CALCI worksop
27/05/2020

Consortia responses to questions regarding cryogenic instrumentation systems

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On behalf of the CALCI consortium

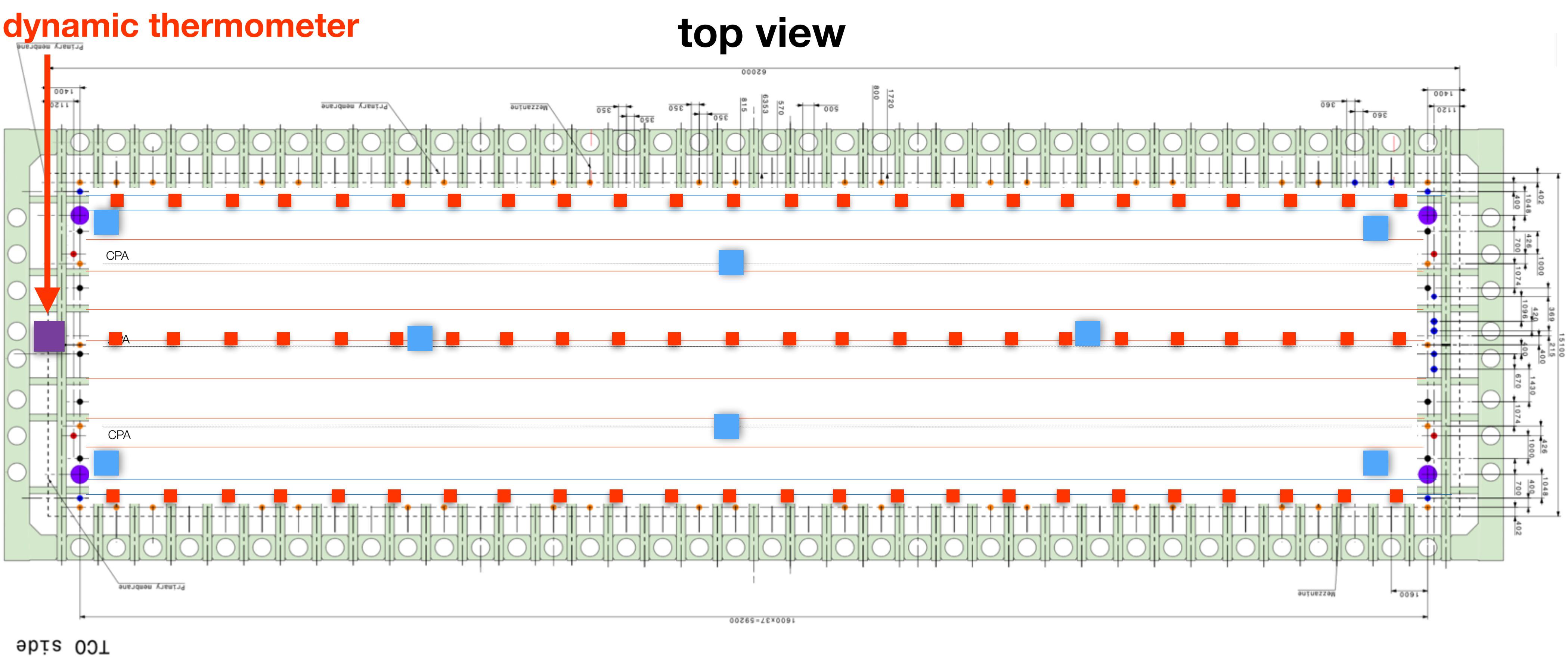
Temperature monitoring system

Question 1

- **What role will a validated CFD model for the Far Detector play in the calibration or analysis of the data?**
- The CFD model will be used to predict the electron lifetime everywhere in the active volume, and especially in regions where other sources cannot reach. This prediction will be used to make a charge attenuation correction. Inputs to CFD model are:
  - **TPC measurements**: cover most of the TPC but cannot provide an frequent electron lifetime measurement
  - **Cryogenic instrumentation (CI)**:cannot map the entire TPC but are run with high frequency
- By combining those two types of data, once the CFD model is validated, the CI data can be used to make time dependent corrections on the nominal electron lifetime map and to compute the systematic uncertainty on those corrections.

Question 2.a

- **How is the calibration obtained from the dynamic temperature sensor extrapolated to the temperature sensors on the APAs?**
  - Direct calibration of APA sensors can only be done for sensors on the APA doublet closer to the dynamic thermometer



DEEP UNDERGROUND NEUTRINO EXPERIMENT

Question 2.a

- The gradient observed by the dynamic thermometer when the pumps are off is extrapolated using the CFD model to the known positions of each of the APA sensors. The error on this recalibration depends on:
  - **the extrapolation model (**CFD simulation**)**: the more homogeneous is the temperature the lower will be the extrapolation error
  - **the error on the laboratory calibration**: this calibration is used to constrain the CFD model with no recirculation**.** 2.5 mK on day 0, but will degrade with time
  - **the granularity of APA sensors**: an extrapolation error of the order of 1 mK can be obtained when using the proposed distribution of APA sensors (covering 40 different heights)**.**
  - **the precision of the dynamic calibration**: 0.5 mK, which essentially does not degrade with time**.**

Question 2.b

- **What is the improvement in resolution of the APA temperature sensor measurement after this step (in comparison to that obtained solely from the laboratory calibration)?**
- On day 0 we expect a calibration error of 1-1.5 mK (0.5 for the dynamic thermometer + 1 mK for the extrapolation error) for all precision sensors in the cryostat. This calibration error can increase with time since the laboratory calibration used to constrain the CFD model for the extrapolation will degrade
- In the absence of the dynamic thermometer, there is not an absolute reference for the recalibration of APA sensors. The reference would be the APA sensors themselves and we would have to assume that sensor degradation is gaussian (or at least symmetric) and that the measured map for pumps-off regime is not biased. The systematic error introduced by those assumptions cannot be known a priori, since it depends on the peculiarities of the sensor degradation.
- Since the dynamic thermometer is calibrated both dynamically and in the laboratory, it is also the perfect tool to estimate systematic errors

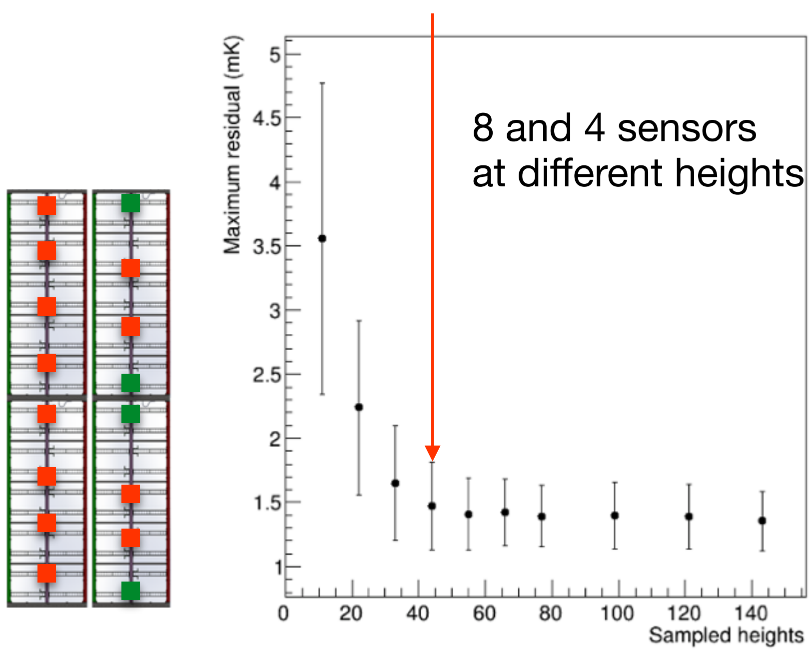
Question 3

- **In terms of understanding the CFD model, which is more important: improving the resolution of measurements made in the bulk (e.g. from 3mK to 1mK) or being able to access additional measurements in key locations (e.g. near the pumps and in the gas)?**
- APA sensors measure the temperature in the bulk. They are used to constrain the CFD model but also to do an actual measurement of the temperature map. The largest the coverage the less we depend on the model for the actual temperature map. The better their resolution the lowest the extrapolation error
- Additional measurements at key locations give extra boundary conditions for CFD model, but don't measure the temperature in the bulk, so they don't contribute to the reduction of the extrapolation error. We believe those additional measurements are very precious handles and add very little complexity and cost.

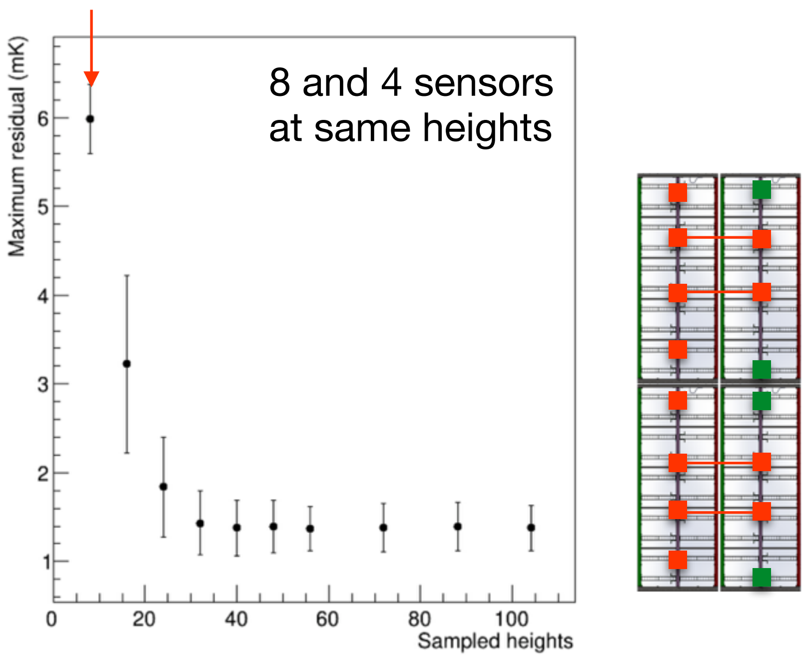
Number of sampled heights

- We have performed several simulations to understand the optimal distribution for a given number of sensors.The FOM is the maximum residual between simulated map and measured map
  - For the 8+4 distribution the FOM saturates at 30-40 different heights (FOM=1.5 mK). For 8 sensors that means **5 different configurations**
  - A single configuration (8 sampled heights) would have FOM>6 mK

5 configurations



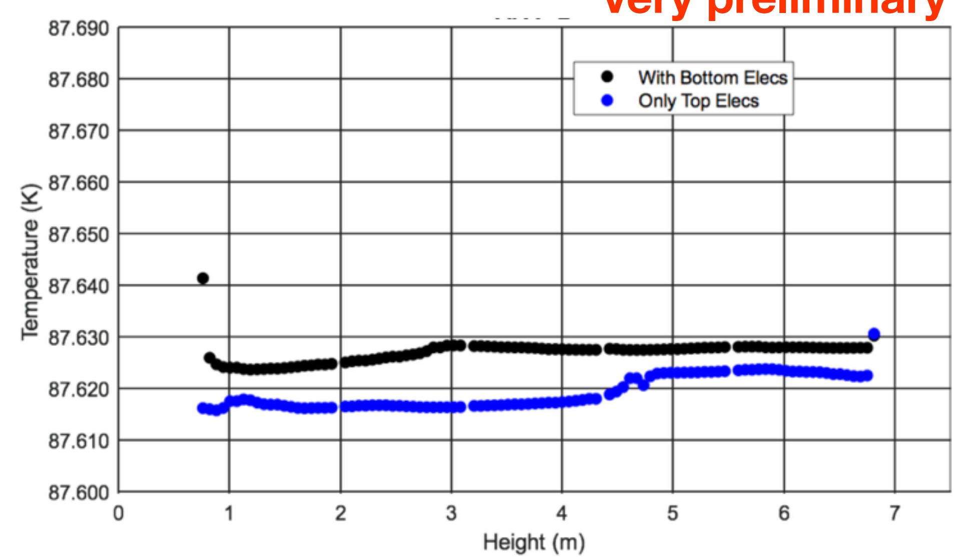
1 configuration



Question 4

- **What is the plan for understanding the effect of the cold electronics on temperature measurements made with the sensors on the APAs?**
- We can face the problem both experimentally and with simulations:
  - SDSU colleagues are already working on that. Preliminary results predict 10 mK difference
  - Marco proposed to do some tests at BNL, where Bo has a setup (DocDB-16670). This needs further investigation.
- We can take temperature maps with the electronics off. This can help in constraining CFD both with and without heat from electronics, which will help in reducing systematics

very preliminary



Question 5

- **How would one make an absolute temperature measurement using the proposed systems?**
- **First method:** relation between pressure in the ullage and the temperature at the LAr surface (~10 mK/mbar). Having a reliable absolute pressure sensor with sub-millibar absolute calibration should be sufficient. As we are doing for ProtoDUNE-SP, the surface temperature will be used as boundary condition for the CFD simulation
- **Second method**: direct measurement with few sensors absolutely calibrated by Lakeshore. This needs additional improvements in the readout:
  - Measure the current delivered to the sensors with high precision resistors and a 24 bits ADC (already done in PD)
  - Subtract readout offsets by averaging the two current polarities
  - Keep electronics at constant temperature

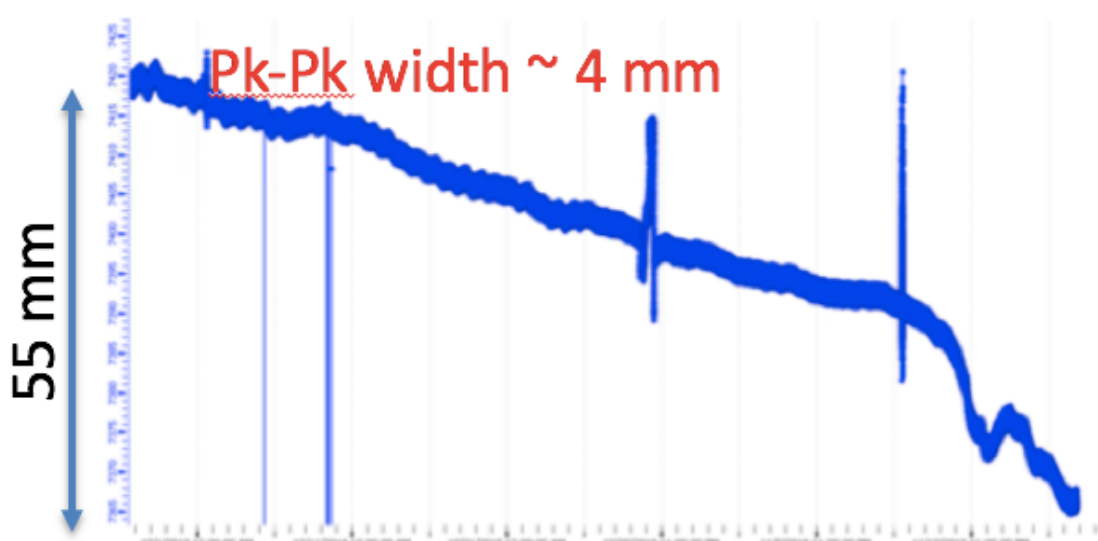
Level meters and pressure sensors

Question 1.a

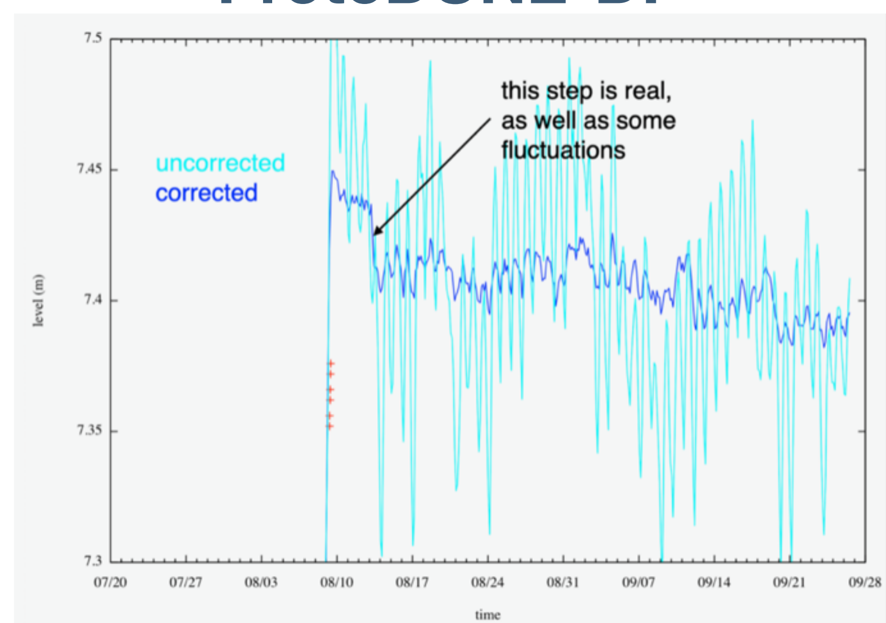
A. Hahn

- **What level of precision has been obtained from the level meters installed in ProtoDUNE-SP and ProtoDUNE-DP?**
  - In PD-SP peak-to-peak fluctuations of 4 mm are observed, which corresponds to about 1 mm RMS
  - In PD-DP a precision of 1.5 cm is reported for the 4 m long capacitive level meter. But there is room for improvement

ProtoDUNE-SP



ProtoDUNE-DP



Question 1.b

A. Hahn

- **Is the obtained level of precision consistent with the stated goals for these devices (e.g. tuning of CFD model, estimation of liquid argon losses relative to expectations, and interlock for turning off HV system if liquid level drops below upper ground planes)?**
  - **Tuning of CFD model**: An absolute calibration better than 1 cm is expected, which is sufficient for constraining CFD simulations.
  - **Estimation of LAr Losses:** with the proposed calibration scheme (next slide) the obtained linearity should allow a relative measurement of the order of 1 mm, sufficient to estimate LAr losses
  - **HV interlock level:** If the upper ground planes are covered by 40 cm of LAr, a conservative value for the interlock level can easily be set

Question 2

A. Hahn

- **What is the planned procedure for calibrating the level meters to obtain an absolute measurement?**
  - During the filling process, as the the capacitive level meters begin to be covered with LAr, their readings can be directly correlated to the known height of the individual RTDs on the APAs, the dynamic thermometer, vertical arrays in the gas and in the lateral membrane (in two opposite corners). Since we know the positions of all temperature sensors in the cryostat to the 1 cm level, this will establish the linearity and absolute calibration of the Level Meters to better than 1 cm.
- **Is there a need for a corresponding set of temperature sensors along the length of the capacitive level meter?**
  - No, because there will be sensors all over the cryostat, some of them reasonably close to the Level Meters

Question 3

A. Hahn

- **What are the specifications for the LBNF-provided pressure sensors in terms of absolute calibration and measurement precision?**
    - 0.05 mbar for the absolute sensor and 0.01 mbar for the gauge sensor. At ~1 Atm, 0.05 mbar change equates to a saturation temperature change of 0.42 mK.
    - For 10 mK absolute measurement we need an absolute calibration of the absolute pressure sensor to the 1 mbar level (feasible).
- **Is there a plan in place to ensure that this system is redundant and fail-proof over long-term operation?**
    - LBNF will provide two sets of sensors (1 set= one absolute and one gauge sensor), which ensure redundancy. Failproof is a function of the control system and how it detects and handles the failure of one sensor.

gas analyzers

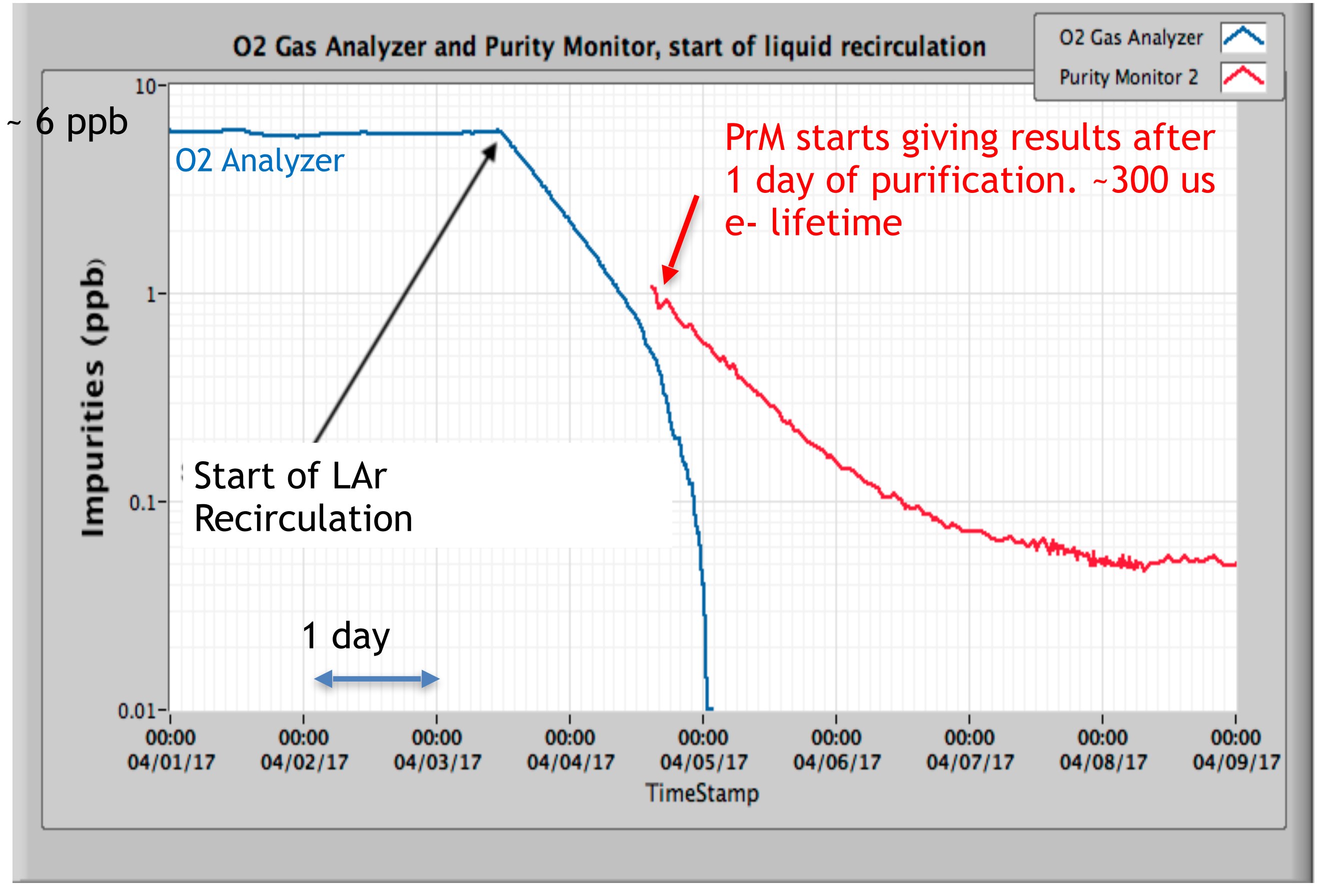
Question 1

A. Hahn

- **What level of precision is required for the gas analyzers to reach the purity levels where measurements from the purity monitors themselves become reliable?**
- On very short PrMs (e.g. ICEBERG, ~ 10 cm), reliable lifetime measurements have been made at 30-50 μs lifetimes. This would correspond to an O2 impurity level of ~ 6-8 ppb.
- Only *high precision* sub-ppb O2 gas analyzer (e.g. Servomex DF560E) could give reliable measurements at this level. This sub-ppb analyzer would also cover lifetimes into the ~1 ms level and lower, depending somewhat on how carefully the analyzer is calibrated and set up (these are details). We do not usually make the effort in normal operations to measure at the ultimate limit (~100 ppt) of this analyzer.
- The 35 Ton Impurity plot comparing the sub-ppb O2 analyzer and PrM that I showed in the presentation (slide 9, right side) was for a normal length PrM (~ 18 cm from cathode to anode), like the ones used in ProtoDUNE-SP.

Question 1

Cryostat Impurities as seen by O_2 Gas Purity Monitor and PrM as LAr purification starts in first 35 Ton HV run



Question 2

A. Hahn

- **Please provide a table based on the perspective of the CALCI consortium indicating the different points within the system from which gas samples should be analyzed. For each proposed sniffing point please describe the rationale for its inclusion, which constituents need to be measured and at what accuracy, and what the proposed measurement duty-cycle would be during different phases of operations. What is the overlap or non-overlap with the proposed LBNF and Integration contributions described in the review documents?**
- LBNF would provide the gas analyzers that are used to test the delivered LAr on the surface. These would measure O2, H2O and N2 at the tens of ppm down to the tens of ppb. I call these "Precision" Gas Analyzers.
- From a presentation by the II group at their Feb 2020 Cost Review, it appears that the overlap between my list of gas analyzers and theirs is nearly 100%.
- There is no need for two sets of identical analyzers.

Question 2

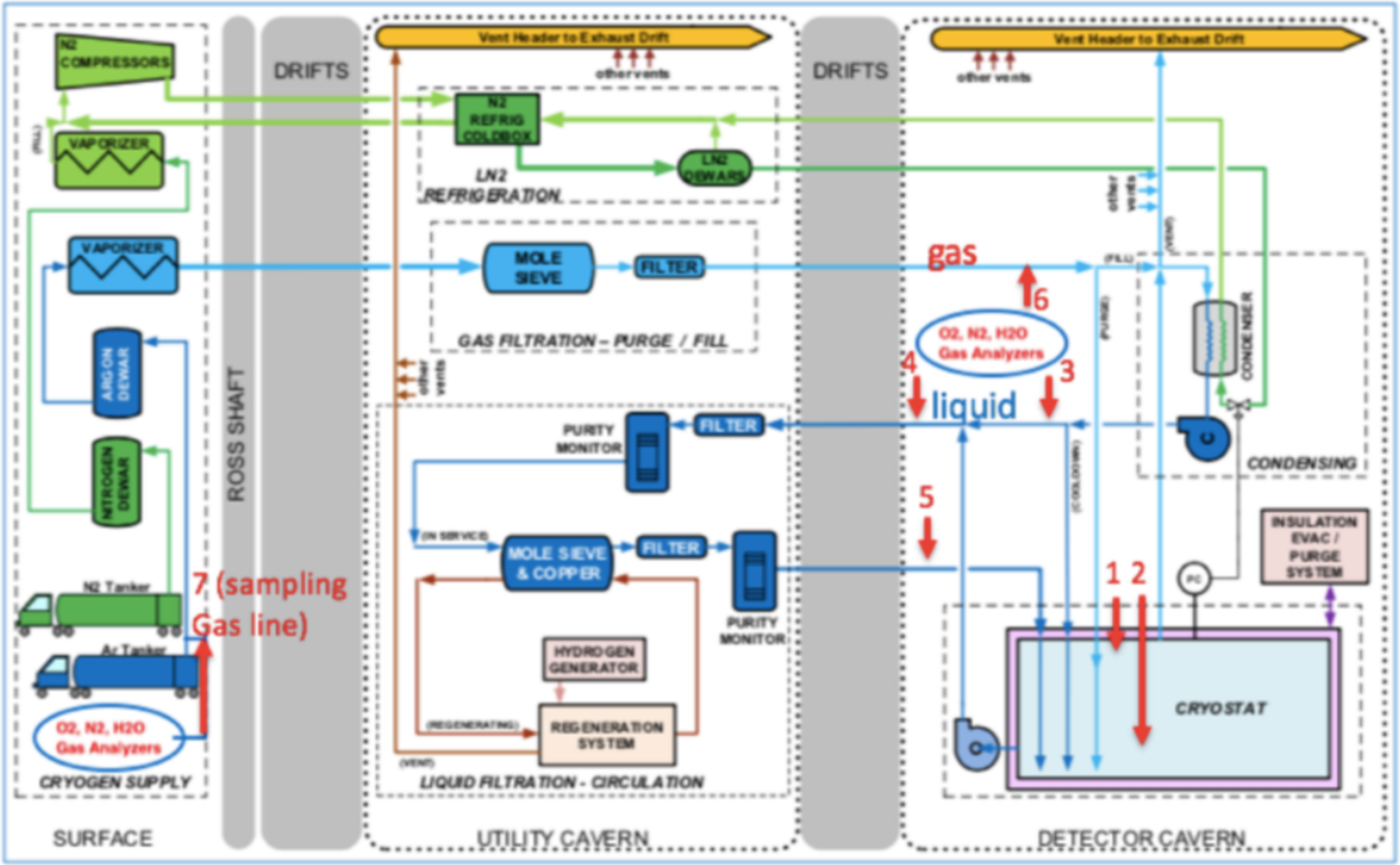
A. Hahn

location (match # to cartoon below	rationale	measurements	duty cycle	comments
1) Cryostat Ullage	1) Monitor upper level of Cryostat during Piston Purge and gas recirculation, cool down and filling. 2) Monitor Water, N2, O2, level in ullage region after LAr fill.	1) H2O, O2, N2 from levels in air to ppm levels 2) H2O & O2 at ppb to sub-ppb level. N2 from sub-ppm to ppm.	1) During gas phase of commissioning. 2) H2O sampling might be continuous after filling. O2, N2 during start of LAr recirculation.	Monitoring the gas phase of Cryostat commissioning seems to be covered by Installation.
2) Cryostat Liquid volume	1) Monitor lower level of cryostat during the piston purge, gas recirculation, cool down, and early filling. 2) Monitor O2, N2 in LAr volume	1) H2O, O2, N2 from levels in air to ppm levels 2) O2 at ppb to sub-ppb level. N2 from sub-ppm to ppm.	1) During gas phase of commissioning. 2) O2, N2 after recirculation— but may be easier to just monitor the Ullage.	
3) Condensed vapor loop, after Vapor Compressor	Look for air leaks from vapor system into LAr recirculation pump.	O2 at sub-ppm, N2 at sub-ppm to 10s of ppm.	1) During filling1) During filling 2) During LAr recirculation	
4) Input to Mole Sieve and Copper Filter	Monitor O2, N2 contamination into filters	O2 at sub-ppm, N2 at sub-ppm to 10s of ppm.	1) During filling 2) During LAr recirculation	
5) Output of Mole Sieve and Coper	Monitor Filter output for O2, N2. Looking for early stages of filter saturation.	O2 at sub-ppb, N2 at sub-ppm to 10s of ppm.	1) During filling 2) During LAr recirculation	
6) Argon Fill line from surface	Monitor GAr as it arrives from surface	O2, H2O, N2	During filling, and during top offs.	
7) Surface Sampling of Delivered Argon	Monitor tanker gas line to confirm delivery specs, and to calculate load on filters	O2, H2O, N2 at 50 ppb to 100 ppm. We have seen levels like this in PAB LAr deliveries	During filling and any later top off deliveries.	Responsibility of LBNF

Question 2

A. Hahn

= sampling port for GA's



Question 3

A. Hahn

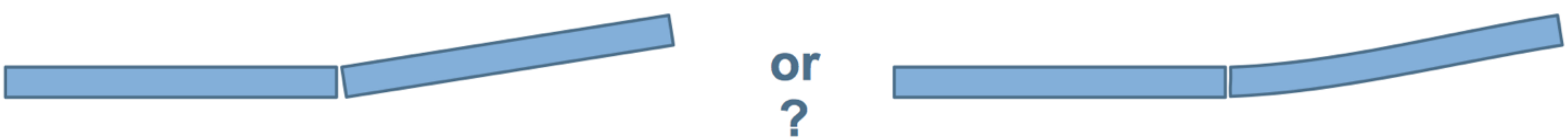
- **Do measurements of Nitrogen and Xenon contributions within the liquid play any role in the analysis of photon detector data?**
- Only if the levels of N2 rise into the 5 ppm or greater will the Ar scintillation light level start to be impacted. This probably would enter into the event energy threshold for the photon detectors.
- The current analyzers as described in the presentation do not detect Xenon. A “Universal Gas Analyzer” (UGA) has the potential to measure Xenon but it isn’t obvious to this writer how well this will work. This depends on the level of doping and the ability to get the Xenon to evaporate along with the LAr in the sample tube. We plan to use a UGA on a Xenon injection run at PAB in the near future, so will be able to comment then on the feasibility to measure the Xenon dissolved in LAr. I think it would be useful to be able to make this measurement.
- Xenon doping alters the photon time distribution seen by the photon detectors (as does N2 contamination), so in principle, the photon detectors should be able to make their own estimate of the percentage of Xenon in the LAr.

Cameras

Question 1

G. Horton-Smith

- **What role if any do the cameras play in helping to understand detector misalignments and what are the requirements associated with this role?**
  - The general idea is that to understand the mechanics of cm-scale misalignments we want mm-scale resolution.
  - Consider the example of the cm-scale tilts and offsets of the PD-SP CPAs found using CPA-APA crossing muons. Vic Guarino has suggested this could be due to pins on the CPAs inadequately constraining such motion. We wish we could look inside the TPC while it is still filled with LAr to see the CPA frames and the gaps between them.



Question 2

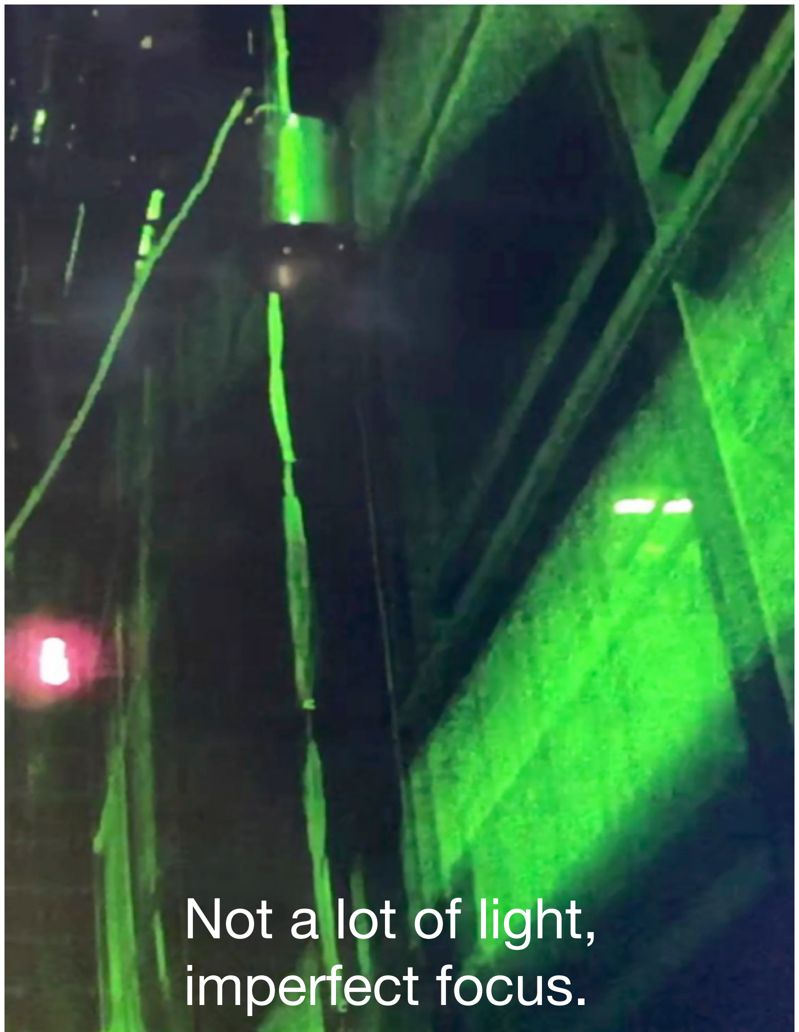
G. Horton-Smith

- **What are the lessons-learned regarding camera failures in ProtoDUNE-SP and ProtoDUNE-DP and has the camera design for DUNE incorporated those lessons-learned?**
- PD-SP cameras had (relatively) poor focus after being cooled, and low sensitivity for given lighting. They were useful for confirming no gross failures or major bubbling, but not as useful as the PD-DP cameras.
- PD-DP had sufficient lighting for the cameras chosen, and cameras pre-focused for cold conditions.
- It is planned to incorporate variable focus into the PD-SP-2 and DUNE cameras, as well as upgraded lighting.
- Much more sensitive cameras will be used in the periscope.

Question 2

G. Horton-Smith

ProtoDUNE-SP



ProtoDUNE-DP

Question 3

G. Horton-Smith

- **Could you describe in more detail the plans for the lighting systems required for both types of camera systems? Are these embedded within the cameras themselves or are they separate devices?**
- Lighting is embedded into fixed cameras for illuminating nearby objects.
- Separate area lighting LED strings will be used for illuminating objects far from fixed cameras and objects to be viewed by periscope, particularly outside the field cage.
- Spotlight illumination is possible inside the field cage using the alignment laser sent through a periscope illuminating the area viewed by another periscope.

Question 3

- There will be a black baffle between the fixed camera lens and the lights window LEDs to prevent the camera seeing the LEDs or reflections of the LED light off of the camera window. (This was a problem for EXO.) Design being advanced now by the HVS consortium.

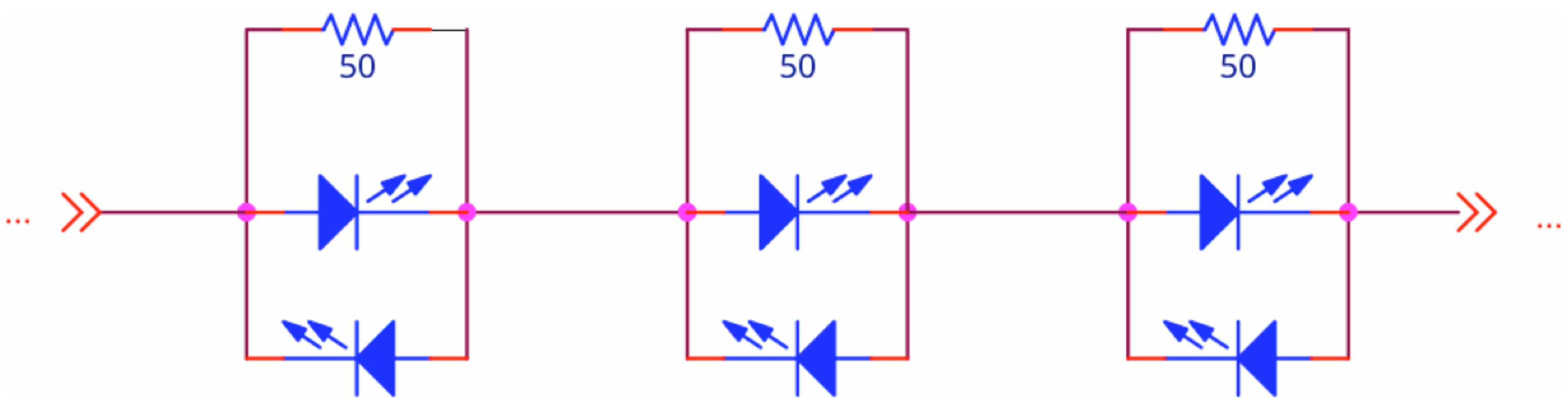
EXO camera thick wall and thick window had many reflective surfaces. JINST 8(12) · Oct. 2013

Lesson learned

LEDs to be added to DUNE HVS camera design with baffle to shadow lens from direct view or reflections off acrylic. (Ask Bo for details.)

Question 3

- LED strings will have parallel resistors (or zener diodes above the nominal LED forward voltage drop) to allow LEDs to fail and current still to be delivered to all other LEDs.
- LED string design also allows for two different kinds of lights if desired. (E.g., HVS might prefer a wider spectrum than periscope can use.)
- Design by Chuck Lane. Schematic from TDR shown.



Question 4

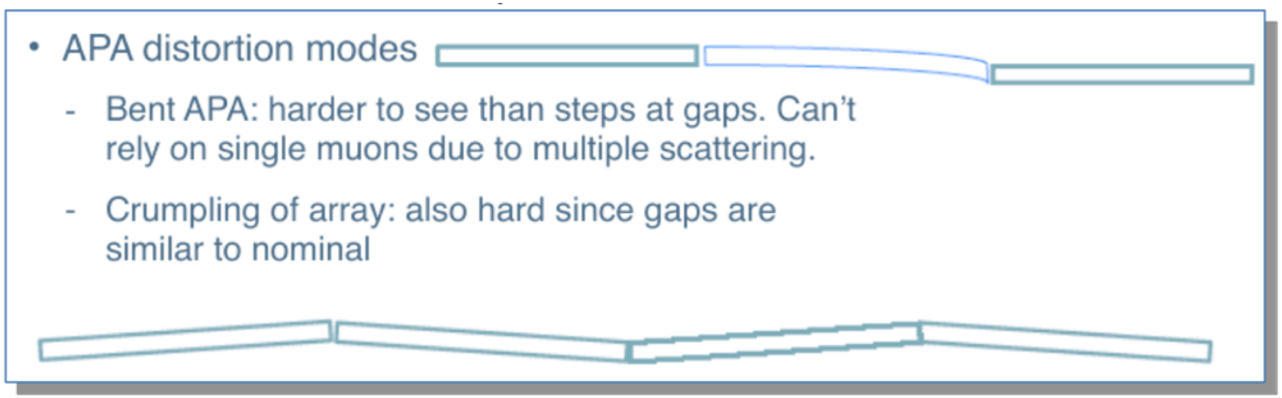
G. Horton-Smith

- **What are the roles of the cameras during cryogenic operations?**
- The cameras have been used in ProtoDUNE to confirm presence/absence of condensation in Ar "spray" during cool-down, state of bubbling in the liquid argon, presence/absence of debris.
- They can be used to confirm the absence of undesirable mechanical changes to the detector during and after gas cooldown, before LAr filling, such as breakage, buckling, warping, etc.
- Examples of such effects were seen in the Overall Calibration Plan and Ionization Laser System presentations yesterday.

Question 4

G. Horton-Smith

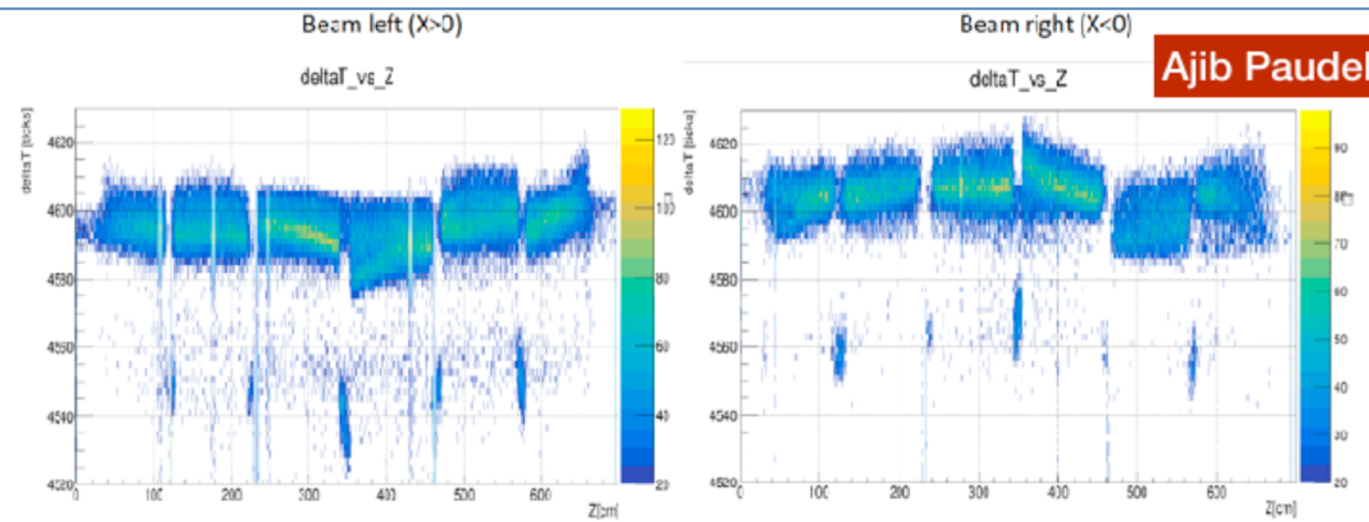
From Overall Calibration Plan presentation, slide 7.



From Ionization Laser presentation (referencing FNAL Indico event 23990 contribution 74793)

Studying APA-CPA crossing tracks in ProtoDUNE-SP led to the discovery of CPA shifts/rotations

(see talk here)



DEEP UNDERGROUND NEUTRINO EXPERIMENT

Question 5

G. Horton-Smith

- **Could you provide additional details on the camera systems incorporated within the laser ports?**
- **What is the focal length needed?**
  - 80 mm for looking at the periscope, 160 mm for looking through the periscope
- **Does a lens with the required focal length and aperture exist?**
  - Yes. (Details on later slide.)
- **Do the optical requirements imply that the images will be too dark to see anything useful?**
  - No. (Details on later slide.)
- **Do the photosensors need to be cooled?**
  - Yes, for best performance in low light. Cooling is built into cameras under consideration.

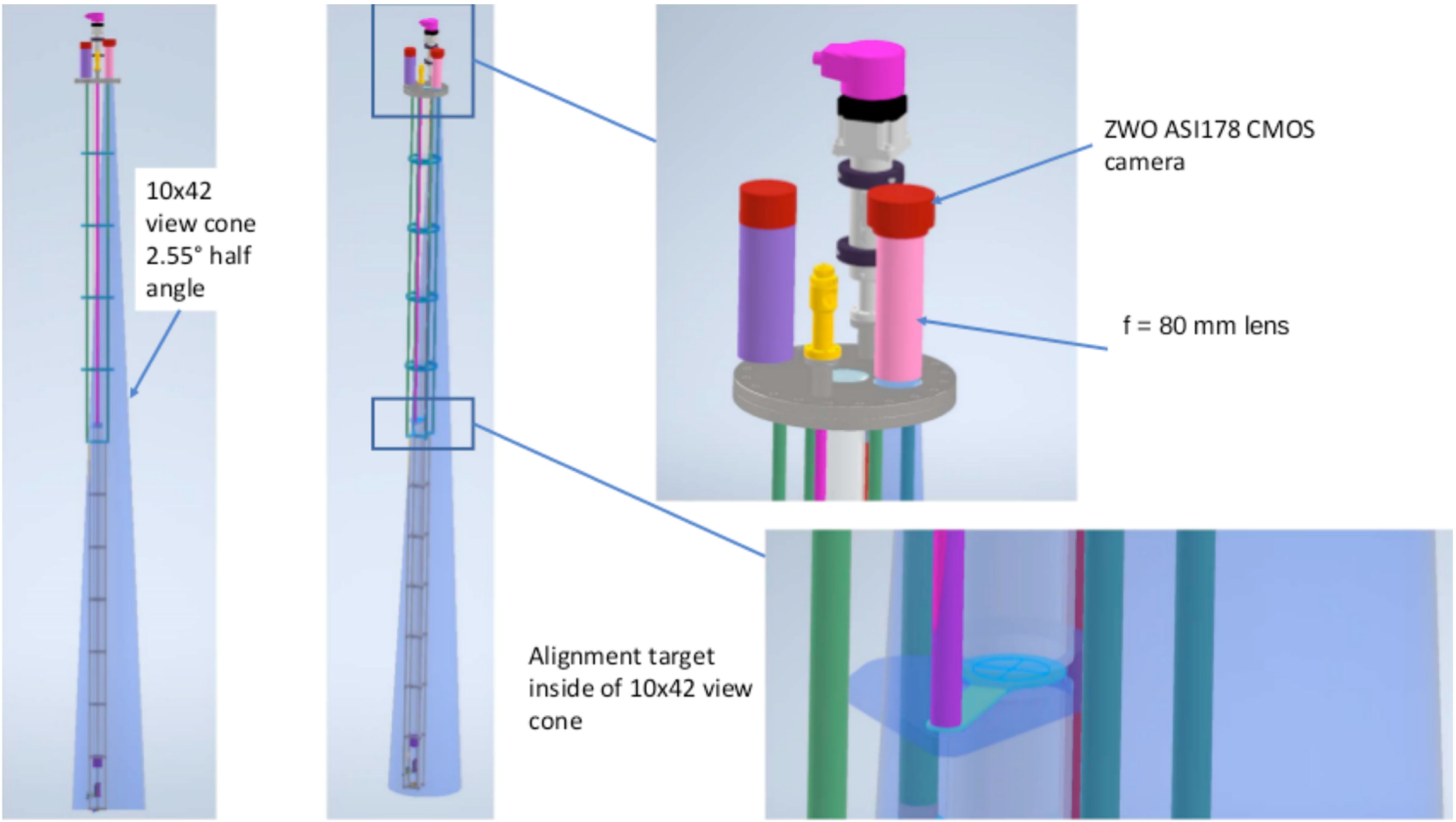
Question 5.a

G. Horton-Smith

- **What is the focal length needed? 80 mm for looking at the periscope, 160 mm for looking through the periscope.**
- An 80 mm focal length objective lens gives a 1.8 degree by 2.6 degree half-angle for 7.4 mm x 5 mm sensor. This is ideal for the off-axis imaging of the target and the bottom of the periscope. (3D model by J. Boissevain on next slide.)
- A 160 mm focal length provides enough magnification that the angular resolution of a 2.4 μm pixel is a little smaller than the diffraction limit. Longer focal lengths could give better position resolution for point or line features.

Question 5.a

G. Horton-Smith



(from Jan Boissevain)

Question 5.b

G. Horton-Smith

- **Does a lens with the required focal length and aperture exist? Yes.**
- Fixed focal length example: MVL75M1 75-mm, f/1.8 fixed focal length lens sold by Thor Labs. Adapters available. https://www.thorlabs.com/thorproduct.cfm?partnumber=MVL75M1
- Zoom lens example: Sony DT 55-200mm FL, f/4-5.6 SAM II telephoto zoom lens. Adapters available. https://www.sony.com/electronics/camera-lenses/sal55200-2

Question 5.c

G. Horton-Smith

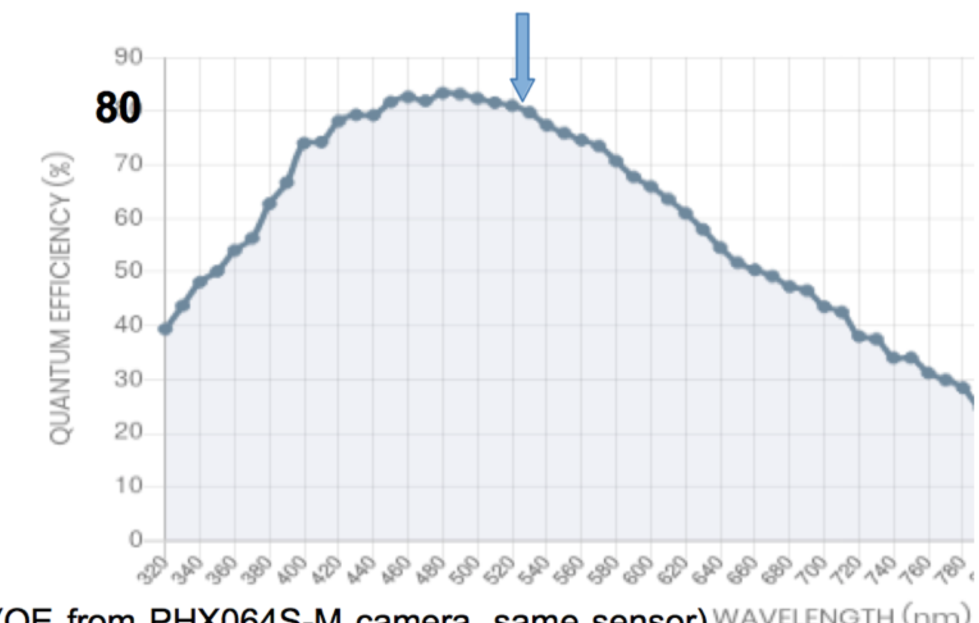
- **Do the optical requirements imply that the images will be too dark to see anything useful? No.**
- Compared to a fixed camera, the solid angle per pixel is many times smaller, but the astroimaging camera sensitivity and noise will be orders of magnitude better, and the exposure time can also be orders of magnitude larger (e.g., 10 s vs 0.1 s).
- Taking all this into account, the lighting requirements for the through-the-periscope views seem to be not too different from the fixed cameras.
- The calculations that have been made all need to be checked, improved to take into account more conditions, and verified empirically.

Question 5.c

G. Horton-Smith

- **Favorite camera so far: ZWO ASI178**
- Well regarded on astronomy forums, some members of Association of Variable Star Observers use for photometry.
- QE=80% at 530 nm, 32 us to 1000 s integration time, total read noise of ~2 e-, CMOS sensor dark current <~0.1 e-/s when cooled, camera has built-in thermoelectric cooling.

(Photo from ASI178 manual.)



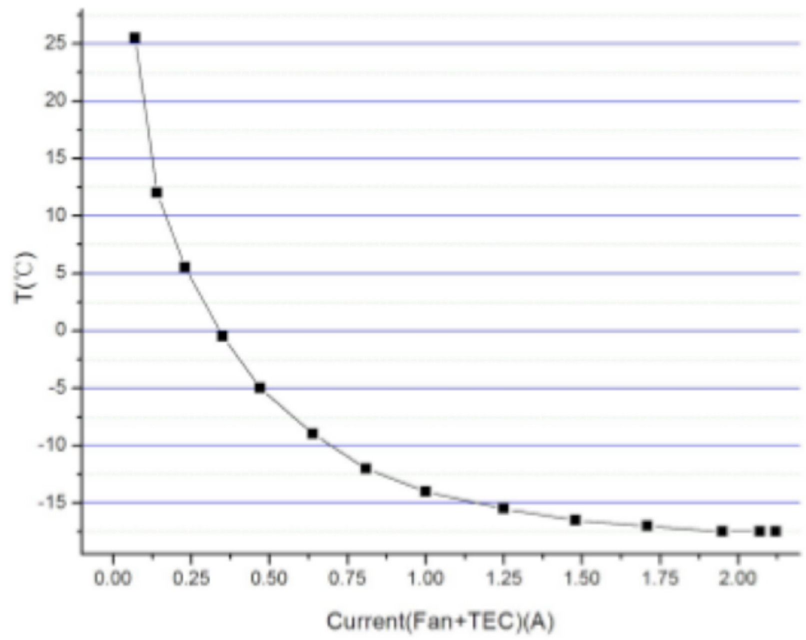
(QE from PHX064S-M camera, same sensor)

Question 5.d

G. Horton-Smith

- **Do the photosensors need to be cooled? Yes, for best performance in low light.**

Here is a test result of the cooler power consumption of our cooled camera. It only needs 0.5A to cool the camera to 30 degree below ambient.



(Figure from ASI178 manual.)

- Photosensors generally perform better when cooled.
- The ZWO ASI178 has a built-in regulated thermoelectric cooler. This is how it gets its low dark current.

Purity monitors

Question 1

J.Bian

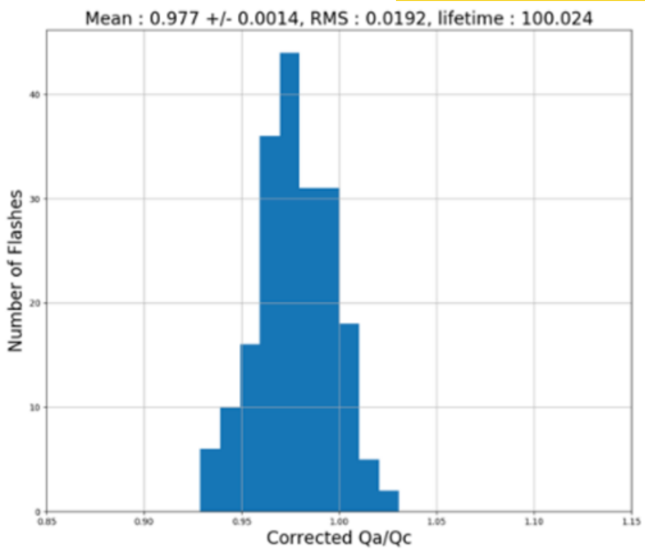
- **Please tell us the precision on the prediction that can be made by the purity monitors for the fraction of charge produced at the TPC cathode arriving at the sense planes, assuming a drift time of 2.3 milliseconds. Please provide this precision for the current-length purity monitor (16 cm drift), a ~50 cm monitor (as also currently exists), and a ~100 cm drift-length device. Please describe the statistical and systematic uncertainties that contribute to the precision. Please do this for the cases of 3 ms, 10 ms, and 100 ms lifetimes.**

Question 1

J.Bian

- Very small statistical uncertainty due to strong signal strength, low noise and large number of flashes in PrM measurement

RMS=2.0% $\Delta_{stat}(Qa/Qc)=2\%/sqrt(N_{flash})=0.14\%$.



Long purity monitor can control uncertainty in PrM Qa/Qc within 2%

- Uncertainties in TPC Qa/Qc calibrated with PrMs depend on LAr purity and precision of PrM-to-TPC extrapolation
- Under high LAr purity or with good extrapolation technique, uncertainty in TPC Qa/Qc is same as PrM Qa/Qc

Table I: Summary of statistical and systematic uncertainties

		16 cm drift length (current) (column 1)	47cm drift length (2.9xcurrent) (column 2)	64cm drift length (4xcurrent) (column 3)
1	Statistical uncertainties in PrM Qa/Qc	0.14%	0.14%	0.14%
2	Run to run fluctuations PrM Qa/Qc	0.7%	0.7%	0.7%
3	Systematic uncertainties in PrM Qa/Qc	5.8%	2.1%	1.4%
4	Overall uncertainties in PrM Qa/Qc (drift time 2.3ms)	5.8%	2.2%	1.5%
5	Precision on TPC Qa/Qc at 3ms, 10ms, 100ms lifetimes (0% non-uniformity of impurity concentration)	5.8%	2.2%	1.5%
6	Precision on TPC Qa/Qc at 3ms lifetime (5% non-uniformity of impurity)	6.9%	4.3%	4.0%
7	Precision on TPC charge at 10ms lifetime (5% non-uniformity of impurity)	5.9%	2.5%	1.9%
8	Precision on TPC charge at 100ms lifetime (5% non-uniformity of impurity)	5.8%	2.2%	1.5%

Question 2.a

J.Bian

- **What would DUNE be giving up by restricting itself to the current-length purity monitors ?**

The current-length purity monitors have an overall uncertainty in Qa/Qc, Δ(Qa/Qc)/(Qa/Qc) = 5.8% which comes largely from the ability to measure the transparency correction. A long monitor as proposed can avoid the need for such correction and thereby reduce the uncertainty on the energy correction to < 2%, which is the goal of the energy response uncertainties in DUNE TDR.

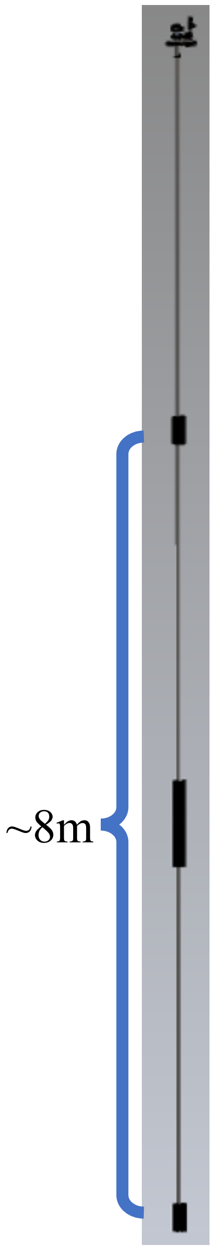
Table I: Summary of statistical and systematic uncertainties

		16 cm drift length (current) (column 1)	47cm drift length (2.9xcurrent) (column 2)	64cm drift length (4xcurrent) (column 3)
1	Statistical uncertainties in PrM Qa/Qc	0.14%	0.14%	0.14%
2	Run to run fluctuations PrM Qa/Qc	0.7%	0.7%	0.7%
3	Systematic uncertainties in PrM Qa/Qc	5.8%	2.1%	1.4%
4	Overall uncertainties in PrM Qa/Qc (drift time 2.3ms)	5.8%	2.2%	1.5%
5	Precision on TPC Qa/Qc at 3ms, 10ms, 100ms lifetimes (0% non-uniformity of impurity concentration)	5.8%	2.2%	1.5%
6	Precision on TPC Qa/Qc at 3ms lifetime (5% non-uniformity of impurity)	6.9%	4.3%	4.0%
7	Precision on TPC charge at 10ms lifetime (5% non-uniformity of impurity)	5.9%	2.5%	1.9%
8	Precision on TPC charge at 100ms lifetime (5% non-uniformity of impurity)	5.8%	2.2%	1.5%

Question 2.b

J.Bian

- **What would DUNE be giving up by installing these only at the top and bottom of the cryostat on both ends (in addition to installing one or two inline monitors)?**
- The liquid argon depth in DUNE is 14 m and the clean argon enters at the bottom of the cryostat. With the middle purity monitor, the impurity stratification can be much better measured.
- Without the middle purity monitor, during liquid argon filling, there will be no information about the contamination close to the liquid argon surface before the argon level reaches the top purity monitor.
- The bottom purity monitor is the most vulnerable one to any signal degradation (longest fiber). If it fails we would only have the top PrM.



DEEP UNDERGROUND NEUTRINO EXPERIMENT

Question 3

J.Bian

- **What do we know about the performance of the purity monitors operated in the ProtoDUNE-DP detector?**
- Running smoothly and continuously taking data.
- Also ran in non-transparent mode to increase the sensitivity of the electron lifetime measurement. One difference is that the transparency correction factor to PrM Qa/Qc at ProtoDUNE-DP is estimated by a field calculation while at ProtoDUNE-SP we use purity monitor data taken at the full transparent mode and the partial transparent mode to calculate the transparency correction factor from data
- ProtDUNE-DP set a limit to the longest lifetime they can measure at Qa/Qc = 0.95, where Qa was corrected for transparency. In recent high purity runs, both ProtoDUNE-DP purity monitors found PrM Qa/Qc is larger than 0.95 (and often greater than 1 after transparency correction) and so they say the lifetime is beyond their sensitivity

Question 4.a

J.Bian

- **Is this an absolute calibration, periodically cross checked against TPC-based measurements or is it a relative calibration (over shorter time scales) normalized to a more precise TPC-based measurement made from data collected over a longer period?**
- After applying the attachment rate correction, that depends on the operation E-fields at purity monitor (10-100V/cm) and TPC (500V/cm), the purity monitors provide a measurement of absolute electron lifetime at the TPC's E-field.
- Combined with other calibration sources/CFD to extrapolate from PrM to TPC volume.
- If the uncertainty of the purity monitor lifetime is turned out to be larger than a direct TPC absolute lifetime measurement at DUNE, the run-by-run lifetimes measured by purity monitors can be normalized to a more precise TPC-based absolute measurement made from data collected over a longer period, providing a relative calibration to the lifetime variation run by run.
- The PrM calibration schemes are being tested at PrototDUNE-SP

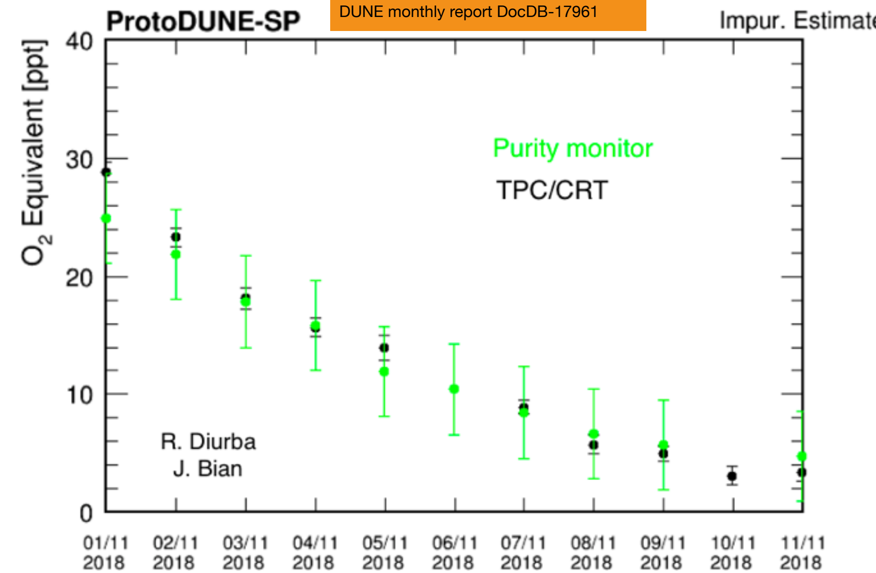
Question 4.a

J.Bian

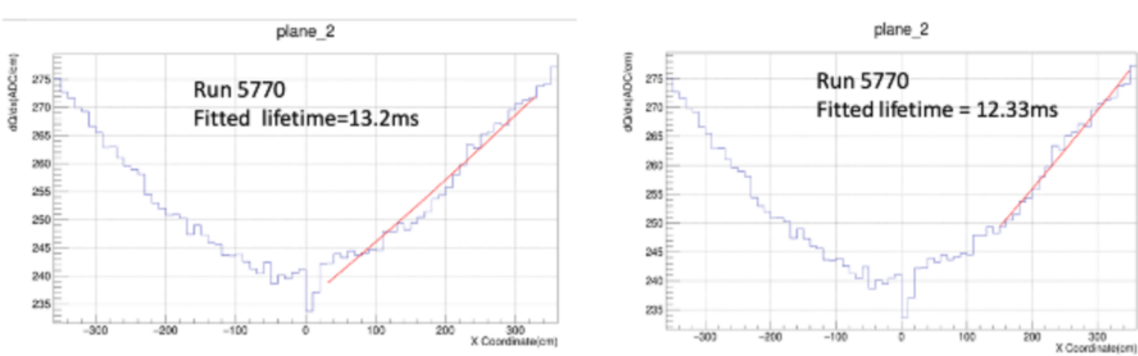
Preliminary tests in ProtoDUNE-SP:

- PrM absolute electron lifetime shows good agreement with CRT tagged and regular TPC cosmic rays.
- Run-by-run PrM lifetime calibration at ProtoDUNE-SP reduces the standard deviation of run-by-run dQ/dx of 6 GeV beam pions from 2.1% to 0.7% at ProtoDUNE-SP

PrM vs. CRT/TPC
DUNE monthly report DocDB-17961

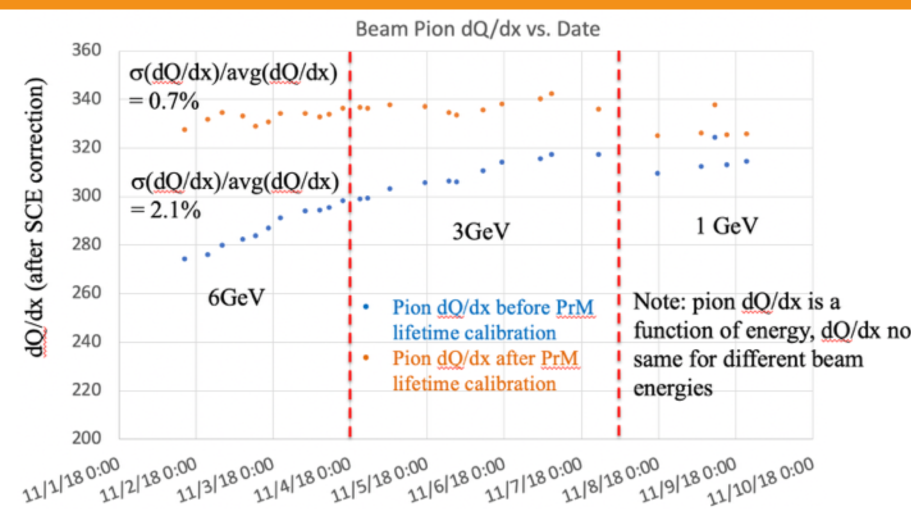


PrM vs. TPC cosmic rays
https://indico.fnal.gov/event/43368/contributions/186124/attachments/128458/155432/DRA_meeting_May19_talk.pdf



PrM lifetime = 12.3ms

PrM run-by-run lifetime calibration for TPC Qa/Qc
https://indico.fnal.gov/event/43368/contributions/186123/attachments/128482/155714/PrM_RunCalib_05_19_2020.pdf



Question 4.b

J.Bian

- **How are the purity monitor measurements extrapolated into the active TPC volume?**
- A combination of calibration sources such as laser, neutron source, Radioactive Source, Ar39, Temperature sensors, and purity monitors will provide measurements of liquid argon non-uniformity, and CFD models will provide the simulation of liquid argon non-uniformity. As discussed in question 1, the effect of impurity non-uniformity depends on the electron lifetime achieved at DUNE. So we will discuss two different scenarios:
    - **Scenario 1**: If purity monitor and other calibration sources find that DUNE can achieve high liquid argon purity, the non-uniformity can be most likely treated as a systematic uncertainty instead of an extrapolation.
    - **Scenario 2**: If the purity at DUNE is not high (<10ms), the extrapolation is needed, and the uncertainty of this extrapolation needs to be well controlled.
- We are working on understanding ProtoDUNE-SP impurity non-uniformity with current cosmic ray data, temperature sensor data, purity monitor data and CFD simulation. In ProtDUNE-SP-II, we plan to develop the proposed combined measurement with purity monitors and other calibration sources when other sources are available.