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Technical Design Report - TDR CYGNO-04/INITIUM

This document identifies and describes the characteristics and technical requirements from the CYGNO-04/INITIUM Experiment related to the installation at Hall F of the Gran Sasso National Laboratories (LNGS)

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Executive Summary

The aim of this Technical Design Report is to illustrate the technological choices foreseen to be implemented in the construction of the CYGNO-04 demonstrator, motivate them against the experiment physics goals of CYGNO-30 and demonstrate the financial sustainability of the project. CYGNO-04 represents PHASE 1 of the long term CYGNO roadmap, towards the development of large high precision tracking gaseous Time Projection Chamber (TPC) for directional Dark Matter searches and solar neutrino spectroscopy.

The CYGNO project[1] peculiarities reside in the optical readout of the light produced during the amplification of the primary ionization electrons in a stack of triple Gas Electron Multipliers (GEMs), thanks to the nice scintillation properties of the chosen He:CF4 gas mixture. To this aim, CYGNO is exploiting the fast progress in commercial scientific Active Pixel Sensors (APS) development for highly performing sCMOS cameras, whose high granularity and sensitivity allow to significantly boost tracking, improve particle identification and lower the energy threshold. The X-Y track project obtained from the reconstruction of the sCMOS images is combined with a PMT measurement to obtain a full 3D track reconstruction.

In addition, several synergic R&Ds based on the CYGNO experimental approach are under development in the CYGNO collaboration (see Sec 2) to further enhance the light yield by means of electro luminescence after the amplification stage, to improve the tracking performances by exploiting negative ion drift operation within the INITIUM ERC Consolidator Grant, and to boost the sensitivity to O(GeV) Dark Matter masses by employing hydrogen rich target towards the development of PHASE 2 (see Sec. 1.2).

While still under optimization and subject to possible significant improvements, the CYGNO experimental approach performances and capabilities demonstrated so far with prototypes allow to foresee the development of an O(30) m^3 experiment by 2026 for a cost of O(10) MEUROs. A CYGNO-30 experiment would be able to give a significant contribution to the search and study of Dark Matter with masses below 10 GeV/c^2 for both SI and SD coupling. In case of a Dark Matter observation claim by other experiments, the information provided by a directional detector such as CYGNO would be fundamental to positively confirm the galactic origin of the allegedly detected Dark Matter signal. CYGNO-30 could furthermore provide the first directional measurement of solar neutrinos from the pp chain, possibly extending to lower energies the Borexino measurement[2].

In order to reach this goal, the CYGNO project is proceeding through a staged approach. The PHASE 0 50 L detector (LIME, recently installed underground LNGS) will validate the full performances of the optical readout via APS commercial cameras and PMTs and the Montecarlo simulation of the expected backgrounds.

[1] F. D. Amaro et al, [CYGNO collaboration] Instruments 6 (2022) 1,6

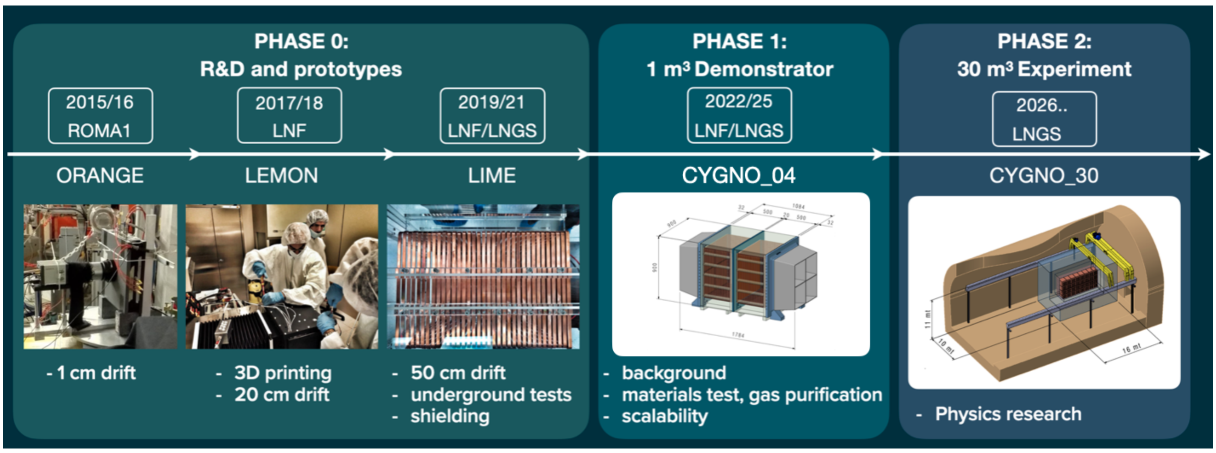
[2] M. Agostini et. al, *Nature* 562 (2018) 7728, 505-510

The full CYGNO-04 demonstrator will be realized with all the technological and material choices foreseen for CYGNO-30, to demonstrate the scalability of the experimental approach and the potentialities of the large PHASE 2 detector to reach the expected physics goals.

The first PHASE 1 design anticipated a 1 m^3 active volume detector with two back-to-back TPCs with a central cathode and 500 mm drift length. Each 1 m^2 readout area would have been composed by 9 + 9 readout modules having the LIME PHASE 0 dimensions and layout. Time (end of INITIUM project by March 2025) and current space availability at underground LNGS (only Hall F) forced the rescaling of the PHASE 1 active volume and design to a 0.4 m^3, hence CYGNO-04. CYGNO-04 will keep the back-to-back double TPC layout with 500 mm drift length each, but with an 800 x 500 mm^2 readout area covered by a 2 + 2 modules based on LIME design. The reduction of the detector volume has no impact on the technological objectives of PHASE 1, since the modular design with central cathode, detector materials and shieldings and auxiliary systems are independent of the total volume. The physics reach (which is a byproduct of PHASE 1 and NOT an explicit goal) will be only very partially reduced (less than a factor 2 overall) since a smaller detector volume implies also a reduced background from internal materials radioactivity. In addition, the cost reduction of CYGNO-04 of about ⅓ with respect to CYGNO-1 illustrated in the CDR effectively makes the overall project more financially sustainable (see CBS in the last section).

In summary this document will explain:

- the physical motivation of the CYGNO project and the technical motivations of the downscale of the PHASE 1 to CYGNO-04, 400 liters of active volume, with respect to the demonstrator presented in the CDR;
- the results of R&D and the Montecarlo expectations for PHASE 0;
- the technical choices, procedures and the executive drawings of CYGNO-04 in the Hall F of the LNGS;
- safety evaluations and the interference/request to the LNGS services;
- Project management, WBS/WBC, WP, GANTT, ecc



1. Scientific Motivations

The goal of the CYGNO project is to boost the advancement of gaseous Time Projection Chamber (TPC) detectors for directional DM searches and solar neutrino spectroscopy. Thanks to recent advances in Micro Pattern Gas Detectors (MPGD) and scientific light sensors based on Active Pixel Sensors (APS), TPC is nowadays a mature technology to aim at developing a large-scale experiment for directional rare event searches. The CYGNO project sets into this context, with the aim of demonstrating the advantages of the combined sCMOS + PMT optical readout of an He:CF_4 gas mixture at atmospheric pressure towards the achievement of this goal, by realizing an O(30) m^3 experiment based on this approach. Table 3 summarizes the expected physics reach and detector physics performance foreseen for CYGNO-30 (together with LIME from PHASE 0 and CYGNO-04 and CYGNO-1), as illustrated and supported by the discussion in Sec. 1.1, 1.2 and 1.3.

From the technological and infrastructural point of view, CYGNO PHASE 2 realization would moreover establish the grounds and serve as a model for the development of a multi-site networks of detectors for the ton-scale international CYGNUS-TPC project[3] (see Sec. 1.4), that through directionality will be able to perform a precise study of DM properties, DM astronomy and solar neutrino physics.

1.1. PHASE 2: directional Dark Matter searches

Figure 2 shows CYGNO-30 sensitivity to Dark Matter Spin Independent and Spin Dependent couplings for 3 years of exposure with different background level assumptions. Details on the Bayesian statistical framework employed to evaluate the experiment sensitivity taking into account the directional capabilities can be found here[1]. As illustrated in details in Chapter 5 of ref.[1], the foreseen sensitivity of CYGNO PHASE 2 will allow to probe low 1-10 GeV Dark Matter mass regions of the Spin Independent coupling not yet explored, therefore significantly contributing to DM searches at low masses. While these are within the expected reach of future SuperCDMS[4], CRESST[5], DarkSide Low Mass[6] and News-G[7] experiments, all these detectors will be realized with modes of operation that strongly reduce (if not completely give up) the capabilities of background discrimination. Each of these approaches implies therefore very strict (and not yet fully demonstrated) requirements on the detector materials radio-purity and the possibility to rely so strongly on the MC simulated estimates of the expected backgrounds. As a consequence, any observed signal in this region by these experiments will be difficult to interpret unambiguously as a DM signal. CYGNO potential of establish the galactic origin of the detected signal through directional correlation with the

[3] S. E. Vahsen et al., arXiv 2008.12587
[4] Agnese R. et al, Phys. Rev D. 2017, 95, 082002
[5] Willers M. et al., J. Phys. Conf. Ser. 2017, 888, 012209
[6] https://indico.cern.ch/event/765096/contributions/3295671/attachments/1785196/2906164/DarkSide-Argo_ESPP_Dec_17_2017.pdf
[7] P. Knights et al., PoS ICHEP 2020 (2021) 639

Cygnus constellation would therefore constitute a compelling and decisive test to any DM claim, being the only existing approach able to provide a positive identification of a DM signal below 50 GeV (with respect to the ability of NEWS-DM[8] at higher masses).

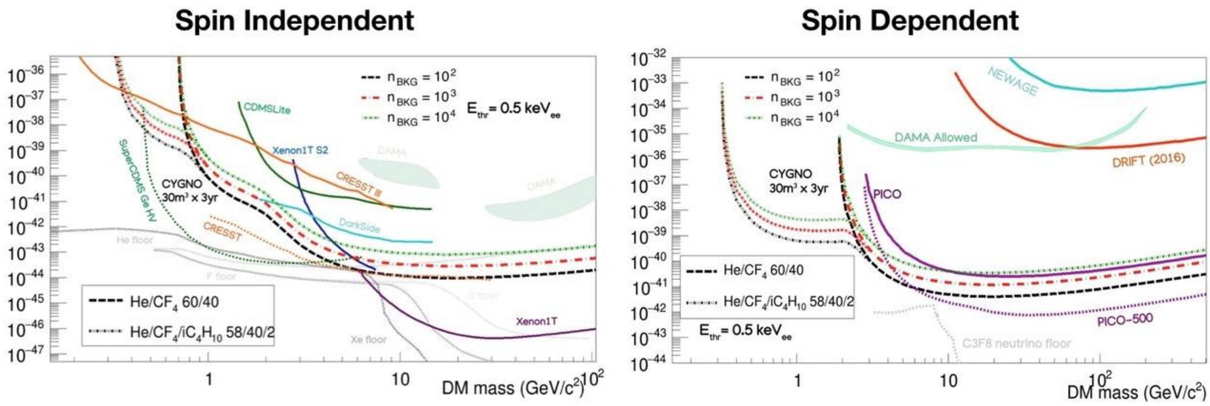


Figure 2: Spin-independent (left) and Spin-dependent (right) sensitivity for Dark Matter-nucleon cross-section for 30 m^3 CYGNO detector for 3 years of exposure with different background level assumptions.

In addition, thanks to the high Flourine content, CYGNO PHASE 2 is expected to significantly contribute to probing the Spin Dependent WIMP coupling, possibly extending the sensitivity in a low mass region expected to be out of reach of the PICO experiment[9]. Moreover, PICO superheated bubble chamber detection technique is based on an energy threshold approach. This implies that signal observation does not allow the measurement of the energy of the nuclear recoil and can not therefore be translated into a constraint in the masses versus coupling parameter space. Hence, also in this context, the confirmation of the galactic origin of the signal by a directional experiment would be even more decisive in order to establish the properties of the detected DM.

The detector physics characteristics and performances assumed in Figure 2 limits evaluation are:

- 0.5 keV_{ee} energy threshold;
- Two gas mixtures: the official He:CF_4 60:40 and the possibility to add a small isobutane content with He:CF_4:iC_4H_{10} to extend sensitivity to Dark Matter masses below 1 GeV/c^2 thanks to the presence of Hydrogen;
- H, He, C, F quenching factor as evaluated from SRIM simulation;
- the probability of each element to be detected as a function of the Dark Matter mass;
- 30° angular resolution across the whole active volume and the entire energy range;

[8] G. De Lellis et al., PoS EPS-HEP 2021 (2022) 157
[9] G. Giroux et al., J. Phys. Conf. Ser. 2156 (2021) 012068

- Full 100% head-tail recognition down to 0.5 keVee;
- 100, 1000 and 10000 background events per year extracted from a Poisson distribution;

In the following we will briefly illustrate how we plan to reach these physics performances starting from results of our R&D and simulations.

1.1.1. Energy Threshold

Studies of simulated nuclear recoil tracks as expected in LIME with the Hamamatsu Orca Fusion sCMOS Camera with Convolution Neural Networks[10] show the possibility of obtaining 70% detection efficiency at 1 keV_{ee}. Given the nearly one order of magnitude improvement in sensitivity of the Orca Quest that will be employed in CYGNO-04, and the fast development of APS sensor, a 0.5 keVee energy threshold represents a realistic expectation for CYGNO-30.

1.1.2. Quenching Factor measurement

We recently got in contact with the research team that developed the COMIMAC facility[11] to set up a dedicated data campaign for the measurement of the Quenching Factors of our interest (H, He, C and F in He:CF_4 at atmospheric pressure). Preliminary setup tests are foreseen by July 2022, with a first data campaign in Fall 2022.

1.1.3. Hydrogen rich gas mixture

Since the maximum efficiency in the momentum exchange between DM particles and targets is achieved when their mass values are the same, the presence of light nuclei in the gas mixture will allow exploration of low DM mass regions. Studies on possible employment of hydrocarbons are being carried on by the CYGNO collaboration as described in Sec. 4.1.

1.1.4. Nuclear recoils angular resolution

Studies with elementary algorithms on simulated nuclear recoil tracks as expected in LIME with the Hamamatsu Orca Fusion sCMOS Camera[12] show the possibility of achieving an average 30° angular resolution at 25 keV_{ee} for Helium recoils in the whole detector volume. The angular resolution obtained with only the X-Y 2D projection provided by the images can be significantly improved with the use of the third Z coordinate measured from the analysis of the PMT waveforms (work on going). The improvement in sCMOS camera performances and the possibility to exploit Machine Learning algorithm to maximize the information extracted from the combined analysis of these and the PMT signal foreseen the possibility to lower this threshold and further improve performances at higher energies (see also Sec below).

[10] https://agenda.infn.it/event/30397/contributions/164070/attachments/88612/118750/Segmentation%20Using%20CNN.pdf
[11] J. F. Muraz et al., NIM A 832 (2016) 214
[12] https://indico.gssi.it/event/334/contributions/886/attachments/430/673/LIME_bkg_collab_meeting_20-12-21.pdf

1.1.5. Nuclear recoil Head-tail recognition

Studies with elementary algorithms on simulated nuclear recoil tracks parallel to the GEM amplification plane as expected in LIME with the Hamamatsu Orca Fusion sCMOS Camera[13] show the possibility of achieving 55% correct head tail recognition on He recoils at 3 keV_{nr}, with 80% efficiency at 60 keV_{nr}. The PMT waveforms information can significantly complement the measurement from the X-Y sCMOS image projection, especially for tracks inclined with respect to the amplification plane. The CYGNUS-HD US project (i.e. our US partner within the CYGNUS proto-collaboration), with a small TPC with ASIC pixels readout and 3D convolutional neural network recently demonstrated the capability of 65% head-tail correct recognition of Helium recoils at 3 keV_{nr} (reaching 90% at 13 keV_{nr}) in He:CO_2 at atmospheric pressure[14]. Since sCMOS cameras are quickly reaching the performances of ASICS charge pixels (see Hamamatsu Orca Quest in Sec 3.2), with the use of Machine Learning techniques it is reasonable to foresee the possibility of achieving correct head-tail identification down to a couple of keVee for CYGNO-30.

1.1.6. Background yield

In Tab. 1 we show the expected total background coming from the detector materials with the largest contribution to the overall radioactivity and the external environmental flux after the shielding, as evaluated for CYGNO-04. For what concerns the internal background, with respect to what employed in LIME manufacturing, for CYGNO-04 we foresee:

- to develop custom low-radioactivity GEMs able to reach the activity level measured in the ones employed by the TREX experiment[15];
- to perform a selection study to find low-radioactivity acrylic for the manufacturing of the detector vessel, with the same level of activity as the one employed by the SNO experiment[16];
- to develop a low radioactivity lens for the camera optical system (see Sec. 3.6)
- to possibly reduce the sCMOS camera radioactivity by developing a custom low-radioactivity sensor (not included in the background evaluation, i.e. Tab.2 contains current camera internal radioactivity);

For what concerns the external environmental neutron and gamma background, we developed a cost-benefit analysis to optimize the thickness of the Copper and Water shieldings in order to reduce the external background component to a few percent of the internal backgrounds. This optimisation resulted in the choice of 100 mm of Copper + 1100 mm of Water for CYGNO-04 (taking into account also the space constraints provided by Hall F).

[13] https://indico.gssi.it/event/309/contributions/722/attachments/330/537/DiGiambattista.pdf
[14] C. A. J. O'Hare et al., 2022 Snowmass Summer Study, arXiv:2203.05914.
[15] J. Castel et al., Eur. Phys. J. C (2019) 79:782
[16] D.S.Leonard et al., Nucl. Instr. and Meth. A 591 (2008)

Detector component	Nuclear recoil [1,20] keV_{ee}/year	Electron recoil [1,20] keV_{ee}/year
GEM[13]	8.44 e+02	7.14 e+04
Acrylic[14]	1.98 e+01	3.02 e+03
Camera body	-	4.41 e+04
Camera lens (Suprasil)	-	0.66 e+01
Cathode (Copper)	1.69 e-01	7.18 e+01
External Background (after shielding)	-	6.40 e+03
Total	8.64 e +02	1.25 e+05

Table 1: Expected electron recoils and nuclear recoils background in CYGNO-04 in the [1,20] keV_{ee} energy band for the detector components displaying the largest radioactivity content, and the external environmental background after 100 mm Copper + 1100 mm Water shielding.

A study on LIME backgrounds[12] has shown how fiducial cuts can reduce the internal gamma and neutron background of 99% and 96% respectively. Given the modular design of both CYGNO-04 and CYGNO-30, we can reasonably expect a similar capability of background reduction with fiducial cuts also within this larger realizations.

Studies on gamma background rejection with Deep Neural Network algorithm based on track shape variables[17] extracted from the sCMOS images demonstrates 98.3% rejection in the whole [1-40] keV_{ee} range with 40% nuclear recoil efficiency (improving on the published performances discussed in Sec. 2.9). The advancement in sCMOS camera sensitivity and the addition of the PMT information can further significantly improve these preliminary results, as well as the use of Convolutional Neural Networks combining sCMOS and PMT information

Overall from the above discussion, we can then anticipate a level of background after all selection cuts and rejection of the order 10-100 events/year in the 1-20 keV_{ee} region for CYGNO-04. By a simplistic argument, we can anticipate the internal backgrounds of CYGNO-30 to scale by about a factor 100. At the same time, the fast development of sCMOS technology and the possibility of light sensors customisation (both in terms of sensitivity and low-radioactivity) for a large realization of the CYGNO experimental approach, together with the R&D under development for PHASE 2 (see Sec. 4) and the better understanding of backgrounds

[17]https://agenda.infn.it/event/31275/contributions/170515/attachments/90401/121765/ER_NR%20discrimination%20%28Autumn21%29.pdfl

that PHASE 0 and PHASE 1 will provide, allow to foresee the possibility to reduce this factor by one or two order of magnitude.

These are the reasons why we choose to evaluate CYGNO-30 sensitivity to Dark Matter searches in Figure 2 with different background scenarios from 100 to 10000 background events per year, reflecting different possible levels of improvement with respect to the results of CYGNO-04.

1.2. PHASE 2: solar neutrino spectroscopy measurements

CYGNO high precision tracking capabilities can open the door to additional interesting physics cases involving, among the others, neutrinos and MeV Dark Matter candidates produced in Supernovae[18]. While more details can be found in the CYGNO paper[1], it interesting here to notice how CYGNO could establish a new directional technique based on gaseous TPCs to measure solar neutrinos by correlating the elastically scattered electron direction with the Sun position for an unambiguous signal identification (as proposed in the '90[19]). This technique could provide the possibility to extend solar neutrino spectroscopy studies beyond the Borexino measurements[2]. A medium size experiment (as CYGNO PHASE 2) would already be able to test the solar pp-chain to about 40-70 keV in neutrino energy, improving over the 160 keV Borexino threshold and demonstrating the potentialities of gaseous TPC for solar neutrino studies . A very large experiment (10 ton, as CYGNUS 10000[12]) could be sensitive to the CNO cycle measurement, possibly helping to finally establish the metallicity of the Sun and the related physics.

A feasibility study for solar neutrino spectroscopy is under development within the CYGNO collaboration to establish the potentialities of this approach to neutrino measurements. The detector physics performances of interest for this physics case are briefly discussed in the following.

1.2.1. Electron recoil energy resolution

LIME detector has been commissioned in overground Laboratori Nazionali of Frascati with X-ray sources of multiple energies, from 3.7 keV_{ee} to 47 keV_{ee}. An analysis with multivariate regression (MVA) show the possibility of achieving about 8% energy resolution when correcting for detector effects[20].

1.2.2. Electron recoil angular resolution

We developed an algorithm based on X-ray polarimetry methods[21] to evaluate CYGNO directionality capability on simulated electron recoil tracks as expected in LIME with the Hamamatsu Orca Fusion sCMOS Camera[22]. With this we

[18] E. Baracchini et al., *Phys.Rev.D* 102 (2020)
[19] J. Seguinot et al., Conf. Proc. C, 1992, 920310, 289-313; C. Arpesella et al, Astropart. Phys. 1996, 4, 333-341
[20] https://indico.gssi.it/event/334/contributions/883/attachments/422/654/2021-12-20-clustering-linearity-collmeeting.pdf
[21] P. Soffitta et al, NIM A 700, (2013) 99-105
[22] https://indico.gssi.it/event/334/contributions/887/attachments/431/669/Pres_CYGNOMeeting_V0.pdf

demonstrated 35° angular resolution at 20 keV_{ee} for tracks with an inclination of < 0.9 rad with respect to the GEM amplification plane, and a directionality threshold[23] of about 10 keV_{ee}. This result can significantly be improved with the addition of the PMT information on the Z coordinate and a Machine Learning approach. Given also the foreseen improvement in light sensors, we can envisage an electron directional threshold of 5 keVee for CYGNO-30, with 35° angular resolution at 10 keV_{ee}. The lower the electron directional energy threshold, the lower the solar neutrino energy range explored, as can be seen from Tab. 3.

	Drift length [cm]	Amplification + Readout	Gas Mixture	Gas Pressure [mbar]	Volume [L]	Energy Threshold [keV]	Active Mass [gr]
DRIFT	50	MWPC	73% CS_2 + 25% CF_4 + 2% O_2	55	800	20	33
NEWAGE	40	1 GEM +muPIC	CF_4	100	37	20	11.5
MIMAC	25	Micromegas	70% CF_4 + 28% CHF_3 + 2% C_4H_{10}	50	5.8	2	1.2
CYGNO-04	50	3 GEMs + sCMOS + PMT	60% He + 40% CF_4	1000	400	1	600

Table 2: Summary of the main characteristics of all the existing gaseous directional Dark Matter search TPCs installed underground, compared to CYGNO-04.

1.3. PHASE 1: CYGNO-04 motivation

As discussed in the Executive Summary, space availability at underground LNGS forced a rescaling of the active volume of the detector from 1 m^3 to 0.4 m^3, with the goal of fitting in the timely available Hall F. CYGNO-04 will keep the modular design of two back-to-back TPCs with a central cathode and 500 mm drift length, but with an 800 x 500 mm^2 readout area covered by a 2 + 2 LIME-like modules. While the reduction of the active volume will not affect the technological and scientific objective of PHASE 1, the new configuration results in an improvement in terms of modularity and scaling capabilities with respect to the 9 + 9 modules foreseen to cover a 1 m^2 area of the detector described in the CDR. This is made possible mainly thanks to the results of the R&D process conducted in the past years, in particular in

[23]We define the directionality threshold as the energy at which the angular resolution is 1 radiant. Two randomly oriented 3d axial vectors will on average be separated by an angle of 1 radian or 57.3°. Hence this value corresponds to no angular sensitivity

the selection of the Hamamatsu Orca Quest qCMOS sensor[24] for the PHASE 1 optical sensors, as discussed in Sec. 2

The main objectives of PHASE 1 are to study and minimize material radioactivity (see Table 1) on a realistic experimental layout and scale, while evaluating the actual potentialities of a large PHASE 2 detector to reach the expected physics goals (as discussed in Sec. 1.1. and 1.2),

Since the modular design with central cathode, detector materials and shieldings and auxiliary systems are independent of the total volume, CYGNO-04 will be able to reach PHASE 1 technological objectives, while also improving on the foreseen scalability with respect to PHASE 1 design. Similarly, PHASE 1 detector performance goals that need to be demonstrated towards PHASE 2 do not depend on actual volume, but rather mainly on drift distance (which is kept the same at 500 mm) and the light sensors (which will be an improved version with respect to the camera foreseen in the CDR).

The physics reach (which is a byproduct of PHASE 1 and NOT an explicit goal) will be only very partially reduced (less than a factor 2 overall) since a smaller detector volume implies also a reduced background from internal materials radioactivity.

In addition, compared to other directional Dark Matter search detectors already developed[25,26,27] (and schematically illustrated in Tab. 2), CYGNO-04 will be the first to work at atmospheric pressure (typical operating pressure 30-100 Torr) with an Helium-rich gas mixture. This feature will provide an increase of a factor 20 in the active mass of the experiment compared to the largest underground realization of a directional detector (DRIFT) and will extend the sensitivity to low Dark Matter masses also for the Spin Independent coupling (while all other directional detectors are limited to Spin Dependent).

In order to reach the physics performances required for CYGNO-30 and discussed in Sec. 1.1. and 1.2, CYGNO-04 will need to reach the following objectives towards the realization of a PHASE 2 detector:

- 0.5 keV_{ee} detection energy threshold;
- 10 keV_ee directional threshold on nuclear and electron recoils;
- 10^5 electron/year rejection at 20 keV;
- Consistency of expected background as predicted from MC simulation and actual data;
- Control of external backgrounds through shielding;
- Understanding of the remaining internal materials background sources;

[24] https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/sys/SCAS0154E_C15550-20UP_tec.pdf

[25] B. R. Battat, et al., Low Threshold Results and Limits from the DRIFT Directional Dark Matter Detector, Astropart. Phys. 91 (2017) 65– 74. arXiv:1701.00171, doi:10.1016/j.astropartphys.2017.03.007

[26] T. Ikeda et al., *PTEP* 2021 (2021) 6, 063F01

[27] Y. Tao et al., *Nucl.Instrum.Meth.A* 1021 (2022) 165412

- Underground operation, calibration and synchronized physics data taking of multiple readouts and acquisition modules with high efficiency and performances;

We would like to stress again here that, while the data that will be acquired with CYGNO PHASE 1 will allow to perform a search for Dark Matter and eventually obtain a not competitive limit in the SI/SD parameter space, the primary aim of PHASE 1 is NOT to reach a physics goal, but to demonstrate the experimental approach scalability and operability, validate the materials choices and show to be able to mitigate/understand the remaining background in order to present a full proposal for CYGNO PHASE 2.

	Phase 0 LIME	Phase 1 CYGNO-04	Phase 1 CYGNO-1	Phase 2 CYGNO-30
mass (kg)	0.08	0.6	1.5	50
Exposure (ton x y)	-	1.8e-3	4.5e-3	0.15
SI sensitivity 10000 bkg/year (cm^2@ GeV/c^2)	-	$4x10^{-41}$@10GeV	$2x10^{-41}$@10GeV	$2 x10^{-40}$@1GeV 10^{-43}@10GeV
SI sensitivity 100 bkg/year (cm^2@ GeV/c^2)	-	$4 x10^{-42}$@10GeV	$2x10^{-42}$@10GeV	10^{-40}@1GeV 10^{-44}@10GeV
SD sensitivity 10000 bkg/year (cm^2@ GeV/c^2)	-	10^{-37} @ 10GeV	5×10^{-38} @ 10GeV	5×10^{-41} @ 10GeV
SD sensitivity 100 bkg/year (cm^2@ GeV/c^2)	-	10^{-38} @ 10GeV	5×10^{-39} @ 10GeV	5×10^{-42} @ 10GeV
neutrino (ev/y)	-	0.4 with 10 keV ER directional	1 with 10 keV ER directional	30 with 5 keV ER directional

		threshold	threshold	threshold
minimum neutrino energy explored	-	55 keV with 10 keV ER directional threshold	55 keV with 10 keV ER directional threshold	40 keV with 5 keV ER directional threshold
Energy threshold [keVee]	1	0.5	0.5	0.5
NR angular resolution [degrees]	35° at 20 keV	35° at 10 keV	35° at 10 keV	35° at 10 keV
ER angular resolution [degrees]	35° at 20 keV	35° at 10 keV	35° at 10 keV	35° at 10 keV
NR directionality threshold (keVee)	20	10	10	1
ER directionality threshold (keVee)	20	10	10	5
Minimum detectable Dark Matter mass [GeV/c2]	0.97 with He	0.69 with He	0.69 with He	0.32 with H
background rejection (ev/y)	10^5 @ 20 keVee	10^5 @ 10 keVee	10^5 @ 10 keVee	10^5 @ 5 keV

Table 3: Summary of the expected physics reach and physics performances of the various PHASE of development of the CYGNO project.

1.4. The CYGNUS project

Recently, most world expertise in DM directional detection, including CYGNO collaboration members, gathered together in the CYGNUS proto-collaboration of ~ 50 people. E. Baracchini is one of the 5 CYGNUS Spokesperson and member of the CYGNUS International Steering Committee. CYGNUS goal[3] is to eventually establish a Galactic Directional Recoil Observatory at the ton-scale that could test the DM hypothesis beyond the Neutrino Floor and measure the coherent scattering of neutrinos from the Sun and possibly Supernovae. CYGNUS key features are a modular design of recoil sensitive TPCs (electron and/or negative ion drift operation), filled with an Helium-Fluorine based gas mixture at atmospheric pressure for sensitivity to low DM masses for both SI and SD couplings. Installation in multiple underground sites (including the Southern Hemisphere) with a staged expansion is foreseen to mitigate contingencies, minimise location systematics and improve sensitivity (Boulby, LNGS, Kamioka, SURF, Stawell).

CYGNUS collaboration is currently performing a cost-benefit analysis through a coherent and coordinated R&D and simulation process, in order to identify the optimal detector configurations in different DM and neutrino physics case scenarios and to soon propose a large scale detector based on these findings. The development of CYGNO-04/INITIUM fits into this context, with the goal of demonstrating the proof-of-principle of the chosen optical CMOS + PMT approach towards the development of a multi-modular ton-scale CYGNUS detector.

2. Research and Development (R&D)

2.1. PHASE 0: R&D results

The design and implementation of the final demonstrator CYGNO-04 is the culmination of a five years long R&D process that led to the optimization of various components.

Main results are summarized in this section:

2.1.1. Gas Mixture Optimisation

The performance obtained with different He/CF4 based gas mixtures were studied in ratios ranging from 40/60 to 80/20[28]. The performed measurements indicate that the ratio 60/40 provides the best light yield achievable in safe detector operation at room temperature and atmospheric pressure.

The main properties of the gas are summarized in the table below.

He and CF_4 ratio	60/40
Density	1.6 grams/liter
Average energy per primary electron	45 eV
Number of emitted photons per secondary electron	0.07
Typical GEM gain operation	10^5-10^6

2.1.2. Electric fields configuration and stability

The electrostatic stability was tested by monitoring the behavior of the prototype for 25 days in a completely unsupervised manner . The detector worked in very stable and safe condition for the whole period resulting in less than 5% of dead time due to recovery procedures [29,30].

The chosen electrical configuration range is listed in the table below.

Voltage difference across each GEM	420-440

[28] Study and optimization of the light-yield of a triple-GEM detector: http://cds.cern.ch/record/2313231
[29] https://doi.org/10.1088/1748-0221/15/10/P10001
[30] https://doi.org/10.1109/NSS/MIC42101.2019.9059722

Electric Field in Drift Region	0.7-1.0 kV/cm
Electric Field in Transfer Region	2.5 kV/cm

2.1.3. Energy Resolution

The detector resolution in evaluating energy release and the minimum energy release that is possible to distinguish from the sensor noise were studied by means of 5.9 keV photons produced by the ^{55}Fe radioactive source[31]. An energy resolution of about 13% was found in the whole detector volume.

2.1.4. Energy Threshold

Based on the study of the CMOS sensor electronic noise[32], its sensitivity and on the detector calibrated response, an operative threshold of 1 keV_{ee} was evaluated[33].

2.1.5. Light yield

The number of photons produced in the He/CF_4 per unit of released energy was studied with slightly different gas gains and gas ratios. A typical value of $2\ 10^3$ photons produced per eV released was found[34].

2.1.6. Space Resolution (X,Y)

The absolute 2D position of the each ionization cluster can be reconstructed with a space resolution of about 100 μm[35].

2.1.7. Space Resolution (Z)

The relative Z coordinate of the different ionization clusters produced by a charged particle can be evaluated by combining the information of the CMOS sensor and a fast PMT. This method allows to evaluate it for each clusters with a resolution of 100 μm[36].

Absolute position of the ionization in the sensitive volume, can be evaluated by exploiting transverse and longitudinal diffusion, with a precision in the range 10% - 20% for both methods[37].

[31] https://arxiv.org/pdf/2007.00608
[32] https://arxiv.org/pdf/1508.07143.pdf
[33] https://arxiv.org/pdf/2005.12272.pdf
[34] https://ieeexplore.ieee.org/document/8069757
[35] https://ieeexplore.ieee.org/document/8123941
[36] https://arxiv.org/pdf/1803.06860.pdf
[37] https://arxiv.org/pdf/2005.12272.pdf

2.1.8. Detection Efficiency

No evidence of a dependence of the detection efficiency of 5.9 keV photons on the source position was found, allowing to conclude that a full detection efficiency is provided in the whole detector volume[38].

2.1.9. Nuclear Recoil Rejection

A multi-stage pattern recognition algorithm based on an advanced clustering technique was developed. A number of cluster shape observables are used to identify nuclear recoils induced by neutrons originated from a AmBe source against X-ray ^{55}Fe photoelectrons. An experimental efficiency of 18% to detect nuclear recoils with an energy of about 6 keV is reached, while suppressing 96% of the ^{55}Fe photoelectrons[39]. Moreover, detailed studies performed on MC simulation are already demonstrating the possibility of reaching better results by applying ML based analysis algorithms (See Sects. Nuclear recoils angular resolution and Nuclear recoil Head-tail recognition).

2.1.10. Analysis software

An offline reconstruction software applies a pixel-wise baseline subtraction and zero-suppression, with a low threshold thanks to the very low noise level of the sensor. This is cardinal in maintaining high efficiency for low energy electron and nuclear recoils signals. The software consecutively applies further, more sophisticated, noise suppressions, and finally applies a clustering algorithm to gather pixels belonging to the same light source. For the image analysis, an algorithm based on an adapted version of the well-known DBSCAN was implemented, called iDBSCAN[40]. A variety of approaches, all based on unsupervised Machine Learning techniques were tested and optimized on the peculiar patterns of our data.

2.2. PHASE 1: R&D on going

Several technical upgrades will be adopted in the realization of the PHASE 1 demonstrator. In most cases they have already been successfully employed in detectors for the search of rare events.

2.2.1. Large Area and Low Radioactivity Gas Electron Multipliers (GEM)

The Gas Electron Multipliers represent one of the crucial components of the apparatus. The ionization produced in the sensitive volume is multiplicated in the GEM channels and during these processes photons are emitted by the gas molecules. These devices are widely used in many different research applications, in

38 https://arxiv.org/pdf/2007.00608.pdf
39 https://arxiv.org/pdf/2007.12508.pdf
40 https://arxiv.org/pdf/2007.01763

particular in triple-stage stacks and the production technology of large area GEM reached a mature and reliable stage[41,42].

The main properties of the standard GEM foreseen for the detector are summarized in the table below.

Materials (Surfaces/Insulator)	Copper/Kapton
Thickness (Surfaces/Insulator)	5 µm / 50 µm
Hole diameter (Internal/External)	50 µm / 70 µm
Hole Pitch	140 µm
Size	50 x 80 cm^2

A long R&D was performed at CERN by the T-REX collaboration allowed to reduce the of more than a factor 4 the contamination of GEM foils[43]. The demonstrator will be instrumented with these "reduced-radioactivity" GEM.

Moreover, starting from their results, we plan to further study the production processes in order to individuate and eliminate other sources of contaminants. In case of important improvements, first prototypes will be tested on the PHASE 1 detector.

2.2.2. Active Pixel Sensor (APS)

The image sensor has an important role in the detector performance, having a direct impact on the sensitivity of the experiment. We studied the performance of different Active Pixel Sensors based on CMOS technology. Their intrinsic noise, spatial non-uniformities and light sensitivity were studie. The best performance was obtained by the Hamamatsu Orca Quest qCMOS sensor[44] .

The main properties of the sensor are summarized in the table below.

41 https://cds.cern.ch/record/1966041/files/nppp273-1042-1047.pdf
42 https://arxiv.org/pdf/1606.04147.pdf
43 https://link.springer.com/article/10.1140/epjc/s10052-019-7282-6
44 https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/sys/SCAS0154E_C15550-20UP_tec.pdf

Effective number of pixels	2304 (H) × 4096 (V)
Pixel size	4.6 μm × 4.6 μm
Effective area	10.598 mm × 18.841 mm
Readout noise (rms)	0.27 electrons
Quantum efficiency @500 nm	90 %
Linearity error	0.5 %

In collaboration with two important sensors producers (Hamamatsu[45] and Teledyne[46]) we are investigating the production of custom cameras with reduced radioactivity. Performance and cleanliness of different sensors were already measured in order to spot nature and position of contaminants. If new prototypes are assembled, after some tests overground, their effectiveness will be evaluated on the PHASE 1 demonstrator.

2.2.3. Photomultiplier (PMT)

The use of a concurrent light readout by means of a photomultiplier and the CMOS-Sensor was tested on 400 MeV electron beam at the Frascati Beam Test Facility[47]. A 3D reconstruction of each single cluster with a relative position resolution of 100 μm on the three coordinates was demonstrated. Several different PMT types were tested to search for the ones providing better time performance and low light response. The best performance were obtained with the Hamamatsu R7378[48], whose main parameters are reported in the table below.

Quantum Efficiency at 550 nm	15%
Photo-Cathode diameter	22 mm
Typical Operating Gain	2×10^5 - 10^6
Anode Pulse Rise Time	1.5 ns
Transit Time Spread	0.9 ns

[45] https://www.hamamatsu.com/jp/en/product/cameras.html
[46] https://andor.oxinst.com/products/scmos-for-physical-science-and-astronomy
[47] https://doi.org/10.1088/1748-0221/13/05/P05001
[48] https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/R7378A_TPMH1288E.pdf

2.2.4. Aluminised Mylar Cathode

One of the key elements of the 0.4 m^3 demonstrator will be the use of a central cathode common to the two face-to-face sensitive volumes. Exploiting the positive experience gained by the DRIFT Collaboration[49], we are going to use a 0.9 μm aluminized thin-film Mylar plane. If, on the one hand, the use of a very thin film, with low radioactive aluminum coating produces very small contamination, on the other hand, the thin film allows the alpha particles from radon daughter decays to enter the fiducial volume and thereby provide a means to tag and remove these events. Moreover, time coincidence between two events in the two sensitive volumes would indicate they are probably due to particles produced in a radioactive decay in the cathode structure.

2.2.5. Kapton/Copper Drift Cage

Current detector manufacturing solution foresees a Field Cage based on Copper Rings connected by a resistors partitor. These, and especially the ceramic present in the resistors, are known to produce a large contribution to the internal detector radioactivity, that we would like to avoid for the larger demonstrators. For this reason we plan to use the technique developed by the DRIFT Collaboration that foresees a kapton foil with deposited copper rings and showed to be able to produce a very uniform electric field together with a stable and reliable operation[50].

2.2.6. Low radioactive lens

The reduction of the radioactivity budget is one of the crucial aspects of the CYGNO phase described in this document. From the measurements performed on the different components of the prototypes, it turned out that the commercial lens in use is one of the principal responsible for the total "internal" activity. A custom lens based on a very radiopure material (SUPRASIL[51]) with good optical properties was designed . A first prototype will be realized and tested in the next months in order to optimize the performance according to the experiment needings.

2.3. PHASE 2: Future R&D

While operating the demonstrator, several R&Ds will be carried on with the aim of improving the performance for the PHASE 2 experiment proposal.

2.3.1. Hydrogen rich gas

Charge and light yield of different mixtures are being studied. In particular, measurements are ongoing to evaluate the performance of hydrogen rich solutions that would further enhance the experiment sensitivity to low O(GeV) WIMP masses.

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[49] https://arxiv.org/pdf/1110.0222.pdf
[50] https://doi.org/10.1051/eas/1253002
[51] https://www.heraeus.com/en/hca/products_and_solutions_hca/material_grades_brands/brands_suprasil.html

2.3.2. Freon-free gas mixtures

Freon-based gasses, such as the CF_4, are going to be banned due to their high greenhouse effect. Our group has started to study the possibility of employing Freon-based eco-friendly gasses to replace it. Light yield studies for He/HFO mixtures already showed interesting results and will be more investigated[52].

2.3.3. Negative ion drift operation

Studies on the effect of a highly electronegative dopant gas such as SF_6 are ongoing to investigate the possibility of exploiting negative ion drift operation, in order to further improve tracking capabilities and provide improved fiducialization of the detector on the *z* coordinate[53].

2.3.4. Enhanced Electro-Luminescence

We demonstrated the possibility of increasing the light yield without increasing the GEM gain by accelerating electrons in a small gap after the charge amplification stage[54]. We are currently extending these studies to different gas mixtures, GEM thickness and stacking options to optimize the light yield and the detector stability.

[52] 10.1109/NSS/MIC42101.2019.9059721
[53] https://arxiv.org/pdf/1710.01994
[54] 10.1088/1748-0221/15/08/P08018

3. Specifications and Parameters

3.1. Parameters

The table below summarizes the parameters obtained in PHASE 0. See chapter 5 for PHASE 1 specifications

	PHASE 0 LIME achievements
Sensor noise (e-/pixel)	0.7
Energy Th (keV)	1.0 keV_{ee}
Energy resolution (sigma)	13%
ER efficiency @ 1 keV	60%
ER efficiency @ 6 keV	99%
XY resolution (µm)	100
Z resolution %	15
transversal diffusion (µm/√z(cm))	110
longitudinal diffusion (µm/√z(cm))	90
discrimination @ 6 keV	10^{-2}

3.2. SWOT Analysis

We realize the following SWOT (Strength, Weakness, Opportunity and Threat) to emphasize the project expected impact and issues related to PHASE 1/PHASE 2

Strength		Weakness	
CYGNO-04	CYGNO-30	CYGNO-04	CYGNO-30
• Technology develop by INFN • Large international interest • Threshold and	• Explore yet uncharted DM mass versus coupling parameter space • Different	• DM sensitivity significantly below current limits • High risk technology	• DM sensitivity and directionality limited to 1 GeV/c2 in DM masses • Low ratio

granularity never obtained with other technology ● Core costs covered by European fundings already secured ● Limited costs for INFN ● Demonstrate the feasibility of large TPC without huge investment	approach to DM/SN discover/measurements ● Boost of high granularity TPC technology ● Imaging and tracking of ER and NR down to keV energies ● No need for cryogenics	● Complex Design due to space constraint ● Need for significant internal background reduction w.r.t. current know-how	mass/volume due to gaseous target ● No self-shielding due to gaseous target ● Need for gas purification plant ● High costs with today knowhow ● Need for significant internal background reduction w.r.t. current know-how
Opportunity		Threat	
CYGNO-04	CYGNO-30	CYGNO-04	CYGNO-30
● International leadership ● Realize the most sensitive directional DM detectors ● Investigate new technological scenarios ● Directional and spectral precise measurement of LNGS underground neutron flux with a innovative technology ● Contribute to the investigation of DAMA puzzle with directionality	● International leadership ● Realize the most sensitive directional DM detectors ● Discover DM ● Make DM astronomy by means of directionality ● Demonstrate directional solar neutrino detection with TPC technology ● Measure solar neutrino pp chain to lower energy threshold w.r.t. Borexino	● Demonstration of better directional DM search performances with alternative (i.e. charge readout based) technology	● All parameter space accessible to CYGNO-30 in both SI and SD couplings already excluded by other experiments ● Demonstration of better directional DM search performances with alternative (i.e. charge readout based) technology ● Demonstration of DM nature different from the one testable with nuclear recoil in the energy range accessible by the experiment

4. Technical Description

In the following paragraphs the technical choices made and the implementation of systems and subsystems needed to construct and install the CYGNO-04 demonstrator in the Hall F at LNGS are reported.

The design of the detector and the choices of the materials are based on the experience gained from previous experiments, on the results from the LIME demonstrator and the many ancillary prototypes and R&Ds done in the past.

4.1. Detector Description

The CYGNO-04 detector consists of several assemblies reported in the list below and summarized in figure 3. The order in the list follows the integration sequence of the detector.

- Field Cage and GEM holders.
- PMMA (Polymethyl methacrylate) vessel.
- Copper box shielding.

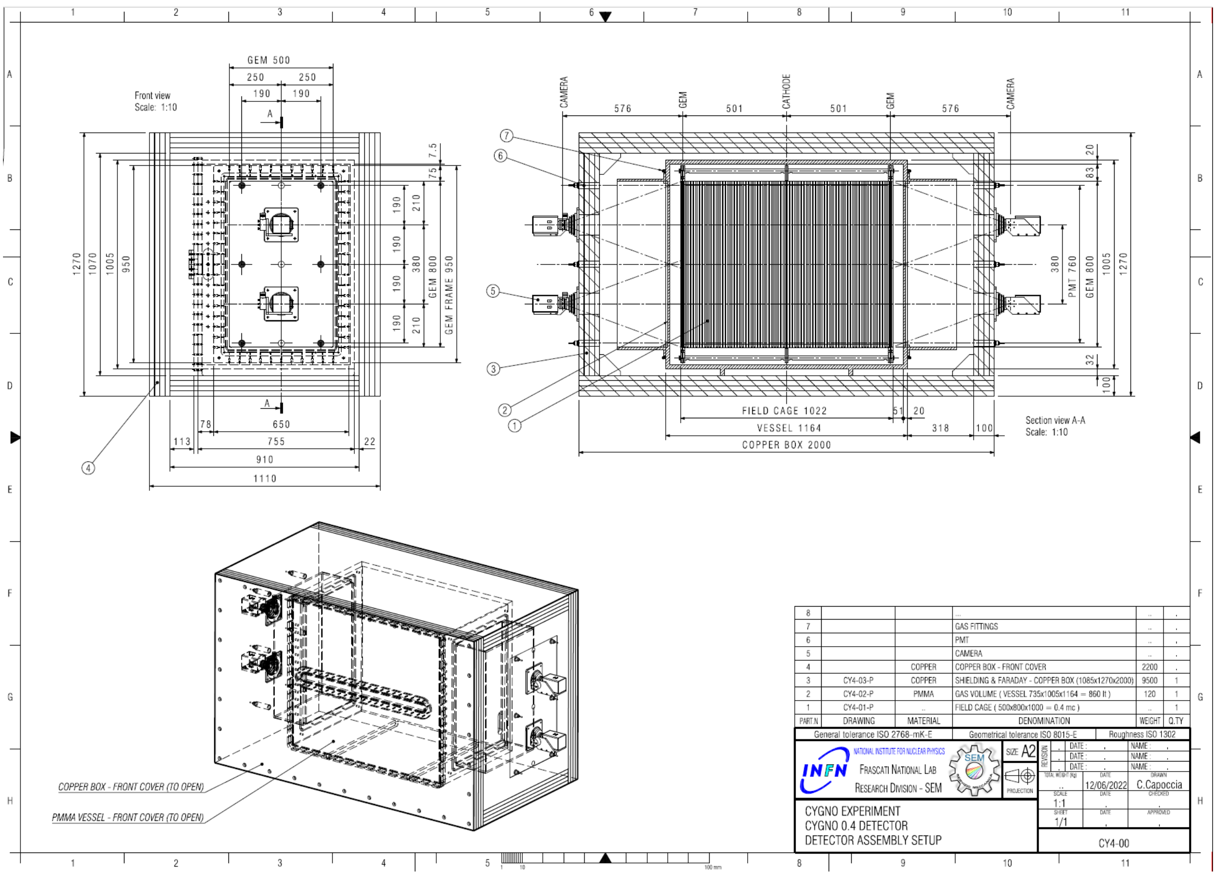


figure 3: detector assembly

The field cage is the core part of the detector (see figure 4). It is made of a kapton foils with printed copper strips to form rings supported by an acrylic structure, able to produce a very uniform electric field using low radioactive materials. The two field cages are installed side by side in one vessel, a common cathode is installed in between them and two GEMs stack 500x800 mm^2 charge amplification stages are located at a distance of about 500 mm from the central cathode. All the elements are assembled with PMMA spacers/holders and frames. The total volume inside the field cage is 0.4 m^3.

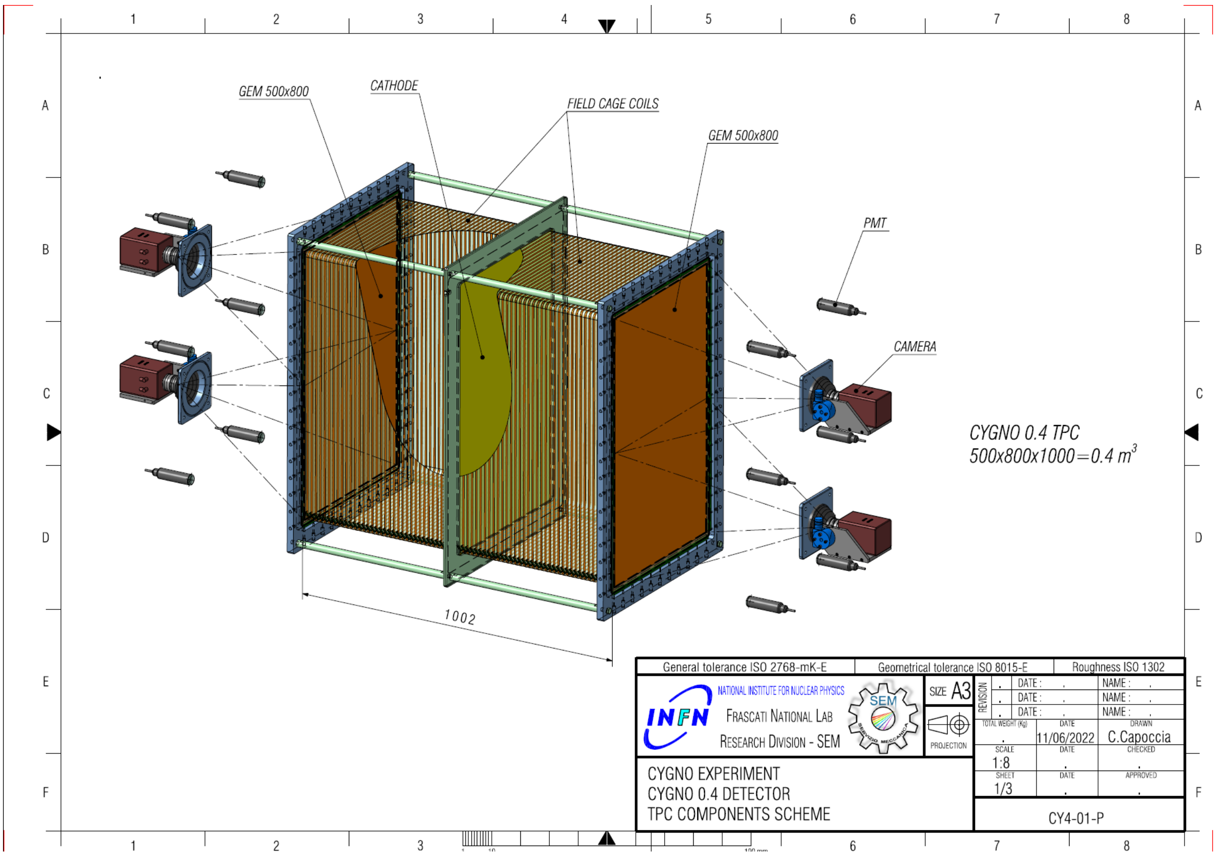


figure 4: field cage and GEM frame assembly sketch out

The detector will be integrated in a transparent, radiopurity[55] PMMA vessel (see figure 5). The wall thickness is 20 mm and the vessel ensures the gas tightness for the total volume of 0.86 m^3.The vessel is designed for an overpressure of 30 mbar wrt the atmospheric pressure. A safety bubbler is installed to avoid the collapse of the vessel for higher Δp. The working condition is 10 mbar wrt the atmospheric pressure.

55 https://doi.org/10.48550/arXiv.1812.04519

On the lateral sides, there are two covers made of sanded black PMMA to shield the cameras and PMTs from unwanted reflected light.

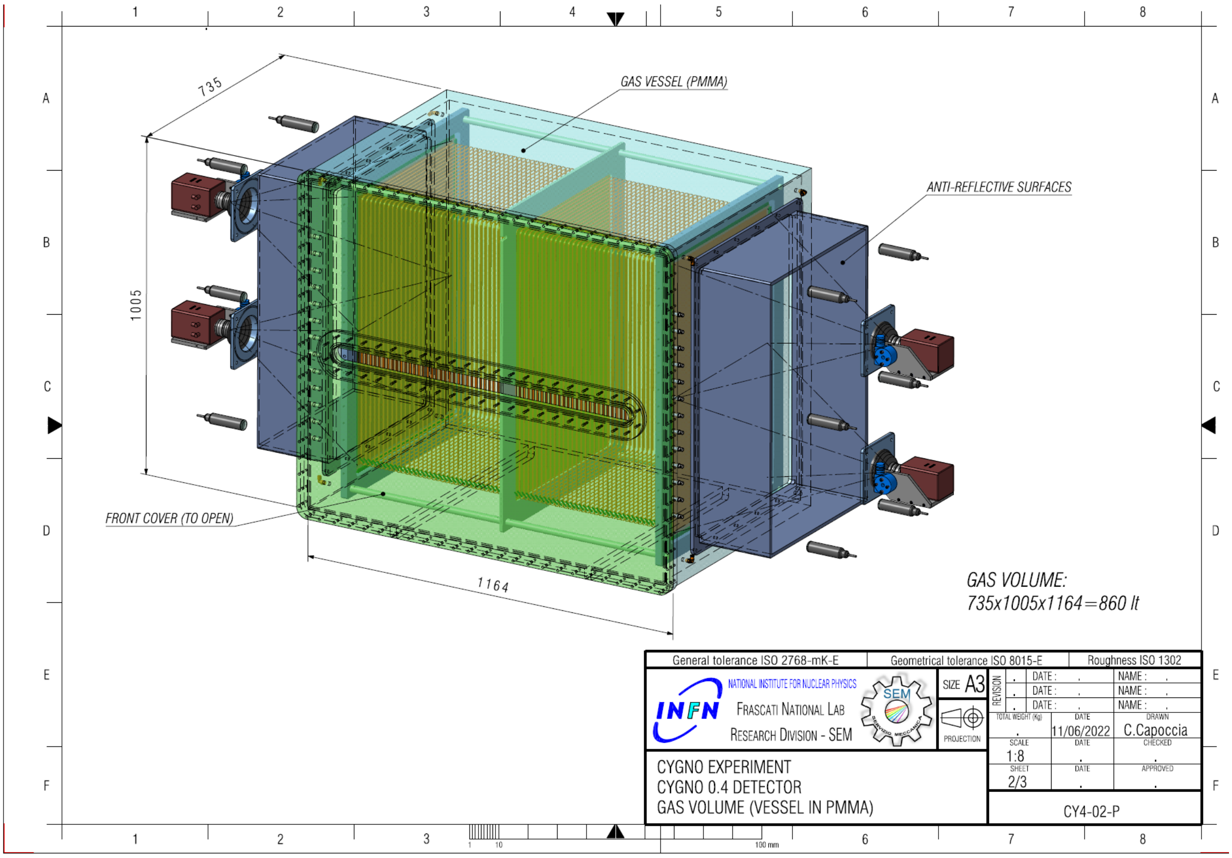


figure 5: vessel and camera assembly

The experimental setup, described before, will be housed inside a copper shielding. The copper shielding (see figure 6) is a box-like structure where each wall is composed of four copper plates 25 mm thick. The total weight of the copper shielding is 9.5 t. The inner volume of the shielding can be accessed by removing the front wall, by means of an especially designed handling tool or by means of a door. The main functions of copper box are:

- Light tightness.
- Faraday cage around the detector.
- Radiation shielding.
- Support the cameras and PMTs.

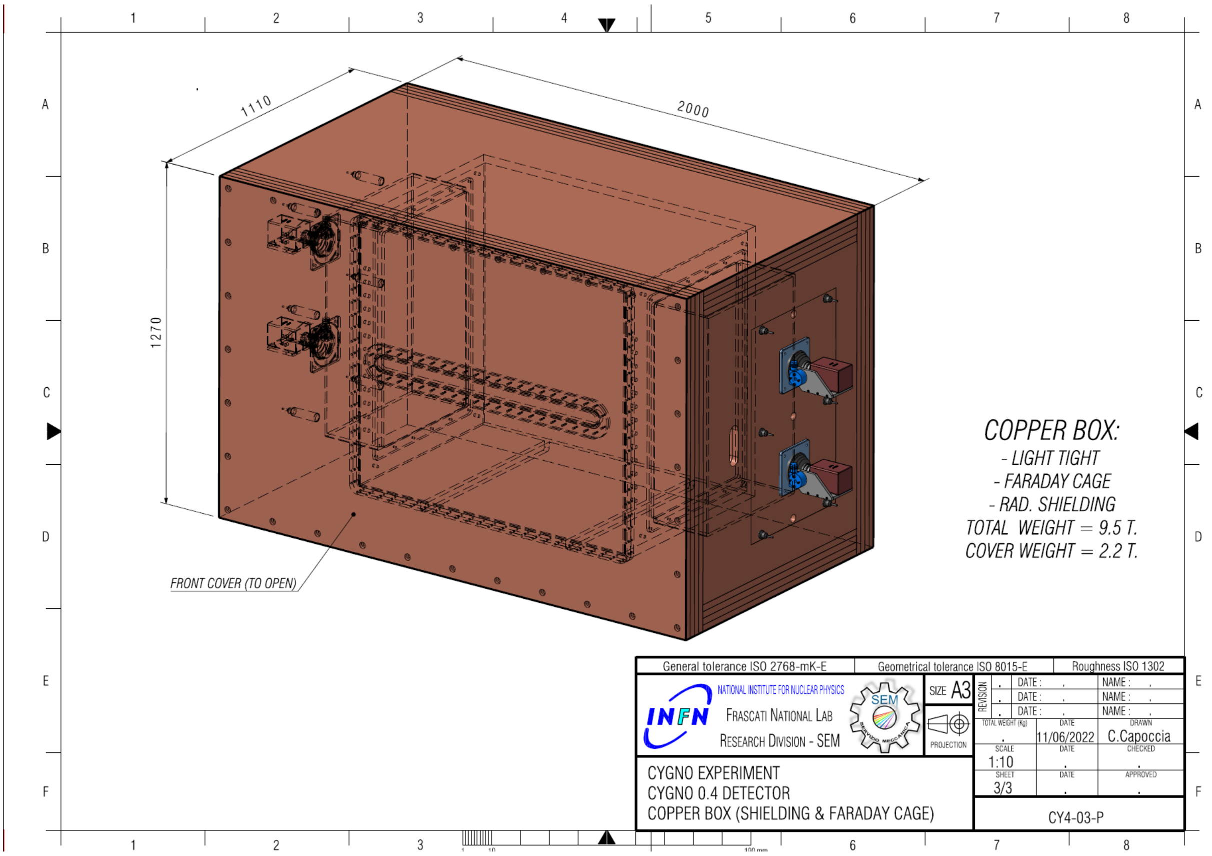


figure 6: copper shielding layout

Outside the copper shielding there is the neutron shielding (see figure 7). Three different custom made tanks, tagged as A,B and C are designed to grant a thickness of 1 m of water shielding all around the detector, for a total of about 40 m^3. They are open vessels to avoid stress on the shell because of temperature variations.

The tanks will be tied together in groups of 2x3 and, at the end, tied together by two straps in order to make them stable.

In case of maintenance or during the experiment integration, to access the detector, the tanks will be emptied of water and removed. Those that will not removed will remain full of water and always tied together.

A containment pool, with a capacity of 3.2 m^3, is foreseen underneath the detector to collect water in case of water leaks.

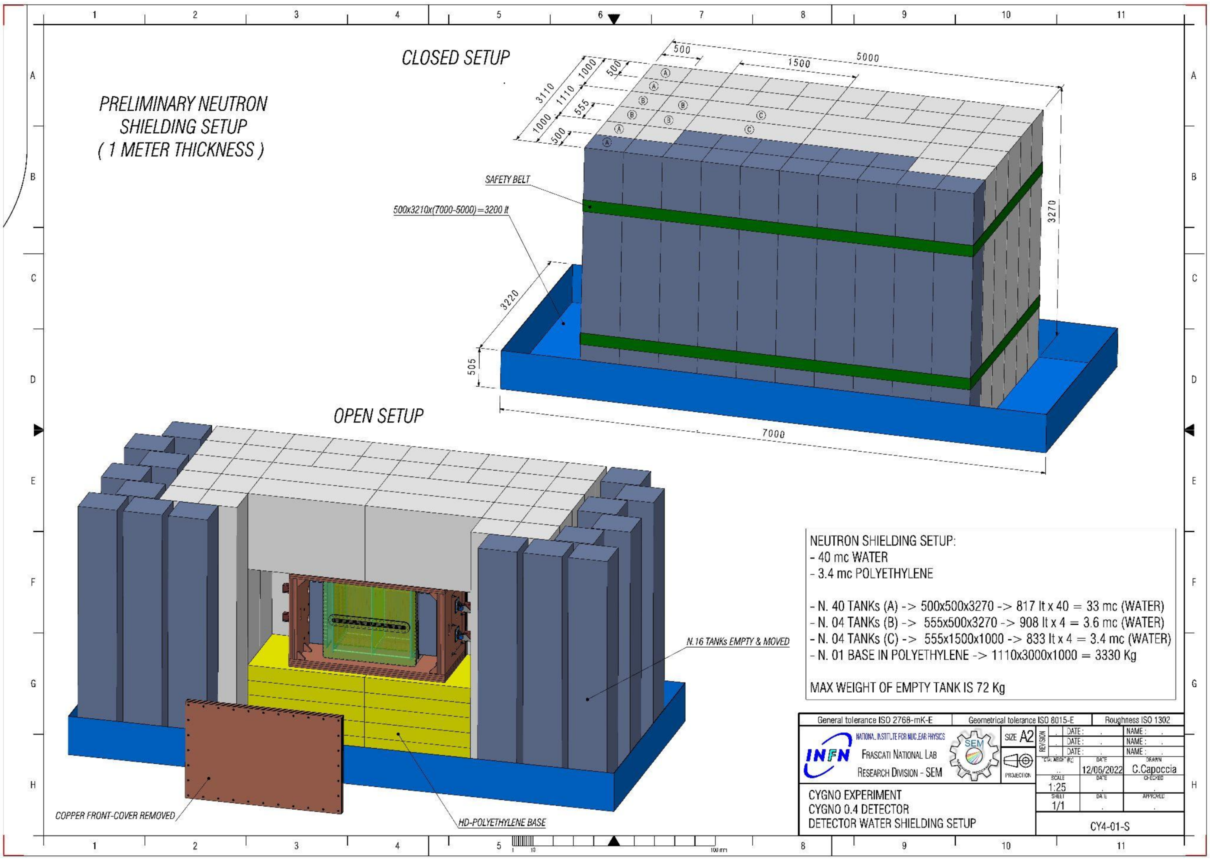


figure 7: water tank layout

Below is the description of the technical characteristics of the main systems and subsystems, for each intervention it will be specified whether it is under LNGS or Experiment responsibility, as already specified at the beginning the activities will be financed from CYGNO funds (see budget paragraf).

DETECTOR components in brief	
Gas Volume 735*1005*1164 mm	860 lt
Copper BOX	9500 kg
Copper DOOR	2200 kg
POLYETHYLEN BASEMENT 1110*3000*1000 mm	3330 kg
40 TANKs 500*500*3270 mm	817 lt * 40 = 33 m^3

4 TANKs 555*500*3270 mm	908 *4 = 3.6 m^3
4 TANKs 555*1500*1000 mm	833 lt * 4 = 3.4 m^3
SAFETY TANKs 7000*3220*505 mm	3.2 m^3

The detector will be installed underground at LNGS hall F, see figure 8 below.

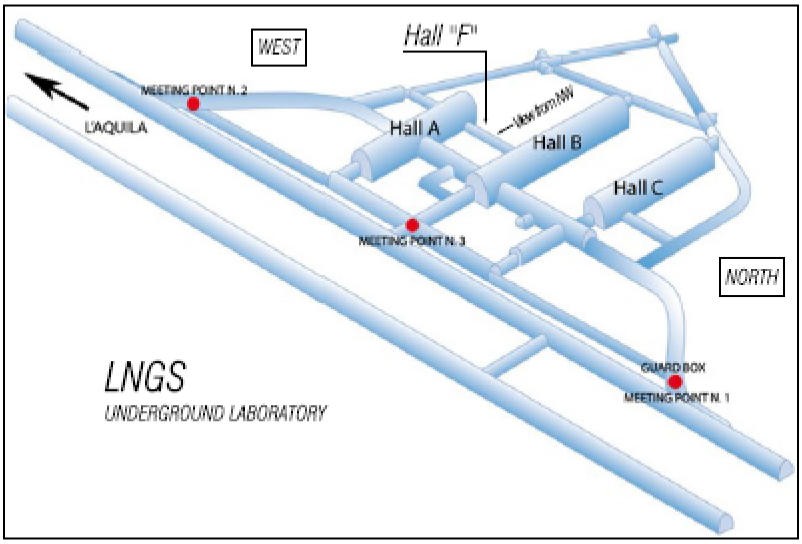


figure 8: Hall F location

The assigned area follows this layout scheme (figure 9):

- CYGNO 0.4 experiment area.
- Open working space.
- Control room.

From the north west wall, we maintain a walkable access of at least 1,2 m for the entire hall F.

The experiment area is 3.3x7 m^2 for a height of 3.28 m. On both sides of the safety pool, areas are provided for the passage.

The open working space is divided in two areas. The first one, opposite to the NW side, is assigned to the services like the electric rack, gas system and air pressure with dedicated panels and filters. The gas cylinders storage is placed on the wall behind the gas system. They are secured on their frame by chains.

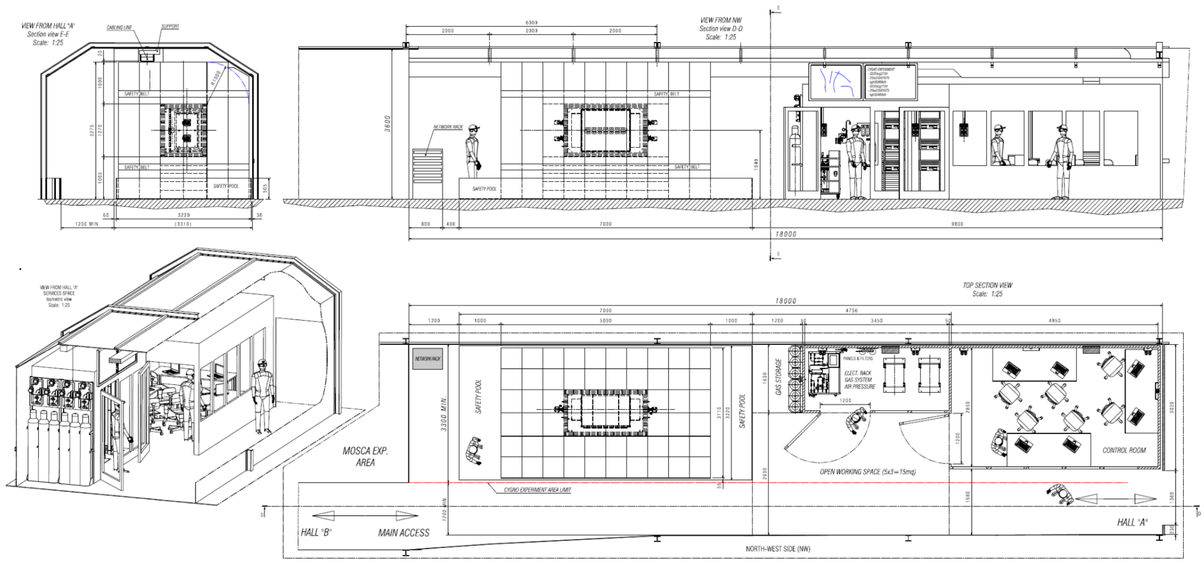


figure 9: layout inside the hall F

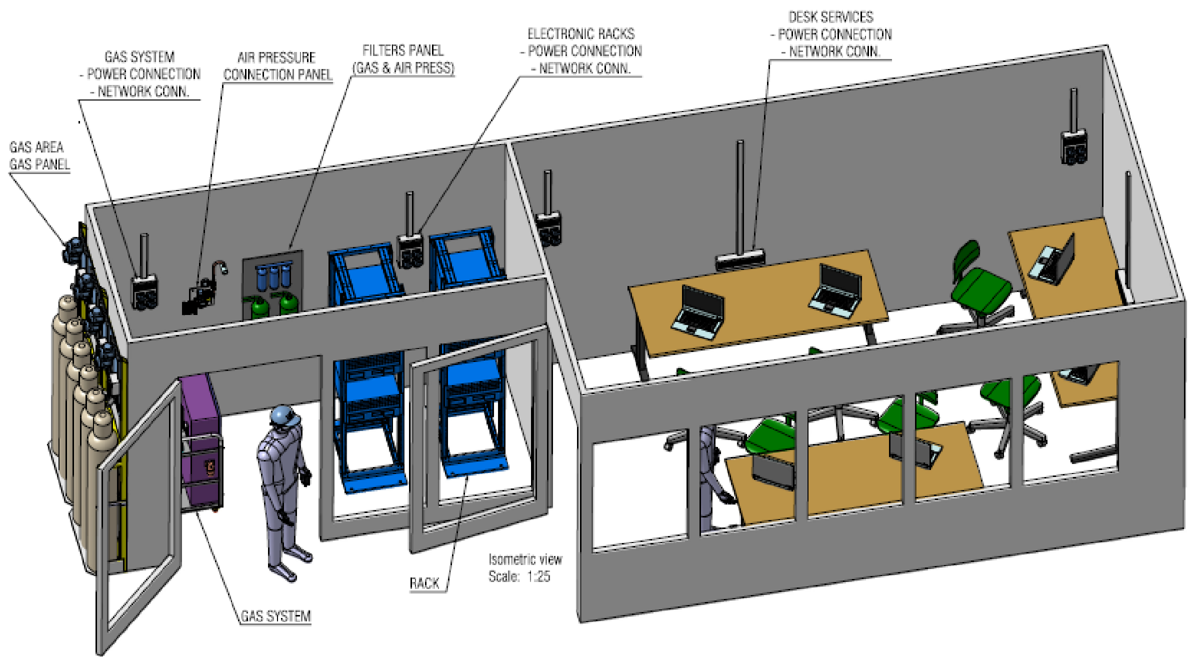


figure 10: 3D view of the services room and the control room

The other one, of 15 m^2 , is a workspace for assembling and eventually handling materials.

The control room has an area of 14 m^2 for workstations served by power and network connections. The openings of the doors are to the outside, to comply with safety standards.

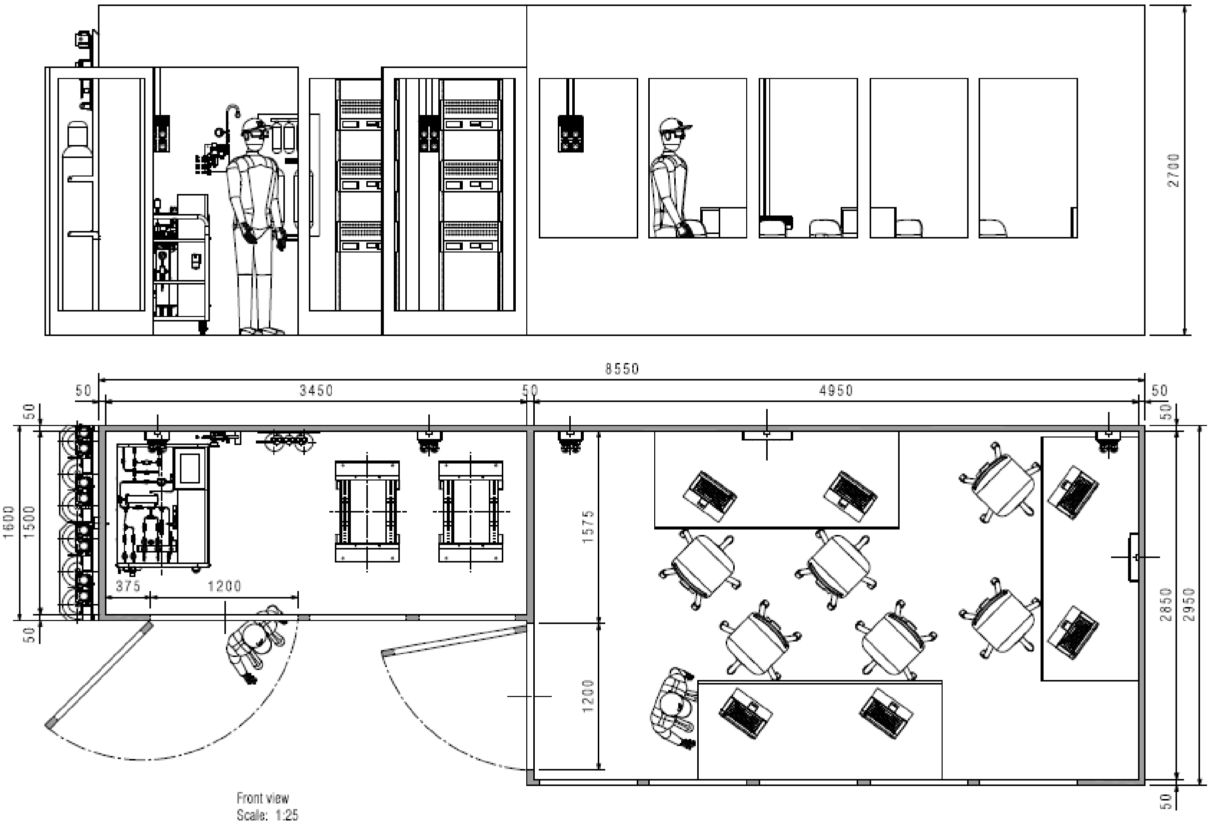


figure 11: detail of services and control rooms area

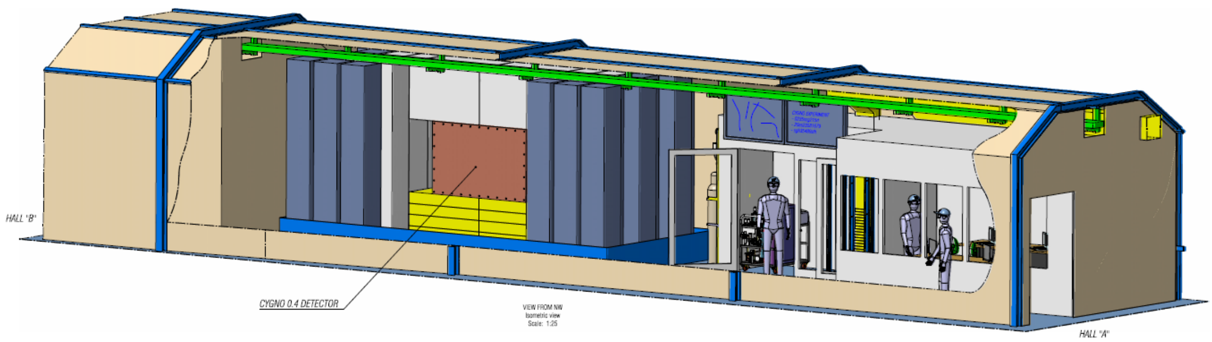


figure 12: 3D view of the assigned area

4.2. Infrastructure and Services

The area, named the hall F, will be renovated in agreement with the LNGS Technical Services and will be covered by CYGNO/INITIUM funds, as follows:

4.2.1. Civil/construction works

The control room and the service box (gas system, air pressure, electronic ...) are built using modular sandwich panels: aluminum, rockwool, aluminum (fireproof) with a total thickness of at least 50 mm.

The doors will be 1200 mm wide, will open outwards and will be equipped with a panic bar (for safety).

The walls will be provided with stained-glass windows (as much as possible) to avoid the "closed space" effect for people working inside, and make possible the surveillance from outside. No excavations and anchorages are planned

All materials and substances used will be declared to the LNGS Environmental Service. Executive materials have to be defined for TDR version 2.0 foreseen in Sep 2022 with the LNGS Services.

LNGS resources support is required for the Design and Building phase.

figure 13: current state of Hall F

4.2.2. Electrical installations

the power consumption of installed devices it is expected:

Name	Specification	Power Estimation (Watt)	UPS	UPS (Watt)
Camera	https://drive.google.com/file/d/14cGAy18Zu29h2wR8F_fwvP7HSNT656CD/	620	yes	620
Chiller	https://www.app-therm.com/Uploaded/1/Documents/Instruction%20Manuals/kt-chiller-brochure.pdf	1200	yes	1200
LW - PS CAEN	https://drive.google.com/drive/u/0/folders/122-c4lnpFMWmFnJEcPtbz55z2fsHuVwC	2000	yes	2000
HV - PS ISEGG	https://drive.google.com/file/d/1F80X7KCwQ0Yh8KExe5DTx573UyqkjqyP/view?usp=sharing	500	yes	500
Gas Sytem	https://drive.google.com/drive/folders/1RNC_mHgvDwibAQr0ETLAllp4N6WyxilL	1000	yes	1000
Crate NIM	https://www.caen.it/products/nim8304/	1450	yes	1450
Crate VME	https://www.caen.it/products/vme8200/	1200	yes	1200
Elettronica	included in the crate			0
Aux Crate (MIDAS)	https://www.psi.ch/sites/default/files/import/ltp-electronics/WwwDocumentsEN/Datasheet_SCS3000.pdf	120	yes	120
Auxiliary device (T, P, ecc)		100	yes	100
1 Network router/switch	https://h20195.www2.hpe.com/v2/GetDocument.aspx?docname=c04347352&doctype=quickspecs&doclang=EN_US&searchquery=&cc=it&lc=it#	500	better	0
1 Front End Server	https://www.supermicro.com/en/products/system/4U/5049/SYS-5049A-T.cfm	1200	yes	1200
2 Auxiliary PC & monitors	device standard	600	better	0

Other: rooms light ecc		200		0
	Total (WATT):	**10490**		**9390**

three 32A distribution systems are expected 2 in the control room and one close to the gas system, part of the power has to be provided under UPS as reported in the table above.

Some of the current lighting in Hall F will have to be moved appropriately to give space for the detector and ensure proper illumination of the area. Moreover, proper lighting will have to be provided for the gas and electronics area and the control room. In general the switchboards available in the area looks to be ready to host the experiment (in terms of power and arrangement). In general what is needed is:

- switchboards for gas system (UPS); switchboards for electronics and low/high voltage power supply (UPS)
- lighting of the area refurbishing
- lighting of gas/electronics area
- emergency lighting
- network connection via optical fiber in gas/electronics area: router and switch will be host there and then distributed in the control room
- network wiring cables (cat 6) and plugs (2 for desk, 6 in total)
- power plugs distribution (3 for desk (2+1 UPS), 9 in total)

The overall distribution of cabling above could be realized through fling cable ducts esly accessible that do not require complicated installation and distillation costs and activities.

Executive layout to be defined for TDR version 2.0 foreseen in Sep 2022 with the LNGS Services.

LNGS resources support is required for the Design and Installation phase.

4.2.3. Compressed air

Compressed air is planned for laboratory use and to support the gas system: we plan to use compressed air to supply equipment requiring normal compressed air (according to European standards) with a pressure rating of 6 bar and a flow rate of 2,000 liters/min. Therefore we require from the LNGS a line supplied between 7 and 10 bar that has, at the end of the branch to us, a compressed air panel equipped as follows:

- Pressure regulator (flow rate greater than 2,000 liters/min) ¼'' or ⅜''
- Oil and condensate recovery filter (standard filter 25 um or better)
- Set (5x) of panel fittings of the ''Quick Connect'' type from ¼''

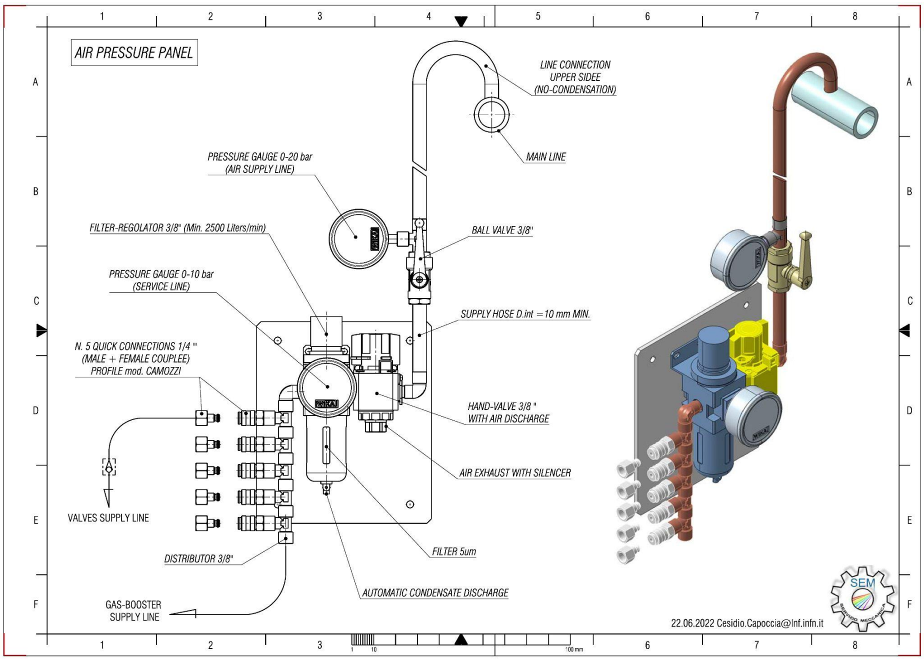


figure 14: detail of air pressure panel: components & connections

Regarding the above accessories we have no special requirements, the commercial products available for normal compressed air systems are fine. In addition, the compressed air system available at LNGS using non-oil-free compressors is compatible with the needs of the experiment.

The panel with the compressed air outlets will have to be located near the gas stand.

LNGS resources support is required for the Design and Installation phase.

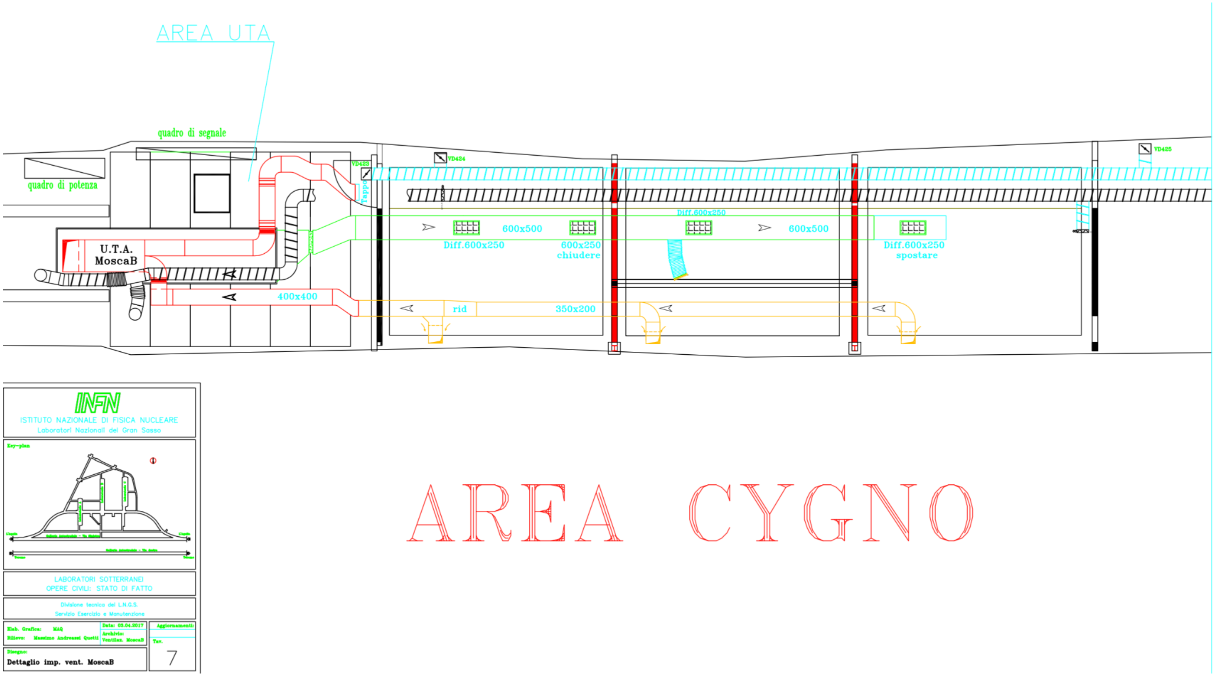
4.2.4. HVAC (heating, ventilation, and air conditioning)

The area (see figure above) is already equipped by an UTA AQ105 with flow rate mc/h :11000[56] able to ensure enough flow for the experiment requirements. Anyhow it will be necessary to provide an air conditioning system in the control room and in the service box in order to have a comfortable temperature and to cool down the power dissipated by electronics by appropriately channeling current flows.

In addition to internal air recirculation, there is the possibility to exchange air with the outside. The ventilation control system ensures different configurations depending on the occurrence of: fire; in cryogenic alarm; emergency evacuation; when rooms are cleaned.

No cooling water systems are required for electronics or other subsystems of the experiment.

[56] https://drive.google.com/file/d/14oX4WX71_VM-e-xEEo7VgKUTZLj3fnkR/view?usp=sharing



Executive layout to be defined for TDR version 2.0 foreseen in Sep 2022 with the LNGS Services.

LNGS resources support is required for the Design and Installation phase.

4.2.5. Deionized water

the use of one of the water systems present at the LNGS is required, regarding the activities of loading/unloading water tanks (see installation procedure in next chapter 8).

4.2.6. Under pressure equipment

He bottles, CF4 and SF6 and exhaust gas recovery, gas distribution system. The previous equipment will be located in the gas closet accessible only to authorized personnel and equipped with oxygen monitors and alarms as required by the PRA and LNGS services.

4.2.7. Vacuum and cryogenic systems

no vacuum or cryogenic systems

4.2.8. Lifting and transport systems

handling/moving for the water and copper shielding and of the detector.

The components will be transported to room ''B'' and positioned near the entrance to room ''F'' using truck and the bridge crane (available in hall ''B'').

The movement inside room ''F'' will be carried out with the use of electric/manual pallet trucks (depending on weight).

All the heavy components will be transported, disassembled and then assembled on site. All parts are designed and built in such a way as to facilitate handling with equipment that can be used in confined spaces.

All these operations (transport and heavy assembling) will be performed with assistance from the LNGS services.

Executive operation to be defined for TDR version 2.0 foreseen in Sep 2022 with the LNGS Services.

4.2.9. Supervision and control

supervision and control systems are available for the flushing, purification, recirculation and recovery of the gas used in CYGNO-04. The Air Liquid Gas Sytes foreseen the remotization of procedures, status, alarms and warnings. All the system has been embedded in the experiment's slow control system already tested for LIME prototype.

4.2.10. Safety

Preliminary Risk Analysis (PRA) and Preliminary Environmental Assessment (PEA) have been made by NIER company, and verified (TDR version 2.0 foreseen for Sep 2022) by SPP-LNGS and Environmental LNGS Services.

4.2.11. IT and networking

network switch dedicated to the experiment and distribution of the network in the experimental space via wall plug; data server, 3 pcs and related monitors to control acquisition, data flow and monitoring of auxiliary systems (see next paragraph).

Specifications of equipment and devices have already been agreed with the Computing and Network Service, purchase of materials has been already done.

LNGS resources support is required for the Design and Installation phase.

4.2.12. Radiation protection

use of calibration sources without risk of ionizing radiation (unexposed worker). The detector will be equipped with a permanent calibration ^{56}Fe source remotely controlled for daily/weekly calibration. The source has been bought by the experiment and is under test in LIME setup in agreement with the LNGS radioprotection safety roles.

4.2.13. Mechanics

mechanics will be our responsibility, except for any inconveniences that can be quickly solved with (occasional) help from your workshop.

4.2.14. Electronics

a rack with standard and certified electronics tied to the acquisition system and for housing power supplies is required. The activity will be managed and implemented by the experiment.

4.3. High Voltage System

The high voltage to the detector will be provided by two different suppliers:

- a CAEN Individual Floating Channel Dual Range Boards for Quadruple and Triple GEM detectors[57], housed in a CAEN SY4527 crate[58], will be employed to set the different electrodes of the GEM stacks to the proper voltage and will allow to readout the currents drawn (see manuals 9.2).
- a single channel ISEG module[59] HPS-350W will be used to supply the voltage to the central cathode (see manuals 7.1).

4.4. Gas System

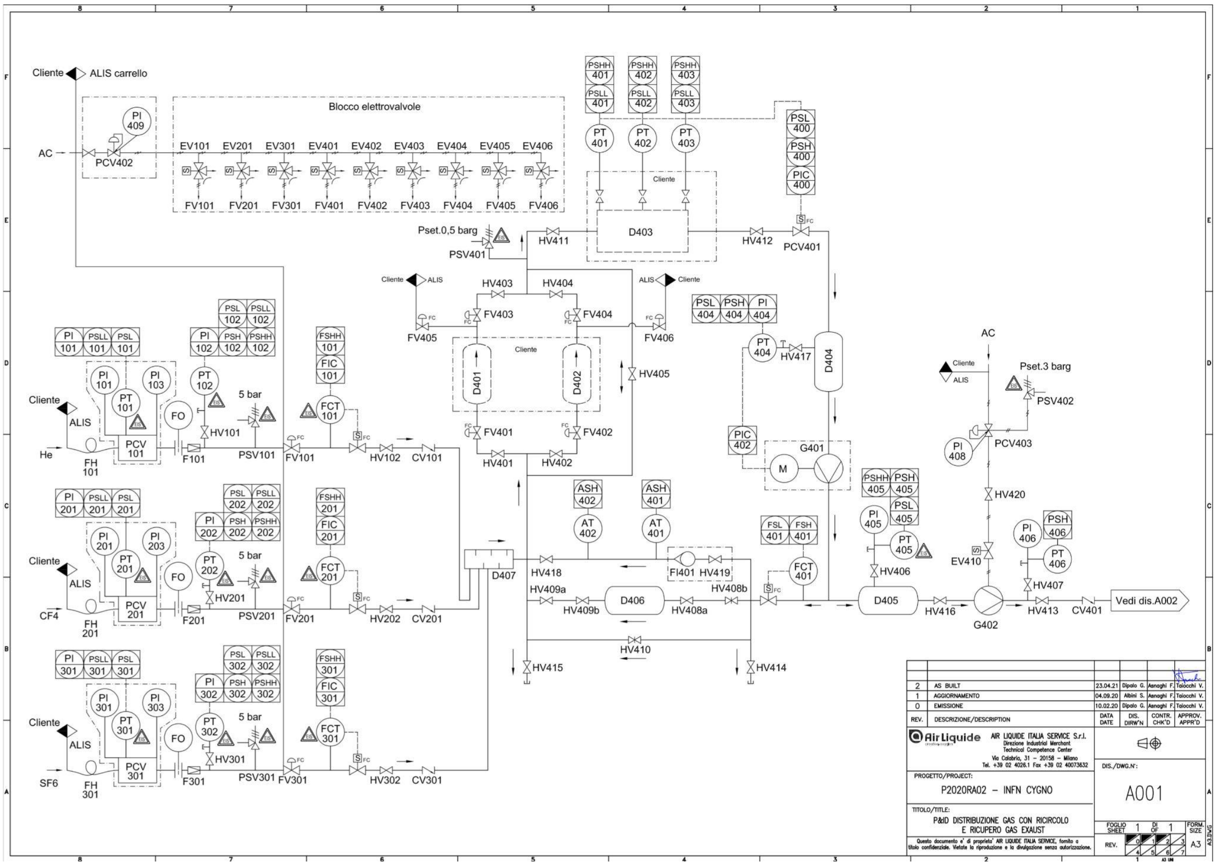
The GAS system that will be used for operations is expertly made by Air Liquid company and has been installed and tested in 2021 at LNGS and is now in operation with the LIME prototype installed since 2022 in TIR gallery at LNGS. This system performs 4 functions: flow of an appropriate gas mixture, HeCF4 typically in 60/40% percentages and no more than 5% of SF6, chemical purification of impurities, recirculation, and recovery. The data sheet is attached in the next chapter item 7.12, within all the operating manuals. The Gas system consists of a cart and a ramp of 4 cylinders: 2 supply (He and CF4 see attached data sheet) and 2 recovery cylinders at

[57] https://www.caen.it/products/a1515b/
[58] https://www.caen.it/products/SY4527/
[59] https://iseg-hv.com/en/products/detail/HPS

a maximum pressure of 40 bar. The gas mixture will be fully recovered from the system and no atmospheric exhaust will be realized.

The system also includes the possibility of a ternary mixture with SF_6 in case the test with negative ion ongoing for the PHASE 2 will be successful.

On the left a picture of the CYGNO gas system installed in the TIR gallery under test with LIME prototype; left gas system trolley; right 4 bottle He, CF_4, SF_6 and recovery bottle;

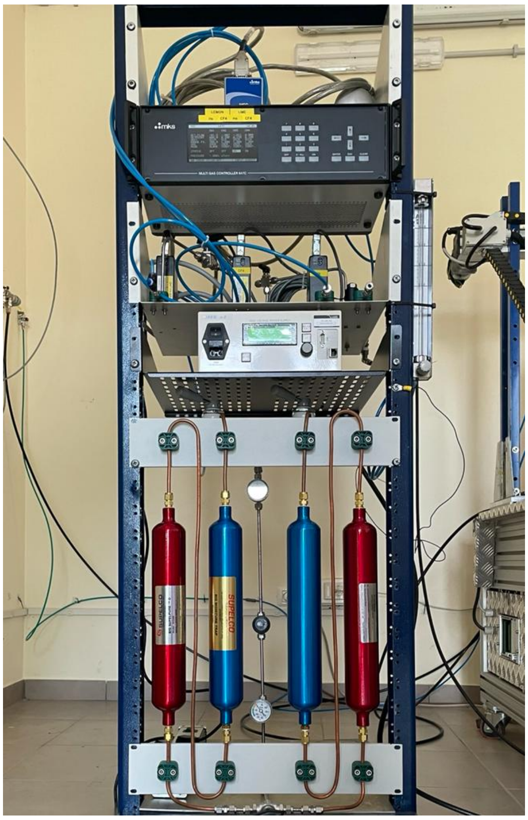


P&I of the CYGNO Gas System designed and realized by Air Liquid company

The recovery bottles are provided by a waste disposal company (today ECORECUPERY see next chapter 7.16) compliant within the requirements of the Air Liquid Gas System, that provides the proper disposal of the gas in accordance with current regulations.

4.5. Gas Purification System

The gas system to be used underground for both the LIME prototype and the CYGNO experiment has been delivered at LNGS in July 2021. The system allows the purification and recirculation of the gas inside the detector and the recovery of the gas for the disposal of greenhouse gasses. The Radon purification system is under design at Sheffield University and is based on 5A molecular sieves customly produced in low-radioactive samples at Nihon University, Japan. 5A molecular sieves have been proved to be very effective in removing Radon contamination from pure Helium and CF4, although a significant absorption of CF4 is also observed. It will require a tuning of the fresh gas mixture, with a CF4 excess, in order to compensate the CF4 loss in the filters and reach an equilibrium with the desired composition Tests of the compensation procedure are currently starting at LNF with commercial molecular sieves (figure below), and will be continued at LNGS with LIME.



The absorption of contaminants in the filters make them ineffective after some time, depending on the total gas flow and the concentration of contaminants. For these reasons, the filters need to be periodically regenerated. The vacuum swing technique is adopted: two sets of filters are installed. While one of the two sets is in operation, the other one is connected to a vacuum pump to remove the absorbed contaminants. Once the first set of filters is starting to become ineffective, the two sets are inverted. The gas system is already provided with connections and remotely controlled valves that are necessary to automate this procedure. Also in this case, tests will be performed at LNGS with LIME in order to characterize the regeneration cycle and to optimize the procedure.

For this purpose, a purification system with commercial molecular sieve filters will be installed and tested underground within the end of the year. The apparatus will be complemented by a slow control system, for which the part procurement is ongoing, that is necessary to monitor and characterize the regeneration cycle.

A revision of the calibration procedures is currently ongoing based on data and simulations for the choice of the best sources to be installed and tested in LIME.

4.6. Data Acquisition (DAQ)

A Trigger and Data Acquisition System (TDAQ) has been designed to accommodate two readout paths, one for the fast signals coming from the photodetectors (PD-path), and the other one for the images provided by sCMOS cameras (sCMOS-path).

The PD-path is implemented on VME commercial digitization boards, while the sCMOS-path is instrumented by a PCIe coaxpress frame grabber that can readout up to 8 cameras. The two paths are connected to a server via an ethernet cable and a PCIe bus respectively. The server runs the TDAQ online software as implemented in the MIDAS framework.

The TDAQ system will be able to collect synchronized data from the two path handling the following specification:

- Camera exposure from 0.2 to 1 second (1-5 Hz frame rate);

- 10 MB of data per picture (5 MP, 16 bits/pixel);
- 12-bit digitization of photodetector waveforms at 250 MS/s in O(1us) windows.

The system is foreseen to run in a triggerless mode acquiring the camera images in a continuum mode. To operate in the triggerless mode and keep the data throughput to disk within 200 MB/s we foresee a software trigger to reconstruct images and perform basic event selection. This will run on a server with CPUs and GPUs with a latency of about 1 event/s.

A hardware trigger signal is also constructed based on the information in the PD-path by combining with logical operations the signals of the photodetectors. Such a hardware trigger could be used online to trigger the cameras, or offline to search for interesting events in the acquired images.

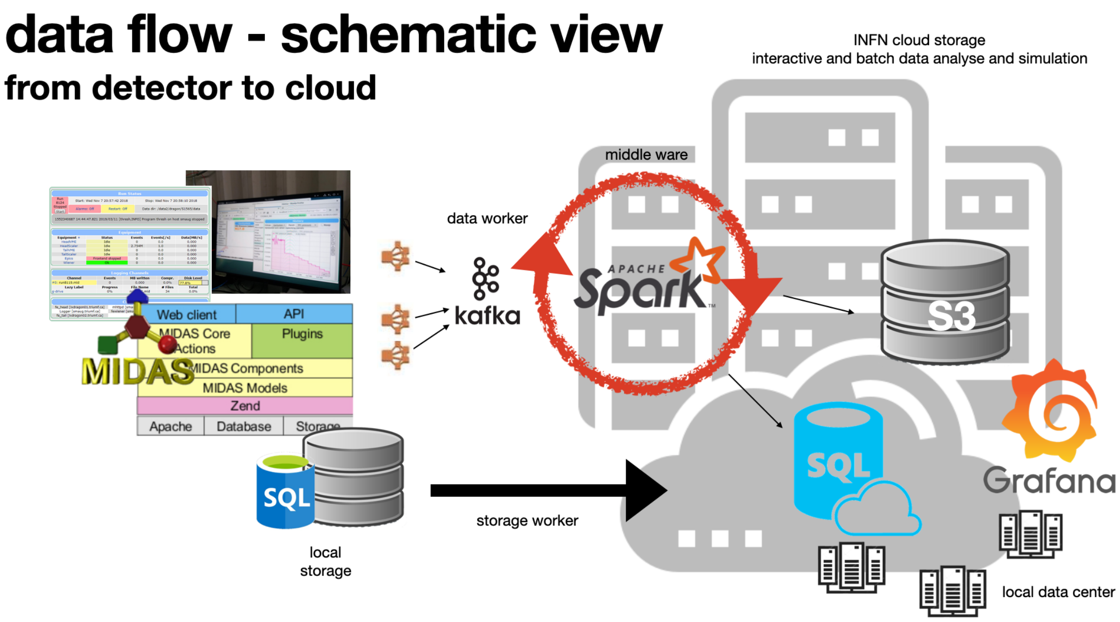
4.7. Computing System

Raw data and metadata are collected and stored underground on local disk (8TB RAID) and SQL db by means of a MIDAS framework, acquiring the cameras, PMTs, auxiliary channels (included gas system) and all run information. Data and metadata are then uploaded on the INFN Cloud S3 stage, for data reconstruction and analysis and then saved on Type.

We expect a trigger rate of 1-0.2Hz and an event size ~10MB (compressed) and thus a throughput of about 100GB per day (40TB/year). These numbers can decrease by about an order of magnitude through a fiducial process (cuts on the accepted volume), which can eliminate the radioactivity mainly generated by the detector material.

On the INFN Cloud the data are available via posix simulated filesystem to CYGNO experiment machines where, docker container applications export "as a service" for the CYGNO users many analysis and simulation tools. The environment is accessible through Jupyter notebooks configured with the necessary packages (python, ROOT, GEANT, GARFIELD, SRIM, and useful lib) for the interactive and batch (HTcondor) reconstruction and calibration, analysis and simulation. HTcondor queues that can be reached either from the cloud or through appropriate docker and raw data are also accessible via open HTTP URL

In parallel to full data calibration and reconstruction an online process hosted on the INFN Cloud integrates a quasi online reconstruction through "Middle Ware" aimed to extract monitor quality and stability of data and evaluate detector performance. A GRAFANA interface is available showing major physical reconstructed outputs performance and to monitoring computing resources.



networking: the area will be equipped with a router dedicated to the experiment and a switch to share the network locally. The router, configured under the supervision of the personnel of LNGS, will share the LNGS in the private CYGNO network where DAQ and auxiliary network device will be connected. Router and switch will be connected via high band optical fiber to the LNGS LAN/WAN and LNGS Computing Center.

All the computing and network infrastructure architecture/devices are under test in the LIME R&D area.

5. Parameters Validation

One of the main goals of CYGNO-04 is to demonstrate the scalability of the performance obtained so far in the R&D phase. Therefore, a crucial aim for PHASE 1 will be to obtain the same resolutions and efficiencies will be achieved with a sensitive volume that will be an order of magnitude larger that the largest prototype realized by the CYGNO collaboration.

In some cases, the upgrades in the technology (in particular in the sensitivity and noise levels of the optical sensors) combined with the development of new data analysis algorithms, are expected to be able to even improve the PHASE 1 performance.

	Phase 0 LIME achievements	Phase 1 CYGNO-04 objectives
Sensor noise (e-/pixel)	0.7	0.3
Energy Th (keV)	1.0 keV_{ee}	0.5 keV_{ee}
Energy resolution (sigma)	13%	8%
ER efficiency @ 1 keV	60%	70%
ER efficiency @ 6 keV	99%	99%
XY resolution (μm)	100	50
Z resolution %	15	10
transversal diffusion (μm/√z(cm))	110	110
longitudinal diffusion (μm/√z(cm))	90	90
discrimination @ 6 keV	10^{-2}	10^{-3}

6. Installation and Commissioning

In the following we report a preliminary description of the procedure foreseen for the experiment installation, operation, maintenance and decommissioning.

Executive operations have to be defined and validated for TDR version 2.0 foreseen in Sep 2022 with the LNGS Services.

6.1. installation procedure

The installation of the detector begins placing the safety pool in the CYGNO 0.4 experiment area. It's made of plastic or metal sheets glued together to obtain the base and then glued to the walls. A sealing test is planned at the end of operations.

Then the HD polyethylene base is positioned, over which we begin the mounting of the copper box base and the back cover. The activities are done using a pallet truck and forklift.

After that, the PPMA vessel with TPC is placed on the top of the basement and the remaining parts of the copper box are mounted, fixing each other with bolted connections.

At this stage, it's possible to close the external layer with water tanks. The tanks array, first are installed and then filled, using a pipe that comes from hall B or hall C, where there is a plant of demineralized water. A pump will give the necessary prevalence. The 16 tanks in the front cover will be moved once empty, to allow access to the detector. They are divided in groups and fixed each other using fixing straps.

Due to a modular design, the following parts will be handled using a forklift and a pallet truck for installation:

- Safety pool plates.
- HD polyethylene base sheets.
- Copper plates.
- Water tanks for shielding.

The materials can be stored, during the assembly, in the dedicated operation area.

6.2. Commissioning

For the commissioning, the PHASE 1 of the project will strongly protif of the experience gained in the current work of PHASE 0.

Services Startup

The ancillary services (high voltage[60] and gas distribution systems[61]) foreseen for CYGNO-04 and the control system based on the MIDAS software will be the same now in use with the LIME prototype. Therefore, we expect a relatively short commissioning phase for them that can be evaluated in 1 month.

On the other hand, DAQ systems and infrastructures, developed for LIME will be scaled to acquire simultaneously data from 4 cameras and 12 PMTs. This system will be tested and debugged overground before the installation and its startup underground can partially proceed in parallel with the commissioning of the ancillary system. We expect 1 more month will be required to have the DAQ running.

Detector Commissioning

Once the ancillary systems are running, the commissioning of the detector will start. From previous experience and test[62], when the proper gas mixture is flushing, high voltage can be turned on, without the need of a long detector conditioning. We expect that this phase can proceed in parallel with the startup of the DAQ system.

Calibration

The calibration of the detector response will be performed by means of radioactive sources:

- A ^{55}Fe source will be employed to produce 5.9 keV ER in the gas. A completely automated system will move the source on one of the detector lateral faces in order to make it possible to check the response absolute calibration and relative uniformity. The plan is to take calibration runs every day, in order to spot possible variations in the response;
- To study the detector response to NR, neutrons provided by an AmBe source will be used. In this case, since we do not expect the relative correction factor between ER and NR to change with time, after a first one-week long test, runs with AmBe will be repeated every 3 months;

The first calibration (data taking and analysis) is expected to last 1 more month.

In total, once all the experimental apparatus will be in place, the commissioning phase is expected to last 3 months. Because of possible issues arising in this delicate phase, a 1-month long contingency is foreseen.

6.3. Data Taking

Once the commissioning and calibration is completed, CYGNO 04 will start to take data.

60

61 Gas System

62 https://arxiv.org/pdf/2007.00608

The data taking period will be separated in 2 phases:

- a first set of data will be taken with the only copper shield. This first phase will have two main aims:
- checking the detector operation stability and reliability before the installation of water tanks will allow to easily intervene in case of any issue;
- it will be useful to cross check the expectations of external background simulation.

According to the experience gained so far with LIME, a 4 months period will be enough to achieve both aims.

- After the installation of the second layer of shield made of water tanks, the start of the 12 months long final data taking is planned. Data taken in this phase will allow a detailed evaluation of all radioactivity background components surviving the shield structure and produced by the internal detector material. Given the relevance of this phase, we want to foresee a 4 months contingency to ensure the success of the project.

During data taking 2 people are provided in the control room or remotely to ensure continuity and stability of data taking.

6.4. Maintenance

During the operation of the demonstrator, in case of critical failures of the inner detector component, the maintenance procedure has to be activated. This foreseen:

- power off all High Voltage/Low Voltage system, DAQ, ecc
- remove external electrical power connection
- recover the gas mixture inside the vessel and after we flushing nitrogen at atmospheric pressure through the gas system until all the He/CF4 mixture is evacuated;
- drain the water from the 16 front shielding tanks to the storage tanks in agreement with LNGS services.
- remove the water tanks and store in the lateral space available in the safety pool
- open the copper shielding front door
- disconnect inner cabling
- remove/open the PMMA vessel.

remove and operate on the damage part and start back from point one.

The PMMA vessel could be removed from the open copper shielding and then opened in a clear room or, thanks to the lateral door, opened locally.

The experiment can create locally, by means of air cleaner, a gray room limiting the contamination of the detector component.

6.5. Decommissioning

The Collaboration will provide a draft decommissioning plan prior to commencement of activities onsite. This plan will provide for the complete removal of all equipment and restoration of the site to its initial condition, unless a mutual agreement is reached with Gran Sasso Laboratory prior to the completion of each phase of the project or the transfer of equipment to a subsequent use/project with Laboratory's concurrence. A more detailed and comprehensive plan and project will be established prior to the commencement of Project decommissioning.

Briefly, the operation above (8.4) will continue by:

- remove the copper box and HD PMMA base.
- removing the water safety pool
- removing gas system, racks of electronics and data acquisition, control room devices and furnishings

All the materials will be disposed of in accordance with the instructions provided by the Environment Service and with the SPP-LNGS requirements.

7. Safety and Radioprotection

in the following a list of manuals and devices that will be used for the experiment. The use of this devices as been discussed with NIER Engineer company who have been take care of Preliminary Risk Assessment Analysis (PRA) and Preliminary Environmental Assessment (ERA) in appendix to this document, to evaluate risks and and eventually elaborate mitigation procedure:

7.1. Powr supply ISEG HV 50kV
http://hv.com/files/media/Manual_HPS_350W_eng.pdf
7.2. Power supply CAEN SYS2527 5kV:
https://drive.google.com/open?id=1jSFRxR8N-ZSXN7YEcpvBaoqJqEeAByUN
7.3. Crate NIM ed elettronica di controllo: https://www.caen.it/products/nim8304/
7.4. Crate VME e schede di acquisizione dati (CPU, ADC, ecc):
https://www.caen.it/products/vme8200/
7.5. Server DAQ:
https://www.supermicro.com/en/products/system/4U/5049/SYS-5049A-T.cfm
7.6. 2 PC auxiliary to control HV/Gas ecc
7.7. Crate SCS3000 Auxiliary Channels:
https://www.psi.ch/sites/default/files/import/ltp-electronics/WwwDocumentsEN/Datasheet_SCS3000.pdf
7.8. Cameras Hamamatsu ORCA Quest:
https://drive.google.com/file/d/14cGAy18Zu29h2wR8F_fwvP7HSNT656CD
7.9. Whater cooling KTD Chiller - 480W
https://www.app-therm.com/Uploaded/1/Documents/Instruction%20Manuals/kt-chiller-brochure.pdf
7.10. Capitolato tecnico sistema di GAS CYGNO: (All. 4)
https://drive.google.com/open?id=1A-C5t-0ZbIXLwUEPgNd-5sZ_Dr61YnhS
7.11. Relazione Tecnica sistema GAS (flussaggio, ricircolo, purificazione e recupero):
https://drive.google.com/file/d/1inEhZ48mb6ba2zCU83A9va2DtgEbVihu
7.12. Documentazione completa Air Liquide Gas System:
https://drive.google.com/drive/folders/1RNC_mHgvDwibAQr0ETLAllp4N6WyxilL
7.13. Scheda di sicurezza del gas He Elio:
https://drive.google.com/file/d/18OiB6qtKPrP70-5q-0y7TWyQ2dUwOGiw
7.14. Scheda di sicurezza del gas CF4 Tetrafluorometano:
https://drive.google.com/file/d/1mHsn5do5gpfR6Q7xm5NvzQ5NwN4XNurB
7.15. Scheda di sicurezza del gas SF6 Esafluoruro:
https://drive.google.com/file/d/10PR9zCEZvyGkkf0GHSIyMb_NtUTkgcGS
7.16. ECORECUPERI Docum. tecnica relativa al Art. 4 del Capitolato Tecnico:
https://drive.google.com/file/d/1d_trN2Q0e1pI552OB_N-xDdPS1N7TdZg

7.17. rivelatore di gas/CO2/ossigeno ecc: https://it.trotec.com/shop/contatore-di-particelle-pc220-incl-certificato-di-calibrazione.html

7.18. The experiment makes use of a mixture of nonflammable He:CF4 gasses that will be flushed through the detector with a system produced by the company Air Liquide Italia Service and certified. The Gas System has been designed to be operated with SF6 for further improvements with negative ions. It also makes use of approved and certified high-voltage apparatus, the details of which (manuals and technical papers) are available at the link: https://drive.google.com/drive/folders/122-c4lnpFMWmFnJEcPtbz55z2fsHuVwC

In attachment to this document we release the Preliminary Risk Assessment (PRA) and the Preliminary Environmental Assessment released by the NIER engineering company. NIER company have long experience in this evaluation for experiments hosted by LNGS in the underground environment, today other Seveso safety regulation, and have already prepared and resled the analogous evaluation for LIME/PHASE 0 and Hazid relative Risk Table.

The personnel present at the same time in the CYGNO areas during the commissioning phase could be 5/6 while during the data taking phase they will definitely be less than 4.

People working in the area will be informed and trained on the specific risks of the experimental area. A document[63] signed by any participant to the shift of LIME has been setup and will be similarly redacted for CYGNO-04.

A procedure[64] for fire-fighting officers concerning intervention in case of problem with the gas system is available for gas trolley and bottles installed in the LIME area, it will be updated when the gas system is moved to the CYGNO-04 area.

In general, experimental activities do not, in compliance with internal radiation protection regulations, involve significant risk of exposure to ionizing radiation to operators. The calibrations that are normally performed require either very low-energy X-ray emitters or other emitters but of low activity.

Use of 55Fe source: the source is slid onto the front PMMA cover of Cygno 0.4, inside by the (100 mm thickness) copper cover. The source will be about 1.5 m from the ground. It will always be contained in the 20 mm diameter tube with which it was delivered with an opening facing downward. Once the source is positioned, the operator will be able to move it from outside the field cage thanks to a remote control actuator. Only one operator is needed for handling operations that take only a few seconds. During data acquisition, there will be no operators in the same room. In general, no more than 10 movements per day will be made.

[63] https://docs.google.com/document/d/1JWlOp4Uh3H-l0tjdEYcL6rjx5LLTkZnQpzgpuS31Kmg/edit?usp=sharing

[64] https://docs.google.com/document/d/188f5fQUfk5t1s8K9EoTf2EdbjQ7FqGSIYVpu5_Zjwwg/edit?usp=sharing

8. Management

8.1. Management and Communication (WP7)

CYGNO/INITIUM collaboration is supported by various funding agencies: INFN-CSN2, ERC and PRIN (through the project *"Zero Background Experiment"*).
The italian component is composed by 4 Institutions:

- INFN (LNF, LNGS, RM1 and RM3);
- Sapienza, University of Roma;
- Gran Sasso Science Institute;
- Università di Roma TRE;

Moreover, the CYGNO/INITIUM project benefits from the support of 5 international partners:

- The CBPF-Brazilian Center for Particle Physics (BRA);
- Universidade Estadual de Campinas (BRA);
- Universidade de Coimbra (PT);
- Universidade Federal de Juiz de Fora (BRA);
- The University of Sheffield (UK);

The total amount of FTE involved in CYGNO project (without taking into account the technical staff) is shown in the table below.

Institution	Total FTE
INFN - RM1	4.6
INFN - LNF	2.7
INFN - LNGS	6
INFN - RM3	1.9
University of Sheffield (UK)	0.45
Universidade de Coimbra (PG)	2.5
Universidade Federal de juiz de Fora (BRA)	2
Centro Brasileiro de Pesquisas Físicas (BRA)	0.6
Universidade Estadual de Campinas (BRA)	0.5
Tot	20.75

Table 8.1 CYGNO/INITIUM FTE in 2022

The management of the project has to take care of representing the interest of the whole of stakeholders.
The project is subdivided in 7 Working Packages (WP), coordinated by 7 WP leaders. Table 1, summarizes the current structure and indicates the main tasks assigned to each WP and the coordinator of each one.

Two spokespersons represent the project. They are equivalent but in charge of specific duty:

- one is also National Responsible in CSN2, designed by election every 5 years, today in charge of D. Pinci, INFN-RM1;
- one is E. Baracchini (GSSI), PI of ERC-INITUM and other external funds who takes care of the international relationship, in particular with CYGNUS international collaboration.

To coordinate the project, the spokespersons are codiuvated by a Technical Coordinator (TC), today in charge of G. Mazzitelli INFN-LNF, and by a Steering Committee, formed by the WP leaders as reported in Table 1.

The TC is also RAE and GLIMOS supervising and taking care of safety and environmental issues.

The proper communication and discussions among the Collaboration is ensured by weekly or fortnightly meetings. A general agenda site collects all needed information and links (https://agenda.infn.it/category/1149/).

Every two weeks, dedicated meetings about Simulation, Reconstruction and Analysis, Trigger and DAQ take place, while a Technical Meeting is held every week. Summaries of the main discussed items are reported to the bi-weekly General Meeting, attended by the whole group.

Whenever a decision has to be taken, a dedicated meeting of the Steering Committee is organized. After a discussion, the decision is taken by simple majority voting and reported to the Collaboration.

Physics WP1		Analysis WP2		Simulation WP3		Detector WP4		Services WP5		R&D WP6		Management WP7	
Elisabetta Baracchini		Emanuele Di Marco		Giulia d'Imperio		Giovanni Mazzitelli		Francesco Renga		Davide Pinci		Elisabetta Baracchini Giovanni Mazzitelli Davide Pinci	
Task	Coordinator	Task	Coordinator	Task	Coordinator	Task	Coordinator	Task	Coordinator	Task	Coordinator	Task	Coordinator
Dark Matter	G. Dho	Reconstruction Development	E. di Marco	Prototypes with GEANT	G. d'Imperio	Design	S. Tomassini	DAQ	A. Messina	ECO-GAS studies	D. Piccolo	INFN Responsible	D. Pinci
Solar Neutrinos	S. Torelli	Online-Offline software integration	G. Mazzitelli	Nuclear interactions with SRIM	F. di Giambattista	Integration	G. Mazzitelli	Trigger	H. Lima	Negative Ions	E. Baracchini	Technical Coordination	G. Mazzitelli
Super Nova DM	E. Baracchini	Data Analysis	E. di Marco	Gas properties with Garfield	D. Pinci	CMOS sensor	R. Nobrega	HV	F. Renga	Gas Mixtures	F. Amaro	Pubblications and Conferences	G. Maccarrone
Sensitivities and discovery potential	G. Dho	Software Maintenance	E. di Marco	Sensor performance	R. Nobrega	GEM	L. Benussi	Gas System and Slow Control	F. Renga	Field Cage	G. Mazzitelli	International Collaborations	E. Baracchini
Migdal	A. Messina	Infrastructures	G. Mazzitelli	Integration	F. Petrucci	Performance Studies	D. Pinci	Gas Purification	R. Gregorio	Gas Luminescence	D. Pinci	Safety and Environment	G. Mazzitelli
LNGS Neutron Flux	F. di Giambattista			Infrastructures	G. Mazzitelli	Light Sensors	F. Iacoangeli	Calibration	G. Cavoto	Alternative MPGD	E. Baracchini	Call Applications	E. Baracchini
								Storage and Networks	G. Mazzitelli				

Table 8.2: Working Packages (WP) and WP leaders of the CYGNO/INITIUM project

8.2. Work Packages Description

The project activities are divided in 7 Working Packages (WP), with WP leader defined.

- WP1 Physics, WP leader Prof. E. Baracchini GSSI, is in charge of studying the discovery potential and application of the project. The expected deliverable by the end of PHASE 1 is to define the physics goals expected for dark matter search and neutrino astronomy for PHASE 2, based on the next physics scenario and the results achieved in PHASE 1. Two milestones are fixed before the final deliverable decisive for writing the PHASE 2 TDR:
    - evaluating the feasibility of solar neutrino measurement (M1.1)
    - evaluating the dark matter sensitivity expected (M1.2)
    - define the physical parameter space for PHASE 2 (D.1.1)
- WP2 Data Analysis, Dr. E. Di Marco INFN-ROMA1. The WP is in charge of developing reconstruction software and analyzing data. The WP will exploit the experience of LIME project and have to:
    - define process to achieve a 3D reconstruction of events and identify of NR and ER candidates to reject background v0 (M2.1)
    - define process to achieve a 3D reconstruction of events and identify of NR and ER candidates to reject background v1 multi camera (M2.2)
    - define procedure to analyze data and characterize the detector performance (D2.2)
- WP3 Detector Simulation, Dr. G. D'Imperio INFN-ROMA1. The WP is in charge to develop fast and full simulation of the detector background and to evaluate systematics and uncertainty of detection resolution, efficiency, discrimination, directionality, ecc, ecc.. The WP can exploit the results of LIME detector by validating the simulation that should be fully scaled and applied to PHASE 2 expected results:
    - validate Montecarlo simulation from the PHASE 0 results (M3.1)

  - implement final Montecarlo for PHASE 1 based on the executive detector layout (M3.2)
  - elaborate the estimation for PHASE 2 (D3.1)
- WP4 Detector Design and Construction, Dr. G. Mazzitelli INFN-LNF, the WP is in charge of the design, construction and implementation of the detector, the shielding and infrastructures. It is also in charge to coordinate installation and maintenance activities and to ensure the application of safety and environmental regulations. The WP is formed mainly by engineers, designers and experienced technicians. The Work Plan foreseen to cover the implementation of TDR chapter 6 to 9 the following milestone and deliverables
  - executive layout of the area and its infrastructure (M4.1)
  - executive layout of the detector (M4.2)
  - procurements of components (M4.3)
  - infrastructure installation (D4.1)
  - detector installation, gas system, electronics, computing, ecc. (D4.2)
  - commissioning and calibration (M4.4)
  - decommissioning (D4.3)
- WP5 Auxiliary Services, Dr. F. Renga INFN-ROMA1. The WP is in charge of all Axillary System (6.3-6.7): Gas System, HV and LV, DAQ and computing. All Hardware of those systems has been purchased for PHASE 0 and is under test at LNGS as well as the software needed to control equipment and acquire data.
  - validating gas system (included purification and recycle) (D5.1)
  - validating DAQ, slow controls and data quality monitor v0 (M5.2)
  - validating DAQ multi camera and data quality monitor v1 (D5.2)
- WP6 Research and Development , Dr. Davide Pinci INFN-ROMA1. The WP is in charge of the development ongoing for PHASE 1 (chapter 3) and the study needed to enhance the performance for PHASE 2 (chapter 4)
  - validating large GEM (M6.1)
  - validating low radioactivity field cage component (D6.1)
  - validating large sensors and low radioactivity lens (D6.2)
  - validating R&D for PHASE 2 (D6.3)
- WP7 Management, WP Leaders Prof E. Baracchini and Dr. D. Pinci, is in charge of the management of the project and is aided by Dr. G. Mazzitelli as Technical Coordinator as described in 8.1. The WP in addition to the management of the project have to respond to the milestones and deliverables required by the PAQ of INFN[65] and the ERC INITIUM that fix the plan:
  - ERC-FRP3, 54 month report (M7.1) Aug 2023,
  - ERC-FRP4, 72 month report (M7.2) Feb 2025,

[65] chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://web.infn.it/csn2/images/Files/Regolamenti/INFN-CSN2-QA-101-10.pdf

- CSN2 Progress Report (M7.3-7) July every year
- ERC-SRP2 72 month report foresee for Feb 2025 (D7.1)
- CSN2 Final Report (D7.2).

Moreover, the collaboration, following the main INFN guidelines concerning the implementation of the project and PAQ requirements, have already started the migration of all the project to CATIA 3D EXPERIENCE, a tool able to manage and archive design, construction and implementation of the whole project.

8.3. GANTT

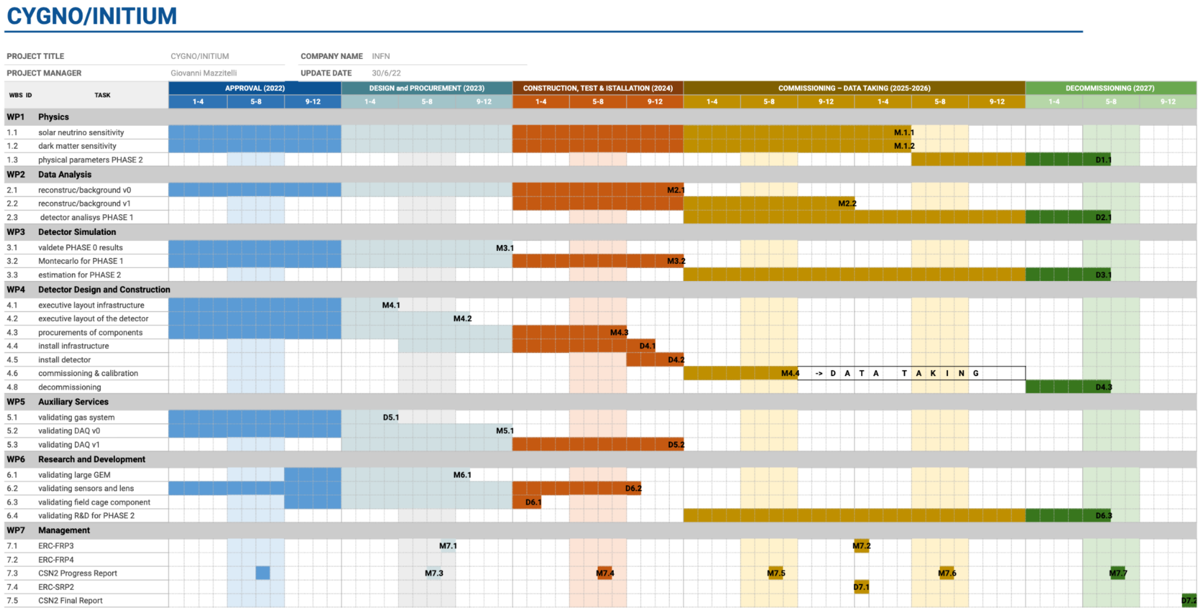
The project is expected to last 5 years starting from the time of approval by the CSN2 and LNGS foreseen for Sep 2022. In the following we report a summary of the plan, milestones and deliverables in a condensed GANTT chart. The reported plan starts before the approval because many tasks and milestones of the project are actually under development and tests in PHASE 0, e.g. all the auxiliary systems, analysis, physics evaluation, part of the R&D, preliminary design, ecc, ecc. An accurate plan is under definition with CATIA 3D EXPERIENCE, devoted to the executive design, construction, installation, maintenance and decommissioning of the detector.

The first year is dedicated to finalizing the design, firstly of the infrastructure, and the R&D for PHASE 1 partially connected to final detector design. Executive designs of the infrastructure and detector components left part to purchase are foreseen in one year from the approval, that based on our experience with PHASE 0 is appropriate. Then another year is foreseen for the detector construction (TPC, GEM, cathode, camera, etc) that will be assembled in the clean room at LNF and then, when tested, delivered for final installation at LNGS (as already done with LIME). This task will be executed in parallel with the installation of infrastructure and service at LNGS.

Then, after a preliminary setup with only the copper shielding installed the real data tacking will start lasting for 12-16 months. Finally in 2027 the detector decommissioning it's expected.

Although the full data taking and the decommissioning could be realistically compressed, two years of commissioning and operation, plus one years of decommissioning has been schedule in order to:

- absorb any possible delay of the design, construction and installation, that are planed based on normal national and international condition due to availability of materials (pandemia, war, ecc)
- been able to understand and modify detectors part during data taking because of unexpected background



summary of the Gantt, dynamically updated[66]

The Collaboration consists of more than 20 FTE, with a large participation of experts from permanent staff (from INFN and other institution), more than 5 PhD students with thesis about physics, technique and implementation of the analysis and daq/controls of the project, and engineering, designer and technicians (2.5 FTE) allocated on the project ensuring the efforts necessary to execute the project activities. The team, in the evaluation of time planning and effort needed, can exploit the successful work done for LIME installation.

8.4. Risk Assessment

Following the previous paragraph we develop the following project risk assessment and contingency plan that take into account accidental events that can occur for installation and construction of the infrastructure and the detector and the fosenable reason of fault of the project from the technical/scientific point of view:

- Possible delay reaching the deliverable D1.1 could come from lack of manpower of people working on this WP. Actually the participation of GSSI and university at international level ensure that this risk is very low and in any way affecting only PHASE 2 that is not the objective of this TDR.
- Possible delay reaching the deliverable D2.1 could come from lack of manpower of peoples on this WP. Actually in the critical phase of data analysis, many physicists today addressed to other tasks can converge on this WP and moreover the collaboration can ask project estition without cost to reach the deliverable.

[66] https://docs.google.com/spreadsheets/d/1hoM_vY4y_PAfyZEkFKgW1qouPJ2JDfJ78x_eBrTiJhw/

- Possible delay reaching the deliverable D3.1 could come from lack of manpower of peoples on this WP. Actually in the critical phase of simulation, many physicists today addressed other tasks that can converge on this WP. This risk is very low and is anyway affecting only the PHASE 2 that is not the objective of this TDR.
- Possible delay reaching the deliverable D4.1 could arise from the difficulty of obtaining offers from companies and/or sending supplies. Due to the national and international situation of commodities, this risk is not irrelevant and the impact would be high. The only way to mitigate this risk is delay the time schedule to the detriment of the technical/scientific programme and/or ask for delay to CSN2/LNGS. This should not increase the core cost (economic inflation excluded) a minor expense on running cost.
- Possible delay reaching the deliverable D4.2 could arise from the difficulty of obtaining offers from companies and/or sending supplies. The experience gained in PHASE 0, allowing us to create a list of companies able to realize detector components, configures this event as very unlikely. Moreover, part of the design came from the outcomes of the WP6 (see below) that could affect the real detector design only due the D6.1 failure that is very unlikely. Anyhow, as for previou deliverable, The only way to mitigate this risk is delay the time schedule to the detriment of the technical/scientific programme and/or ask for delay to CSN2/LNGS. This should not increase the core cost (economic inflation excluded) a minor expense on running cost.
- Possible delay reaching the deliverable D4.3 could arise from previous issue avaluted in general at the decommission phase very unlucky and and also the impact to the project is very low. Anyhow the only way to mitigate this event is to ask for delay to CSN2/LNGS.
- Detector component faults - the detector components are very simple and inexpensive: the most critical part could be the vessel made of PMMA, that has to be gas tight (see chapter 4), and could be damaged by accidental bumps or by over/under pressure operation. Make a new one takes 2/3 month and 30ke creating a small delay and impact on the project; the filed cage cost about 5ke and 1 month to substitute with a new one, we plan to have materials spare; the cathode cost about 10ke and 1 month to substitute with a new one, we plan to have materials spare; The GEM costs about 1 ke and 10 days to substitute with a new one, we plan to have materials spare. In case of malfunction or damage of one of the 4 cameras we lost 1/4 of the sensitivity and anyway we plan to have a spare part or use an old model as spare temporary, the camera cost 32ke and the substitution can be made in one day; in view of this we don't expect critical issues related to the detector components.
- The gas system is already 90% commissioned and tested in PHASE 0, final tests, including the recycling of gas mixture, are foreseen before Sep 2022. Chemical filters are under test at LNF and isotope traps at Sheffield (UK)

university. Than the two purification subsystem have to be installed and tested on LIME; the probability of fails is then really very unlikely and it's really not affecting any time schedule; a delay of the milestone is expected to be enough to cover any possible faults of D5.1

- The version v0 of the DAQ is under test at LIME, further implementations are foreseen to minimize deadtime and improve the trigger threshold sensitivity actually moving to a triggerless configuration. The plans are clear and under development. The multi camera DAQ v1 requires only the design and implementation of multi buffer memory and the optimization of the code under completion for PHASE 0; all the hardware (cameras, and DAQ server, see 7.5 for specification) need are available and a time delay is not critical for project completion; in conclusion although the impact of D5.2 could be very high the the probability it's really very low.
- Auxiliary services faults: all che auxiliary system, cathode power supply, GEM power supply, DAQ electronics, DAQ servers, ecc have spare parts already acquired by the collaboration. Actually at LNF there is a copy one to one of all the subsystems running underground at LNGS and in HdM at LNGS there is a second copy (except for the DAQ server) with the same electronics and power supplies. The only exception is the gas system. The gas system up to now is under warranty, but we already discussed with the Air Liquide a maintenance service. In view of this we don't expect critical issues related to the auxiliary services.
- Data Storage and Preservation faults: data are acquired locally by the DAQ on 8TB (about 2 months of buffer) disk in RAID 0, when a run is closed it's copied on the INFN Cloud S3 storage, where then are reconstructed, analyzed and backup on TAPE; the time of stage of an run only locally is of order 10 minutes. The network unavailability (< 0.01%) and local storage faults are very unlikely and preserved by RAID redundancy. Local storage could be replaced by available spares in a very short time (<one day). Moreover, data Preservation and Disaster Recovery are guaranteed by the use of INFN Cloud storage and backup system (see specification of CNAF infrastructure); although the impact of losing data could be important, the probability to lose a consistent amount of data it's negligible. Moreover, because of data related to a technical demonstrator and not to physical expectation we can evaluate the loss of data of low impact.
- Possible issues in the completion of D6.1 can have an important impact on the project, because these are connected to the core detector design, actually the activities exploit the results of other experiments that are part of the CYGNO collaboration, ensuring the technical expectation. Moreover, possible companies that can provide the hardware have been already screened and have delivered preliminary estimation. Finally our colleagues have some spares materials that could be used with a minimal effort to review parts of the mechanics without affecting the detector performance.

- Although D6.2 is a critical part of the internal background expectation and has to be implemented for the project, any delay in this deliverable it's not really crucial because cameras and lenses can be changed in any time of the data taking (they are external to the detector core part). Moreover, contacts with companies to design low radioactivity lenses and with Hamamatsu to understand the camera radioactivity, have already started strongly reducing possible delay in the deliverable completion.
- Finally, the deliverable D6.3 it's very high risk because it includes subsets of R&D very challenging to enhance the performance of PHASE 2; because of those R&D are related to PHASE 2 that is not the objectives of this TDR their impact it's foreseen very low on PHASE 1. In this case the contingency plan is to sturdy different approach to enhance sensitivity the could come from the international community working on gaseous TCP for rare events

Risk	Probability	Impact	Contingency
delay in the parameter space for PHASE 2 (D1.1)	low	low	enforce teams by means of GSSI/university personnel
delay in data analysis (D2.1)	low	medium	enforce teams with people coming from other WPs, ask for extension to CSN2 to elaborate data
delay in estimation for PHASE 2 (D3.1)	low	low	enforce teams with people coming from other WPs
delay in infrastructure installation (D4.1)	medium	hight	delay the time schedule to the detriment of the technical/scientific programme; ask for delay to CSN2/LNGS
delay in detector installation (D4.2)	low	hight	delay the time schedule to the detriment of the technical/scientific programme; ask for delay to CSN2/LNGS
delay in decommissioning (D4.3)	very low	low	ask for extension to CSN2/LNGS
detector components faults	low	low	replace with spares part

delay in gas system (D5.1)	very low	very low	start commissioning without radio and chemical purification; not critical for the project
delay in delivery DAQ v1 (D5.2)	very low	low	delay in the achievement of the deliverable
auxiliary services faults	low	low	replace with spares part or use of support services
data storage and preservation	very low	low	enforce the usage of INFN IT services; use spares for local buffer
delay in field cage component (D6.1)	very low	medium	adapt the mechanics to accommodate available spares
delay in large sensors lens (D6.2)	very low	medium	use standard cameras and lens until available on the market
delay in R&D for PHASE 2 (D6.3)	high	very low	sturdy different approach to enhance sensitivity

This risk assessment does not include catastrophic events like pandemias, war, earthquakes, floods and fires that, apart from safety issues addressed in previous chapter, can forbid the access to LNGS or strongly compromise the availability of economical resources for the project completion. Before 2020 we were not envisaging such kinds of possibilities, but given recent developments in the world we can not bet on that. We trust in the mercy of nature and the goodness of mankind!

Anyway the national and international economic conditions and growth of commodities prices require a strong contingency plan that we can only amortize through a delay on the project and a contingency on the budget.

8.5. Available funds in July 2022 to cover CYGNO-04 Core Cost

Currently, from the ERC fundings, to cover the core costs of PHASE 1, there are 157 k€ available at INFN and 508.2 k€ at GSSI (139.6 k€ NDR) for a total of 665 k€

Unit	Available funds (k€)
INFN - RM1	128

INFN - LNF	29
GSSI	508
Total	**665**

8.6. Cost Breakdown Structure (CBS)

A CBS has been developed to evaluate the core cost of the project needed to cover the infrastructures (civil work, control room, gas box, ecc) and subsystems (gas system, computing, ecc), safety (fire, gas monitor, ecc) and detector components (GEM, electronics, camera, TPC, ecc). Costs of R&D for PHASE 1 and 2, consumable (gas and gas disposal services, gas system maintenance ecc), supports to transport are not included. All spare parts of the eltronics, DAQ and power supplies have been already acquired, anyway a possible upgrade would be possible during the project lifetime.

Whereas it has been possible, costs have been estimated with direct quotations provided by the companies.

The collaboration also expects the review of the LNGS services to better estimate costs of the infrastructure and services LNGS services for TDR version 2.0 foreseen in Sep 2022 with the LNGS Services. The costs for these items introduced in the CBS are based on the experience made with LIME where the area has been completely renovated. Hall F it's already equipped with electrical power distributions, air conditioning system ecc. and we expect that the introduced values are actually upper limits to real costs.

Ref.	WBS NUMBER							DESCRIPTION	UNIT	QUANTITY AT WBS LEVEL							TOTAL		COMPONENT COST AT WBS LEVEL (kEuro)							CORE COST already covered	CORE COST to be covered	NOTES
	1	2	3	4	5	6	7			1	2	3	4	5	6	7	(kEuro)	Unit Cost	7	6	5	4	3	2	1			
GM	1							CYGNO/INITIUM Project	EACH	1															876.75		643.45	
GM	1	1						DETECTOR	EACH		1													752.75				
GM	1	1	1					TPC	EACH			1											268.20					
GM	1	1	1	1				GAS VOLUME	EACH				1									33.20						
ST	1	1	1	1	1			PMMA gas vessel	EACH					1				30.00			30.00							estimation based on PALAZZI quotation
ST	1	1	1	1	2			PMMA cameras cones	EACH					4				0.30			1.20							estimation based on PALAZZI quotation
ST	1	1	1	1	3			PMMA GEM frame holder	EACH					2				1.00			2.00							LNF workshop estimation based on LIME costs
DP	1	1	1	2				READOUT	EACH					4								190.00						
LB	1	1	1	2	1			GEM foil	EACH						2			3.00		6.00								quotation by CERN
CC	1	1	1	2	2			GEM frame	EACH						2			0.20		0.40								quotation by CERN
LB	1	1	1	2	3			GEM holder	EACH						3			0.20		0.60								quotation by CERN
LB	1	1	1	2	4			GEM connectors	SET						2			0.20		0.40								quotation by CERN
DP	1	1	1	2	5			Cameras	EACH						1			32.00		32.00								estimation based on Hamamatsu quotation
DP	1	1	1	2	6			Optics	SET						1			2.20		2.20								estimation based on snheider quotatiom
RO	1	1	1	2	7			Cameras holedrs mechanics	SET						1			3.00		3.00								
DP	1	1	1	2	9			PMTs	EACH						3			0.80		2.40						4.8		estimation based on Hamamatsu quotation (partialy purchased)
DP	1	1	1	2	10			Cable & connectors	SET						1			0.50		0.50								
	1	1	1	3				CATHODE	EACH				1									17.00						
	1	1	1	3	1			Feed through	SET					1				1.00			1.00							
CC	1	1	1	3	2			Cathode frame	SET					1				1.00			1.00							
	1	1	1	3	3			Cathode foil	SET					1				15.00			15.00							quotation based on experince of DRIFT collaborator
	1	1	1	4				FIELD CAGE	EACH				1									13.00						
CC	1	1	1	4	1			Cu rings	EACH					100				0.10			10.00							quotation by ELTOS
	1	1	1	4	2			Resistors	EACH					100				0.01			1.00							quotation by RS for standard restori
CC	1	1	1	4	3			PMMA box	EACH					1				2.00			2.00							
RO	1	1	1	5				CALIBRATION SYSTEM	EACH					1								15.00						
	1	1	1	5	1			Calibration source	EACH					1				5.00			5.00					5.00		device purchased
RO	1	1	1	5	2			Mechanics	EACH					1				5.00			5.00							cost based on LIME experince
RO	1	1	1	5	3			Stepper motors	SET					1				5.00			5.00							cost based on LIME experince
	1	1	2					SHIELDING	EACH			1											281.05					
CC	1	1	2	1				Cu bricks	SET				9500					0.019				180.50						estimation based on CSN Carl Schreiber GmbH quotation
CC	1	1	2	2				Water tanks	SET				48					1.300				62.40						estimation based on MULDING quotation
CC	1	1	2	3				Frame (consumable/carpentry)	SET				1					20.000				20.00						cost based on LIME experince
CC	1	1	2	4				Politilene base	SET				3300					0.006				18.15						estimation based on ADVIPLAST quotation
	1	1	3					GAS SYSTEM	EACH			1											123.00					
	1	1	3	1				gas system	EACH				1					85.00				85.00				85.00		device purchased
	1	1	3	2				gas distribution	SET				1					5.00				5.00						
	1	1	3	3				gas system mechanics	SET				1					5.00				5.00						
	1	1	3	4				gas contingency (consumable)	SET				1					5.00				5.00						
	1	1	3	5				gas purification system	SET				1					10.00				10.00				10.00		device purchased
	1	1	3	6				CF4 analyzer	SET				1					13.00				13.00				13.00		device purchased
	1	1	4					HV SYSTEM	EACH			1											35.00			35.00		device purchased
	1	1	4	1				CAEN LV crate	SET				2					5.00				10.00						
	1	1	4	1				CAEN LV board	SET				2					5.00				10.00						
	1	1	4	1				ISEG HV PS	SET				3					5.00				15.00						
	1	1	5					DAQ & SLOW CONTROLS	EACH			1											45.50			45.50		device purchased
	1	1	5	1				server	SET				2					10.00				20.00						
	1	1	5	2				aux pc	SET				4					1.00				4.00						
	1	1	5	3				monitors	SET				5					0.30				1.50						
	1	1	5	3				aux readout board	SET				1					5.00				5.00						
	1	1	5	4				aux readout sensor	SET				1					5.00				5.00						
	1	1	5	5				trigger system	SET				1					5.00				5.00						
	1	1	5	6				cables & connectors	SET				1					5.00				5.00						
	1	2						COMPRESSED AIR SYSTEM	EACH		1													12.00				
	1	2	1					air distribution system	SET			1						5.00					5.00			5.00		device purchased
	1	2	2					air filter	SET			1						2.00					2.00			2.00		device purchased
	1	2	3					tubes & connectors	SET			1						5.00					5.00					
	1	3						ELECTRIC SERVICES	EACH		1													15.00				cost based on LIME experince to be cofirm by LNGS services
	1	3	1					power distribution system	SET			1						5.00					5.00					
	1	3	2					cables & connectors	SET			1						5.00					5.00					
	1	3	3					UPS	SET			1						5.00					5.00					
	1	4						NETWORK DISTRIBUTION	EACH		1													13.00		13.00		device purchased
	1	4	1					network distribution system	SET			1						5.00					5.00					
	1	4	1					switch	SET			1						1.00					1.00					
	1	4	2					router	SET			1						5.00					5.00					
	1	4	3					cables & connectors	SET			1						2.00					2.00					
	1	5	4					COOLING and CONDITIONING	EACH		1													19.00				
	1	5	1					Conditioning	SET			1						10.00					10.00					cost based on LIME experince to be cofirm by LNGS services
	1	5	2					Cameras chiller	SET			1						5.00					5.00			5.00		device purchased
	1	5	3					PMTs flow system	SET			1						2.00					2.00					
	1	5	4					Cables & connectors	SET			1						2.00					2.00					
	1	6						SAFETY (PRA-VIA)	EACH		1													30.00				
	1	6	1					PRA	SET			1						2.50					2.50			2.50		device purchased
	1	6	2					VIA	SET			1						2.50					2.50			2.50		device purchased
	1	6	3					fire detection system	SET			1						10.00					10.00					cost based on LIME experince to be cofirm by LNGS services
	1	6	4					gas monitor system	SET			1						15.00					15.00					cost based on LIME experince to be cofirm by LNGS services
	1	7						CIVIL WORK	EACH		1													30.00				
	1	7	1					controll room container	SET			1						15.00					15.00					cost based on LNGS services experince for NEWS
								gas system box										10.00										cost based on LNGS services experince for NEWS
	1	7	2					water tub	SET			1						15.00					15.00					cost based on LIME experince to be cofirm by LNGS services
	1	8						DESIGN AND DOCUMENTATION	EACH		1													5.00				
	1	8	1	1				software	SET			1						5.00					5.00			5.00		

screenshot of the CBS[67]

The core cost for the realization of CYGNO-04 is estimated to be 877 k€: of these, 233 k€ of equipments and spares have already been purchased, leaving a total of 643 k€ to be covered by the fundings illustrated in Sec. 8.5. In addition, 4500 kg of Copper bars (9000*100*10 mm) for a value of 90 k€ have been secured by the CYGNO collaboration from the decommissioning of the OPERA experiment. While this Copper is not at the level of radiopurity required for the internal part of the gamma shielding, simulation shows that it could still be successfully employed in the external layers without generating additional background in the active volume (since it would be shielded by the internal radio-pure Copper layers), creating a contingency budget for the project.

All costs do not include VAT in agreement with the ERC INITIUM EU project policy.

[67] https://docs.google.com/spreadsheets/d/1ldVnZN-t4iXgnNmQ8otjlN_2WeyrBTSeeFI_lVX8w14/

8.7. Budget Profile

Starting from 2023 material procurement for the detector will start. In the next 2 years and half, all materials needed will be procured and relative core costs funded by the INITIUM project.

After the construction, installation and commissioning phases, the collaboration activity will be focused on the running of the experiment, the data acquisition and the analysis.

The INFN-CSN2 funds will be needed to run the experiment and to carry on the R&D that can be exploited to upgrade the PHASE 1 performance and to evaluate possible solutions for PHASE 2.

Based on the experience gained with the on-going R&D and the construction, commissioning and running of LIME, we expect:

- 10 k€/year of gas bottles for LIME;
- 15 k€/year of gas bottles for CYGNO-04;
- 15 k€/year of gas recovery for LIME;
- 20 k€/year of gas recover for CYGNO-04;
- 10-20 k€/year of consumable for detector maintenance or construction;
- 50 k€/year of R&D before CYGNO-04 installation and 20/30 k€/year for the last R&Ds toward PHASE 2;
- 30 k€/year of travels for the technical operation (installation, commissioning and decommissioning);
- 20 k€/year of travels for the data acquisition shifts;

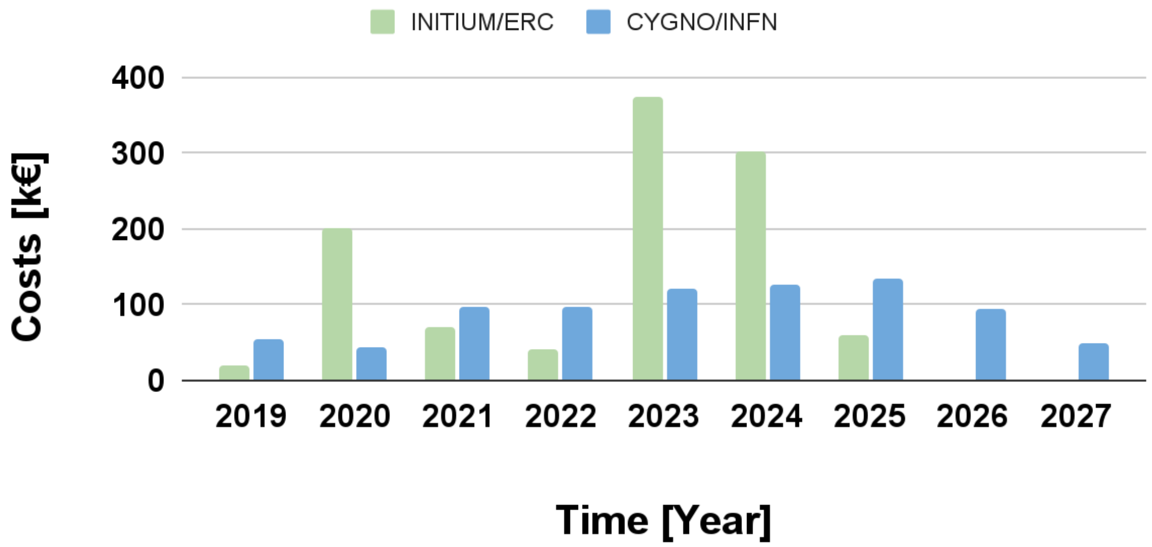
Details on costs foreseen for INFN-CSN2 are reported in the following table

INFN - CSN2	2023	2024	2025	2026	2027
Gas Bottle	10	5	15	15	0
Gas Recovery	10	0	20	20	0
Consumables	10	20	20	10	20
R&D	50	50	30	20	0
Tot w/o Travels (k€)	80	75	85	65	20
Travels - Shift	30	20	20	30	0
Travels - Installation	10	30	30	0	30
Tot Travels (k€)	40	50	50	30	30
Tot (k€)	**120**	**125**	**135**	**95**	**50**

A summary of the costs per year already covered and foreseen for the next 5 years for the ERC funds and the INFN-CSN2 is presented in the table below.

Year	INITIUM/ERC	CYGNO/INFN
2019	20	54
2020	201	44
2021	71	96
2022	40	96
2023	374	120
2024	302	125
2025	60	135
2026	0	95
2027	0	50
Tot 23-27	736	525
Tot	**1068**	**815**

The profile of the funds per year used in the past and foreseen in the future are reported in the plot below.

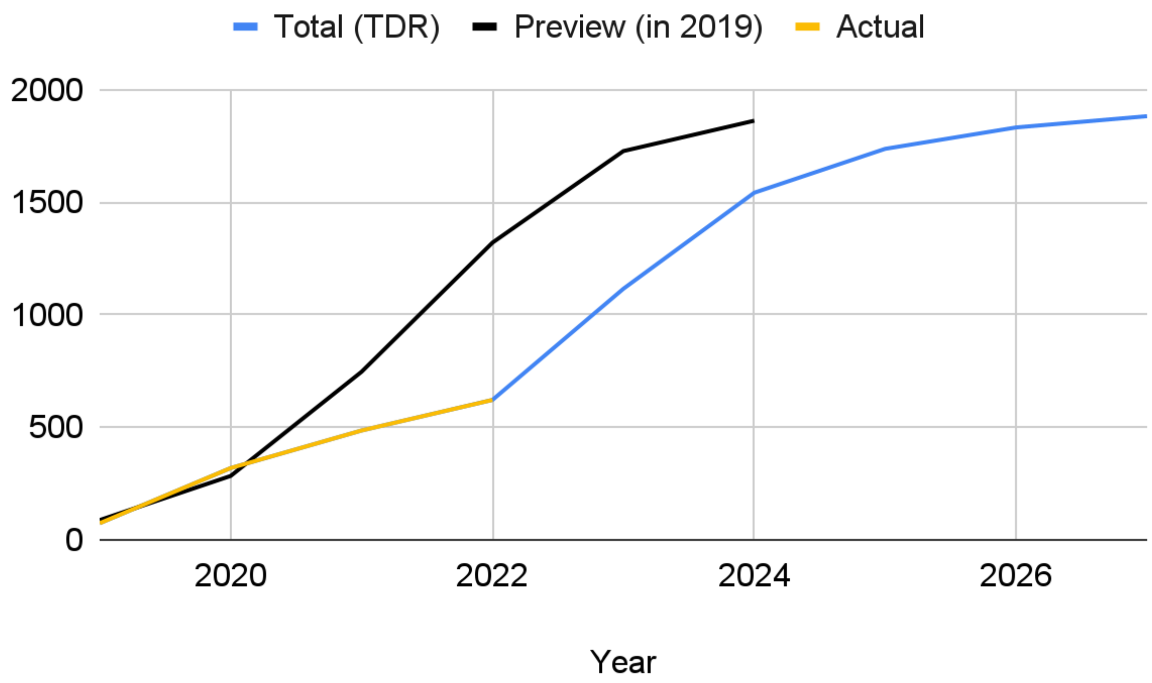


budget profile by year

The integral of the total costs sustained is shown in the following graph together with the expenditure estimated by the Collaboration in 2020 and reported in the following progress report[68]. Even if one year shift is well visible mainly due to the

[68]https://docs.google.com/document/d/1G3OV1UpqWWV4HevJzu-jzzCJqL_R96MYbFIN8tqJStA/edit?usp=sharing

delayed setup and run of the LIME prototype in the underground site, due to delays in site preparation related to the pandemic situation, the evaluation of the total cost for the project is confirmed.



EVM plot for CYGNO/INITIUM