The laser diode calibration system of the ICARUS T600 detector at FNAL

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Abstract: The ICARUS T600 LAr TPC is the far detector of the Short Baseline Program at FNAL. As it will have to work at shallow depth in the Booster Neutrino Beam, a large cosmic rays background (~ 11 kHz) will be present. To reduce it, precise timing information is needed from the new light detection system, based on 360 large area photomultipliers. For precise time measurements a calibration system based on a fast laser diode and a system based on one optical switch, several 1 x 10 fused fiber splitters, ultra-high vacuum optical feedthroughs and multimode optical patchcords up to 20 m long, to distribute the laser pulses to each single PMT, was designed. The time evolution of the PMTs’ gain/timing and possibly their initial calibrations at a time $t_0$ will be done by using this system. The expected time resolution of this calibration system will be around 100 ps. The laboratory tests needed to set up the system are reported.

Keywords: Detector alignment and calibration methods (lasers, sources, particle-beams); Neutrino detectors; Time projection Chambers (TPC)

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1 Introduction

The ICARUS T600 is the largest Liquid Argon Projection Chamber (LAr TPC) in operation. It took data at LNGS INFN laboratory from 2010 to 2013 on the CNGS neutrino beam [1]. It was then refurbished at CERN in the framework of the WA104/NP01 project from 2015 to 2017 and then moved to FNAL [2–4]. The improvements introduced during these operations were:

- new cold vessels, with purely passive insulation;
- a renovated cryogenics for the LAr;
- upgrade of the scintillation detector system by using 360 new large area photomultipliers (PMTs), to provide a time resolution around 1 ns;
- new electronics for the wire chambers’ readout.

The refurbished ICARUS T600 detector has been installed at FNAL on the Booster Neutrino Beam (BNB), to search for sterile neutrinos [5]. The new light collection system is based on 360 8” Hamamatsu R5912-MOD PMTs (5% coverage, 15 p.e./MeV), providing sensitivity down to ~ 100 MeV, good spatial resolution (≤ 50 cm), and good timing resolution (~ 1 ns) [6]. The readout is made through CAEN V1730 digitizers.\(^1\)

The time resolution of ~ 1 ns will allow to exploit the BNB bunch structure, for further rejection of out-of-bunch cosmic events. To obtain a good time resolution an accurate PMTs’ time calibration system will be necessary to handle electronics time drift due to temperature excursions and other effects.

\(^1\)500 Ms/s, 14 bit, 2 V pp dynamic range, in VME standard.
Figure 1. Schematic layout of the system proposed for the time calibration of the 360 PMTs of the ICARUS T600 detector. While the laser diode is put in an alcove on a mezzanine of the far detector building, the rest of the system is positioned on the T600 roof.

2 Layout of the laser calibration system

PMTs’ timing calibration requires the precise determination of time delays, that may drift for temperature excursions, at an initial time $t_0$ and the monitoring of their evolution along the data-taking. This may be done with cosmic rays or by delivering a fast calibration pulse to each individual channel. The proposed layout for the time calibration of the 360 PMTs of the ICARUS T600 detector is outlined in figure 1 and is based on a previous design for the MICE experiment at RAL [7]. Fast light pulses from an Hamamatsu PLP10 laser diode are distributed via a 1x36 optical switch to 20 m long optical patch cables, that come to optical ultra high vacuum (UHV) FC/FC feedthroughs on CF 40 flanges, mounted on CF40-CF200 adapters. Inside the T600 tank, 1x10 fused optical splitters are attached to each adapter to deliver the input laser signal to ten 7 meter long injection fibers that convey the calibration signal to each PMT, see figure 2 for details. The inner part of the PMTs’ calibration system is fully described in reference [8]. The laser stability is monitored by a reference photodiode (currently a Thorlabs DET02AFC). The main requirement on the calibration system is that the laser pulses can be delivered to the PMTs’ photocathode with a minimal attenuation and without a deterioration of their original timing characteristics.

260 ps FWHM, 100-200 mW peak power, emission at 405 nm.

Si photodiode with FC fiber input, 1 ns risetime/falltime, 1 GHz bandwidth.
3 Components characterization

The laser pulses may be sent to one of N output channels by means of an optical switch and splitted between M output channels by suitable fused optical splitters. Transmission of light between two points is made via optical fiber patches with FC/PC ("fiber channel") multimode connectors. The used optical components (1xN optical switches, patch cables, 1xM optical splitters, optical feedthroughs) were characterized at the used wavelength (~ 405 nm) for attenuation and timing properties with a test setup available at INFN Milano Bicocca (see figure 3 for details). The main problem is that these components are easily available at Telecom wavelengths (~ 850 – 1300 nm) but not in the visible range. As a consequence, a lot of dedicated tests had to be done. In the test setup, the laser light is fed into a ModCon mode scrambler by Arden Photonics\(^4\) to ensure the same distribution of launched modes into the fiber. The optical components under test (fiber patches or others) are then connected in between. The output is analyzed either by a powermeter\(^5\) for transmission tests or fed into a fast detector connected to a sampling scope for the analysis of the pulse characteristics, such as risetime/falltime, FWHM or peak values.\(^6\)

The main characteristics of the used fast photodetectors are shown in table 1. While the G4176-03 photodetector from Hamamatsu is a free space detector,\(^7\) powered by a Picosecond Pulse Lab 5550B bias tee and is used together with an Alphalas BBA-3 amplifier, the Picometrix D30 is a complete detector with a FC fiber input.

The sampling scopes used were either a HP54750A with a HP54751A sampling head or a Picoscope 9311. Both had a bandwidth of 20 GHz, a transition time $\leq 17.5$ ps and a minimum sensitivity of 1 mV/div. The maximum noise was respectively $\leq 1$ mV and 1.5 mV.

3.1 The laser source

For a calibration system aiming at a resolution $\sim 0.1$ ns, a laser source providing fast pulses with FWHM around 50 ps is needed. Low cost laser sources based on laser diodes have power in the

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\(^4\)Insertion loss at 850 nm $\leq 3$ dB, max power throughput $< 10$ mW.
\(^5\)Model OPHIR Nova with PD300 head.
\(^6\)InGaAs G4176 from Hamamatsu or D30 from Picometrix.
\(^7\)It is packaged in a coaxial metal can, easy to connect to an electrical SMA connector.
Figure 3. Test setup used for characterization of optical components. In part of the tests the Hamamatsu G4176 photodiode was replaced by a Picometrix D30 photodetector, with FWHM ~ 30 ps. The thermal bath of the Lauda machine was used only for some tests.

Table 1. Main characteristics of the used Hamamatsu G4176-03 and Picometrix D30 detectors. Contributions from bias tee and amplifier are included in (*)

|                | Picometrix D30 | Hamamatsu G4176-03 |
|----------------|----------------|---------------------|
| type           | MSM            | InGaAs MSM          |
| FWHM           | 30 ps          | 70 ps (*)           |
| bandwidth      | 15 GHz         | ~ 10 GHz            |
| mount          | fiber input    | free space          |
| range          | (FC input)     | 0.2 x 0.2 mm² sensitive area |
|                | 400-1700 nm    | 450-870 nm          |

range 100 mW - 1 W and therefore injection into the fiber delivery system must be optimal. Two different laser systems have been used during laboratory tests. At first a free space Pilas 040 laser diode from Advanced Laser Systems was used. Fiber injection was obtained with an Olympus 20x microscope objective, with 0.4 N/A and 1.2 mm working distance, mounted on a x-y-z flexure stage with micrometric precision. Afterwards the system was replaced by an Hamamatsu PLP10 laser diode with a direct injection system in fiber, via an FC connector mounted on the laser head. Their main characteristics are summarized in table 2.

FWHM, risetime and max pulse height ($V_{max}$) have been measured with an Arden Photonics mode scrambler followed by a Picometrix D30 fast detector, connected to an HP5475 or a Picoscope 9311 sampling scope using the setup of figure 3. Figure 4 shows a screenshot of laser pulses from
Table 2. Main characteristics of the used laser diodes.

|                      | ALS Pilas 040 | Hamamatsu PLP10 |
|----------------------|---------------|-----------------|
| nominal mean power   | 1 W           | 120 mW          |
| repetition rate       | < 1 MHz       | 2–100 MHz       |
| beam head optics      | free space    | FC fiber input  |
| FWHM                 | 50.7 ± 0.5 ps | 62.1 ± 0.1 ps   |
| risetime             | 31.2 ± 0.7 ps | 34.1 ± 0.1 ps   |
| pulse height         | 338 ± 2 mV    | 429 ± 1 mV      |

Figure 4. Screenshot of laser pulses from Hamamatsu PLP10 laser diode, as seen on a Picoscope 9311 sampling scope.

the Hamamatsu PLP10 laser diode as measured on a Picoscope 9311 sampling scope, after the Picometric D30 fast detector.

The short-time PLP10 laser diode stability was tested over a period of ∼ 3 hours of continuous operation and its power was within ±1% as measured with a power meter. Long-term stability will be monitored instead by a fast photodiode as shown in figure 1.

3.2 Optical fibers

Single mode (SM) optical fibers provide negligible dispersion at a given wavelength for distances up to some kilometers, but they need very accurate injection devices, because of their very limited acceptance angle and core dimensions (few times the optimized light wavelength). On the other hand, multimode fibers (MM) do not present injection difficulties but, due to modal dispersion up to 30 ps/m, are useless for precise timing over distances larger than a few meters. In the visible range a compromise may be found by using MM fibers of small core diameter, around 50 µm or less,
that behave as limited mode fibers [9, 10]. Results on the attenuation and timing spread in typical multimode (MM) 50 µm core fibers are summarized in table 3. As optical patches up to 20 m were needed, the choice was the IRVIS OZ/Optics fiber working in the range 400-1800 nm, with a 0.20 numerical aperture.

### 3.3 Optical switches

An optical switch $1 \times N$ conveys the input signal to one of the $N$ output channels. Main requirements are a minimal insertion loss (IL) and signal equality between the different output ports. In addition the fact that the channel to channel cross-talk be minimal is needed. Different optical switches from PiezoJena, Leoni and Agiltron were tested. The choice of a suitable optical switch was the critical point of all the project. This device is quite common in the Telecom application range ($\lambda \sim 1300$ nm) but it was very difficult to obtain a custom device working in the visible range.

The main characteristics of the optical switches, both provided by the producer and measured by us are shown in table 4. For the tests the Arden Photonics mode scrambler was used before the optical switch, followed by a 1m OZ/Optics IRVIS patchcord after it. The laser was operated at 1 MHz and the optical power measured with a Thorlabs PM20 powermeter. All switches, except the one from Agiltron US, had performances far below the nominal ones at the reference wavelength of 400 nm. Their performances, using an Hamamatsu PLP10 laser diode, are reported in table 4. The main problems are related to bad uniformity of the IL between different pigtails, high IL at 400 nm and unstability of the response vs operation time. The evolution of the average insertion loss (IL) as a function of the elapsed time from switch delivery is shown in figure 5. The only optical switch with acceptable performances was the one provided by Agiltron.

### 3.4 Fused optical splitters

Extensive tests were done on $1 \times 10$ fused optical splitters from Comcore, OZ/Optics and Lightel for uniformity of output attenuation, delays and time spread (FWHM) in the different pigtails. The total insertion loss (tot. IL) is defined at the power ratio between the sum of the output channels and the input one. The splitting ratio is defined as the power ratio between one channel output and the total input power. Results are reported as averages $\pm$ RMS over the ten channels of a splitter.

| fiber type                  | N/A | range (nm) | Att. (dB/m) | $\Delta t$ FWHM (ps/m) | delay (ns/m) |
|-----------------------------|-----|------------|-------------|-----------------------|--------------|
| IRVIS OZ/Optics (G)         | 0.20| 400–1800   | 0.06        | 0.99                  | 5.11         |
| UVVIS OZ/Optics (S)         | 0.22| 200–900    | 0.12        | 2.21                  | 5.05         |
| Corning 50/125 (G)          | 0.20| 800–1600   | 0.09        | 1.63                  | 6.4          |
| Thorlabs AFS 50/125 (S)     | 0.22| 400–2400   | 0.08        | 2.71                  | 5.11         |
| Thorlabs SFS 50/125 (S)     | 0.22| 250–1200   | 0.07        | 0.63                  | —            |
Table 4. Main characteristics of tested optical switches.

|                  | PiezoJena F109-05 | Leoni MOL 1 × 12 | Leoni MOL 1 × 36 | Agiltron SelfAlign |
|------------------|--------------------|------------------|------------------|--------------------|
| fiber type       | SFS 50/125         | SIF 50/125 UV    | SIF 50/125 UV    | IRVIS 50/125       |
| no. ports        | 9                  | 12               | 36               | 46                 |
| nominal IL (dB)  | 1.4                | 2.0              | 3.0              | < 0.5 at 400 nm    |
| nominal cross-talk (dB) | -60              | -45              | -45              | -50                |
| max power (mW)   | 300                |                  |                  | 300                |
| IL(dB) at 400 nm | 4.36 ± 0.18        | 1.72 ± 0.26      | 4.81 ± 0.90      | 0.32 ± 0.12        |
| $\frac{FWHM}{FWHM_0}$ | 1.03 ± 0.01       | 1.21 ± 0.02      | 1.94 ± 0.09      | 1.03 ± 0.02        |
| delay spread (ns)| 0.29               | 1.63             | 0.07             | 0.05               |

Figure 5. Average insertion loss with RMS spread over the switch pigtails, as measured at different times from delivery.
A typical fused fiber splitter has a leading pigtail that, due to the production process, conveys up to 40-50% more power than the other ones. This effect is amplified at 400 nm, as the production of splitters is usually made at higher wavelengths. To reduce this problem an in-line attenuator is used for this leading channel to equalize the response.

Some test results are reported in table 5.

Table 5. Measured characteristics of typical 1 × 10 MM optical splitters. Results are reported as averages ± RMS, to give an idea of the distribution width over the pigtails of a specimen. In (*) two pigtails have delays different by more than 10 ns from the others and have been excluded in the calculation of the delay spread.

|                | Comcore no 1 | Comcore no 2 | Lightel no 1 | Lightel no 2 | OZ/Optics no 1 | OZ/Optics no 2 |
|----------------|--------------|--------------|--------------|--------------|----------------|----------------|
| splitting ratio (%) | 2.74 ± 0.69 | 3.95 ± 0.40  | 5.47 ± 1.16  | 4.46 ± 0.90  | 4.06 ± 1.34    | 4.16 ± 1.23    |
| FWHM/FWHM<sub>0</sub> | 1.07 ± 0.03 | 1.04 ± 0.01  | 1.03 ± 0.01  | 1.04 ± 0.01  | 1.04 ± 0.02    | 1.02 ± 0.02    |
| tot. IL (dB)     | 5.66         | 4.03         | 2.62         | 3.50         | 2.62           | 3.81           |
| delay spread (ns)| 0.55         | 0.12         | 0.004        | 0.019        | 0.053 (*)      | 0.046 (*)      |

The best solution was obtained with Lightel splitters built for operation at 600 nm with Corning 50/125 fibers.

3.5 UHV optical feedthrough

UHV optical feedthroughs must convey the laser pulse inside the ICARUS cryogenic tank. Many different solutions were tested from glued fiber feedthroughs from OZ/Optics to FC/FC feedthrough realized with an inner internal fiber. The adopted solution from VACOM, with a MM 50 µm core fiber, had a measured transmission at 405 nm around 90%, introduced an additional delay ∼130 ps and a negligible additional time dispersion (FWHM). Test results are summarized in table 6. To adapt these flanges to the existing T600 chimneys custom CF40-CF200 adapters from Lesker Ltd U.K. are used, see figure 6 for details. On the inner side of the CF40-CF200 adapters, the 1 × 10 fused fiber splitters were mounted. Their pigtails then go to a FC/FC patch panel, to which the 7 m long injection patches to the PMTs are connected.

Table 6. Characteristics of the VACOM optical feedthrough on CF flanges. Results are reported as averages ± RMS.

| fiber type He leak rate | MM 50µm core 1 × 10<sup>−10</sup> mbar l/s |
|------------------------|---------------------------------------------|
| IL (dB)                | 0.38 ± 0.06                               |
| ∆T (ps)                | 133.2 ± 7.4                               |
| Δ(FWHM)(ps)            | 0.32 ± 0.28                               |

3.6 Temperature dependence tests

While the laser, optical switches and 20 m patch cables must work on the roof of the ICARUS detector, at room temperature, the 1x10 splitters have to work inside the T600 chimneys at a slightly
lower temperature and the 7m injection patches at cryogenic temperatures, inside the LAr bath. Tests were done to assess the dependence from temperature, using a Lauda thermal machine (precision 0.1 °C) in the range 0-50 °C and with LN2 inside a dewar. For the chosen fiber IRVIS OZ/Optics the temperature dependence of the delays is 106 fs/m °C. For the 7m injection patch at cryogenic temperature the pulse FWHM increases by 10%. Other parameters, such as attenuation and delays, are compatible with room temperature ones. In addition, the selected splitters 1 × 10 were tested in the temperature range [-10,+15] °C without no evidence of effects.

4 Installation of the system at FNAL and preliminary tests

As all the measurements of the used optical components gave a good transmission and pulse width spreads well below 50 ps, a resolution of the timing calibration procedure below ~ 100 ps is within reach.

The laser calibration system was deployed on the top of the T600 detector during 2019. From the laser source to the entrance of the UHV feedthrough, placed on the chimneys, a mean attenuation of 4.59 dB with an RMS spread of 0.16 dB was measured. This value includes contributions from the Mode Scrambler, the 12 m long armed patch cable going from the laser source to the optical switch put on the T600 roof, the optical switch and the 20 m long patch cables going to each flange.

5 Conclusions

The layout of the laser diode calibration system of the ICARUS T600 detector is described. The expected performances, such as a resolution of ~ 100 ps, fit well the ICARUS light detection system calibration requirements for timings at the 1 ns level.

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