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Calibration of the ICARUS cryogenic photo-detection system at FNAL

M.Bonesini[1], R. Benocci[1], R.Bertoni[1], A. Chatterjee[2], M. Diwan[3], A. Menegolli[4], G. Raselli[4], M. Rossella[4], A. Scarpelli[3], N. Suarez[2]

for the ICARUS Collaboration

[1]University and INFN Sezione di Milano Bicocca (Italy) ; [2]University of Pittsburg (USA); [3] BNL (USA),

[4] University and INFN Sezione di Pavia (Italy)

maurizio.bonesini@unimib.it

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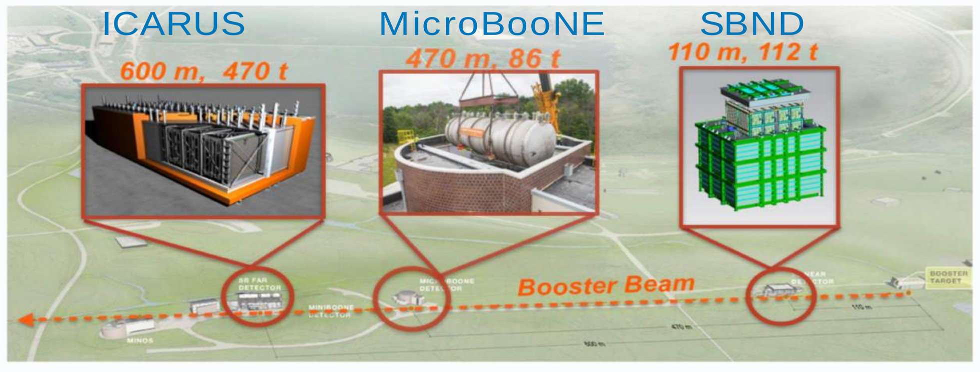
The ICARUS-T600 Liquid Argon (LAr) Time Projection Chamber (TPC) is presently used as a far detector of the Short Baseline Neutrino (SBN) program at Fermilab (USA) to search for a possible LSND-like sterile neutrino signal at $\Delta m^2 \sim O(eV^2)$. It is placed at shallow depth on the Booster Neutrino 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 to a 1x46 optical switch and then to UHV flanges, by 20 meters long optical patches. Light is then delivered to the ten PMTs connected to a single flange, 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 with minimal distortion to each PMT, as respect to the original one, even in a situation where available power is low. Gain equalization of PMTs has reached a 1% resolution. In this procedure data from background photons were also used. Timing calibration of the different channels is still in progress. The status of the laser system with its possible upgrades will be reported, together with present performances of the calibration procedure.

1 – Introduction

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

- the well characterized FNAL Booster ν beamline;
- three detectors 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.

2 – The ICARUS T600 detector and its light detection system

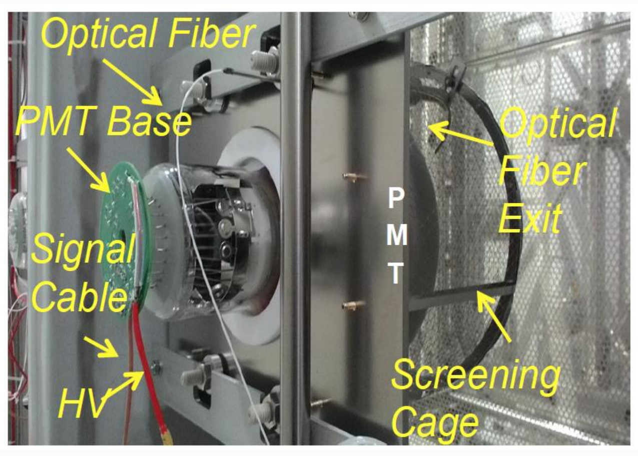
ICARUS T600 detector is made of two identical cryostats, filled with about 760 tons of ultra-pure liquid Argon. Each cryostat houses two TPCs with 1.5 m maximum drift path, sharing a common central cathode. Charged particles interacting in liquid argon produce both scintillation light and ionization 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 mm^3. Scintillation light (at 128 nm) is detected by a system of 360 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

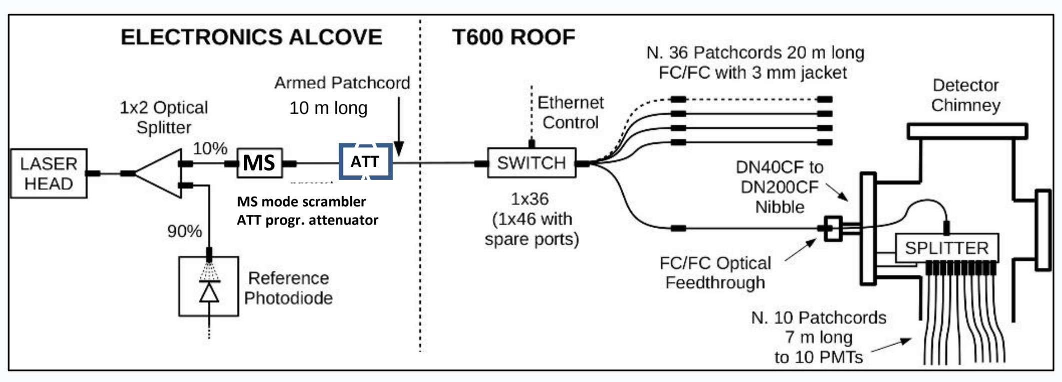
360 HAMAMATSU R5912-MOD (8" diameter) PMTs mounted behind the TPC wire planes.

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.

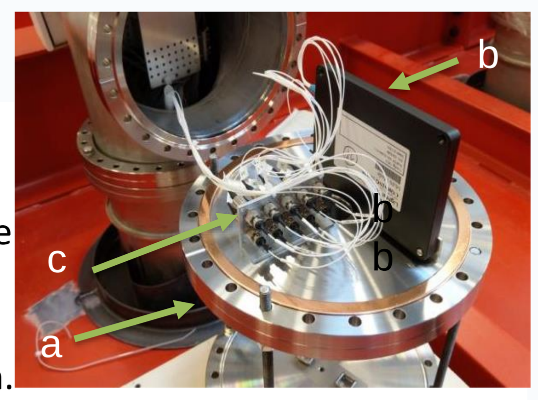
3 – The ICARUS laser calibration system



Layout of the ICARUS laser calibration system



Picture of one PMT mounting



The PMTs timing/gain equalization may be performed by using fast laser pulses . The laser pulse is sent to each PMT (360) 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.

Layout of one UHV flange (a) with a mounted 1x10 splitter (b) and the injection fibers patch panel (c)

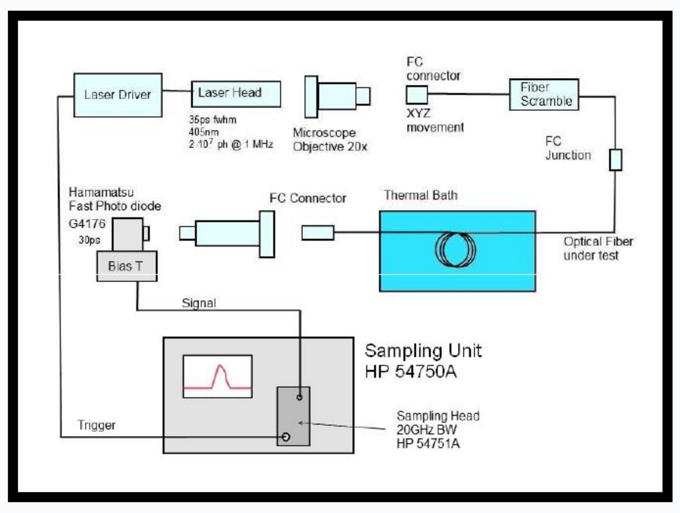
Problem: light pulses must have minimal time dispersion and signal attenuation at delivery point in front of the PMTs. In addition the system must have a minimal spread in channel to channel total delay (ΔT) and delivered power of the signal in front of the PMTs.

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*

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 …)

4 – Laboratory tests to qualify system components



- INFN MIB test system: the laser pulse is detected by an Hamamatsu G4176 (t_R,t_F ~40 ps) or a Picometrix D30 (FWHM ~ 30 ps) photodetector and measured by a 20 GHz HP 54750 sampling scope (timing studies) or by an OPHIR powermeter (attenuation studies)
- For temperature dependence studies we used either a LAUDA thermal machine (precision 0.1 C) or a LN$_2$ bath (tests at cryo temp)

- To minimize injection problems, MM instead of SM fibers → typical timing spread increase (σ_t) vs fiber length for a MM fiber (IRVIS 50/125 OZ/OPTICS) : 1 ps/m. Similar results for other fibers.
- Optical switch: to send input signal to 1 of M 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.

Optical switch

1x10 splitter

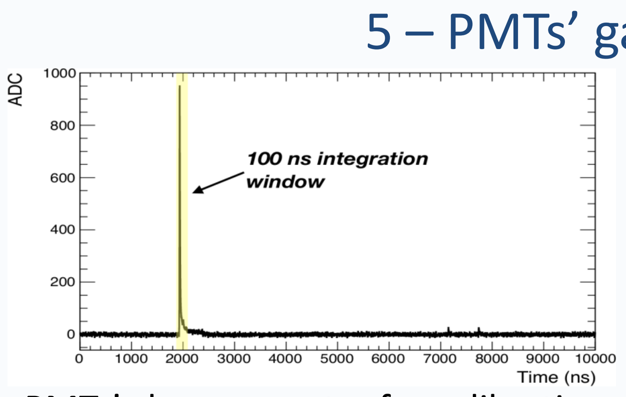
Laboratory test results:

- Laser pulse FWHM after the optical switch (Agiltron LBSC) is increased at most of ~ 3%. Insertion loss (IL) is < 0.5 dB, cross talk is ~50 dB. Channel to channel light output uniformity is better than 10%. Delays of output channels have an RMS of 11 ps. Control is via RSR232.
- A Lightel 1x10 fused optical splitter [36 tested] increases pulse FWHM of < 4%. IL is ~3 dB. Uniformy of output signals is within 5% with typically 1 leading signal out of 40- 50% by construction [to be attenuated]. Delays from pigtails are within 10-20 ps.
- VACOM UHV optical feedthroughs [36 tested] have no effect on the FWHM of the incoming pulse and have negligible effects on delay (~ 100 ps). Light attenuation is ~0.71 dB.

Overall system results:

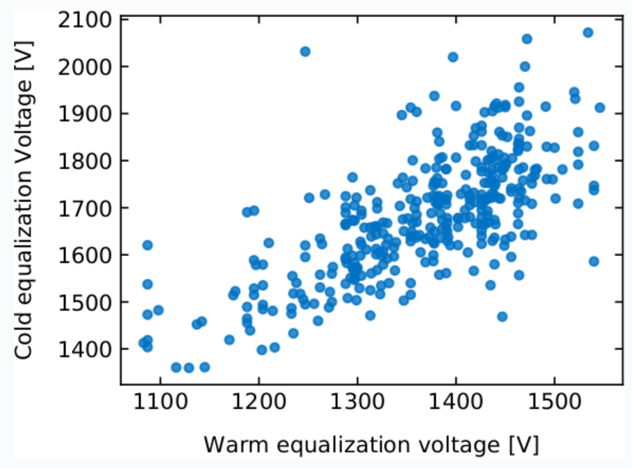
- *Total delays (ΔT):* ~250 ns with a spread over 360 channels < 200 ps, measured both in situ and in lab
- *Attenuation (up to UHV flanges): 4.59 ±0.16 dB over 36 flanges*
- *Attenuation of 7m injection patches: 0.61±0.06* **dB** (over the full 410 sample, the best 360 were used).
- The system was designed with a spread < 5% for the light output of the 360 calibration channels [worse in situ due to mechanics alignment problem of the injection fiber holder vs PMTs' surface] and a spread in total delays < 0.1% .

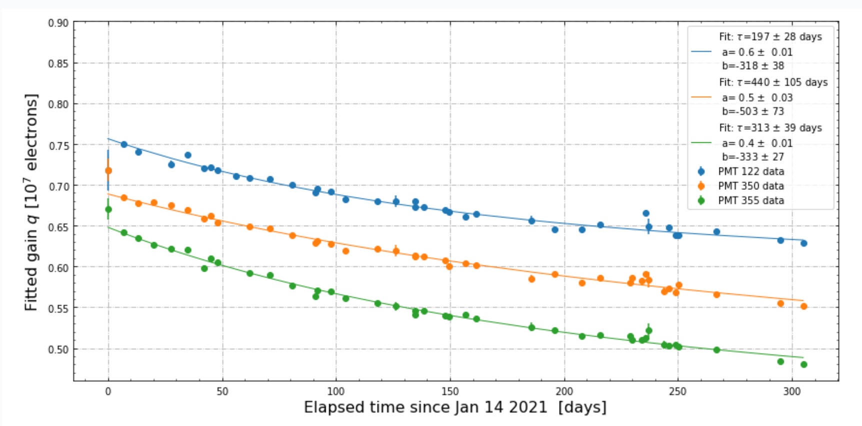
5 – PMTs' gain calibration performances



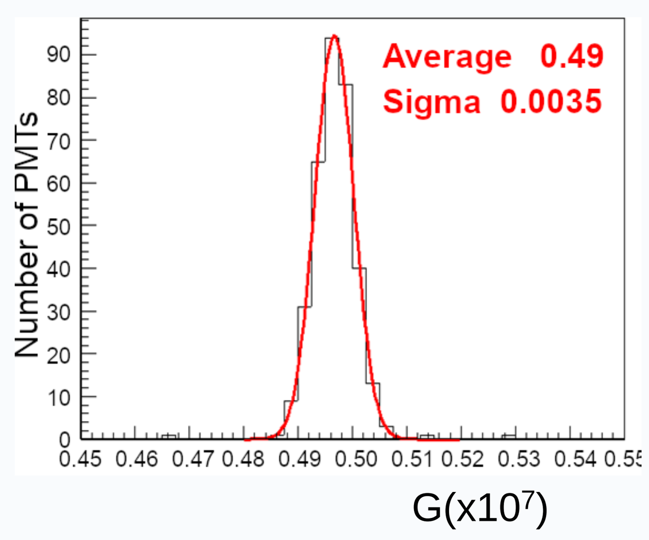
PMTs' charge spectra for calibration are obtained by integrating recorded signals by CAEN V1730 digitizers.

Warm vs cold PMTs' equalization





Time evolution of PMT's gain



- ❑ The PMT gain monitoring revealed a decrease with time
- ❑ 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

Equalization at 1% level using SER (final tuning with background γ's)

6 – Foreseen upgrades

Timing calibration of PMTs' is under study: the delays (fundamental for the correct time reconstruction of events) can be measured by sending laser pulses to the PMTs, provided that the delays of the optical distribution system are well known (see before).

- ❑ To reduce the time for laser calibration, where only 10 PMTs are flashed by laser light in the same time (one optical switch channel) we plan to replace the optical switch with a passive MAGIC BOX based on passive splitters where all the 36 lines, each going to 10 PMTs, are flashed in the same time
- ❑ Requirements are:
  - Spread of channel to channel light output at % level
  - Channel to channel similar time delays ΔT
  - Minimal insertion loss (IL)

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