will look for coincident regions of low-energy deposits, below 10 MeV, across an entire module and in a 10 s period. An extended high-energy trigger will open a readout window of 100 s to capture a full SNB. The upstream DAQ identifies per-channel regions of interest and forms them into trigger primitives. These are then formed into trigger candidates that contain information from an entire module; on these trigger candidates, trigger decisions are made. Once a trigger decision has been made, this will be communicated to the surface, and the data buffered underground until the DAQ BE indicates it is ready to receive data.

The DAQ must also provide the system clock that keeps the detector components synchronized and provides the timestamp for all data. The timestamp derives from a GPS 1PPS signal that is fed into the DAQ with 1 µs precision, adequate to timestamp beam and supernova events. To provide the finer synchronization between detector components, a 10 MHz reference clock drives the module's 62.5 MHz master clock, which is fanned out to all detector components, providing an overall synchronization to a precision of 1 ns.

1.10 Calibration

The challenge of calibrating the DUNE FD is to control the response of a huge cryogenic detector over a period of decades, a challenge amplified by the detector's location deep underground and therefore shielded from the cosmic muons that were typically used as standard candles by previous LArTPCs.

To achieve our $\mathcal{O}$(GeV) oscillation and nucleon decay physics goals, we must know our fiducial volume to 1–2% and have a similar understanding of the vertex position resolution; understand the ν_e event rate to 2%; and control our lepton and hadron energy scales to 1% and 3%, respectively. At the $\mathcal{O}$(MeV) scale our physics requirements are driven by our goal of identifying, and measuring the spectral structure of, a SNB; here, we must achieve a 20–30% energy resolution, understand our event timing to the 1 µs level, and measure our trigger efficiency and levels of radiological background. These are all high-level calibration requirements, but the underlying detector parameters that we are characterizing are parameters such as the energy deposited per unit length ($\mathrm{d}E/\mathrm{d}x$), ionization electron drift-lifetimes, scintillation light yield and detection efficiency, E field maps, timing precision, TPC alignment, and the behavior (noise, gain, cross-talk, linearity, etc.) of electronics channels.

The tools available to us for calibration include the LBNF beam, atmospheric neutrinos, atmospheric muons, radiological backgrounds, and dedicated calibration devices that will be installed in the detector. At the lowest energies, we have deployable neutron sources and intrinsic radioactive sources; in particular the natural ^{39}Ar component of the LAr with its 565 keV end-point can, given its pervasive nature across the detector, be used to measure the spatial and temporal variations in electron lifetime. The possibility of deploying radioactive sources is also being explored. In the 10 MeV to 100 MeV energy range we will use Michel electrons, photons from π^0 decay, stopping protons and both stopping and through-going muons. We will also have built-in lasers, purity monitors and thermometers, and the ability to inject charge into the readout electronics. Finally, data from the ProtoDUNE detectors will be invaluable in understanding the response and particle-identification capabilities of the FD.

Once the first 10 kt module is switched on, there will be a period of years before LBNF beam sources are available for calibration — and even then the statistics will be limited. In this time, cosmic muons will be available, but the low rate of these means that it will take months to years to build up the necessary statistics for calibration. The inclusive cosmic muon rate for each 10 kt module is 1.3×10^6 per year. However, for calibrations such as APA alignment, the typical rate of useful muons is 3000–4000 per APA per year. For energy-scale calibrations, stopping cosmic muons are the most relevant and here the rate is 11000 per 10 kt module per year. Therefore the earliest calibrations will come from dedicated calibration hardware systems and intrinsic radiological sources.

A 266 nm laser will be used to ionize the argon, and this can be used to map the E field and to make early measurements of APA alignment. The laser system will be used throughout the lifetime of the detector to measure the gradual changes in the E field map as positive ions accumulate and flow around the detector. An externally deployed pulsed neutron source provides a triggered, well defined energy deposition from neutron capture in argon which is an important component of signal processes for SNB and long-baseline (LBL) physics. A radioactive source deployment system, which is complementary to the pulsed neutron system, can provide at known locations inside the detector a source of gamma rays in the same energy range as SNB and solar neutrino physics

Over time, the FD calibration program will evolve as statistics from the cosmic rays and the LBNF beam amass and add to the information gained from the calibration hardware systems. These numerous calibration tools will work alongside the detector monitoring system, the computational fluid dynamics models of the argon flow, and ProtoDUNE data to give us a detailed understanding of the FD response across the DUNE physics program.

1.11 Installation

A major challenge in building the DUNE SP modules is transporting all the detector and infrastructure components down the 1500 m Ross shaft, to the detector caverns. To aid the planning of the installation phase, installation tests will be performed at the NOvA FD site in Ash River, Minnesota, USA. These tests will allow us to develop our procedures, train the installation workers, and develop our labor planning through time and motion studies.

Once the module's cryostat has been installed, a temporary construction opening (TCO) is left open at one end through which the detector components are installed. A cleanroom is built around the TCO to prevent any contamination entering the cryostat during installation. The detector support system (DSS) is then installed into the cryostat, ready to receive the TPC components.

Inside the cryostat, the various monitor devices (temperature, purity, argon level) are installed at the end furthest from the TCO. The far end of the FC is then installed. Rows of APAs and CPAs, along with the top and bottom FC sections, are then installed and cabled, working from the far end of the detector towards the TCO. The integration of the PDs and CE with the APA happens