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The light detection system of the ICARUS detector in the Short Baseline Neutrino program at Fermilab

M. Babicz[1] on behalf of ICARUS collaboration

H. Niewodniczanski Institute of Nuclear Physics PAN, ul. Radzikowskiego 152, Krakow, Poland

E-mail: marta.babicz@physik.uzh.ch

Abstract: The Short Baseline Neutrino (SBN) program at Fermilab is an extensive experimental programme aiming at searching for sterile neutrino(s) [1], whose existence is one of the fundamental open questions of neutrino physics. It employs three Liquid Argon Time Projection Chamber (LArTPC) detectors, called ICARUS, MicroBooNE and SBND, sampling the Booster Neutrino Beam (BNB) at different locations from its target. The SBN detectors, working near the Earth's surface, are subjected to a substantial cosmic background, which can mimic genuine neutrino interactions. Thus, it is essential to distinguish the signals related to the neutrino beams from those induced by the cosmic rays. The light detection system is a vital part of LArTPCs, but its role is even more critical for surface-operating detectors like ICARUS. The ICARUS light detection system is based on 360 Photomultiplier Tubes (PMTs). Its main role is to provide an efficient trigger and contribute to the 3D reconstruction of detected events. The light detection system calibration and further trigger system improvements were performed for the final detector configuration during the detector commissioning at Fermilab. The trigger system effectively exploits the information given by the PMTs. To further increase that system's efficiency in event filtering, an alternative method based on Convolutional Neural Network (CNN) has been developed. Simulation-based results show that this technique can reduce the cosmic background by up to 76% with a neutrino selection efficiency of 99%. However, to filter the real data cases, which are usually not identical to the simulated ones, this method was improved by applying Domain Adversarial Neural Network (DANN). The results prove that adversarial training through a DANN

*Corresponding author.
[1]Currently employed at University of Zurich, Winterthurerstrasse 190, Zurich, Switzerland.

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2023 JINST 18 C02056

can alleviate the simulation bias, demonstrating the first successful application of DANN for CNN as an event classifier for a LArTPC.

Keywords: Large detector systems for particle and astroparticle physics; Neutrino detectors; Particle identification methods; Time projection chambers

2023 JINST 18 C02056

Contents

1 Introduction

The Short Baseline Neutrino (SBN) program at the Fermi National Laboratory (Fermilab) in the US aims to definitely solve the sterile neutrino puzzle by employing three Liquid Argon Time Projection Chamber (LArTPC) detectors sampling the same neutrino beam. One of the detectors is ICARUS, located at 600 m on-axis from the Booster Neutrino Beam (BNB) target. In addition, the ICARUS detector will also be exposed to off-axis Neutrinos at the Main Injector (NuMI) beam. The ICARUS detector has successfully operated at Gran Sasso National Laboratory (LNGS) from 2010 to 2013, taking both the CNGS neutrino beam and atmospheric data with high purity Argon and good detector stability. The detector was later moved to CERN, where it was subjected to significant refurbishment and later installed at Fermilab. It is now taking data at shallow depths, exposed to the substantial cosmic background, which can mimic genuine neutrino interactions. Therefore, distinguishing signals related to the neutrino beam from those induced by cosmic background is fundamental. For this purpose, a high-performance light detection system has been developed and tested.

2 ICARUS detector

The concept of LArTPC for neutrino studies was developed by C. Rubbia in 1977 [2]. The ICARUS detector was the first full-size LArTPC to study neutrinos. The detector consists of two identical adjacent modules, dimensions of $3.6\,\mathrm{m} \times 3.9\,\mathrm{m} \times 19.6\,\mathrm{m}$ externally surrounded by thermal insulation layers. Each module houses an inner detector composed of two TPCs with a shared cathode. Each TPC is equipped with an anode, a field-shaping system, and scintillation light detectors. Each TPC anode is made of three parallel wire planes with a 3 mm spacing between neighbouring planes and a 3 mm wire pitch. The total number of wires and electronic channels in the detector is 53,248. For each TPC, the wires in three anode planes are mounted at 0°, +60°

and -60° with respect to the long edge of the modules. They are biased so that the first two planes work in an induction mode and the ionisation electrons pass them almost unaffected. The third plane works in a collection mode, i.e., the ionisation electrons are collected by its wires.

The cathode plane is mounted symmetrically at a distance of 1.5 m from the wires on each side of every module. This distance defines the maximum drift path of ionisation electrons. At the nominal electric field of 500 V/cm, the maximum drift time of these electrons in LAr is about 1 ms. Hence, it is possible to obtain projection views of the same event for all three wire planes, with one coordinate related to the wires and another related to the drift time. The 3D reconstruction based on three projections results in precise spatial imaging of events recorded in the detector's fiducial volume. Very good calorimetric measurements can also be obtained from the charge collected by the third wire plane.

3 ICARUS light detection system

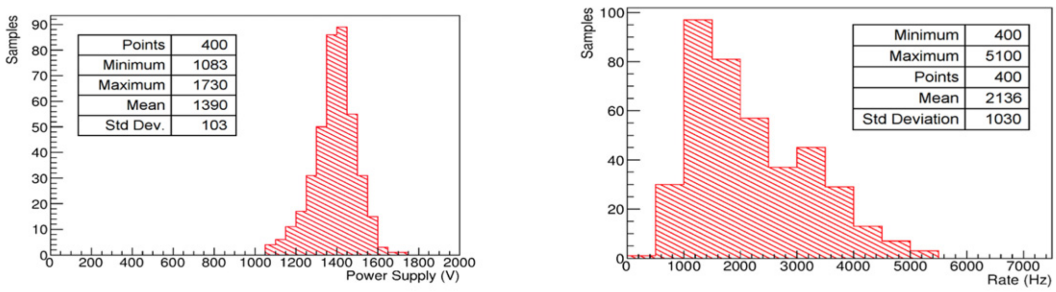
The ICARUS light detection system comprises 360 Hamamatsu R5912-MOD 8″ PMTs. The PMTs are distributed among four detector walls, 90 units installed behind the anode wire planes of each wall. The main task of the light detection system is to provide time information based on fast LAr scintillation light, which forms the basis of the trigger system and complements the information available from the anode wires to determine the spatial positions of tracks in the detector. To handle the expected substantial cosmic background, the light detection system upgrade at CERN was critical for the ICARUS operation at a shallow depth at Fermilab [5].

3.1 PMT tests and measurements at CERN

The ICARUS PMTs have 10 dynodes and hemispherical bialkali photocathode (K_2CsSb) with platinum undercoating. Each PMT is provided with a custom-made base circuit to supply the voltage and to read the signal directly from the PMT anode. For the LAr scintillation light (λ = 128 nm) detection, a uniform layer of the TPB (Tetraphenyl Butadiene) wavelength shifter of a thickness of ~210 μg/cm^2 was deposited by the ICARUS collaboration on the sensitive surface of each PMT by using a dedicated evaporation system [3].

The ICARUS light detection system was characterised and installed during the detector overhauling at CERN after studies based on simulations and laboratory tests devoted to optimising its performance. The 400 PMTs (360 plus 40 spares) were tested at room temperature, and 60 of them were also tested at cryogenic temperature. Moreover, specific tests, such as the signal linearity as a function of supply voltage and light intensity, were performed for a smaller number of PMTs [4]. Tests at room temperature took place in a specially arranged dark room at CERN. Tests at cryogenic temperature were carried out in groups of 10 PMTs directly immersed inside a large dewar filled with LAr (T = 87 K), maintaining darkness and thermal isolation. The measurement apparatus was based on a laser diode (λ = 405 nm), a charge preamplifier (CANBERRA 2005), and an amplifier (ORTEC 570). The PMT charge distribution was recorded by a multichannel analyser (CAEN N915), and the PMT waveforms by a 10 GSa/s oscilloscope (LeCroyWaveRunner 104MXI).

The PMT gain and dark current were derived from the output charge distribution for a single photoelectron excitation. The PMT charge distributions were fitted with an analytical expression consisting of an exponential function that accounts for PMT and electronic noise and one, two or three Gaussian functions that describe the PMT response to one, two or three photoelectrons. The position of the first peak allows the PMT gain extraction. During the tests, the PMT nominal voltage was defined as the value needed to obtain $G = 10^7$. The nominal voltage distribution for the whole set of 400 PMTs operating at room temperature is shown in figure 1(a). The distribution has a mean value of 1390 V and $\sigma \approx 100$ V, so the differences among the ICARUS PMTs are relatively small. The PMTs can experience a decrease in gain at LAr temperatures, which could be recovered by increasing the supply voltage. The PMT dark current was estimated by measuring the pulse rate in dark conditions. The discrimination threshold level was set to the minimum value between the pedestal and the single photoelectron response peak. The histogram of the dark current rate for 400 PMTs tested at room temperature is shown in figure 1(b). The average dark current rate is below 5 kHz, which was the maximum value reported by the manufacturer at room temperature. Maintaining a stable and controlled environment may help minimize the increase in dark current rate in LAr.



(a) The PMT supply voltages distribution.

(b) The PMT dark current rate.

Figure 1. Left: distribution of supply voltages to achieve a nominal gain $G = 10^7$ for the total set of 400 PMTs operating at room temperature. Right: the PMT dark current rate measured at room temperature for the 400 PMTs, with supplied voltage assuring gains at the level of 10^7 [6].

Tests of 60 PMTs at $G = 10^7$ were performed to check their timing characteristics at both room and LAr temperatures [5]. No significant variations were observed among the different tested samples. The same mean values resulted at room and LAr temperatures: a rise time of 3.9 ± 1.1 ns, a FWHM of 5.6 ± 1.1 ns and a fall time of 10.3 ± 1.6 ns [6], in good agreement with the nominal values indicated by the manufacturer. The PMT time characteristics were also performed depending on the voltage, the position of photoelectron emission on the photocathode and the orientation of the PMT relative to the Earth's magnetic field. The measurements were made at room temperature for 7 PMTs without TPB coating, and some of them were repeated at LAr temperature.

As expected, the results of the measurements showed that increasing the inter-dynodic electric field by increasing the supplied voltage leads to an improvement in electron speed, resulting in a

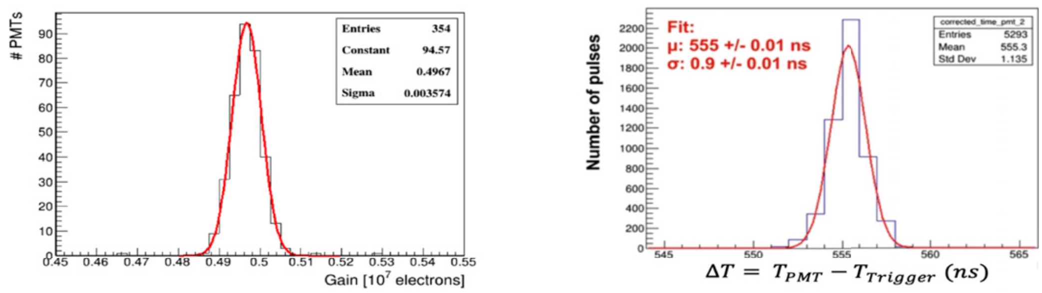
2023 JINST 18 C02056

decrease in electron transit time, a reduction in signal rise time and width, and a decrease in time spread. The measured electron transit response of a single PMT as a function of the power supply voltage followed the assumption that the transit time improves in inverse proportion to the square root of the supplied voltage. The observed variation of the electron transit time between the two temperatures of ~0.8 ns is within the systematic error of the measurement of ~1 ns. All tested PMT samples indicated good uniformity of their responses and that their time characteristics are preserved at the LAr temperature.

3.2 Gain and timing calibration at Fermilab

The light detection system was tested at Fermilab after transport and before the cool-down of the detector. The number of 357 out of 360 working PMTs were found, with performances consistent with the test realised at CERN. A fast laser-based calibration system [7] allows for gain/time calibration, equalisation and monitoring of each PMT channel. The system is based on a laser diode (Hamamatsu PLP10, λ = 405 nm, FWHM = 100 ps), whose pulses are delivered to each PMT via optical fibres. The system is also equipped with a programmable optical attenuator, optical switch and mode scrambler. A set of 36 fibre optic patch cords (each 20 m long) permits the light pulses to be delivered to UHV pass flanges mounted on 36 detector chimneys. Inside each chimney, the light pulses are distributed to 10 PMTs using a 1 × 10 optical splitter and 7 m long fibre patch cords. Thus, 10 out of 360 PMTs can be illuminated simultaneously by using an optical switch.

The recorded PMT signals caused by laser pulses are integrated over a 100 ns window to acquire the charge spectra. As a result, gain curves can be produced as a function of the voltages applied to the PMT, and thus it is possible to extract the voltage corresponding to the nominal gain of $G = 0.5 \times 10^7$. An automated tuning algorithm, based on PMT gain measurement from single background photoelectrons, was applied to the voltage values to reduce the relative gain spread below 1%, as shown in figure 2(a), and continuously monitor the level of PMTs' gain.



(a) PMT gain distribution.

(b) PMT time response.

Figure 2. Left: the distribution of PMT gain equalised at $G = 0.5 \times 10^7$ for 354 PMTs after the fine-tuning of voltage values, resulting in a gain spread less than 1%. Right: PMT time response equalised by the laser to trigger signal with 1 ns resolution.

2023 JINST 18 C02056

The achievement of spatially accurate tracking of events inside the TPC and temporal correlation with the BNB structure requires precise knowledge of the time response of each PMT at the ≈1 ns level. The PMT time response varies channel by channel due to the different PMT transit times and cable effects and may change over time. The delay between the generation of the detector trigger signal and the arrival time of photons to the PMT is measured for each channel with a dedicated laser run with precision at the level of 1 ns, as shown in figure 2(b).

4 Proposal for event filtering using deep learning

The PMT-based trigger system effectively exploits the information given by the LAr scintillation light. For each beam spill window, the ICARUS trigger system can assess which PMTs have a signal exceeding a predefined threshold, at what time that signal is recorded with respect to the start of the beam window and how many times the PMT registered an *opening* above the threshold. A new opening is counted every 0.16 µs that the PMT signal remains above a pre-set threshold. Thus the number of openings acts as a discretised measurement of the time over the threshold, which is highly correlated with the signal amplitude. The BNB delivers neutrinos in a bunch at a rate up to 5 Hz. The accelerator complex informs the trigger system of the arrival time of each bunch and, consequently, the timing of the beam spill window, during which the detector may issue a trigger if there is a signal in PMTs above the threshold. This results in about 5% of beam spills being recorded. Despite a large reduction factor, the recorded events are still dominated by cosmic backgrounds due to an accidental coincidence of the beam window and optical signals produced by cosmic rays. Thus, using the PMT timing information for event filtering by applying a Convolutional Neural Network (CNN) has been proposed [8–10]. The simulation-based results show that with this method, the cosmic background can be reduced by up to 76% with a neutrino selection efficiency of 99% unbiased by various tested kinematic observables [9].

However, the CNN trained on simulated event samples is prone to errors due to simulation mismodelling, potentially causing the inadvertent rejection of neutrino events. To address this issue, adversarial training methods using Domain Adversarial Neural Networks (DANNs) were employed to prevent neural networks from exploiting features only present in one of two domains (i.e., simulation or real data). With this approach, the features learnt by the DANN are simultaneously discriminative and domain invariant. In order to test the effectiveness of DANN as a method of reducing simulation dependence, a series of mock-data studies were performed [9]. The results showed that, without adversarial training, the original CNN can reject a sizeable portion of neutrino interactions in the mock data. However, once the adversarial training is used, the network can mitigate the bias and maintain a very high neutrino selection efficiency (the primary goal of the filter) whilst continuing to achieve a notable rejection of cosmic-ray backgrounds. It was also shown that the background rejection might be improved through semi-supervised domain adaptation of the DANN using labelled real cosmic ray events.

2023 JINST 18 C02056

5 Conclusions

The ICARUS light detection is a fundamental part of the detector allowing the precise timing and interpretation of a TPC event. Tests and evaluations of the PMTs' performance at CERN proved to fulfil the requirements of the SBN program. ICARUS' light detection system is up and running, enabling the detector to acquire data regularly. A possible CNN-based event filter to separate neutrino interactions from the cosmic background has been developed using the PMT information. Current ICARUS simulation showed that the filter based on Domain Adversarial Neural Network mitigates the potential loss of efficiency at the cost of some reduced background rejection. The event filter can be implemented as a part of the ICARUS production workflow, and its output can become the input to higher-level analyses.

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