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Calibration and Timing Performance of the Light Detection System in the ICARUS Detector

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ABSTRACT: ICARUS is the largest Liquid Argon Time Projection Chamber (LArTPC) in operation and serves as the Far Detector of the Short Baseline Neutrino (SBN) program at Fermilab. It aims to investigate the possible existence of sterile neutrinos with $\Delta m^2 \approx 1\ \text{eV}^2$ using the Booster Neutrino Beam (BNB) and explore physics beyond the Standard Model with the Neutrinos at the Main Injector (NuMI) beam. The ICARUS light detection system, comprising 360 TPB-coated large-area Photo-Multiplier Tubes (PMTs), is crucial for triggering and event reconstruction. Due to its shallow installation, the detector is exposed to a high flux of cosmic rays, necessitating precise timing to reject background events and align neutrino interactions with the beam time profile. This talk will detail the timing inter-calibration procedures for the ICARUS light detection system, which achieve sub-nanosecond resolution. Additionally, the performance of the system in reconstructing the timing of neutrino interactions from the BNB and NuMI beams will be discussed. The results highlight the effectiveness of the ICARUS light detection system in enhancing the detector's capability for precise and reliable neutrino selection.

KEYWORDS: Noble liquid detectors (scintillation, ionization, double-phase); Neutrino detectors; Time projection chambers (TPC)

Contents

1 The ICARUS detector at Fermilab

ICARUS is the Far Detector of the Short Baseline Neutrino (SBN) program at Fermilab, sitting 600 m on-axis on the Booster Neutrino Beam (BNB) [1] and 6° off-axis from the Neutrinos at the Main Injector (NuMI) beam [2]. Its ultimate goal is to provide the oscillated neutrino spectra for the SBN program, allowing to measure both ν_μ disappearance and ν_e appearance in the BNB beam with two detectors and definitively resolve the sterile neutrino puzzle in the $\Delta m^2 \sim 1$ eV^2 range [3].

ICARUS is the largest liquid argon (LAr) time projection chamber (TPC) detector currently in operation, totaling about 476 active tons divided into two independent, but identical and adjacent modules. The interior of the modules is about 19.6 m long in the BNB direction, 3.6 m wide, and 3.9 m high. Each module hosts two TPCs that share the same central cathode plane. Three parallel wire planes are located on either side of the drift regions, just before the walls of the cryostat. Photomultiplier tubes (PMT) are mounted behind the anode wires to collect scintillation light. The cathode is transparent so the PMT walls see light from both TPC volumes. Since the ICARUS detector sits on the surface, the modules are enclosed in a cosmic ray tagger (CRT) system and shielded by a $\sim$ 3 m concrete overburden to reduce the cosmic muons flux.

While waiting for commissioning of the SBN near detector, ICARUS has been pursuing its standalone physics program that includes a ν_μ disappearance search with BNB, $\nu - Ar$ cross-section measurements and sub-GeV beyond the Standard Model (BSM) searches with the NuMI beam [4]. Its third physics run recently concluded in July 2024.

2 Light readout and timing calibration strategy

The ICARUS light collection system comprises 360 large-area (8") Hamamatsu R5912-MOD photomultiplier tubes (PMTs) arranged in a honeycomb pattern along the inner walls of the two cryostats. Each cryostat features 180 PMTs, with 90 mounted per wall. Signal waveforms are digitized at 500 MSa/s using a total of 24 CAEN V1730B boards [5, 6]. Each board reads-out 15

PMT channels, plus an additional reference or accelerator signal for timing synchronization [7]. The PMTs are coated with tetraphenyl-butadiene (TPB) for sensitivity to 128 nm light [8].

Precise timing is a powerful tool for identifying accelerator neutrino interactions. The timing profile of accelerator neutrinos reflects the bunch structure of the proton beam. For instance, BNB features a 1.6 μs spill with 81 bunches separated by 18.9 ns (52.8 MHz) [1]. This corresponds to a spatial separation of approximately 6 m, meaning up to four neutrino bunches can be simultaneously traversing the length of ICARUS during a spill. Accurate event timing enables direct tagging of neutrino interactions that adhere to this time-spatial correlation, without relying on charge reconstruction. This capability significantly improves event selection and background rejection. To achieve the required nanosecond-level timing resolution, ICARUS employs a three-tiered calibration strategy to align the PMT times:

1. Hardware synchronization. This step removes timing jitters between the CAEN V1730B readout boards and the trigger hardware, ensuring consistent synchronization.
2. Laser Calibrations. Simultaneous laser pulses are used to cancel differences due to the PMT transit times and cable delays.
3. Cosmics Calibration. Downward-going cosmic muons provide a natural timing reference, enabling further equalization across the PMTs.

These inter-calibration methods align all PMT signals to sub-nanosecond precision. This accurate reconstruction of interaction times is essential for the synchronization with the beam profile.

3 Laser calibrations

The first stage of timing calibrations exploits the laser system installed at ICARUS. An Hamamatsu PLP10 laser diode head generates pulses (λ = 405 nm, FWHM = 60 ps) which are then distributed to all 360 PMTs by a system of optical fibers, light splitters and optical feed-through flanges [9, 10].

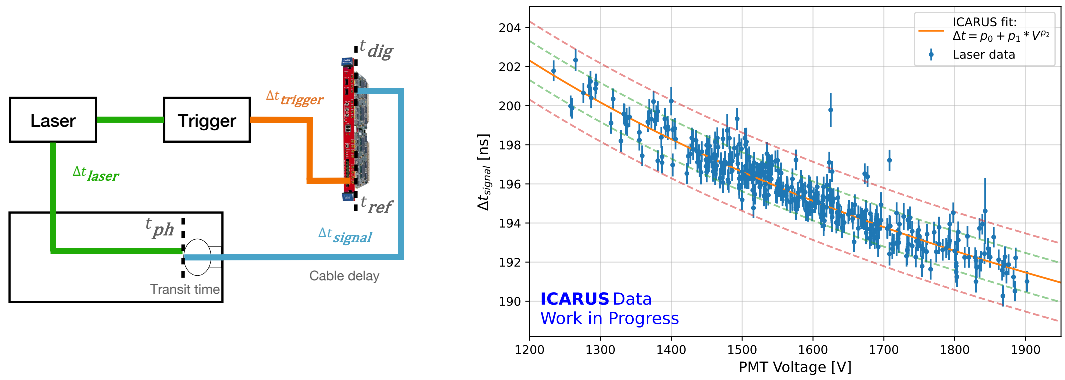

Figure 1. Left: Measurement scheme for the laser calibrations. Right: Distribution of Δt_{signal} delays from the laser measurement as a function of the applied PMT voltage.

The purpose of the laser calibrations is to factor out the propagation delays between the moment a photon hits the photocathode (t_{ph}) and the one its pulse is recorded in the readout electronics (t_{dig}). This time difference (Δt_{signal}) is dominated by the signal cable delay from the PMT to the digitizer board and the transit time inside the tube itself. An external pulser is used to trigger the laser system. After characterizing the delays in the laser system (Δt_{laser}) and the trigger line ($\Delta t_{\text{trigger}}$) with sub-nanosecond precision [9, 10], the signal delays are extracted by measuring the difference between t_{dig} and t_{ref} as

$$\Delta t_{\text{signal}} = (t_{\text{dig}} - t_{\text{ref}}) + \Delta t_{\text{trigger}} - \Delta t_{\text{laser}}. \tag{3.1}$$

The result of this measurement is shown in Fig. 1 as a function of the PMT voltage, alongside a scheme of the setup. The delays have a constant offset of $O(200$ ns) which is expected from the signal cable length. A 10 ns spread is clearly visible on top of it and correlated with the applied voltage, representing the contribution from the different electron transit times in the PMTs.

4 Cosmics calibrations

Laser calibrations are limited by the fact that the laser light is point-like and shines on a specific spot on the photocathode. This depends on where the fiber is pointing, which might be different PMT to PMT. As a result, the time response with the laser is different than in the case of uniform illumination up to a few nanoseconds. Moreover, 5 – 7% of PMTs do not see direct laser light. The second calibration step exploits the abundant downward-going cosmic muons crossing the detector to remove these biases. Muon tracks shine uniformly on the PMTs, and can also be spatially selected and constrained with TPC (or CRT) reconstruction.

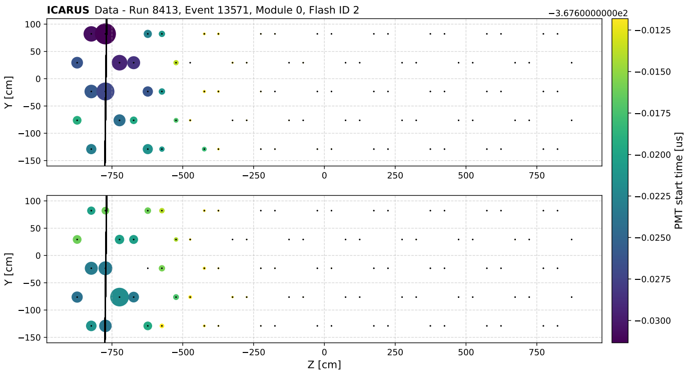

Figure 2. Optical event display of a cosmic muon track on the two walls of a module. Each point represents a tube: the size is proportional to the photoelectrons collected, while the color is time.

Considering vertical downward-going muons, a linear relationship is expected between the PMT y-coordinate and the time light is collected. However, deviations arise depending on the relative position between the track and each tube. If a track gets closer to one wall, a x-coordinate dependence is introduced by the shorter light propagation time to that wall. Similarly, a z-dependence exists if a PMT is not in front of the track as light needs additional propagation time even for the same quota. An optical data event display of a cosmic track is shown in Fig. 2. Additional selection criteria can be applied event-by-event to recover the linear relationship. For instance, a cut on the collected photoelectrons (PE) can be used to exclude PMTs that lie far from the track. The x-dependence can instead be addressed by averaging the times across the two opposite walls.

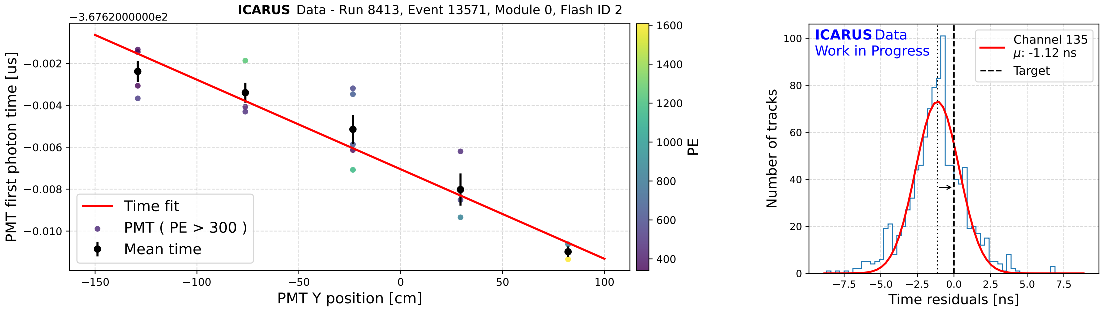

Figure 3. Left: PMT times as a function of their quota. Colors represent the total collected PE. A 300 PE cut is applied. The black points are the mean times, averaged across the opposite walls. Right: Distribution of time residuals over multiple tracks for a single PMT channel, whose mean is taken as the correction factor.

The plot on the left of Fig. 3 shows the mean PMT times at a given quota averaged across the two walls after a 300 PE cut. The linear fit represents the expected timing trend. Time residuals can therefore be computed between single PMT times and the expected value at that quota from the linear fit. Considering a large sample of tracks, a distribution of residuals is obtained for each PMT channel. An example of that is shown on the right of Fig. 3. The means of these distributions are subsequently used as channel-by-channel correction factors to further align the PMT times.

The performance of the timing corrections is validated on an independent dataset of cosmic muons. Fig. 4 shows the resulting time equalization after applying in sequence the two calibration stages to the validation sample. While the laser corrections bring the inter-calibration to $O(1\text{ ns})$, the cosmics calibrations push it further to sub-nanosecond level.

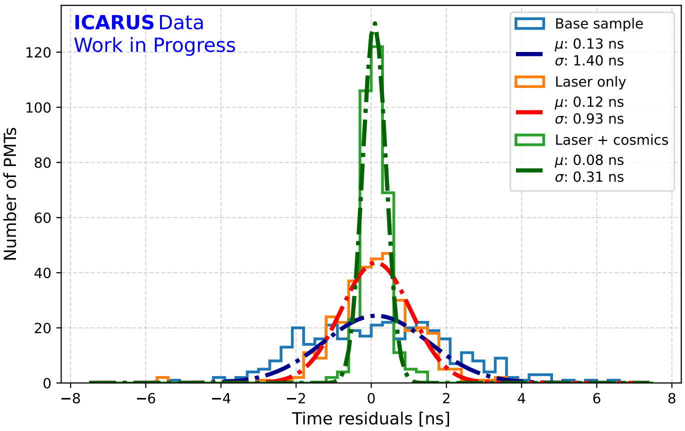

Figure 4. Time residuals from downward-going muon tracks in an independent validation sample after applying in sequence all available timing corrections. The final timing equalization is $O(300\text{ ps})$.

5 Beam event timing

Building on its precise PMT inter-calibration, ICARUS employs a light-only reconstruction method that determines the time and spatial location of scintillation events to relate them to the beam structure. Visualizing the beam bunches requires comparing the times of neutrinos that traveled the same distance from the target. Since neutrinos interact anywhere, a time-of-flight (ToF) correction is applied to refer their times to the crossing of the entry plane into ICARUS. This is achieved by averaging the first PMT times from the opposite walls of a module, which removes dependence on the (x, y) position, and then using the barycenter of the detected light flash as the z position of the event for the ToF correction. As a result, no charge information or reconstruction is used.

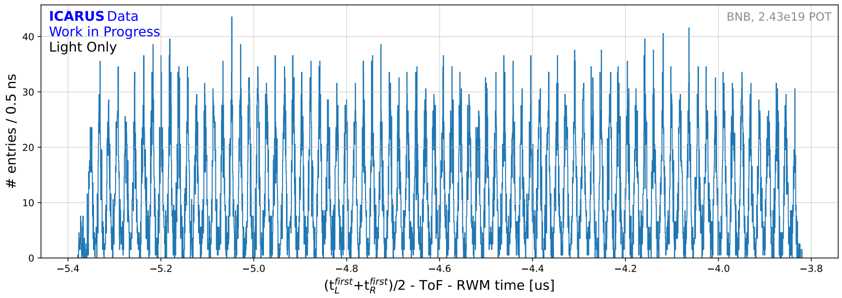

Figure 5. Interaction times at the ICARUS entry plane relative to the RWM time, showing the bunched structure of the BNB spill. No charge information is used.

Fig. 5 shows these interaction times relative to an accelerator-synchronous signal (RWM) which marks the arrival time of the first proton bunch at the target. After rejecting cosmics, the bunched BNB spill is clearly resolved. Despite the simplicity of the light-only extraction method, the bunch structure exhibits a high signal-to-noise ratio. Fig. 6 shows the extracted bunch spacing (18.935 ± 0.001 ns) and average width (σ = 2.99 ± 0.04 ns) from the fit to the BNB spill. The bunch width resolution is currently far from the intrinsic size ($\sigma \sim$ 1.3 ns), but improvements are expected by developing a more refined algorithm or exploiting charge information.

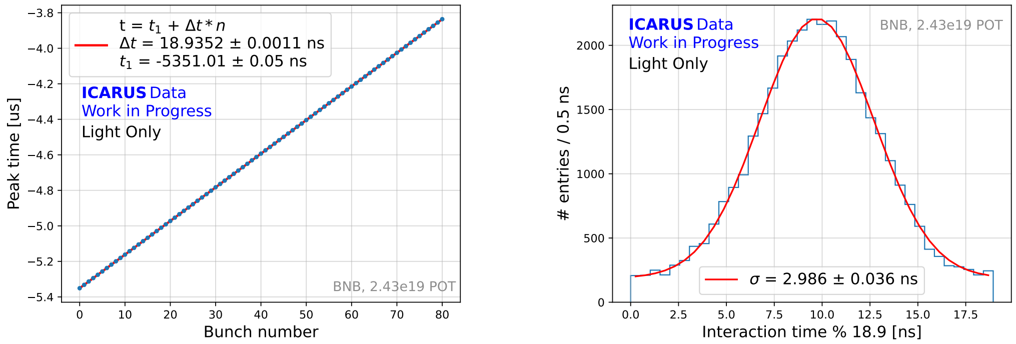

Figure 6. Bunch spacing (bunch peak time vs bunch number) and average width from the BNB structure as reconstructed with the light-only method.

Acknowledgments

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