ProtoDUNE-SP Photon Detection System Design Review
University of Chicago – August 2-3, 2016

Introduction

The Review Committee (see Appendix) was requested to evaluate the status of the design of the Photon Detection System (PDS) of the DUNE Single-Phase prototype, protoDUNE-SP. Specifically, we were asked to address, via a 9-item Charge (see Appendix), whether the PDS design was advanced enough for production of components and assembly and installation at CERN.

The Committee met with DUNE collaborators August 2-3, 2016, with some documentation provided a week prior to the meeting for review. The first day of the meeting was devoted to presentations by DUNE and extensive discussion, both of which proved to be very informative. The Committee spent most of the second day in internal discussion and preparing the initial version of this report, which was reviewed with the collaboration in a 1-hour closeout session.

After discussing our impressions and determining the main conclusions we had drawn, the Committee divided to draft responses to the Charge items in four areas:

- Optical system
- Mechanical
- Silicon Photomultipliers (SiPMs)
- Electronics

Our report consists of responses in each of these areas (where appropriate) to each Charge item (when applicable). The complete set of recommendations is collected in a separate list at the end of the report.

1. Does the Photon Detector System design enable validation and refinement of the DUNE photon detector requirements?

Optical system

Answer: Yes, but.

Finding:

- The design requirement for the PDS light yield for DUNE and protoDUNE is 0.1 pe/MeV for events at the Cathode Plane Assembly (CPA). The PDS is primarily needed for proton decay, atmospheric neutrinos, and Supernova neutrino bursts. The typical energy of neutrinos from a SN extends to below 10 MeV, giving 1 pe at the CPA at the design requirement.

Comments:

- The 0.1 pe/MeV requirement seems marginal for DUNE, and hence is a marginal design goal for protoDUNE.
- Details of the SN burst trigger still need to be worked out. It seems likely that a TPC-based trigger, rather than a PDS trigger, will be developed.

Recommendation:

- Efforts should continue to improve both main light collection schemes and to develop the ARAPUCA scheme. Further R&D should continue in parallel with protoDUNE toward higher-light-yield schemes.

Mechanical

Answer: Yes.

Comment:

- The level of design and planning prior to the shipment to CERN is impressive.
- It is expected that the development of the mechanical system of the photon detectors for DUNE will be similar. Therefore, lessons learned while assembling protoDUNE-SP will be valuable for DUNE itself.

SiPM

Answer: Yes.

Finding:

- The photon detector system will deploy sixty PD modules, each with 12 SiPMs.

Comment:

- Although the system is small and the duration short, operating this sizable number of SiPMs at cryogenic temperatures as part of a full system will be a significant step towards validation of the choice of SiPM for DUNE.

Electronics

Answer: Maybe.

Findings:

- The peak-to-peak noise in the digitized waveforms recorded from three ganged SiPMs in small scale tests is approximately 10 ADC counts. This noise level is low enough so that single PE signals can easily be resolved from noise.

- The peak-to-peak noise in “good” digitized waveforms recorded in the 35-ton test with TPC electronics off is 20-30 ADC counts.
- The peak-to-peak noise in digitized waveforms recorded in the 35-ton tests with TPC electronics on and reading out is approximately 250 ADC counts.
- See also Item 5.

Comments:

- Small scale tests demonstrate that the SSP digitizer system has low enough intrinsic noise to distinguish single PE signals from three SensL MicroFC-60035-SMT SiPMs ganged together. However, even with the TPC electronics turned off, the noise observed in the 35-ton test was at least 2 times higher than this level. One third of the SiPM channels had anomalous noise significantly higher than this. When the TPC was on and reading out, the noise in the SiPM waveforms was approximately 25 times the level present in small scale tests. ProtoDUNE-SP will operate approximately 3 times more SiPM readout channels than the 35-ton test. There is a significant risk that excessive noise will severely compromise the test of photon detectors in protoDUNE-SP.
- There is a serious risk that excessive noise in the SiPM readout will prevent the protoDUNE-SP test from providing a validation of the DUNE photon detector requirements or information that would lead to refinements to those requirements.

2. Are Photon Detector System risks captured and is there a plan for managing and mitigating these risks?

Captured risks considered here are those called out in Mualem, slide 15. These apply either to ProtoDUNE-SP or to the DUNE Far Detector PDS generally. One of these is "Schedule Risk – protoDUNE-SP schedule end date is driven by Long Shutdown at CERN," which applies to all areas of protoDUNE-SP. The collaboration is well aware of this issue, and we address schedule issues here and under other Charge items.

Optical system

Answer: Not completely.

Findings:

- Two risks are identified: FD-073 – Photon light yield too low; FD-098 – ProtoDUNE-SP Degraded Photon Detectors.
- Estimates that predict meeting the 0.1 pe/MeV requirement are based on an estimate that 0.5% of the primary UV ends up wave-shifted and captured in the lightguide bars (Himmel, Slide 14). Actual measurements of this quantity with recent prototypes give ~0.1% (Whittington, Slides 14, 16), with recently-achieved improvements of about factor of 2 (Mufson, Slide 13).
- MicroBooNE saw huge rates of single pe's.

Comments:

- The Committee thanks the presenters for walking us through the capture-efficiency issue.
- While the light-yield risk is identified, neither current default scheme appears likely to meet the requirement.
- The QA/QC plan presented to us should successfully mitigate the risk of degraded PD modules.
- MicroBooNE is a different experiment, but efforts to understand the high photon rate and understand its origin are needed to know if the protoDUNE-SP's PDS will be crippled by the same effect.

Recommendations:

- See Charge 1.
- Add MicroBooNE-like photon rates to the ProtoDUNE Risk Registry.

Mechanical

Answer: Not completely.

Comment:

- Once the detectors reach CERN, the procedures are in outline form only. These need to be fleshed out and solidified by next May when delivery is expected there. This will require the approval of CERN, and the proponents have little experience with working at CERN. While the proponents may understand this, these procedures may add bureaucratic delays that the experiment may not be able to absorb. Also, getting permission for testing procedures with radioactive sources at CERN needs to be obtained as quickly as possible. The time risk associated with this integration is not in the registry. Efforts should start immediately to mitigate these risks and complete and get approval for the assembly procedures at CERN as quickly as possible.

Recommendation:

- Add time risk associated with integration to the risk registry.

SiPM

Answer: Yes.

Findings:

- One risk is identified: FD-089 – Photon detector SiPMs are not qualified for cryogenic use.
- Extensive stress tests have been conducted on SiPMs at LN_2 temperatures. For example, in a presented test, their performance with time has been monitored for >400 days with very high illumination (saturation). No degradation of the performance or stability of the sensors was recorded.

Comments:

- The stress tests conducted on SiPM in cold (at LN) are very valuable. Given the relatively small number of SiPMs in use in protoDUNE-SP we think that the risks of SiPM mechanical failures will be minimal.
- The tests performed by the PDS group are adequate given the relatively small number of channels that will be deployed in protoDUNE-SP and the relatively short duration of the tests. However, the test program should continue in order to be confident of deploying SiPMs in cryogenic temperatures over the lifetime of DUNE. Tests to estimate the lifetime could be performed. For example, temperature cycling of the SiPM boards until the solder joints fail.
- Room temperature testing of the breakdown voltage will be performed on each SiPM before assembling them onto SiPM sensor boards. However, no plan was presented to verify that the breakdown voltage evolves with temperature in a compatible way within a group of ganged SiPMs. This could be done with tests on a small sample. Alternatively, by flashing light onto each SiPM in turn in each ganged group of three, variations in break-down voltage could be measured cold.

Recommendation:

- The SiPM tests for protoDUNE-SP should be developed into a program of tests for the PDS at DUNE.

Electronics

Answer: No.

Findings:

- See Item 1.

Comments:

- See Item 1.
- Chasing down noise issues can be very time-consuming. Even fixable noise problems could derail the already-tight schedule with respect to beam before the CERN Long Shutdown.

Recommendation:

- Add to the risk registry the risk that the protoDUNE-SP photodetector system will not provide information of sufficient quality to inform the DUNE design because excess noise degrades the quality of waveform digitization. Pursue mitigation of this risk with an aggressive attempt to understand the sources of noise in the 35-ton test (as is being done for the APA readout).

- Add to the risk registry schedule risk from having to hunt down and fix noise. Mitigation strategies include prototype testing (described under Item 9) and early operation of electronics on assembled APAs, which could be interleaved with installation tasks.

3. Does the design lead to a reasonable production schedule, including QA, transport, installation and commissioning?

Mechanical

Answer: Yes, with two exceptions.

Findings:

- Estimated production time of the radiator plates is 8 months, including initial QA, putting pressure on the schedule.

Comments:

- The design seems well in hand for production. The collaboration is to be complemented on the vigilance that has been placed on wiring mistakes, a lesson learned from the 35-ton experience.
- The ARAPUCA arrays lack an installation plan, drawings, cable plant, etc. Extra engineering needs to be added at this point to assure that these can be installed in the given APA design. As per item 2, the existing engineering resources are going to be saturated with the transition of the detectors to CERN.

Recommendation:

- Added manpower for production and testing of radiator plates is needed.
- Added resources for the detailed ARAPUCA design must be identified.

SiPM

Answer: Yes.

Comment:

- Procurement of SiPMs should be rather fast. The number of SiPMs required for protoDUNE-SP is a small quantity for a company like SensL to supply.

Recommendation:

- The existing measurements on the SiPMs and SiPM assemblies should be developed into a set of specific acceptance criteria, "go/no-go" limits as in the mechanical tolerances, when testing SiPMs for use in protoDUNE.

Electronics

Answer:

Findings:

- See Item 1.

Comments:

- See Item 1. The commissioning plan does not include sufficient time to mitigate excessive noise if noise similar to that found in the 35-ton test is present in protoDUNE-SP.

4. Does the documentation of the Photon Detector System technical design provide sufficiently comprehensive analysis and justification for the Photon Detector System design adopted?

Optical system

Answer: Not addressed by committee.

Comment:

- The committee was not presented with discussion of alternate designs, except for the three to be implemented in protoDUNE-SP. At this point, it didn't seem useful to dig into this, as the designs presented to us will be implemented. However, as we have reservations about the light yield (both the requirement and that achieved so far) and have recommended (see Charge items 1 and 2) that variants be explored in parallel with protoDUNE, we present a recommendation anyway.

Recommendation:

- Though we were shown (Himmel, slides 15-16) projected efficiencies vs. distance from anode plane for various thresholds (in pe), the impact of these efficiencies on the physics that can be extracted, especially from SN bursts, has not been studied in detail. A study should be performed documenting the impact of PDS light yield on SN physics, specifically at values of 0.1, 0.05, 0.02 pe/MeV at the CPA.

SiPM

Answer: Not addressed by committee.

Comment:

- The choice of SiPMs as the photosensors for protoDUNE-SP was not discussed, but, given the performance demonstrated, appears to be sensible.
- A comprehensive analysis and justification for the choice of the specific SiPM chosen was not presented. Although many results on testing SensL C-series-60035 SiPMs were presented there was little consideration of other SiPMs (other models or from other producers). No plans for testing better performance SiPMs (available on the market) were presented. However, the chosen SiPM appears sufficient for protoDUNE-SP.
- The Committee would have liked the study of "ganging" multiple SiPMs to be matched with circuit simulation. We would suggest making a simulation of the full electronic chain to better understand the degradation of the signal when SiPMs are "ganged". For example, it was not clear to the committee the dominant factors that control the slow rise time of single SiPMs (>20ns) after digitization.
- There is recent literature on use of amplification and summing of SiPM signals in the cold. We would suggest the collaboration investigate use of cold amplification after protoDUNE.
- The constraints on the number of channels (feedthroughs, cabling) were not clearly presented. Hence it wasn't clear what design parameters could be varied, but channel-count was suggested as a key driver of the ganging scheme.

5. Is the Photon Detector system scope well defined and complete?

Answer: Yes, in all areas.

Are all Photon Detector System interfaces to other detector components: APA, cryostat and DAQ systems documented, clearly identified and complete?

Answers: APA, cryostat: Yes, with exceptions below;

DAQ: No.

Comment:

- The path from the PDS's SSPs to protoDUNE-SP's overall readout has not been detailed, but should be within the capabilities of the hardware to be used.

Do the electronics feedthrough port and TPC integrated 3D models adequately represent the mechanical, electrical and electronic interfaces to the Photon Detector System?

Answers: TPC: Yes;

Electronics feedthrough port: No.

Comment:

- The TPC 3D models are quite detailed.
- The PDS feedthroughs are currently being redesigned to accommodate new connectors. The general design is meant to be similar to the TPC feedthroughs and should not be a problem, but this is a crucial item.

Is the cabling, power and calibration well defined and understood? Is the grounding and shielding understood and adequate?

Mechanical

Answer: Yes, with one exception.

Comment:

- The ARAPUCA cabling within the PD modules differs from the other optical schemes: cables extend across the APA and there are different numbers of SiPMs and readout channels. This is one of many issues with the ARAPUCAs that must be worked out, but it is understood that the ARAPUCA's are to be installed last, so there is some time.

Electronics

Answer: Maybe.

Findings:

- See also Item 1.
- All small scale tests of DUNE photon detectors in liquid argon performed to date have used Gore twinax cables. Plans for protoDUNE-SP call for the use of Cat 6 cables.

Comments:

- Tests of prototype photon detectors done to date have used Gore cables with high quality braided shields. The plan is to use commercial Cat 6 cables in protoDUNE-SP. We suggest testing the new cables for noise immunity soon to validate the soundness of this plan.
- The 35-ton test has shown that noise pickup is a concern for the photon system. It is likely that this pickup can be minimized by minimizing the length of cable outside the cryostat.

The use of 48-volt DC for the power will also minimize the possibility of noise pickup from external sources.

Recommendations:

- The new Cat 6 cables should be tested for noise immunity soon to validate the soundness of this plan.
- We recommend that the SSPs be mounted on top of the cryostat as proposed and as close to the feedthrough ports as possible.

6. Are the Photon Detector System 3D model(s), top level assembly drawings, detail/part drawings and material and process specifications sufficiently complete to demonstrate that the design can be constructed and installed?

Answer: Yes.

Comments:

- Photon detector mechanical system design, scope and interfaces seem to be well defined up to the flange.
- Cable strain due to thermal contraction is a concern. Are the connectors and strain relief sufficient to absorb this strain?
- Drawings for the photon detector bars and the SiPM holders are well advanced.
- Assembly of the SiPM boards is unlikely to be problematic, since it will take place in, or close to, PDS home institutes.
- Note that, as discussed in item 5, the PDS feedthrough design is not yet complete.

Recommendation:

- Testing of cable and connector strain relief under thermal contraction are needed.

7. Are operation conditions listed, understood and comprehensive?

Comment:

- The Committee never understood this part of the charge.

Is there an adequate calibration plan?

Answer: Partly.

Finding:

- A UV-LED/optical fiber/diffuser system will have diffusers mounted on the CPAs.

Comment:

- The design of the UV-LED system is nearing completion and was presented in detail to us.
- The LED system is more a monitoring system (devices working and stable) than a calibration system.

Recommendation:

- A calibration plan, including, for example, channel-to-channel timing offsets, t_0 timing for the TPC, light yield and resolution vs. 3D position, should be developed.

8. Are the Photon Detector System engineering analyses sufficiently comprehensive for safe handling, installation and operation at the CERN Neutrino Platform?

Note: the Committee and everyone we consulted interpreted "safe" as applying to the PD modules, rather than to personnel.

Comment:

- Nonetheless, each of the presentations addressed the relevant ESH issues and how the collaboration was addressing/mitigating them. In addition, they addressed the integration of both their home institutions' ESH support and oversight, as well as interfaces with Fermilab ESH support when necessary.

Mechanical

Answer: Yes.

Comment:

- An engineering analysis of the deflection of the channels that support the plastic bars was done and deflection was found to be minimal. Studies of the torsion in the APA during handling are still underway, but the attachment of the channels to the APA was designed to be tolerant of APA torsion.

SiPM

Answer: Yes.

Comment:

- The SiPMs to be used have an epoxy layer on top and are relatively robust.

Is the installation plan sufficiently well developed?

Mechanical

Answer: Partly.

Comments:

- The schedule is tight. Schedules exist at each partner institute. Integrated schedule was shown, but not discussed. Worry is that overlaps and double counting of staff (between institutes and at CERN) are not properly taken care off. Who is in charge of monitoring the schedule?
- We discussed that CSU has a plan of sending people to CERN for installation and commissioning. What about the other institutes?

Recommendations:

- Project and institute leaders to produce installation and commissioning plan with staff profiles making sure that there is no double counting of staff at the institutes and at CERN.
- A plan for the coordination APA installation/testing with PD installation/testing is necessary. No plan was shown to us.

Is the design for installation tooling adequate for installing the photon system?

Mechanical

Answer: Yes.

Comment:

- The needed tooling is modest in scope and well-along in its design.

9. Have applicable lessons-learned from previous LArTPC devices been documented and implemented into the QA plan?

SiPM

Answer: Partly.

Comment:

- Use of SiPMs in large LAr detectors is novel, so there is relatively little experience from previous devices. Lessons learned about the SiPMs from the 35-ton prototype were not presented, but this can be justified since noise issues with the readout system precluded systematic study of SiPM performance in the system.
- Part of the QA plan is to derive a full understanding of the response of the SiPMs before installation. But see comments under Charge item 2.

Electronics

Answer: Partly.

Findings:

- See Item 1.

Comments:

- See Item 1.
- There appears to be no plan to test the photon detector system in conjunction with the new APA systems in either the FNAL or BNL test stands. In light of the results of the 35-ton test, this appears to be a serious oversight.

Recommendation:

- As part of the effort to avoid excess noise in the SiPM readout, we recommend tests of the readout of (even a partial) APA assembly including both TPC electronics and photon detectors. Either or both of the FNAL and BNL test systems could be modified to include SiPM readout.

Are the Photon Detector System quality control test plans and inspection regimes sufficiently comprehensive to assure efficient commissioning and adequate operational performance of the NP04 experiment?

Optical system, Mechanical, and SiPM

Answer: Yes.

Findings:

- The attention to QA/QC was addressed within the presentations.
- This attention included tolerance issues that could affect installation, and optical and SiPM performance.

Comments:

- Test plans for the PD modules are highly developed and involve detailed tests after each assembly step.
- The plans for a QC database are being developed, but are still at an early stage.
- While plans for commissioning exist, some open issues have been identified. Group should be commended to have established a rapport with the protoDUNE safety officer at CERN. Details of installation need to be decided and planned with the protoDUNE team at CERN.

Recommendations:

- The Photon Detector group should continue to develop a draft of their Quality Control Plan which reference the specific QC procedures that were discussed throughout the presentations. This will help with consistency in understanding the process.
- The QC database plan should be completed and the database in place before the start of production.
- Establish close contact between PD and CERN teams on installation issues.

Collection of all Recommendations

Charge 1

- Efforts should continue to improve both main light collection schemes and to develop the ARAPUCA scheme. Further R&D should continue in parallel with protoDUNE toward higher-light-yield schemes.

Charge 2

- Add MicroBooNE-like photon rates to the ProtoDUNE Risk Registry.
- Add time risk associated with integration to the risk registry.
- The SiPM tests for protoDUNE-SP should be developed into a program of tests for the PDS at DUNE.
- Add to the risk registry the risk that the protoDUNE-SP photodetector system will not provide information of sufficient quality to inform the DUNE design because excess noise degrades the quality of waveform digitization. Pursue mitigation of this risk with an aggressive attempt to understand the sources of noise in the 35-ton test (as is being done for the APA readout).
- Add to the risk registry schedule risk from having to hunt down and fix noise. Mitigation strategies include prototype testing (described under Item 9) and early operation of electronics on assembled APAs, which could be interleaved with installation tasks.

Charge 3

- Added manpower for production and testing of radiator plates is needed.
- Added resources for the detailed ARAPUCA design must be identified.
- The existing measurements on the SiPMs and SiPM assemblies should be developed into a set of specific acceptance criteria, "go/no-go" limits as in the mechanical tolerances, when testing SiPMs for use in protoDUNE.

Charge 4

- Though we were shown (Himmel, slides 15-16) projected efficiencies vs. distance from anode plane for various thresholds (in pe), the impact of these efficiencies on the physics that can be extracted, especially from SN bursts, has not been studied in detail. A study should be performed documenting the impact of PDS light yield on SN physics, specifically at values of 0.1, 0.05, 0.02 pe/MeV at the CPA.

Charge 5

- The new Cat 6 cables should be tested for noise immunity soon to validate the soundness of this plan.
- We recommend that the SSPs be mounted on top of the cryostat as proposed and as close to the feedthrough ports as possible.

Charge 6

- Testing of cable and connector strain relief under thermal contraction are needed.

Charge 7

- A calibration plan, including, for example, channel-to-channel timing offsets, t_0 timing for the TPC, light yield and resolution vs. 3D position, should be developed.

Charge 8

- Project and institute leaders to produce installation and commissioning plan with staff profiles making sure that there is no double counting of staff at the institutes and at CERN.
- A plan for the coordination APA installation/testing with PD installation/testing is necessary. No plan was shown to us.

Charge 9

- As part of the effort to avoid excess noise in the SiPM readout, we recommend tests of the readout of (even a partial) APA assembly including both TPC electronics and photon detectors. Either or both of the FNAL and BNL test systems could be modified to include SiPM readout.
- The Photon Detector group should continue to develop a draft of their Quality Control Plan which reference the specific QC procedures that were discussed throughout the presentations. This will help with consistency in understanding the process.
- The QC database plan should be completed and the database in place before the start of production.
- Establish close contact between PD and CERN teams on installation issues.

Appendix: Review Committee and Charge

Review Committee:

Peter Meyers (chair)

Randy Johnson

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David Cussans

David Christian

Biagio Rossi

Design Review

ProtoDUNE Single Phase Photon Detector System

2–3 August 2016

Charge

The Committee is requested to review the ProtoDUNE Single Phase Photon Detector system technical design and determine if it is at a state commensurate with that needed for producing the photon system needed for the NP04 ProtoDUNE prototype detector operation at the CERN Neutrino Platform in 2018.

In particular, the review team is asked to address the following questions:

1. Does the Photon Detector System design enable validation and refinement of the DUNE photon detector requirements?
2. Are Photon Detector System risks captured and is there a plan for managing and mitigating these risks?
3. Does the design lead to a reasonable production schedule, including QA, transport, installation and commissioning?
4. Does the documentation of the Photon Detector System technical design provide sufficiently comprehensive analysis and justification for the Photon Detector System design adopted?
5. Is the Photon Detector system scope well defined and complete? Are all Photon Detector System interfaces to other detector components: APA, cryostat and DAQ systems documented, clearly identified and complete? Do the electronics feedthrough port and TPC integrated 3D models adequately represent the mechanical, electrical and electronic interfaces to the Photon Detector System? Is the cabling, power and calibration well defined and understood? Is the grounding and shielding understood and adequate?
6. Are the Photon Detector System 3D model(s), top level assembly drawings, detail/part drawings and material and process specifications sufficiently complete to demonstrate that the design can be constructed and installed?
7. Are operation conditions listed, understood and comprehensive? Is there an adequate calibration plan?
8. Are the Photon Detector System engineering analyses sufficiently comprehensive for safe handling, installation and operation at the CERN Neutrino Platform? Is the installation plan sufficiently well developed? Is the design for installation tooling adequate for installing the photon system?
9. Have applicable lessons-learned from previous LArTPC devices been documented and implemented into the QA plan? Are the Photon Detector System quality control test plans and inspection regimes sufficiently comprehensive to assure efficient commissioning and adequate operational performance of the NP04 experiment?

The committee should present its findings, comments, and recommendations in a closeout meeting with DUNE management on August 3. The committee should provide a final written report by August 12.