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Scintillation Light Detection System in LArIAT

Pawel Kryczynski for the LArIAT collaboration[a]

[a] *Institute of Nuclear Physics,*
Polish Academy of Sciences,
ul. Radzikowskiego 152,
31-342 Krakow, Poland
and
Fermi National Accelerator Laboratory,
60510, Batavia, IL
United States
E-mail: pkryczyn@fnal.gov

ABSTRACT: The LArIAT experiment is currently taking data at Fermilab using a Liquid Argon TPC, with the aim of studying particle interactions and characterizing detector response for neutrino detectors using argon. In parallel, it serves as a test-bench to develop and evaluate the performance of the simulation, reconstruction, and analysis software used in LAr neutrino experiments. LArIAT also takes advantage of the scintillating capabilities of liquid argon and will evaluate the feasibility of using the light signal to determine calorimetric information and particle identification. To test this possibility, a scintillation light detection system consisting of high Quantum Efficiency (QE) PMT and Silicon Photomultiplier (SiPM) devices is installed in the cryostat, viewing the interior of the TPC. Light collection efficiency is maximized by means of lining the walls with reflector foils covered by a wavelength shifter layer. Collecting the light reflected at the boundaries of the active volume greatly improves also the uniformity of the light yield. Presented here are initial results of the LArIAT light detection system calibration together with the preliminary results of the dedicated simulation and its application in future LAr TPC experiments

KEYWORDS: Cryogenic detectors; Time projection chambers; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators).

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Contents

1. LArIAT experiment and its physics goals

The LArIAT [1] experiment is operating a Liquid Argon Time Projection Chamber (LArTPC) detector in a dedicated charged particle beam in Fermilab. The physics program revolves around exploration of charged particle interactions with LAr in the energy range relevant for neutrino experiments [1]. The experiment will measure cross sections of charged pions, kaons and protons interacting with argon and will study muon capture. These particles will be present in LArIAT's dedicated test beam at energies for which precise measurements are scarce. Another topic which LArIAT will address is a direct measurement of the ability of LArTPCs to distinguish between electron-induced and photon-induced showers. This is critical for neutrino experiments where π^0s will contribute to background of ν_e oscillation signals when one of the photons from the π^0 decay is missed and the detected one is mistaken for an electron. An example is MicroBooNE [3], which will investigate the source of the MiniBooNE low-energy e-like event excess in the FNAL BNB [2]. These efforts, among others, will be also used to validate relevant Geant4 simulation package models ([4] and [5]).

1.1 LArIAT R&D program

The LArIAT R&D program contains both hardware and software development for future experiments, including a novel light collection system and accurate simulations for it, which are the focus of this paper. A special emphasis in a program is put on development of 2D/3D track reconstruction. Likewise, efforts are made to improve calorimetric reconstruction with charge and light seen by the TPC PMTs. Last but not least, part of the analysis program will lead to testing Pulse Shape Discrimination methods in the neutrino physics energy range.

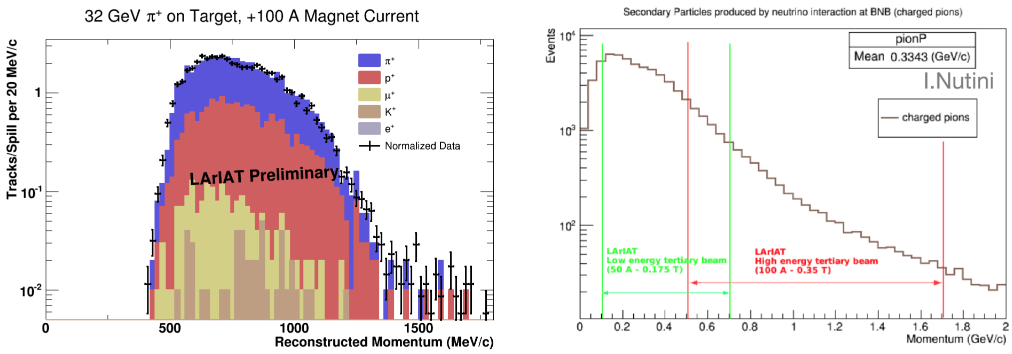

Figure 1. Simulated momentum spectrum and composition of LArIAT beam compared with data (left) and the range covered by two of the beam tunes overlaid with a spectrum of secondary charged pions produced in BNB neutrino interactions (right).

1.2 LArIAT detectors

The TPC, previously used by the ArgoNeuT experiment [6], has dimensions of 47 cm x 40 cm x 90 cm. Five different photosensitive detectors look through its wireplanes: a non-instrumented shield plane with 200 vertical wires and two instrumented planes, each with 240 angled wires [1]. Despite its small, almost table-top size, LArIAT is in a good position to provide valuable input to other experiments within the scope of the US-based neutrino program.

The first run of data-taking was successfully completed from April 30th - July 3rd, 2015. The LArIAT measurement was made possible thanks to a dedicated tertiary beamline at the Fermilab Test Beam Facility (FTBF [9]). It forms a part of the LArIAT experiment and the particle content and energies are widely tunable to suit experimental needs and thus cover the range relevant for other neutrino experiments (see e.g., Fig. 1 right - a comparison with the Booster Neutrino Beamline). The tertiary beamline includes detectors, like wire chambers used for tracking, Aerogel

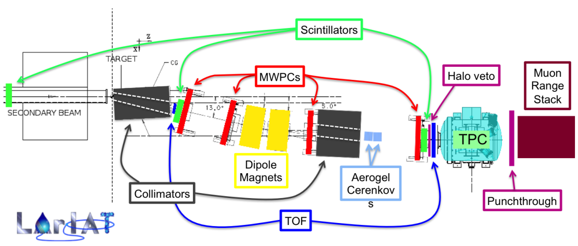

Figure 2. LArIAT tertiary beamline layout

Cherenkov, Time Of Flight counters and muon detectors used for particle identification as well as bending magnets allowing for momentum selection (Fig 2). Scintillator paddles are also positioned on the sides of the TPC cryostat to provide a cosmic ray-based trigger signal.

2. Light Detection system in LArIAT

The light detection system of LArIAT (Fig. 3) consists of 2 cryogenic PMTs – one standard and one high quantum efficiency of 2” and 3” diameter respectively. This system is augmented with silicon photomultipliers (SiPMs) with custom-made electronic boards – two 13 mm^2 size and one 6mm^2. To achieve uniform light distribution, the walls of the TPC are lined with a dielectric reflector, covered by TPB (Tetraphenylbutadiene) for the purpose of wavelength shifting, as the PMT windows are opaque to the 128 nm LAr scintillation light.

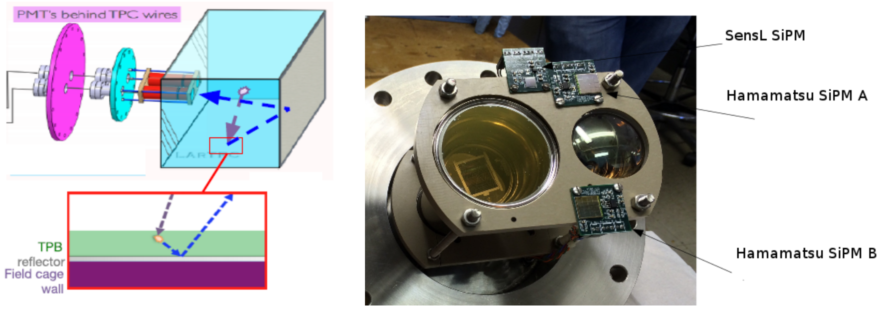

Figure 3. Light detection system scheme in LArIAT (left) and the photodetectors in the holder (right)

Such a system presents many challenges in each stage: simulation, running, and data analysis. The TPC interior is constructed of materials of differing optical properties, which is especially demanding for simulations and must be properly addressed to make sure that the correct light yield value and uniformity are obtained. Furthermore, the whole system must be thoroughly calibrated using real data. This will then feed back to simulation.

3. Light detection system MC simulation and calibration

The Monte Carlo simulation of the light detection system in LAr TPCs is a challenging effort, as the liquid argon is a well known prominent scintillator, capable of producing about 40k photons per each MeV of deposited energy. Given LArIAT test beam energies span between 0.1 and 1.5 GeV, resulting number of photons is not easy to handle in MC. The light is emitted by excited states of argon dimers created due to the ionization. They may be found as singlet, decaying in 5-10 ns or a triplet with a decay time above 1 μs. This leads to detection of slow and fast light components. Following are the descriptions of the MC simulations and first calibration results for this system.

3.1 Light simulation in LArIAT

A solution to efficiently simulate light in the LAr TPC was proposed and implemented in LArSoft [10] - by dividing the detector into cuboidal regions called voxels. The simulation is then performed in two steps: first, from each voxel the same number of photons is shot and the number of photons detected in PMTs is stored in a so-called fast lookup library. Since in the LArIAT detector the wavelength shifting material is placed on the walls and not on the PMTs, optical properties can no longer be folded into one constant, but must be simulated in more detail. This is only possible by enabling the TPB wavelength shifting process and adding material properties found in published data as well as measured in situ, using methods described in [11] and [12]. In the second step of the simulation, energy deposited by the passing particle in each voxel is converted to the number of detected photons using the library created previously and then to the waveform observed by the PMTs .

3.2 Single Electron Response

In order to obtain the number of photons detected by the PMTs, one has to convert the signal in ADC units into photoelectrons. To do this, the response of the PMTs to a single photoelectron (p.e.) has to be calculated. In LArIAT, this is done by looking at the tail of the signal and finding single p.e peaks above the baseline. Then, the peak area is integrated and the obtained distribution is fitted with a gaussian. An example of such distribution can be seen in Fig 4 (left). The Single Electron Response (SER) peak is visible at around 130 ADCs (at 1420V during test run) and noise is manifested as a sharp structure below 50 ADCs. Performing a scan for different values allows for

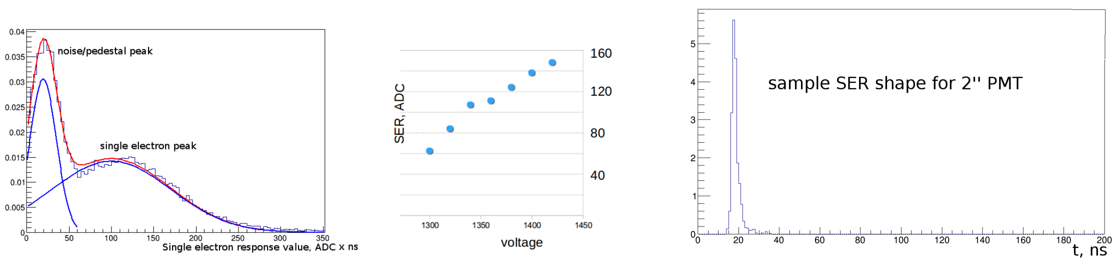

Figure 4. Single electron response distribution for a given voltage on the ETL 2" PMT (left), gain curve of the ETL PMT(middle) and the average time distribution of a single photoelectron (right).

obtaining a gain curve (Fig. 4 center), essential for the further studies using light signals saved in data. The shape of a single photoelectron (Fig. 4 right) will then be used to perform more accurate simulation of electronics response to light signal. The same procedure was repeated for the silicon photomultipliers.

3.3 Nitrogen contamination

An important application of light detection in LArTPCs is the measurement of the nitrogen contamination, as the purity of liquid argon changes the decay time of the slow component. With the increase of the nitrogen concentration, the decay time of scintillation light becomes shorter [13]. The results (Fig. 5) obtained in comparison with the nitrogen sensor installed in the LArIAT gas analyser agree with the expectations based on [13]. The inset in Fig. 5 presents an example fit of exponentials to the waveform.

3.4 Light yield

For the physics analyses involving calorimetry studies and particle identification, the value of the light yield of the system is an essential input. It offers an immediate conversion from the number of detected photons to the energy deposited. One result of the preliminary MC studies, showing a comparison of the light yield obtained with different electric field values, is presented in Fig. 6. A light yield value is calculated by dividing the number of detected photons by the deposited energy (obtained from MC true information).

A similar light yield study, helping to validate MC, is in progress using muons from the beam. A sample of single-track events longer than 60 cm and having a vertex at the upstream side of the TPC, like that shown in Fig. 7, are selected. Using the gain curve, the Single Electron Response

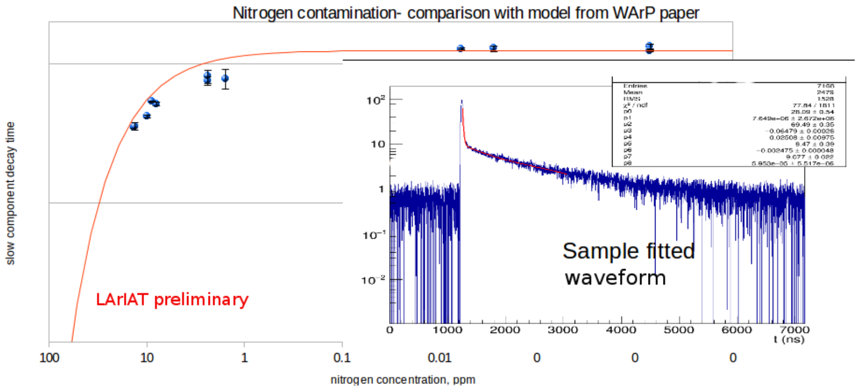

Figure 5. Decay time of the slow component in liquid argon scintillation light changing with the nitrogen concentration. The orange line is a model based on WArP data [13], dots are data from LArIAT, extracted from exponential fits as shown in inset.

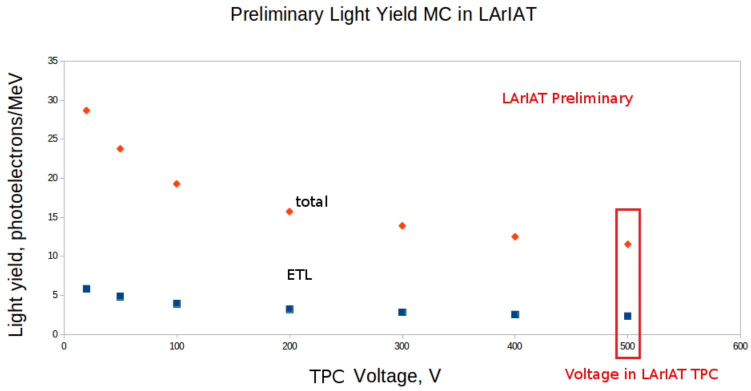

Figure 6. Light yield in LArIAT at different electric field values simulated in LArSoft using NEST ([7]). In red frame – value used in LArIAT during data taking. ETL sees only a fraction of a total light (blue dots).

(SER) value for the dataset will be extrapolated from exponential fits, and energy deposits will be calculated from the charge signal on the TPC wires.

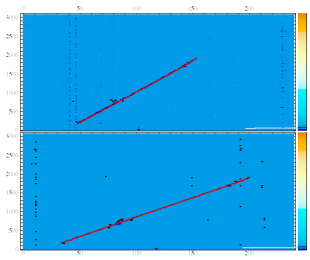

Figure 7. A sample crossing track.

4. Summary and plans for future

LArIAT has successfully completed its first run and is preparing for another one at the beginning of 2016. Many physics analyses are under way as well as refining of the reconstruction algorithms. The latter emphasizes the role of this experiment as a development platform for reconstruction in all LArTPC experiments. The light detection system works well and efforts are currently underway to combine collected light with collected charge information. This will be a important step towards a light-augmented calorimetry and particle identification in LAr TPCs.

Acknowledgments

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