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Letter of Intent for the PTOLEMY project

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Contents

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Abstract

This document outlines the **activities** involved in drafting the **Conceptual Design Report** (CDR) for the PTOLEMY demonstrator, which is part of a broader program aimed at the direct detection of the Cosmological Neutrino Background (CNB) using an atomic tritium target: achieving this would offer a unique glimpse into the Universe's first second—when the CNB decoupled—fulfilling a long-standing aspiration in the field of cosmology. Due to the extremely high energy resolution required to distinguish electrons emitted beyond the tritium beta-decay endpoint from those produced by beta decays, the **measurement of the neutrino mass** emerges as a necessary intermediate milestone. In view of this, we describe below the 2-years activity plan (**Phase-0**) needed to write a CDR that will describe the Phase-1 of the project, devoted to the direct measurement of the neutrino mass. The PTOLEMY collaboration is currently focusing on the demonstration of the technique based on an innovative compact dynamical electromagnetic filter. This is meant to be able to select the endpoint of the beta-electron spectrum from tritium nuclei by finely adjusting an electric field in presence of a static non-uniform magnetic field. Exploiting the custom magnet already designed and being manufactured and on the basis of the R&D developed in the last years, the PTOLEMY collaboration proposes in the Phase-0 to demonstrate the filtering concept and at the same time finalize the design of the detector for the neutrino mass measurement integrating various systems (a graphene-suspended tritium target, a cyclotron radiation detector and a final electron detector). **At the end of this 2 year** program we anticipate that PTOLEMY might be able to **propose** a measurement of the absolute neutrino mass from a fit to the tritium endpoint spectrum with a 150 meV sensitivity employing a tritium mass up to 1-10 μg.

1 Introduction

The PTOLEMY collaboration believes that the project is now at a turning point.
Over the past few years, significant experimental R&D efforts have been undertaken, particularly within INFN groups supported by CNS V, as well as by INRIM, Princeton University, the Radboud University and University of Amsterdam. These efforts have led to promising results across a range of experimental techniques. Therefore we now want to move towards an experiment aimed at measuring the absolute neutrino mass by analyzing the endpoint of the electron energy spectrum resulting from the β decay of tritium atoms. This step is essential to demonstrate that the innovative technologies developed so far can be further advanced and potentially scaled-up in a future experiment targeting the detection of the cosmic neutrino background. This document summarizes the current status of the PTOLEMY project, highlighting its strengths, and acknowledging its present limitations. Therefore, given this status, we believe that the proposed path forward must involve a staged approach:

- **Phase-0**, focused on the complete experimental validation of the concept and the development of a conceptual design;
- **Phase-1**, in which a fully operational detector capable of measuring the tritium endpoint will be constructed and operated.

The key **innovation** of the PTOLEMY project lies in a **compact electromagnetic filter**, whose operating principle was first described in [1]. A first realistic design of this filter, along with a data/Monte Carlo comparison for an exponentially decreasing magnetic field, was presented in [2]. The sensitivity of an experiment with a β electron energy resolution of 50 meV to neutrino physics was then discussed in [3].
This document describes the Phase-0 of the project.

Neutrino mass Sensitivity estimate

In Fig. 1 sensitivity graphs are reported for a Phase-1 experiment. The smallest instrumented mass considered corresponds to a graphene substrate of 7x7 cm^2, loaded with approximately 1 μg of tritium, yielding nearly $5{\times}10^{16}$ decay events over three years of data taking. We assume an experimental efficiency of 50% obtaining approximately 10^7 events in a region interest of about 10 eV near tritium endpoint. No significant effort has been spent so far to include the effect of possible background events.
Given that the most stringent current experimental upper limit on the neutrino mass — set by the KATRIN experiment [4] — is 450 meV (at 90% C.L.), **any future experiment** seeking to improve upon this limit must address a **major challenge**: *understanding how the nuclear physics of beta decay is influenced by condensed matter effects, which operate at comparable energy scales.* To this end, the collaboration has also undertaken a significant **theoretical effort** to study the interaction of tritium atoms chemically adsorbed onto monolayer of graphene, which is the baseline option of the PTOLEMY experiment for the target. The first results of this work were recently published [5] and are reflected in the sensitivity projections shown in Fig. 1. Previously the collaboration examined the impact of zero-point motion [6, 7, 8] on the beta spectrum in [9]. In Fig. 1, we show the 90% C.L. exclusion sensitivity and the 3σ C.L. discovery sensitivity obtained through a Profile Likelihood analysis. A noteworthy aspect of the plots in Figure 1 is that, for each value of instrumented mass, a band is shown. This bands are obtained by considering different theoretical models, developed to account for the fast nuclear time scale within the slow response of the solid state substrate. While further theoretical studies are needed, and more accurate predictions are possible, we believe that the bands presented here provide a conservative upper limit on the achievable sensitivity, including a conservative estimate of theory uncertainties. When interpreting these curves, it is important to remember that achieving this level of sensitivity requires the successful completion of the technological program described in this document, a period of construction of the PTOLEMY demonstrator as well as at least three years of data taking with the full demonstrator. This program of construction and operation is **not** within the scope of the current document but will be addressed in the CDR.

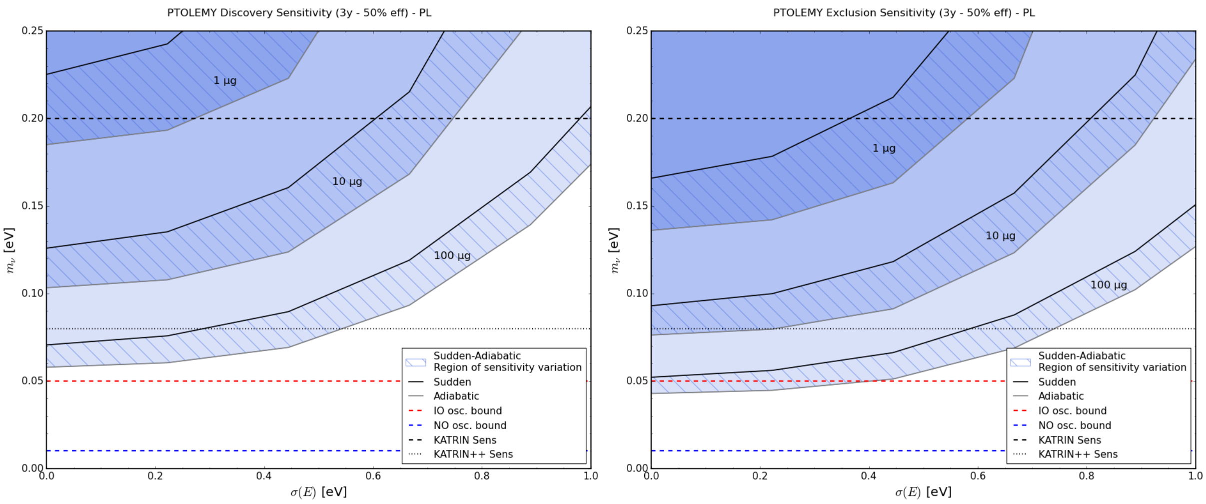

Figure 1: Discovery and exclusion sensitivity to neutrino mass as a function of the energy resolution, ranging from 50 meV to 1 eV, for different instrumented tritium masses: 1, 10 and 100 μg, respectively, assuming a 50% experimental efficiency. In both plots, the dashed bands depict the uncertainty due to different theoretical models adopted to describe the beta-decay endpoint. The Figure also reports the projected KATRIN sensitivity at the end of the data taking (*dashed black*), along with the inverted (*red*) and normal (*blue*) ordering oscillation bounds for the effective neutrino mass.

2 Scientific case

2.1 PTOLEMY concept in short

The PTOLEMY concept is based on exploiting a magnetic field with an exponential gradient to steer electrons spiralling along magnetic field lines. This is achieved by a magnetic force acting on the orbital magnetic moment of the electrons and redirecting the electrons along the $\vec{\nabla} B \times \vec{B}$ direction. In the same spatial region where this magnetic field gradient is present, an opposing electric field with a tuned gradient is applied to decelerate electrons from their initial 18.6 keV energy (the endpoint of the tritium β decay spectrum) down to a few tens of eV. This configuration enables efficient filtering of unwanted lower energy electrons. A key advantage of this approach is that it can be implemented in a compact apparatus just a few meters in length, making it feasible to scale up the technology in the future. In the current PTOLEMY design, atomic tritium is bound to monolayer graphene sheets, which serve as an effective voltage reference and allow several micrograms of tritium to be stored on a surface area of just a few tens of cm^2. The magnetic field gradient is generated by shaping the fringe field of a high-field (1 T) dipole magnet using custom iron pole pieces. Within this high-field region, an antenna detects the cyclotron radiation emitted by the electrons in the radio-frequency range ($\sim$27 GHz), enabling both time-tagging of the electrons and a coarse measurement of their momentum. This trigger information is used to dynamically and precisely adjust the electric field in the filter for each electron of interest. Finally, the residual kinetic energy of the filtered electron is measured using either a cryogenic micro-calorimeter or an electrostatic hemispherical analyzer. This final detection stage operates in a region of very low magnetic field, simplifying the detector's operation.

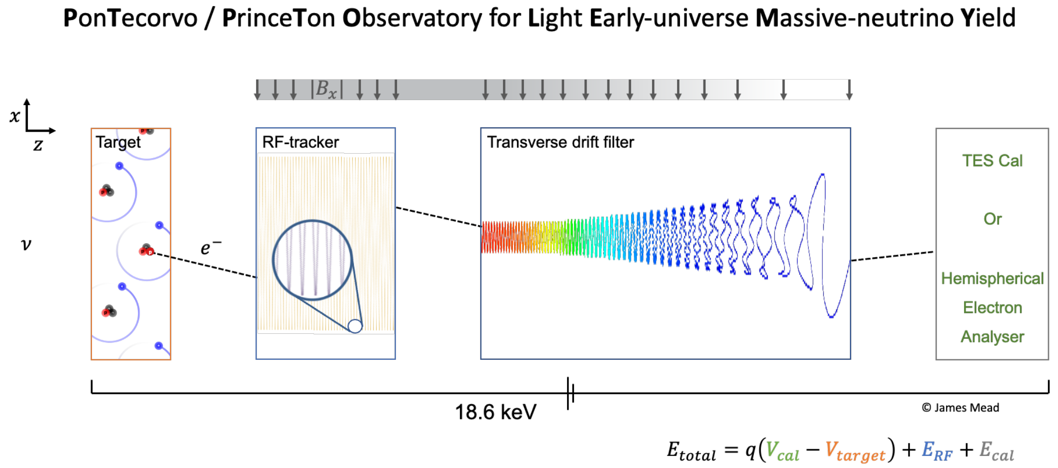

Figure 2: PTOLEMY detector block diagram showing its 4 main sections: the atomic tritium target, the RF-tracker which acts as a trigger and preselector providing rough mesurement of electron kinematic variables, the transverse drift filter which slows down the selected electrons to few tens of electronvolts, the residual electron energy measurement system.

The goal of the PTOLEMY demonstrator is to integrate and test all of these components:

1. The atomic tritium target source
2. The RF cyclotron radiation detector
3. The compact, dynamically tunable filter
4. The high energy resolution detector for the filtered electrons

2.2 State of the art

Before summarizing the status of the R&D activities ongoing in the framework of the PTOLEMY experimental effort we think it is instructive to look at the timeline of the knowledge evolution that this project has produced.

Timeline of knowledge advances in the PTOLEMY project

1. In 2017, the maximum graphene loading reached 40%. By 2024, the collaboration successfully achieved 100% loading by using hydrogen and deuterium [10, 11].
2. In 2016, the stability of the T bond was unknown. The current measurement, performed in vacuum with hydrogen, is now limited primarily by the duration of the observation, over 4 months [13], while it is expected to last much more.

3. In 2024, electron transmission through a single graphene layer was extensively measured for energies below 1 keV (in the 30–900 eV range) [12]. Transmission increases monotonically, approaching nearly 90% at 900 eV and a clear trend to rise at higher value is visible.

4. In 2024, a comprehensive theoretical study led to an unprecedented understanding of the characteristics of the bound state of T on a graphene substrate [5].

5. In 2024, a suitable experimental facility was selected that permits T loading.

6. In 2016, the use of a Transition Edge Sensor (TES) as an electron calorimeter was still a working hypothesis. The device is now undergoing experimental evaluation. Initial measurements in 2024 confirmed the technique's feasibility, achieving an energy resolution of 1 eV. Shortly thereafter, a resolution of 0.3 eV was attained on the full absorption peak of the electron.

7. In 2013, the Project 8 experiment demonstrated detection of radio-frequency emission from a single electron in a 1 T magnetic field. This technique was adopted by the PTOLEMY project. In the current PTOLEMY setup, electron signals are captured over a 50 μs timescale, allowing simultaneous extraction of kinematic variables — an improvement over the millisecond-scale signals in Project 8. This capability is key to implementing the PTOLEMY dynamic (triggered) filter.

8. In 2016, there was no clear strategy for selecting electrons within the region of interest amid high event rates, nor for enabling differential energy measurements. Today, the PTOLEMY project is guided by the theoretical framework of the dynamic filter, as detailed in two foundational papers published in [1, 2].

9. In 2016, no suitable magnetic field configuration was known that could accommodate a high-performance energy-measuring device at a zero magnetic field point. Now, a detailed magnetic field map with a saddle point at zero field has been developed—overcoming a critical limitation of the KATRIN project for the intergration of a high-resolution detector. The corresponding magnet has been designed and is currently under construction.

2.2.1 Tritium target

The technique to deposit atomic tritium on graphene has been thoroughly investigated by the Roma Sapienza and RomaTre groups during the last years with hydrogen and deuterium (avoiding therefore radio-safety issues). Very high coverage (close to one H atom per each C atom) has been reached in different laboratories by thermally cracking in vacuum the hydrogen molecules [10]. This was repeated with various type of nanostructured graphene (nanoporous graphene, mono-layer graphene, carbon nanotubes) with excellent and compatibile results [11]. Moreover, the characterization of graphene and hydrogenated graphene using microscopic and spectroscopic techniques is well established within the PTOLEMY collaboration. It must be noticed that this expertise is critical for advancing the understanding of condensed matter effects in the context of β decay. Measurements of graphene's transparency to low-energy electrons have been carried out within the collaboration using an innovative technique [12]. Currently, this method is being extended to higher electron energies relevant to the PTOLEMY project, supported by an INFN CNS5 young researcher grant awarded in 2024 [17]. A recent result achieved within the collaboration demonstrated that a hydrogenated monolayer graphene sample remains stable in vacuum for an extended period up to 4 months, which was the duration limit of the measurement [13]. This finding opens the possibility of applying the same technique to tritium handling, enabling the development of a solid atomic tritium target, as envisioned in the PTOLEMY concept. Currently, the technique for tritium deposition on graphene is under review by the UK Atomic Energy Authority (UKAEA), which is conducting a feasibility study with the PTOLEMY collaboration to obtain tritium from the AGHS (Active Gas Handling System, Culham, UK) and to transport it to other laboratories, such as INFN LNGS, above ground. It is important to note that the handling and storage of tritium absorbed on metal supports require a properly equipped laboratory. A functioning example of such a facility in Italy is the ENEA Frascati Neutron Generator site, which uses tritium absorbed in metal beds as target for the deuterium beam. ENEA personnel is joining the collaboration and has already been helping with the porting of the graphene hydrogenation technique to tritium.

2.2.2 RF radiation detection

Cyclotron Radiation Emission Spectroscopy (CRES) is a technique currently being developed primarily by the Project 8 collaboration to measure the total kinetic energy of beta electrons emitted from tritium decay. This measurement enables the reconstruction of the tritium beta decay spectrum near its endpoint, which is critical for determining the neutrino mass. The PTOLEMY collaboration has implemented a CRES setup at INFN LNGS to study cyclotron radiation in the radio-frequency range, specifically around 26 GHz, aiming at detecting CRES in a much shorter time than Project8 (50μ s instead of 1 ms). At INFN LNGS a sealed (gaseous) atomic krypton (Kr) radioactive source was used to produce 30 keV electrons, which were confined in an electron trap designed and constructed at INFN LNGS. This trap consists of specially shaped electrodes immersed in a 1 T small dipole magnetic field. The detection system includes a cryogenic low-noise amplifier (LNA) and a custom-built down-converter developed by the Nikhef group. Decays from Kr were successfully observed by analyzing the Fourier spectrum of the emitted RF radiation along with the corresponding power. From these measurements, both the energy of the electrons and their pitch angle relative to the magnetic field lines can be inferred. These capabilities form the foundation for the development of the PTOLEMY demonstrator's trigger system and its dynamic filter tuning.

2.2.3 High precision HV measurements

The INFN LNGS group has developed a high-voltage stability monitoring system with the primary objective of verifying the accuracy of the electrode reference voltage to within 0.5 ppm at approximately 20 kV. This system is based on a modular chain of high-precision reference diodes, read out by a field mill device housed within a climatic chamber. The best results achieved so far correspond to an electron energy resolution of 70 meV at the tritium endpoint, which translates to a voltage precision of $\frac{\Delta V}{V} = 3.8$ ppm. Ongoing work focuses on further improving the system's electromechanical stability and grounding. Additional techniques for monitoring high voltage at the desired precision level are currently being explored in collaboration with the Department of Astronautical, Electrical, and Energy Engineering at Sapienza University of Rome. Furthermore, the development of a fast-switching system for the dynamic filter is also under investigation. Prototype designs and tests are in progress, involving low-noise, high-voltage relays.

2.2.4 Detection of 100 eV electrons

Transition-edge sensors (TES) are advanced microcalorimeters capable of single-photon detection with exceptional energy resolution over a broad energy spectrum. These sensors absorb photons in an ultra-thin superconducting film, converting the photon energy into heat that induces a transition from the superconducting to the normal conducting state [19]. By measuring the electrical current during this transition, the INRIM group has demonstrated an energy resolution of 50 meV for photons of 0.8 eV. The INRIM, INFN Roma, and Roma Tre groups have also reported the first electron measurements using TES technology, achieving a Gaussian energy resolution between 0.8 eV and 1.8 eV for fully contained electrons in the 95–105 eV energy range [18]. Building on this result, very recent advancements have significantly improved electron containment within the TES, leading to a almost factor 4 enhancement in energy resolution. As an alternative to TES-based electron calorimetry, a hemispherical electron energy analyzer is being considered. This instrument is optimized for detecting low-energy electrons, down to 10 eV, and is widely used in synchrotron beamline experiments and condensed matter physics since many years. With the integration of a suitable electrostatic lens, the analyzer can accept a large portion of the electron phase space emerging from the filter. The exit position of the electron within the hemispheres is linearly correlated with its initial energy. Electron detection is typically performed using a multi-channel plate and delayed-line readout, achieving energy resolutions as fine as 10 meV at 10 eV. This system is currently being incorporated into the design of the PTOLEMY demonstrator. As a commercially available, room-temperature-operable device — unlike the cryogenic TES — it presents a practical solution for the final-stage electron detector in the demonstrator setup.

2.2.5 Demonstrator magnet

A key component in demonstrating the PTOLEMY concept of dynamic filtering is the availability of a custom-designed magnet with a tailored magnetic field gradient. This development builds on the studies presented in [1, 2]. More recently, a small-scale setup successfully demonstrated the $\mathbf{E}\times\mathbf{B}$ drift of single electrons along with their detection [14]. Matching our results with CST Studio Suite simulations, we deduce a capacity to increase particle time of flight by a factor of 5 (roughly from 11 ns to 55 ns) in the field cage's slow drift region. Limited only by the dimensions of our system, we assert that drift speed can be arbitrarily slowed to meet the needs of PTOLEMY's future detector. A superconducting MgB_2 magnet currently under production by ASG Superconductors (Genoa), is expected to be delivered to CERN for initial magnetic field characterization. Following these measurements, the magnet will be transferred to INFN LNGS, specifically to the Hall di Montaggio, in early 2026. There, it will be integrated with a vacuum chamber already procured but to be equipped with a series of electrodes to realize the filter in the fringe field of this magnet. A rendering of the demonstrator assembly is shown in Fig. 3. Notably, the is field is generated by super-conducting coils operated at 20 K, eliminating the need for costly liquid helium consumption.

2.3 Current strengths and limitation of the PTOLEMY project

2.3.1 Current Strength of the PTOLEMY project

The filter idea. The electromagnetic filter described in the PTOLEMY publications represents a potentially revolutionary approach for analyzing the tritium beta-decay end-point spectrum. The filter has a longitudinal extent of approximately 1 meter and a transverse size of a few tens of centimeters. Moreover, the exponentially decreasing magnetic field creates a region of a near-zero field, which can be used to host the final stage electron detector. Experience with magnetic field measurements and simulation is now present within the collaboration (INFN Genova and LNGS). Collaboration with CERN on this aspect is also in place.
Tritiated graphene. The PTOLEMY groups working on graphene and its hydrogenation are developing strong expertise in the relevant techniques and have initiated the design of a dedicated vacuum chamber for handling tritium. Some of the required equipment is already available, including a commercial hydrogen thermal cracker. Monolayer graphene is readily available because of a well-established collaboration between the Roma Tre group, IIT Pisa, and CNR Pisa. Collaborations with AGHS at the UK Atomic Energy Authority (UKAEA) in Culham are at an advanced stage, and a feasibility study for the adaptation of this technique is planned for the second half of 2025. The shipment of tritiated graphene samples under vacuum is considered technically feasible using commercial vacuum suitcase systems. The legal aspects related to the transfer of tritium will be addressed in coordination with the UKAEA. Additionally, in Italy, the ENEA-INMRI (National Institute for Ionizing Radiation Metrology) has expressed interest in providing the official certification of tritiated graphene as a solid-state radioactive source.
RF radiation detection. The INFN LNGS and Nikhef groups have successfully built and operated a complete data acquisition chain for detecting RF cyclotron radiation from the small electron trap developed at LNGS. Both custom-built and commercial equipment for advanced signal processing are available on-site at LNGS. The CST Studio Suite has been used to simulate and predict the behavior of the electron trap, yielding results in good agreement with experimental observations. The design of the antenna for the PTOLEMY demonstrator, as well as the electronic chain for the dynamic control of the filter, will be guided by the experience gained in these developments. Optimizing the electrodes and the antenna to pick up the signal in the field of the Demonstrator will be one of the topics on which we will focus.
Electron detection. The PTOLEMY collaboration has extensive experience in operating low-energy electron detectors (10–1000 eV) in a vacuum environment. This expertise spans from more standard and commercially available devices such as avalanche photodiodes (APDs) and microchannel plates (MCPs) to more advanced instrumentation like hemispherical electrostatic analyzers. These systems are part of the experimental setups at Roma Tre and Roma Sapienza laboratories, which are routinely used for X-ray and

UV photoelectron spectroscopy as well as electron energy loss spectroscopy (EELS). The Roma Tre group has long-standing expertise in the design and construction of electrostatic analyzers, including those developed for synchrotron beamlines. With optimized operational parameters, energy resolutions below 50 meV can be achieved. The group also has solid experience in simulating electrostatic lenses for efficiently steering electrons into the analyzers. On another front, promising results have been obtained by the INRIM and INFN Roma groups using TES for electron detection. Although current performance is not yet at the resolution required by the PTOLEMY design goals, TES technology remains a compelling option for future upgrades, especially given ongoing improvements. A crucial asset within the collaboration is the experience in electron calibration sources. A commercial electron gun, funded by CNS2, is currently in operation at LNGS and is being considered for the first tests of the dynamic filter concept. Roma Tre also brings expertise in designing custom electron guns with exceptionally good energy resolution, based on the same electrostatic technologies used in their analyzers. Additionally, compact electron sources based on CNT field emission and built at INFN Roma have been successfully operated at both room temperature and cryogenic conditions.

Theoretical effort. A group of theoretical physicists is actively involved in ongoing discussions within the PTOLEMY collaboration. This close interaction is essential for evaluating the intrinsic theoretical systematic uncertainties related to the interaction between the β-decaying nucleus and the substrate, which, in the current PTOLEMY design, is graphene. This collaboration has already contributed to the incorporation of final-state interaction effects into the neutrino mass sensitivity estimates. Furthermore, the strong synergy between theory and experiment opens the door to exploring additional physics opportunities with the PTOLEMY setup—such as the investigation of Mössbauer-like effects in beta decay, the evaluation of alternative substrates for hosting atomic tritium, or even more exotic applications related to dark matter searches.

Considerations on systematics and background. So far the most relevant contribution to the systematics that have been studied matters to the uncertainty on the knowledge of the bound state of T to graphene which has been extensively treated in [5]. The outcome of the [5] is that the true exclusion or discovery must be contained in the limit of the dashed zone of Fig. 1. On the detector side the uncertainty of the knowledge of the voltage of the tritium target, which directly affect the overall energy scale has been show to be well below specifications (50 mV over 20000 V). Then we have to consider a possible correction on the energy loss by RF emission. Although the energy loss of 18 keV electron in 1 T magnetic field is only 7 meV/μs this correction must be taken into account. In fact, we are able to measure accurately the drift time in strong magnetic field and also the emitted power. This gives us two handles to correct for energy lost because of RF emission. Concerning possible background sources we quote the Project8 results [20] where they claim 1 event of background per eV per 100 years while measuring event of electrons spiralling in 1 T magnetic field. It is worth pointing out that in the Project8 case tritium is used in a gaseous form thus the detector is designed to collect electrons from any direction efficiently. While, in our case spurious electrons, coming form surrounding environment, can not enter into the strong magnetic field region (i.e. bottle effect), where only electrons from target region can efficiently penetrate.

2.3.2 Current limitations of the PTOLEMY project

The filter. An experimental demonstration of the dynamic filter—designed to decelerate electrons as they move from a high to a low magnetic field region—is still pending. The dipole magnet currently under construction will generate an exponentially decreasing magnetic field. With a carefully designed system of electrodes and an electron source (such as an electron gun), this setup will enable a first test of the filtering concept in a static configuration, prior to advancing toward the full-scale design of a neutrino mass experiment incorporating the dynamic filter feature.

Tritium. Tritium is a rare and tightly regulated material, and only a few laboratories worldwide are equipped to handle it in gaseous form. While contacts with the UKAEA are promising for adapting the graphene hydrogenation technique to tritium, LNGS currently lacks a dedicated and properly equipped laboratory (such as the ENEA FNG facility) to host a solid tritium source. We expect that, within a few years, LNGS could establish such a facility by obtaining the necessary radiological safety authorizations and installing a system of glove boxes and monitoring sensors. To date, approximately 1 ng of hydrogen has been deposited on graphene samples with an area of a few mm^2. However, a full engineering design for a 1 μg tritium target — corresponding to the desired 50 cm^2 active area— is still lacking. This includes the development of a suitable substrate to support the graphene, a production cycle capable of fabricating and assembling multiple samples. Also a proper integration into the demonstrator geometry, potentially with additional magnetic elements to guide the electrons into high-field regions must be studied.

End-to-end simulation. Despite substantial expertise with CST software and the availability of various custom codes (such as Lorent4) within the collaboration, a complete simulation to define the conceptual design of a neutrino mass experiment based on the magnet currently under construction is still lacking. We anticipate that such a simulation will be available within the timeframe in which the filter concept is experimentally demonstrated. This comprehensive design will incorporate a realistic tritium source geometry, the integration of the RF antenna, and the final electron detector — potentially optimized according to the electron's residual kinetic energy after passing through the filter.

Theoretical uncertainty. The shape of the tritium beta decay endpoint is influenced by the interaction between the tritium nuclei and the hosting substrate. Although promising theoretical studies have recently been published on this topic, a complete evaluation of the associated theoretical systematic uncertainty in the extraction of the neutrino mass is still lacking. However, a program is being developed to propose ancillary measurements — such as atomic recoil studies via photoelectron spectroscopy—to better constrain this uncertainty.

3 Proposal

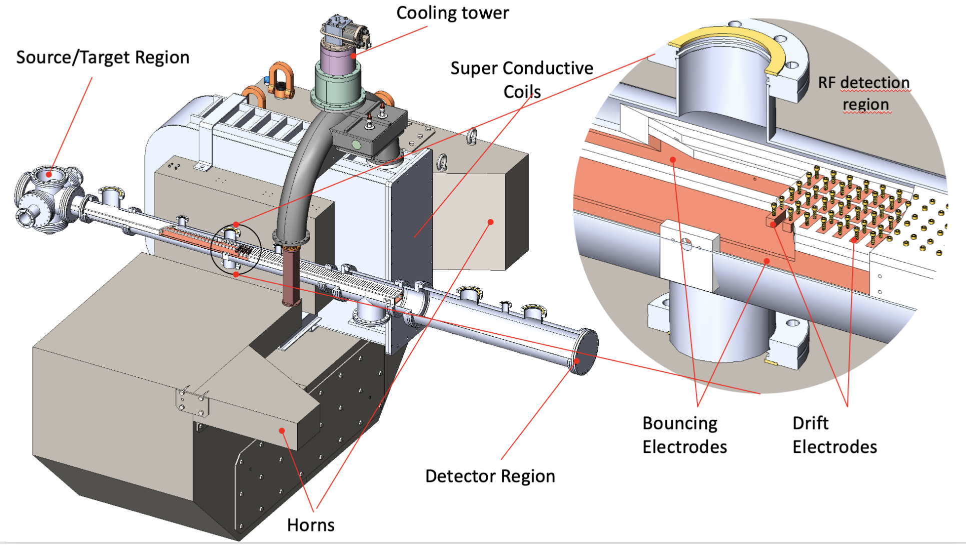

Figure 3: Schematic representation of the PTOLEMY demonstrator with superconductive cooling MgB_2 coils. Electrons are emitted from the source/target region and enter the uniform **B**-field region, where a transverse electric field induces an $\mathbf{E} \times \mathbf{B}$ drift. RF tracking occurs in the uniform **B**-field between the pole faces, while transverse drift takes place in the decaying **B**-field region, guided by fringe field shaping extensions. Electrons are then directed toward the detector, where their residual energy is precisely measured.

Given the current status of the project as outlined above, we propose a staged approach to developing a tritium-based neutrino mass measurement. Notice that during Phase-0 no tritium will be employed in the demonstrator set-up.

Phase-0: Experimental Demonstration of the Filter Concept (Milestone 1)

The objective of Phase-0 is to demonstrate the core functionality of the electromagnetic filter. This will be achieved through the following steps:

- **Electron Injection:** Electrons with a known, fixed energy will be injected from a source located outside the magnet. This can be achieved either via an electron gun or a gaseous krypton (Kr) source.
- **Guiding into the High-Field Region:** If the electron gun is used, a properly designed electrode system will guide the electrons into the high magnetic field region of the PTOLEMY magnet
- **Energy Filtering:** The electrons will then enter the shaped fringe field region. Here, a dedicated electrode configuration will be used to remove most of their kinetic energy.

- **Detection:** The filtered electrons will be detected by an electron sensor, either a microchannel plate (MCP) or a silicon drift detector (SDD). The detector might be mounted on a translation stage to map the final phase space of the electrons.

Intermediate Results and Required Actions

1. **Infrastructure at LNGS**
   Responsible groups: *[LNGS]*
   Installation of a reinforced floor free of ferromagnetic materials and a 50 kW busway is planned. Both components will be implemented under the supervision of the LNGS Civil Engineering and Technical Divisions. While the busway installation is already funded and underway, the floor modification will be partially supported by LNGS and partially funded through the collaboration's own budget.

2. **Vacuum Chamber**
   Responsible groups: *[LNGS]*
   The vacuum chamber has been designed, and the blueprints are ready to be delivered by the manufacturer. Some delays in the schedule are due to difficulties in procuring the required amount of a-magnetic stainless steel (SS 316 LN), given the relatively small quantity needed. An Italian supplier is currently exploring the possibility of sourcing the material from a stainless steel provider, likely based in Albania or Turkey.

3. **Magnetic Field Mapping**
   Responsible groups: *[INFN-GE]*
   This task will be performed at CERN upon delivery of the magnet. It is supervised by INFN GE. The preliminary field map, provided by the ASG company as specified in the contract, will be repeated with higher precision (better than one part per thousand) under the supervision of M. Buzio from the CERN Magnet Division.

4. **Electron injection tests with permanent magnet**
   Responsible groups: *[LNGS]*
   To calibrate the filter, electrons of known energy generated by the electron gun can be used, provided that a suitable injection electrode system is available. This topic is currently being studied by PhD student F.M. Pofi at GSSI. The 1 T permanent magnet allows meaningful tests to be conducted before the final magnet with the desired magnetic field map becomes available.

5. **Electron Detectors**
   Responsible groups: *[Sapienza/Roma Tre]*
   This project will initially provide detectors for electron counting, and installation of MCP and/or SDD inside the vacuum chamber. A possible translation support to be able to swap from one detector to another is considered. As performance improvements are demonstrated, the detectors will be progressively upgraded until the final energy resolution is achieved.

6. **Transport of the Magnet to LNGS**
   Responsible groups: *[INFN-GE]*

From CERN to the Hall di Montaggio at LNGS. The LNGS group will organize the shipment from CERN to LNGS.

7. **Electrode System**
   Responsible groups: *[Princeton]*
   Design and fabrication to be carried out by the electronic and mechanical workshops at LNGS. The conceptual design of the electrodes will be provided by the Princeton group, while the blueprints will be prepared at LNGS by the mechanical division. The main challenges of the electrode project lie in the design details, whereas the actual production can be carried out at the LNGS workshop, as it does not require large-scale manufacturing. A new full-time position for a mechanical engineer fully dedicated to the project was recently opened.

8. **Magnet commissioning**
   Responsible groups: *[LNGS]*
   The authorization process to operate a 1 T magnetic field at the experimental site (HdM at LNGS) has already begun. Safety devices, including a field monitoring system and an interlock system to prevent access to the experimental area during magnetic field operation, are being implemented.

9. **High Voltage System**
   Responsible groups: *[LNGS]*
   Procurement and delivery in progress. The system must support independent control of N HV channels.
   The HV system consists of a high-stability power supply already designed and built at LNGS, as described in [21]. The HV project also includes the development of a circuit capable of switching the HV in response to a trigger generated by the RF measurement — this enables the dynamic behavior of the filter. The LNGS electronics workshop has agreed to contribute to this project, as they have previously developed a similar system for the biasing of the Resistive Plate Chamber (RPC) of the OPERA experiment. It is important to note that, during the initial phase of filter operation aimed at demonstrating its core functionality, the system will operate in a static mode. Simulation results will determine the exact number of channels required for the dynamic configuration.

10. **First Filter tests**
    Responsible groups: *[LNGS/Princeton]*
    Following the installation and activation of the PTOLEMY magnet, and leveraging the results from prior injection and extraction tests of electrons, through the permanent magnet, a first filter test will be conducted by using the electron gun. In this first measurement campaign two different steps. The first will consist on running the filter in a static mode, without the trigger form RF detection. The second step, we plan to use the RF measurement to exploit the dynamic behavior of the filter.

11. **First characterization of full chain electrodes**
    Responsible groups: *[Princeton]*
    A first measurement aims at evaluating the efficiency of electron transport across

the system by using an electron detector, e.g a micro-channel plate. In a second stage, the setup will enable the first energy-resolved measurements of the electrons from the e-gun. This has an intrinsic energy spread of up to 0.5 eV, which sets the best achievable resolution. However, at this level the energy resolution of the commercial electron detector (SDD or similar) will be the dominant contribution.
This test will provide essential insights into the system's performance and guide further the optimization of the filter.

Phase-0: Feasibility study of tritium on graphene production (Milestone 2)

As of June 2025, the PTOLEMY collaboration is initiating a feasibility study in partnership with the UK Atomic Energy Authority (UK AEA) to evaluate several key aspects of integrating tritium into the experiment. The study will focus on:

- Assessing the compatibility of the current PTOLEMY sample preparation system design—including the primary vacuum chamber and the thermal cracker—with tritium handling requirements.
- Evaluating the viability of integrating PTOLEMY systems with AGHS tritium infrastructure under the vacuum conditions and timelines required by the project.
- Investigating the regulatory framework and export logistics to ensure that tritium can be handled and transported in full compliance with international safety and legal standards.

This feasibility study will be conducted as a commercial service at an estimated cost of 100k€. It is expected to take approximately six months and will include multiple technical meetings with PTOLEMY collaborators, culminating in a comprehensive final report, where a clear answer to the items listed above will be delivered. Based on the outcomes of this study, the actual design and construction of a dedicated vacuum chamber for tritium deposition will be carried out during Phase-1 of the project.
Responsible groups: INFN Roma1 and INFN Roma Tre

Phase-0: realistic design of 1 μg tritium target (Milestone 3)

At present, we have tested H loading for several graphene structures, namely single layer graphene transferred onto TEM grid, nanoporous graphene (NPG) and carbon nanotubes (CNT). We reached very high H uptake for each tested graphene sample leading to host approximately 1 ng of tritium. To scale this laboratory-sized sample up to the 1000-fold larger target required for PTOLEMY Phase-1, a dedicated design study must be carried out along several coordinated lines of action:

1. **Target Geometry**
   A full simulation using CST or Lorentz4 is needed to define the optimal geometry of the 1 μg tritium target. The goal is to ensure that beta electrons emitted from the source are efficiently guided into the high-field region.
   Responsible groups: INFN Roma Tre and LNGS

2. **Production of Nano-structured Graphene Samples and their hydrogenation**
   Currently, graphene samples are produced in small quantities through academic collaborations. During the Phase-0 we will continue to explore different carbon-based nano-structured systems in order to identify the best sample for hydrogen storage in the smallest possible surface. In parallel, we will explore the possibility to scale up to the desired mass. This includes engaging with industrial partners to develop a streamlined, scalable production process for carbon-based nano-structures and their hydrogenation. Issues about quality assurance process must be identified.
   Responsible groups: INFN Roma Tre and INFN Roma1

Phase-0: RF (Milestone 4)

Radio-frequency (RF) detection is a central focus of F. Virzi's PhD thesis (University of L'Aquila) and is currently being investigated at the LNGS cryogenic facility within the PTOLEMY experiment. To date, 26 GHz RF signals—corresponding to the cyclotron emission of 30 keV electrons in a 1 T magnetic field—have been successfully identified and recorded over time intervals of 50 μs or longer. Ongoing efforts are focused on developing real-time analysis tools to promptly extract the kinematic properties of electrons through online Fast Fourier Transforms (FFTs). This capability would allow for the activation of a dynamic filter, targeting an energy and momentum resolution better than 1%. Two key performance parameters of the RF detection system are:

1. The resolution in measuring the electron's kinematic variables.
2. The time window over which these measurements are made.

Optimizing these parameters will inform the design of the electrode system, which will be a critical component of the overall conceptual detector layout. In Phase-0, the filter will operate in a static configuration. However, a dedicated circuit is currently under development at the LNGS electronics workshop to enable high-voltage switching, which

would allow for dynamic filter operation. This functionality is expected to be implemented in Phase-1, or earlier, depending on the readiness of the switching system.
Responsible groups: LNGS and Princeton

Phase-0: Full simulation of a filter for neutrino mass experiment (Milestone 5)

With the expertise gained from using CST and the increased flexibility of the Lorentz4 software, this milestone can be successfully achieved.
Responsible groups: LNGS and Princeton

Phase-0: Conceptual design report ready (Milestone 6)

The CDR will be delivered to INFN in a suitable format at the end of the Phase-0.
Responsible groups: The PTOLEMY collaboration

4 Costs, schedule and resources

This LoI develops in a 2-years time frame, during which we want to stimulate the growth of a larger collaboration supporting the project. As detailed below the costs to deliver the CDR have been largely covered, and large part of the equipment is already in the hands of the collaboration. To be fair, the following phase, which will be focused on the direct neutrino mass measurement will be submitted to the CSN II approval in 2-years form now and will require additional costs. Those will be driven by tritium target production and installation, and purchasing of electrostatic analyzer; we estimate both this topics to cost roughly 250 kE each. The rest are minor costs to support experimental activities and data taking at LNGS, networking among different groups, and support for conferences and outreach activities.

4.1 Available components of the Demonstrator setup and residual costs estimate

Here we elaborate an estimate of residual costs needed to support the experimental effort in the 2-years plan on which is focused this document. For this reason the budget request is dominated by

- Collaboration meetings, 2 per year in Italy.
- Travel of WG chair, technical coordinator
- Networking (Seminar in other institutes)
- Travel towards LNGS to support experimental activities

Component	**Value (kE)**	**Available**
Experimental space at LNGS (above ground)		INFN
Non magnetic concrete leveling	6	Company contacted by INFN
Bus-way 50 kW at PTOLEMY site	5	under installation by INFN
Magnet core setup	380	Princeton
Magnet horns, power supply and safety system	115	LNGS external funds
Vacuum chamber and supports	25	INFN CNS5
Vacuuming system	15+15	*turbo and primary available one at LNGS, one at Sapienza(Princeton property)*
Vacuum gauges	5	*2 available at LNGS*
Low T diodes	3	*2 available at LNGS*
Low T diodes monitor	LNGS-Cryogenic Service	*Single channel*
Electrodes	in kind INFN	Conceptual Design Princeton/LNGS
Electrodes	in kind INFN	Executive Design and construction INFN-GE/LNGS mechanical workshops
Low performance electron detector?	in kind INFN	INFN Roma1-RomaTre
HV feed-through, 12 channels rated up to 20 kV	in kind LNGS	available
HV power supply, 30 kV maximum voltage	35	Princeton property now at LNGS
Cold source to cool down thermal screen	borrowed by other collaboration	

Table 1: List of components and availability status

INFN unit	FTE per INFN unit	Travel (kE)	hardware (kE)
CA	1.5	5	
GE	0.25	3	
NA	0.4	2	
LNGS	4.1	8.5	6 magnet transport
PI	0.8	2	
Roma1	3.6	9.5	6 e-detector
Roma2	0.9	3	
Roma Tre	1.0	3	5 graphene test production
To	0.2	1	
Tot	12.75	37	11

Table 2: Residual costs for year 2026

INFN unit	FTE per INFN unit	Travel	hardware
CA	1.5	5	
GE	0.25	3	
NA	0.4	2	
LNGS	4.1	8.5	
PI	0.8	2	
Roma1	3.6	9	
Roma2	0.9	3	
Roma Tre	1.0	3	
TO	0.2	1	
Tot	12.75	37	

Table 3: Residual costs for year 2027 (expected)

4.2 Schedule and GANTT chart

This project aims at defining the PTOLEMY Conceptual Design Report over a two-year time-frame. Although the official schedule begins in January 2026, many of the proposed activities are already underway and funded. We advocate for a coordinated effort within the neutrino physics community to pursue these shared scientific objectives and firmly believe that CSN II's support is essential for the successful completion of this program.

4.3 Notes on Phase-1

We anticipate that the primary objective of Phase-1 will be to lay the groundwork for the full construction of the neutrino mass experiment, leading into a three-year data-taking period. Compared to Phase-0, three key components must be developed and integrated into the magnetic system:

- Complete production of a 1 μg tritium target.
- Installation of an RF antenna for electron triggering.
- Implementation of a final electron detector with an energy resolution of 50 meV.

The tritium target will require the construction of a dedicated reaction chamber to be operated at UK AEA. Once prepared, the target will be transferred to LNGS and installed in the Phase-1 demonstrator. In parallel, production of high-quality graphene substrates must proceed to support the target fabrication. For the final electron detector, a hemispherical electron analyzer will be procured from a commercial supplier. While minor adaptations will be necessary to interface the detector with the demonstrator setup, no significant R&D effort is anticipated. The conceptual design report, to be finalized at the end of Phase-0, will define the major technical milestones for Phase-1 and provide a detailed breakdown of the required costs and resources.

4.4 Resources for Phase-0

Fig. 5 show the management structure with two spokespersons, a technical coordinator interacting with the LNGS and WG in which the technical work is defined, organized and realized.

Name	**FTE**	**Institute**	**Task / Responsibility**
PI A.P. Colijn		University of Amsterdam and Nikhef	Analogical and Digital electronics
P. Bos			
J. Mead			
M. Naafs			
G. Visser			
PI Prof. C.G. Tully		Princeton University	Filter design/simulation and tests, Magnet, RF Antenna
A. Tan			
W. Chung			
M. Farino			
A. Langella			
PI N. de Groot		University of Radboud	Graphene studies and measurement
I. van Rens			
PI C. Perez de los Heros		Uppsala University	Editorial board
PI M. Cadeddu	30%	INFN-CA	T handling, safety procedure and authorizations
V. Narcisi	30%		
L. Ferro (PhD)	30%		
A. Santucci	30%		
M. Sestu (PhD)	30%		
PI E. Celasco	15%	University of Genova and INFN-GE	Magnetic field measurement and cryogenics
S. Farinon	5%		
PI G.P. Mangano	20%	University of Napoli and INFN-NA	Theorist
O. Pisanti	20%		theorist
PI M. Messina	60%	INFN-LNGS	Infrastructure, Magnet, Calibration, RF
A.G. Cocco	60%		
N. D'Ambrosio	20%		
A. Ferella	30%		
G. Benato	0%		
N. Rossi	40%		
F.M. Pofi (PhD)	100 %		
F. Virzi (PhD)	100%		

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Name	FTE	Institute	Task / Responsibility
PI V. Tozzini	20%	INFN-PI and NANO-CNR Pisa	Theorist
L.E. Marcucci	20%		theorist
G. Menichetti	20%		theorist
M. Viviani	20%		theorist
PI G.L. Cavoto	30%	Sapienza University and INFN-Roma1	Tritium loading on graphene
M.G. Betti	20%		
B. Corcione (PhD)	100%		Electron detection
G. De Bellis	30%		HV developments
A. Esposito	20%		Theorist
L. Ficcadenti	30%		
G. Galbato Muscio (PhD)	30%		HV developments
C. Mariani	30%		Tritium loading on graphene
F. Pandolfi	30%		Electron detection
A.D. Polosa	10%		Theorist
I. Rago	30%		Graphene scale-up
PI G. Salina	30%	INFN-Roma2	DAQ and FPGA programming
Roberto Ammendola	10%		
Cosmin Marin(PhD)	50%		
PI A. Ruocco	40%	Roma Tre University and INFN-Roma3	Graphene target scale-up
A. Apponi	20%		CNS5 grant synergic (GREEAT)
O. Castellano (PhD)	40%		Nanostructures hydrogenation
PI S. Gariazzo	20%	INFN-TO	

Table 4: Collaborators actively working on the PTOLEMY project that makes the PTOLEMY Collaboration. For Italian participants, the INFN FTEs will be reported in the INFN database.

It is worth highlighting some special cases concerning FTE allocation for S. Farinon (INFN-GE) and G. Benato (INFN-LNGS), both of whom made significant contributions to the project. S. Farinon supervised a master's student, calculated the magnetic field map (B-field), and defined the number of measurement points required to achieve the desired precision in characterizing the field. Despite this substantial involvement, S. Farinon's FTE cannot exceed 5%. A similar situation applies to G. Benato, who supervised a PhD student tasked with evaluating the sensitivity curves—presented in this document—for three different theoretical models of the tritium bound state. This work was critical for assessing the potential of the technology and estimating systematic uncertainties arising from theoretical assumptions.

5 Relationships with stakeholders of the PTOLEMY Project

The PTOLEMY project, aimed at developing advanced techniques for direct neutrino mass measurement and the potential detection of the Cosmic Neutrino Background (CνB), involves a diverse group of stakeholders from fundamental physics, applied research, and the industrial sector. Below is an overview of the key communities and institutions involved or potentially impacted.

1) Neutrino and Particle Physics Community

Currently, the global neutrino physics community lacks an operational next-generation experiment (at the level of a Technical Design Report) that can surpass the sensitivity of the KATRIN experiment (mass limit < 0.45 eV at 90% C.L.). Various R&D initiatives are underway (e.g., KATRIN++, HOLMES, Project8, QTMN). PTOLEMY is part of this broader research effort. Its proponents argue that at the national level (INFN in Italy), there should be greater synergy between these efforts to maximize their collective impact. This could eventually lead to a unified initiative within CNS2. We anticipate here a number of synergic activities that could be the basis for a more extended collaboration among different current initiatives.

1. theoretical analysis of condensed matter effects (relevant for solid state target as in PTOLEMY and Holmes) to obtain a more detailed description of the electron spectrum
2. TES developments, in particular calibration source to be operated in a cryogenic environment (also relevant for Holmes)
3. more advanced amplification stage in the micro-wave range (relevant for PTOLEMY RF antenna and for Holmes readout)
4. silicon particle sensor with moderate energy resolution (already developed for Tristan and useful for PTOLEMY Phase-0)

2) Cosmology Community

The cosmology community has a strong interest in direct neutrino mass measurements due to their relevance in large-scale structure formation and cosmological models. A model-independent laboratory measurement of the absolute neutrino mass would complement and cross-check cosmological constraints.

3) LNGS (Gran Sasso National Laboratory)

LNGS is currently hosting key PTOLEMY hardware and has invested in its R&D phase. If tritium is to be used in the experiment, LNGS will need to provide a fully equipped laboratory compliant with radioprotection regulations. This includes glove boxes, monitoring systems, and proper authorization for handling tritium sources.

4) ENEA-INMRI (National Institute for Metrology Research)

ENEA-INMRI is particularly interested in PTOLEMY's advancements in atomic tritium sources deposited on graphene substrates. These developments have potential applications not only in particle physics but also in precision radioactivity measurement. Future tritium exploitation in fusion reactors requires in fact novel tools to monitor low-Q beta sources.

5) Fusion Technology Sector

The fusion energy sector is interested in technologies developed by PTOLEMY, particularly those related to the transport and storage of tritium from production facilities (such as CANDU reactors) to commercial fusion reactors. In Italy, ENI is already collaborating with UKAEA in this context.

6) UKAEA (United Kingdom Atomic Energy Authority)

As a major global provider of tritium, UKAEA is interested in PTOLEMY's work for similar reasons—developing scalable and safe methods for tritium handling and transport. UKAEA is currently engaged in a feasibility study with the PTOLEMY team to evaluate the integration of tritium subsystems and compliance with international regulations for tritium shipment.

6) Particle Accelerator community

Devoloping compact superconducting magnet with 20K operation temperature in a closed cryogenic circuit will open the opportunity to replace electromagnets now operated with normal conductors. This might a represent a major step towards more sustainable and green accelerators.

Scientists supporting the PTOLEMY project:

R. Ammendola, A. Apponi, G. Benato, M.G. Betti, M. Borghesi, P. Bos, M. Cadeddu, N. Canci, O. Castellano, G. Cavoto, E. Celasco, W. Chung, A. Cocco, A. Colijn, B. Corcione, D. Cortis, N. D'Ambrosio, F Di Capua, G. De Bellis, N. de Groot, A. Esposito, M. Farino, S. Farinon, M. Faverzani, A.D. Ferella, E. Ferri, L.Ferro, L. Ficcadenti, G. Galbato Muscio, S. Gariazzo, H. Garrone, F. Gatti, A. Giachero, Y. Iwasaki, A. Langella, M. Laubenstein, L. Manenti, G. Mangano, L.E. Marcucci, C. Mariani, G. Mazzitelli, J. Mead, G. Menichetti, M. Messina, P. Migliozzi, C.M. Mollo, E. Monticone, M. Naafs, V. Narcisi A. Nucciotti, F. Pandolfi, D. Paoloni, C. Pepe, C. Pérez de los Heros, O. Pisanti, F.M. Pofi, A.D. Polosa, A. Puiu, I. Rago, M. Rajteri, N. Rossi, A. Ruocco, G. Salina, G. Santucci, G. Sestu, A. Simonelli, A. Tan, V. Tozzini, C.G. Tully, I. van Rens, F. Virzi, G. Visser, M. Viviani, D. Vivolo,U. Zeitler, O. Zheliuk, F. Zimmer.

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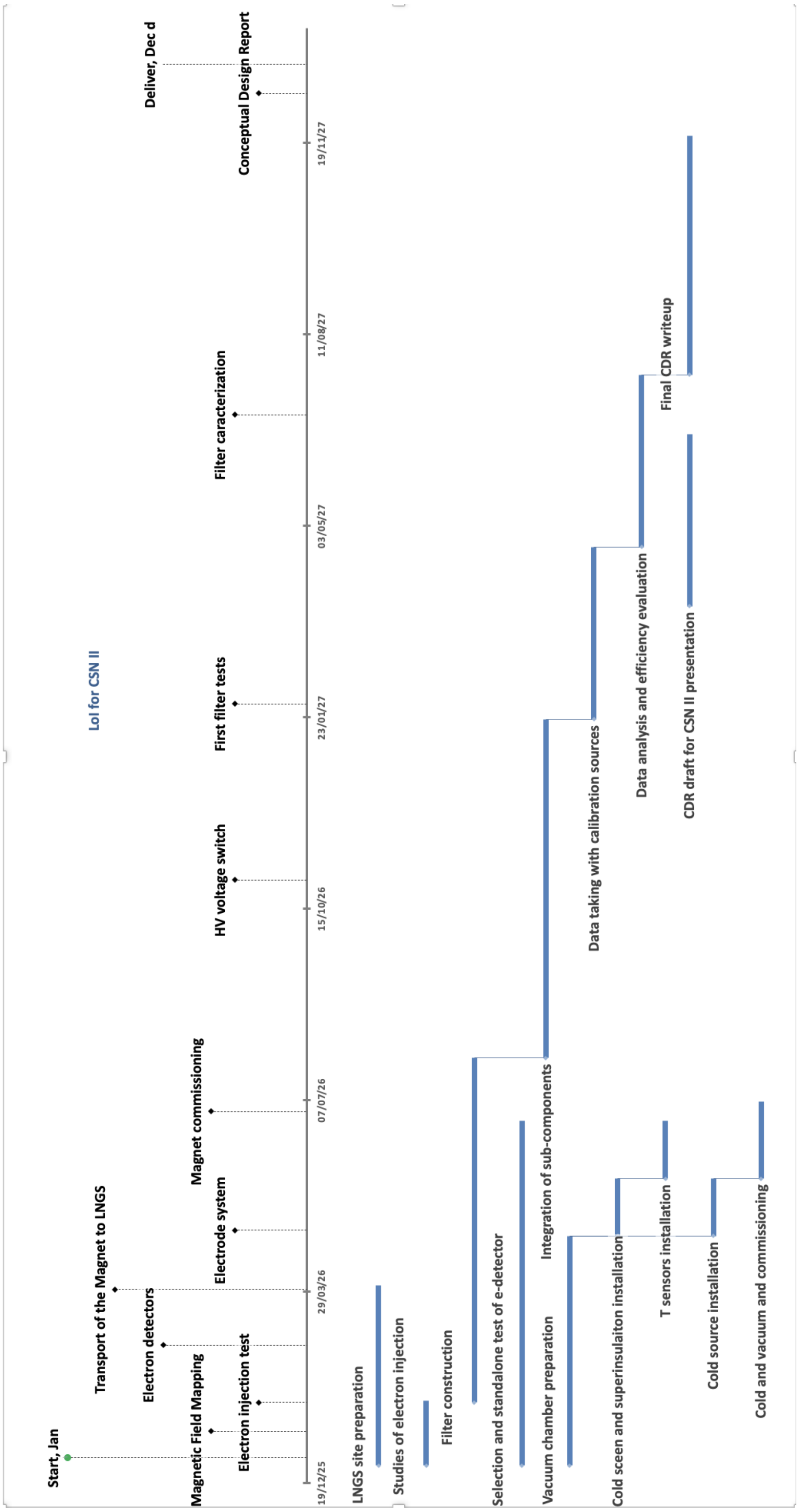

Figure 4: GANTT chart with milestones and tasks for two-years schedule.

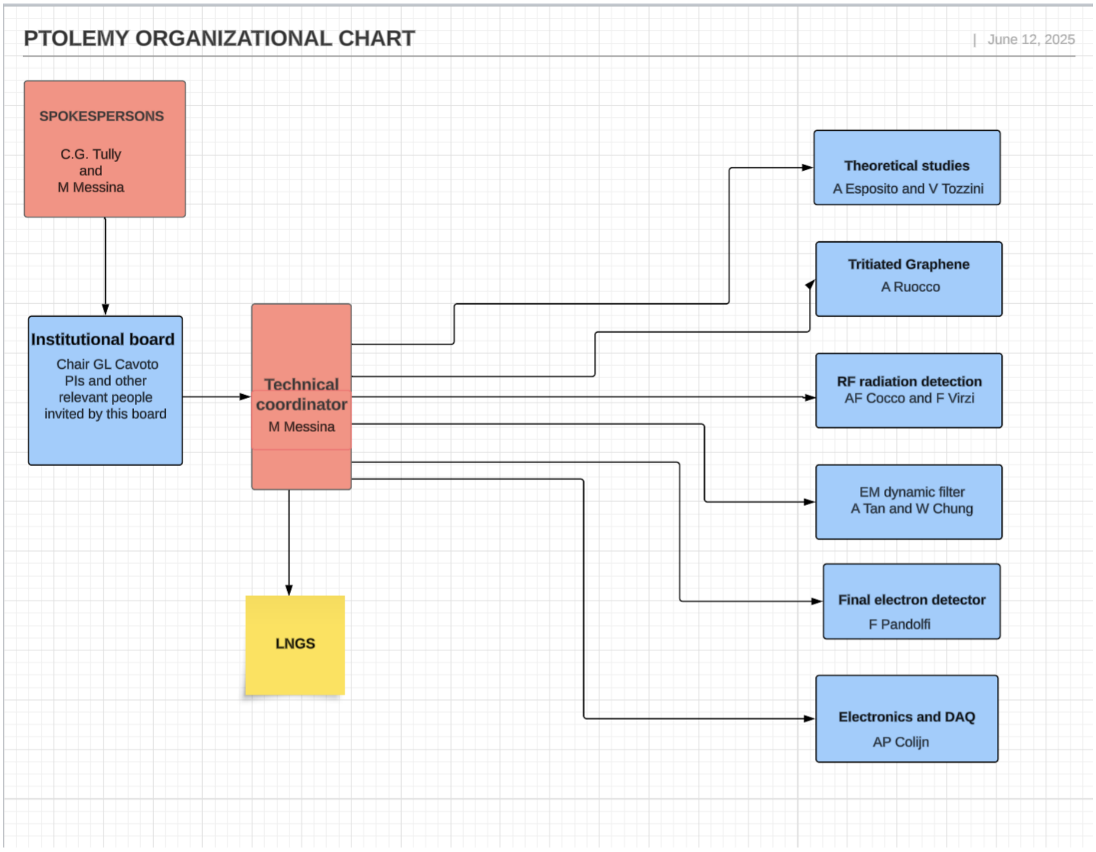

Figure 5: Management organization