The upgraded laser calibration system of the ICARUS experiment at FNAL

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Imaging Cosmic And Rare Underground Signals

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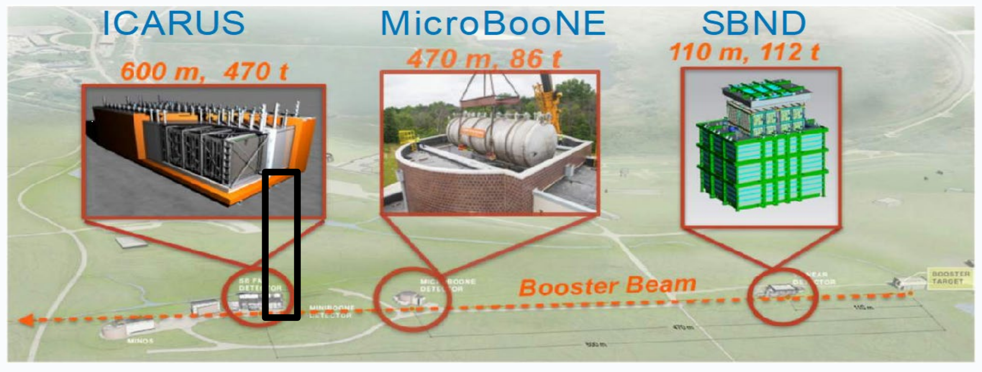
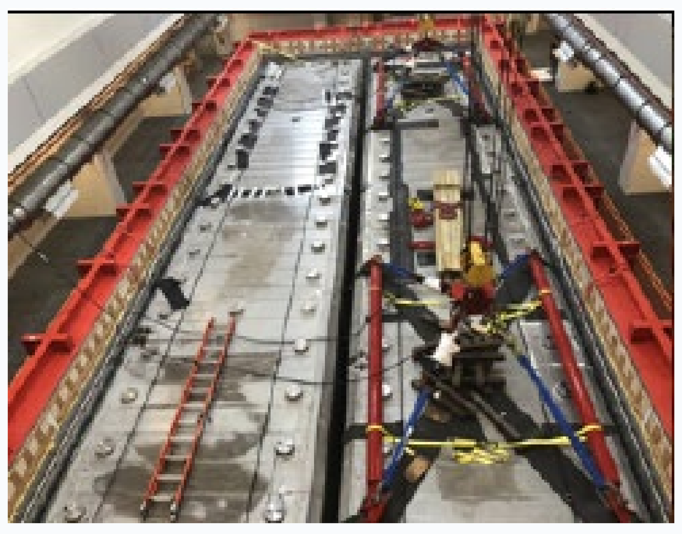
The ICARUS-T600 Liquid Argon (LAr) Time Projection Chamber (TPC) is presently used as a far detector of the Short Baseline Neutrino (SBN) program at Fermilab (USA) to search for a possible LSND-like sterile neutrino signal at $\Delta m^2 \sim O(eV^2)$. It is placed at shallow depth on the Booster Neutrino beam (BNB). To reduce the cosmic ray background, in addition to a full coverage cosmic ray tagger (CRT), a system based on 360 large area Hamamatsu R5912-MOD photomultipliers (PMTs) is used to detect scintillation light at 128 nm from ionizing particles. An important requirement for this system is the calibration in gain and time of each PMT. Calibration is based on a custom system based on a low-power laser diode at 405 nm. Laser pulses arrive now, after the upgrade, to a 1x40 custom optical splitter (MAGIC BOX) and then to UHV flanges, by 20 meters long optical patches. Light is then delivered to the 360 PMTs connected to a single flange in group of 10 , by 7m long injection optical patches. Extensive tests of the used components and care in the design of the optical system have guaranteed a sizeable calibration signal, even in a situation where available power is low. Gain equalization of PMTs has reached a 1.5% resolution and timing calibration is within 1 ns. The status of the upgraded laser system will be reported, together with present performances of the calibration procedure.

1 – Introduction

The SBN Program aims at definitely solving the "sterile neutrino puzzle" by exploiting:

- the well characterized FNAL Booster ν beamline (BNB) in addition to the NuMi beamline;
- A far detector (Icarus) and a near detector (SBND) based on the same liquid argon TPC technique.
- In addition CARUS alone can confirm or refute the Neutrino-4 claim, at the SM-3 reactor (Russia) , of a disappearance neutrino signal with L/E ~1-3 m/MeV in less than one year





- **SBND:** BNB @ 0.25 Hz, 0.03 Hz cosmics
- **ICARUS:** BNB @ 0.03 Hz, 0.14 Hz cosmics
  NUMI @ 0.014 Hz, 0.08 Hz cosmics

Thanks to the simultaneous study at different baselines, with similar detectors, of ν_e appearance and of ν_μ disappearance, SBN will cover much of the oscillation parameters allowed by past anomalies.

Icarus location at shallow depth requires to mitigate the large cosmic ray background

2 - The ICARUS T600 detector and its light detection system

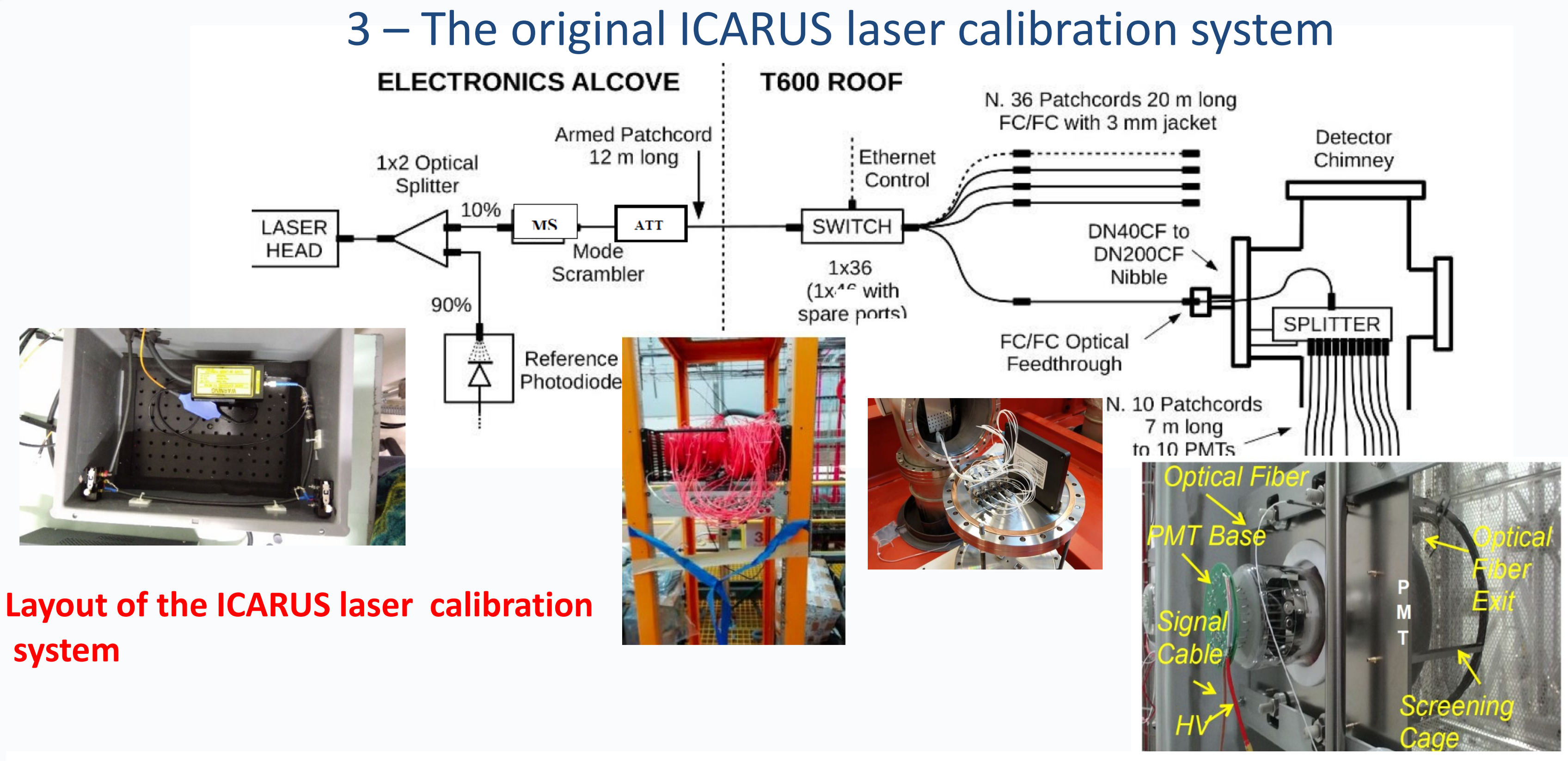
ICARUS T600 detector is made of two identical cryostats, filled with about 760 tons of ultra-pure liquid Argon. Each cryostat houses two TPCs with 1.5 m maximum drift path, sharing a common central cathode. Charged particles interacting in liquid argon produce both scintillation light and ionization electrons. The TPC electronics is designed to allow continuos read-out, digitization and waveform recording of signals, allowing a full 3D reconstruction of tracks, with a resolution of 1 mm³. Scintillation light (at 128 nm) is detected by a system of 360 Hamamatsu 8" PMTs directly immersed in liquid Argon (5% coverage, 15 p.e./MeV). The photo-detection system will allow to:

- Identify the time of occurrence (t_0) of any ionizing event in the TPC with O(1 ns) resolution
- Localize events with < 50 cm spatial resolution and determine their rough topology
- Generate a trigger signal for readout

360 HAMAMATSU R5912-MOD (8" diameter) PMTs mounted behind the TPC wire planes.

The ICARUS PMTs system, together with the CRT will allow to mitigate the large rate (~10 kHz) of cosmic ray events through the LAr TPCs, due to its location at shallow depth with a limited overburden.

3 – The original ICARUS laser calibration system



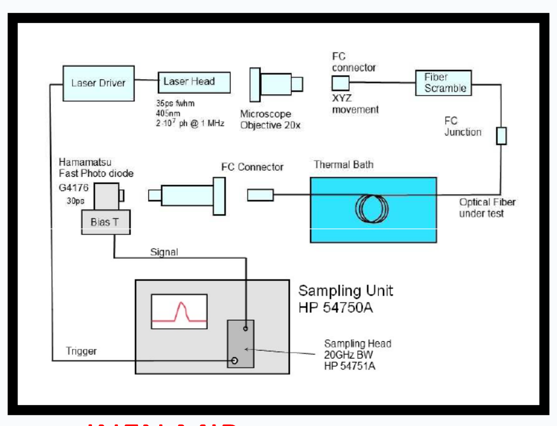
Layout of the ICARUS laser calibration system

The PMTs timing/gain equalization may be performed by using fast laser pulses . The laser pulse is sent to each PMT via a distribution system based on a Hamamatsu PLP10 diode laser, a Mode Scrambler (MS), a programmable attenuator(ATT), a 10 m armed fiber patch cable, 20m fiber patch cords (36), VACOM UHV optical feed-throughs (36), fused fiber splitters (36) and one Agiltron optical switch.

Problem: light pulses must have minimal time dispersion and signal attenuation at delivery point in front of the PMTs. In addition the system must have a minimal spread in channel to channel total delay (ΔT) and delivered power of the signal in front of the PMTs.

Strategy:

- *characterize components for use at 400 nm, taking into account timing properties /attenuation*
- *use low cost components, e.g. laser diodes ($) instead of Q-switched lasers ($$) and Telecom ready components*



INFN MIB test system

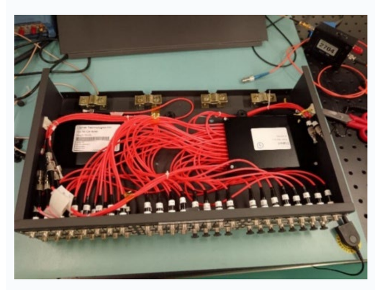
Cons:

- **low peak power (< 1 W) power budget in the calibration system is a *must* (use multimode (MM) fibers instead of single mode(SM) fibers to reduce injection problems, losses …)**
- **A full calibration takes 1 full day (36 runs, long startup time for DAQ)**

4 – the upgrade of the ICARUS laser calibration system

- Optical switch: input signal to 1 of N output lines. MM fiber type to work at 400 nm. Needs minimal insertion loss (IL) and response uniformity.
- Optical splitters 1xN : divide input signal to N output lines. Fused 1xN splitters are cheaper ($), but usually available for Telecom (850/1300 nm) wavelengths. Needs minimal IL and response uniformity.
- As the power budget is tight, initially an optical switch was used.
- In-situ measurements demonstrated the feasibility of a 1x40 custom optical splitter approach
- Signals are a factor 1/40 lower at least, BUT found enough for calibration
- Calibration in the same-go of 360 PMTs instead of 10 (one row connected to a single output of the optcal switch)

Optical switch

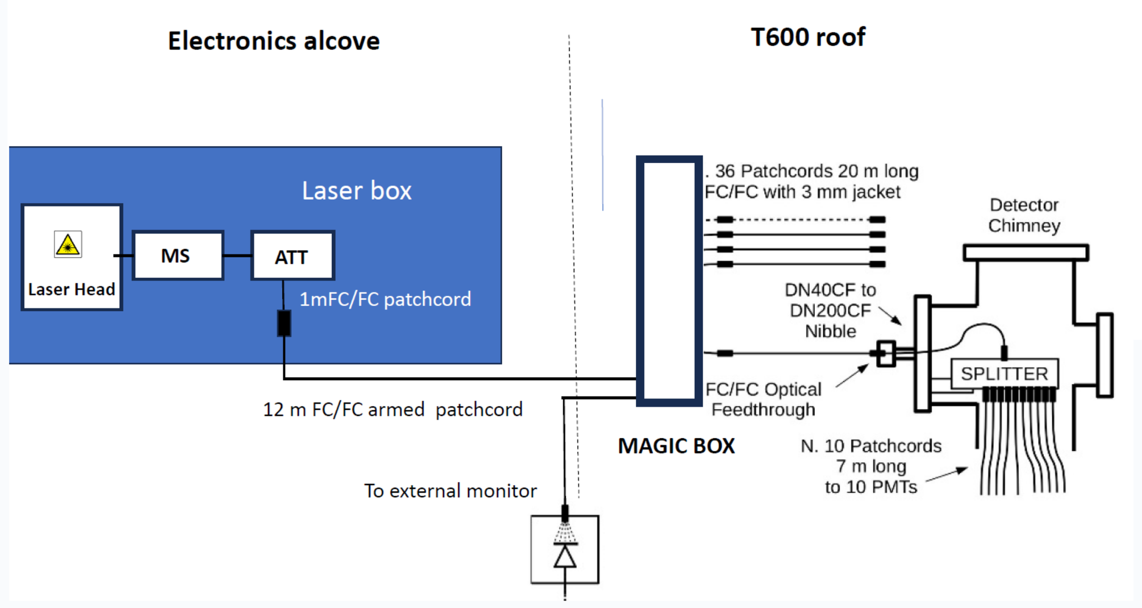


Magic box

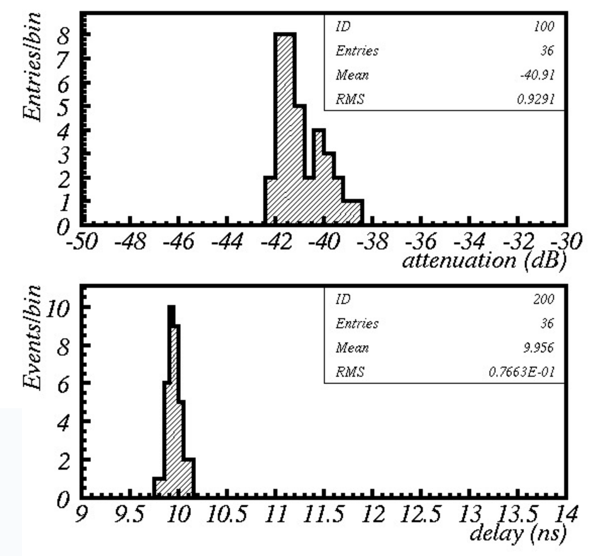
Laboratory test results:

- The custom splitter (MAGIC BOX) was assembled cascading a 1x6 splitter, with 4 1x10 splitters
- All components were tested accurately in laboratory (as an example 1x10 splitters were selected from a 10 pcs sample)
- The distribution of attenuation (in dB) and delays at the pigtails of the MAGIC BOX are shown in figure

Cons: a full calibration (360 PMTs) in one run (< 20 mins)

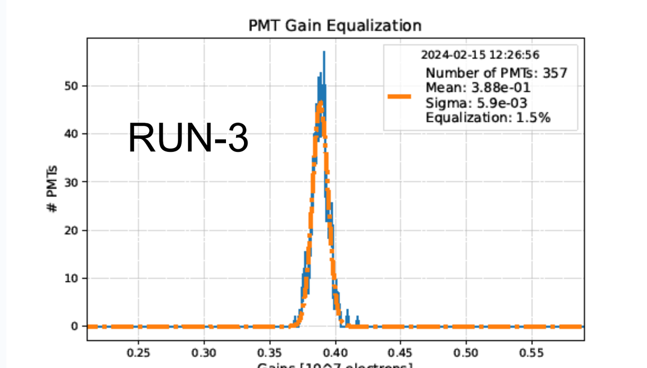


Upgraded setup of the ICARUS laser calibration system

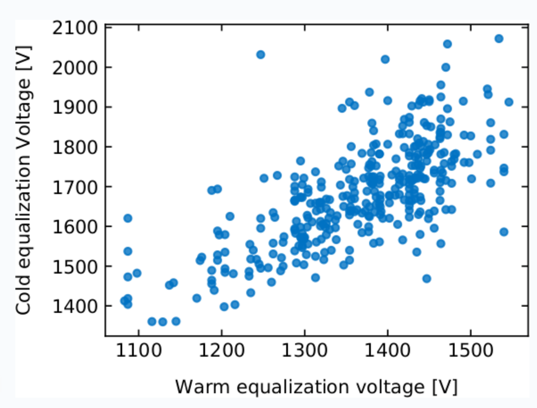


Test results: attenuation & delays

5 – PMTs' gain

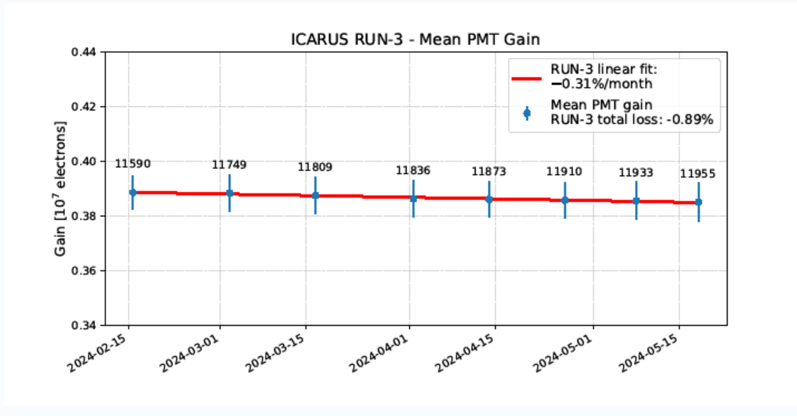


Warm vs cold PMTs' equalization (during commissioning)



Equalization at 1.5% level using SER (during commissioning with laser system, after with background γ for better precision)

- The PMT gain monitoring revealed a decrease with time: RUN2 PMT gain loss ~-0.67% per month; RUN 3 ~-0.31% per month (PMTs signal cables were changed)
- fatigue of the PMT dynodes due to the high current value induced by the high photon rates (~250 kHz) produced by cosmic rays at shallow depth and ^{39}Ar



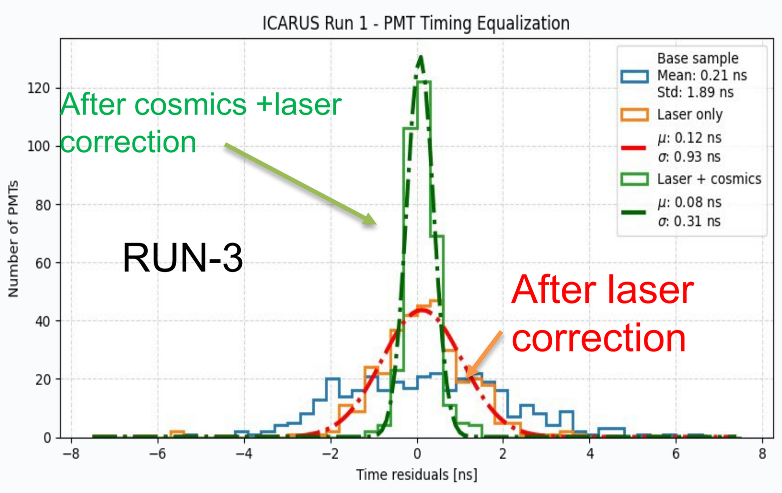
Time evolution of PMT's gain

6 – PMTs'timing

To reject cosmic rays background, neutrino interactions inside the detector must be reconstructed with a < 1 ns precision. This is achieved via the scintillating light PMTs system, after a proper calibration based on the laser system (to correct differences in the PMTs transit time and readout delays) and downward-going cosmic muons (to improve results: as 10% of PMTs do not see laser light well & laser light is a single spot on the large PMT surface.)

- **Laser corrections bring the timing equalization across all PMTs to 1 ns (design value of the system)**
- **Cosmic muons correction push it to < 1 ns**

Time residual for every PMT is defined as the time difference between the recorded signal in each tube and the expected signal time given the PMT vertical coordinate.



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