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The CYGNO experiment: a directional Dark Matter detector with optical readout

The CYGNO collaboration

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Abstract: We are going to discuss the R&D and the prospects for the CYGNO project, towards the development of an innovative, high precision 3D tracking Time Projection Chamber with optical readout using He:CF_4 gas at 1 bar. CYGNO uses a stack of triple thin GEMs for charge multiplication, this induces scintillation in CF_4 gas, which is readout by PMTs and sCMOS cameras. High granularity and low readout noise of sCMOS along with high sampling of PMT allows CYGNO to have 3D tracking with head tail capability and particle identification down to O(keV) energy for directional Dark Matter searches and solar neutrino spectroscopy. We will present the most recent R&D results from the CYGNO project, and in particular the overground commissioning of the largest prototype developed so far, LIME with a 33×33 cm^2 readout plane and 50 cm of drift length, for a total of 50 litres active volume. We will illustrate the LIME response characterisation between 3.7 keV and 44 keV by means of multiple X-ray sources, and the data Monte-Carlo comparison of simulated sCMOS images in this energy range. Furthermore, we will present current LIME installation, operation and data taking at underground Laboratori Nazionali del Gran Sasso (LNGS), serving as demonstrator for the development of a 0.4 m^3 CYGNO detector. We will conclude by mentioning the technical choices and the prospects of the 0.4 m^3 detector, as laid out in the Technical Design Report (TDR) recently produced by our collaboration.

Keywords: Dark Matter detectors (WIMPs, axions, etc.); Gaseous imaging and tracking detectors; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Time projection Chambers (TPC)

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1 The CYGNO experiment

The goal of the CYGNO project is to develop a TPC with optical readout for application to rare events searches as solar neutrinos or Dark Matter (DM) interactions. The search for DM is one of the most pressing tasks for fundamental physics. In the context of the direct detection of light WIMP DM, the expected anisotropic angular distribution of the nuclear recoils induced by DM interaction is considered one of the few, if not the only, handles for a positive claim of DM discovery. Therefore, an increasing effort in the directional detection of these low energy nuclear recoils is being put by the scientific community [1].

In the detector proposed by the CYGNO collaboration [2], the TPC is filled with a gaseous mixture of He and CF_4 60:40% at atmospheric pressure and room temperature. The amplification stage consists in three Gas Electron Multipliers (GEMs). In the multiplication process, secondary light is produced by the de-excitation of CF_4 molecules. The light is eventually read out by scientific CMOS (sCMOS) cameras, providing a high granularity 2D image of the ionization track, and by photomultiplier tubes (PMTs) that allow to measure the tilt of the track along the drift direction measuring the different arrival times of the clusters. The combined reconstruction allows a 3D directional reconstruction of the track.

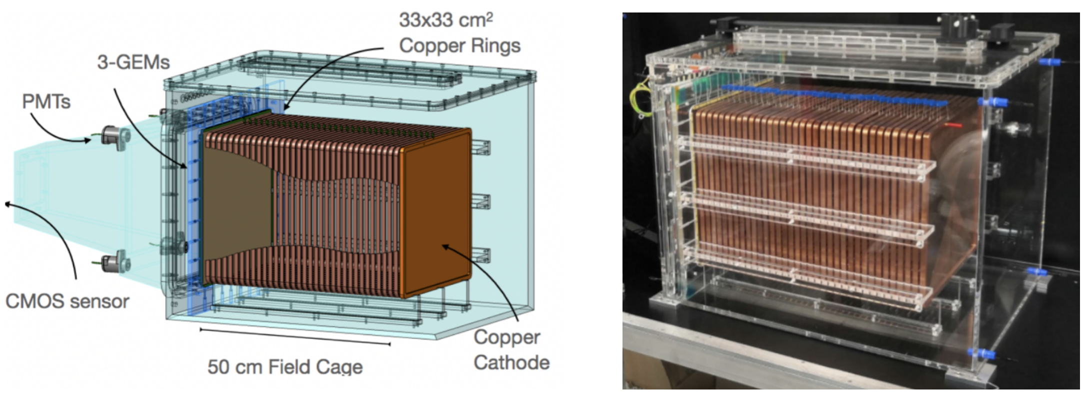

Figure 1. Scheme (left) and picture (right) of the LIME prototype. The field cage structure, and the cathode can be seen inside the plexiglass vessel.

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The latest prototype developed by our collaboration is the Large Imaging ModulE (LIME) (figure 1). LIME has a 50 cm drift length and a readout area of 33×33 cm^2, for a total volume of 50 liters. The electric field in the TPC is controlled by a field cage composed of 35 copper rings that keep the electric field uniform in the whole detection volume. The amplification stage is a stack of 3 standard GEMs with holes with an internal diameter of 50 µm and pitch of 140 µm, placed 2 mm apart from each other and 7 mm from the beginning of the field cage. One Orca Fusion sCMOS camera from Hamamatsu reads out the entire area and 4 PMTs are used, placed at the corners of the readout plane.

2 Commissioning of the large size prototype

The LIME prototype was operated at the Frascati National Laboratories of INFN (LNF) during the 2021 summer and autumn to test the detector stability. Data were acquired using a multi-energy X-ray source to study the sCMOS sensor detector response in terms of linearity and energy resolution. The voltage difference across the two sides of each GEM foil was set at 440 V. This value was chosen to have a very stable detector operation; the light yield of the GEM stack as a function of the applied voltage difference was studied and reported in a previous work [3]. X-ray interactions are individually seen in the images from the sCMOS sensor as spots or longer tracks depending on their energy.

A dedicated simulation was developed starting from a *Geant4* simulation of the detector that produces the particle tracks inside the gas. The detector response in then obtained exploiting a model that takes into account the most relevant effects and fluctuations: ionization, diffusion, absorption, amplification and its saturation, light production and collection. The free parameters of the model were fixed comparing the simulation result with data taken with a ^{55}Fe source in different positions and at different detector operating conditions.

With the sCMOS sensor we can measure the collected light. As can be seen in figure 2(left) a linear energy response was found between 3.7 keV and 44 keV.

Moreover, an energy resolution of about 14% in the whole volume was measured, figure 2(right). A very good agreement between the measurements and our simulation is found. In addition, a 100% reconstruction efficiency was measured at 5.9 keV in the whole volume exploiting a ^{55}Fe source [4].

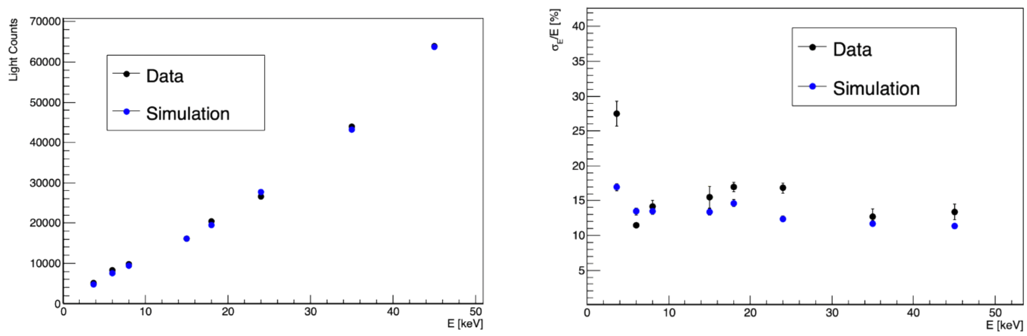

Figure 2. Energy response linearity (left) and resolution as a function of the energy (right) as measured with the LIME prototype.

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3 Prototype underground operation

The LIME prototype was installed underground at National Laboratories of Gran Sasso (3600 m.w.e.) early in 2022 and different data taking periods started since then in different conditions. An automated system allows to control remotely the gas system, the environmental sensors, the High Voltage and the data acquisition system. Continuous data taking periods are therefore possible to further test the detector stability.

Underground data are being collected and analysed to be compared with MC simulations aiming for the characterization of the background in different phases. Without any external shielding the external background can be measured. Adding a 10 cm copper shielding, the external gamma background is reduced to measure the external neutron background alone. The final configuration exploits water tanks (40 cm) plus the copper shielding to measure the internal background and perform tests in the final low background and low pile up conditions. Concerning the internal background, preliminary measurements of the radioactivity from all main detector components were already measured with HPGe detectors. The most radioactive components for this prototype resulted to be the copper rings, the resistors and the GEM/cathode.

4 Future developments

The underground operation of the large prototype, which was successfully achieved, and the tests and measurements in the final low background conditions were the mandatory steps to ensure the continuation of the project. The next step in our R&D project (called *Phase 1*) is the CYGNO-04 demonstrator with the goal of demonstrating the full scalability of the technique starting from the LIME design. A detailed TDR [5] was produced and the demonstrator has already been funded. It consists in a 0.4 m^3 detector to be hosted in LNGS Hall F. The $50{\times}80{\times}100$ cm^3 volume is divided into two back-to-back chambers with a common cathode that will be read out by 4 sCMOS cameras and 12 PMTs. One of the major efforts is being put in reducing the internal background trying to exploit low radioactivity camera sensors, lens and windows in Suprasil, PMMA or polycarbonate.

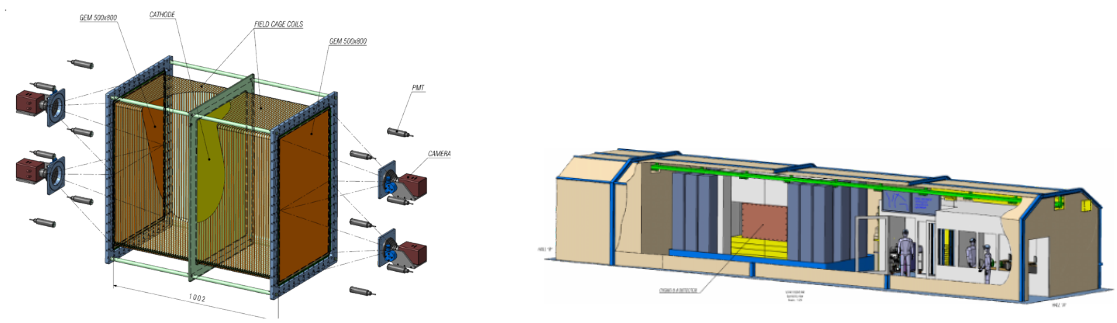

Figure 3. Drawings of the CYGNO-04 demonstrator showing the internal details (left) and its positioning inside its shielding layers in LNGS Hall F.

Acknowledgments

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