Large (and Small) Size ALD MCP Photodetectors: Status & Results

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for Argonne MCP Photodetector Group

Micro-Pattern Gas Detector Workshop
CERN, June 10-11, 2015

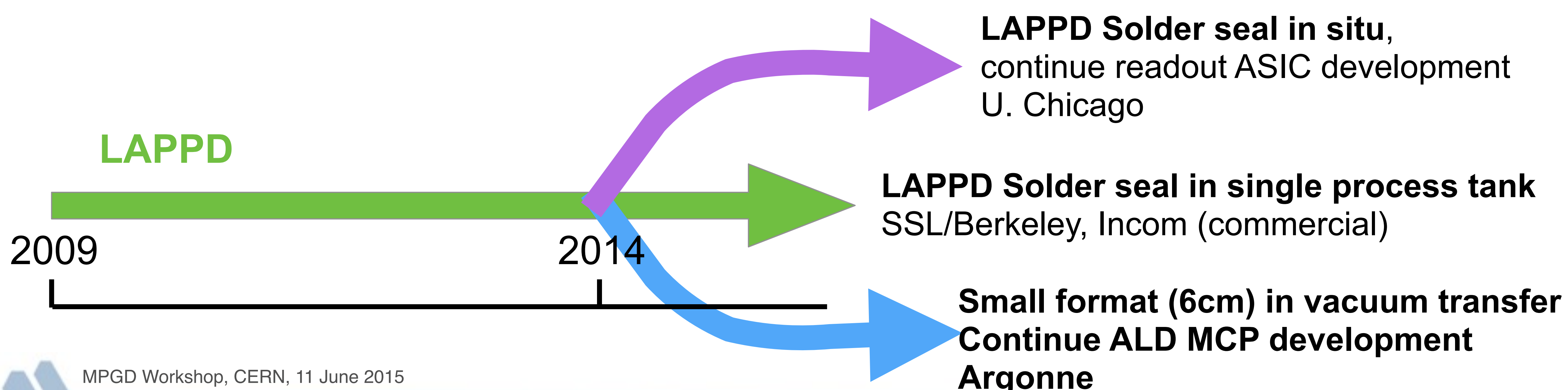
Outline

- LAPPD very brief history and current efforts
- Development of Atomic Layer Deposition (ALD) functionalized MCPs
- Review status of Large Area (20cm x 20cm) Picosecond Photodetectors (LAPPD)
- Development of Argonne Small Format 6cm x 6cm MCP-PMT Processing System
- Results from Argonne Initial Baseline production tubes
- Future Plans for Argonne Small Format Photodetector

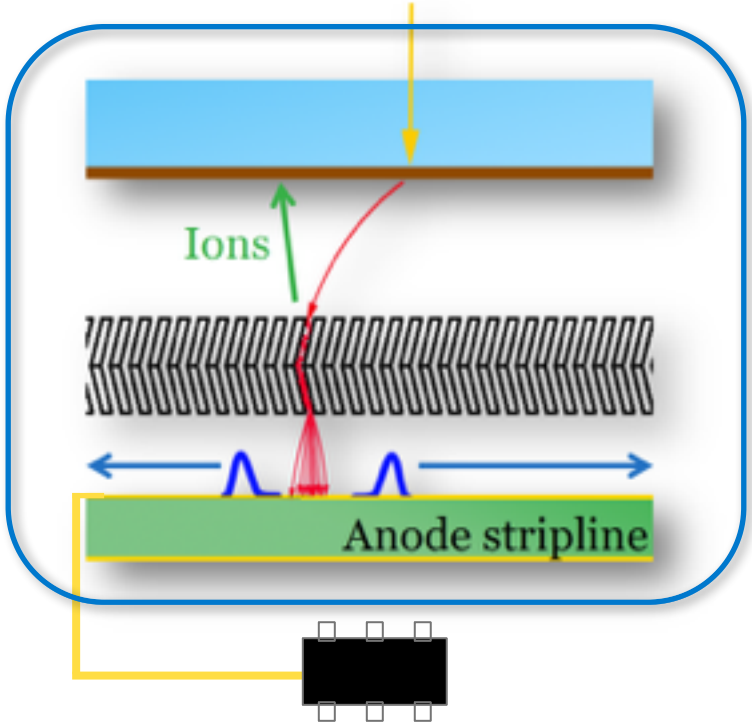
Very good detector seminar on MCPs by Thierry Gys
7 Feb 2014 CERN
https://indico.cern.ch/event/288433/

Large Area Picosecond Photodetector Collaboration

- Project initiated in 2009 to develop large active area ALD functionalized MCP detectors
  - Dramatically reduce cost using borosilicate glass body, supports and MCPs
  - Separate functional optimization from substrate optimization
  - Criteria for success (next slide)
- Applications for precision time-of-flight, optical TPC, Cherenkov imaging particle ID Also interest from medical imaging, nuclear security
- Success with high gain, uniform ALD MCPs; PSEC-4 waveform sampling ASIC; 25% QE large area photocathodes
- **Hermetic package seal was much harder than anticipated**
- In 2014 Groups continued development along separate technology paths



Microchannel Plate Photomultipliers



Typical pore size 6-40μm

Existing commercial MCP-PMTs:

- MCP fabrication constrained by common material (lead glass) for substrate, resistive and emission layers
- Generally ≤ ~25cm^2 active area
- Expensive

Focus of Large Area Picosecond Photodetector Development:

- **Microchannel Plates:** Transformation of fabrication and size
  - 20cm×20cm borosilicate glass: ~80x10^6 20μm pores
  - Separate resistive & secondary emissive functions into 2 materials via Atomic Layer Deposition (ALD) coating
- **Photocathodes:** Develop planar, large-area photocathodes with good quantum efficiency
- **Electronics:** Waveform sampling 10GSa/s, high bandwidth ASIC for best time resolution
- **Hermetic Package:**
  - Standard ceramic package w/InBi hot seal & HV/signal pins feedthrough — SSL/UC-Berkeley
  - Less expensive borosilicate all-glass, pressure In seal, **pinless** — Argonne/UChicago

Atomic Layer Deposition MCPs

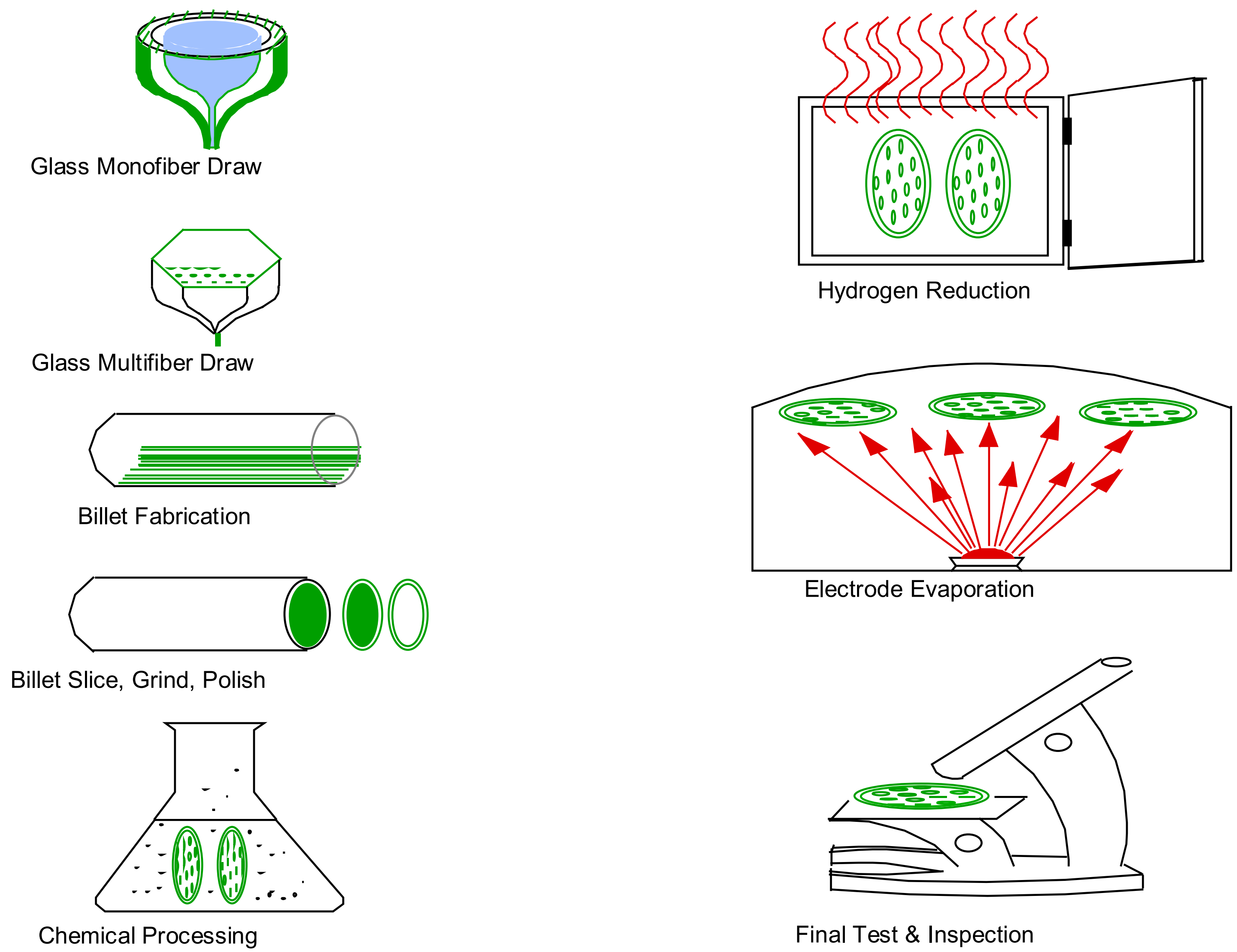
Commercial Microchannel Plate Fabrication

Graphic Credit: B. Laprade & R. Starcher, Burle (2001)

Glass is gravity-fed via cylindrical furnace

Glass is typically lead glass tube with solid soft glass core

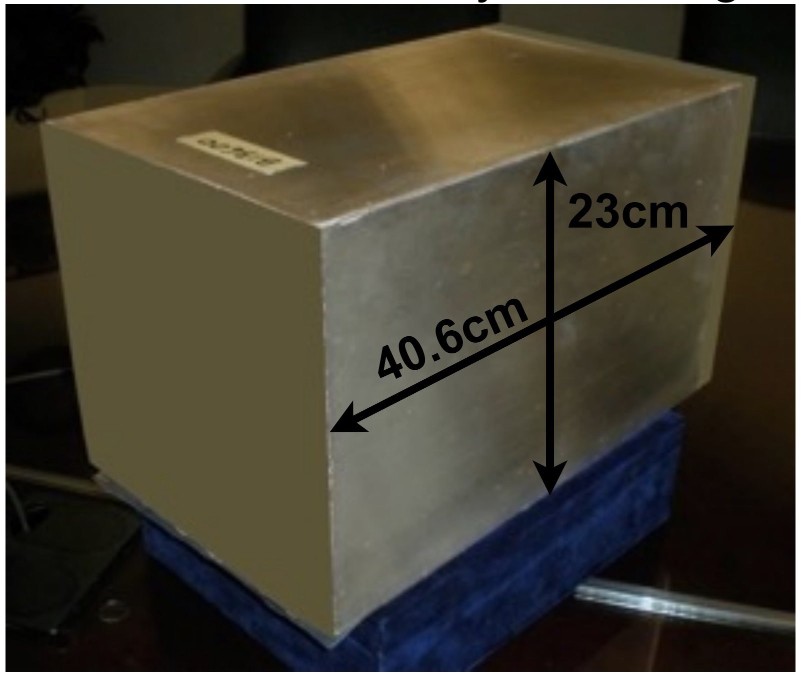
Chemical processing to remove soft core glass



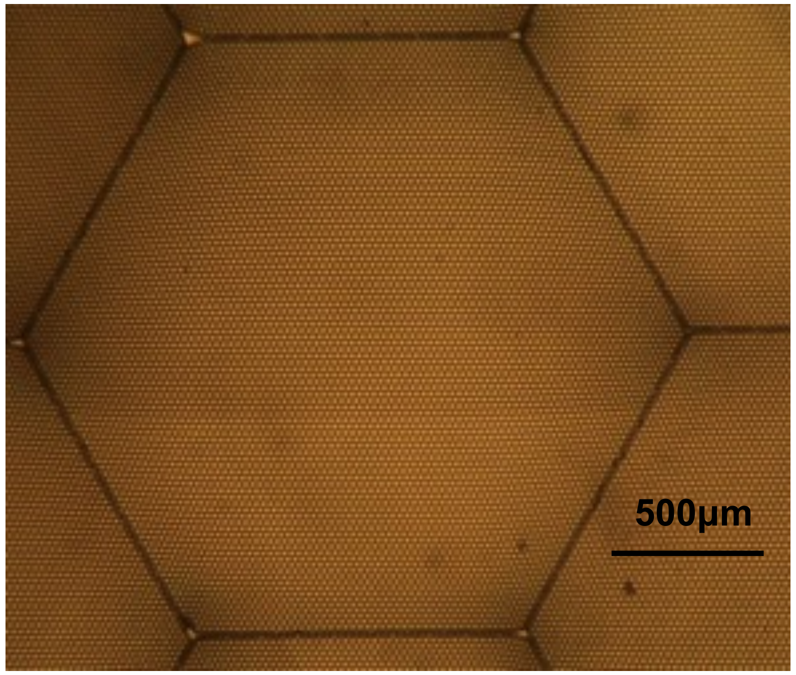
Before sealing in tube, plate must be subjected to prolonged exposure to electrons at low voltage to outgas H_2 and other material

Development of Economical Borosilicate Capillary Arrays for MCPs — Industrial Partnership w/Incom, Inc

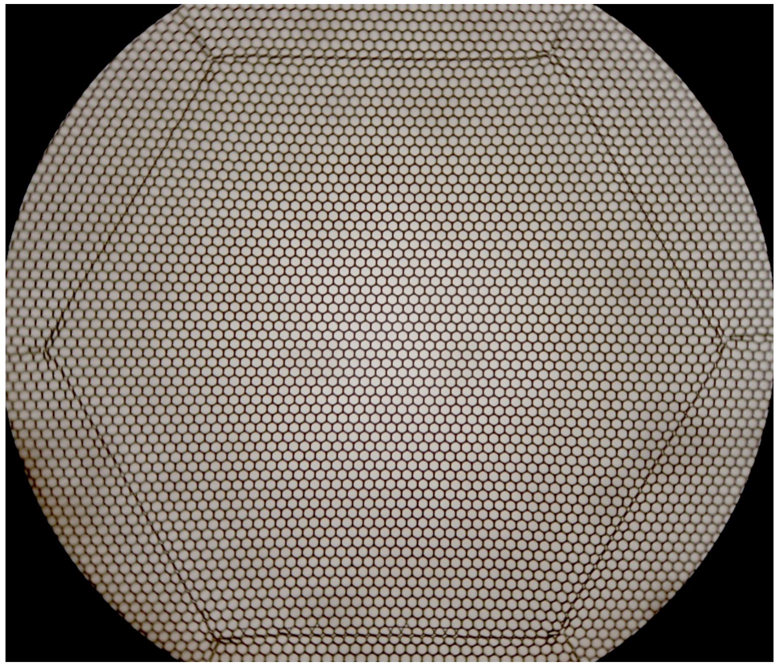
Fused block ready for slicing

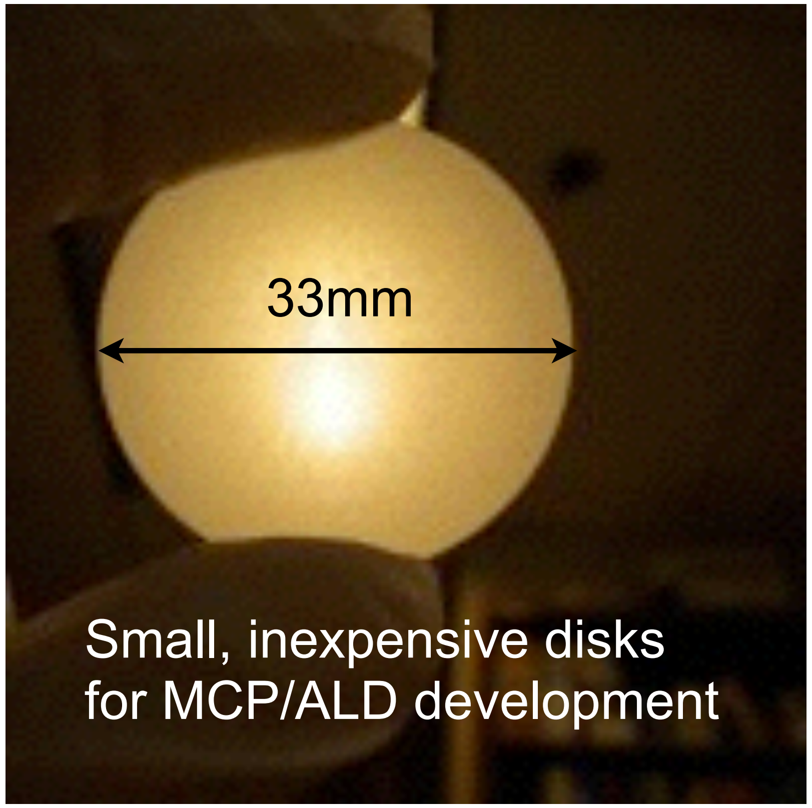


First block



More recent block



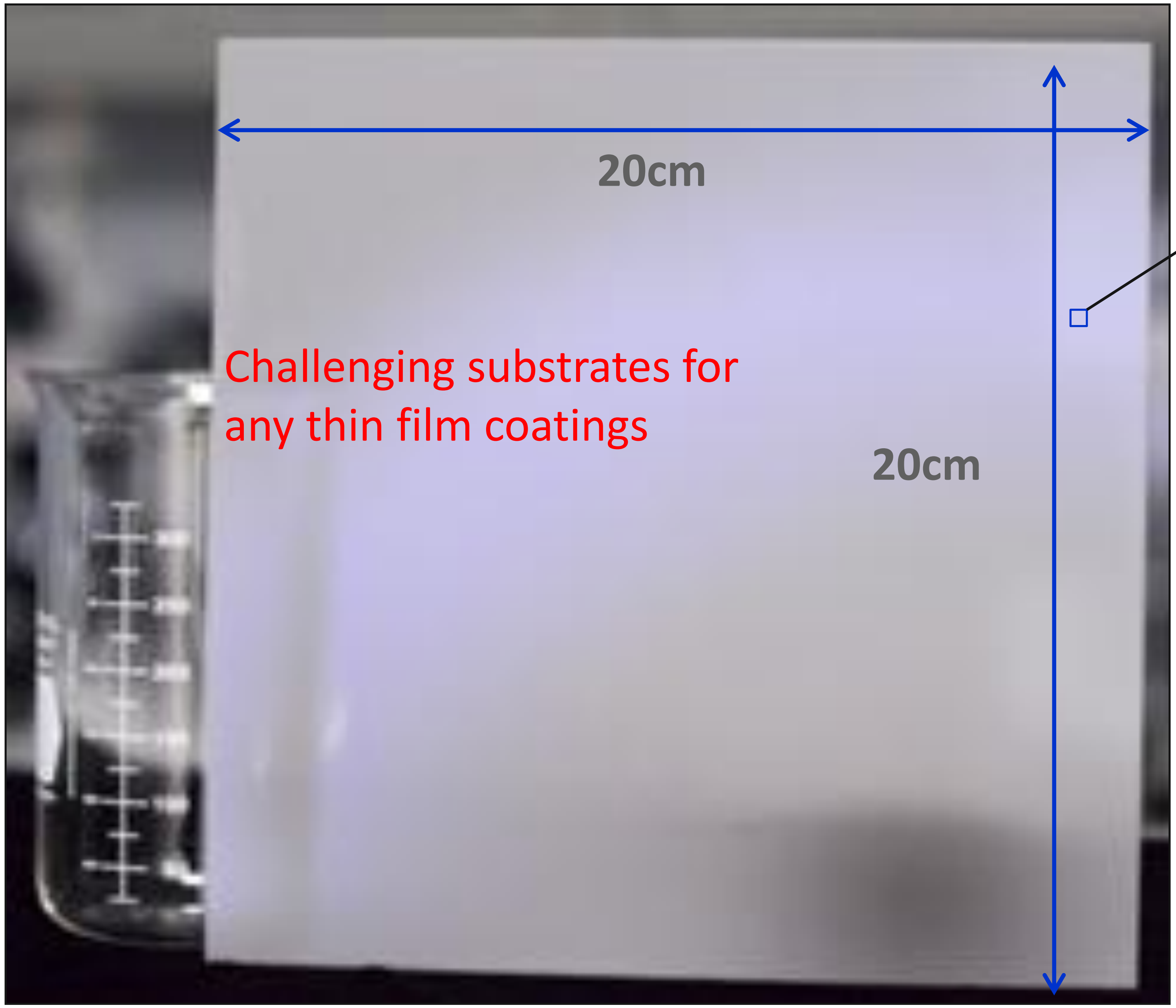


- Multifiber stacking
- Triple point gaps
- Pore crushing at multifiber boundaries

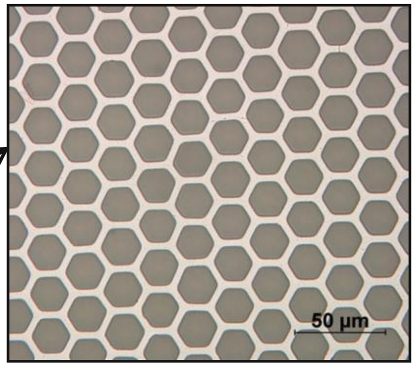
- Triple points eliminated
- Minimal boundary pore distortion

GCA Property	Value
Plate Area	203x203 mm^2
L/D, Thickness	60:1, 1.2mm
Pore Pitch	25μm
Pore Size	20μm
Bias Angle	$8^o \pm 1^o$
Open Area ratio	> 60%
Material	Borofloat 33

Glass Capillary Arrays for MCP Substrates

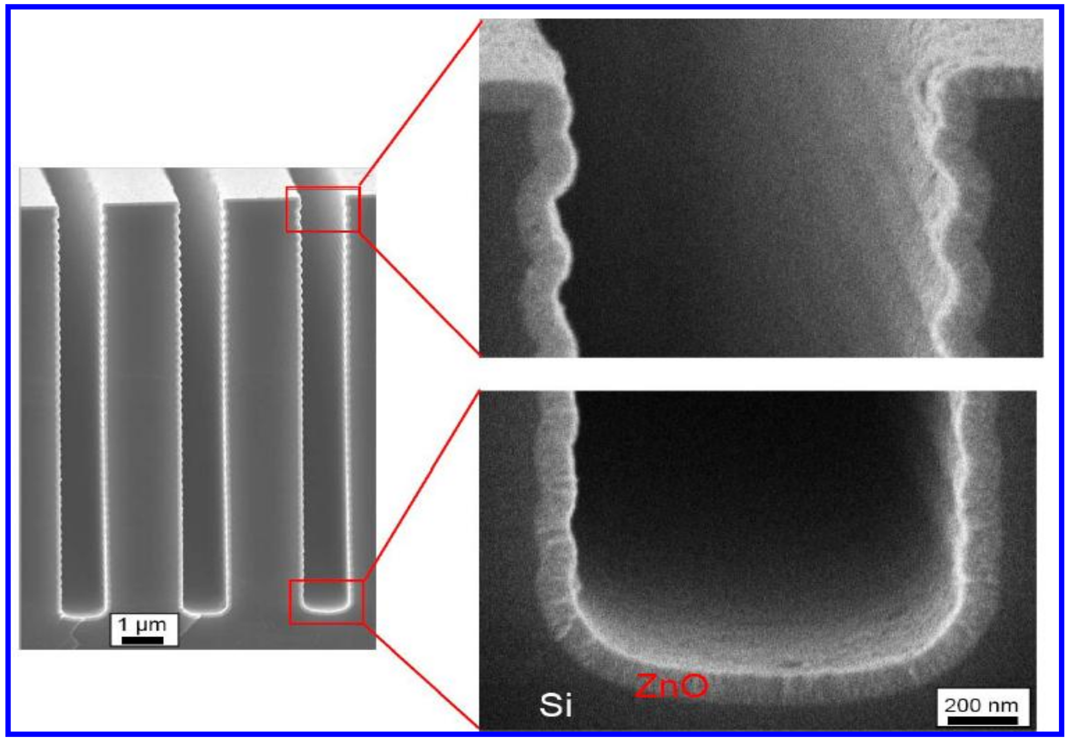


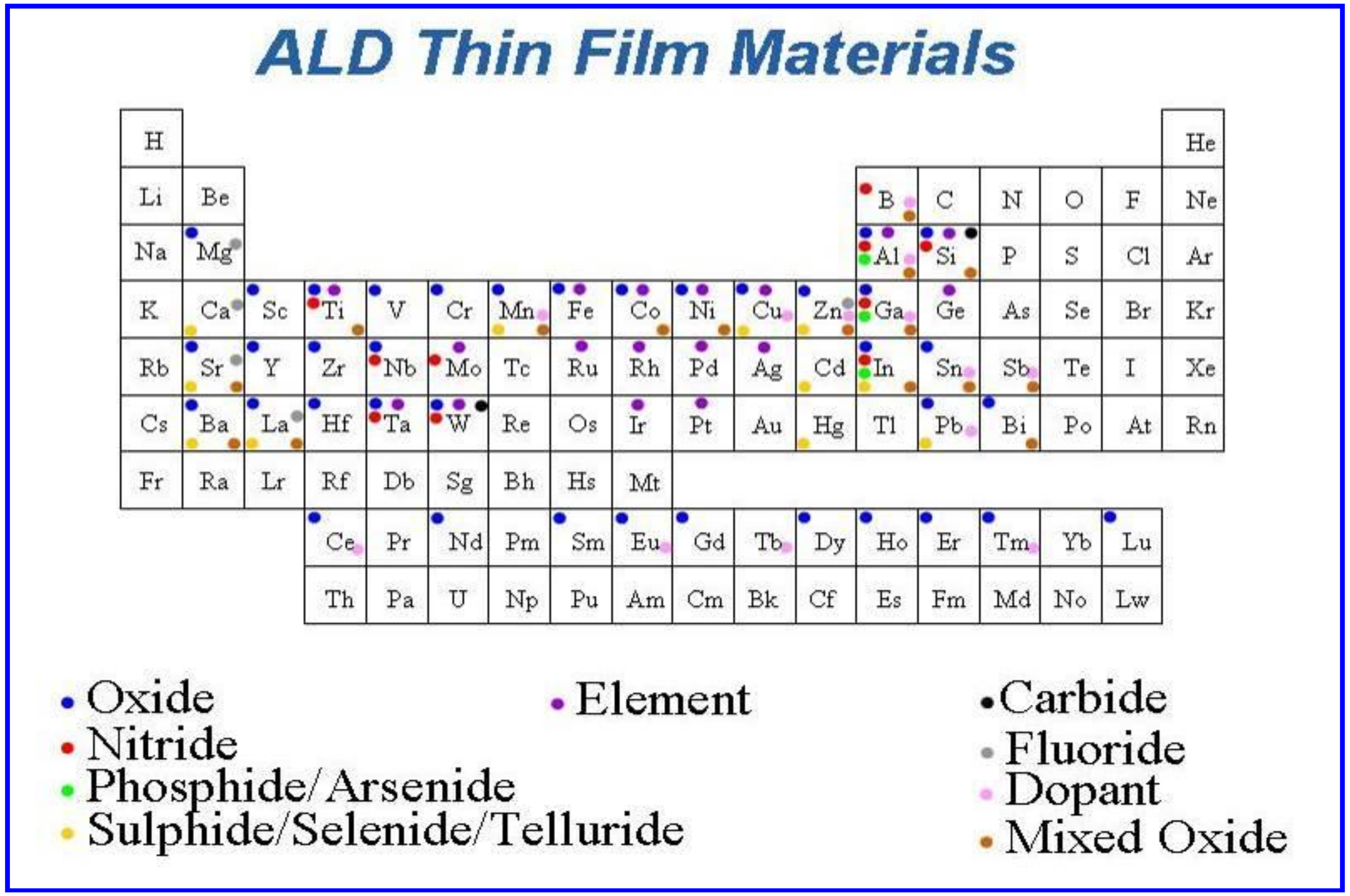
Produced by Incom, Inc



- Surface area = 6.0 m^2
- Pore size = 20µm
- Plate thickness = 1.2mm
- Length/Pore (L/d) = 60
- # pores = 79 × 10^6
- Open Area = 60%
- Pore Bias Angle = 8°
- Sensitive surface to OH

Pore Activation via Atomic Layer Deposition



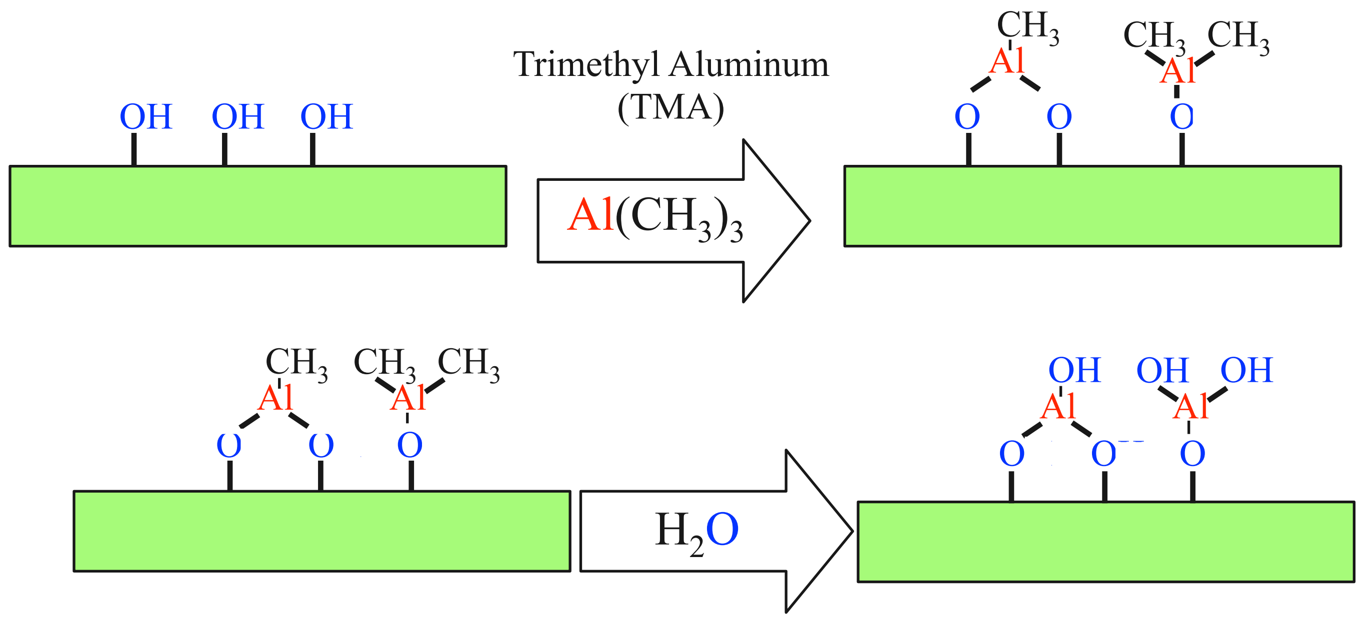


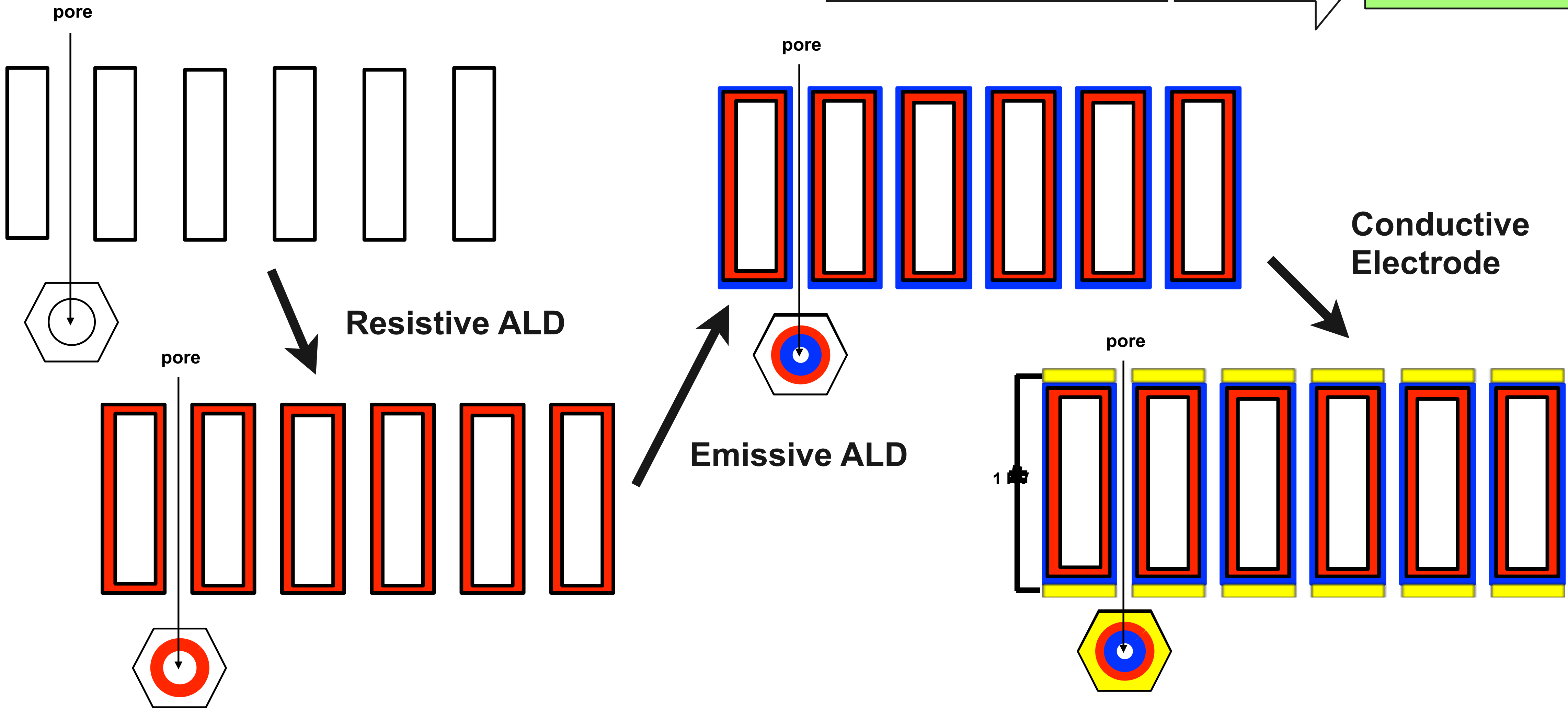
- Conformal, self-limiting process
- Molecular mono-layer thickness control
- Large variety of applicable materials

Pore Activation via Atomic Layer Deposition (ALD)

Example:

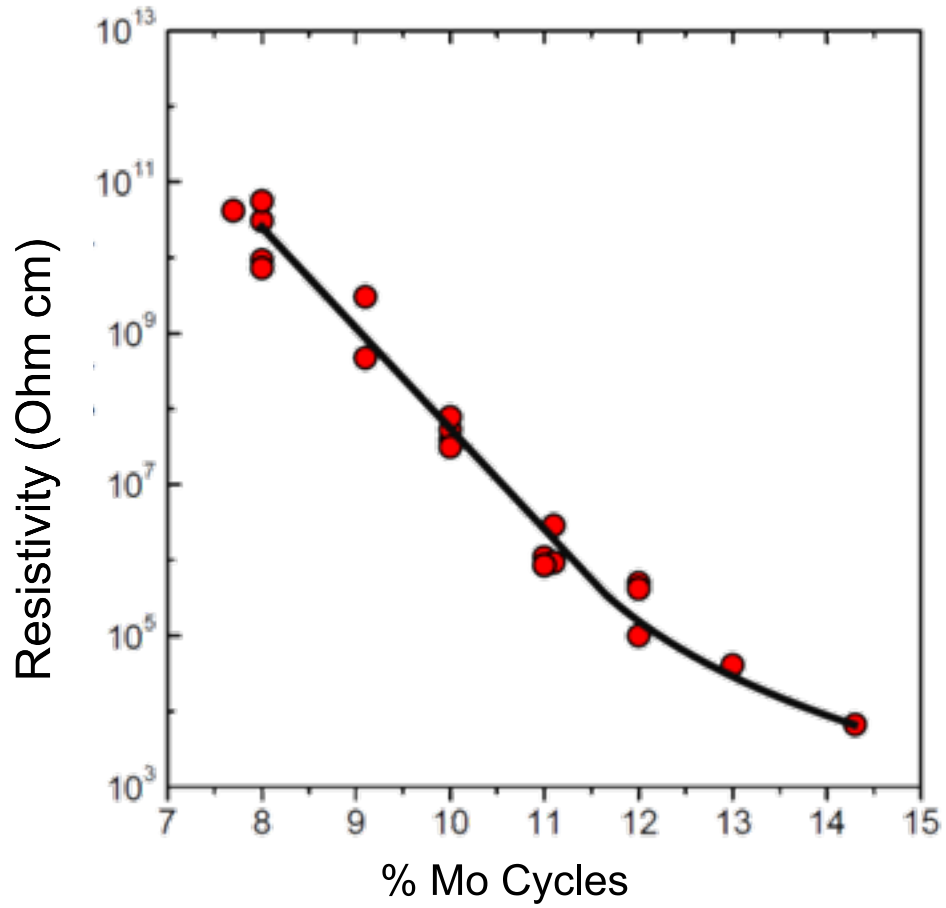
- OH on surface provide reaction sites
- Trimethyl aluminum reacts liberating methane, forms Al_2O_3 layer. Leaves methyl group inhibiting further reaction on surface
- Exposure to H_2O removes methyl group. Leaves OH sites for next reaction



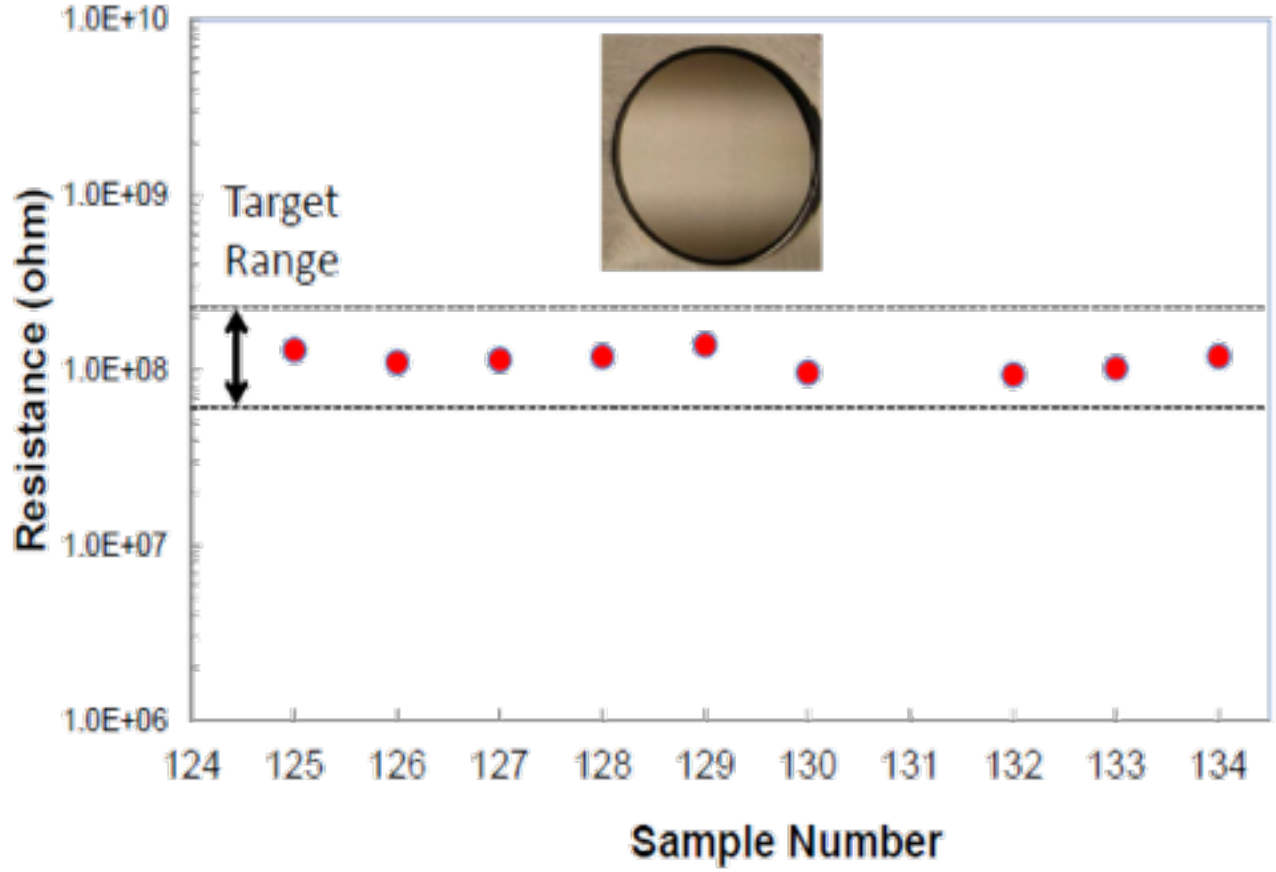


ALD of Metal-Al_2O_3 Composite Films for Resistivity

- Combination of 2 ALD Processes:
  - Trimethyl Aluminum (TMA)/H_2O ➛ Al_2O_3 : insulator $\rho \sim 10^{16}$ Ω-cm
  - Metal-F_6/Si_2H_6 ➛ Metal = Mo, W : conductors $\rho \sim 10^{-4}$ Ω-cm



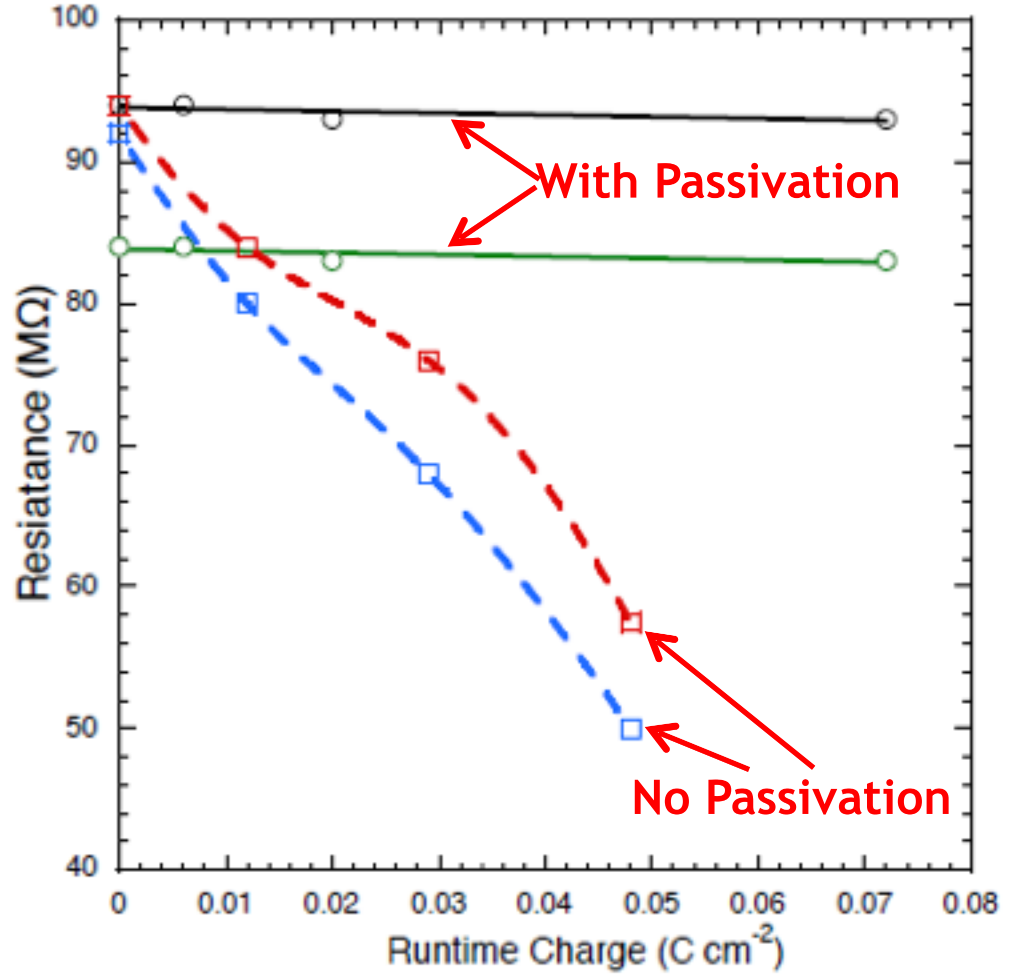
Allows resistance tuning over several orders of magnitude



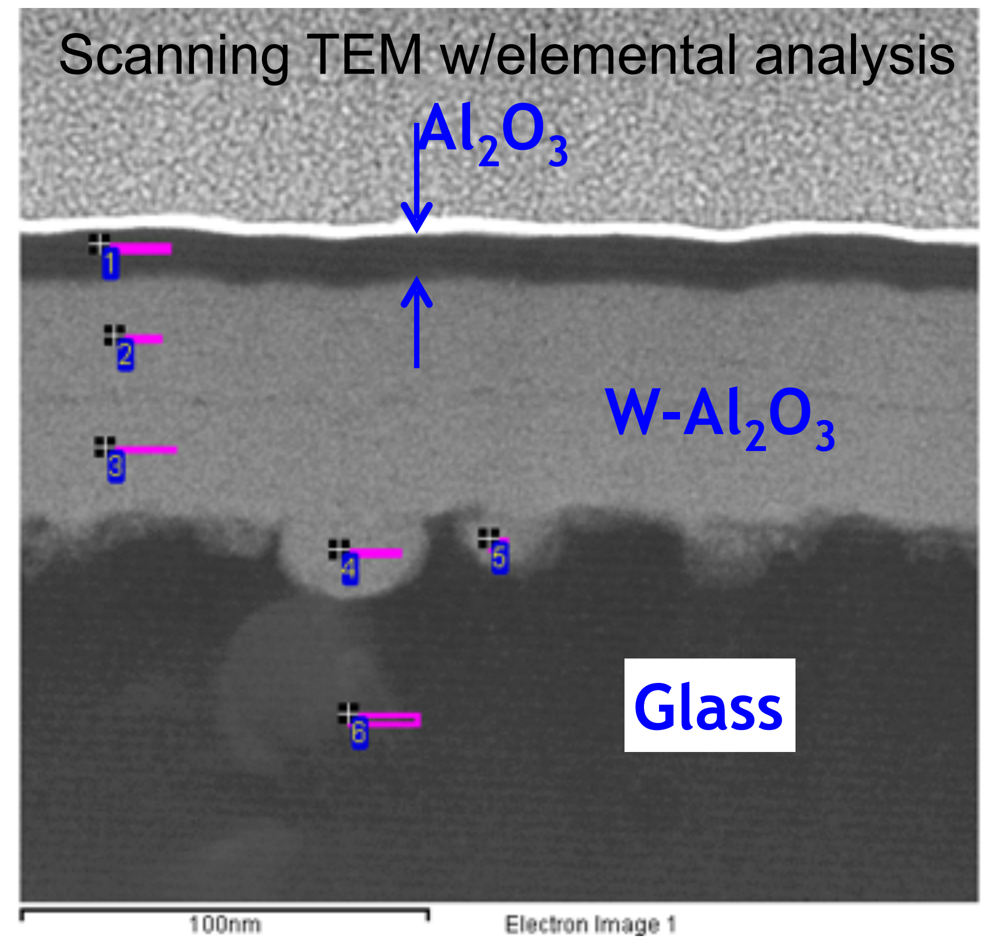
Process is highly reproducible

Resistance Change Prevention with Passivation Layer

Resistance Stability During Scrub for 33mm, Chem1 + Al_2O_3 SEE



- 100nm ALD Al_2O_3 passivation layer stabilizes MCP resistance
- Further work shows 10-20nm layer is sufficient for stability

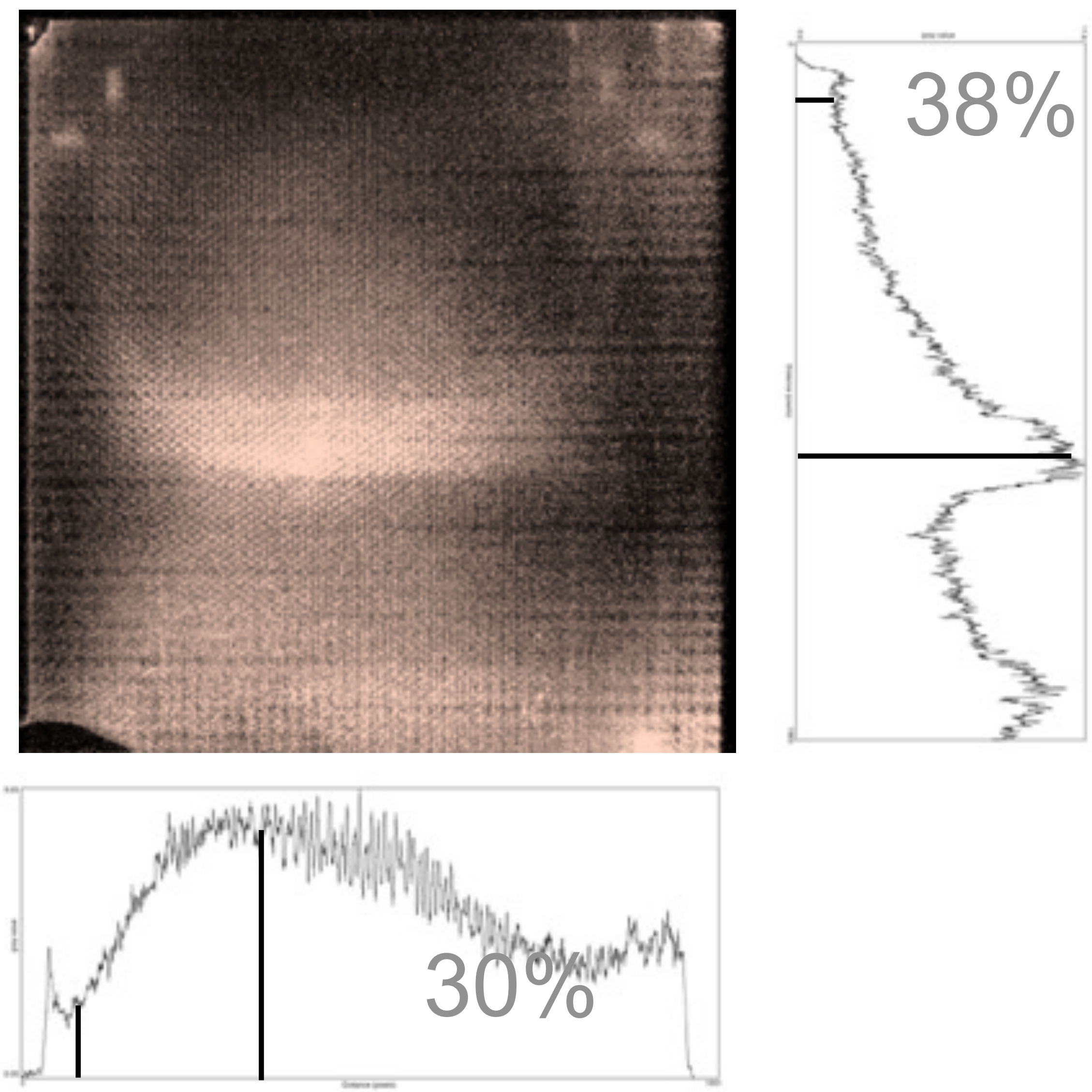


Spectrum	In stats.	O	F	Na	Al	Si	W
2	Yes	56.3	11.8	6.2	18.4		7.3
3	Yes	52.8	11.4	6.7	20.9		8.2

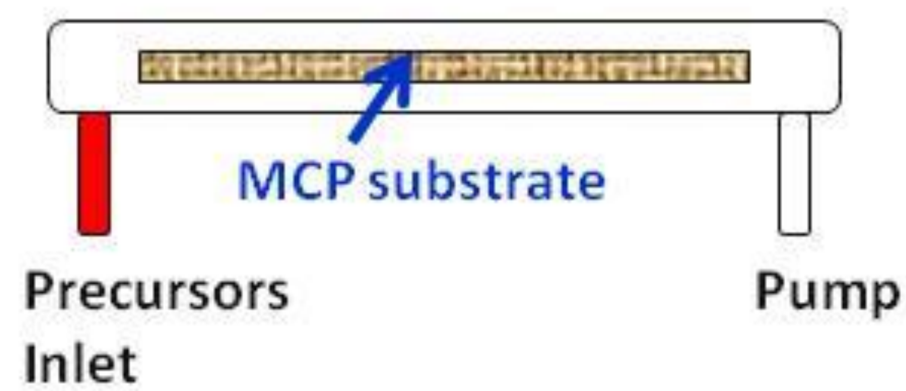
Possible cause of change is Na diffusion into resistive coating w/o passivation layer

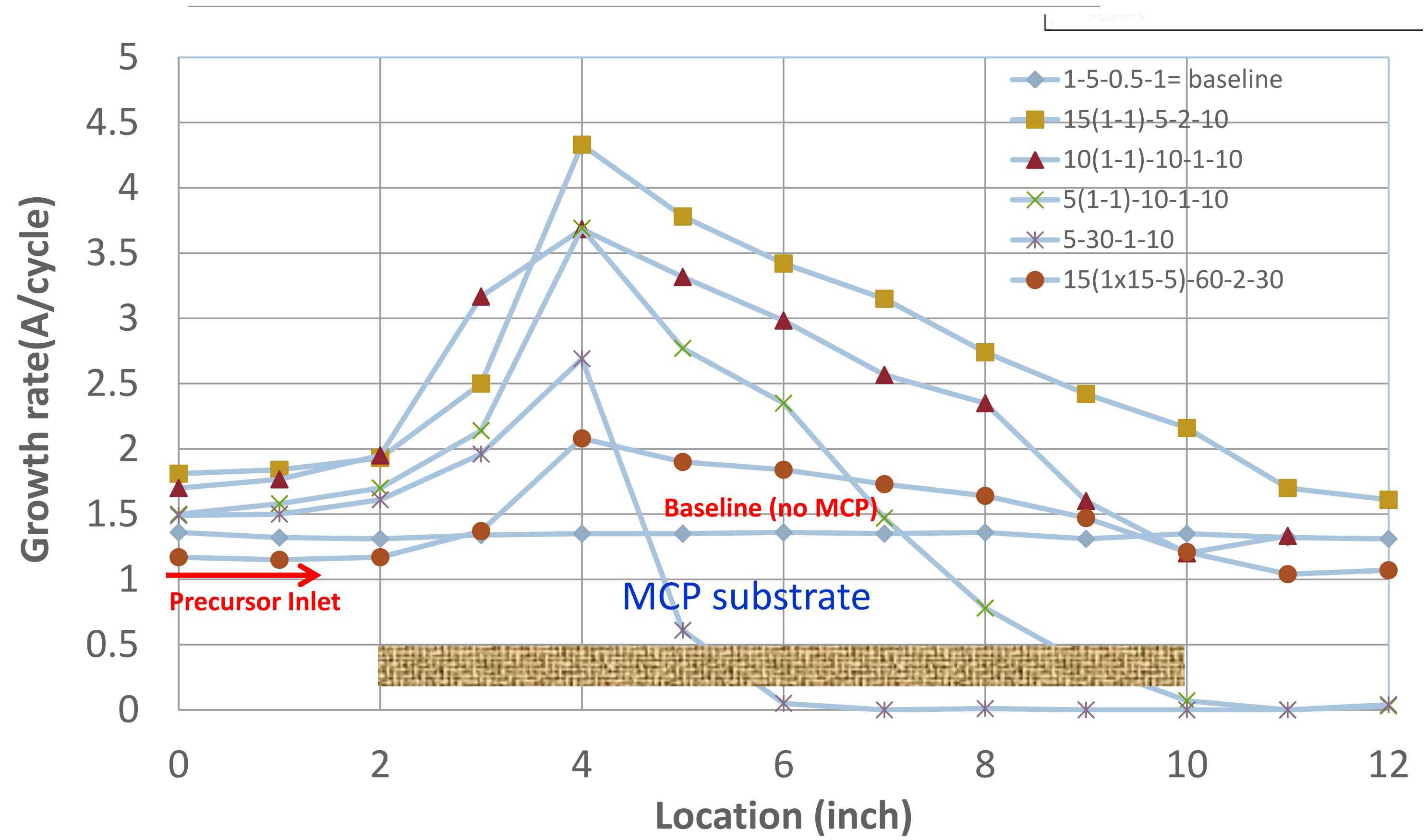
Initial Non-Uniformity of 20cm MCP Gain Using Cross-Flow ALD Method

Cross-flow Chem2



Cross-Flow ALD reactor

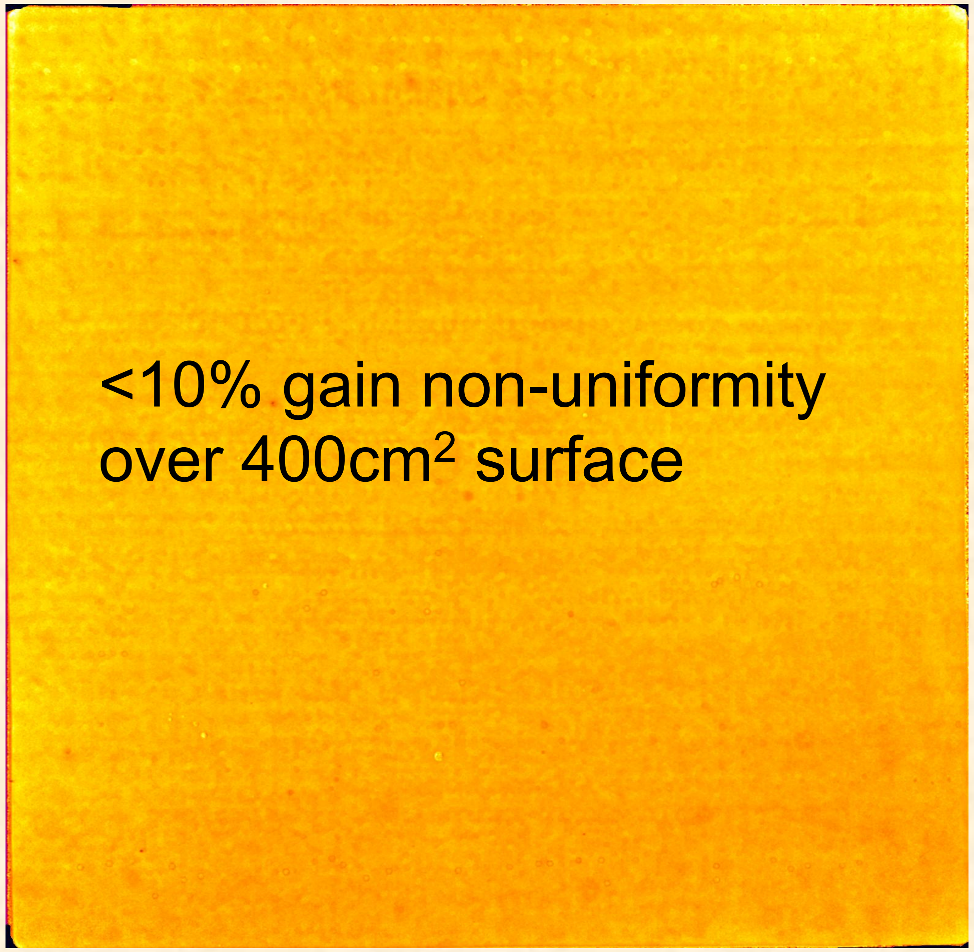




Non-uniformity = (Max-Min)/Mean * 100%

MCP Gain Uniformity

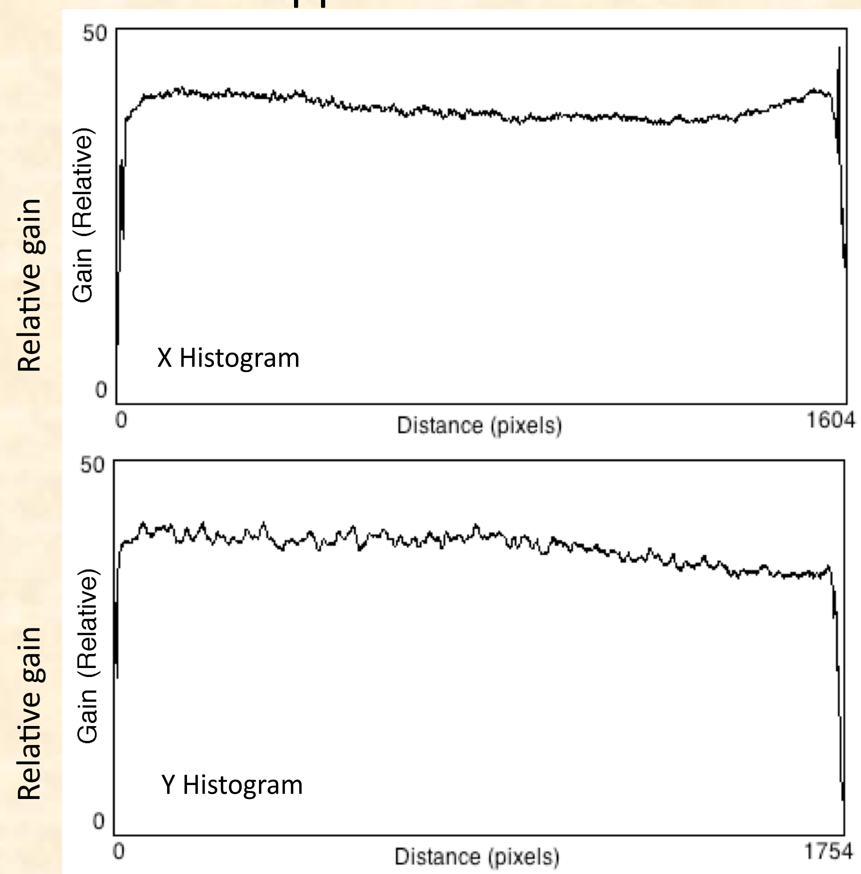
Average gain image "map"



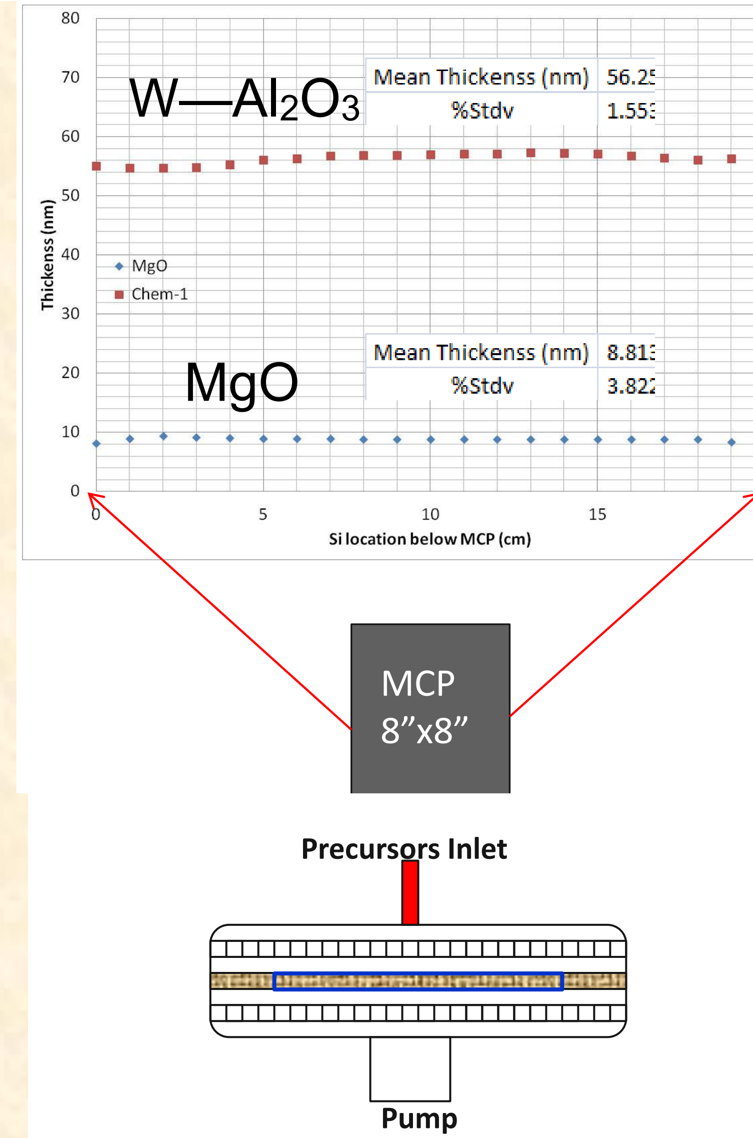
8" MCP pair average gain map image

Mean gain ~7 x 10^6

20µm pore, 60:1 L/d ALD-MCP pair. Average gain image map shows the MCP gain variations are adequate for use in a sealed tube application.



Histograms show the gain modest variation



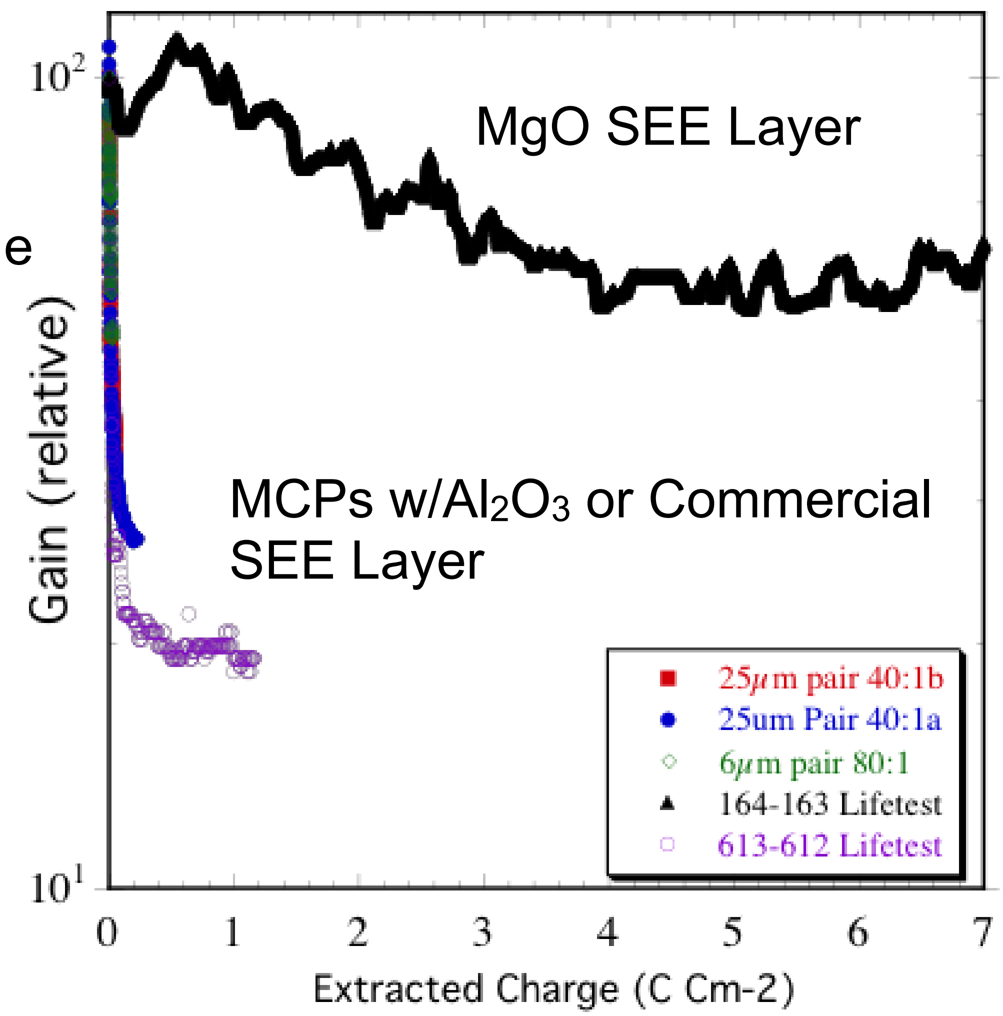
"showerhead" dosing of pre-cursors

- Uniformity achieved after extensive development of pre-cursor flow technique
- 20cm x 20cm MCP pair with MgO Secondary Emission Layer

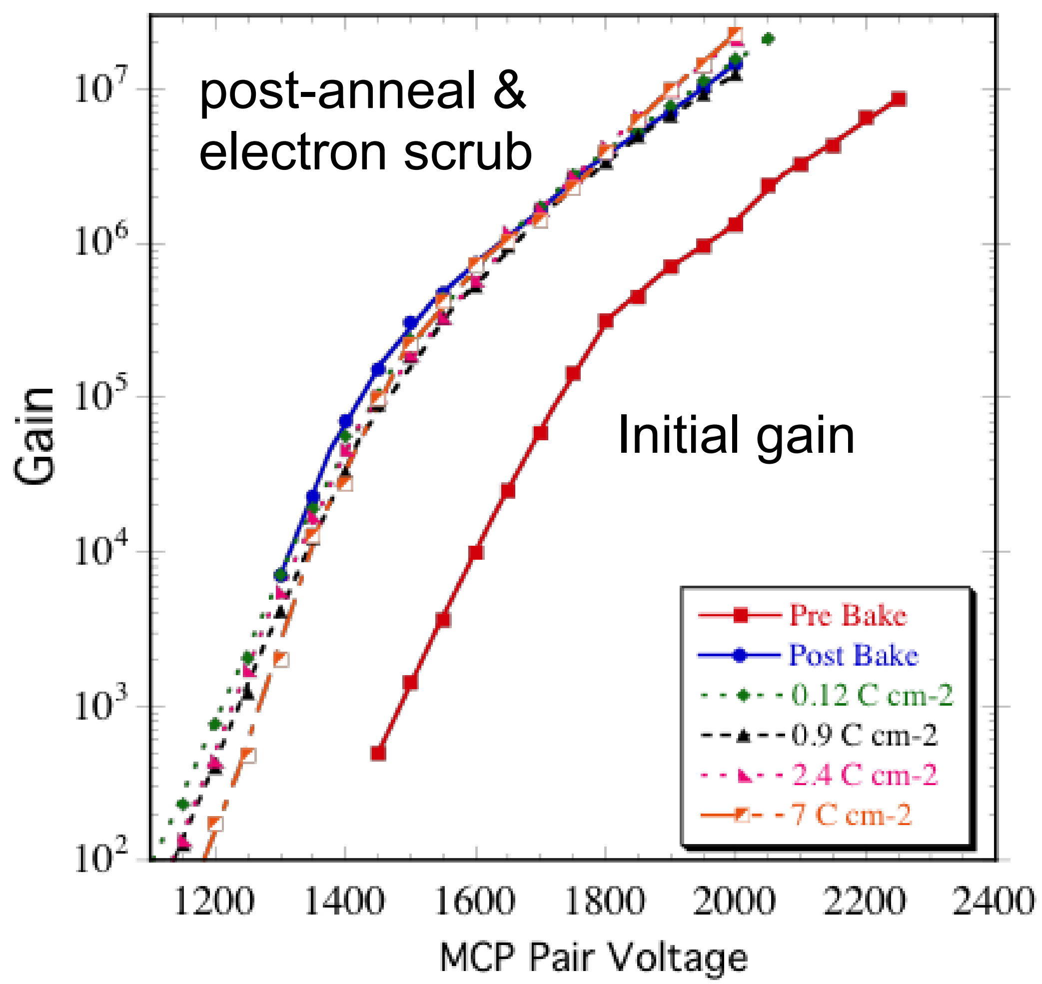
Plot courtesy of Ossy Siegmund, SSL

MgO vs Al_2O_3 vs Commercial SEE Layer

Note:
Log Scale



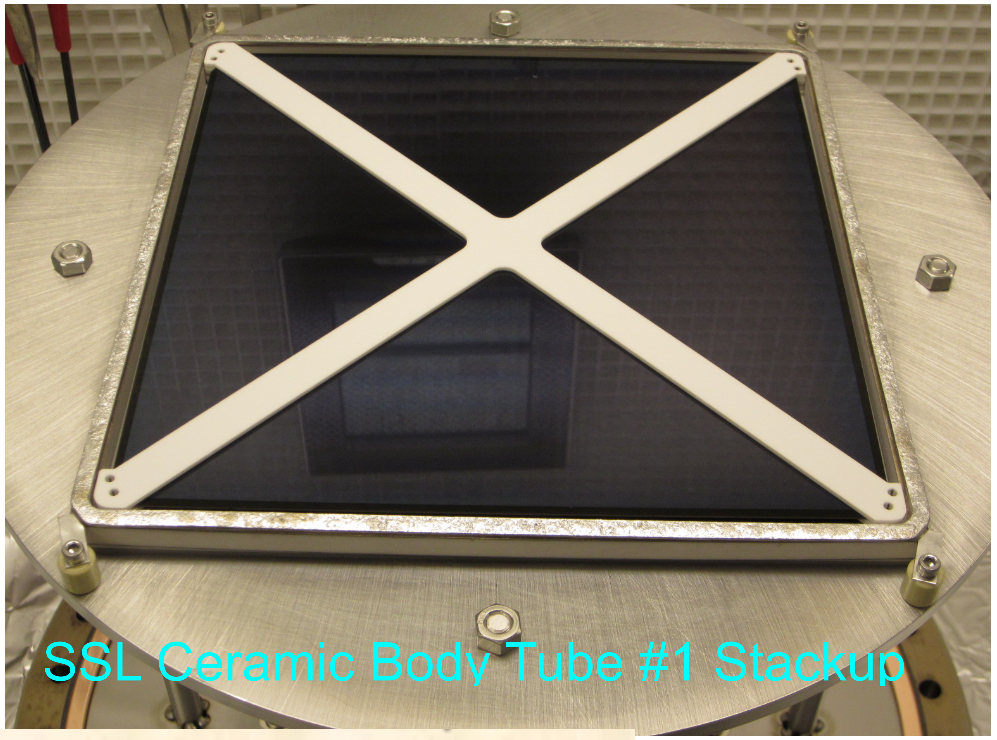
MgO SEE Layer

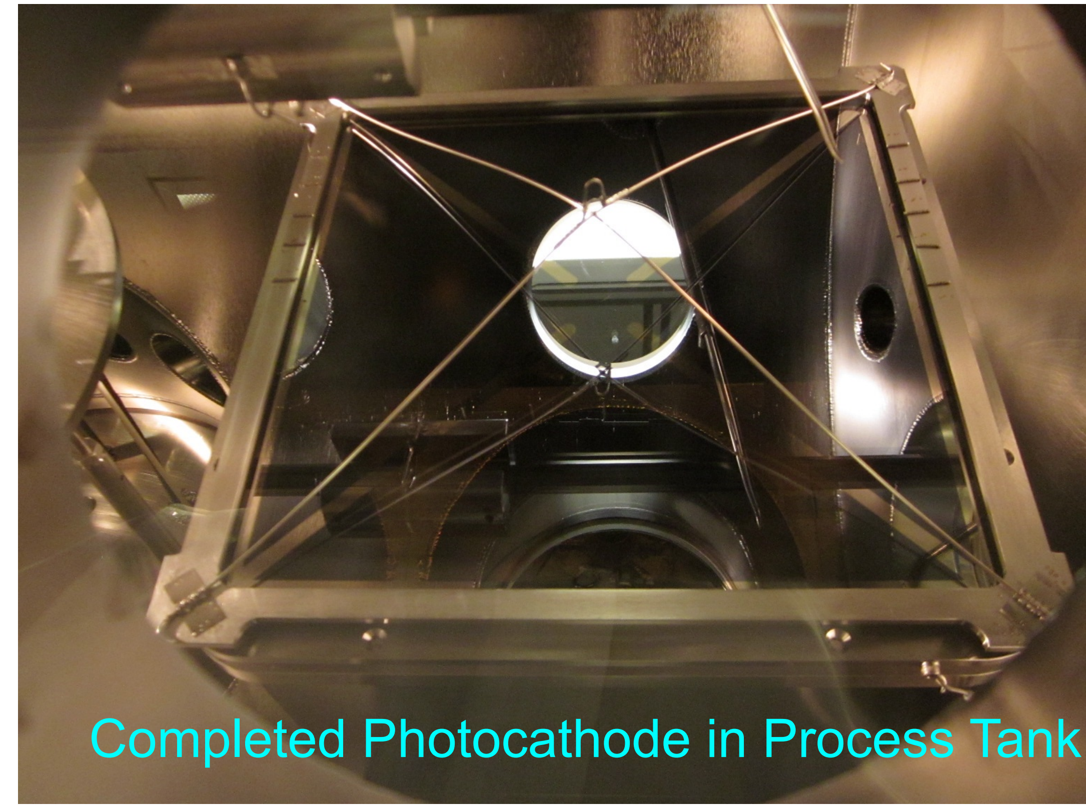


- Standard Secondary Emission Layer (SEE) for production of MCP gain is currently MgO
- Gain increases upon annealing or with initial scrub, then extremely stable

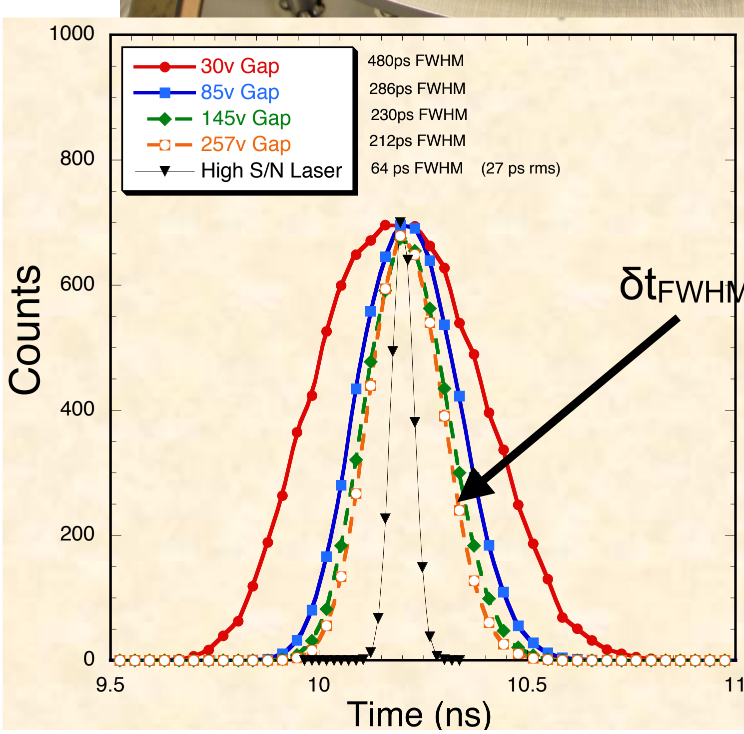
Progress on LAPPDs Devices

SSL/Berkeley Ceramic Tube #1, 20cm x 20cm, 20μm pore

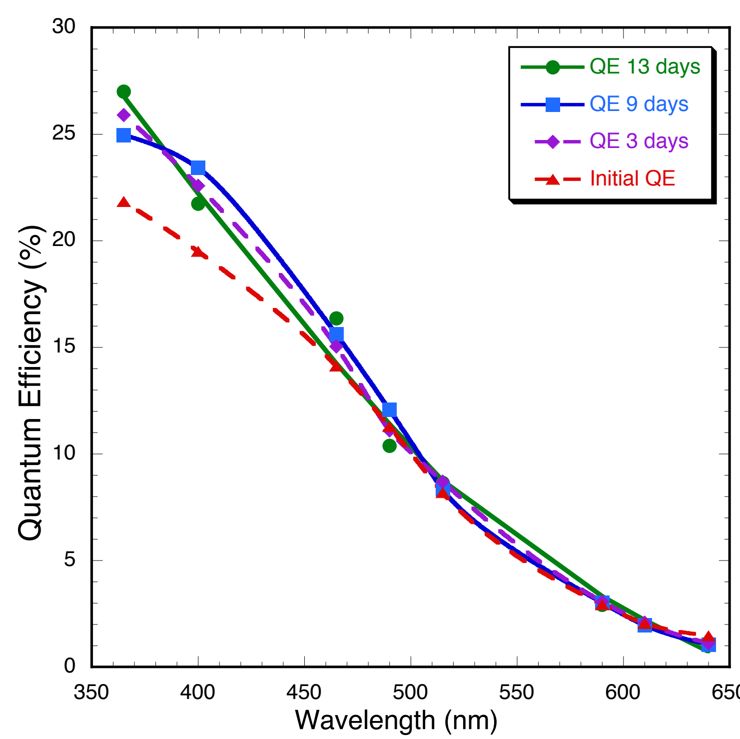


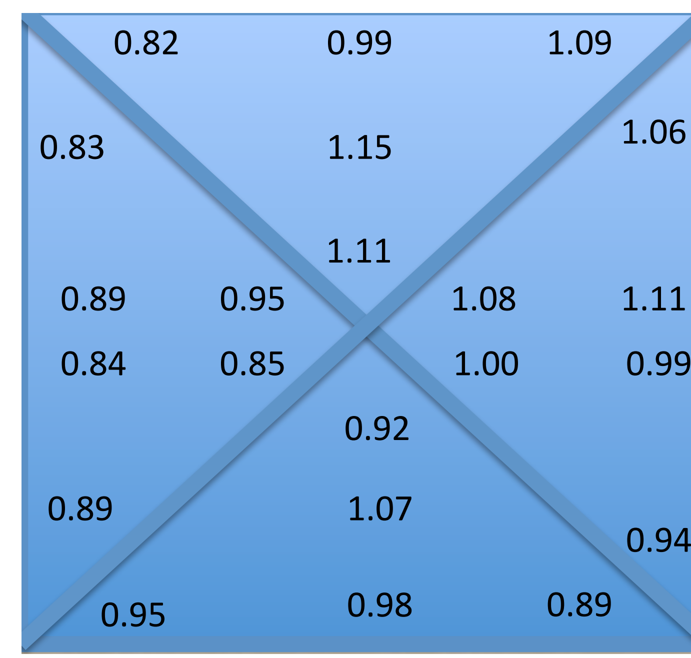


Na_2KSb Photocathode chosen for low background and stability



Time resolution for varying MCP gap voltage.
Limited by impedance mismatch of vacuum feedthru



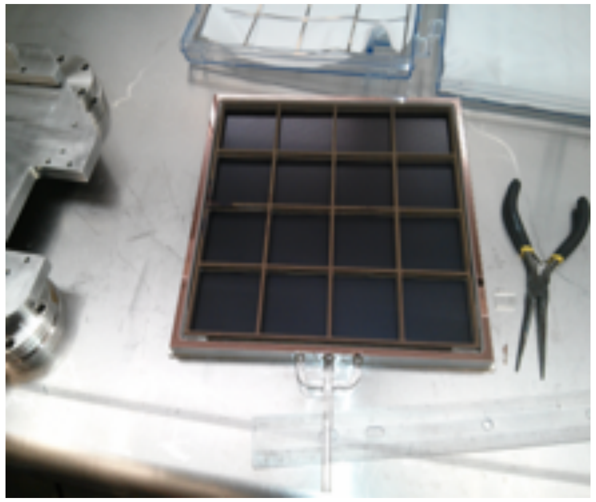


Relative QE map for photocathode

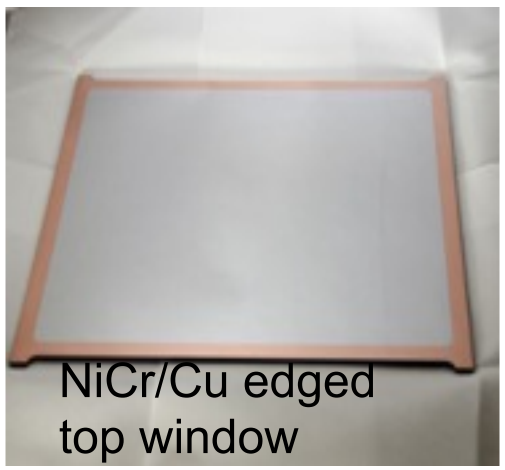
Status of 20cm x 20cm Glass Body Detectors

- SSL processing Ceramic Body Tube #2. Completion expected in June, 2015
- SSL will next process several glass body detectors in collaboration with NGA & Incom, Inc.
  - Glass bodies, top windows, and internal "hold-downs" provided by Incom, Inc.
  - First qualification of design planned for Incom commercial production
- Incom pushing hard on establishing commercial 20cm x 20cm Glass-Body MCP Photodetector
  - Constructed clean room for location of processing equipment
  - Purchase of commercial ALD reactor (same as Argonne ALD reactor used to produce current MCPs).
  - Process tank (mini-SSL) nearing completion at vendor
  - Purchased new thermal evaporation system for electroding MCPs and other tasks
  - Equiping clean area with test and measure tools
  - Expect first Glass-Body MCP Photodetector produced ~January, 2016

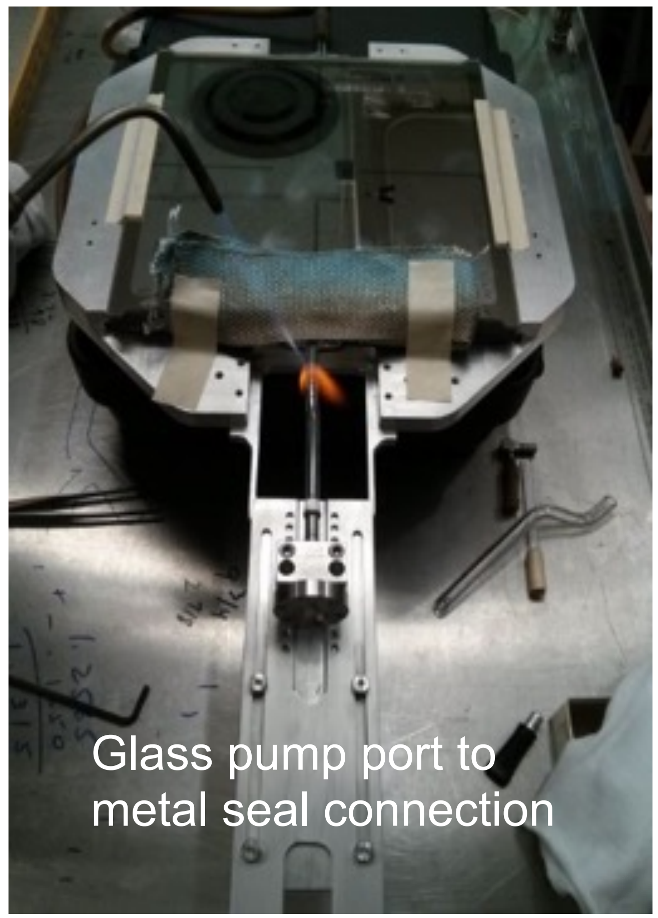
In Situ MCP Photodetector Assembly at U. Chicago



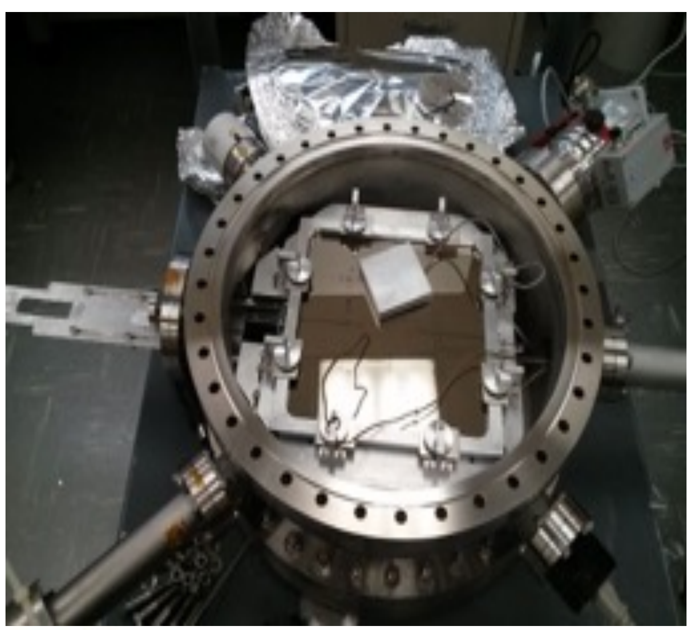
20cm x 20cm tile
with pump port



NiCr/Cu edged
top window



Glass pump port to
metal seal connection



Assembled detector
in vacuum bakeout
chamber

Goal: Avoid vacuum transfer process with PMT-style photocathode fabrication by introducing alkali's externally through glass tube

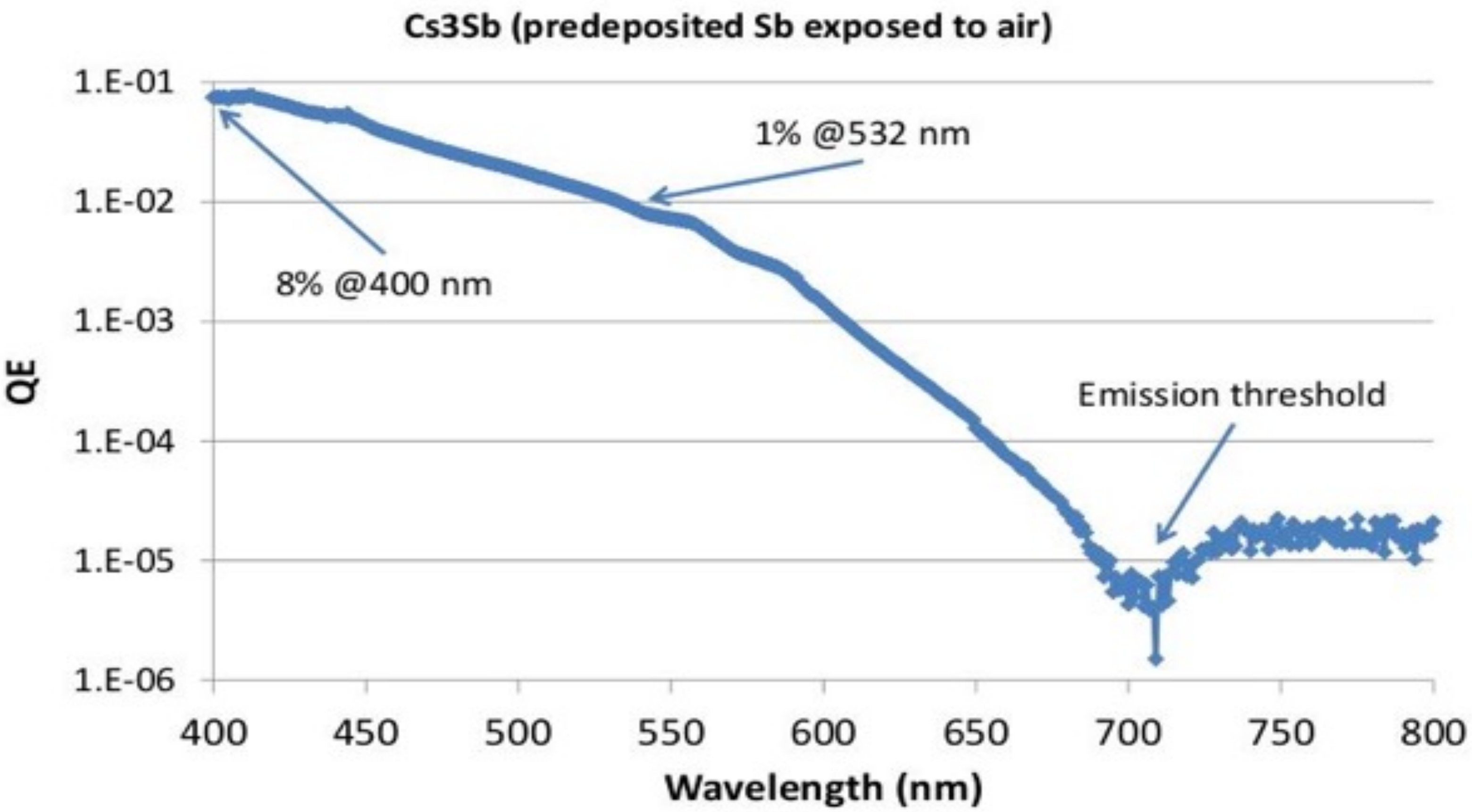
Process:

1. Deposit Sb on top window (air stable, thin oxide layer forms on surface)
2. Hermetic indium seal on NiCr/Cu metallizations on window and glass-body sidewall
3. Bake for outgassing MCPs at high T
4. Activate photocathode by evaporation of Cs/K through glass tube on detector body
5. Flame seal glass tube to complete detector

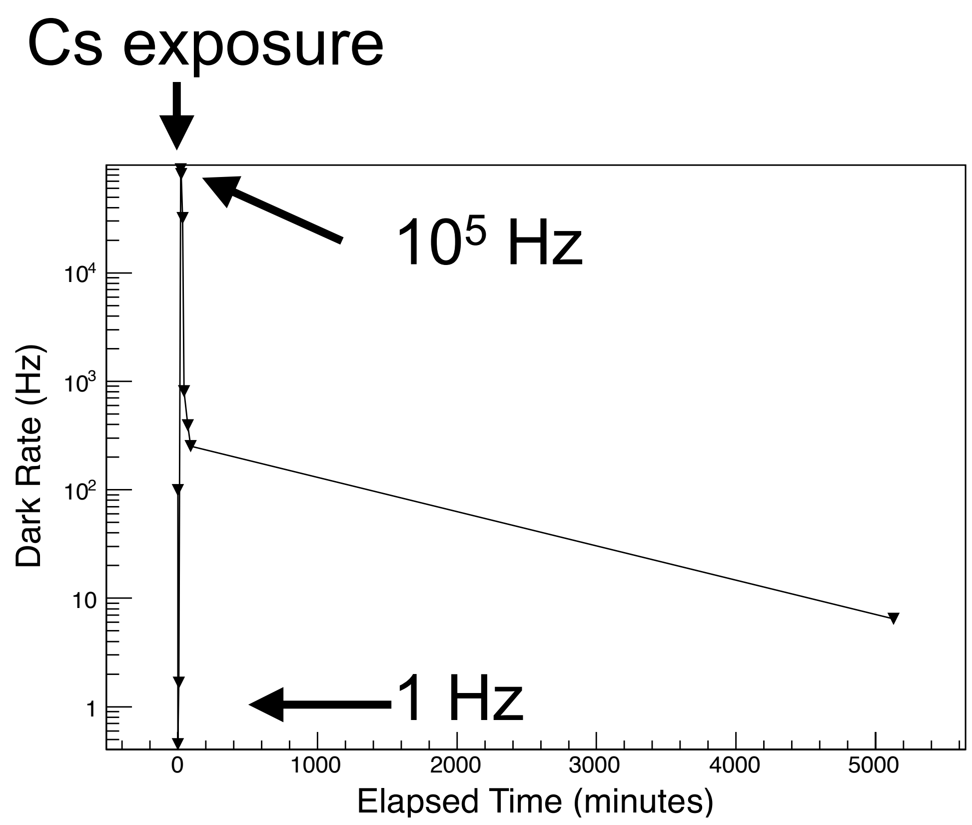
- Light weight processing chamber
- Potential for high yield production using multiple chambers

In Situ LAPPD Assembly at U. Chicago
Critical Component #2: *In Situ* Photocathode Fabrication

Working closely with Cornell group (Luca Cultera and Ivan Bazarov) to optimize photocathode activation step



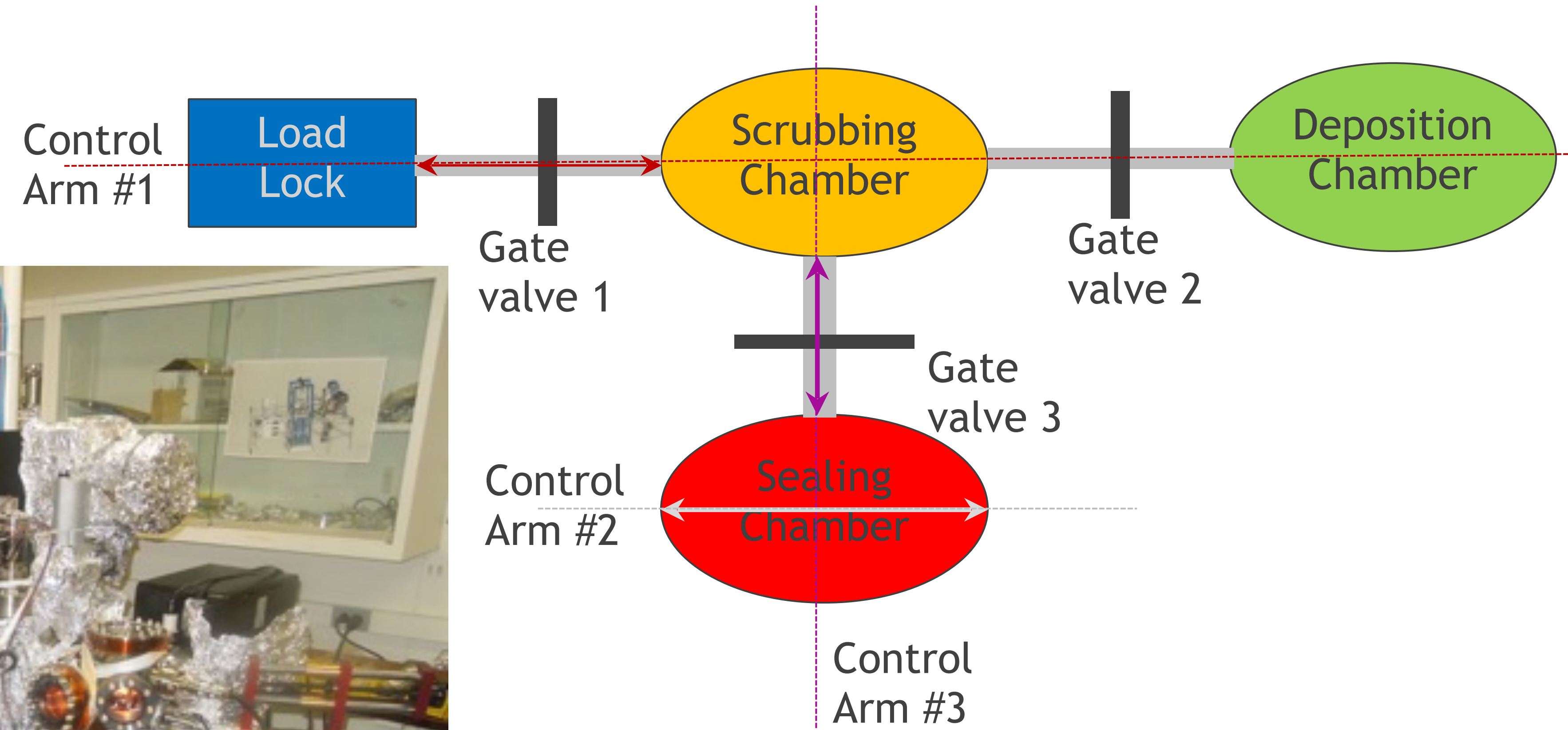
First attempt by L.Cultera to make $SbCs_3$ photocathode using pre-deposited layer of Sb exposed to air

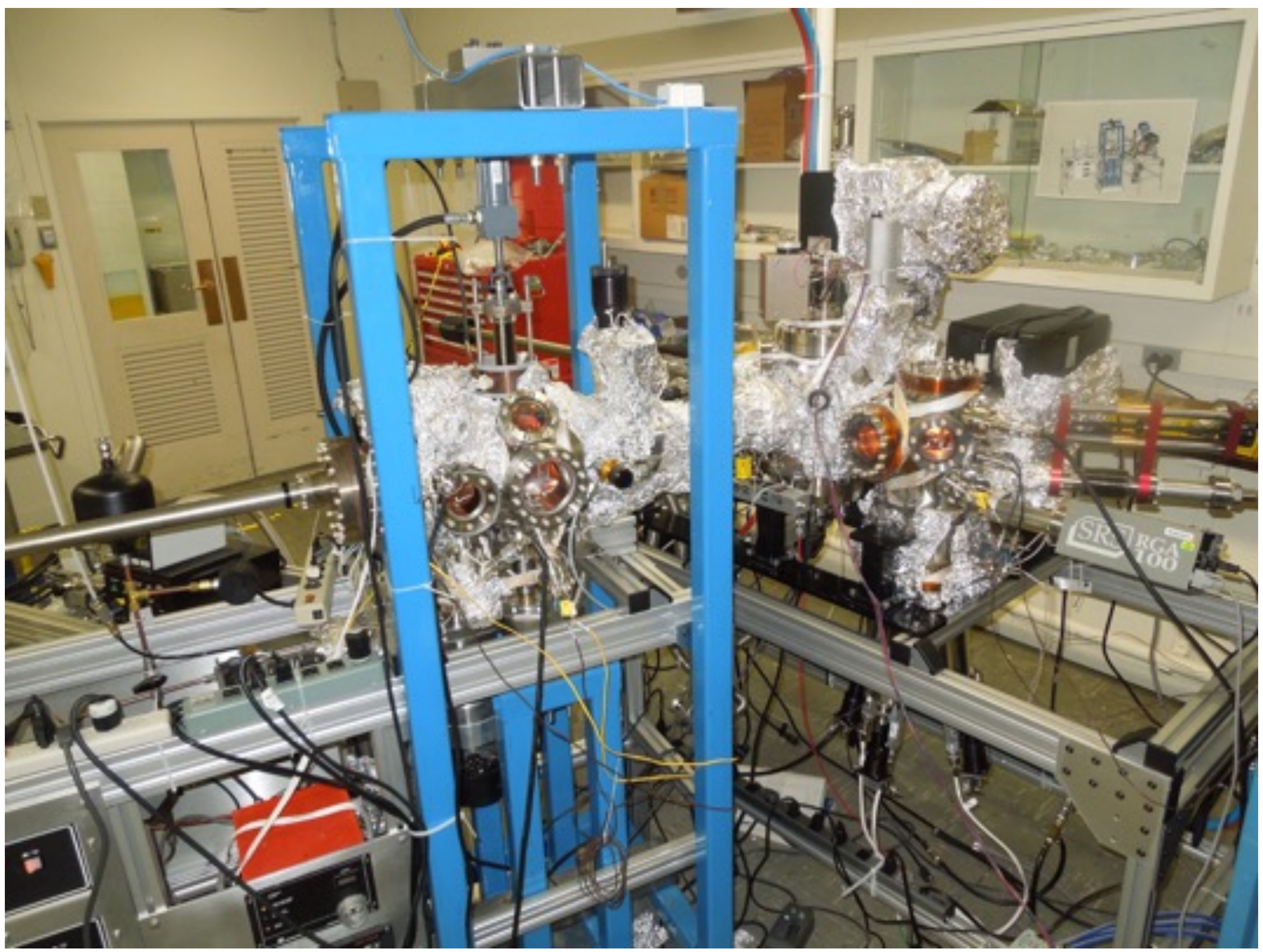


n.b. MCPs exposed to Cs vapor become noisy. Noise rapidly decreases then decays slowly over several days back to pre-exposure level

Argonne 6cm x 6cm MCP Photodetector Production

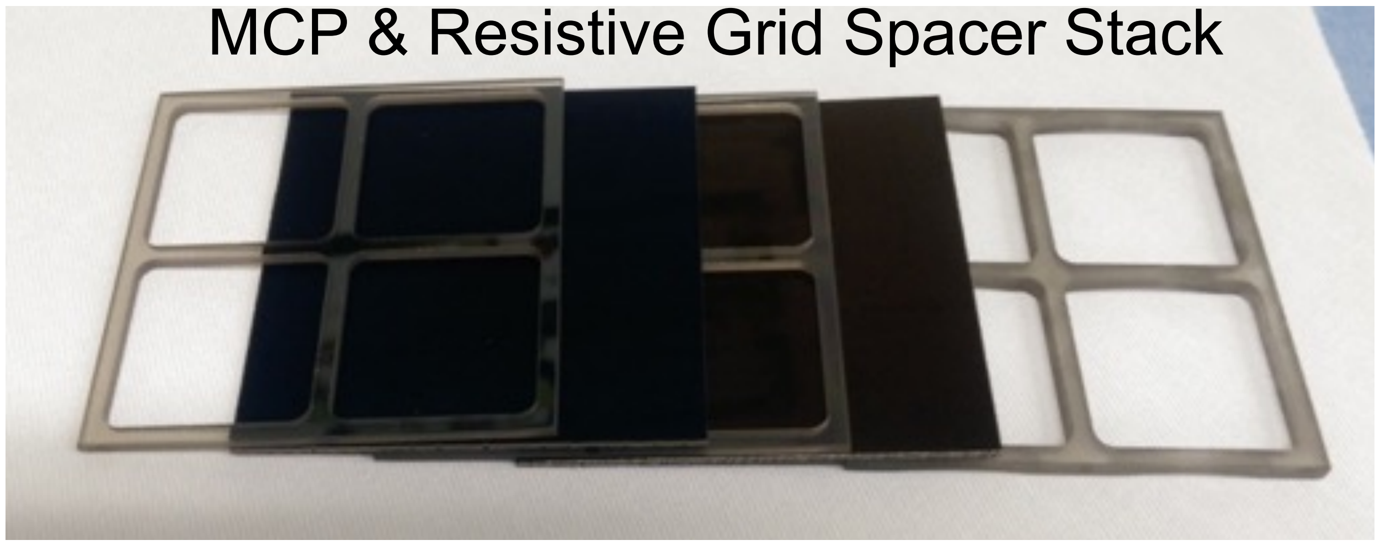
Argonne Small Single Tube Processing System (SmSTPS)

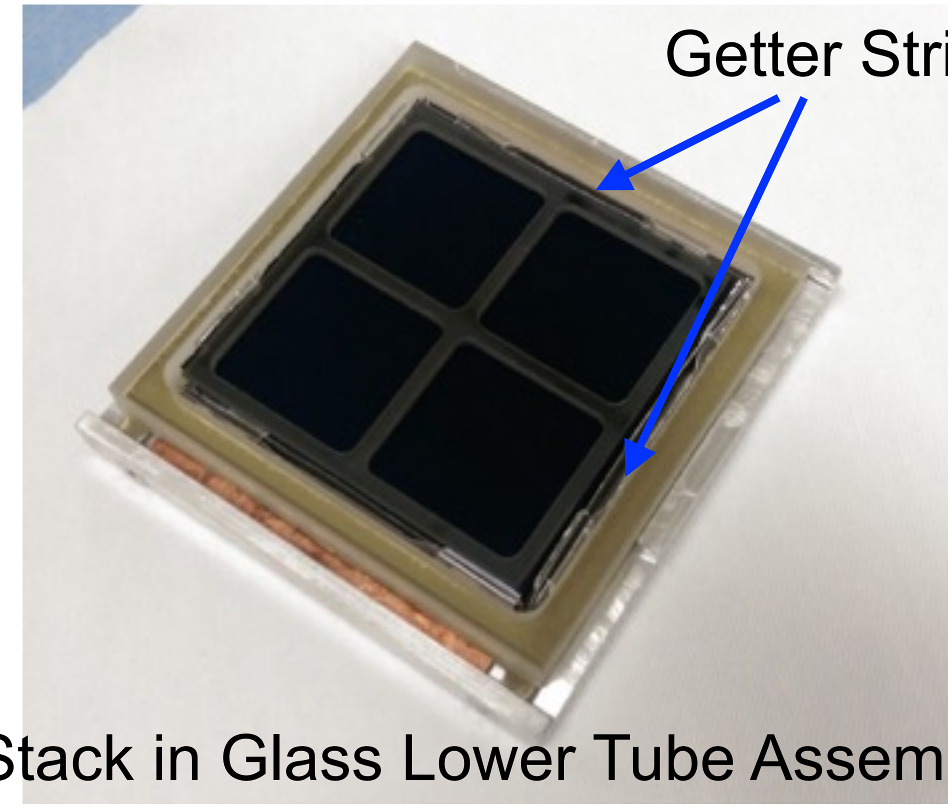




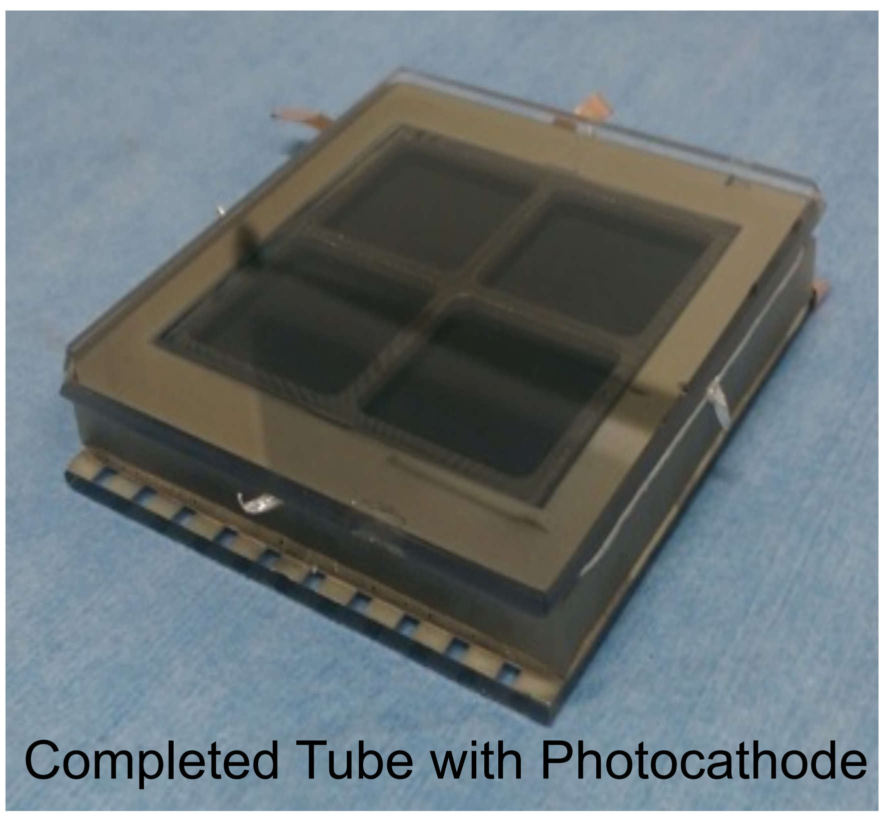
- Based on techniques developed for LAPPD Collaboration
- Unique features
  - Local heating w/ halogen lamps
  - Each process step has dedicated chamber
  - Photocathode evaporative deposition using effusion cells

6cm x 6cm Active Area MCP Photodetector Composition


MCP & Resistive Grid Spacer Stack

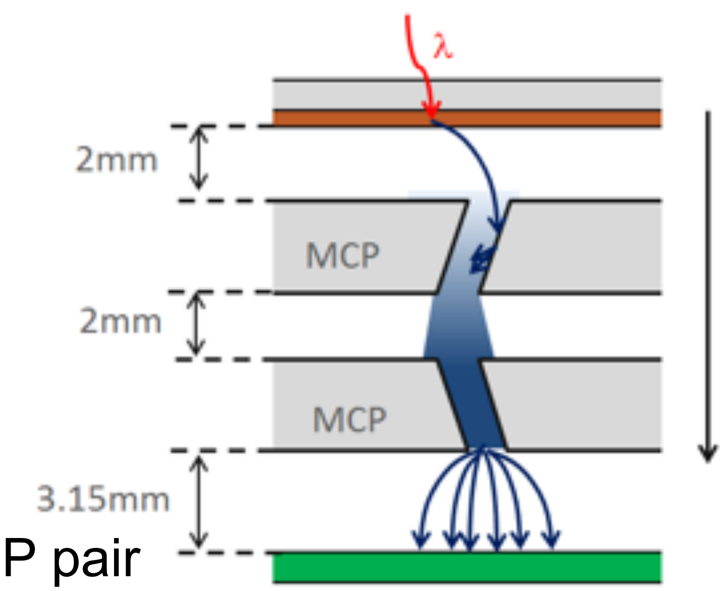


Stack in Glass Lower Tube Assembly


Completed Tube with Photocathode

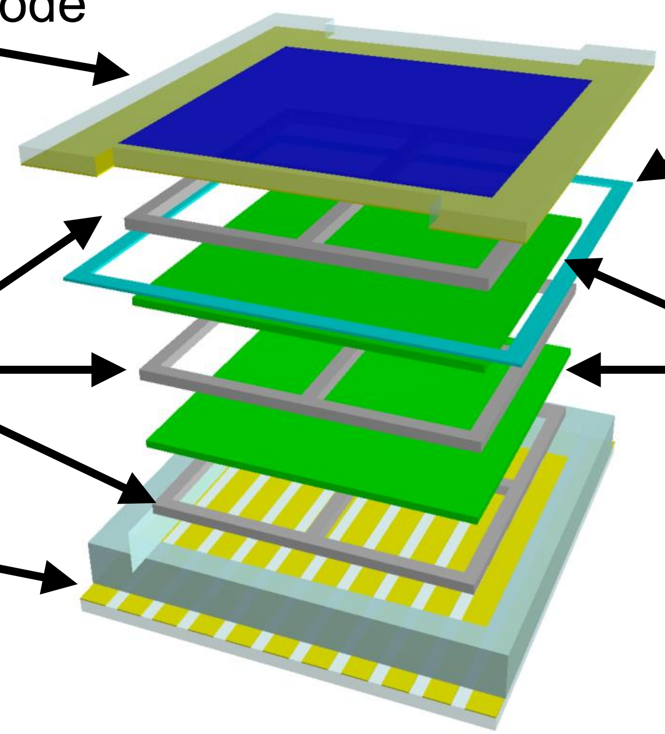
Double-ended readout via 9 anode strip lines

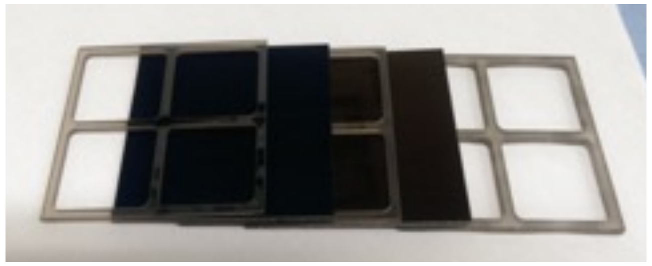
Top window seal made via thermocompression of indium wire

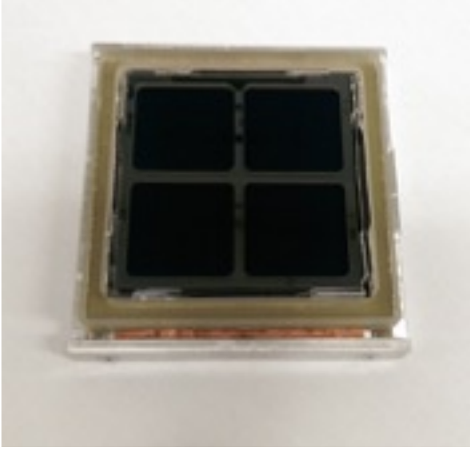


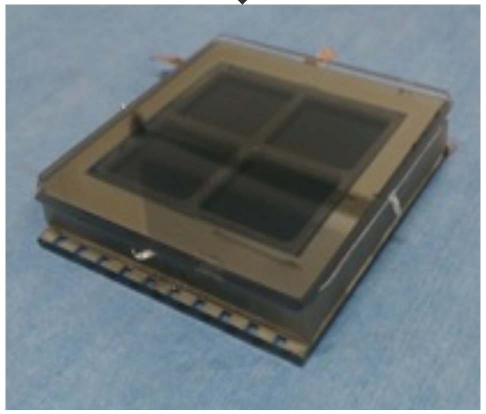
Tube contains MCP pair arranged with 8° pore bias angle in “chevron” configuration

Tube Processing





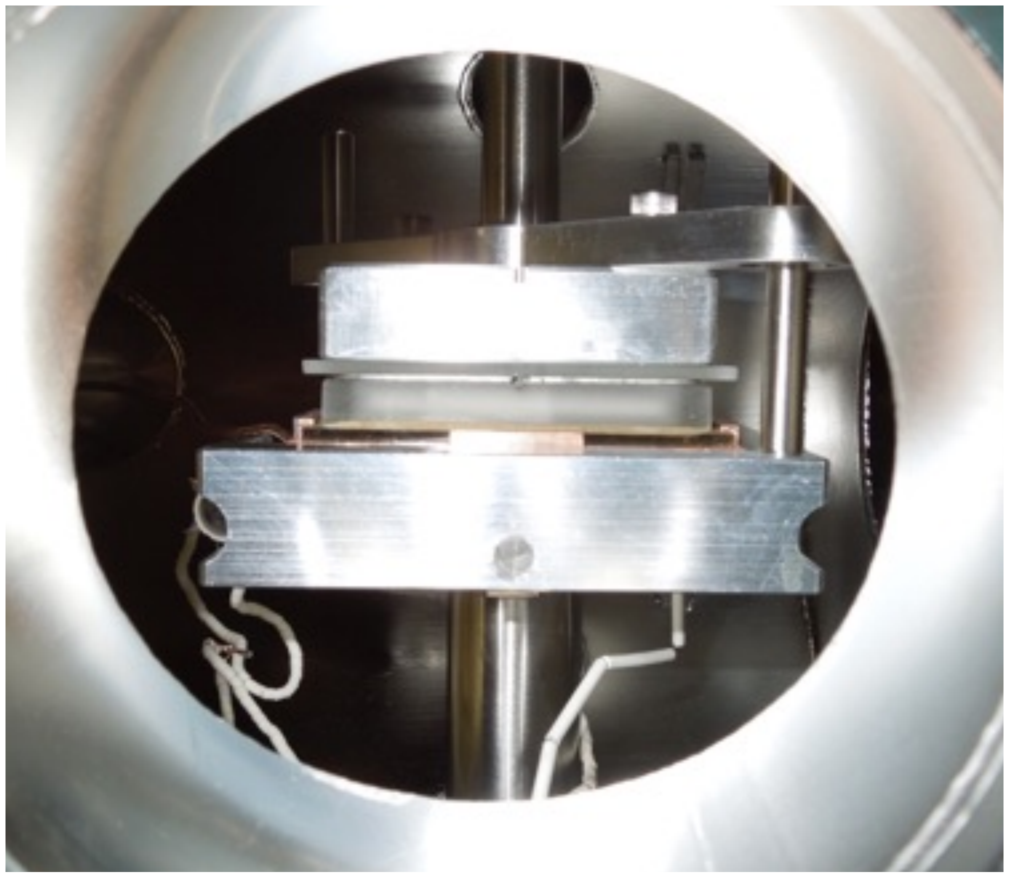


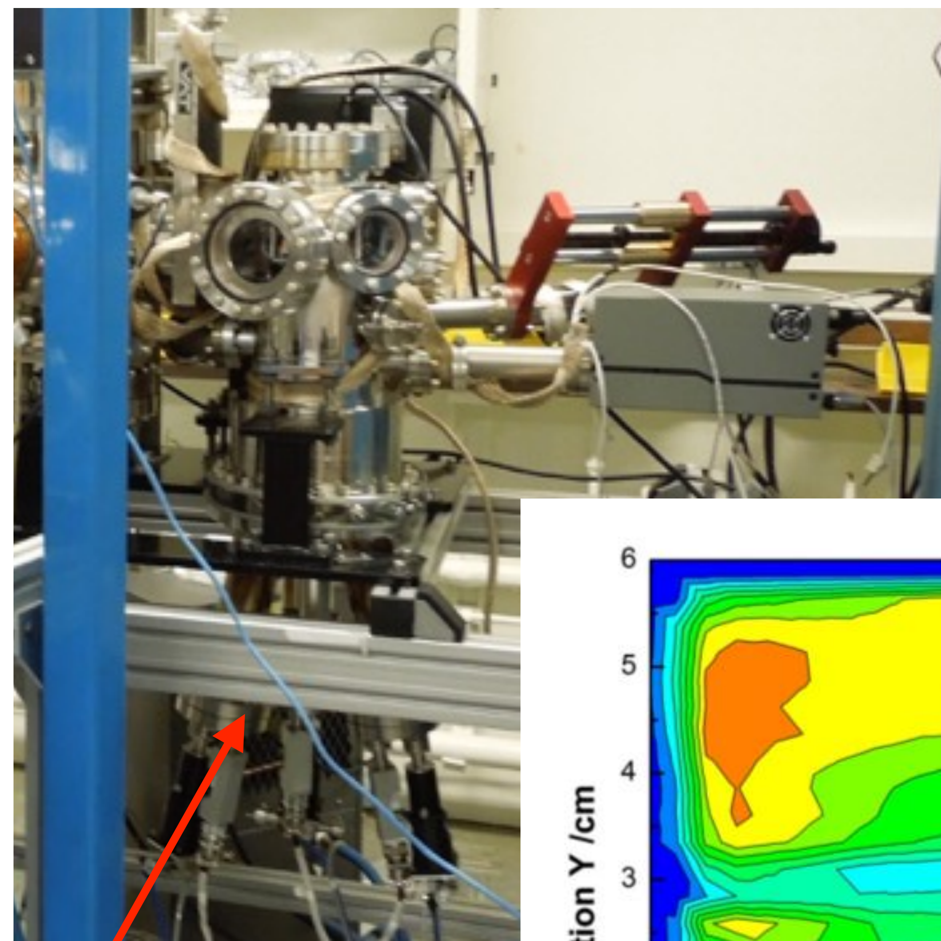


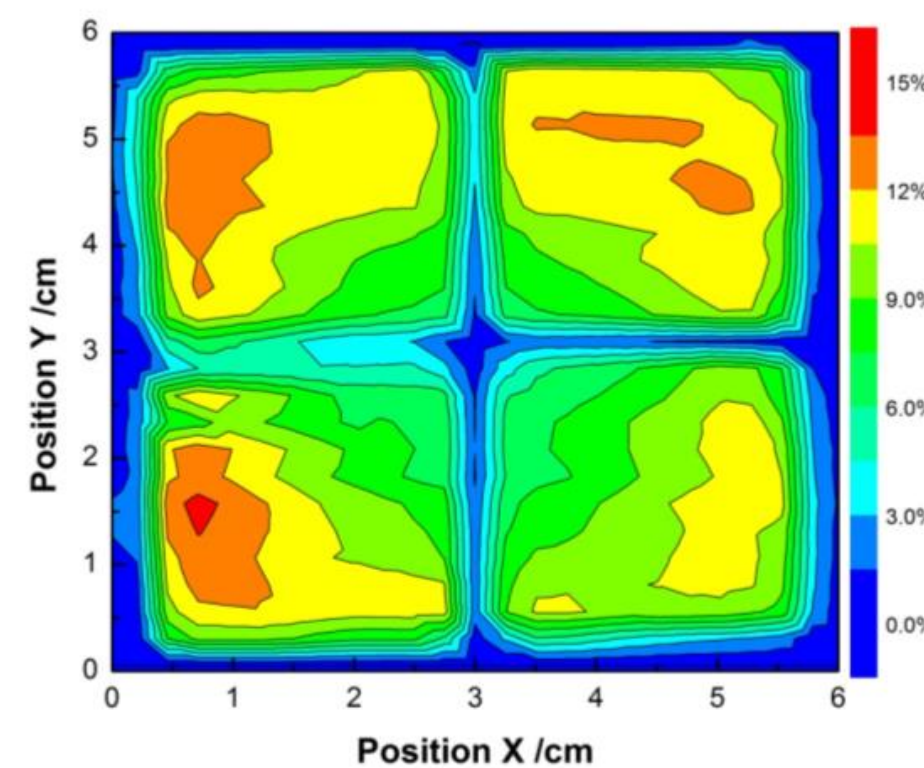
- **Detector tiles are processed in the 6cm system following these major steps**
  - Clean parts to UHV standards; MCP's cleaned & baked prior to functionalization
  - Bake tube body & MCP "stack" in vacuum (3-4 days)
  - Tube ➛ air. Insert getter strips ➛ back to Scrub Chamber (<20 minutes)
  - Scrub MCP's with electron gun (1 day)
  - low temperature bake for outgas; activate getters (2-3 days)
  - Load & bake top window in Deposition Chamber, photocathode deposition (2 days)
  - Press indium wire between window and tube body for detector sealing (1 day)
  - Finished detector in Sealing Chamber ➛ air
- **Total processing time ~ 2 weeks/tube**

Details on Photocathode & Sealing

- Monitor photocathode with
  - Quartz crystal µ-balance (QCM)
  - Photocurrent response during growth
- QE Uniformity ~ ±30%



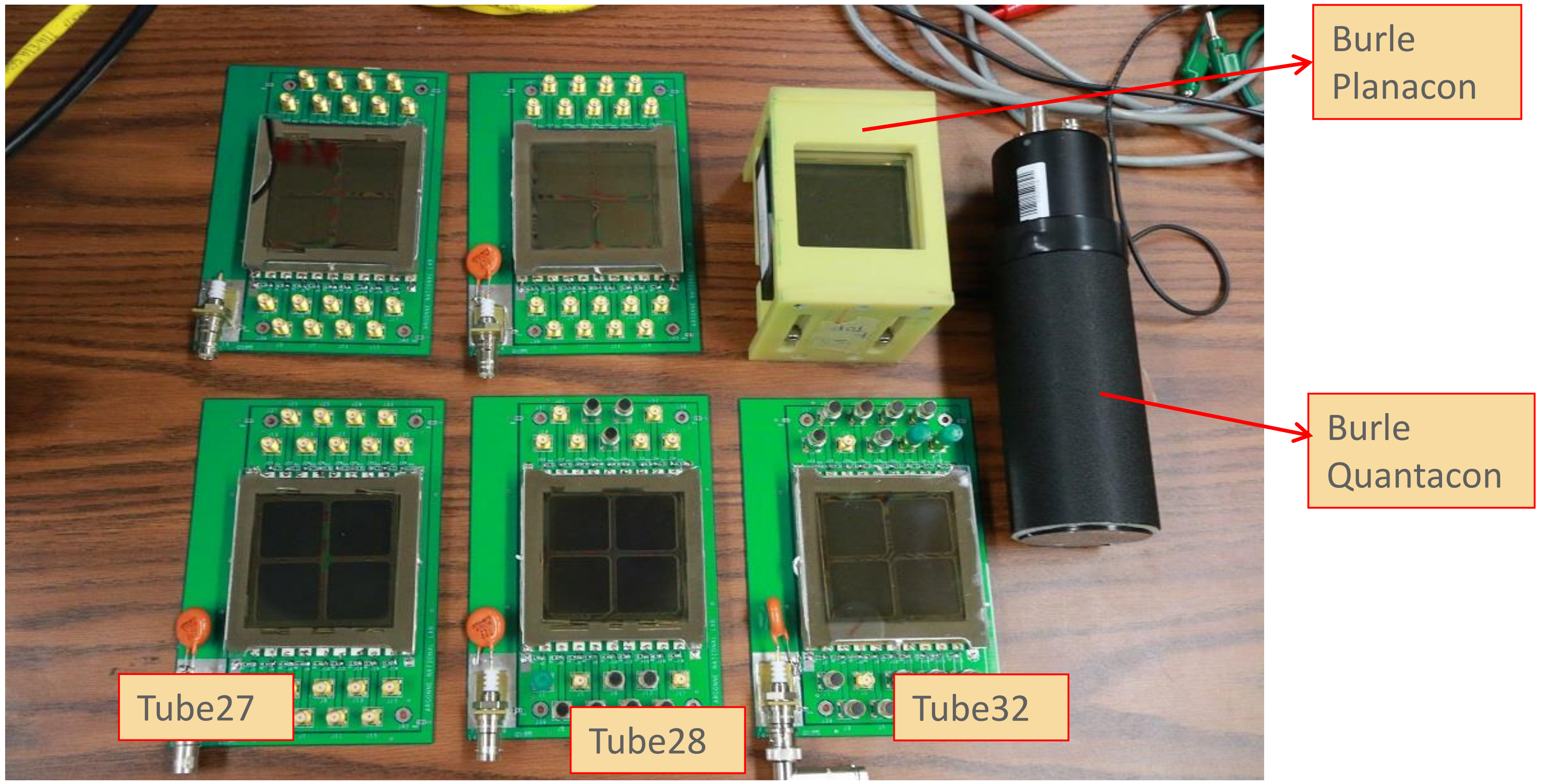




- Sealing uses hydraulic driven platens to crush indium wire between top window & sidewall
- Heaters used to raise glass to ~80°C to improve seal quality

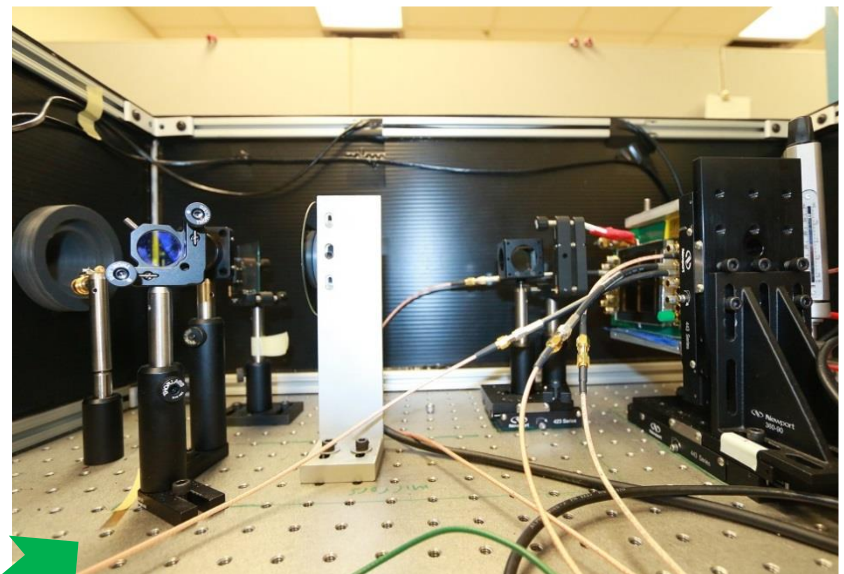
6cm Phototube Characterization Studies

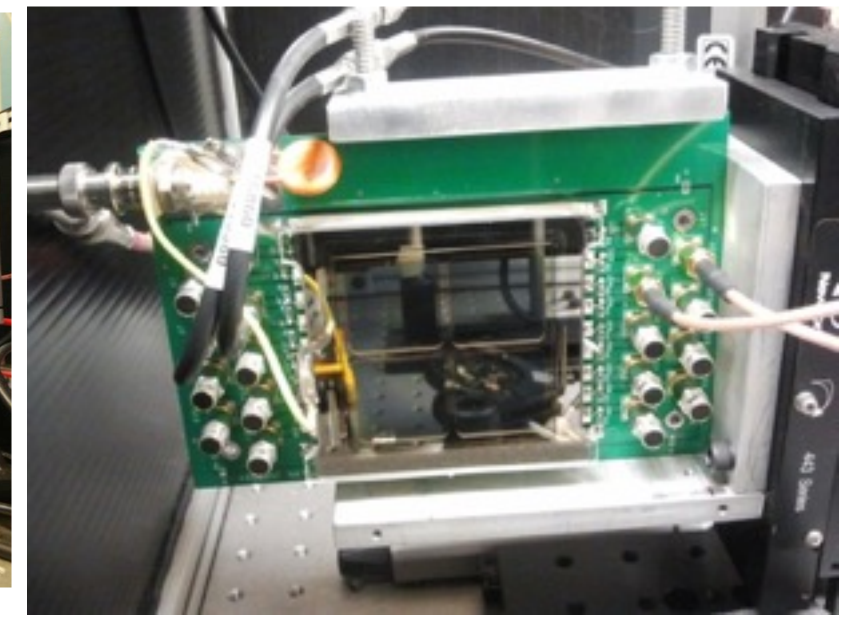
- Quantacon and Planacon MCP-PMT serve as known performance references
- Testing performed with Hamamatsu diode laser using 405nm head
- Read-out mainly thanks to UChicago 40 GS/s Tektronix oscilloscope
- Long-life tubes: 27, 28, 32 operating since Sept/Oct 2014

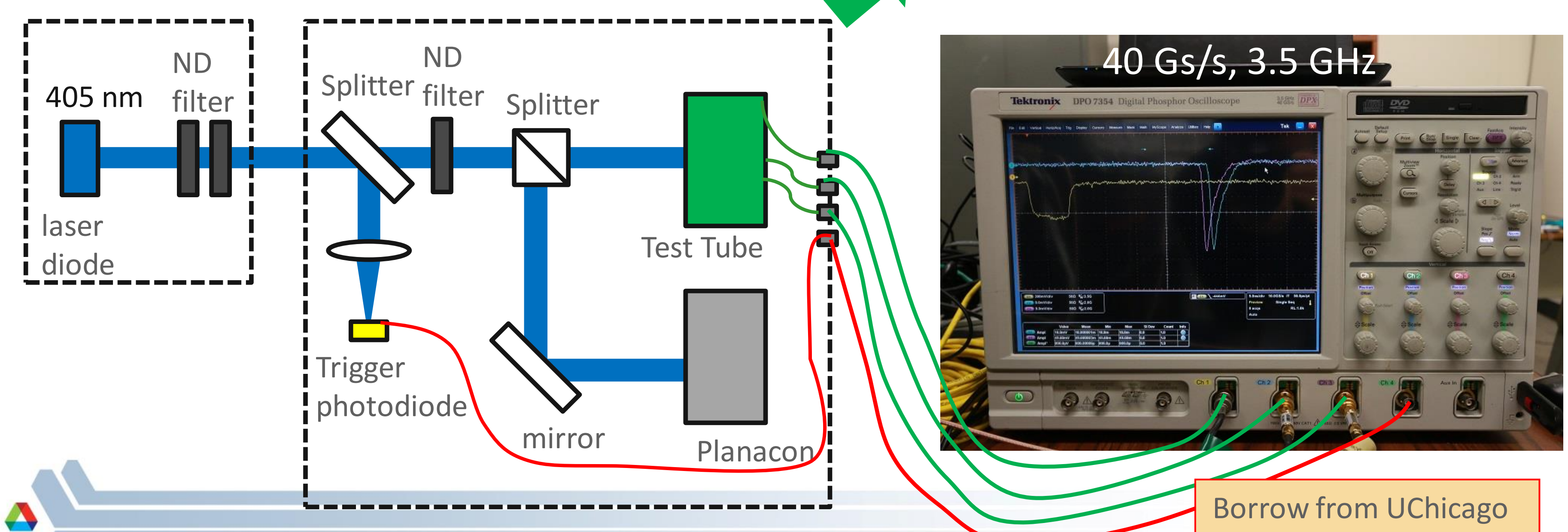


Tube Testing at Argonne HEP Laser Test Facility

- 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

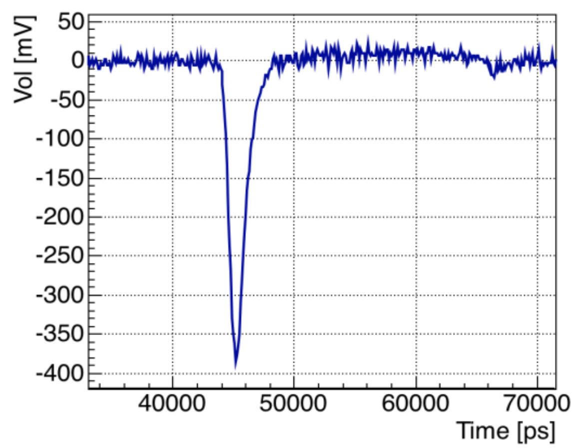






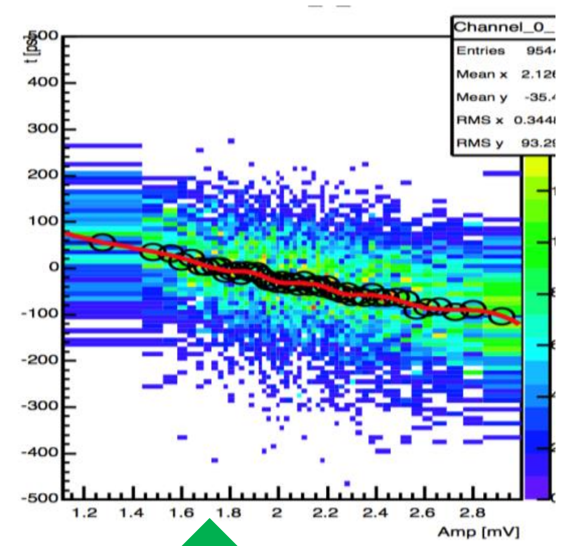
Data Analysis Flow

Raw MCP waveform

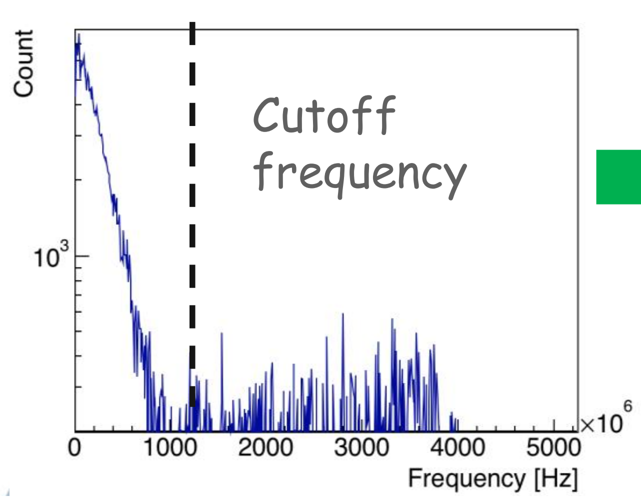


1. Record digitized waveforms
2. Fast Fourier Transformation (FFT)
3. Frequency filtering
4. Constant Fraction Discriminator (CFD)
5. Slewing correction

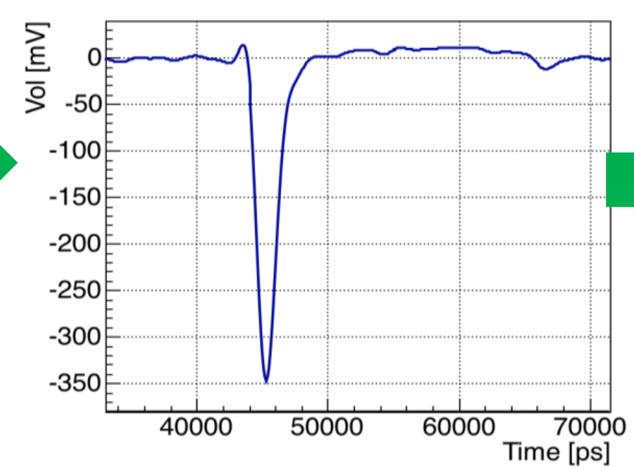
Slewing correction



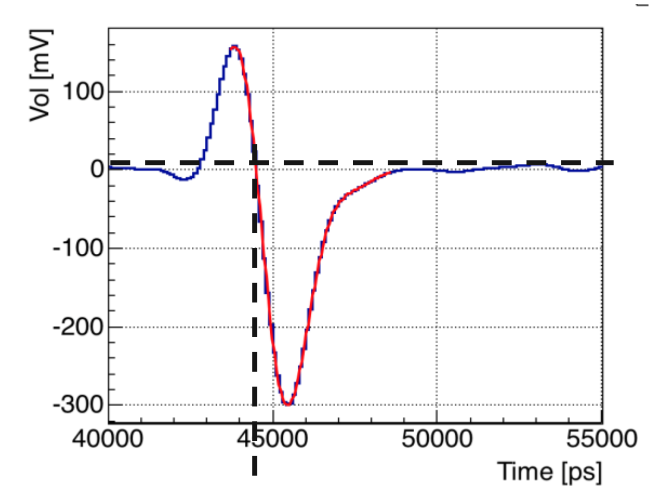
Frequency spectrum



Filtered MCP waveform

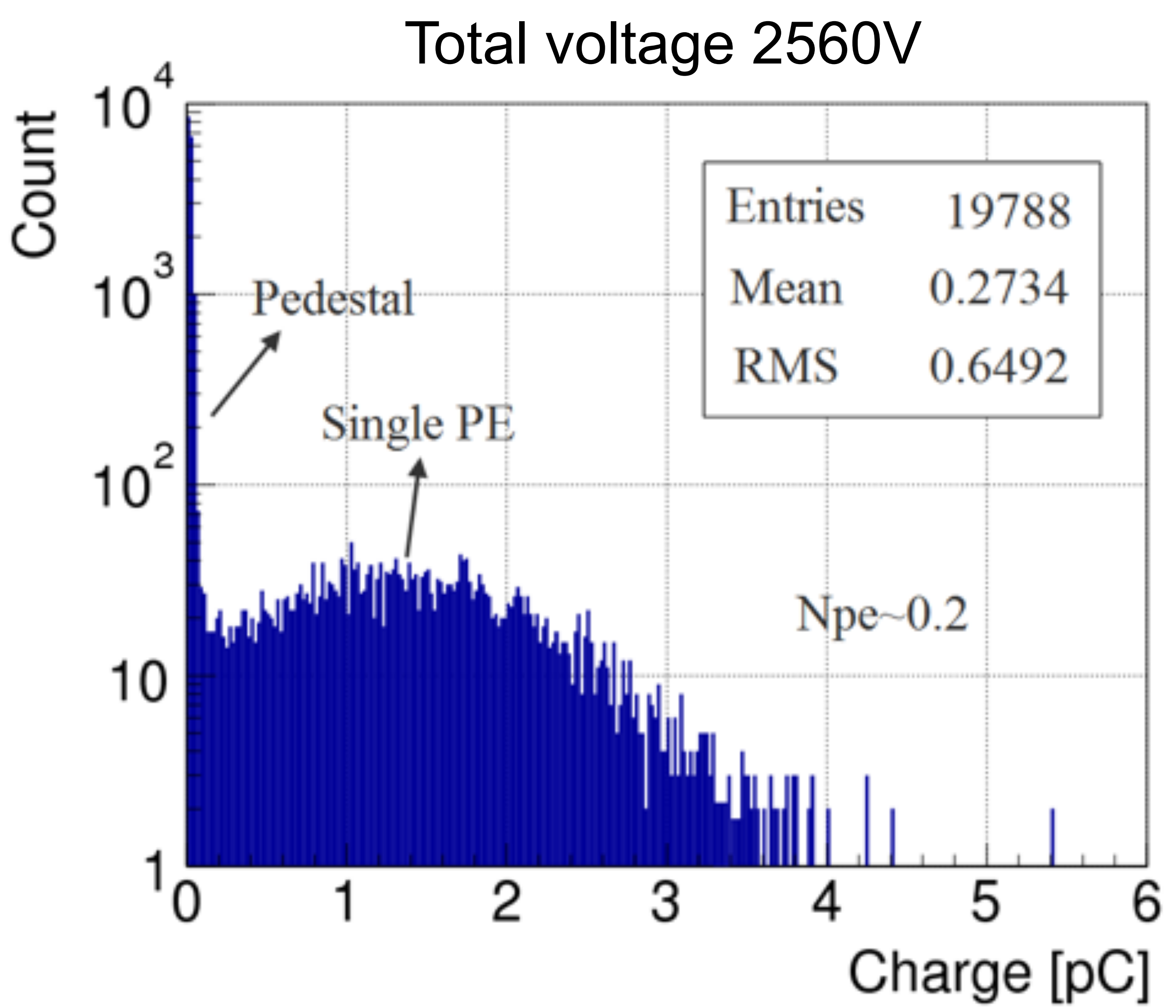


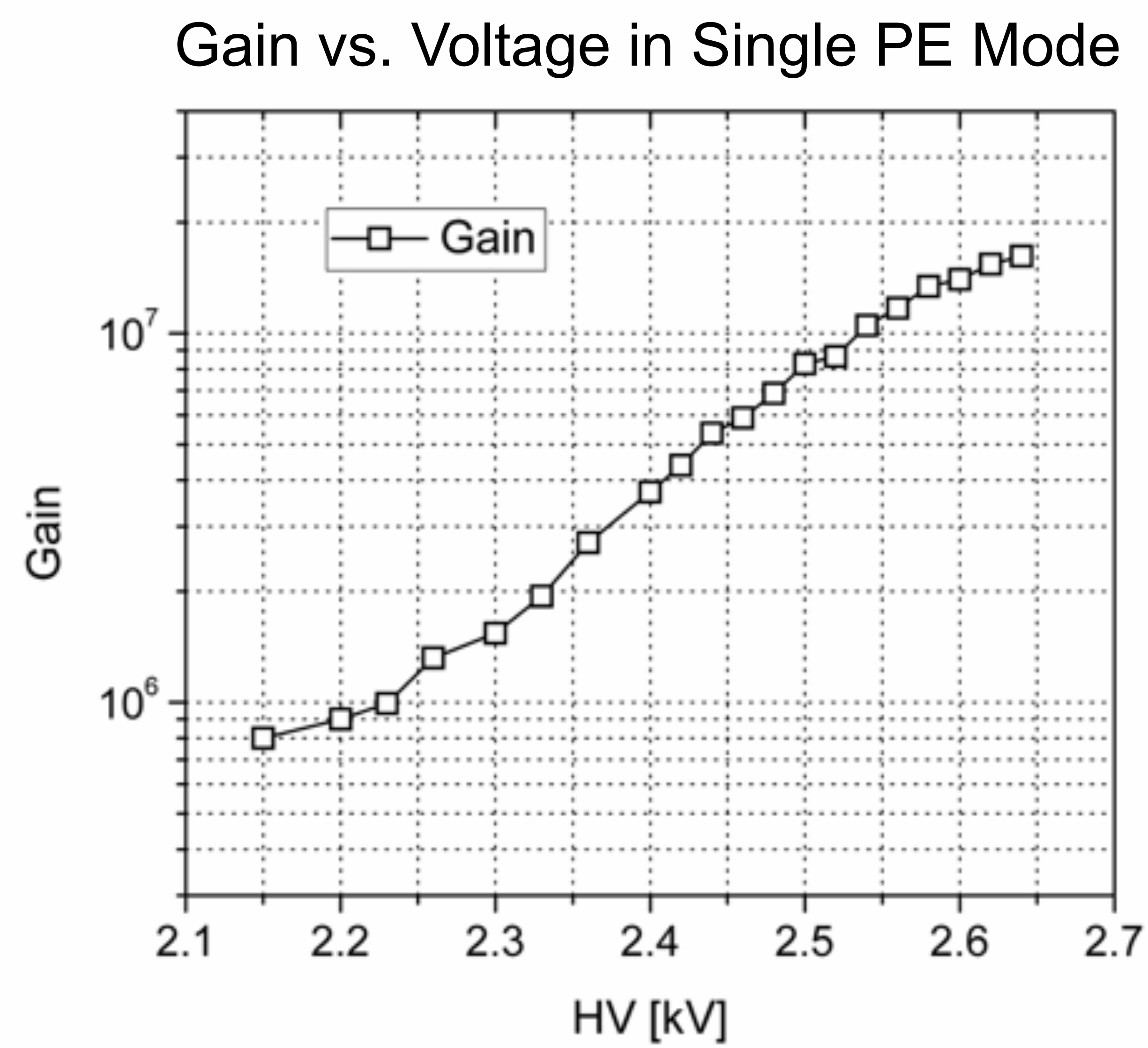
Standard CFD/ARC



Timing

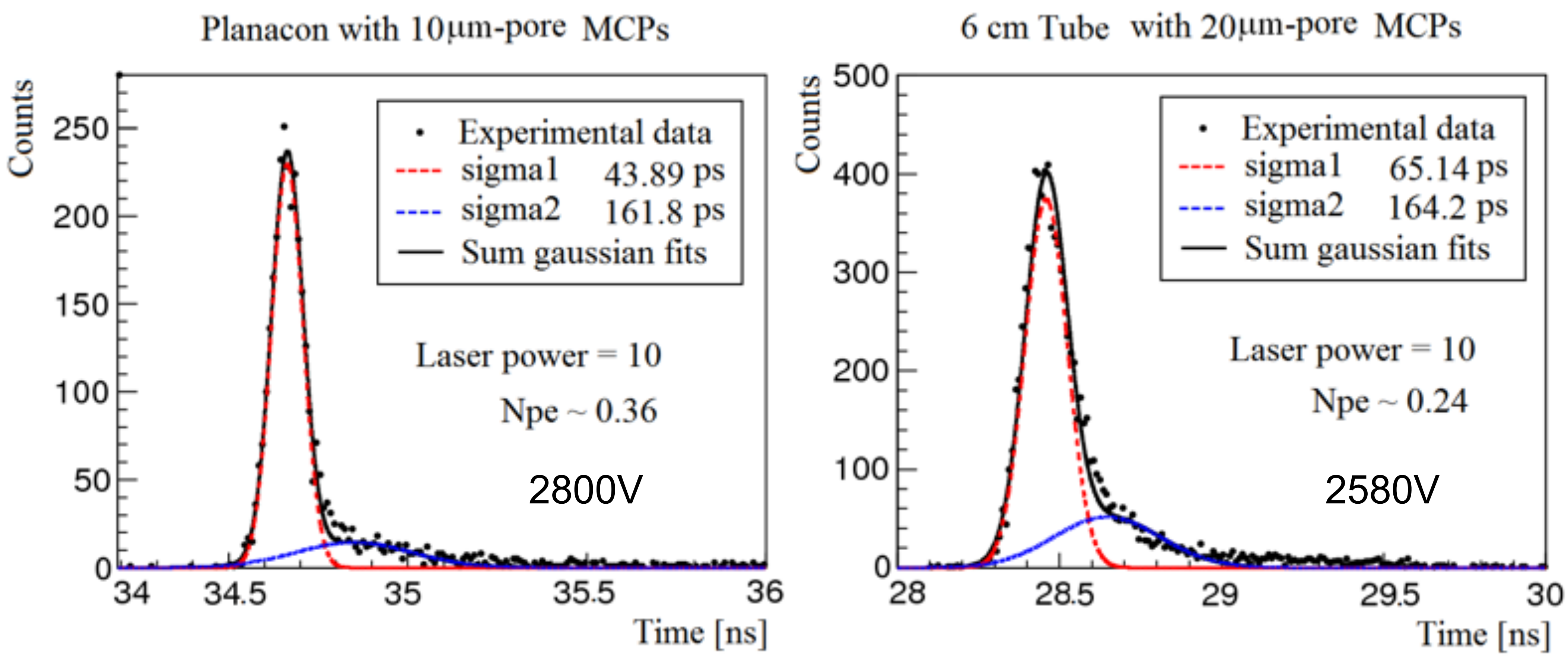
Single Photoelectron and Gain Measurement





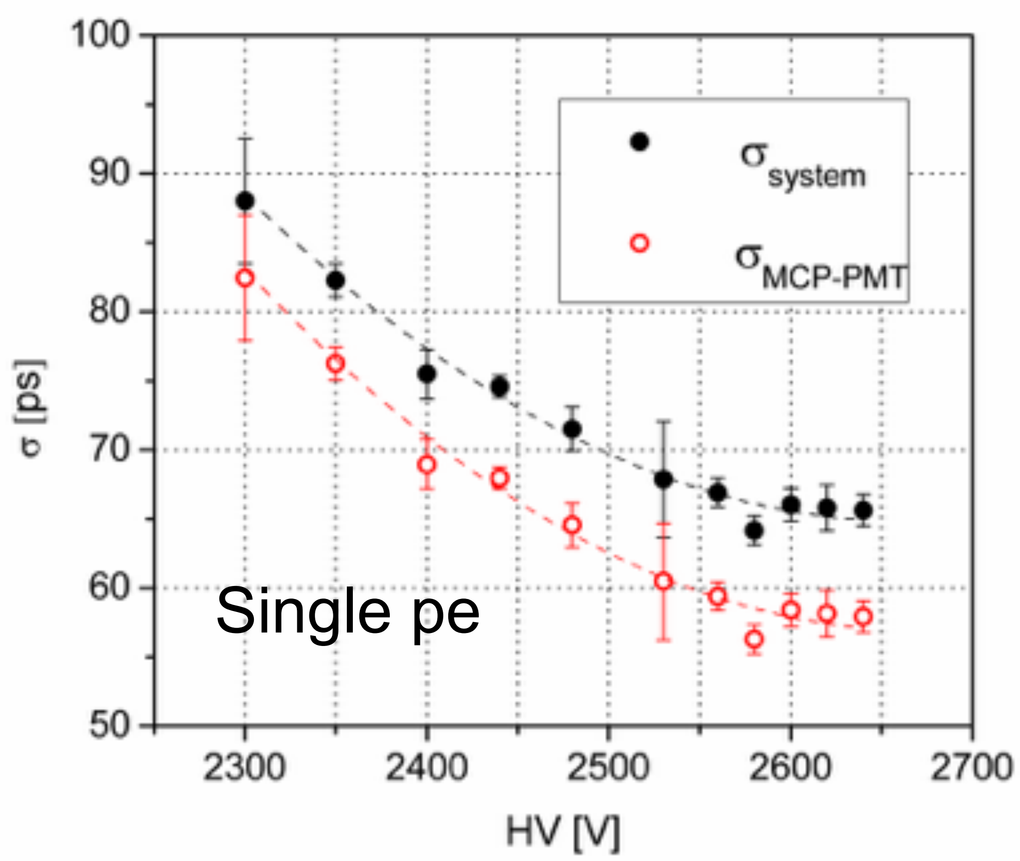
Attenuate laser intensity to produce <N_{pe}> ~ 0.2

Single Photoelectron Time Response



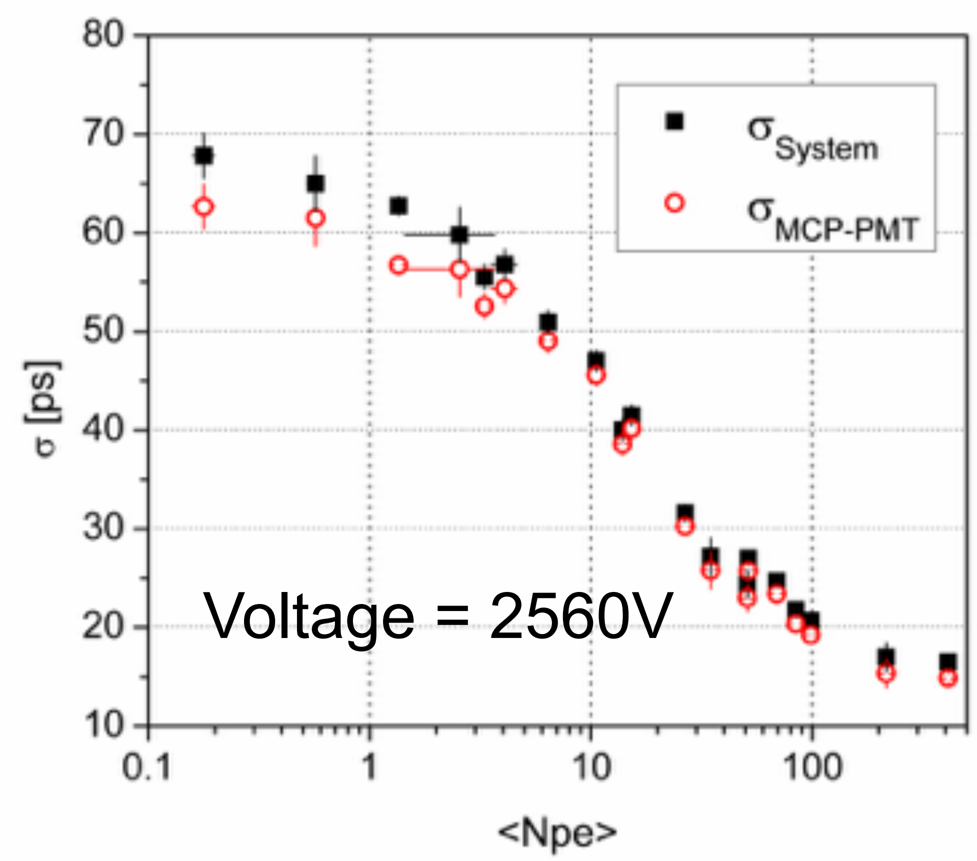
Comparison of single photoelectron time resolution between
10µm pore Burle Planacon (δt ~ 44ps) and
20µm pore Argonne 6cm tube (δt ~ 65ps)

Time Resolution vs Voltage & <N_{pe}>



Time resolution vs. Voltage for 6cm Tube

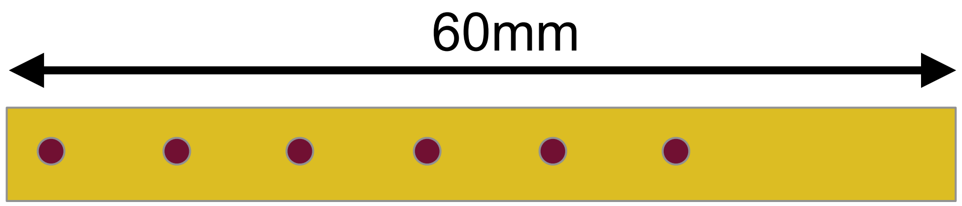
σ_{system} includes
30 ps from laser
7 ps from electronics

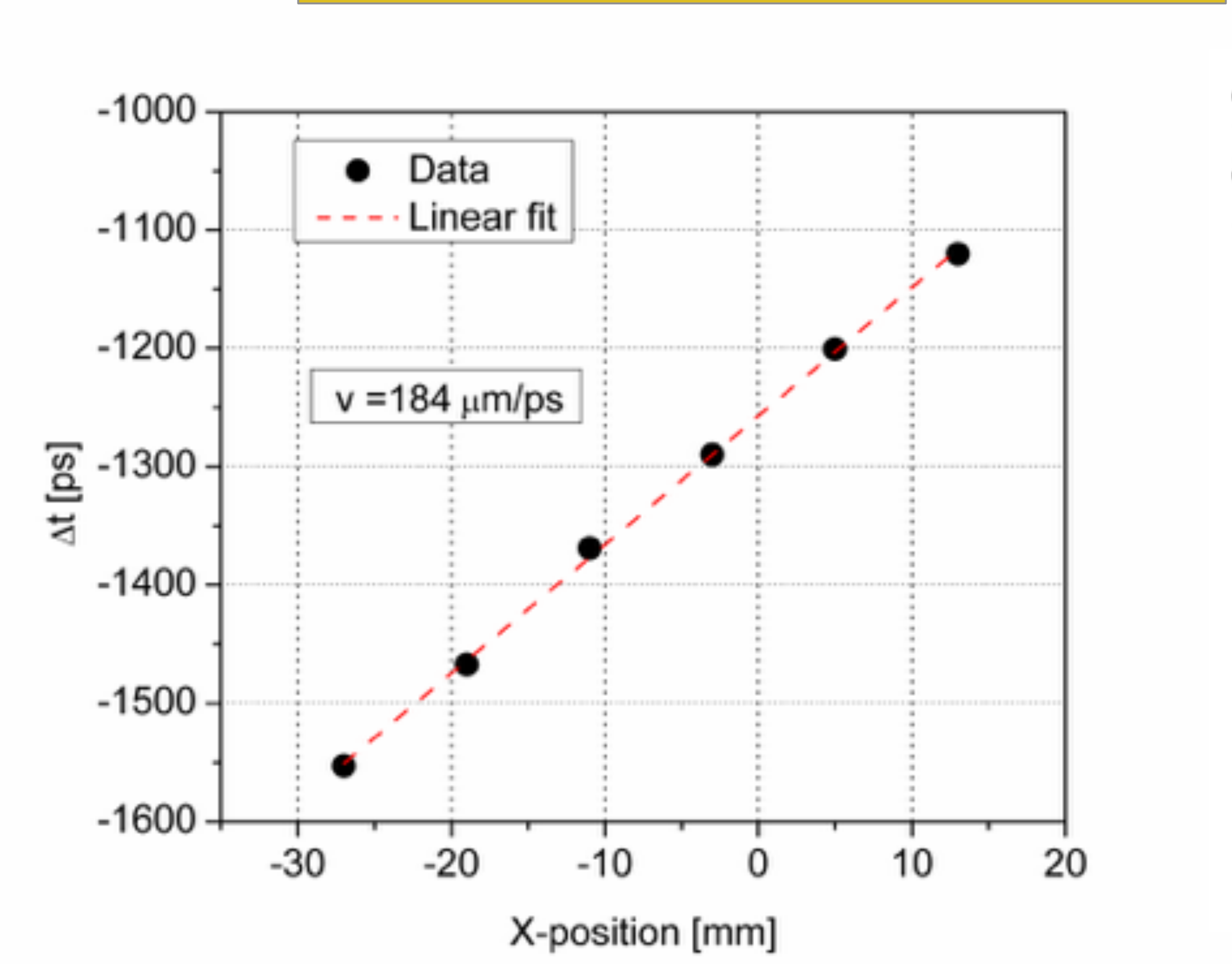


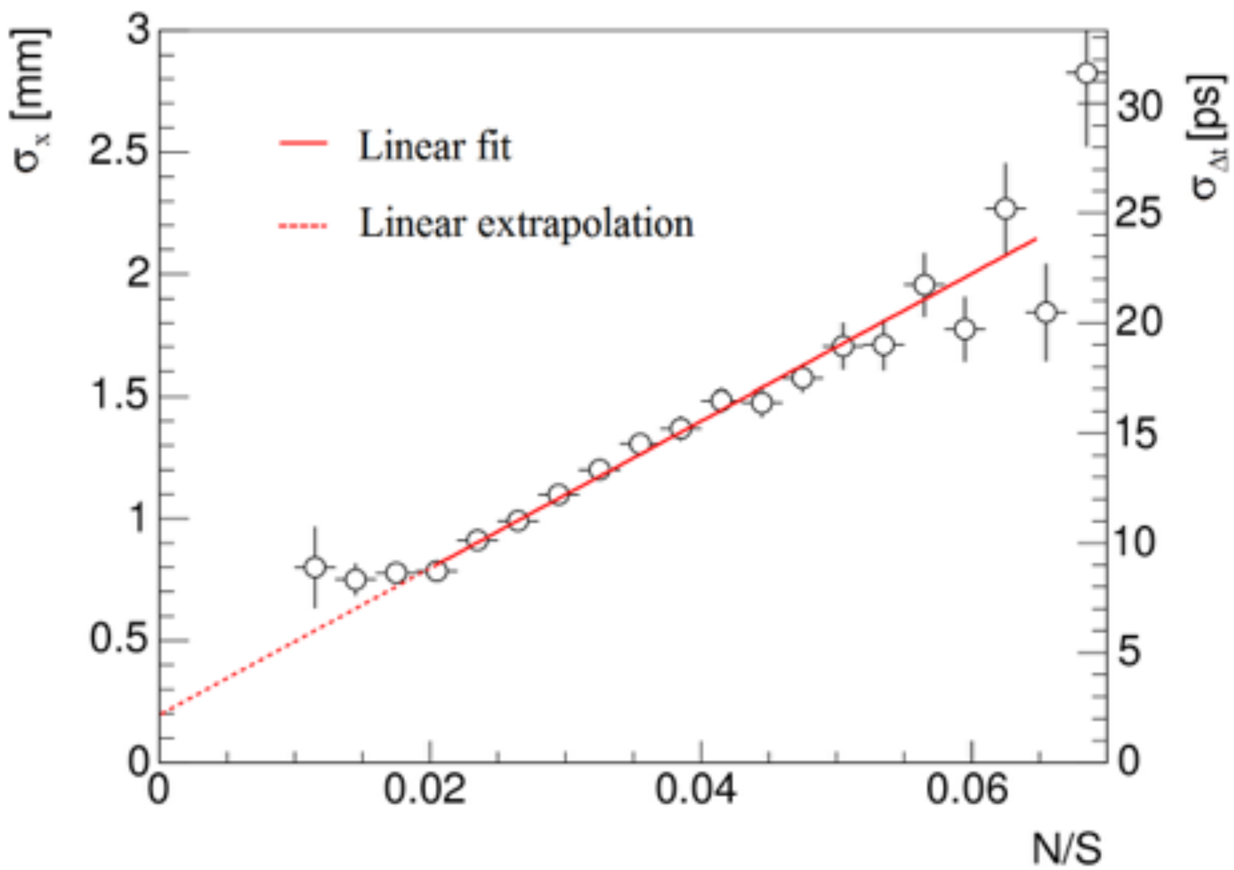
Asymptotic δt ~ 15ps at high light level

Position Resolution

1-2mm laser spot scan 60mm active strip length







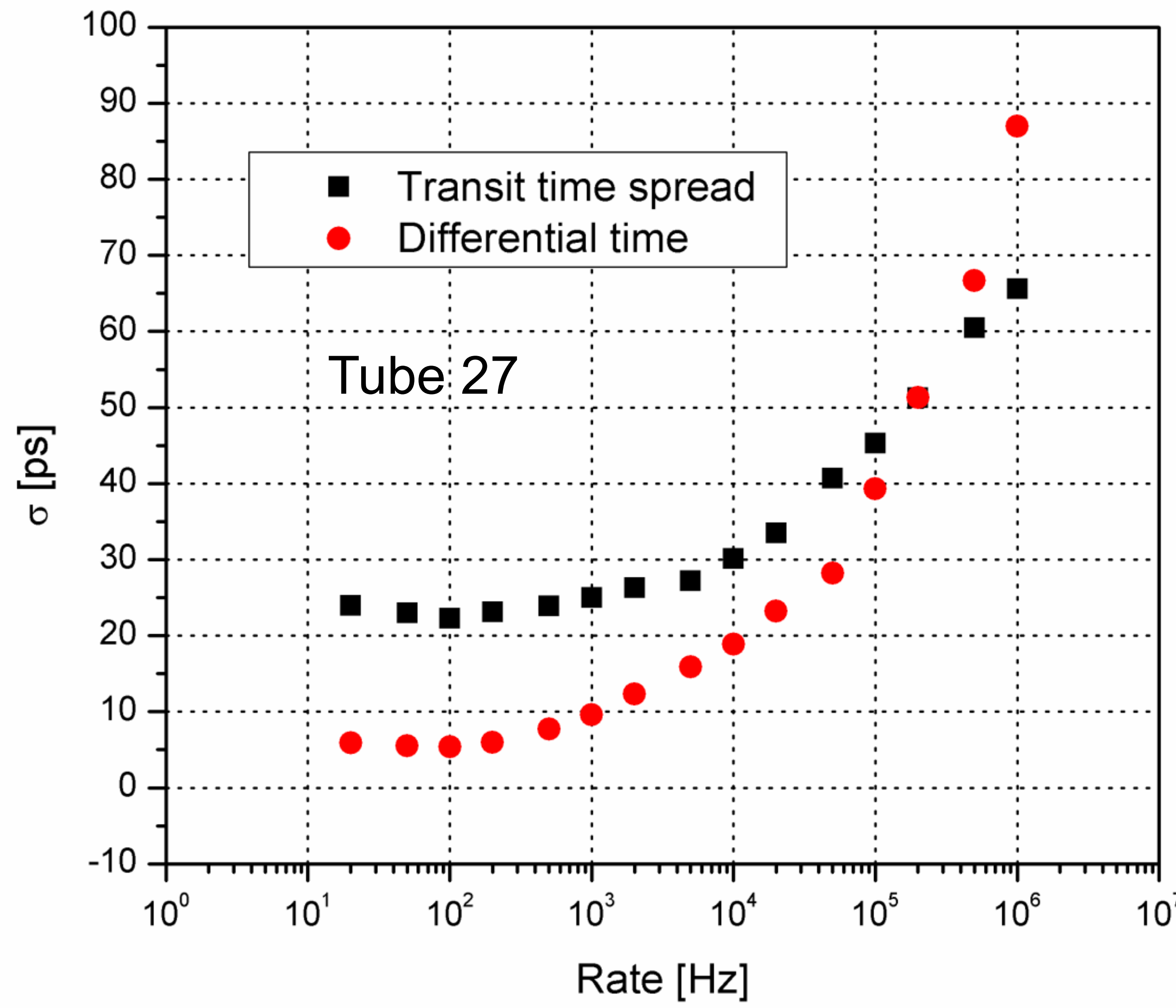
Position resolution limited by beam spot size at high light levels

Rate Scan: Time Resolution vs Spot Pulse Rate

Measure time resolution for laser illuminating fixed 1-2mm spot

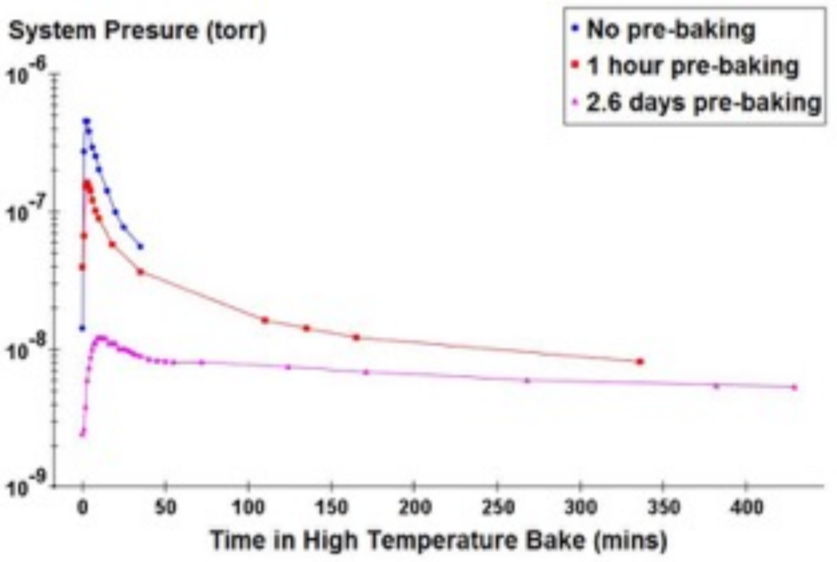
Use high light light level

Timing performance degrades above 10kHz but <70ps up to 1MHz



Near Future Plans: Improving Tube Performance & Lifetime

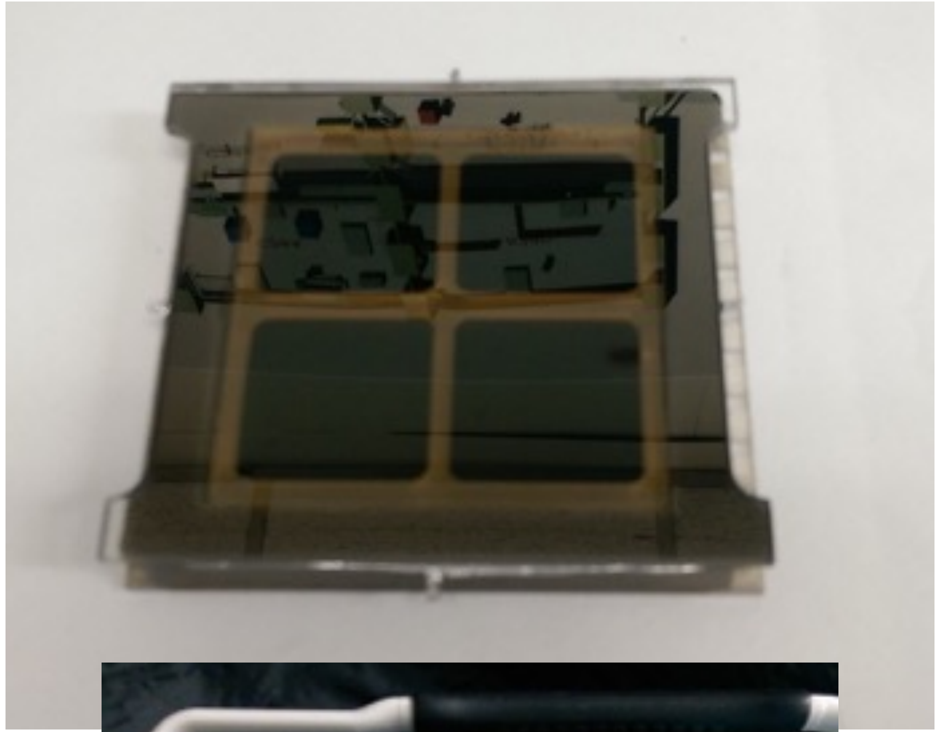
- Qualifying new tube biasing design
  - Initial baseline design used internal grid spacer/MCP resistor chain scheme. Has several fundamental issues:
    - Component resistance changes during tube processing
    - Requires close matching of MCP and grid spacer resistances
    - Standing current (few µA) prevents direct photocathode QE measurement (few nA)
    - Cannot individually optimize MCP HV for best performance
  - New independently biased (IBD-1) design has individual connections to all MCP surfaces
    - No standing current ⇒ Straightforward QE measurement
    - Adjust bias to each MCP for best overall performance
- Achieve reliable tube processing
  - **Goal: 50% overall yield (successful seal, 30 day lifetime)**
  - Systematic studies to improve processing:
    - Sealing study with improved fixturing
    - MCP baking study to reduce residual outgassing
    - Getter activation process study:
      - avoid exposing getter to higher pressure at high T activation



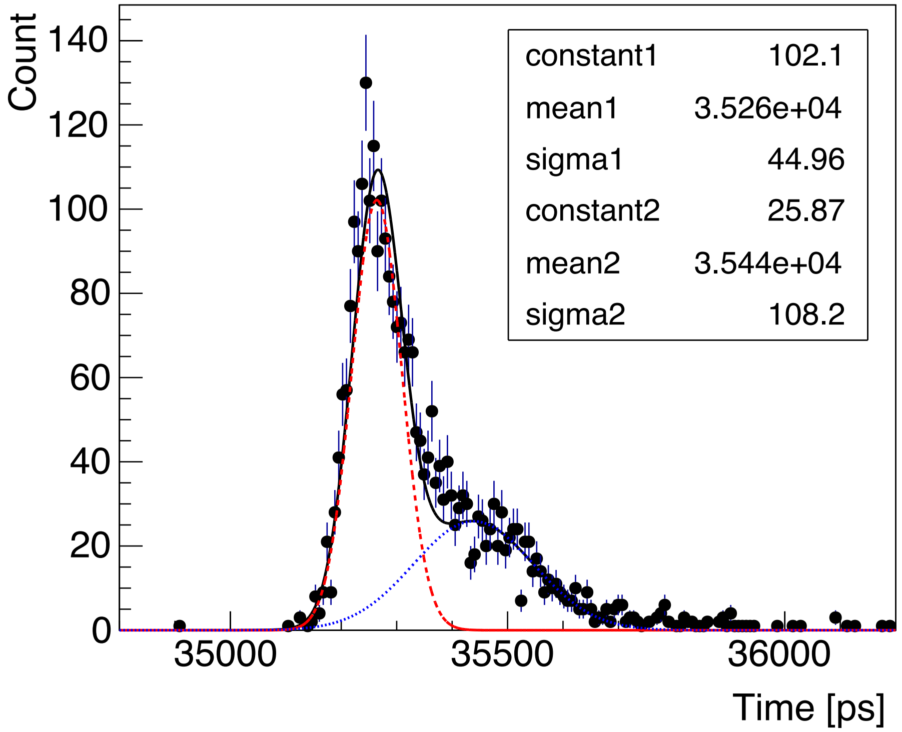
Measurement of MCP outgassing at getter activation stage, as a function of different pre-baking condition

Next tube fabrication completed yesterday

First Results from Initial IBD-1 Type Tube

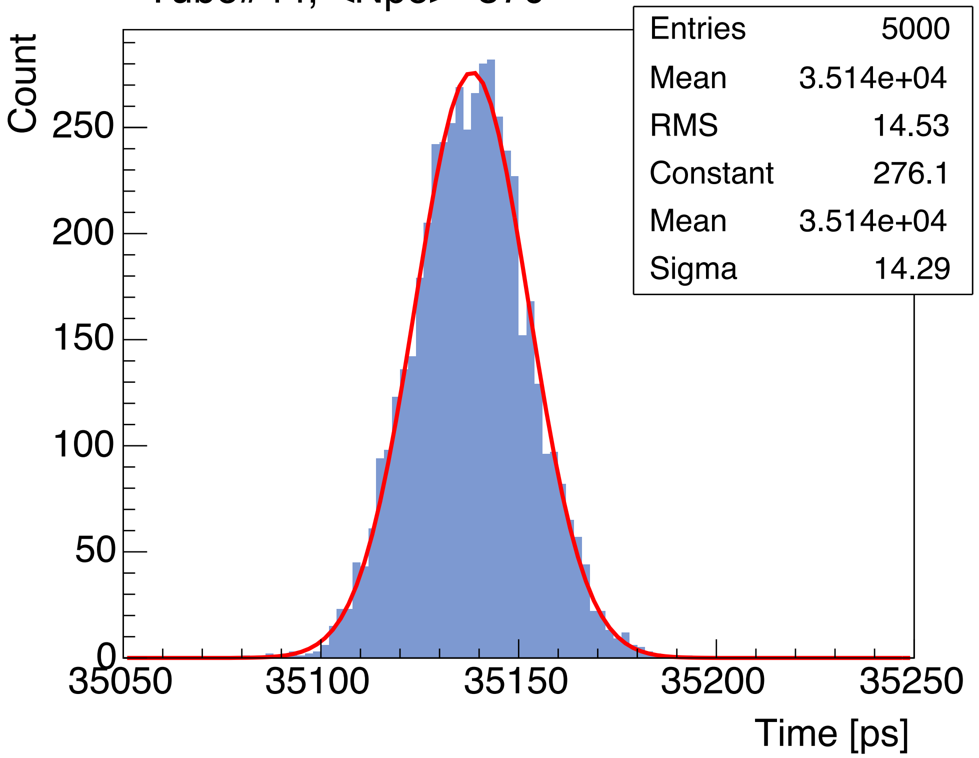


Single PE
δt~45ps



Pulses from strip lines

Large PE
δt~14-15ps



Summary

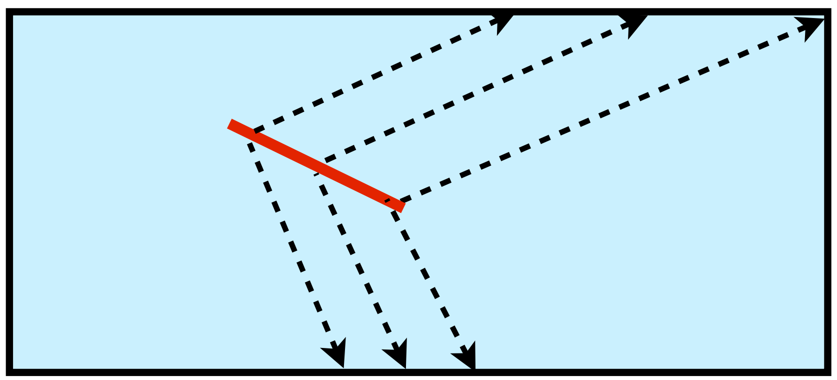
- Atomic Layer Deposited (ALD) MCP fabrication has achieved reliable production of high, uniform gain MCPs. Future work to
  - understand characteristics of baseline ALD materials
  - develop new materials for lower cost, better stability, improved performance
- ALD MCP Photodetectors progressing along several efforts
  - LAPPD 20cm x 20cm active area commercialization in progress at Incom, Inc
    - Following Space Sciences Lab/Berkeley (SSL) scheme for Process Tank and Sealing
    - SSL producing initial all-glass tubes following Incom tube body design
  - In situ assembly design with PMT-style photocathode deposition in progress at Univ. of Chicago
  - Argonne 6cm x 6cm small format MCP photodetector has produced several working tubes demonstrating good timing and position resolution. Have distributed first tubes to physics community. Work in progress to
    - Improve production reliability and tube lifetime
    - Qualify new independent MCP biasing scheme
    - Improve photocathode uniformity and quantum efficiency

Looking to have more tubes, small & large, into HEP community in near future

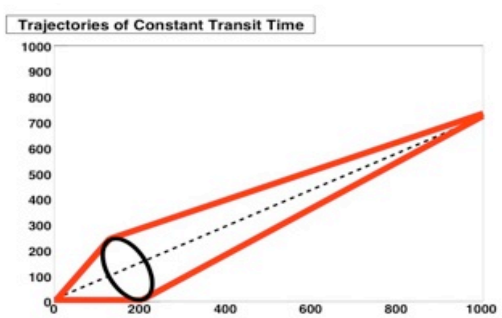
Backup Slides

Applications - Optical Time Projection Chamber
Atmospheric Neutrino Neutron Interaction Experiment (ANNIE)

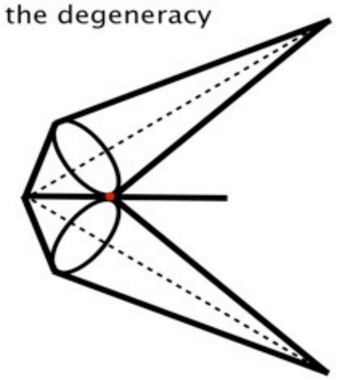
Signal: 20 photons/mm Cherenkov
Drift time: 225 m/μs
Track trajectory -> drift distances

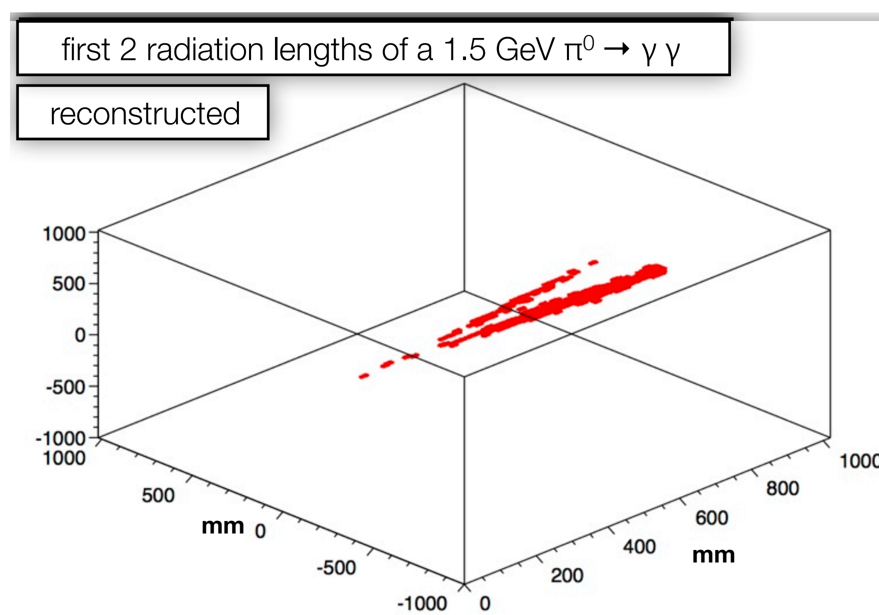


For a single PMT, there is a rotational degeneracy (many solutions).



But, multiple hits from the same track will intersect maximally around their common emission point, resolving the degeneracy





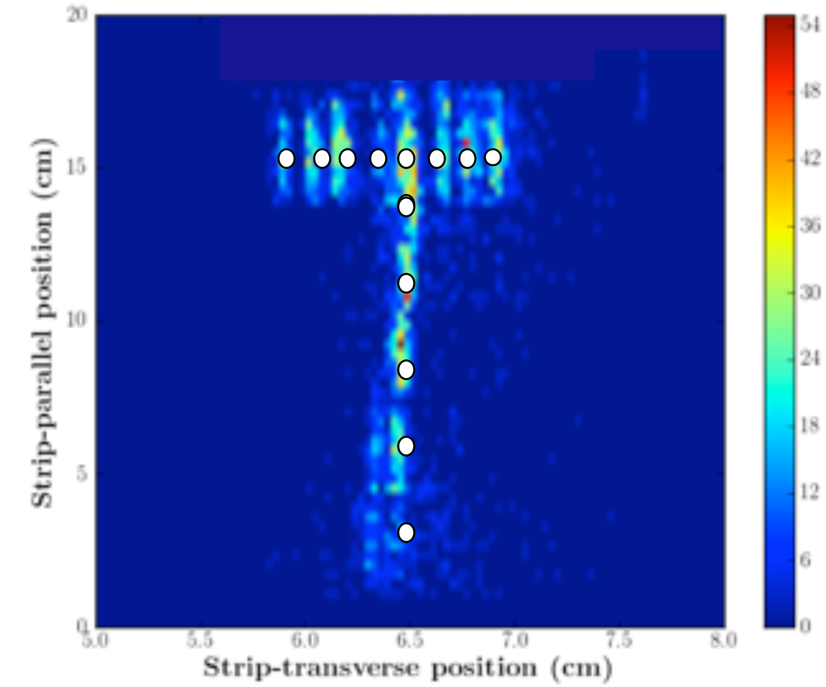
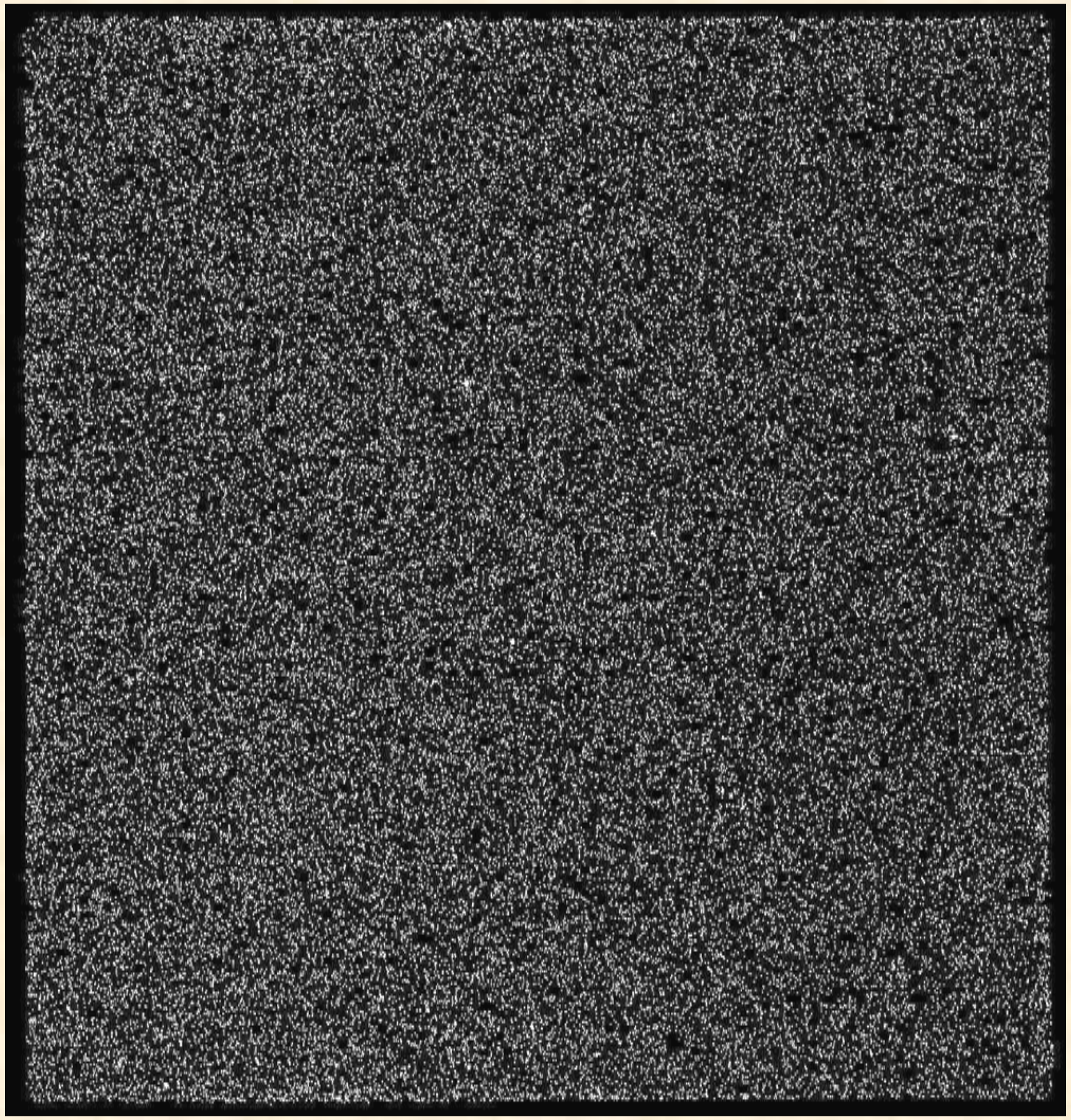


Image from UV laser scan on 20cm LAPPD MCP Detector: n.b. o-ring sealed, continuously pumped prototype

graphic credit: Matt Wetstein

Background 20cm x 20cm 20µm pore MCP Pair

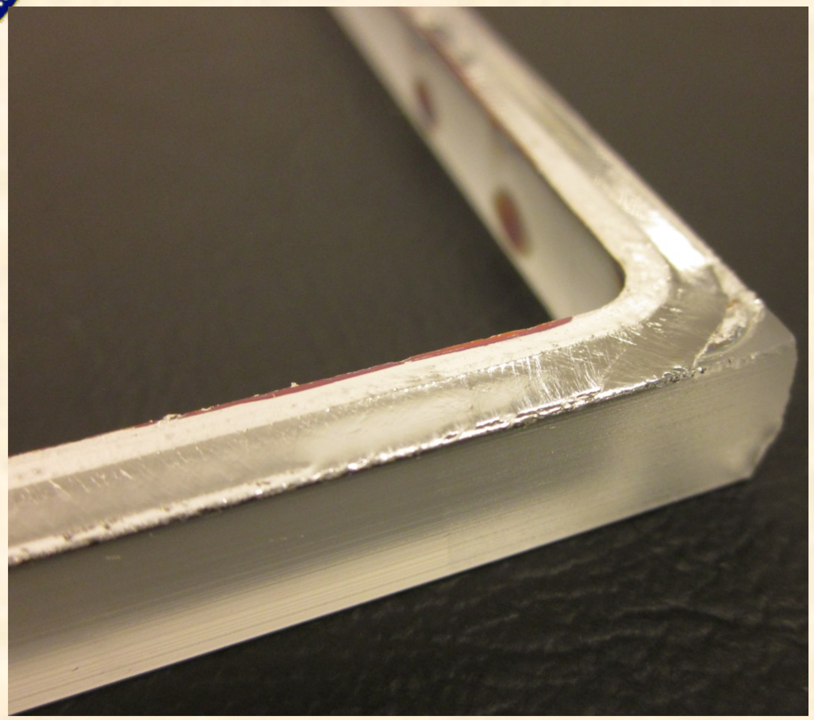


20cm MCP pair background, 2000 sec, 0.055 cnts sec^{-1} cm^{-2}. 2k x 2k pixel imaging.

- 20µm pore, 60:1 L/d ALD-MCP pair, 0.7mm gap/200v.
- Background very low !! 0.068 cnts sec^{-1} cm^{-2} is a factor of 4 lower than normal glass MCPs.
- This is a consistent observation for all MCPs with this substrate material and relates to the low intrinsic radioactivity of the glass.
- Without lead content the cross section for high energy events is also lower than standard glasses.
- There are issues with hotspots on some substrates, however this can be addressed

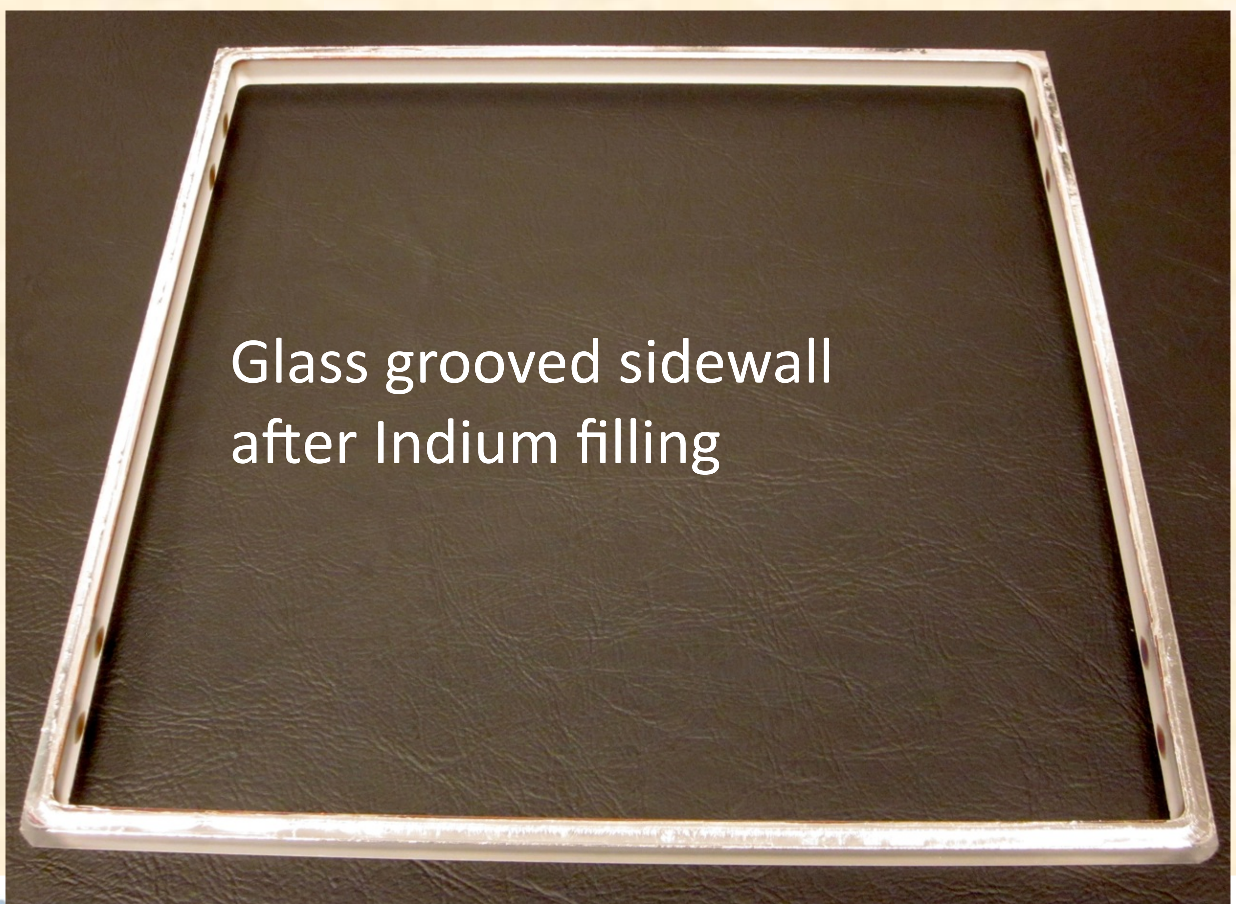
Slide courtesy of Ossy Siegmund, SSL

Glass Grooved Sidewall 8in Indium Seal.

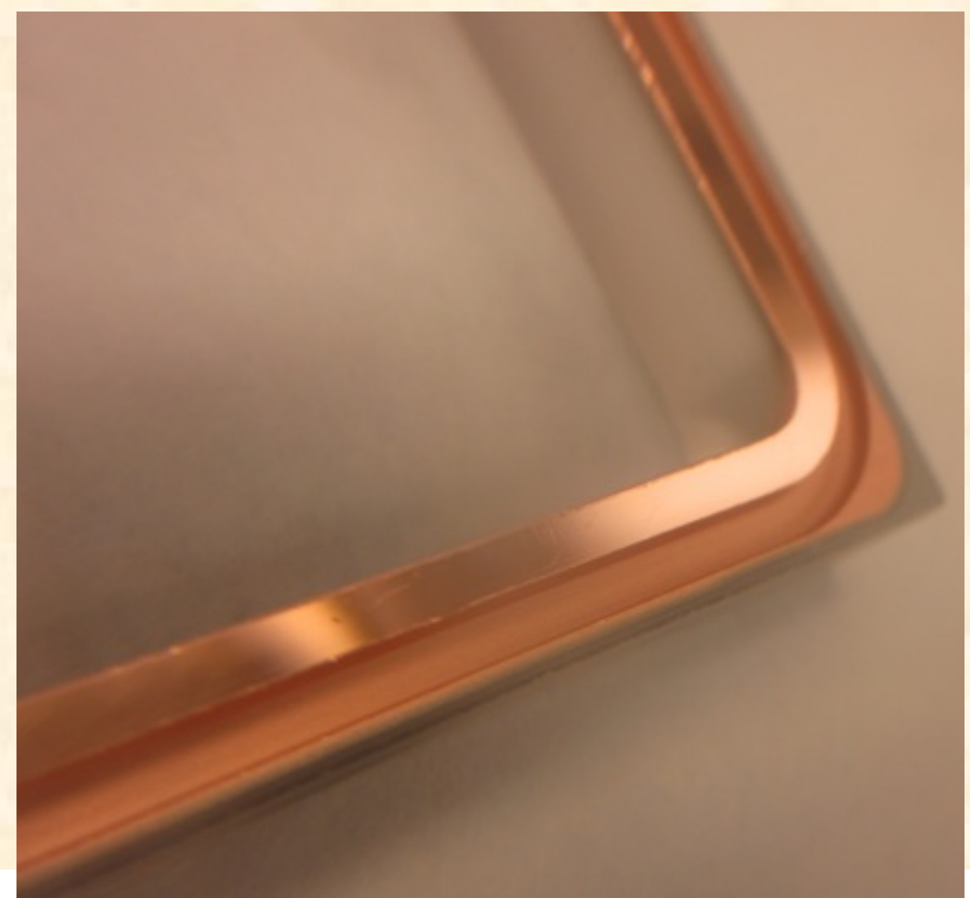


Glass grooved sidewall
after Indium filling

Indium filled grooved sidewall was electroded and vacuum baked, then was used to seal to an 8” window in the vacuum process tank after going through all the processes to simulate a real tube seal.

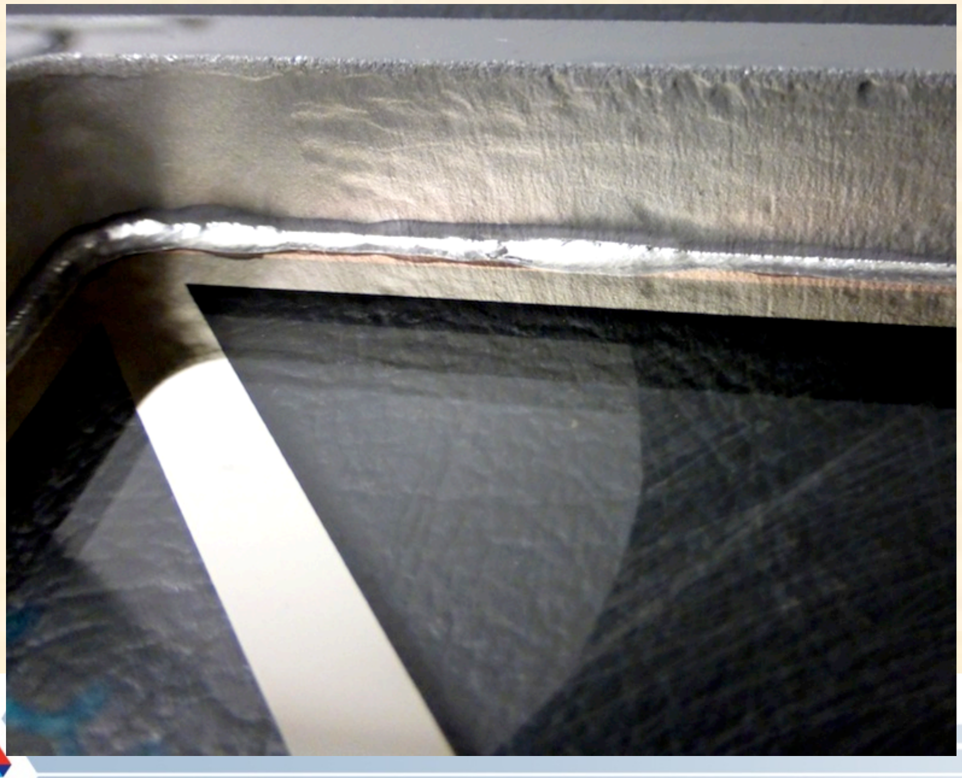


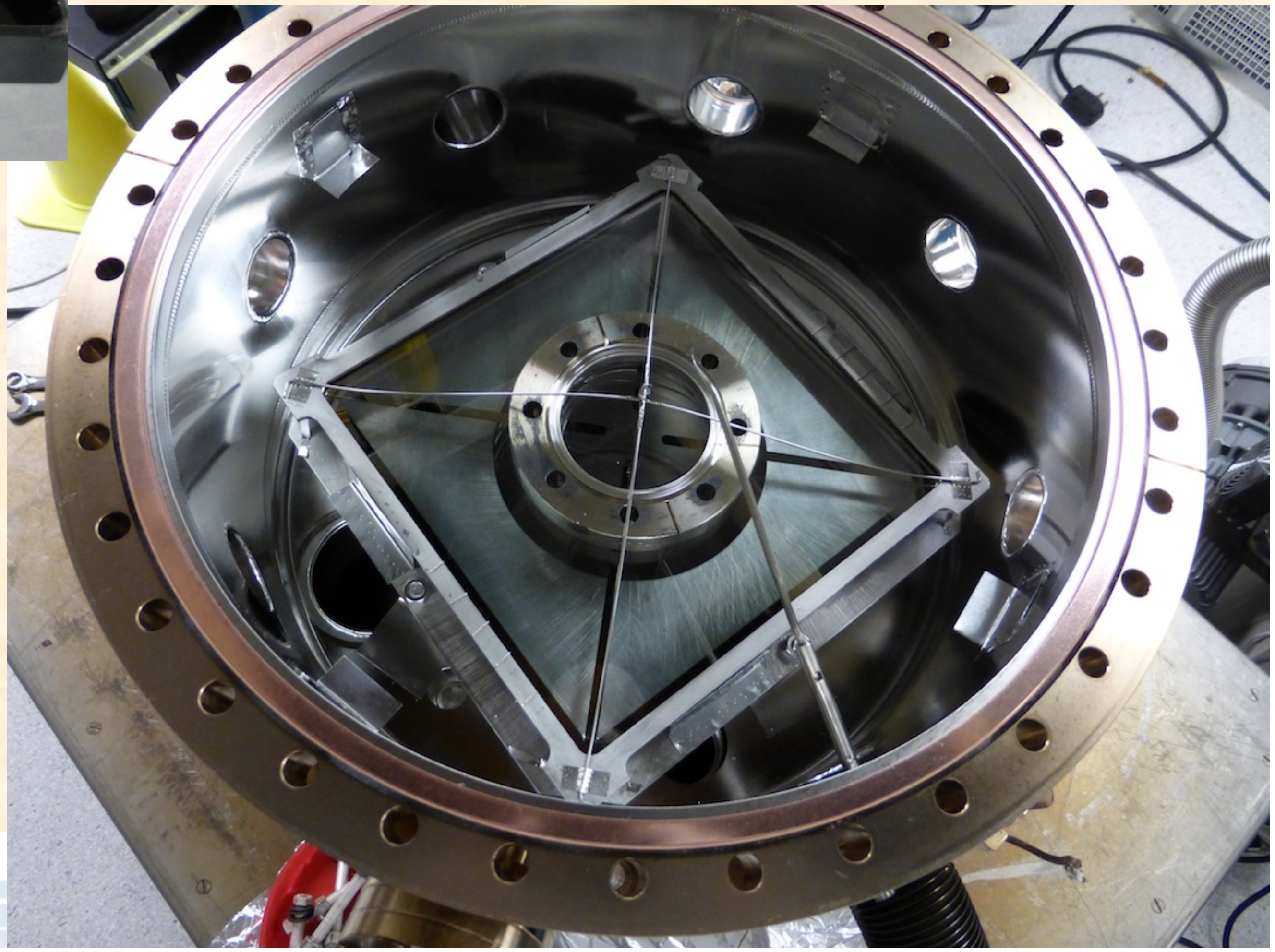
Glass grooved sidewall after NiCr
and Cu evaporations



Glass Grooved Sidewall Seal Test

Used the same processes developed for the ceramic sidewall to do the seal test on the glass grooved sidewall. Weight was used on the window to accommodate stress relief and guides were used to establish seal positioning. Final alignment was better than 0.5mm



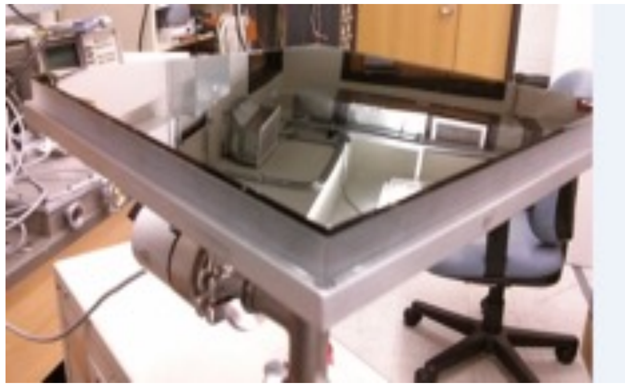
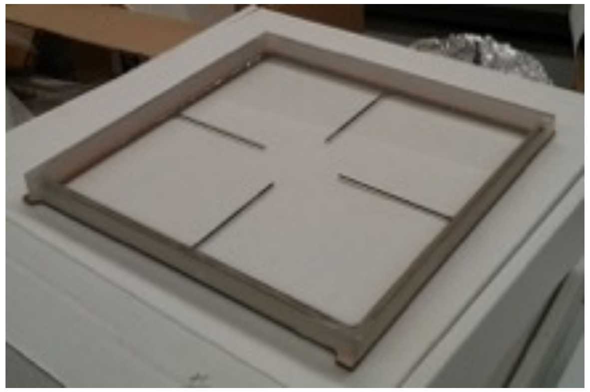
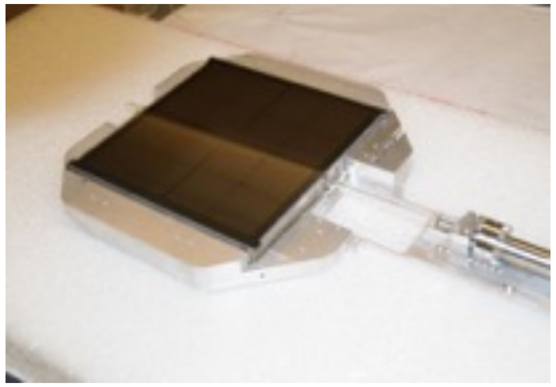


Graphic courtesy of Ossy Siegmund, SSL

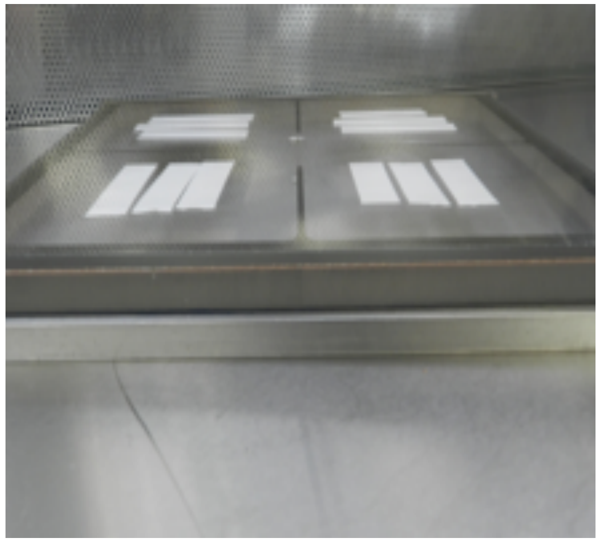
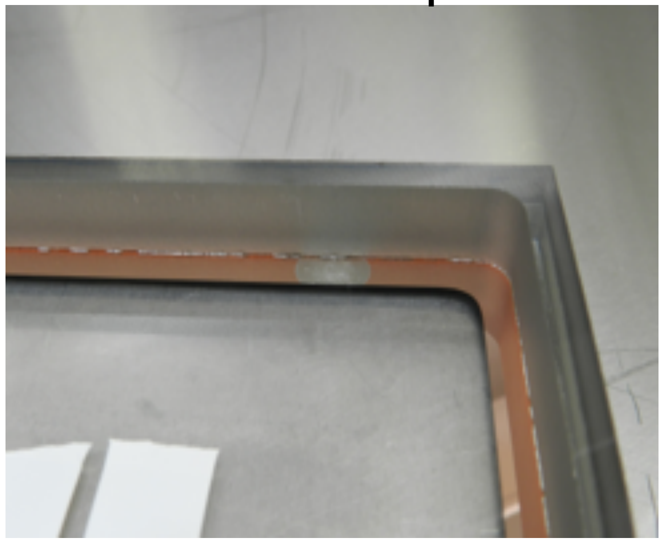
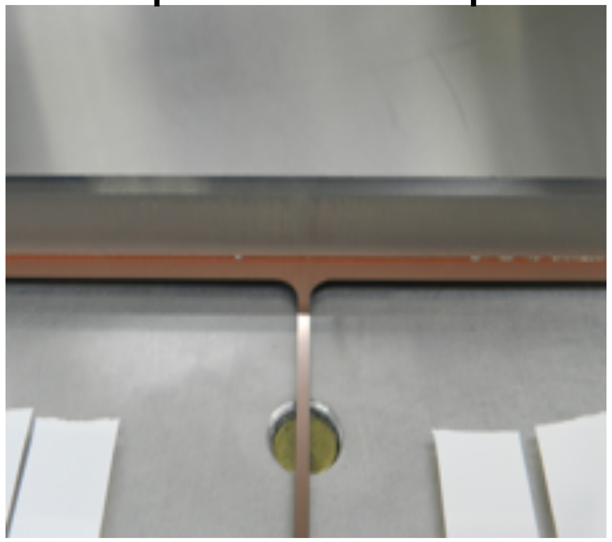
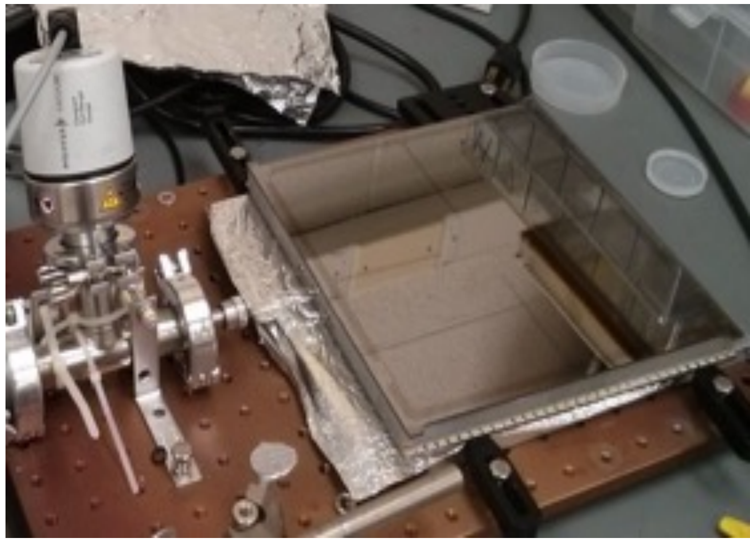
In Situ LAPPD Assembly at U. Chicago
Critical Component #1: Top Window Seal

Developed two techniques for solder seal between flat glass surfaces

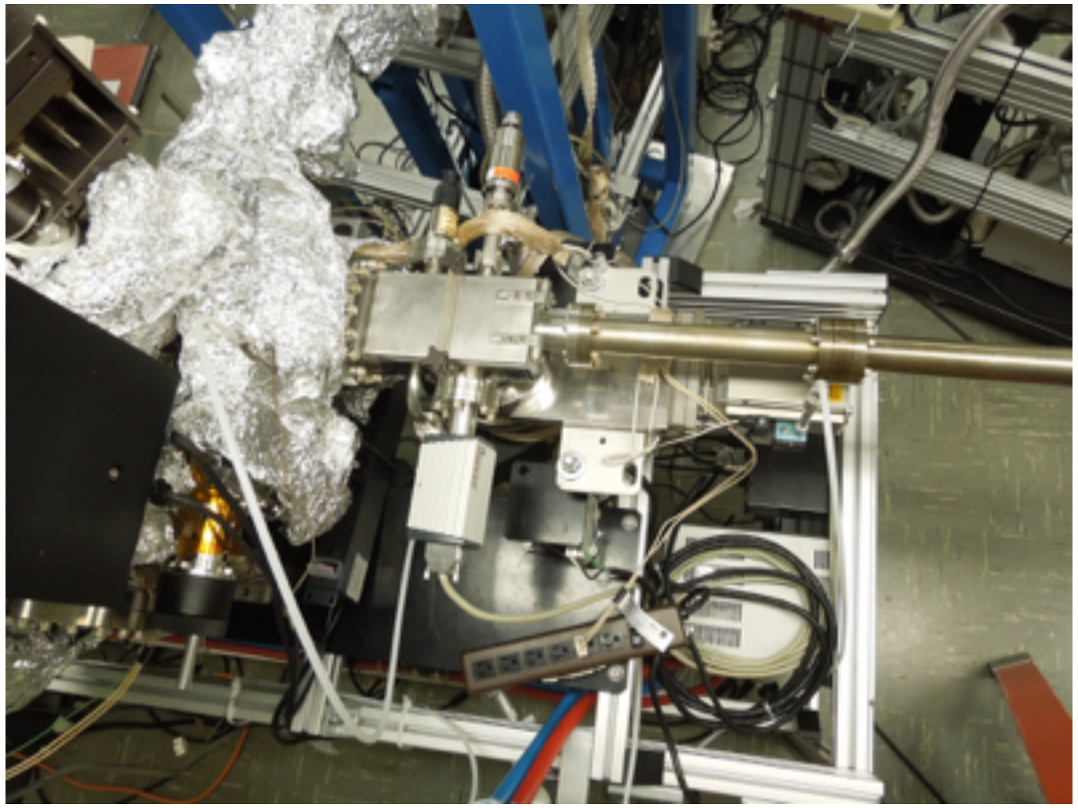
I) InBi alloy solder seal in inert atmosphere (N_2 filled glove box)
- low temperature seal (~73°C)

II) Pure indium solder seal (~157°C) in vacuum
- high temperature seal (350°C), done in the processing chamber during the bake
- better suited for Cs/K photocathode deposition temperature

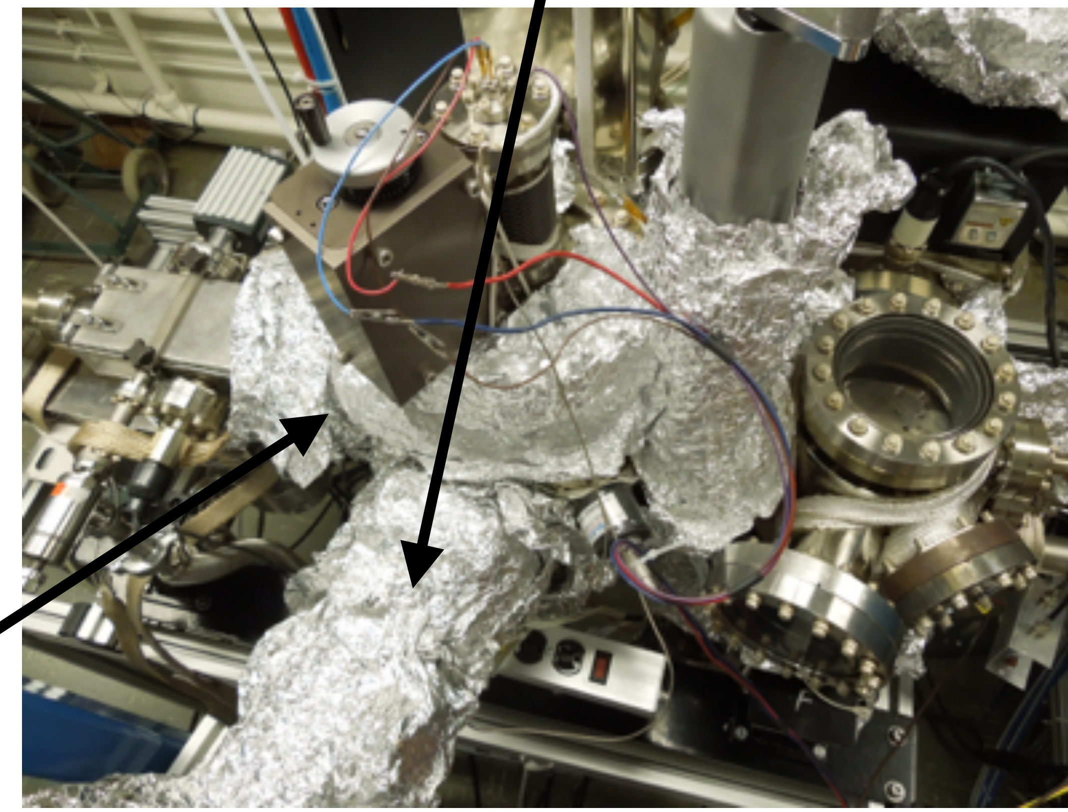
SmSTPS Chambers

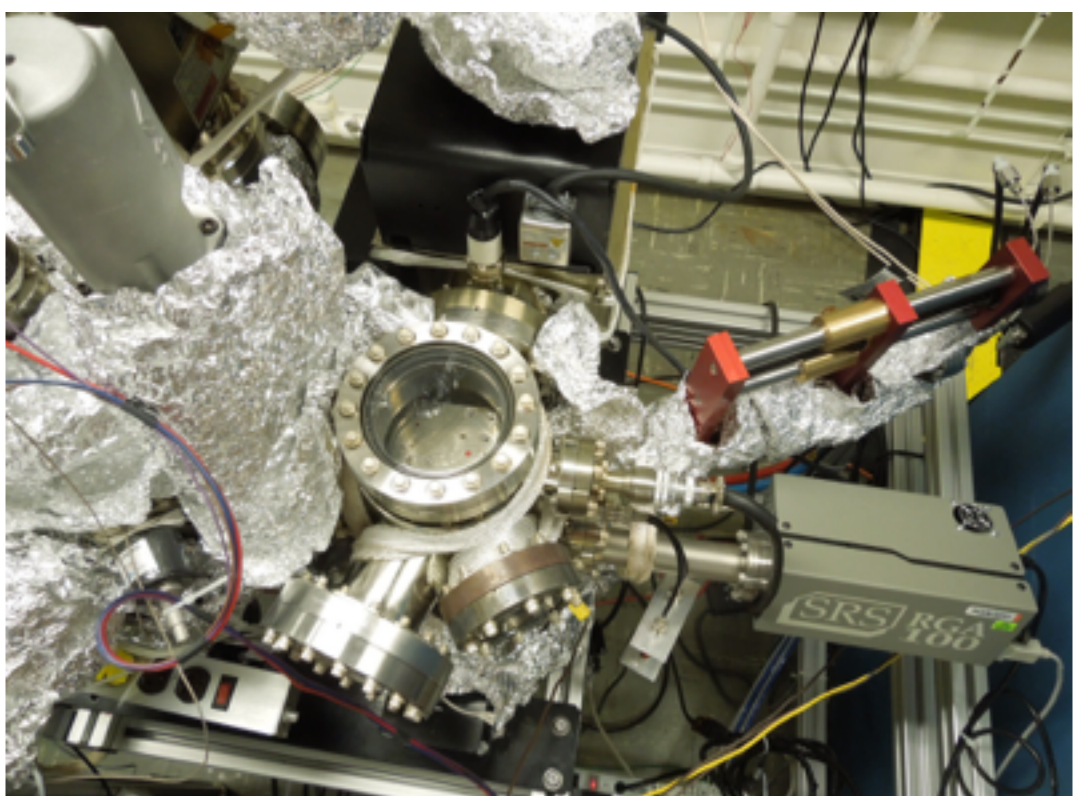


Loadlock

Connection to Sealing Chamber

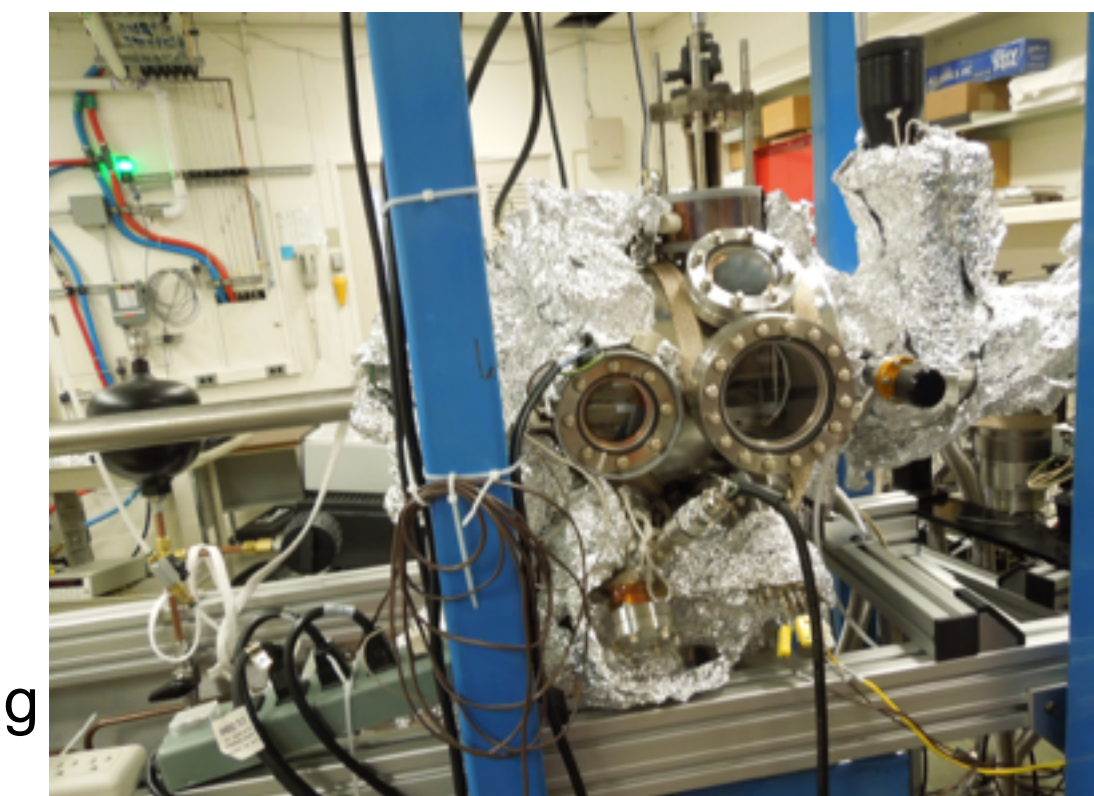
Bake &
Scrub





Deposition

Sealing



Example of 20cm Resistance Uniformity

Dice 20cm x 20cm plate for 6cm x 6cm MCPs

Resistance shows good uniformity across plate

R=47MΩ	R=53MΩ	R=41MΩ
R=48MΩ	R=57MΩ	R=41MΩ
R=42MΩ	R=45MΩ	R=39MΩ

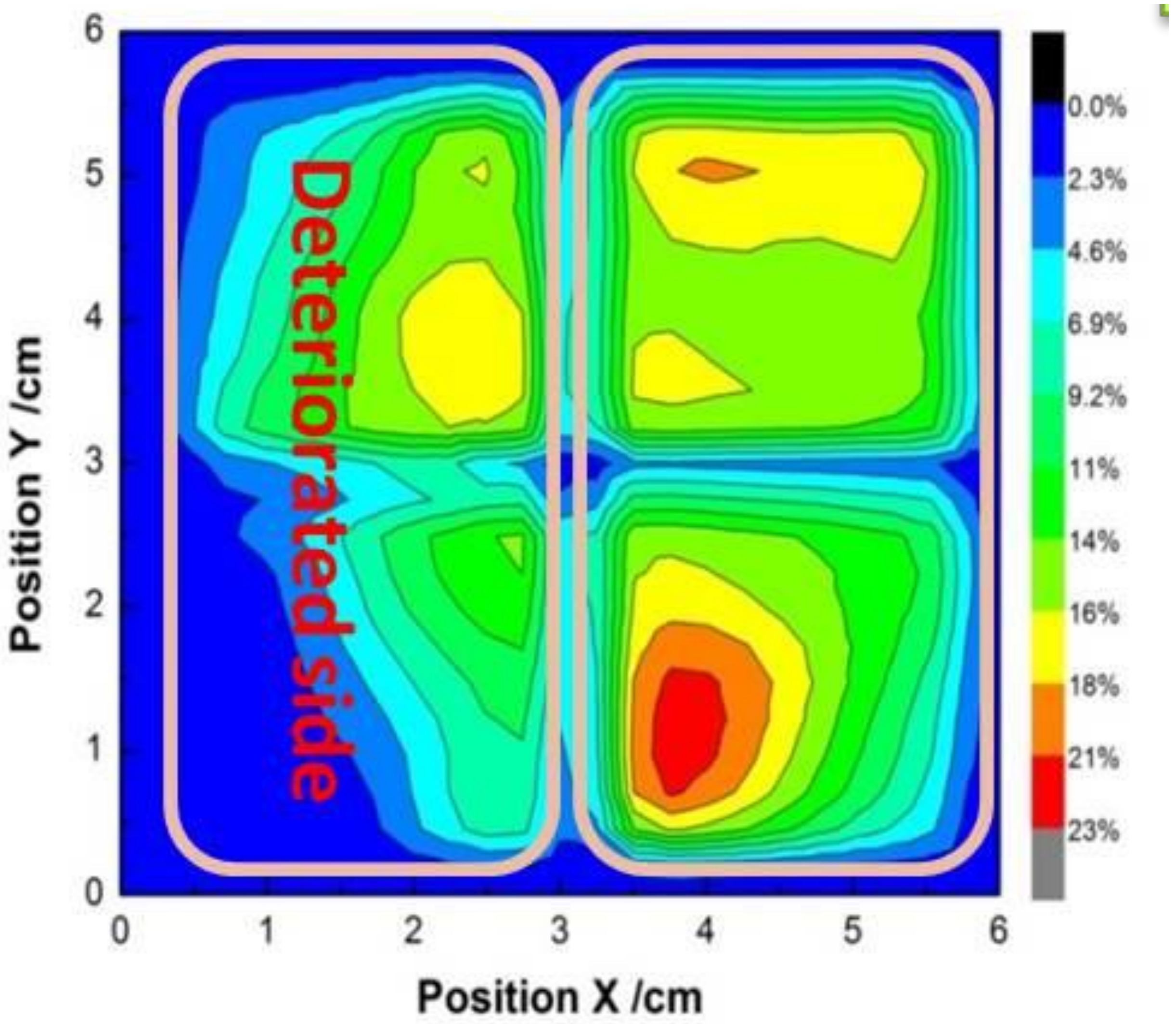
1x(8”x8”) MCP= 9x ($6x6cm^2$) MCPs

Example of 6cm Photocathode with 22% QE Region

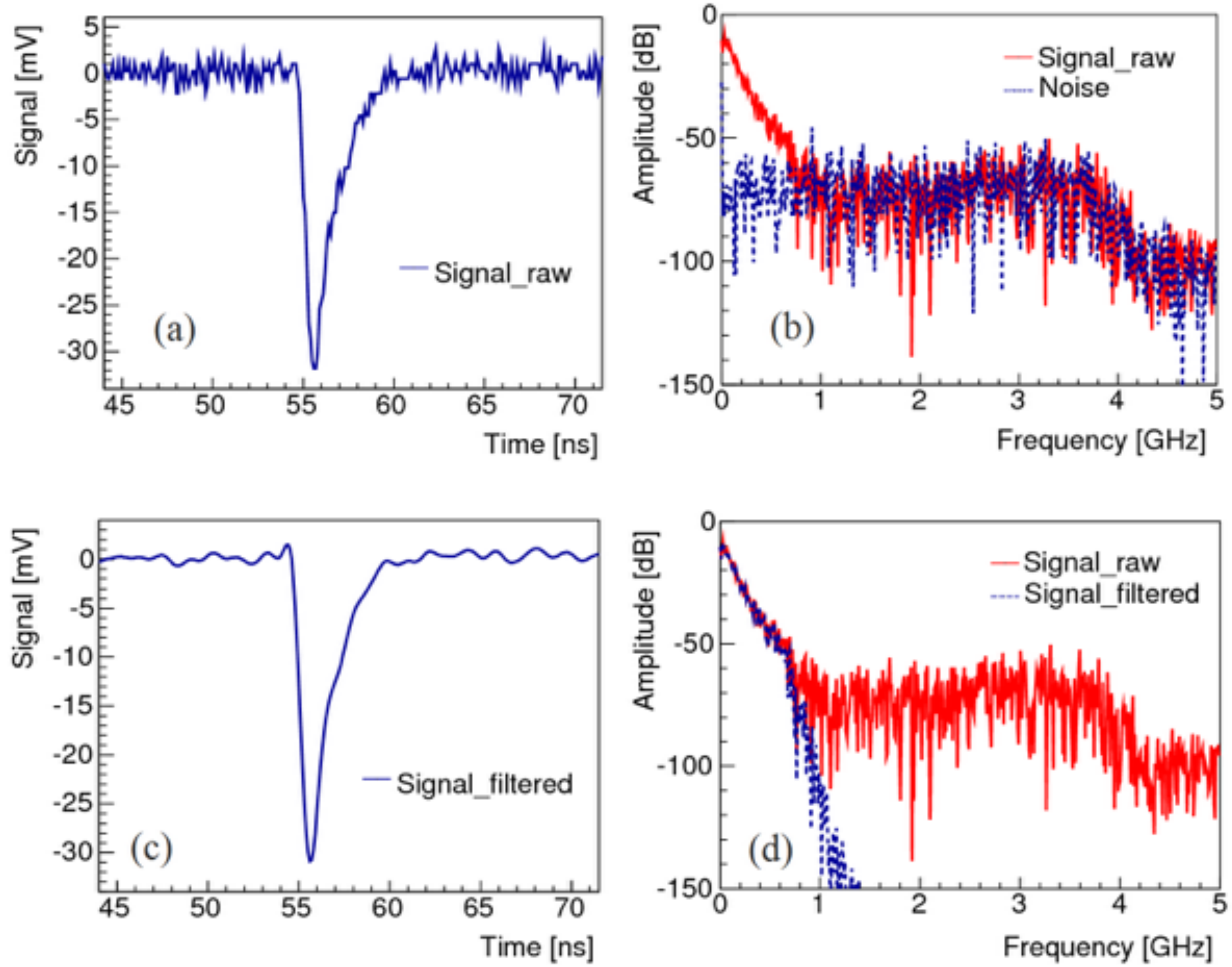
Prototype IBD-1 tube allowing direct QE measure

Average QE ~ 15%, Max ~23%

Cathode deteriorated due to small leak in bottom frit seal



Noise Removal from MCP Laser Signal for 6cm Characterization



Butterworth noise filter applied to improve signal shape for timing

6cm MCP-PMT Position Resolution Improvment at Higher Incident Number of Photons