Letter of Intent: ARIADNE, a Photographic LAr TPC at the CERN Neutrino Platform

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Abstract

This letter of intent describes a novel and innovative two-phase LAr TPC with photographic capabilities as an attractive alternative readout method to the currently accepted segmented THGEMs which will require many thousands of charge readout channels for kton-scale two-phase TPCs. These colossal LAr TPCs will be used for the future long-baseline-neutrino-oscillation experiments. Optical readout also presents many other clear advantages over current readout techniques such as ease of scalability, upgrade, installation and maintenance, and cost effectiveness. This technology has already been demonstrated at the Liverpool LAr facility with the photographic capturing of cosmic muon tracks and single gammas using a 40-litre prototype. We have now secured ERC funding to develop this further with the ARIADNE programme. ARIADNE will be a 1-ton two-phase LAr TPC utilizing THGEM and EMCCD camera readouts in order to photograph interactions, allowing for track reconstruction and particle identification. We are requesting for ARIADNE to be given time at a charged particle beam within the CERN Neutrino Platform, a facility dedicated to Neutrino detector R&D. This will allow for characterization of calorimetric and particle identification capabilities. ARIADNE will mature and validate the photographic readout technology, informing future LAr TPC design.

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1 Introduction

Colossal LAr TPCs are considered by many to be the future for long-baseline-neutrino-oscillation physics around which the international neutrino community is rallying, with the common goal of discovering new physics beyond the Standard Model, which holds the key to our understanding of phenomena such as dark matter and the matter-antimatter asymmetry. Realisation of these colossal-scale LAr TPCs for long-baseline neutrino physics is underway, with international efforts such as the DUNE collaboration bringing together the single and two-phase LAr TPC technologies [1, 2, 3, 4]. Full-scale prototypes, ProtoDUNE and WA105, will be positioned at the CERN Neutrino Platform [5, 6].

This document presents ARIADNE, an ERC funded project for the development of an innovative new two-phase LAr TPC utilizing a novel and alternative photographic read-out. Optical readout presents many clear advantages when compared to currently accepted segmented THGEM (THick Gaseous Electron Multiplier) charge readout technologies, such as ease of scalability, upgrade, installation and maintenance, cost effectiveness and elegant simplicity without the need for many thousands of charge readout channels that are currently required for the colossal-scale two-phase detectors. ARIADNE, a 1-ton two-phase TPC, will be built and initial characterizations performed at the Liverpool LAr facility, drawing upon a highly successful prototype. We would then like to place ARIADNE in a charged particle beam at the CERN Neutrino Platform to allow for characterisation of calorimetric and particle identification capabilities.

1.1 Two-Phase LAr TPC Readout Options

Small scale two-phase LAr TPCs have demonstrated excellent calorimetric and tracking capabilities using a charge readout approach with THGEMs [7, 8]. Two-phase LAr TPCs detect the prompt scintillation light (S1) produced in the liquid phase and free-ionised electrons, generated during an interaction, are drifted to the liquid surface where they are extracted to the gas phase producing secondary delayed electroluminescence light (S2). These electrons then enter THGEM holes and are amplified by the high electric field, producing further secondary scintillation light as a result of electroluminescence. With application of a high enough electric field across the THGEM holes, avalanche is induced and the electroluminescence produced increases exponentially with THGEM electric field [9, 10, 11, 12]. In the case of the proposed future giant scale two-phase LAr TPCs the amplified electrons are drifted to a segmented anode plane for charge readout.

Whilst THGEMs provide excellent gain resulting in good signal-to-noise ratios, the current THGEM charge readout approach has challenges with respect to scale-up: separate readout channels are required for every anode strip, which can number in the order of up to a million for the colossal scale detectors, and the resolution of tracking reconstruction is limited by the pitch of the strips. An alternative readout method could involve the exploitation of the secondary scintillation light produced in the THGEM holes [11, 13, 14, 15]. We have already demonstrated for the first time the imaging of cosmic muons with the Liverpool 40 litre LAr TPC utilizing a THGEM and Electron Multiplier CCD (EMCCD) camera [16]. We have now secured ERC funding for the development of this technology, with the vision of maturing and optimizing this approach in a larger volume TPC containing enough tracking information for full characterization, and to inform the design of the future detectors.

2 The Liverpool LAr Research Program

The Liverpool LAr Lab houses a 40 litre TPC that has been designed to allow for adaptable use in a diverse range of R&D efforts in support of large-scale LAr detectors. To date, our research has focused primarily on argon purification and recirculation studies [17], optimization of light collection using wavelength shifter and reflector combinations [18] and alternative readout systems such as MicroMegas and THGEMs combined with CCD cameras [19]. Achievements include a novel LAr recirculation and purification system, an innovative HV feed-though design, characterization of bulk MicroMegas in both single and two-phase operation and internal cryogenic camera monitors. Most recently we have successfully demonstrated the feasibility of optical imaging of muon tracks and single gammas in our two-phase TPC using a CCD camera and THGEM.

2.1 The Liverpool LAr Setup and First Demonstration of Photographic Imaging of Cosmic Muons

The Liverpool 40 litre LAr TPC assembly consists of an 8-inch Hamamatsu cryogenic PMT coated with wavelength shifter looking upwards towards the fiducial volume, which is defined by the 20 cm long field cage. Above the extraction region there is the facility to mount various charge multiplication devices, such as THGEMs and MicroMegas. In photographic mode, a single THGEM is placed above the extraction region, and an EMCCD camera is mounted outside the detector, looking in via a view port at a distance of 1 m from the THGEM (see Figure 1).

When an incoming particle passes through the detector medium it causes prompt scintillation light and ionisation. The prompt scintillation light is detected immediately by the PMT whereas the free ionised electrons are drifted to the surface of the liquid through a typical electric field of 0.5 kV/cm. At the surface of the liquid, the electrons experience a higher electric field ($\sim$3 kV/cm) in order to be extracted to the gas phase. Once in the gas phase the electrons enter the THGEM 500 μm ID copper clad holes, in which an electric field of around 40 kV/cm is generated causing avalanche and secondary scintillation light. This light is captured by the bottom PMT and additionally by the externally mounted EMCCD camera. The x,y coordinates of the event are reconstructed by the camera, whereas the depth position of the event (z coordinate) is determined by the time difference between the secondary scintillation light and prompt scintillation light seen by the PMT. The operation principle for this type of detector is shown in Figure 4b.

We successfully tackled challenges such as the VUV nature of the light produced, the cryogenic conditions and the amount of light production to successfully demonstrate the feasibility of this optical imaging method [19]. The VUV nature of the secondary scintillation light was considered in the field as a show-stopper for the use of camera technology, however we circumvented this problem, not by coating the lenses with wavelength shifters (which was ineffec-

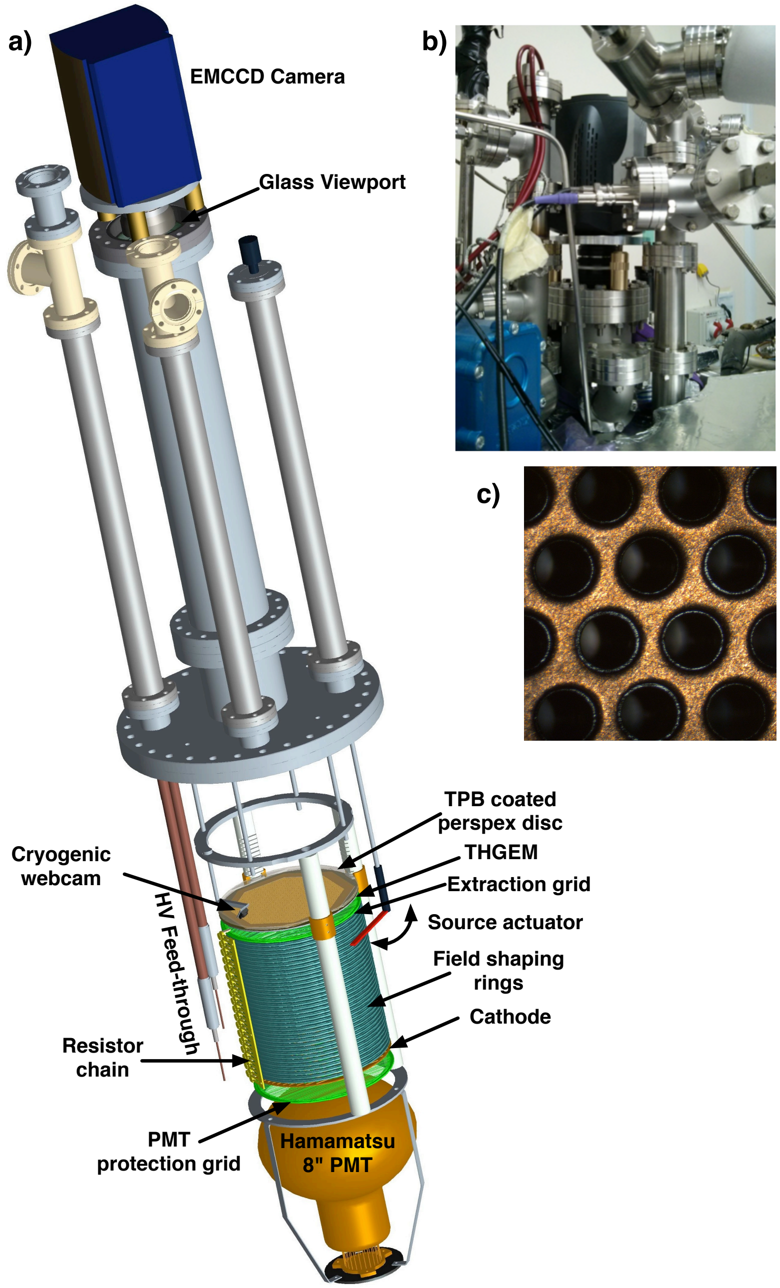

Figure 1: *a) A 3D CAD model of the Liverpool 40-litre LAr detector assembly, b) the EMCCD camera, c) zoom of the THGEM holes*

tive) but by coating an optical disk with wavelength shifter and mounting this at an optimal distance above the THGEM, thus shifting the light to 430 nm (blue) before it reached the lenses. In terms of cryogenic operation, after initially (and successfully) separating camera electronics from the chip externally from the detector, i.e. at ambient temperature, we have now moved on to mounting an EMCCD camera externally looking in to the detector via a view port. This is a simpler approach and allows for ease of mounting and upgrading of different camera systems. This camera/THGEM system has captured fantastic images of cosmic ray tracks and single gamma events with energies as low as 100 keV. Sample images of cosmic ray events passing through the LAr detector medium are shown in Figure 2.

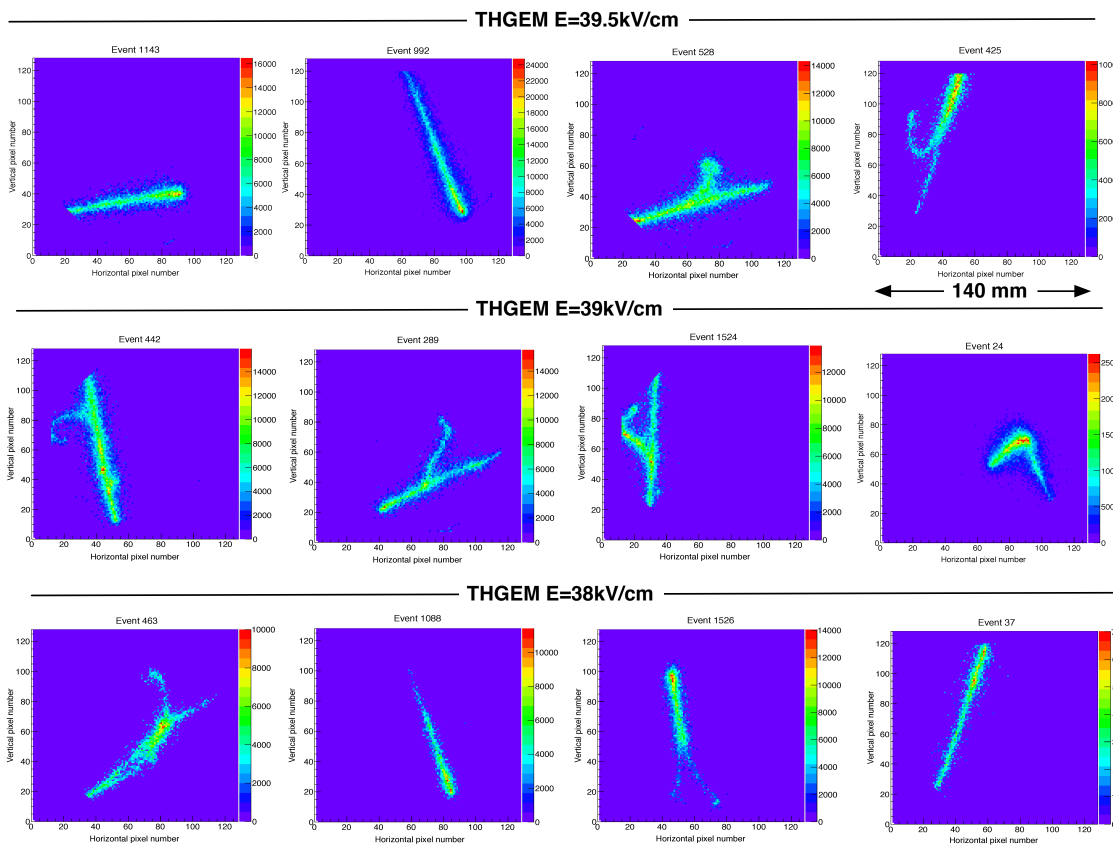

Figure 2: *Photographs of cosmic events passing through the Liverpool 40-litre detector medium for various THGEM electric fields. The events were captured using 4×4 binning, 1 msec exposure and an EMCCD of gain 1000. One pixel corresponds to 1.1 mm.*

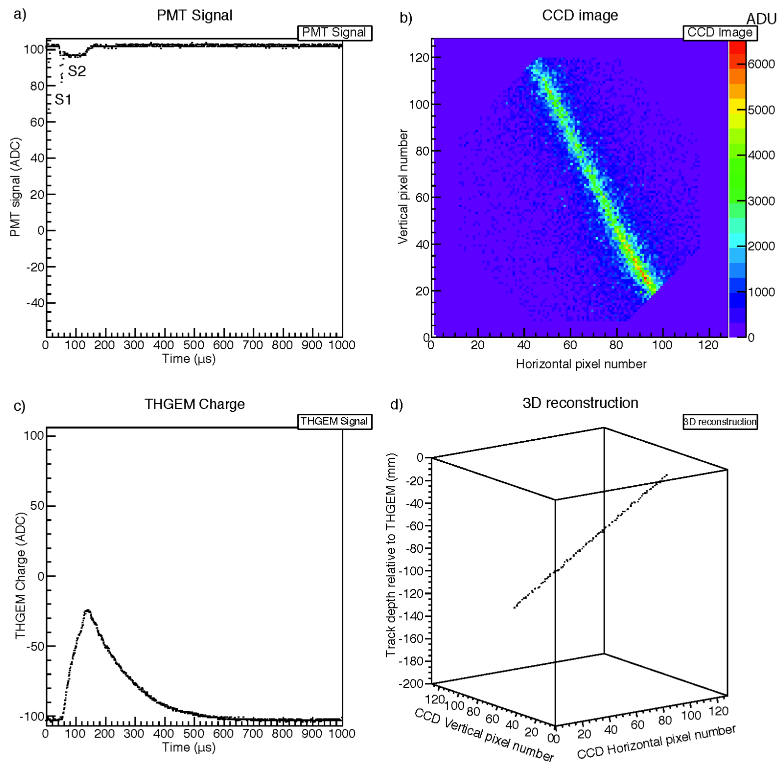

Figure 3: *a) The primary and secondary scintillation signal seen by the PMT as a cosmic muon passes through the detector medium; b) The same secondary scintillation signal captured by the EMCCD camera (raw data); c) The overall charge collected by the THGEM; d) A 3D reconstruction of the cosmic muon by correlating the PMT data, THGEM charge and EMCCD photograph.*

By combining the PMT prompt (S1) and secondary (S2) scintillation light signals, the THGEM charge signal and the EMCCD image data, we have developed a preliminary 3D reconstruction algorithm for straight-line tracks. The depth of the interaction was determined from the time difference between the secondary and prompt scintillation pulses seen by the PMT. The x, y co-ordinates were known from the EMCCD image; a linear 2D fit on the EMCCD image provides a plane in the detector volume where the track has occurred. The path length (dx) was determined by:

$$\mathrm{d}x = \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2} \tag{1}$$

where z_0 is the delay between the S1 signal and the start of the charge rise time and z is the charge rise time plus z_0. The charge rise time is converted to mm; 120 μs e^- drift time $\approx$190 mm at 0.5 kV/cm. A 3D event reconstruction sample is shown in Figure 3.

This is the first time a photograph has been taken of a particle interacting in a LAr TPC, and is reminiscent of bubble chamber detector technologies. This hassle free approach, with demonstrated high spatial resolution and low energy thresholds (currently reaching 100 keV) represents a powerful tool for imaging and disentangling complex vertices allowing for particle identification, and has applications in both neutrino and lower energy physics. This entirely new readout approach has already attracted much interest from the wider LAr neutrino community.

3 ARgon ImAging DetectioN ChambEr, ARIADNE; an ERC Funded Project

Based on the success of the above-described research programme, and the potential impact of a photographic readout alternative to segmented anode plane multiple channel charge readout for two-phase LAr TPCs, the ARIADNE project to develop photographic readout technology was proposed. The PI (K. Mavrokoridis) has now been awarded an ERC 1.8M Euro grant for ARIADNE. This cutting edge research has the potential of influencing the design of future giant LAr neutrino experiments, impacting on the highly anticipated future discoveries.

ARIADNE will be an upgraded scale-up (1-ton) of the current Liverpool 40 litre LAr TPC with which we have already demonstrated the feasibility and potential of this new optical readout avenue. A conceptual model of ARIADNE is given in Figure 4a.

ARIADNE will consist of an array of 4 8-inch Hamamatsu PMTs at the bottom looking up towards a 50×50 cm^2 THGEM at the top, which will be electrically segmented into 16 pads for complementary charge readout data. A field cage will provide a uniform electric field, defining an electron drift distance in the direction of the THGEM of 80 cm. Four Andor iXon Ultra (model 888) cameras will be positioned looking down towards the top of the THGEM 500 μm ID holes via windows, each viewing a 25×25 cm^2 optical area (See Figure 5b). The Andor EMCCD camera utilises a 1024×1024 back illuminated e2v sensor with high pixel well depth capacity and a high quantum efficiency in the region of 80 % at 430 nm. Advantageously over conventional CCD cameras, the EMCCD camera features an electron multiplication capability

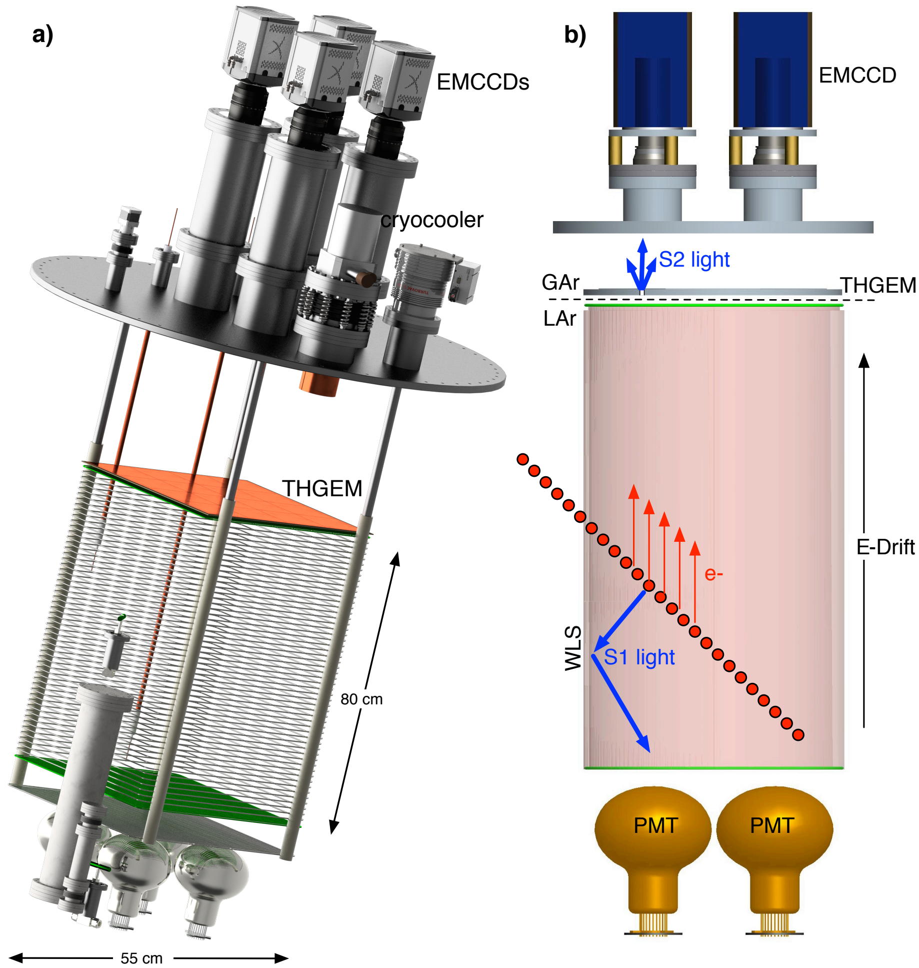

Figure 4: *a) A conceptual CAD model of ARIADNE. b)The detection principle of ARIADNE.*

with a gain of up to 1000, allowing for an effective readout noise of less than 1 electron therefore making the camera single photon sensitive [20].

The cryogenic temperature of the system will be maintained with a cryomech AL300 cryocooler positioned at the top of the detector via a DN160CF flange. The purification and recirculation system will be based on the current bellows system and purification cartridges already developed at Liverpool. ARIADNE will be constructed at the Liverpool Mechanical workshop. Prior to commissioning at the CERN Neutrino Platform, ARIADNE will be characterised at Liverpool with cosmic ray events and with the use of a UV laser.

3.1 ARIADNE at the CERN Neutrino Platform

ARIADNE needs to be placed in a charged particle beam to allow for characterisation of calorimetric and particle identification capabilities, including electron gamma separation studies. The CERN Neutrino Platform would be an excellent option for ARIADNE, being a dedicated facility to support LAr Neutrino detector development [21]. ARIADNE would fit in well at either the H2 or H4 charged particle beam lines, in the extension of the EHN1 experimental hall [22], where it could take advantage of the infrastructure being put in place for the WA105 double and ProtoDUNE single phase detectors. ARIADNE will have a mobile design and will be relatively small, which will allow it to be easily moved into and out of the beam, thus accommodating for other experiments at the beam or surrounding working environment. We will make use of the series of detectors being installed along the beam line to measure the particle momentum, identify particle type, and track the particle trajectory prior to entry into ARIADNE. A conceptual design of the cryostat with a beam window to accommodate for particle entry is shown in Figure 5a. It is estimated that 3 months of beam-time will be required in order to perform precise calibration and characterisation studies.

Charged particles of known mass, momentum and direction, including protons, kaons, pions, electrons and muons, will accommodate particle identification studies. The charged particles will deposit their energy inside the LAr volume of the TPC producing tracks with increasing charge density toward the track end as a consequence of the increasing stopping power at decreasing kinetic energy. Particle identification within the LAr TPC will be made by making measurements of $\mathrm{d}E/\mathrm{d}x$ versus the residual range along the track. This approach is a common and effective method for particle identification with LAr TPCs.

The ability to separate electron and gamma electromagnetic (EM) showers is one key element of LAr TPC technology. Separation of electron and gamma EM showers can be made with the proposed ARIADNE two-phase detector since the crucial information required is contained in the initial part of the shower, and therefore is contained within the detector volume. This is because the gamma converts to an electron positron pair producing double ionisation at the shower start. Additional studies could be made on determining charge recombination factors for different particle species through $\mathrm{d}E/\mathrm{d}x$ measurements and to evaluate the impact of charge recombination on particle identification capability.

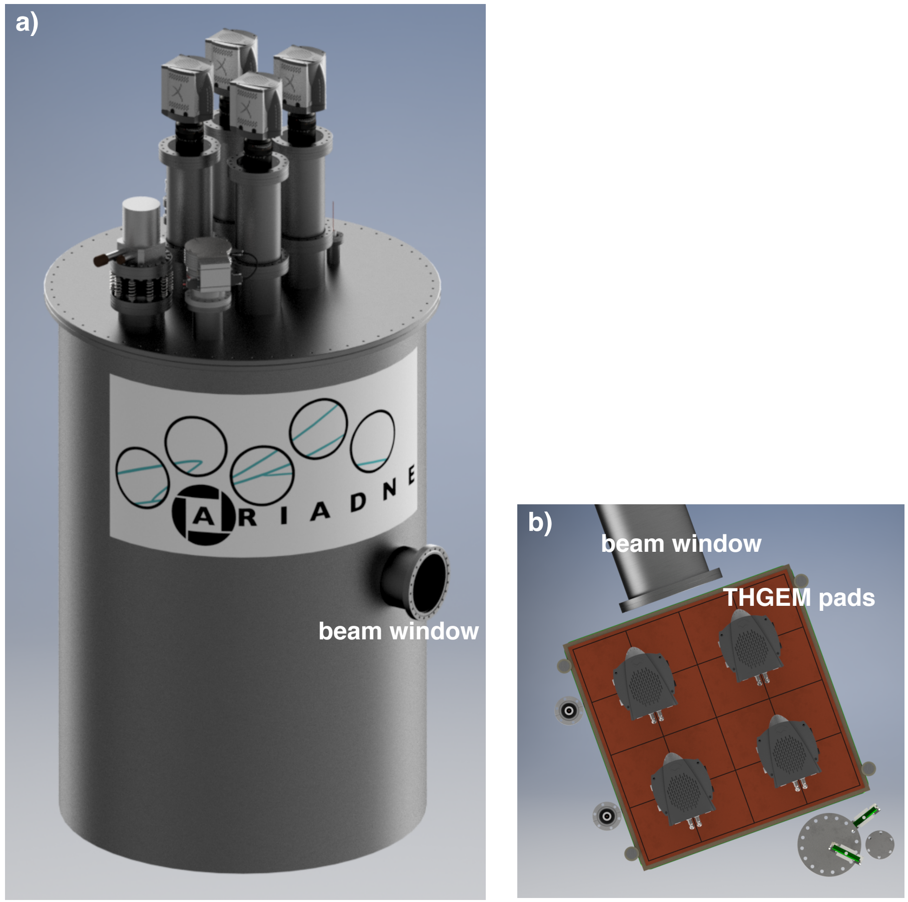

Figure 5: *a) The ARIADNE cryostat showing the beam window. b) Top-down view showing cameras and the 16 THGEM pads.*

Event reconstruction and analysis of the data will be performed off-line. In particular this optical technology will be evaluated in complex vertices where the fine granularity offered by the camera optical system will be crucial for disentangling tracks. This novel approach of using images in track reconstruction will be of great interest to LAr event reconstruction groups within the wider neutrino community.

3.2 ARIADNE Requirements at CERN

ARIADNE is a fully funded project, and will be constructed and initially characterised at the Liverpool LAr facility. Once at CERN, ARIADNE will be easily integrated into one of the charged particle beam-lines, and will only require a relatively small working space and short duration of beam time. ARIADNE will have a cylindrical cryostat with a diameter of about 1.3 m and a height of 2 m. ARIADNE will be designed to be easily mobile, allowing it to be moved into and out of the beam, thus accommodating for other experiments at the beam or surrounding working environment. ARIADNE will take advantage of the infrastructure being put in place for the larger LAr detectors. The beam lines at the H2 and H4 extension will have an energy range from 0.2 to 20 GeV, and associated detectors for particle ID; this will be suitable for our purposes. We aim to commission ARIADNE at the CERN Neutrino Platform in autumn 2017, once the facility is ready. A Gantt chart showing an overview of the ARIADNE programme, highlighting where the potential beam-time at CERN would fit, is shown in Figure 6.

Specifically, ARIADNE will require the following in addition to the infrastructure already in place:

- Approval from the CERN SPSC as a CERN project
- 3 months of beam-time in order to perform precise calibration and characterisation studies
- Interface of the detector with the beam
- A detector space of about 3×3 m^2, and a slow control monitoring space in the extension of the EHN1 experimental hall
- 2-month use of an area with a crane for assembly and commissioning of the detector at CERN after transportation, and the same for decommissioning
- Supply of pure LAr; approximately 1500 litres and related servicing infrastructure

4 Discussion & Summary

ARIADNE represents an attractive alternative readout method for two-phase LAr TPCs. We have already provided first demonstration of optical readout using an EMCCD camera and THGEM with the 40-litre Liverpool LAr prototype. We have shown that optical readout presents many clear advantages when compared to currently accepted segmented THGEM charge

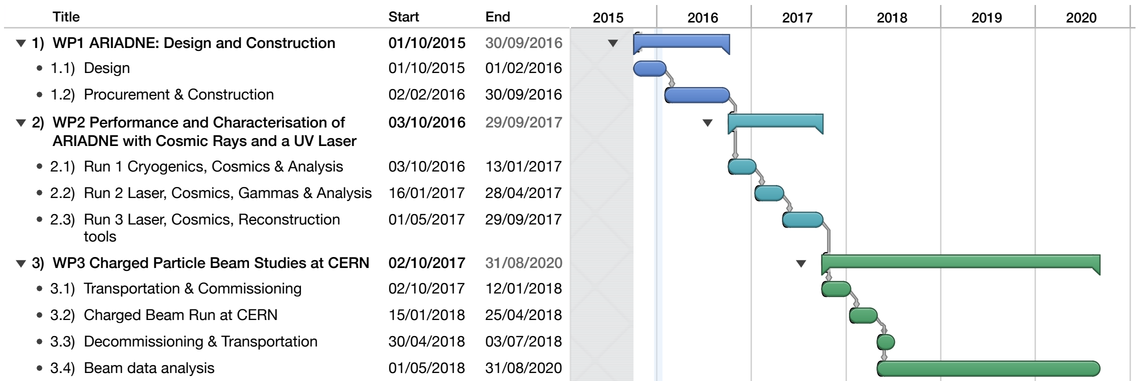

Figure 6: *ARIADNE Gantt chart overview.*

readout technologies. Optical readout is scalable, without introducing the complexity and cost required by the vast segmented charge readout anode planes placed above the THGEMs. Mounted externally from the TPC, the EMCCD cameras are easily accessible, simplifying detector maintenance and allowing for uncomplicated installation of detector upgrades as camera technology develops, whereas upgrade of currently proposed segmented anode planes would require TPC disassembly, introducing significant cost and time expenditure. The range of settings available with camera technology, such as binning, readout speed and exposure time, allows for detector readout customisation on the fly and customisation to suit the needs of a range of different experiments from precision track reconstruction using full camera resolution to the search for low energy interactions at very high camera binning using the same TPC.

ARIADNE is an ERC funded project for the maturation and characterisation of this optical readout technology. We will design, build and perform initial characterisations of ARIADNE at the Liverpool LAr facility, and we would then like to request time in a charged particle beam-line at the CERN Neutrino Platform for 3 months duration. We will be performing calorimetric and particle identification studies, including electron gamma separation, maturing and validating the novel optical readout technology. We will make use of the infrastructure and beam-line specifications that are already being planned for the CERN Neutrino Platform at the EHN1 experimental hall. We hope this innovative readout method will have a positive impact on the way we approach the design of LAr TPCs in the future.

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