17th International Neutrino Summer School 2026

Performance and Stability Characterization of the ICARUS Light Detection System

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for the ICARUS collaboration

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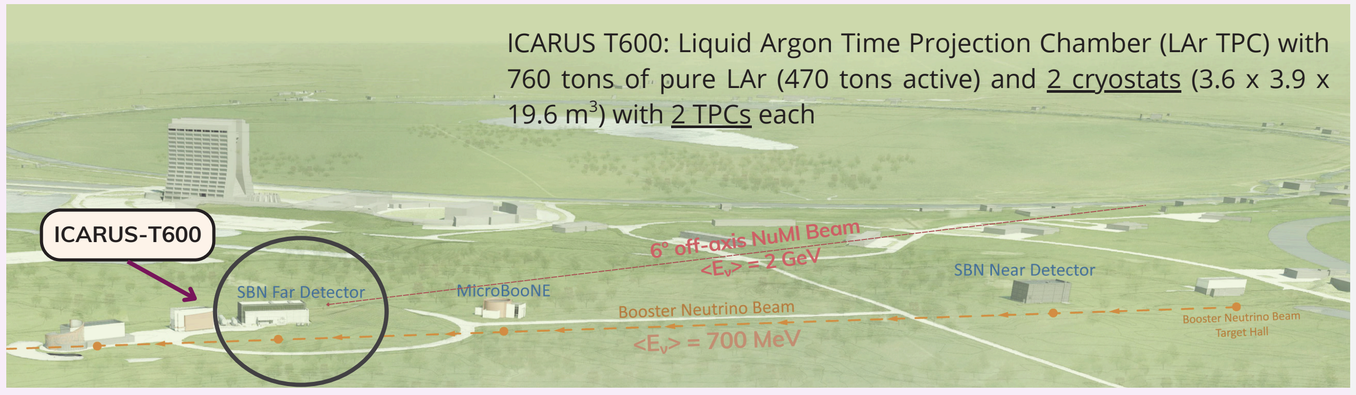
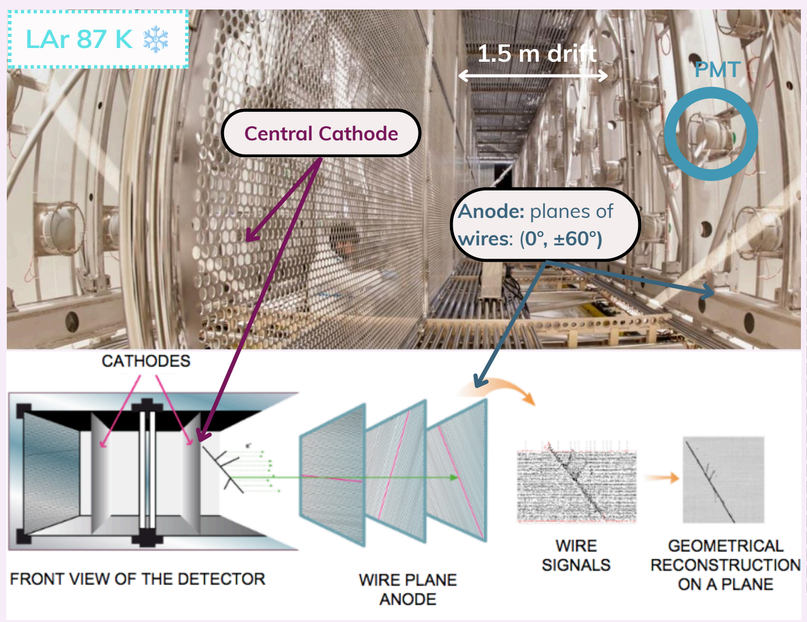
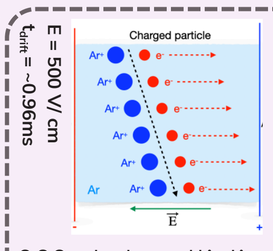
The ultimate goal for ICARUS is to provide oscillated neutrino spectrum as Far Detector of the Short Baseline Neutrino (SBN) Program and measure disappearance + appearance with two detectors to resolve the sterile neutrino puzzle. While SBND progresses through commissioning, ICARUS has been pursuing single-detector physics: • disappearance with BNB + disappearance with NuMI (Neutrino-4 claim). • cross-section measurements with NuMI. • Sub-GeV BSM searches with NuMI **[a]**.

SBN Far Detector: ICARUS-T600

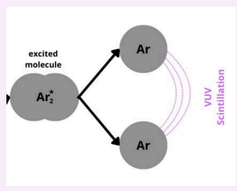






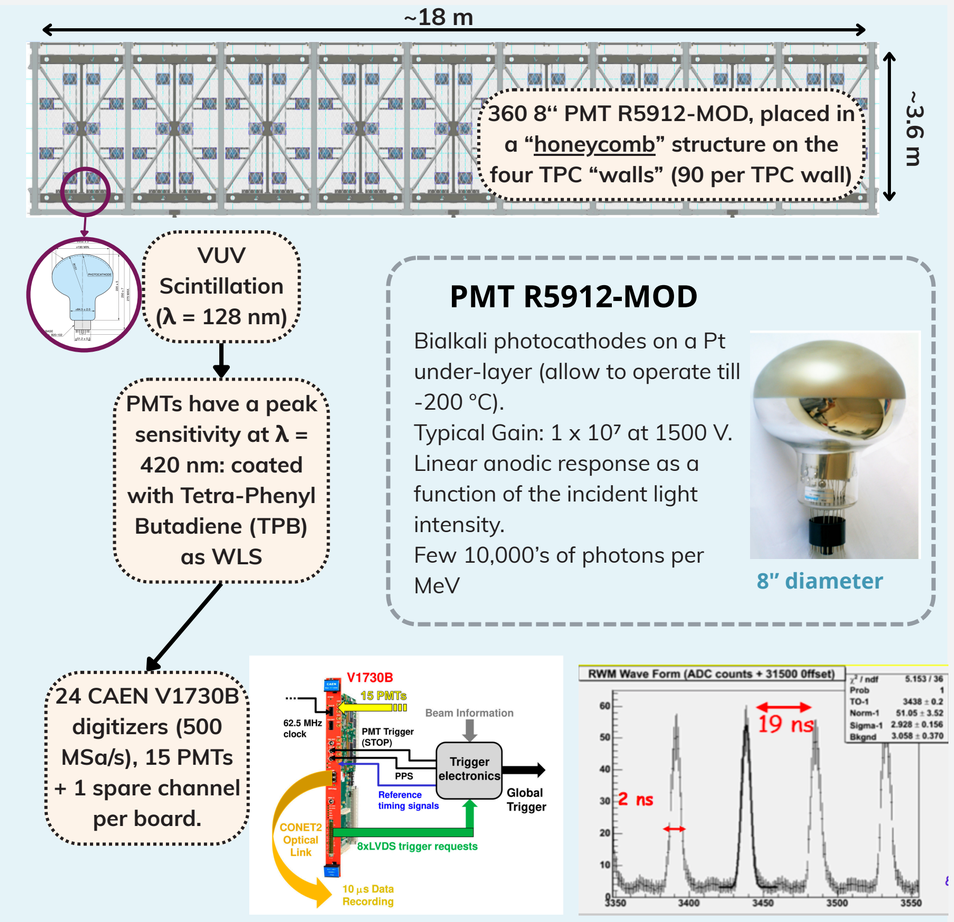
3 wire planes at different orientation (54000 wires, 3 mm pitch) to measure the **ionization** signal

360 photomultipliers (**PMTs**) behind the wires measure **scintillation light** providing timing and trigger



2.85 m **concrete overburden** to suppress and external **Cosmic Ray Tagger** (**CRT**) to tag **cosmic rays background**

ICARUS-T600: Light Detection System

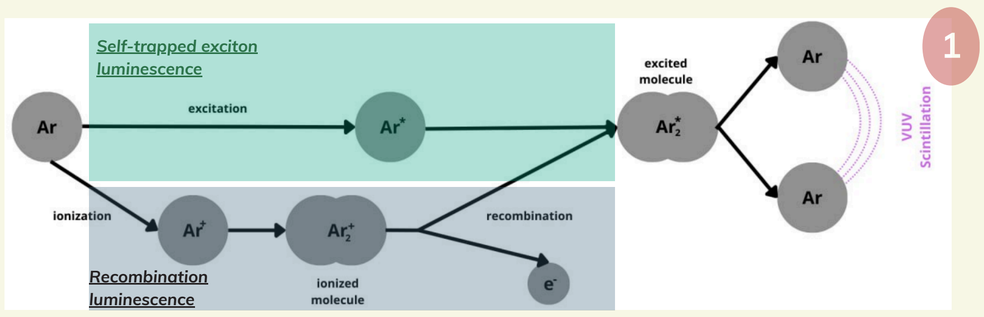


Goals:

- identify the occurrence time t_0 of each interaction inside the TPCs with O(ns) precision → **within 2 ns beam spills**
- improve spatial resolution of the events reconstruction along the longitudinal direction with O(m) precision.
- fundamental element for the **trigger system** for events and for cosmic ray veto (in anti-coincidence with Cosmic Ray Tagger signals) **[b]**.

Scintillation light in LAr: Waveforms Analysis

Waveform analysis enables the extraction of key scintillation parameters, including the fast and slow components and their decay times. This analysis aims both to validate Data–Monte Carlo comparison, investigating current residual discrepancies, and to measure possible correlations between scintillation timing and liquid argon purity.



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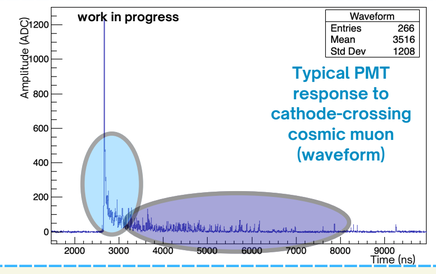
Light with two characteristic time constants (tau):

*Decay of the singlet state of Ar*₂* → Fast component 6-7 ns (25-30%)

*Decay of the triplet state of Ar*₂* → Slow component 1500 -1600 ns (70-75%)

2 → Intermediate component (PMT instrumental effect)



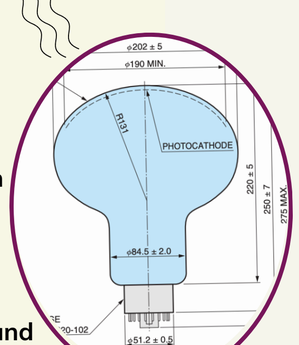
3

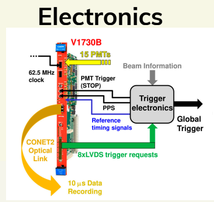
few scintillation photons

Photocathode Quantum Efficiency

1 Photoelectron

Dynodic chain and Electronics





→ Single Photoelecton Response (SPR)

4

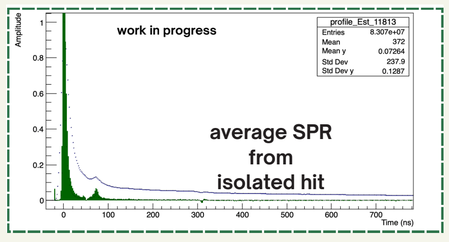
Vertical Tracks Selection → vertical cosmic muon tracks (cathode-crossing)

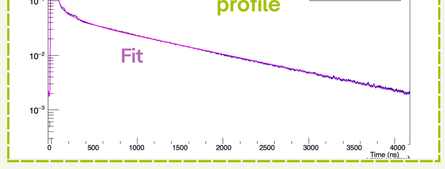
Extraction of waveforms

Selection of waveforms → Selection of the **12 brightest PMTs for each flash;**
• Alignment of all waveforms at t_0=0;
• Normalization of the aligned waveforms;

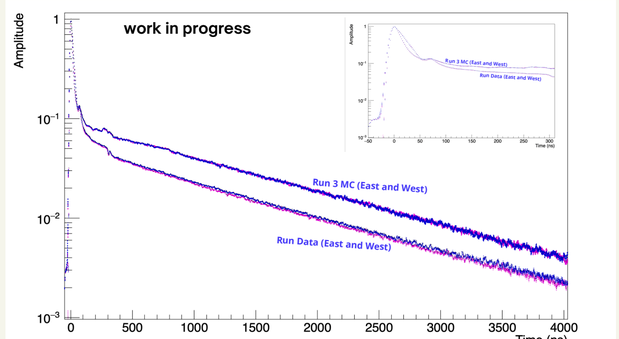
Average waveform → Average waveform over all the flashes of the selection

Fit on the average wf → **Fit function** + SPR convolution





$$f(t) = \sum_{j=f,i,s} \frac{A_j}{2\tau_j} \exp\left[\frac{1}{2}\left(\frac{\sigma}{\tau_j}\right)^2 - \left(\frac{t-t_m}{\tau_j}\right)\right]\left[1 - \mathrm{erf}\left(\frac{1}{\sqrt{2}}\left(\frac{\sigma}{\tau_j} - \frac{(t-t_m)}{\sigma}\right)\right)\right]$$



Examples of a Data–Monte Carlo comparison showing residual discrepancies in the scintillation waveform shape and timing. The analysis is in progress with different Monte Carlo variations.

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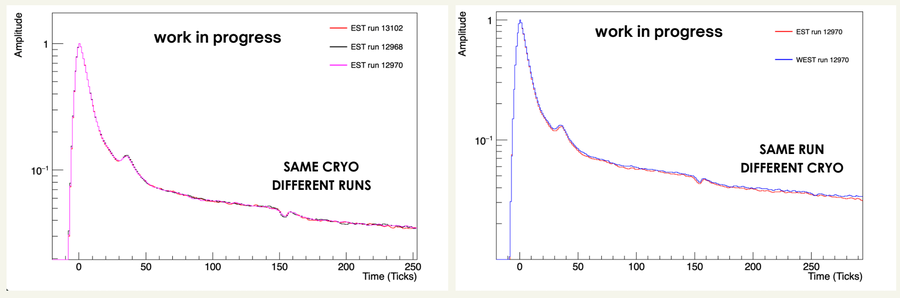
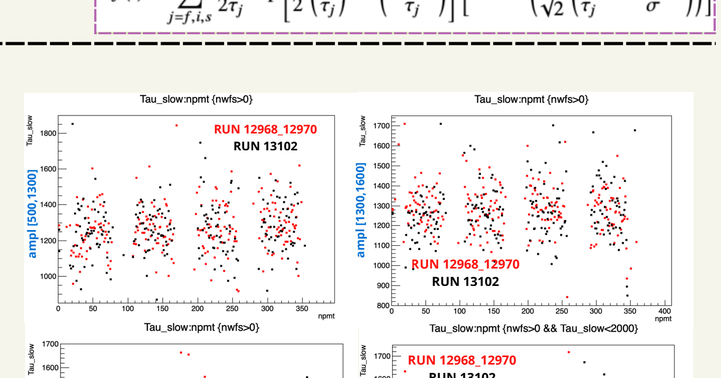


Electron Lifetime (ms)	West	East
Run 12968	6,310	4,656
Run 12970	6,300	4,606
Run 13012	8,177	6,512

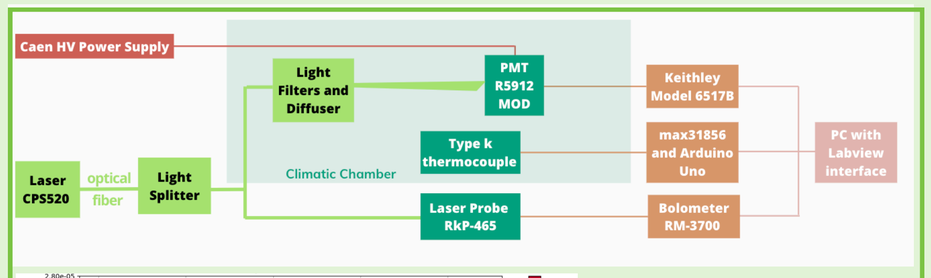
Previous studies have shown that impurities such as O_2 and N_2 can affect liquid argon scintillation by reducing the slow-component decay time and light yield.

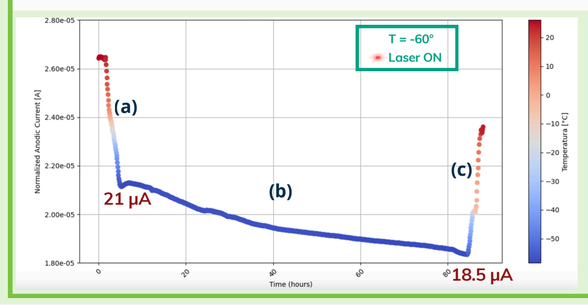
6 In ICARUS, where electronegative contaminants are maintained at sub-ppb levels, no significant variations in waveform shape or scintillation timing have been observed through this analysis methodology **[c]**.



PMT Gain Stability

During ICARUS operations at Fermilab, the Light Detection System exhibited a progressive reduction in PMTs gain under cryogenic conditions. Since stable gain is essential for accurate timing, event reconstruction, and trigger efficiency, a dedicated R&D campaign was carried out @ INFN Catania (my master thesis!) to investigate the origin of the effect. Laboratory measurements were performed under controlled temperature conditions to characterize the gain evolution and guide the development of effective mitigation strategies for long-term detector operation.





During each cooling we identified three phases:

- (a) gain loss during cooling from room temperature
- (b) gain loss at a fixed low temperature (permanent loss);
- (c) gain increase during temperature raising.

From January to November 2021 (Commissioning)

Preliminary measurements on PMTs gain ~15% gain loss in 250 days (1.80 %/month) with PMTs gain ~0.7 × 10^7

A dedicated laboratory setup was developed to measure PMT gain stability as a function of time (current mode). A single PMT was operated in an environmental chamber down to −60 °C under continuous illumination: stable gain was observed at room temperature, while cooling cycles produced a significant and irreversible gain degradation **[d]**.

RUN 1-2: 2022/23

Installation of 2.85-meter concrete overburden (June 2022): PMTs were equalized in gain at 0.46 × 10^7 ± 2.1% and showed a gain loss rate of 0.64 %/month.

From RUN 3: 2023 till now

Installation of new signal cables and the overall reduction in the PMTs voltage. current average gain is 0.39 × 10^7 ± 0.7% and the gain loss rate is 0.31 %/month.

[a] P. Abratenko et al., Eur. Phys. J. C (2023), *doi.org/10.1140/epjc/s10052-023-11610-y*
[b] B. Ali-Mohammadzadeh et al, JINST (2020), *10.1088/1748-0221/15/10/T10007*
[c] C. Saia, JINST (2026) *10.1088/1748-0221/21/04/C04038*
[d] C. Saia et al., NIMA (2024), *10.1016/j.nima.2024.169861*
C. Saia et al., pre-print (2025) *arxiv.org/abs/2605.31327*