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Scintillation light detection performance for the DUNE ND-LAr 2 × 2 modules

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ABSTRACT: The Deep Underground Neutrino Experiment (DUNE) will be using a liquid argon time projection chamber (LAr TPC) with optically separated modules in the Near Detector (ND) complex. A prototype experiment, DUNE ND-LAr 2×2, is composed of four test modules. They detect ionization charge through a pixel-based readout and scintillation light through fibers in light collection modules and light traps called ArCLights. The light detection performance for two modules of DUNE ND-LAr 2×2 that took cosmic ray data at the University of Bern is shown. We present further the role of the 2×2 prototype in DUNE and how it is used to demonstrate the reconstruction capabilities of its light detectors in terms of energy thresholds and timing resolution.

KEYWORDS: Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Charge transport and multiplication in liquid media; Time projection chambers (TPC); Cryogenic detectors

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Contents

1 Introduction

The Deep Underground Neutrino Experiment (DUNE) is one of the leading experiments in the field of the long-baseline neutrino oscillation physics. DUNE foresees a near detector located at Fermi National Accelerator Laboratory (FNAL) and a far detector placed at the Sanford Underground Research Facility (SURF). The two facilities are 1300 km apart. An intense neutrino beam of 1.2 MW power, which can be upgraded to 2.4 MW, will be used [1]. The main goals of the long-baseline neutrino physics with the DUNE experiment are to measure the CP-violating phase in the leptonic sector and determine the neutrino mass hierarchy. The near detector site at the start of physics data-taking will consist of three sub-detectors: the ND-LAr, TMS and SAND [2]. The main purpose of TMS is to track and measure the momentum and sign of charged particles exiting ND-LAr. SAND is used to continuously monitor the on-axis beam, as ND-LAr and TMS are moved off-axis [2]. ND-LAr is a pixelated LAr TPC and will have 35 optically separated modules, placed in a matrix of 5 by 7. Each module has a size of $1 \times 1 \times 3$ m^3. The modularity permits to handle the pile-up of interactions from the intense neutrino beam. A simulated beam spill in the liquid argon near detector is shown in figure 1. The tracks from charged particles as well as neutron-induced recoiling proton tracks with an energy greater than 10 MeV [2] are shown. The modularity allows for individual neutrino interactions to be identified by light signals induced from neutrino interactions to individual modules, that is not efficient with monolithic designs.

2 ProtoDUNE-ND module tests at Bern

A ND-LAr prototype, called ProtoDUNE-ND, is composed of four modules positioned in a 2×2 array. The four devices have a size of $0.7 \times 0.7 \times 1.4$ m^3 and are smaller than the final modules of the DUNE ND-LAr detector. The four single modules will operate at Fermilab in the NuMI beam [3] for testing the capabilities to measure neutrino interactions with modular detectors in a shared LAr bath [4]. A schematic drawing of a single module is shown in figure 2, where the charge and light readout are visible.

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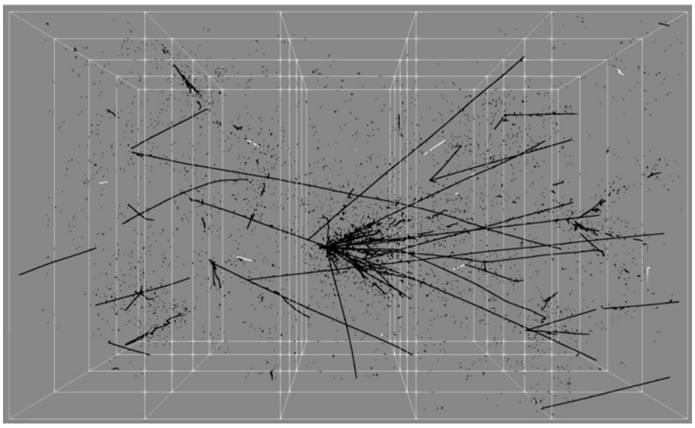

Figure 1. A simulated beam spill in the liquid argon near detector. The black tracks are energy deposits from charged particles with sufficient ionization charge to be collected at the pixel planes. The white tracks are specifically neutron-induced recoiling proton tracks with an energy greater than 10 MeV. The white frame represents the 35 modules of DUNE ND-LAr.

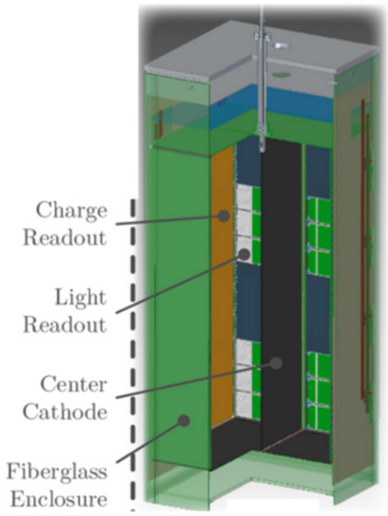

Figure 2. Schematic drawing of a single module with the charge and light readout.

2.1 Light readout system for DUNE ND-LAr

The light readout system (LRS) provides optical coverage over 30% of the inner surface of each module. Two different light detection technologies are used in the ProtoDUNE-ND modules. The light collection modules (LCMs) produced at JINR, Dubna, are shown in figure 3, and the ArCLights [5] (ACLs) produced at LHEP in Bern are shown in figure 4. The ArCLights [5] and LCMs are based on the ARAPUCA principle of light trapping [6].

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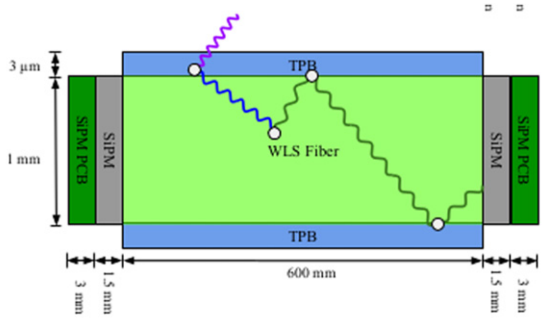

Figure 3. Schematic drawings of the working principle for the LCM module. The vacuum ultraviolet scintillation light shifts wavelength when traveling through the TPB coated surface of the fiber, which acts as light trap and guide. The photons are measured by SiPMs at each side of the fiber.

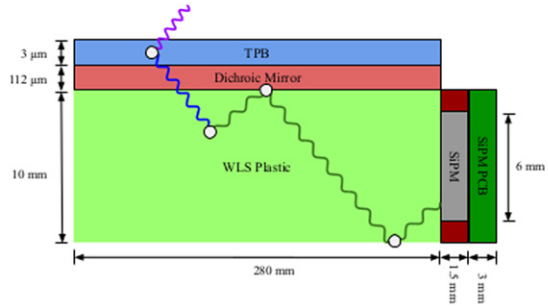

Figure 4. Schematic drawings of the working principle for ArCLight [5]. The vacuum ultraviolet scintillation shifts wavelength when traveling through the TPB coated surface. The bulk structure which the light enters then acts as light trap. The photons are measured by SiPMs located at one side. Reproduced from [5]. CC BY 4.0.

The ACL's process the scintillation light in three stages. First, a TPB layer which shifts the VUV scintillation light with a wavelength of 128 nm to 430 nm. A dichroic mirror then lets the photons through into WLS plastic, where they get shifted to 490 nm. The dichroic mirror reflects those photons. They are trapped inside the WLS plastic until they reach one of six SiPMs placed on one side of the ACL. The LCM is made out of WLS fiber which are coated with TPB. The TPB shifts the VUV photons similar to the ACL. The photons are trapped in two bundles of WLS fibers that guide them to the SiPMs.

In each module of the ProtoDUNE-ND 24 LCMs grouped in pairs of three and 8 ACLs are installed. The reason to use two systems is to take advantage of the better spacial resolution of the ACLs with respect to the LCMs. With better spacial resolution the charge light matching improves. The LCMs have the better timing resolution than the ACLs. A good timing resolution is needed to study event pile-up in neutrino interactions. Both systems have large-surface coverage for an efficient collection of UV photons. The photon detection efficiency of both LRS is further discussed at the end of section 2.2. The ACLs and LCMs can be placed inside the field-shaping structure to increase light yield and decrease dead space. Photomultiplier tubes (PMTs) are not used in DUNE ND-LAr because they are too big for modular TPCs.

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2.2 ProtoDUNE-ND module tests at LHEP Bern

Module 0 and Module 1 are the first two of the in total four ND-LAr demonstrator modules. Module 0's commissioning run collected around 60 million self-triggered cosmic ray-induced events over eight days in March 2021. Module 1 collected 20 million self-triggered cosmic ray-induced events over three days in February 2022. In figure 5 the fully assembled Module 0 is shown.

Figure 5. Module 0 before being placed in a cryostat for commissioning at the University of Bern. Visible is the back of the anode plane (pixelated charge readout) with the light readouts placed on the sides. At the top of the module one finds the vacuum insulation and feed-throughs.

In the charge readout system a self triggering hit occurs when the accumulated charge on a single pixel exceeds a configurable preset threshold level that is equivalent to an energy threshold of typically 100 keV [7]. The LCMs provides an external trigger to the charge readout system with a threshold of 30 photoelectrons (PE). The light readout system information is merged with the charge readout data by adding it to the data stream. This is done for greater precision in timing-level information.

Before each data taking campaign, a SiPM gain calibration is performed using calibration UV-LEDs, mounted inside the detector. Hamamatsu S13360-6050CS SiPMs are used in both modules. They operate at around 46 V at LAr temperature. The bias voltage of the SiPM channel are tuned to obtain uniform gain distribution with a mean of 200 ADC/PE across the channels.

To separate event pile-up, a t_0 time for the charge readout needs to be set with a timing resolution which is less than 20 ns [2]. The timing resolution is extracted by using cosmic muons traveling through the entire length of the TPC. The waveforms from the LCMs are pre-processed with a Fourier transform to increase the ability to measure the front edge. Then, a linear fit to the baseline and front edge is applied. The crossing point of these lines provide a robust single-channel

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event time. A Gaussian curve is fitted to a histogram of cross-points and the fit results displayed as a function of light intensity as shown in figure 6. For large light signals the timing resolution approaches about 2 ns. This timing resolution satisfies the requirement to identify Michel electrons and to disentangle event pile-up in neutrino interactions. In figure 7 the light signal of a stopping muon and a delayed Michel electron is shown. The second peak arrived 2.5 μs after the first peak in this event.

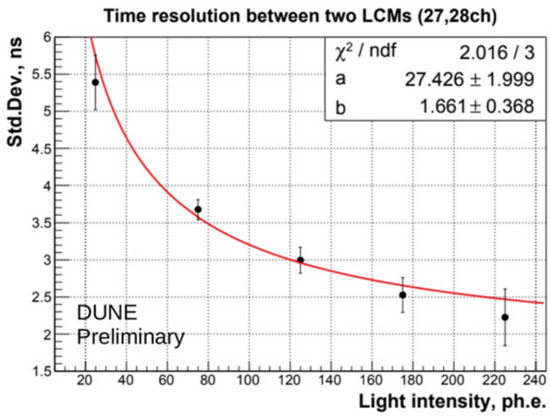

Figure 6. Time resolution as a function of the signal response.

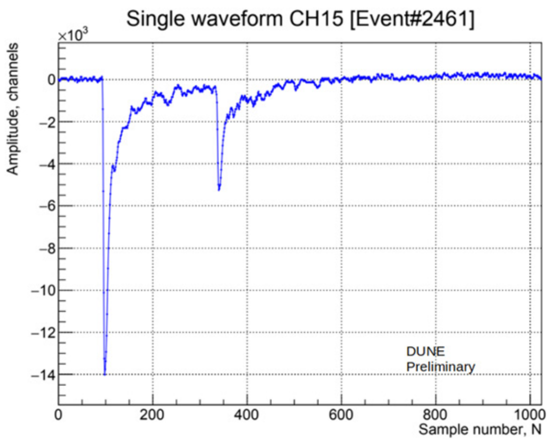

Figure 7. Wave form of a muon with a delayed Michel electron during the Module 0 test. The sample number is in units of 10 ns.

To determine the trigger threshold of the LRS in terms of deposited energy, a gamma conversion event with a total energy deposit of about 20 MeV was chosen. An energy threshold as low as 5 MeV must be achieved to measure the energy spectrum of protons emitted in charged current interactions [2]. Both readouts, also the charge readout, are self-triggered. Therefore, the triggering threshold of the LRS determines which light signals are recorded and can thus be matched to charge signals.

The trigger signal is based on the digital sum (ADC) of all channels of the LCM light readout. The LCM sum signal peaks at −24000 ADC counts for the 20 MeV event shown in figure 8. The effective threshold (2000 ADC counts) in this event was therefore at 1.7 MeV. Given the signal clarity, operation well below a threshold of 1 MeV is possible.

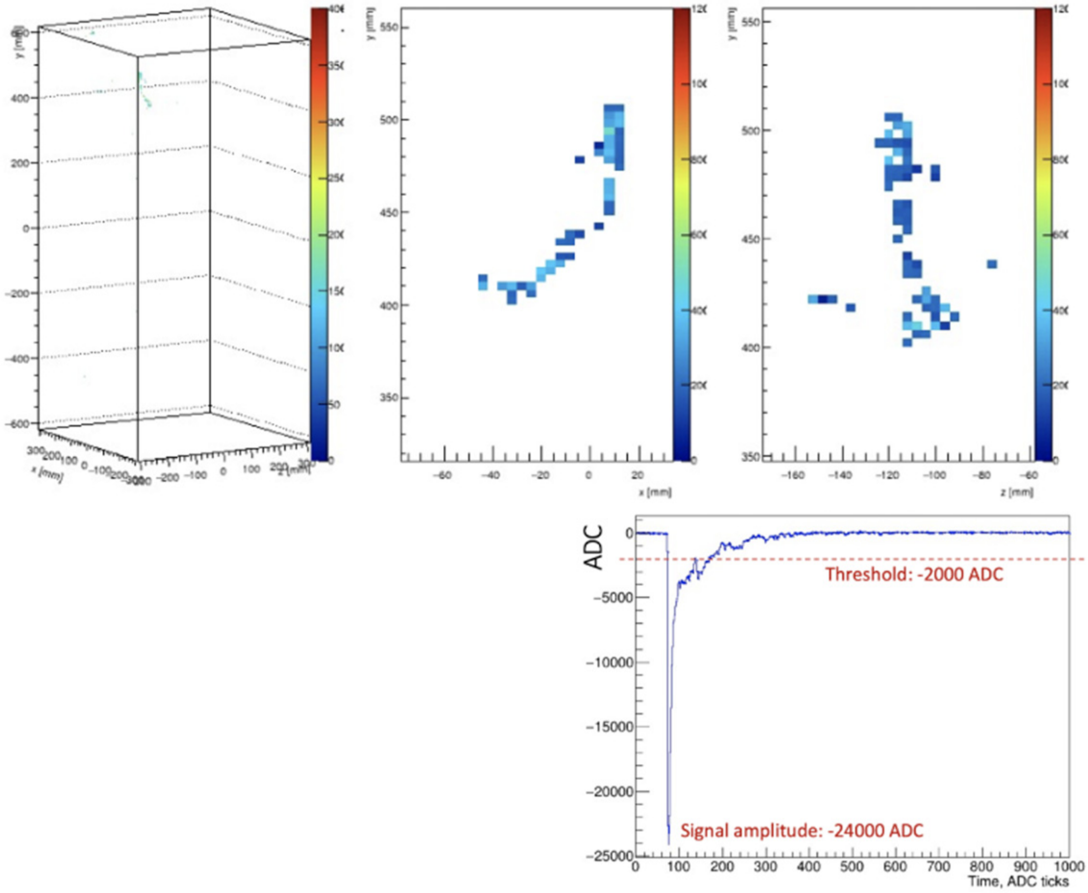

Figure 8. The charge pixel view of the gamma conversion event is visible, the SiPM sum channel is shown with the threshold marked at −2000 ADC. The charge view is on the top (left 3D, middle and right 2D), and the light waveform on the bottom right.

The photon detection efficiency (PDE) is dependent on the efficiency of the TPB layer, the WLS and the SiPMs, the average spectral acceptance and the efficiency of the reflecting surfaces to deliver photons to the SiPM area. The PDE is estimated by comparing the data and Geant4 simulation. We determine a PDE for the ACL in Module 0 of 0.06% and for the LCMs of 0.6%. For the Module 1 run the ArCLights were modified, adding an extra mirror to the lateral edges, increasing the PDE to 0.2%. The PDE is shown, separately, for each ACL tile and each LCM tile in Module 0 and Module 1 in figure 9.

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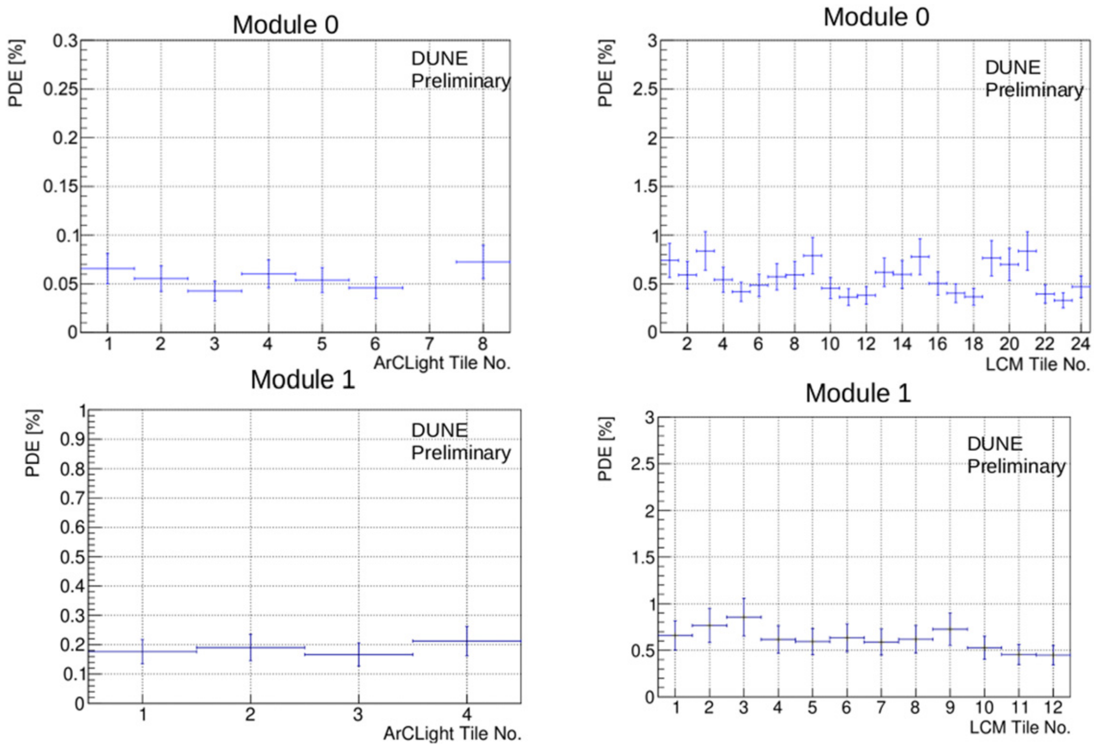

Figure 9. PDE of both modules for each LCM and ACL. For Module 1 the PDE values of one TPC are missing. The increase in the PDE for the ACL from Module 0 to Module 1 is due to additional mirrors on the ACL.

3 Conclusion

Four test modules for the DUNE ND-LAr 2 × 2 were assembled and tested at the University of Bern. Each module consists of two TPC volumes, detecting ionization charge through a pixel-based readout and scintillation light through LCMs and ACLs. The commissioning runs of the first two modules collected in total 80 million self-triggered cosmic ray-induced events. We presented studies showing that the light readout system has a timing resolution of as low as 2 ns, exceeding the required timing resolution of 20 ns. We demonstrated that the light signals of a muon and a delayed Michel electron can be separated. The triggering energy threshold of 5 MeV or better is reached as well, with a typical threshold around 1 MeV. The PDE for the ACL was improved from the first to the second module from 0.06% to 0.2%.

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