Study of long term stability of a 50 liters TPC, based on TRIPLE-GEM with optical readout, for the CYGNO experiment

RITA ANTONIETTI - UNIVERSITÀ DI ROMA TRE & INFN ROMA TRE
ON BEHALF OF:

The presence in the Universe of large amount of non-luminous matter, **Dark Matter (DM)** is nowadays a paradigm.

One of the DM particle candidates are the **WIMPs** (Weakly Interactive Massive Particles):

- Electrically neutral;
- Very low interacting particles;
- Large mass range, CYGNO will look low mass range (0.5-10 GeV)
Travelling through DM

- Dark Matter forms a halo around Our Galaxy;
- Our Solar system rotates around galaxy center apparently in the direction of the Cygnus constellation;
- Motion of our Galaxy creates an apparent wind of DM coming from Cygnus constellation towards Earth.

In the Earth rotation around the Sun: a seasonal modulation of few percent in the signal is expected;

Due to the Earth rotation around its axis, an observer on Earth would see the average DM incoming direction changing every 12 hours.
To not relativistic speed, elastic scattering with ordinary matter, are expected to be the most evidence of WIMP interactions.

Directional discrimination is the only way to unambiguously identify a DM signal given the anisotropy in the angular distribution that no background can mimic.

Directional measurements can discriminate between various DM halo models and provide constrints on WIMP properties, like no other non-directional detector.
Background

Challenge -> to discriminate the low energy nuclear recoil from interactions induced by other particles.
The CYGNO experiment goal is to deploy underground at the LNGS a high-resolution Time Projection Chamber (TPC) with Optical readout for the study of rare events as interaction of low mass DM particles.

**Strategy:**

- He:CF$_4$ (60:40) gas mixture at atmospheric pressure and room temperature:
  - Helium -> light, O(GeV) dark matter sensitivity;
  - Fluorine-> Spin dipendent sensitivity

The possibility of operation at atmospheric pressure guarantees a reasonable volume to target mass ratio

- Triple GEM amplification stage;
- 3D reconstruction of the track;
- NR/ER discrimination capability;

The results obtained with current prototypes are the basis for the 0.4m$^3$ demonstrator
The optical readout

Ionization

Charged particles traveling in the gas can ionize atoms and molecules but can also excite them. During the de-excitation processes, photons are emitted.

Amplification

A Triple Gas Electron Multiplier (GEM) stack is used to multiply the signal, photons are produced during the amplification.

Readout

Hamamatsu R7378 PMT
- Fast light sensor;
- For Δz component;

Hamamatsu Orca-Fusion camera
- Single photon sensitivity;
- High granularity;
- For x-y projection;
The CYGNO experiment - TIMELINE

**PHASE 0:** R&D and prototypes
- 2015/16 ROMA1
- 2017/18 LNF
- 2019/22 LNF/LNGS

**PHASE 1:** 1 m³ Demonstrator
- 2022/27 LNF/LNGS
- CYGNO_04
- 1 cm drift
- 3D printing
- 50 cm drift
- underground tests
- shielding
- background
- materials test, gas purification
- scalability

**PHASE 2:** 30 m³ Experiment
- 2027...
- LNGS
- CYGNO_30
- Physics research
LIME: the Long Imaging Module

**LIME** (Long Imaging Module) is the largest prototype built which is currently installed underground at LNGS:

- Filled with He:CF$_4$ (60:40) gas mixture;
- 50 cm drift distance;
- A triple 33 x 33 cm$^2$ stack of thin GEMs;
- 1 sCMOS camera (Hamatsu ORCA Fusion):
  - 2304 x 2304 pixels;
  - Low noise (1 ph/pixel);
  - High granularity;
- 4 PMT
- The fieldcage is composed by copper rings, roundly shaped to avoid discharges.

The Hamamatsu ORCA_Fusion Camera Has 80% QE at 600nm
The output gas is sent to an exhaust line connected to the external environment via a water bubbler ensuring the small (3 mBar) required overpressure.

A trolley is mounted on the vessel to move an iron calibration source along the z axis from 5 cm to 45 cm far from the GEMs.

Some tracks at different energies

The tracks are reconstructed using an algorithm based on DBSCAN.
The $^{55}\text{Fe}$ source is used to calibrate the prototype. It emits X-rays with an energy of about 5.9 keV, with an additional emission at around 6.4 keV. The interactions of low energy photons with atoms in the gas mixtures create photo-electrons.

The images acquired by the sCMOS are reconstructed and one of the most important information saved is the light of each cluster:

These events produce round-like spots on the CMOS sensor with diameters of 2-3 mm.

**Light distribution**

A fit with the Cruijff function on the $^{55}\text{Fe}$ peak is performed to evaluate the mean value:

$$f(x) = \exp\left(-\frac{(x - m)^2}{2\sigma_{E,R}^2 + \alpha_{l,R}(x - m)^2}\right)$$
A DM search detector must guarantee uninterrupted and reliable and very long data taking periods

--- LIME operated for several months overground at Frascati National Laboratories (LNF – INFN):

The $^{55}$Fe source has been placed 25cm far from the GEMs and for two weeks recorded the data

The room temperature has been quite stable, with an average value of $298.7 \text{ K}$

The $^{55}$Fe peak is normalised to the first acquired run, The $^{55}$Fe peak vs the Pressure is plotted and a linear fit is performed and a light yeald decrease of about 0.6% per mBar is found

The analyses shown are made using the data taken by the sCMOS camera
The GEM's currents are recorded.

To study the long term stability, the currents of the third GEM are studied in one month of operation.

If the GEM's HV is stable and the current value is higher than 1nA, it is counted like a spike. The time between two spikes has been evaluated.

An exponential fit on the time between two spikes distribution is performed.
LIME underground @ LNGS

The LIME prototype has been installed underground at Gran Sasso National Laboratories (LNGS) at the beginning of 2022:

• To test the detector performance in low radioactivity and low pile-up configuration;

• To characterise the radioactive background present in the site and then to validate the GEANT4 simulation.

LIME has been equipped with the Gas-System, the same one which will be used for the demonstrator.
The acquisition data and the control of the system is based on the MIDAS framework.
Acquisition data & Monitoring

The detector needs to work for a long period, thanks to the control page we can acquire data automatically, without human intervention.

Thanks to the the Graphana system, we can monitor the data quality.
Long Term Stability Test @LNCS

Run 1
No shield
November – December 2022
The temperature is kept constant ~ 290 K by a heating system

2 different gas flows:

<table>
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<th>Decrease [%]/[mBar]</th>
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<tr>
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Compatible with LNF results
Long Term Stability Test @ LNGS

Run 3
10 cm Cu shield
May 2023
The temperature is kept constant ~293 K by a heating system
A humidity sensor has been installed

The $^{55}$Fe peak is normalised to the first run and it is plotted vs the Humidity, an exponential fit is performed

Increasing the humidity --> The $^{55}$Fe_Peak decreases

On the y axis the relative humidity is reported with an offset

Slope – 0.059 ± 0.001
Hot-spots and noise studies @ LNGS

Hot-spots = Appearance of small luminous and low energy spots on the GEM surface which are not due to the particle's interaction with the gas. Some of these spots fade out with the time.

Mean position of each cluster taken in 400 images

There is a cluster in each image = hot-spot
Next phase will show achievability of CYGNO_30 physics performances
● Study and minimize radioactivity
● Develop modular readout and DAQ
● To test scalability to $m^3$ volumes

➔ Back-to-back 0.4 $m^3$ gaseous TPC, with central cathode.
➔ At atm pressure, room temperature and He:CF$_4$
➔ Triple 50 x 80 cm$^2$ GEM stack for amplification
➔ Projected shielding composed of 10 cm Cu + 100 cm H$_2$O
➔ To be installed in Hall F @LNGS

Optical readout:
-4 qCMOS cameras (Hamamatsu ORCA Quest);
-12 PMTs;
Conclusions

- The CYGNO collaboration is developing a high-precision gaseous TPC at atmospheric pressure with optical readout.
- The main focus is the direct search of DM WIMP-like particles in the low mass range (0.5-10 GeV).
- Through directionality, solar neutrinos can be discriminated and unambiguous confirmation of DM is possible.
- The 50L LIME prototype is currently taking data at the underground LNGS facilities.
- Analysis of underground data is ongoing;
- CYGNO_04, already funded and with a TDR submitted, will allow us to test the experiments scalability.
- CYGNO_30 is under study, with its sensitivities looking promising.
- What is next:
  ● Spectral (and directional) neutron flux measurement underground at LNGS
  ● Water shielding installation and final test of LIME operation
Backup
Background simulation

The detector and the shielding geometry has been simulated with GEANT4

Inputs:
- External radioactivity measure on site;
- Activity of all main components measured underground@ LNGS (rings, resistors, cathode, GEMs, camera components)

Data/MC comparison

Internal background
7.45x10⁶ ev/yr
Reduced by 96% with fiducial cuts