The LArIAT Experiment at Fermilab

Irene Nutini, on behalf of LArIAT Collaboration
Università degli Studi di Firenze - Piazza di San Marco, 4, 50121 Firenze, Italy
Fermi National Accelerator Laboratory, U.S. Department of Energy - Neutrino Division
GSSI - Gran Sasso Science Institute, Viale F. Crispi, 7, 67100 L'Aquila, Italy

E-mail: irene.nutini@gssi.infn.it

Abstract. The LArIAT experiment at Fermilab is part of the International Neutrino program recently approved in the US. LArIAT aims to measure the main features of charged particles interactions in Argon in the energy range (0.2 - 2.0 GeV) corresponding to the energy spectrum of the same particles when produced in a neutrino-Argon interaction (neutrino energies of few GeV) typical of the short- and long-baseline neutrino beams (SBN, LBN) of the Neutrino Program.
Data collected from the 1^{st} Run are being analyzed for both Physics studies and a technical characterization of the scintillation light collection system. Two analysis topics are reported: the method developed for charged pion cross section measurement, based on the specific features of the LArTPC, and the development and test of the LArIAT custom-designed cold front-end electronics for SiPM devices to collect LAr scintillation light.

1. Introduction

The LArIAT experiment stands for Liquid Argon (Time Projection Chamber) In A Testbeam [1, 2].

Main purpose of the experiment is to perform a precise calibration of the Liquid Argon TPC detector. The LArIAT experiment is focused on the study of all the charged particles that could emerge from (ν,Ar) interaction, for neutrino energies E_ν of few GeV, typical of the SBN and LBN programs. Therefore the detector is placed on a dedicated, low momentum TestBeam line at Fermilab (FTBF) which provides a controlled environment to produce and select particles of several species, momentum and charge (mainly pions $\pi^{\pm}$, protons p, muons $\mu^{\pm}$, electrons $e^{\pm}$, kaons $K^{\pm}$...). The main goals are the characterization of the signal from different particles in the LArTPC and the optimization of the offline algorithms for Particle IDentification and calorimetric reconstruction for Liquid Argon detector technology, both TPC wires signals and LAr scintillation light collection.

The LArIAT detector combines the "traditional" Liquid Argon TPC (LArTPC) design for the ionization track imaging [3] with a new scintillation light collection system (LCS) providing enhanced light collection efficiency and uniformity [4]. The LArIAT TPC and the vacuum-insulated cryostat in which it is hosted are pre-existing components from the ArgoNeuT experiment [5]. The LArTPC consists of a rectangular box structure in which anode wires are tensioned at one side while at the other side we find the cathode plane. It has an active volume of 47 cm (width) x 40 cm (height) x 90 cm (length, along beam axis), corresponding to 170 litres of LAr (@ 90 K). There are three wire planes to see the drifting electrons inside the TPC. Induction and collection planes wires are read with dedicated cold electronics. Pulse signals are

processed and analyzed through LArSoft, a dedicated framework for Liquid Argon TPC tracks reconstruction. The 3-D reconstruction of the event (tracks and energy deposit) in the TPC is made by matching the hits/clusters on the two wire planes having the same drift time in the two views. The LArIAT light collection system consists of an array of two high quantum efficiency cryogenic photomultiplier tubes (PMT) and three Silicon PhotoMultiplier Detectors (SiPM). They are deployed in Liquid Argon and mounted behind the wire planes of the TPC. Since the light collection is performed with these optical devices Very-UltraViolet LAr scintillation photons are wavelength-shifted into optical (blue) ones by covering the boundaries of the TPC volume with TPB coated reflective foils.
A schematic representation of the LArIAT assembled system is shown in Fig. 1. In Fig. 2 the LArIAT cryostat placed along the beamline is reported .

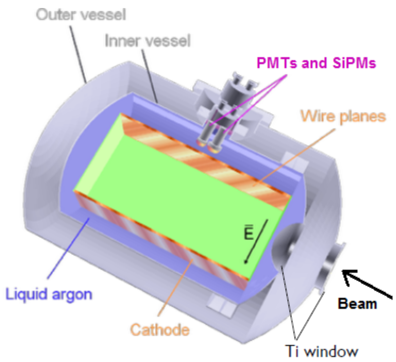

Figure 1. Schematic representation of LArIAT detector.

Figure 2. LArIAT cryostat hosting the TPC placed in the beamline at FTBF - MCenter.

The 1^{st} Runs of the LArIAT experiment lasted from April, 30^{th} to July, 7^{th} 2015. The analysis of the collected data are on going both for Physics studies (pion interaction total and exclusive cross sections, kaon interactions and decays, muon/pion separation) and for a technical characterization of the LCS - the new scintillation light collection system implemented in LArIAT. Some preliminary results have been shown in the poster presented at YRM2015 and are here briefly discussed.

2. LArIAT goal: Charged pion on Ar total cross section measurement

Charged pions are produced in a noticeable number in neutrino interactions with nuclei, like Ar, for neutrino energies of few GeV. They have very large interaction cross sections with nuclei, especially nearby the Δ resonance energy region. This is the reason why pions have been chosen as one of the main components of the charged particle TestBeam for the LArIAT experiment.

One of the goals of the LArIAT experiment is the experimental measurement of charged pion cross section on Ar in the (0.2 - 2.0) GeV energy range. Actually there are no experimental measurements for pions on Ar in this energy range. Current MonteCarlo (MC) simulation codes, like Geant4, use interaction models for Ar based on extrapolations from data with lighter or heavier elements. The goal of a dedicated pion run with LArIAT is to develop pion identification algorithms based on their interaction modes in Argon and to exploit direct and precise measurement of the pion-nucleus cross section. This in turn will reduce the uncertainty on the hadron interaction models adopted in MC simulations for Ar target when dealing with neutrino interaction products (neutrino energy reconstruction and event topology recognition in future experiments with LAr detectors).

Let us consider the **pion-nucleus total cross section** σ_{tot} for a pion traveling through a target. In general the target is not a single particle, but a slab of material containing many diffusion centers. If we assume the target centers uniformly distributed and the target thin enough not to have one center sitting in front of another one, we are in the so called **thin target** approximation. To first order, we will consider the pion in the nucleus interacting with individual "free" nucleons either p or n. To perform an experimental measurement of the σ_{tot} dependence on energy, we aim to scan different pion initial kinetic energies (N_{inc}, number of pions shot onto the target) and to count how many pions have experienced an interaction (N_{int}) and how many of them have crossed the thin target without interacting (N_{surv}). From the rate of interactions at each energy we can calculate the total cross section σ_{tot} from:

$$N_{int}(x, E) = (1 - N_{inc}e^{-\sigma_{tot}(E)Nx}) \tag{1}$$

where x is the target thickness (in cm), along the incident pion direction, N is the scattering center density in the target $N = \frac{\rho N_A}{A}$ (in cm^{-3}) and and σ_{tot} is the total cross section per nucleon (in cm^2) .

When the "thin target" approach is not applicable, i.e. in the case of **thick target** experiments, to get a precise evaluation of the pion cross section dependence on energy, it is necessary to know the energy lost by the pion while crossing the target before the interaction, i.e the energy of the primary particle at the interaction point. For this reason we have to take into account the primary particle energy deposition by collisions with atoms of the medium before the interaction. When the target is thin, it is reasonable to consider only the pion-nucleus hadronic interactions, while for thick target experiments we should also consider the possibility of **pion decay** (in flight and at rest) in the target volume and the **capture at rest** on target nuclei for negative pions π^- at the end of range (near stopping).

The LArIAT TPC active volume is equivalent to a "thick target" for charged pion interactions. To estimate the charged pion cross section on Ar from the data acquired in LArIAT, we developed a new offline analysis method, the "Sliced TPC" approach, that makes use of the fine granularity and the high spatial resolution of the detector to "slice" the thick TPC target volume into many thin target LAr slabs [8]. The two wire planes of the TPC are composed by 240 wires oriented at +/- 60° at 4 mm distance. Each wire thus collects signals ($\propto$ released energy) in a 60° inclined 4 mm thin slab of Liquid Ar. It is rather "natural" to subdivide the TPC volume in 240 slices of $\Delta x = 4$ mm/sin(60°) $\approx$ 5 mm thickness along the x axis, i.e. direction of the incident particle (pions). Each slice n can be now considered as a "thin target" and we can apply the cross section calculation from Eq.1 iteratively, evaluating the actual kinetic energy of the particle at that slab E_n^{kin}:

$$E_n^{kin} = E_{inc}^{kin} - \Sigma_{i=1}^{n}(\frac{dE}{dx})_i \Delta x \tag{2}$$

The results here reported come from **MC simulation studies** of charged pion interactions in Liquid Argon target. I did a comparison at MC simulation level between ($\pi^{\pm}$, Ar) cross section results in a thin target and in a thick target, the last treated with the method previously described.

A prediction of the total hadronic interaction ($\pi^{\pm}$,Ar) cross section dependence on the kinetic energy of the pion has been produced from "thin target" simulations with two different MC generators (Geant4 [version 10.1] using FTFP_BERT physics list - Bertini Cascade model [6, 7] and Genie [version 2.8.2] using Intranuke hA model). It appears that the two MC generators pretty well reproduce the cross section at high energy for several targets, while they give slightly different predictions for the total cross section in the Δ resonance energy region. We think that the simulation models for elastic interactions need to be better tuned. The "thick target" simulation was performed with Geant4 "at particle level", i.e. no other detector features were taken into account and simulated, except for the slices geometry in the LAr TPC volume. At each step/slice the MC returns the kinetic energy of the pion entering the slice and the information whether an interaction occurred or not in the slice, the same information it is possible to extract from the energy deposition along the track for real events. Using Eq.1 for a target thickness x = 1 cm (two slices), the pion cross section $\sigma_{tot}(E)$ is finally obtained for several energies.

The comparison between cross section results in thin and thick target with Geant4 has validated the "Sliced TPC" method for a high accuracy and statistically precise measurement of the ($\pi^{\pm}$, Ar) cross section with the LArTPC from the LArIAT experiment. In Fig. 3 the total cross section MC results for π^- are shown. The ongoing analysis on LArIAT collected data deals with the reconstruction and selection of charged pion events, the analysis of the calorimetric information along the track in the TPC, the hadronic interactions tagging and vertex finding and the evaluation of the total cross section applying the "Sliced TPC" method. The systematic errors are going to be estimated by varying the track reconstruction and pion tagging parameters both at the MC level and on the data.

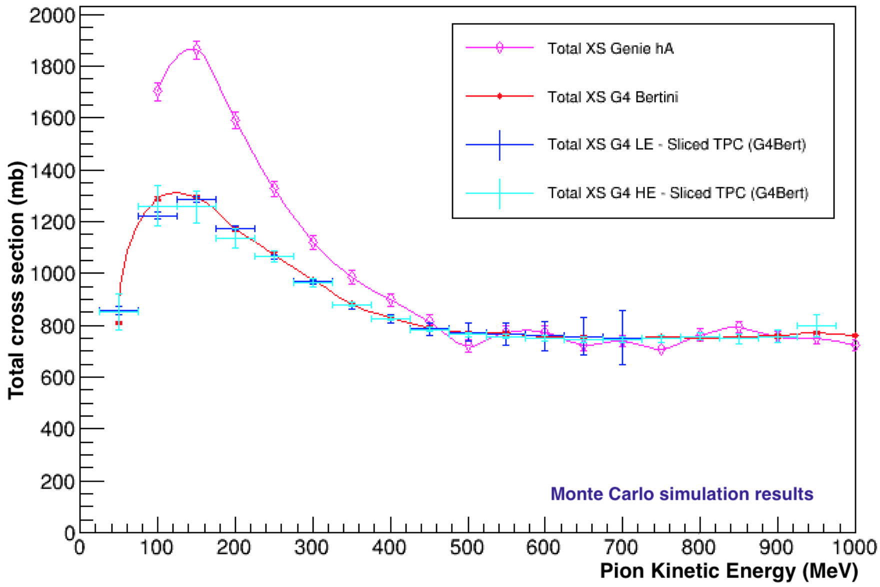

Figure 3. π^- on Ar total cross section dependence on the kinetic energy from MC simulations: comparison between Geant4 and Genie predictions for a LAr thin target and extrapolated cross section with the "Sliced TPC" approach with a Geant4 Bertini based simulation of the LArTPC thick target [8].

3. LArIAT goal: LAr scintillaton light collection with SiPMs with cold front-end electronics

One more technical goal for the LArIAT experiment is the development, test and characterization of dedicated devices for LAr scintillation light collection. In addition to the collection of the ionization charge from the TPC, the detection of the scintillation light produced in LAr is an actual point of interest, both for its trigger function for the TPC events collection and for the possibility of using also this information to improve the energy resolution of this detector technology. Actually two different light collection systems have been implemented in the LArIAT cryostat: two PMTs and three SiPM readout boards. The development and test of LAr light collection optical devices, especially dedicated cold front-end electronics for SiPM devices, for LArIAT will be here briefly reported.

The common approach for SiPM front-end electronics consists in reading the SiPM signals directly (without a preamplification stage) or with a preamplification stage outside the detector (or outside the cryostat, for cryogenic detectors), using warm electronics [9]. We decided to follow a new different way, reading these signals with front-end electronics (amplification-integration step) directly deployed in LAr working at cryogenic temperatures. Since there is a great interest and effort in SiPM commercial production and development, we decided to use and test devices from different producers in LArIAT: two Hamamatsu SiPM MPPC Arrays S11828-3344M and one single channel SiPM SensL MicroFB 60035 [10]. We designed, produced and tested (both at room temperature, 300 K, and in LN_2, 77 K) three different preamplification boards with dedicated cold electronics for the three SiPMs. Then we mounted the boards on the cryostat optical flange and deployed them in LAr behind the TPC wire planes, as shown in Fig.4.

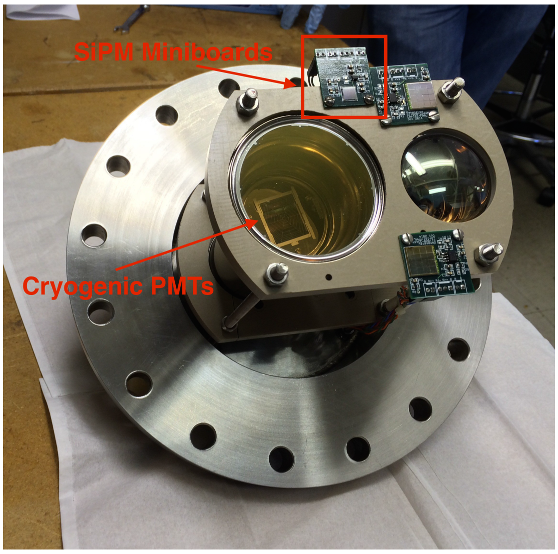

Figure 4. PMTs and SiPMs boards mounted on the inner flange of the LArIAT cryostat.

A brief comment about the preliminary characterization of the SensL SiPM (0.36 cm^2 active surface, coupled with OPA656 cold amplifier [11]) response to LAr scintillation light produced by cosmic rays in the TPC volume is here reported.

The SiPM preamplified signal is higher in amplitude and faster than the direct signal and reproduces multiple and single photoelectron pulses. The average waveform for signals collected with similar trigger conditions (e.g. cosmic trigger) has a shape comparable with the LAr scintillation time distribution and its area corresponds to the average number of photoelectrons collected by the SiPM. Studying the single photoelectrons pulses due to LAr late light in the signal tails we obtained the SER (Single Electron Response) plot from which we had an estimate of the Gain of the readout setup in LAr for a fixed bias voltage. A preliminary estimate of the SiPM Light Yield (LY) in the LArTPC has then been evaluated: $LY_{SensL} = 0.12$ pe/MeV. This value is consistent with the predictions from the comparison with the PMT LY and with the light collection simulations.

A more complete characterization of all the three SiPMs response in LAr and the comparison with the PMT results is planned for these next months. Moreover the ongoing development for light collection for LArIAT 2^{nd} Run is related to the possibility of making SiPM matrices that could cover the same area of a PMT photocathode. We designed and produced four cold-readout boards for SensL SiPM arrays. Tests and characterization of the response of these boards in cryogenics are ongoing.

4. Conclusions

The LArIAT collaboration effort is focused on the data analysis from the 1^{st} Run, both for Physics studies (e.g charged pion total cross section on Ar, ...) and for technical improvements (SiPM cold readout boards tests and characterization, ...). Results are expected to improve particle ID and event reconstruction in Liquid Argon while also contributing to useful physics that will aid analyses in other LArTPC experiments, as MicroBooNE, SBND, DUNE...

The 2^{nd} Run will begin in February 2016 after some minor changes (cryogenic technical improvements, anode wires electronics modifications, installation of new larger SiPMs mounted to custom readout boards...).

References

[1] Cavanna F, Kordosky M, Raaf J, Rebel B and LArIAT collaboration, LArIAT: Liquid Argon In A Testbeam, *arXiv:1406.5560 [physics.ins-det]*, June 2014

[2] LArIAT/T-1034: Liquid Argon TPC In A Test beam, TSW - Technical Scope of Work for the 2013 FERMILAB Test Beam Facility Program, February 2013.

[3] Rubbia C, The Liquid-Argon Time Projection Chamber: a new concept for neutrino detectors, *CERN EP Internal Report* pp 77-8, 16 May 1977

[4] Szelc A M, The LArIAT light readout system, *JINST 8 C09011.*, September 2013

[5] Anderson C et al,The ArgoNeuT detector in the NuMI low-energy beam line at Fermilab, *JINST 7 P10019*, October 2012

[6] Agostinelli S (GEANT4 Collaboration), Geant4 - a simulation toolkit, *Nucl. Instrum. Methods A 506* (2003) pp 250-303

[7] Heikkinen A, Stepanov N, Wellisch J P, Bertini intra-nuclear cascade implementation in Geant4, *Computing in High Energy and Nuclear Physics*, pp 24-28, March 2003

[8] Nutini I, Study of charged particles interaction processes on Ar in the 0.2 - 2.0 GeV energy range through combined information from ionization free charge and scintillation light., *FERMILAB-MASTERS-2015-03*

[9] Collazuol G, The SiPM Physics and Technology- a Review, LAL Orsay, June 2012

[10] SensL Single Channel SiPM MicroFB 60035, datasheet

[11] OPA656, Wideband, Unity-Gain Stable, FET-Input Operational Amplifier, Texas Instruments, datasheet (2008)