Large Area Picosecond Photon Detector

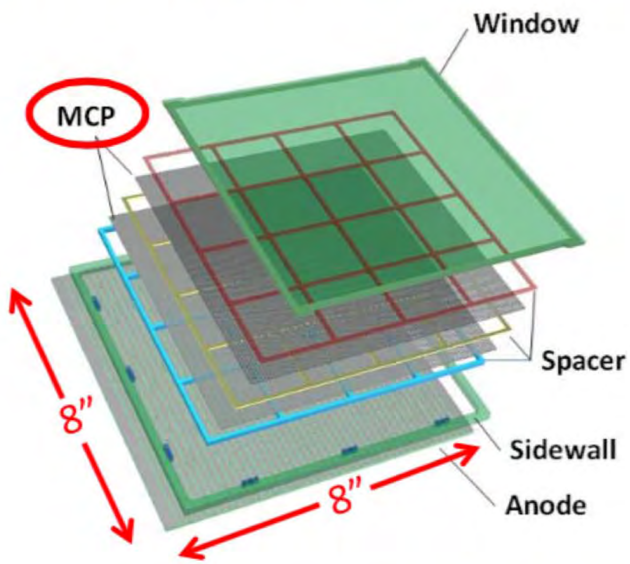
Picosecond Timing Project
Present 6 cm Program
Summary of Current Results
Future Plans

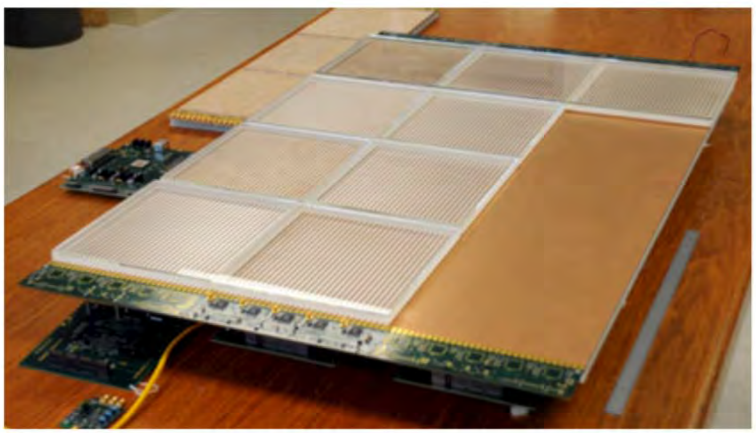
Carl Zorn
Jefferson Lab

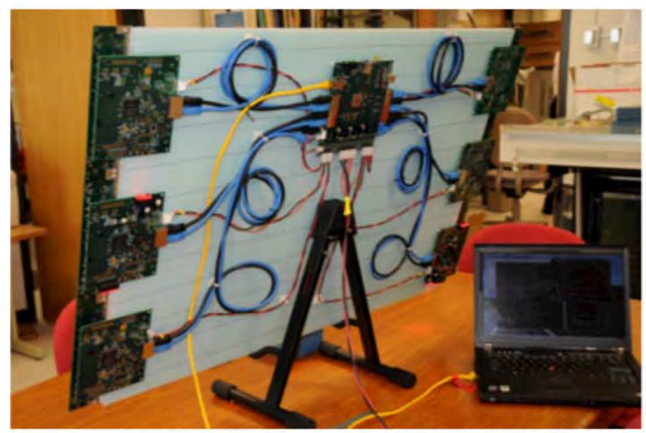
April 20, 2015

Large Area Picosecond Photodetector Project (LAPPD)

- Develop **cheap**, **large**-area photodetectors with ps timing resolution for large, high-energy physics installations *requiring 10's of thousands of tiles.*





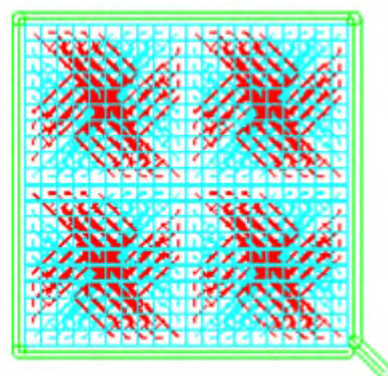


Large Area Picosecond Photon Detector

Picosecond Timing Project
http://psec.uchicago.edu

Large-Area Picosecond Photo-Detectors Project

Home | People | Library | Data/Analysis | Blogs | Databases | Psec Links



A group of us from The University of Chicago, Argonne, Fermilab and Berkeley are interested in the development of large-area systems to measure the time-of-arrival of relativistic particles with (ultimately) 1 pico-second resolution, and for signals typical of Positron-Emission Tomography (PET), a resolution of 30 pico-seconds (sigma on one channel). These are respectively a factor of 100 and 20 better than the present state-of-the-art. This would involve development in a number of intellectually challenging areas: three-dimensional modeling of photo-optical devices, the design and construction of fast, economical, low-power electronics, the `end-to-end' (i.e. complete) simulation of large systems, real-time image processing and reconstruction, and the optimization of large detector and analysis systems for medical imaging. In each of these areas there is immense room for creative and innovative thinking, as the underlying technologies have moved faster than the applications. We collectively are an interdisciplinary (High Energy Physics, Radiology, and Electrical Engineering) group working on these problems, and it's interesting and rewarding to cross the knowledge bases of different intellectual disciplines. We welcome inquiries and, even better, help.

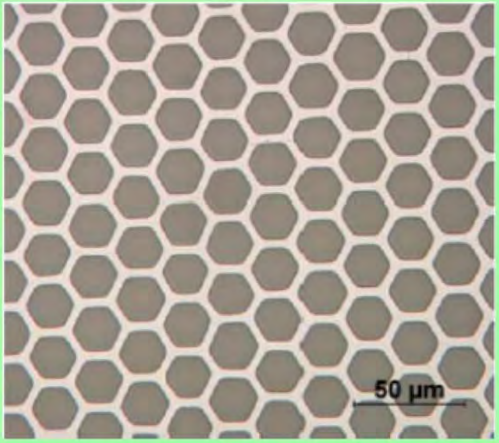
Program Summary

- **LAPPD program began August, 2009**
  - Included diverse group of national labs, universities, and commercial companies: Argonne, Fermilab, Space Sciences Lab/UC-Berkeley, U. Chicago, U. Hawaii, U. Illinois-Chicago & Urbana, Washington U., Incom, Arradiance, Muons, Inc., Minotech, Synkera + apologies to any overlooked
  - Have progressed in 5 years from tabula rasa to demonstration of working ALD-MCP photodetectors with few picosecond time resolution
- **Groups now are following separate parallel paths of advancement and sharing technology where applicable**
  - Small form factor tube facility: Argonne (glass package, support Incom glass package)
  - Industrialization: SSL (ceramic and glass package), Incom (glass package)
  - Next generation R&D: U. Chicago, BNL, RMD, Cornell, … (photocathode development, readout and electronics development, sealing, industrialization of LAPPD detectors)
  - Argonne ALD group provides common support to all paths via ALD-MCPs

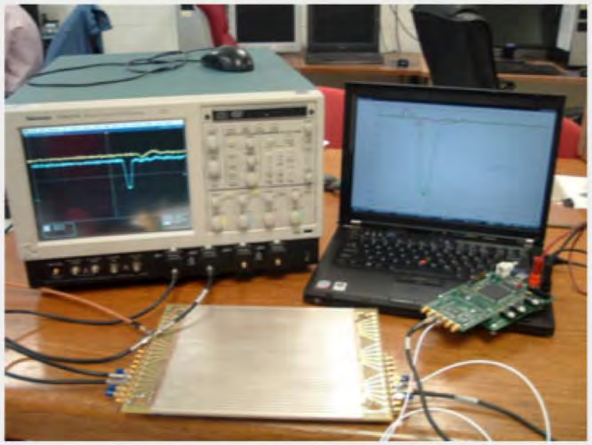
Four Key Areas

Four Main Areas of LAPPD

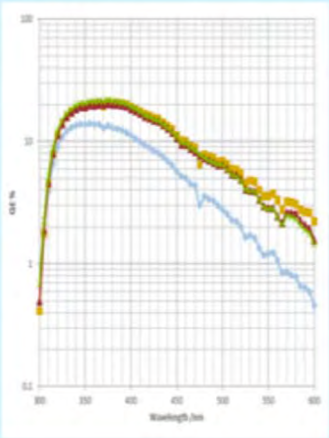
Micro-Channel Plates



Electronics / Integration



Photocathode



Hermetic Package

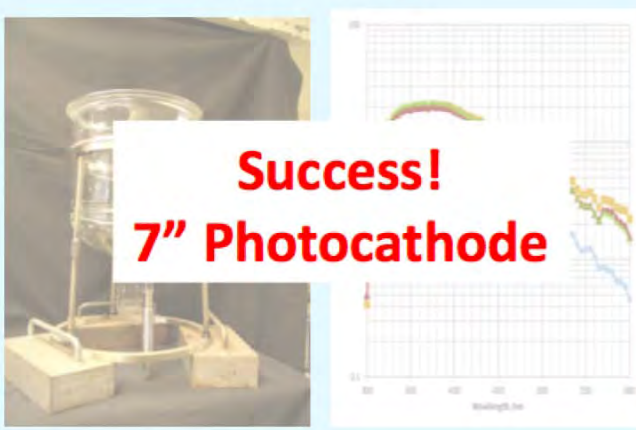
Four Key Areas

Four Main Areas of LAPPD

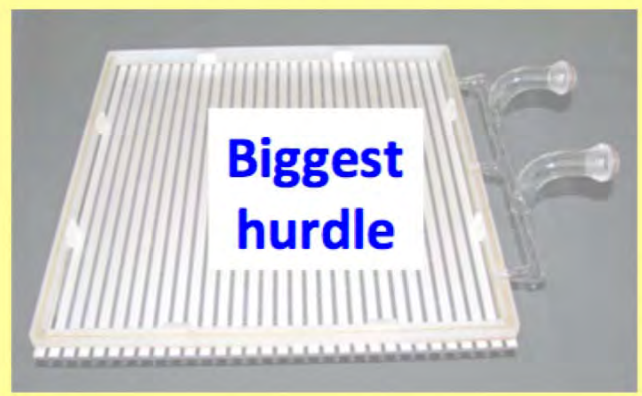
Micro-Channel Plates

Electronics / Integration

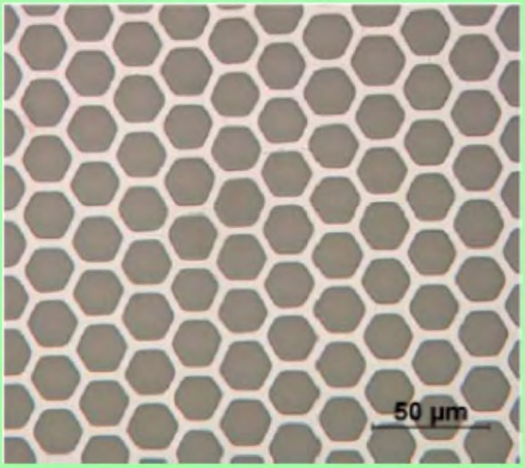
Photocathode

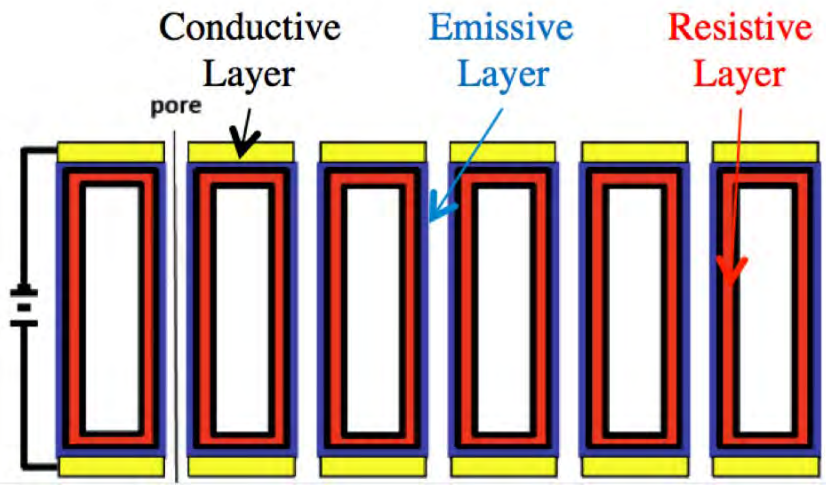


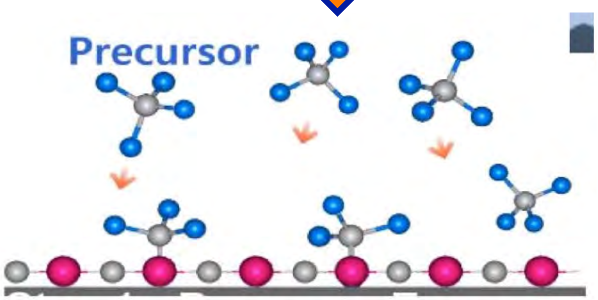
Hermetic Package



Micro-Channel Plates

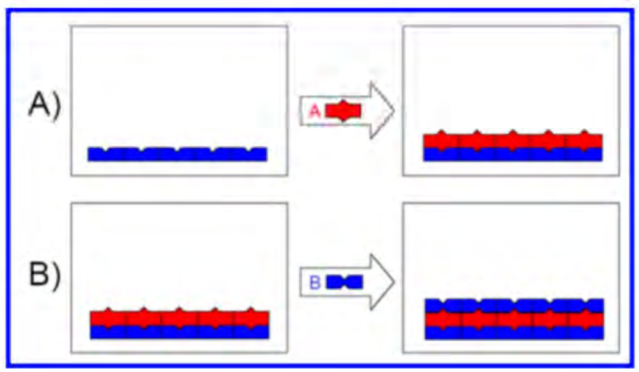


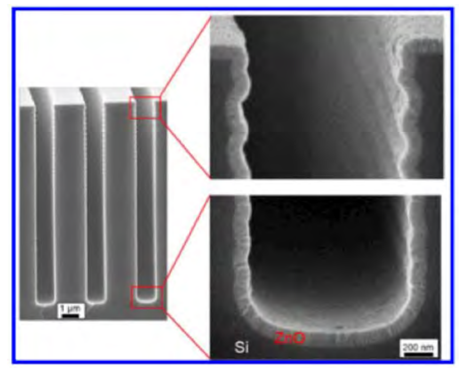




atomic layer deposition (ALD)

Borosilicate porous glass – 20 μm (Incom)
Atomic Layer Deposition (ANL)
Al_2O_3 or MgO – secondary emission





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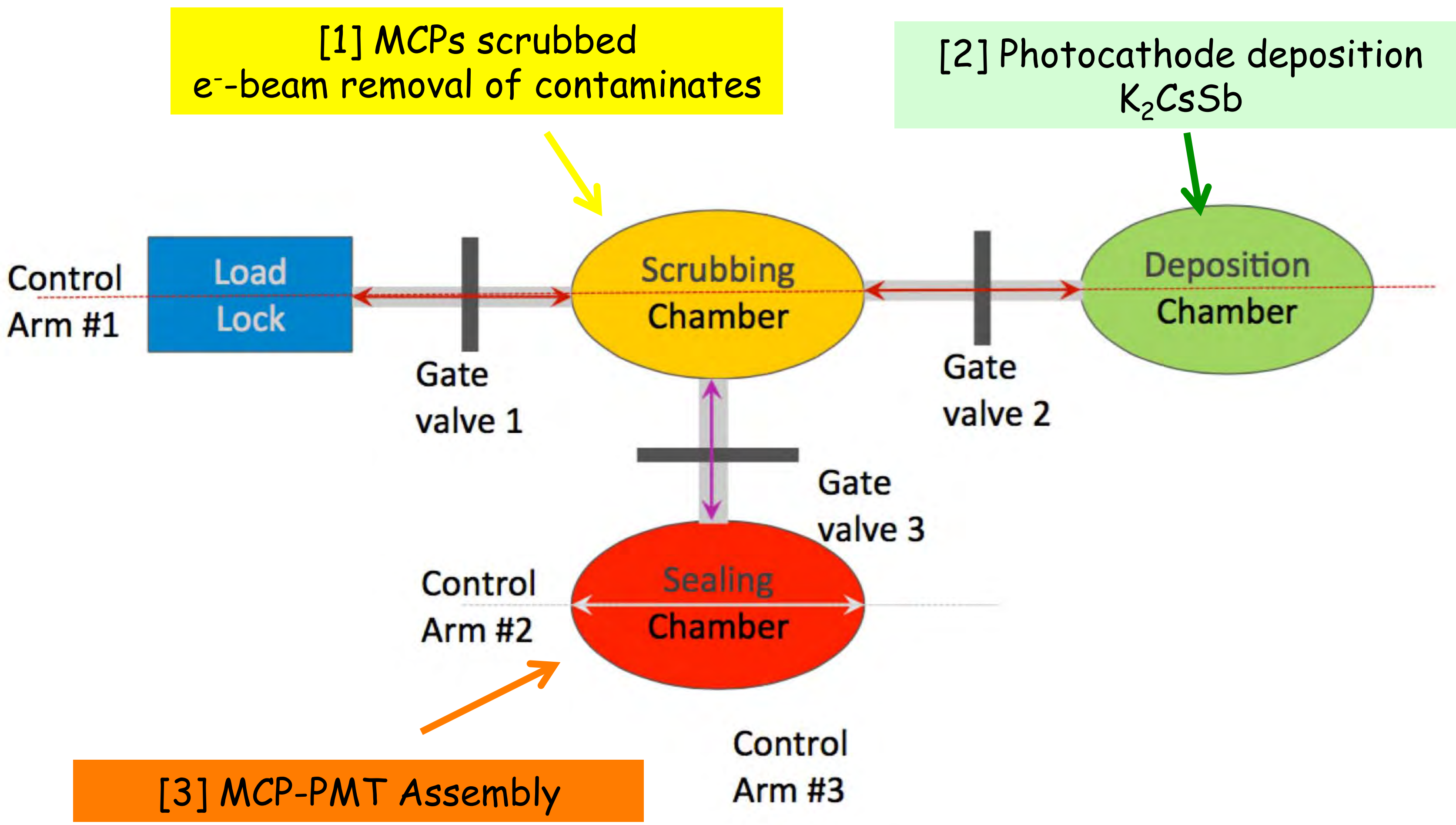
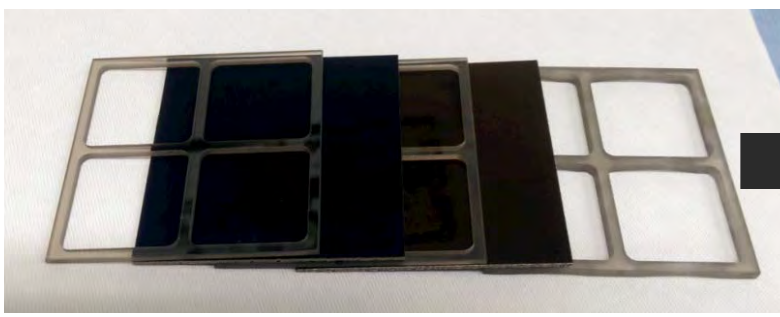
Small Tile Processing and Assembly System

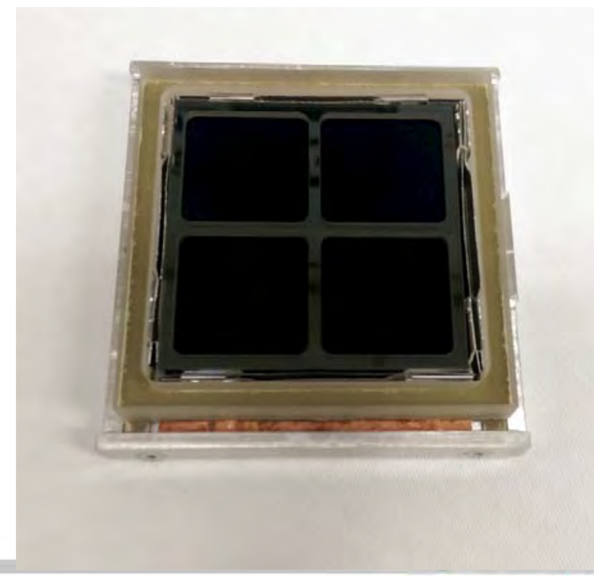
Small Tile Processing and Assembly System



Small Tile Processing and Assembly System

- Detector tiles are processed in the 6cm system following these steps
  - Clean all parts for detector tile
  - Load indium gasket into sealing chamber
  - Load Lower Tile Assembly (LTA: tile base, MCP's, spacers, getter strips on tile fixture)
  - **Scrub MCP's with electron gun**
  - **Bake LTA, activate getter strips**
  - Move LTA to sealing chamber, load top window
  - **Photocathode deposition**
  - Move top window to sealing chamber, assemble detector
  - **Press indium gasket to finish detector sealing**
  - Take out finished detector from sealing chamber





→ 1-2

Current (?) Sample Set

@JLAB

Serial #	27	28	29	30	31	32	33
Seal	Good	Good	Bad	Good	Good	Good	Bad
MCP	Gen I	Gen II	(none)	Gen I Gen II	Gen I Gen II	Gen II	Gen I Gen II
Getter	Good	Good	---	Bad	Bad	Good	Bad
lifetime	Since 9/17/14	Since 9/24/14	---	1 day	2 days	Since 10/15/14	---

Small Tile Performance Testing

Most results from Jingbo Wang et al., ANL

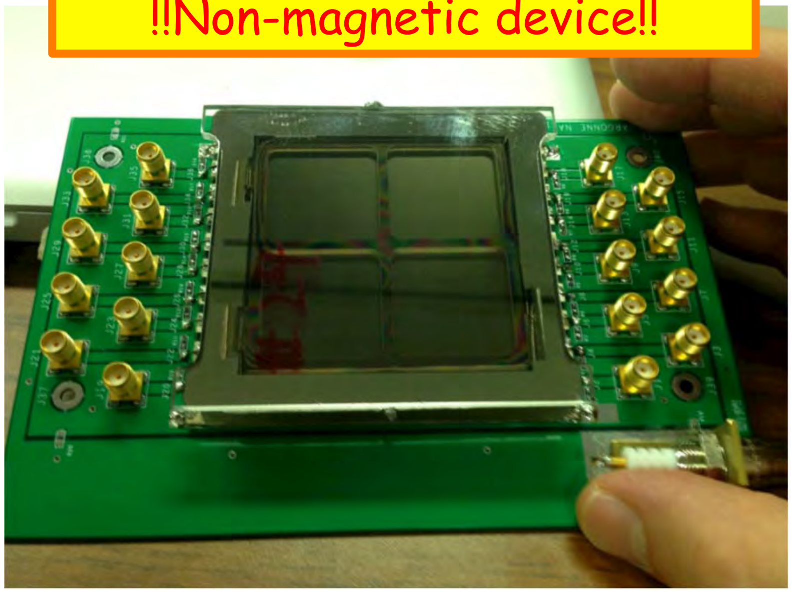
- Transit Time Spread (TTS)
- Position Resolution
- Uniformity
- Rate Capability
- Photon Detection Efficiency

JLAB has sample 28

R. Mendez, Y. Qiang, C. Zorn

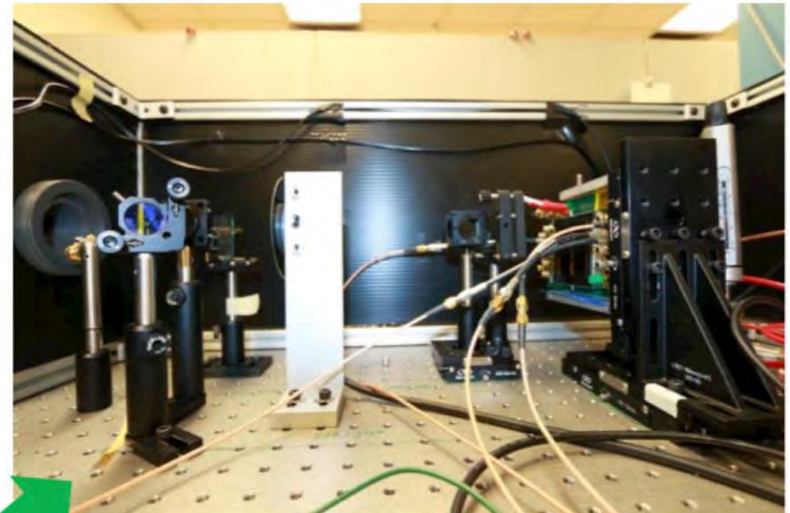
- Can verify some of ANL results
- Main focus
  - ✓ Magnetic field sensitivity
  - ✓ Radiation Damage (neutrons)
  - ✓ Problem – cannot resolve Single Photoelectron Peak

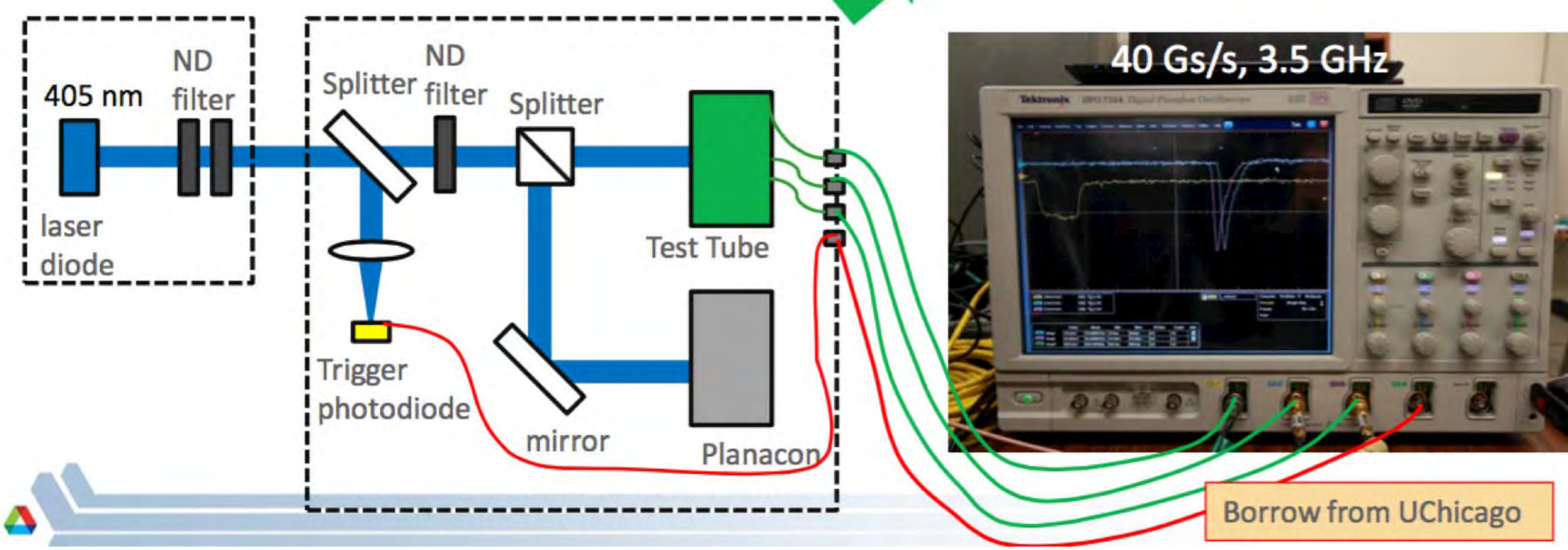
!!Non-magnetic device!!



Laser facility @ANL-HEP

- Wavelength: 405 nm
- Pulse duration: FWHM = 70 ps (σ = 30ps)
- Frequency: 2 Hz – 10 MHz
- Beam size: 1-2 mm
- Start signal: Photodiode (<3 ps)
  laser pulse (~7 ps)
- Readout: 40 Gs/s Oscilloscope
- Transition stage: um level precision
- Data analysis: Offline in software





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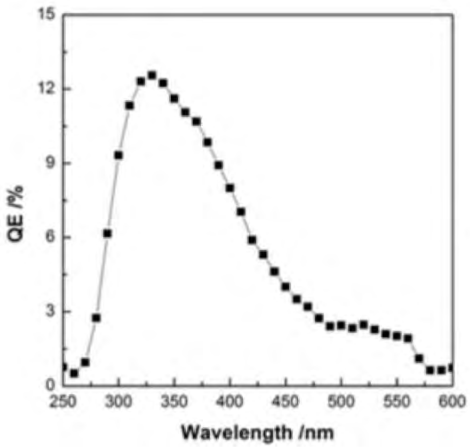
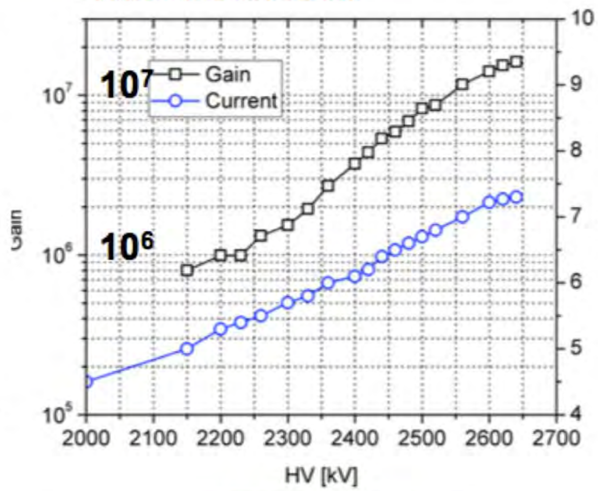
Comparison of 6cm Tube Performance with Commercial MCP-PMT

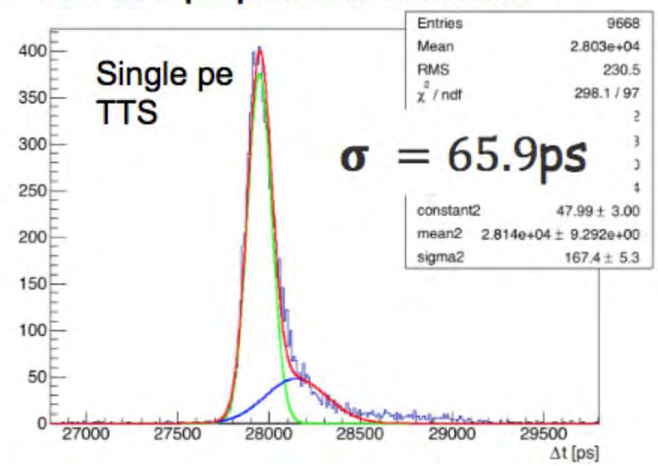
Tube 39 Photocathode QE



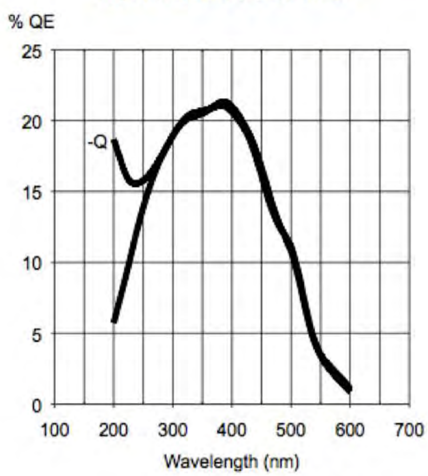
Tube 32 Gain vs HV



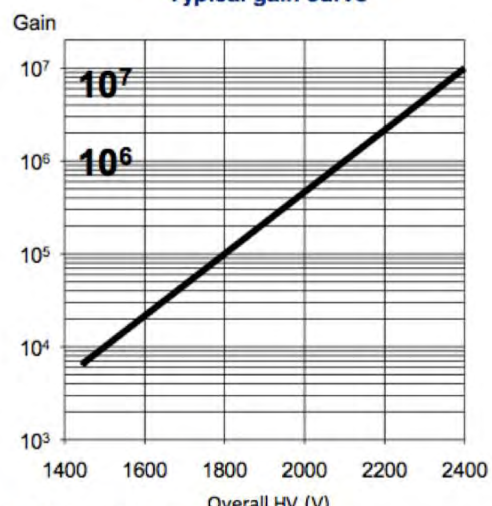
Tube 32 20μm pore Time Resolution

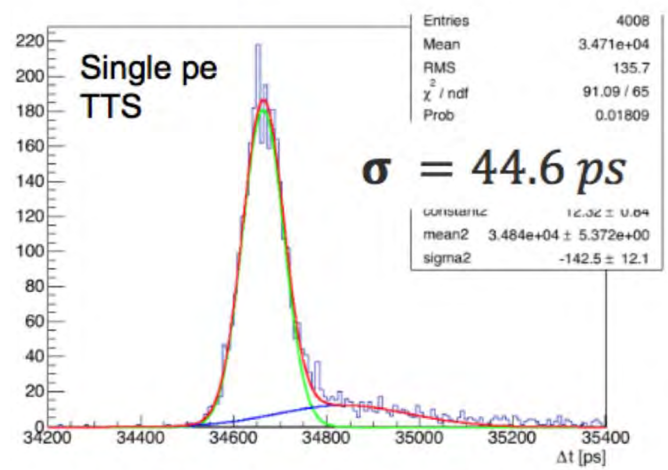


Typical spectral response



Typical gain curve

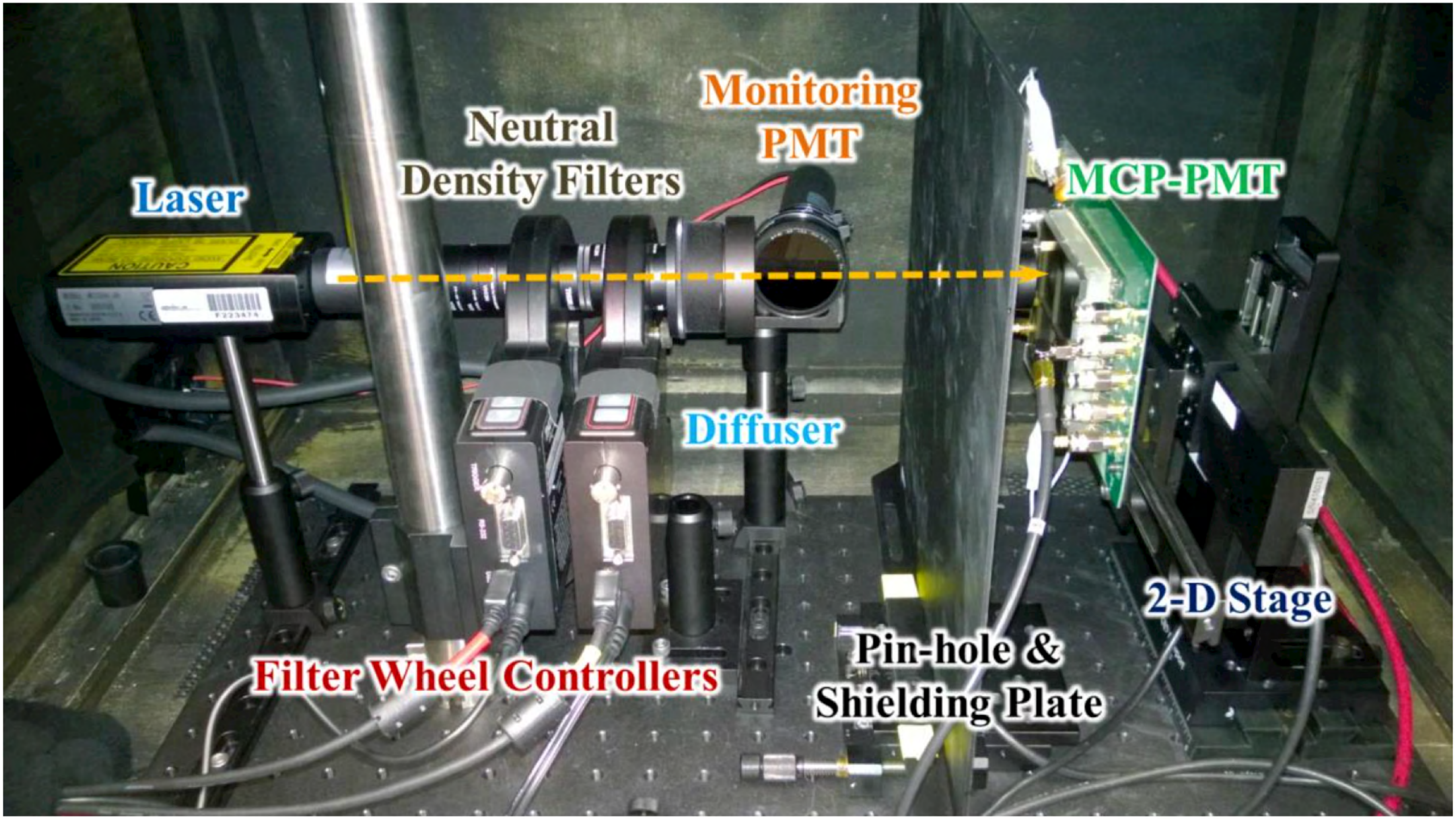




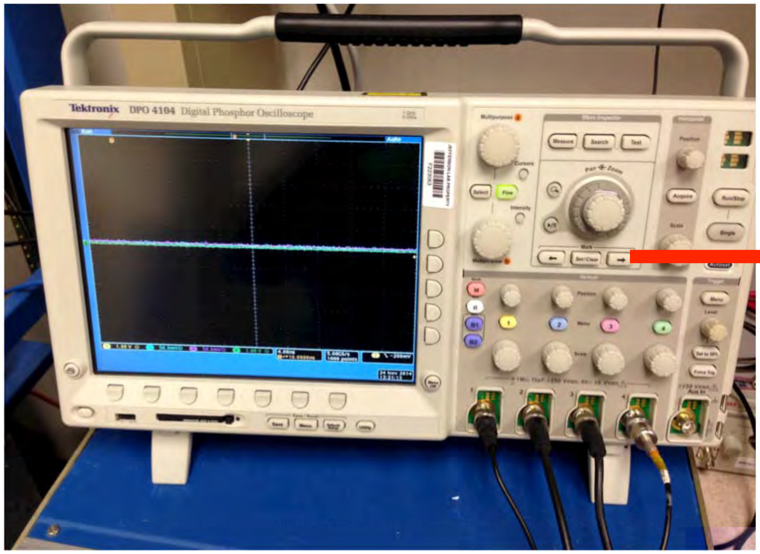
Photonis Planacon Data Sheet Graphs

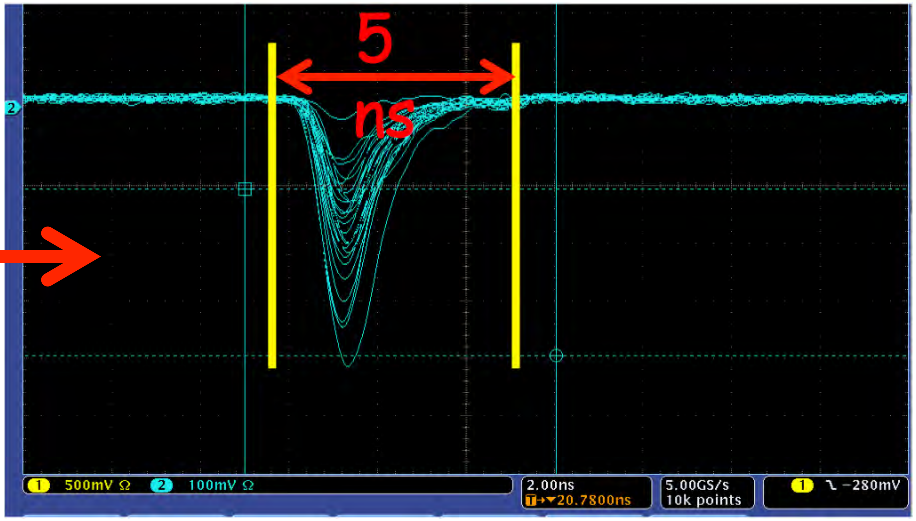
10μm pore Planacon Measd. at ANL

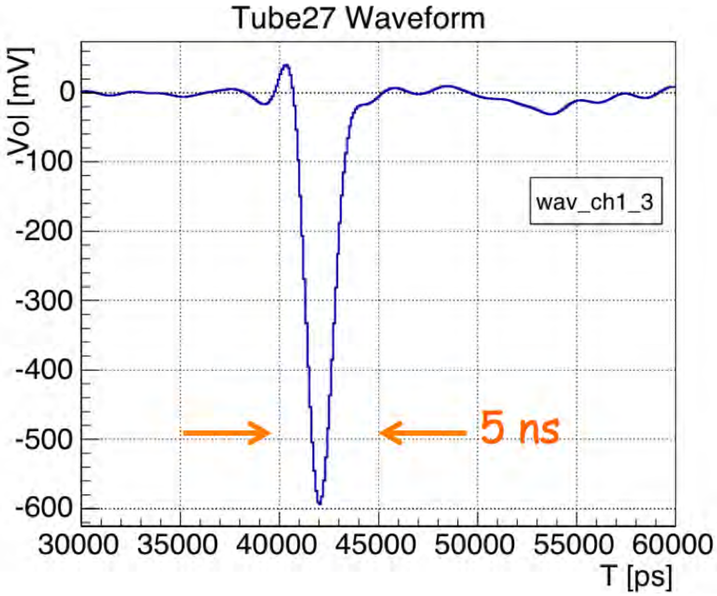
JLAB Test Setup



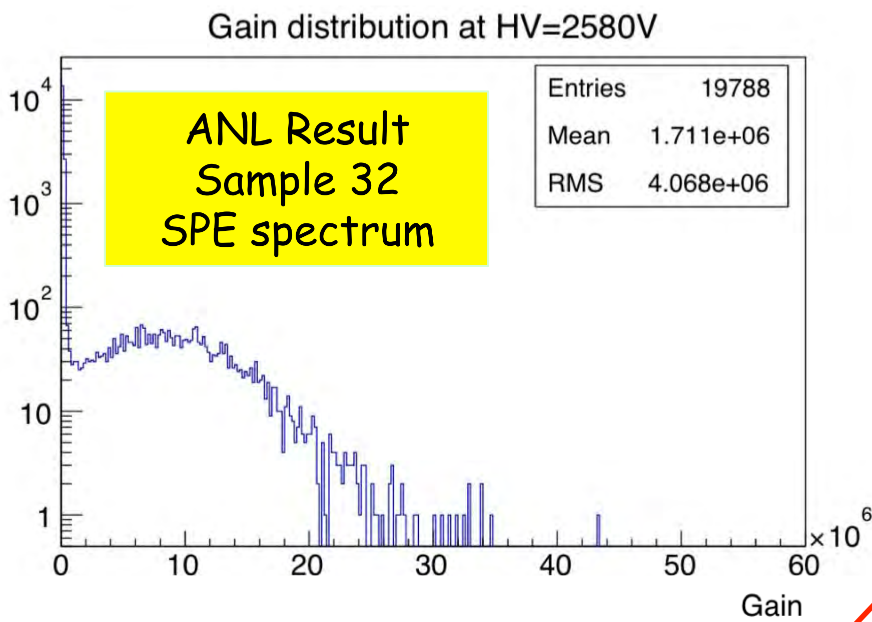
Initial DAQ – 1 GHz BW, 5 Gs/s scope



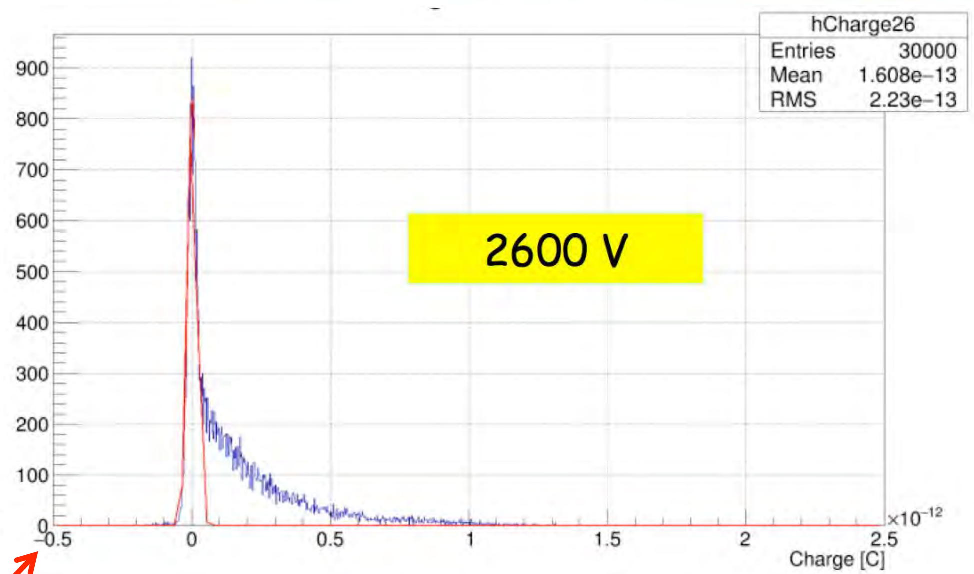


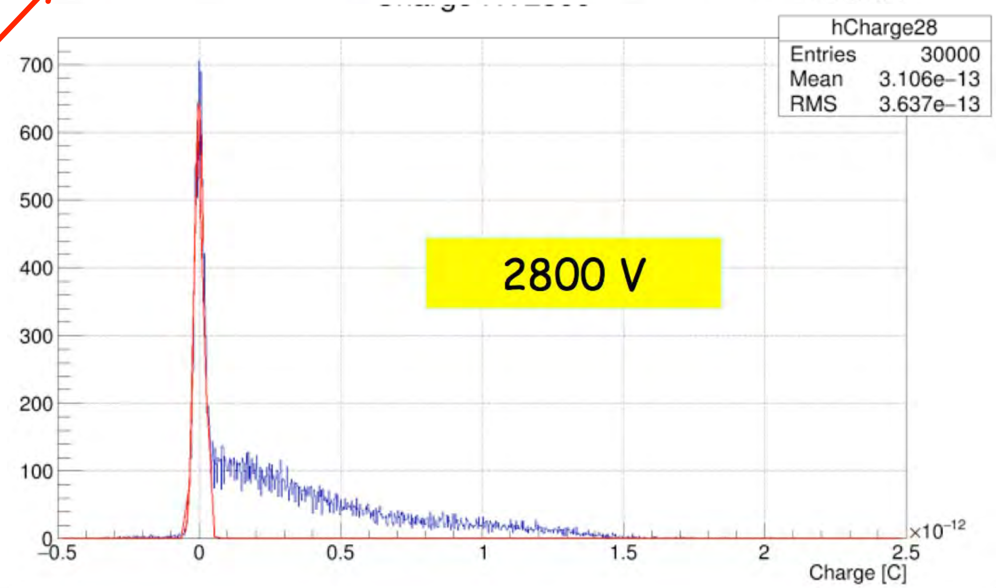


Gain Estimates from SPE spectra

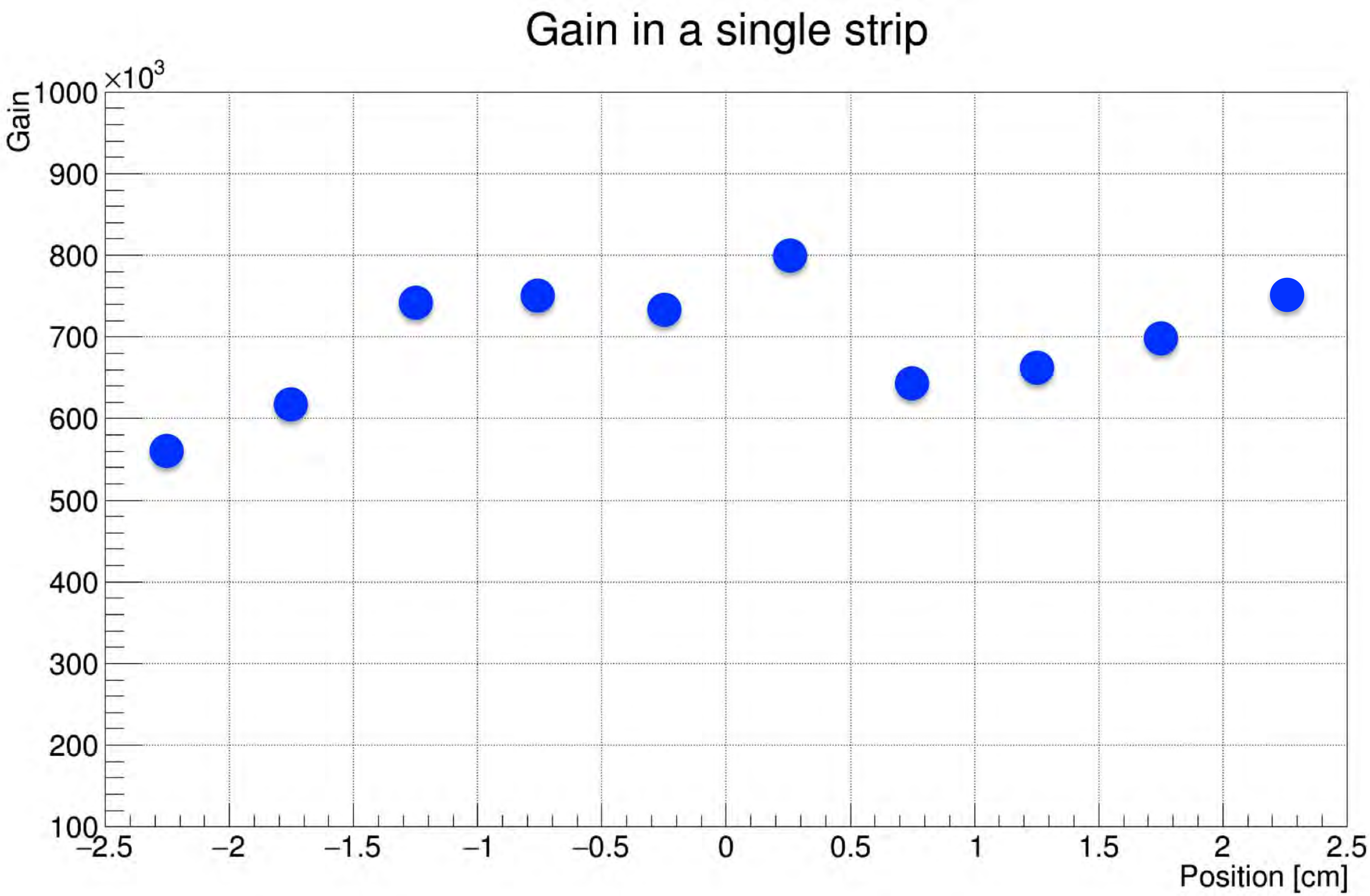


JLAB Results
Sample 28
Poor SPE resolution





Estimated Gain across (length) one readout strip



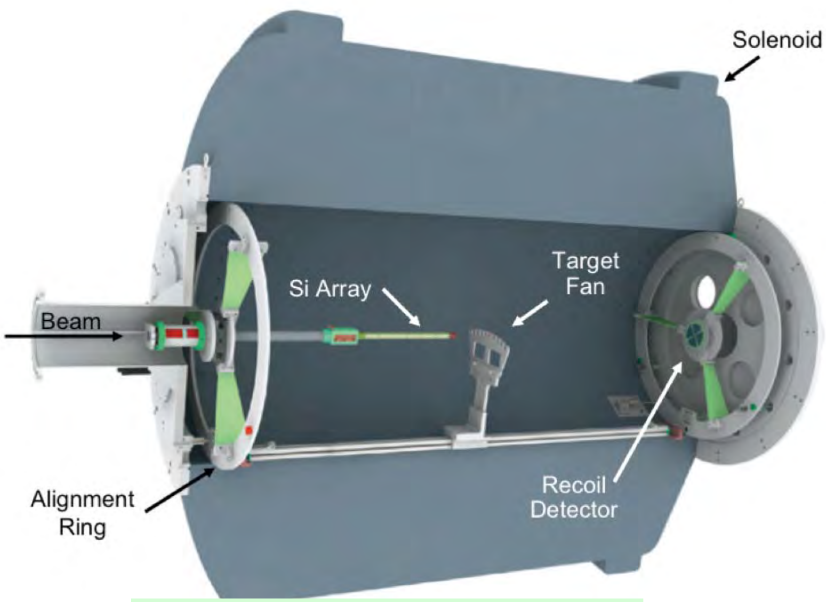
➔ 7-8

PDE – Photon Detection Efficiency

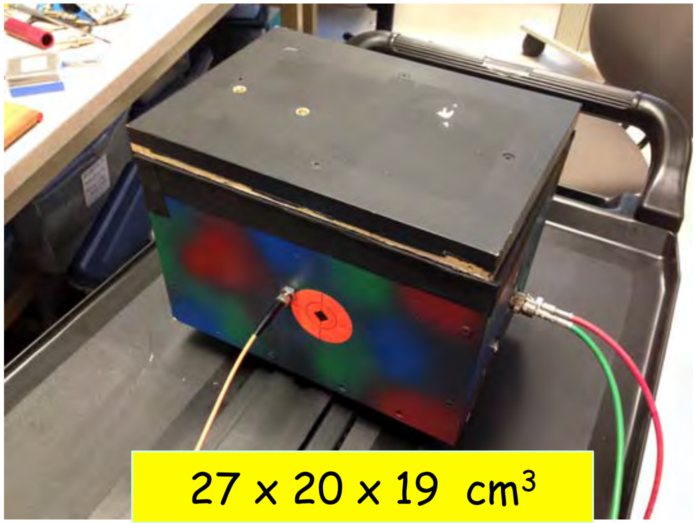
- ❖ Use filter wheel system to control intensity
- ❖ Use calibrated photodiode (Hamamatsu S2281 – 100 mm^2) to measure photon flux
- ❖ At single photon level – measure mean #photoelectrons at several gains for trigger phototube (Hamamatsu R4998) which has well-resolved single photoelectron spectrum
- ❖ Find mean PDE = 20.6% ± 1.2% ➔ consistent with data sheet (20%)
- ❖ Redo with LAPPD sample using estimated gain and mean photoelectron level ➔ find estimated PDE ~ 2% ➔ consistent with ANL estimates

Magnetic Field Sensitivity

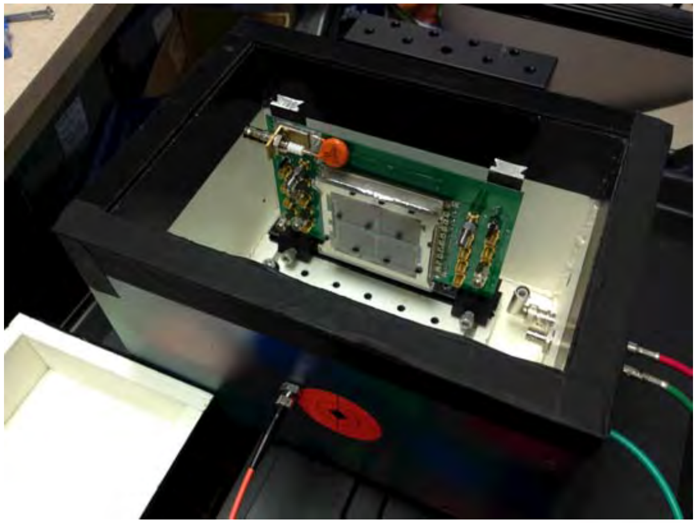
Place sample in mini-dark box
Need large bore high-field magnet
Plan to test at ANL or UVA medical center (MRI magnets)



HELIOS @ ANL



$27 \times 20 \times 19\ cm^3$



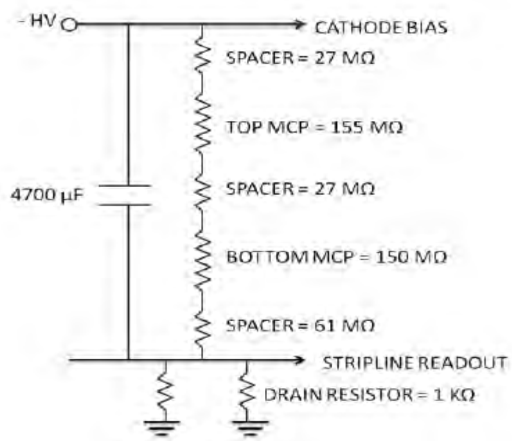
Summary – JLAB sample 28

Lab Tests of the LAPPD prototype mini-sample (Oscope DAQ):

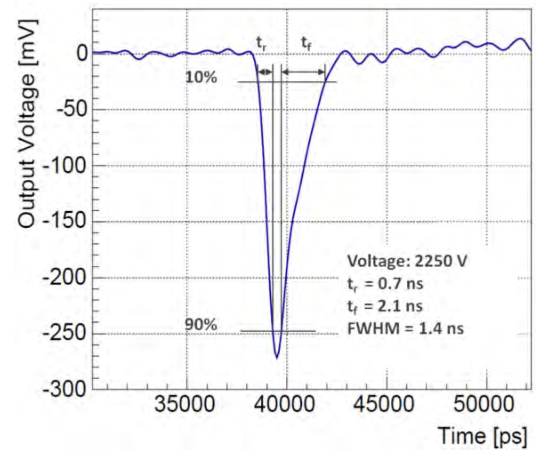
- Good clean signals, but poorly resolved single photoelectron spectrum
- PDE is low
- Uniformity behavior consistent with ANL test cases
    - photocathode nonuniformities?
- Wish list
    - Improved SPE – trade out with new sample?
    - Better (safer!) HV connection
    - Longer term ➔ alternate readout ➔ pixel matrix?
- Redo some tests with high data-taking rate VME DAQ system
    - Extract measure of gain and PDE
    - High rate test with dual light sources
        - Low intensity, low rate signal
        - Coupled with very low intensity, variable frequency load
- ***Priority in short term: Magnetic field test***
- Neutron radiation hardness test

Next Steps in Improvement (ANL)

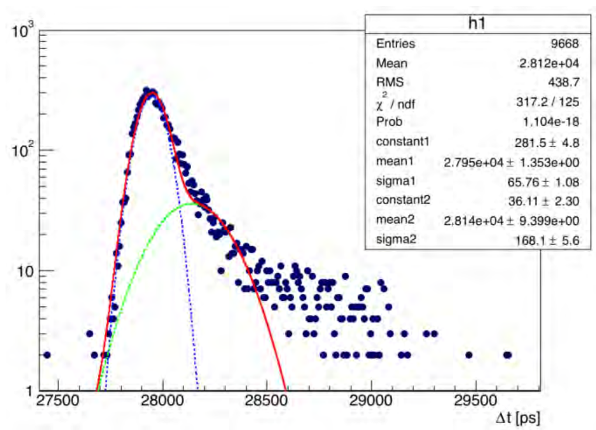
(1) Resistor HV chain design



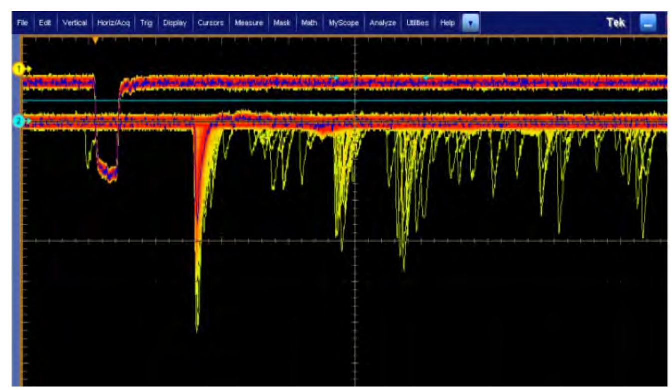
(2) Rise time



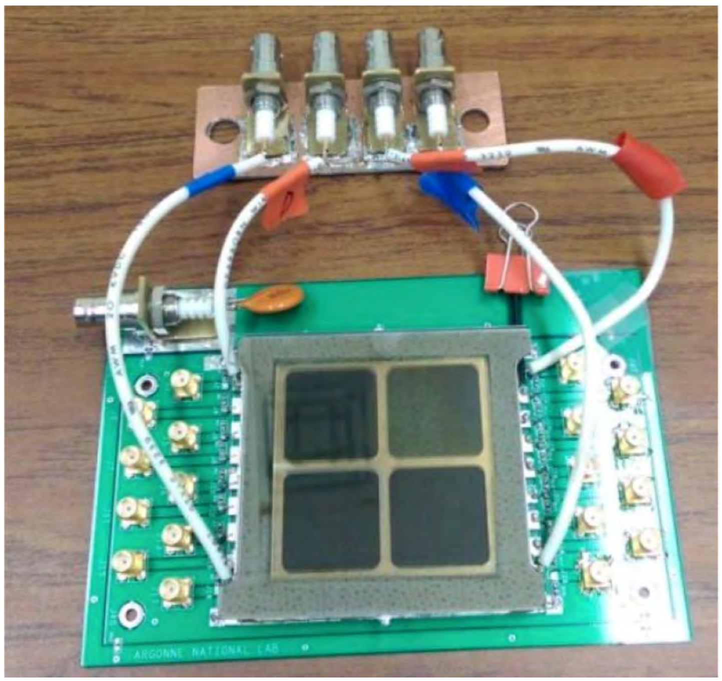
(3) Timing distribution



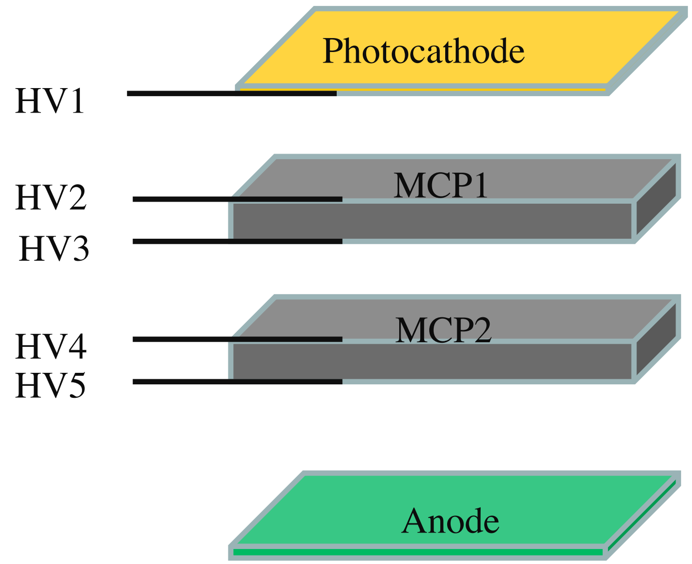
(4) After pulses



Next Samples – Individual Bias Adjustments



Individual bias design



Benefits from a new design

- Direct measurement of QE
- HV optimization
- Allow for monitoring of all components
- Lifetime test
- Study on MCP working principle

Next Samples – Data Sheets

Argonne NATIONAL LABORATORY

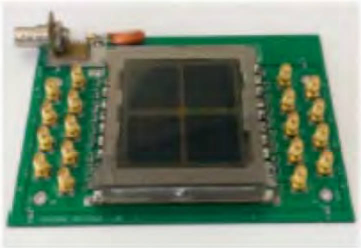
High Energy Physics Division

6cm x 6cm Photodetector Data Sheet

Photodetector Tube No.: # 32
Mfg Date: Oct. 15, 2014

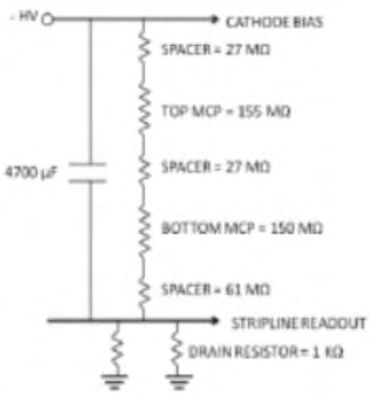
SECTION 1: DESCRIPTION

Window material	Borosilicate glass
Window mask	NiCr
Photocathode type	Bialkali
Multiplier structure	MCP chevron (2), 20 µm pore, 60:1 L:D ratio
Stack structure	Resistor chain design
Anode structure	0.47 cm sliver strip line, 0.23 cm space
Active area	6 cm x 6 cm
Package open-area-ratio	65 %



SECTION 2: CHARACTERISTICS

Photocathode Characteristic	
Spectra response range	300 nm ~ 600 nm
Quantum efficiency	Max: 20%
Timing Characteristic	
Operation voltage	2100 V - 2600 V
Transition speed	1.8 mm/ns
Gain	1e6 - 1e7
Single Photoelectron	
Time resolution	57 ps
Position resolution	/
Multi Photoelectron	
Time resolution	15 ps
Position resolution	<0.5 mm



Backup Slides

LAPPD Terminology

- **6cm MCPs** — Two varieties of MCPs for 6cm x 6cm photodetector
  - GenI with Chem. 1 & Al_2O_3 for secondary emission layer (earlier 6cm)
  - GenII with Chem. 1 & MgO for secondary emission layer (recent 6cm)

- **6cm "Regular" or baseline design** — Voltage biasing of MCP pair attained by single HV connection to photocathode with resistively coated glass grid spacers used to create an internal resistive chain through the photodetector as well as provide mechanical support

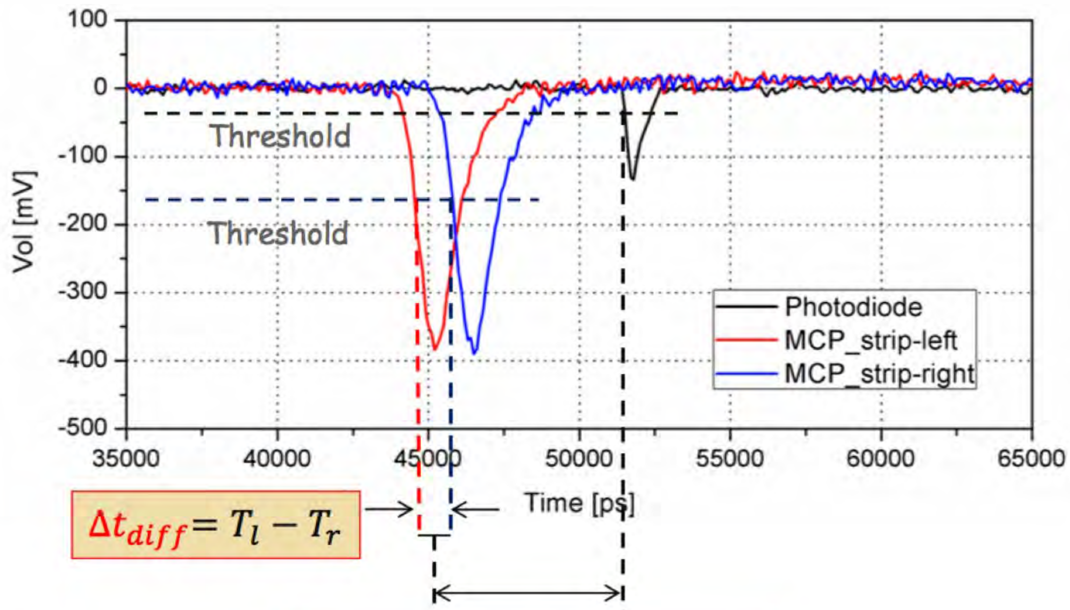
- **6cm New or re-design** — Independent voltage biasing of photocathode and each of 4 MCP pair surfaces. Grid spacers become insulating bare glass supports. Modest perturbation of baseline configuration

LAPPD Terminology

- **Glass Capillary Arrays (GCA)** — bare glass plates or disks made from fused hollow core capillaries
  - **Generation I (GenI)** — final finish by traditional grit with wax filler in pores
  - **Generation II (GenII)** — improved wax-free polishing giving cleaner surface and reduced pore contamination

- **Functionalization of GCAs into Microchannel Plates (MCPs)**
  - **Passivation** — Atomic Layer Deposition (ALD) Coating of Al_2O_3 applied to baked and electroded GCA to isolate substrate from subsequent ALD coatings
  - **Chem. 1** — ALD coating of W, Al_2O_3 mix to provide targeted MCP resistance
  - **Chem. 2** — similar to Chem. 1 with Mo replacing W
  - **Secondary Emission Layer** — Either Al_2O_3 or MgO layer to produce gain electrons

Timing Tests Setup

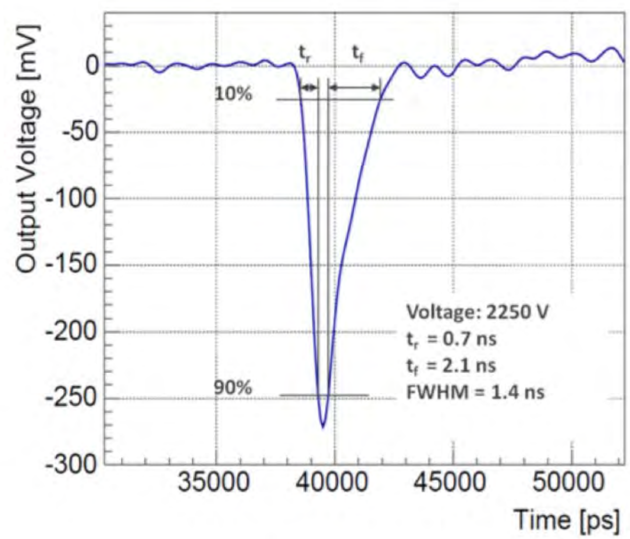


$\Delta t_{diff} = T_l - T_r$

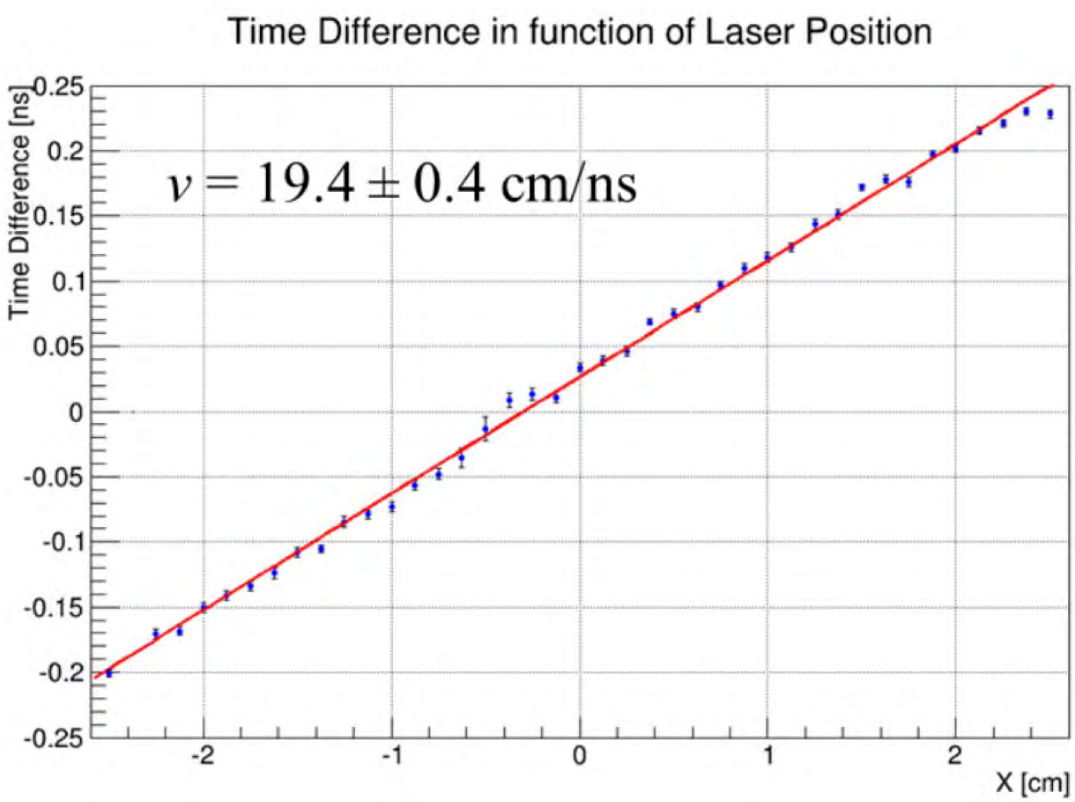
$\Delta t_{abs} = T_{MCP} - T_{Photodiode}$

$\sigma(\Delta t_{abs})$:
Absolute transit time spread resolution

$\sigma(\Delta t_{diff})$:
Differential transit time spread resolution



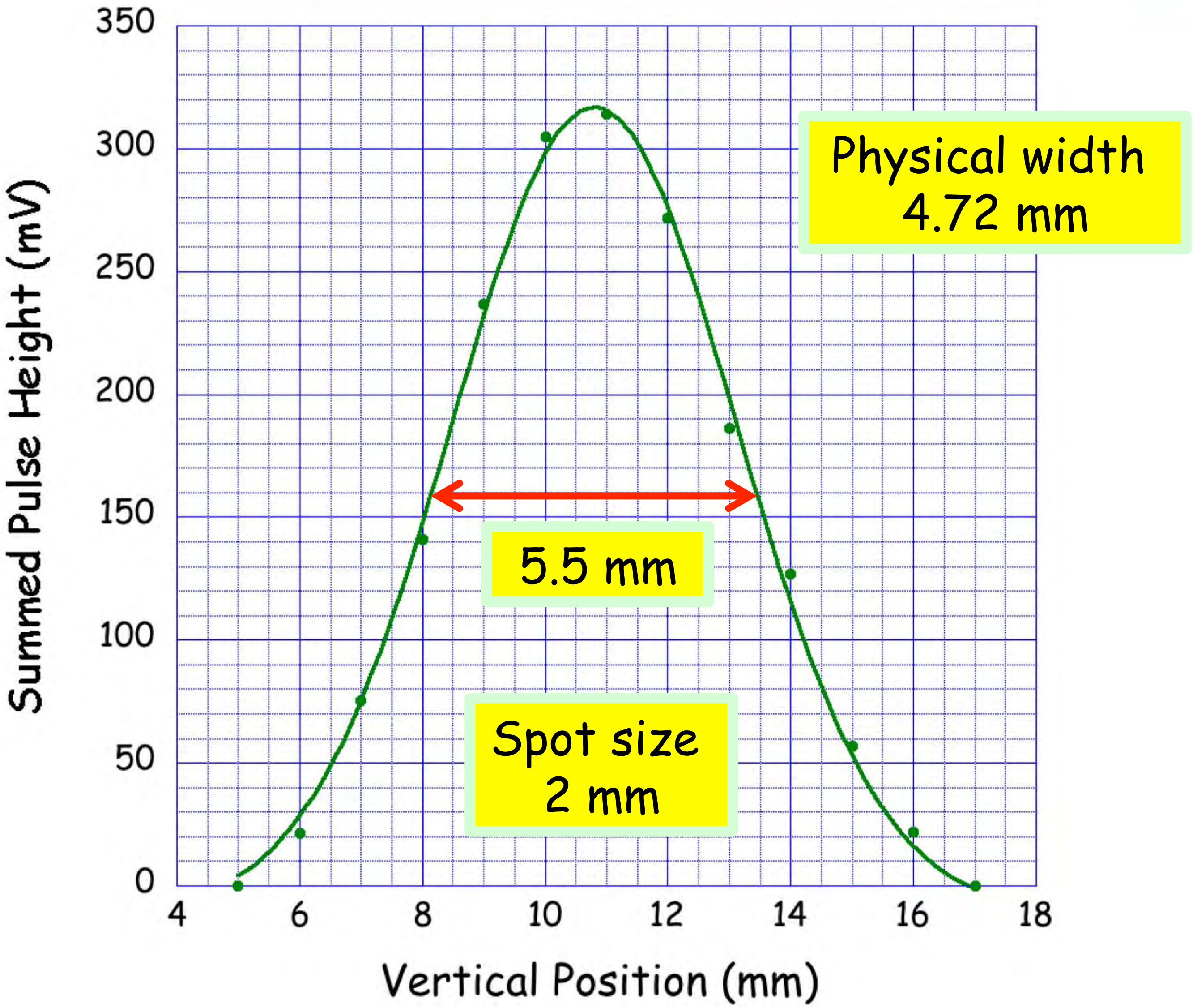
Signal Strip Transmission Speed (JLAB)



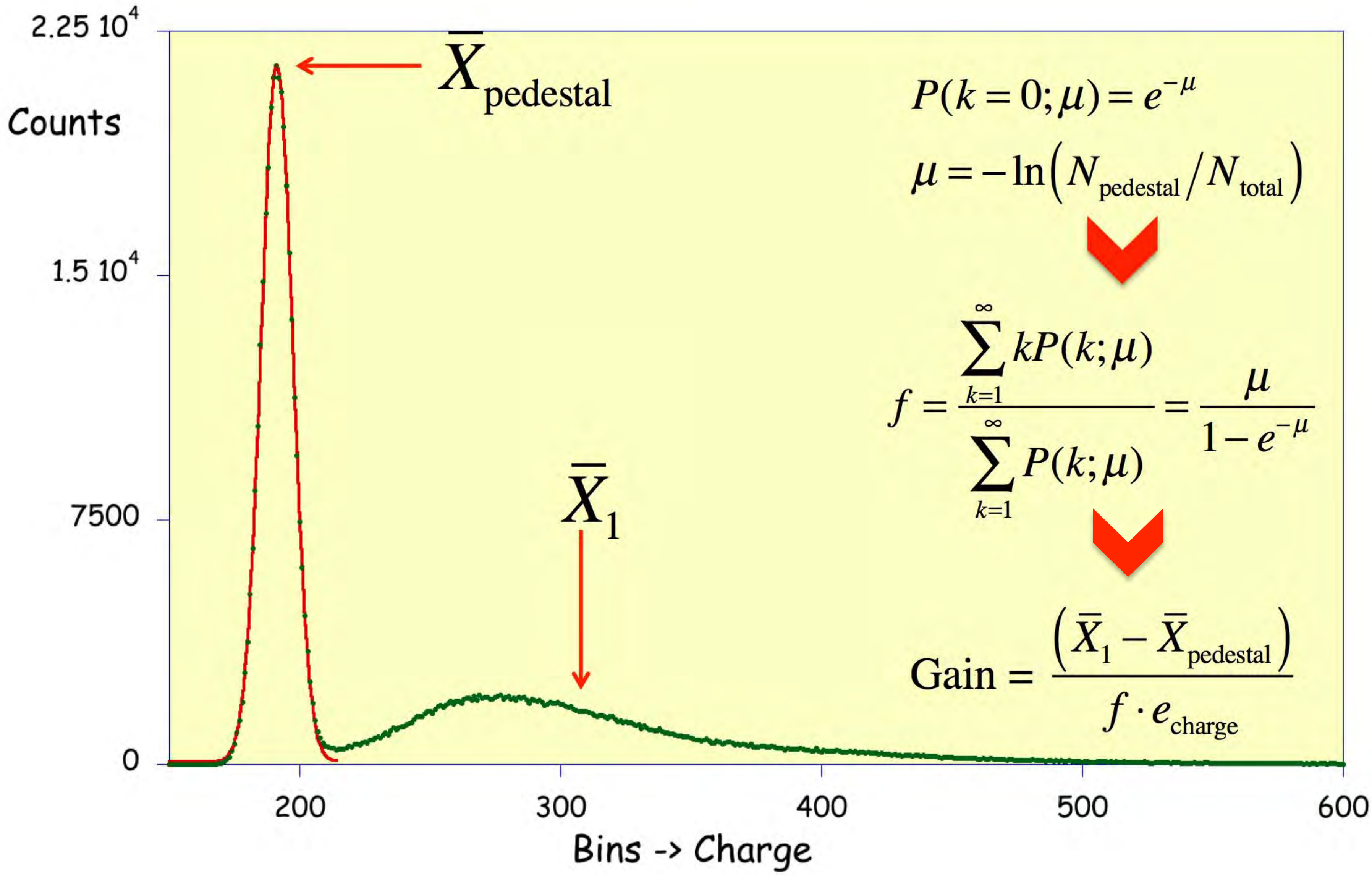
Measured at single photoelectron level

Strip Signal transmission speed
178 μm/ps (ANL)
194 μm/ps (JLAB)

Vertical scan across one readout strip



Estimating the Gain with Poisson Stats



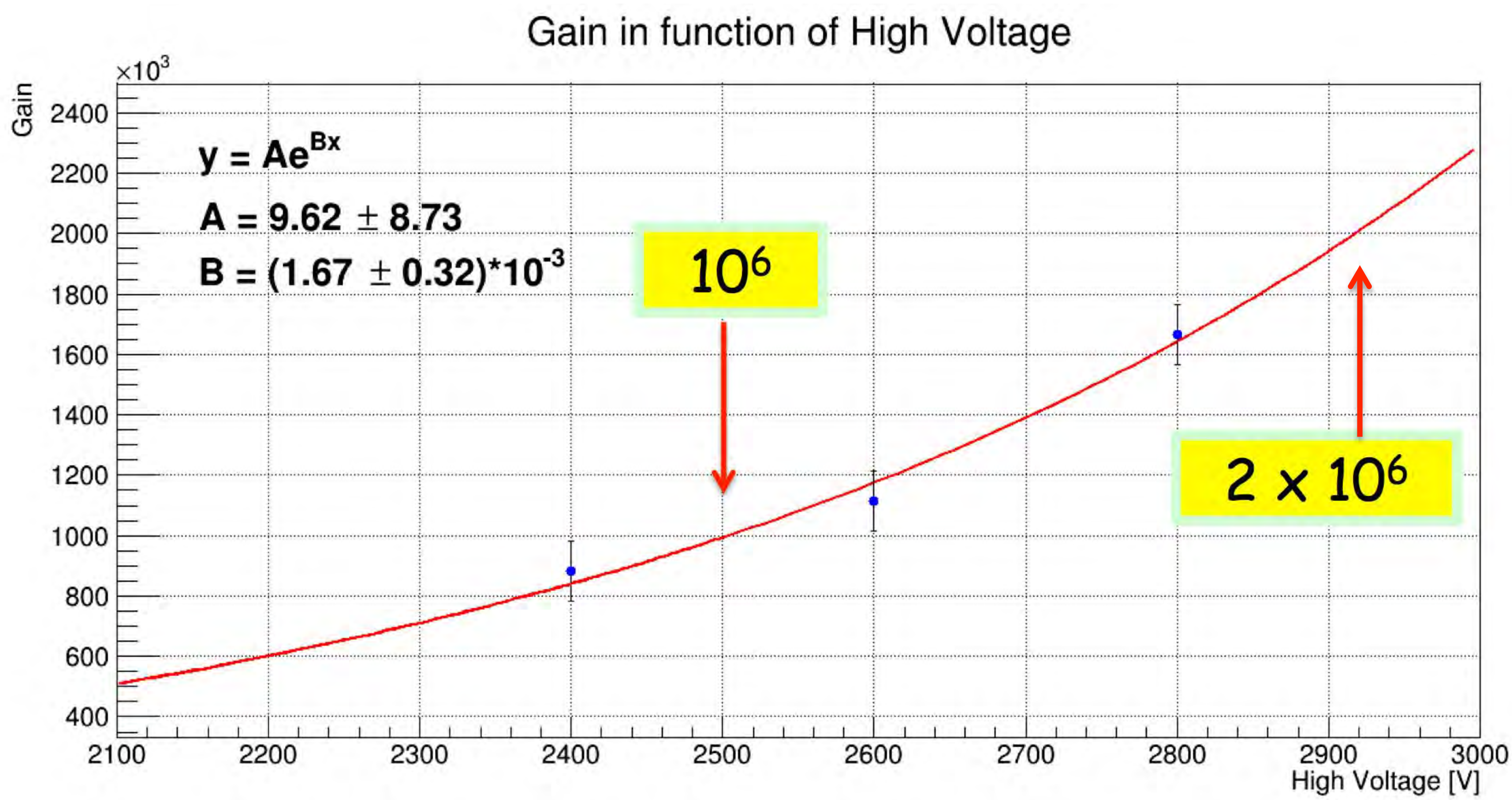
$$P(k=0;\mu) = e^{-\mu}$$

$$\mu = -\ln\left(N_{\text{pedestal}}/N_{\text{total}}\right)$$

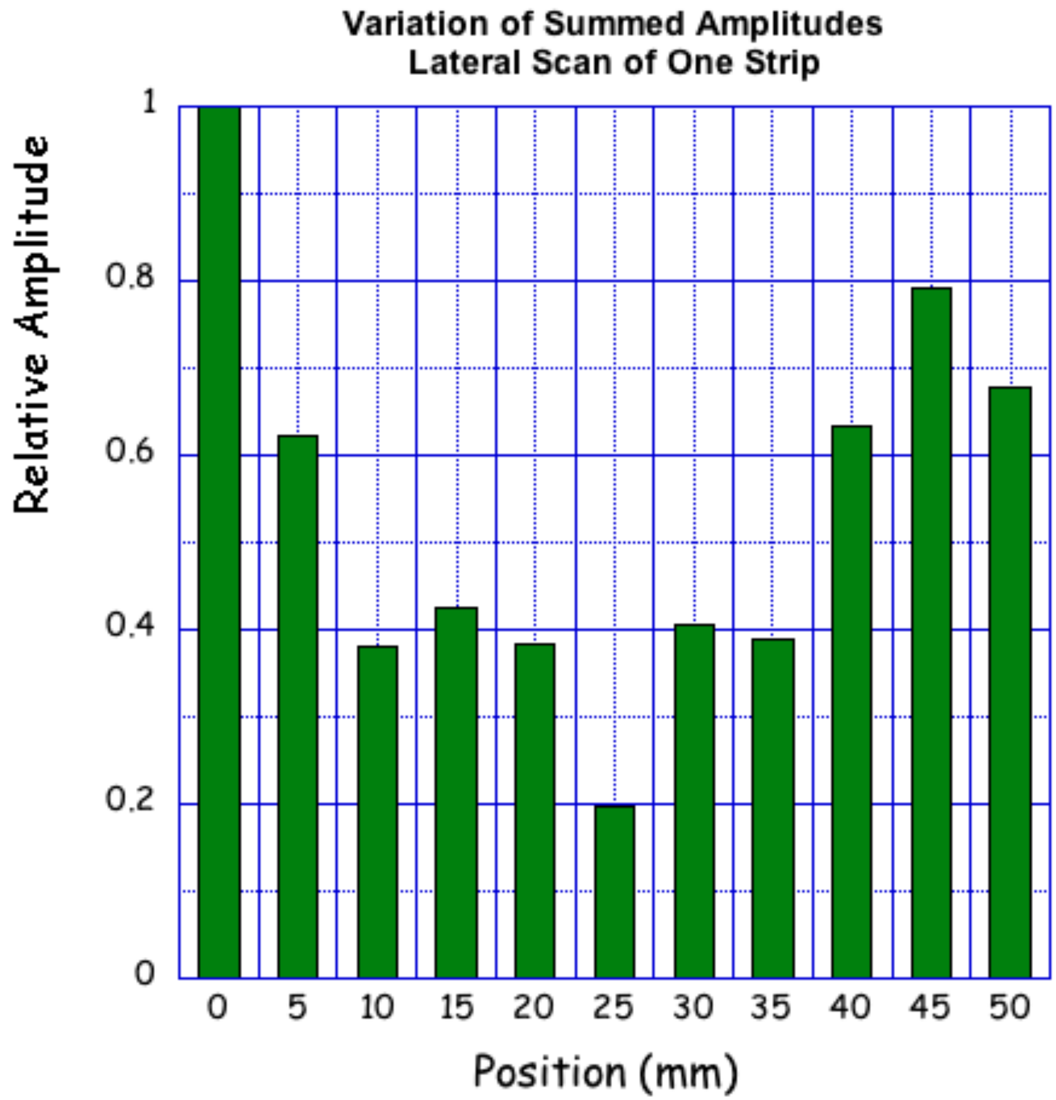
$$f = \frac{\sum_{k=1}^{\infty} kP(k;\mu)}{\sum_{k=1}^{\infty} P(k;\mu)} = \frac{\mu}{1-e^{-\mu}}$$

$$\text{Gain} = \frac{\left(\bar{X}_1 - \bar{X}_{\text{pedestal}}\right)}{f \cdot e_{\text{charge}}}$$

Gain Estimates from SPE spectra

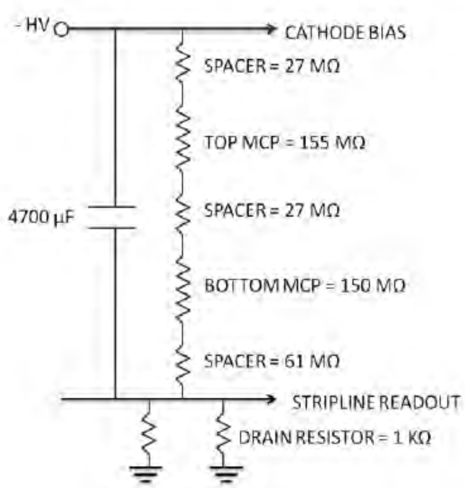


Amplitude variation (horizontal) across one readout strip



Resistor chain to individually biased HV

Present Resistor chain design

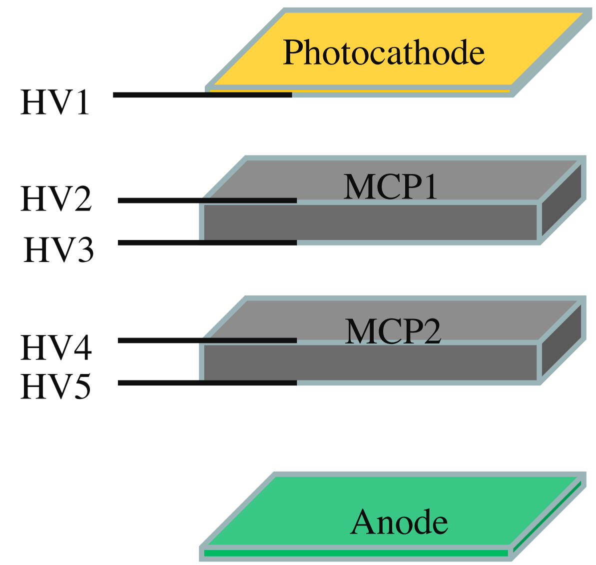


Limitation of current design

- No way to directly measure QE
- No way to monitor the internal components
- No way to optimize the working HV
- Always difficult to resistively match components
- The resistor changes during tile processing

Limits our future progress!

Individual bias design

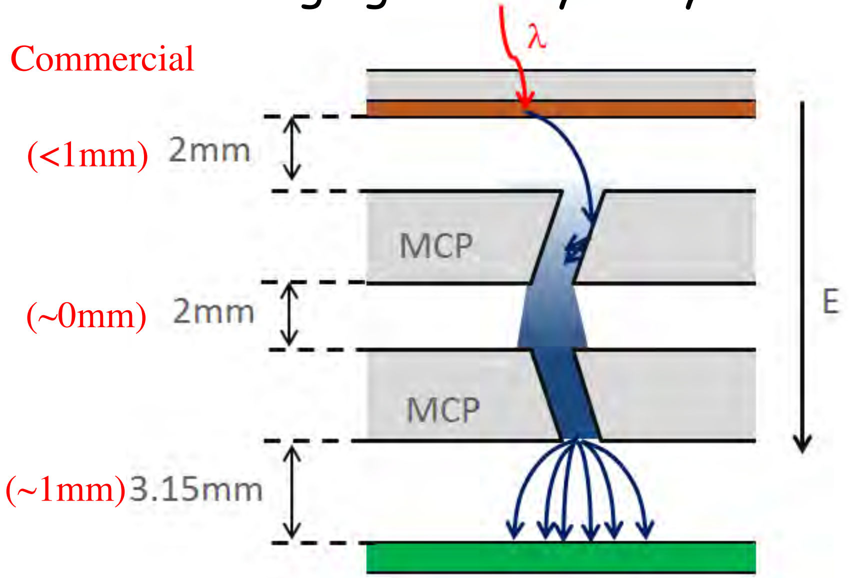


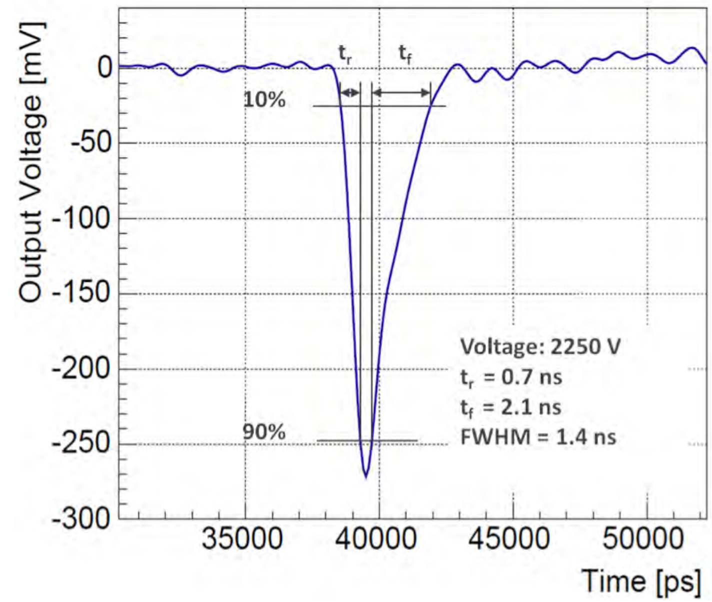
Benefits from a new design

- Direct measurement of QE
- HV optimization
- Allow for monitoring of all components
- Lifetime test
- Study on MCP working principle

Signal shape

Design guided by early LAPPD simulations





Main source of rise time:
- Cathode-to-MCP gap
- MCP pore size
- MCP-to-Anode gap

Main source of fall time:
- Anode capacitance
- Transmission line impedance

Rise time: ~700 ps
Fall time: ~2.1 ns
FWHM: ~1.4 ns

Commercial device: 100-300ps

We need to make the signal faster!

Rise time

Rise time is defined as time interval between 10% to 90% of the amplitude.

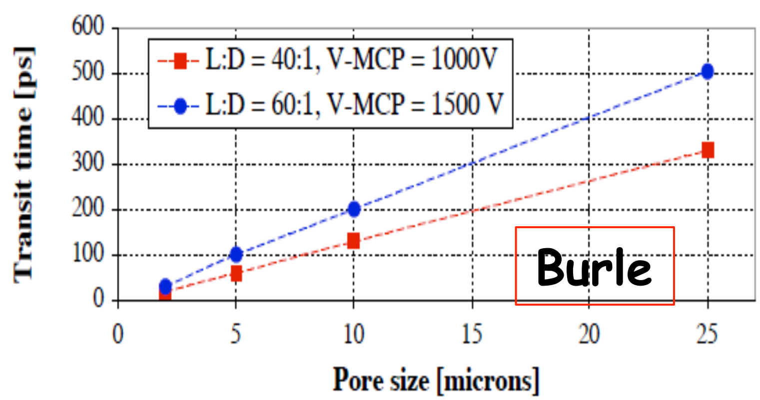
- Cathode-to-MCP gap has a negligible effect on the rise time. The innitial electron has a few eV energy. Induce signal from a single electron drifting in this gap is very small.
- MCP pore size is the main source of the rise time. The electrons have various possible drifting paths, and a radial distribution of the electron swarm causes the rise time spread.
- MCP-to-anode HV has a big effect on the rise time. Electrons emitted from the 2nd MCP have a large velocity variation.

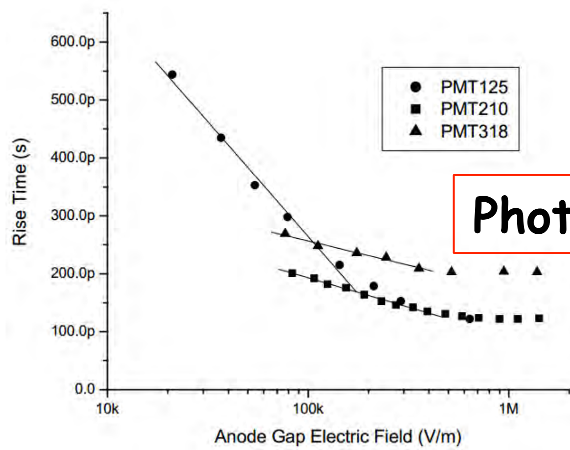
MCP-to-Anode HV should be high

Pore size should be small

$$\frac{dt}{dv} = \frac{1}{a}\left[\frac{v}{\sqrt{v^2+2ad}} - 1\right]$$

$$BW(\mathrm{GHz}) = \frac{350}{t_r}$$





Electron backscattering

Photoelectron travel time:

$$t_0 = \sqrt{\frac{2m_e l^2}{Ue_0}}$$

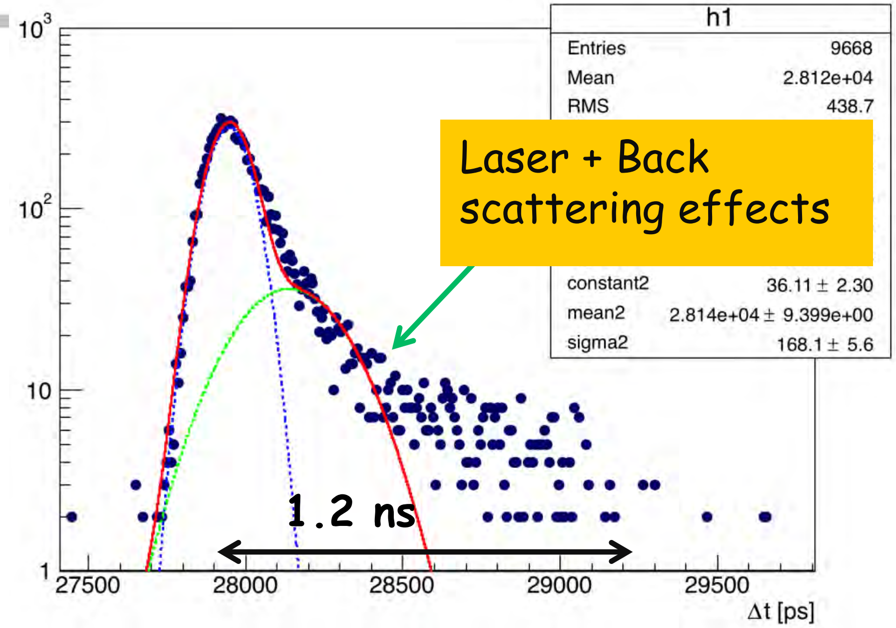
Delay and range of backscattered photoelectrons:

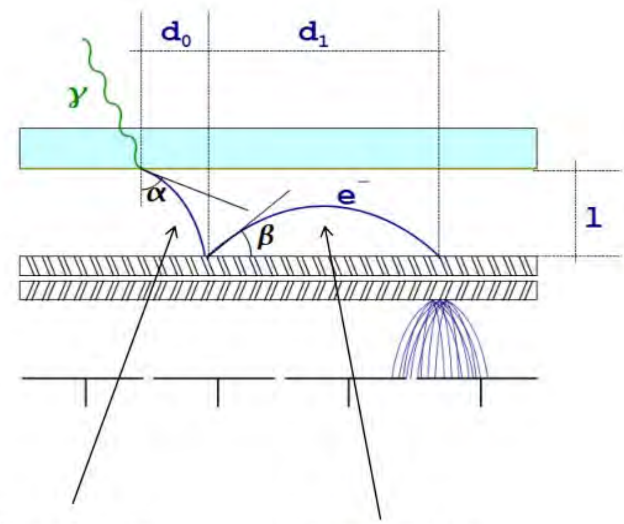
$$t_1 \approx 2t_0 \sin\beta \qquad d_1 \approx 2l \sin\beta$$

Maximum backscattered time:

$$\boxed{(t_1)_{\max} \approx 2t_0} \qquad \boxed{(d_1)_{\max} \approx 2l}$$

L (cathode-to-MCP) should be small (to <1mm)



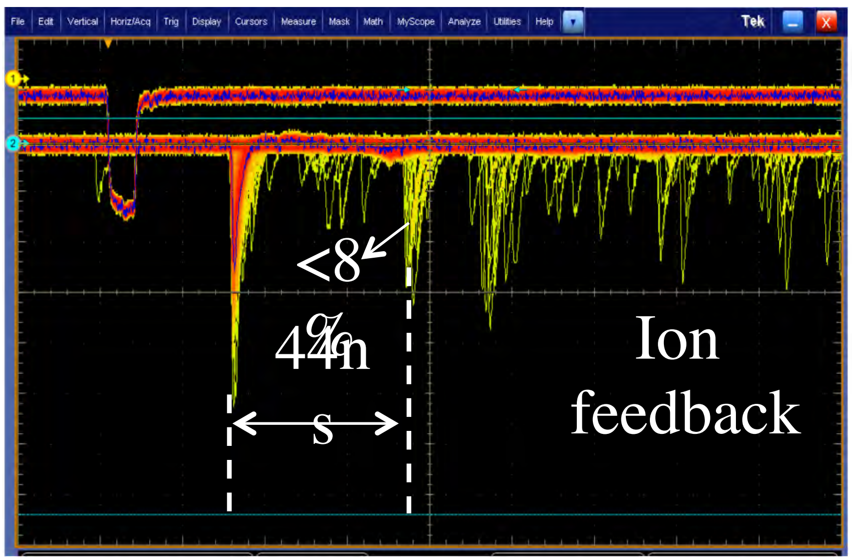


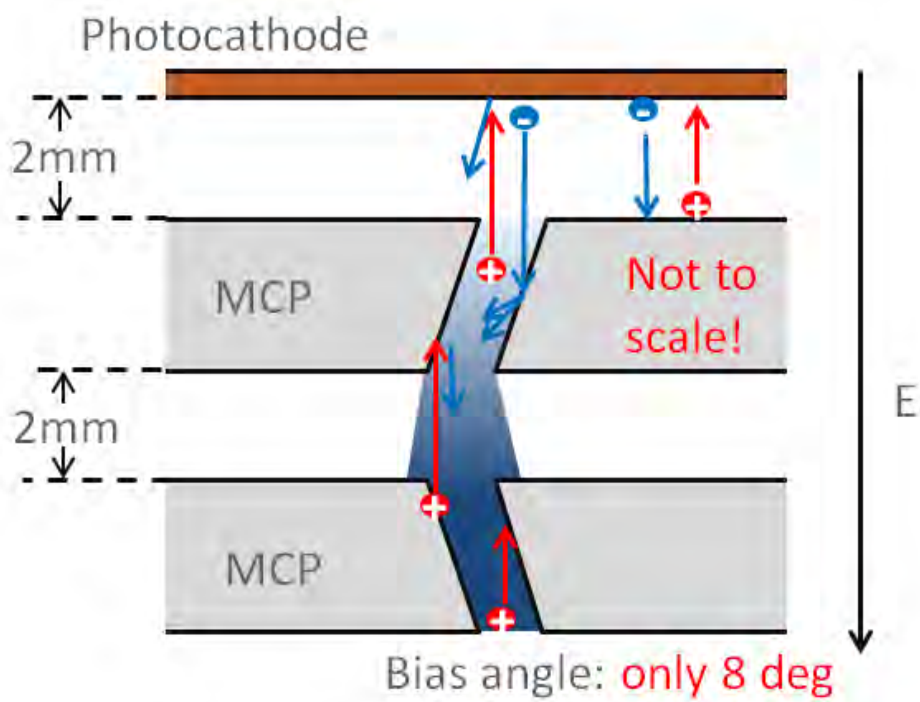
Ion feedback

Ion feedback (a few ns to 100 ns)

- As electron avalanche grows, residual gas can be ionized. If no care is taken, the ions can gain enough energy from the electrical field, and release secondary electrons from the MCP wall or the photocathode.
- Ion feed back limits the photocathode lifetime. The ions affect the work function of the photocathode, and may damage the photocathode.

After pulse problem



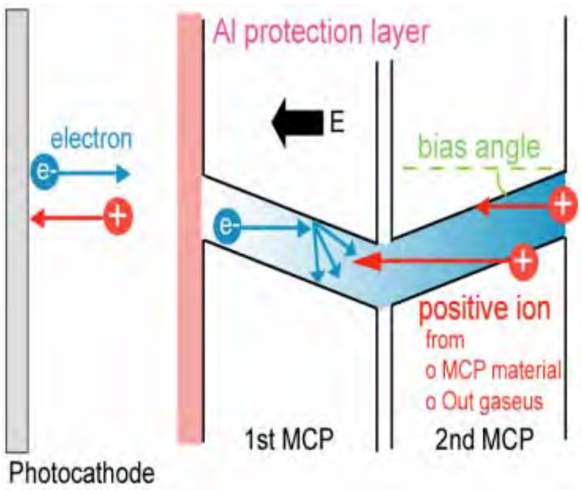


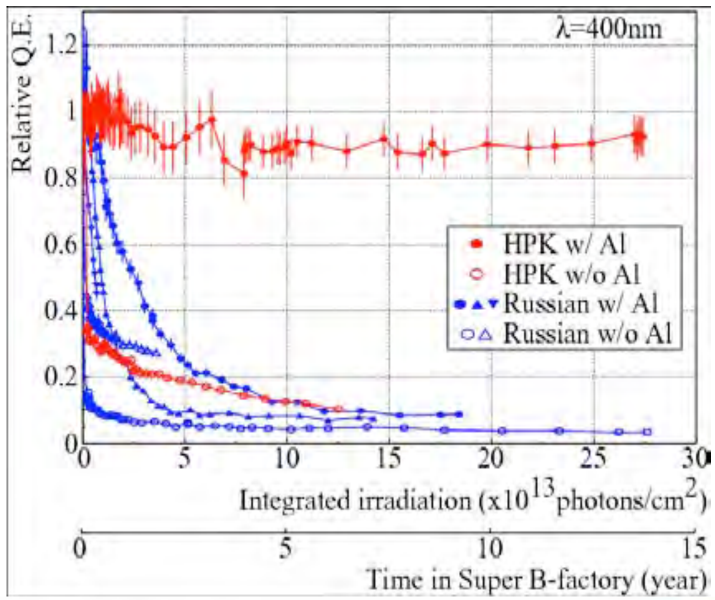
Ion feedback suppression

Four ways to suppress the ion feedback:

- Better vacuum
- Better scrubbing of MCPs
- Bigger MCP bias angle.
- Protective layer

Kenji Inami, **Nagoya University,** 2015 MCP workshop at ANL



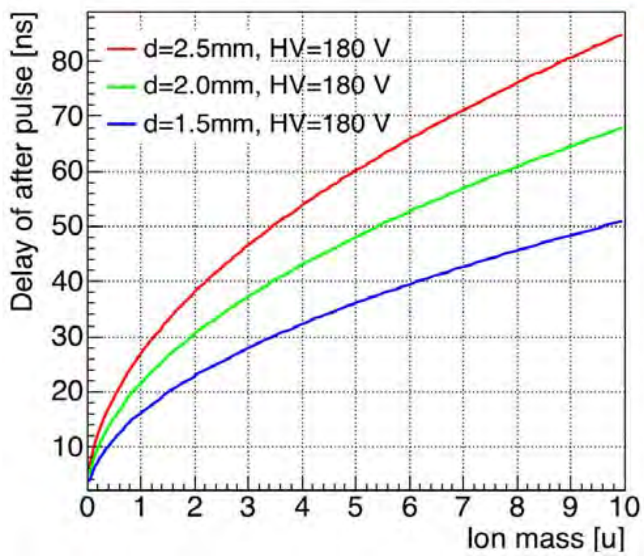


Ion feedback

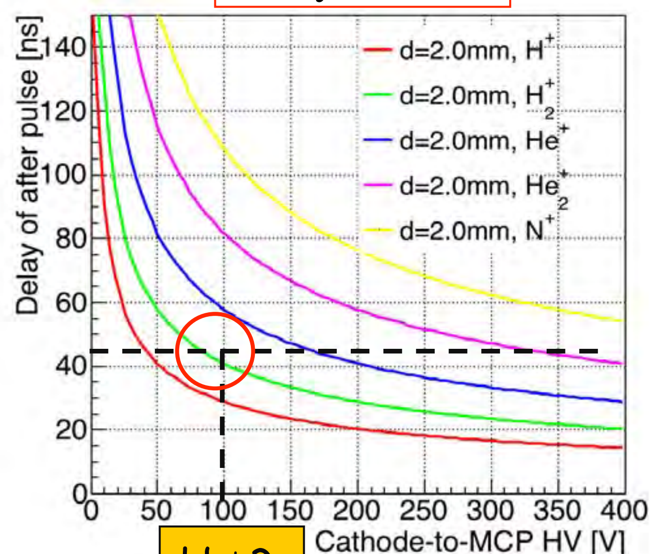
- We need a better understanding of the residual gas in the tile processing system, and the outgas species.
- We need do a better scrubbing for the MCPs

Ion drifting time: $t_0 = \sqrt{\frac{2m_{ion}l^2}{Uq_{ion}}}, l = 2mm, U = 180V$??

Delay VS Ion mass



Delay VS HV



H_2^+?

Individually biased HV design makes it possible to study the ion feedback

Further Readings on Future Developments

Public Domain Presentations: LAPPD Review – Feb. 2015

1) Tube Performance Optimization – Jingbo Wang
2) Testing of 6 cm Photodetectors – Jingbo Wang
3) ALD on MCPs: Progress and Status – Anil Mane et al.
4) Argonne R&D Program: Photocathode Development – Junqi Xie
5) Argonne R&D program: New Directions in ALD Coatings for MCPs – Jeffrey Elam
6) Argonne R&D program: Technical Work to build a new Photodetector Facility – Lei Xia
7) Photocathode Development for 6 cm Photodetectors – Junqi Xie
8) Production of 6 cm Photodetector in Small Tile Processing System: - Lei Xia

Available for download at https://anl.app.box.com/s/q0s1fs102oi9vltzsucccy2mpdpey3yd