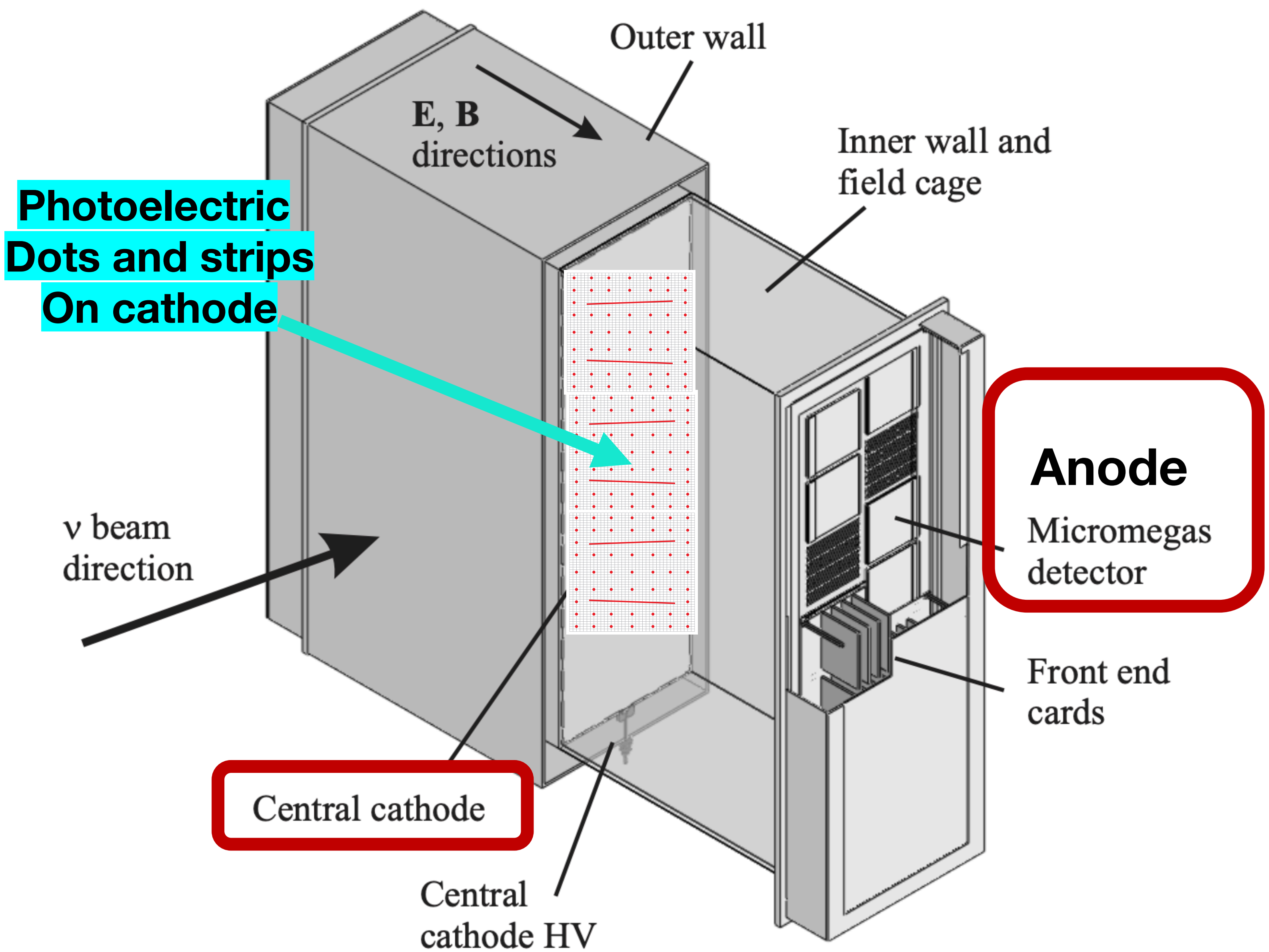
# Q1. How was this system used in the T2K near detector?

**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.

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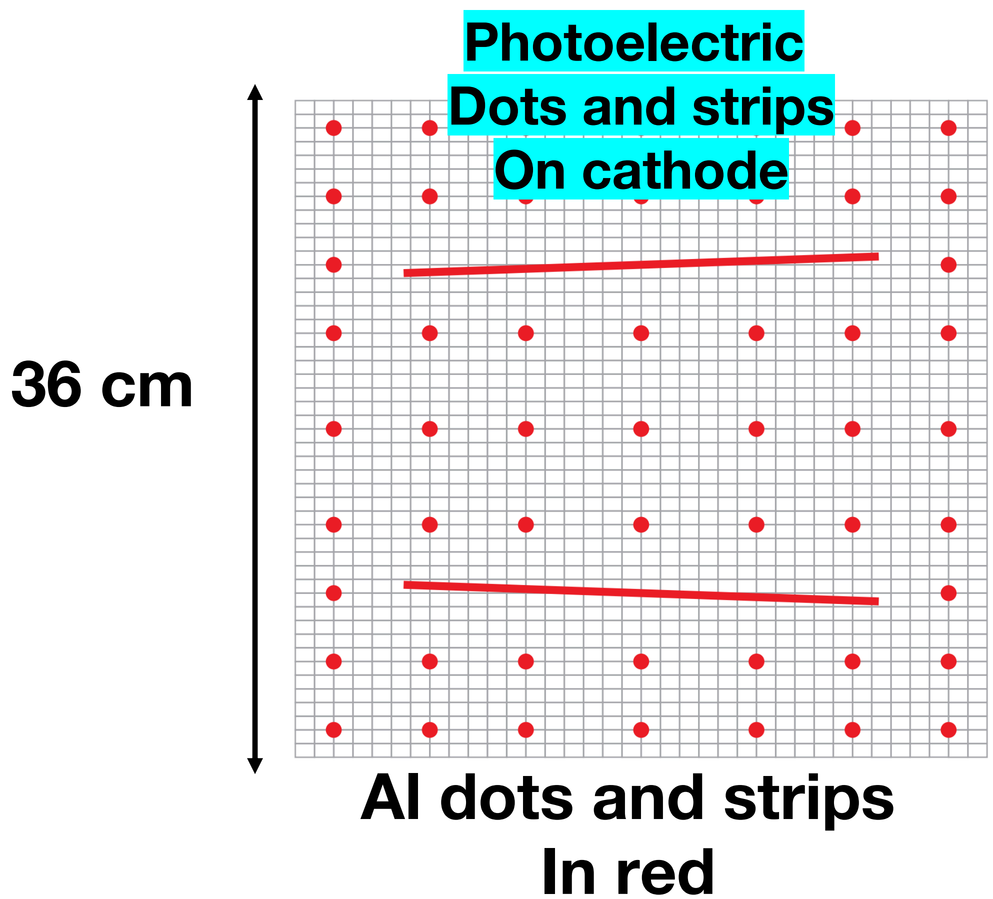
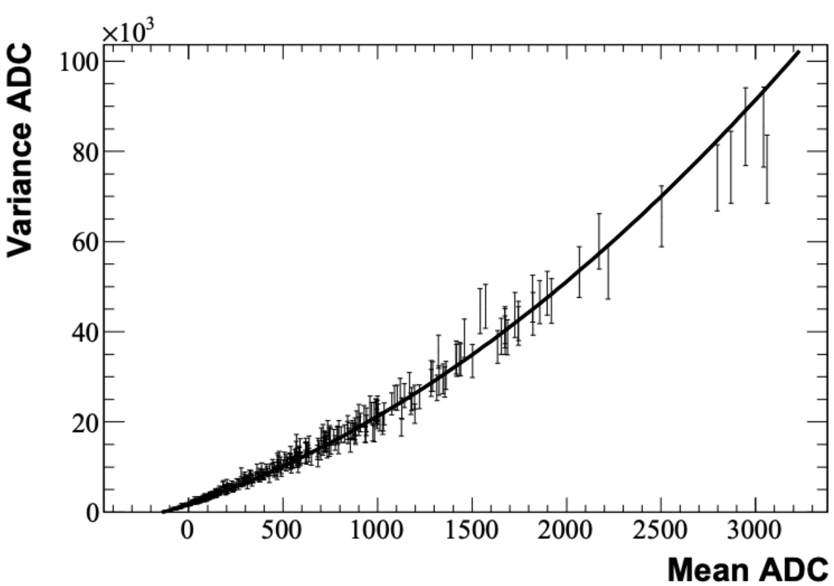



[https://arxiv.org/abs/1012.0865](https://arxiv.org/abs/1012.0865)

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

- 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

# Q1. 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. 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. 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.**

*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 | $6.7 \cdot 10^{16}$ photons per pulse |
| UV fiber coupling (80% vendor spec sheet) | *50%* | $3.35 \cdot 10^{16}$ photons per pulse |
| Attenuation in fiber -0.235 dB/m at 25 m | 0.258 tran. factor | $8.6 \cdot 10^{15}$ photons |
| Distance to CPA center: SQRT($3.53^2+6.1^2$) = 7 m | At 10 diameter | $9.3 \cdot 10^{9}$ photons/cm$^2$ |
| Distance to CPA center sqrt ($3.53^2+6.1^2$) = 7 m | At 2.7 m diameter | $1.5 \cdot 10^{11}$ 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° | **$1.5 \cdot 10^5$ pe's/cm$^2$** |

**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.**

**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/cm²** | Insufficient (multiplexer necessary) |
| PE yield (Polymicro UV quartz fibers with built-in diffusers thanks to side cut fiber tip termination) | Opening angle 22° | **$1.2\cdot10^{10}$ pe's/cm²** | 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 $\sim 10^{-6}$
- 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 radius 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?**

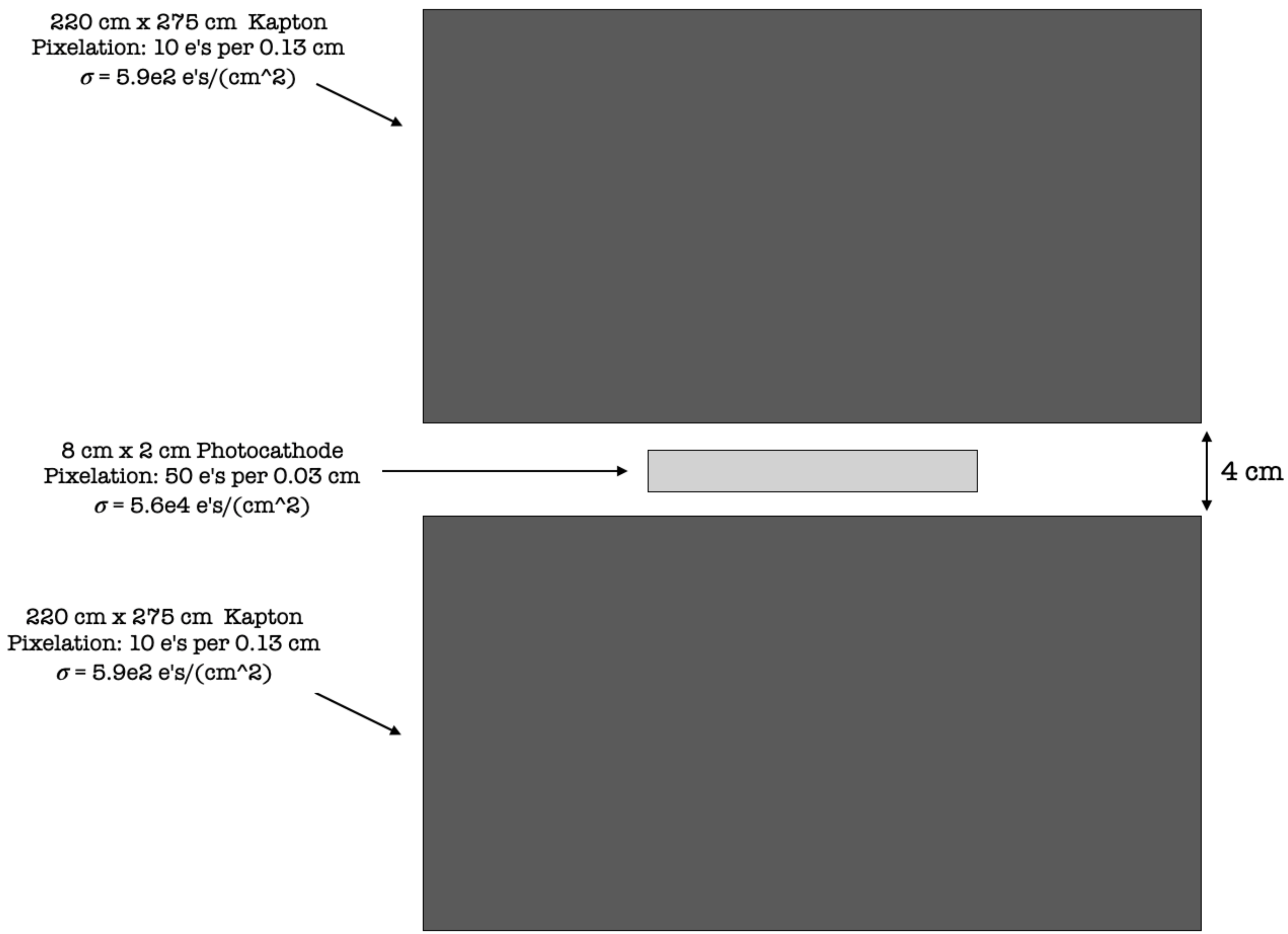
Carried out simulation studies of photoelectric effect in Kapton and how to observe the reconstructed signal from photoelectric targets on top of Kapton.

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

# 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).

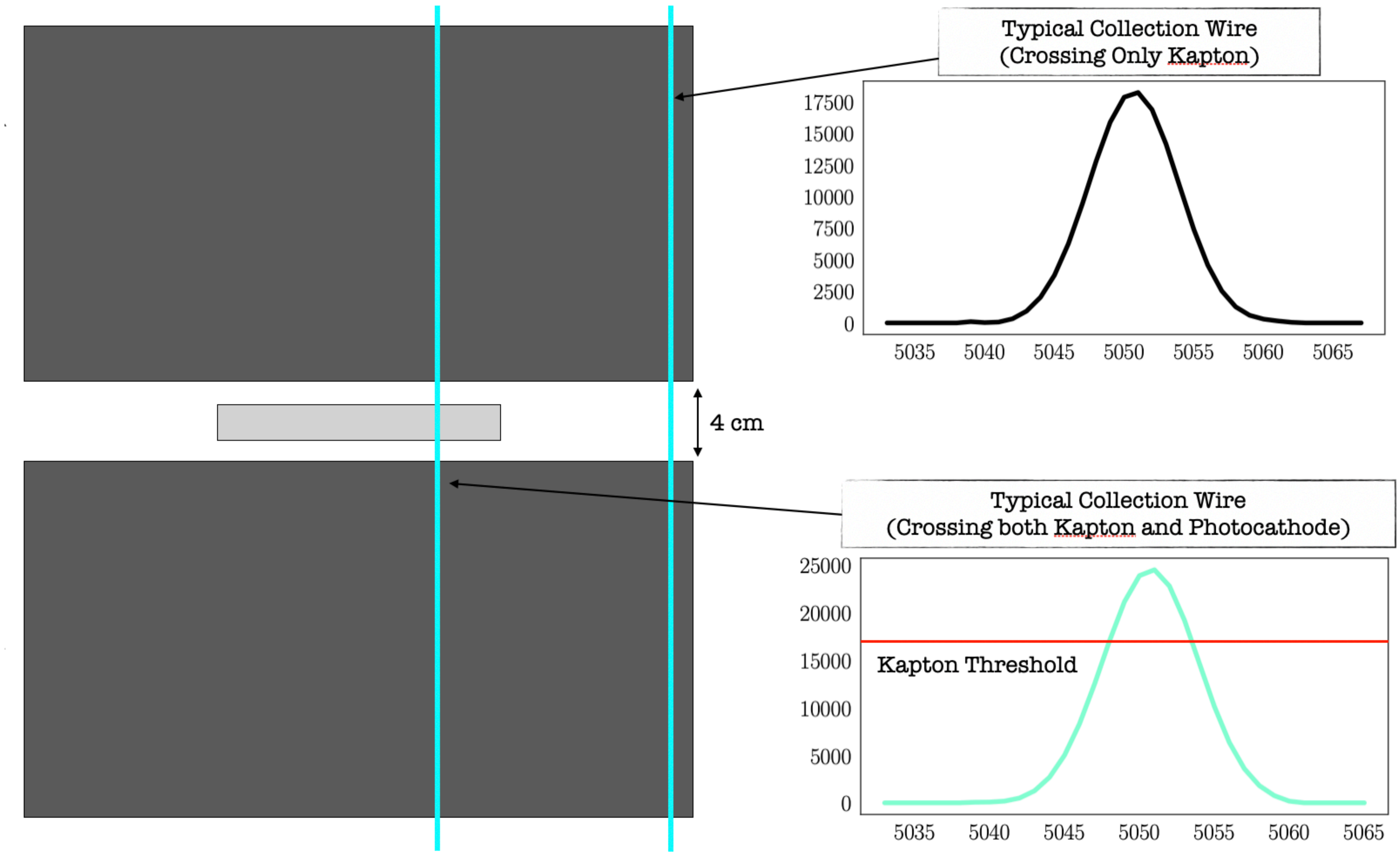
Simulation includes photoelectric emission from Al strip 8 cm x 2 cm.



# 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.

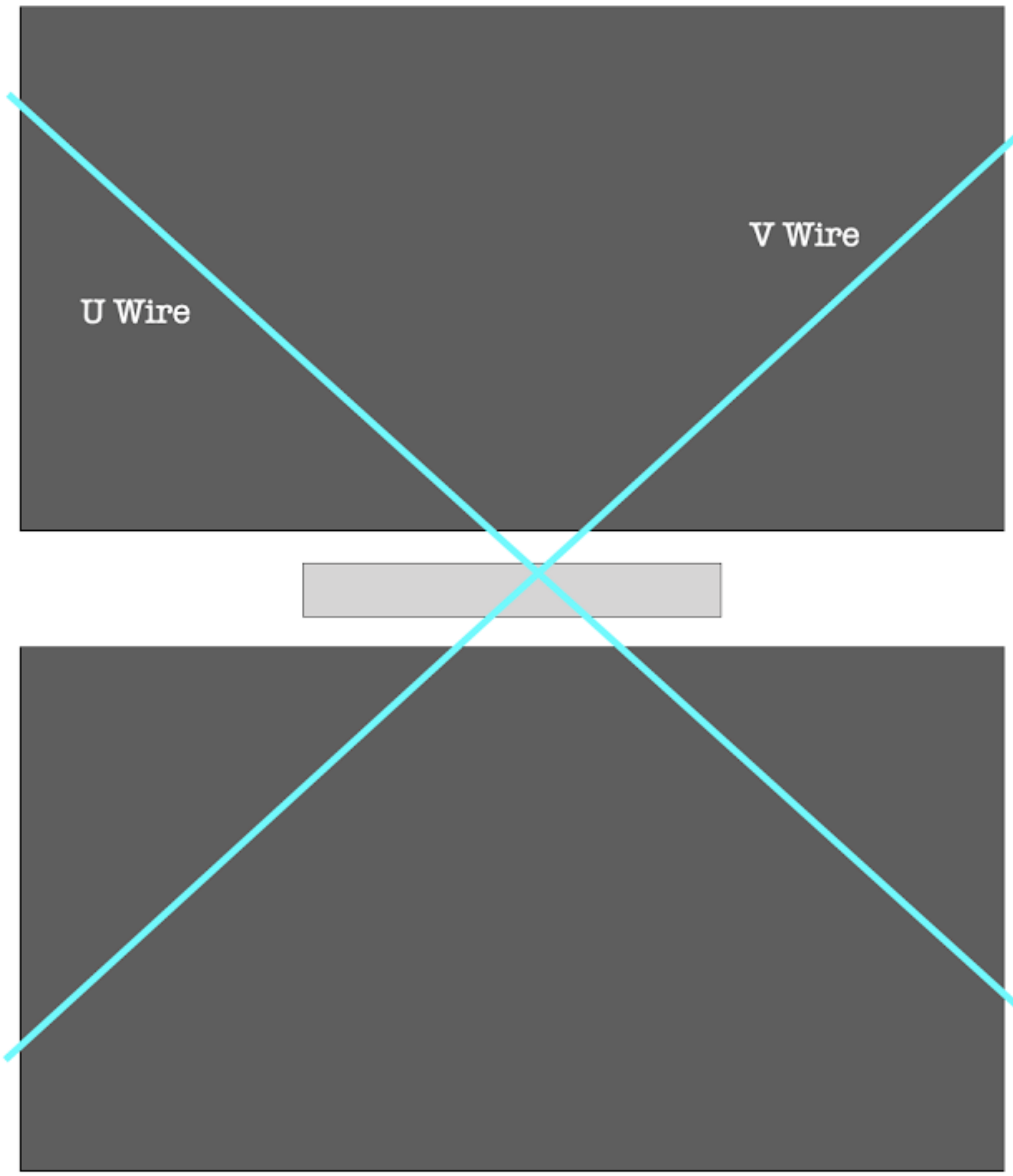


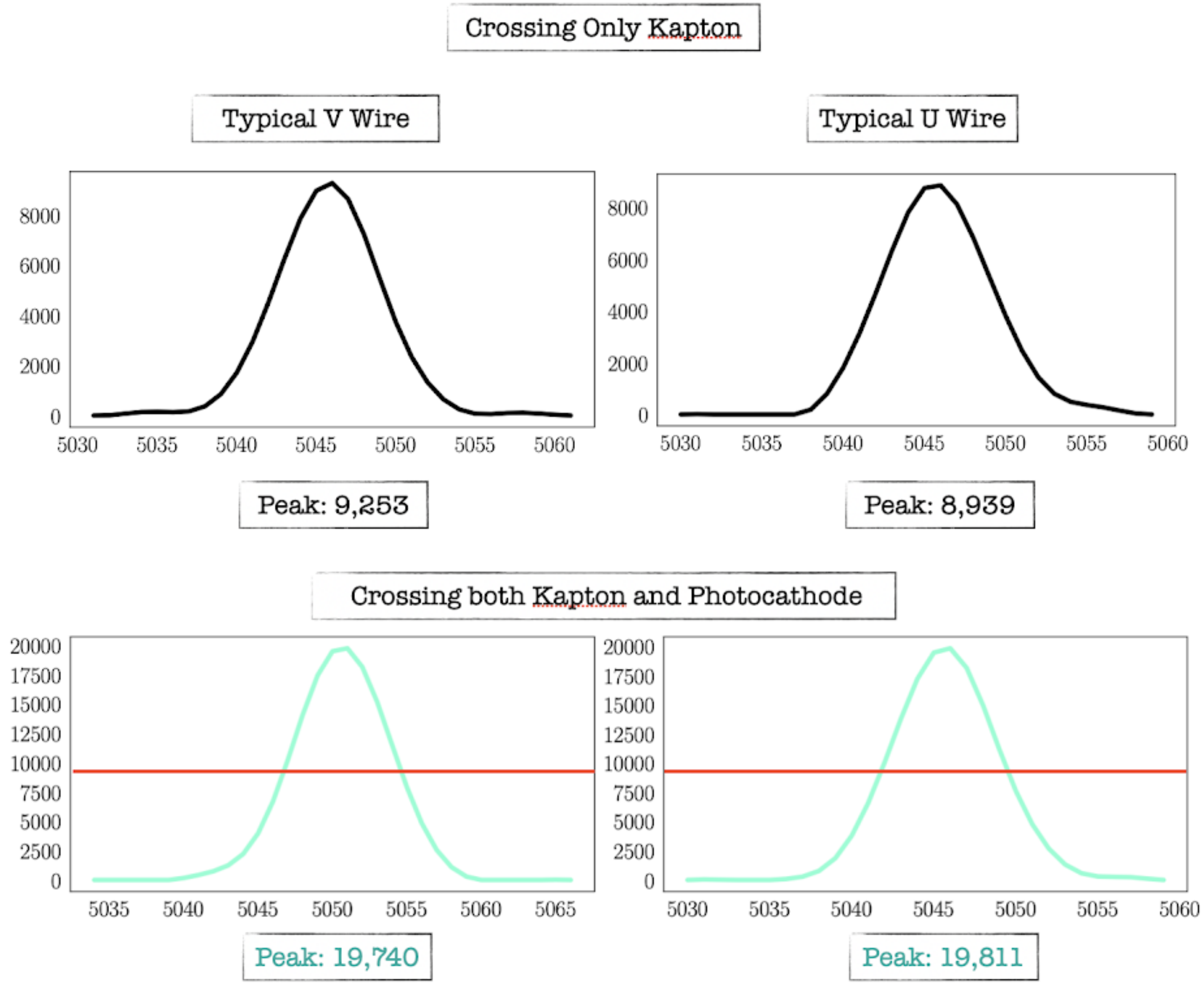
# Kapton Simulation Results – Induction Wires

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.



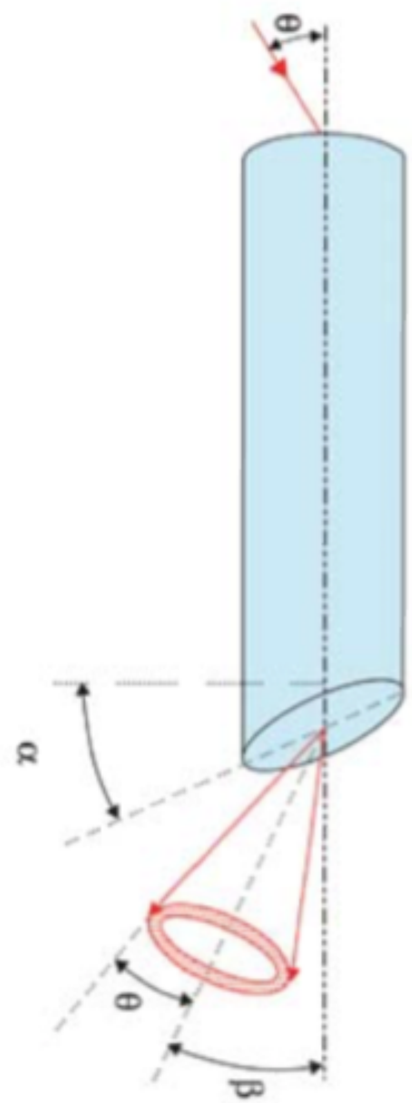
## Q5. For a diameter this large, how non-uniform is the light over the illuminated area and does the non-uniformity remain consistent pulse to pulse?

- 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 LAr?**

- 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) |

## 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 LAr?

- 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