**CYGNO/INITIUM - Annual Report**

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CYGNO collaboration: INFN (LNF, RM1, RM3),
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Università di Roma Tre, GSSI, Centro Fermi
University of Sheffield (GB), University of Coimbra (PT)
and University of UFJF and CBPF (BR)

The activity of the LNF CYGNO [1)] in 2025 was mainly devoted to finalize the CYGNO-04 detector hosting infrastructure, validating the electromechanical and radiosensitive properties of the materials for the detector construction, to test improvements on Gas Electron Multiplier (GEM) behaviour for optical readout, to coordinate and improve the data analysis of LIME/GIN and MANGO prototypes, to design, develop and put in operation the computing model on the INFN DataCloud infrastructure. In the following, a brief report of tasks under the responsibility of LNF in the CYGNO collaboration developed in 2025 is presented.

## 1 Design, construction and test of R&D prototypes and CYGNO-04 detector

The LNF group is in charge of the design, installation and test of all the prototypes/detectors [2)] of the CYGNO project. During 2025 this has included operation with the GIN prototype, devoted to test the performances of GEM treated with the V-Bond technique to make them opaque to light reflection, avoiding relevant noise in CYGNO optical readout. The GEMs were tested exploiting high energy natural radioactivity-induced alpha tracks to determine the reflectivity (paper in preparation). In addition, this treatment turned out to be extremely effective in reducing the space-charge saturation of the gain. This was thoroughly studied by Borsista Bonali who took and analyzed data with a modified GIN setup rigged with a muon tag system. This way, low energy depositing muon and higher energy depositing 5.9 keV electrons could be compared to estimate absolute saturation (paper in preparation). As a result, the V-Bond GEM were chosen for CYGNO-04 demonstrator detector.

Meanwhile, the design service has completed the design of the internal components of CYGNO-04 and almost finished the ones for the copper shielding. The field cage foils, the PMMA gas-tight internal box and the internal field cage support structure in Nylon66 were all delivered to LNF by the end of the year.

Finally, the detector construction service is supporting data collection at LNGS for the LIME prototype by managing the gas system, electronics, and computing infrastructure.

In the context of the R&D of gaseous detector for rare events searches, in 2025, G.Dho was confirmed as project leader of the Work Package 9 Project D for the DRD1 collaboration.

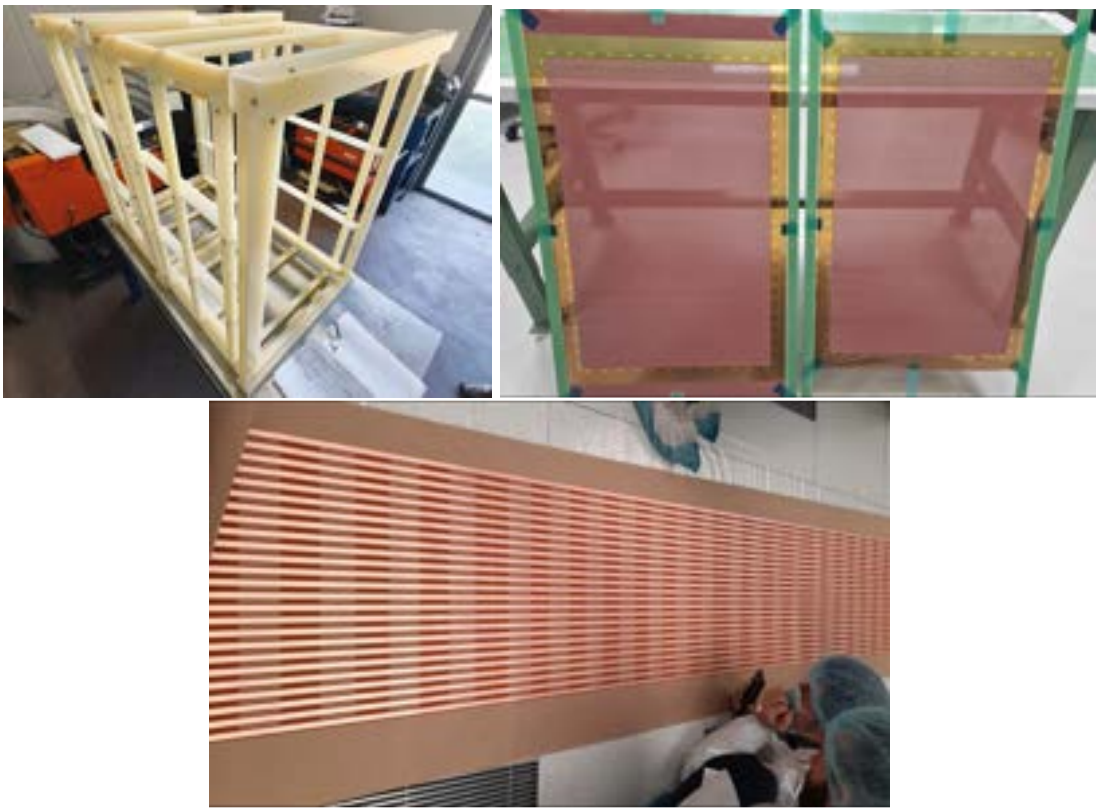

Figure 1: Top left: Inner detector in Nylon66. Top right: CYGNO-04 GEM foils. Bottom: FC foil before installation.

## 2 Data Analysis

Also during 2025, LNF was in charge of data analysis coordination of the CYGNO experiment. The organization of the principal and long term goals of the collaboration have been thought upon and divided among the man-power available in the different CYGNO groups. Tasks span from the analysis of the underground data of the LIME prototype, to machine learning techniques applied to signal-background discrimination, from studies on the stability of the detector to the development of the fitting procedure of the data to estimate dark matter and neutrino limits/measurements and to the study of the directional capabilities of the detection technique. Meetings are organized every other Thursday.

Together with the analysis coordination, the LNF are in charge of the maintenance and development of the main reconstruction algorithm used to analyze the raw data of the experiment. Continuous checks on performance, bug fixes, improvements, introduction of new and more complete features of data reconstruction have been undertaken with the goal of restructuring and improving the algorithm to match the large data output of the CYGNO-04 future detector.

As a specific analysis task undertaken by Master's student Scamporlino, GIN was exploited taking a series of data sets of muons and 5.9 keV photoelectron at different drift distances from the

anode. This allowed to estimate the gas diffusion, and to develop a machine learning-based method to determine the absolute drift distance and afterward deconvolve the experimentally measured diffusion to extract topological features from the observed tracks. The absolute drift distance determination improved current CYGNO state of the art on average by a factor two.

## 3 Design and development of the CYGNO computing model

The LNF are responsible to design and implement the experiment computing model and infrastructure.

The computing model (CM) for CYGNO [3], which is the benchmark and beta-tester for all small/medium experiments in the astroparticle physics community supported by the PNRR Spoke2, was improved since last year. The software architecture has been designed and is hosted on the INFN cloud infrastructure. The INFN cloud is providing the Virtual Machines (VM) where services, by means of a set of docker containers, are developed and under operation. The CM design consists in a set of services for data streaming, data management, data visualization, data analysis and simulation. In particular, simulation and analysis were boosted by employing jupyter notebooks structure available for all users. The infrastructure was further enhanced by the introduction of CVMFS-based software, handling of the data management on disk and tape via the RUCIO application, and by setting up the environment to exploit CNAF tier1 queues. The services developed during LIME data taking allowed smooth data taking, online reconstruction, automatic storage of metadata and analysis and simulation. In the following, the data collected during 2024 and 2025 are listed

| Data set (%) | Time slot | Number of images |
|---|---|---|
| Run1 : No shielding | 3/11/2022 - 15/12/2022 | 4 $10^6$ |
| Run2 : 4 cm Cu shielding | 15/02/2023 - 15/03/2023 | 5 $10^5$ |
| Run3 : 10 cm Cu shielding | 05/05/2023 - 16/11/2023 | 7.3 $10^6$ |
| Run4 : Cu + water shielding | 30/11/2023 - 31/03/2024 | 6 $10^6$ |
| Run5 : Cu shielding | 17/05/2024 - 01/12/2024 | 5.4 $10^6$ |
| Data R&D : Cu shielding | 07/01/2024 - 15/05/2025 | 4 $10^6$ |

Table 1: Data sets of LIME.

## 4 List of Conference Talks by LNF Authors in Year 2024

1. G. Dho - X-ray polarization from astrophysical sources. Current status and future prospects with HypeX project, at General Seminar of INFN, Frascati, Italy - 18th February 2025 (seminar) [invited]

2. G. Dho - Importance of directionality in the search for dark matter below the neutrino fog. The CYGNO Experiment, at International Astrocent Seminar series, Warsaw, Poland - 15th May 2025 (seminar) [invited]

3. G. Dho - Project D - Radiopure and/or low-energy TPCs for precise track imaging and/or calorimetry with avalanche-based readouts, at 5th DRD1 Collaboration meeting, CERN, Switzerland - 16 to 20 June (online) 2025

4. G. Dho - X-ray Polarimetry with Optical Time projection chamber within HypeX project, at High Precision X-ray Measurements 2025, LNF, Frascati - 16 to 20 June 2025

5. G. Dho - X-ray polarization from astrophysical sources. Development and early results of a large volume Time Projection Chamber (TPC) from HypeX project, at EPS-HEP 2025, Marseille, France - 7 to 11 July 2025 (poster)

6. G. Mazzitelli - Sviluppo del PoC di computing model per piccoli/medi esperimenti di astroparticelle, Workshop sul Calcolo nell'INFN: La Biodola, 26 - 30 maggio 2025

## 5 List of Publications signed by LNF Authors in Year 2024

1. Amaro, F.D., Antonietti, R., Baracchini, E. et al., Bayesian network 3D event reconstruction in the Cygno optical TPC for dark matter direct detection, Eur. Phys. J. C 85, 1261 (2025). https://doi.org/10.1140/epjc/s10052-025-14965-6

2. Fiorina et al., X-POT: x-ray polarimetry with optical time projection chamber,Proceedings Volume 13621, Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XXVII; 136210B, October 2025, DOI: https://doi.org/10.1117/12.3065680

3. Antonietti et al., The CYGNO Experiment, Nuovo Cimento, C 48; May 2025, DOI: https://doi.org/10.1393/ncc/i2025-25095-0

## Bibliography


1. F. D. Amaro, E. Baracchini, L. Benussi, S. Bianco, C. Capoccia, M. Caponero, D. S. Cardoso, G. Cavoto, A. Cortez and I. A. Costa, *et al.* "The CYGNO Experiment," Instruments **6** (2022) no.1, 6 doi:10.3390/instruments6010006 [arXiv:2202.05480 [physics.ins-det]].

   X-ray polarization from astrophysical sources. Current status and future prospects with HypeX project, at General Seminar of INFN, Frascati, Italy, 18 February 2025 (seminar) https://agenda.infn.it/event/45029/

2. G. Mazzitelli et al, Technical Design Report - TDR CYGNO-04/INITIUM (2022) Technical note - INFN-23-06-LNF doi:10.15161/oar.it/76967

3. `https://github.com/CYGNUS-RD/middleware`