

CALCI Workshop/Scope Review Final Report

Executive Summary

Over the period of May 11 through June 24, 2020, a review of the proposed calibration systems and cryogenic Instrumentation for the first DUNE Far Detector module was carried out. All sessions were via Zoom. The first set of sessions covered the cryogenic instrumentation scope, and a second set of sessions focused on the calibration systems. All presentation sessions were open to the Collaboration. The Charge for the Review is attached as Appendix A of this report. The review committee membership is attached as Appendix B.

The format of the review was presentations from the CALCI Consortia on the various sub-systems followed by time for questions and discussion. The agenda for the review presentations can be found at <https://indico.fnal.gov/event/24155/>. The review committee members then composed specific questions that were distributed back to the Consortia, which in turn prepared formal answers to the questions that were presented back to the review committee.

The committee notes that the quality of the presentations was high and that the proponents did an excellent job in responding to questions.

After completion of the presentations and discussion on the cryogenic instrumentation and calibration systems, committee members were asked to evaluate the subsystem elements in terms of criticality for their inclusion in the first DUNE detector module as either essential, highly-desirable, advantageous, or low-impact. Starting from the individual evaluations the committee met to discuss the rankings and come to a general consensus on an evaluation for each subsystem. In the sections below this introduction, high-level summaries of these evaluations are presented. The remainder of the report is organized by subsystem to present standard findings, comments, and recommendations, as well as committee answers to the questions posed in the review charge.

As an overall conclusion to the review, the committee felt strongly that cryogenic instrumentation and calibration hardware is essential for monitoring the status and performance of the DUNE detector over the lifetime of the experiment. The final configuration of devices to be installed in the detector will be developed and incorporated into installation planning based on information obtained from future prototyping efforts, in particular from ProtoDUNE-II, and the identification of required resources. Installation of systems or devices not ready for deployment in ProtoDUNE-II may still be considered for

installation in DUNE, but it should be expected that a rigorous evaluation of performance and suitability will be required.

Cryogenic Instrumentation

Cryogenic instrumentation includes purity monitors, temperature sensors, cameras, gas analyzers, level meters, and pressure sensors. The committee recognizes that some elements of cryogenic instrumentation are the responsibility of the CALCI consortia while others fall under the scopes of the LBNF cryogenic group and the LBNF/DUNE Integration Team. The committee encourages all parties to work together to clearly define and document the deliverables to be provided by each group.

Purity Monitors:

The committee believes it is essential to have an inline purity monitor somewhere between the outlet of the filtration system and the fluid input to the cryostat. The committee also considers it highly-desirable to have a second inline purity monitor between the liquid return line from the cryostat and the filter to catch liquid contamination issues prior to the filter material being exhausted.

The committee believes it is essential to have at least four purity monitors located at two different heights in both ends of the cryostat and highly-desirable that at least two of these four are longer-length purity monitors. The committee believes that the installation of additional purity monitors (beyond these first four) to probe additional regions would be advantageous but not critical. The technical risks associated with the proposed deployment method using 12m support rods would need to be carefully studied before the committee would be willing to sign off on this approach.

The committee views the installation of additional, smaller purity monitors in the cryostat for use during the cryogenics commissioning phase as advantageous, but not critical since the gas analyzers already provide this functionality at some level.

The committee strongly supports the development and deployment of a longer-length purity monitor for ProtoDUNE-II. The committee also recommends developing alternative fixturing methods for ProtoDUNE-II to eliminate the need for long, vertical support rods inside the cryostat, which are viewed to carry technical risks for the DUNE far detectors. Additionally, cryogenics infrastructure to support an inline purity monitor should be added and a device installed prior to the start of ProtoDUNE-II operations.

Temperature Sensors:

The committee believes it is highly-desirable to have some temperature sensors installed on the APAs. The committee is skeptical that one can obtain better than a 2-3 mK resolution on the temperature profile in the TPC due to the effects of local heat sources from the APA cold electronics and issues with transferring a precision calibration from the dynamic T-gradient vertical array into the TPC active volume.

The committee believes it is essential to have vertical arrays of standard sensors attached to the cryostat walls to monitor the filling process.

The committee believes it is advantageous to have standard sensors attached to the cryostat floor, but not critical since the warm cameras can also be used to identify the presence of the liquid argon.

The committee believes it is advantageous to have an array of precision sensors attached to the top ground plane, but not critical since the committee is skeptical that a horizontal temperature profile obtained above the ground plane can be extrapolated into the active volume.

The committee believes it is highly-desirable to have precision temperature sensors located near the fluid inlets and outlets of the cryostat to assist in constraining the fluid flow model.

For the same reason, the committee believes it is highly-desirable to have some number of vertical temperature sensor arrays in the gas ullage at the ends of the cryostat. Additional vertical temperature sensor arrays in the gas ullage over the TPC are seen by the committee as advantageous with the caveat that cryostat penetrations to support these devices are not currently available unless the scope of the baseline laser system is reduced.

The committee is not convinced that an extrapolation of precision calibration data from the proposed dynamic T-gradient vertical array into the TPC active volume is possible. The ability of the device to measure a precise vertical temperature profile at one specific location in the cryostat outside the active volume is viewed by the committee as potentially advantageous in the context of being used as an additional input to fluid flow modeling. The committee also views the ability of the device to confirm a uniform vertical temperature profile when the cryogenic pumps are off as potentially advantageous, although there are concerns about whether this result can be extrapolated directly into the active TPC volume. In addition, the committee has concerns about technical risks associated with installing and operating such a device along the full 12m height of the far detector TPC.

The committee recommends continuing forward with the plan to install temperature sensors on the APAs for ProtoDUNE-II to further study the issues associated with measuring a precise temperature profile inside the active TPC volume. The committee also supports installation of precision sensors near the fluid inlets and outlets and some number of vertical temperature sensor arrays in the ullage with the goal of obtaining an improved understanding of the CFD model. The committee suggests studying whether an instrumentation package incorporating a vertical temperature sensor array, a capacitive-level meter, and some number of cameras could be supported from a single cryostat penetration. The committee recognizes that this effort will require coordination with LBNF and the I&I team. The DUNE Technical Coordination team should take the lead on launching this effort. The committee does not recommend moving forward with the development of a next-generation version of the dynamic T-gradient array for ProtoDUNE-II.

Cameras:

The committee considers cameras to be essential for monitoring critical areas of the HV system and the detector cool-down process. The exact number of cameras needed to provide these functions should continue to be studied. Although some of the cameras are expected to have their own, internal lighting sources, the committee believes it is also essential to have some number of additional lighting sources in the cryostat to assist in viewing areas far away from the cameras.

The committee believes it is highly-desirable to incorporate periscope cameras as part of the laser feedthroughs. In the absence of laser feedthroughs, the committee believes that the presence of such cameras would be advantageous, but not critical.

The committee's recommendation for ProtoDUNE-II is to continue forward with the current plan, identifying the locations for the necessary cameras and additional lighting systems and moving forward with the development of the periscope camera integrated within the laser feedthroughs.

Gas Analyzers:

The committee believes it is essential to have gas analyzers with ppm precision for monitoring O₂, H₂O, and N₂ and highly-desirable to have one high-sensitivity (sub-ppb precision) analyzer for O₂.

In terms of what these gas analyzers should measure, the committee believes it is essential that there be continuous monitoring of the liquid supply line to the cryostat; highly-desirable

that there be monitoring of the cryostat ullage, cryostat liquid return line, and cryostat gas return line, and advantageous that there be monitoring of the cryostat liquid volume itself.

The committee's recommendation for ProtoDUNE-II is to work through with the Integration Office through the DUNE Technical Coordination team to implement any additional, agreed-to system elements.

Level Meters:

The committee believes it is essential to have capacitive level meters in at least three of the four cryostat corners and that it is highly-desirable to have them in all four corners. Additional capacitive level meters over the TPC are seen by the committee as advantageous with the caveat that cryostat penetrations to support these devices are not currently available unless the scope of the baseline laser system is reduced.

The committee considers a differential pressure level meter to be essential for cryostat filling.

The committee's recommendation for ProtoDUNE-II is to further develop and install capacitive level meters. The committee also recommends studying whether an instrumentation package incorporating a vertical temperature sensor array, a capacitive-level meter, and some number of cameras could be supported from a single cryostat penetration.

Pressure Sensors:

Similarly, the committee believes it essential to have both gauge pressure sensors and absolute pressure sensors in the cryostat to facilitate operations. To ensure long-term operations, the committee also considers it essential that there be more than one of each type of sensor in the cryostat.

Calibration Systems

The Calibration systems presented include ionization lasers, laser beam location systems, a photo-electron laser system, pulsed neutron sources, and radioactive sources.

Ionization Lasers:

The committee is convinced that there is an essential role for a system that can monitor the detector and diagnose significant mechanical or electrical issues that arise during operations. The committee notes that planned operation of a prototype ionization laser system in ProtoDUNE-II is critical for establishing its capabilities in this regard.

Assuming successful implementation in ProtoDUNE-II, the committee views an ionization laser system that incorporates eight upper field cage penetrations to provide single beam coverage over the entire detector as highly-desirable. In this scenario, the committee considers having one or two additional laser penetrations that allow for enhanced studies in specific regions of the TPC (e.g. to provide crossing beams in one central drift region and one corner of the TPC) advantageous.

The committee considers an expanded laser system capable of providing regular calibrations of the electric field and TPC alignment at the 1% level as potentially advantageous if this level of performance can be established in ProtoDUNE-II.

The committee believes it is very important to move forward with the current plan for installing a prototype laser system in ProtoDUNE-II to validate the technical design. The committee notes that installation of a two-laser system, enabling a demonstration of the system's ability to perform calibrations at the 1% level, would be optimal. However, limited technical and financial resources should be directed first towards the successful deployment of a single laser penetrating the upper TPC field cage.

Laser Beam Location Systems:

The committee believes that for an ionization laser system, it is essential to have the capability to measure the position of the ionization laser heads relative to the TPC.

The committee views the proposed mirror arrays located within the TPC field cage profiles as highly-desirable for carrying out this function and notes that having additional mirror arrays on different field cage elements accessible to the same lasers would also be highly-desirable.

The committee considers the use of pin-diode sensors to monitor laser beam intensities as potentially advantageous. However, the committee views sensors attached to the cryostat floor as low-impact since position measurements made with these devices will be difficult to extrapolate into the TPC geometry. The committee also notes technical risks with pin-diode sensors attached to the TPC itself as the wiring used to read out the sensors is a potential source of electronics noise.

The committee's recommendation for ProtoDUNE-II is to install some number of mirror arrays in the field cage elements accessible to the ionization laser(s) to allow for tests of proposed system functionality.

Photo-electron Laser System:

The committee has significant questions about the technical viability of this system and believes that a number of basic measurements are still necessary to establish the concept.

With that said, if the concept were to be established, the committee would consider such a system to be potentially advantageous for measuring electron drift times across the TPC and mapping out potential mis-alignments of the CPA planes.

Until the concept is more fully vetted, the committee does not recommend moving further forward with the development of this system for ProtoDUNE-II.

Pulsed Neutron Source and Radioactive Source System:

The committee believes it is essential to have at least one system that can be used to study detector response to low-energy interactions.

If the technique can be validated, the committee views a system that injects low-energy neutrons from an external pulsed source into the cryostat as highly-desirable (due at least in part to the minimal risks associated with deploying such a system).

Injection of neutrons from a pulsed source is expected to be tested initially in the ProtoDUNE-I cryostat over the course of the next month. Results of this test should be used to determine whether additional testing in ProtoDUNE-II is warranted or if further underground testing will be required to validate system functionality.

The committee supports the idea of being able to conduct in-situ test beam measurements with a deployed radioactive source and for that reason considers it highly-desirable to have the ability to deploy a single radioactive source in one specific region near the top of the DUNE TPC.

The committee considers it advantageous to have the ability to perform such measurements over the lifetime of the entire experiment. On the other hand, the committee views the ability to deploy such a source along the entire height of the TPC end-wall or in multiple locations as low-impact since coverage over the full TPC will be extremely limited in any case.

The committee recommends the development of a simpler delivery system for the radioactive source system based on the above criteria. Once such a design is realized, consideration can be given as to the usefulness of conducting a technical demonstration in ProtoDUNE-II versus

moving directly into underground tests focused on demonstrating system functionality, or possibly doing both.

Subsystem Reports

Cryogenic Instrumentation:

Temperature Sensors:

Findings:

- The main goal of the temperature measurement system is to monitor the cryogenic system behavior during operation and provide input to the computational fluid dynamics (CFD) simulations required for understanding the distribution of the LAr purity in the cryostat, which in turns affects the charge attenuation and the e^- lifetime. The dependence of the drift velocity on the temperature is a smaller effect on the scale of the variation of the temperature within the cryostat.
- In order to achieve this goal, relative temperature measurements with a precision of few mK are required, which necessitate the use of more expensive precision sensors.
- A secondary goal of the temperature measurement system is to monitor the status of the cryostat and of the APAs during the filling process. Standard (and less expensive) RTDs can be used for these measurements that do not require the same level of precision as the one needed to provide input to the CFD simulations.
- In addition to precise relative temperature measurements, a few absolute measurements are also required to correctly set the scale of the drift velocity in the LAr.
- A system of standard RTDs to measure the temperature profile in the gas ullage is being proposed to further constrain and validate the CFD simulations.
- For the precision RTDs different calibration methods have been used in ProtoDUNE: calibration against precision RTDs in the laboratory, a calibration in-situ using sensors that can be moved vertically, and a calibration with the pump off assuming a homogeneous temperature distribution when the recirculation is turned off.
- CFD simulations of ProtoDUNE reproduce rather well the temperature distributions in the cryostat. The agreement of the simulations with the data becomes worse near the surface of the liquid (where the temperature fluctuations are larger) and near the LAr distribution system at the bottom of the cryostat.
- The system proposed for DUNE includes a dynamic T-gradient array, a set of 452 precision sensors supported by the APAs (replacing the system of static arrays in the gap between the APAs and the cryostat wall), complemented by additional sensors to measure temperatures on the APA frames, in the gas ullage, in the vicinity of the LAr

pumps and inlets, on the upper TPC ground plane, and along the floors and walls of the cryostat.

- The new design of the dynamic T-gradient array should allow for a relative calibration of its 48 sensors to an accuracy better than 0.5 mK.
- A design was presented for supporting the precision RTDs on the APA frames.
- The total cost of the proposed system is \$142k (M&S only).
- The total number of precision sensors supported by the APA and the dynamic T-gradient mechanism are the cost drivers for this project, with 45% of the costs in the precision sensors supported by the APAs, and 15% of the costs in the mechanism for the dynamic T-gradient.
- The first simulations of the heat produced by the FEMBs for the lower APA indicate that this has an impact of the order of 10 mK even at a distance of meters from the FEMBs.

Comments:

- A system of RTDs measuring the temperature profile in the gas is, in the words of the CALCI consortium, a new idea that has not been fully developed.
- Efforts to further refine the ProtoDUNE CFD simulations so that they can reproduce the details of the measured temperature gradient profiles should continue to be pursued.
- Additional temperature sensors in the regions of the cryostat where the agreement of CFD simulations with the ProtoDUNE data is perceived as insufficient are viewed as valued additions.
- The CALCI consortium has identified lessons learned from the ProtoDUNE data that have inspired the proposed design changes for the system.
- In ProtoDUNE a 15 mK temperature gradient is observed and CFD predicts a 5% impurity variation that would translate into a 5% variation of the charge attenuation for a 15 ms lifetime. From these numbers the CALCI consortium argues that a 1.5 mK precision would be required for a 0.5% absolute error on the charge attenuation correction. In DUNE the impurity distribution is expected to be homogenous within 1% and the CALCI consortium argues that the same 1.5 mK precision would be required to map impurities at the level of 5%.
- No direct connection is established between the impurity level and the energy resolution or the tracking efficiency.

- The relation between drift velocity and temperature is such that the precision required on the relative temperature measurements is at the level of tens of mK.
- The CALCI consortium would like to see the precision RTDs supported by the APAs mounted in multiple configurations. There is agreement that this is mostly a logistic problem, to ensure that APAs with different RTD configurations are installed in a proper way.
- It is recognized that the stepper motor associated with the dynamic T-gradient array and the multiplexer used for the readout of the RTDs may generate noise on the TPC electronics. Tests are planned and as a possible mitigation both systems may provide a signal to the DUNE trigger system.
- An initial analysis of system risks has been presented but further studies are needed (e.g. risks associated with sensors close to pumps and LAr inlets).
- No justification is provided for the number of precision RTDs supported by the APAs.
- The presentations did not provide sufficient information on the methodologies required to obtain an absolute temperature measurement.
- Preliminary CFD simulations show that the impact of the heat generated by the TPC readout electronics attached to the lower APA on the precision temperature measurement could be as high as 10 mK. During the presentation it was suggested that tests could be performed in a test stand available at BNL or at CERN. If this local heating effect is confirmed, it could invalidate the assumption that the RTDs on the APAs can be used to constrain the CFD simulations. It is not clear that comparisons between recirculation on/off, electronics on/off (although we note that there could be multiple configurations of this kind, where subsets of FEMBs are turned off) would be sufficient to fully understand the impact of the heat generated by the FEMBs. It should also be noted that there are additional sources of heat that have yet to be considered in the simulations (heats in the cold electronics for the photon detector, heat in the cold cables providing power to the FEMBs).

Recommendations:

- The committee recommends that the CALCI consortium continues to address technical issues related to the following systems: RTDs mounted on the APAs, static vertical arrays, RTDs near the inlets and outlets of the LAr, and RTDs in the gas ullage.
- The committee recommends that tests with the TPC readout electronics be performed well ahead of the 2nd run of ProtoDUNE to ensure that the RTDs do not induce electronics noise.

- The committee recommends that the CALCI consortium continues to work on understanding the impact of the heat generated by the TPC electronics on the temperature measurements, including additional heat sources (active electronics for the photon detectors and heat dissipation in the cables for the FEMBs). Multiple scenarios should be investigated (recirculation on/off and TPC electronics completely on, partially on, completely off) to understand whether it is really feasible to constrain via high precision RTDs the CFD simulations at the few mK level.

Answers to charge questions:

1. Does the system have a well-justified role in safeguarding the far detectors and facilitating their operation, and if so, what is the minimum amount of system scope needed to carry out this role?
 - a. **Yes, in part.** The committee agrees that some of the proposed systems provide crucial inputs to the CFD simulations (static vertical arrays, RTDs at the inlet and pumps, RTDs in the gas ullage near the end wall of the cryostats) and to monitor the status of the APAs during cooldown and filling. RTDs on the bottom of the cryostat are of limited use (only during the initial filling, and cameras can also be used to demonstrate that liquid is forming at the bottom of the cryostat). Other RTD systems (additional strings in the gas ullage, the dynamic temperature gradient monitor) are also not seen as well justified, either because of the technical difficulties (gas ullage) or because it is not thought feasible to reach the 1 mK level in the extrapolation from the dynamic gradient array to the static array. The committee does not think that the system of RTDs mounted on the APAs needs to be as extensive as proposed by the CALCI consortium, since it is not clear how useful the measurements will be in the presence of the heat generated by the TPC readout electronics.
 - b. The committee recommends a configuration with the minimum number of RTDs to monitor the APA temperatures, RTDs near the LAr inlets and outlets, vertical static strings as requested by the cryogenic group, and vertical temperature sensor arrays in the gas ullage at the ends of the cryostat.
2. Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfil this role?
 - a. **Yes, in part.** The committee thinks that the minimum scope given above in question 1) is sufficient to constrain the CFD simulations at the level required to know the variations of the e- lifetime, drift velocity, and ion-flow throughout the detector, which are required as input to event reconstruction and physics analysis.
3. Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?
 - a. **Yes, in part.** The committee acknowledges the work done for the RTDs mounted on the APAs and looks forward to tests that shall demonstrate that the readout of the RTDs does not generate noise on the TPC readout electronics.

- Further work is required to demonstrate and test a fully integrated system with the APAs.
- b. General issues like the routing of cables and the anchoring of strings of RTDs still require additional work.
 - c. The new design of the dynamic temperature gradient array appears to be a step in the right direction addressing some of the questions raised in the Summer 2019 review. This new design still needs to be demonstrated experimentally.
4. Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?
 - a. **Yes, in part.** In all cases, the risk mitigation strategy appears to be that of not reading out the RTDs in case of problems. This shall be considered only as an ultimate backup solution. The proponents recognize the importance of performing tests of the RTD system mounted on the APA well ahead of the 2nd run of ProtoDUNE-SP. They are encouraged to perform these tests as early as allowed by the current laboratory access rules.
 - b. For all other RTD systems ProtoDUNE-SP seems to be the only way to assess the experimental risks.
 5. Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?
 - a. **Yes, in part.** The CALCI consortium has presented a plan for the implementation of all RTD systems for the 2nd run of ProtoDUNE-SP. The proponents have developed a plan for the construction and calibration of the RTDs, but it is not clear that funding is available for all the scope, and that all technical details related to integration have been addressed. The CALCI consortium has also not presented plans for addressing the issue of the heat generated by the TPC readout electronics. A thorough understanding of the impact of this heat source via CFD simulations would be required to make sense of the measurements.
 6. Does the functionality of the system justify its overall cost?
 - a. **No, at least in the current configuration.** Based on the recent results on the impact of the heat generated by the TPC electronics and on the difficulty of extrapolating the dynamic T gradient measurements to the static arrays, the committee believes that the cost of the overall system could probably be reduced significantly.

Purity Monitors:

Findings:

- After revised off-line PrM data analysis, the concentration of impurities that affect the electron transport measured by purity monitors and by CRT tracks in TPC and expressed in O₂ equivalent concentration, are found to be in good agreement in the first run of ProtoDUNE-SP.

- Two sets of PrM's with different purposes are proposed:
 - one set of two external inline PurMon's are envisaged/proposed for alarm purposes, one before the filter signaling accidental air leaks generating sudden purity drop in the liquid inside the cryostat, and one after the filter giving early alert of filter saturation. These PrM's are outside and in case of issues/aging can be replaced. So, these are guaranteed to last the entire life of the experiment.
 - One other set made by 2-4 vertical strings of at least two (possibly three) PrM inside the cryostat for frequent survey of LAr purity in different locations. The proposed goal is to provide run-by-run charge loss calibration for data analysis. These should be compared with other measurements (e.g. from cosmic in the TPC or other methods) when available.
- Sensitivity to purity stratification (and thus to test aspects of Computational Fluid Dynamics (CFD) results) is the main goal of the PrMs along the vertical string.
- Stratification of impurities is NOT anticipated in current CFD calculations (for ProtoDUNE-SP, nor for DUNE FD).
- Dedicated PrMs with enhanced sensitivity to very high purity (long PrM in the Vert string) and with enhanced sensitivity to very low purity (short PrM on the bottom of the cryostat, mainly for purity survey during filling) are proposed.
- No details on the design and procedure are available/given for the installation of the very long PrM Vertical strings inside 12 m deep LAr volume of DUNE FD.

Comments:

- The PrMs located inside the cryostat cannot be repaired/maintained and should thus be used in a way that does not degrade the Qc signal amplitude.
- The utility of the inline monitor(s) is as an alarm, together with the gas analyzers, for low argon purity coming in (from the cryostat) and out of the filters.
- The PrMs located inside the cryostat are invaluable for commissioning while the cosmic measurement algorithm is being developed/tested/cross checked. Once steady state running is achieved, the lifetime measurement of the PrMs inside the cryostat will likely be complementary to the measurement of the lifetime with cosmics except during periods where the TPC is not operational. The PrMs can extrapolate between successive cosmic measurements.
- Evidence for Stratification from PrM in pDUNE-SP is not fully demonstrated. Still persist possibilities of systematics faking an apparent stratification.

- During the one year it takes to fill the cryostat, having a purity monitor sensitive to low lifetime values near the bottom of the cryostat provides information on the liquid itself. This is an important validation/calibration of what the gas analyzers are reporting during the beginning months of the filling process. This PrM can use the external electronics, power and light source of a long purity monitor during the filling period, and thus could be added to the system for a very modest cost.
- The lifetime of the cathode in the purity monitor (and to a lesser extent the transparency of the fiber carrying the light to the cathode) degrade with the frequency of the calibration (particularly for operation in low purity Ar). No degradation of the system is expected for steady operations, where the purity is measured on a daily basis.
- The installation of the very long PrM Vertical strings inside 12 m deep LAr volume of DUNE FD requires extremely careful mechanical design and deployment procedure.

Recommendations:

- The committee's recommendation for ProtoDUNE-II is to move forward with the current plan for developing a longer-length purity monitor and using it to replace one of the three purity monitors on the current ProtoDUNE string.
- The cryogenics infrastructure to support an inline monitor should be added and an inline purity monitor installed prior to the start of ProtoDUNE-II operations.

Answers to charge questions:

1. Does the system have a well-justified role in safeguarding the far detectors and facilitating their operation, and if so, what is the minimum amount of system scope needed to carry out this role?
 - a. **Yes.** The system has a well-justified role to protect the detector against contamination of the argon and to monitor the filters for saturation. The PrMs provide immediate information from simple, pre-calibrated devices, and are essential during the commissioning of the cryogenic system. The minimum scope is one inline monitor (between the inlet to the cryostat and the outlet of the filtration system) and two strings of 2 PrMs each, one string at each end of the cryostat.
2. Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfil this role?
 - a. **Yes.** The system has a well-justified role to measure the electron lifetime, an important parameter for TPC calibration. The PrMs perform an instantaneous measurement once or twice daily during the physics run that provides different information than the measurement from cosmics which are averaged over one to several days of data. The minimum scope is the same as 1, with the

- additional specification that one of the two PrMs in each string is a long one to achieve the calibration-level precision over a larger range of lifetime values.
3. Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?
 - a. **Yes.**
 4. Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?
 - a. **Yes,** some risks may be associated with the implementation of the PrM vertical strings with support rods, inside 12 m deep the LAr volume of the DUNE-FD. Risk mitigation should be put in place with a fully developed design and insertion procedure.
 5. Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?
 - a. **Yes.** There is a credible plan for testing the long PrM in ProtoDUNE-II, however it is not clear that the R&D needed to finalize the design of the long PrM can be completed in time. The mechanical design and deployment of the 12m long string cannot be tested in ProtoDUNE-II.
 6. Does the functionality of the system justify its overall cost?
 - a. **Yes.** This system provides critical information on the performance of cryogenic system during its commissioning. Having a precise lifetime measurement during physics running is crucial for TPC performance. No single technique for monitoring the lifetime has decisively shown yet that it can achieve the required precision alone in the DUNE-FD, but the PrM system has the potential to do this. The PrM data bring unique information to a measurement that combines multiple systems.

Pressure Sensors and Level Meters:

Findings:

- Level meters with differential pressure transducers are supplied by LBNF Cryo they work throughout the entire height of the cryostat. Claimed precision is 0.1% of 14 m range. In ProtoDUNE-SP an accuracy of 0.3% was measured, but they were not used during filling.
- The proposal from the CALCI consortium is to install six capacitive level meters, of which 4 are placed at the corners of the cryostat and 2 midways on opposite 58 m sides. They would only instrument the top 1-2 m of LAr to ensure that the LAr level is above TPC upper ground planes. It was claimed that they would need to be 3.5-4 m long to reach the cryostat flange. The proposal is to interlock the TPC HV to the level meters.

- For commercial capacitive level meters, it was quoted that a precision of 0.25% of full length is achievable. It was also shown that in ProtoDUNE-SP the capacitive level meter provided a precision of ~ 4 mm for an active length of 60 cm.
- The calibration of the capacitive level meters can be done also in-situ, using the known height of the vertical temperature sensor arrays (not necessarily in the vicinity of the level meters).
- Costs of capacitive level meters are on the order of $\sim \$2.2$ k per device (including flange) + wiring to the control system.
- A system of absolute and gauge pressure sensors located inside the cryostat will be supplied by LBNF Cryo.

Comments:

- The plan to instrument the DUNE cryostat with multiple capacitive level meters is justified, given the large size of the cryostat. The committee thinks that the minimum number of capacitive level meters is 3 in the corners of the cryostat, with incremental gains from the addition of a level meter in the 4th corner and smaller gains from the addition of level meters in the middle of the detector.
- The liquid argon level can be used to detect and estimate globally the liquid argon losses. For instance, at ProtoDUNE-DP the level decrease is compatible with the amount of argon sent to the gas analyzers, at ProtoDUNE-SP, instead, the level decreases faster, indicating the presence of a leak. Are the characteristics (precision and stability) of the level meters defined including also the requirements for this measurement?
- No institution is presently assigned to the capacitive level meters. Since the proposal is to use them as part of the detector safety system, which requires understanding in detail absolute calibration, precision and reliability of the system, it is necessary to find an institution to commit to this task asap.
- In the discussion following the presentation it was stressed the need of measuring the LAr level at the bottom of the cryostat during the initial filling phase, possibly by using a short level meter at the bottom of the cryostat. It was also proposed a vertical array of temperature sensors of appropriate granularity for this purpose. A quantitative comparison between the two systems is necessary, both for granularity/accuracy and cost. A continuous measurement of the liquid at the bottom could be used to better understand the cryogenic system, i.e. balance LAr input vs level in the cryostat.

- Absolute and gauge pressure sensors located inside the cryostat are an essential part of the safety system, and their readout should be made available to the DUNE Slow Control system.
- The (relative) pressure of the insulation space is not in the CALCI scope, but it should be clarified that cryo takes care of the measurement in compliance of the detector ground separation.
- Drift velocity has a dependence on the temperature of LAr. The LAr temperature depends on the pressure. The absolute pressure can therefore give a precise measurement of the temperature at the liquid surface.

Recommendations:

- Assign an institution to the capacitive level meters. Such institution should take full responsibility for this system, starting with their deployment in ProtoDUNE-II, and their final integration with the DUNE detector safety system.

Answers to charge questions:

1. Does the system have a well-justified role in safeguarding the far detectors and facilitating their operation, and if so, what is the minimum amount of system scope needed to carry out this role?
 - a. **Yes.** The liquid argon level should be monitored during the filling. Level meters should act as an interlock for the HV, APA and Electronics systems. Level meters should be able to measure global argon losses with sensitivity that must be defined in conjunction with cryogenic group.
Liquid argon level should be monitored with enough precision also to follow deformations of the cryostat and changes in the liquid argon temperature (thermal expansion).
The pressure sensors should monitor the absolute and relative pressure and they are input to the cryogenic system that guarantee stability in the absolute pressure and that the gauge pressure is always within the operational range.
2. Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfil this role?
 - a. **Yes.** The knowledge of the liquid argon level will be an input of the CFD calculations to estimate the liquid argon flow and its impact on the distribution of impurities.
The pressure measurement is a sensitive, though indirect, measurement of the average temperature of the liquid surface. Liquid argon temperature affects, for instance, the electron drift velocity.
3. Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?

- a. **Yes.** For the pressure sensors, the commercial systems have sufficient sensitivity and stability, and they are used successfully in a number of liquid argon TPCs.
The level meters are also commercially available and are used in these kinds of applications.
4. Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?
 - a. **Yes, but based on past experience the risk is minimal.** The main risk relates to the noise induced by the capacitive level meters, that are anyway successfully used in other LAr TPC with extremely sensitive electronics.
5. Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?
 - a. **Yes, in part.** An institution who would take responsibility for the capacitive level meters should be identified asap. Work is needed to develop the interface to the slow controls and/or to the DUNE detector safety system.
6. Does the functionality of the system justify its overall cost?
 - a. **Yes,** the cost is reasonable.

Cameras:

Findings:

- The plan is to have 12 general purpose cold cameras - 6 above the TPC and 6 below.
- Some (their number was not specified) cold cameras, in particular those that are intended to help monitor the HV system, are to be provided under the auspices of the HV consortium.
- The cameras are stated to have 4k x 3k pixels and have remote focusing capability.
- No explicit plan for lighting was presented.
- A new design for cameras incorporated in the laser periscopes was presented. These cameras are designed to be used both to align the laser and verify the periscope position, with a possible capability for inspecting the TPC (from above the field cage or from inside the field cage, depending on the position of the periscope).

Comments:

- The cameras in both the single and the dual phase ProtoDUNEs were useful for cryogenic inspection during cool down and filling (viewing the sprayers and the exits of the liquid pipes.) It was stated that there was consideration of this function in the planned deployment.

- Some of the experiences of ProtoDUNE seem to have been recognized. One of the lessons learned from ProtoDUNE should also be the noise issues that prevented the cameras from operating while the TPC was taking data and generated interference with other devices such as the long purity monitor.
- No plans for the distribution in real time, nor for recording and analyzing data from the cameras were shown.
- The intriguing possibility of detecting distortions in the detector was mentioned. It would be helpful to explore this possibility and clarify its feasibility.
- For inspection purposes, the periscope cameras should have zoom capabilities, in addition to the already required remote focusing capability needed for the laser alignment and for the verification of the periscope position.
- Validation of the operation and performance of the camera integrated in the periscope in ProtoDUNE-SP 2 is an important step for its integration into DUNE.

Recommendations:

- Continue to work in close coordination with the PDS consortium to ensure that the camera lighting system does not compromise the performance of the PDS.
- Continue to work closely with the DUNE grounding and shielding experts to ensure that operating the camera system does not interfere with operation of the TPC.
- Create and maintain a document showing the position of all the lighting and all the non-laser associated cameras including those planned by the HV consortium.
- Continue the development of the cameras for the laser periscopes with the goal of validation in ProtoDUNE-II.

Answers to charge questions:

1. Does the system have a well-justified role in safeguarding the far detectors and facilitating their operation, and if so, what is the minimum amount of system scope needed to carry out this role?
 - a. The cameras are essential for monitoring the cool-down and filling process, and for verifying the state of the TPC (APAs, CPAs, and FCs) during the cooldown, prior to and during the filling, prior to the HV ramp-up, and throughout commissioning. The periscope cameras are an essential part of the laser system and may provide a long-term inspection capability that would aid the diagnosis and the solution of any mechanical alignment problem that cannot be addressed with the fixed cameras.

2. Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfil this role?
 - a. The camera system can aid in establishing the integrity of the detector and that the argon is in a state suitable for data-taking (for example that the liquid surface is not too perturbed). The minimal system requires 12 wide-field cameras with lighting to provide full coverage of the detector. Each periscope needs a camera for its operation. The addition of the inspection capability to the cameras already planned for the periscope operation could be extremely useful.
3. Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?
 - a. Most of the technical issues that affect the image quality of the present camera design for the fixed cameras have been resolved as demonstrated by the performance of the camera and lighting system in NP02. The electronics noise issues remain to be resolved.
 - b. The feasibility of the inspection cameras proposed for the periscopes remains to be demonstrated.
4. Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?
 - a. Aside from the electronics noise, the risk from the fixed cameras is considered low based on the ProtoDUNE experience. The addition of the cameras in the periscopes should reduce the risks associated with the laser operations.
5. Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?
 - a. The new fixed cameras could be demonstrated in ProtoDUNE-II.
6. Does the functionality of the system justify its overall cost?
 - a. The cost of the fixed cameras and the additional cost of the camera on the laser periscopes are both small.

Gas Analyzers:

Findings:

- The I&I consortium, the CALCI consortium and LBNF all seem to have some responsibility for and notions about gas analyzers and their implementation.
- It was stated that operational sensitivities of interest for oxygen range from 20% to sub ppb; for nitrogen > 1 ppm
- Oxygen analyzers have a typical range in sensitivity of a factor of 1000 between the Idl (lowest detectable level) and their maximum value.
- Gas analyzers would be separated by dielectric breaks from the detector common to avoid interfering with the detector electronics.

- It is proposed to use a long manifold of pipes from several pickup points to the analyzers that are located at a single location (possibly to serve two cryostats - under discussion).
- It is possible that a pump would be needed to increase the pressure of cryostat gas to allow sampling.
- We were told that no institution in the CALCI consortium is proposing to fund gas analyzers.
- A set of gas analyzers will be used by LBNF to ensure that the delivered argon meets specifications.

Comments:

- It was not clear what level of coherence there is between LBNF, I&I, and CALCI in the responsibility, design, provision or integration of the analyzer system.
- It is expected that the LBNF will provide analyzers to verify that the argon delivered meets specifications. Management should ensure that this understanding is correct and should understand the intended use and availability of these devices once delivery is complete.
- There is a difficult range between an oxygen equivalent contamination of 20 ppb (15 us lifetime) where a purity monitor begins to see a signal and 1 ppb (300 us lifetime) where the monitor can make a reasonable measurement. It would be helpful to investigate if there is an oxygen analyzer that covers this range.
- Gas monitors have the feature that they are continuously live and typically come with electronics that allow them to be incorporated into alarm systems. This feature needs to be exploited in the DUNE detector control system.
- The suggested sample points seem to be the most relevant ones. It may also be worth monitoring the cable penetrations using the existing purge pipes.
- It seems that the valves to switch between the different pickup points are located only at the analyzers, far from the pickup points themselves. It would be appropriate to evaluate the speed of response due to the time taken for a fresh sample to flow from the sample-point to the analyzer.
- It will be particularly challenging to use a single set of analyzers for more than one cryostat given the distances involved between source and analysis.
- Measurement of water contamination of a gas stream is likely to be dominated by the outgassing of or plating out of water along long pipes. Water monitors would need to

be located close to the source or some other mitigation such as maintaining a continuous stream of gas may need to be implemented.

- The filter system should be followed immediately by a high sensitivity, but not necessarily the ultimate sensitivity oxygen analyzer (ten ppb threshold) at its output as a monitor of filter saturation.
- It would be preferable given past experience to avoid the use of gas pumps, anywhere in the apparatus. Any system that includes a pump acting on the gas-phase needs to be designed to ensure that any pump failure does not lead to contamination of the argon.
- If it is decided to add xenon to the argon, it would be useful to see if it is practical to monitor the xenon concentration using some form of gas analysis and compare the sensitivity to other techniques such as monitoring the signals from the photodetectors themselves.

Recommendations:

- The I&I group, the facility (LBNF), and the CALCI consortium should work together to develop an integrated plan for the gas analysis system, including locations, piping, equipment and integration into the cryogenics and detector control, monitoring and safety systems.

Answers to charge questions:

1. Does the system have a well-justified role in safeguarding the far detectors and facilitating their operation, and if so, what is the minimum amount of system scope needed to carry out this role?
 - a. Analyzers will be required to verify that the incoming argon meets specifications. They will also act as a monitoring and alarm system during operation. Analyzers capable of measuring: oxygen with an LDL (lowest detectable level) 0.5 ppb, nitrogen to LDL of 0.2 ppm, and water to LDL 0.2 ppm are a minimum capability to have robust measurements in the regions of interest.
2. Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfil this role?
 - a. It is not in the primary scope of these devices to facilitate the analysis of data - they serve to assure that high quality data can be taken. The minimal system would be a set of analyzers as described above.
3. Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?
 - a. Although relatively few details of the specific implementation of the system for (the first cryostat of) DUNE were presented, an overall scheme was shown, and

gas analyzer systems have been used successfully on previous installations. It is expected that a system adequate to the needs will be technically feasible.

4. Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?
 - a. There is the risk of the introduction of leaks as for all additions to the cryogenics system and a plan for extensive leak-testing will be in place.
5. Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?
 - a. Plans for ProtoDUNE-II were not presented. The performance of similar systems, however, is well demonstrated.
6. Does the functionality of the system justify its overall cost?

The cost is reasonable given the importance of the measurements being made.

Cryo-Instrumentation Coordination:

Findings:

- Six cryogenics Instrumentation items are proposed for the DUNE-FD:
 1. Purity Monitors - for LAr purity monitoring and periodic charge attenuation calibration
 2. Temperature Sensors - for cryogenics system monitoring and to constrain/validate CFD simulations
 3. Cameras - for monitoring critical high-voltage system components, the alignment of the TPC structures, and the LAr surface
 4. Gas Analyzers - for continuous GAr and LAr purity monitoring (including N₂)
 5. Levels Meters - for LAr level measurement during filling and monitoring variation/loss during operation
 6. Pressure Sensors - for cryostat regulation and absolute LAr temperature determination at saturation.
- All proposed cryogenic instrumentation items were implemented in ProtoDUNE-I (in some cases with prototype or preliminary design). Each of these demonstrated to operate adequately, showing the maturity, robustness and reliability of the solutions adopted, and the relevance of their role as part of the overall operational success of the LAr-TPC.
- Possible improvement in the design for some of the cryogenic instrumentation items or optimization in the distribution or location inside the cryostat were also identified from the experience of ProtoDUNE-I. The proposed solutions for DUNE-FD retain in all cases the original design but in some cases include from slight to significant modifications.

Comments:

- The set of cryogenic instrumentation items, based on their extended operation in real experimental conditions with ProtoDUNE-I, showed themselves to be adequate and reliable for monitoring all relevant functioning parameters of the system, from the cryostat to the detector(s) and the liquid inside it.

- No evident risks of interference of cryogenic instrumentation operation with regular operation of the LArTPC+CE and PDS have been found.
- The overall design and the plan of installation of the proposed set of cryogenic instrumentation items appear coherent and address all currently identified needs of monitoring for the complex cryogenics system of DUNE-FD. On the other hand, the different items appear as stand-alone systems with no attempt to find common or integrated solutions for deployment in the LAr cryostat (e.g. the sharing of cryostat penetrations). One exception is the camera on the laser periscope. This appears as an optimal, mutually beneficial solution.
- Compared to the installations in ProtoDUNE-I, some limitations and/or advantages in the proposed solution for DUNE-FD have been identified for each item:
 1. Purity Monitors - Addition of inline purity monitor, outside the cryostat, before and after the filter, addition to a longer purity monitor that extends sensitivity to higher Qa/Qc (closer to 1). Possible addition of short purity monitors with sensitivity to low Qa/Qc for operation during filling time.
 2. Temperature Sensors - Change of design for Dynamic Vertical T-gradient array. Major change in distribution of Static Vertical T-gradient sensors (on APAs inside TPC volume). Cross-calibration from precise dynamic sensors to static sensors at far distance appears problematic. Addition of temperature sensors in gas ullage volume. Addition of precision temperature sensors near fluid inlets and outlets of the cryostat to help with constraining CFD model.
 3. Cameras - Purpose for cameras extended to monitoring for bubble appearance on LAr surface and providing close inspection of TPC parts (e.g. alignment of CPA, FC panels). A system of fixed cold cameras and additional inspection cameras on laser periscopes is proposed.
 4. Gas Analyzers - Addition of O₂ gas analyzer with extended sensitivity/precision to low contamination down to 100 ppb or less for O₂. Addition of gas and liquid extraction points for more extended monitoring.
 5. Levels Meters - Multiple Capacitive level meters at the corners of the cryostat.
 6. Pressure Sensors - Addition of precision pressure sensor for measuring the absolute temperature of the liquid.
- Based on ProtoDUNE-I experience, all of the additional cryogenic instrumentation proposed for the DUNE-FD appears to be well-motivated. Some of the proposed solutions need a more careful engineering design study, e.g. the 12 m long vertical support/rod for the PurMon string. The achievement of higher resolution for some of the proposed instrumentation appears ambitious and may require demonstration, e.g. cameras with <1 mm resolution in surveying alignment of TPC components.

Recommendations:

- The implementation of the proposed cryogenic instrumentation items, in their basic configuration option, is considered essential for DUNE-FD. Items proposed with major upgrades or substantial design modifications compared to the solutions implemented in ProtoDUNE-I, are recommended to provide adequate engineering design for installation and risk analysis/mitigation plan that ensures no interferences with other inner detector components. Specifically, for the purity monitor string, for the Dynamic

Vertical T-gradient Array, for the RTDs mounted on the APAs, and for the inspection Cameras on the laser periscopes.

- Integration of different items within the cryogenics instrumentation scope deployed from single multipurpose flange/penetrations is encouraged.
- Demonstration of high precision sensitivity, beyond current achievement, is needed possibly through dedicated R&D or bench tests prior to implementation for ProtoDUNE-II. Specifically, for the long purity monitor including an electrostatic simulation, for the short purity monitor located on the bottom of cryostat necessitating a very long fiber, and for the inspection cameras.

Calibration Systems:

Ionization Laser System:

Findings:

- A lot of progress has been made on design and integration of the laser system. However, few details exist on how the calibration will be carried out, associated calibration time scales, and coordination with measurements of other systems and natural sources.
- In the overall calibration plan, this system is the only one ensuring the determination of calibration parameters for E field distortions, drift velocity, and detector alignment throughout the entire TPC.
- Simulations of E field distortions at the penetrations (detector top) have been provided recently by Bo Yu.
- Scenarios have been worked out with incremental system scope (and cost); already the full scope scenario is minimalistic to achieve the goals and poses some risks.
- System tests are pursued at very few institutions, primarily at LANL, LIP and KSU.
- Technical issues related to glass tube height, coverage, and maintenance have been studied and mostly addressed. Recommendations from June 2019 have been taken into account.

Comments:

- The camera system for alignment and guiding to the bottom mirror is a very useful addition.
- Crossing tracks for calibration have been discussed by the proponents of the system, though laser track end points will also provide unambiguous 3D corrections in some parts of the detector.
- Cosmic muons may provide a second track for a crossing track pair (one cosmic muon and one UV laser track), given that muons will not undergo much MCS at the energies observed underground. However, these muons will be quite downward going, unlike the end-wall lasers, and so the extended scope including end-wall lasers will still provide unique angular coverage, though limited to the ends of the detector in the Z direction.

- Some concerns have been raised regarding potential damage to the detector if the top UV laser system touches the field cage when being lowered into the active volume. The committee acknowledges that “port-aligners” incorporated within the mechanical design, the proposed periscope camera system, and inclinometers on the laser feedthroughs are useful in helping to mitigate this risk.
- Planning for ProtoDUNE-II measurement is advanced and seems suitable given the stated scope of the system.

Recommendations:

- Define soon a plan on how the calibration from the UV laser system will be carried out. This should include time scales and frequency, as well as some basics about methodology. And furthermore, the data taking rate, per drift and total, the triggering scheme, and data size, as well as how laser energy, mirror/FT positions, angles and other laser system parameters are integrated with the TPC data.
- Related to the above, it should be stated clearly if the measurements from natural sources or other hardware systems are needed for the UV laser system calibrations to be used, and what exactly the UV laser system provides in this coordinated effort. For E field determination, the UV laser system is expected to directly measure the E field on its own, but what about parts of the detector that it cannot access, and what about variations on short timescales? For other measurements, such as electron lifetime, would the UV laser system measurement need to be combined with other measurements to fully cover knowledge of the detector parameter in time/space?
- We recommend running simulation-based studies showing how the E field distortions would be extracted from UV laser beam data, including the precision of these measurements given expected bias/smearing of true laser paths. While these studies cannot be done quickly, it is important to carry these studies out as soon as possible.
- In a collaborative effort between the CALCI consortia and the calibration physics working group,
 - Perform simulation studies to determine the effect of position distortions and energy scale/resolution smearing on physics object reconstruction and measurements.
 - Consider the use of the laser track end points in calibrations (which also should provide unambiguous 3D corrections), as well as combining laser tracks with cosmic muon tracks.

- Work on ensuring that we can simulate E fields associated with the top field cage openings for the baseline UV laser system in our detector simulation (i.e. in LArSoft), using the E field distortion simulation already provided by Bo Yu.
- What is the risk of the top UV laser system touching the field cage as it is extended down into the active volume of the detector? If non-negligible, can this be addressed by redesign of the system?
- Continue work on small-scale testing ahead of the deployment of the UV laser system tests at ProtoDUNE II to ensure the system design will not introduce unnecessary risk to ProtoDUNE II.
- Related to the above, we recommend extending the system tests pursued at universities/laboratories in addition to the ProtoDUNE tests.
- Additional scientific and engineering support should be identified in order to address the above recommendations in view of ProtoDUNE-II and the final system for DUNE.

Answers to charge questions:

- Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfil this role?
 - **Yes.** The committee sees an important role for the ionization laser system in diagnosing significant mechanical and electrical detector issues. The minimum scope to fulfill this role is full coverage by a single laser beam, though it is possible that crossing laser beams will further allow for a precision calibration of the TPC electric field. This system relies on independent position measurements (and their deviation from expectation), while all other systems (other than cosmic muons) aim at the charge measurement. Additional scientific support is desirable for ensuring the development of the calibration methodology and evaluation of the expected system performance.
- Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?
 - **Yes, mostly.** There is still some question about possible detector injuries associated with operation of the top laser periscopes. Whether or not this is an issue should be demonstrated at ProtoDUNE-II. This system would benefit from additional engineering support to address technical risks.
- Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?
 - **Maybe.** Electric field distortions can appear from the top laser periscope penetration in the field cage. These are likely far away from where they would lead to degradation of the physics performance. Additionally, as mentioned above, the potentiality for collisions of the top laser periscope with the field cage

should be better understood at ProtoDUNE-II. Cameras can mitigate this latter risk.

- Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?
 - **Yes.** However, as mentioned above, additional scientific and engineering support would be very beneficial to achieving goals at ProtoDUNE-II.
- Does the functionality of the system justify its overall cost?
 - **Maybe.** If a calibration of the electric field and fiducial volume turns out to be required at the 1-2% level and the system is demonstrated to fulfil this requirement in ProtoDUNE-II, then this system will be the only one to achieve that.

Laser Beam Location Systems:

Findings:

- The goal of the LBLS is to achieve a laser beam position precision of 5 mm at 10 m distance. Each laser should be less than 15 m from a LBLS pad to assure precise measurement.
- There are two different designs: PIN diode pads and mirror pads. PIN pads can be used early on, before LAr fill and HV ramp-up. Mirror pads need to be used after LAr fill in order to reconstruct the reflected laser beam.
- The PIN pads are placed on the cryostat floor under the FC, close to APA plane to avoid high electric field region and obstruction from the ground plane.
- Each PIN diode pad consists of 10 pin diodes, placed in 2 rows (5x2) for easier localization, imaging and redundancy.
- Signal cables routed along the floor, grouped together with the cryogenic pipe structure.
- Different signal heights from the three adjacent illuminated PIN diodes allow for reconstruction of the center of the beam spot by looking for the peak weighted average center of the signal. The pulse height information can be used for tuning and monitoring laser intensity.
- PIN pads provide measurement of laser beam position in the cryostat reference frame.
- In ProtoDUNE-II, the plan is to install PIN pads at two dedicated locations, close to APA and attached to the cryostat floor using cryogenic glue.

- The mirror pads are attached to the inner FC profile gap. They are 1 m away from CPA in the drift direction and roughly half-way between laser periscopes in the beam direction.
- Each mirror pad consists of 5 mirrors, each mirror with a different angle.
- Mirror angles are chosen to be well away from the APAs to avoid damage to the PDS.
- Laser reflection should be at least 1 m long and will be reconstructed by the collection plane of the TPC. Laser reflection provides a small increase in coverage but is limited by the less intensity and wider profile than the unreflected laser beam.
- Mirror pads provide measurement of laser beam position in the FC reference frame.
- In ProtoDUNE-II, the plan is to install mirror pads on both the bottom and end-wall FC.

Comments:

- The committee believes that for an ionization laser system, it is essential to have the capability to measure the position of the ionization laser heads relative to the TPC.
- The committee views mirror arrays located within the TPC field cage profiles as highly-desirable for carrying out this function and notes that having additional mirror arrays on different field cage elements accessible to the same lasers would also be highly-desirable.
- The committee considers the use of pin-diode sensors to monitor laser beam intensities as potentially advantageous. However, the committee views sensors attached to the cryostat floor as low-impact since the position measurements made with these devices will be difficult to translate into the TPC geometry and notes that sensors attached to the TPC itself are technically risky due to the need for attached wires to read out the sensors.

Recommendations:

- The committee's recommendation for ProtoDUNE-II is to install some number of mirror arrays in the field cage elements accessible to the ionization laser(s) to allow for tests of proposed system functionality.

Answers to charge questions:

Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfill this role?

This system is an addition to the ionization laser system, the answer with respect to the analysis is given there. There is a clear role for the laser position system in order to improve the usability of the ionization laser. The diodes' ability to measure the laser intensity is advantageous, but also adds risk as stated below.

- Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?

Mostly. For both the mirrors and the diodes the designs are close to being ready for testing in ProtoDUNE-II.

- Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?

We find negligible risk from the mirror system. The active nature of the diode does introduce risks of connectivity and related risk for discharges by adding conducting material close to the field cage.

- Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?

Yes

- Does the functionality of the system justify its overall cost?

The cost of the systems is very small, compared to the benefit. With a very small risk for the mirror system, while it is medium for the diodes.

Photo-electron Laser System:

Findings:

- The PE laser system offers a novel source of drifting electrons at known locations near the cathode.
- The system involves UV laser light routed via fibers to the APAs and diffused and directed toward targets affixed to the CPAs.
- The system under design aims to provide input on thresholds, E-field distortions, drift velocity, diffusion, SPE, CPA planarity, and charge collection efficiency and linearity.

Comments:

- The intended capabilities would be a boon for the calibration and detector modeling program of DUNE. There are, however, significant technical concerns, and many aspects of the system are untested.
- Assumptions about emission efficiency and intrinsic spread, light source uniformity (or ability to map non-uniformities), and cathode plane background emissions are all critical to the performance yet have not been addressed to a sufficient level. Benchtop demonstrations of these basic performance assumptions are essential to validate the simulations.
- It is unclear whether the technical work could be completed on the required timescales, even with a significant increase in support / FTEs.
- The presence of fibers in the detector entails some risk.

Recommendations:

- Clarify what piece or pieces of the calibration program of DUNE this system provides that more technically mature options are unable to provide.
- Provide a detailed timeline from R&D through to a test deployment (ProtoDUNE or otherwise), including an approximate personnel matrix, to aid in assessing whether this system can be realized in practice.

Responses to charge questions:

Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfill this role?

- The system offers sources of drifting electrons at the cathode with designed spatial patterns and known emission times. Such sources can be used for a number of calibration and detector modeling purposes and would be beneficial to the data analysis. The precise minimum scope is unclear given the technical status of the system.

Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?

- No, the system has a number of technical aspects that are not yet demonstrated. Assumptions about emission efficiency and intrinsic spread, light source uniformity (or ability to map non-uniformities), and cathode plane background emissions are all critical to the performance yet have not been addressed to a sufficient level. Benchtop demonstrations of these basic performance assumptions are essential to validate the simulations.

Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?

- The relatively early stage of the design of the system makes concrete risks hard to identify, but some amount of fiber routing to the APAs will be required and would entail some low level of risk.

Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?

- No. Per the recommendations, a detailed timeline of R&D toward a viable deployable system is needed.

Does the functionality of the system justify its overall cost?

- The basic system as outlined should be fairly minimal in cost in comparison to its functionality, but the costs needed to complete the R&D and final design of the system are unclear as there is significant work still needed.

Pulsed Neutron Source:

Findings:

- The main advantage of using a neutron source is to produce, via neutron capture on argon nuclei, a diffused “6.1 MeV standard candle” for energy calibration that could fill the detector from very few localized neutron generators sitting outside of the cryostat.
- Electron lifetime measurements in the TPC could also be obtained, complementary to cosmic rays (and laser?).
- According to the simulations, the time required for the calibration is quite limited and this could be performed without affecting the normal detector operations.

Comments:

- The effectiveness of the method relies on several assumptions, some of which still require validation. For instance:
 - the kinematics of neutron crossing the anti-resonance at 57 keV which at the base to achieve the diffusion in LAr
 - the ability to fully identify and reconstruct a cascade of Compton electrons, where a relevant fraction of them could relate charge close or smaller than the detection threshold on APA single wires
- The present design seems to be not very invasive, requiring the positioning of the neutron generator and its shielding on top of available ports of the far detector cryostat.

- The plan to validate the neutron source calibration principle includes fundamental tests at ProtoDUNE (phase I and phase II). These tests could be seriously affected by the on-surface operation of the LAr TPC where collected events are overcrowded with cosmic rays induced energy depositions down to few MeV.
- It may be worthwhile to define an alternative validation plan in case the ProtoDUNE tests are difficult to interpret.

Recommendations:

- Continue to fulfill the recommendations of the last year review. In particular the issue of the lifetime measurement is not completely understood. It should be further clarified to answer the questions reported above. In addition, the realistic resolution of measuring the energy released by the neutron capture should also be investigated, taking into account the reconstruction capabilities that have been developed on the ProtoDUNE data.
- Clarify the risks in the overall effectiveness of the neutron calibration system if deployment at the center of the detector is not supported.
- Develop an alternative R&D program in case the tests at ProtoDUNE-I are not conclusive.

Answers to charge questions:

- Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfill this role?
 - Yes. It is justified as part of the calibration of the low energy response of the Lar-TPC. The system complements effectively the calibration performed with natural sources such as Ar39 or Ar42 adding a higher energy point (~6 MeV).
- Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?
 - Partly. Technical issues are limited to the identification of the location of the neutron Generator (NG) on the cryostat roof and its shielding; they are both mostly understood. The feasibility is more related to the effectiveness of the concept of the anti-resonance at 57 keV, allowing neutrons diffuse into the LAr volume. The ProtoDUNE tests are essential.
- Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?
 - Partly. Risks for detector performance are minimal. The presence of the neutron generator in underground confined areas may require special

treatments for storage and handling. Shielding for operation could interfere with other detector operational devices on top of the cryostat roof.

- Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?
 - Not fully yet. The credibility of the plan strongly depends on the ProtoDUNE-1 preliminary run. Alternative R&D plans could be necessary if it is realized that the crowded cosmic ray environment seriously affects the ability of detecting neutron captures in LAr.
- Does the functionality of the system justify its overall cost?
 - Yes. The cost is relatively low and practically limited to the acquisition of the neutron generator. To be remarked however that the NG has a relatively short lifetime and periodic renewals are required.

Radioactive Source System:

Findings:

- The baseline design uses ^{252}Cf neutron source, and natural nickel target, both sealed inside at the Delrin moderator's center. Using ^{252}Cf would significantly reduce the size of source, so it would fit a 25-cm diameter feedthrough.
- The γ -ray source will be deployed at 40 cm outside of the field cage, 220 cm away from the anode plane and can be placed at any height using nylon fish-line and guild strings.
- The rounded Delrin moderator is 20 cm in diameter and 30 cm in height.
- A Mechanical Source Deployment System is designed based on a similar system used by Double Chooz with a new cryo-glovebox design. It requires addition of guild strings to stabilize the source with respect to the field cage.
- GAr cooling tests and deployment operations are defined to address gas purity requirements.
- The current design is optimized to avoid the distortions of the E field by using insulator materials (braided nylon strings and Delrin fixtures).
- The next steps are cryogenic material compatibility/survival testing in LN2 dewar and breaking strength testing on cryotest bench at SDSMT, high-bay testing of new guide string system at SDSMT over at least a single APA height (6 m) with deployment system and constructing new innovative cryogenic purge box with sealable glove ports.

- The plan is to test RSDS at ProtoDUNE-II with a dummy radioactive source and possibly a camera, temperature logger to demonstrate a safe mechanical deployment.

Comments:

- The RSDS has a clear physics motivation to use 9 MeV photons to study the detector response to low energy photons.
- Photons that go through pair production can provide a monochromatic reference energy, both for energy scale and for the resolution determination at 9 MeV.
- RSDS has the potential to measure the electric field strength and the electron lifetime.
- The source box is potentially suspended with thin 12m long nylon wires. In this configuration, the possibility that the system tends to float and to oscillate under residual LAr flow is not negligible. The mechanical stability in LAr has to be well studied and certified.
- Multiple types of sources may be desirable to deploy.
- The committee supports the idea of being able to conduct an in-situ test beam measurement with a deployed radioactive source and for that reason considers it highly-desirable to be able to deploy a single radioactive source in one specific region near the top of the TPC.
- The committee is not convinced about the value of the radioactive source system as a regular calibration tool and therefore considers a source deployment system allowing access to the full set of heights along the end-wall of the TPC to be low-impact.

Recommendations:

- The committee recommends the development of a simpler delivery system for the radioactive source system based on the above criteria. Once such a design is realized, consideration can be given as to usefulness of conducting a technical demonstration in ProtoDUNE-II versus moving directly into underground testing focused on demonstrating system functionality.

Answers to charge questions:

- Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfill this role?
 - Yes, the RSDS has a clear physics motivation to use 9 MeV photons to study the detector response to low energy photons.
- Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?
 - In part. The main concerns are the cryo-glovebox design and the 12m long nylon wires which can float and oscillate under residual LAr flow.
- Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?
 - In part. The current design is optimized to avoid the distortions of the E field by using insulator materials (braided nylon strings and Delrin fixtures). GAR cooling tests and deployment operations are defined to address gas purity requirements.
- Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?
 - The committee recommends the development of a simpler delivery system for the radioactive source system.
- Does the functionality of the system justify its overall cost?
 - Yes. The cost is relatively low.

Calibration Program Coordination:

Findings:

- Various hardware systems were summarized, and a lot of useful information was presented, showing calibration coverage of most of the detector effects we are most concerned with.
- Some detail has been given on overlap of scope between the different hardware systems and calibrations with natural sources, including how measurements with different systems/sources might complement each other. This has been summarized in a table presented by the consortium.

Comments:

- Very little information was presented on how the measurements would be carried out, including calibration methodology, timescales for performing the calibrations, and frequency of calibration runs. This sort of information is necessary to fully evaluate the expected performance of each system, as well as operational risks (too much detector downtime).

- A requirement of E field measurements made to the 1% level of precision has been stated, which is based primarily on considerations of dE/dx measurements and fiducial volume precision. A more robust E field requirement for the DUNE FD needs to be established, taking into account more than just impact on dE/dx measurements (or fiducial volume) and including impact on neutrino reconstruction in general, or degradation of e.g. CP violation measurement sensitivity. These studies need to be undertaken within the physics working group structure.

Recommendations:

- Provide more information on how measurements will be carried out for each hardware system, including calibration methodology, timescales of calibration, and frequency of calibration. Indicate the impact on data collection due to nominal running of calibrations from each hardware system.
- If a two-laser system is installed in ProtoDUNE-II, demonstrate that you can achieve knowledge of energy scale to the 1-2% level without relying on cosmic muons beyond the level expected at DUNE FD per unit time. This would help to motivate the need for the proposed hardware systems. Here things are expected to be more difficult due to large space charge effects, so some extrapolation of results to DUNE FD conditions may be appropriate.
- The CALCI consortia in collaboration with the calibration working group should develop a more coherent/complete calibration program using both hardware systems and natural sources, presenting the unique scope of each hardware system very clearly. This should include impact to physics measurements (sensitivity/precision), which is the ultimate indicator of need by the experiment.
- The CALCI consortia in collaboration with the calibration working group should provide a more robust requirement for E field uncertainty throughout the detector after all calibrations have been carried out, including impact on neutrino reconstruction in general and/or physics measurement sensitivity (e.g. CP violation, supernova neutrinos, etc.). The current requirement seems incomplete as it only addresses very specific ways that measurements may be impacted.

APPENDIX A

Calibration/Cryogenic Instrumentation

Workshop/Scope Review

May 11 – June 5, 2020

Charge

Context: Initial workshops focusing on the scope of calibration and cryogenic instrumentation systems for the DUNE Far Detectors were held on June 18-19, 2019 at CERN. Review committees were assigned for each topic and responded to sets of charge questions drafted prior to the workshop. The final reports from the calibration and cryogenic instrumentation review committees are posted to DUNE DocDB 15812 and DUNE DocDB 16034. Follow-up workshops on the time scale of 6-9 months were deemed necessary to address the issues raised by the review committees in these reports. Initially DUNE was planning to hold these follow-up workshops on May 7-9, 2020 at CERN. Due to the current situation with the world-wide pandemic the workshop will now be held remotely over a multi-week period beginning on May 11 and culminating on June 5, 2020. The Agenda can be found in <https://indico.fnal.gov/event/24155/>.

Several different types of cryogenic instrumentation were deployed in ProtoDUNE-SP, for which performance information is available. DUNE also has some operational experience with alternative instrumentation currently deployed in the ProtoDUNE-DP detector. Except for the photon detection monitoring systems, no calibration systems were in place for the initial running of either ProtoDUNE detector.

An established DUNE policy is that any piece of instrumentation to be deployed in the Far Detectors must first be deployed and validated in one of the ProtoDUNE detectors. A second period of ProtoDUNE-SP operations based on updated “Module Zero” far detector components is planned for 2022. All instrumentation to be installed in the ProtoDUNE-II SP detector must be produced and available at CERN by September 2021.

Currently, funding has been identified for only a small fraction of the proposed calibration and cryogenic instrumentation systems for the DUNE Far Detectors. Ideally, the CALCI consortium will work with DUNE management to identify institutions/funding agencies that can provide resources for currently unfunded systems. If there are essential systems for which resources cannot be identified, DUNE will need to look for alternative methods for delivering these systems such as tapping into common collaboration resources. Module Zero Far Detector components to be installed in ProtoDUNE-II SP are ideally to be provided by the institution/funding agency that will deliver these components for the DUNE Far Detectors. In the case of some critical systems for which funding has not yet been identified (e.g. the ionization laser system and pulsed neutron source), the DUNE-US project is currently supporting the development of necessary instrumentation for the ProtoDUNE-II SP

detector with the expectation that another partner will be able to step in and deliver these systems for the Far Detectors.

Two sub-committees have been established to review the scope proposed for Cryogenic Instrumentation and Calibrations systems, respectively.

Review Committee Charge – Part I: The review committees are asked to look at each of the proposed systems and evaluate the following:

- Does the system have a well-justified role in safeguarding the far detectors and facilitating their operation, and if so, what is the minimum amount of system scope needed to carry out this role? (Cryogenic Instrumentation only)
- Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfill this role?
- Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?
- Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?
- Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?
- Does the functionality of the system justify its overall cost?

Note that the workshop is not intended to serve as a design review for the systems under discussion. As stated above, the review committees should attempt to assess the technical viability of each proposed system but not worry directly about more detailed technical questions such as how cryostat penetrations will be allocated among the different systems. The intention is to first define the overall required scope for calibration and cryogenic instrumentation systems and then work to figure out how to best globally integrate them. If the committees believe that certain calibration and cryogenics instrumentation systems are likely to have interference issues with other existing detector systems, these concerns would be appropriately be addressed as part of their evaluation of potential risks to overall detector performance.

Review Committee Charge – Part II: Based on their evaluations of the individual systems, the review committees are asked to classify each of the proposed systems in terms of the following categorizations:

1. Essential – Experiment should not be run without this system in place.

2. Highly-desirable – Strong justification for including this system but not viewed as absolutely necessary.
3. Advantageous – Good arguments exist for why this system might be useful but not fully justified in terms of its contribution to overall detector performance.
4. Debatable – System could potentially be useful but not fully supportable based on current arguments.

Note that when making these assignments, the committees should do so within the context of the full list of proposed systems. If the functionality of one system is seen as fully or partially redundant with another on the list, this information should be accounted for when making the individual assignments. In some cases, it may also be appropriate to place a single system into multiple categories based on differing levels of scope. A hypothetical example would be if one were to classify an ionization laser system with 6 lasers as essential, with 12 lasers as highly-desirable, and with 20 lasers as advantageous. As a final step, we also ask the review committees to attempt to prioritize the systems that are assigned within each of the above categorizations. The current list of proposed calibration and cryogenic instrumentation systems are provided here for reference.

Proposed Calibration Systems:

1. Ionization Laser System
 - a. Twelve laser ports penetrating TPC through top field cage modules (baseline)
 - b. Additional eight laser ports outside TPC volume that direct beams through the profiles of end-wall field cage modules (proposed upgrade)
2. Laser Beam Location Systems (proposed PIN-diode and Mirror options)
3. Photo-electron Laser System (fibers attached to APAs direct light onto photo-electric targets attached to CPA planes)
4. Pulsed Neutron Source
 - a. Two sources located above two of the existing four cryostat manholes (baseline)
 - b. Additional source locations in central region of cryostat (proposed upgrade)
5. Radioactive Source System (deployment system for lowering a radioactive source along outside ends of TPC drift volume)

Proposed Cryogenic Instrumentation Systems:

1. Temperature Sensors
 - a. Within the TPC volume (attached directly to the APAs)
 - b. Outside of the TPC volume
 - c. Static temperature monitors
 - d. Dynamic temperature monitors
2. Purity Monitors

- a. Inline monitors for cryogenic system
 - b. Monitors sitting inside of cryostat (short and long options)
- 3. Level Meters and Pressure Sensors
- 4. Cameras
 - a. Warm (in ullage)
 - b. Cold (in liquid)
- 5. Gas Analyzers

APPENDIX B – Review Committee

Committee Co-Chairs: Eric James, Gina Rameika

Committee Members: Flavio Cavanna, Alberto Marchionni, Michael Moody, Ryan Patterson, Francesco Pietropaolo, Stephen Pordes, Filippo Resnati, Kate Scholberg, Michelle Stancari, Marco Verzocchi, Michele Weber, Tingjun Yang

Ex-officio Committee Members: Ed Blucher, Marzio Nessi, Stefan Soldner-Rembold