Draft report

Introduction

## **Photon Collection System**

**Findings**

* The ARAPUCA photon collector is a modular light trap which uses one or two dichroic filters which allow photons to pass into the module but not to exit, but rather stay trapped via reflection off the inner surface of the box, ultimately eventually getting absorbed or collected by photo-sensors mounted along a surface of the box.
* Two ARAPUCA modules have been installed in the ProtoDUNE detector. One is on the beam right side which sees many beam interactions, and the second is on the beam left side which sees a much lower beam rate. Analysis of the ProtoDUNE data is on-going. In ProtoDUNE each ARAPUCA array holds 16 cells(10 cm x 8 cm) and each cell is read-out by either 12 or 6 Hamamatsu SiPM passively ganged together.
* For the DUNE Single Phase detector, the baseline photodetector is called the X-ARAPUCA. The X-ARAPUCA is a hybrid solutionbetween the basic ARAPUCA and a light guideas it includes a wavelength shifting plate.
* An X-ARAPUCA modulefor DUNE will have dimensions approximately 210 cm x 12 cm, segmented into four cells called supercells. Each supercell will host 48 SiPMsread-out by one single electronic channel. There are 10 modules per APA.
* Two tests will happen in the short term (before the end of 2018):
* A small 10 cm x 8 cm X-ARAPUCA will be tested in LAr at UNICAMP and X-ARAPUCAs supercells will be tested in the ICEBERG set-up at Fermilab (joint test with Cold Electronics Consortium)
* The main objectives of the tests are measuring the X-ARAPUCA detection efficiency (and comparing with MC expectations), studying interferences with CE, test of the active ganging and read-out electronics.

**Comments**

* The X-ARAPUCA is an evolutionary version of the ARAPUCA technology which has been developed over the past several years. It was presented that analytical calculations and MC simulations point to an enhancement between 40% and 70%with respect to the standard ARAPUCA. It is proposed that the X-ARAPUCA has a detection efficiency larger than 3% (on the basis on analytical calculations, MC simulations and experimental tests), however, no direct measurements from an X-ARAPUCA were shown.
* It was presented that the X-ARAPUCA design is expected to be >10 times more efficient than the most efficient light-guide bar installed in protoDUNE, however this has not yet been demonstrated.
* The up-coming tests which will compare the different types of modules is extremely important. Prompt analysis of the data will be necessary to validate the proposed baseline design and aid in validating simulations.
* Good progress is being made on the simulation effort, which needs to continue to be refined and validated with data.
* The schedule for accomplishing all necessary tasks prior to completing the TDR is very tight.
* A second ProtoDUNE run with the final design of the photon detectors is important and should be planned for.

**Recommendations**

Since the performance of X-ARAPUCA and the potential improvement compared with the previous design have not yet been demonstrated, priority should be given to the validation of X-ARAPUCA both through a substantial improvement of the simulation and by direct experimental tests. In particular:

* Conduct the proposed hardware tests (Brazil and Fermilab) as soon as possible and put the analysis turnaround at high priority.
* Continue to develop detailed simulations of the proposed design and compare with measurements.

## **1.2 Photosensors**

## **Findings**

* The baseline design of the PDS (X-ARAPUCA) employs up to 48 SiPM per supercell The SiPM are actively ganged with one operational amplifier.
* Dark count rate (<0.06 Hz/mm2), reliability in liquid argon and maximum reduction of the number of channels are the main critical parameters that drive the choice of the photosensors
* Ganging with a S/N>4 and rise-time within the 1 mus requirement has already been achieved with the Hamamatsu MPPC
* Given the large number of SiPM needed in the baseline design (3 105 for the 10kton module), there is room to get a product optimized for the needs of DUNE and two vendors/developers expressed interest to carry on optimization (Hamamatsu and FBK)
* The 48 SiPM on an active ganging board has been successfully interfaced with a mu2e board and reached S/N=4. The same board coupled with an SSP achieved S/N=5.

**Comments**

* Most of the electrical and mechanical specifications are available and well justified. The optimal sensor dimension, the cell pitch and the dynamic range of the photosensor are still unknown although they do not seem to be critical for the performance of the X-ARAPUCA
* Packaging is critical for the long term reliability of SiPM and the best choice has not been identified, yet. Naked SiPMs are the safest solution but increase the complexity of handling, installation and mechanical/thermal constraints
* Active ganging is compatible with the 1 mus time resolution requirement but the 100 ns goal might require a re-optimization of the ganging board and/or an increase of the number of active components.
* The duration of the optimization phase and the delivery time are not fully defined. A delivery time of about one year is a reasonable extrapolation from 104 scale productions performed for other experiments.

· **Recommendations**

* Define as soon as possible the missing specifications for the SiPMs (number of cell per sensor, cell-pitch dimension, dimension of the sensor) in order to start the customization of the photosensors on a firm ground
* If ganging up to 48 SiPMs is the optimal configuration, special emphasis should be given to the uniformity of response of the photosensors and, in particular, to the gain at given overvoltage. This may require dedicated customization with the vendors or countermeasures to cope with different operating voltages within the same production batch.
* Define a validation procedure to ensure reliability of the packaging over a high number of thermal cycles, determine long term degassing and optical deterioration, and downselect the packaging options.
* Since accessibility and reliability is a unique challenge of DUNE, it is important that the vendors are engaged in developing product specifically designed for cryogenic operation.
* As soon as the X-ARAPUCA design is validated, define the production centers and the resources needed to produce the boards with the SiPM. Quality assessment procedures during production and installation have not been detailed, yet.
* Utilize the protodune data to assess the performance of the existing sensors, including backgrounds and assess their stability,

## **1.3 Electronics**

· **Findings**

* The active ganging of 48 SiPM Hamamatsu was tested : 8 groups of 6 SiPM connected in parallel summed by one OpAmp. Signal readout by SSP digitizer
  + At - 70°C rise time is 60 ns ; fall time is 660 ns, baseline recovery 5 µsec
  + Rise time and Fall time determined by the capacitance of the 6 SiPM connected in parallel (~8 nF)
  + Undershoot due to a impedance mismatch with the SSP
  + Noise is 10 nV/sqrt(Hz), not much sensitive to T and Vbias
  + The power consumption with 2 stage OpAmp is about 10 mW at 85 K
* The simulation tool of the equivalent circuit of SiPM and ganging electronics has been set up. Simulation is in agreement with data. A prototype has been realized.
* Output of active ganging board successfully fed into the mu2e FEB
* The mu2e Cosmic Ray Veto FEB is a 64 channel board based on 8 commercial ADCs (80MS/s, 12 bit) readout by 4 Spartan-6 FPGAs
* Single photon resolution was demonstrated by using mu2e FEB and the SNR=4 measured. The use of this board as FEB for the DUNE PDS would be more cost effective than the more sophisticated SSP solution, that would be an overkill
* Alternative active ganging was simulated : the signal of 12 SiPM connected in

parallel amplified either by a transimpedance amplifier or a charge integrator

amplifier - 4 such groups are then summed by a second stage OpAmp.

* + No significant difference between the two amplification schemes.
  + Also in this scheme single photon resolution was achieved with SNR of 8 dB
* The grounding scheme was verbally confirmed to follow what was done at ProtoDUNE.
* Active electronics are being considered in the cold to amplify the ganged SiPM signals.

**Comments**

* About the mu2e FEB: -the Spartan-6 FPGA can go out of production soon; - the Xilinx programming software for this device is towards the end of support; -the channel multiplicity does not match the foreseen ganging scheme of 48 channels; -many functionalities of this board are not suited for this application.
* In comparing the different schemes of the active ganging of 48 SiPM the total number of used operational amplifiers should be taken into account as well as the power consumption and the final SNR.
* No plan was presented for how power was going to be brought down for the active electronics in the cold.
* Noise tests in ICEBERG are essential in testing for any interaction between the Cold Electronics and the active PD cold ganging/amplifier electronics

**Recommendations**

* Study the timing performances of the active ganging scheme at LAr temperature and the requirements on the uniformity in breakdown voltage of ganged sensors
* A Front End board specifically designed for DUNE PDS requirements should be considered, starting from the existing mu2e design.
* The adopted solution for the front end electronics has to take into account the extended dynamic range of signals expected from SN neutrinos or neutrino beam events.
* The system grounding plans should be documented.
* The cable run between the readout electronics and the DAQ must be fiber optic.
* A plan to qualify all “cold” components should be developed.
* A plan for supplying power for active cold electronic amplifiers should be developed.
* Evaluate the impact of supernovae burst triggering on the front-end electronics

## **1.4 Installation and calibration**

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**Findings**

* X-ARAPUCA is made into bars approximately 2100 mm long x 118 mm wide x 23 mm thick.
* 5 Bars are inserted from each side of the APA.
* The slot in the APA is 136 mm wide x 25 mm high.
* There are rails installed inside the APA frame that allow for insertion of the bar.
* ProtoDUNE bars were inserted the same way.
* Each bar is subdivided into 4 supercells; each supercell is divided into 6 cells.
* Each supercell made from FR4 parts that are water-jet cut from sheets. The parts are assembled using small fasteners.
* The 4 supercells are held together with side strips made from FR4. There are 4 side strips, two on each side, which are 1050 mm long each. The connection is made via the central block.
* The middle of the bar, between supercell 2 and 3, is where there is a connection to a circuit board that is on the APA middle tube.
* The bar is fixed on the outer APA tubes on the side it is inserted.
* Bar shrinks more than the SS frame of the APA. So the connection in the middle tube has to allow for the pins to slide in sockets about 1.5 mm. This has been tested.
* There are passages in the cells to allow for air to exit and LAr to circulate.
* Cable routing through APA frame has been determined. Cables are installed before APA wire winding.
* A concept for a Photon Detector calibration & monitoring system was presented, that relies on the experience from the 35 ton prototype and ProtoDUNE. The system transports light from 275 nm UV LED sources through quartz fibers to diffusers located on the cathode plane.
* Preliminary integration and installation plans were presented.

**Comments**

* The middle joint between the side strips is potentially a high-stress point. This should be studied.
* There are many small fasteners. A bonding method for some, or all the pieces should be investigated.
* A cross section view of the assembly showing components, dimensions and clearances would be very helpful.
* Cable connection of lower APA to upper APA requires manipulation of cables. This should be tested.
* Proceed with the analysis of the calibration & monitoring system in ProtoDUNE
* The Consortium should continue to work with the APA/CE consortium and Technical coordination to finalize integration and installation plans..

**Recommendations**

* Make a test of cable connection of lower APA to upper APA using actual APA frame parts, PD cables and proposed connectors. The test should be performed at Ash River with the final prototype frames for the upper and lower APA.
* Once the design of the X-ARAPUCA has been finalized, make a mechanical prototype of the rails and of an X-ARAPUCA bar, including the signal connector, to be inserted in a prototype APA frame equipped with photon detector cables.
* Perform a final integration test of PDs on pre-production APAs, equipped with Cold Electronics, and test it at CERN in the cold box, and later in ProtoDUNE-SP Run II. This test is preliminary to start mass production of APAs/CE/PDs.
* Consider to investigate the aging of the quartz fibers to be used for the calibration system.

**Answers to charge questions**

1. Does the design address detector requirements: performance, installation, grounding, testing,calibration, commissioning, operation and maintenance? Are the impacts of detector capabilities and goals on physics performance well documented?

Partly. The design addresses the physics requirements on proton decay and beam events. The goals for SN detection are under development. Some of the goals (i.e. Michel electron) are still in an early phase of development. The design addresses installation, grounding, testing and calibration. Commissioning, operation and maintenance have not been discussed in detail because they are not in the scope of this conceptual design review.

2. Are results from R&D well understood and documented?

o How well do relevant functional parameters measured from ARAPUCA detector characterization tests match simulations and/or calculations?

The ARAPUCA tests demonstrated agreement with simulation at the level of 50%. The Consortium proposes a new baseline design that is based on X-ARAPUCA. The update of the simulation to describe the X-ARAPUCA configuration is still underway. No direct comparison with data are available, yet.

o Has the ARAPUCA light collector concept been demonstrated to meet the performance requirements with a satisfactory safety margin?

The small tests of ARAPUCA done so far support that the ARAPUCA light collection concept matches the DUNE requirements for nucleon decay and beam events. The preliminary analysis of PROTODUNE-SP looks promising as well. The X-ARAPUCA design, however, has still to be validated.

o What additional performance improvements may be realized prior to the TDR/Pre-production review?

X-ARAPUCA is a potential major improvement compared with ARAPUCA. Tests are planned before the TDR both in Brazil and at Fermilab (ICEBERG) to validate this solution.

o Is there a well-defined R&D plan to achieve the optimal performance?

Yes. There is a defined plan to validate the X-ARAPUCA design in the short term. In the mid term additional tests will be needed to optimize the performance in view of the PROTODUNE-SP Run II.

o Is sufficient information available from the readout electronics R&D to ensure that the readout requirements will be met?

Yes, at this stage of the project (Conceptual Design Review) the results are sufficient.

o Is the performance of the gain monitoring system well enough understood to judge if it is needed in DUNE?

The monitoring system has been installed in Protodune-SP and the analysis is underway. The overall calibration of DUNE is under the scope of the Calibration Consortium and we have not considered this item in details. We believe, anyway, that the LED-based monitoring will be a valuable system for DUNE.

o Are components adequately qualified for operation in liquid argon?

Tests of compatibility of material for liquid argon purity have been done for most of the components. A plan to qualify all cold components for operation in liquid argon has to be developed and the consortium is already making proposals.

3. Do preliminary engineering drawings, schematics and models provide sufficient information to ascertain constructability and functionality?

Yes. The material provided is sufficient for the Conceptual design review. Full mechanical tests should be performed as soon as the design evolves.

4. Have interfaces with other detector components been identified and addressed? Are the interfaces with the cryostat, APA, HV, DSS and CE well defined and understood?

Yes. This is sufficient for the Conceptual design review. Tests - in particular for the cabling inside the APA will need to be performed quite soon to finalize the APA frame design.

5. Have sufficient prototype tests been performed/planned to demonstrate the viability of the design? Have preliminary engineering calculations been planned or conducted to validate the design?

The validation tests for X-ARAPUCA are planned (see above). No engineering calculations were presented in this review.

6. Are installation plans in accordance with detector requirements, and are similarities and differences to ProtoDUNE taken into account?

Yes for the present stage. The installation plan has still to be fully developed but the Consortium is aware of the main issues and the level of development is appropriate for the present stage of the project.

7. Have appropriate manufacturing methods been identified and rough cost estimates and schedule been determined? Are plans for required resources consistent with scope of work?

Yes, for the present stage. The main cost were identified and the Consortium is working on understanding the optimal manufacturing plans.

8. Are operation conditions listed, understood and comprehensive? Is there an adequate calibration plan?

The operation conditions are captured by the present design. The assessment of the long-term reliability of the detector in liquid argon remains to be done.

The overall calibration of DUNE is under the scope of the Calibration Consortium and we have not considered this item in details.

9. Have issues from the ProtoDUNE-SP Photon Detector Review held August 2, 2016 (https://indico.fnal.gov/event/12081/) been appropriately addressed?

Yes. Note however that major changes have been made in the design and some of the issues are now superseded.