] H.P. Lima Júnior,[f] A.S. Lopes Júnior,[i] G. Maccarrone,[d] R.D.P. Mano,[a] M. Marafini,[k,h] R.R. Marcelo Gregorio,[j] D. Marques,[b,c] G. Mazzitelli,[d] A.G. McLean,[j] A. Messina,[g,h,*] C.M.B. Monteiro,[a] R.A. Nobrega,[i] I.F. Pains,[i] E. Paoletti,[d] L. Passamonti,[d] S. Pelosi,[h] F. Petrucci,[l,m] S. Piacentini,[g,h] D. Piccolo,[d] D. Pierluigi,[d] D. Pinci,[h] A. Prajapati,[b,c] F. Renga,[h] R.J.C. Roque,[a] F. Rosatelli,[d] A. Russo,[d] J.M.F. dos Santos,[a] G. Saviano,[n,d] N. Spooner,[j] R. Tesauro,[d] S. Tomassini[d] and S. Torelli[b,c]

[a] *LIBPhys-UC, Department of Physics, University of Coimbra, P-3004-516 Coimbra, Portugal*
[b] *Gran Sasso Science Institute, L'Aquila, I-67100, Italy*
[c] *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Gran Sasso, Assergi, L'Aquila, I-67100, Italy*
[d] *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, Frascati, Roma, I-00044, Italy*
[e] *ENEA Centro Ricerche Frascati, Frascati, Roma, I-00044, Italy*
[f] *Centro Brasileiro de Pesquisas Físicas, Rio de Janerio, RJ, 22290-180, Brazil*
[g] *Dipartimento di Fisica Sapienza Università di Roma, Roma, I-00185, Italy*
[h] *Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Roma, I-00185, Italy*
[i] *Universidade Federal de Juiz de Fora, Juiz de Fora, MG, 36036-900, Brazil*
[j] *Dept. of Physics and Astronomy, University of Sheffield, Hicks Building, Hounsfield Road, Sheffield, S3 7RH, UK*
[k] *Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Roma, I-00184, Italy*
[l] *Dipartimento di Matematica e Fisica, Università Roma TRE, Roma, I-00146, Italy*
[m] *Istituto Nazionale di Fisica Nucleare, Sezione di Roma TRE, Roma, I-00146, Italy*
[n] *Dipartimento di Ingegneria Chimica, Materiali e Ambiente, Sapienza Università di Roma, Roma, I-00184, Italy*

E-mail: andrea.messina@uniroma1.it

*Speaker

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Gaseous Time Projection Chambers (TPC) with optical readout are an innovative and very promising detection technique to enhance the the sensitivity for light dark matter candidates. The Cygno experiment is pursuing this technique by developing a TPC operated with gas mixtures at atmospheric pressure equipped with a Gas Electron Multipliers (GEM) amplification stage that produces visible light. Light is collected by a high sensitivity and resolution scientific CMOS camera, while a fast photodetector is used to measure the drift time of the primary ionization electrons and thus reconstruct the third coordinate of the ionization track. In this contribution, we illustrate the technical solutions developed to construct detector prototypes and discuss their performances when exposed to radioactive sources. We present results in terms of electro-luminescence yield and charge gain when operated with gas mixtures based on He:CF_4 and He:CF_4-isobutane, and different electric field configurations. We also discuss the solutions adopted for the DAQ and trigger systems and the performances of an innovative multi-stage pattern recognition algorithm based on advanced clustering techniques. We show how such solutions are essential to identify and select interesting events and how we plan to have them online to cope with the data throughput. Finally, we show the evolution of the project from small size detectors to the current 50 litres prototype which will be installed and tested underground at LNGS this year. A 1 m^3 demonstrator is expected to be built in 2021/22 and subsequently installed and commissioned at LNGS aiming at a large scale apparatus in a later stage.

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1. Introduction

Time Projection Chambers (TPC) are an ideal detector technique to search for dark matter (DM). This is a challenging task because of the huge background rate and the small energy expected to be released in the detector. DM candidates, after hitting atomic nuclei, transfer order of a few keV of energy to the nuclear recoils (NR) which then loose it leaving a detectable trace.

The innovative strategy of the Cygno collaboration is to photograph nuclear recoil events that take place in a TPC operated with a He:CF_4 gas mixture at atmospheric pressure. The ionization signal is amplified on the anode by a stage of three Gas Electron Multipliers (GEMs) where, thanks to the presence of CF_4, also visible light is emitted. Light is read out by a high sensitivity CMOS camera and photomultipliers (PMT). The camera provides high granularity and low noise images of the plane perpendicular to the drift field of the TPC. This information complemented with that from the PMT provides three dimensional reconstruction capabilities. The optical coupling allows placing the sensor outside the detector volume and enables the acquisition of large surfaces with small sensors.

The Cygno project started in 2015 with an intense activity dedicated to the development of our initial idea, the definition of the gas mixture and the readout strategy. During this phase we progressively increased the sensitive volume from the 0.1 litre to the present 50 litre prototype called LIME. We are currently in our CYGNO-phase0. We are finishing the assessment of the performance of LIME on surface at the INFN Laboratori Nazionali di Frascati (LNF), and we plan to take the detector underground at the INFN Laboratori Nazionali del Gran Sasso (LNGS) by this year. This would lead to the CYGNO-phase1 where we intend to build a 1 m^3 detector consisting of several modules identical to LIME. This detector will be commissioned and operated at LNGS in 2022/23. The final goal is to propose CYGNO, a larger apparatus of 30 to 100 m^3.

2. Prototypes performances

LEMON is one of the detector prototypes which has been extensively used to asses the performances of our experimental technique [1]. It has a 24×20 cm^2 readout area and a 20 cm drift length. The sensitive volume is enclosed by an elliptical field cage and closed on one side by the cathode on the other by the GEMs. One PMT is located on the cathode side, while on the opposite side there is an adjustable-length bellow and a lens that allows to focus the light onto the CMOS sensor. We used the scientific CMOS (sCMOS) camera Orca-Flash4.0 by Hamamatsu. This camera is based on a 1.33×1.33 cm^2 sCMOS sensor comprising 2048×2048 pixel with a readout noise of 1.4 electrons rms and a quantum efficiency of 70% at 600 nm where there is a sizable contribution from the CF_4 light emission spectrum.

2.1 Energy resolution and detector efficiency

To assess the energy resolution of LEMON, a ^{55}Fe X-ray source was placed inside the gas volume at about 20 cm far from the GEMs [1, 2]. The events were reconstructed with an elementary clustering algorithm based on nearest to neighbor-cluster. Fig. 1 shows on the left the distribution of the light of the clusters, and on the right the charge measured by the PMT. The light distribution is fitted with an exponential function to model the background plus a Polya function to model the

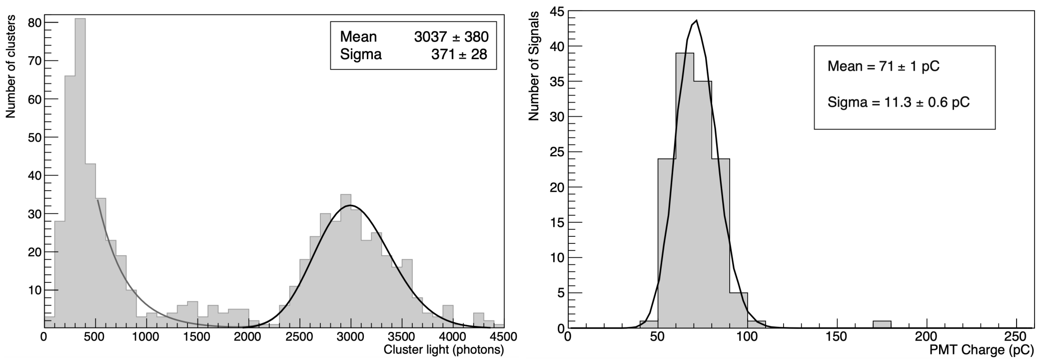

Figure 1: Distribution of the light (left) and charge (right) yield for collected respectively with the sCOMS sensor and PMT by exposing the LEMON detector to a ^{55}Fe X-ray source.

^{55}Fe signal at 5.9 keV. The average light yield is 514 ± 63 detected photons per keV, with an energy resolution of 12%. This result confirms that the noise of the sensor is well below 400 eV and the detector can safely be operated with an energy threshold of 1 keV. For the PMT we obtained a similar result with an energy resolution of 16%.

The detection efficiency was studied varying the drift electric field. A plateau was reached for electric fields values larger than 300 V/cm. In addition, changing the position of the ^{55}Fe source, the effect of the distance between the primary ionization cluster and the amplification stage was studied showing no significant change in the detection efficiency [1].

2.2 Position resolution

The ability to reconstruct the event z position was studied using the 450 MeV electrons provided from the LNF-BTF facility. LEMON was placed such that the electrons traversed the sensitive volume parallel to the GEMs plane at an adjustable distance z. Given the energy of the electrons, they cross the entire detector on a straight line leaving an ionization trace. We studied the transverse diffusion in the drift gap, and used it to extract the drift length and thus infer the z position of the ionization clusters [3]. We first measured the x-y resolution as a function of z, we found 100 μm close to the GEMs increasing to 300 μm 20 cm away from them. The amplitude A of the light distribution decreases while the width σ increases with longer drift distance z. We used the ratio $\eta = \sigma/A$ to enhance the dependence on z and we fitted it with a second order polynomial function to extract the z position of the event. With this technique we obtained a 15% resolution on the z position. A similar strategy leading to the same resolution can be used for events acquired with the PMT. In this case is the longitudinal diffusion to impact on the time width of the signal.

We are working on a much more performing strategy to determine the z position using negative ions. Negative ions produced by electronegative gas as for example SF_6 have a much reduced mobility and thus exhibit smaller diffusion. In addition, ions of different masses arrive at the anode at different times allowing a determination of the z position by a measurement of the difference in the time of arrival of different clusters [4].

2.3 Response to nuclear recoils

To Study the detector response to nuclear recoils we used an AmBe radioactive source [5]. The challenge is to properly reconstruct the recoil trace being able to associate to it each single pixel hit by photons originating from the NR energy deposit. To accomplish this task, we first use iDBSCAN [6] an iterative and customised version of the DBSCAN algorithm to find isolated clusters, then we process clusters iteratively with a morphological geodesic active contour algorithm (GAC) to connect clusters together in a long trace. The GAC algorithm, using the light intensity as an additional variable, can successfully disentangle overlapping clusters belonging to different kinds of particles. Once the trace of the particle is reconstructed we can determine the track parameters such a length, width, total light and light density among others. These variables are the input for the event recognition. Our basic algorithm to separate NR and ER events is relatively simple and uses only the light density δ. Its performances have been assessed on the 5.9 keV energy deposit from ^{55}Fe for the ER and AmBe for the NR. A cut at $\delta = 10$ is used to obtain for an energy deposit around 5.9 keV a background rejection of 96% against ER and a signal efficiency of 40% for NR.

2.4 Electro-luminescence studies

We are currently studying the light yield produced by accelerated electrons before they reach the regime where a sizable ionization occurs. The experimental setup for these measurements exploits a detector based on the LEMON prototype with the addition of an anode constituted by a mesh after the GEMs amplification stage. By varying the electric field after the GEMs electrons are extracted and accelerated towards the mesh. We placed a ^{55}Fe radioactive source on the side of the active volume and measured the charge collected by the mesh and the light yield as a function of the applied electric field from 0 to 15 kV/cm. An increase of light yield was clearly observed in the long exposure images as well as on the total light collected in the reconstructed clusters. Comparing this behaviour with that of the measured current on the mesh we observed a much steeper increase in the number of photons than electrons, resulting in an overall increase in the photon-to-electron ratio as a function of the applied field. This has been the first demonstration of electro-luminescence with CF_4 gas [7]. We are presently conducting further investigations studying the interplay between the GEMs station and the electric field below them, exploring different solutions to increase the electric field, and different gas mixtures.

2.5 Ternary mixtures with hydrocarbons

One of the main objectives of the Cygno project is to be sensitive to light DM. This is at the basis of the choice of a gas mixture containing helium. To further increase the sensitivity to light DM we are currently studying the possibility to add a small percentage of isobutane, which having 10 hydrogen atoms per molecule, would result in an atomic number density comparable with those of the other elements in the gas mixture. The drawback of isobutane is the fact that it absorbs visible light. We observe about an 8 fold decrease in the number of photons per electron. However, we also observe a 2.7 fold increase in the total number of electrons and thus only an overall 2.8 decrease in photons per absorbed keV. Together with the studies on electro-luminescence described in the previous section this result opens the road to the usage of isobutane in our project.

3. The LIME prototype and the CYGNO 1 m^3 demonstrator

LIME is our current detector prototype. It is the largest to date: 33×353 cm^2 of sensitive area times 50 cm of drift length for a volume of about 0.05 m^3. LIME is equipped with an improved version of the sCMOS camera, the Orca-Fusion by Hamamatsu, which has more pixels (2304×2304), a larger quantum efficiency (80%), and a reduced noise from 1.4 to 0.7 electrons rms. Also thanks to these improvements in the sCOMS sensor we obtain a similar energy resolution at 5.9 keV of about 15% and the possibility to lower the energy threshold to 0.7 keV with a larger detector. It features 4 PMT hosted on the same side of the GEMs plate. LIME has been designed, constructed, and commissioned overground at LNF. During the commissioning LIME has proven to be very stable against hot spots and discharges. It has been running smoothly for several days with less than 1 hot spot event every hour. These events are resolved with a recovery procedure consisting in lowering the GEMs voltage to zero and raising it again in steps of 100 V, such a procedure introduces a minimal deadtime of less than 3 minutes. LIME will be moved underground at LNGS by 2021. For this campaign it will be surrounded by a radiation shielding consisting of a 10 cm copper and a half a meter water.

After the commissioning of LIME underground we will move to CYGNO-phase1 with the aim of studying and minimizing the radioactivity effects on a larger scale, close to real experiments. For this purpose we have concluded at LNF the technical design of the 1 m^3 demonstrator of the CYGNO experiment. It consists of 2 field cages on the opposite side of a common cathode closed by 2 matrices of 3×3 GEMs stages, each stage is readout by a module identical to LIME. For such a larger prototype we are also developing an appropriate data acquisition and trigger system. It will consist of two paths: one for the cameras and the other for the PMTs. Each camera, operated with an exposure that varies from 0.2 to 1 second, will be acquired with a camera link PCIe Frame grabber. Approximately each picture will consist of 10 MB of data (5 MP, 16 bits/pixels). The PMTs will be readout by 12 bit digitizers at 250 MS/s in a time window of about 1μs. So far we have operated the camera in a trigger-less continuum mode. In the future we are studying the possibility to trigger the acquisition of the camera based on a minimal hardware logic on the PMT signals. To operate in the trigger-less mode and keep the data throughput to disk within the 200 MB/s we also foresee a software trigger to reconstruct images and perform basic event selection. This will run on a farm of CPUs or GPUs within a latency of about 1 evt/second. This detector has been funded and it will be installed at LNGS by 2023.

4. Conclusions

In summary, the Cygno collaboration is developing a GEM based TPC operated with a He:CF_4 gas mixture at atmospheric pressure and readout optically by means of a sCMOS camera and photodetectors. The first detector prototypes demonstrated to have very good energy and position resolution together with a high discriminating power between electron and nuclear recoils. There are several ongoing studies devoted to the optimisation of the detector performances. Among others we have presented the three most relevant ones: (i) the deployment of electronegative gas mixture to improve the resolution in the determination of the event distance from the GEMs plane; (ii) the increase of the light yield exploiting the electro-luminesce to improve the energy resolution while operating the GEMs at moderate voltages; (iii) the inclusion of isobutane in the gas mixture to improve the detector performance in the low DM mass region. We are currently working on commissioning the LIME prototype including an underground campaign at LNGS that will start by the end of this year, and to build a 1 m^3 Cygno demonstrator to be installed and operated at LNGS.

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