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Deep Underground Neutrino Experiment (DUNE)

DRAFT Technical Design Report

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(Calibration Information for SP volumes)

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The DUNE Collaboration

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Chapter 1

Calibration Hardware for Single-Phase

1.1 Calibration Hardware Overview

1.1.1 Introduction

A detailed understanding of the overall detector response is essential for DUNE physics goal. The precision with which each calibration parameter needs to be measured is set by the systematic uncertainties for the long-baseline (LBL) and other physics programs at DUNE. Chapter 4 of the Physics volume of the TDR provides a detailed description of the calibration strategy for DUNE using existing sources of particles (e.g. cosmic ray muons), external measurements (e.g. ProtoDUNE), monitors (e.g. purity monitors) and dedicated calibration hardware systems.

Chapters 3, 4, 5 and 8 describe other hardware that are essential for calibration such as cold electronics (CE) external charge injection systems, high voltage (HV) monitoring devices, photon detection system (PDS) stability monitoring system, and cryogenic instrumentation and detector monitoring devices, respectively. The usage of existing sources of particles, and external measurements is discussed in the physics volume of the TDR. This chapter describes the dedicated calibration systems, to be deployed for the DUNE SP detector module which are intended to provide information beyond the reach of the other calibration sources. These include an ionization laser system, a photoelectron laser system and a pulsed neutron source system. The possibility of deploying a radioactive source system is also currently being explored.

Section 1.1.2 describes the baseline hardware designs, and outlines alternative designs which may improve physics capability and/or reduce overall cost. Section 1.2 describes the baseline design for the ionization laser system, used to map out the electric field throughout the detector. Section **??** describes the baseline design for the pulsed neutron source, which can be used to provide a known deposit of energy across the entire detector volume.

The Calibration Consortium was formed in November 2018. As such, significant development plans exist and the timeline for these is outlined in Section 1.15.

1.1.2 Scope

1.1.3 Requirements

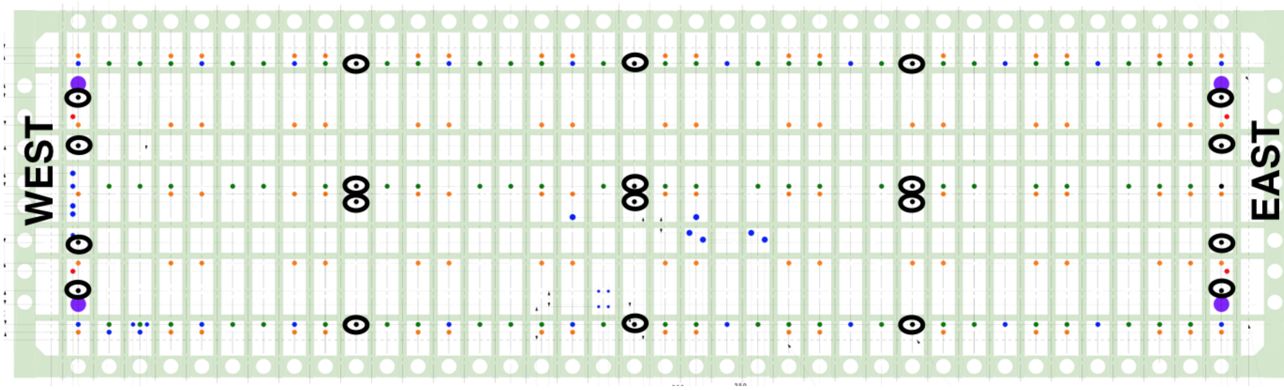

Figure 1.1: Top view of the SP detector module cryostat showing various penetrations. Highlighted in black circles are multi-purpose calibration penetrations. The orange dots are TPC signal cable penetrations. The blue ports are DSS penetrations. The orange ports are TPC signal cable penetrations. The larger purple ports at the four corners of the cryostat are manholes.

1.1.4 Design Considerations

1.1.4.1 Cryostat Configuration for Calibration

The current cryostat design for the SP detector module with penetrations for various sub-systems is shown in Figure 1.1. The penetrations dedicated for calibrations are highlighted in black circles. The ports on far east and far west are located outside the field cage. The current plan is to use these penetrations for multiple purposes. For example, the penetrations on the far east and west will be used both by laser and radioactive source deployment systems. In addition to these dedicated ports, the Detector Support System (DSS) and cryogenic ports (orange and blue dots in Figure 1.1, respectively) will also be used as needed to route cables for the single phase photon detector calibration system. The DSS and cryogenic ports are accommodated with feedthroughs with a CF63 side flange for this purpose.

The placement of these penetrations was driven by the ionization track laser and radioactive source system requirements. The ports that are closer to the center of the cryostat are placed near the APAs (similarly to what is planned for SBND) to minimize any risks due to the HV discharge. For the far east and west ports, HV is not an issue as they are located outside the field cage (FC) and the penetrations are located near mid-drift to meet radioactive source requirements. Implementation of the ionization track laser system proposed in Section 1.2.1, requires 20 feedthroughs to cover the four TPC drift volumes; this arrangement is needed for lasers to be used for full volume calibration of the electric field and associated diagnostics (e.g. HV).

The distance between any two consecutive feedthrough columns in Figure 1.1 is assumed to be about 15 m. This is considered reasonable since the experience from the MicroBooNE laser system has shown that tracks will propagate over that detector's full 10 m length. Assuming that the effects of Rayleigh scattering and self-focusing (Kerr effect) do not limit the laser track length, this laser arrangement could illuminate the full volume with crossing track data. It is important to note that at this point in time, a maximum usable track length is unknown and it is not excluded that the full 60 m detector module length could be achieved by the laser system after optimization.

1.2 Laser Calibration Systems

1.2.1 Ionization Laser System

1.2.1.1 Physics Motivation

The primary purpose of a laser system is to provide an independent, fine-grained estimate of the E field in space and time. Through its effect on drift velocity and recombination, the E field is a critical parameter for physics signals as it ultimately impacts the spatial resolution and energy response of the detector.

There are multiple sources which may distort the electric field temporally or spatially in the detector. Current simulation studies indicate that positive ion accumulation and drift (space charge) due to ionization sources such as cosmic rays or ^{39}Ar is small in the DUNE far detector (FD); however, not enough is known yet about the fluid flow pattern in the FD to exclude the possibility of stable eddies which may amplify the effect for both SP and DP modules. This effect can get further amplified significantly in the DP module due to ion accumulation at the liquid-gas interface. Additionally, other sources in the detector (especially detector imperfections) can cause E field distortions. For example, field cage resistor failures, non-uniform resistivity in the voltage dividers, CPA misalignment, CPA structural deformations, and APA and CPA offsets and deviations from flatness can create localized E field distortions. In both SP and DP systems, the failure of a resistor will create significant, local electric field distortions which will need to be identified[1]. While the resistor failure will be detected temporally, its location in space is not possible to determine from monitoring data. Misalignments of detector objects or deformations may also create (small) electric field distortions; while individual effects may be small, it is possible to have a combined, significant effect. Each individual E field distortion may add in quadrature with other effects, and can reach 4% under certain conditions. Understanding all these effects require in-situ measurement of E field for proper calibration.

Many useful secondary uses of laser include alignment (especially modes that are weakly constrained by cosmic rays), stability monitoring, and diagnosing detector failures (e.g., HV). Misalignment may include physical deformation and/or rotations of objects within the detector. Certain alignment “directions” difficult to assess with cosmic rays alone, such as distortions of the detector that preserve the gap widths and do not shift the anode plane assemblies (APAs) in x near the gaps relative to one another are difficult to assess with cosmic rays alone. These distortions include global shifts and rotations in the locations of all detector elements, and crumpling modes where the edges of the anode plane assemblies hold together but angles are slightly different from nominal.

[1] In the DP system, four registers would have to fail to cause a failure across the field cage gap, but even one failure in the SP can have an impact; this may be partially mitigated by modifying the HV, but not completely.

A laser system also has the intrinsic advantage of being immune to recombination, thus eliminating particle-dependent effects.

1.2.1.2 Requirements

The energy and position reconstruction requirements for physics measurements lead to requirements on the necessary precision of the calibration E field measurement and its spatial granularity.

As mentioned in the DUNE Physics TDR (Section 4.4.1.1), a 1% bias in the lepton energy scale is significant for the LBL sensitivity to CPV. Since a smaller E field leads to higher electron/ion recombination and therefore a lower collected charge, distortions of the E field are one of the possible causes of an energy scale bias. According to [4], a 1% distortion on E field leads to a 0.3% bias on collected charge. Since other effects will contribute to the lepton energy scale uncertainty budget, we consider a goal for the calibration system to measure the E field to a precision of $\sim 1\%$ so that its impact on the collected charge is well below 1%.

The IDR states that a fiducial volume uncertainty of 1% is required (ref. [5], p. 4-46) and that this translates to a position uncertainty of 1.5 cm in each coordinate (ref. [6], p. 2-12). Also that in the y and z coordinates, the wire pitch of 4.7 mm achieves that while in the drift (x) direction, the position is calculated from timing so it is claimed it should be known better.

But the position uncertainty depends also on the electric field, via the drift velocity. Since the position distortions accumulate over the drift path of the electron, it is not enough to specify an uncertainty on the field, we must accompany it by specifying the size of the spatial region of that distortion. i.e. a 10% distortion would not be relevant if it was confined to a 2 cm region, for instance, and the rest of the drift region was nominal. So what matters is the product of [size of region]x[distortion]. Moreover, we should distinguish distortions of two types:

1. affecting the magnitude of the field. Then the effect on the drift velocity v is also a change of magnitude. According to the function provided in [7], close to 500 V/cm, the variation of the velocity with the field is such that a 4 % variation in E leads to a 1.5 % variation in v.

2. affecting the direction of the field. Nominally, the field E should be along x, so $E = E_L$ (the longitudinal component). If we consider that the distortions introduce a new transverse component E_T, in this case this translates directly into the same effect in the drift velocity, that gains a v_T component that is $v_T = v_L E_T / E_L$, i.e. a4 % transverse distortion on the field leads to a 4 % transverse distortion on the drift velocity.

So, a 1.5 cm shift comes about from a constant 1.5 % distortion in the velocity field over a region of 1 m. In terms of electric field, that could be from a 1.5 % distortion in ET over 1 m or a 4 % distortion in EL over the same distance.

From ref. [5], page 4-53, E field distortions can be caused by space-charge effects due to accumulation of positive ions caused by ^{39}Ar decays (cosmic rate is low in FD), or detector defects, such as field cage resistor failures, resistivity disuniformities, etc... The total effects added in quadrature can be as high as 4 %. From ref. [4], the space charge effects due to ^{39}Ar can be of the order of 0.1 % for the single phase (SP), and 1 % for the dual phase (DP), so in practice that kind of distortion needs to cover several meters in order to be relevant. Other effects due to cathode plane assembly (CPA) or field cage (FC) imperfections can be higher than those due to space charge, but they are also much more localized. If we assume that there are no foreseeable effects that would distort the field more than 4 %, and considering the worst case (transverse distortions), then the smallest region that would produce a 1.5 cm shift is 1.5/0.04 = 37.5 cm. That provides a target for the granularity of the measurement of the E field distortions in x, with of course a larger region if the distortions are smaller. Given the above considerations, then a voxel size of 10x10x10 cm appears to be enough to measure the E field with the granularity needed for a good position reconstruction precision. In fact, since the effects that can likely cause bigger E field distortions are the problems or alignments in the CPA (or APA), or in the FC, it could be conceivable to have different size voxels for different regions, saving the highest granularity of the probing for the walls/edges of the drift volume.

1.2.1.3 Design

1.2.1.3.1 Baseline design

The design of the laser calibration system for DUNE is strongly based on the design of the system built for MicroBooNE [2], that was based on several previous developments[8, 9, 10, 11]. A similar system was also built for CAPTAIN[12] and SBND[1]. Operation of the MicroBooNE system has already taken place and a preliminary report was given in[13].

Ionization of liquid argon (LAr) by laser can occur via a multiphoton process in which a two-photon absorption[14] leads the atom to the excited states band, and a third photon can cause ionization. This can only occur with high photon fluxes, and so the employed lasers need to be pulsed and have pulse energies of 60 mJ or more. Contrary to muons, the laser beams do not suffer multiple scattering and travel along straight lines determined by the steering mirror optics. The basic measurement consists in recording the laser beams with the TPC and comparing the reconstructed tracks with the direction known from the steering hardware. An apparent curvature of the measured track is attributed to E field distortions (either in direction or magnitude).

An unambiguous field map requires crossing laser tracks in every relevant "voxel" of the detector. If two tracks that enter the same spatial voxel ($10 \times 10 \times 10\text{cm}^3$ volume) in the detector module, the relative position of the tracks provides an estimate of the local 3D E field.

With a single, steerable laser track, there would be ambiguity in the direction/magnitude of the position displacement and so the information obtained would be limited.Even if not crossing, a set of several tracks from opposite directions can still be used to obtain a displacement map via an iterative procedure[13].

Laser beams with lengths of 10 m in LAr have been observed in MicroBooNE, and beams with 20 m (possibly more) are reasonably expected to be possible to obtain with a similar system. While the

Rayleigh scattering of the laser light is about 40 m, additional optics effects, including self-focusing (Kerr) effects may limit the maximum practical range. This has determined the choice of locating 5 calibration ports in the cryostat roof at 15 m intervals along each of the 4 drift volumes of the SP module, for a total of 20 ports. In fact, there are 4 ports just outside each of the FC end-walls, and 12 ports located over the top FC, close to the APA of each drift volume, as shown in Fig. 1.1.

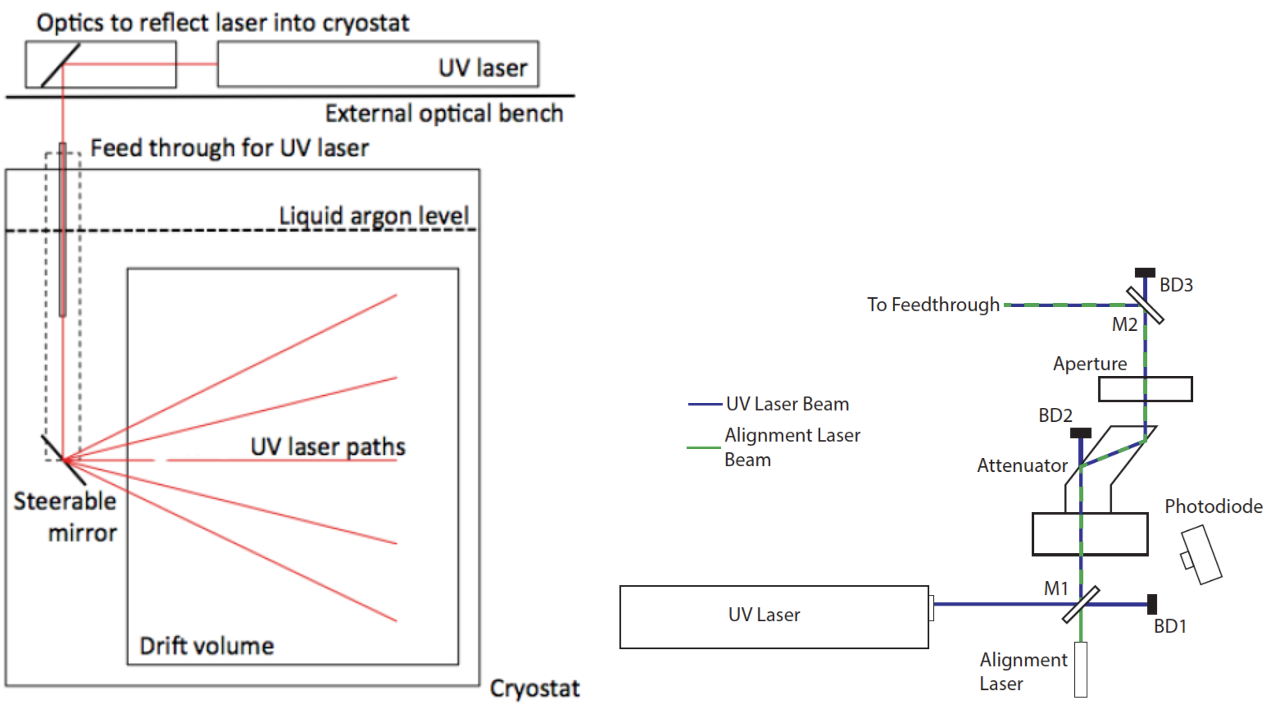

Figure 1.2: Left: Schematics of the ionization laser system in one port (from[1]). Right: Schematics of the laser box (from[2]).

For each of those 20 ports, a laser module can be schematically represented by Fig. 1.2 (Left), and consists of the following elements:

- a laser box Fig. 1.2 (Right) that provides:
  - an attenuator and a collimator to control the intensity and size of the beam;
  - a photodiode that gives a TPC-independent trigger signal;
  - a low-power red laser, aligned with the UV one, to facilitate alignment operations;
  - a Faraday cage to shield the surrounding electronics from the accompanying EM pulse.
- a feedthrough (Fig. 1.3 (Left)) into the cryostat that provides:
  - and optical coupling that allows the UV light to pass through into the cryostat directly into the liquid phase, avoiding distortions due to the gas-liquid interface and the gas itself;

– a rotational coupling that allows the whole structure to rotate while maintaing the cryostat seal;

– a periscope structure (Fig. 1.3 (Right)) mounted under that rotating coupling, that supports a mirror within the LAr;

– the additional theta rotation of the mirror is accomplished by a precision mechanism coupled to an external linear actuator;

– both the rotation and linear movements of the steering mechanism are read-out by precision encoders.

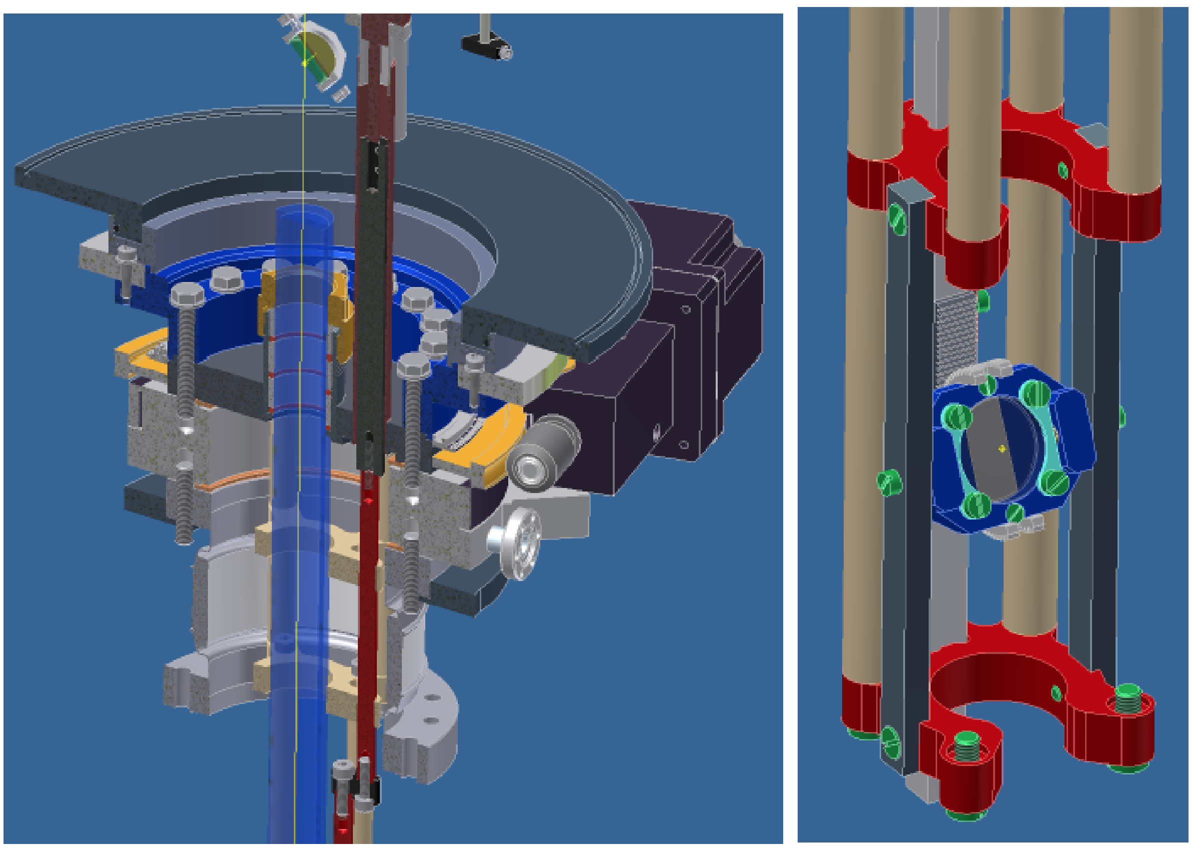

Figure 1.3: Left: CAD drawing of the MicroBooNE feedthrough. Right: CAD drawing of the MicroBooNE periscope. Both figures from[2].

In the case of the lasers in the end-wall ports, the beams enter the FC laterally, while in the case of the lasers in the ports over the TPC, the beams enter the TPC from the top. In both cases, the laser beam can enter the FC only through the gaps between the FC electrodes. These gaps are 1.4 cm wide and the electrodes themselves are 4.6 cm wide, so it's clear that the shadowed regions are very significant. In one of the alternative designs, the top FC is modified as to allow small openings for the bottom of the periscope to penetrate within the FC, significantly increasing coverage.

For the six most central ports, the distance between them is small enough that we can consider having the same laser box serving two feedthroughs, in order to reduce the costs associated with the laser and its optics.

A scan of the full detector using 1 L volume elements would require a number of tracks on the order of 800k, would take about three days. It is expected that shorter runs could be done to investigate specific regions. The sampling granularity, and therefore the amount of data taken, is dependent on data acquisition (DAQ) requirements. In fact, even to be able to record the desired 800k tracks, a dedicated data reduction algorithm will have to be devised, so that only a drift window of about $100 \mu s$ of data is recorded, and the position of that window depends on the beam position and direction and which wire is being read out.

1.2.1.3.2 Alternative design 1: Top FC penetration

Given that the FC electrodes are 4.6 cm wide with only a small 1.4 cm gap between them, the shadows caused when the laser source is outside the FC are substantial. We estimate that the maximum angle at which beams can go through is about 45 deg. Given the limitations of the region above the FC, especially the geometry of the ground plane, it is likely that the mirror cannot be placed much higher up than 40 cm away from the FC. That means that, close to the top FC, the covered region will be only about 40-60 cm long, in each 3.6 m long drift volume. Considering for simplicity no limitations to movement along the direction of the FC electrodes, that means that only about 10-15% of the top area of the FC would be covered by the laser system. On the bottom FC, that ratio would be slightly higher, corresponding to the ratio of gap (1.4 cm) to total (1.4+4.6 cm) width, i.e. about 25%.

Penetration of the FC would eliminate those shadows and allow a practically unimpeded coverage. Fig. 1.4 shows a possible way to accomplish this for the top-of-TPC ports. In practice, it might be necessary to remove two FC electrodes, to achieve a 10 cm diameter free circle.

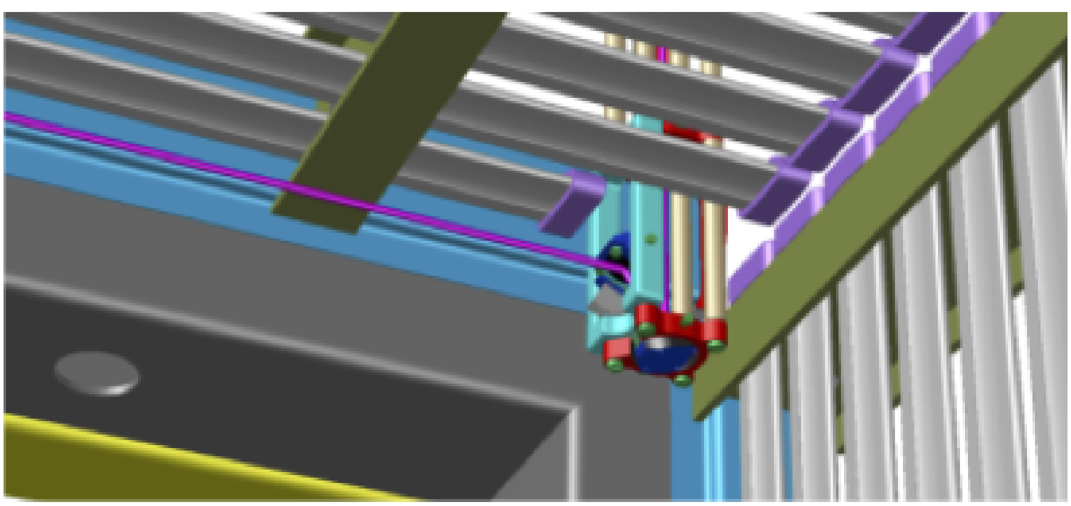

Figure 1.4: CAD drawing of a possible way for the periscope to penetrate the FC.

In the end-walls, such a solution is not possible since the ports are on the side, not on top of the FC. Alternative 2 addresses the coverage issues with that design.

1.2.1.3.3 Alternative design 2: End-wall horizontal track

The baseline design is based on laser entry points in which the movement of the steering mirror has two angular degrees of freedom.

A possible alternative design would change that end part of the system so that there is a translation and a rotation movement. A mirror at a 45 deg angle would send the beam horizontally, perpendicular to the APA/CPA, but externally to the field cage. A horizontal track, installed in that same direction, would allow the translation movement of a secondary mirror (or two of them, one on each side), mounted with an angle of 45 deg with respect to the incident beam. This allows the mirror to be aligned with the 1.4 cm wide gaps between the field cage profiles. This second mirror would have a rotation movement, around the same axis, keeping the 45 deg angle to the beam, but causing its reflection to sweep a vertical plane.

In terms of cryostat penetration, the design of the feedthrough and periscope would follow the baseline one, but the theta angle would be practicall always num45 deg, with only minor adjustments, and the angle would flip between 0 and 180 deg. The reflected beam is parallel to the FC wall and perpendicular to the APA. There would have to be a new 14 m long tray for the movement of the secondary mirror(s). Long plastic threaded rods could be used for the movement along the tray. Rotation of the first rod would push/pull a small platform along the tray, and the rotation of the second rod is transmitted to a mechanism on that platform to achieve the rotation around the x axis.

The FC profiles are 4.6 cm wide with a 1.4 cm gap between. That's the gap close to which the mirror needs to stop. That means that there is a finite amount of x values where we can position the mirror, effectively every 6 cm. In order to correct for possible FC shifts, one can use the laser positioning system to see if beam is passing to the other side. Choosing the z coordinate of the tray to be located close to an edge of the drift volume, the the angular range of movement needed to fully cover a vertical plane with the rotation of the mirror is only 90 deg.

The advantages of this mirror movement system are the following:

- should allow a good coverage of most of the active volume, even coming from outside the FC;
- one can use the same calibration port laser to illuminate all drift volumes;
- the beam is always parallel to the APA, especially the PDS, so has less risk of hitting it directly or though reflections on the cathode (but by reflections on the FC electrodes, that's still possible);

With respect to the reference system, possible disadvantages are the following:

- in terms of construction, this option has more moving parts and movement transmitted at long distances, so it can be more challenging to reach the same kind of mechanical precision as the baseline one;

- if the field cage profiles shift during cooling, there will be the need to fine-tune the alignment of the mirror with the FC gaps. This could be accomplished with the laser positioning system;

1.2.1.4 Possible Measurements

The method for measurement is based on the measurement of position displacements. The laser produces straight tracks in a known position and deviations from that seen in reconstructed tracks are attributed to E field distortions. Therefore the precision with which the E field distortions can be measured depends on the precision with which we can know the laser track position and the TPC position reconstruction precision. The TPC precision is given primarily by the wire spacing of 4.7 mm in the y,z coordinates and a bit better than that (maybe 2 mm) on the z coordinate, determined by the $1\mu s$ peaking time of the electronics. Given infinite laser positioning accuracy, the smallest measurable E field distortions would be those that cause displacements of this magnitude – 2 mm in x and 5 mm in y,z. The precision on the drift velocity distortions depends on the size of the spatial region where they are present. For distortions present in regions of 0.5 m and larger, drift velocity distortions can therefore be measured with an accuracy of 1% in y,z and 0.4% in x. In y,z, 1% precision on drift velocity distortions translates to a 1% precision on the transverse field distortions. Along x, one must consider that, at 500 V/cm, a 1% change in E field leads to 0.375 % change in drift velocity. So finally, this means that the smallest measurable distortions given the TPC design (wire pitch, timing precision) are of 1% in if they are present in regions of 0.5 m and above (smaller field distortions could be in principle be measurable if they are present over larger regions, so that their effect accumulates over the drift path). On one side, this gives us an ultimate limit to the E field precision achievable with the laser system, but on the other side, since these TPC precision considerations apply to physics events too, it also tells us that an E field precision much better than 1% should not have an impact on physics.

In principle, if we were confident about the field in one detector region and would like to probe another, we could use tracks that cross both regions and use the TPC measurements in the ”good” region as the ”true” track direction, without needing the hardware information on the mirror angles, etc... But in a general case, the TPC precision is only one of the components of the laser measurement precision, the other being the mechanical beam positioning accuracy. The goal of the mechanical design of the system is to achieve a precision close to that of the TPC measurements, so that no single factor is dominant in the overall systematics. The starting point of the laser beams is given by the position of the mirror in the periscope, that is known from construction drawings and cool-down calculations. Warm surveys might be necessary. The angle of the beam is given the angles (theta, phi) of the mirror, that are set by the periscope motors and read-out by the encoders. Reference[13] quotes a mechanical precision of 0.05 mrad for the MicroBooNE system, for both angles. At 10 m, the maximum in MicroBooNE, that’s 0.5 mm. In DUNE, we count on having 20 m long beams, so the precision is 1 mm at that distance, if we equal the precision of the MicroBooNE system. The beam itself is wider than that. In fact, with a 0.5 mrad divergence, we expect the beam to be 1 cm wide at 20 m. The profile is gaussian, so the centroid of the charge creation should be more accurate. During cool-down there can be shifts that need to be measured and corrected for, so we aim to have a system that can measure the beam position in a few positions, at least one per drift volume and laser beam. Our goal is to provide the position of the beam to an accuracy of 5 mm at 15 to 20 m.

1.2.2 Photoelectron Laser System

1.2.2.1 Physics Motivation

Well localized electron sources represent excellent calibration tool for study of the electron transport in the LAr TPC, identification of the inhomogeneities in the TPC electric field in all directions, and precise determination of the electron drift velocity. Verification and calibration of the electric filed distortion plays an important role in particle vertex reconstruction and identification and affects the associates systematic errors, leading to increased rate of misidentification and poorer energy reconstruction. Photoelectron laser can provide well localized electron sources on the cathode at predetermined locations leading to improved characterization of the electric field, and consequent reduction of detector instrumentation systematic error.

1.2.2.2 Design

In order to produce localized clouds of electrons using a photoelectric effect, small aluminum discs or thin discs with evaporated gold film, will be used as targets. As stated in the **??** gold film can be just 22 nm thick. Several photoelectric strips will compliment the circular targets to calibrate the rate of transverse diffusion in LAr. Based on the experience from T2K and BNL LAr test-stand, 8-10 mm diameter targets are sufficient. Targets will be placed on the cathode and distance between the dots will be determined based on the calibration needs and simulations outcome. It will be essential to conduct a survey of the photocathode disc locations on the cathode after installation and prior to detector closing. In this way, the absolute spacial calibration of the electric field can be achieved. At 266 nm NdYag quadrupled wavelength, photon energy of 4.66 eV is sufficient to generate photoelectrons from both aluminum and gold. While aluminum has a lower associated cost, gold film surface is easier to protect from contamination. A couple of hundred electrons are expected per spill from each dot. Laser beam will be coming from the anode injection points, used as sources, guided to injection points via cryogenic optical fibers with defocusing element on the other end.

Much lower energy required for photoelectric laser, opens the possibility for a rather efficient calibration of the each drift volume. Namely, laser pulse can be distributed to two drift volumes at the time in order, while illuminating the entire cathode assembly. Since the photoelectron clouds from different dots are very well localized, calibration of the electric field distortion in the entire drift volume can be done with a single laser trigger, if the light is distributed to all injection fibers for one drift volume.

Photoelectron laser will use the same lasers used for argon ionization. Stability of the laser pulses will be monitored with powermeter. Dielectric mirrors will guide the laser light to injection points, but fraction of the light will be transmitted instead of reflected to the power meter behind the mirror.

Laser will also send forced trigger signal to the DAQ based on the photodiode that will be triggered on the fraction of the light passing through the dielectric mirror. Special mirrors reflective to 266 nm light will be utilized.

1.2.2.3 Possible Measurements

Several measurements should be conducted to optimize the design of the photoelectron laser calibration system. The first thing that needs to be tested is the mounting of the targets on the cathode plane assembly. In addition, survey of the dots position to the required level of precision. Thickness of the target and photoelectron yield as a function of target choice, laser power and attenuation of the laser light in the optical fibers.

1.2.3 Laser positioning system

1.2.3.1 Physics Motivation

While the direction of the laser beam will be very well known based on the reading from the encoders on the laser beam steering mechanism, there will still be some residual uncertainty or unpredictable shift in the pointing direction. Having in mind long length of the ionization track of more than 15 m, even a small offset in the pointing direction can lead to vastly different ionization track location, especially close to the end of the track. Such inaccuracies will directly impact the ability to precisely calibrate any variations in the electric drift field.

1.2.3.2 Design

Laser positioning system (LPS) is designed to address the problem of precise and accurate knowledge of the laser track coordinates. University of Hawaii group has built an LPS for the miniCAPTAIN experiment. LPS consists of groups of 9 pin diodes, operating in passive, photovoltaic mode. These are GaP diodes which sensitivity range extends down to 200 nm wavelength, thus detecting 266 nm light is straightforward. Fig. 1.5 and Fig. 1.6 show signal detected at room and cryogenic temperatures. PIN diode was illuminated by the 266 nm light from the NdYag laser (in the lab at University of Hawaii) set at lowest possible setting for minimal power. Pin diode pads receive light via optical fiber bundles that are mounted on the opposite side from the laser injection points to eliminate issues with field cage interference. Drawings of one such group of pin diodes is shown in Figs. 1.7 and Fig. 1.8. With the group of 9 photodiodes, one cannot only detect the beam but also crudely characterize its profile, giving a more precise location of the central beam pulse axis.

There will be one LPS pad per laser. Laser would always send the first pulse in the direction of the LPS before proceeding into a calibration sequence. The electronics used to collect signals from

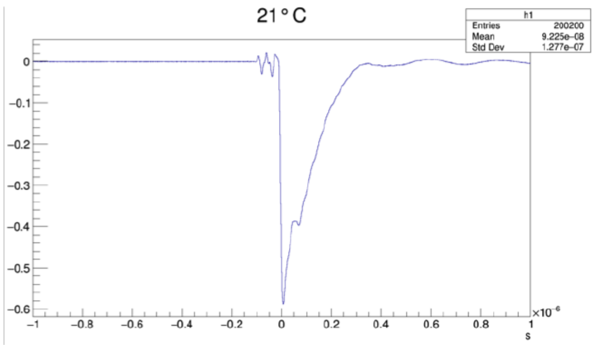

Figure 1.5: Signal from the GaP pin diode. The signal was result of illumination of the PIN diode face with 266 nm at room temperature.

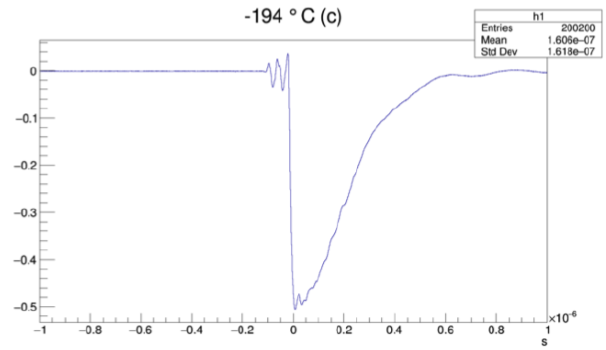

Figure 1.6: Signal from the GaP pin diode. The signal was result of illumination of the PIN diode face with 266 nm at cryogenic temperature.

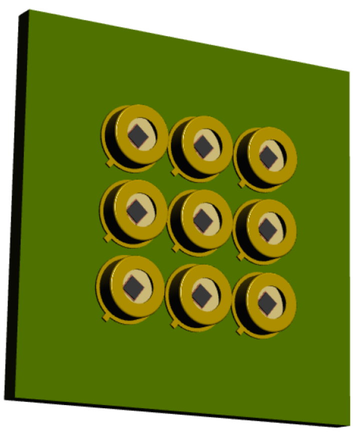

Figure 1.7: LPS cluster that is mounted on the opposite wall from the laser periscope to detect and accurately determine the end point of the laser beam.

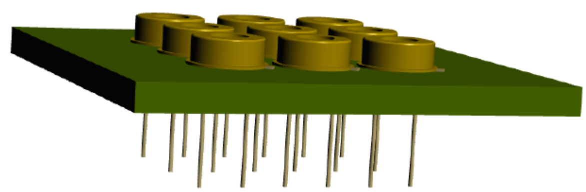

Figure 1.8: Profile of the LPS group mounted on the PCB. GaP diodes come with pins that utilize twisted pair to transport the signal.

the LPS will be provided by the slow control group.

1.2.3.3 Possible measurements

The utilization of the fiber bundle to deliver the 266 nm photons to LPS needs to be verified in the lab. Further optimization of the LPS assembly to reduce electronic noise and interference is required, among other things.

1.3 Pulsed Neutron Source Calibration System

1.3.1 Physics Motivation

In a TPC the energy reconstruction of a track depends on the amount of charge detected from electrons drifting from the track to the collection plane. For a fixed amount of ionization deposited at a point in the TPC, the amount of charge produced and collected depends on several factors:

1. The local electric field strength affects the fraction of charge that recombines before drifting. The stronger the field, the less immediate recombination takes place, and thus the ratio of drifting electrons to energy deposited increases.

2. The electron lifetime depends strongly on the purity of the argon liquid. Given the large size of the DUNE TPC, the restrictions to flow in the active volume, and a likely temperature gradient inside the liquid - it can be expected that there will be parts of the detecter where the electron lifetime will be shorter than others. The prediction of exactly how this manifests is difficult to predict *ab initio*.

3. The distance electroncs have to drift to be collected depends on the location of the vertex inside the volume. The longer the drift, the more likeley it is an electron will be absorbed.

4. Some parts of the detector can, in principle. be better or worse than others in terms of noise. This can affect the threshold charge collection systematically for different areas or the detector.

Given these facts, it is highly desirable to be able to have a "standard candle" energy deposition of known energy that can be detected throughout the volume. Such a standard deposition would reveal variations in the local electron collection efficiency, especially if the source could be triggered such that the t_0 of the interaction was known. In principle, radioactive sources of known energy distribution could be deployed throughout the detector, but there are several problems with this approach: (1) the source must be physically placed at the point one wishes to check, requiring multiple deployments in order to sample a significant volume of the detector, (2) the presence of the source itself can alter the electric field and ionization yield, and (3) the introduction of a foreign object into the active volume of the detector carries the risk of introducing impurities and/or radioactive contaminants. In addition, in order to have a triggered source (and hence some idea of t_0) one would have to introduce trigger electronics or other instrumentation - further complicating the deployment and increasing the risk.

A way around this dilemma is to introduce short-lived radioactive atoms into the liquid argon itself, but this has the disadvantage that there is no trigger and no way to ensure the standard candle decays spread out through the whole volume. In addition, to be useful such isotopes would have to have appreciable half-lives in order to have time to spread around the detector, and thus the whole process might take many hours. Finally, such isotopes would likely need to be made locally, which can be expensive and difficult.

One way around these issues is to take advantage of a remarkable property of argon - the near transparency to neutrons with an energy near 57 keV due to an anti-resonance in the cross-section caused by the destructive interference between two high level states of the 40-Ar nucleus. The cross-section at the anti-resonance "dip" is about 10 keV wide, and at the bottom the cross section of $1.6 \times 10^{-4}\ b$ implies an elastic scattering length of over $2,000\ m$. Thus to neutrons of this energy the DUNE TPC is essentially transparent, and thus if injected from the top of the detector would reach energy part of the active volume. Of course, natural argon has three major isotopes: 36-Ar (0.3336%), 38-Ar (0.0834%), and 40-Ar (99.6035%) each with a slightly different anti-resonance. Those that do scatter lose energy, leave the anti-resonance (where the scattering length is about 70 cm), quickly slow down and are captured. Each capture releases exactly the binding energy difference between 40-Ar and 41-Ar, about 6.1 MeV in the form of gamma rays. As will be described below, by using a *DD Generator*[2], a triggered pulse of neutrons can be generated outside the TPC, then injected via a dedicated hole in the insulation into the liquid argon, where is spreads through the entire volume to produce "standard candle" 6.1 MeV energy depositions. Using this method, there would be no need for internal deployments, the calibration procedure would be quick (likely less than 30 minutes), and there is no need to manufacture short-lived isotopes at an external facility.

A relevant question is what fraction of neutrons slowing down from higher energy will fall into the anti-resonance. Since the the average fractional energy loss of a neutron elastically scattering off a 40-Argon nucleus is 4.8%, in the region of the anti-resonance the average energy loss per scatter is about 3 keV. Therefore, estimating the width of the anti-resonance to be about 10 keV, a large fraction of the neutrons injected can be expected to fall into the cross-section hole. Indeed, as will be shown in preliminary simulations - many neutrons scatter several times before escaping to lower energies to be captured. This simple phenomenon tends to scatter neutrons isotropically around the liquid argon.

The neutron capture gamma spectrum has been measured and characterized. Recently, the ACED Collaboration performed a neutron capture experiment using the Detector for Advanced Neutron Capture Experiments (DANCE) at the Los Alamos Neutron Science Center (LANSCE). The result was published [15] and will be used to prepare a database for the neutron capture studies.

1.3.2 Design

The basic design concept of such a pulsed neutron source has been used successfully for Boron Neutron Capture Therapy[16]. The Pulsed Neutron Source will consist of three main components: a DD generator, an energy moderator reducing the energy of the DD neutrons down to the desired level, and the shielding materials.
DD generators are commercial devices that can be readily obtained from several vendors at a cost of about \$ 125k each, which includes all control electronics. Pulse widths can be delivered from about 10-150 μs (which affects total output). A feasible moderator has been designed using a Moderator(Fe or Si)-Filter(S)- Absorber(6-Li) layered configuration. An iron moderator is used to cut down the neutron energy from 2.5 MeV to below 1 MeV. Then an energy filter made of sulfur

[2] *DD* stands for "Deuterium-Deuterium"

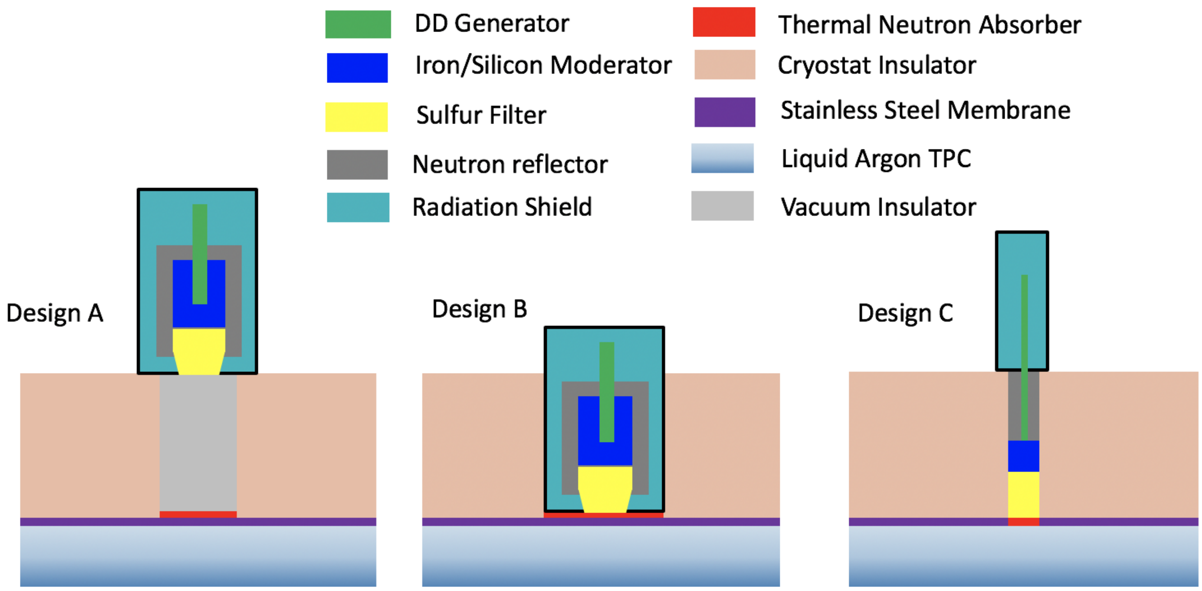

Figure 1.9: Three designs of the Pulsed Neutron Source

powder is used to further select the neutrons with desired anti-resonance energy. The neutron anti-resonance energy in 32-S is 73 keV, right above the 57 keV anti-resonance energy in 40-Ar. The neutrons at this energy lose about 3.0 keV per elastic scattering length. After a few elastic scattering interactions, most of the 73 keV neutrons selected by the sulfur filter will fall into the 57 keV anti-resonance energy region in liquid argon. These materials require no cooling or special handling. Finally, a thermal absorbing volume of Lithium is placed at the entry to the argon pool in order to capture any neutrons that may have fallen below the 57 keV threshold. The reflecting volume is added around the DD generator and the neutron moderator to increase downward neutron flux. The whole source will be encased in a shielding volume for safety.

Based on the general concept, two different designs were studied with GEANT4 simulation. Figure 1.9 shows a conceptual layout of the neutron injection system.

- Design A: Large format Moderator;
  The neutron source is about 0.7 m wide 1 m high. It would sit above the cryostat insulator. Beneath the neutron source, a cylinder insulator volume with 50 cm diameter has to be removed to allow the neutrons to get into the cryostat. A vacuum chamber will fill the cylinder volume providing heat insulation. The cryostat stainless steel membrane will be kept closed, so no cryostat penetration is needed. The neutron source weights about 2 tons and will hang on the I-beam supporting structure. This design allows a permanent deployment of the neutron source. GEANT4 simulation has shown that 0.16 % of the neutrons generated by the DD generator are expected to be captured inside the liquid argon TPC.

- Design B: Large format Moderator; no insulation between Moderator and cryostat membrane
  The design of the the neutron source itself would be same as Design A. The only difference is that the neutron source will be placed inside a hole on the cryostat insulator. The cryostat

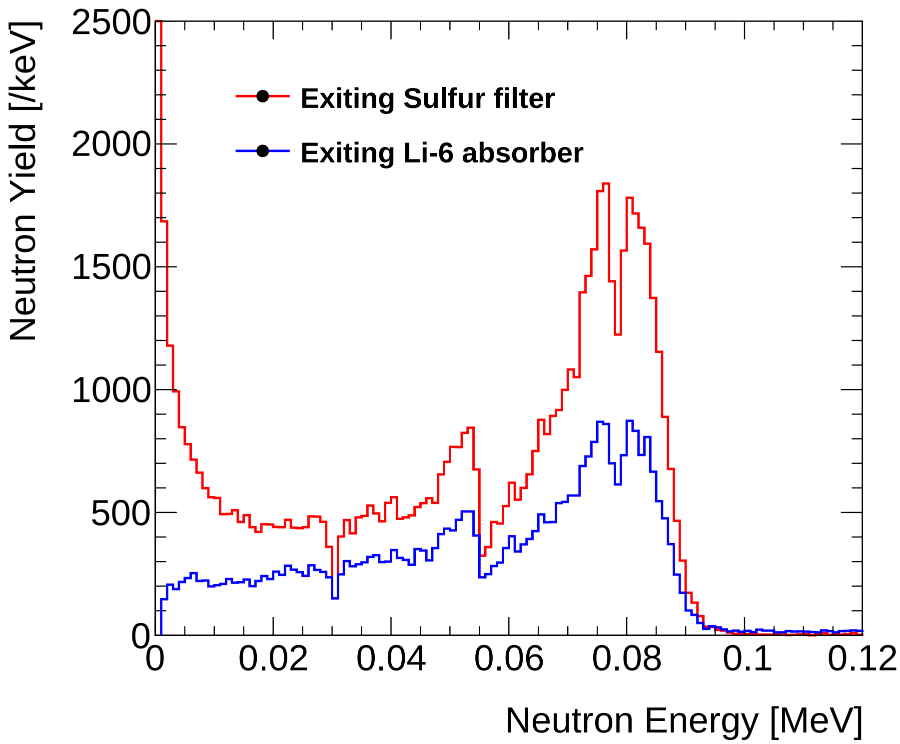

Figure 1.10: Energy of neutrons injected to the liquid argon TPC volume.Simulation based one Design B.

will be kept closed, but there is no vacuum insulation between the neutron moderator and the stainless steel membrane. As the neutron source is closer to the liquid argon cryostat, the neutron flux is expected to be a factor of 10 higher than that of Design A. However, the neutron source must be removed and the insulator has to be recovered after the calibration run.

- Design C: Small format Moderator; no insulation between Moderator liquid argon Design A and B require to remove a part of the cryostat insulator beneath the neutron source. If this is not available, an alternative method for delivering the neutrons is to use the existing calibration feedthroughs. In the current Cryostat design, 20 calibration feedthroughs with a 20 cm diameter will be opened on top of the cryostat. One can design the neutron source with an ultra-thin DD generator that fits the size of the feedthrough. The problem is that there will be no space in the feedthrough for the shielding materials to fit in, so the neutron and gamma shield has to rely on the cryostat insulator. The weight of this compact neutron source will be about 140 kg, sufficiently low to be carried by two people. The effective neutron flux is expected to be similar as that of Design A.

The three designs were simulated in GEANT4. Initial simulation results indicate that two Pulsed Neutron Sources would illuminate the whole TPC volume of the DUNE far detector. Figure 1.10 shows the energy spectrum of the neutrons moderated and injected to the liquid argon TPC, based on Design B. The neutron energy is moderated from 2.5 MeV to below 100 keV.

1.3.3 Possible Measurements

The path to a deployable Pulsed Neutron Source is straightforward, with measurements that confirm the operation parameters, simulation results, and safety considerations. These are described below.

1.3.3.1 Capture Cross-Section and Gamma Cascade

The cross-section for thermal neutron capture on argon has not been measured since the 1960's [17, 18, 19]and there are differences up to 40% between the central values. In addition, while the integral gamma spectra has been measured via cryogenic gamma spectroscopy [**?**] an event-by-event measurement has not yet been done. Currently, the ACED (Argon Capture Experiment at DANCE) [**?**] is analyzing data from a November 2017 two week beam run at LANSCE that will yield a cross-section measurement as a function of energy from about 0.01 eV to 1 eV (room temperature thermal average is 0.0253 eV), and will also provide a library of individual capture gamma cascades to put into LarSoft. It is thought that the results should be of sufficient precision for use in PNS calibration design.

1.3.3.2 Cryostat Materials Activation Measurement

While DD Generators produce neutrons with relatively modest fluxes and most materials do not have significant activation (which is why they are typically not used for activation studies), it is prudent to have actual measurements of the activation of materials in the vicinity of the PNS to be able to predict accurately the long-term activation. We propose to use the UC Berkeley DD Generator facility in the Advanced Technology and Innovation Laboratory (ATIL) to exposure cryostat materials to many orders of DD flux (2.45 MeV) than they will see from the PNS over the lifetime of DUNE. ATIL will let us use their facility for a small charge, and results will be used to ensure no long-term significant activation will occur.

1.3.3.3 Scattering Cross-Section Measurement

The scattering length at the ^{40}Ar 57 keV anti-resonance has been theoretically calculated to be 1400 m, but since argon is 0.0629% ^{38}Ar and 0.3336% ^{36}Ar with scattering lengths of 542 m and 33 m respectively, the overall scattering length of 30 m does not depend significantly on the exact depth of the anti-resonance. Nevertheless, it is desirable to verify the overall scattering length with a measurement at a dedicated scattering facility such as LANSCE. LANSCE has a neutron Time-Of-Flight (TOF) beam with good resolution in the $10 - 100$ keV range and so a simple transmission experiment using a liquid argon cylindrical target of diameter 5 cm and length $100 - 200$ cm should be more than sufficient to measure the scattering cross-section in the region of interest.

Such an experiment will be proposed to LANSCE in March 2019 to run in early Fall 2019. Costs will be minimal - with only the need to provide a LAr target with a small $2\ cm$ thin window on both ends, plus perhaps a small halo counter to reject double scatters and a collimated neutron TOF detector (LANL may be able to provide this). While desirable to do, this is not critical.

1.3.3.4 Test Deployment in ProtoDUNE-SP

The post-beam run being proposed for ProtoDUNE-SP offers the opportunity to test the full system (DD Generator, Moderator, Transport Model, Data Analysis) in a definitive way before investing in the full PNS calibration for DUNE. The PNS group proposes to make such a run as soon as resources can be identified (independent of the other measurements above), starting with a commitment of engineering resources at CERN required to complete the necessary radiation safety shield design, and the mechanical design necessary to support the DD Generator and Moderator. The system used for ProtoDUNE-SP could also be used for ProtoDUNE-DP, and later installed in the DUNE detector.

1.4 Alternative System: Radioactive Source Calibration System

1.4.1 Physics Motivation

Radioactive source deployment provides an in-situ source of the electrons and de-excitation products (gamma rays) which are directly relevant of physics signals from supernova neutrino and/or ^8B solar neutrinos. Secondary measurements from the source deployment include electro-magnetic (EM) shower characterization for long-baseline ν_e CC events, electron-lifetime as a function of cryostat vertical position, and help determine radiative components of the decay electron energy spectrum.

1.4.2 Design

In order to be able to observe γ-signals inside the active volume of the LArTPC from a radioactive source deployed outside of the field cage, the γ-energy has be about 10 MeV. The source (for safety) would be deployed about 30 cm from the field cage, so the γ-energy would need to travel two attenuation lengths. Such high γ-energies are typically only achieved by thermal neutron capture, which invokes a neutron source surrounded by a large amount of moderator, thus making such an externally deployed (n, γ) source 20 cm to 50 cm large in diameter. In [**?**], a ^{58}Ni (n,γ) source, triggered by an AmBe neutron source, was successfully built, yielding high γ-energies of 9 MeV. We propose to use a ^{252}Cf or AmLi neutron source with lower neutron energies, that requires less than half of the surrounding moderator, and making the ^{58}Ni (n, γ) source only 20 cm or less in diameter. The multi-purpose instrumentation feedthroughs currently planned are sufficient for this, and have an inner diameter of 25 cm.

The activity of the radioactive source is chosen such that no more than one 9 MeV capture γ-event occurs during a single 2.2 ms drift period. This allows one to use the arrival time of the measured light as *t0* and then measure the average drift time of the corresponding charge signal(s). The resulting drift velocity yields in turn the electric field strength, averaged over the variations encountered during the drifting of the charge(s). This can be repeated for each single 9 MeV capture γ-event that occurs during a 2.2 ms drift period and where visible γ-energy is deposited inside the active volume of the TPC. This restricts the maximally permissible rate of 9 MeV capture γ-events occurring inside the radioactive source to be less than 1 kHz, given a spill-in efficiency into the active liquid argon of less than 10%.

A successfully employed multipurpose fish-line calibration system <insert ref> for the Double Chooz reactor neutrino experiment will become available for DUNE after the decommissioning of Double Chooz in 2018. The system can be easily refitted for use in DUNE. The system would be deployed in four cryostat penetration multipurpose feedthroughs on the east and west ends of the cryostat, which are placed at half-drift position. The sources would be deployed outside the field cage within the cryostat to avoid regions with a high electric field. Also, if the source is in close proximity of an APA wire frame, lower energetic radiological backgrounds become problematic as the source light and charge yield is reduced exponentially with distance. The sources are removable and stored outside the cryostat.

The commissioning plan for the source deployment system will include a dummy source deployment (within 2 months of the commissioning) followed by first real source deployment (within 3-4 months of the commissioning) and a second real source deployment (within 6 months of the commissioning). In terms of the run plan, assuming stable detector conditions, radioactive source will be deployed every half a year. Ideally, a deployment before a run period and after the run period are desired so at least two data points are available for calibration and it verifies if the state of the system has changed before and after the physics data run. If stability fluctuates for any reason (e.g. electronic response changes over time) at a particular location, one would want to deploy the source at that location once a month or more often depending on how bad the stability is. It is expected that it will take a few hours (e.g. 8 hours) to deploy the system at one feedthrough location and a full radioactive source calibration campaign might take at least a week.

1.4.3 Possible Measurements

Discuss development plan on way to building

1.5 DAQ Requirements

The calibration system must interface with the DUNE data acquisition system, discussed in detail in Section **??**. The primary interface with calibrations will be through the DUNE Timing System, which is responsible for providing synchronization across all subsystems and absolute time stamps, as well as for distributing triggers. Whenever possible, it is preferred that subsystems like calibrations are triggered *by* the DAQ rather than providing a trigger *to* the DAQ. Therefore the calibration systems must be designed to accept such triggers (which will have the form of a timestamp for when a trigger should occur) and it must have a way of accepting general timing information so that it is synchronized to the rest of DUNE.

Each calibration system will nevertheless be handled slightly differently, and each will have a different way for the DAQ to handle its data. The calibration systems could easily dominate the entire data volume for DUNE, and thus exceptions to the standard triggering and readout discussed in Section **??** are needed. We discuss below these details and the associated differences.

Add or reference DAQ summary table that has been prepared

1.5.1 Laser Calibration

The proposed laser source is the only practical way to unambiguously measure the electric field vectors within the detector. The field vector is determined by looking at the deflection of crossing tracks within detector voxels. The calibration group has suggested that the size of these voxels might be $10 \times 10 \times 10$ cm^3. Because any given laser track illuminates many such voxels, one laser pulse can be used for multiple measurements—essentially the number that matters is the area of each voxel. The calibration group estimates that the number of total laser "events" would be about 800,000—about half the rate of cosmic rays, and thus nominally a substantial total data volume.

Fortunately, unlike every other event type in the detector, the laser track has both a reasonably well known position and time; thus tight zero-suppression can be done for both collection and induction wires. Brett Viren suggests that a 100 μs zero suppression window is wide enough to avoid windowing problems in the induction wire deconvolution process, and we therefore assume such a window for the laser pulses. Note that the zero suppression happens *after* the trigger, not at the front-end or in the DAQ readout; thus the rate that the laser can be run will have to take into account the bandwidth through the Event Builder (where the zero-suppression would occur). From the standpoint of data volume, however, the total assuming the 100 μs zero-suppression window is:

$$800,000/\text{cal}/10\text{ ktonne} \times 100\mu\text{s} \times 1.5\text{Bytes/sample} \times 2\text{ MHz} \times 384000\text{ channels} = 92\text{ TB/cal/10ktonne} \quad (1.1)$$

If such a calibration were done twice/year, then the total annual data volume for the laser is 184 TB/year/10ktonne.

1.5.2 Radioactive Sources

There are two radioactive sources suggested to provide low-energy calibration data for DUNE: a neutron generator source, and a γ source.

The neutron generator source creates a burst of neutrons which, because of the interesting neutron cross section of argon, get captured throughout a large fraction of the total cryostat volume. From a triggering and data volume standpoint, this is very convenient: the existing scheme of taking 5.4 ms of data for each trigger means all of these neutrons will be collected in a single DUNE event. Thus the data volume is simply 6.22 GB times the total number of such pulses, but these are likely to be few: a single burst can produce tens of thousands of neutrons whose t_0 is known up to the neutron capture time of 200 μs or so.

The γ source is somewhat more complicated to handle in the DAQ, depending on its rate. An initial proposal suggests 8 hour runs at 4 feedthroughs, and because only a single APA is being illuminated typically, the Module Level trigger could reduce the total data rate by issuing trigger commands only to the readout of the currently active APA. Nevertheless, if the rate of such a source is anywhere close to 1/5.4 ms, the detector would be running in "DC" in the current scheme. Therefore we assume that the interaction rate in the detector is 10 Hz or less. With this rate, and with localization of events to one APA, the total data volume would be

$$8 \text{ hours} \times 4 \text{ FTs} \times 10\ Hz \times 1.5 \text{ Bytes} \times 2 \text{ MHz} \times 5.4 \text{ ms} \times 2560 \text{ channels} = 50 \text{ TB/run}. \quad (1.2)$$

Running this calibration 4 times/year would yield 200 TB of data in 10 ktonnes per year.

1.5.3 Intrinsic Radioactivity

Mike Mooney has suggested using the intrinsic ^{39}Ar as a calibration source. This has many advantages over either of the radioactive source calibrations, in particular the known level of ^{39}Ar, its uniform distribution in the detector, and the fact that it is always there and therefore integrates correctly over the detector livetime. The difficulty is that because any individual ^{39}Ar event's x position is not known (because there is no t_0, the distribution of these events must be used to make measurements, thus requiring fairly high statistics.

Mooney's proposal is that roughly 250,000 ^{39}Ar can provide a 1% measurement of electron lifetime. (Note that 1% is a reaonable goal; if the lifetime and maximum drift time are the same, this results in a 2% uncertainty on energy scale which would begin to compromise DUNE's physics program). This number of events is easily obtained with the existing random triggers as well as every other trigger source excluding laser pulses and front-end calibrations.

Like all other parameters that must be calibrated, however, what is not clear is what the spatial and temporal variations will be in the detector. Other LAr TPCs have performed lifetime calibrations daily (using cosmic rays primarily), and a pixelization of 1 m^2 is not unreasonable, leading to a need for 250,000 events for every m^2 in the detector each day, or about a 1 Hz trigger rate.

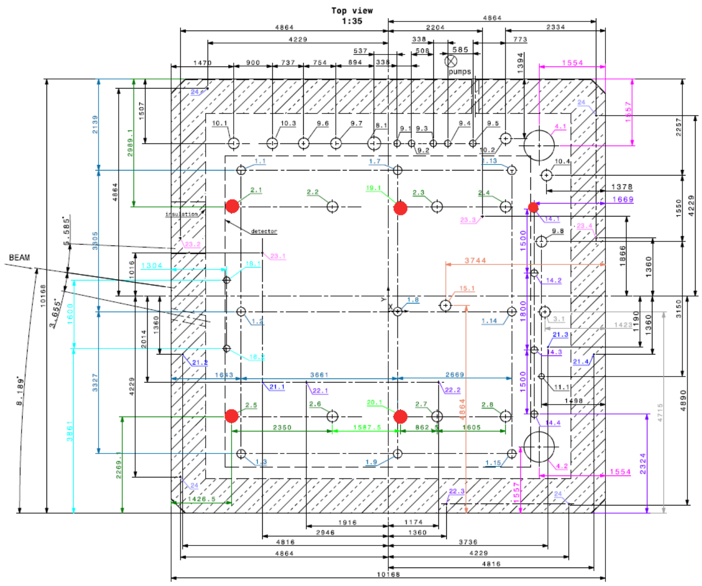

Figure 1.11: Top view of the protoDUNE-SP cryostat showing various penetrations. Ports marked in red are present free and they could be used for tests of the calibration systems. The four largest ones have the same diameter (250 mm) of the calibration ports of DUNE-FD, and are located over the TPC. The two larger ports at the right-hand side corners of the cryostat are the human access ports (or manholes).

In the existing scheme, this would be overwhelmingly the dominant source of data. Thus either the pixelization would need to be reduced (say, to each of the TPC volumes) or a zero-suppression scheme would have to be used. Such a zero-suppression scheme would happen post-trigger—for example, running random triggers at 1 Hz and based upon that trigger type, zero suppressing signals. In the current scheme, this would happen in the Event Builder but at 1 Hz the data rate would be too high. To do zero suppression upstream—say in the APA-level readout—based on the trigger type will likely require more hardware resources.

1.6 Validation of Calibration Hardware Systems

1.6.1 Validation in ProtoDUNE

All the designs presented above have aspects that warrant a validation in a situation as close as possible to the final one to be deployed in DUNE-FD. Even if there are laser calibration systems in operation in other LAr TPC experiments, the stringent requirements of such a system in terms of mechanical and optical precision, long-term reliability, track length, impact on in case of the alternative design, and DAQ interface all lead to corresponding goals of a test installation and operation in protoDUNE, that could be accomplished in the post-LS2 run. As can be seen in Fig. 1.11, there are currently ports of the same size as DUNE-FD that could possibly be used for these tests. If a pair of ports are used, then one could even have crossing tracks within a single drift volume.

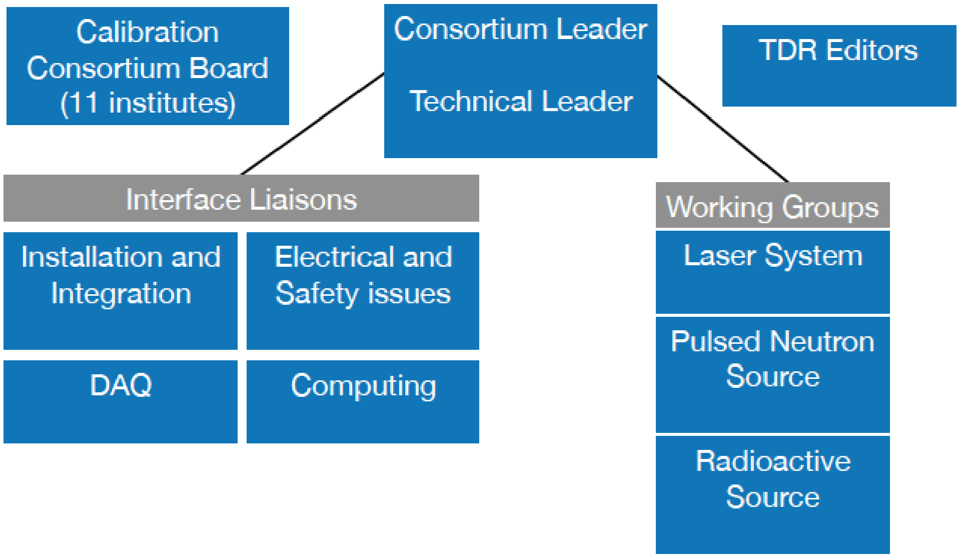

Figure 1.12: Organizational chart for the Calibration Consortium.

The pulsed neutron source is a new idea that has never been used in other experiments, so a protoDUNE test is especially important. The corner human access ports similar to DUNE-FD could be used for that deployment.

With respect to the radioactive source, the external neutron background rate is too high at surface to tests the actual gamma source. However, tests of functionality and reliability of the mechanical system are needed to demonstrate the source can be deployed and retrieved with no issues.

1.6.2 Validation in Other Experiments

1.7 Organization and Management

The Calibration Consortium was formed in November 2018 as a joint single and dual phase consortium, with a Consortium Leader and a Technical Lead.

Its initial mandate is the design and prototyping of a laser calibration system, a neutron generator, and a possible radioactive source system and therefore the Consortium is organized in three working groups, each dedicated to each of these systems. Each group has a designated WG leader.

In addition, as shown in Fig. 1.12, several liaison roles are also planned to facilitate the connection with other groups and activities:

- Detector Installation and Installation
- Electrical and Safety Issues

- DAQ
- Computing

There are 11 institutes in the Consortium and, as the activities progress from design to prototyping, formalization of a Consortium Board is also planned.

1.8 Interfaces

Interfaces between calibration and other consortia have been identified and the appropriate documents are being developed. The main interfacing systems are High Voltage (HV), Photon Detection System (PDS) and Data Acquisition (DAQ) and the main issues that need to be considered are listed below.

HV Evaluate the effect of the calibration HW, especially the laser system periscopes, on the E field, even in case of no penetration of the FC; Evaluate the effect of the incident laser beam on the CPA material (kapton); Integrate the HW of the alternative photoelectron laser system (targets) and the laser positioning system (diodes) within the HV system components.

PDS Evaluate long term effects of laser light, even if just diffuse or reflected, on the scintillating components (TPB plates) of the PDS; Establish a laser run plan to avoid direct hits; Evaluate the impact of laser light on alternative PDS ideas, such as having reflectors on the CPAs.

DAQ Evaluate DAQ constraints on the total volume of calibration data that can be acquired, and develop strategies to maximize the data taking efficiency with data reduction methods; Study how to implement a way to for the calibration systems to receive trigger signals from DAQ, in order to maximize SN livetime.

1.9 Cost

The costs of equipment and materials and supplies for the baseline systems are described in Table 1.1. To serve one SP volume, there are 20 ports for the laser; 14 ports will need one laser and one feedthrough interface, but for the 6 central ports one laser will service two ports. Therefore the total cost of the laser system is $2.85M. Two pulsed neutron systems are needed for one SP volume.

Add estimate of laser positioning system, DAQ/computers, racks? cables?

Table 1.1: Calibration System Cost Summary

System	Quantity	Cost (k$ US)	Description
laser device	17	50.0	Laser system
feedthrough interface	20	100.0	Laser system; includes insulator ingress into detector and flange interface, mirrors
DD generator device	2	102.5	Pulsed Neutron Source
Moderator	2	25.1	Pulsed Neutron Source: materials to degrade neutrons to correct energy
Shielding	2	24.0	Pulsed Neutron Source: surrounding shielding
Monitor	2	16.7	Pulsed Neutron Source: Neutron monitor (device) and colimator (materials)

1.10 Risks

sample from HV - use as template

Table 1.2: High Voltage System Risk Summary

ID	Risk
(id 1)	risk text
(id 2)	risk text
...	...
(last id)	risk text

1.11 Quality Control

This is a copy of text we sent to Jim Stewart for the integration chapter.

The QA/QC of the calibration system parts will be done in three major steps: i) at each institute, prior to shipping to ITF; ii) in ITF, prior to shipping underground; iii) a final check during/after installation.

At ITF:

- Laser: Assembly and operation of the laser and feedthrogh interface will be carried out in ITF, on a mockup flange, for each of the full HW sets (periscope, feedthrough, laser, power supply, electronics). All operational parts - UV laser, red alignment laser, trigger photodiode, attenuator, diaphragm, movement motors, encoders - should be tested for functionality.

- Pulsed Neutron Source: Test operation with shielding assembled to confirm safe operating conditions and sufficient neutron yields with an external dosimeter as well as with the installed neutron monitor. The entire system, once assembled, may be brought down the Ross shaft
- Radioactive Source Deployment System: Mechanical tests including a mockup flange are done at ITF. Safety checks will also be done for the source and storage above and underground.
- Radioactive Source Deployment System: Mechanical tests including a mockup flange are done at ITF. Safety checks will also be done for the source and storage above and underground.
- Power supply and racks: Each of the electronics and racks will be tested prior to bringing underground associated to each full system.

1.12 Safety

We consider two categories of hazards: personal risk to humans and risks of the damaging the systems and/or other DUNE detector components, discussed in the following subsections. These risks apply in the prototyping phase, including ProtoDUNE deployment, and also during integration and commissioning at the DUNE far detector site.

1.12.1 Human Safety

We also want to reference common installation and commissioning safety concerns– like work at heights, falling object risk, overhead crane operation, heavy objects, electrical safety etc. Is there a common document/section we can reference for this?

Eye safety: The laser system requires the operation of a class 4 laser. This requires an interlock on the laser box enclosure, and only trained personnel present in the cavern for the one-time alignment of the laser upon installation in the feedthroughs.

Radiation: The gammas from neutron capture on hydrogen could bring a potential radiation safety concern for the PNS. The design of key safety systems (custom shielding and moderator) for the PNS will be discussed with safety experts at CERN and at MSU prior to operation at ProtoDUNE. In particular, the entire system will be assembled in a neutron shielded room and tested to confirm there is no leak of neutrons. The system will also have a neutron monitor which can be used to provide an interlock.

The RS also poses a radiation risk, which will be mitigated with a glovebox for handling, and a shielded storage box and area.

1.12.2 Detector and System Safety

We consider risks to the calibration systems themselves, and also to other DUNE materials or systems.

This may be a shared concern. We want to avoid bumping/breaking components as they are checked, installed and commissioned in DUNE. Special care will need to be taken to install components and do checks stepwise.

Mechanical damage: The deployed radioactive source can potentially swing into detector elements if not controlled or if large currents exist in the liquid argone. Guidewires mitigate this risk.

Laser system protection: If the too much water enters the laser system port, then ice may block the laser.

Jose, mitigation is?

Damage to the photon detection system by the laser: To mitigate possible damage to the PD system, software will be used to block the beam while the mirrors are stopped or when laser light is directed at the PD system. Initial discussion with PDS indicates that this may not be a significant issue.

relationship between this and interface with PD?

Radiation damage to DUNE components: The activation caused by the PNS is being studied and will be known by ProtoDUNE testing for the PNS at neutron flux intensities and durations well above the run plan.

May also need to reference background TF. Add RS system.

We have started discussions about electrical safety and grounding, and will update this once formal documents are prepared for that.

1.13 Installation, Integration and Commissioning

This is a copy of text we sent to Jim Stewart for the integration chapter. We need guidance for how this chapter and that chapter need to reference each other.

1.13.1 ITF integration

The laser positioning system has to be integrated with the HV system in the ITF before shipping underground (underground). Two components (baseline design: mirror clusters, and alternative design: diodes) would require interface with the HV and field cage structural systems, discussed below.

The baseline consists of a set of about 40 mirror clusters - a plastic piece holding 4 to 6 small mirrors (5 mm diameter), each at a different angle - to which the ionization laser will point in order to obtain an absolute pointing reference. These clusters will the attached to the bottom field cage cross bars facing into the TPC. These cross bars must contain small alignment slots, matching the cluster pieces, in order for us to know the exact position of each cluster. This attachment/assembly of the mirror clusters on corresponding the FC cross-bars must be done in the ITF before shipping the HV system underground.

An alternative design, that can be done in addition to the mirror clusters, which, following on the mini-CAPTAIN experience, is based on a set of diodes that fire when the laser beam hits them. Since the laser shoots from above, and the diodes need to be in a low voltage region, the plan is to attach them to the bottom ground plane, facing into the bottom FC. For the pointing measurement, the beams will pass through the FC electrodes and hit the diodes below. At least 20 of these diode clusters would be installed, and this assembly on the ground planes needs to be done in the ITF as well.

1.13.2 Installation

Only the laser system alternative design has components that need to installed inside the cryostat via the TCO. The pulsed neutron source and radioactive source deployment systems are installed only using the cryostat roof ports.

Laser, inside TCO: A long horizontal track system is to be installed outside the end-wall field cage, directly below the corresponding calibration ports, and suspended by them. The system farthest away from the TCO must be installed before TPC (FC/APA/CPA) installation begins. This installation requires the simultaneous installation of the corresponding periscopes, from the calibration ports, so that the two systems can be properly connected. The relevant QC is essentially alignment test.

In addition, the alternative laser positioning system has sets of photo-diodes pre-mounted on the HV system bottom ground planes. The only step that needs to be done inside the TCO is connecting the cabling to available flange (still working out how to route cables and which flange to use).

Laser, outside TCO: The periscopes on the top of the TPC in the center can be installed after the relevant structural elements (e.g. field cage), these proceed in sequence with the assembly of other components (furthest from TCO is assembled first) and alignments can be done as elements are installed with the alignment laser system. Once for each periscope/laser system, prior to the installation of further TPC components, we will need to clear the cavern to align the UV (Class 4) and visible lasers this will need special safety precautions. It may be possible to do this special alignment operation for all lasers at roughly the same time, to minimize the disruption.

A support beam structure closest to the TCO temporarily blocks the calibration ports, this is removed after the last TPC component. After that, the final calibration components can be installed, including the the periscopes on the TCO endwall and the horizontal track closest to the TCO would be the last items to be installed.

Pulsed Neutron Source: The pulsed neutron source will be installed after the human access ports are closed as it sits above them. Final QC will be operating the source and measuring the flux with integrated monitor and dosimeter.

Power supply and racks: Space on mezzanine close to each calibration port is important in order to power and operate the calibration systems (laser and PNS). They can be installed following the associated periscope installation.

Radioactive Source Deployment System: The RSDS guide system can be installed as the first element before TPC elements for the endwall furthest from the TCO, and the last system (concurrent and coordinated with the alternative laser system). The RSDS is installed at the top of the cryostat and can be installed when DUNE is working.

1.14 Institutional Responsibilities

Currently, the calibration consortium has the following member institutions: University of Bern (Bern), Boston University (BU), Colorado State University (CSU), University of California, Davis (UC Davis) University of Hawaii (Hawaii), University of Iowa (Iowa), LIP, Michigan State University (MSU), University of Pittsburgh (Pitt), South Dakota School of Mine Technology (SDSMT), and University of Tennessee, Knoxville (UTK). The responsibilities of each group are described in Table 1.3.

Need to confirm this with groups, esp CSU, Pitt doing general simulation work and understand what further subdivision is useful. We are also seeking new groups.

Table 1.3: Institutional responsibilities in the Calibration Consortium

System	Institutional Responsibility
Laser System	Bern, Hawaii, LIP, Pitt, UTK
Pulsed Neutron Source	BU, CSU, UC Davis, Iowa, LIP, MSU, SDSMT

1.15 Schedule and Milestones

Table 1.4 shows the milestones for the Pulsed Neutron System.

The laser system schedule will look similar to the pulsed neutron source– but we need to confirm the TCO closing/installation period before filling in a table for it.

Table 1.4: Pulsed Neutron Source Schedule

Milestone	Date (Month YYYY)
Design optimization process: beam width, moderator, shielding and cryostat interface	Mar 2020
Perform neutron moderator test and cryostat material activation test	Mar 2020
Complete instrument safety and neutron yield test. Confirm remote operation.	Mar 2021
Demonstration test at ProtoDUNE	Aug 2022
Assembly of additional device	Mar 2023
Installation and commissioning	Jun 2023

Glossary

anode plane assembly (APA) A unit of the SP detector module containing the elements sensitive to ionization in the LAr. It contains two faces each of three planes of wires, and interfaces to the cold electronics and photon detection system. 4

cold electronics (CE) Refers to readout electronics that operate at cryogenic temperatures. 1

data acquisition (DAQ) The data acquisition system accepts data from the detector FE electronics, buffers the data, performs a trigger decision, builds events from the selected data and delivers the result to the offline secondary DAQ buffer. 9

detector module The entire DUNE far detector is segmented into four modules, each with a nominal 10 kt fiducial mass. 6, 34

secondary DAQ buffer A secondary DAQ buffer holds a small subset of the full rate as selected by a trigger command. This buffer also marks the interface with the DUNE Offline. 33

DP module dual-phase detector module. 4

detector support system (DSS) The system used to support the SP detector within the cryostat. iii, 3

field cage (FC) The component of a LArTPC that contains and shapes the applied E field. 3

far detector (FD) Refers to the 40 kt fiducial mass DUNE detector to be installed at the far site at SURF in Lead, SD, to be composed of four 10 kt modules. 4

high voltage (HV) Generally describes a voltage applied to drive the motion of free electrons through some media. 1, 4

liquid argon (LAr) The liquid phase of argon. 6, 8, 24

long-baseline (LBL) Refers to the distance between the neutrino source and the far detector. It can also refer to the distance between the near and far detectors. The "long" designation is an approximate and relative distinction. For DUNE, this distance (between Fermilab and SURF) is approximately 1300 km. 1

MicroBooNE The LArTPC-based MicroBooNE neutrino oscillation experiment at Fermilab. iii, 6, 8, 11

photon detection system (PDS) The detector subsystem sensitive to light produced in the LAr. 1

trigger candidate Summary information derived from the full data stream and representing a contribution toward forming a trigger decision. 34

trigger command Information derived from one or more trigger candidates that directs elements of the detector module to read out a portion of the data stream. 33, 34

trigger decision The process by which trigger candidates are converted into trigger commands. 33, 34

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