Questions for DUNE following the LBNC Review of Vertical Drift on April 28, 2021

May 10, 2021

1. Please comment on level of manpower need vs available, and engagement of the consortia in the design and R&D.
   a. In particular, the PDS and HVS consortia contribute to the HTPC project as well as this VTPC design and R&D. How is this organized to ensure leadership and effort dedicated to the VTPC R&D?

      HVS: The operating principle and electrical characteristics of the cathode and field cage (FC) are nearly identical between the horizontal drift TPC (HTPC) and vertical drift (VTPC) regardless of their orientation and construction. The knowledge and experience gained from HTPC, dual-phase (DP), NP04 (ProtoDUNE-SP), NP02 (ProtoDUNE-DP) have enabled the core HVS consortium team to develop a VTPC conceptual design very quickly and with good confidence. The consortia is fully engaged in the R&D for vertical drift. The new team from IN2P3 has joined the HVS consortium and dedicated their efforts to the cathode design, construction and installation. The FC design and construction are very similar to that of NP02 and NP04. One or more of the existing, and more new institutions will contribute to the construction and installation of the VTPC FC. Human resources for both HTPC and VTPC design and prototyping are sufficient, although we are currently suffering in terms of our ability to get collaborators to travel to CERN and this may become more serious over time if quarantine and travel restrictions by CERN and DOE are not relaxed soon. The design, planning and R&D for HTPC and VTPC are well in control by the current core HVS consortium team. More institutions will join to insure sufficient resources during the execution phase.

      PDS: Arapuca design concepts are very similar between HTPC and VTPC. Many areas of development, including SiPMs are identical. The team clearly needs to grow. Many new collaborators are now very active in the R&D for cold readout at HV and we expect the team to grow further. Additional resources are needed to more rapidly advance the Xe optimization and optimization of large area Arapuca modules.

   b. What is the role of DUNE Technical Coordination in the current VTPC effort? (Again, responsibility is shared with other DUNE subprojects.)

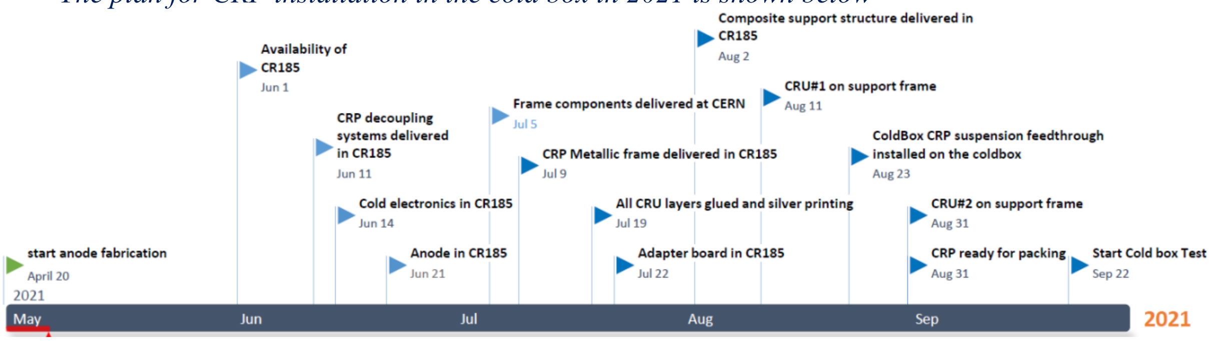
      VTPC effort for detectors components is based on the DUNE consortium system. The DUNE TC is in charge of all consortia and therefore he is well positioned in this process. The deputy TC has been mandated to overview the VTPC process and is very active in steering the various activities and keeping close contact with the consortia.

      VTPC is strongly based on international partners, TCn is distributed across several institutes and laboratories. The engineering effort is very visible as is demonstrated by the enormous progress achieved in the last 6 months.

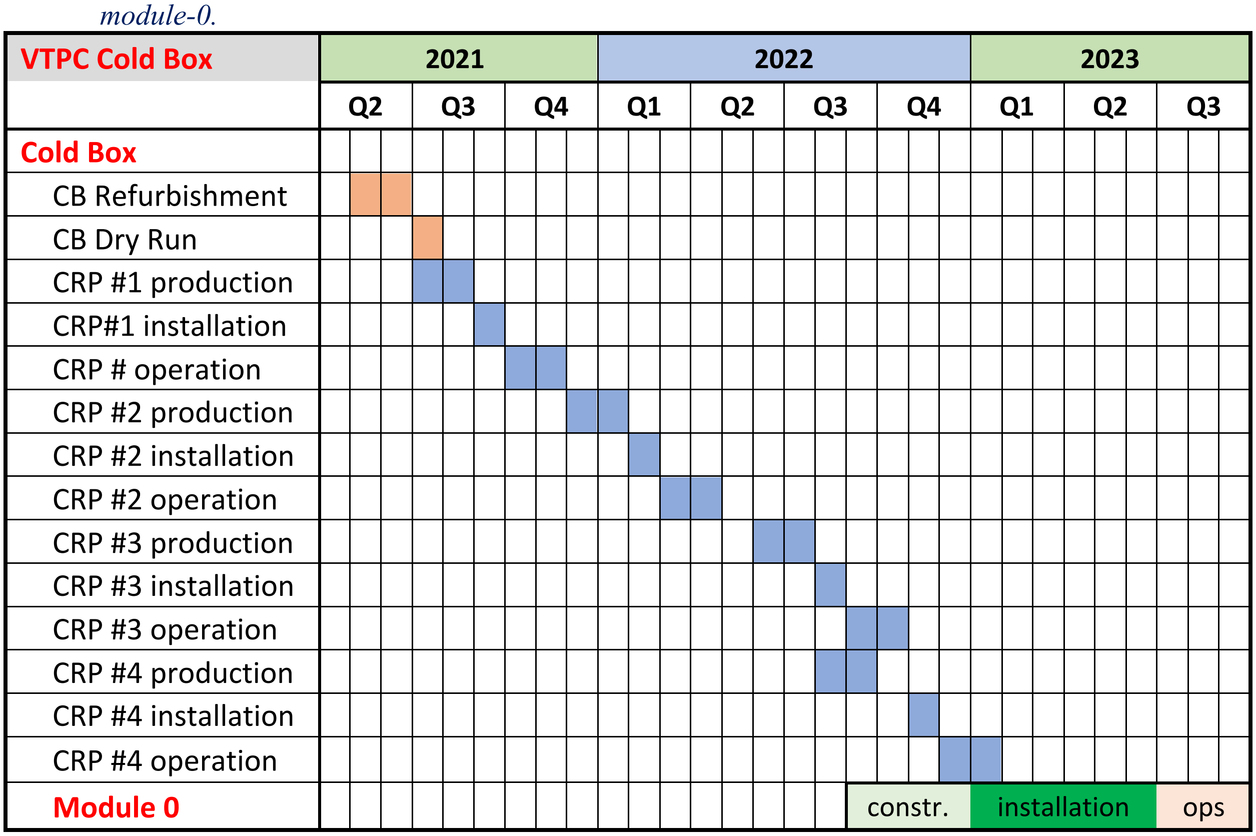
      On top of this the LBNF I&I project is very active and works very closely with DUNE TCn. FNAL, BNL, IN2P3, INFN and CERN are very active in all of the R&D and demonstrator activities which are now in full swing. With VTPC the DUNE TCn has become more efficient and more proactive, helping in an important way the various consortia. The IPO is fully engaged in VTPC and is helping with reviews, ESH, QA and systems engineering.

2. Please provide a more detailed integrated schedule in the form of a Gant chart for all R&D work through mid-2022, including key milestones. Please provide a brief description of the development/test goals for each task/milestone in the schedule. The schedule should include:
    a. Preparation and dummy run of the coldbox, completion of the design and assembly of the CRP, installation and operation of the CRP in the coldbox. And a second round of CRP testing.

The plan for CRP installation in the cold box in 2021 is shown below



The CRP plan for 2022 includes construction and installation of a second CRP to test of different strip orientation (bottom CRP) in March 2022, followed by a third final top CRP after decision on strip orientation in May 2022. A fourth (final bottom CRP) is expected possibly from one of the US factories by fall 2022. These tests will allow a complete definition and fully instrument module-0.



b. Development of PoF and optical readout for the PDS, coldbox tests, decision points prior to module-0 and leading to final decision

		2021						
	Notes	May	Jun	Jul	Aug	Sep	Oct	Nov
PDS	Pair-wise integration of most promising phase 1 candidate components and Power-over-fiber.	X						
	Analog Front-end integration Prototype in cold validated.		X					
	SERDES Tx integration Prototype in cold validated.		X					
	SERDES Rx integration Prototype in cold validated.		X					
	Downselect ADC/SERDES/digital Tx or analog Tx Prototype final candidate.		X					
	ADC+SERDES+Optical Rx/Tx integration Prototype **OR** Analog Optical Tx integration Prototype in cold validated.			X				
	1-channel waveform readout integration Prototype in cold validated.			X				
	Full modules waveform readout integration Prototype in cold validated.				X			
	Two synchronized integration Prototype modules in cold validated.				X			
	Two synchronized integration Prototype modules in cold <10KV plane validated. Or documented as not needed.				X			
	Two Prototype v1 modules installed at CERN Cold Box Test Part-A.					X		
	Two Prototype v2 modules installed at CERN Cold Box Test Part-B.							X
	Synchronized waveform readout of two Prototype modes in CERN Cold Box Test.							X

c. The test program for the HV system in NP02.

The HVS test program for NP02 conservatively plans a minimal test in 2021, in which modifications are minimized: the old extender and its connections will be removed and the new extender will be installed and connected to the cathode. The new extender will include the connectors to the feedthrough that will have been tested in IceBerg, and the HV feedthrough that will have been tested in the 1-ton cryostat at CERN. New resistive filters integrated into the HV cable terminations will be adopted (operation with and without them could also be envisaged).

The subsequent NP02 HVS test will be for module-0 in 2022–23. Assuming no modifications of the extender or its connectors are necessary, then the primary planned change will be to remove one FC wall and replace it with 70% optically transparent profiles down to the level required by the final VTPC design and previously validated in the 1-ton cryostat at CERN. Additional modifications may be made if needed.

d. Analysis and decision points for finalizing plans to build the HV components, CRPs and PDS for module-0 in NP02

Key decision points by subsystem are listed below:

HV: Analysis/decision points

1) *June 2021: decide if new coupler (feedthrough to extender) works sufficiently well for NP02 extender test (and/or if additional R&D should be pursued).*
2) *December 2021: decide if new feedthrough/coupler/extender works sufficiently well for module-0 test (and/or if additional R&D should be pursued).*

3) *January 2022: decide if 70% transparent FC test in 1-ton works sufficiently well to design one wall of NP02 with 70% transparency for module-0.*
4) *September 2023: decide if 70% transparent FC works sufficiently well for DUNE. Decide if feedthrough/coupler/extender works sufficiently well for DUNE.*

CRP: Analysis/decision points

1) *November 2020: validate 2-view perforated anode in 50l test.*
2) *April 2021: validate 3-view anode (0, 48, 90) in 50l test.*
3) *August 2021: validate 3-view anode (-30, +30, 90) in 50l test.*
4) *November 2021: validate full scale CRP 3-view anode (0, 48, 90) and mechanical support in cold box.*
5) *March 2022: validate full CRP (-30, +30, 90) in cold box.*
6) *May 2022: final decision on strip configuration and orientation*
7) *September 2022: validate full top CRP with its mechanical support in cold box.*
8) *November 2022: validate full bottom CRP production from US factory.*
9) *December 2022: full assessment of data from both top and bottom CRP and associated electronics in order to freeze CRP configuration for module-0.*

PDS: Analysis/decision points

1) *September 2021: analyze all 50l and other test stand data. Decide on power/readout for October coldbox test.*
2) *November 2021: Assess and decide if cold box runs validates PDS on cathode for module-0.*
3) *March 2022: Assess/decide if 2nd cold box run validates PDS on cathode for module-0.*
4) *June 2022: Assess/decide if 3rd cold box run validates PDS on cathode for module-0.*
5) *November 2022: Assess any potential risks of installing PDS on cathode of module-0. Decide PDS configuration on cathode and membrane.*
6) *June 2023: Assess PDS performance from module-0 to begin production.*

3. Please discuss the schedule risk associated with the Coldbox migration and refurbishment.

The cold box and its cryogenic system will be refurbished and upgraded to meet the requirements for the test of the full-scale VTPC CRP. The main risks associated are:

- *Delays due to material delivery or lack of manpower (most importantly for the upgrade of the cryogenic, where some components are outsources to external companies) as a result of the evolution of the pandemic.*
- *During the commissioning, the performance of the cold box does not meet the requirements, above all the requirement on the purity, which would require some hardware modifications.*
- *Delays due to unforeseen difficulties in operating simultaneously the cold box and NP02.*

The cold box commissioning is foreseen in July and the CRP test will start in October. This gives additional time to react to these risks.

4. Please provide the pros and cons for having different readout electronics on the top and bottom CRPs, and the judgment for choosing the two-system solution.

The vertical drift concept evolves naturally from the dual-phase design as implemented on NP02. The top drift volume is very similar to a dual-phase detector with the CRPs suspended from the cryostat roof. Our scheme allows use of the existing dual-phase electronics that was designed to read strips at high capacitance and performed well on NP02. In particular, this VTPC design preserves the possibility of accessing the cryogenic amplifiers in the signal feedthrough chimneys, at any time without interfering with the detector functioning while keeping the *digitization electronics on the cryostat roof. The access to the cryogenic electronics in the signal feedthrough chimneys is a simple operation, which has been routinely exploited during NP02 operation. The accessibility to the electronics provides the opportunity to profit from technological evolutions, in particular for the uTCA digital components as already witnessed with time, and of additional costs reductions. The top and bottom CRPs integration aspects in the detector are different and it is natural to expect that also the electronics can be customized accordingly. The bottom CRPs are lying on the cryostat floor simply standing on feet with the electronic cards attached to the bottom side of the CRPs. The top drift CRPs are suspended from the cryostat roof by superstructures which is also suspending the cathode modules. The layout of the top CRPs presents then a few differences for what concerns the mechanical structures and offers naturally the electronics accessibility via the cryostat roof. The top drift CRPs may be also exposed to formation of bubbles or dust contamination on the liquid surface pushed up during the detector filling that could trigger sparking in the anodes. Although this risk is very low, the accessibility of the electronics is an additional guarantee of perfect functioning of the detector over a very long lifetime span. Complete accessibility, in addition to the possibility to fix any malfunctioning risk more in general provides risks mitigation factors in the installation schedule and simplifies the CRP production tests since the CRPs do not have bounded electronics onboard. The weight of the electronics also does not affect at all the mechanical structure of the CRPs suspended from the cryostat roof. The risks (bubbling/dust contamination) related to the top CRPs' position, just below the LAr level, are absent for the electronics used for the readout of the bottom drift CRPs which sit on the cryostat floor. Given the distance from the roof of the cryostat the only implementable readout scheme corresponds to the single-phase electronics, which was designed to operate in a similar condition to collect signals at the bottom of the APAs. These electronics cards for the bottom CRPs are indeed not accessible, being completely immersed in liquid argon. The heat dissipation issues are also different in the two cases. For the top electronics there is no heat dissipation by the electronics directly on the CRPs. For the bottom CRPs heat dissipation aspects were studied and showed that there are no issues of local heat accumulation. Semantically a two-system solution may sound as requiring additional efforts but this impression is largely overturned by the advantage related to the availability of support from dedicated international manpower and non-US funding for the top electronics. The top electronics has been supported very early since 2006 by a dedicated R&D program and implemented in NP02 for 1/20 of what foreseen for a DP far detector module, having a comparable number of channels as the Vertical Drift top drift CRPs with two views*

5. What aspects of the design will not be demonstrated in module-0, and what are the plans to validate these aspects? Aspects include the bottom CRP mechanics, service routing, HV structures... will the cathode plane and support system be fully demonstrated in module-0?

   Module-0 VTPC will have a drift of 6m, instead of the 2×6.5m FD2 drift. As with HTPC it is not possible to simultaneously mount the top and bottom of the full 13m height system. The HTPC module-0 will turn two APAs upside down to simulate the DUNE FD1 configuration and the VTPC module-0 will simulate the lower CRPs on the floor of DUNE FD2 by positioning them upside down on the top, side by side with the top CRPs.

   The penetration layout in ProtoDUNE cannot be changed and the large feedthrough which will host 50 readout cards cannot be used. The feedthroughs will be the same as ProtoDUNE-DP.

   The CRP roof supports will depend on the existing penetrations; therefore, the supports will be different from DUNE FD2.

For cost reasons we will probably modify just one of the 4 walls of the FC, with high transparency profiles. This should be enough to prove the new FC concept.

For the rest we should be in line with the DUNE layout in particular for all issues of integration.

6. How/when will the decision be made between the reference and fallback layout of the PDS? What are the intermediate test milestones? (Can reference the schedule in Question 2.) The PDS talk indicated that the down-select can be delayed until the PRR. Given the need to proceed rapidly with full fabrication following the PDR, should there not be a specific decision milestone earlier, allowing the full development of final plans ahead of the PRR. Clearly one earlier decision point is whether the module-0 cathode incorporates PDS modules.

We have made the decision to pursue the reference design — cathode and partial membrane mounted optical coverage. This is what will be described in the CDR and is being implemented into P6. We assume that the question is about under what conditions we would abandon this plan and terminate support for the R&D? We have a number of opportunities to decide whether the R&D has encountered insurmountable difficulties. We expect many intermediate indications of the progress towards a successful cathode mount system design. These include:

- *Mounting PDS prototypes in the VTPC cathode cold-box tests at CERN in the fall of 2021*
- *VTPC Preliminary Design Review at the end of 2021*
- *Additional PDS modules at CERN cold-box tests in 2022*
- *VTPC Final Design Review in February 2023*
- *Demonstration of both cathode and membrane mount PDS modules in the VTPC ProtoDUNE-II-VTPC Module-0 test in 2023*
- *VTPC Production Readiness Review at the end of 2023.*

Insufficient progress at any of these points could trigger us to consider switching tactics and adopting the fallback (we need to call it one thing— fallback or back-up) membrane-only solution as the reference option. It is important to note that fabrication of the membrane mounted PDS system required for the fallback solution is a required part of the reference design, so both options will be fully tested in the Module-0 test stand if the reference design remains as it is currently. Also, a full fabrication plan for all membrane-mounted PDS components will be required in any case. All of the required tooling, procurement, and planning steps will be in place, and in case we need to adapt the fallback solution only minor changes in focus at production sites would be required to adapt to the change. Contingency plans will be in place in case this should be required. This represents a very solid mitigation of any risk involved in continuing the reference/fallback design strategy at least through the Module-0 test.

7. Can you quantify the role of / need for reflection from the anode surfaces? Are there specifications on the anode metallization or coating?

*The role of the light reflection from the anode surface has been analyzed with the help of MC simulation for the VTPC PDS, where several values of the reflectance index for the metallization of the perforated PCB have been introduced for the 175nm Xenon wavelength (no reflectivity for the 128nm Argon wavelength is assumed). A typical value of ~50% is derived from available data in the literature and is similar for most metals normally used for PCB coating (copper, gold, silver, nickel, chrome). The metallized solid surface of the anode amounts to ~40% of the total area, hence in the simulations the reference overall reflectivity of the anode surface is taken around 25% (R_overall = R_metal * f_metallized_area).*

The results from simulation, added to the presentation at the Review (slide#13), demonstrate that a slight (few %) overall light yield increase and a more notable improvement in uniformity of the response are expected when comparing 25% overall anode reflectivity with higher values. The 0% reflectivity case is being calculated but the possible slight yield decrease is not expected to affect the overall performance of the PDS system.

In the reference CRP design, no specific surface treatment on the anode PCB is planned; however, in case the reflectivity has to be maximized, investigations are ongoing to identify possible coating processes available for large PCBs, that can ensure high reflectivity and minimize oxidation effects. Measurements of the reflectivity for copper and other metals (with/without oxidation) in the VUV range are being setup at IFIC-Valencia.

Finally, note that Aluminum has the best reflectivity in the VUV range. If Aluminum is properly treated (possibly with a similar treatment as the FC), it can be as high as 50-90% reflectivity even at the Argon scintillation wavelength. Replacing copper with aluminum in the PCB construction is feasible (at least on small sizes) although engraving is known to be less precise than with copper and fewer PCB producers can process Aluminum metallization. In addition, the Aluminum option would require intensive R&D to demonstrate compatibility with cryogenic conditions and to deal with possible oxidation at the locations of the contacts and connectors.

8. Please provide the committee with the most recent technical notes/papers on the Arapuca design and performance. What future notes/papers are planned?

A complete characterization of the ARAPUCA device (sensitivity to single PE, calibration, correlated noise and Signal-to-Noise evaluation, stability in time of the response, detection efficiency, energy resolution) can be found in the ***ProtoDUNE-SP performance paper*** *(https://arxiv.org/pdf/2007.06722.pdf or https://iopscience.iop.org/article/10.1088/1748-0221/15/12/P12004).*

ARAPUCA represented the base of the development for the X-ARAPUCA design and in particular the ARAPUCA detection efficiency, cleanly measured in ProtoDUNE-SP, combined with detailed MC simulation of both ARAPUCA and X-ARPUCA allows us to optimize the number and geometrical distribution of SiPMs in the X-ARAPUCA final design.

The most recent X-ARAPUCA performance paper, https://arxiv.org/abs/2104.07548, describes the full characterization of an X-ARAPUCA prototype with two dichroic filters (1/3 of a supercell). The X-ARAPUCA was exposed to a mono-energetic alpha source in LAr and its total detection efficiency was evaluated with two candidate wavelength shifting bars: Eljen and Glass2Power. These measurements were performed at Milano Bicocca. A second paper detailing a similar test, performed on a smaller prototype with just one dichroic filter and Eljen lightguide (1/6 of a supercell) will appear on arXiv shortly. A preprint can be download https://drive.google.com/file/d/1sG8ypVv7QmG6zE1-rVe547WGq0yT2m4m/view?usp=sharing (we will update this link as soon as the paper appears on arXiv). In this case the X-ARAPUCA was exposed to alpha particles, gammas and muons at UNICAMP.

The consortium is planning the following papers in the next months:

- ***Complete Characterization of the Hamamatsu MPPCs*** *specifically developed for DUNE. Will describe the characterization of the devices at room and cryogenic temperature (I-V curve, gain, crosstalk, after-pulses) with large statistic (hundreds of sensors). The paper will also contain the results of many-SiPM (48) ganging studies. The* *writing of the paper will start just after the completion of the down-selection process (one week) and we expect that it will be ready on a timescale of two months.*

- ***Complete Characterization of the FBK SiPMs*** *specifically developed for DUNE. It will contain the complete characterization of the FBK sensors with the same level of detail of the Hamamatsu MPPC paper and will be written after completion of the Hamamatsu MPPC paper.*
- ***Complete characterization of the X-ARAPUCA supercell****. This paper will report the outcome of supercell tests in LAr. These tests are currently in preparation and will happen in two labs of the Consortium: Milano Bicocca and CIEMAT-Madrid. The goal of the tests is to measure the total detection efficiency and uniformity of response of supercells in their final configuration with the down-selected SiPMs and MPPCs. We expect that this paper will be available before the end of 2021.*

9. Can you characterize the synergy between the HTPC and VTPC Arapuca R&D? Are they connected? How does this affect the availability of effort?

The choice of the SiPM-based readout of X-ARAPUCA light traps as the baseline light collection technology for the Vertical Drift allows for a broad range of synergies, some obvious, some less so, mitigating many of the risks associated with the rapid development cycle needed for the FD2 fabrication plan. These include, but are not limited to, the following:

- *Consortium infrastructure: A strong, multi-national team is in place for the horizontal drift consortium team. The long-established working relationships and integration between these groups has been demonstrated and provides a strong backbone to support the new management, the new groups joining the effort and the new readout electronics & transmission dedicated team needed to support the cathode-based portion of the VTPC PDS system. This flexibility was already demonstrated with the smooth integration of much of the dual-phase PDS team into the PDS consortium.*
- *Simulation: A team of experts is already in place to do performance analysis of the PDS system design and physics performance. This was largely settled for the HTPC system, but a sub-team moved promptly to support the needed analyses and detailed MC simulation for the VTPC PDS design. New groups and individual experts have joined, expanding the availability of effort.*
- *X-ARAPUCA module design: The basic mechanics of the X-ARAPUCA modules is already being developed and validated for the HTPC system, including photosensors (SiPMs), filter plates and coatings, WLS bars, and mechanical frames. These are directly applicable to the VTPC system, at minimal increase in complexity to work already being undertaken for the HTPC. Teams of experts exist in many countries already working on these problems within the PDS consortium, allowing a rapid development of module designs for the VTPC system with very minimal impact on existing consortium commitments.*
- *Membrane-mount detector system: Nearly the entire HTPC PDS X-ARAPUCA system, including everything from the SiPM ganging, readout cables, cryostat flanges, warm readout electronics and power supplies can be directly copied from the HTPC system, greatly mitigating any additional development cost or risks for that portion of the project. Active teams are supporting this work.*
- *The HTPC PDS has extensive plans for integration into the SURF infrastructure and is developing a team in South Dakota to support the integration and installation effort. This represents a significant base to support the I&I plans for the VTPC system.*
- *Resource-loaded schedule: the existence of a full resource-loaded schedule in P6 for the HTPC system has provided a skeleton for implementing a similar structure for the VTPC system.*
- *Additional resources: The VTPC PDS system has brought a large new team of power over fiber, fiber readout and cold signal processing experts, greatly minimizing the impact on the existing*

team and indeed providing expertise which can support the HTPC effort, particularly with the warm readout electronics.

In sum, the strength of the existing team for the HTPC and the additional resources brought to the table as part of the new VTPC system has resulted in a stronger, more capable team for the Photon Detector Consortium, allowing it to meet the existing HTPC commitments while including the new VTPC effort.

10. Please explain the driving considerations for the cathode support system (why the Dyneema cables) and for the choice of material for the cathode structure (why change from the material used in ProtoDUNE-SP)?

    The Dyneema cable was mentioned because it has low creep at room temperature under load. We will consider many properties in determining the final choice of the support cable, including CTE, ductility, elongation at stress, and creep at both room and cryogenic temperatures.
    In ProtoDUNE HTPC, the cathode plane was supported by G10 bars. The ideal material for the cathode support in VTPC is actually FRP rods, which match with the CTE of the FRP I-beams supporting the FC. However, rigid FRP rods pose some challenges in the installation of the cathode, therefore we are looking at flexible cables first.

11. Proper engineering of the suspension system of the top anode planes and cathode planes from the same 'ceiling' can ensure that the drift distance can be maintained in the upper half of the detector. What is the method for ensuring and maintaining the cathode-to-anode distance in the lower half of the detector?

    At this moment, the entire TPC except the bottom anode is designed to shrink toward the top when cooled down. The upward displacements of the cathode, and the FC are predictable better than the flatness requirements of the cathode or anode plane. The installed height of the bottom anode and the bottom position of the FC will be determined after careful calculations and tests of the system movement due to shrinkage and cryostat deformation after LAr filling, such that during normal operation, the correct alignment between the bottom anode and the FC is maintained.

    The low voltage ends of each FC column are connected to power supplies that can be adjusted to minimize the E-field distortions caused by small misalignment between the FC and bottom anode plane. The FC supermodules are independently supported on the cryostat roof in case height adjustment is needed.

12. The HV extender is identified as a single-point-failure risk, violating the principle of requirement SP-HV-2. Is this really unavoidable? What does a failure-mode analysis of this new design indicate for the risk? Is it not possible to install a second extender in the FD, connected to the cathode but "floating" at a second feed-through such that it could be connected to the power source if needed? Are there failure modes for which this would provide redundancy?

    Based on the experience from NP02, the new extender has been designed to overcome single-point-failure risks. The extender itself is a simple ~6m long metallic tube with a highly polished surface and fully immersed in LAr which acts as an insulator (this is the same concept as for the FC, where all insulation supporting materials have been moved inside of the FC where the electric field is low and parallel to the surfaces of the FC supporting beams).

The HV stability of this design is the main subject of the R&D and the NP02 run in 2021. If the validity of this design is confirmed, the additional failure points that have been identified are:

- *Connection from the Extender to the FC/Cathode. This will be not accessible, but it is be easily mitigated with the already assumed multiple flexible-wired connections.*
- *Connection from the Extender to the HVFT. This is fully accessible as the HVFT can be extracted and replaced. Note that this operation has been successfully performed several times in several different LArTPC based detectors.*
- *Failure of the Extender hanging structure. In this case the effects will not be minimal or with high impact for the detector operation, depending on the failure degree (the extender could fall down or change position). Mitigation (under implementation) is to use multiple hanging rods.*
- *Occasional HV instabilities due to hopefully rare discharges to the cryostat walls or the FC. HV current limitation and resistive filtering stages along the warm cable will slow down the discharge thus limiting the effect of the stored energy release.*

In all these scenarios, the second extender would not mitigate these issues but rather increase the possibility of failures, being the additional extender at the same HV as the one connected to the HVFT. For this reason, we do not consider a second extender as a way to mitigate the HV single-point-failure risks.

13. Please clarify the role of the DP CRP and PDS systems in the HV extender test in NP02. How will the system be stressed to provide confidence in the design, for example long running period, multiple power cycles…?

The NP02 detector readout system was left essentially intact to enable future HV extender tests. Several electronics components could have been recycled for the cold-box tests of the top CRPs. However, it was preferred to duplicate these parts in order to offer complete flexibility and the opportunity of using the NP02 installation as extra monitoring handles in the NP02 extender test. From the point of view of testing the achievement of the 300kV at the cathode and the assessment of the stability with time of the HV system, it is not required to operate continuously the detector readout system but the HV stability can be monitored by the HV system itself. The HV system and its robustness will be indeed stressed by operating it for long running periods of several months and repeated ramp up/down cycles. As additional handle to acquire information giving confidence on the performance of the HV system, we foresee to operate the readout system on NP02. The PDS system can be operated in order to monitor the presence of light from possible presence of sparking, as already demonstrated in the August 2020 run when light from flashover along the extender was visible. The CRP can be operated to measure tracks along the complete drift distance and monitor the noise from the HV system. CRP operations can be performed, as in the previous run of NP02, in dedicated periods even if surface bubbling occurs, by operating pressure cycles from time to time during the long HVS running period or when needed to perform dedicated investigations. We are confident that availability of all these monitoring tools from the HV system itself and the detector readout offers the best set of handles in order to investigate and document the HVS stability and performance.

14. In the CFD studies, we suggest that DUNE perform a sensitivity analysis regarding the LAr behavior as a function of porosity of the cathode plane, including nonuniformities. The purpose would be to check that the possible presence of warmer LAr trapped below the cathode plane does not cause any liquid flow instabilities or problems with vapor formation.

Additional CFD studies are ongoing with 50% and 10% cathode transparency. In general, changes in transparency can change velocity gradients inside and outside detector volume. For example, zero transparency means higher fluid velocity around the perimeter of the objects that *the fluid has to navigate around. Given the size of the cryostat and the average velocity in the full cryostat volume, ~15mm/sec with peaks of ~120mm/sec (for the nominal heat load), it seems like instabilities should not be an issue.*

15. The approximation of the 'average porosity' is necessary and probably quite adequate for the anode planes. The cathode plane has large areas (ARAPUCAs) which are totally non-porous and may significantly impact the flow pattern. Can/will this be included in the CFD calculations?

    Additional CFD studies are on-going with 50% and 10% cathode transparency and will provide additional information. In general, changes in transparency can change velocity gradients inside and outside the detector volume. For example, zero transparency means higher fluid velocity around the perimeter of the objects that the fluid has to navigate around. Preliminary indications suggest that 10% transparency across the whole cathode is worse than 50% transparency everywhere and 0% through the ARAPUCAs. The ARAPUCAS are well distributed over the cathode and given the size of the cryostat and the average velocity in the full cryostat volume, ~15mm/sec with peaks of ~120mm/sec (for the nominal heat load), it seems like the flow pattern should adjust to the presence of non-transparent objects by moving around them. Ongoing CFD studies will provide additional information also about the presence of non-transparent objects.

16. Will the CFD studies include the PoF heat source for the PDS elements on the cathode? Where are the PoF units located in the current design?

    PoF heat and the location of PoF receivers around the perimeter of the cathode plane are (preliminarily) defined (slide #26) and depend on the configuration of the readout electronics and transmission (analog or digital options under R&D). The analog solution would require 600–800W distributed in 80 units: 10W point like heat sources. For the digital system we currently envisage 2–2.5kW distributed over the cathode (80 receiving points of 25W each). As far as the fluid dynamics calculation, the current CFD model does not yet include PoF distribution to the cathode. It will be included in the next development of the model.

17. In Filippo Resnati's presentation, Demonstrator: Cold Box TPC in 2021, we saw: "The absolute vapor pressure needs to be controlled, this implies a valve at the output: the cryostat cannot be considered anymore an "open bath" Dewar." Are there any implications from this experience or other experience for the full-scale detector cryogenics design? (For example, a need for more precise pressure control.)

    As in NP02 and NP04, the absolute pressure must be controlled. The standard way to achieve this result is controlling the amount of gas entering into the condenser acting on a control valve between the cold box and the condenser. A precise measurement of the absolute pressure is also required. There is no implication for the full-scale detector cryogenic design since it is already supposed to work in this way (including the HTPC).

18. We saw in David Montanari's Cryogenics presentation, slide 22: "Isosurface of Zero K superheat @ average of 26.2 cm below liquid surface." Is bubble formation in the top 26 cm acceptable? This analytical estimate may differ from actual liquid behavior to be seen. If so, what is the requirement for maximum depth of superheat, and approximately what is the uncertainty in this analysis?

    The region down to 26cm of superheated argon below liquid level is a relatively small value and in line with observations at ProtoDUNE-DP. The value is acceptable from a detector point of *view. This value is for the nominal heat load of the electronics. The maximum acceptable depth of superheat is 35cm, which is the level of the perforated anode of the top CRP, where we would like to avoid bubbles in the holes in the top anode.*

As comparison, the case of x3 the heat load shows a depth of superheated argon 37.1cm below the liquid argon surface. If the heat load of the electronics is somewhere between the nominal expected value and about x2.5 that, the depth of superheating would be acceptable.

19. Xenon freezes at about 160 K, well above the 88 K boiling point of Ar, so presumably behaves like a dissolved solid in Argon. Is there any risk of Xe precipitating out?

    Several measurements are available showing that Xenon can dissolve in LAr at 87K in concentration considerably higher than 1000ppm; the simple explanation could be that Xenon in Argon should not be considered as a solid but most likely as isolated atoms or dimers immersed in the LAr bath. However, most data available in the literature were obtained with small detectors and limited operation time. This is why we performed the doping test on NP04 where we demonstrated that Xe doping up to ~20ppm (mass) is very uniformly distributed over a large scale (kton) detector and with high stability over a time period of several months. The presence of both the LAr and GAr recirculation systems (7Ton/hour and 50g/s respectively) do not trap the Xenon and possibly help improving the uniformity of the Xenon. These results are being published and are compatible with many previous small-scale tests.

    Remember as well, that at the end of NP04 operations, part of the LAr (doped with ~20ppm Xenon) was transferred through cryogenic pipes (tens of meters long) to NP02 where it mixed with the pure LAr (in the ratio of ¼ to ¾) already in the NP02 cryostat. Measurements performed with the NP02 PDS were compatible with all the Xenon being transferred and uniformly distributed without being trapped through the cryogenic piping (doping ~5ppm).

20. Stability condition of cryogenic tanks can be formulated as dQ/dt = L dm/dt where the Q is the total heat load, m is the mass of the evaporated liquid, and L is the enthalpy of vaporization. What are these quantities for the expected geometry of the tank and how do they depend on the assumed transparency of the anode and cathode planes?

    If dQ/dt is the total heat load, inclusive of all sources of heat into the LAr mass, the boil off rate dm/dt can be easily calculated with the enthalpy of vaporization of LAr, L. The enthalpy of vaporization is a function of the ullage pressure, which is controlled to a fixed value. Under nominal conditions:
    P_ullage = 50mBarg
    L (@ P_Ullage) = 160.80kJ/kg
    dQ/dt (nominal) = 49,562W (nominal electronics contribution).
    dQ/dt (x3 electronics) = 76,186 (x3 electronics contribution).
    dm/dt (nominal) = 49,562/160,800 = 308gr/sec (nominal electronics contribution).
    dm/dt (x3 electronics) = 76,186/160,800 = 474gr/sec (x3 electronics contribution).
    A change in geometry or transparency will not affect these quantities directly.
    If, as a result of a different geometry, the overall surface of the cryostat changes, then the static heat load of the cryostat may change: an increase in surface will increase dQ/dt, and dm/dt of the corresponding amount; a decrease will decrease dQ/dt, and dm/dt of the corresponding amount.
    A change in detector electronics may change the electronics contribution to the heat load: an increase in detector electronics will increase dQ/dt and dm/dt of the corresponding amount; a decrease will decrease dQ/dt, and dm/dt of the corresponding amount.