CALCI Consortium Responses to Questions on Calibration

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CALCI Scope Review Workshop

Responses to Committee Questions

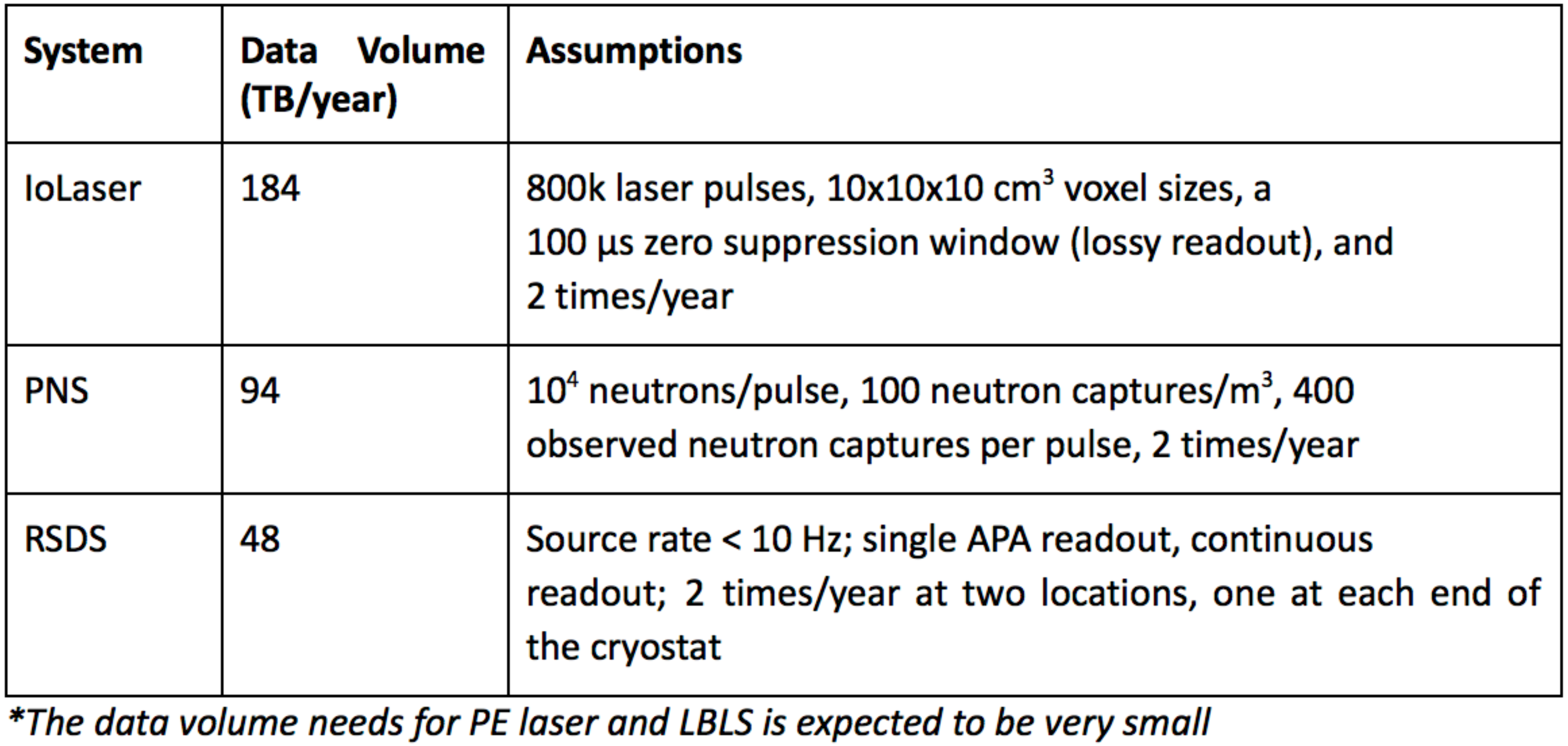
- We have received a total of 25 questions from the review committee
  - General (3)
  - IoLaser (5)
  - LBLS (4)
  - PE Laser (6)
  - PNS (3)
  - RSDS (4)
- This presentation will highlight core points for each response
- Detailed responses have been circulated to the committee yesterday as a PDF file that is also linked here: https://drive.google.com/file/d/11DOswsrW3iEgozHcjBeyXL5weyaNVQUn/view?usp=sharing

General

Q1. For each calibration technique, what is the estimated time required to perform a calibration, how often will the calibration need to be performed, and what is the expected size of the calibration data sample that needs to be collected and analyzed?

- General Strategy for calibration runs
  - *Before beam:*
    - Dedicated fine-grained laser scans + PNS/RSDS as frequently as possible (taking care to avoid being SNB-blind)
  - *After beam:*
    - Take full IoLaser, PNS and RSDS scans every 6 months, with PE laser (shorter) scans in between
    - “Calibrations-of-opportunity”: Beam-on data taking will take priority but use beam-off periods for additional calibrations as needed.
    - “Calibrations-of-need”: If variations are noted, do a fine shorter scan in affected regions

Q1 Continued



System	Data Volume (TB/year)	Assumptions
IoLaser	184	800k laser pulses, 10x10x10 cm^3 voxel sizes, a 100 μs zero suppression window (lossy readout), and 2 times/year
PNS	94	10^4 neutrons/pulse, 100 neutron captures/m^3, 400 observed neutron captures per pulse, 2 times/year
RSDS	48	Source rate < 10 Hz; single APA readout, continuous readout; 2 times/year at two locations, one at each end of the cryostat

**The data volume needs for PE laser and LBLS is expected to be very small*

IoLaser

- ~800,000 tracks for 10x10x10 cm^3 voxel sizes and assuming data reduction to 100 μs window results in:

800,000 tracks x 100 μs x 1.5 Bytes/sample x 2MHz x 384,000 channels = 92 TB/scan10 kt

- One full scan is estimated to take about *3 days* assuming running at 4 Hz at 80% efficiency.
- 2 runs/year are nominal full scans. But, the frequency of scans can be more e.g. for alignment checks and charge-based measurements.

Q1 Continued

- **PNS**
  - Assuming 10^4 neutrons/pulse, 100 neutron captures/m^3 and 400 observed neutron captures/pulse, a total of 1500 pulses is needed. Assuming two identical PNS systems operating in synchronization mode, 750 triggers are needed per calibration run.

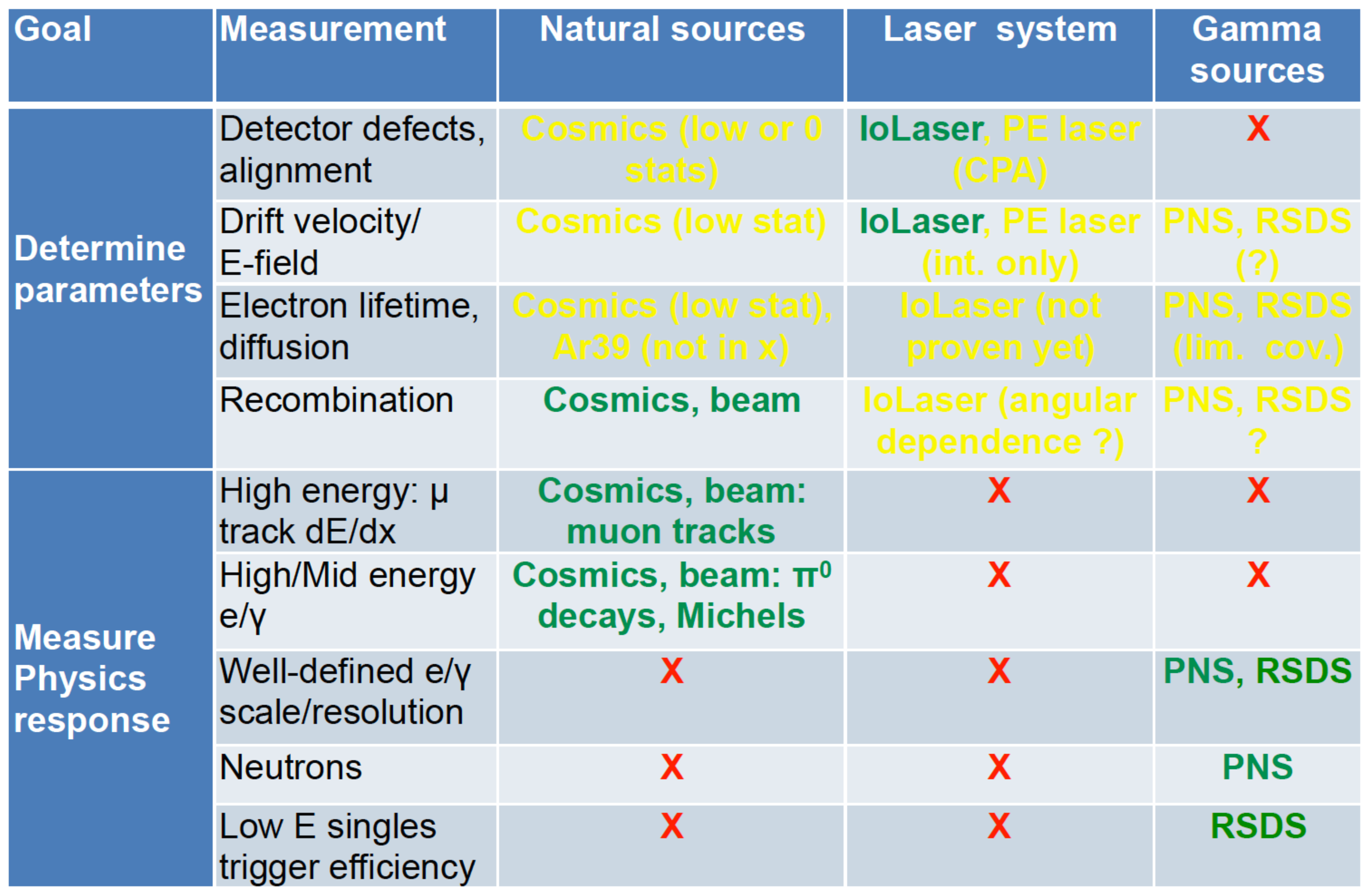
    750 triggers x 1.5 Bytes x 2 MHz x 5.4 ms x 384,000 channels = 4.7 TB/run
  - If spatial distribution of neutron captures is near-uniform, calibration run would be 25 *minutes.*
  - If neutron capture distribution is non-uniform (more realistic case)
    - Run time 10 times longer i.e., 250 minutes or ~4 hours/run.
    - Data size per calibration run would be 47 TB/run
- **RSDS**
  - With 10 Hz or less interaction rate, and with localization of events to one APA, ***8 hrs x 2 FTs x 10 Hz x 1.5 Bytes/sample x 2 MHz x 5.4 ms x 2560 channels = 24 TB/scan/ 10 kt***
  - One full scan with source deployments at 2 feedthroughs and assuming 8 hours per location, results in a total of 32 hours for a full scan, plus preparation and moving source b/n runs will roughly result in a total of ~1 day.

Q2. Please describe in greater detail the overlaps and complementarities between the different proposed calibration techniques including those based on natural sources.

- More generally, no single source can provide all calibrations and a combination of sources will need to be used. In some cases, dedicated sources play a primary role with natural sources providing partial inputs, cross checks etc. and in some other cases vice-versa.
  - **Dedicated sources** provide higher statistics, have known input parameters and are controllable (e.g. steerability, targeting specific regions). These are ideal sources to do fine mappings and as such these play a primary role in determining calibration parameters.
  - **Natural sources** such as cosmics, Ar39 have limited statistics and are good for cross-checks. In particular cases they can complement the dedicated sources in a few regions where they have limited coverage (E.g. coverage of the top FC modules with laser will have some limitations; recombination model parameters will be measured essentially with cosmics events.
  - In the high energy (e.g. muon dE/dx) and in high to mid-energy range (e.g. e/gamma response), cosmics and beam particles will play a primary role in measuring particle response. In the case of Low energy response, dedicated sources such as PNS, RSDS play a primary role.
- More details on this in our response to the next question.

Q3. The committee is expressing interest in the table on slide 31 of Jose's overview talk. What is the intention of the color-coding (green versus yellow)? Which of the listed calibration techniques do you expect to be the primary one for making each type of measurement? What additional information is available from the other calibration techniques listed for each measurement (e.g. helps reduce systematic uncertainties, allows for more frequent calibration, or simply a cross-check)?

- ***Green:*** primary or best source for the measurement; ***Red:*** not possible to measure
- ***Yellow:*** while the source can be used it has limitations e.g. low or 0 statistics; technique not proven/ demonstrated yet; limited coverage; partial/targeted measurement; not understood yet; or other specific limitations.



Goal	Measurement	Natural sources	Laser system	Gamma sources
Determine parameters	Detector defects, alignment	Cosmics (low or 0 stats)	IoLaser, PE laser (CPA)	X
	Drift velocity/ E-field	Cosmics (low stat)	IoLaser, PE laser (int. only)	PNS, RSDS (?)
	Electron lifetime, diffusion	Cosmics (low stat), Ar39 (not in x)	IoLaser (not proven yet)	PNS, RSDS (lim. cov.)
	Recombination	Cosmics, beam	IoLaser (angular dependence ?)	PNS, RSDS ?
Measure Physics response	High energy: μ track dE/dx	Cosmics, beam: muon tracks	X	X
	High/Mid energy e/γ	Cosmics, beam: π^0 decays, Michels	X	X
	Well-defined e/γ scale/resolution	X	X	PNS, RSDS
	Neutrons	X	X	PNS
	Low E singles trigger efficiency	X	X	RSDS

Q2. The committee is expressing interest in the table on slide 31 of Jose's overview talk. What is the intention of the color-coding (green versus yellow)? **Which of the listed calibration techniques do you expect to be the primary one for making each type of measurement? What additional information is available from the other calibration techniques listed for each measurement (e.g. helps reduce systematic uncertainties, allows for more frequent calibration, or simply a cross-check)?**

- **Charge Readout/Electronics:**
  - Primary: Internal calibration pulser
- **Wire Capacitance:** *All sources have limitations*
  - Cosmics necessary to determine an overall calibration scale factor, including the effect of charge loss in the wire capacitance, since with stopping muons, absolute charge that was produced can be well predicted. Cosmics will likely not be capable of measuring variations of this effect across the detector.
  - Ar39 can be used for this. Advantage is high statistics. Disadvantage is that several effects (e.g. gain, noise, lifetime, diffusion, wire response) contribute to the collected charge, and correlations must be well understood for a precise measurement.
  - Dedicated sources such as PNS, but especially the laser, might play a role for the determination of wire response relative corrections. No dedicated studies exist yet, but laser tracks can be made parallel (and close) to the APA in order to eliminate drift-dependent effects, and the collected charge is well above the noise.
- **Charge Collection:**
  - Primary: IoLaser (excellent coverage, plentiful tracks and can be parallel to APA so no drift dependent effects)
  - Cosmics provide cross checks (low statistics; wait until enough stats are accumulated)

Q2 Continued

- **Detector defects/alignment:**
  - Primary: Iolaser (high statistics; fine mapping, excellent coverage)
  - PE laser: quick, coarse scans; targeted scans e.g. CPA tilts/rotations
  - Cosmics: low or zero statistics; cross check once enough stats are accumulated in some cases
  - CFD maps: cross check
- **Drift velocity/E-field:**
  - Primary: Iolaser (high statistics; fine mapping, excellent coverage)
  - PE Laser: integrated E-field only. Cross check.
  - Cosmics: low statistics and no independent position measurement except for a very small data sample (crossing two APAs, no showering). Can be used to cross check displacement measurements in some of the TPC boundaries (but not all, and not the bulk) once enough stats are accumulated.
- **Electron Lifetime:**
  - All sources have limitations. Will require a combination of information to calibrate
  - Cosmics: low stats
  - Ar39: cannot give measurement in X; quite low energy (1/4 mip on average), therefore sensitive to noise and threshold
  - IoLaser: plentiful stats; technique not proven yet in large LArTPCs, but could become a primary method if its performance is verified.
  - PNS, RSDS (limited coverage)
  - Purity Monitors (limited coverage)
  - CFD: use input from purity monitors and other measurements for prediction across the detector.

Q2 Continued

- **Diffusion:**
  - Cosmics: low stats
  - IoLaser: Plentiful stats; technique not proven yet in large LArTPCs, but could become a primary method if its performance is verified.
- **Recombination:**
  - Primary: Cosmics (low statistics), beam
  - IoLaser cannot measure parameters but can provide angular dependence of parameters (technique to be proven yet). Helps reduce the overall uncertainty.
- **High Energy: muon track dE/dx:**
  - Primary: Stopping muon tracks (limited statistics), beam
  - Not possible with dedicated sources.
- **High/Mid energy e/gamma:**
  - Primary: Pi0 decays, Michels from cosmics (limited statistics), beam
  - Not possible with dedicated sources.
- **Well-defined e/gamma scale/resolution:**
  - Primary: PNS, RSDS
  - Not possible with other sources
- **Neutrons:**
  - Primary: PNS
  - Not possible with other sources
- **Low E singles trigger efficiency:**
  - Primary: RSDS
  - Not possible with other sources

Ionization Laser
(IoLaser)

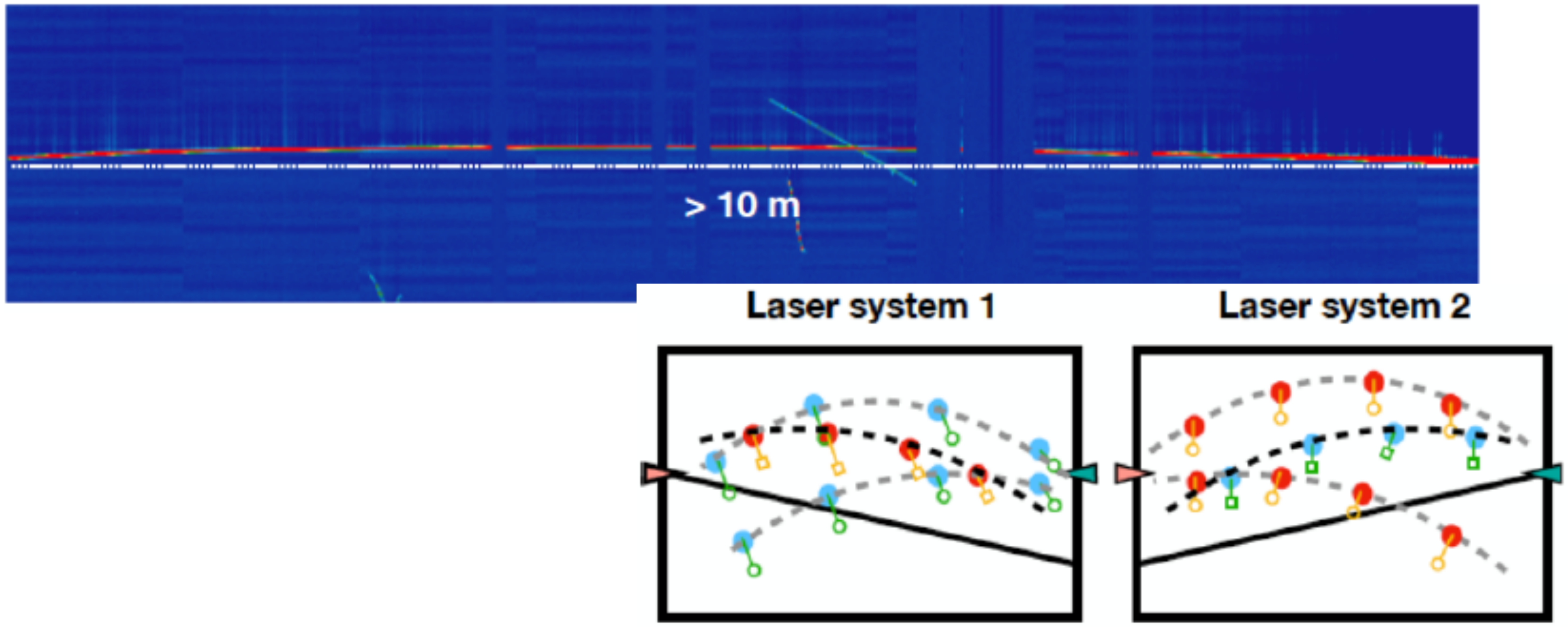
IoLaser Q1. If the lack of crossing laser tracks creates two-fold ambiguities in the electric field map, why can't these ambiguities be resolved using beam or cosmic data (in particular from the unambiguous corrections available from the end points of single tracks)? Once the ambiguities are resolved initially, are the identities of the correct solutions likely to change based on future small changes in the electric field map?

- A very big advantage of laser over cosmics for position-based measurements is that we can know the true direction for all tracks and laser tracks are straight and don't shower.
- Direct combination with laser tracks to resolve the ambiguities ?
  - Only 2-APA crossing muon tracks can have a TPC-independent direction and would be useful
  - After removal of tracks with showers, < 70/day/10 kt remain
  - Of those, some (not sure yet how many) will have MCS causing shifts > 1 cm. That means averaging may be necessary.
- Using cosmics-based displacement maps to complement some regions where laser has poor coverage (like top of FC) should be possible and useful

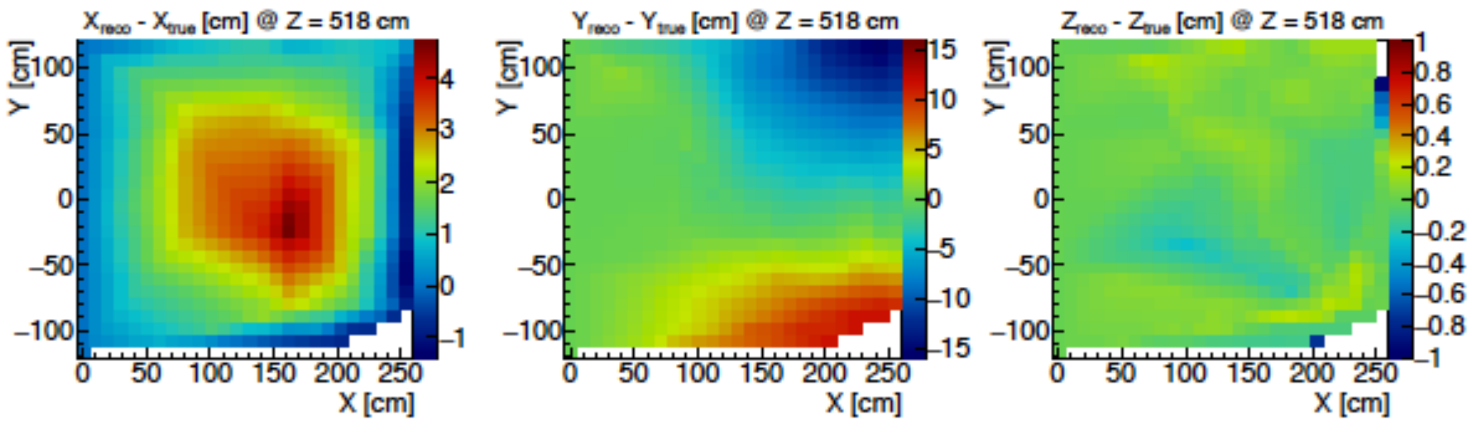
Q1 Continued

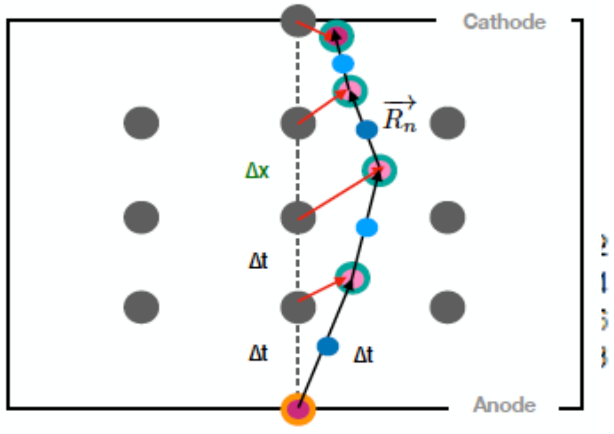
Drift/E-field measurement - laser

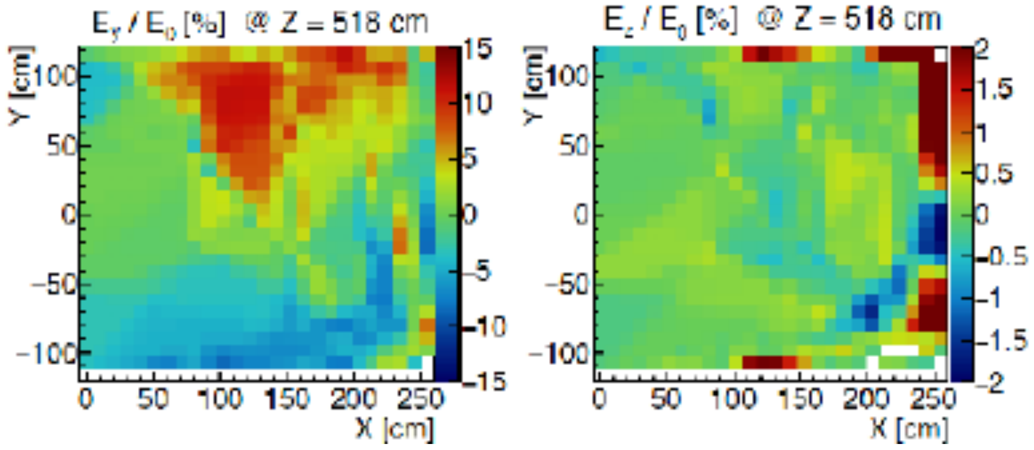
1. Compare reco to true tracks. With laser we know the “true” from mechanical system.
2. Use non-collinear tracks to measure **3D displacement maps everywhere coverage allows**
3. Interpolate remaining regions
4. Fit model of drift velocity distortion maps



MicroBooNE Preliminary



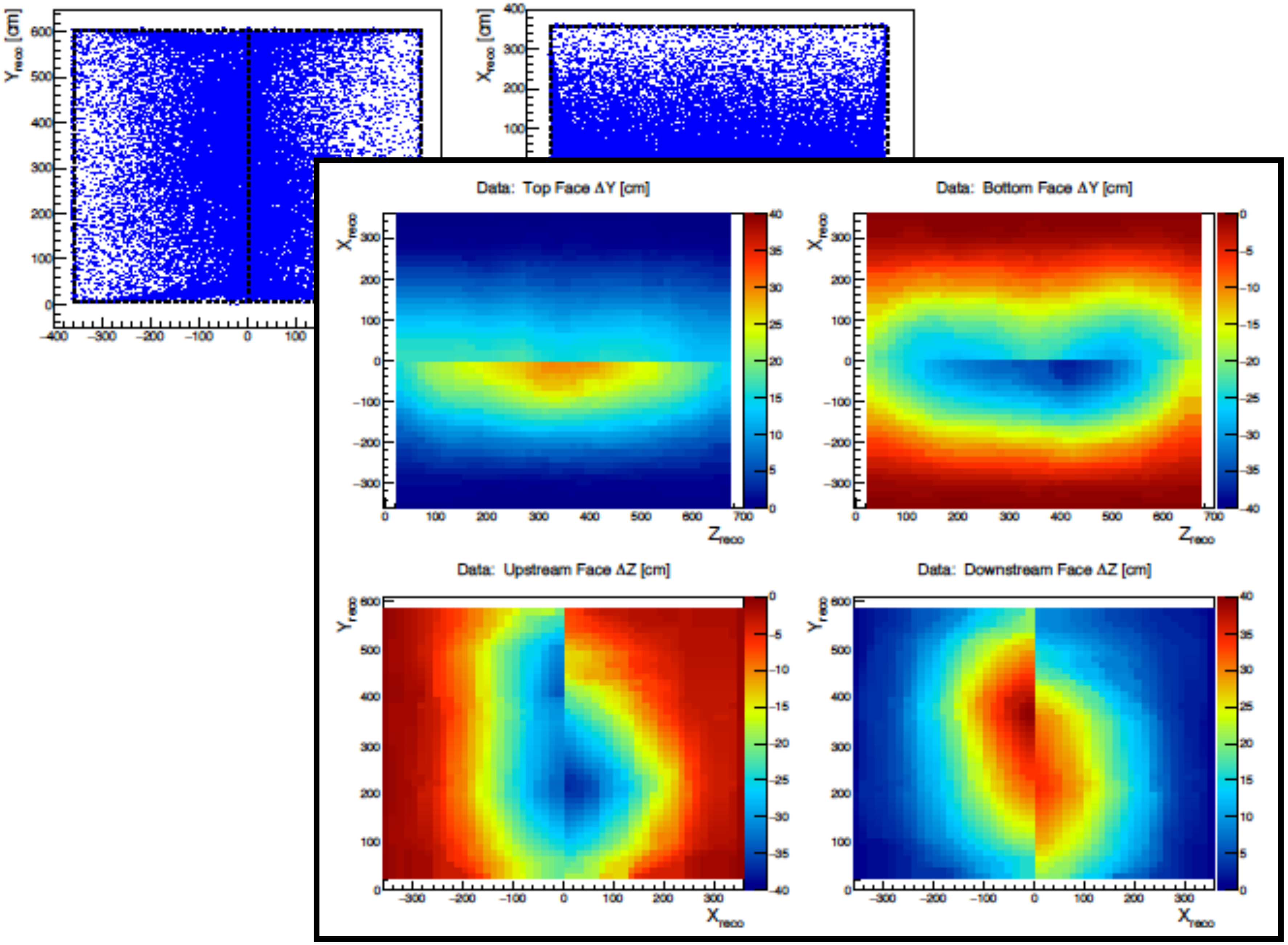


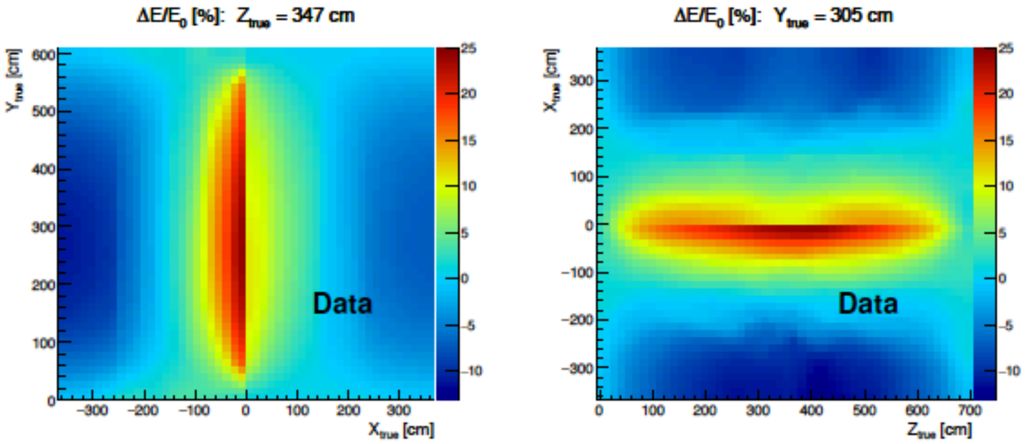


Q1 Continued

Drift/E-field measurement - cosmics

1. Compare reco tracks to known TPC boundaries. No other way to know “true direction.
2. Measure **1D displacement maps at 4 boundaries (FC)**
3. Interpolate across **the whole detector**
4. Fit model of drift velocity distortion maps





Q1 Continued

Limitations of cosmics for DUNE FC E-field measurement

- **Method 1** *(same as ProtoDUNE)*
    - Based on 1D displacement maps at FC boundaries. Everywhere else, use interpolation. How much do we trust this across 12 and 58 m?
        - in our opinion, those displacement maps are useful to complement laser, but should not be interpolated across such wide distances
- **Method 2** *(use 2-APA crossers and "laser method", potentially to complement laser in the end-wall region?)*
    - At high depth, showering is frequent (~40%). At high slant, likely more.
    - Can't guarantee that all tracks are as straight as laser due to multiple scattering (1 or 2 cm can already give a bias). Will likely need averaging over many tracks.
    - Low statistics (less than 70/day/10 kt) mean this can likely be a coarse cross-check but not a primary measurement

Q2. To obtain full coverage over the TPC drift volume, laser tracks must penetrate into the liquid argon slightly more than 20m. Are there any technical concerns associated with this requirement?

- There is still no proof that 20 m tracks can be obtained. 20 m is based on the fact that MicroBooNE observed 10 m long tracks (while not at full laser intensity).
- Size and divergence of the laser beam are main limitations.
  - For the Surelite I-10 laser, nominal beam diameter is 6 mm and divergence is 0.5 mrad. MicroBooNE used an iris to restrict the beam to 1 mm diameter.
  - This beam size is not finalized for DUNE yet, but assuming 2 mm from Iris, the spread at 20 m can be calculated to be 12 mm (6 times wider).
  - B/n the cold mirror and a distance of 20 m, the beam size is multiplied by 2.7 and so the photon density is ~7 times smaller.
  - MicroBooNE observed 10 m long tracks, for which the photon density is 4 times smaller than at the cold mirror.
- Rayleigh scattering also contributes to decrease the beam photon density but, with a scattering length of 40 m, its effect should be smaller than the beam divergence.
- *These considerations motivate that one should not increase the laser beam paths by further reducing the number of ports used by laser.*

Q3. What limits the range of the laser beam? What is the transverse spread of the laser beam over this range in mm? **What is the MicroBooNE experience with the ionization density along the length of the beam? Is it constant? Is it reproducible? What is the dynamic range covered by the beam in units of MIPs, for example?**

- For the first 2 parts of this question, see response to the question before this.
- For the rest, here is what we know:
  - MicroBooNE did observe some non-uniformities in the ionization density along the beam, attributed to self-ionization or Kerr effect.
  - uB colleagues have indicated that this effect was dependent on intensity and that an optimal intensity setting could be found, where there was enough ionization to see a track, but not so much that it would be distorted.
  - We expect the need to have a very good intensity control, and therefore we will have a remotely controlled attenuator in the laser box, plus an adjustable iris to limit the beam diameter.
  - MicroBooNE observed laser tracks with “visible dE/dx” of a few mips (the “actual dE/dx” is smaller as the beam is broader than a particle track).
  - uB observed that once the attenuator is tuned to take into account the angle-dependent mirror reflectivity, the track charge is well reproducible. The dynamic range is quite wide: few mips and up to saturating the ADC...

Q3 Continued

- Moreover, for all charge-based measurements with laser, our plan is to calibrate it with an extensive scan of tracks parallel to the APA (to remove drift-dependent effects) at different laser intensities.
- One can also explore shooting multiple laser tracks at the same location to average out fluctuations (like in ArgonTUBE), taking care to not create additional space charge along the tracks.

Q4. How closely does the electronics pulse shape associated with the laser beam mimic the pulse shape from particles? Is the angular dependence on recombination something that can be extracted from laser beam tracks to tracks from charged particles?

- The beam width is expected to be between 4.5 and 12 mm (assuming 2 mm laser beam diameter). It is possible that the laser tracks will lead to slightly wider pulses than mips. But, these differences can be addressed at the hit reconstruction level
- The dE/dx of laser tracks is expected to be smaller and surely much harder to predict than for particles. That implies an actual measurement of the recombination model parameters will be very hard with laser.
- But, laser can be useful to measure the relative dependence of the recombination factor on the angle ϕ w.r.t. E-field, essentially to confirm or disprove dependence according to $A/(1+ B/\sin \phi)$.
- Small-scale measurements with laser at Bern show a decrease of the collected charge when the E-field is decreased, showing that the dE/dx ionization regime for lasers is small but measurable.

Q4 Continued

- In ProtoDUNE and DUNE we can increase the effect by decreasing the angle w/ r to the field. We can then compare the collected charge versus ϕ for very small values of ϕ, therefore enhancing the B/sin ϕ term.

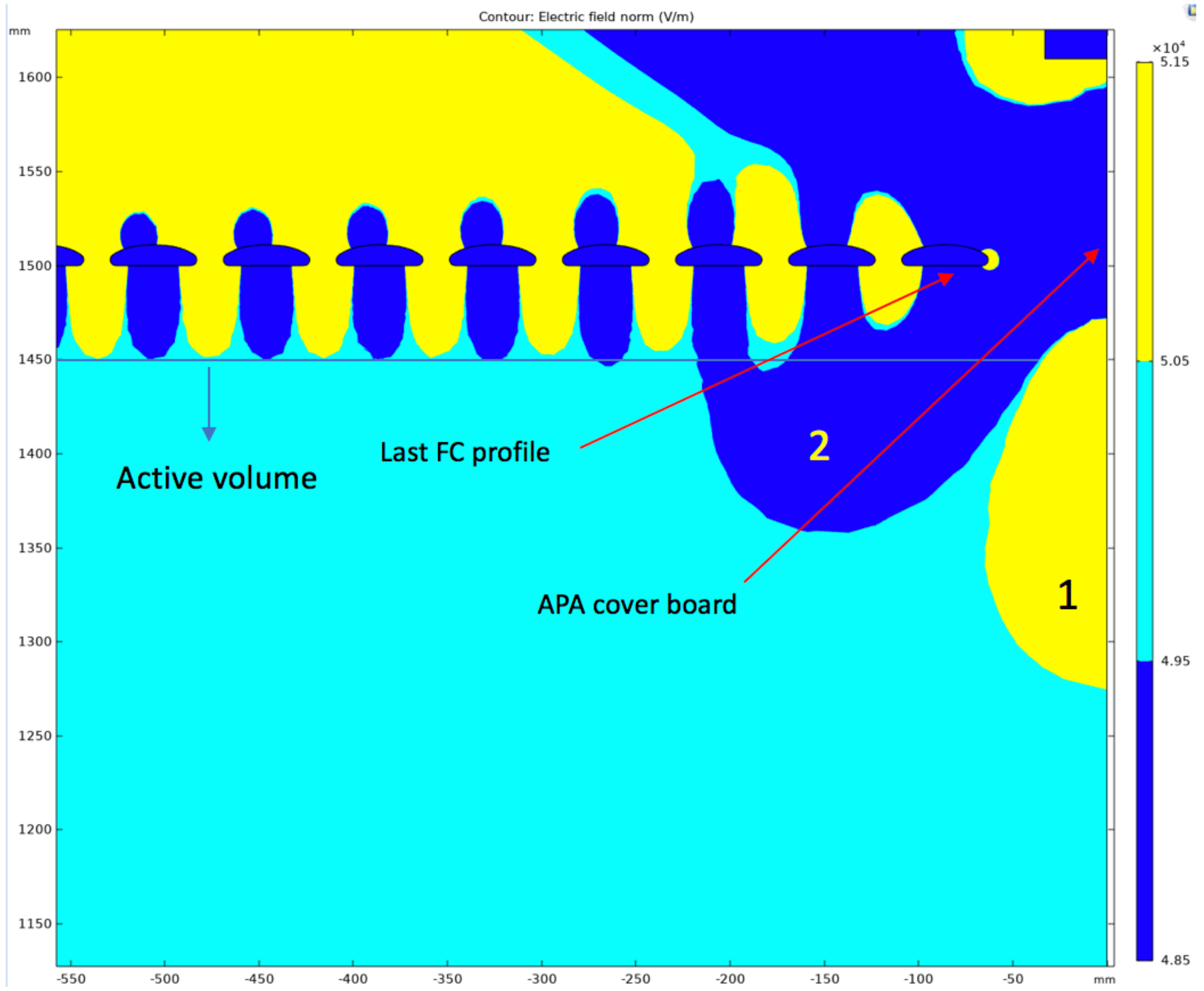
- A general procedure for energy-based measurements with laser is as follows:
  - Using attenuator and iris, find intensity and collimation parameters leading to the lowest self-focusing effects
  - *Calibrate* intensity along track using laser tracks parallel to APA (keep the effects from drift constant)
  - Use non-parallel tracks, corrected with the previous, to measure effects of drift
  - Low-angle tracks may give indication of recombination angular dependence

Q5. Based on Bo’s electric field map of the active volume surrounding the laser penetration field cage opening, please specify the boundaries of the region within this active volume with >1% shifts in the electric field relative to nominal.

It is relevant to discuss 4 cases here.

Case 1: No FC opening (nominal E-field)

- Even without any FC opening, due to the larger gaps between APA and the first FC profile of the top and bottom FC modules, there are >1% distortions seen within the active volume (AV). This extends to ~20 cm in X and ~15 cm in Y into the AV.
- Because these distortions are present across the full length of the TPC, **the total active volume impacted is of the order of 10 m^3 (0.1% of 10^4 m^3).**



“No FC opening” case.

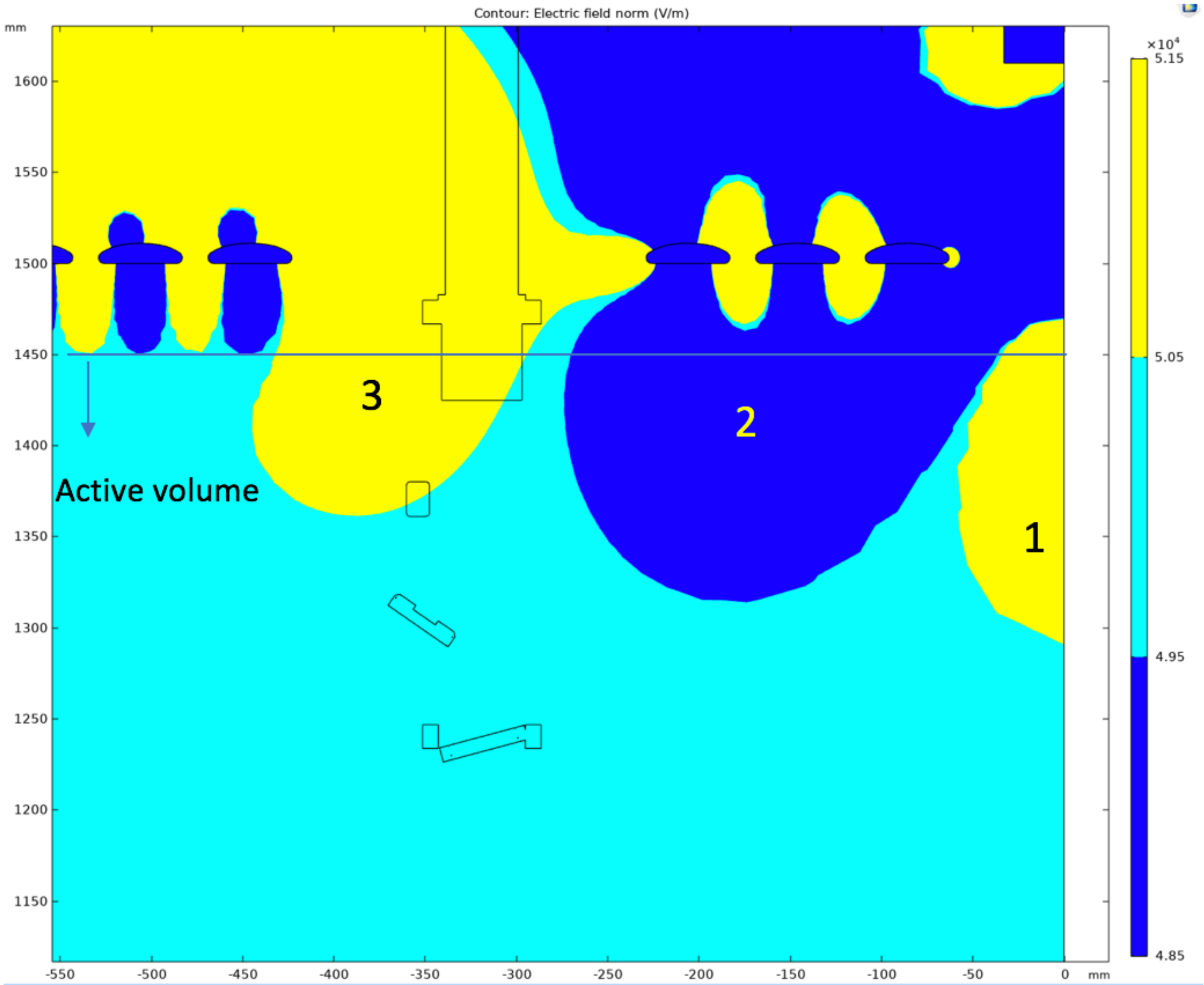
Distortions due to the larger gap b/n APA and the first FC profile. Cyan region is < 1%, Blue and yellow are > 1% effects (same definition holds for all figures below).

Active volume starts at 1450 mm.

Q5 Continued

Case 2: FC opening only

- In this case, the affected region of >1% distortions is increased. It extends to ~45 cm in X and stays at ~15 cm in Y into the AV.
- **The impacted volume due to each FC opening is about 0.007 m^3. And for 12 FC openings, this results in a total of about 0.085 m^3.**



"FC opening only" case.

Affected active volume is increased compared to nominal.

Two 0.1 m hemispheres (for yellow region 3 and blue region 2) are used to estimate the impacted active volume. Region 1 remains same.

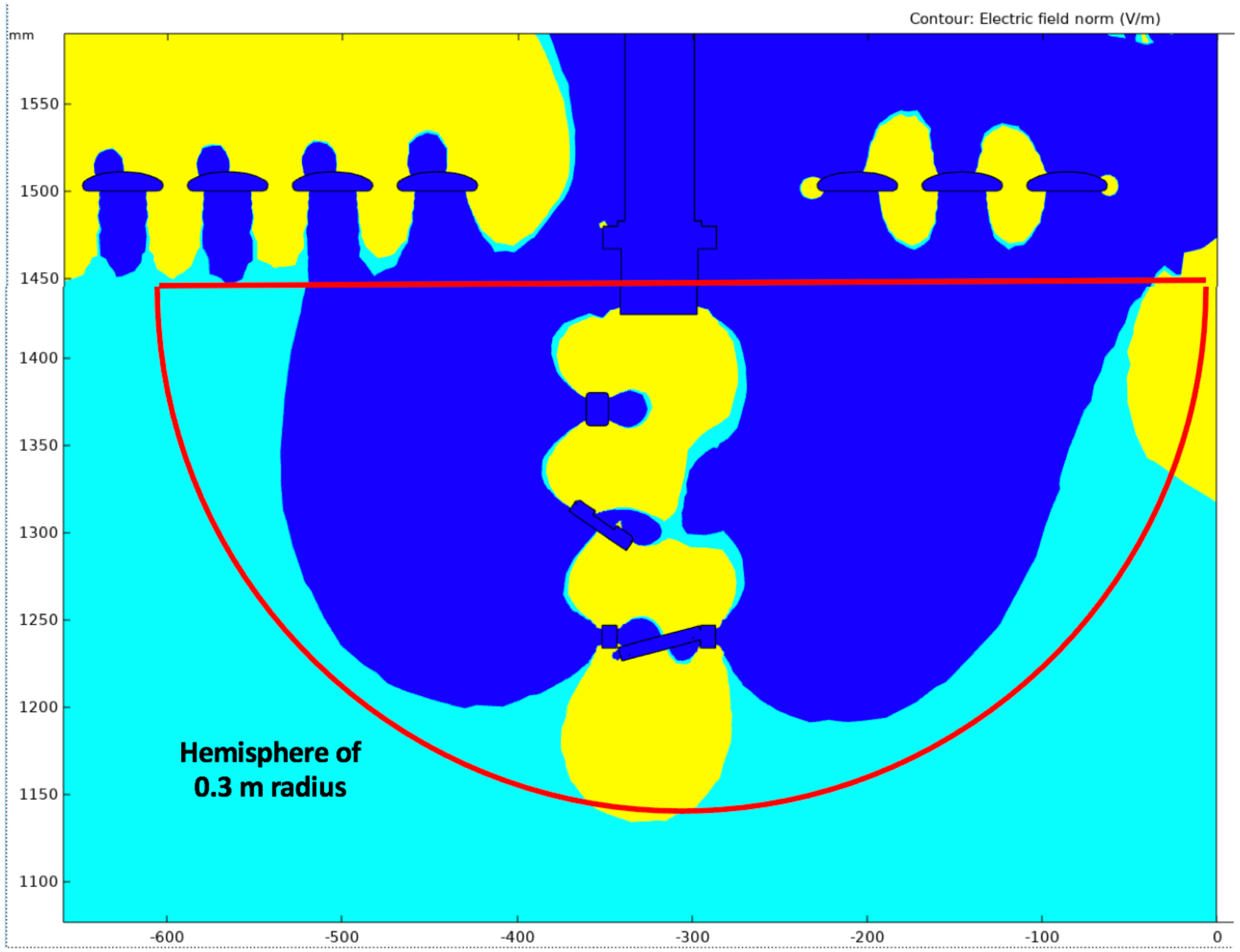
Case 3: FC opening with periscope retracted to 10 cm or beyond above the top FC

- In this case, there is no additional noticeable effect on the AV w.r.t. the "FC opening only" case.

Q5 Continued

Case 4: FC opening with laser inserted at ~25 cm below the top FC

- Why ~25 cm? This is motivated by the requirement to have the periscope mirror below the FC I-beam by ~10 cm to prevent shadowing.
- Affected region of >1% distortions is further increased w.r.t. the “FC opening only” case. It extends to ~50 cm in X and ~30 cm in Y into the AV.
- **The impacted volume due to each FC opening is about 0.056 m^3. And for 12 FC openings, this results in a total of about 0.7 m^3.**
- **This is a 7% effect compared to the nominal loss due to the APA gaps (case 1) and is a 7×10^{-5} fraction of the total AV.**



“FC opening + Periscope” case.

Affected active volume is increased compared to “FC opening only” case.

Active volume starts at 1450 mm.

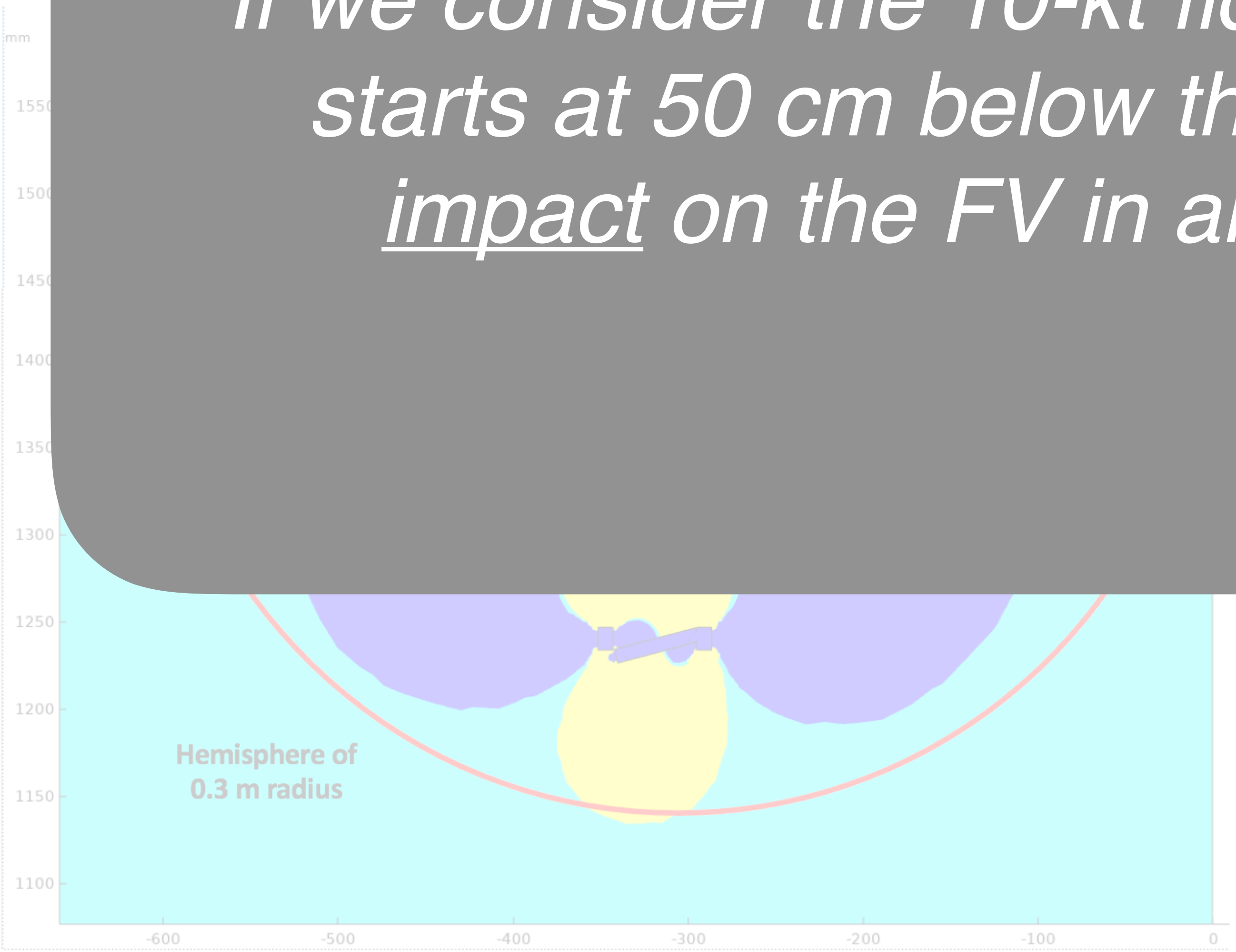
A hemisphere of 0.3 m radius is drawn to estimate the impact on the active volume; as clearly seen this overestimates the impacted volume.

Q5 Continued

Case 4: FC opening with laser inserted at ~25 cm below the top FC

- Why ~25 cm? This is motivated by the requirement to have the periscope mirror below the FC I-beam by ~10 cm to prevent shadowing.
- Affected region of >1% distortions is further increased w.r.t. the "FC opening only" case. It extends to ~50 cm in X and ~30 cm in Y into the AV.

If we consider the 10-kt fiducial volume (FV) which starts at 50 cm below the top FC, there is <u>zero impact</u> on the FV in all 4 cases listed here.



A hemisphere of 0.3 m radius is drawn to estimate the impact on the active volume; as clearly seen this overestimates the impacted volume.

Laser Beam Location System (LBLS)

Q1. The TPC will move relative to the cryostat during the cool-down process. How can measurements made at the pin diode sensors be used to calibrate the position of a laser track relative to the TPC based on survey measurements of the pin diode pad locations relative to the APAs and CPAs made in the warm?

- Both pin diode system and laser periscope are in the cryostat reference frame
- Mirror pads are on the FC reference frame
- Combination of the data obtained with the mirror system and with the pin diode system can better pinpoint localization of the laser periscope during the actual cool-down.
- Alternatively, one can consider two options
    - hang the LBLS PIN diode pads at the floor level from the FC supports (possibly I-beams). (*see figure on next slide*). This way the diodes remain at the floor level (far from FC), but follow the motion of the FC, retaining consistency between survey measurements in warm and actual positions in cold.
    - Hang some of the PIN diode pads from the FC supports (TPC frame) and some glued to the cryostat floor

Q1 Continued

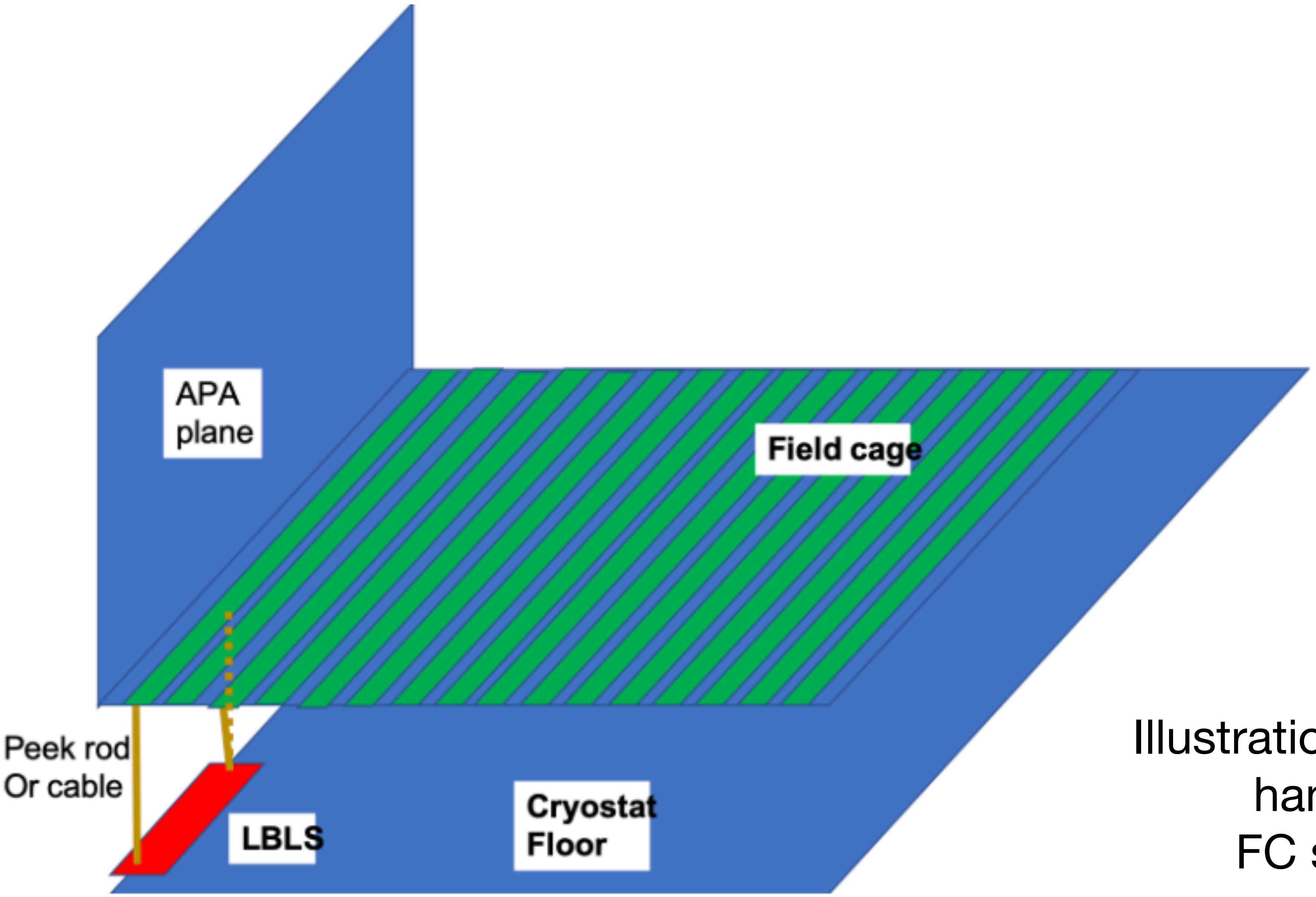


Illustration of pin diode pads
hanging from the
FC support beams

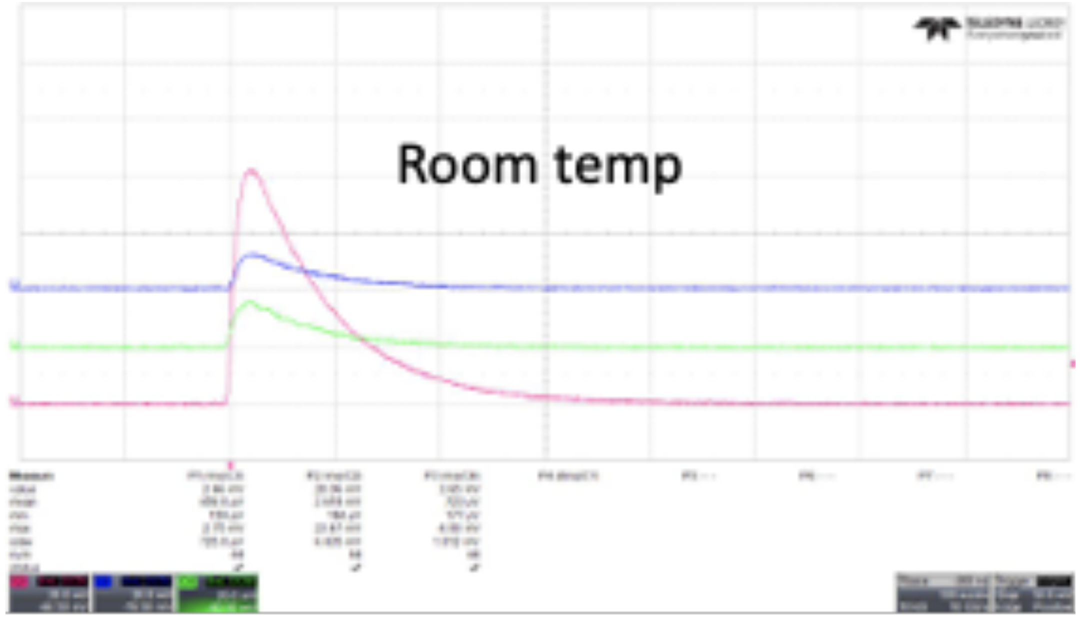
Q2. Are the mirror pads inserted in the top or bottom field cage panels (or both)? The proposed layout seems to provide two geometric points within the TPC that can be measured relative to the position of each laser penetration. Since both points are located within a single TPC plane, does this really fully constrain the orientation of the TPC relative to the location of each laser penetration? Would it be better to develop an arrangement of mirror pads (e.g. pads on the top, bottom, and end-wall field cage modules) that could provide at least three independent TPC space points relative to each laser penetration?

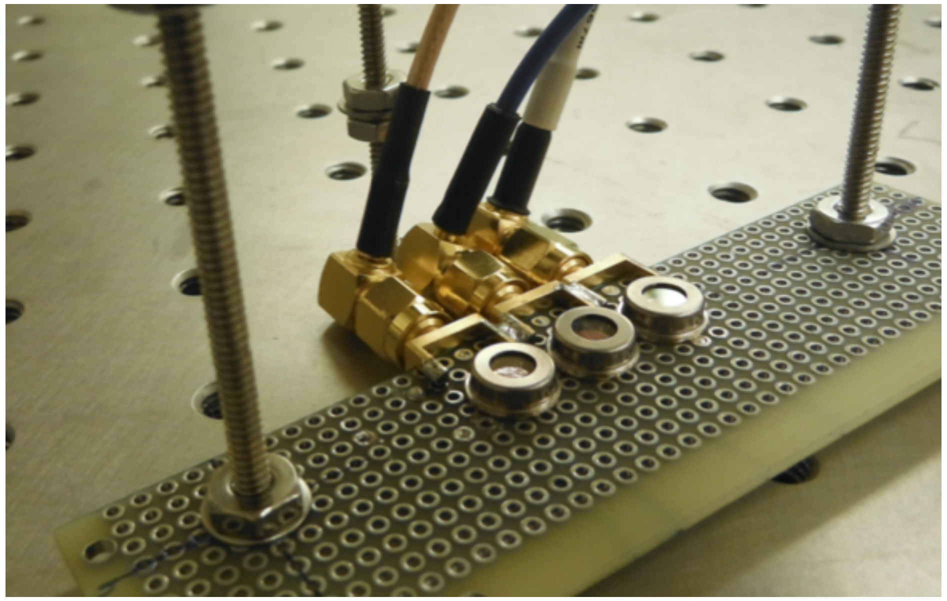
- In the standard configuration, the mirror pads are planned for the bottom FC modules, and in the “extended” configuration, in the end-wall FC modules as well.
- In PD-II, we plan to install pads on both the bottom and end-wall FC. We do not plan to install pads on the top FC modules because the FC I-beams block the path to pads located beyond the I-beams (located at distances between 30 cm and ~1.5 m away from the laser system cold mirror, depending on the location).
- It could be possible to hit a pad located within maybe a 1 m or so, but the angular precision of that calibration would be much worse than hitting a pad at 12 or 15 m
- Still, if it could be useful in order to constrain cool-down effects, the pads should be low-cost enough that we could think of having a few of them close to some periscopes on the top FC.
-

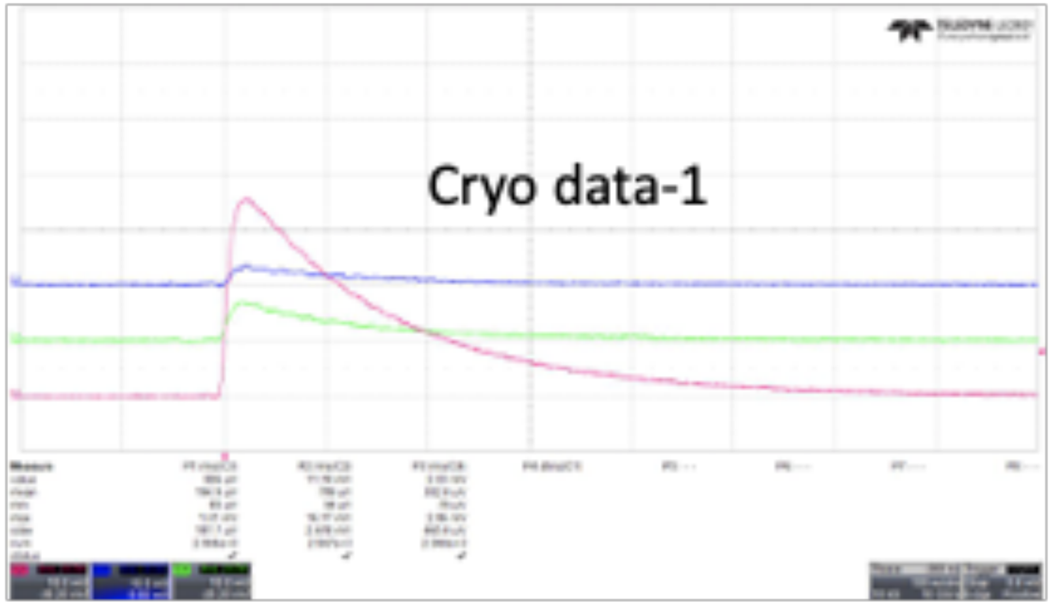
Q3. Do the pin diode sensors provide pulse height information that would be potentially useful for tuning and monitoring the laser intensity?

- Yes, the PIN diode sensors provide pulse height information and can be used for tuning and monitoring laser intensity.
- 3 pin diodes illuminated by 266 nm NdYag laser
- Different signal heights from the three adjacent illuminated PIN diodes allow for reconstruction of the center of the beam spot by looking for the peak weighted average center of the signal.
- Signal features fast rise time

Magenta: central diode
Green, Blue: outer diodes

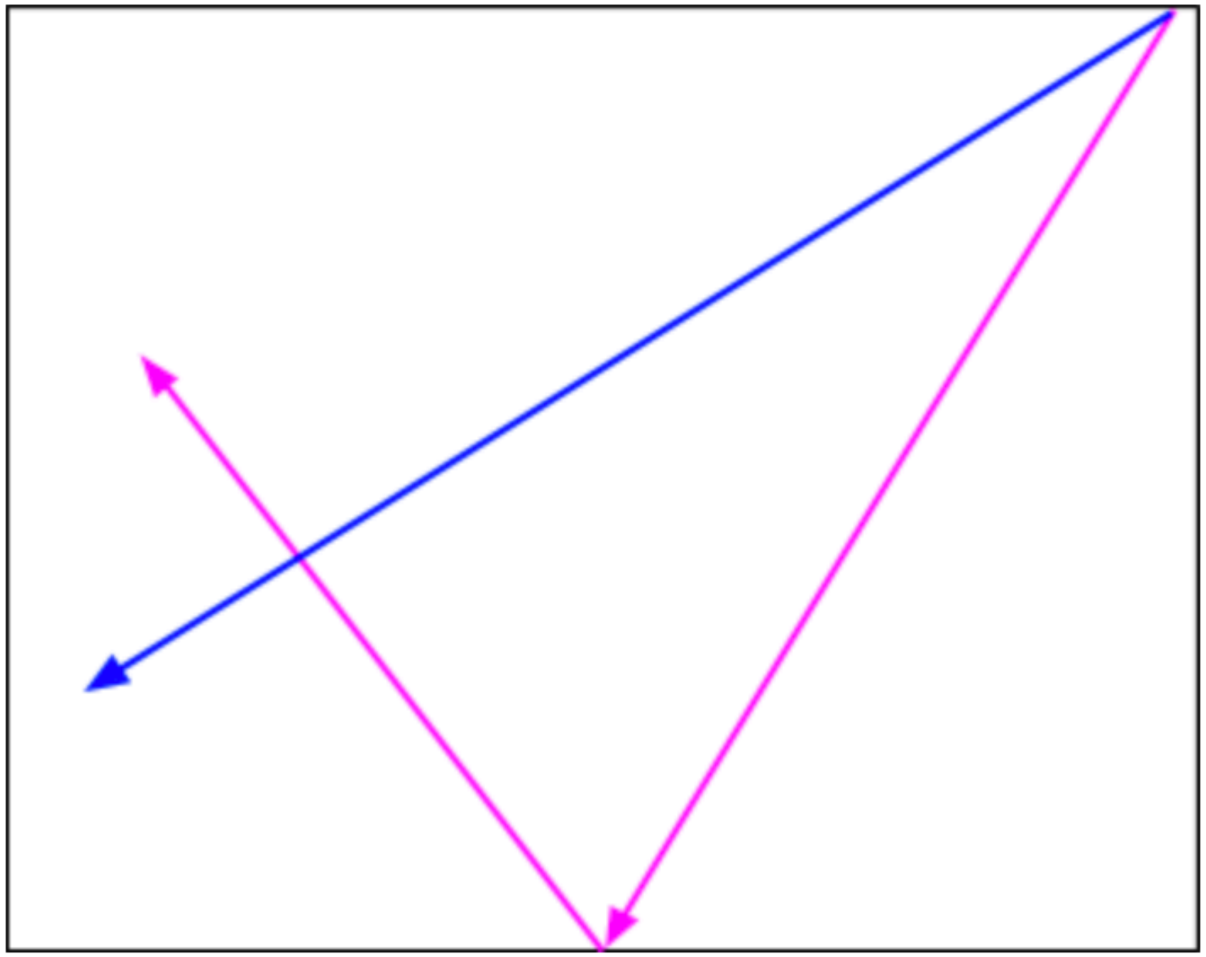






Q4. Do the mirrors play a role in increasing the overall laser coverage? Could the mirrors play the role in creating additional tracks to help resolve ambiguities?

- Yes, but in practice that increase in coverage would be very small.
- It is true that a single laser periscope can create tracks of different angles in the same region. As an example, in the next figure the blue and second magenta lines have different angles and can cross even if they are coming from the same laser.



The requirement on the straightness of the FC profiles would be very stringent. A small tilt of 0.1 deg on the profiles causes a 1cm beam deviation at 6 m from the mirror.

Q4 Continued

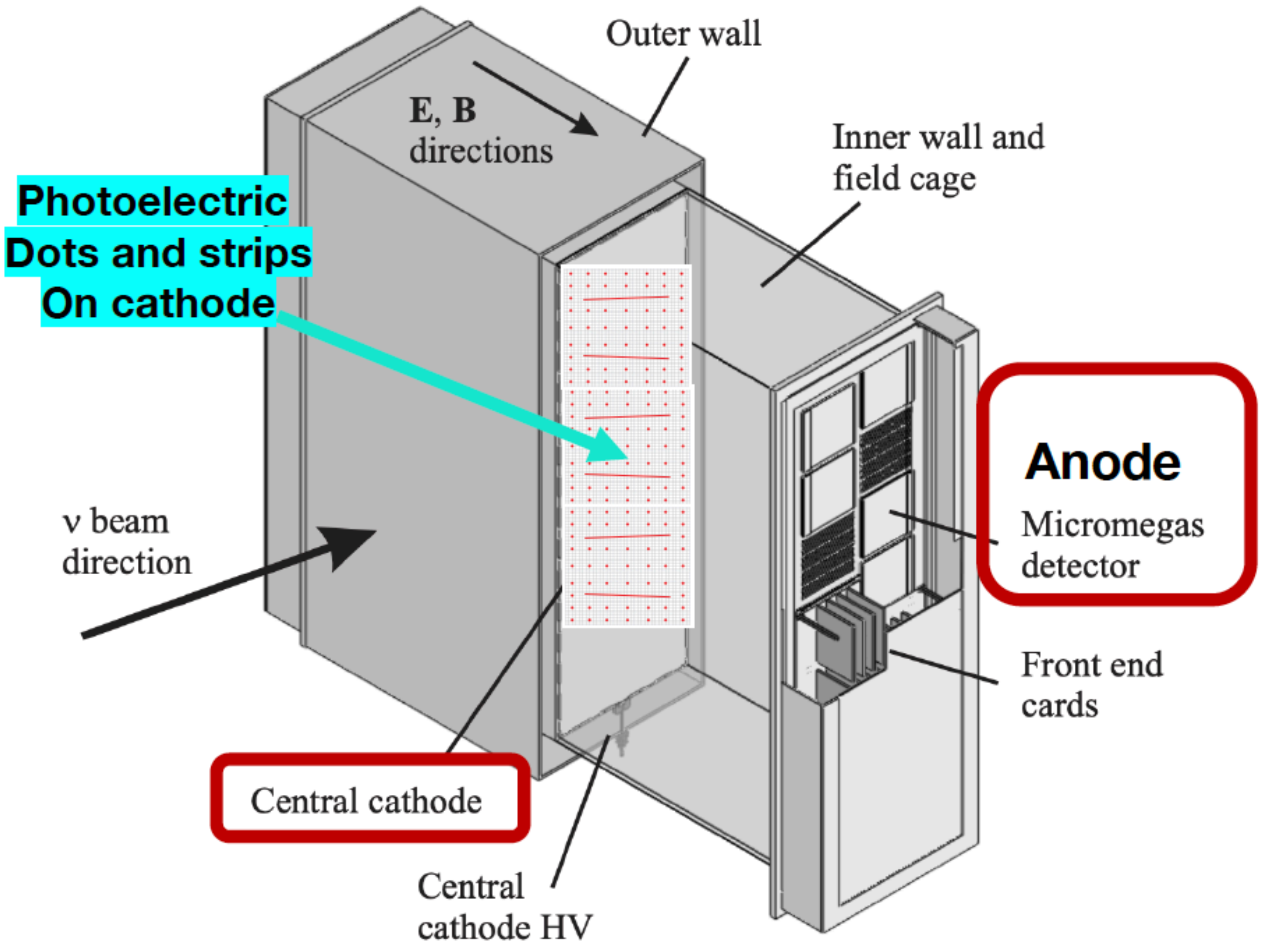
- The limitations of this scheme are the following:
  - The reflected beam (magenta) will be less intense and wider than the direct one (blue) because it is longer and has been reflected (depends on mirror reflectivity). We still don't know what length of the reflected beam could be useful for a calibration. The requirements on the beam quality are less stringent if the only desire is to identify which of the 5 mirrors was hit.
  - We chose the location of the pads (1 m away from CPA) and the tilt angle (10 deg) with the intention to limit any possibility that the reflected beam hits the PDS within the APA. That implies that the spatial region where we get reflected beams is limited: close to CPA, low in y and close to [0/15/29/44/58 m] in z.
    - And even in that region, the number of mirrors per pad is 5, so the number of useful tracks is also fairly limited.
  - We will learn more about this in PD-II.

Photoelectron Laser
(PE Laser)

Q1. **How was this system used in the T2K near detector** and what is the applicability of that system to a liquid argon detector?

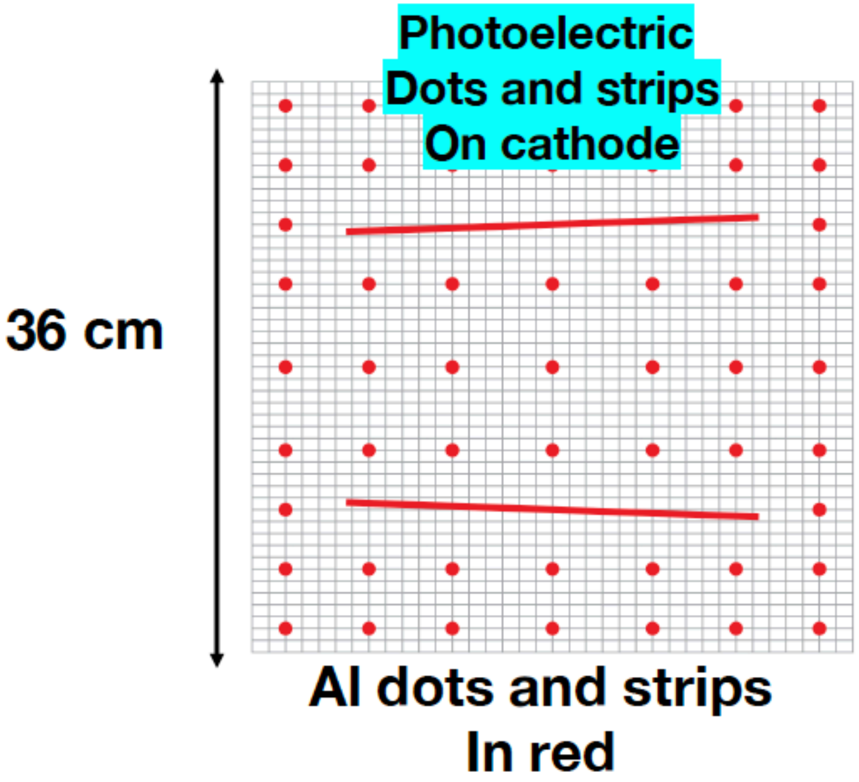
Schematics of gaseous TPC –
part of T2K Near Detector complex.

https://arxiv.org/abs/1012.0865



- In T2K, PE laser was deployed in gaseous TPC.
- TPC: 95% Ar gas, 3% CF_4 and 2% C_4H_{10}.
- Bulk micromegas are used for charge readout.
- 8 mm Al dots and 20 cm long Al strips glued on copper cathode as photoelectric targets.

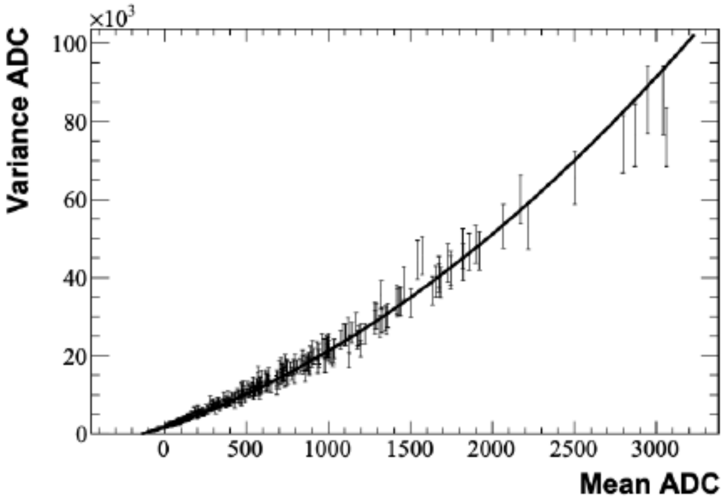
Q1. **How was this system used in the T2K near detector** and what is the applicability of that system to a liquid argon detector?



- 266 nm NdYag laser used for illumination
- 100 pe's per dot
- 2 pe/mm^2 from Al and 0.03 pe/mm^2 from Cu
- Data collected during 3. 5 s inter-spill periods during the beam run

$$t_{drift} = t_{anode} - t_{laser\_pulse}$$

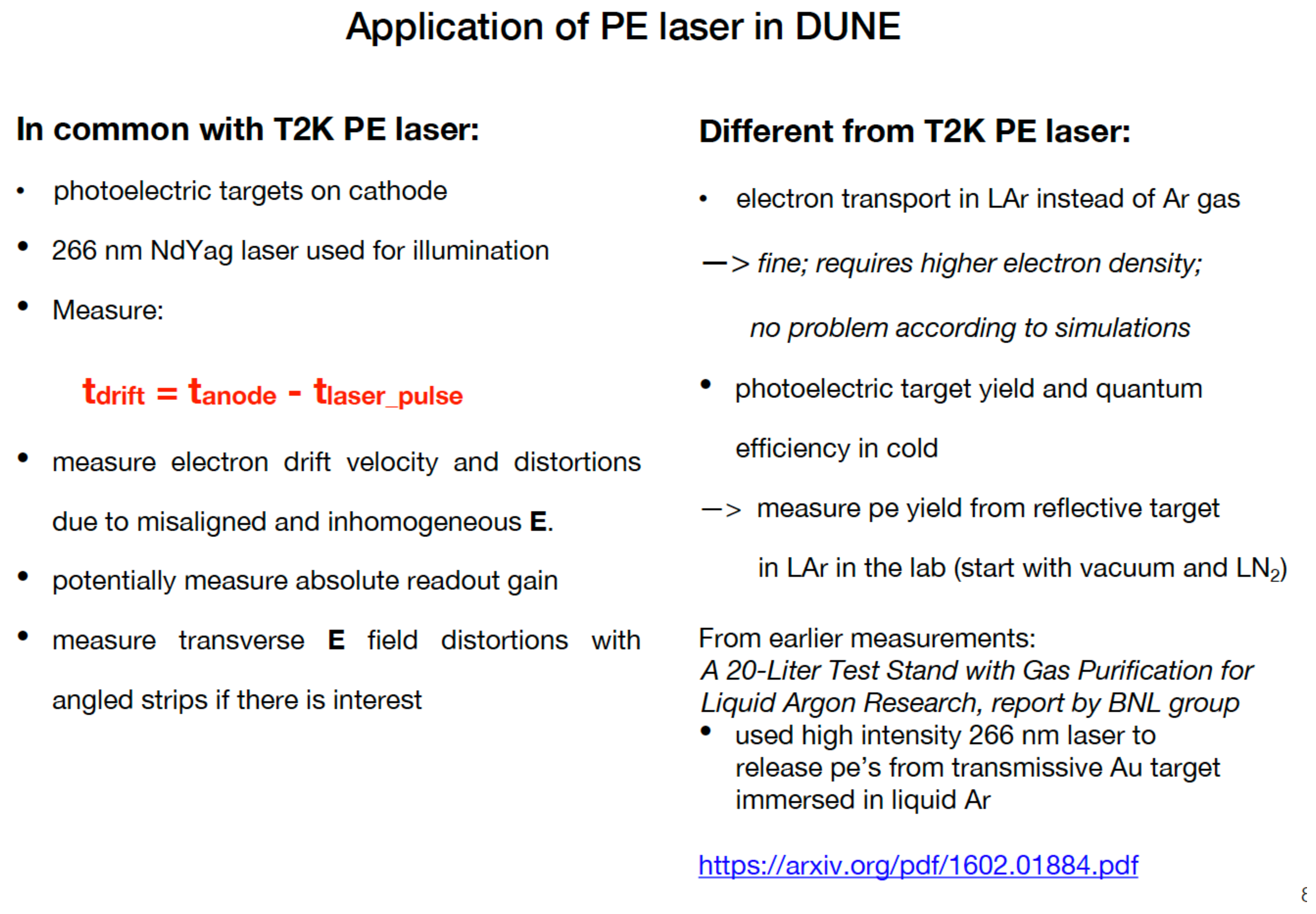
- measured electron drift velocity and distortions due to misaligned and inhomogeneous **E** and **B**.
- displacements measured at 0.1 mm
- measure absolute readout gain
- angled strips used to measure transverse **E** field distortions



Fit to estimate the gain, magnitude of opposite polarity pulses, and laser variation

https://arxiv.org/abs/1012.0865

Q1. How was this system used in the T2K near detector and **what is the applicability of that system to a liquid argon detector?**



Application of PE laser in DUNE

In common with T2K PE laser:

- photoelectric targets on cathode
- 266 nm NdYag laser used for illumination
- Measure:

$$t_{drift} = t_{anode} - t_{laser\_pulse}$$

- measure electron drift velocity and distortions due to misaligned and inhomogeneous **E**.
- potentially measure absolute readout gain
- measure transverse **E** field distortions with angled strips if there is interest

Different from T2K PE laser:

- electron transport in LAr instead of Ar gas

—> *fine; requires higher electron density;*

no problem according to simulations

- photoelectric target yield and quantum efficiency in cold

—> measure pe yield from reflective target in LAr in the lab (start with vacuum and LN_2)

From earlier measurements:
A 20-Liter Test Stand with Gas Purification for Liquid Argon Research, report by BNL group

- used high intensity 266 nm laser to release pe's from transmissive Au target immersed in liquid Ar

https://arxiv.org/pdf/1602.01884.pdf

Q1. How was this system used in the T2K near detector and **what is the applicability of that system to a liquid argon detector?**

Application of PE laser in DUNE

- Ongoing simulation studies with pe clouds in LArSoft to understand the expected performance for DUNE in the following areas:
  - Drift velocity measurement throughout the TPC volume
    - Peak arrival times on collection wires
  - Drift velocity, E-field distortions and reconstruction capability.
    - PE target position displacement on APA
  - Transverse diffusion measurement
    - Horizontal and vertical strip signals: compare locations with their collection wire images.
  - Charge collection efficiency and reconstruction: compare collected and emitted charge from the PE target.
    - Dependence on the laser beam injection efficiency, light attenuation in fibers, illumination opening angle, reflective quantum efficiency of photoelectric effect in LAr.
  - CPA planarity with a sufficient network of targets and illumination.

Q2. What is the rationale for 18 fibers per drift volume (6 locations x 3 heights)? Is this driven by technological constraints (e.g. the maximum number of fibers that can be driven by a fixed number of lasers) or is it driven by calibration requirements? APA doublets define 25 independent drift regions within a given drift volume and only a limited number of these would be probed with the current system configuration.

- There is no technical requirement that prevents us from increasing the number of fibers for better coverage of photoelectric targets on CPA.
  - We can use multiplexers for light injection and inject light in a fraction of fibers at the time.
  - In T2K, an electro-mechanical multiplexer was built to direct the UV light pulses from the laser into any one of the fibers by moving a mirror.

- Original (historical) argument for 6 locations: maximize illumination area by each fiber:
  - Assume an average 10 m diameter illuminating circle by each fiber
  - 6 locations cover the entire detector length (6 x 10 m = 60 m detector length)
  - Sufficient number of photoelectrons generated from the target, based on crude estimate.
- *More recently, explore fibers with built-in diffusers, but limited opening angle.*

Q2 Continued

The purpose of this estimate is to establish upper limit in the PE yield based on a set of assumptions in order to understand the limitations of the system. The PE yield can be lowered with variable attenuator to desired level.

Laser power	50 mJ	$6.7\cdot10^{16}$ photons per pulse
UV fiber coupling (80% vendor spec sheet)	*50%*	$3.35\cdot10^{16}$ photons per pulse
Attenuation in fiber -0.235 dB/m at 25 m	0.258 tran. factor	$8.6\cdot10^{15}$ photons
Distance to CPA center: SQRT($3.53^2+6.1^2$) = 7 m	At 10 diameter	$9.3\cdot10^{9}$ photons/cm^2
Distance to CPA center sqrt ($3.53^2+6.1^2$) = 7 m	At 2.7 m diameter	$1.5\cdot10^{11}$ photons/cm^2
Quantum efficiency (reflective) of Al PE target	10^{-6}	
PE yield (with added diffusers at the end of fiber – example Edmund Optics UV holographic diffusers)	Opening angle 71°	**10^4 pe's/cm^2**
PE yield (Polymicro UV quartz fibers with built-in diffusers thanks to side cut fiber tip termination)	Opening angle 22°	**$1.5\cdot10^5$ pe's/cm^2**

Q2 Continued

Assumptions used for estimation:

- Use IO laser planned power
- 50% beam injection in the fiber (will be tested in the lab using power meter)
- Attenuation in the fiber based on fiber specs.
- Utilize a diffuser with a controlled opening angle
- Assume a single average distance between fiber and target. Distance between fibers and targets will vary:
  - from 3.4 m - flux is 4 times higher
  - to 12 m - flux is 3 times lower
- Assumes a uniform illumination within the fiber light cone
  - light illumination uniformity will be characterized in the lab
- Quantum efficiency for reflective photoelectric target is taken from the literature
  - will be measured in the lab

More detailed calculations taking into account the variation in distances between fibers and targets, fiber aperture and other considerations will be performed soon.

Q3. In the current scheme (12 fibers per laser and 20m long optical fibers), what is the estimated number of photons per pulse per fiber arriving at the cathode plane?

PE yield (with added diffusers at the end of fiber – example Edmund Optics UV holographic diffusers)	Opening angle 71°	**830 pe's/cm^2**	Insufficient (multiplexer necessary)
PE yield (Polymicro UV quartz fibers with built-in diffusers thanks to side cut fiber tip termination)	Opening angle 22°	**$1.2\cdot 10^{10}$ pe's/cm^2**	Sufficient

Illumination of the entire CPA plane with Polymicro style fibers would require 20 locations with 3 fibers per location per detector volume.

The same lasers can still serve all fibers, by injecting light in the fraction of the fibers at the time.

- This was done in T2K as well: the same laser injected light in the fraction of the fibers at the time.

Q4. What are the expected yields (electrons per incident photon) for the proposed targets? Several committee members have concerns that the yields from metallic targets will be substantially smaller in liquid argon than in vacuum. What is the plan for testing photo-electric target yields in liquid argon?

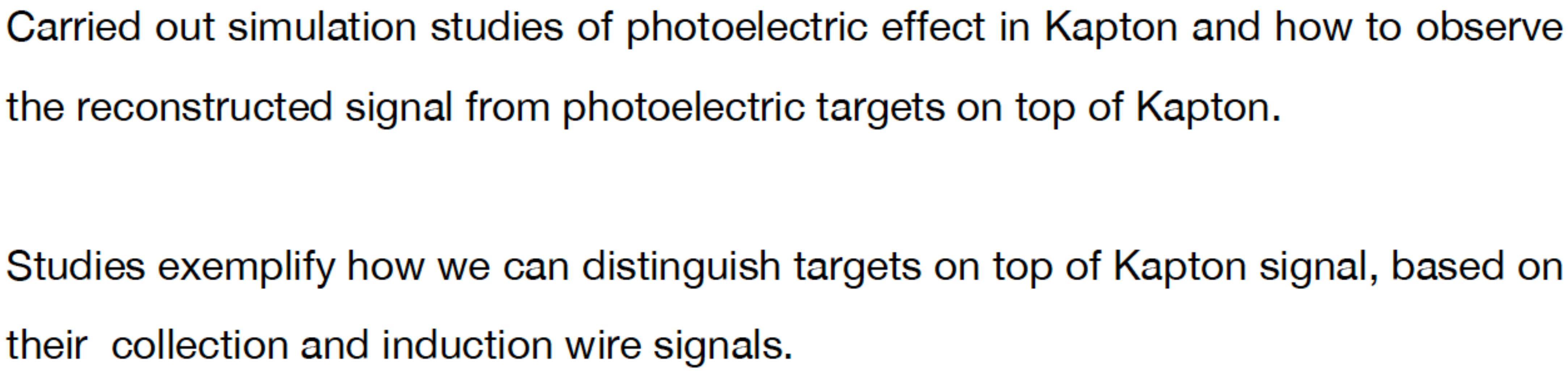
- Quoted reflection quantum efficiency for most metallic targets is ~10^{-6}
- These were all measurements performed in vacuum.

- Encouraging results from the BNL test stand:
  - Golden photoelectric target immersed in LAr used to generating pe's and drifting them in LAr to study electric field.
  - Application described in the following paper: "A 20-Liter Test Stand with Gas Purification for Liquid Argon Research", at https://arxiv.org/pdf/1602.01884.pdf

- We have built a small vacuum chamber for initial tests.
- It can be retrofitted for LAr. The difficulty is the purification system that would need to be added for proper measurement.

Due to COVID-19, all lab work was slowed down significantly.

Q5. On slide 20 of Jelena's presentation, it indicates that a 5m illumination diameter is anticipated. Is this from a single fiber? This would be about the correct size to illuminate the entire cathode plane surface parallel to a single APA. Should we be concerned that the resulting emission of electrons from all of the targets and brass connectors will produce a signal in every readout channel of the APA making it impossible to identify the electrons associated with specific targets? For a diameter this large, how non-uniform is the light over the illuminated area and does the non-uniformity remain consistent pulse to pulse?



Carried out simulation studies of photoelectric effect in Kapton and how to observe the reconstructed signal from photoelectric targets on top of Kapton.

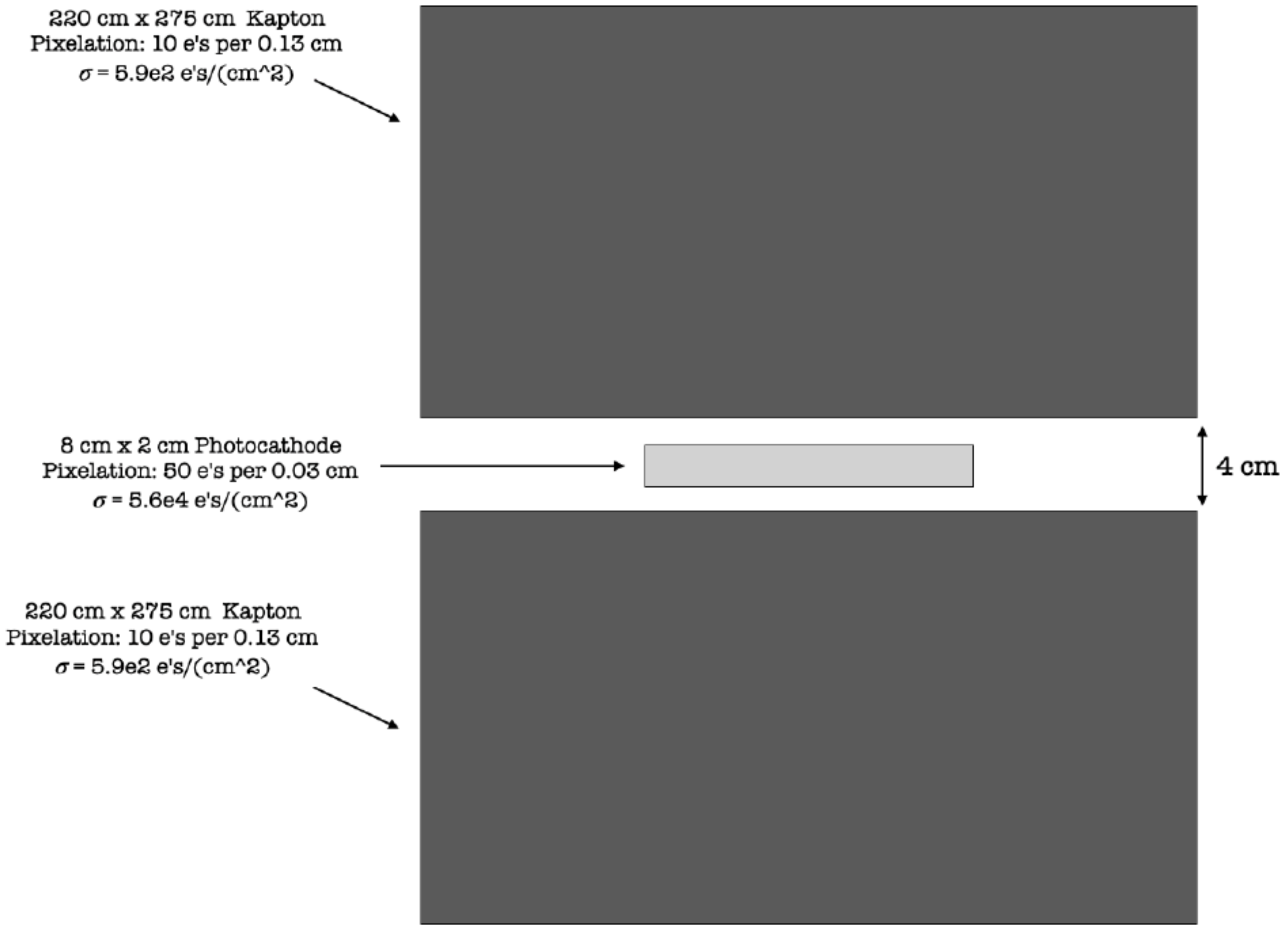
Studies exemplify how we can distinguish targets on top of Kapton signal, based on their collection and induction wire signals.

Q5 Continued

Kapton Simulation

Simulation includes photoelectric emission from two large Kapton areas (220 cm x 275 cm) with 100 times lower QE than Al (will be tested in the lab).

Simulation includes photoelectric emission from Al strip 8 cm x 2 cm.

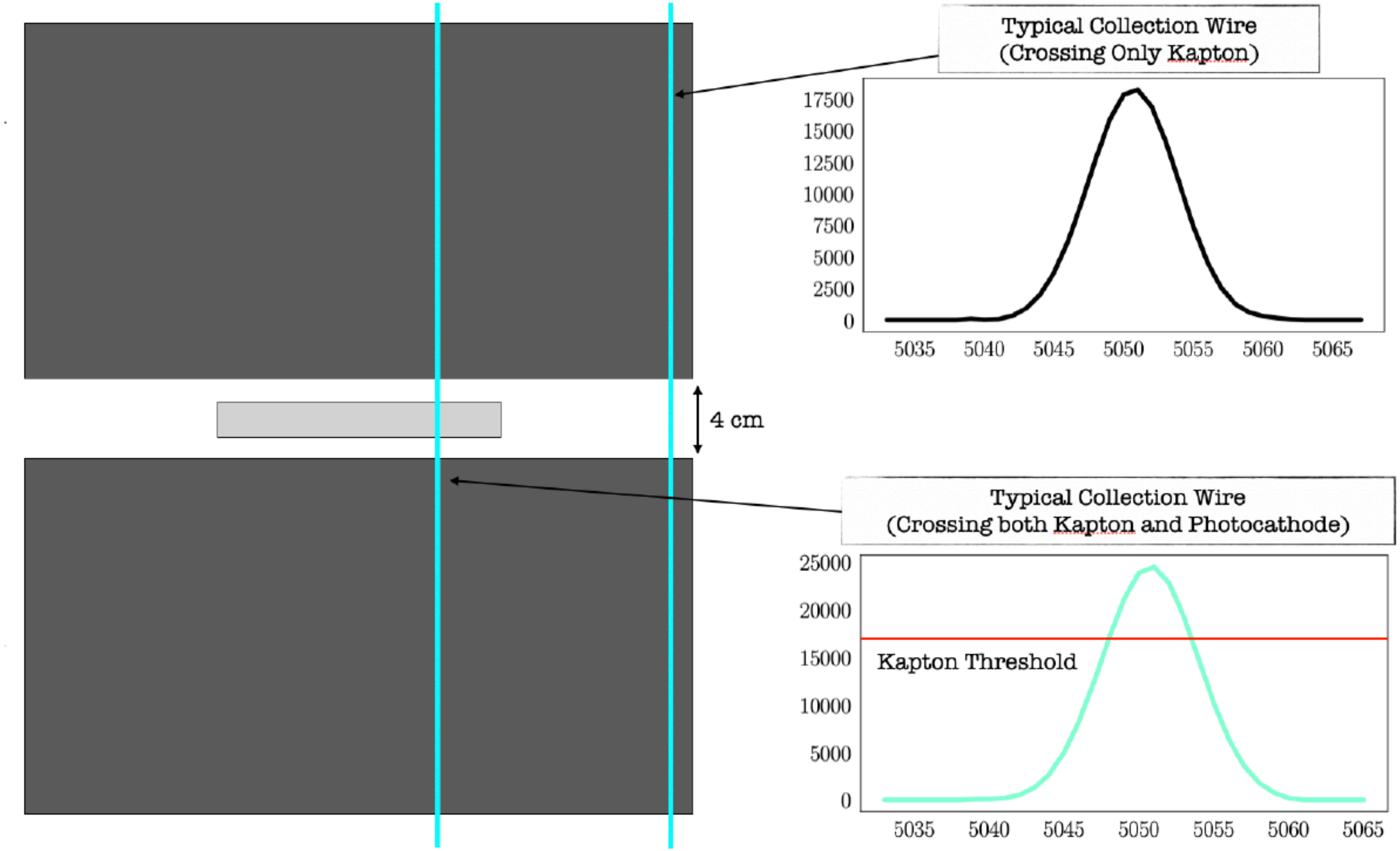


Q5 Continued

Kapton Simulation Results

Typical collection wire signal crossing Kapton strip peaks at ~24,000 (arb. units), while Collection wires that do not cross Kapton peak at ~18,000 (arb. units).

Thus, Kapton related background will be removed with threshold cut.

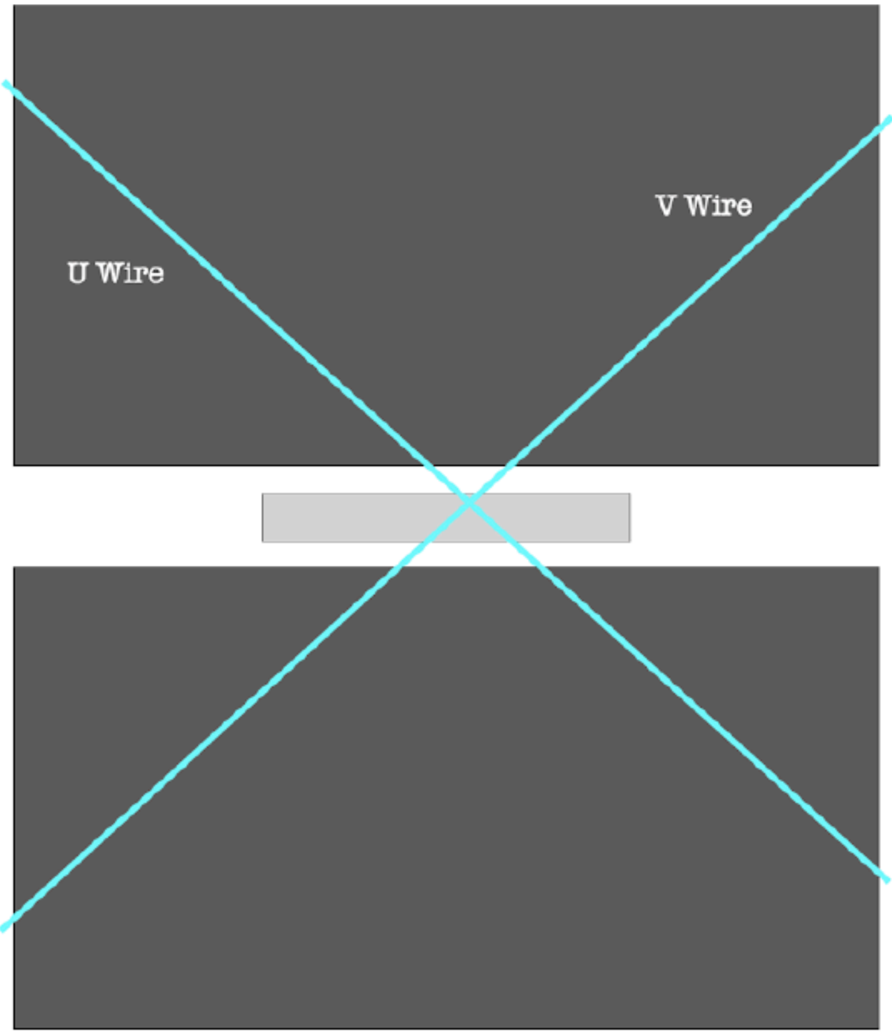


Q5 Continued

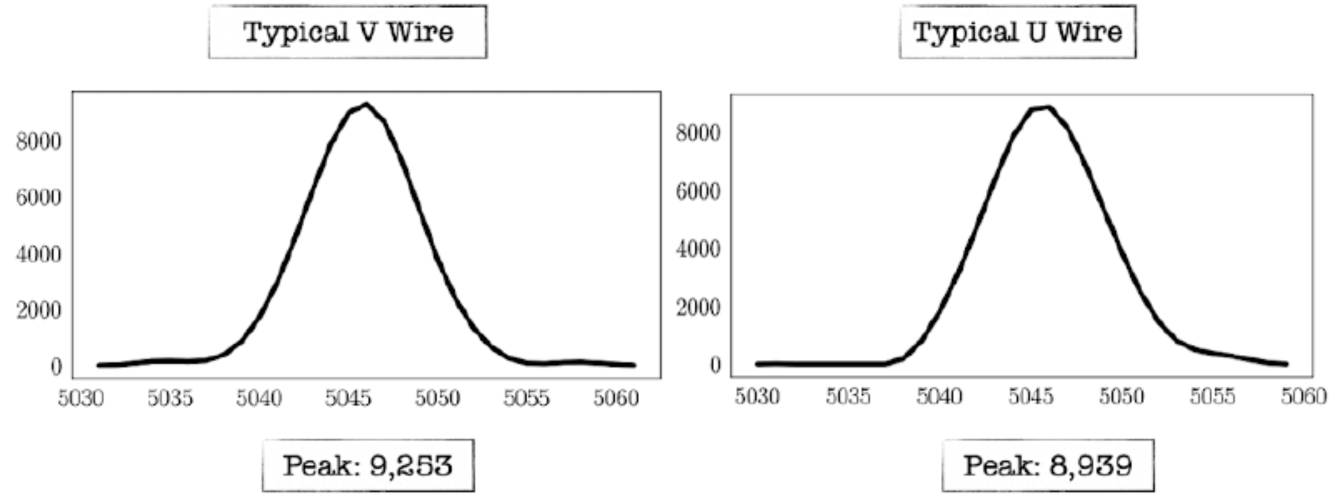
Kapton Simulation Results – Induction Wires

Typical induction wire signal crossing Kapton strip peaks at ~19,000 (arb. units), while Induction wires that do not cross Kapton peak at ~9,000 (arb. units).

Thus, Kapton related background will be removed with threshold cut.



Crossing Only Kapton



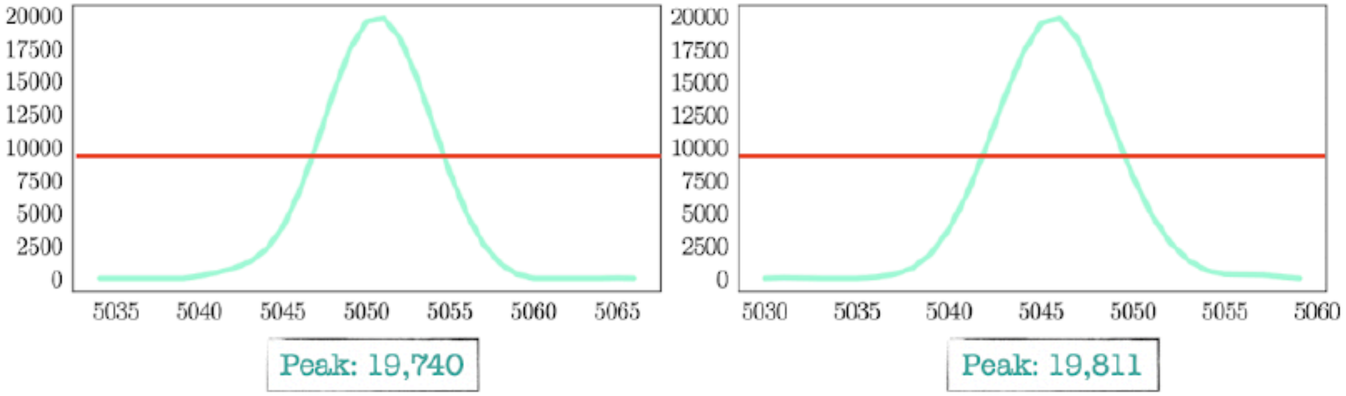
Typical V Wire

Peak: 9,253

Typical U Wire

Peak: 8,939

Crossing both Kapton and Photocathode



Peak: 19,740

Peak: 19,811

Q5 Continued

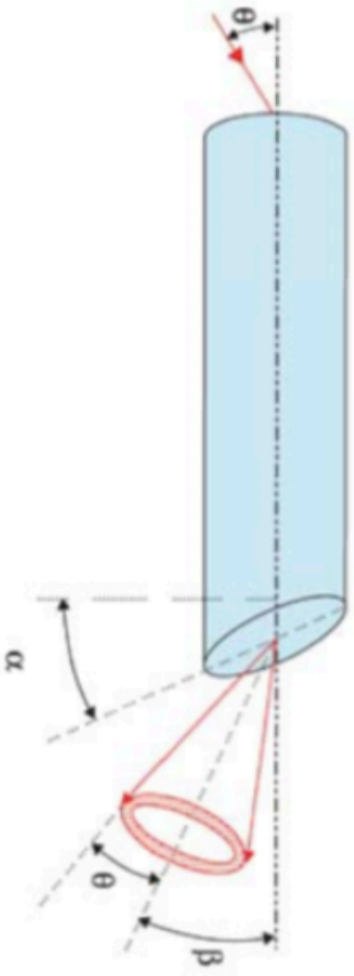
On slide 20 of Jelena’s presentation, it indicates that a 5m illumination diameter is anticipated. Is this from a single fiber? This would be about the correct size to illuminate the entire cathode plane surface parallel to a single APA. Should we be concerned that the resulting emission of electrons from all of the targets and brass connectors will produce a signal in every readout channel of the APA making it impossible to identify the electrons associated with specific targets? **For a diameter this large, how non-uniform is the light over the illuminated area and does the non-uniformity remain consistent pulse to pulse?**

- We have done simulation studies that show how we can observe the reconstructed signal on top of Kapton. Since, QE of Kapton is 100 lower, variation in non-uniformity over large area should not have significant effect except when they include PE target illumination.
- The signal to noise ratio can be better with a non-uniform light distribution (more realistic case) centered on the target.
- It could be worse if the target is on the periphery of the illumination spot.

- We do expect non-uniformity of the light coming out of the fibers and we will characterize the Polymicro fibers in the lab setting. (Set back due to COVID-19).

Q6. What is the range of opening angles for the Polymicro quartz fibers? How small of an illumination diameter is possible including the effects of diffusion in the liquid argon?

- The angle of divergence (opening angle) θ is 25.4° deg in air and 20.6° in LAr.
- It is equal to the angle that the traveling light makes with the axis of the beam, so it cannot be varied by more than a few degrees as can be seen in the picture.
- The pointing angle (β) depends on the angle (α) at which the “distal” end is cut. We can thus illuminate entire length of CPA from fibers at the top of APA.
- There is enough space between the APA and we can modify the holder to accommodate more fibers.



Side-Fire		Distal	Redirect light sideways	Tissue ablation and perforation (e.g. Urological procedures)

2

Q6 Continued

- Photo of the preliminary test to check the angular light output as claimed by the manufacturer.
- Accurate tests of light intensity and spread will use better light injection, not a handheld laser pointer like in the photo.
- In addition to subpar injection the phone camera sensor response also played into the image shown.
- The measurement setup will include a light sensor with powermeter. that can be moved in x-y direction on the screen to characterize light pattern.
- In order to accurately orient fiber, we will use a fabricated holder which is in the works.

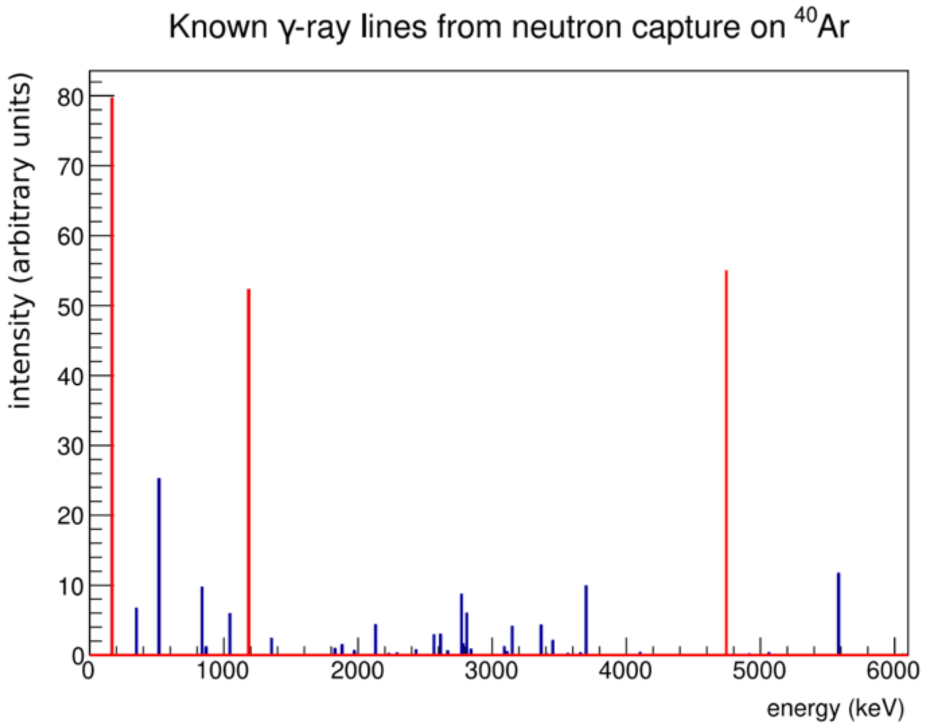
94 deg
112 deg
spread=18 deg

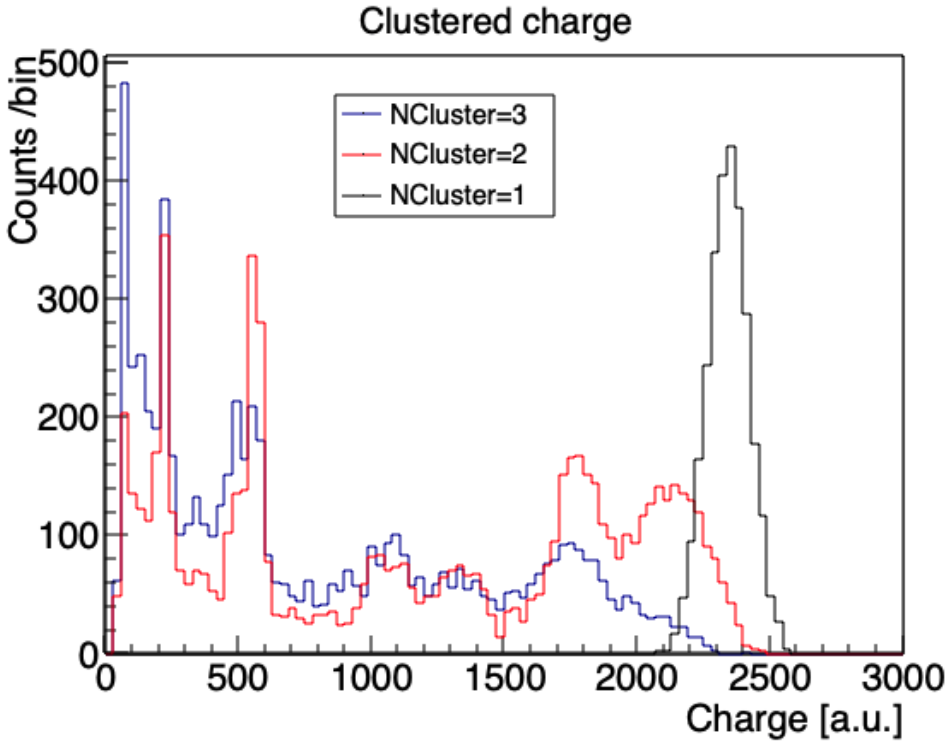
Opening angle from spec. =22 deg

Pulsed Neutron Source (PNS)

Q1. Are there simulation studies that show the energies from all gamma cascade daughters produced by the neutron capture in Argon are in fact detectable (e.g. a few hundred KeV photons undergoing Compton scattering will produce electrons with energies less than 100 KeV)?

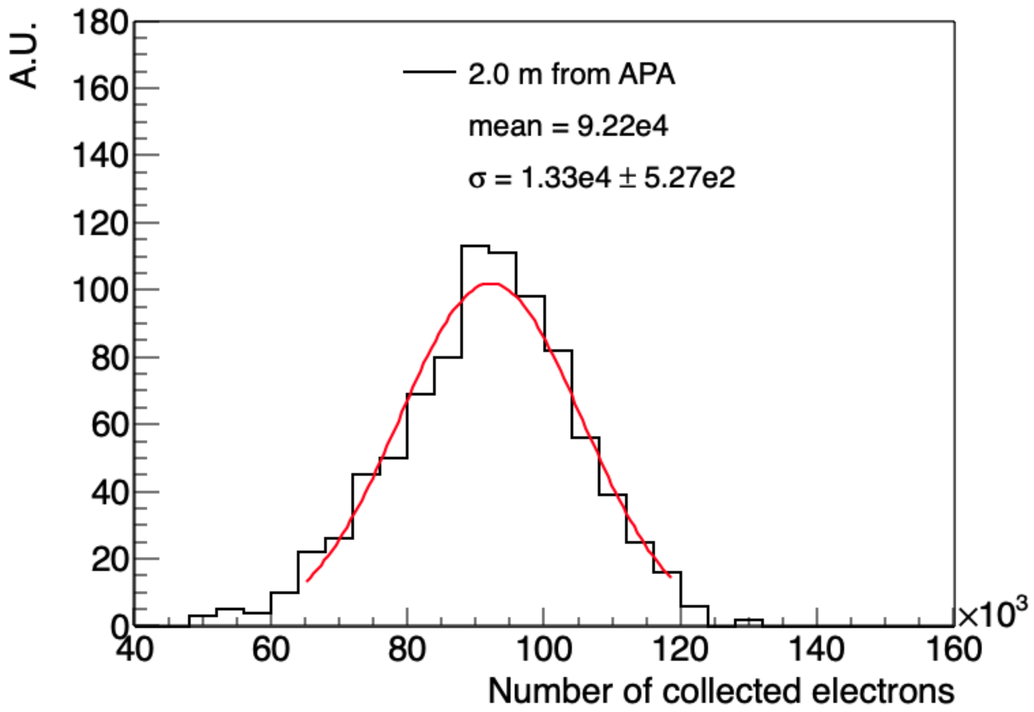
- The reconstruction of each individual gamma is not necessarily needed for calibration, but could improve the data selection. Geant4 simulation has shown that the clustering method can reveal the characteristic energy lines of individual gammas, which can help suppress the background and select pure neutron capture samples. The clustering algorithm will be verified using full LArSoft reconstruction procedures.





Q1 Continued

- 100 keV energy deposition can produce about 2000 drift electrons, which is well above the Equivalent Noise Charge (ENC~500). The energy deposition below 100 keV may not be detectable due to threshold effect.
- 6.1 MeV total energy deposition can produce ~10^5 drift electrons. If we use a threshold of 5*ENC, the contribution from the noise fluctuation to the reconstructed gammas is about ~2.5%. Standard
- LArsoft simulation and reconstruction has shown that we expect to get ~1e5 collected electrons for a 6.1 MeV gamma cascade. We will use simulation and test data to understand the threshold effect.

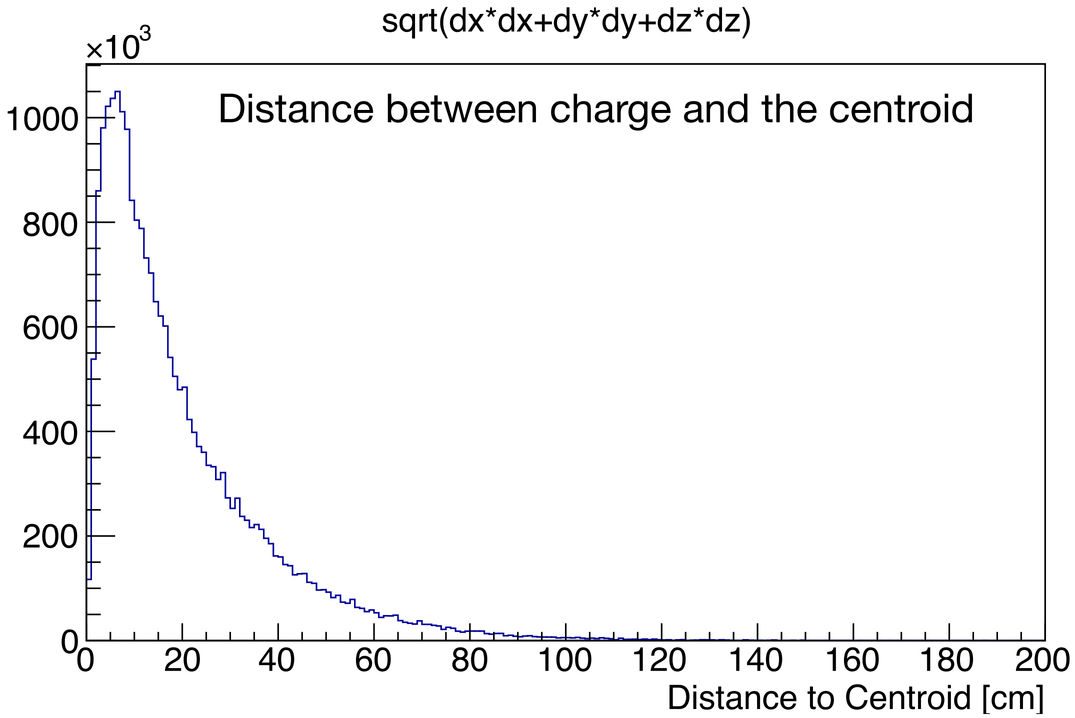


Idealized LArsoft Simulation:

- 1000 neutron capture cascades at fixed location that is 2m from APA
- Charge reconstructed as the sum of all collected electrons.
- No corrections for recombination and electron lifetime
- No noise added. No background added

Q2. Are the cascade decays from the gamma close enough in time such that a single t0 obtained from the photon detection system is sufficient for reconstructing the decay products? Does overlap of neutron capture events or the rate of background Ar39 decays in the far detector lead to difficulties in assigning a correct t0 to each neutron capture?

- The gammas from neutron capture are emitted within picoseconds of each other, and since the distances traveled before Compton scattering range from 5 cm at 100 keV to 20 cm at 5 MeV (implying a time delay of less than 1 ns) there is no issue with gamma emission times.
- ^{39}Ar decays with a single electron with an endpoint energy of 565 keV. The activity in liquid argon made from argon extracted from the air is about 1 Bq/kg. The chance of seeing an ^{39}Ar decay within the neutron capture event is 18%, but this can be corrected based on our knowledge of ^{39}Ar decay rates and energy deposition.



Geant4 Simulation of neutron capture shows the distance of the charge from the centroid of the charge for each event. 90% of the charge is absorbed within 45 cm of the centroid.

Q2 Continued

Calculation for the chance of seeing an ^{39}Ar event:

1. Liquid argon within 45 cm of the centroid of the neutron capture event corresponds to a mass of about 530 kg, or 530 Bq.
2. There are two cases for setting a time window:
   A. No PDS t0 is possible: The PNS is a triggered source with 5-100 usec pulse width (adjustable) and 240 µsec average capture time, so let's take 340 µsec as the event window. The chance of an ^{39}Ar event overlapping within the neutron capture event is (3.4E-4 s)*(530/s) = 0.18, or 18%. If we can make a correction for the presence of ^{39}Ar decay with 5% uncertainty (conservative, as we understand the rates and event energy depositions) then the uncertainty introduced is only about 0.9%. *(Note: numbers updated from what was in the responses document; results are similar)*
   B. PDS t0 is possible: The time window shrinks by three orders of magnitude and the contribution from ^{39}Ar becomes negligible. More detailed calculations on this can be performed in the future

- We plan to operate the generator at an intensity and time period that is variable for the depth in the detector we are calibrating. When calibrating near the top, the intensity needs to be low and the times can be short in order to collect sufficient data. When calibrating near the bottom we will operate at high intensity for longer periods and simply ignore the data near the top, where events would overlap.

Q3. Due to the difficulties associated with large rates of cosmic ray events on the surface, what is our level of confidence that we will actually be able to demonstrate the feasibility of performing calibrations with the Pulsed Neutron Source at ProtoDUNE?

- We will use the event selection method that is similar to the one used in ArgoNeuT (*PHYSICAL REVIEW D 99, 012002 2019*). The plan is to identify the cosmic rays using standard ProtoDUNE TPC reconstruction, and then remove all the activities related to the cosmic rays. First, the track-like activities are rejected. Secondly, all the point-like activities that are close to the cosmic rays tracks are rejected.
- We are performing a detailed LArSoft simulation and reconstruction to demonstrate the feasibility of the calibration in ProtoDUNE using PNS.
- The neutron capture analysis will be soon tested at ProtoDUNE-SP at CERN, using a DD generator.

Radioactive Source Deployment System (RSDS)

Q1. Can you describe the procedure for triggering on source events?

1st baseline procedure:

- To trigger on source events is to record one APA (two if the source is near the intersection of an upper and lower APA) with ‘partitioned’ DAQ trigger setup.
- In this setup, the rest of the detector runs with normal DAQ trigger, whereas the selected APA to be calibrated is recorded in a continuous readout mode during which all wire signals and PDS signals of that APA are fully recorded with zero suppression and possibly a low cut-off threshold that defines zero for each wire signal (<~0.5 MeV ^= 100 ADCU per single wire set to zero just near endpoint of Ar-39) for each deployment position and calibration run time.
- The baseline analysis will then be performed offline by applying trigger primitives and data selection and higher level cuts to the already recorded calibration data.

2nd baseline trigger method *(applying regular trigger to single APA that is calibrated and separately read-out)*:

- As for baseline method 1, record one APA with ‘partitioned’ DAQ trigger setup for which now both the rest of the detector runs with normal DAQ trigger, and the selected APA to be calibrated is recorded with the regular trigger for each deployment position and calibration run time.
- The partitioned DAQ setup and split readout is not necessary but helps to reduce the data volume and keeps the vast majority of the detector still online for physics.
- For the single APA the trigger threshold (TP and DS settings) could then be varied to perform a sweep of the trigger efficiency vs threshold.

Q1 Continued

3rd trigger method using PDS *(complementary):*

- The read-out of the APA to be calibrated is triggered by the local PDS signals above a certain threshold (~3 MeV equivalent PE yield, and ‘ophits’, respectively). The rest of the detector runs with normal DAQ trigger setup.
- This method will help develop and validate potentially more efficient combined APA and PDS DAQ trigger setups and will be less calibration data intensive regarding the recorded amount of data.Â

4th trigger method using pre-scaling *(backup in case data rate is too high because zero suppression does not work properly):*

- One APA is fully read-out as in the baseline method 1, but with a pre-scale trigger that substantially reduces the data rate.
- In this “partitioned” DAQ trigger setup for which the rest of the detector runs again with normal DAQ trigger, the selected APA to be calibrated is triggered only at a pre-defined rate that is technically provided by an external pulser (logical signal with length of two drift periods ~4.5 microseconds) or ideally if the DAQ features allow all the settings like frequency and length are setup using the Run Control GUI.
- Analysis will then be performed offline as for trigger method 1 by applying trigger primitives and DS and higher level cuts to the already recorded calibration data.

Q2. Would a radioactive source deployment system that only needed to reach down below the top end of the TPC be significantly simpler in terms of its design?

- In principle yes, because one could probably design a rigid short deployment arm that articulates, instead of the fishline system with guide strings and pre-installed fixtures inside the cryostat.
- However, a cryogenic glove box is still needed to handle and manipulate the source before and after each deployment (Cf-252 has a half-life of only 2.65 years and the source will be safely stored away from cryostat when not being deployed).

Q3. Could you summarize the different types of sources considered for deployment?

- Baseline is a Cf-252 infused 58Ni(n, gamma) source for 9 MeV gamma-rays embedded in a 30 cm high and 20 cm wide cylindrical Delrin moderator with rounded edges to minimize potential E-field distortion effects.
- Further, we might consider bare neutron sources with or without a moderator to study radiological neutron backgrounds and/or calibrate larger volumes of the detector (larger penetration depth of neutrons allows for calibrating multiple APAs at the same time).
  - Candidate neutron sources are Cf-252, AmBe, AmLi. They could potentially allow for calibrating possibly a third of the full 10 kton detector with a RSDS system.
- An Am-241 or thoron alpha source could potentially be utilized to create 15 MeV gamma-rays for RSDS calibrations, as well as neutrons from (alpha, n) reactions on argon.
  - The 15 MeV gamma-rays would yield a lot of pair production events for calibration and could also be used to study internal radon induced backgrounds.

Q4. What is the plan for extrapolating trigger efficiency results obtained at the edges of the detector into the main bulk of the TPC?

- Obviously, the more detector coverage the RSDS will get, in the ideal case with all 8 endwall penetrations over the full detector height, the simpler and the more justified the extrapolation to the full detector volume will become. With 8 deployment locations, 12 APAs out of 150 per 10 kton module can be calibrated, i.e. 8% of all APAs, and 7.7% (= 2x active 2.3m / 60m) of the full volume of a 10 kton module, respectively.
- The systematic comparison of RSDS obtained trigger efficiencies at different deployment locations in combination with uniformity calibrations performed around the same time with the PNS system throughout the full detector volume, will give rise to the residual uncertainty in extrapolating the RSDS obtained trigger efficiency to the full detector.
- Detailed analysis of selected radiological backgrounds that are uniformly distributed throughout the full detector will also enable an extrapolation of the RSDS obtained trigger efficiency to the full detector volume.
- Last but not least, the obvious first step is to use our MC simulation to extrapolate the trigger efficiency from the RSDS calibration data to the full detector volume and further from gamma-rays to different particle types like electrons.