Photoelectron Laser and Laser Positioning System

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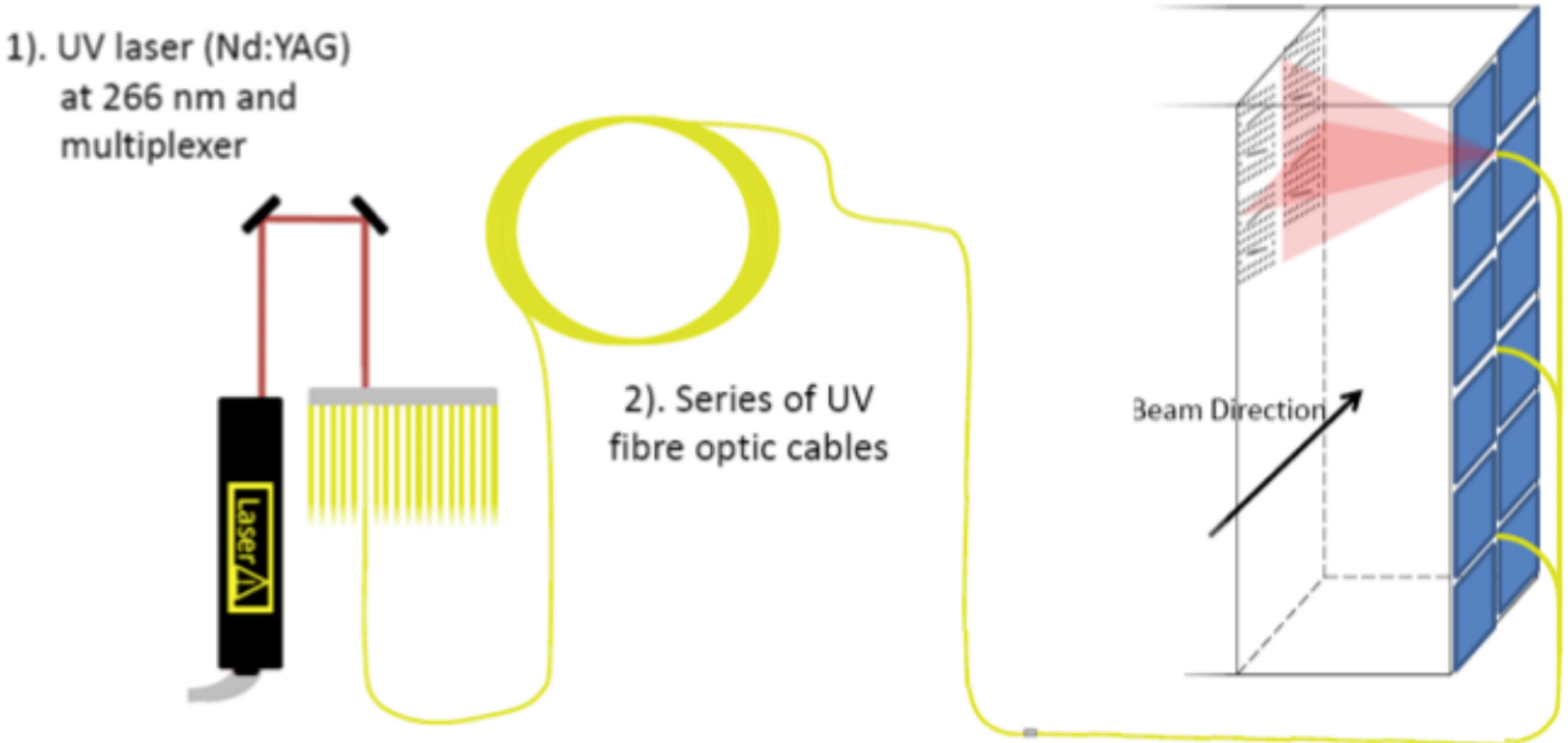
DUNE Calibration Workshop

June 2019

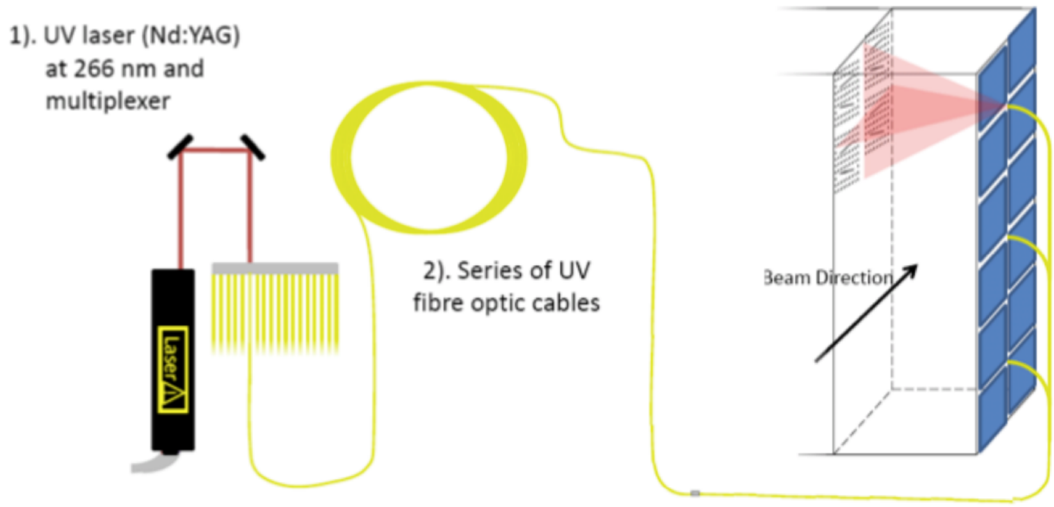
Photoelectron Laser (PhEL) Overview

- Photoelectron laser (PhEL) consists of:
  - Small metal targets (dots and strips) attached to CPAs in predetermined locations
  - UV light source (UV laser) used to illuminate metal targets that release electrons via photoelectric effect



Photoelectron Laser (PhEL) Benefits

- Cost-effective system – main cost are optical fibers used to deliver UV light to TPC and illuminate targets (~$60k per SP FD module).
- PhEL generates well localized electron clouds on the CPA at predetermined locations released after every laser trigger.
- Thus, ***PhEL provides electron sources with well know position and time of release*.**
- Generated electron clouds drift in the TPC electric field until they are collected on the APA.



Photoelectron Laser for TPC calibration

- Thanks to PhEL we can measure electron drift time throughout detector volume:

$$t_{electron\ drift} = t_{electron\ detection\ on\ APA} - t_{laser\ pulse\ trigger}$$

→ *PhEL provides means to measure and monitor electron transport in the TPC.*

- PhEL enables:
  - **detector wake-up to quickly diagnose if the detector is alive, since the rate of cosmic rays is low underground**
  - **precise** determination of electron drift velocity throughout the TPC volume
  - **measurement of distortions** in the electron drift due to inhomogeneous and misaligned electric field
  - **vertex reconstruction calibration** on CPAs
    - Secondary goal: measurement of **transverse size of ionization** with photoelectric strips

Photoelectron targets

- Plan to use the same NdYag laser 266 nm with 4.66 eV photons --> no cost associated with buying lasers.
- Photoelectron candidates for targets based on experiences in the past

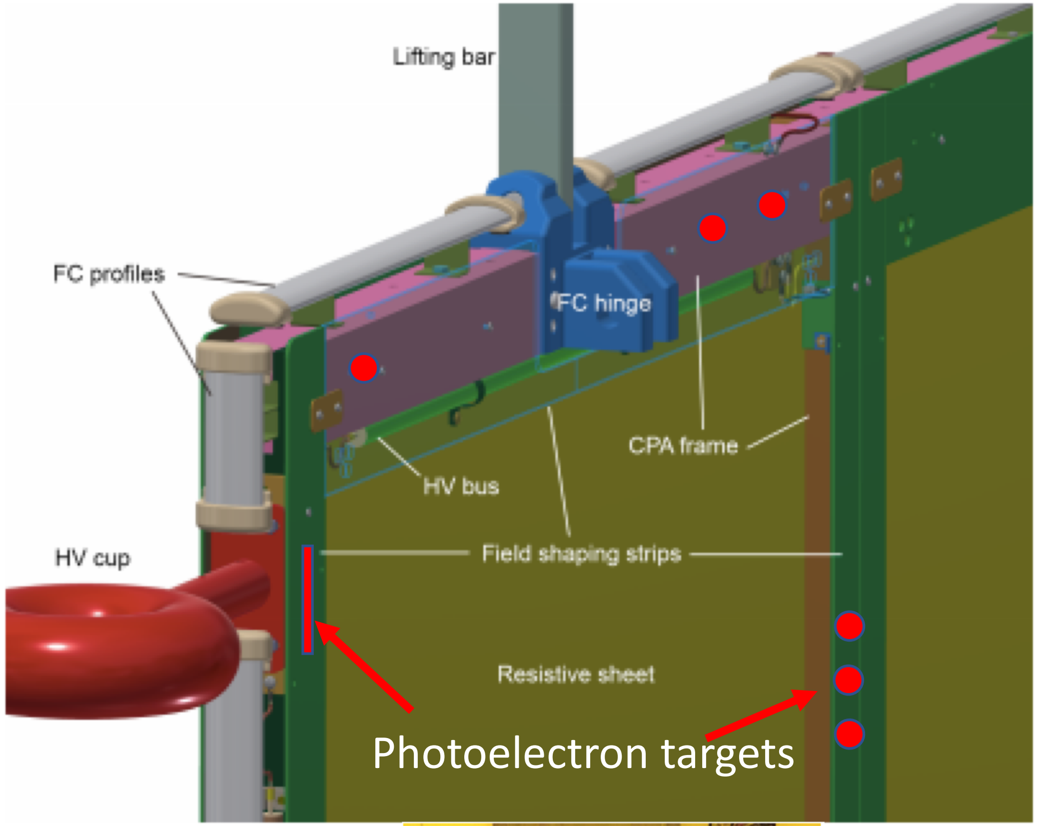
Target material	Work function (eV)	λ_{max} (nm)	Comparison to 266 nm NdYag	Oxidization in air	Type of oxidization
Gold	5.1 – 5.47	243 - 226	<	No	None
Nickel	5.04 – 5.35	246 - 232	<	Yes	Surface layer
Silver	4.26 – 4.74	291 - 262	>	Yes	Surface layer
Aluminum	4.06 – 4.26	305 - 291	>	Yes	Surface layer

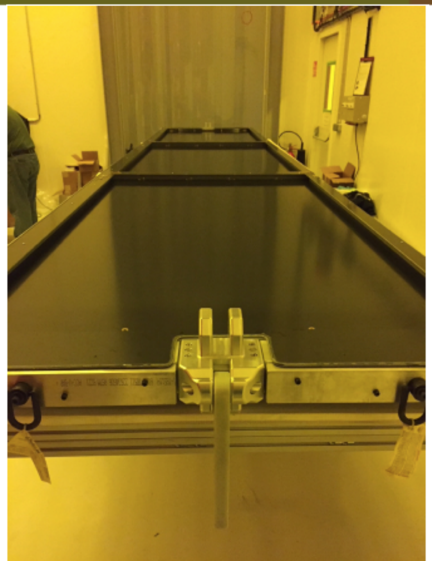
Note: aluminum develops surface layer (70 Angstrems), does not change over time (Al_2O_3 work function 3.9.

Aluminum is the preferred candidate – excellent experience from T2K TPC where photoelectron laser was implemented and successfully utilized.

Photoelectron Laser Implementation

- 5 mm and 10 mm diameter target discs placed on the field shaping strips on CPA
- 0.5 x 10 cm target strips (if OK for HV on CPA) placed on the field shaping strips on CPA
- Optical fibers with diffuser routed to APA and fastened between APA planes to illuminate the photoelectron targets located across the TPC on the CPA
- Details of interface with APA under consideration
- If it is possible to mount fibers on the sides of APAs, that would help further reduce the number of fibers and associated cost.
- Utilize DSS ports to insert the fibers in the TPC





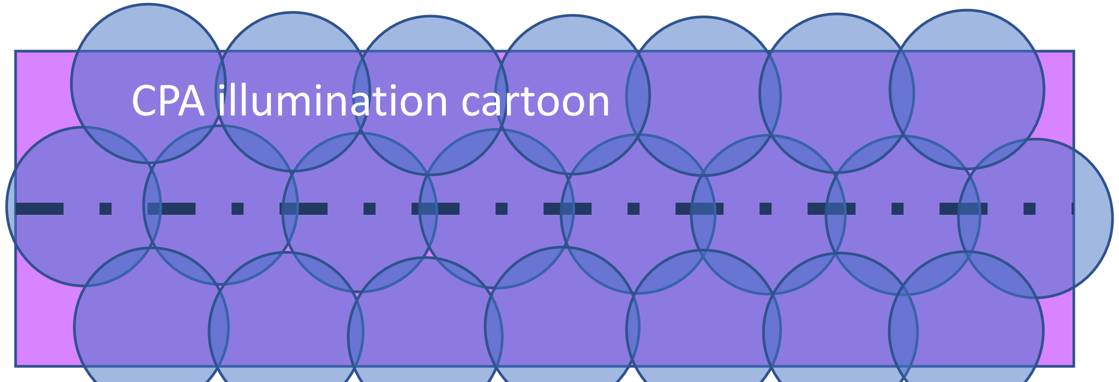
Area Illumination from a Single Fiber

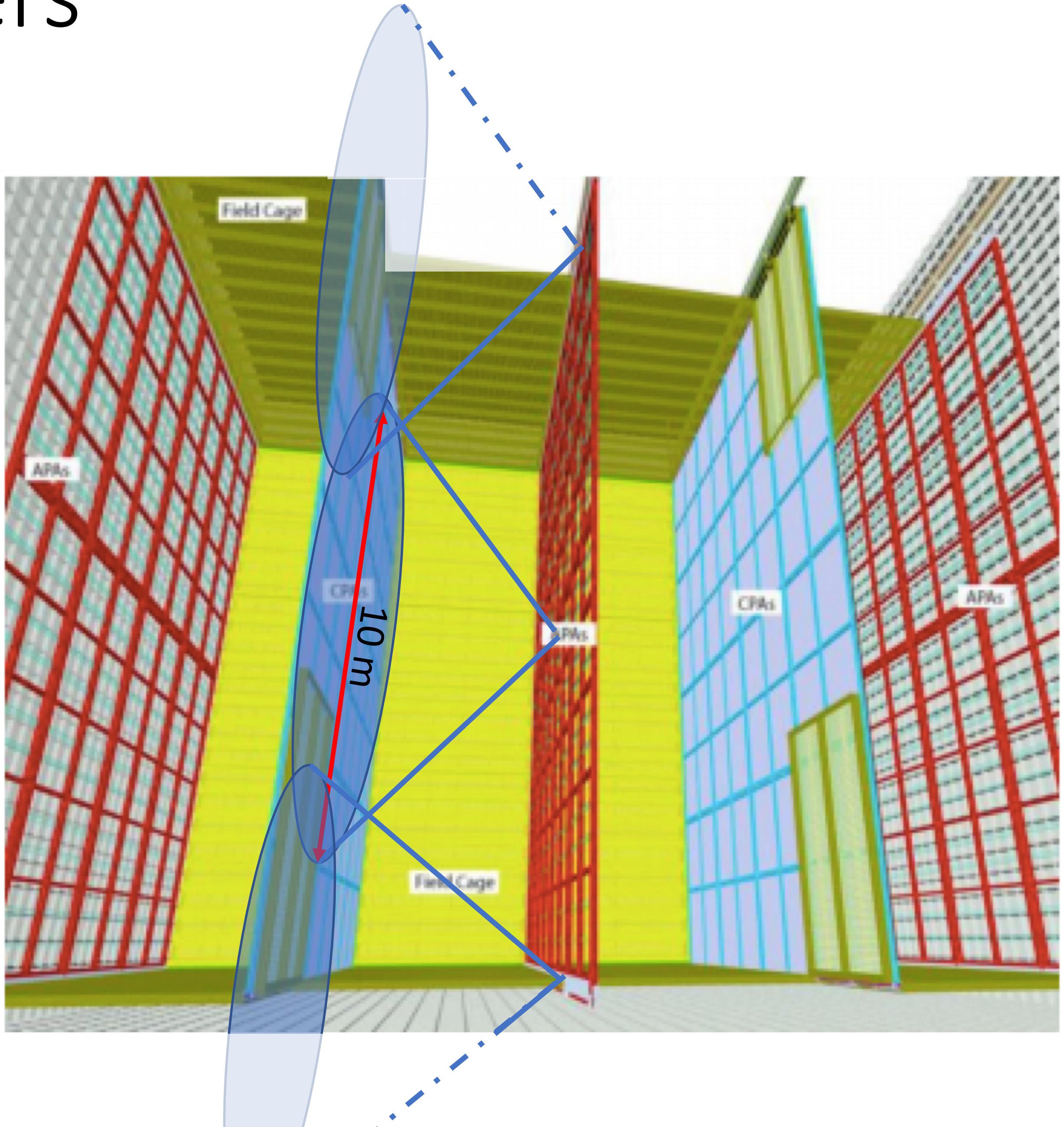
- Pulse power 50 mJ (can go up to 100 mJ without large cost increase), pulse length 5 ns
- Efficiency of injecting light in the UV fiber 2% (rather conservative estimate)
- Number of photons per pulse 6.7×10^{14} photons/pulse
- Assume 5 m radius illumination on CPA (optical element diffusing light coming out of fiber)
- Phototarget radius 5 mm (2.5 mm)
- Quantum efficiency 5×10^{-6} at 266 nm
- Attenuation in 20 m of optical fiber ~ 7.5 at 0.22 dB/m at 266 nm
- Number of photoelectrons from a single target 9000 (2500+)

- *Note 1: Signals on APAs identified by time correlation with trigger pulse*
- *Note 2: Neglect Rayleigh scattering (40 m at 266 nm in Ar)*
- *Note 3: Further tuning of the photoelectron yield achieved via tuning of the laser power*

Required number of fibers

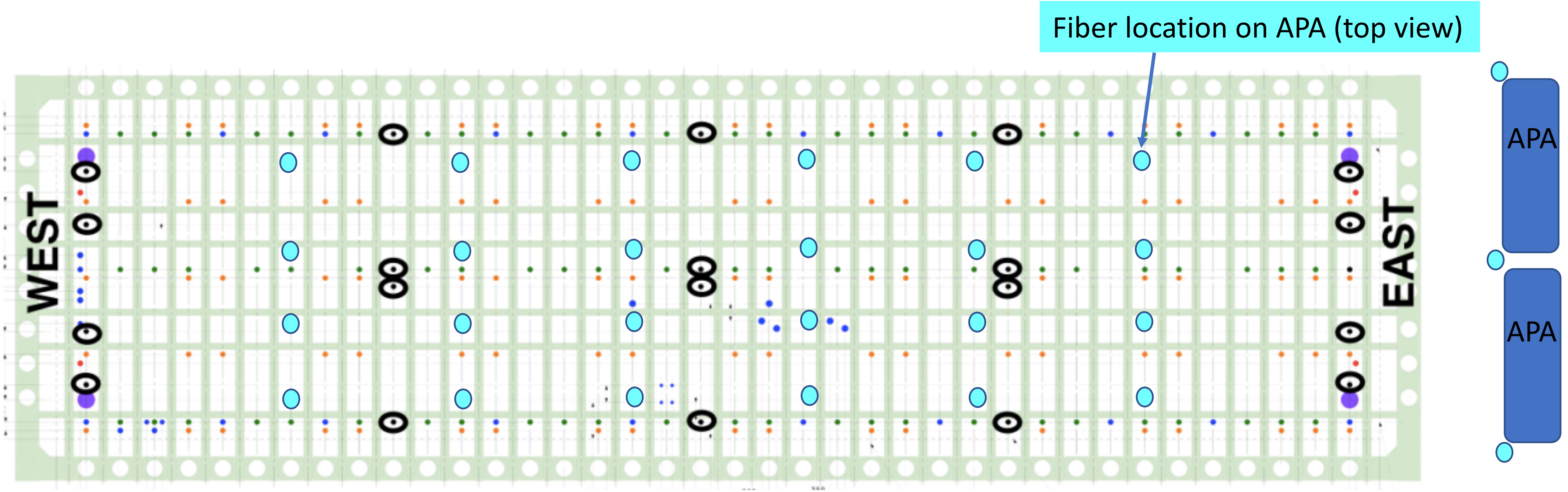
- We need several thousand photons per target
- Single fiber from a single laser can be used to illuminate 10 m diameter area (due to the Gaussian shape of the beam this will be less)
- Baseline for fiber locations:
  - along central line between upper and lower level APAs
  - on the top of upper APAs (pointing down)
  - On the bottom of lower APAs (pointing up)





Locations

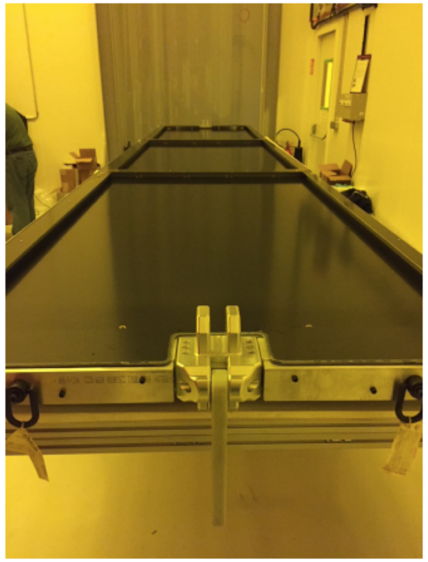
- Utilize existing track lasers for illumination of photoelectron targets
- Two fibers per laser.
- 6 laser fibers along central line + 6 laser fibers on top and 6 on the bottom for each CPA side. The total number of fibers is 18 x 4 = 72.
- Fiber routing plan needs to be finalized.
- Assume average 20 m fiber length (vary from 10 – 30 m).
- Excellent TPC resolution allows for illumination of large number of targets in parallel.



Multiplexing option (under consideration)

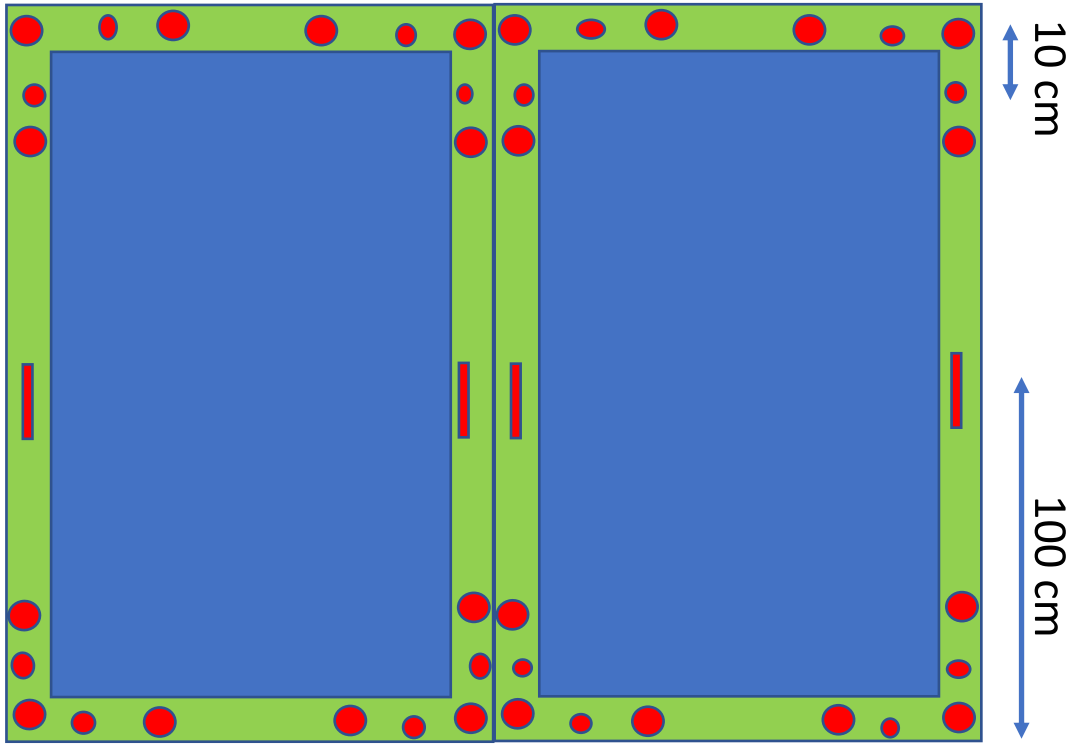
- We are also considering use of optical multiplexer
- Advantages:
  - Illuminate each of the 4 volumes with a single laser
  - Single trigger signal
  - Less variation in laser pulse
- Disadvantages:
  - Longer calibration sequence
  - Longer laser fibers – added cost and complicated routing
  - Added cost of multiplexers.

Photoelectron Target Locations



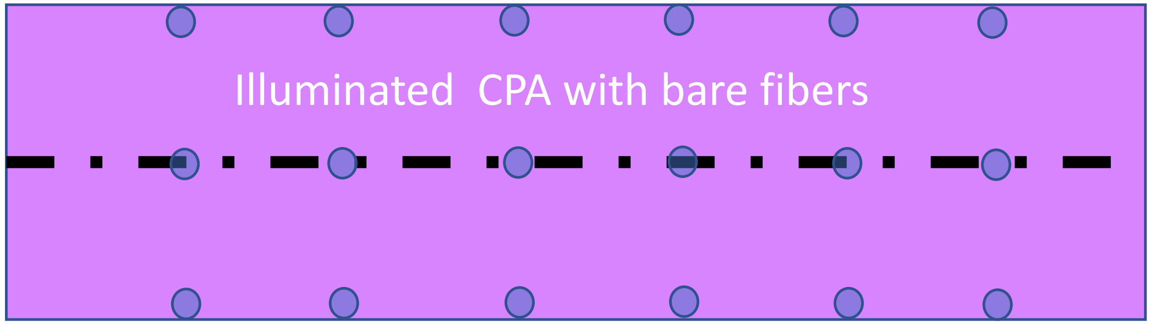
- Targets will be placed on the corners of Resistive Panels (RPs) that are 1.2 x 2 m in dimensions on field shaping strip surfaces.
- 20 dot targets with 10 cm spacing placed as shown
- Small and large targets
- 2 0.5 x 10 cm strips per RP
- Targets placed on every RP
- Total number of RPs per SP module is 600
- Total number: 12,000 dot targets and 1200 strip targets.

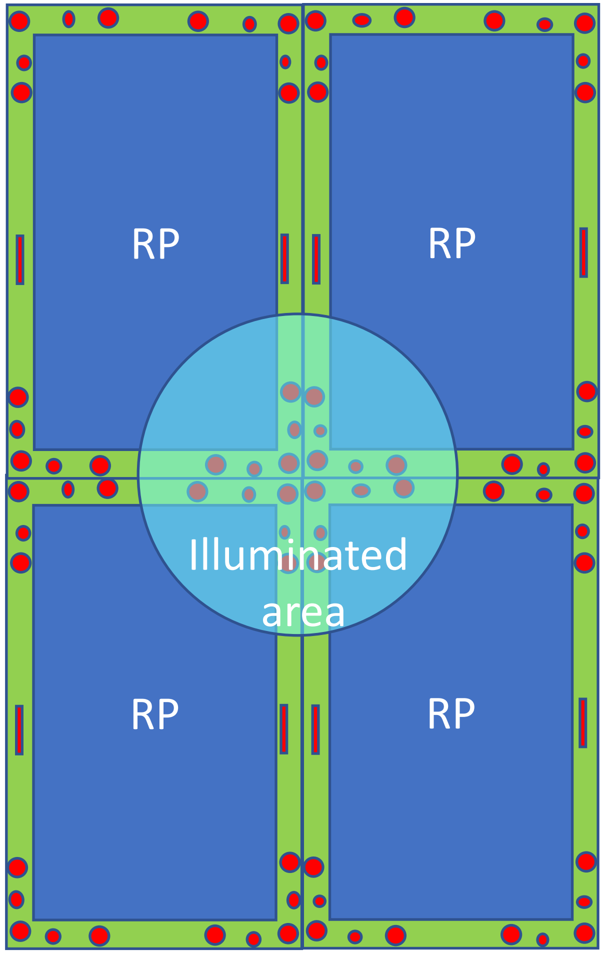
- *Note: this is a baseline, but can easily be changed to smaller or larger number of targets in response to simulation outcomes that will guide detailed design.*



Detector Illumination: diffuser vs bare fiber

- Kapton that composes majority of CPA undergoes photoelectric effect, albeit with three orders of magnitude lower efficiency at 266 nm when compared to Ag or Al in LAr.
- In case Kapton turns out to be a significant source of photoelectron noise, we need to reduce exposure to 266 nm light.
- Kapton photoelectron noise mitigation: replace diffusers with bare fibers.
- With typical UV fiber, half-opening angle is 10∘ which is 1.3 m diameter illumination → illuminate a single corner where 4 RPs meet.
- In this case, keeping the number of fibers the same, there will be 18 calibration points in each of 4 volumes.
- Single laser can illuminate all 18 fibers at once.





Calibration Campaign

- Assuming parallel running of lasers, photoelectron targets in 3 out of 4 volumes can be illuminated at once, assuming that laser firing can be coordinated or calibrated with sufficient precision and that volume 2 and 3 share lasers
- Lasers operate at 10 Hz frequency.
- Assuming 10000 pulses per laser, about 15 minutes is needed per laser.
- If we utilize one multiplexer per each volume, then 1 hour per volume is sufficient.
- Depending whether the lasers are run in parallel or series, the entire calibration campaign will take between 15 minutes or up to 1 – 5 hours, depending on the final calibration scheme.

Budget Estimate of the Photoelectron Laser

- Given the ability to use track laser for the photoelectron calibration, the main cost of the system are fibers

Fiber core (um)	Bending Radius (mm)	Cost per meter ($)	Total cost for 1440 m ($)
300	30	19	27,360
400	**50**	**29**	**41,760**
600	65	50	36,000

Item	Cost ($)
Optical fibers	42,000
Target production, diffusers, connectors	5,000
Multiplexers(3)	9,000 (if needed)
Contingency (10%)	5,000
Total	**52,000 (61,000 with multiplexers)**

Review Committee Charge Questions

Charge Question: Is the current proposal to add photoelectron targets to the cathode plane a useful addition to the primary system?

- Thanks to PhEL we can measure electron drift time throughout detector volume:

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→ *PhEL provides means to measure and monitor electron transport in the TPC.*

- PhEL enables:
  - **detector wake-up routine to quickly diagnose if the detector is alive, since the rate of cosmic rays is low underground**
  - **precise** determination of electron drift velocity throughout the TPC volume
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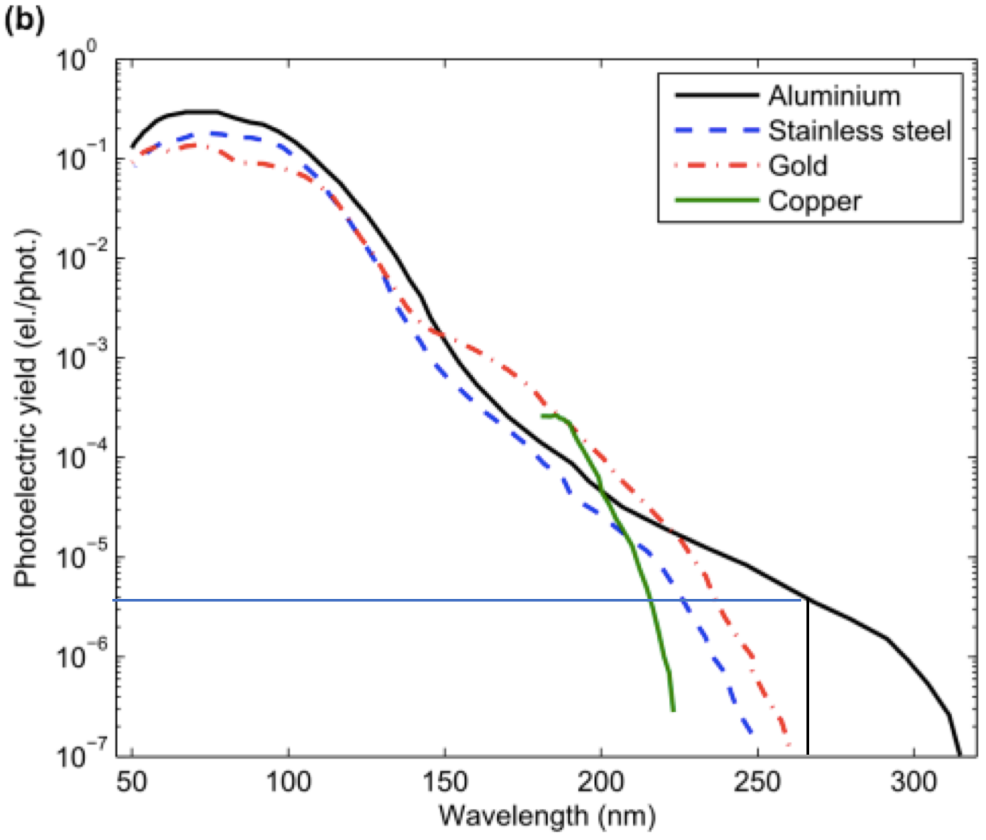
    - Secondary goal: measurement of **transverse size of ionization** with photoelectric strips

Charge Question: Are there any potential risks associated with installing photoelectron targets on CPA or from the light that they emit?

- **Potential risk**: Random photoelectrons from exposed aluminum surfaces hit by 266 nm laser light
  - Reflection coefficient at 266 nm from Al is 90%
  - Abundant scattered light will hit exposed aluminum surfaces such as FC
  - Photoelectron quantum efficiency for aluminum at 266 nm is of the order 10^{-6}

Emission of photoelectrons from aluminum surfaces in the TPC is negligible



Charge Question: Are there any potential risks associated with installing photoelectron targets on CPA or from the light that they emit?

- **Potential risk:** Random Argon Scintillation Light (9.68 eV) inducing photoelectric effect from photoelectron targets
  - Argon scintillation light has 9.68 eV energy- far above work function of any metal.
  - Utilized photon detector (PD) simulation to estimate electron noise coming from argon scintillation photons (due to radiological backgrounds) hitting the photocathode targets.
  - PD simulations predicts number of photoelectrons on SiPMs
    → convert # of photoelectrons on SiPMs to number of photons per area of photon detector module → number of photons per surface

Photon Rate Calculation

The length of the time window per event :

4.492 ms

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T0:                [ -2246000 ]
T1:                [  2246000. ] # ending time in ns
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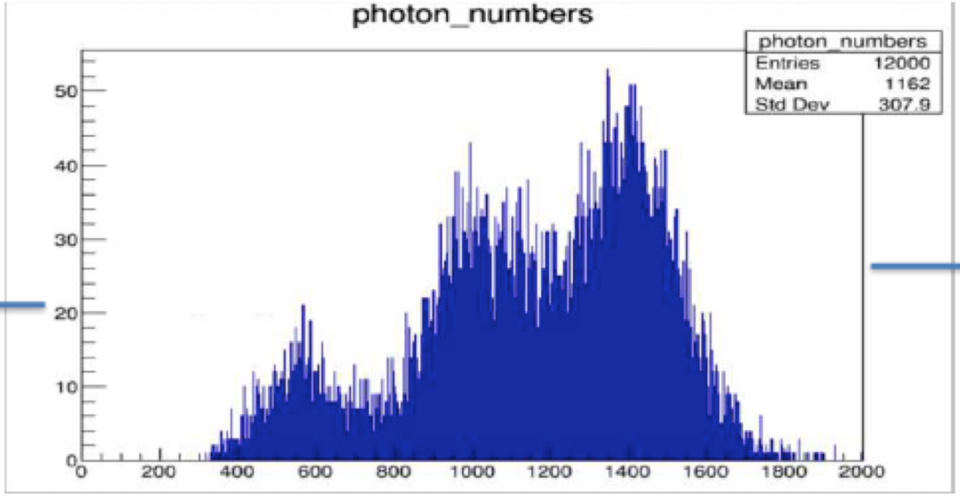


Mean: 1162
Maximum: 2000
Center of the 3rd peak :1400

N_photons	Area (cm^2)	Time window Length(ms)	Per Area(cm^2) Per event time window	Per Area (cm^2) Per ms
2000	2130.3742	4.492	0.938802207	0.208994258
1400			0.657161545	0.146295981
1162			0.545444082	0.121425664

The average photon rates is therefore 0.146 photons per cm^2 per ms

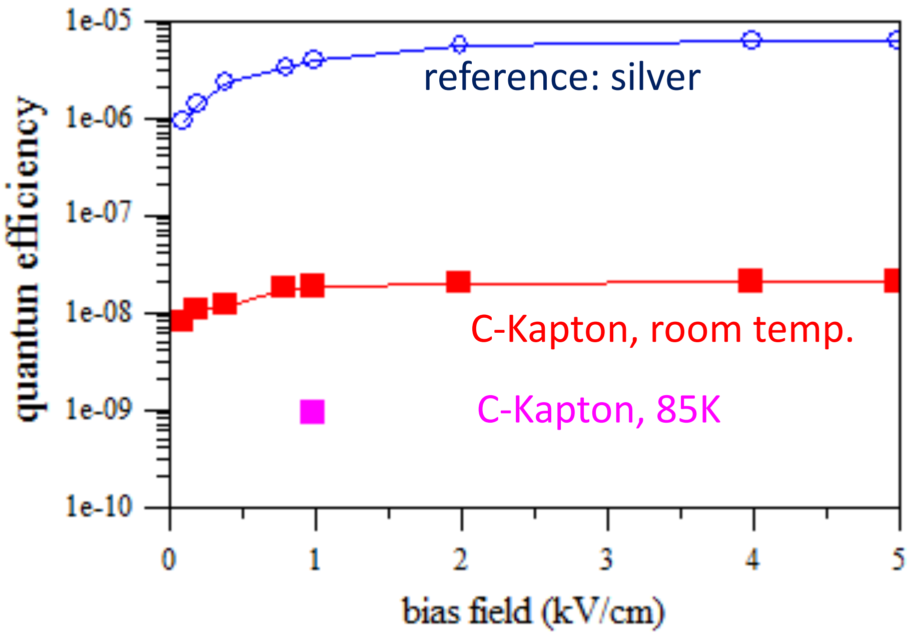
Noise in the detector induced by photoelectron targets is negligible considering low quantum efficiency of aluminum .

Charge Question: Are there any potential risks associated with installing photoelectron targets on CPA or from the light that they emit?

- From Bo Yu: "*Electron emission from carbon-loaded Kapton is low but **non-zero.** At UV 266nm, electron emission is linear with laser intensity. At room temp in vacuum, its quantum efficiency (QE) is ~10^{-8} drops to below ~10^{-9} in cold, its QE is expected to continue drop in LAr.*"

- Since Al is similar to Ag, the quantum efficiency is 5,000 smaller for Kapton in LAr.
- Number of photoelectrons from 5 mm diameter target, equivalent to 25x0.005 m strip of Kapton.
- **Thus, electron noise per wire due to Kapton seems to be much smaller than electron cloud from photoelectric target.**

- Nevertheless, due to large area of Kapton material, this issue requires further study with simulations and quantum efficiency measurement.
- **In case of Kapton being an issue, we will resort to bare fibers, illuminating corners of RPs.**



Charge Question: *Is the planned testing program for ProtoDUNE-II adequate to ensure that the system meets requirements and mitigates as much as possible identified risks to stable TPC operation?*

- ✓ Glue targets in predetermined locations on the CPA – several targets sufficient to validate system
- ✓ Use different target materials to compare their performance
- ✓ Verify the potential of targets to generate several 1000 electron clouds and their potential to diagnose electric field distortions and vertex reconstruction
- ✓ Search for noise related to photoelectron targets in the ProtoDUNE-II data
- ✓ Search for noise related to running the PhEL in the ProtoDUNE-II data from Kapton and other sources
- ✓ Allocate port to insert laser fibers used for illumination
- ✓ Validate interface with track laser in order to inject 266 nm photons into fibers
- ✓ Validate efficiency of laser light injection in the optical fiber
- ✓ Validate light attenuation in fibers
- ✓ Validate design interface with APA and optimized locations of fibers between top and bottom APAs
- ✓ Validate diffuser design and light losses in the diffuser as well as its ability to illuminate large areas of CPAs.
- ✓ Validate bare fiber CPA illumination.

Conclusion

- Photoelectron laser is a simple, low cost system that complements the track laser well.
- PhEL is uniquely suited to provide a detector wake-up routine to quickly diagnose if the detector is alive, since the rate of cosmic rays is low underground.
- PhEL is an effective diagnostic and calibration tool, that can quickly and accurately sample the electron drift velocity in the entire detector
- PhEL can be used to identify electric field distortions due to space charge effects.
- Exact knowledge of the timing and position of the generated electron clouds is useful for vertex calibration.