Argonne NATIONAL LABORATORY

Status & Perspectives of Large-Size MCPs

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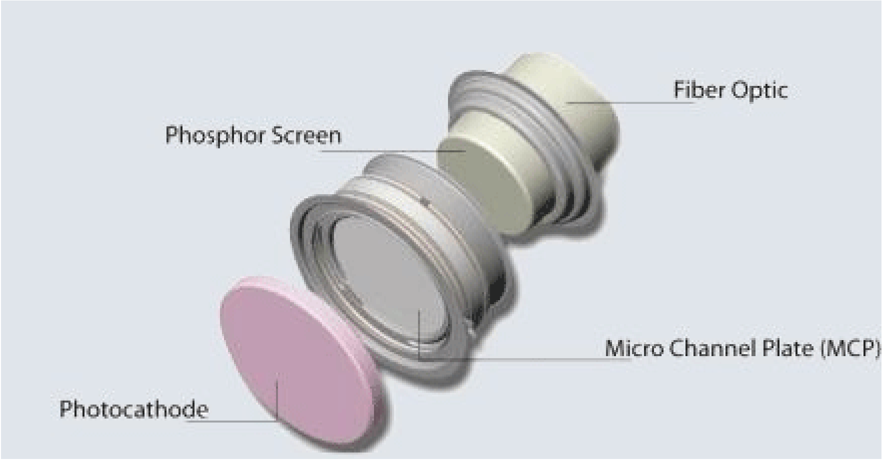
for the Argonne MCP Photodetector Group

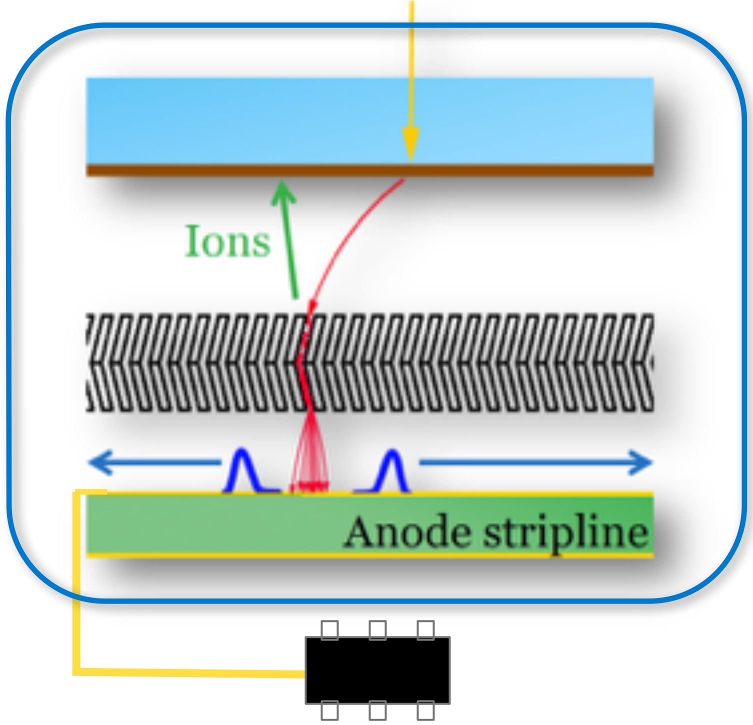
4th Conference on Micro-Pattern Gas Detectors
Trieste
13 October 2015

U.S. DEPARTMENT OF ENERGY

Microchannel Plates (MCPs): Electron Multiplication for Diverse Applications



Typical pore size 6-40μm

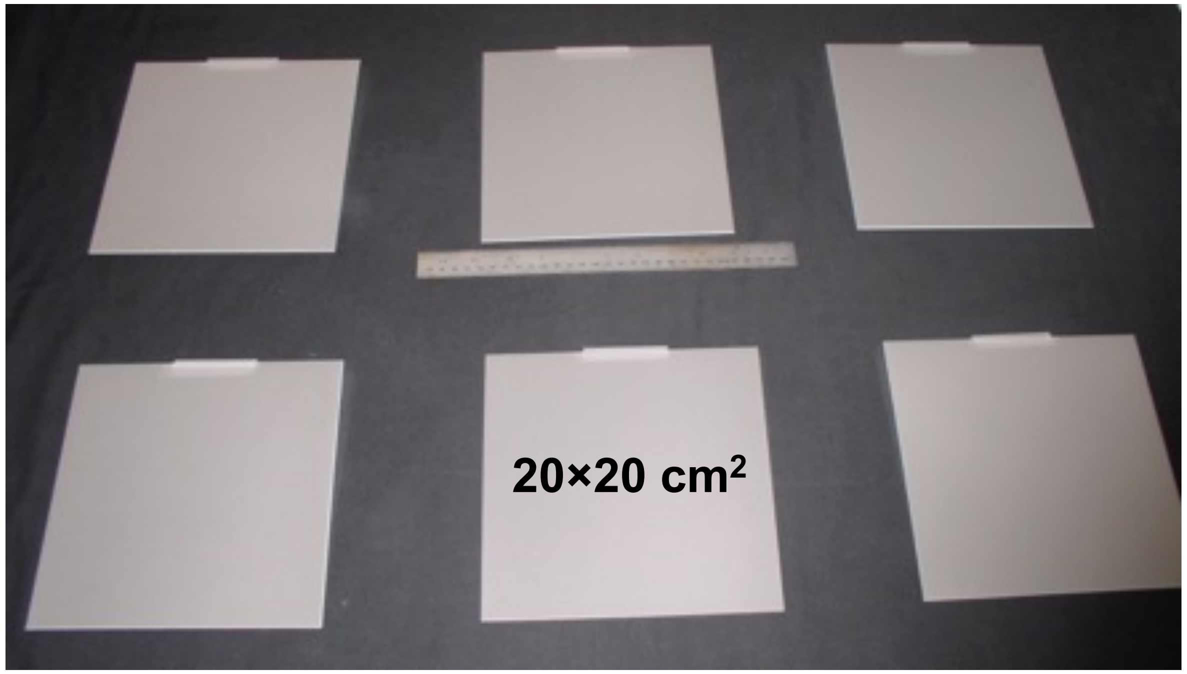


- Largest market
  - Night vision
  - Image intensification
- Particle & Nuclear Physics Applications
  - Precision timing
  - Fine spatial resolution imaging
  - Bare use of MCPs for accelerator beam positioning, mass spec., electron microscopy
- Advantages
  - High gain, single photon/photoelectron sensitivity
  - Compact structure, ability to pack for dense coverage
  - Position resolution; pore-size limit for anode geometry
  - Good magnetic field performance
- Like anything else, not all advantage
  - High cost
  - Fragile, high physisorption (can cause fracture)
  - Limited size areas

Large Area Picosecond Photodetector Collaboration

Focus of Development: Address limitations of commercial MCPs

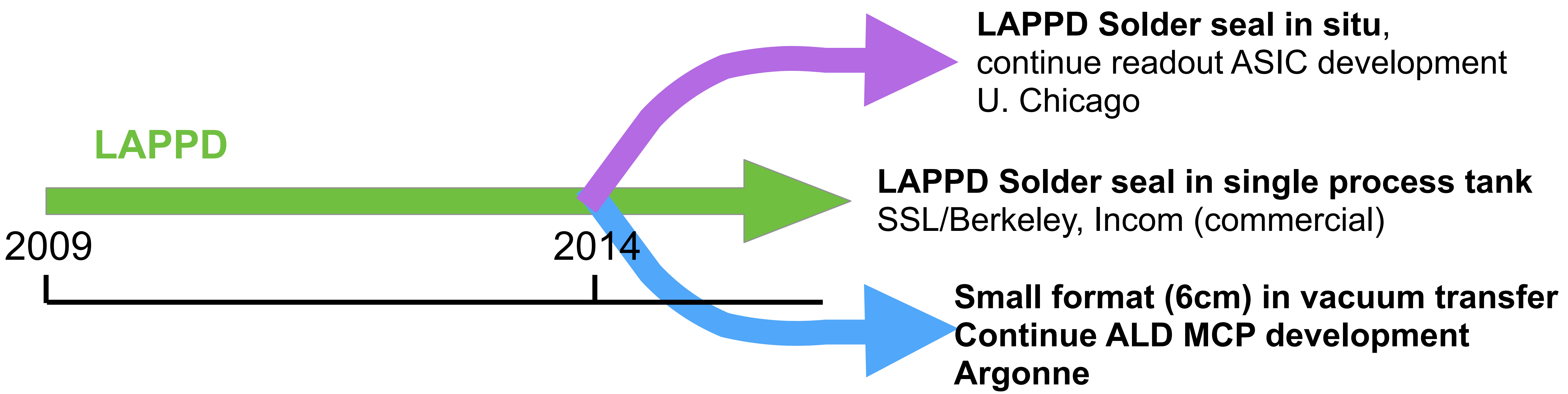
- Eliminate constraints of common material (lead glass) for substrate, resistive and emission layers
- Transformation in size
- Reduce production cost
- Incorporate improved MCP into large area photodetector



- **Microchannel Plates:**
  - Block fabrication using hollow core drawn capillary tubes
  - Use lower cost borosilicate glass: ~80×10^6 20µm pores in 20cm×20cm capillary array
  - 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:** (Has proved to be most challenging part)
  - Standard ceramic package w/InBi hot seal & HV/signal pins feedthrough — SSL/UC-Berkeley
  - Less expensive borosilicate all-glass package, pressure In seal, **pinless** — Argonne/UChicago

Large Area Picosecond Photodetector Collaboration

- Project initiated in 2009
- 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**
  - ★ Large area Indium alloy solder seal still in development and qualification
  - ★ Thermopressure indium seal is mature process and in production at Argonne in small format devices
- Applications for precision time-of-flight, optical TPC, Cherenkov imaging particle ID Also interest from medical imaging, nuclear security
- Since 2014 Groups have continued development along separate technology paths



Outline for Remainder of Presentation

- Development of Atomic Layer Deposition (ALD) functionalized MCPs
- Status of Large Area (20cm x 20cm) Picosecond Photodetectors (LAPPD)
  - New developments since similar talk at CERN MPGD Workshop June, 2015
- Development of Argonne Small Format 6cm x 6cm MCP-PMT Processing System
  - New results from Independently Biased Design production
- Future Plans

Atomic Layer Deposition MCPs

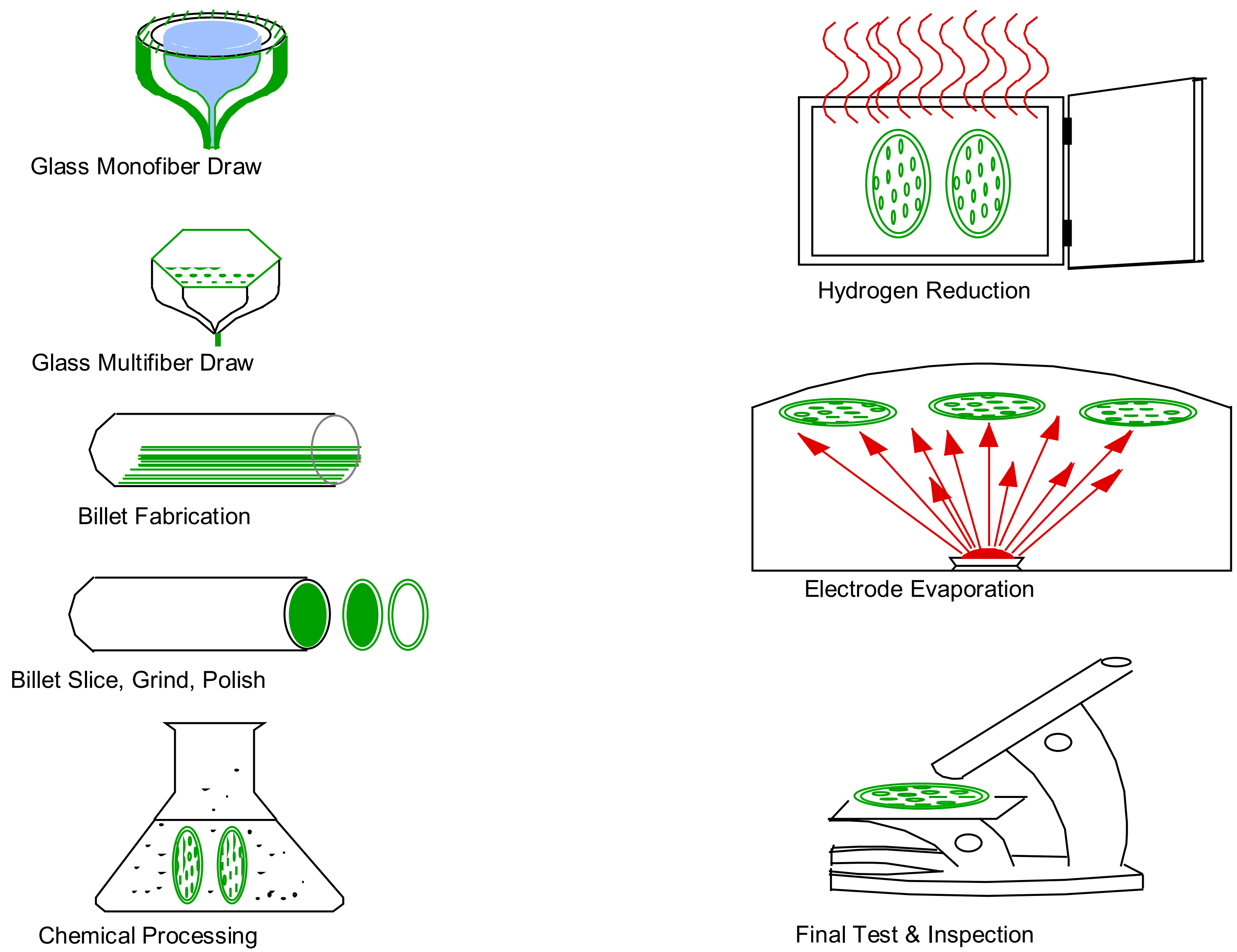
Commercial Microchannel Plate Fabrication

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

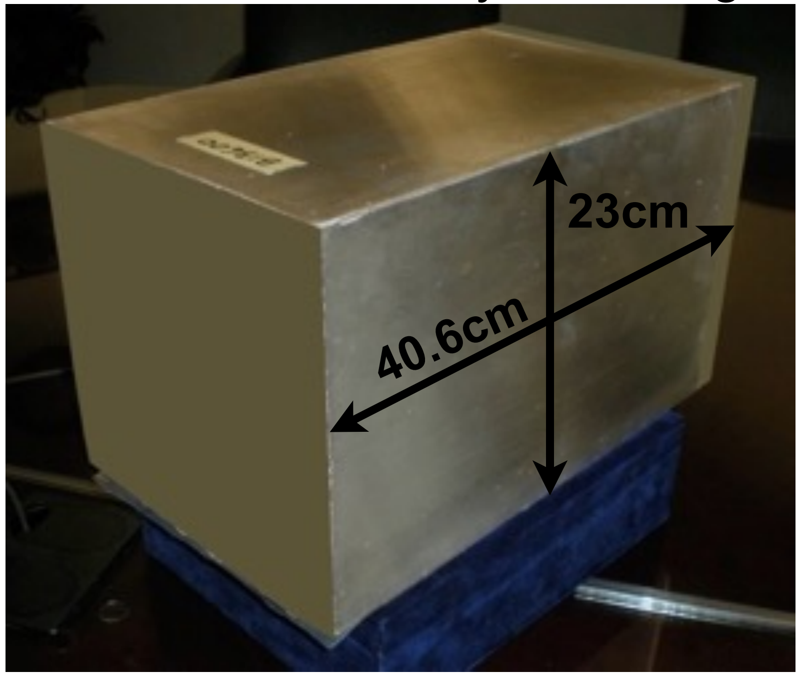
Graphic Credit: B. Laprade & R. Starcher, Burle (2001)

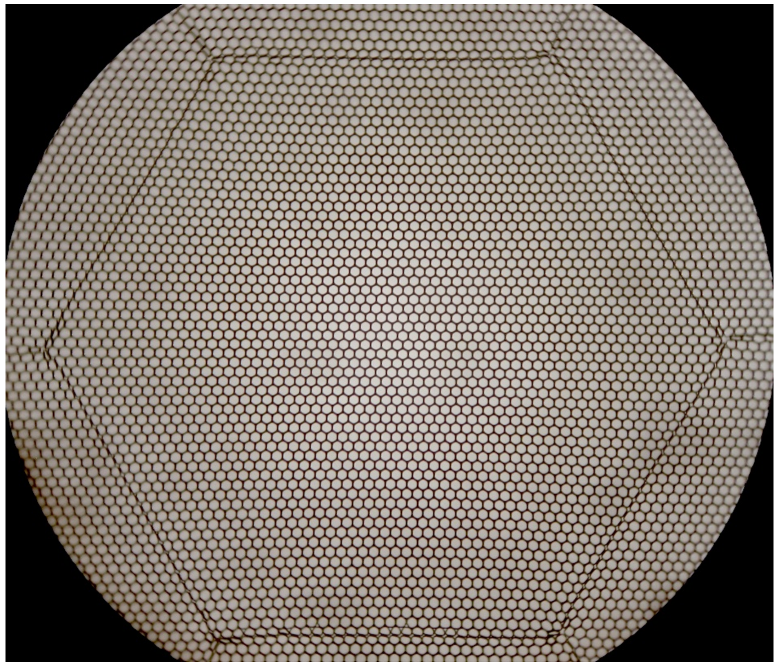


Before sealing in tube, plate must be subjected to prolonged exposure to electrons at low voltage to outgas H_2 and other material

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

Fused block ready for slicing

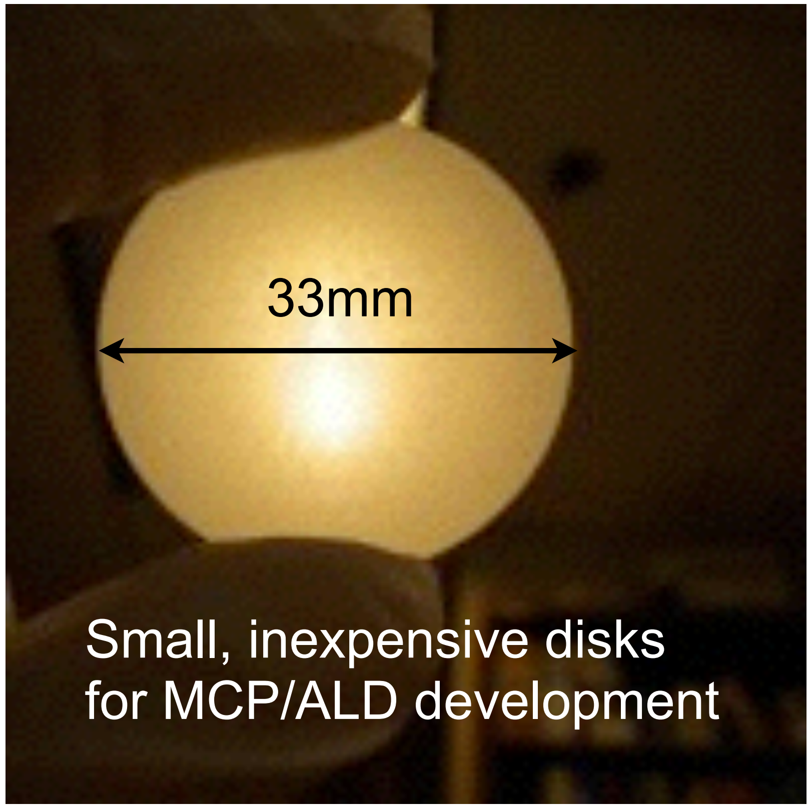




Multifiber bundle in fused block

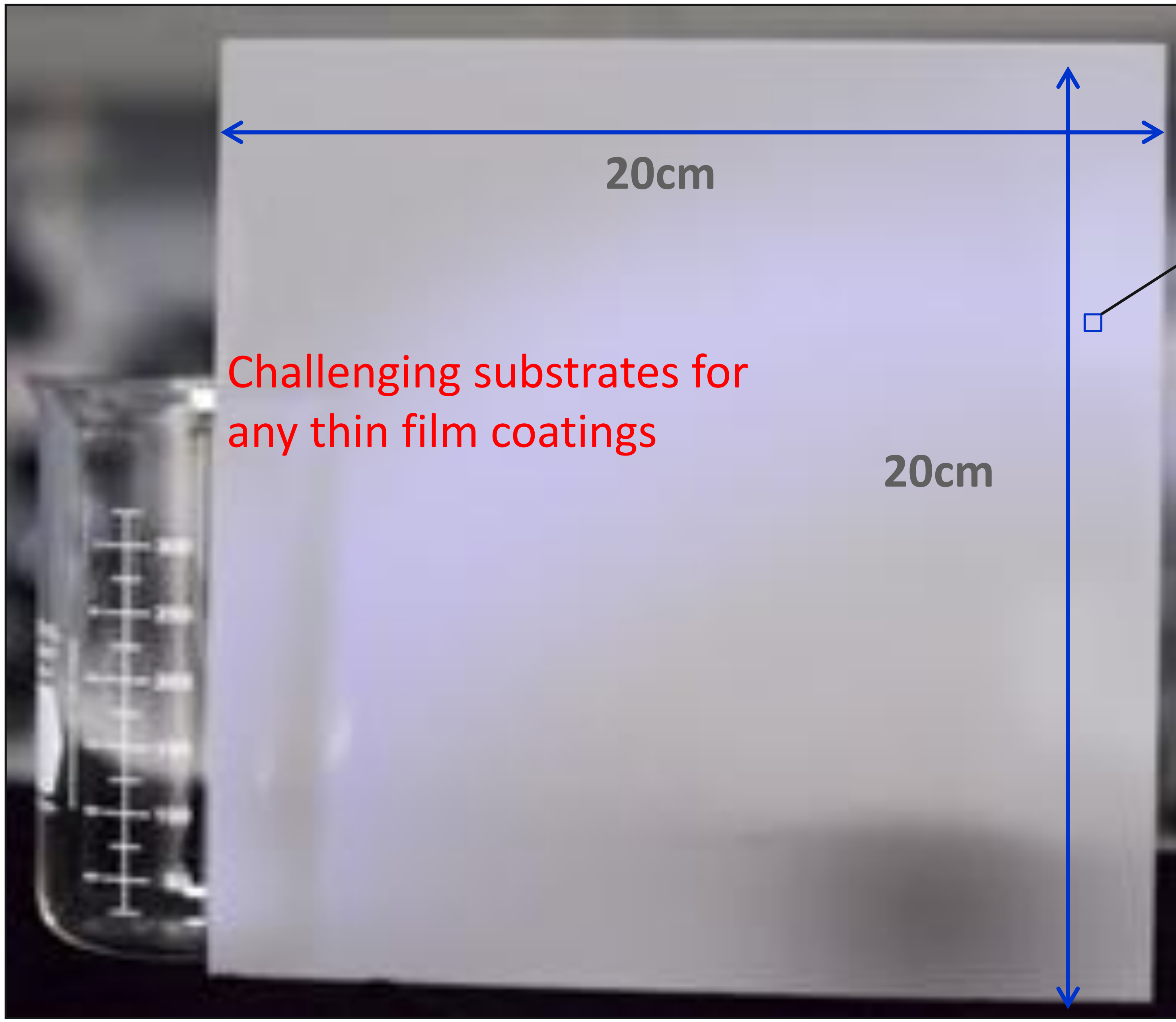
Individual pores visible within "multi"

Some distortion of pores at "multi" boundaries

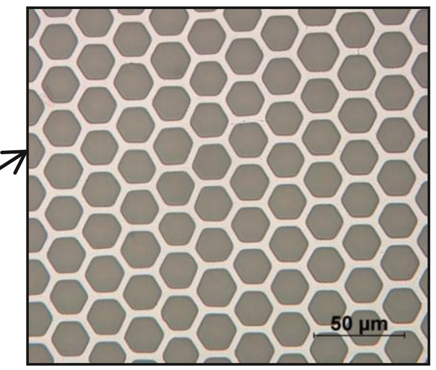


GCA Property	Value
Plate Area	203x203 mm^2
L/D, Thickness	60:1, 1.2mm
Pore Pitch	25µm
Pore Size	20µm
Bias Angle	$8^o \pm 1^o$
Open Area ratio	> 60%
Material	Borofloat 33

Glass Capillary Arrays for MCP Substrates

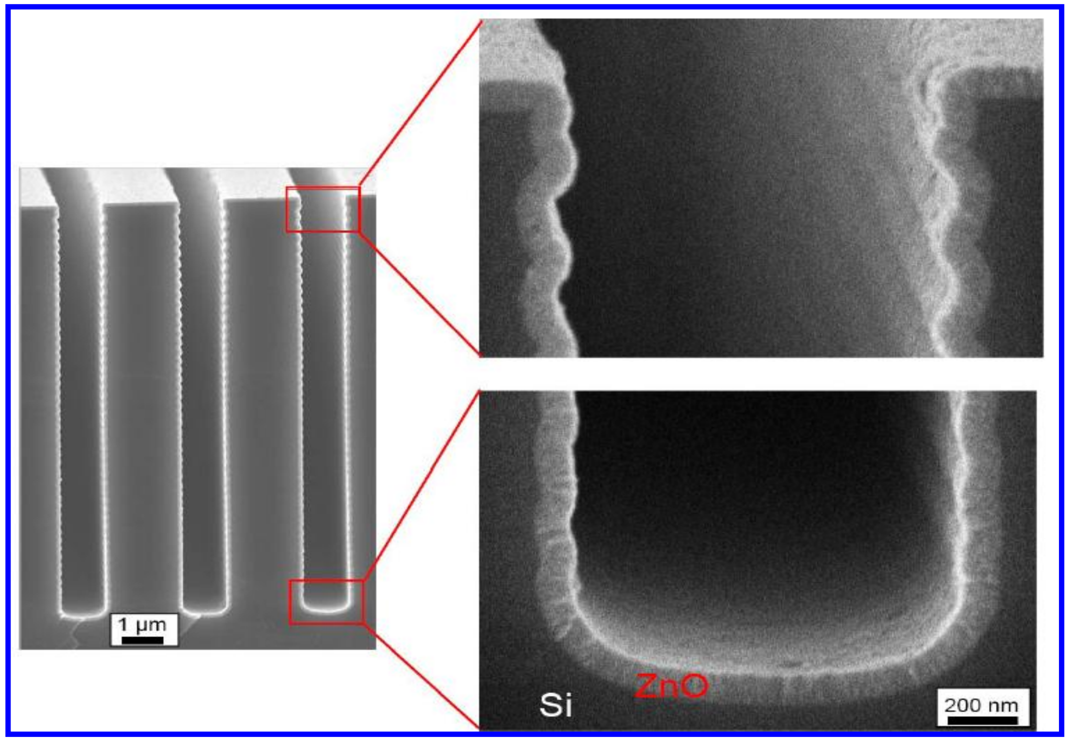


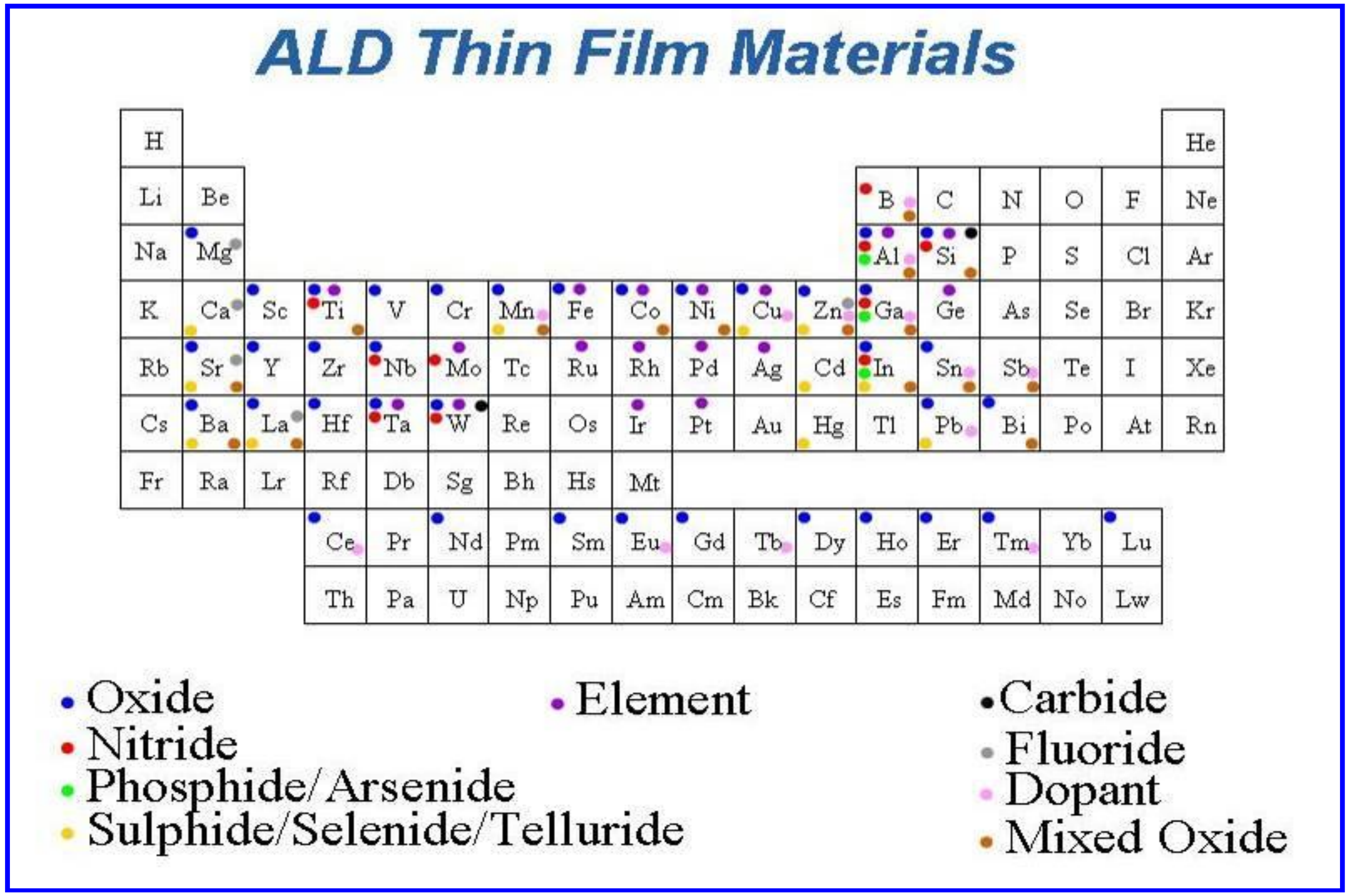
Produced by Incom, Inc



- 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°

Pore Activation via Atomic Layer Deposition



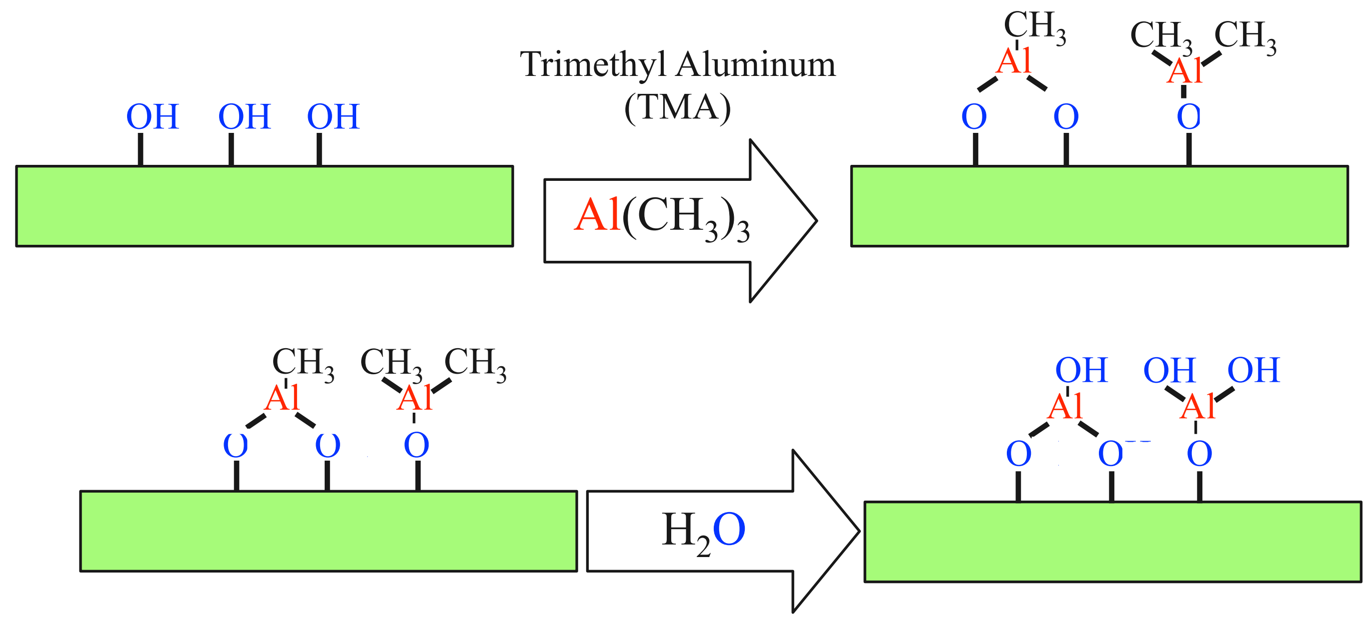


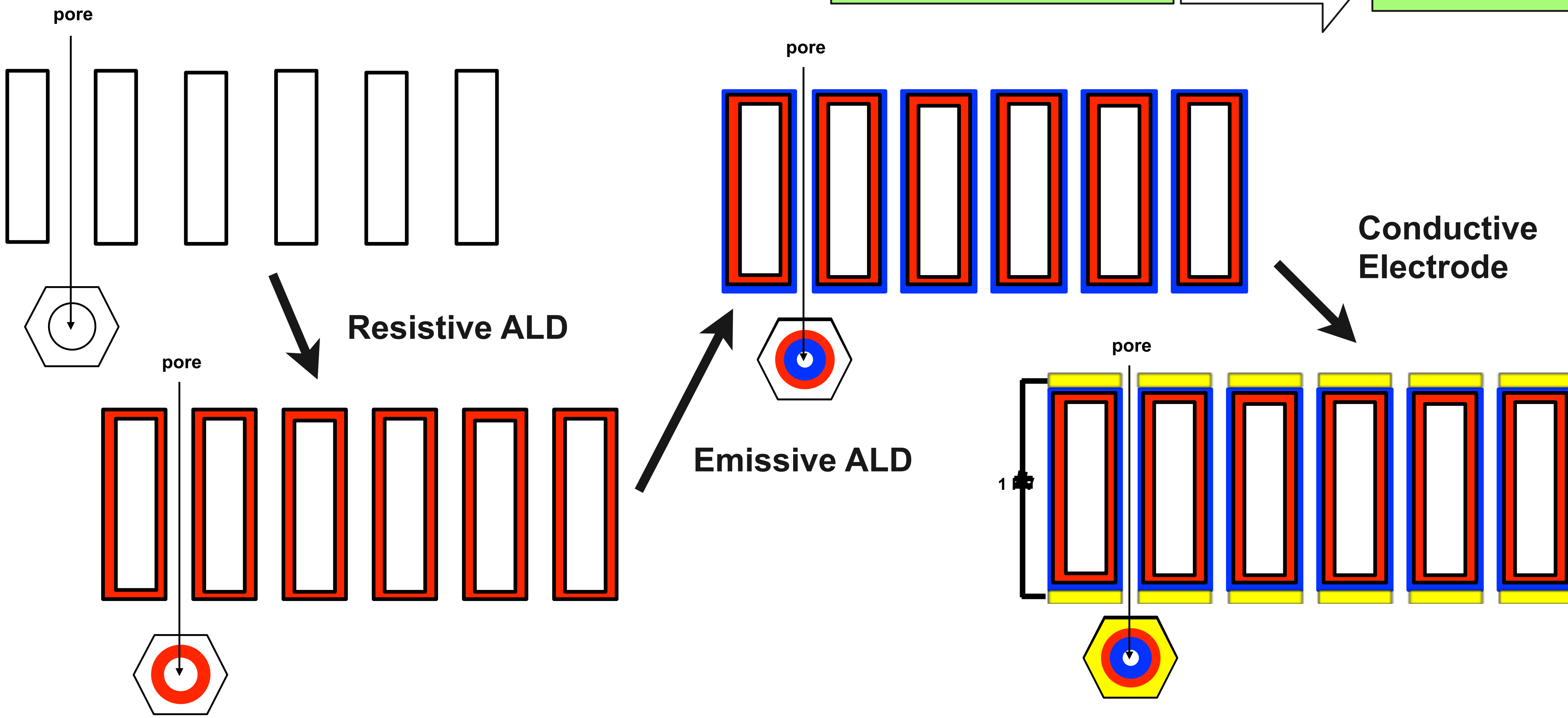
- Conformal, self-limiting process
- Molecular mono-layer thickness control
- Large variety of applicable materials

Pore Activation via Atomic Layer Deposition (ALD)

Example:

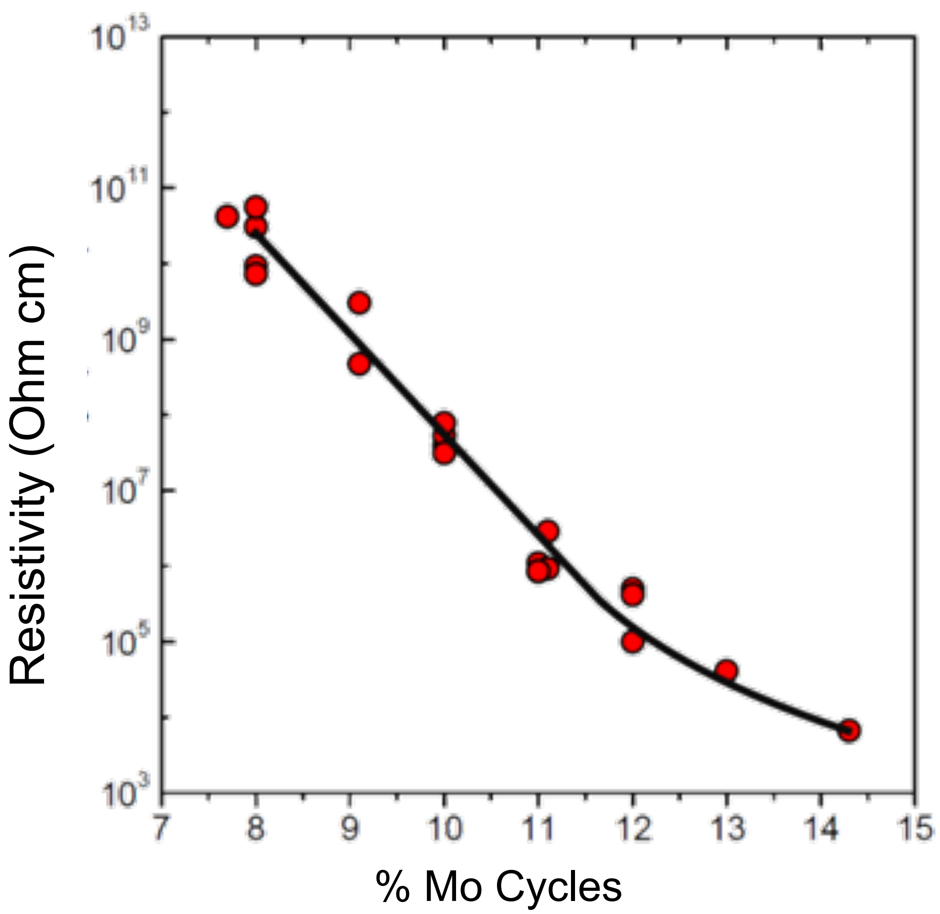
- OH on surface provide reaction sites
- Trimethyl aluminum reacts liberating methane, forms Al_2O_3 layer. Leaves methyl group inhibiting further reaction on surface
- Exposure to H_2O removes methyl group. Leaves OH sites for next reaction



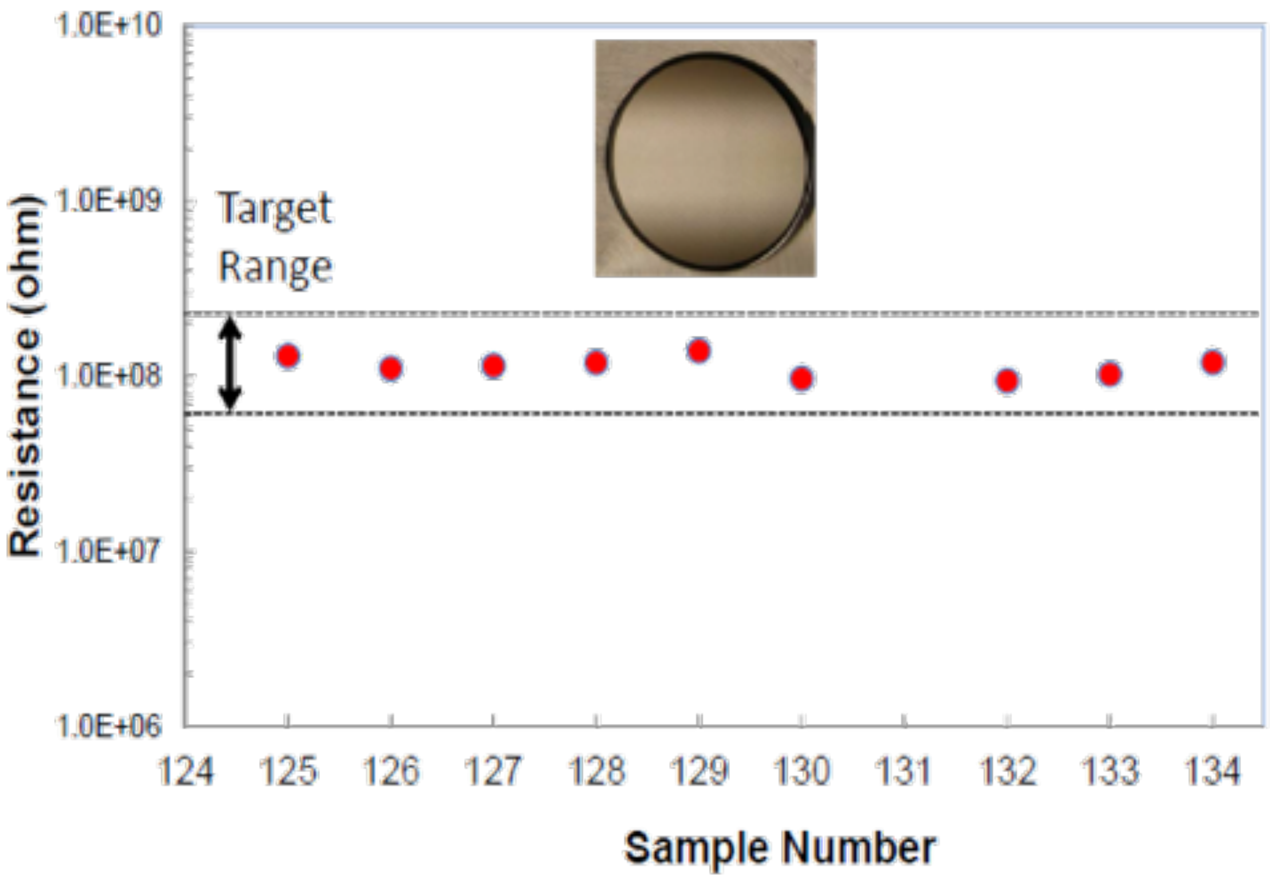


ALD of Metal-Al_2O_3 Composite Films for Resistivity

- 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



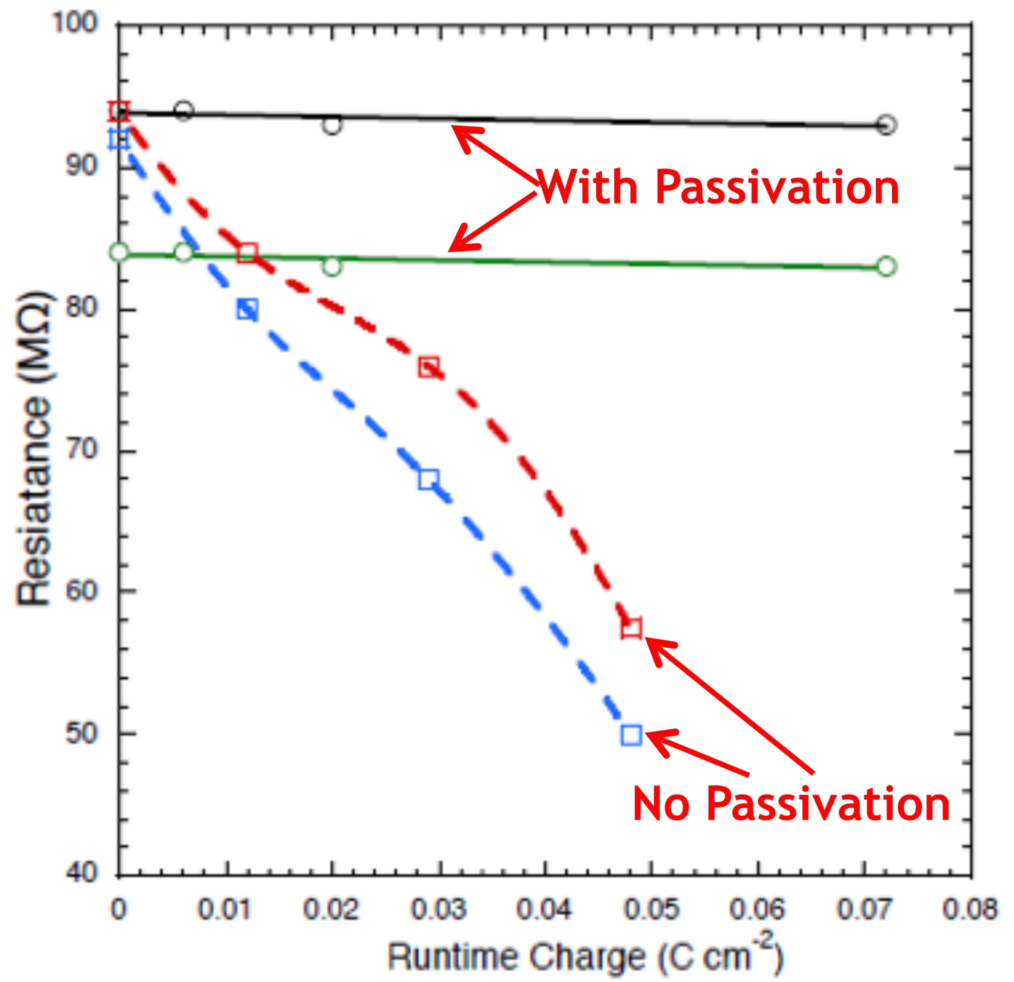
Allows resistance tuning over several orders of magnitude

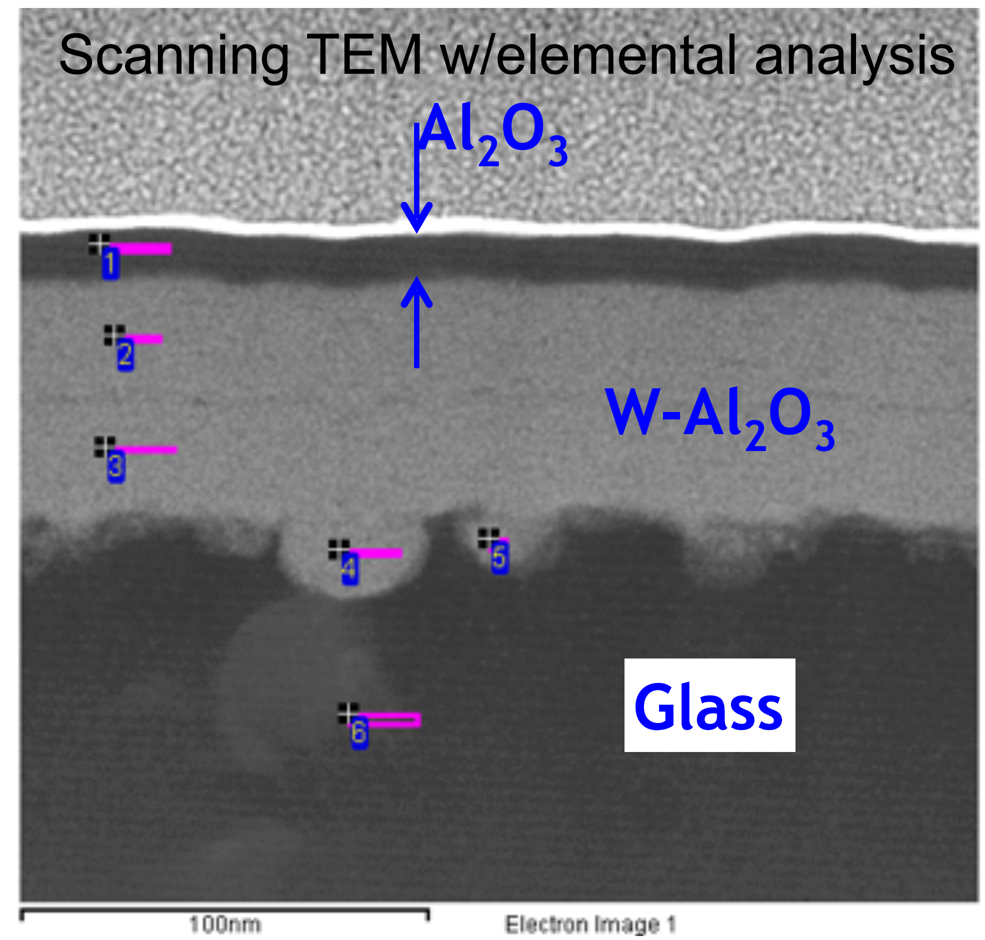


Process is highly reproducible

Resistance Change Prevention with Passivation Layer

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





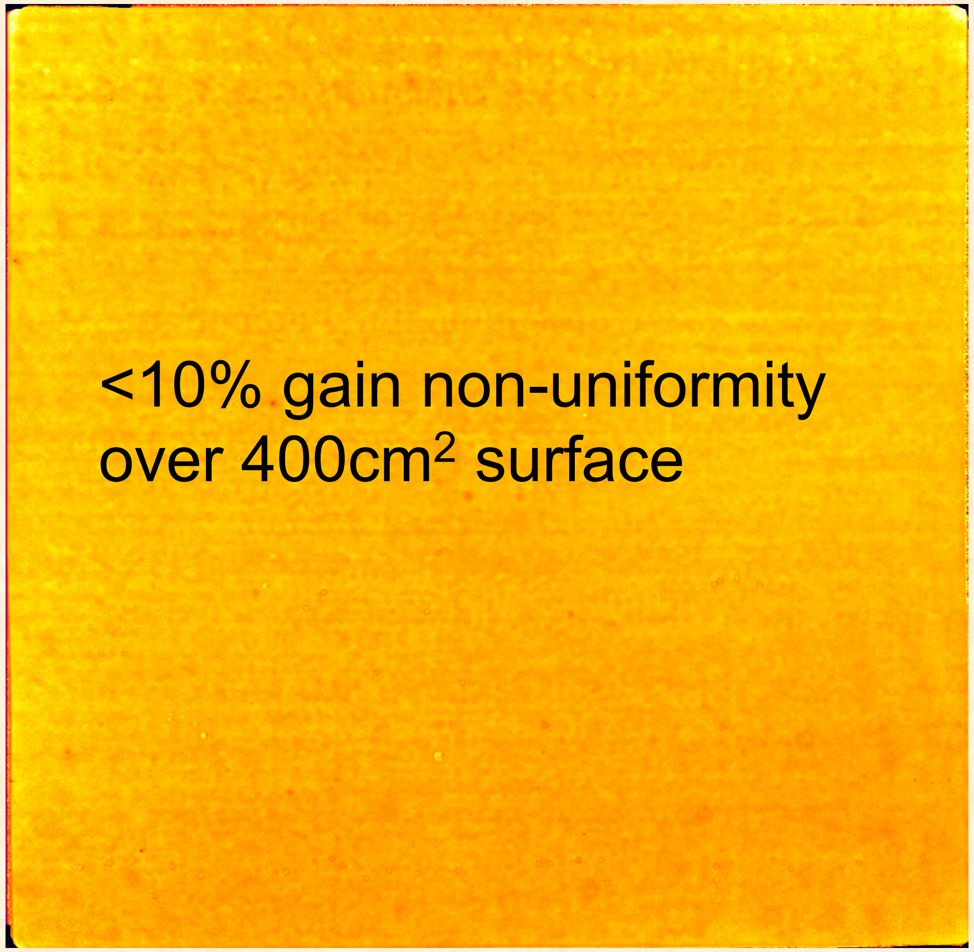
Spectrum	In stats.	O	F	Na	Al	Si	W
2	Yes	56.3	11.8	6.2	18.4		7.3
3	Yes	52.8	11.4	6.7	20.9		8.2

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

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

MCP Gain Uniformity

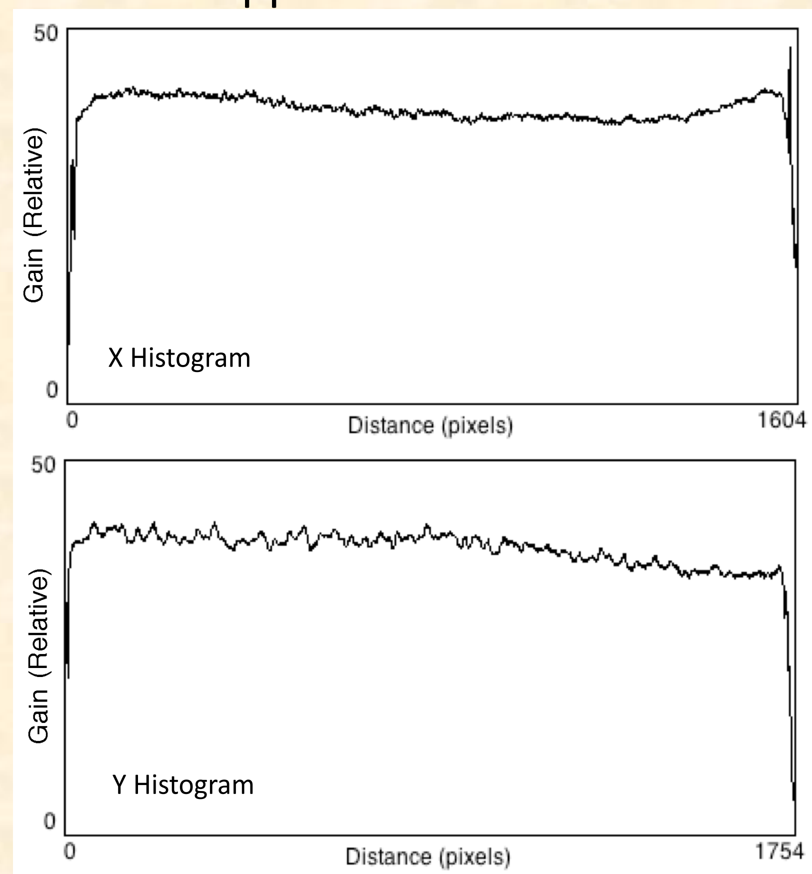
Average gain image "map"



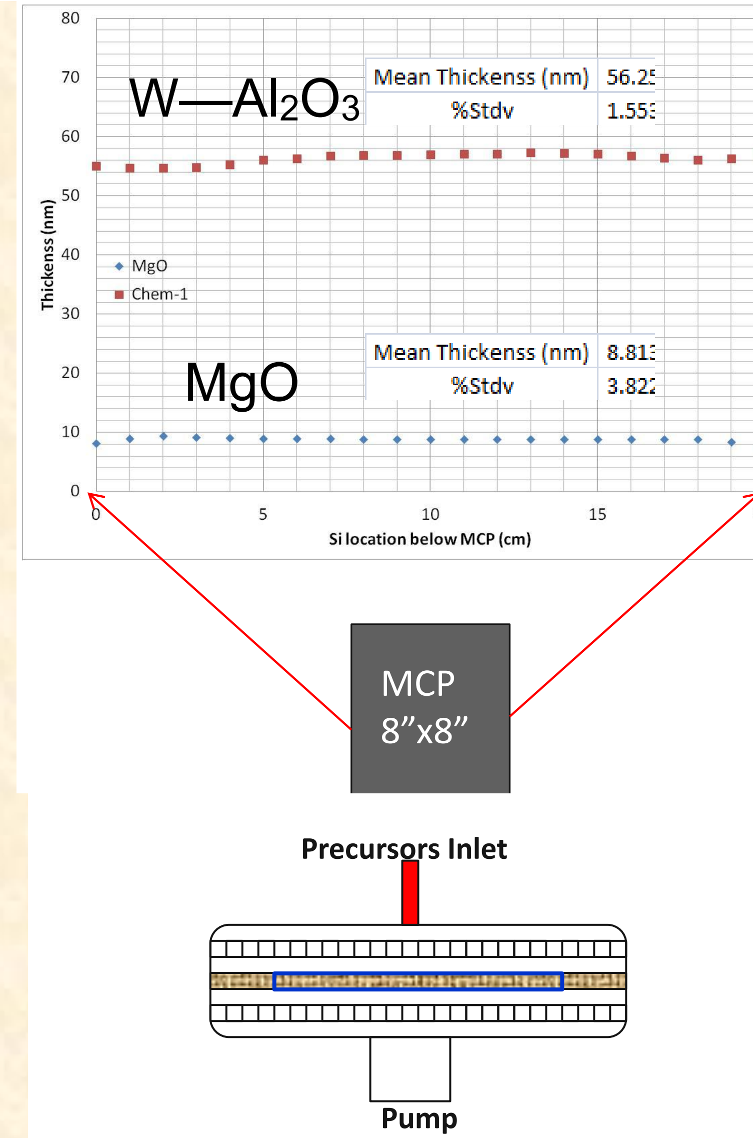
8" MCP pair average gain map image

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

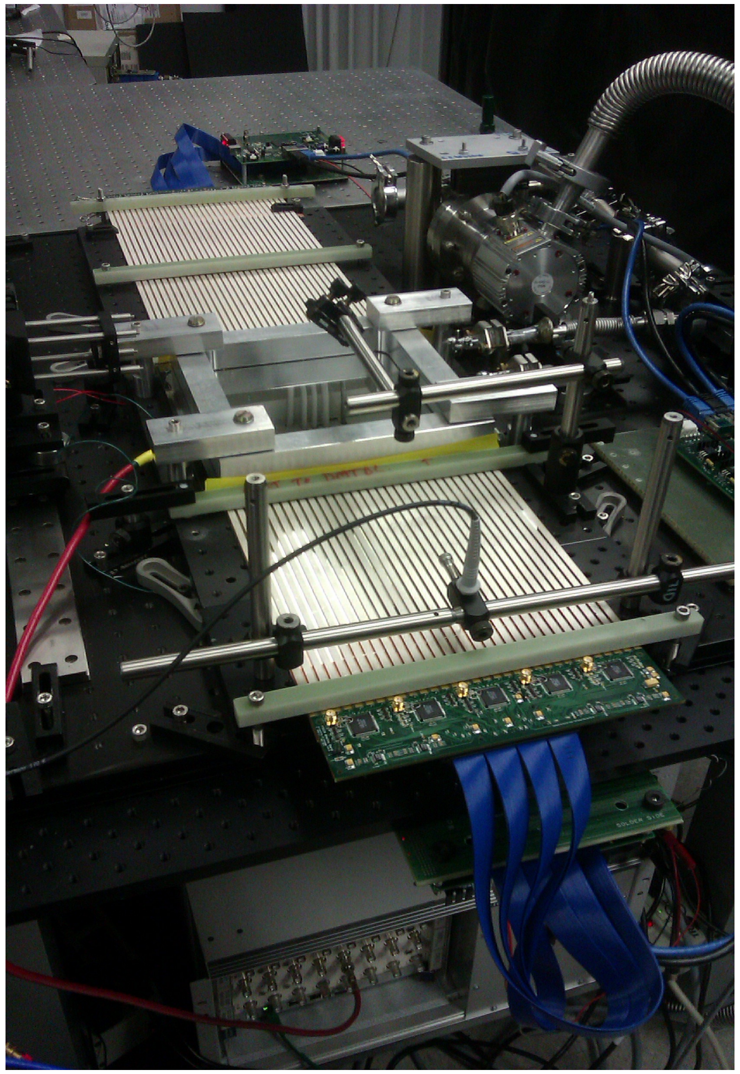
Plot courtesy of Ossy Siegmund, SSL

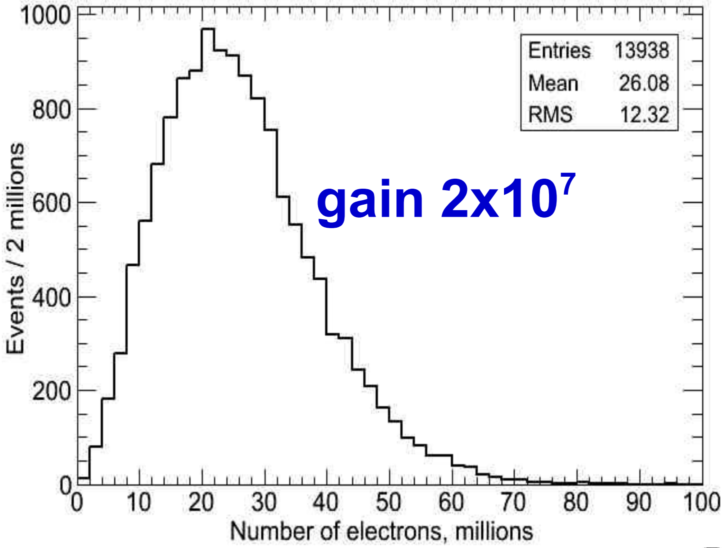
Progress on LAPPDs Devices

LAPPD “Demountable” Prototype

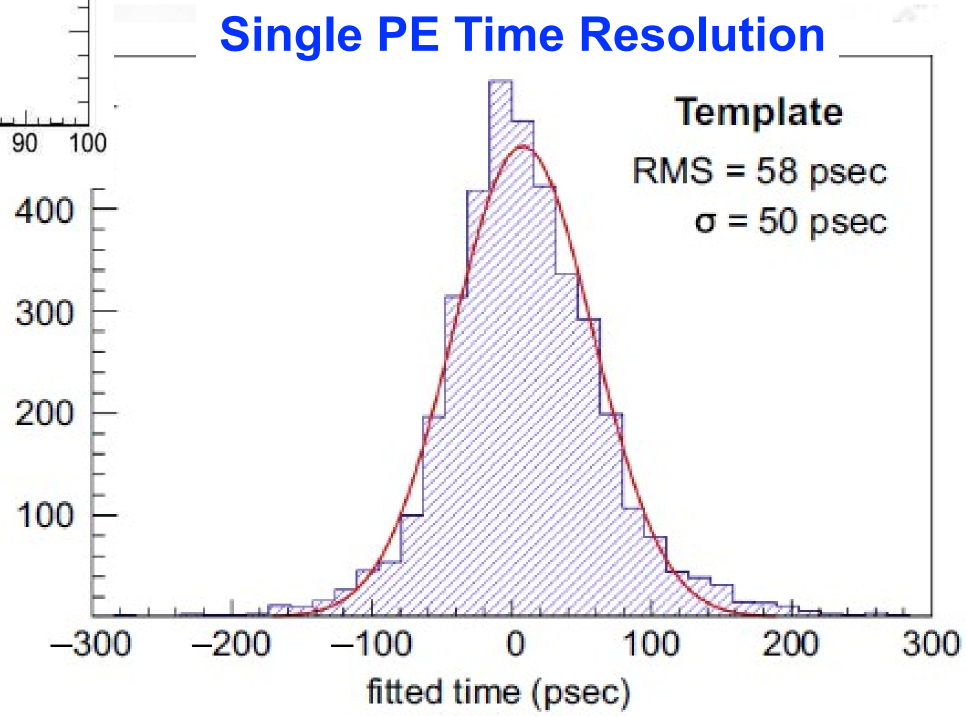
First working LAPPD MCP Detector

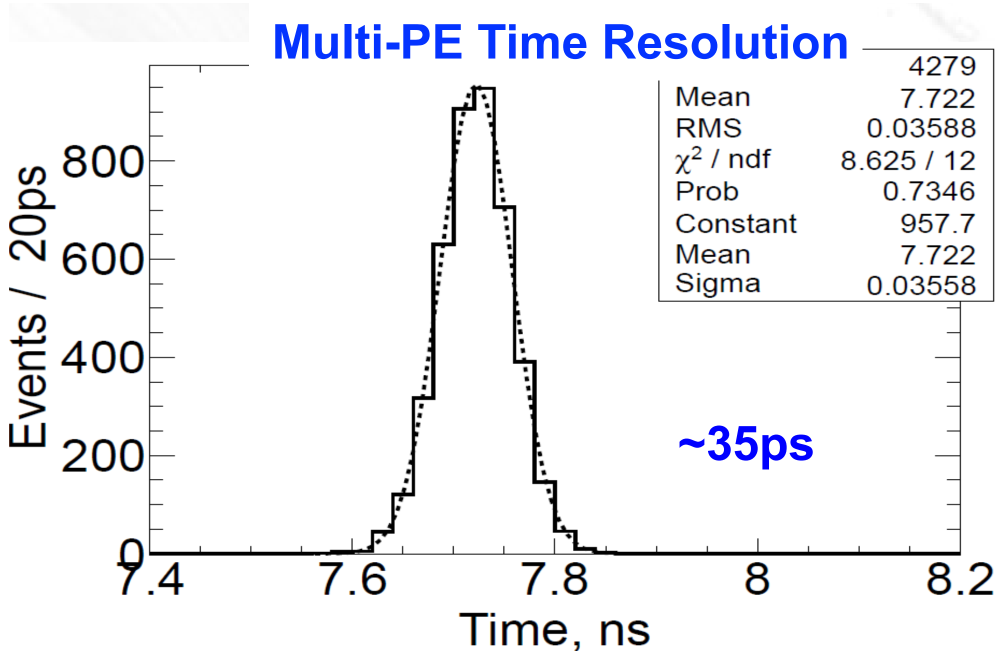
- Operated starting May, 2012 through early 2015
- Aluminum photocathode
  - Detector sealed in air, so no alkalis
  - poor QE but produced photoelectrons with UV laser
- O-ring sealed and continuously pumped



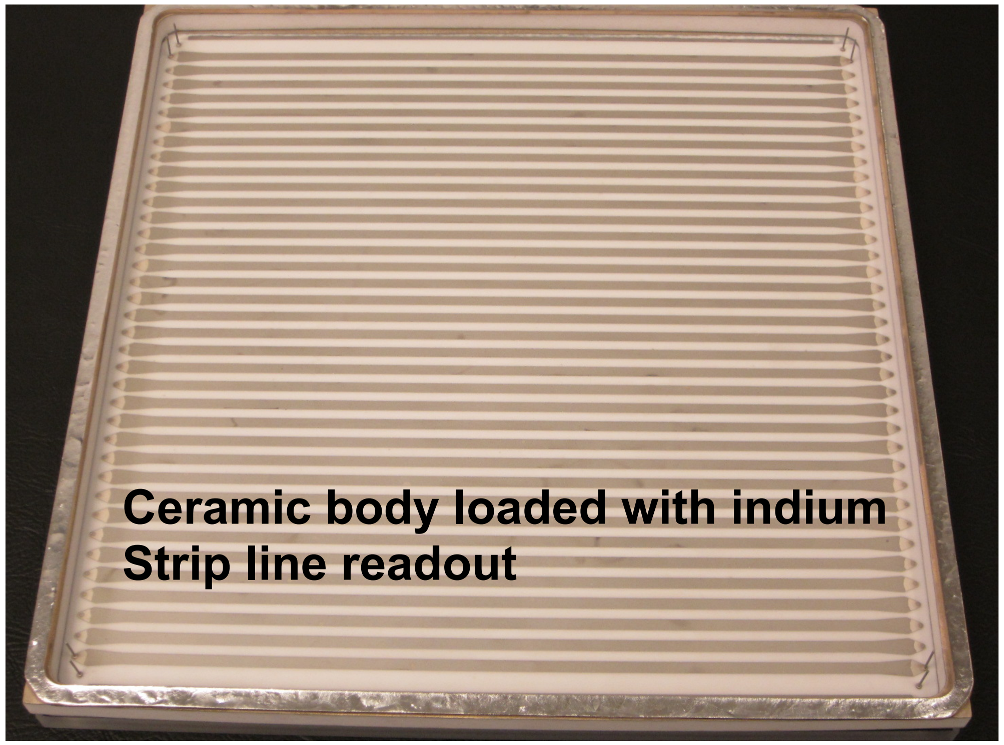


NIM A732 (2013) 392
NIM A795 (2015) 1

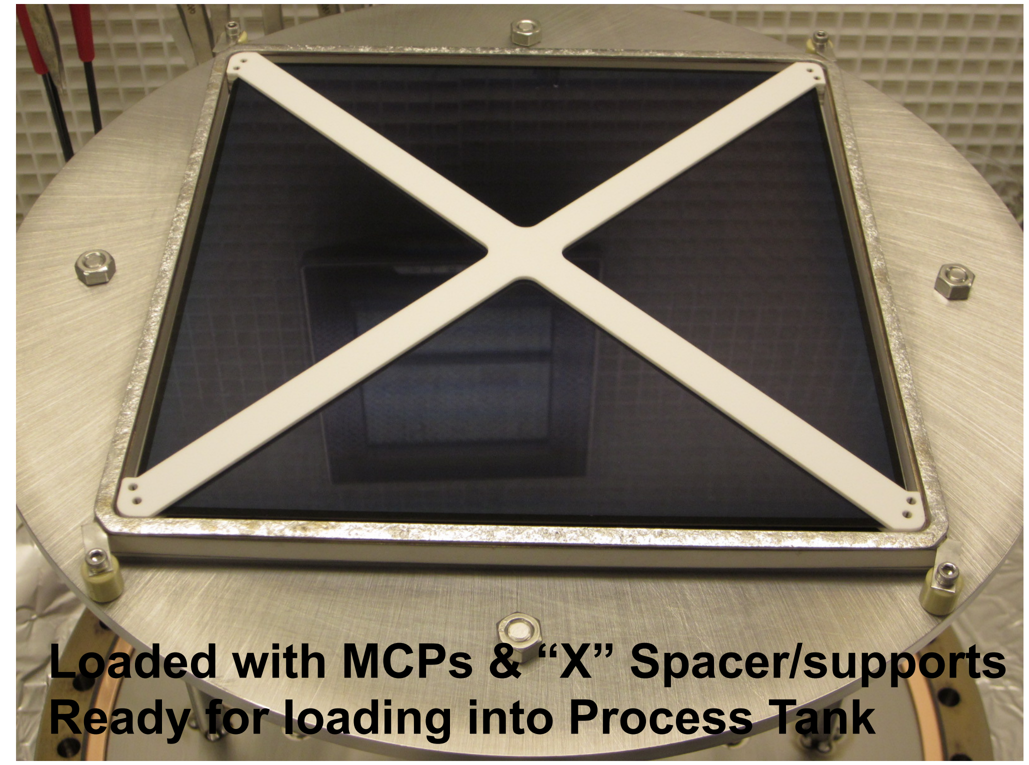




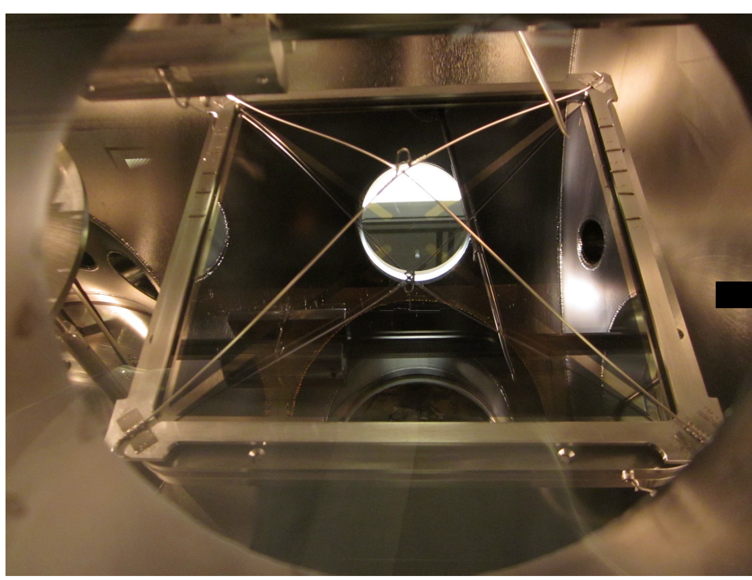
Space Sciences Lab/Berkeley
Ceramic Tube #1 Assembly - 20cm x 20cm, 20µm pores



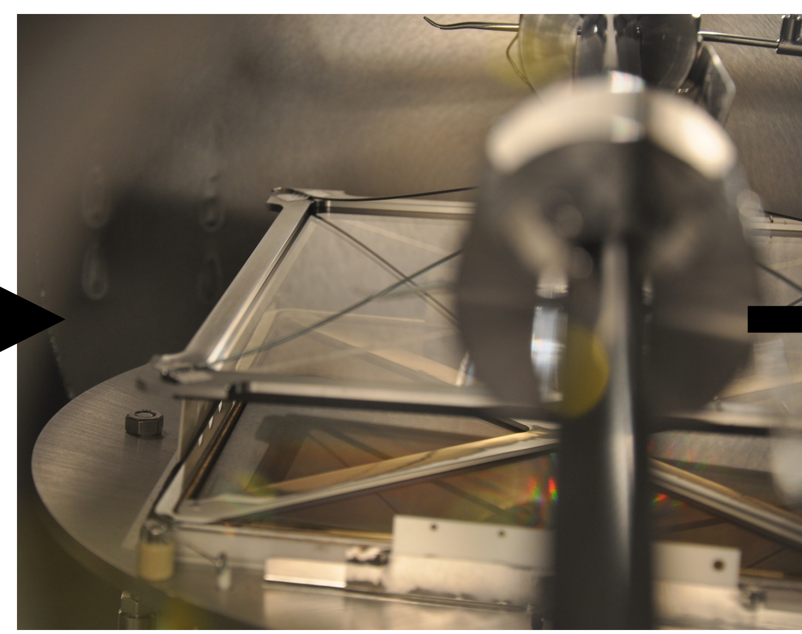
Ceramic body loaded with indium
Strip line readout



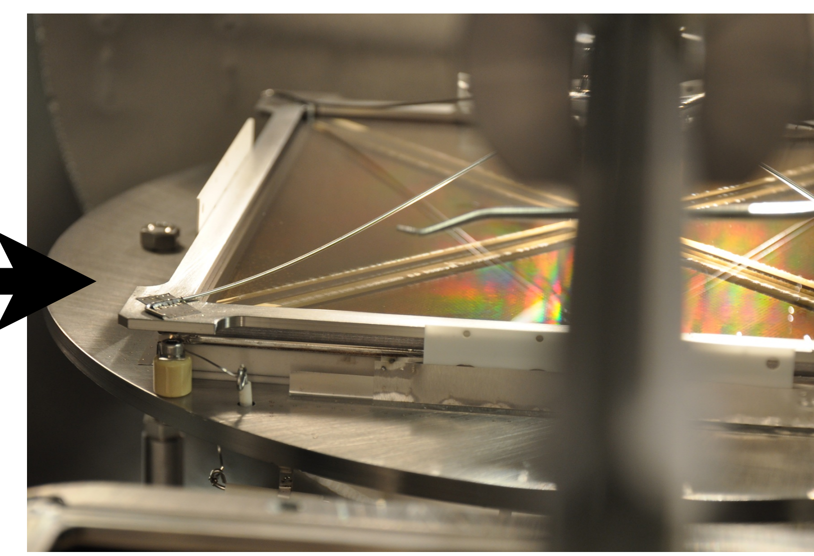
Loaded with MCPs & "X" Spacer/supports
Ready for loading into Process Tank



Completed Photocathode Window



Hot indium seal in progress



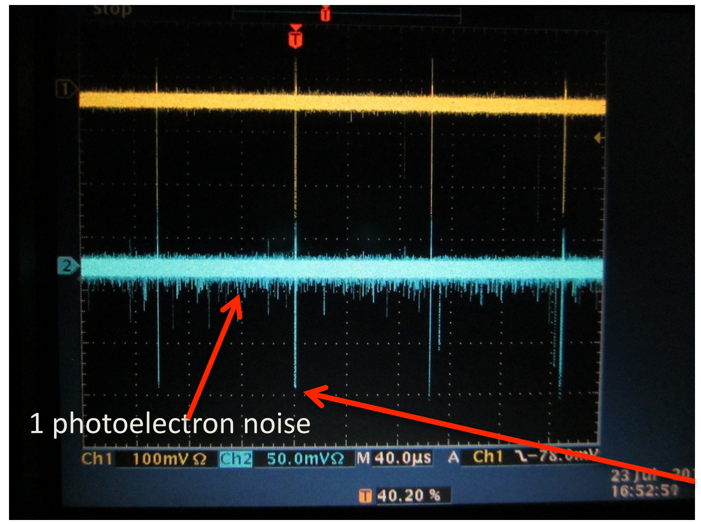
Completed Sealed Tube
August, 2013

Photos Courtesy Ossy Siegmund & Jason McPhate, SSL

SSL/Berkeley Ceramic Tube #1 (cont)

Characterization in process tank showed good performance

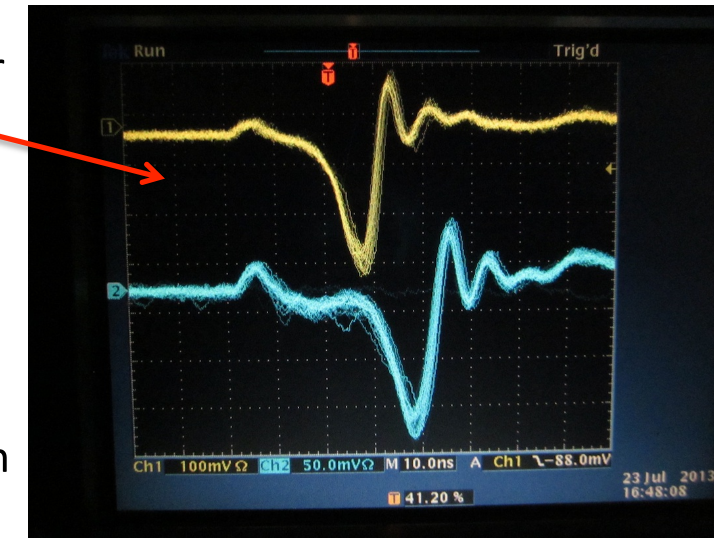
Unfortunately, tube failed to seal completely and was lost upon bringing out to air

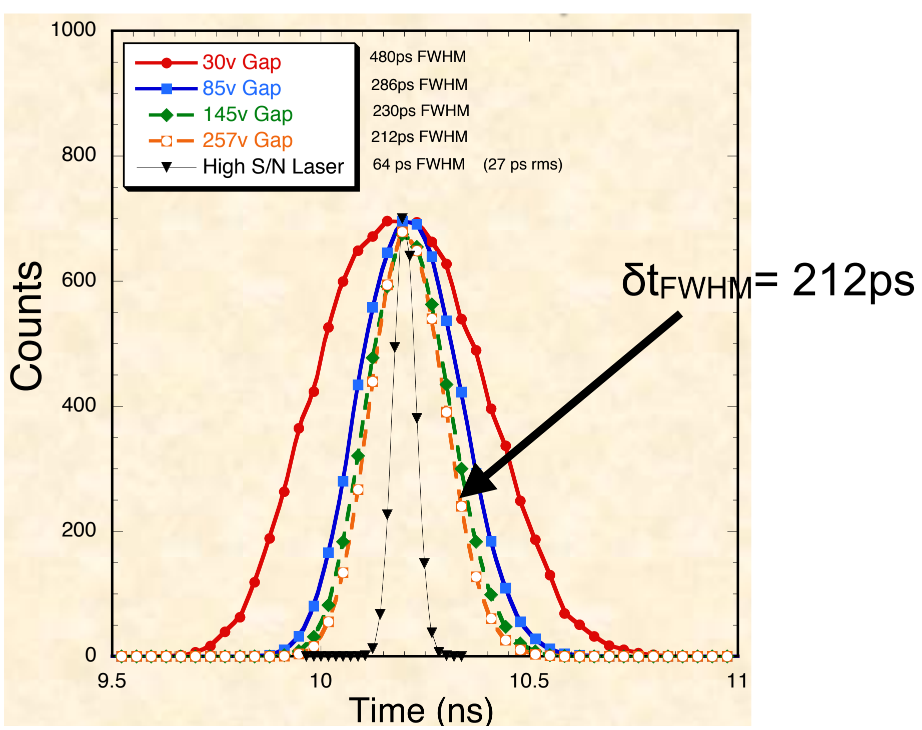


Laser spot pulses for ~10 photoelectron pulses (100ps laser)

10kHz laser rep rate for ~10 photoelectron pulses (100ps laser)

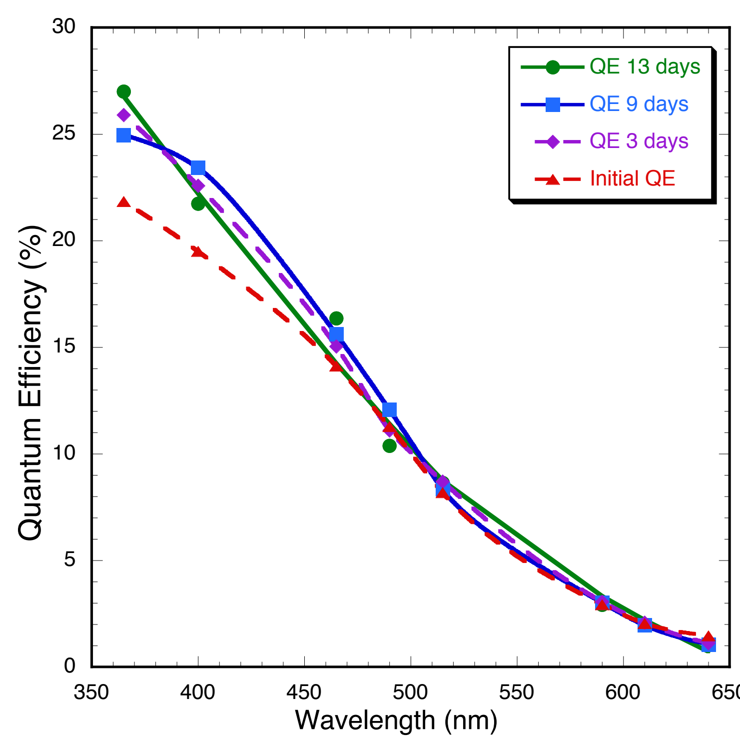
Anode delay line start/stop pulses

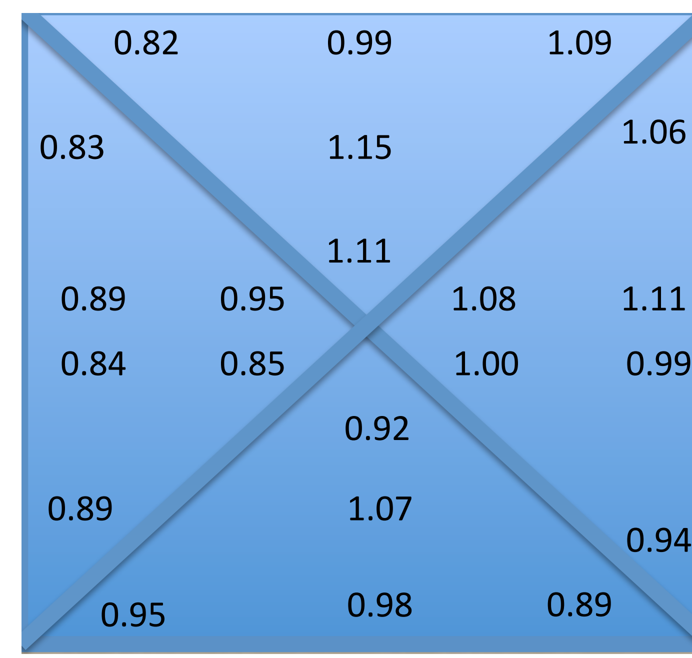




Time resolution for varying MCP gap voltage.
Limited by impedance mismatch of vacuum feedthru

Na_2KSb Photocathode chosen for low background and stability



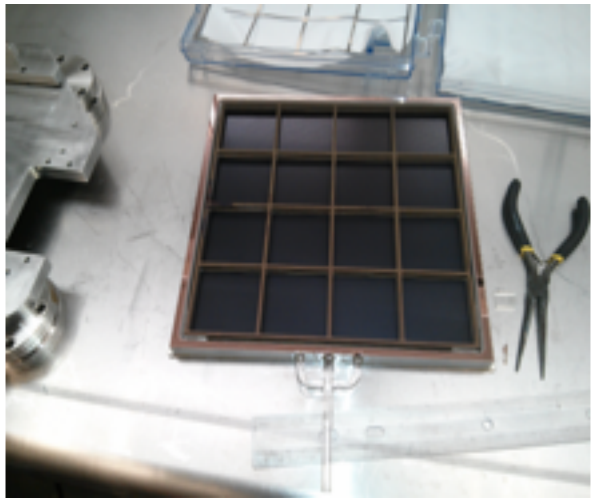


Relative QE map for photocathode

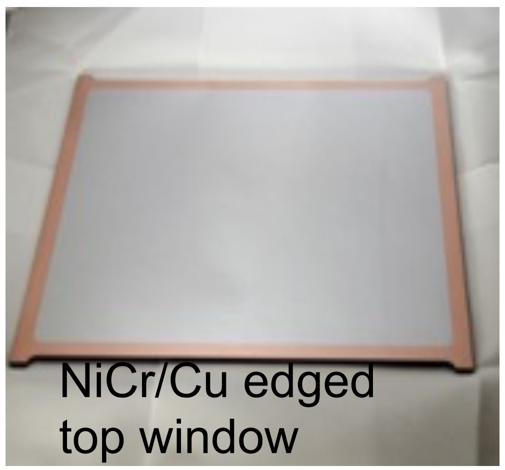
Recent Developments
20cm x 20cm Ceramic & Glass Body Detectors

- Ceramic Body Tube #2 at SSL processed in July, 2015
  - Also showed a leak with process tank back-filled with nitrogen
  - Re-pumping restored photocathode and tube operation but can't bring to air
  - Further ceramic body work suspended
- SSL will produce 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
  - **Targeting 2 detectors by end of January, 2016**
- Incom is completing installation of final piece of equipment for producing commercial 20cm x 20cm Glass-Body MCP Photodetector (LAPPD) in Massachusetts
  - Functionalized MCPs can be ordered
  - ALD reactor is being commissioned and will operate soon
  - Process tank in place
  - **Targeting first tube fabrication by end of 2015**

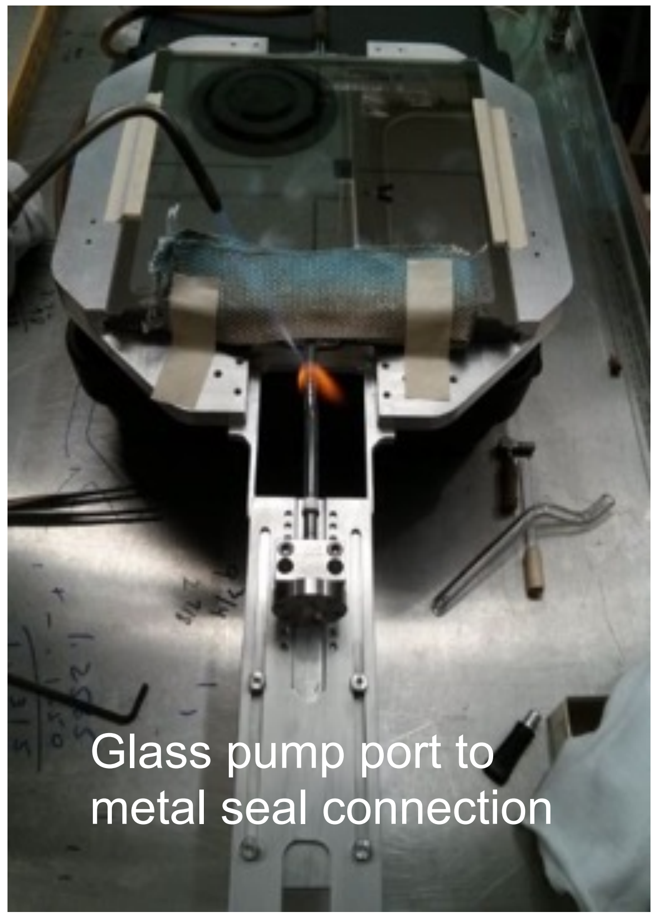
In Situ MCP Photodetector Assembly at U. Chicago



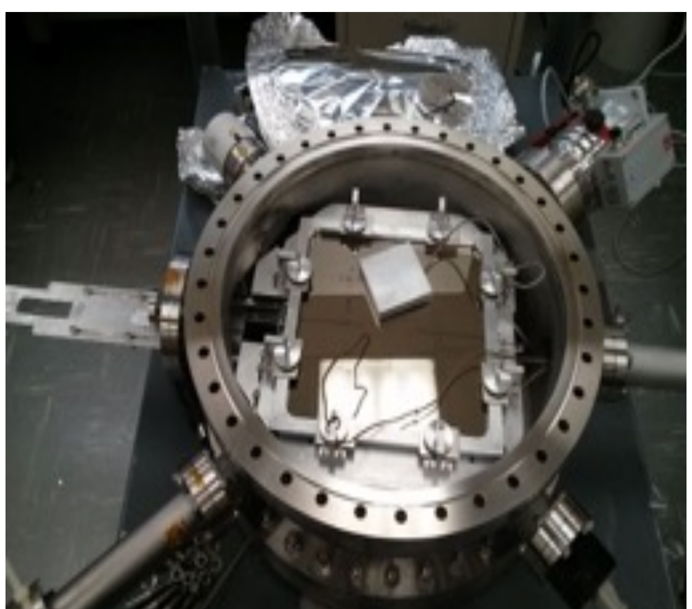
20cm x 20cm tile
with pump port



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

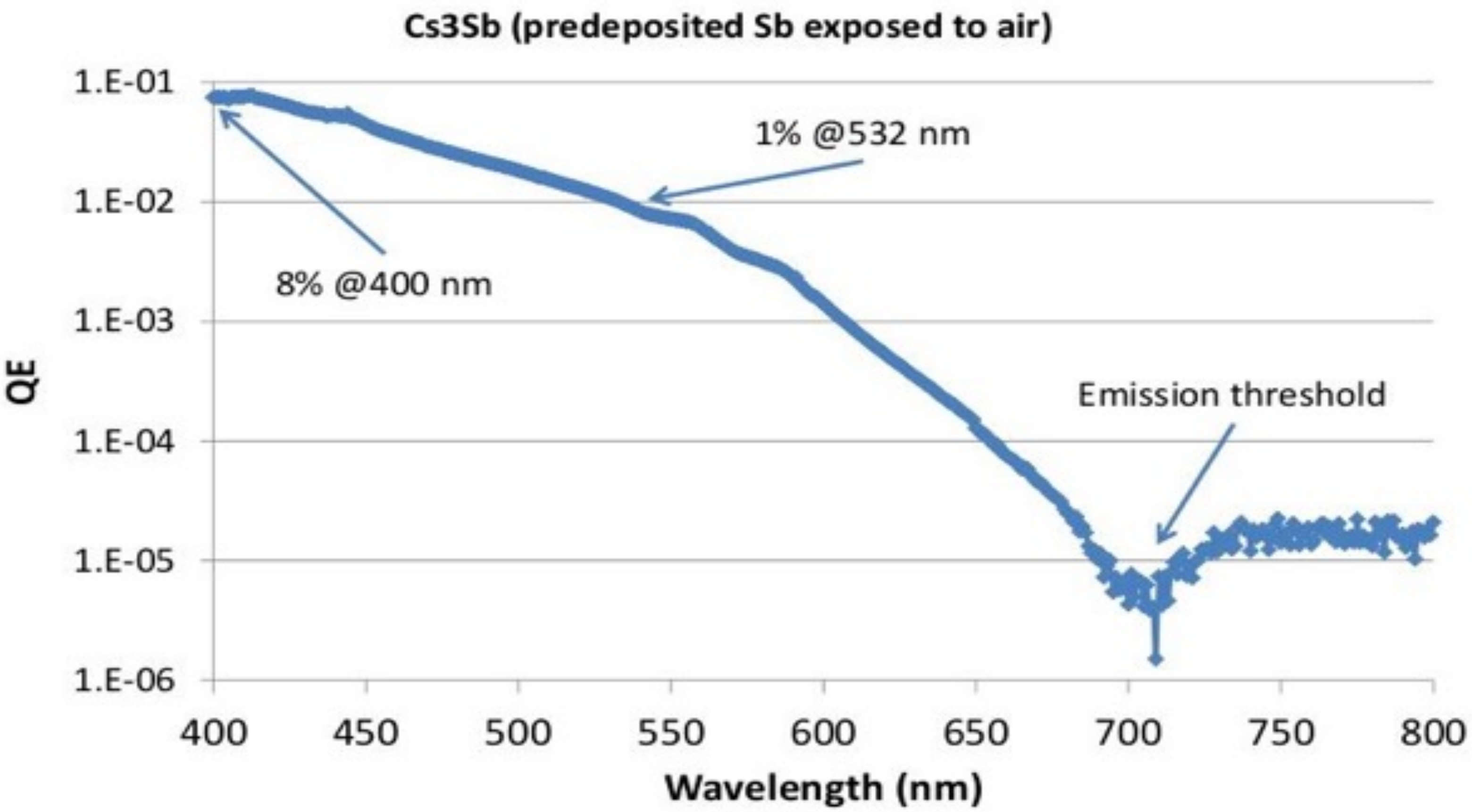
Process:

1. Deposit Sb on top window (air stable, thin oxide layer forms on surface)
2. Hermetic indium seal on 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

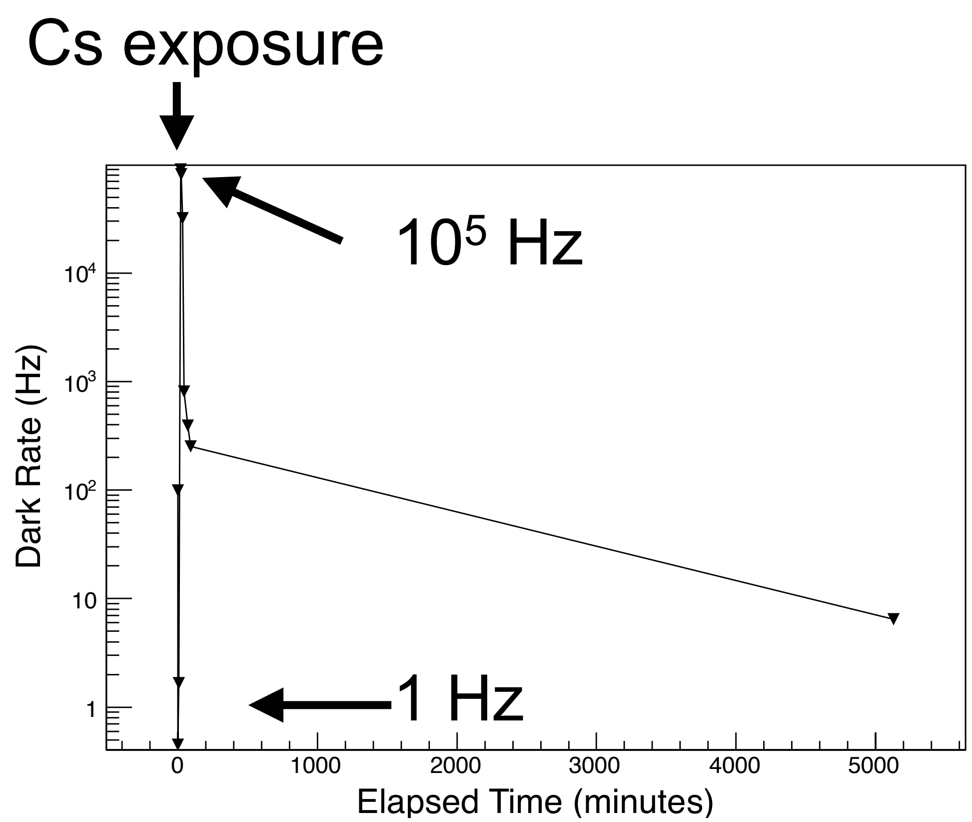
- Light weight processing chamber
- Potential for high yield production using multiple chambers

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



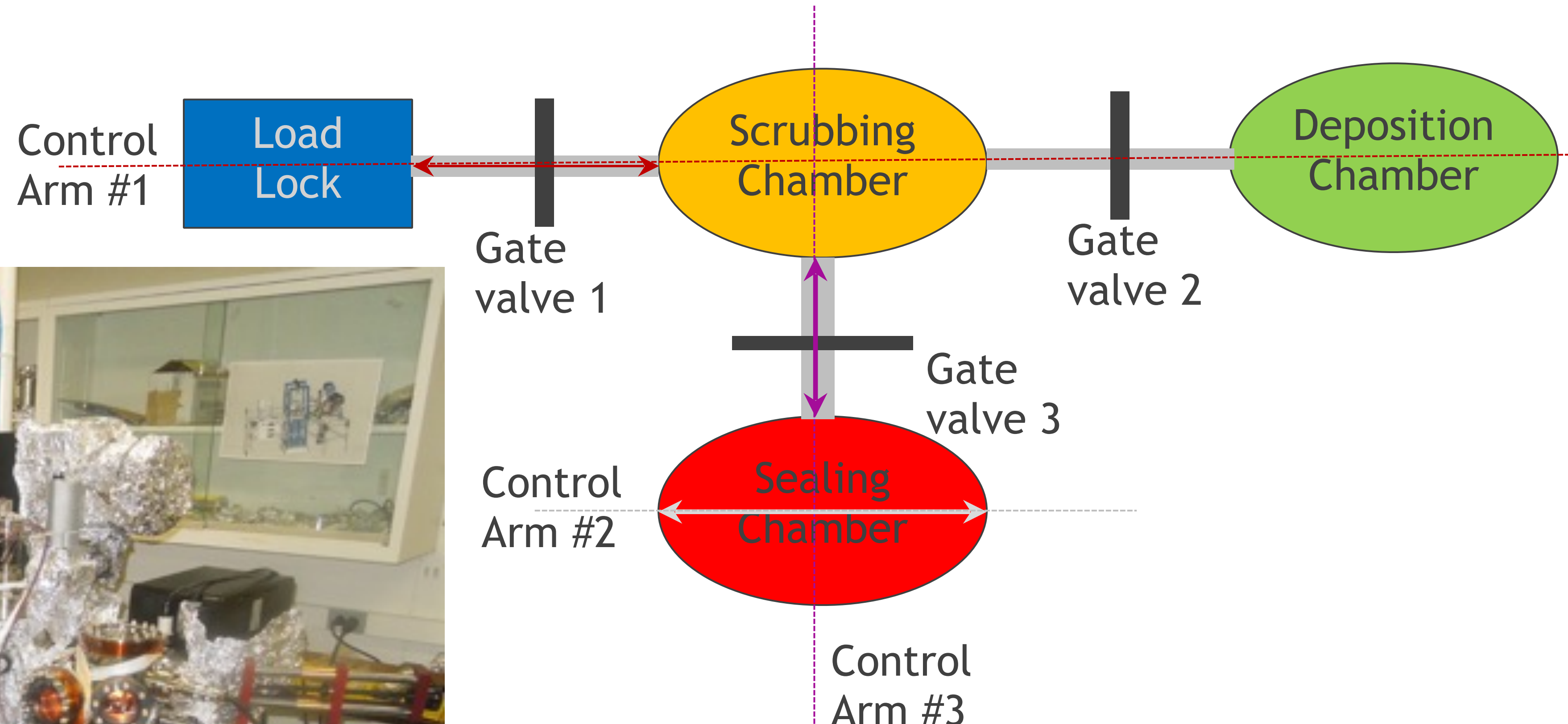
First attempt by L.Cultera to make $SbCs_3$ photocathode using pre-deposited layer of Sb exposed to air

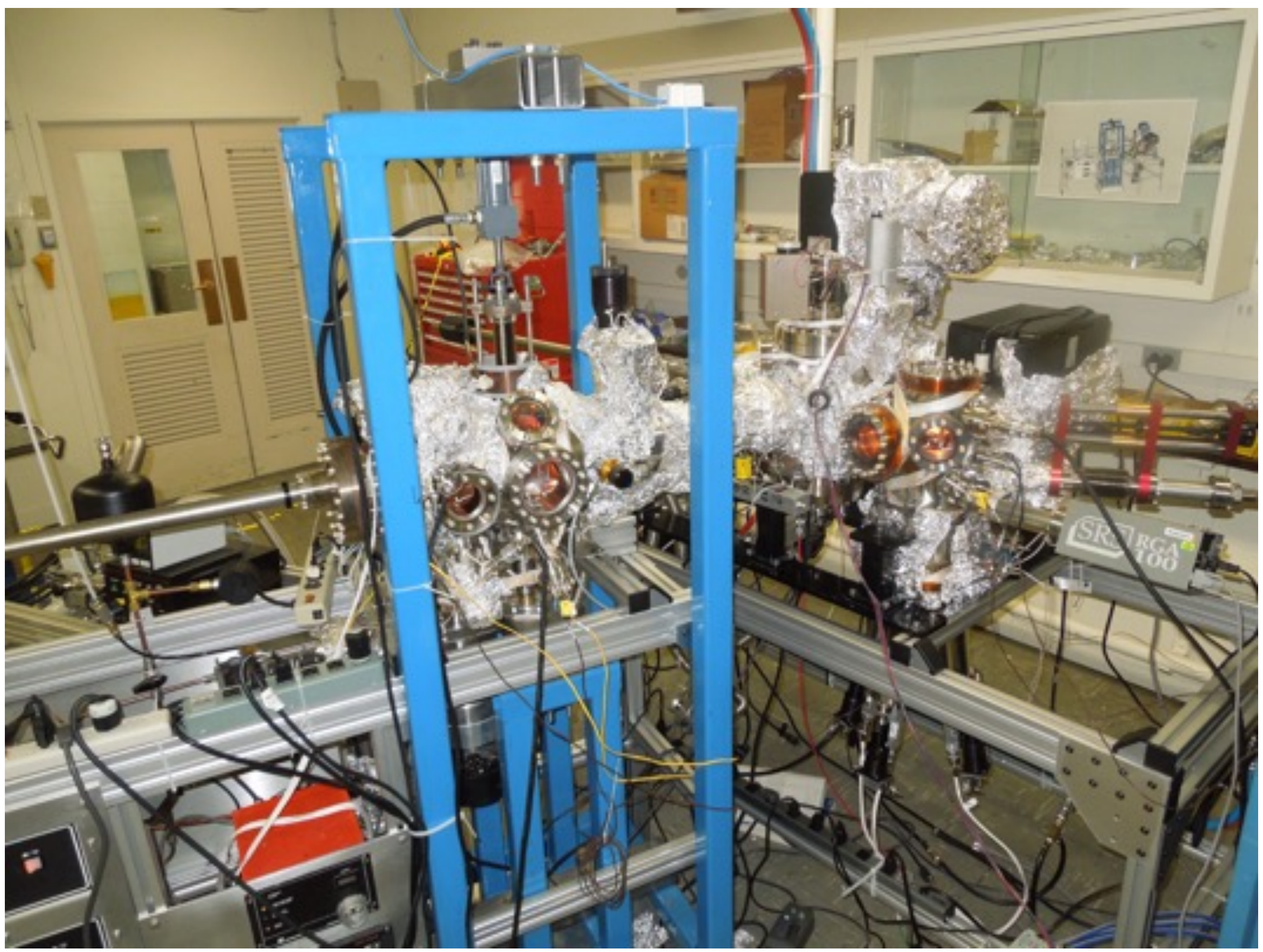


n.b. MCPs exposed to Cs vapor become noisy. Noise rapidly decreases then decays slowly over several days back to pre-exposure level

Argonne 6cm x 6cm MCP Photodetector Production

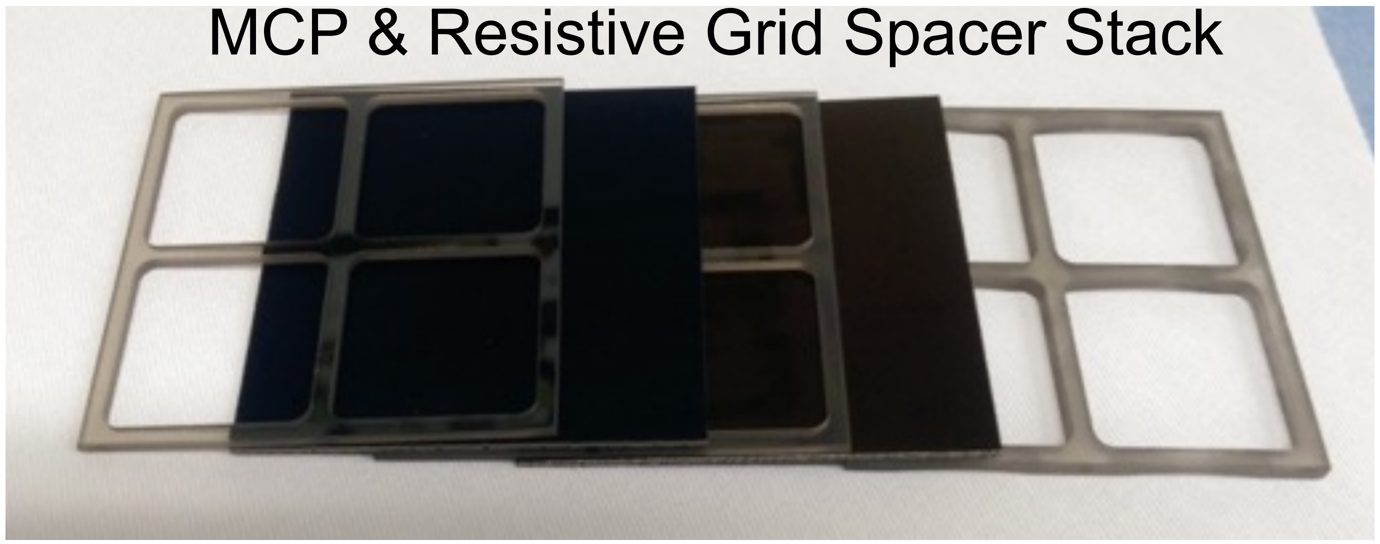
Argonne Small Single Tube Processing System (SmSTPS)

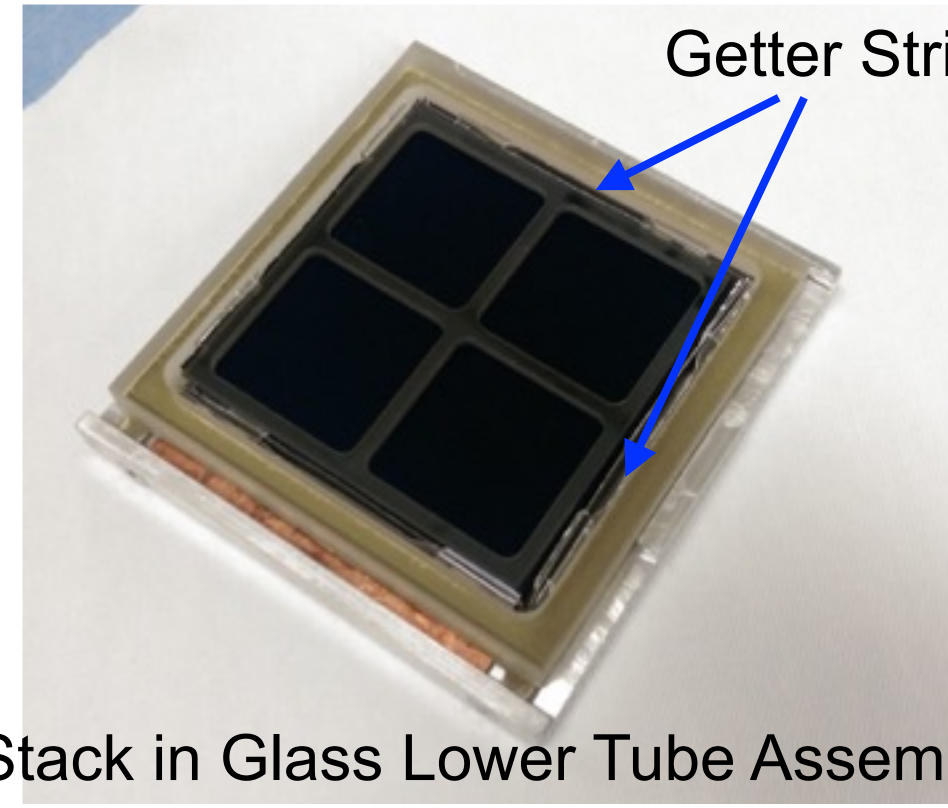




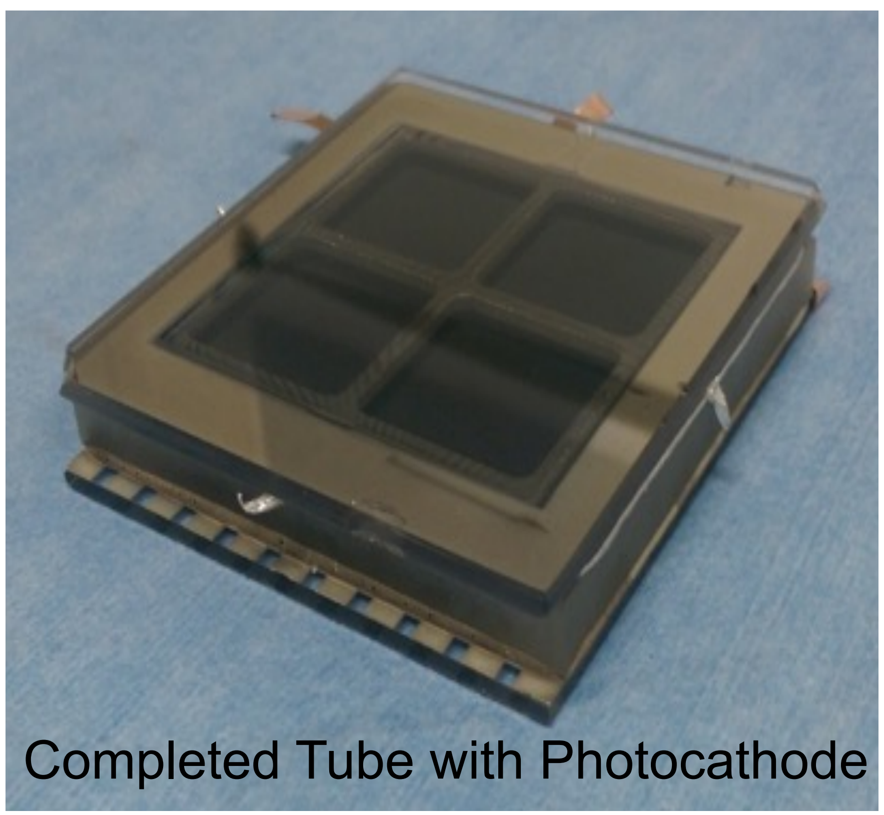
- Based on techniques developed for LAPPD Collaboration
- Unique features
  - Local heating w/ halogen lamps
  - Each process step has dedicated chamber
  - Photocathode evaporative deposition using effusion cells

6cm x 6cm Active Area MCP Photodetector Composition


MCP & Resistive Grid Spacer Stack

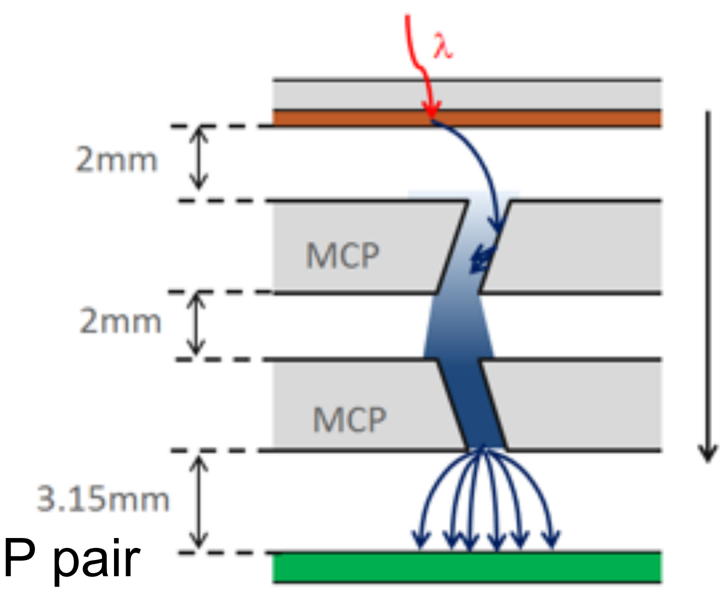


Stack in Glass Lower Tube Assembly


Completed Tube with Photocathode

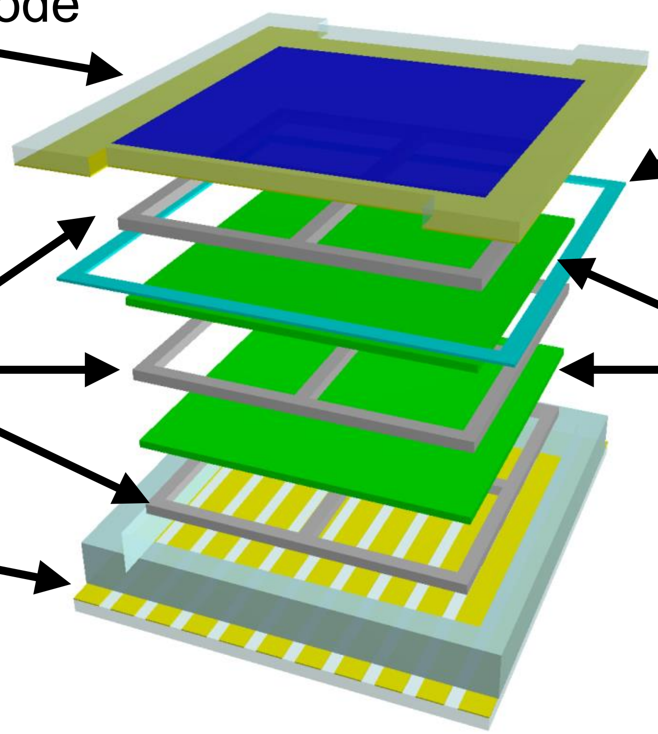
Double-ended readout via 7 or 9 anode strip lines

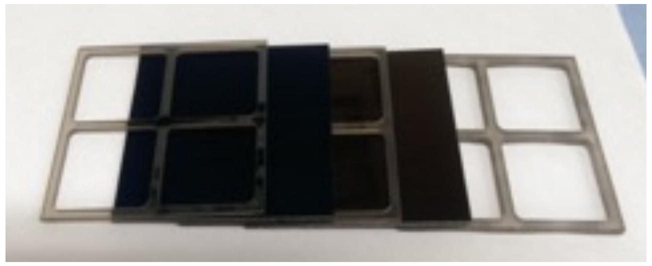
Top window seal made via thermocompression of indium wire

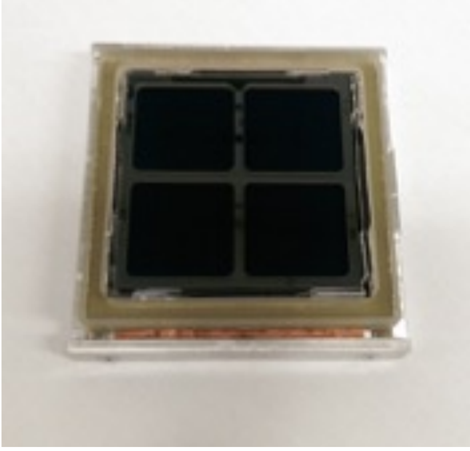


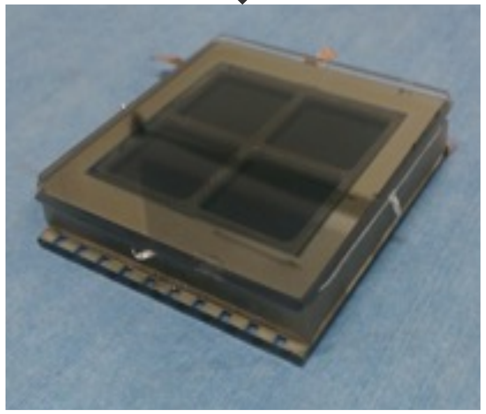
Tube contains MCP pair arranged with 8° pore bias angle in “chevron” configuration

Tube Processing



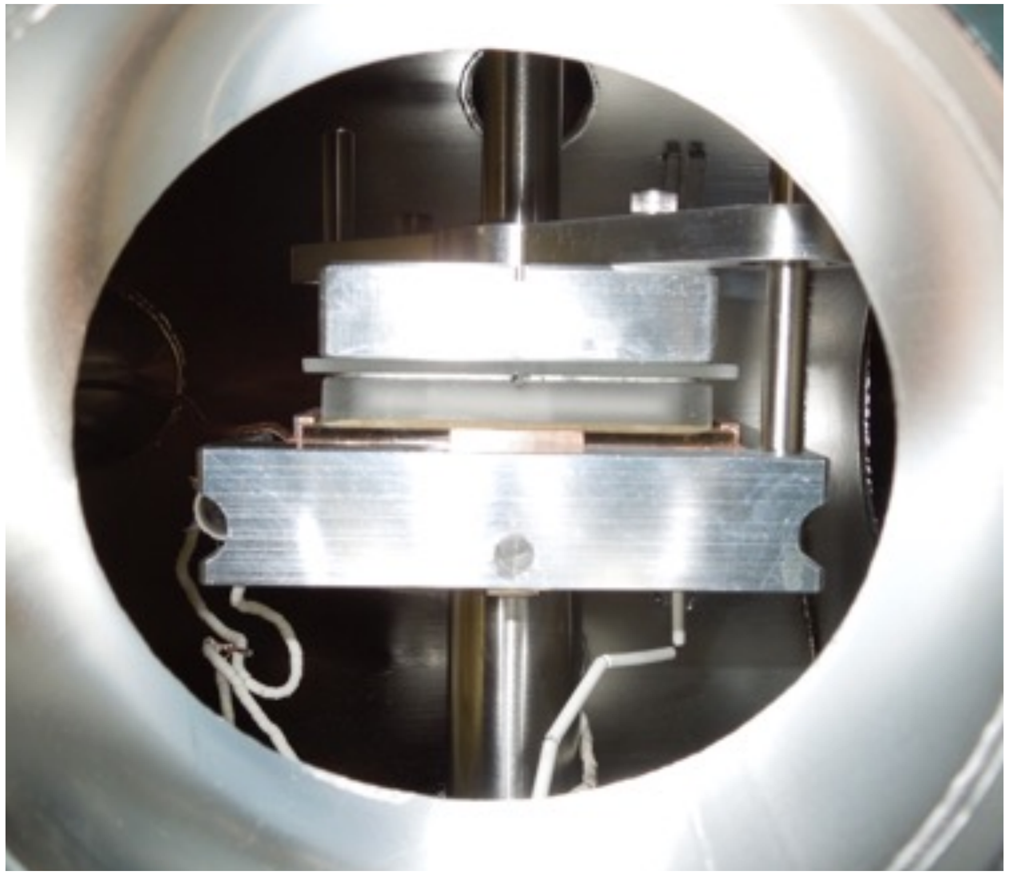






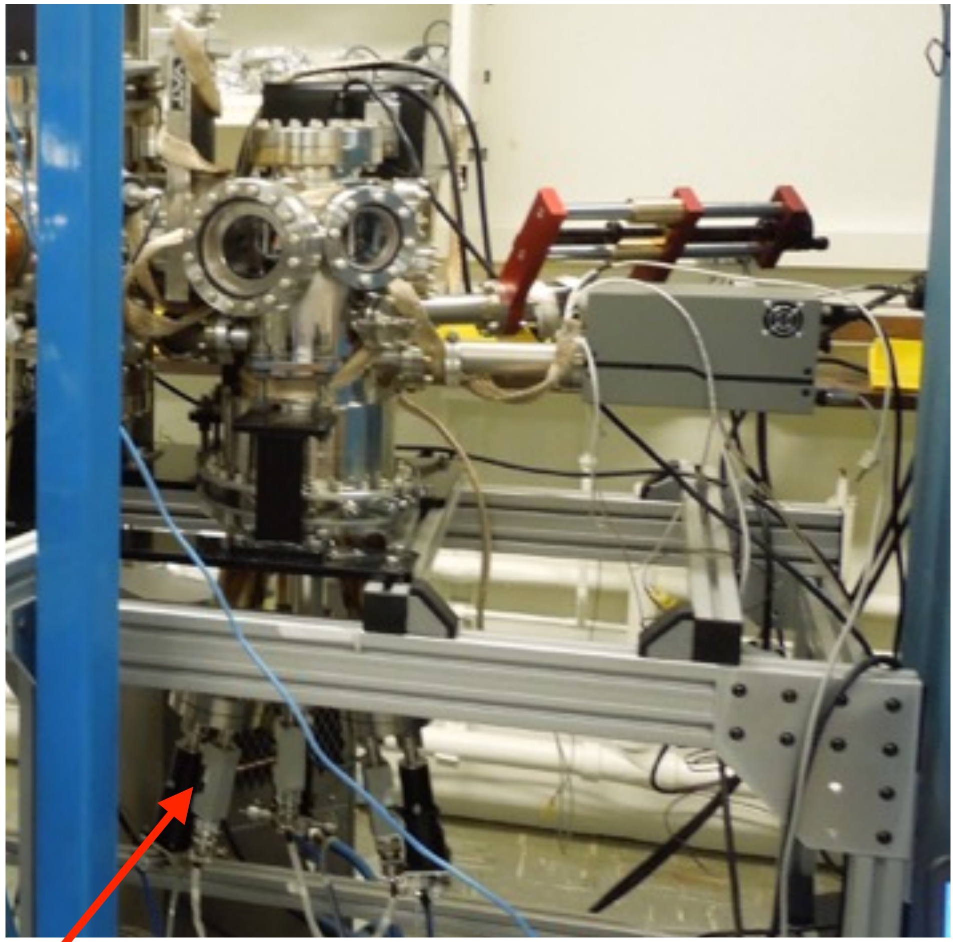
- **Detector tiles are processed in the 6cm system following these major steps**
  - Clean parts to UHV standards; MCP's cleaned & baked prior to functionalization
  - Bake tube body & MCP "stack" in vacuum; scrub MCPs (3-4 days)
  - Tube ➛ air. Insert getter strips ➛ back to Scrub Chamber (<20 minutes)
  - 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



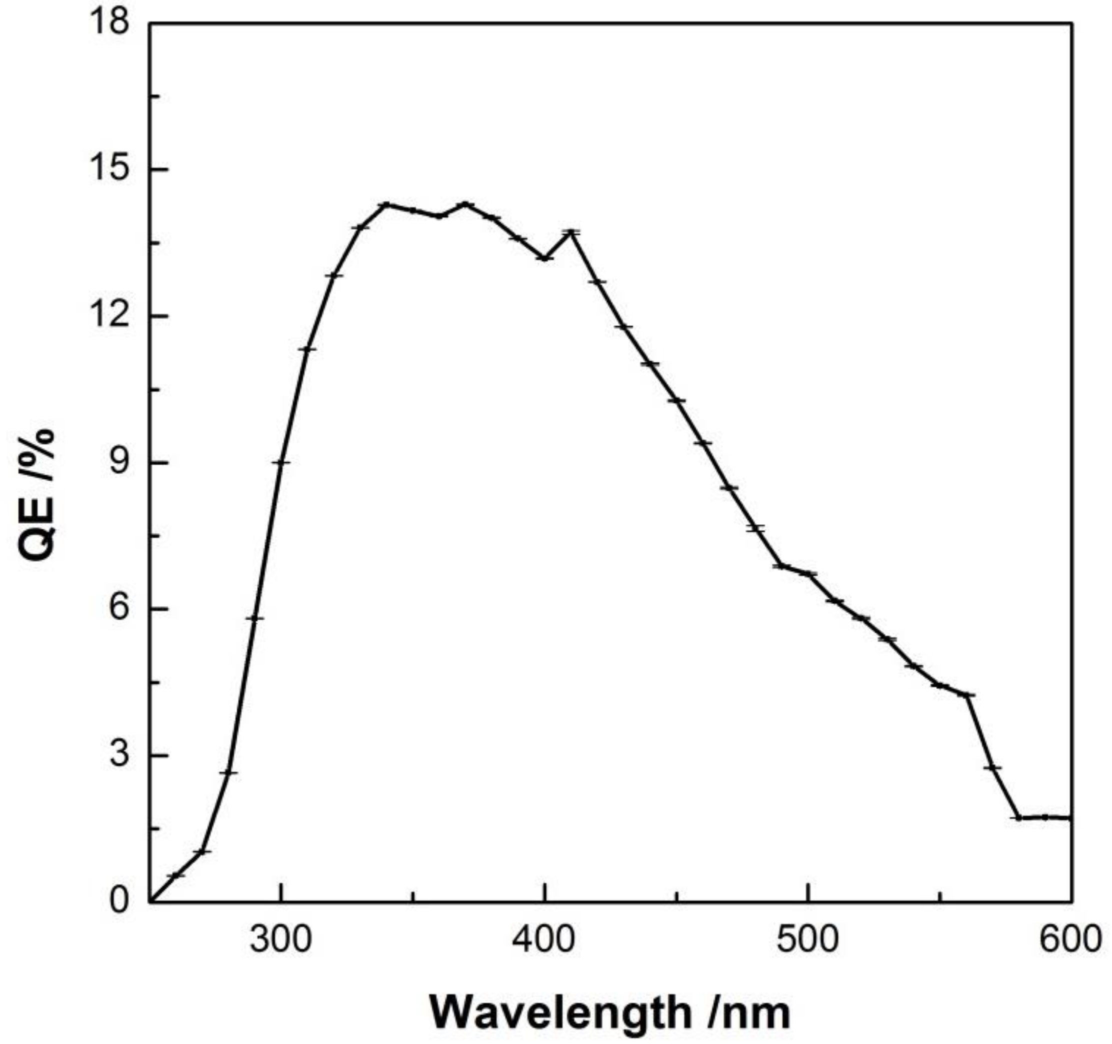
- Sealing uses hydraulic driven platens to crush indium wire between top window & sidewall
- Heaters used to raise glass to ~80°C to improve seal quality

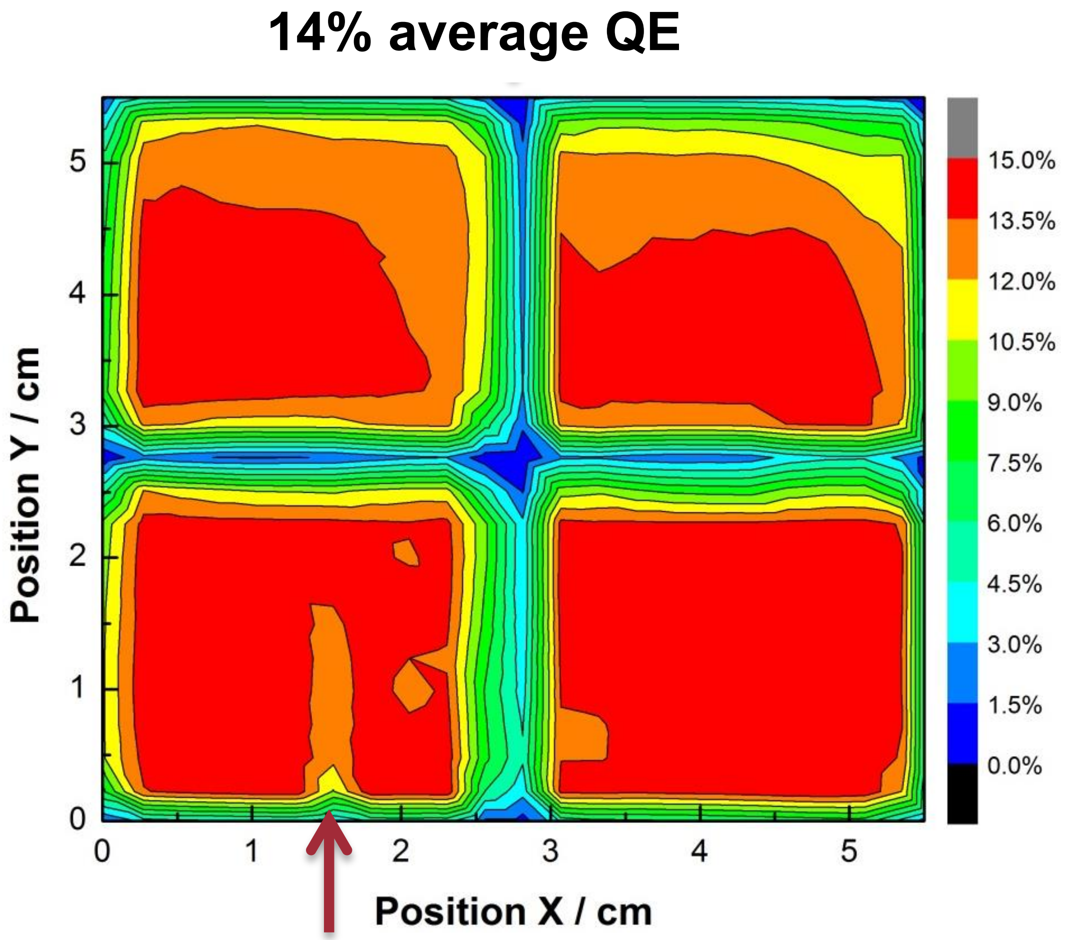
- Monitor photocathode with
  - Quartz crystal µ-balance (QCM)
  - Photocurrent response during growth
- QE Uniformity ~ ±15%; improving



Sb, K, Cs
effusion cells

Photocathode Quantum Efficiency & Uniformity



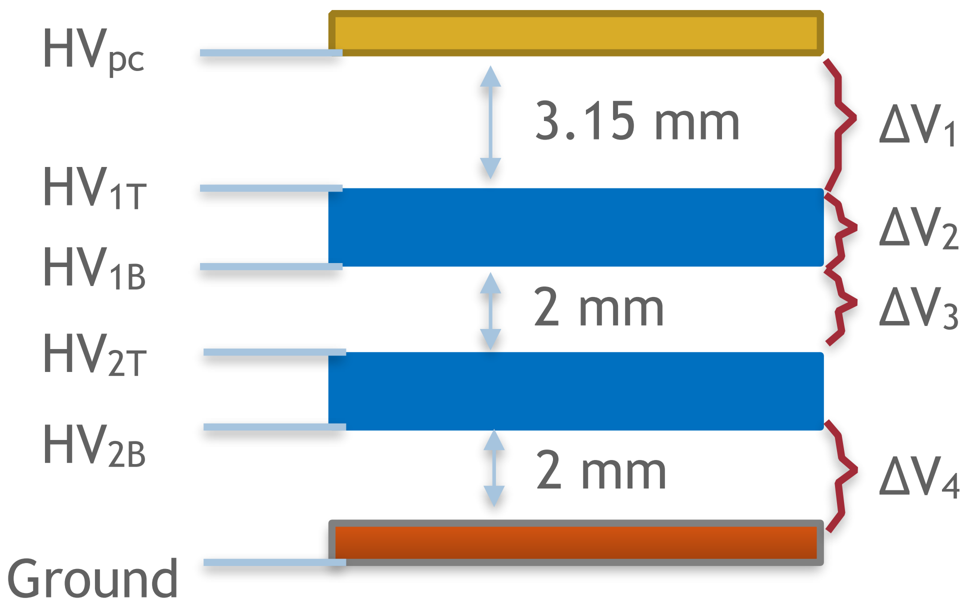


Photocurrent monitoring pin shadow

- Quantum Efficiency of recent tube (#47)
- Improvements made in deposition process after this fabrication
  Believe we can soon achieve ~20%
- Effusion cells refilled last week; chamber cleaned and in bakeout now

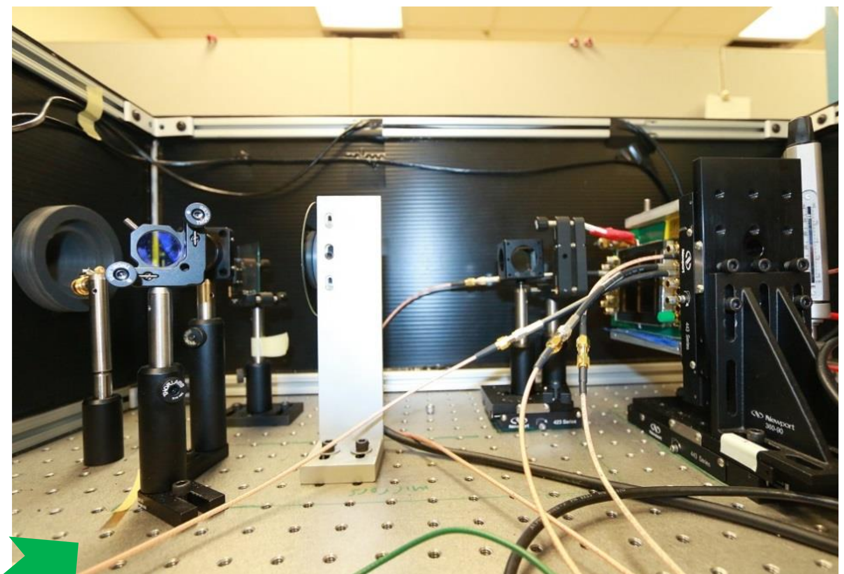
Recent Results on Small Format MCP from Argonne

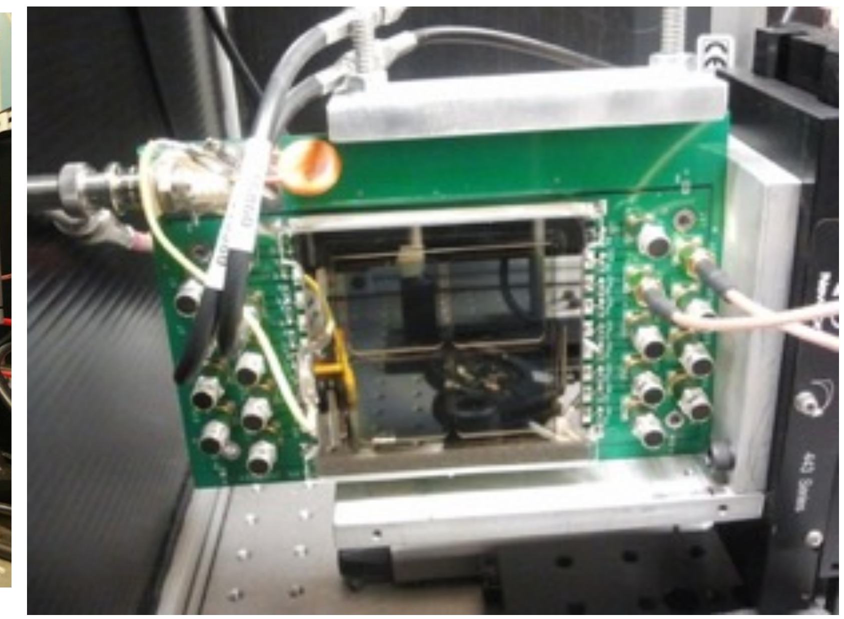
- Produced 6 functional tubes with internal resistance biasing chain
  - 3 have worked for over 1 year
  - Internal resistance limits performance
    - Need fine matching between component resistances
    - No direct QE measurement in sealed tube
    - Can't optimize each stage
- Have qualified Independently Biased Design (IBD-1) and producing tubes
  - 5 working tubes; process yield > 80%
    - first tube out during MPGD Workshop at CERN, June 2015
    - 6th tube MCP resistance degraded during processing
  - On track for 10 functional tubes by year end
  - Will release first tubes to outside users in near future (few weeks)
  - Can now optimize performance of each stage
  - Next improvement: adjust gap spacings

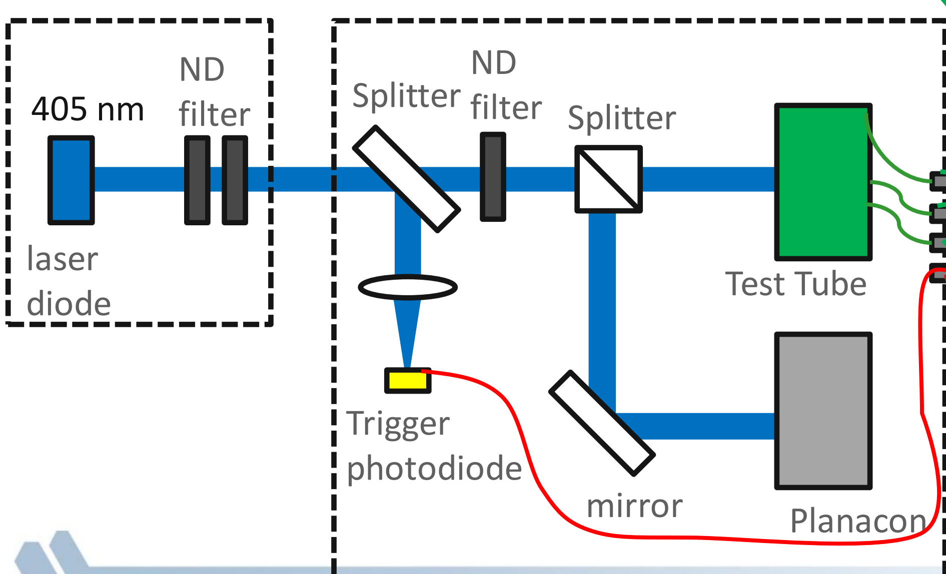


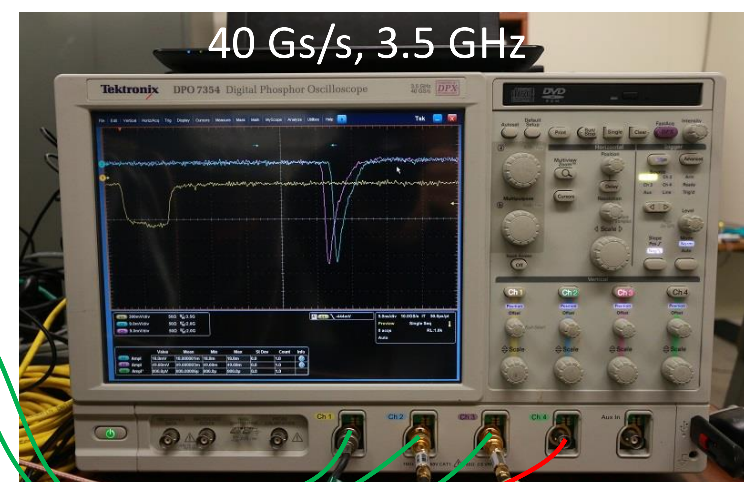
Tube Testing at Argonne HEP Laser Test Facility

- Wavelength: 405nm
- Pulse Duration: FWHM 70ps (σ=30ps)
- Frequency: 2Hz - 10MHz
- Beam size: 1-2mm
- Start signal: Photodiode (<3ps)
  Laser pulse (~7ps)
- Readout: 20S/s Oscilloscope
- Translation Stage: μm precision
- Analysis: Waveform samples offline





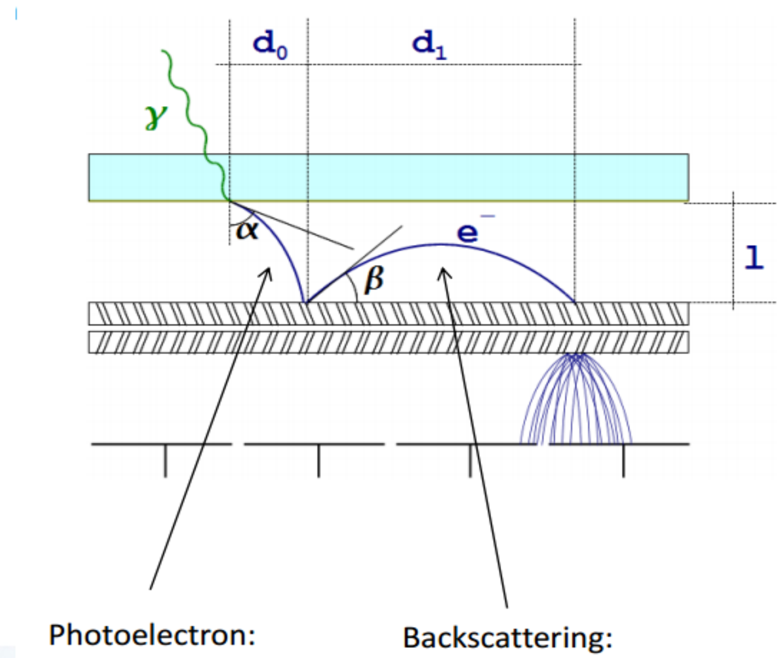




6 GHz BW 20 Gs/s scope added May 2015

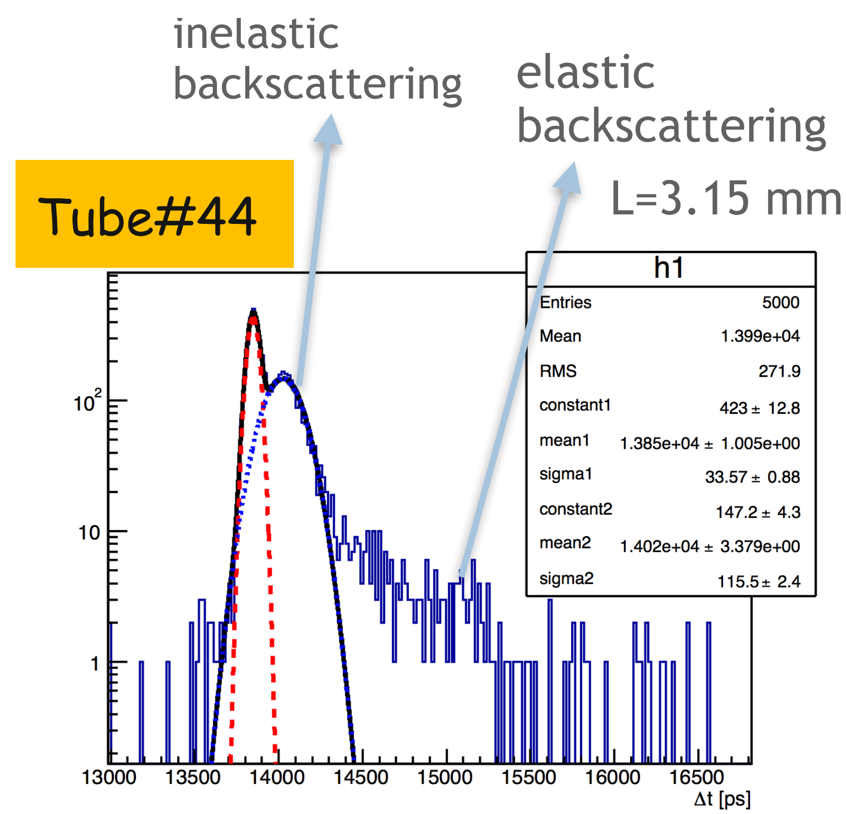
Results from Optimization (I): Backscatter

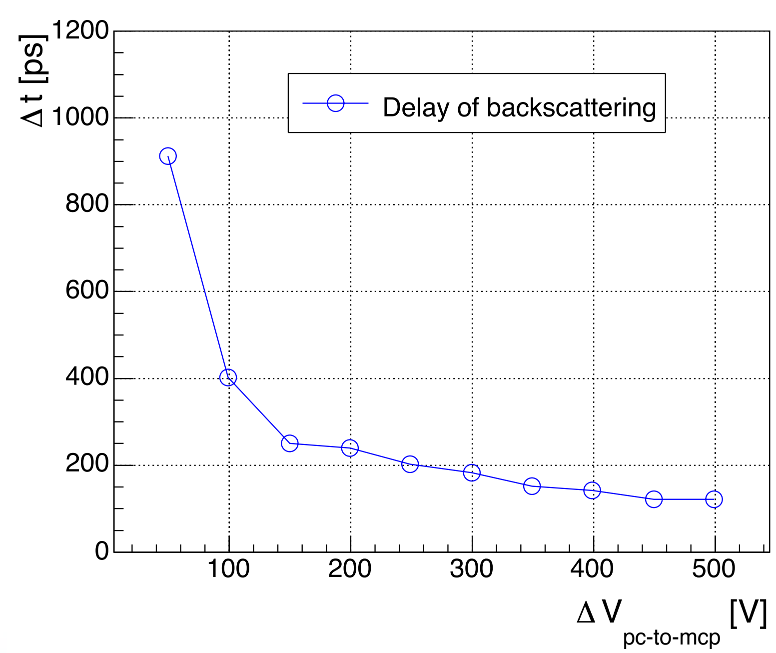
- Photoelectrons can backscatter from MCP surface
  - causes tail in single PE timing distribution
  - can be reduced by smaller gap
  - reduced by larger $\Delta V_{pc\text{-}MCP}$
  - 300-500V gives best result

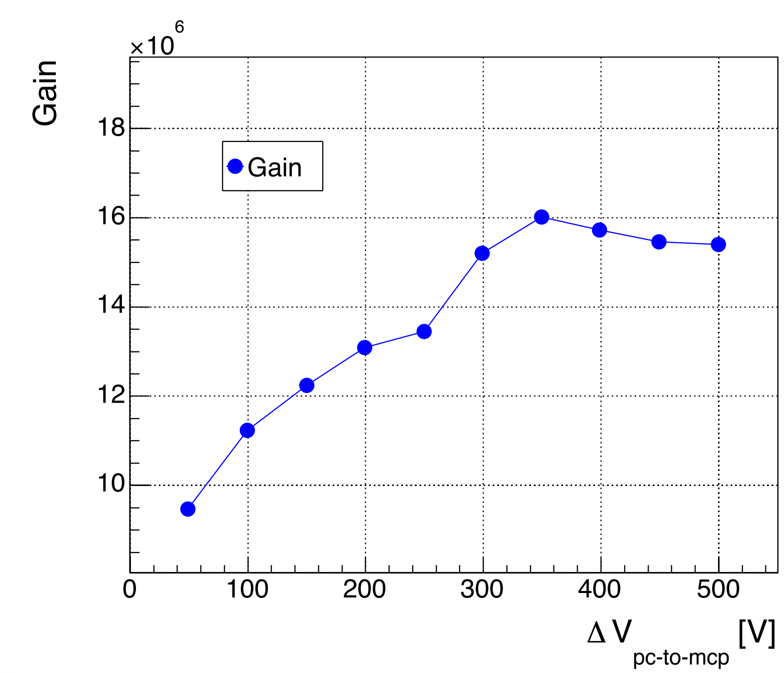


Single pe
δt resolution = 34ps

backscatter peak
has δt = 115ps

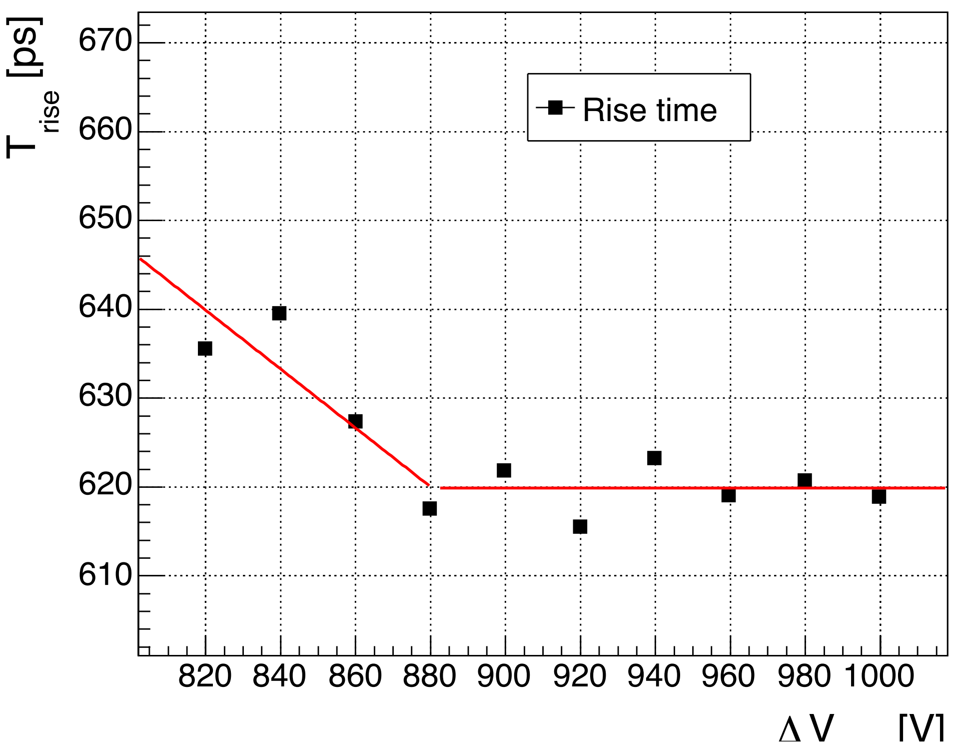


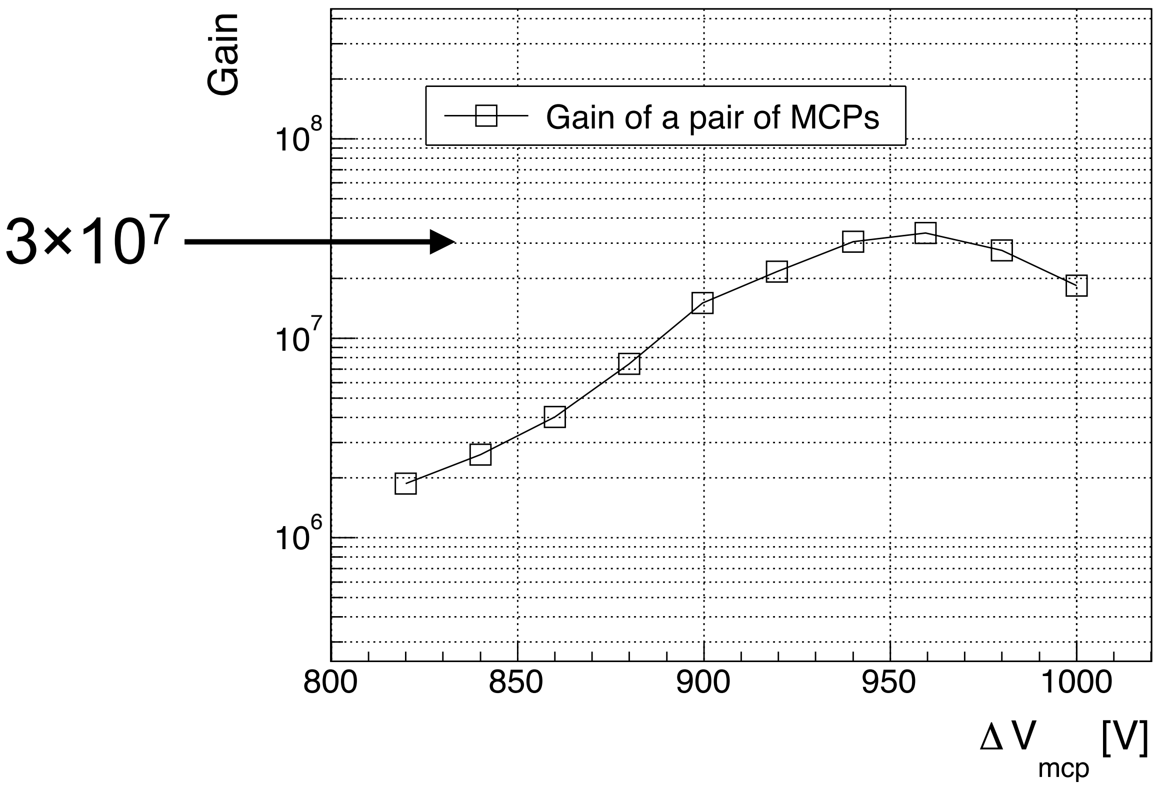


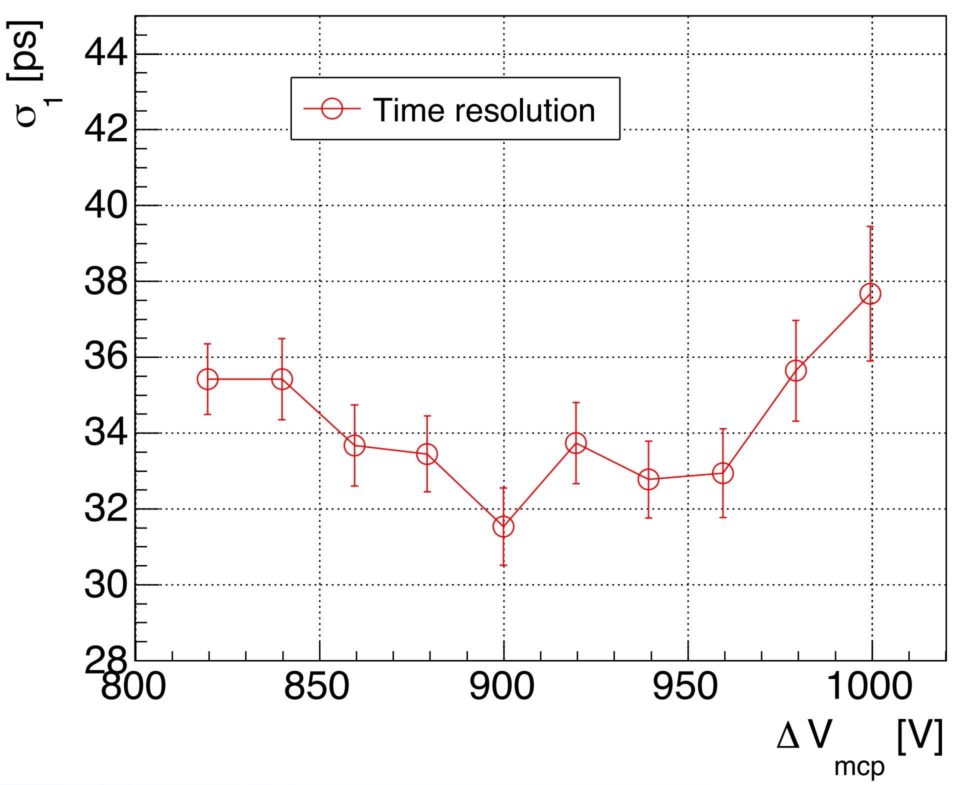


Results from Optimization (II): MCP Voltage

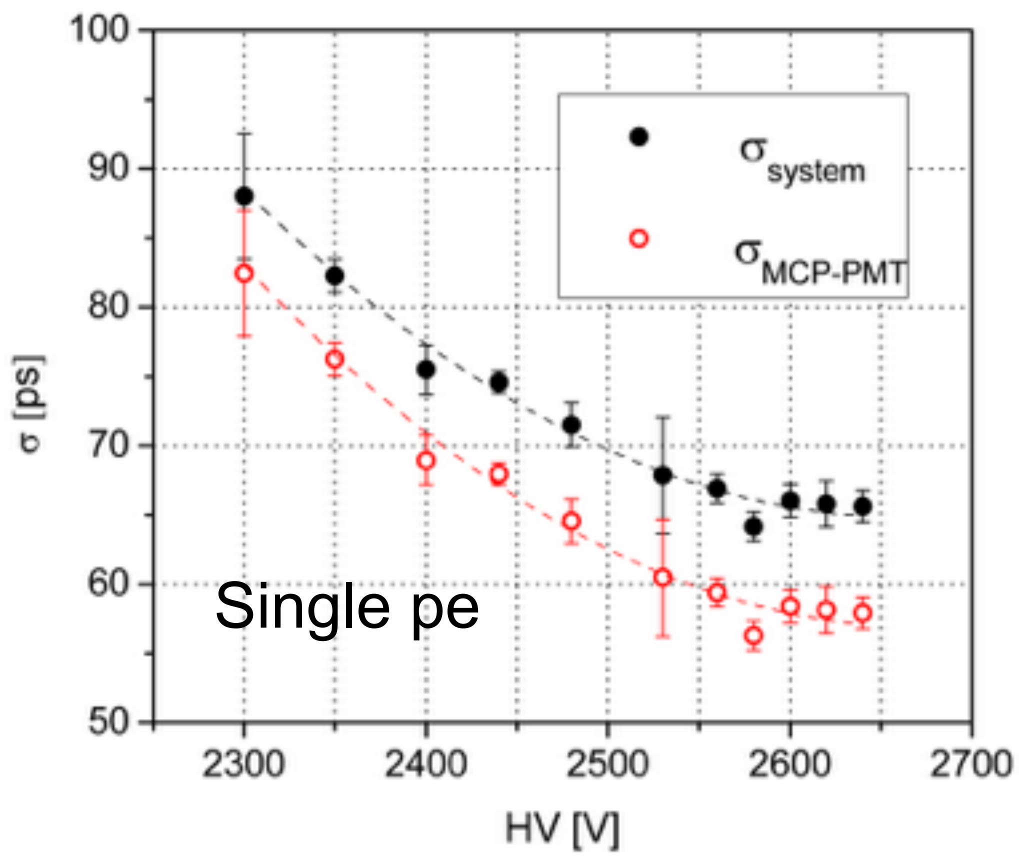
- Scan individual MCP voltages
  - Used identical values on each MCP
  - Rise time improves with gain
  - Timing resolution flat over MCP operating voltage
  - Optimal voltage for tubes is 860-1000V



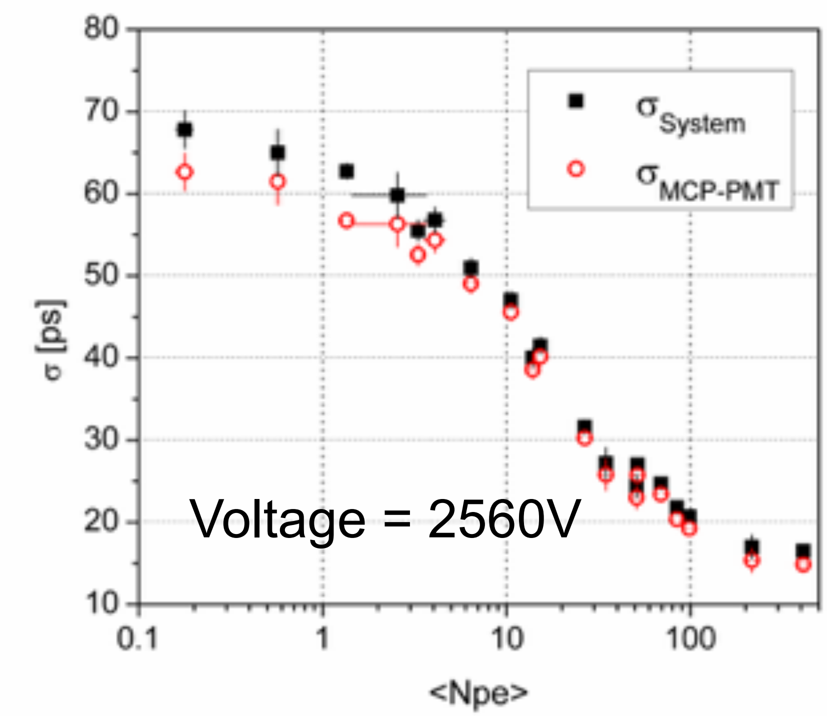




Time Resolution vs Voltage & <N_{pe}>



Asymptotic δt ~ 15ps at high light level



Time resolution vs. Voltage for 6cm Tube

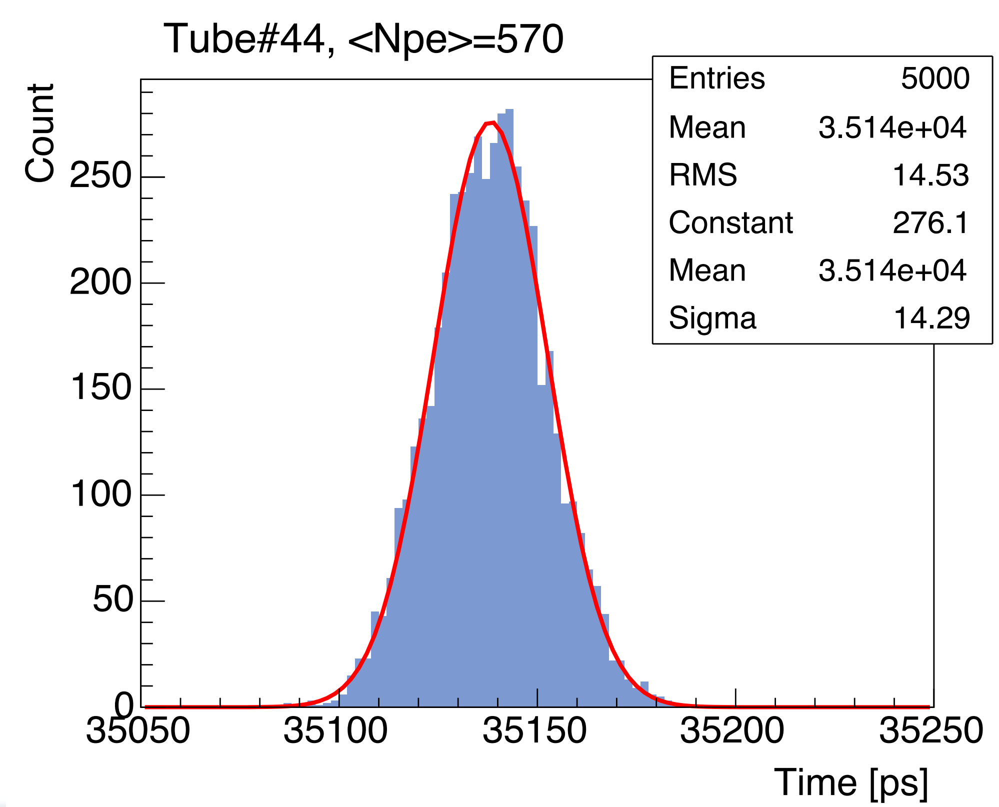
σ_{system} includes

30 ps from laser

7 ps from electronics

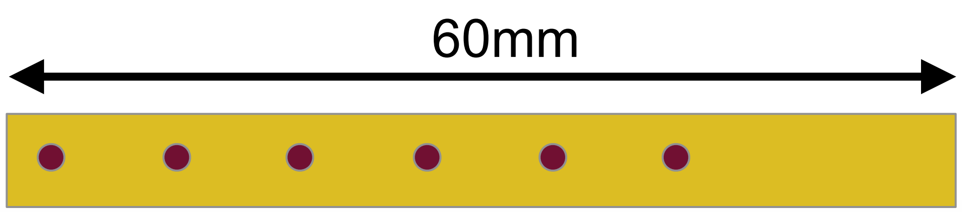
Measurements from older internal resistance tube

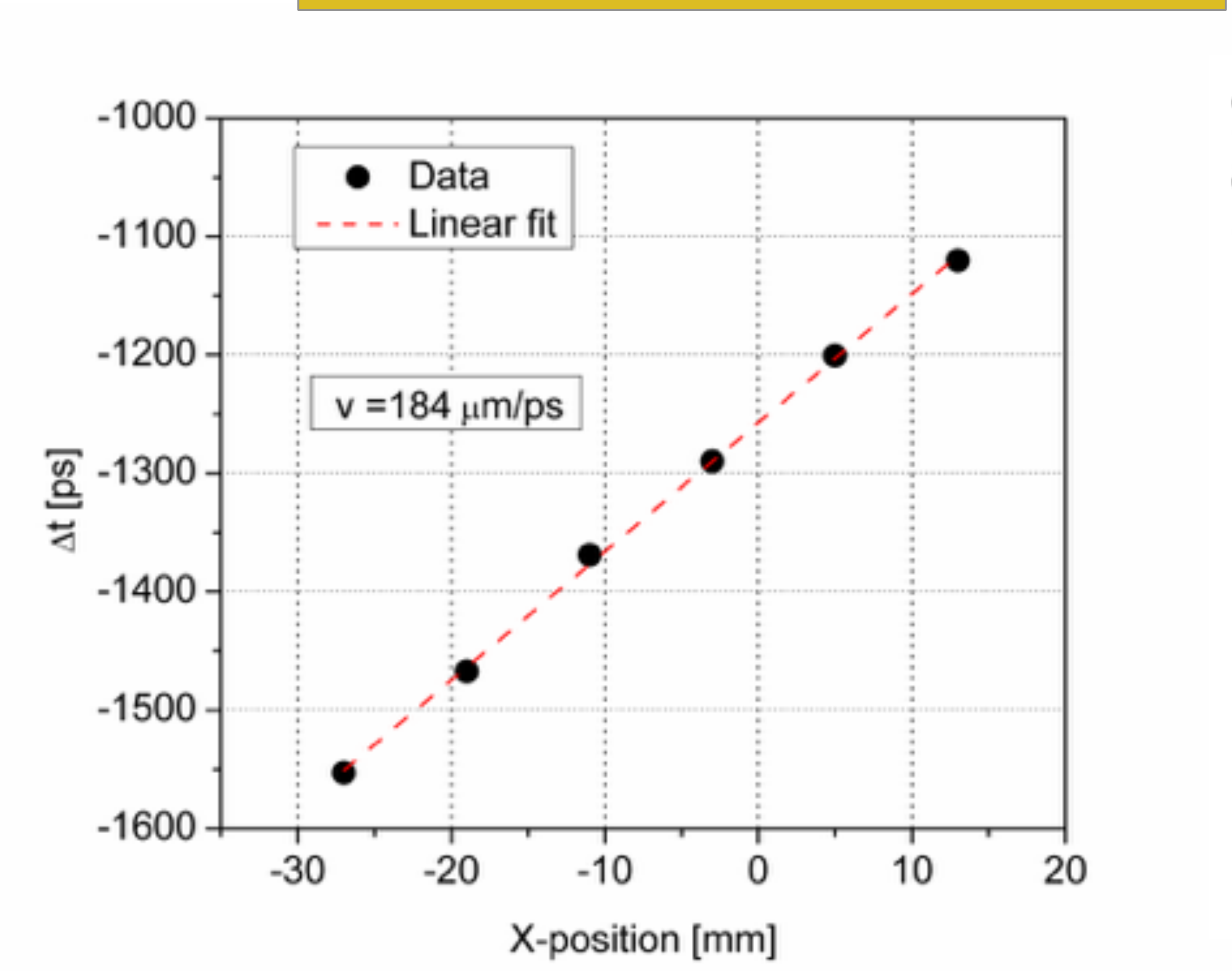
Result from newer IBD-1 tube

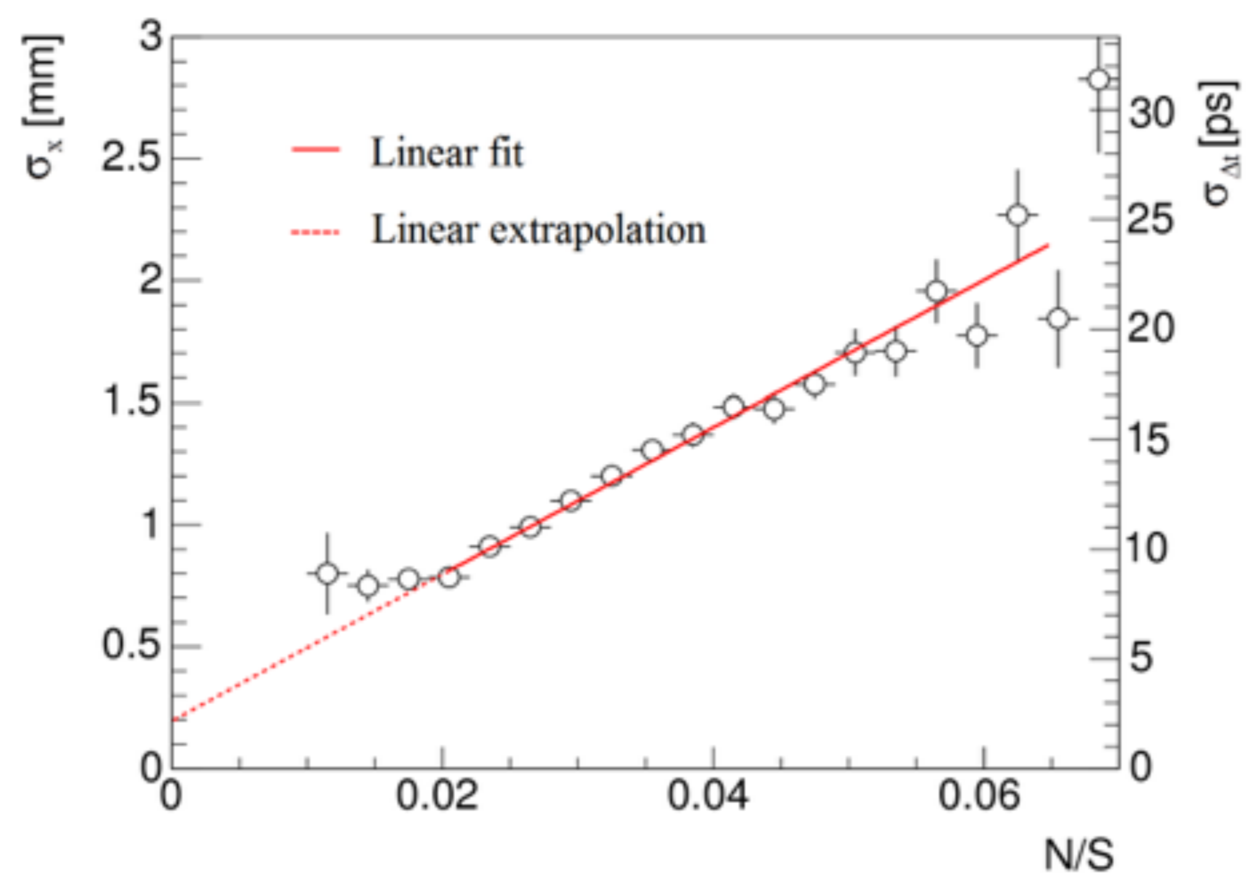


Position Resolution

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







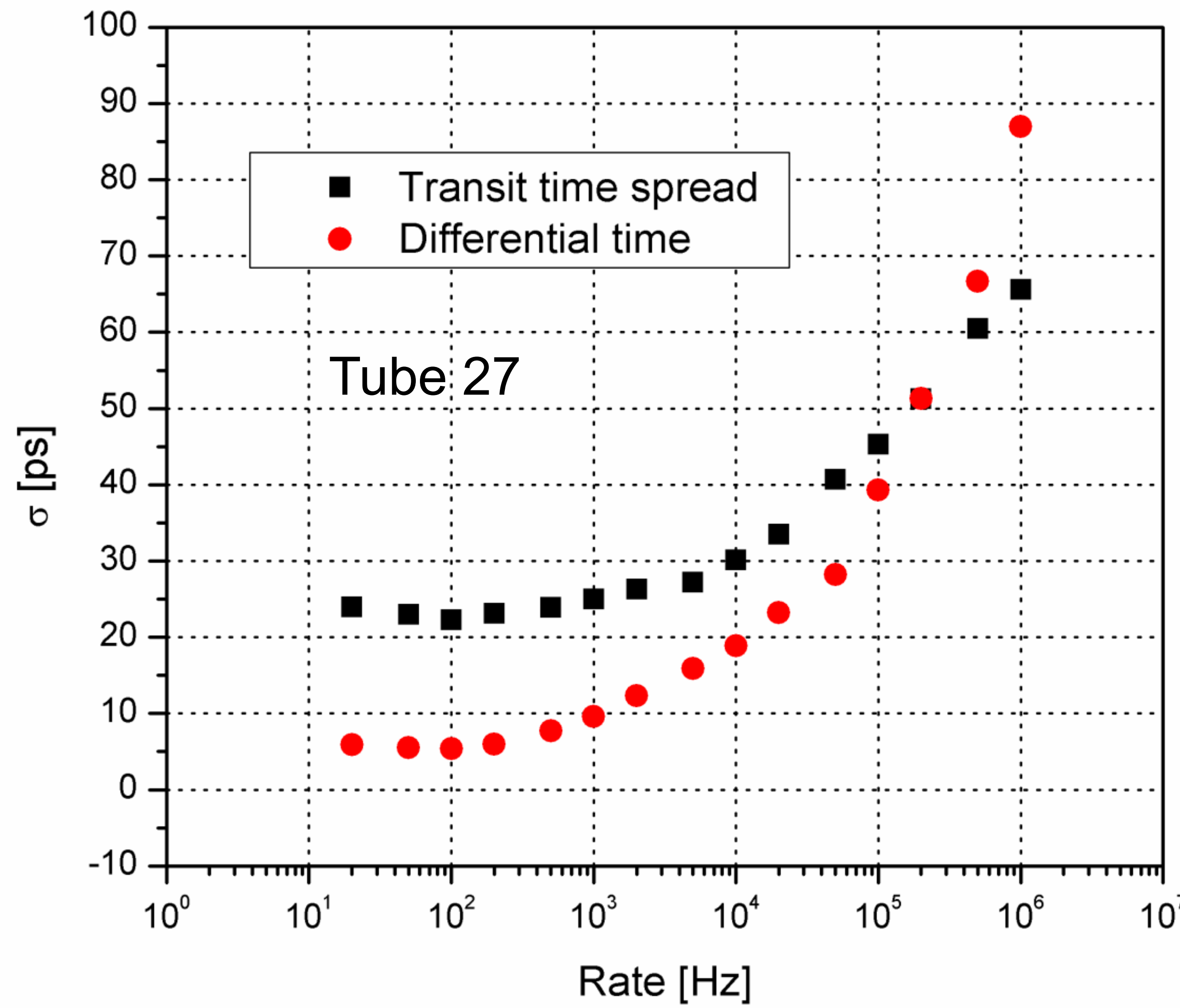
Position resolution limited by beam spot size at high light levels

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



6cm Tube Summary & Near Future Plans

- New tube biasing design qualified and in production
- Reliable tube processing achieved
  - **Goal: 50% overall yield (successful seal, 30 day lifetime) seems realized**
- Working to reduce process time (2 weeks ➛ 1 week)
  - Constructing separate Bake & Scrub Chamber to pre-process MCPs
- Photocathode QE still needs work
  - Continual thought and effort on fabrication improvement
  - Studying possibilities for VUV sensitive photocathode for LAr and LXe use
- Ongoing work on readout improvement for users
  - New board design in fabrication for IBD-1; user-friendly for distributed tubes
  - Pixel anode is needed; dependent on effort and funding availability
- **Getting ready to try 3D printing of glass capillaries arrays**
  - May reduce cost: no capillary drawing; no slicing, grinding, polishing
  - Surface roughness could be a noise issue though
- **Beginning study of feasibility of using MCPs in gas for X-ray polarization detection**
  - Supported by “seed” grant from Argonne lab management
  - Formation of electron cloud in gas; drift to MCP for proportional amplification

Overall Summary

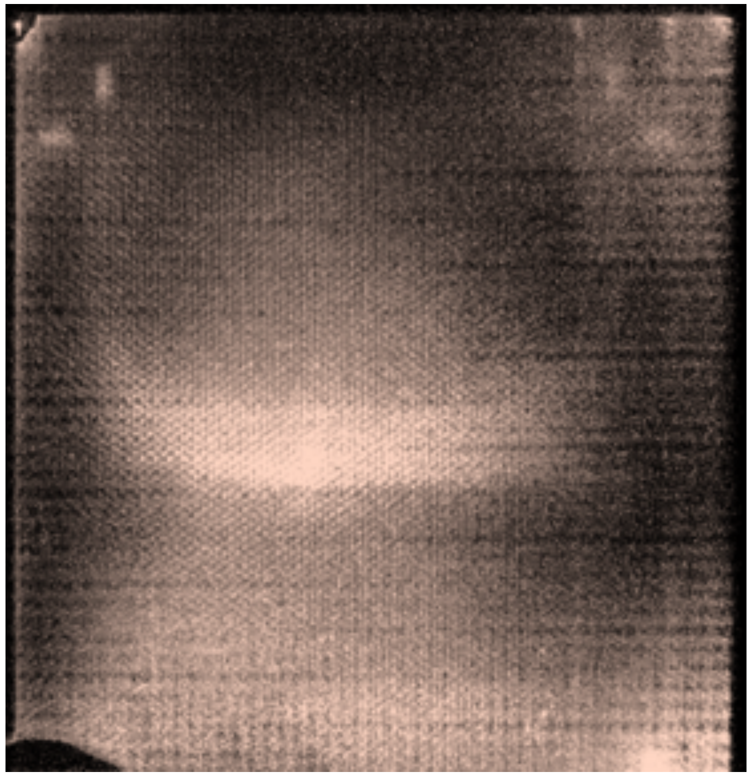
- Atomic Layer Deposited (ALD) MCP fabrication has achieved reliable production of high, uniform gain MCPs. Future work to
  - understand characteristics of baseline ALD materials
  - develop new materials for lower cost, better stability, improved performance
- ALD MCP Photodetectors progressing along several efforts
  - LAPPD 20cm x 20cm active area commercialization in progress at Incom, Inc
    - Production equipment all delivered and being commissioned
    - Hope to fabricate tube by year end
    - Look for tube production in 2016
  - Glass-body tubes set for fabrication at Space Sciences Lab/Berkeley
  - In situ assembly design with PMT-style photocathode deposition work at Univ. of Chicago
  - Argonne 6cm x 6cm small format MCP photodetector tubes being produced

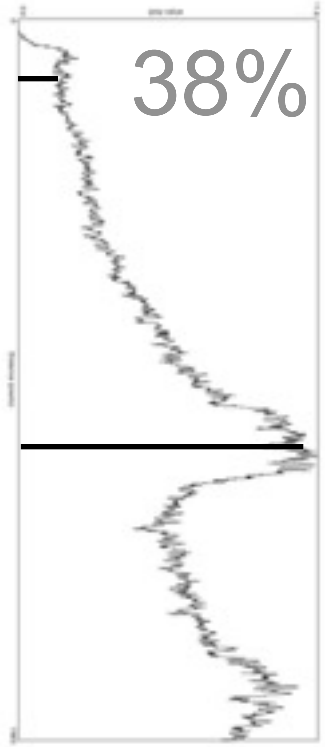
Looking to have more tubes, small & large, into HEP community in near future

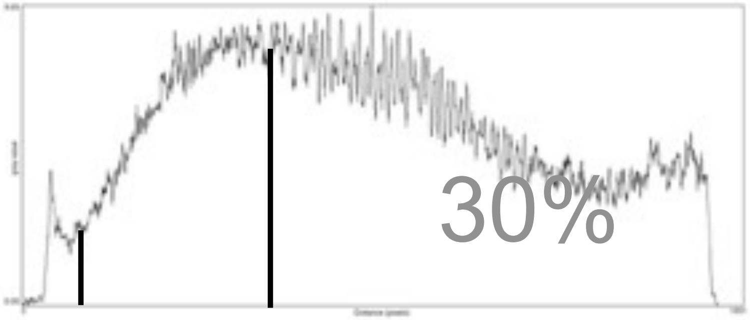
Backup Slides

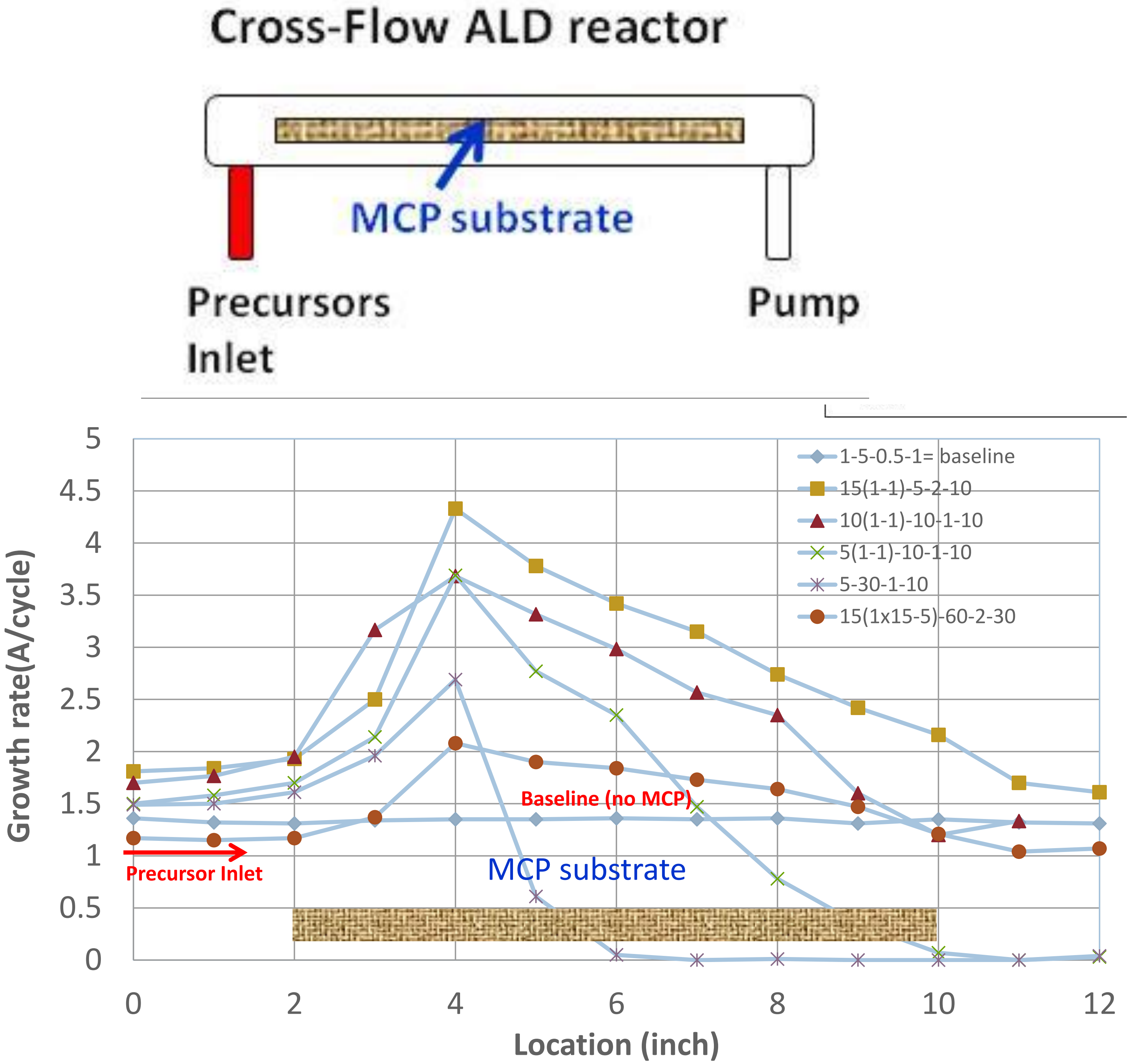
Initial Non-Uniformity of 20cm MCP Gain Using Cross-Flow ALD Method

Cross-flow Chem2





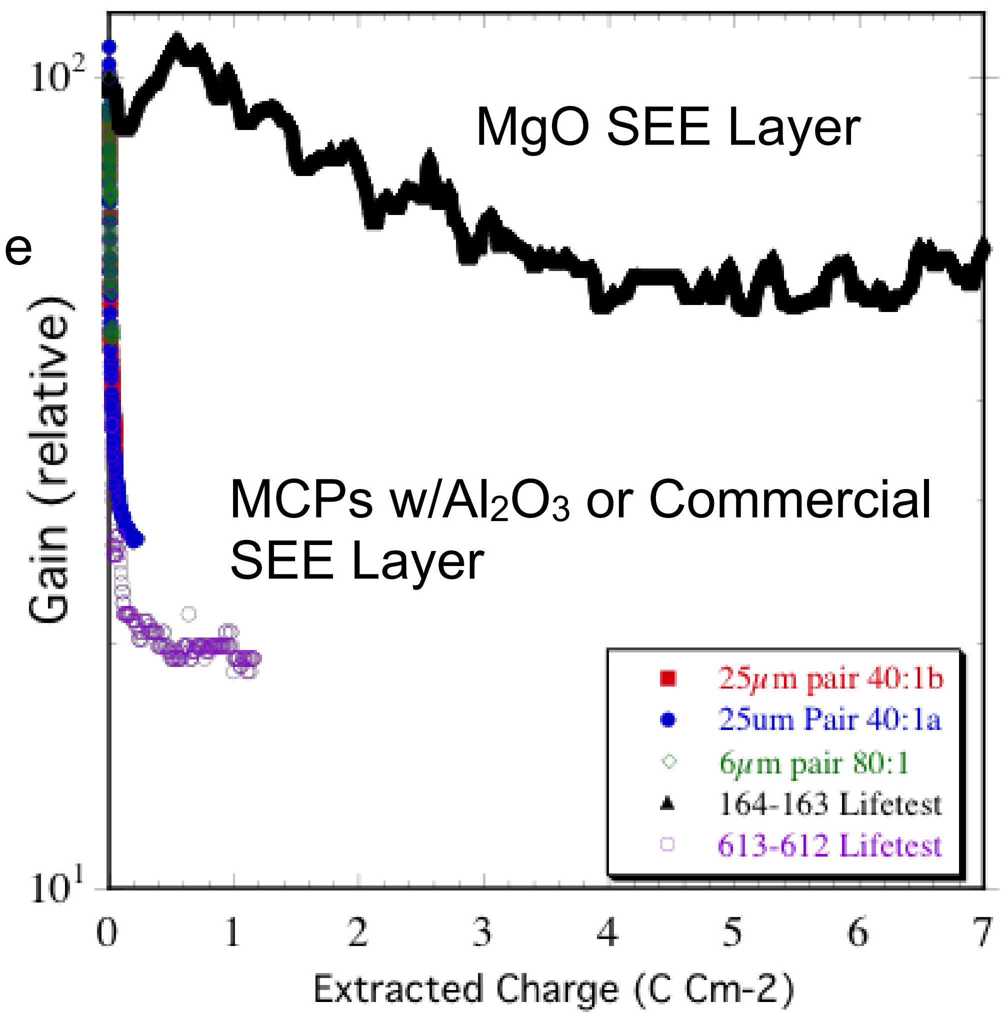




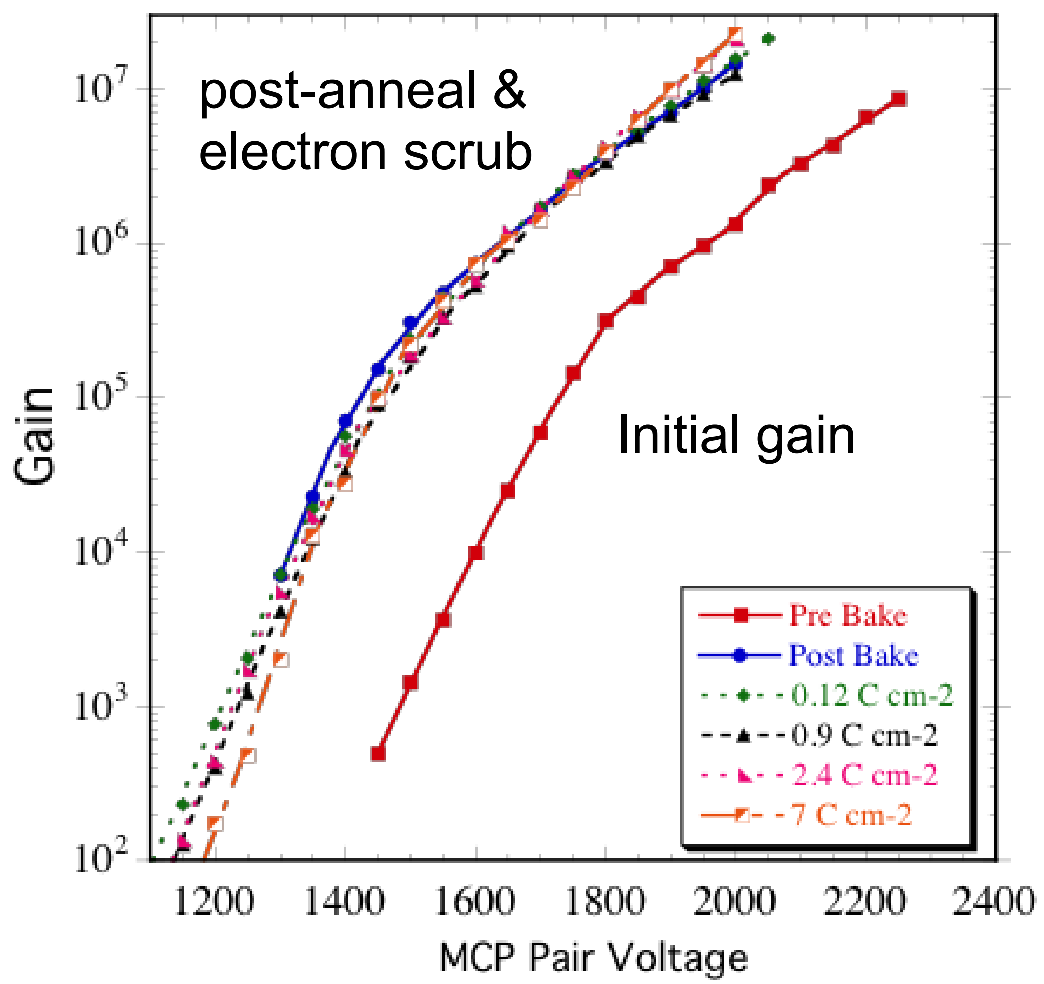
Non-uniformity = (Max-Min)/Mean * 100%

MgO vs Al_2O_3 vs Commercial SEE Layer

Note:
Log Scale



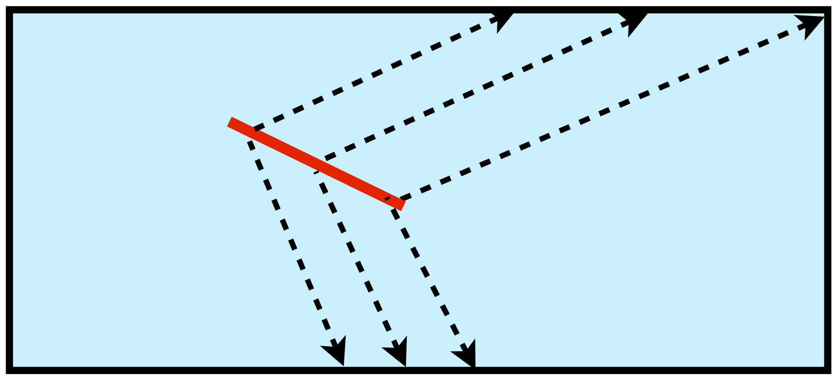
MgO SEE Layer



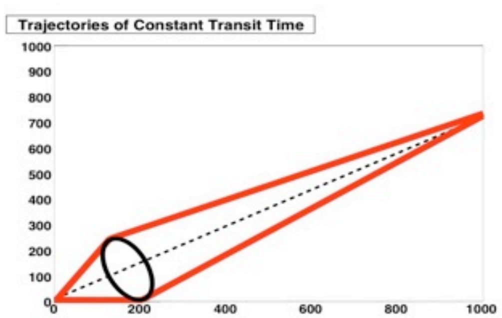
- Standard Secondary Emission Layer (SEE) for production of MCP gain is currently MgO
- Gain increases upon annealing or with initial scrub, then extremely stable

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

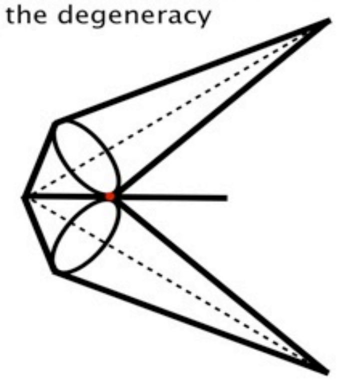
Signal: 20 photons/mm Cherenkov
Drift time: 225 m/μs
Track trajectory -> drift distances

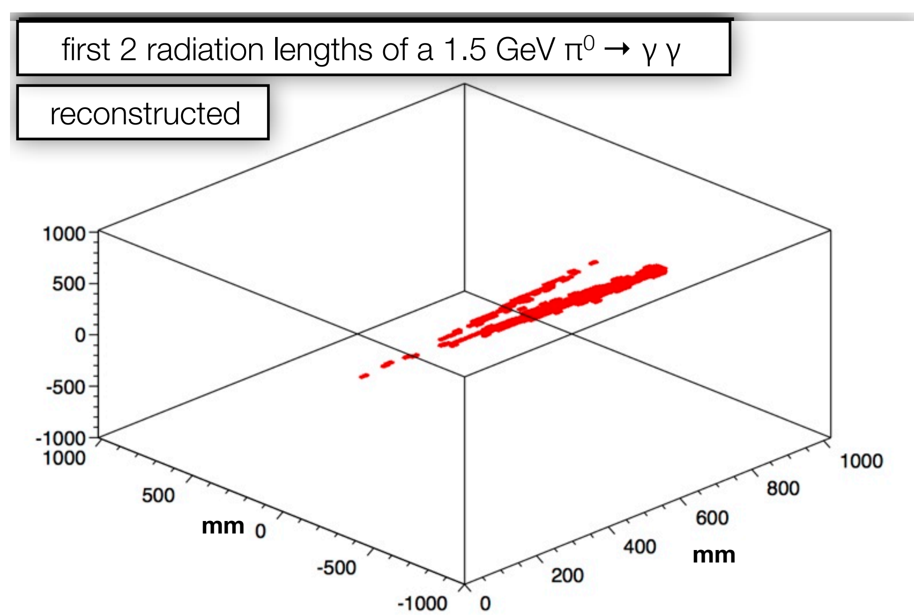


For a single PMT, there is a rotational degeneracy (many solutions).



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





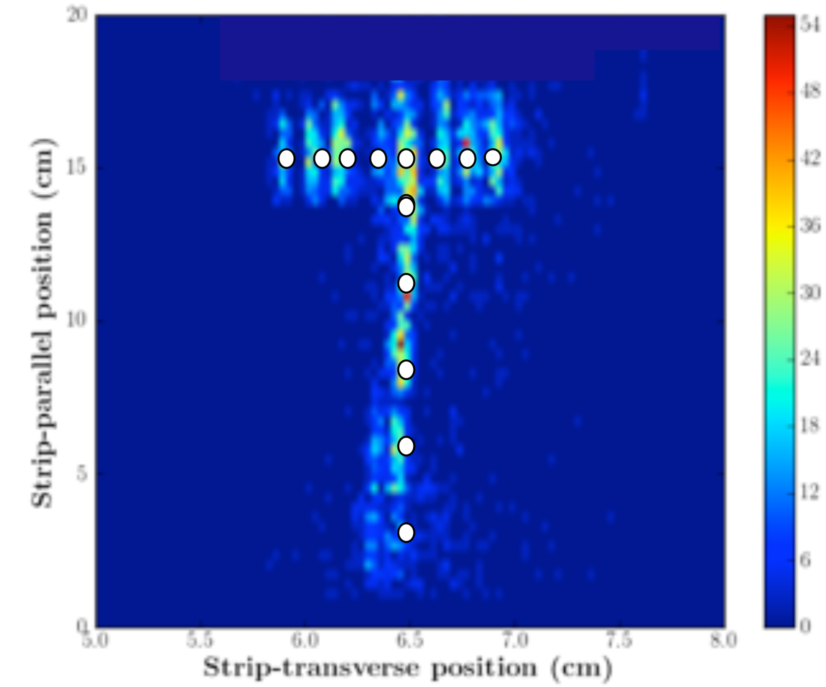
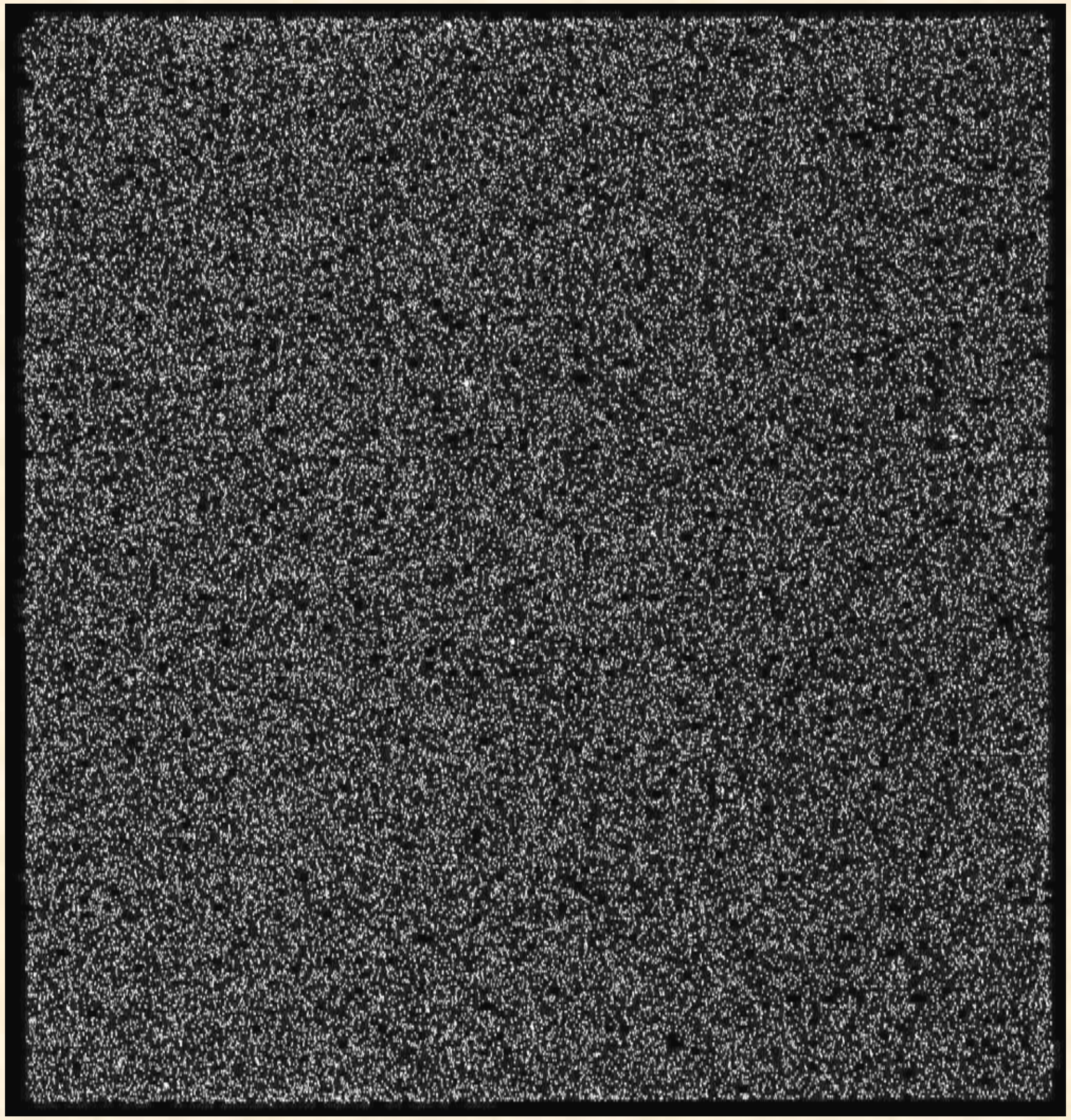


Image from UV laser scan on 20cm LAPPD MCP Detector: n.b. o-ring sealed, continuously pumped prototype

graphic credit: Matt Wetstein

Background 20cm x 20cm 20μm pore MCP Pair



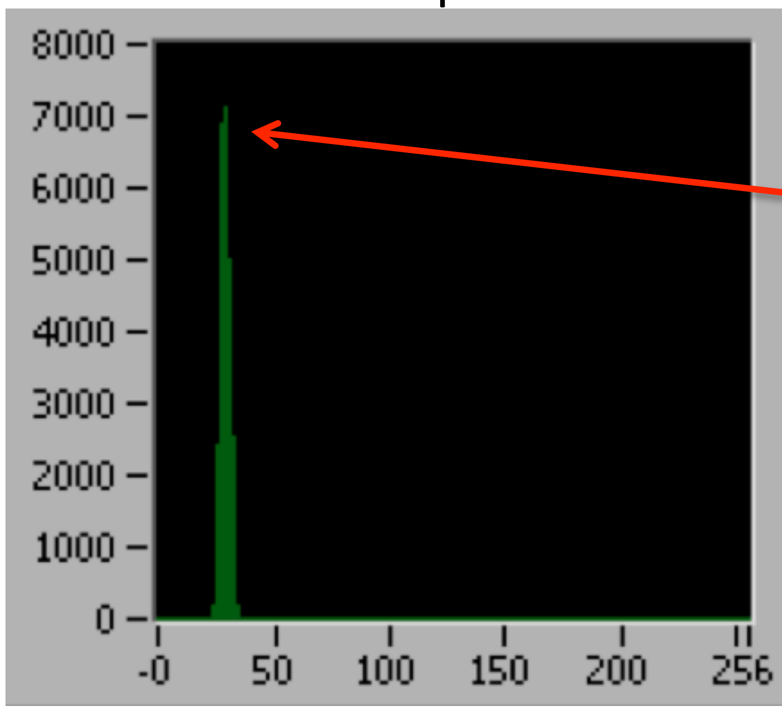
20cm MCP pair background, 2000 sec, 0.055 cnts sec^{-1} cm^{-2}. 2k x 2k pixel imaging.

- 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

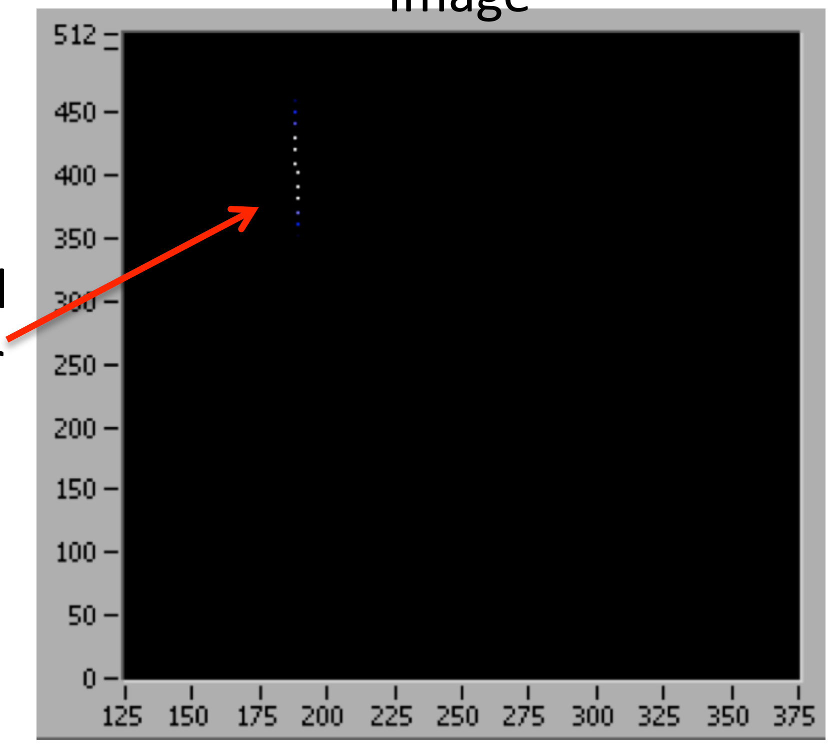
Ceramic Body Tube #1
Pulse Amplitude and Imaging

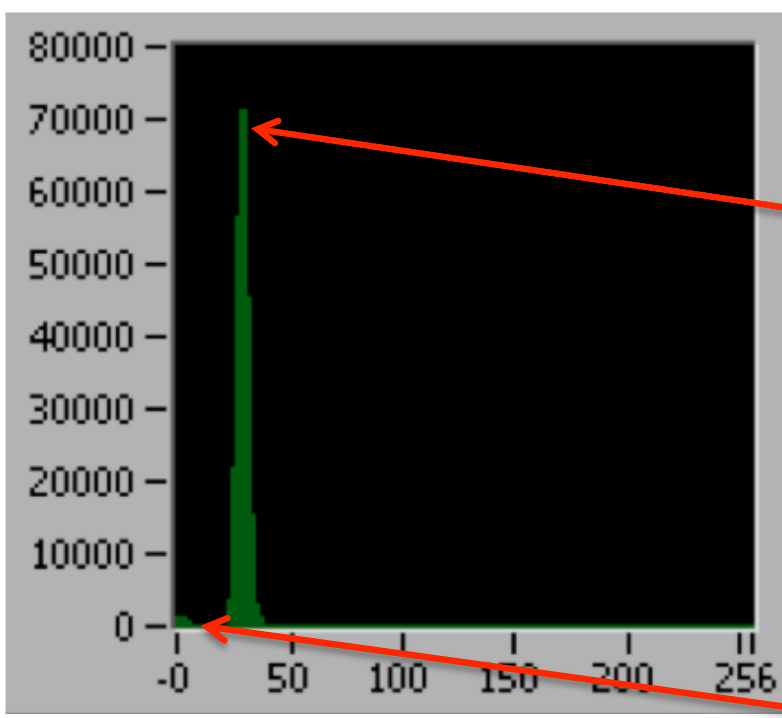
Pulse amplitude



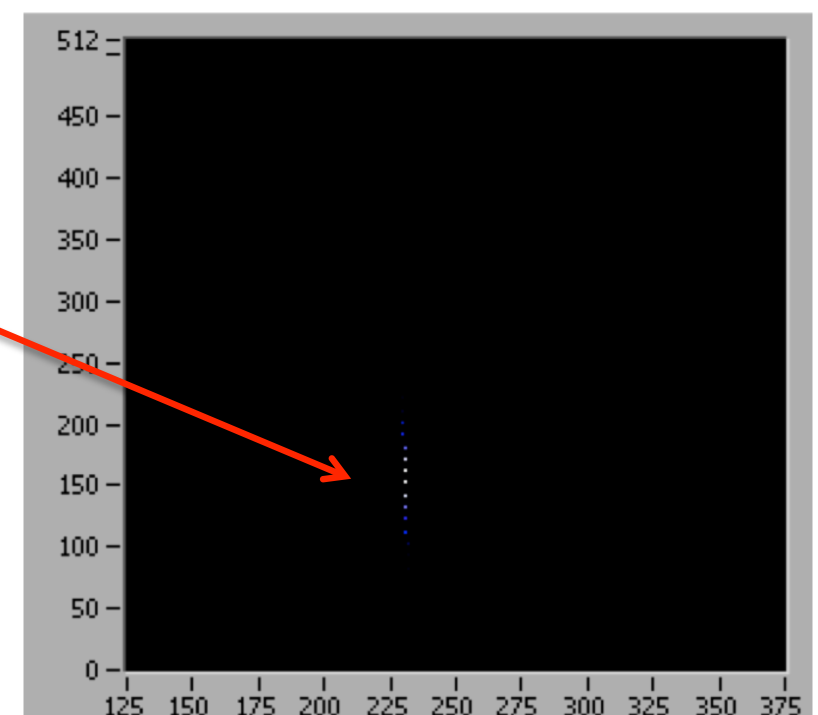
Pulse amplitude and Laser spot image for ~30 photoelectron Pulses (100ps laser)

Image



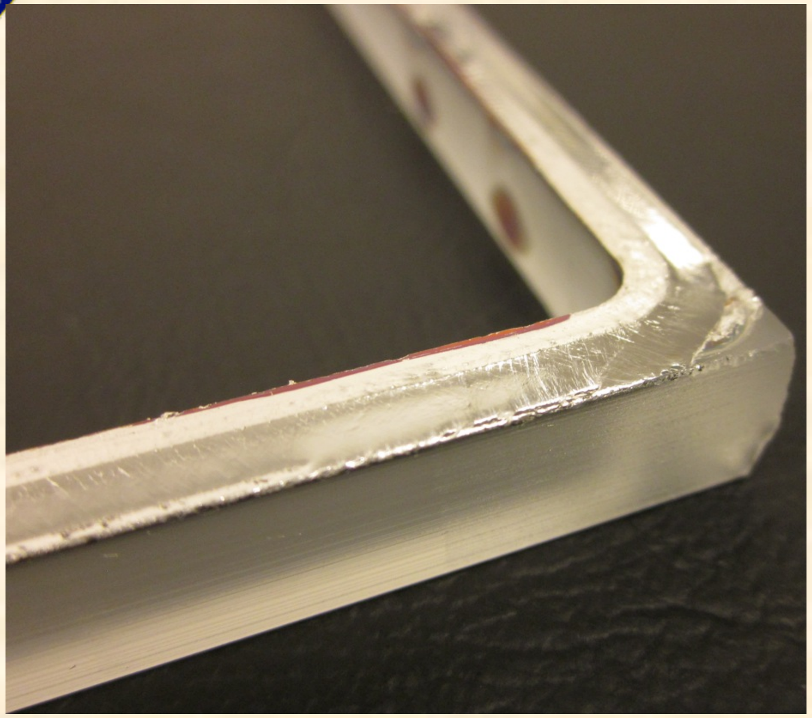


Pulse amplitude and Laser spot image for ~10 photoelectron pulses (100ps laser), at higher tube gain, See single electron noise in PHD!



Graphics Courtesy Ossy Siegmund & Jason McPhate, SSL

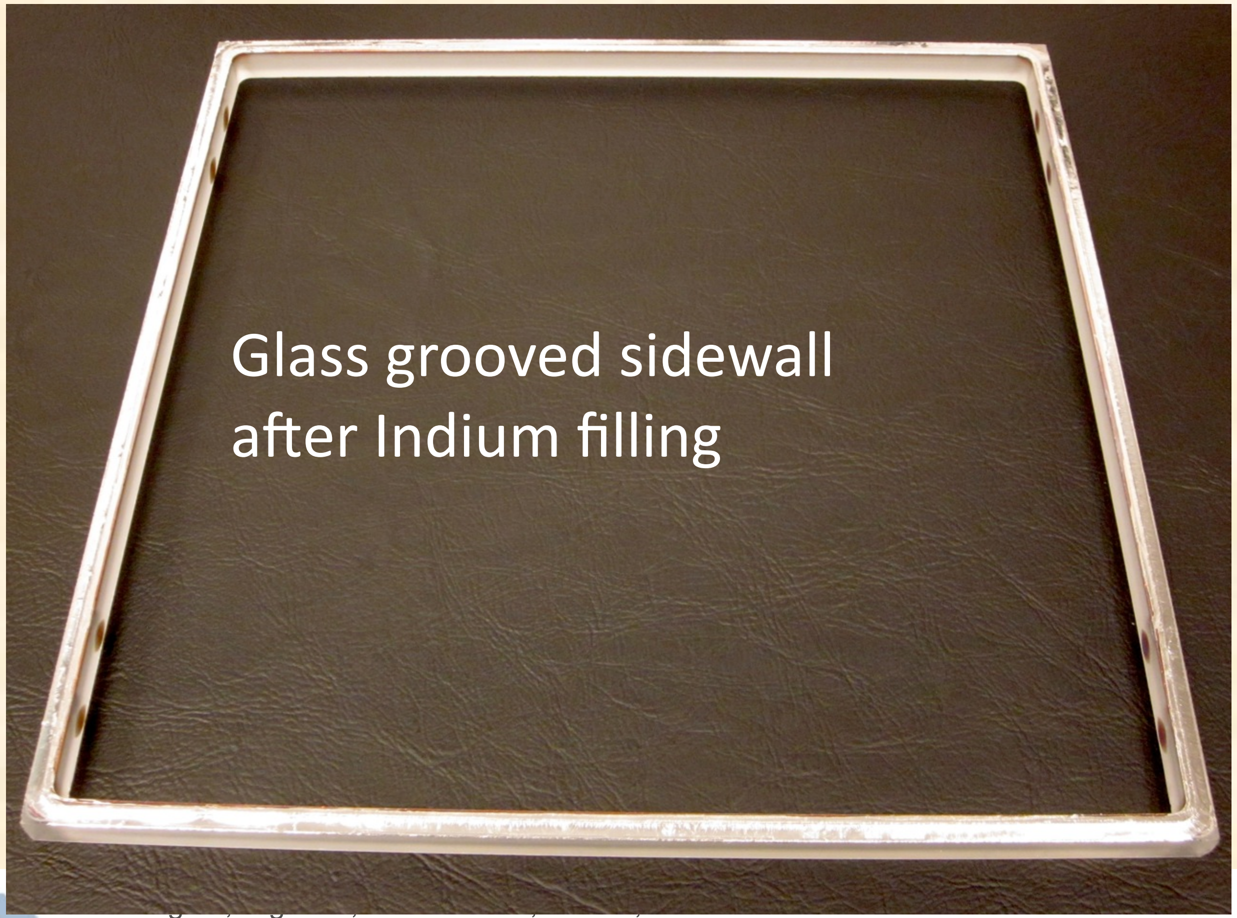
Glass Grooved Sidewall 8in Indium Seal.

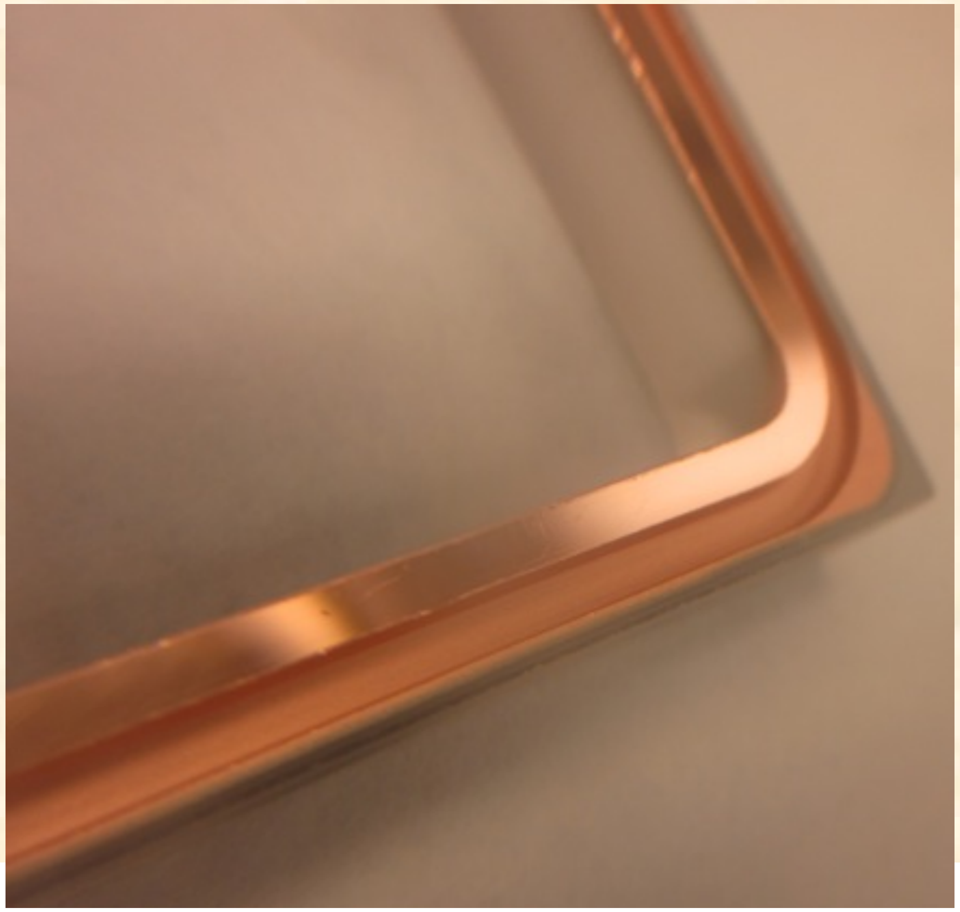


Glass grooved sidewall
after Indium filling

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.

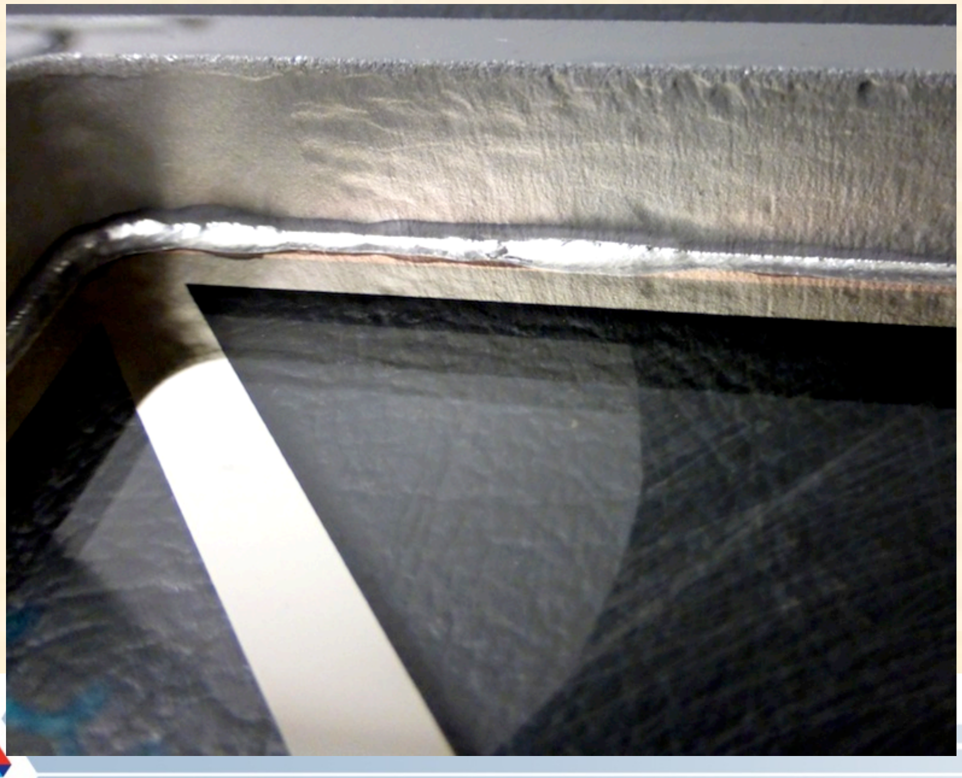
Glass grooved sidewall after NiCr
and Cu evaporations

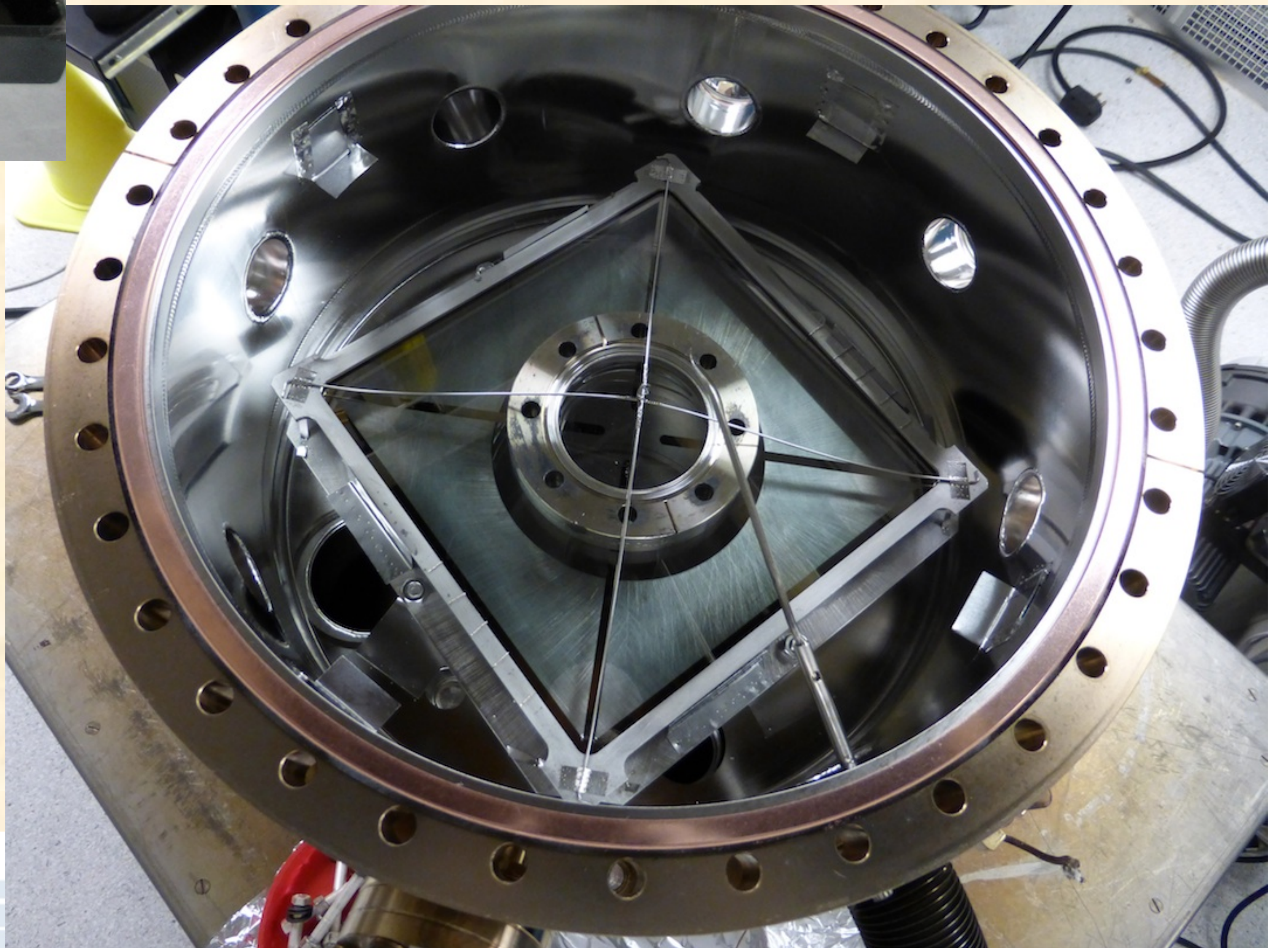




Glass Grooved Sidewall Seal Test

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

INCOM

Bright Ideas in Fiberoptics

Recent Incom Equipment Installations

Plasma cleaner rec'd 9/2015

Vacuum oven due 10/2015

LAPPD integration and sealing tank rec'd 9/2015

Beneq ALD coater with load-lock installed 6/2015

Thermal evaporator commissioned 12/2014

Measurement & test station, commissioned 8/2015

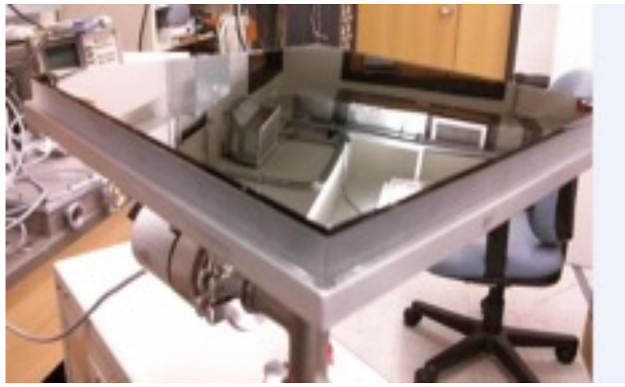
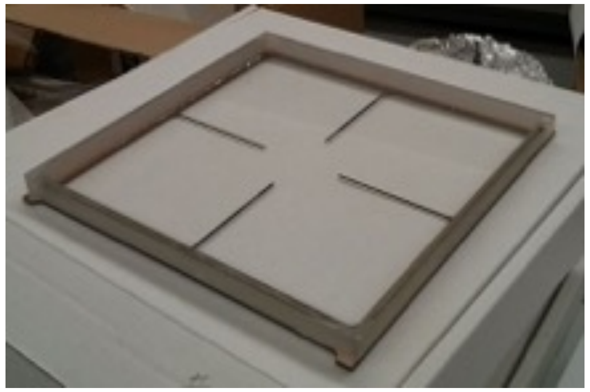
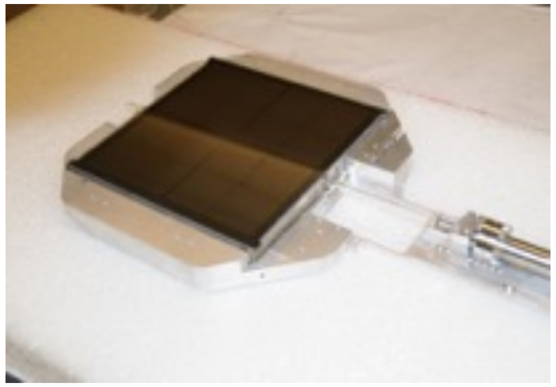
Vacuum oven is final major piece of equipment needed for fabrication of LAPPDs at Incom

Slide credit: Chris Craven

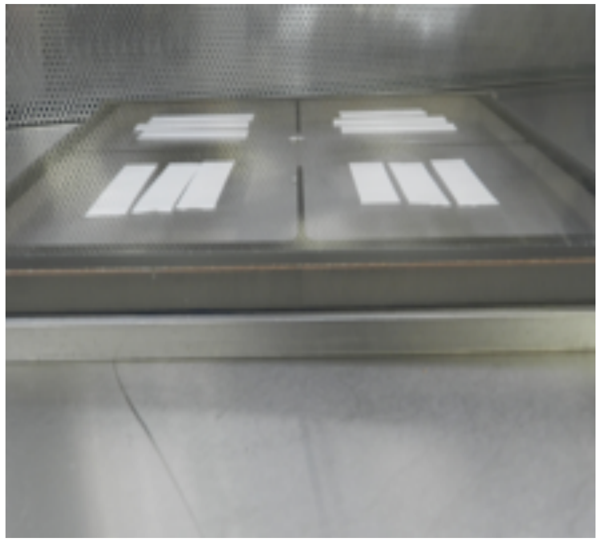
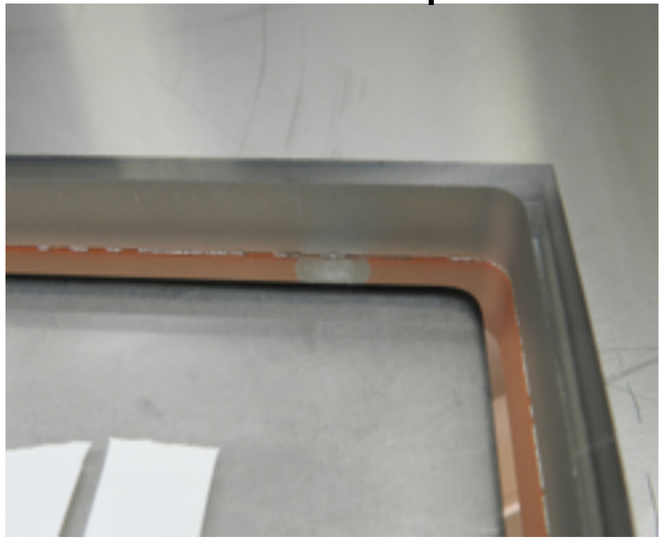
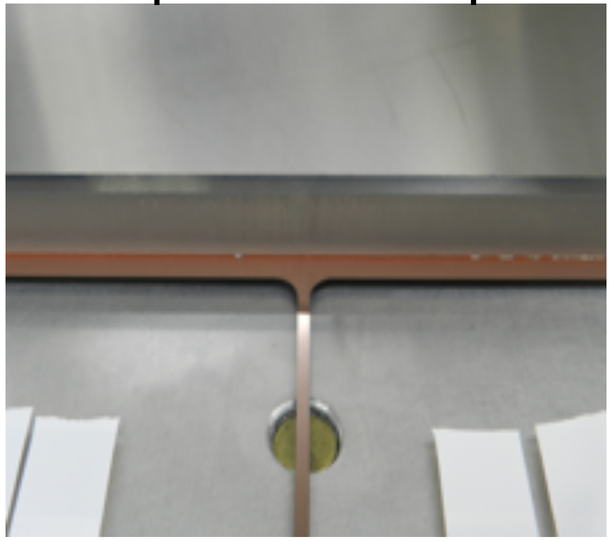
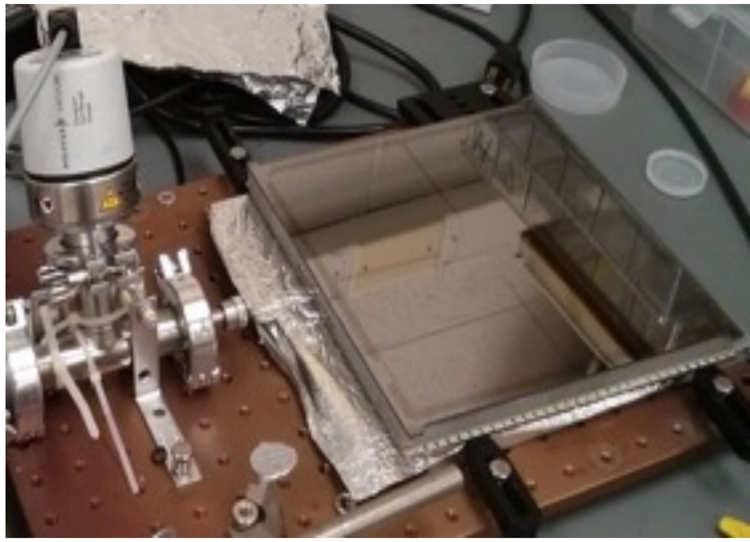
In Situ LAPPD Assembly at U. Chicago
Critical Component #1: Top Window Seal

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)

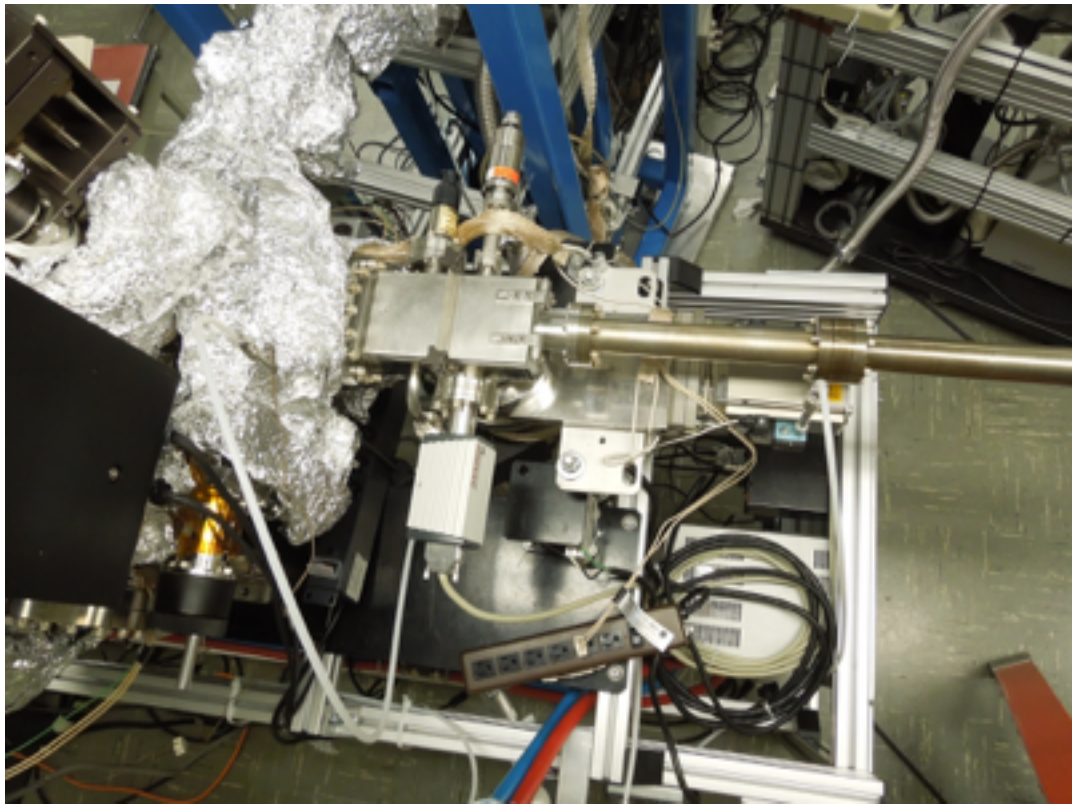




II) Pure indium solder seal (~157°C) in vacuum
- high temperature seal (350°C), done in the processing chamber during the bake
- better suited for Cs/K photocathode deposition temperature

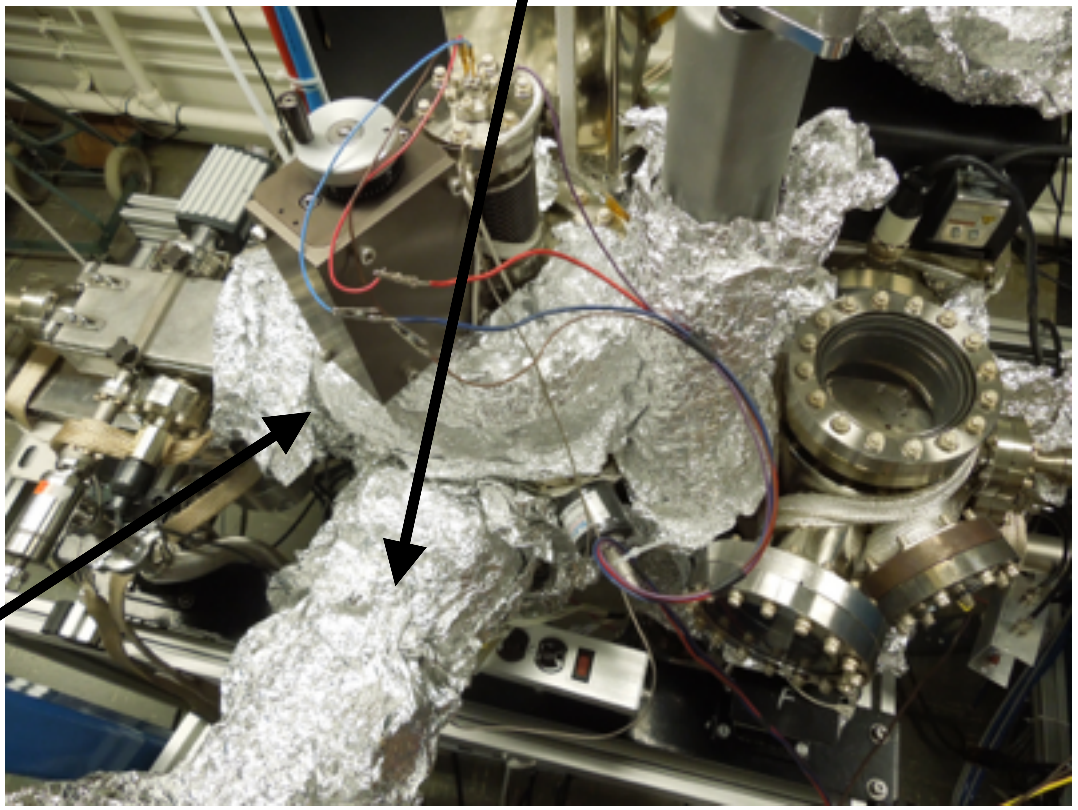
SmSTPS Chambers

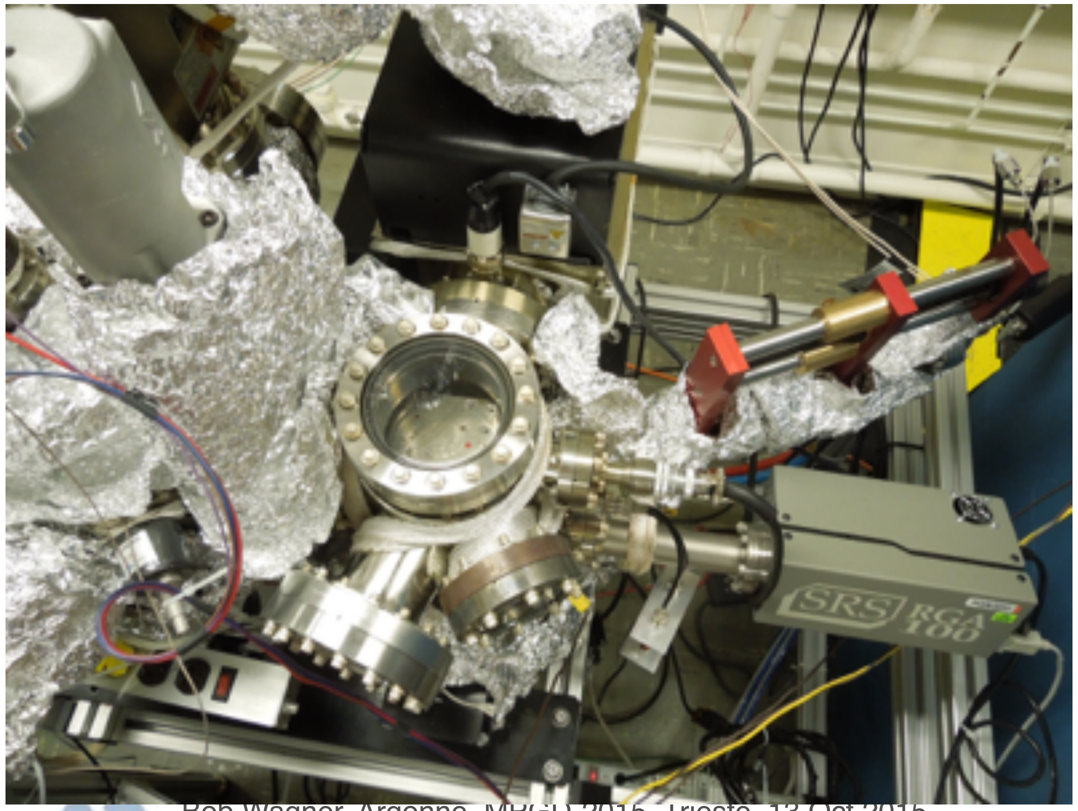
Connection to Sealing Chamber



Loadlock

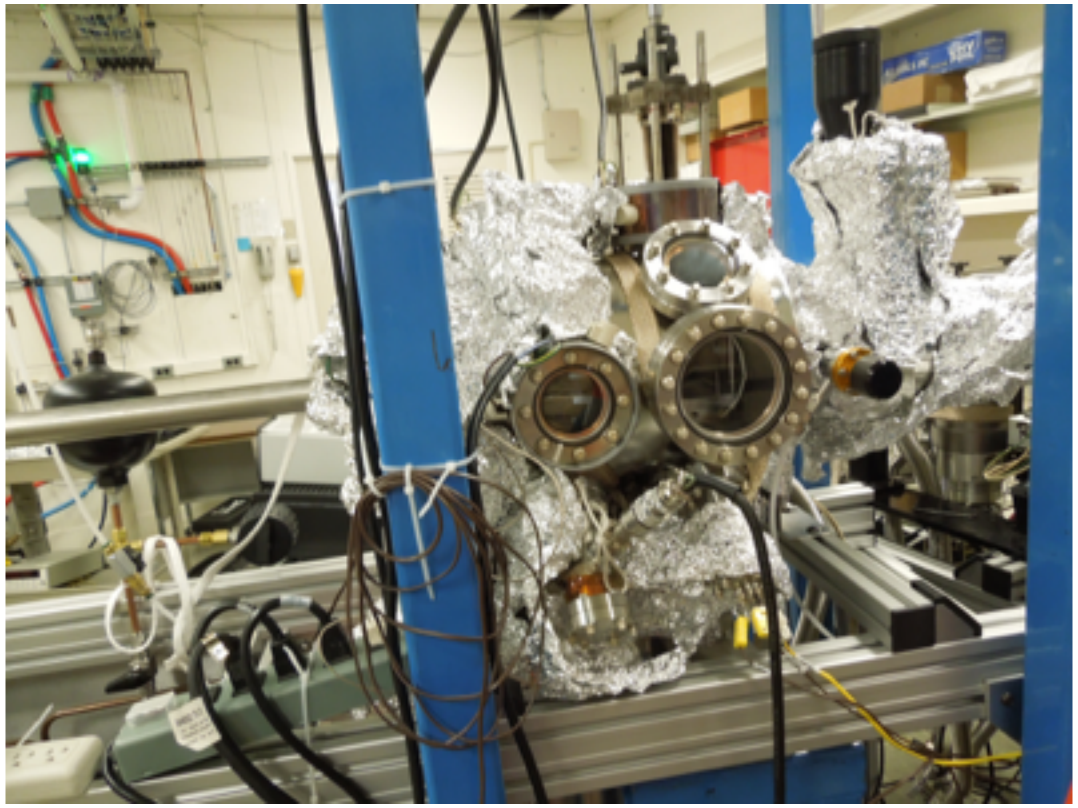
Bake &
Scrub





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

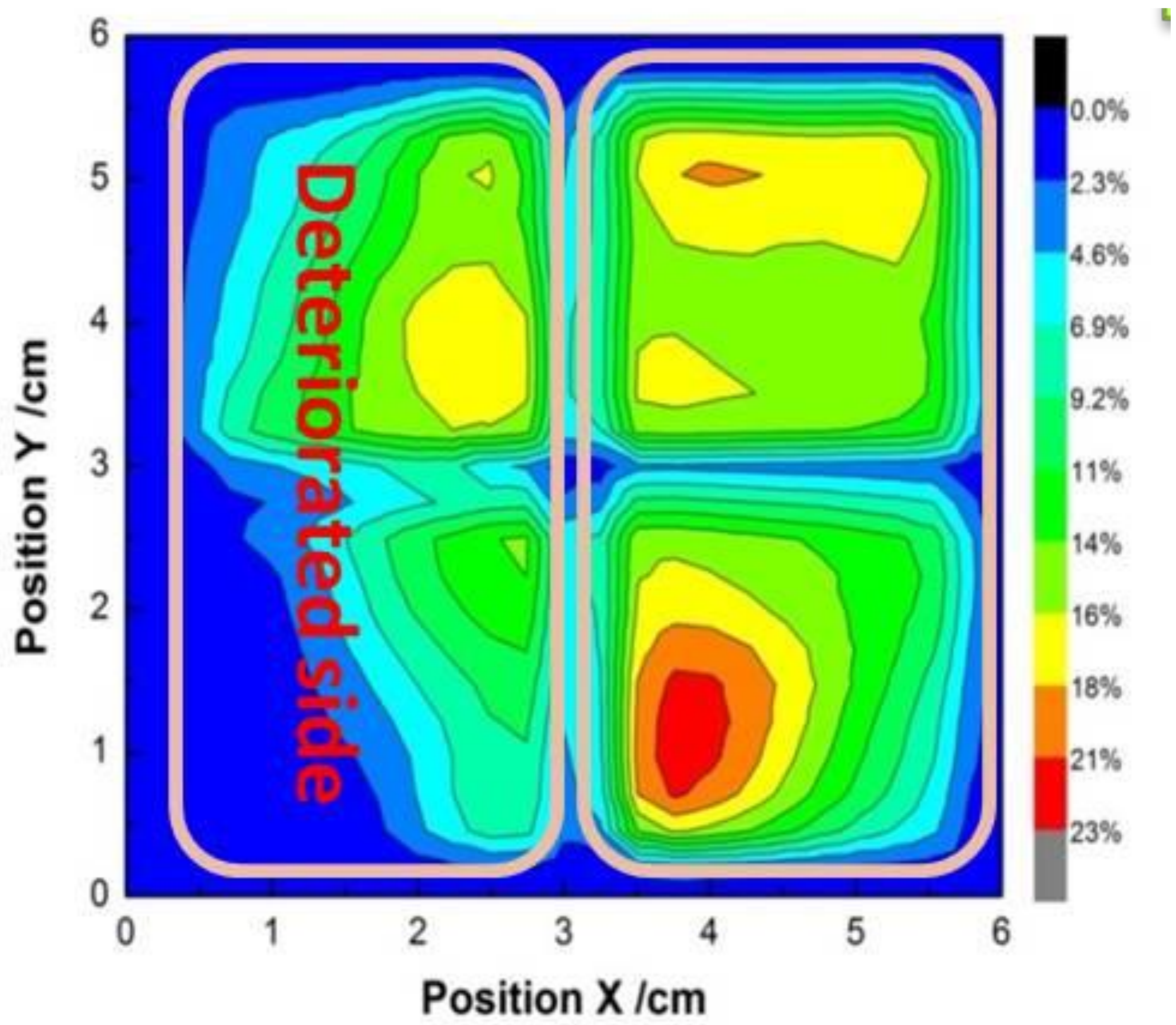
1x(8”x8”) MCP= 9x ($6x6cm^2$) MCPs

Example of 6cm Photocathode with 22% QE Region

Prototype IBD-1 tube allowing direct QE measure

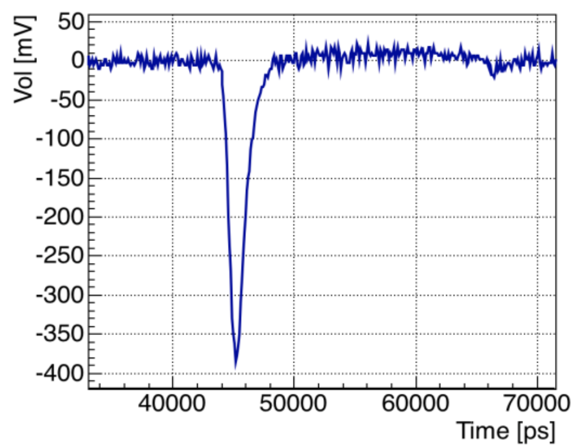
Average QE ~ 15%, Max ~23%

Cathode deteriorated due to small leak in bottom frit seal



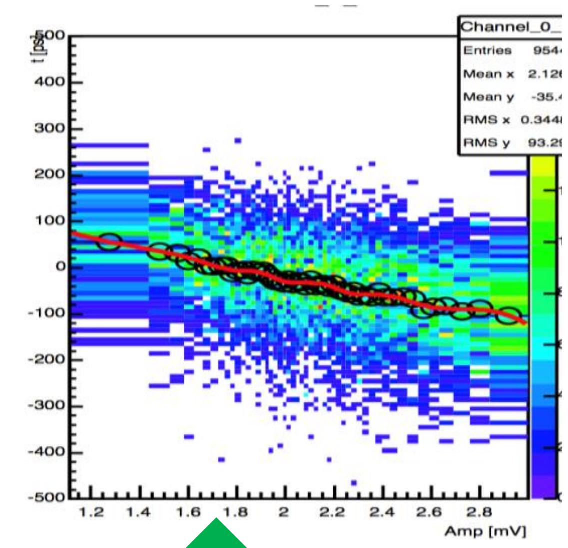
Data Analysis Flow

Raw MCP waveform

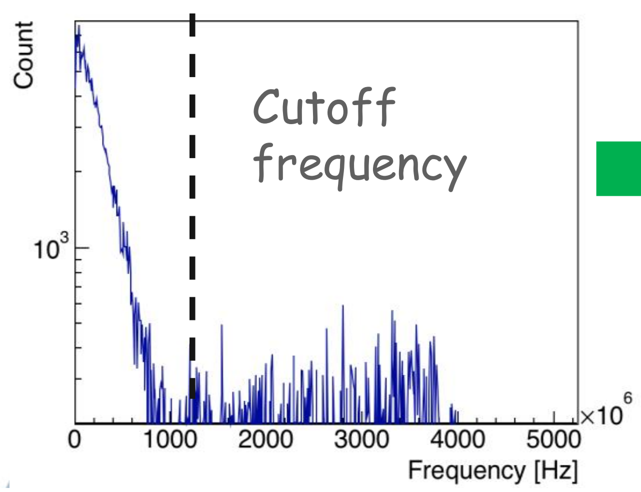


1. Record digitized waveforms
2. Fast Fourier Transformation (FFT)
3. Frequency filtering
4. Constant Fraction Discriminator (CFD)
5. Slewing correction

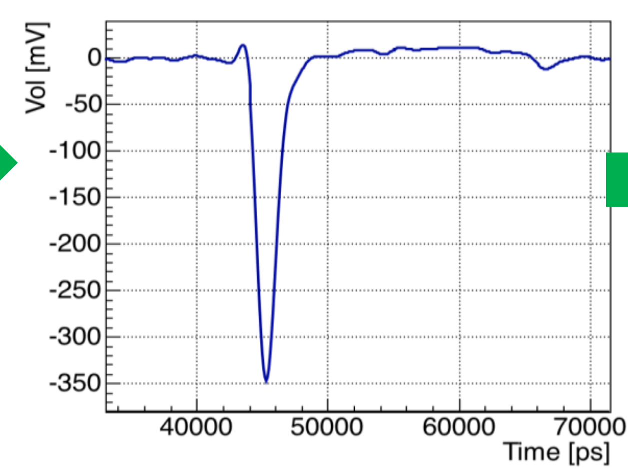
Slewing correction



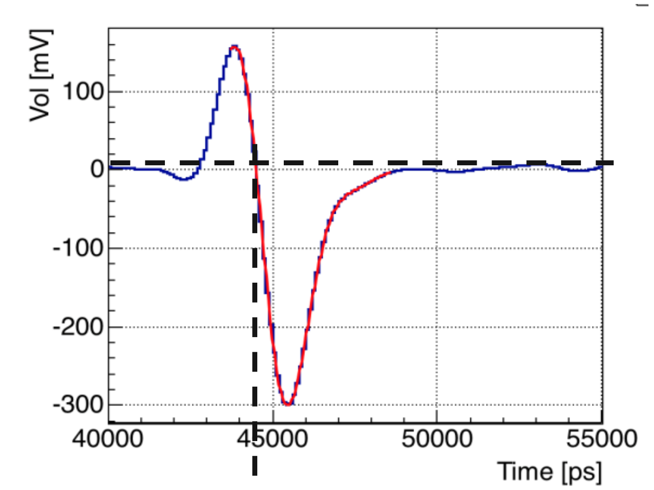
Frequency spectrum



Filtered MCP waveform

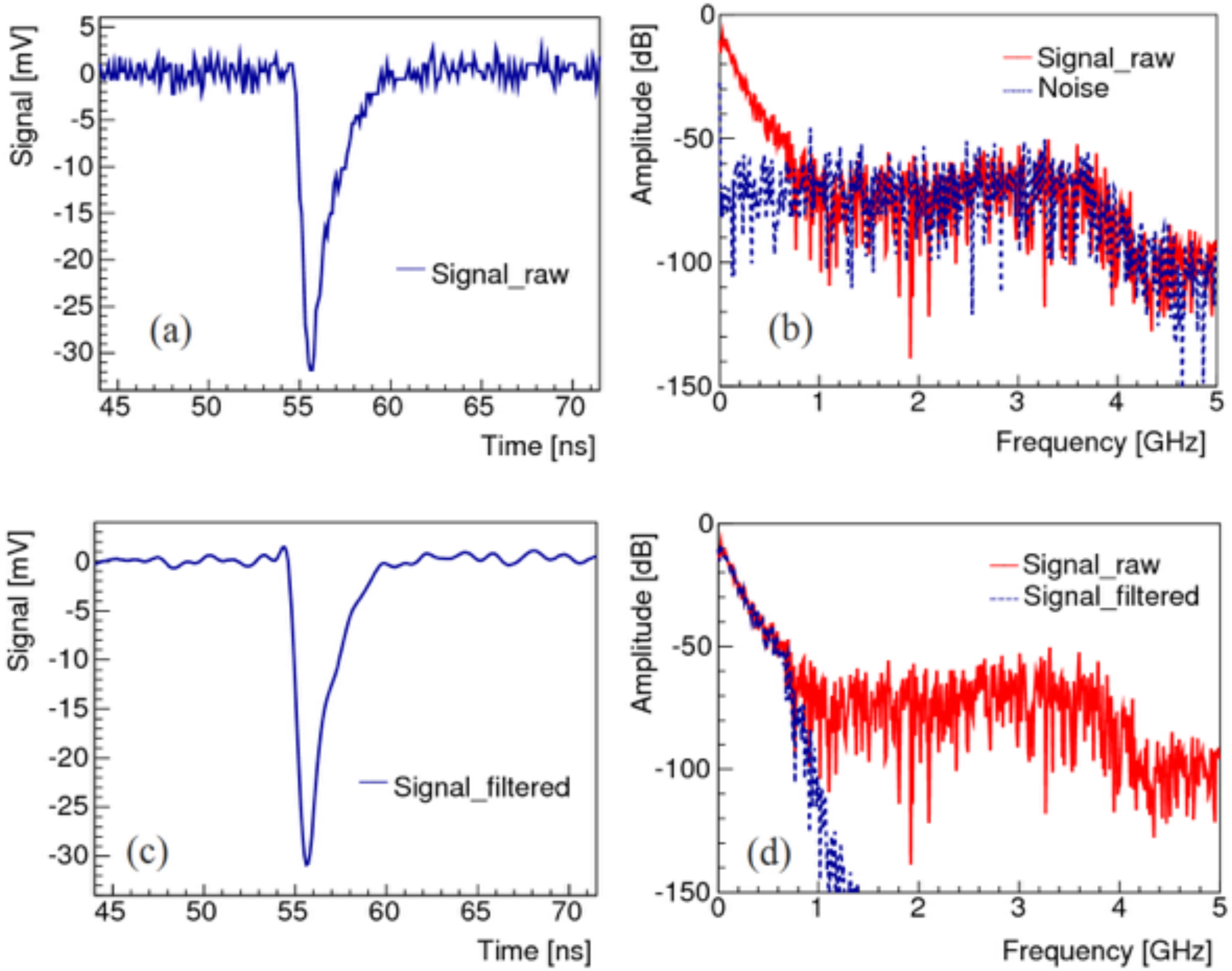


Standard CFD/ARC



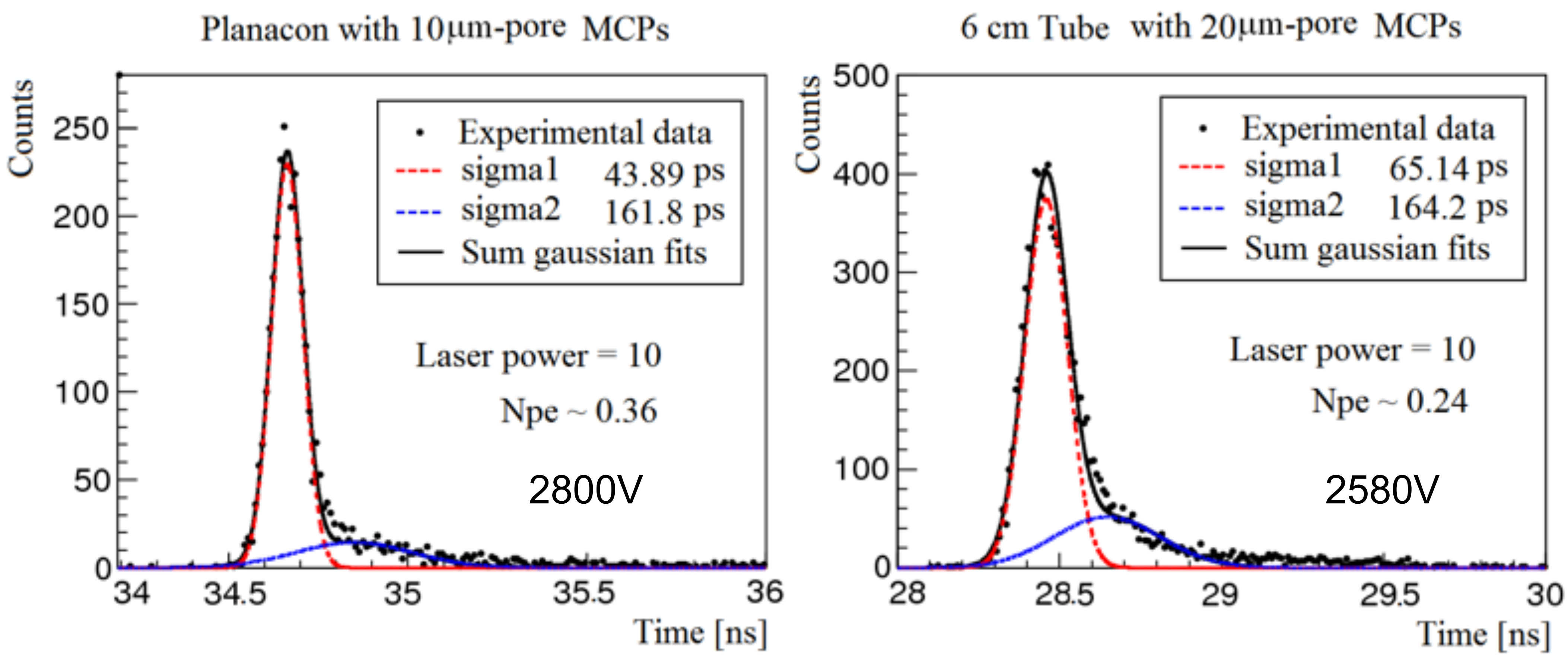
Timing

Noise Removal from MCP Laser Signal for 6cm Characterization



Butterworth noise filter applied to improve signal shape for timing

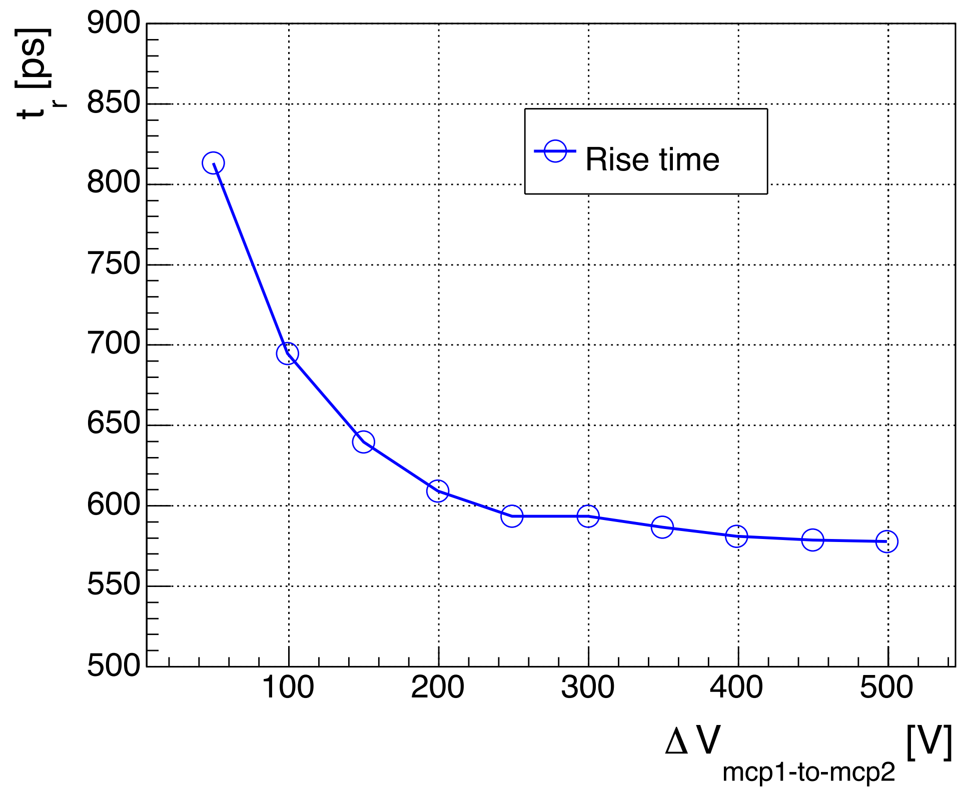
Single Photoelectron Time Response

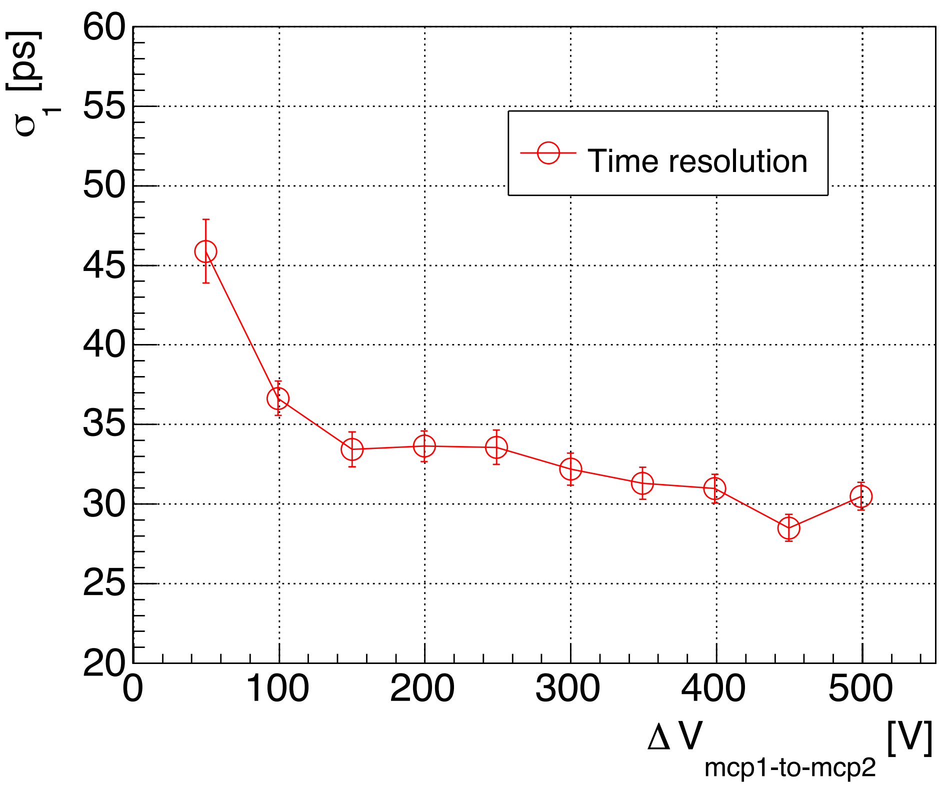


Comparison of single photoelectron time resolution between
10µm pore Burle Planacon (δt ~ 44ps) and
20µm pore Argonne 6cm tube (δt ~ 65ps)

Results from Optimization (III): Gap Voltage

- Voltage between MCPs
  - Wide angle spread of electrons from 1st MCP
  - Keep Gap V moderate to distribute electrons over several pores in 2nd MCP
  - Optimal voltage for tubes is ~200-400V





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