THE CYGNO PROJECT: PERFORMANCE AND STABILITY OF AN OPTICALLY READOUT GEM-TPC

The aim of CYGNO project is the development and realisation of a **GEM-based Optically Readout Time Projection Chamber** for the study of rare events with energy releases in the range 1-100 keV.

Expected performance is:

- High **detection efficiency** down to 1 keV;
- **Directionality** at 10 keV;
- Background **rejection below 10 keV**;

Main ideas of the technology are:

- **He/CF\textsubscript{4}** based gas target (atmospheric pressure);
- **GEM** amplification stage;
- **Combined optical readout** CMOS + PMT;
PROJECT PHASES

PHASE 0: R&D
- 1 cm drift
- 3D printing
- 20 cm drift

PHASE 1: ~1M³ DEMONSTRATOR
- background
- materials test
- gas purification
- scalability
- reliability

2016/17 @ ROMA1/LNF
ORANGE
- 1 cm drift

2018/19 @ LNF
LEMON
- 3D printing
- 20 cm drift

2019/20 @ LNF/LNGS
LIME
- 50 cm drift
- underground tests
- shielding

2021/22 @ LNF/LNGS
Construction & test

2023 @ LNGS
Installation & commissioning

30-100 m³ CYGNUS
PERFORMANCE WITH $^{55}\text{Fe}$: SPOT SIGNALS

5.9 keV photons from $^{55}\text{Fe}$ source were used to test detection efficiency and light yield.

Energy resolution of 15% with CMOS and PMT

Full detection efficiency in all tested depth

500 photons collected per keV

Sensor noise below 200 photons (i.e. 400 eV)

CMOS

PMT

Energy resolution of 15% with CMOS and PMT
PERFORMANCE ON ELECTRON BEAM: LONG TRACKS

Analysis was performed by splitting tracks in 36 slices 7 mm long (i.e. 1.6 keV)

Diffusion can be exploited to evaluate absolute Z position with an average resolution of 15%

Relative position evaluated with a resolution between 100 μm and 300 μm
PERFORMANCE WITH NUCLEAR RECOILS

Detector was tested with AmBe source:

- 1-10 MeV neutrons -> nuclear recoils
- 4 MeV photons -> high energy electrons
- 59 keV photons -> 59 keV electrons

A 5 cm Pb shield was used.

Shapes and light densities clearly different.
PERFORMANCE WITH NUCLEAR RECOILS

A sizeable efficiency in the range 5-10 keV was measured while more than 95% (99%) \(^{55}\)Fe photons were rejected.

<table>
<thead>
<tr>
<th>Working Point</th>
<th>Signal Efficiency</th>
<th>Background Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\varepsilon_S^{\text{preset}})</td>
<td>(\varepsilon_S^{\delta})</td>
</tr>
<tr>
<td>WP(_{50})</td>
<td>0.98</td>
<td>0.51</td>
</tr>
<tr>
<td>WP(_{40})</td>
<td>0.98</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Nuclear recoil signals well visible even below 10 keV.
Detector high voltage was kept ON for a 25 day period, while currents were monitored and logged. Stable and smooth operation without any “human” intervention.

Two kinds of instabilities were discovered in current behaviour:

- **Discharges**: rapid and very high increases in current with a complete drop of the GEM voltage;
- **Hot spots**: small and stable increases in current accompanied by the appearing of a luminous spot on the GEM surface (likely due to self-sustaining micro-discharges).

An **automatic** high voltage power cycle was developed to **dump hot-spots** that resulted very effective.
DETECTOR STABILITY

The **time intervals** between the occurrence of two subsequent events were evaluated for two different He/CF$_4$ proportions.

- their distributions showed a negative exponential behaviour typical of **non-correlated events**;
- mixture with less CF$_4$ resulted less stable with a larger frequency of instability events

### Table

<table>
<thead>
<tr>
<th>He/CF$_4$</th>
<th>Hot-spot frequency</th>
<th>Discharge frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>60/40</td>
<td>0.6/hour</td>
<td>2.5/hour</td>
</tr>
<tr>
<td>70/30</td>
<td>0.16/hour</td>
<td>1.0/hour</td>
</tr>
</tbody>
</table>
**LIME**

**50 litre** sensitive volume:

- **33 x 33 ~ 1000 cm²** GEM surface;
- **50 cm** drift path;

**Copper ring** field cage

**Acrylic** gas vessel
LIME: FIRST IMAGES

33 cm
LIME - 55 FE SPOTS

- 5 cm from GEMs
- 20 cm from GEMs
- 45 cm from GEMs

$V_{\text{GEM}} = 440$, $E_D = 0.8$ kV/cm

No evidence of large efficiency drop
LIME - 55 FE SPOTS (ZOOM)

- 5 cm from GEMs
- 20 cm from GEMs
- 45 cm from GEMs

$V_{\text{GEM}} = 440, \ E_D = 0.8 \text{ kV/cm}$

Diffusion effect visible

Spectra of charge on the last GEM shows an Energy resolution of 15% in the whole volume

45 cm from GEMs
BACKGROUND STUDIES: EXTERNAL

Full Detector simulation in **GEANT4**

**Gamma** and **neutron** background due to external radioactivity simulated

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200 cm water + 5 cm Cu

**Expected background coming from outside of** $5 \times 10^2$ cpy in the [1-20] keV;

**Gamma Flux at LNGS** $0.56 \text{ cm}^{-1} \text{s}^{-1}$

**Gamma Flux after 2 m water shield** $1.4 \times 10^{-6} \text{ cm}^{-1} \text{s}^{-1}$

**Gamma Flux after 5 cm Cu shield** $1.8 \times 10^{-7} \text{ cm}^{-1} \text{s}^{-1}$
**BACKGROUND STUDIES: INTERNAL**

Measured radioactivity of different Cameras and GEMs

<table>
<thead>
<tr>
<th>Camera</th>
<th>Sensitivity (eV/count)</th>
<th>Resolution (%)</th>
<th>Noise (eV)</th>
<th>$^{226}$Ra (Bq)</th>
<th>$^{232}$Th (Bq)</th>
<th>$^{238}$Ra (Bq)</th>
<th>$^{234}$Pa (Bq)</th>
<th>$^{40}$K (Bq)</th>
<th>Total activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamamatsu ORCA FLASH 4.0</td>
<td>2.96</td>
<td>15.2</td>
<td>4.6</td>
<td>2.1</td>
<td>2.1</td>
<td>1.9</td>
<td>7.0</td>
<td>1.9</td>
<td>15.0</td>
</tr>
<tr>
<td>ORCA FLASH sensor</td>
<td>2.6</td>
<td>15.2</td>
<td>8</td>
<td>1.0</td>
<td>1.0</td>
<td>1.1</td>
<td>1.1</td>
<td>4.3</td>
<td>8.5</td>
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<tr>
<td>Photometrics Prime BSI Mode 1</td>
<td>3.3</td>
<td>19.0</td>
<td>9.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Photometrics Prime BSI Mode 2</td>
<td>1.12</td>
<td>16.4</td>
<td>4.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Photometrics BSI Express Mode 2</td>
<td>0.84</td>
<td>13.4</td>
<td>3.0</td>
<td>1.3</td>
<td>1.8</td>
<td>1.0</td>
<td>6.0</td>
<td>3.6</td>
<td>13.7</td>
</tr>
<tr>
<td>Hamamatsu Fusion Closer (LEMON)</td>
<td>0.65</td>
<td>17.5</td>
<td>1.58</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hamamatsu Fusion Farther (LIME)</td>
<td>0.85</td>
<td>16.4</td>
<td>2.06</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Thorlab Quantalux</td>
<td>tbm</td>
<td>tbm</td>
<td>tbm</td>
<td>0.3</td>
<td>0.6</td>
<td>0.2</td>
<td>3.0</td>
<td>1.2</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Internal background $5 \times 10^5$ cpy in 1-20 keV

Cameras and GEM are responsible of main radioactivity budget within the detector.

With a rejection of $10^2-10^3$ an avoidable internal bkg of several hundreds of events/year expected.

Studies on how to reduce it needed
SIGNAL SIMULATION

Interactions of recoils in gas simulated:

- **GEANT** for electrons;
- **SRIM** for nuclei;

Gas parameters (ionization, diffusion, drift velocity, attachment) simulated with **GARFIELD**;

**Sensor noise** studied and **simulated** accordingly to data.
1 m³ of He/CF₄ 60/40 (1.6 kg) at **atmospheric pressure** subdivided in two 50 cm long parts by the cathode with a drift field of about 1 kV/cm;

Acrylic vessel ensuring gas tightness and high voltage insulation;

Each side equipped by a 3x3 matrix of LIME-like:
- sCMOS sensor 65 cm away;
- Fast light detector (PMT or SiPM).

Radioactivity shielding:
- **5 cm** thick copper box (Faraday cage too);
- **200 cm** of water.
Because of the low mass of Helium nuclei, CYGNO can be very sensitive to light DM (~1 keV released per GeV)

DAMA region covered even with 15 keV and 1000 bkg events

If DM is found, directionality will be crucial to confirm discovery and individuate its source

With 30 m³, a 100 kg-year exposure can be achieved in 3 years
WHAT CYGNO CAN DO: NEUTRINO SPECTROSCOPY

Elastic neutrino - electron scattering with gaseous TPC: revitalising old ideas

- sub-millimetre tracking capability (Borexino is 12 cm)
- 10 keV directional threshold (Borexino has 160 keV)
- keV energy resolution
- low mass

For 1 m$^3$ of He:CF$_4$ 60:40 with 20 keV threshold

$$R = N_e \cdot \int_{E_{min}}^{E_{max}} w(E) \varphi_{ppl}(E) \sigma(E) dE$$

$$R = 2.9 \cdot 10^{-8} \frac{\text{events}}{s \cdot m^3} = 0.9 \frac{\text{events}}{y \cdot m^3}$$

Given the Sun position, recoils in opposite direction are kinematically forbidden

Differently from WIMPs, background can be measured on sidebands data
CONCLUSION

CYGNO project is developing a **GEM-based TPC optically readout** for rare event studies.

Very promising performance was found in the (few) keV region.

CYGNO is working in the framework of CYGNUS: an international Collaboration aiming at the realisation of Multi-site Recoil Directional Observatory for WIMPs and neutrinos;

More than 50 signed members UK, Japan, Italy, Spain, China focused on gas TPCs with 2D or 3D direction sensitivity;
THANKS!
SPARES
Please, keep in mind that only 1 m³ year exposure is shown for CYGNO.

get up to ± 100 kg year exposure with 30 m³ 3 years

0 bkg & 1000 bkg shown for each threshold
The maximum energy that can be transferred by a DM particle to a recoil of mass $m_N$, is given by:

$$\epsilon = \frac{4\rho}{(\rho + 1)^2}$$

where

$$\rho = \frac{m_N}{m_{WIMP}}$$

<table>
<thead>
<tr>
<th>Element</th>
<th>Max E transferred by a 1GeV DM particle</th>
<th>Min DM particle mass with 1 keV threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>0.2 keV</td>
<td>5.25 GeV</td>
</tr>
<tr>
<td>He</td>
<td>1.2 keV</td>
<td>0.78 GeV</td>
</tr>
<tr>
<td>F</td>
<td>0.4 keV</td>
<td>2.63 GeV</td>
</tr>
<tr>
<td>Xe</td>
<td>0.06 keV</td>
<td>16.6 GeV</td>
</tr>
</tbody>
</table>

Sensitivity to direction:

- for nuclear recoils starting from energies larger than 10 keV;
- for electron recoils starting from 2 keV (useful for separation)