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Techniques for TPC Calibration: Application to Liquid Ar-TPCs

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Abstract: Large liquid argon TPCs are playing an increasingly important role in neutrino physics, and their calibration will be an essential component of their capability to reach the required performance and precision. Natural sources are extensively used but present limitations, since natural radioactivity from ^{39}Ar is of low energy, and the rate of cosmic ray muons is low when the detectors are placed deep underground. Argon gas TPCs have been calibrated with ionizing laser beams for several decades, and more recently the technique has been further developed for use in liquid TPCs. Other recent ideas include the use of external neutron generators creating pulses that propagate into the detector. This paper reviews the development of the laser and neutron methods for the calibration of argon TPCs and describes their planned implementation in the upcoming DUNE experiment.

Keywords: liquid argon; TPC; calibration

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1. Introduction

The technology of liquid argon (LAr) time projection chambers (TPC) is increasingly important in neutrino physics today, having been chosen for all three detectors—ICARUS, MicroBooNE and Short Baseline Near Detector (SBND)—of the Fermilab Short Baseline neutrino program as well as for the long-baseline Deep Underground Neutrino Experiment (DUNE). This puts more stringent requirements on the performance and precision of the detector models for simulation and reconstruction, and therefore on the capabilities of calibration techniques. This section will review the basic features of LAr TPCs, and describe its most relevant model parameters and performance metrics.

The LAr TPC detector concept was introduced for neutrino physics almost simultaneously in the late 1970's by C. Rubbia [1] and H. Chen with J. Lathrop [2]. The technology was developed by many groups over the years [3], with the ICARUS collaboration having pioneered the techniques for the most massive detectors [4]. The more recent realizations of large LAr TPCs are for the FNAL short- and long-baseline neutrino oscillations program [5,6]. Both are based on intense muon neutrino beams and different detectors located at different distances. In the case of the short-baseline program, MicroBooNE [7] (90 tons active mass) and ICARUS (476 tons active mass) are at the longer distances (hundreds of m) and the upcoming SBND (112 tons active mass) will be that beamline's near detector. For DUNE, a multi-technology Near Detector complex will characterize the beam's flux, spectrum and cross sections. The beam itself will be the world's most intense. The very massive far detector, made of four modules of 17 kton total mass (∼13–15 kton active mass, depending on the module) will be located on-axis at a distance of 1285 km. The technology of the DUNE far detectors is a significant step up from existing detectors in terms of scale, and therefore is being demonstrated at CERN with two prototype detectors [8,9] (active mass 420 tons).

The operation principles of the single-phase (SP) LAr TPC is illustrated in Figure 1. Neutrinos can interact in various ways in the LAr target. Charged current interactions will produce either an energetic muon or electron, depending on the neutrino flavor, often accompanied by one or more hadrons (e.g., pions, protons). In the case of neutral currents, no primary charged leptons are expected in the final state. Knowing precisely the cross-sections of the different reactions is essential, and one of the goals of the DUNE near detector. Electromagnetic showers, muon, pion or proton tracks, all will cause ionization of the LAr according to different energy loss functions. The amount of ion/electron pairs created in the ionization process is determined by the work function [10]. The fraction of those electrons that escape recombination back into neutral atoms is typically described by the Birks or Box models [11]. The free electrons drift towards the anode with a drift velocity collinear and opposite to the electric field, and a magnitude that depends on the field too. Drifting electrons can become attached to impurities in the argon. The electron charge attenuation (typically parametrized as a drift-lifetime) strongly depends on the LAr purity and in fact this requires constant recirculation and purification. In addition to this, the spatial distribution of the drifting electron clouds can be spread out laterally and longitudinally. This is parametrized by diffusion coefficients. Finally at the anode, the wire voltages are set such that the electron clouds will cause induction in the first plane(s) of wires, and collected in the last. The possibility that a part of the clouds are captured by the first induction wires and don't reach the collection plane is parametrized by the transparency parameter.

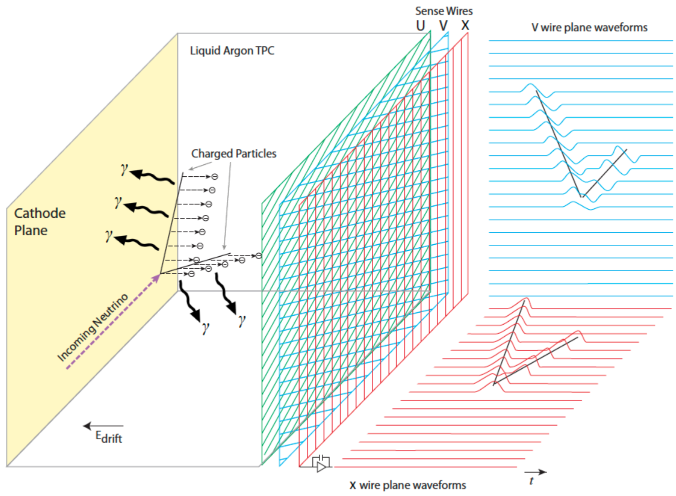

Figure 1. General operating principle of the SP LAr TPC. Charged particles from the neutrino interaction ionize the argon, and the ionization electrons drift horizontally towards the read-out wire planes. The right hand side of the image represents the time projections for two of the wire sets. Scintillation light is also produced and can be detected by photon sensors. From [6].

The reconstruction of the original neutrino interaction from the charge signals collected at the wires, or its complementary, the simulation of detector signals from the underlying physics, both require the knowledge of all the parameters mentioned above, and that is a goal of calibrations.

Low-level calibrations aim at the measurement with some time and space granularity, of the parameters determining the various physical steps in the process of signal formation, or possibly also at effective detector response maps that perform the same function. High-level calibrations, on the other hand, aim at describing the performance of the event reconstruction, by determining scale, and resolution functions of key parameters such as energy, position, direction, particle identification, and especially, their systematic uncertainties.

The need for different types of calibrations, with intrinsic sources or deployed systems, depends on the particular physics requirements of the experiment. As an example, the DUNE long-baseline neutrino oscillations measurements require an energy scale uncertainty of 2% (5%) for leptons (hadrons) in the energy range of GeV. For Supernova neutrino burst physics, energy resolutions of about 20–30%, in the tens of MeV range, are needed [12].

This paper will briefly review some of the methods used to calibrate LAr TPCs. Section 2 will highlight measurements carried out with cosmic ray muons and beam events. Other sources used for calibrations include ^{39}Ar intrinsic radioactivity. Section 3 addresses the development of laser-based systems, and Section 4 outlines a new idea for DUNE based on external neutron sources. In addition to the systems mentioned here, small gridded ionization-chambers deployed inside the cryostats are also extremely useful LAr purity monitors and instruments for in-situ measurements of electron lifetime [13].

2. Calibration with Natural or Intrinsic Sources

Several calibration measurements can be carried out without the need for dedicated systems, using sources such as cosmic ray muons, natural radioactivity or neutrino beam events. Cosmic ray muons are quite extensively used in current LAr TPCs, for both low- and high-level calibration. Both MicroBooNE [7] and the DUNE prototype ProtoDUNE [8] at CERN, employ cosmic-ray taggers in order to provide clean cosmic ray muon data samples for calibration.

Samples of stopping charged particles, typically muons and protons, where the energy loss can be precisely estimated from the track range, are used to measure the recombination model parameters and a work function scaling [11], both needed for the absolute energy scale. The calibration of the electromagnetic energy scale is also extremely important, especially for the search of electron neutrino appearance. This can typically be done with Michel electrons in the tens of MeV range or, at higher energies, with π^0 decay samples, whether from cosmic ray or beam events. Figure 2 (right) shows a distribution of invariant mass for $\pi^0 \to \gamma\gamma$ decays present in MicroBooNE neutrino beam events.

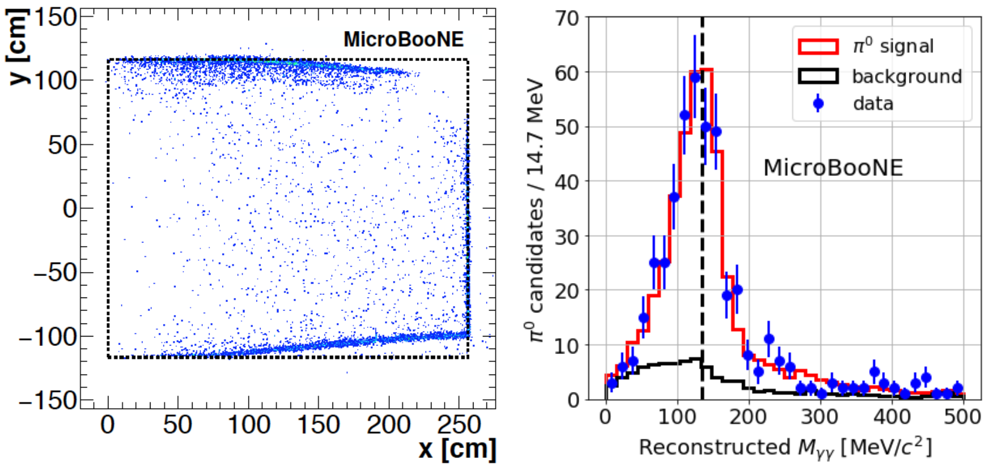

Figure 2. Calibrations of MicroBooNE with: (**left**) Cosmic ray muons: Entry/exit points of reconstructed muon tracks, showing a clear non-alignment with the TPC boundaries. Reproduced with permission from [14]. (**right**) Neutrino beam data: reconstructed invariant mass $M_{\gamma\gamma}$ from candidate ν_μ CC π^0 events after applying photon-shower energy corrections. Reproduced with permission from [15].

For large detectors, though, monitoring variations of response is important. Since the entry and exit-points of through-going tracks must be at the known TPC boundaries, they can be used to obtain estimates of muon track direction that can be independently compared to the reconstructed one. Discrepancies between the two therefore indicate distortions with respect to a uniform electric field assumption (that can be due for instance to the space-charge effect, i.e., the accumulation of slow-moving ions), and may be used to derive corrections. Figure 2 (left) presents a distribution of the entry and exit points of reconstructed muon tracks into the TPC showing that they are clearly not aligned with the

TPC boundaries in some regions (closer to the cathode). This type of observed distortions were used to measure and correct for the space-charge effect in MicroBooNE [14].

Knowing the electron lifetime along the drift, due to impurities in the LAr, is fundamental for a good energy resolution. Using through-going tagged cosmic ray muons (and also dedicated purity monitors), ProtoDUNE monitored the electron lifetime, having measured values up to 100 ms, much longer than its drift time (about 2.2 ms) With this method, and with the high statistics due to the surface location of the detector, uncertainties as low as 0.5% on the charge ratio (leading directly to the energy uncertainty) were achieved [16].

The high statistics at surface also allow for a fine mapping of the charge collection efficiency in the anode readout (100 k tracks for a 2% precision), that also includes the effects of diffusion. However, with underground locations such as DUNE, the cosmic ray muon statistics is severely reduced. In order to carry out at the DUNE far detectors the same kind of fine mapping done at ProtoDUNE, would take about 14 months with a loose track selection (all tracks, 50% efficiency) or several years for anode crossing tracks. Furthermore, at the depth of DUNE, cosmic ray muons have a mean energy of 282 GeV, much higher than at surface, and therefore suffer the effects of multiple scattering more.

3. Ionization with UV Lasers

Due to the comparatively limited statistics of cosmic ray muons underground, the usage of UV lasers was proposed for the calibration of the DUNE far detectors [17].

The usage of UV lasers for the calibration of TPCs was first proposed in 1979 for drift chambers [18]. With appropriate gas mixtures and an ionization potential of 6.5 eV, ionization could be achieved with two-photon absorption from an N_2 laser. Studies of ionization density were carried out as a function of the gas mixture and laser wavelength [19]. With the fourth harmonic of the Nd-YAG laser (266 nm) and the appropriate additives (e.g., TMA), large ionization densities (higher than for particles) could be reached, even with moderate laser intensities (1 μJ/mm^2). This idea was at the basis of the calibration system for the ALEPH detector gas TPC [20]. A schematic of this system is presented in Figure 3 (left), showing an innovative mirror arrangement, that can lead the laser tracks to mimic the tracks of particles coming from the LEP collider interaction point. Several measurements, including regular monitoring of the TPC drift velocity, were carried out with the laser system.

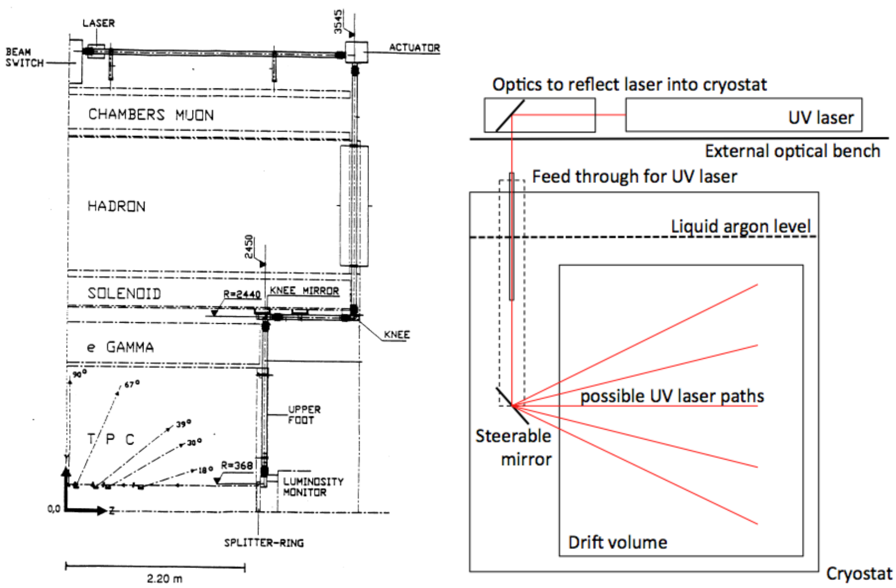

Figure 3. (**left**) Schematics of the ALEPH TPC laser calibration systems. Reused with permission from [20]. (**right**) Schematics of the MicroBooNE TPC laser calibration system. Reproduced with permission from [21].

The liquid argon ionization potential is 13.84 eV and, since the medium purity is essential, there are no low ionization potential states that can be used, like in gas. The process of two-photon absorption (with 266 nm light, 4.67 eV) only leads to excitation, so a third photon is needed for ionization. This means that much higher laser intensities—about 0.5 mJ/mm^2—are needed for the ionization of LAr via the three-photon process.

The first such measurement was carried out for the ICARUS experiment in 1996 [22]. Following that, the technique to use UV laser beams to calibrate LAr TPCs was further developed [23,24], with the goal of applying it to large detectors. Figure 3 (right) shows a schematic of the system initially proposed for MicroBooNE [21], that illustrates the main elements of this type of system:

1. An intense UV laser, typically a 266 nm (Nd-YAG fourth harmonic), and with intensities of 10 mJ per pulse or higher;
2. A quartz window that allows the beam into the cryostat while keeping its coherence;
3. A periscope structure with a movable mirror at the end, that steers the beam into the TPC active region.

Before its implementation in MicroBooNE, development of this technique was carried out at smaller dedicated experiments. Of particular note is the ArgonTube [25] setup, that achieved for the first time a 5 m long drift. Figure 4 shows the superposition of 100 tracks created by UV laser ionization, demonstrating their potential to achieve long lengths. It clearly shows that the tracks are not fully straight, indicating distortions of the electric field.

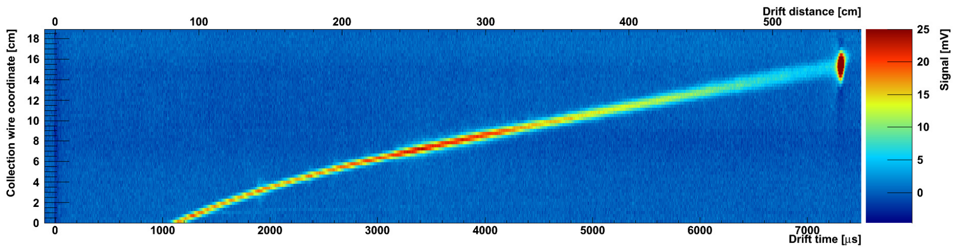

Figure 4. Ionization tracks caused by UV laser beam in a 5 m long drift liquid argon TPC. 100 tracks superimposed. Reproduced with permission from [25].

The capability of laser tracks to calibrate LAr TPCs was confirmed via measurements of drift velocity, based on comparing the known and reconstructed track positions, as illustrated in Figure 5 (left). As shown in Figure 5 (right), measuring the laser track's charge density as a function of drift distance could potentially also lead to its use to measure electron lifetime.

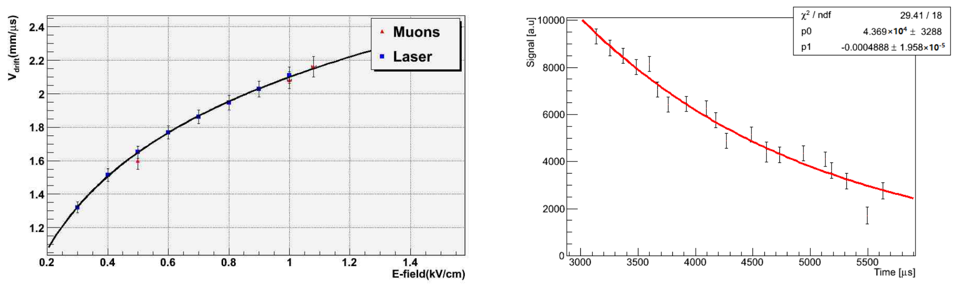

Figure 5. (**left**) Measurement of electron drift velocity in liquid argon with cosmic ray muons and UV laser. Reproduced with permission from [23]. (**right**) Measurement of electron charge attenuation in liquid argon with UV laser beams. Reproduced with permission from [25].

The first large LAr TPC experiment to use a laser-based calibration system was MicroBooNE, deploying two systems as shown in Figure 3 (right) on opposite ends of the detector. All beams entering into the detector active region must pass through the gaps in the field cage array, causing a shadowing pattern observable in the images of the reconstructed laser tracks shown in Figure 6. The use of two laser systems on the same detector volume allowed an important feature in the analysis. If done with only a single track, the comparison of the true track direction (known from the mirror angles) and the reconstructed track direction (in the assumption of uniform, nominal electric field) is not enough to determine how the field might be distorted, since there can be multiple point-to-point displacements that give the same result. In order to disentangle this ambiguity, it is essential to observe the displacement of different tracks that are concurrent in the same point. Using this method to measure the track displacements, MicroBooNE measured electric field maps in various sub-regions of the TPC [26]. Statistical and systematic uncertainties (obtained from comparisons with Monte Carlo simulations) were estimated each at levels of the order of 2% or less, depending on the region. The fraction of mapped regions was somewhat limited, due to the limitations of the laser track coverage, that are clear in Figure 6.

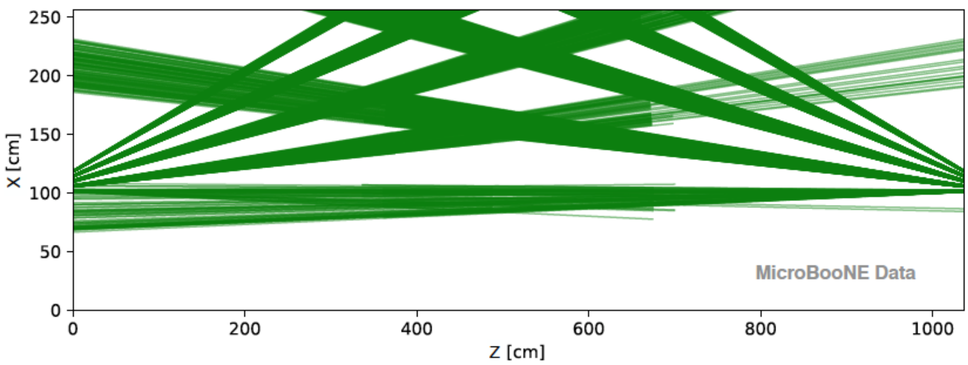

Figure 6. Reconstructed laser tracks in the MicroBooNE detector. From [26].

The underground location, with limited cosmic ray statistics, and the stringent physics requirement of the DUNE experiment led to the proposal of a set of dedicated calibration systems, including a laser-based one [17]. The design of the DUNE laser system is based substantially on the MicroBooNE system. It will be based on the same laser but with new design features aimed at overcoming some of its limitations. The two designs of the new DUNE periscopes are shown in Figure 7. In both cases the beam enters the cryostat through a quartz window on the top flange inside the Safety Cover, and then passes through two long evacuated quartz tubes mounted on a long periscope structure, that can rotate azimuthally. The bottom part of that structure is made of non-conductive material (Torlon) and holds the cold mirror that can also be rotated along the polar angle. Some of the DUNE periscopes will employ design 1, shown on the left, in which the periscope will enter the field cage through dedicated openings, virtually eliminating the shadowing effect. Several simulations show that the effect of this setup on the electric field in the active region is very small, but for additional safety it will be possible to retract the periscope above the field cage opening. For the periscopes located besides the vertical field cage, it is not practical to enter it, so the periscope will have an extra rotational degree of freedom, allowing the bottom mirror to pivot its position and avoid the shadowing of the field cage profiles. This design is illustrated in Figure 7 (right), showing the two eccentric rotary stages that provide this feature.

The DUNE laser system will be integrated with the experiment's DAQ, both to ensure adequate synchronization with the mirror movement and to prevent the laser from firing in case of physics triggers. In addition to the measurements of electric field uniformity mentioned above, the plan for DUNE laser calibrations included validation of the readout uniformity and other charge-based measurements, such as that of the electron lifetime, diffusion and wire transparency.

As can be seen in Figure 6, tracks of up to 10 m length have been produced, and lengths of 20 m are expected to be possible. Based on this assumption, a set of at least eight laser periscopes should provide a single-beam coverage of the first DUNE far detector, with additional ones allowing for the double-beam coverage in some regions. The full scope of the calibration systems for the DUNE far detectors will be finalized in the coming years. The technical feasibility of these designs and methods will be tested in the upcoming second run of the DUNE prototype at CERN, ProtoDUNE, from 2022 onwards.

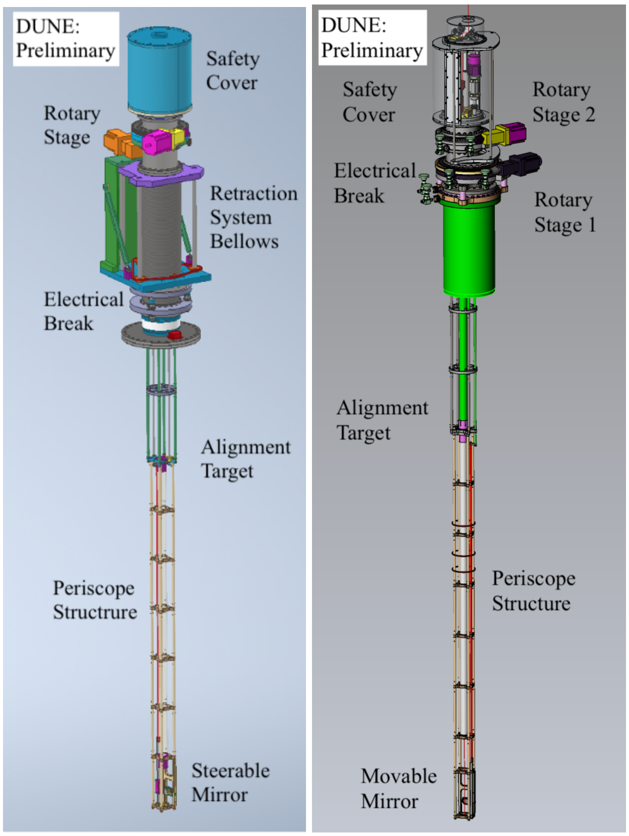

Figure 7. Schematics of the two periscope designs for DUNE laser calibrations: (**left**) Periscope 1, for penetration into the top (horizontal) TPC field cage, includes a retraction mechanism. (**right**) Periscope 2, for deployment next to the lateral (vertical) field cage, provides two eccentric rotation movements, to minimize shadowing effects.

4. Pulsed Neutron Source, a New Idea for DUNE

While the laser system will be dedicated essentially to low-level measurements of parameters needed for the detector model, there is also the need for high-level measurements of detector performance, especially at the MeV level energies not covered by Michel electrons or π^0 events. DUNE is developing a new idea based on the propagation and capture of neutrons in the LAr. The capture of neutrons in ^{40}Ar leads to a 6.1 MeV (total) gamma ray cascade, that has been characterized in detail in a dedicated experiment [27]. In terms of triggering, the low energy threshold of DUNE is expected to be between 5 and 10 MeV, and therefore a calibration source in this range is potentially quite valuable for measurements of energy scale and resolution, and trigger efficiency, that could benefit the DUNE supernova and solar neutrino physics program.

It was recognized that the neutron scattering in ^{40}Ar has a predicted anti-resonance at 57 keV, where the elastic scattering cross-section can be quite low, of the order of mb. That, coupled with the small energy loss per scatter, leads to a potentially large range for neutrons, estimated at tens of meters for the natural isotopic composition of argon. Therefore, it should be possible to cause neutron capture cascades in the whole DUNE detector with only a small number of neutron sources. The idea for the neutron source system for DUNE [17] makes use of pulsed commercial neutron DD (deuterium-deuterium) generators (neutron energy 2.5 MeV) installed on a few adequate locations on top of the cryostat (see Figure 8). The current plan for DUNE far detector 1 is to position DD generators over the flanges of two of the human access ports (in opposite corners). The large diameter (80 cm) of these flanges ensures that no hydrogen-rich insulation will reduce the neutron flux before reaching the argon. In this way, the generators are completely external to the cryostat, facilitating installation, operation and maintenance. On the other hand, they will require both neutron and gamma shielding for the safety of personnel. Nearby neutron monitors, providing pulse timing information to the DUNE DAQ, will complete the system.

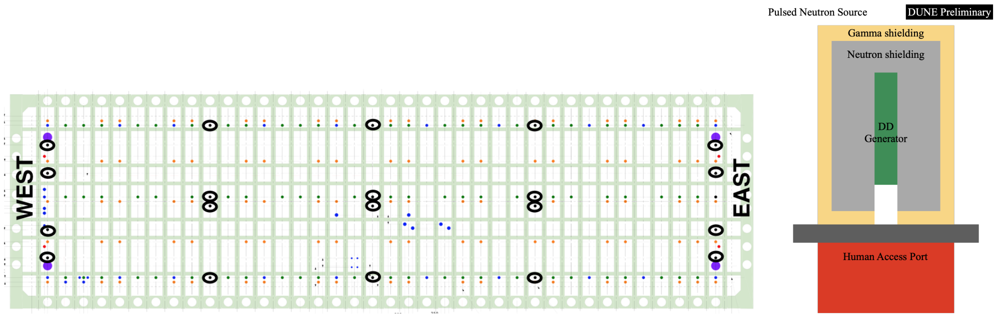

Figure 8. (**left**) Schematic of the DUNE far detector 1 cryostat roof showing the large human access ports (in purple), where the pulsed neutron sources are planned to be installed (in two opposite corners). The possible locations for the laser system are also shown (black ellipses). From [17]. (**right**) Schematic of a pulsed neutron source, including neutron and gamma shielding, mounted on top of a human access port.

Simulations of neutron propagation and capture in DUNE, illustrated in Figure 9, show that even with just two external DD generators, there are neutron captures in a very large fraction of the DUNE detector. Different source configurations were also compared, some including different layers of material aimed at the moderation of the neutron energy before reaching the argon, but it was concluded that the gain with moderators was not significant. Therefore the planned design involved only the generators and the necessary shielding.

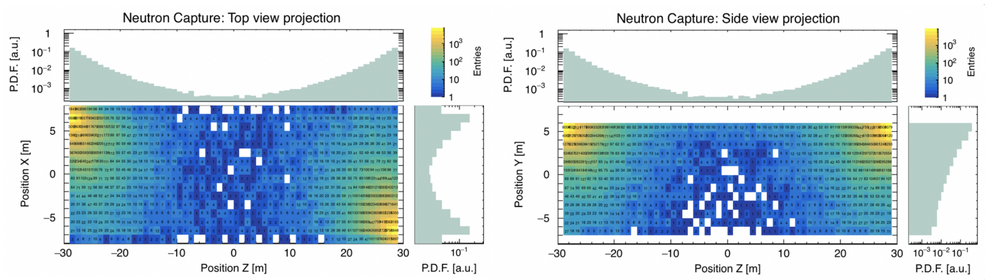

Figure 9. Simulations of spatial distribution of neutron captures in the DUNE far detector, from two pulse neutron sources located externally, at the top of the detector in two opposite corners. From [17].

The design of this system hinges crucially on the existence of the predicted anti-resonance in ^{40}Ar at 57 keV. The only existing experimental measurement did not observe it [28], but that could be due to its use of a gas target and consequently, on a low sensitivity to small cross-sections. Another dedicated experiment, has since measured the neutron cross-section with a liquid argon target, confirming the existence of the predicted anti-resonance [29]. Initial tests at ProtoDUNE in 2020 also confirm the expectations about neutron propagation, but further work is planned at ProtoDUNE phase II run in 2022 in order to validate the identification of the gamma cascade.

5. Outlook

The technique of liquid argon TPCs is playing an increasingly important role in neutrino and rare event physics, with increasing demands in terms of detector performance systematics. The development of various types of calibration methods, with and without dedicated systems, is accompanying that trend. For DUNE, there are two main dedicated systems in development—with UV laser beams creating long ionization tracks, and external neutron generators creating distributed gamma cascades. On the path to their use in the DUNE far detectors, further validation of these methods is expected in the upcoming run of ProtoDUNE-II.

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