Large Area Picosecond Microchannel Plate Photodetectors

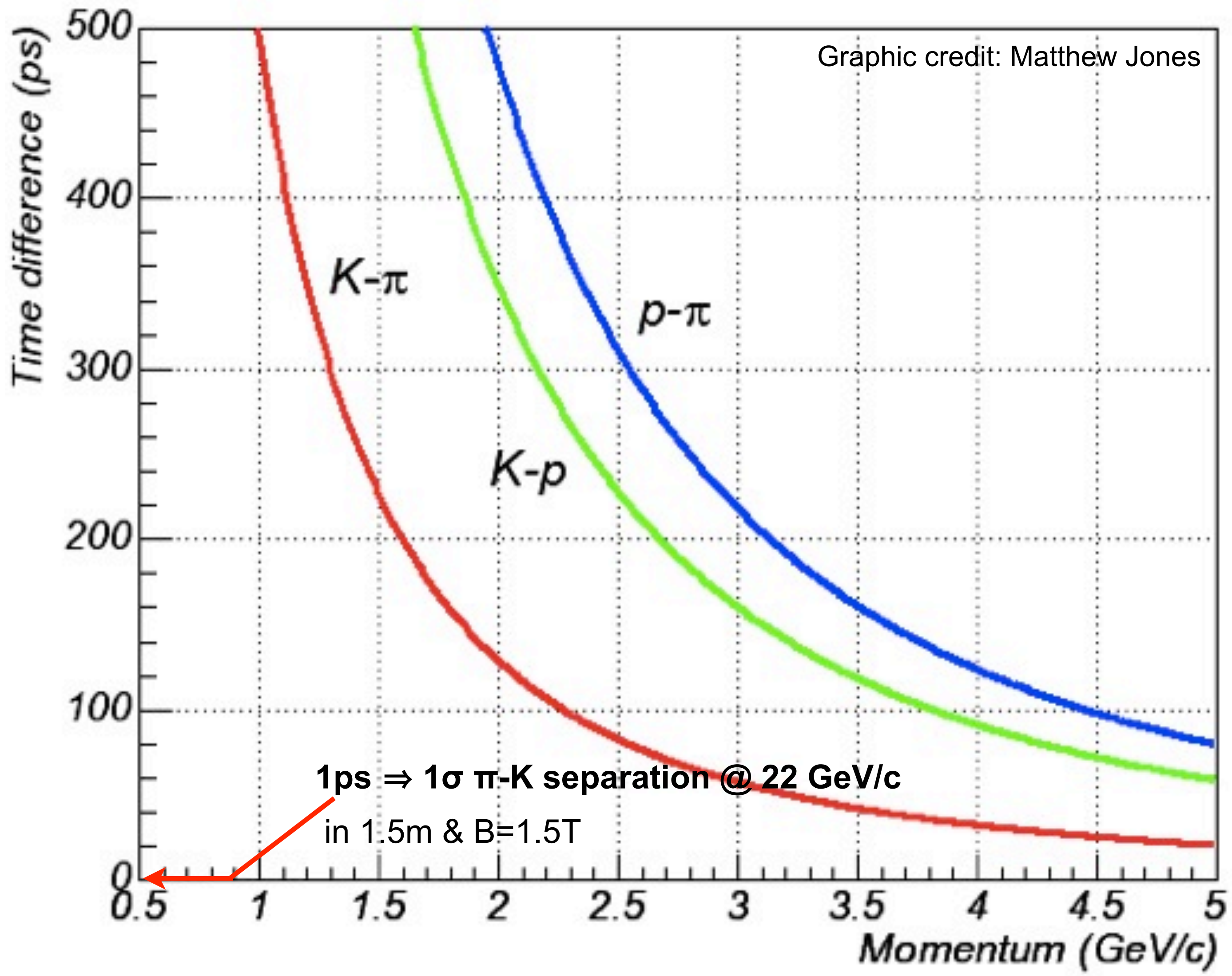
Bob Wagner
Argonne National Laboratory
HEP Division
Wednesday 13 November 2013
for the LAPPD2 Collaboration

The Large Area Picosecond Photodetector Participants During the First 4 Years

- National Labs
  - Argonne
    - HEP Division
    - Energy Systems Division
    - Nuclear Engineering Division
    - Glass Shop
    - X-ray Sciences Division
    - Materials Science Division
    - Mathematics and Computer Science Division
  - Fermilab
- Universities
  - University of Chicago
  - Space Sciences Lab/UC-Berkeley
  - University of Hawaii
  - Washington University
  - University of Illinois — Chicago
  - University of Illinois — Urbana/Champaign
- U.S. Companies
  - Incom, Inc.
  - Arradiance, Inc.
  - Synkera Technologies, Inc.
  - Minotech, Inc.
  - Muons, Inc.

Motivation — Pushing the Limits of Time Resolution

- Project evolved from lab seed grant to improve Particle ID in colliding beam experiments



Goal is to measure ALL information allowing for identification of quarks producing the jets. Requires particle ID for momentum of 10's of GeV/c

Several components contribute to time resolution limit:

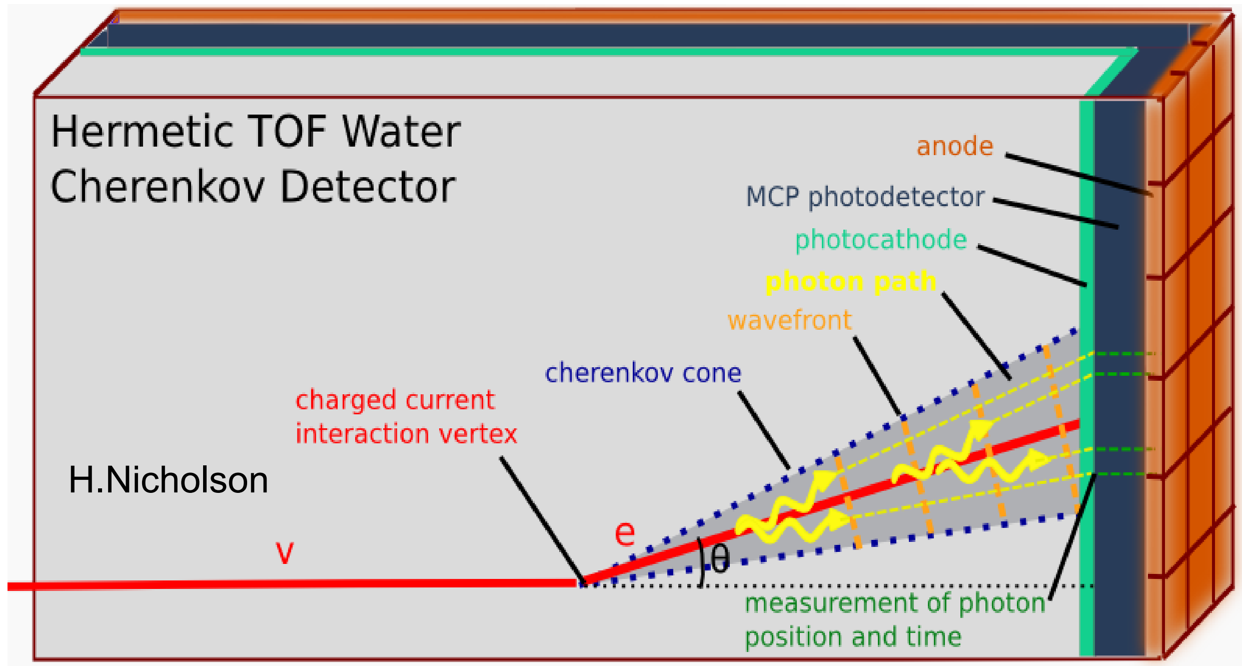
- Signal source - absorption, scattering, thresholds
- Detector limits - efficiency, coverage, noise, dispersion
- Electronics - bandwidth, slewing, sampling speed, noise

Complete particle measurement: E, p + m(PID)

1ps time & 1mm space resolution

Applications — Tracking Neutrino Water Cherenkov Detector

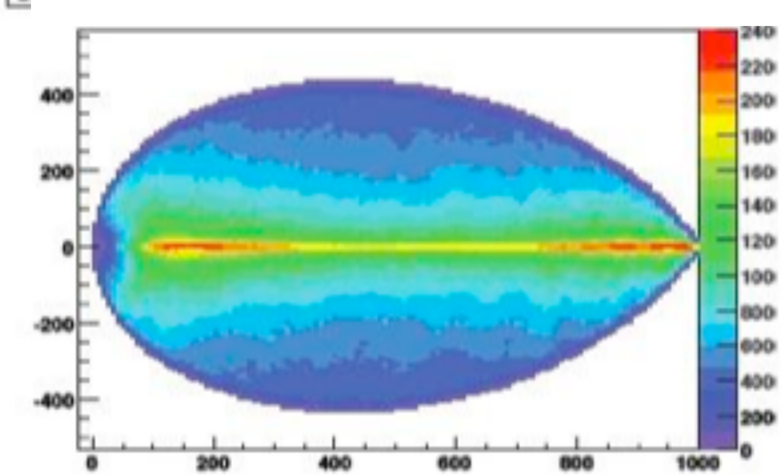
Technique: measure arrival time and position of photons and reconstruct tracks in water



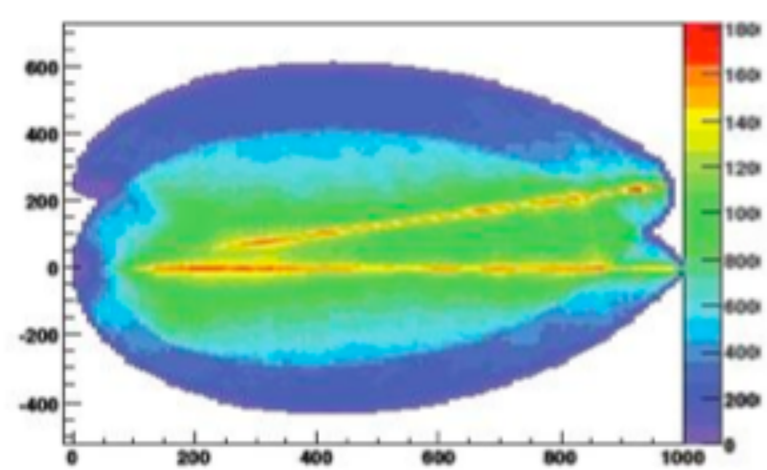
Tesselation of detector with Large Area MCP-PMTs

Results of a toy Monte Carlo with perfect resolution

Color scale shows the likelihood that light on the Cherenkov ring came from a particular point in space. Concentration of red and yellow pixels cluster around likely tracks



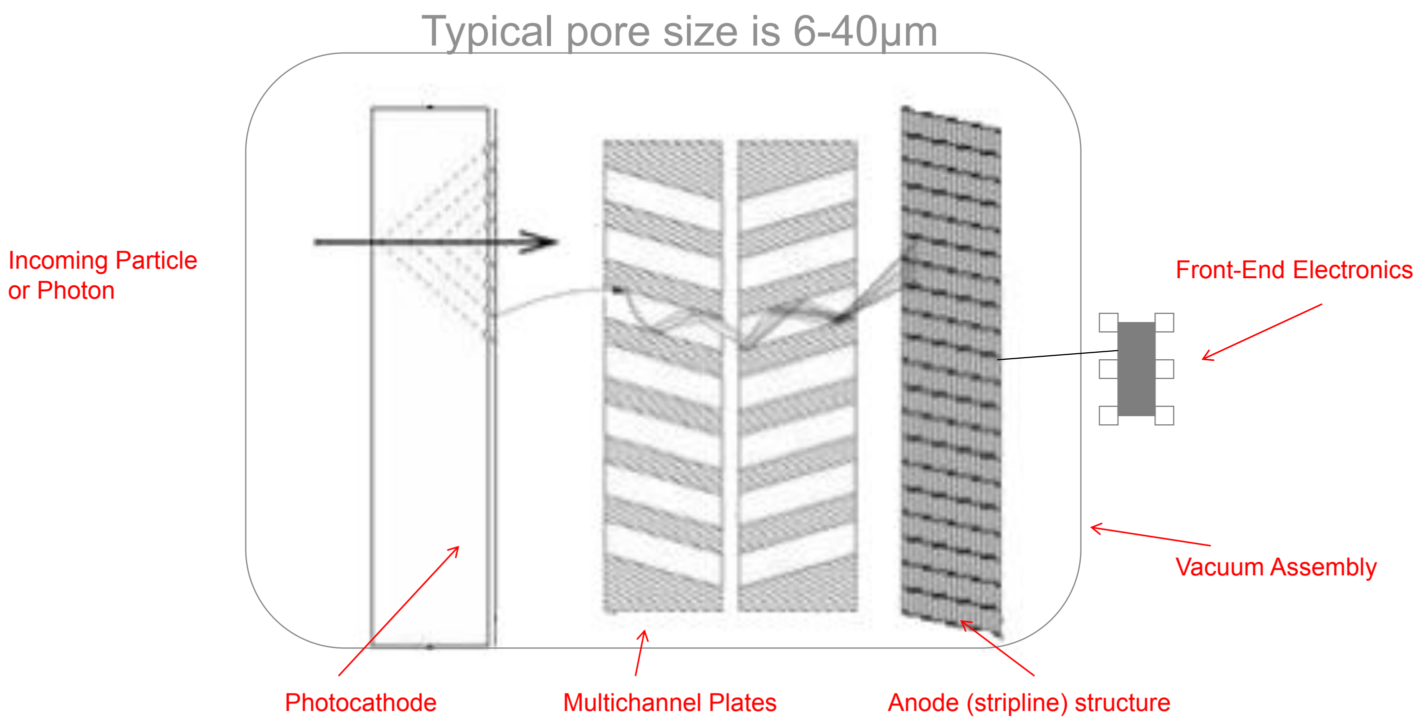
Single track



Two tracks displaced from a common vertex

graphic credit: Matt Wetstein

Microchannel Plate Photomultipliers



Existing commercial MCP-PMTs:

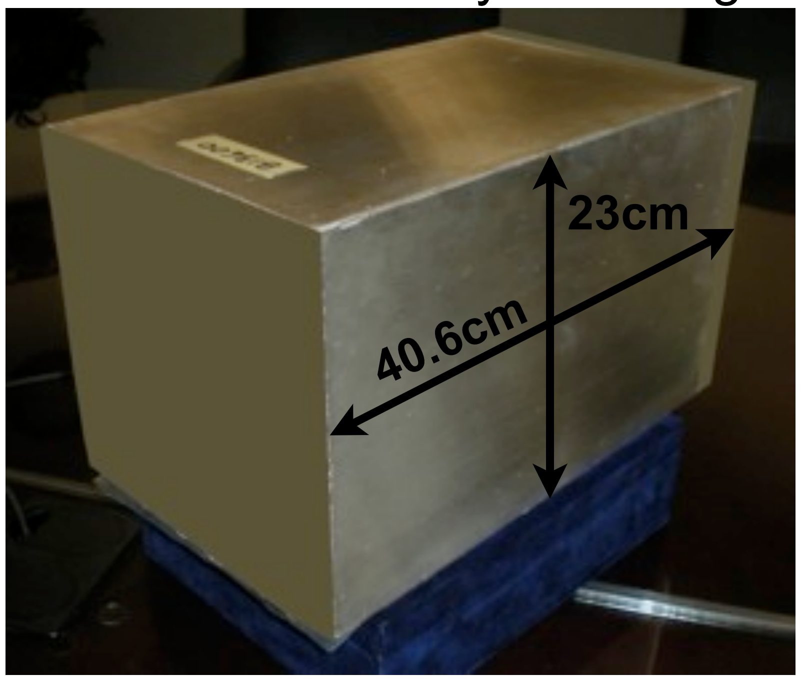
- MCP fabrication constrained by common material for substrate, resistive and emission layers
- ≤ ~25mm^2 active area
- Expensive

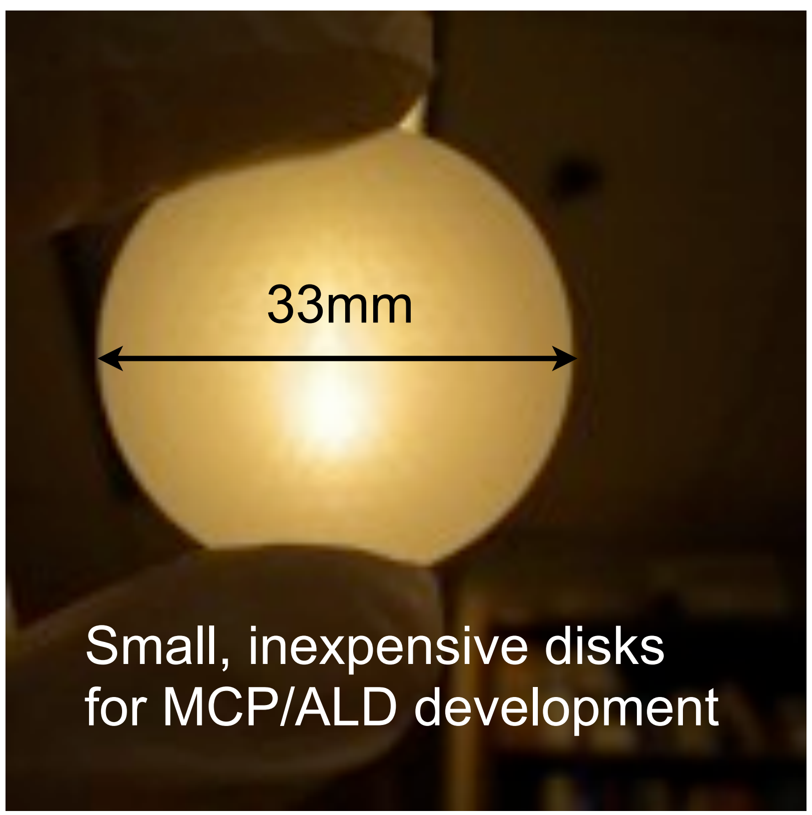
Components of the Large Area Picosecond Photodetector Development:

- Transformational improvement of MCP fabrication and size
  - 20cm×20cm borosilicate glass: ~80x10^6 20µm pore
  - Separate resistive & secondary emissive functions into 2 materials via Atomic Layer Deposition (ALD) coating
- Development of planar, large-area photocathodes
- Waveform sampling 10GSa/s electronics readout for best time resolution
- Development of economical hermetic packaging
  - Standard ceramic package w/InBi hot seal & HV/signal pins feedthru — SSL/UC-Berkeley
  - Less expensive borosilicate all-glass, pressure In seal, pinless — Argonne/UChicago

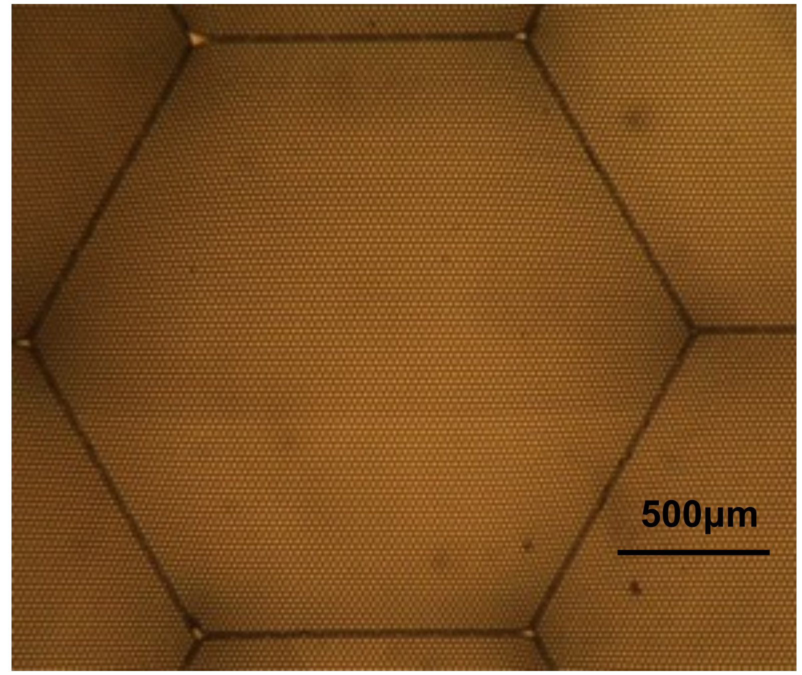
Development of Economical Borosilicate Capillary Arrays for MCPs — Industrial Partnership w/Incom, Inc

Fused block ready for slicing





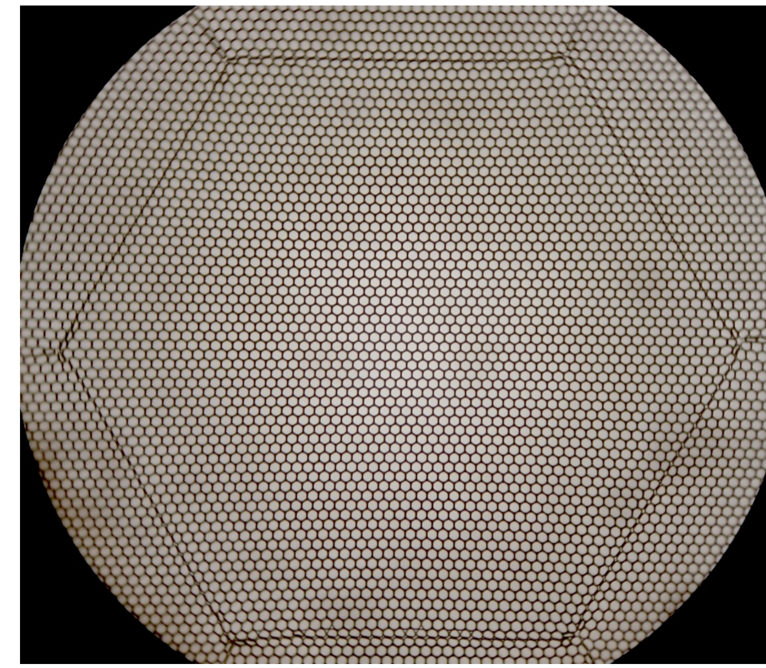
First block



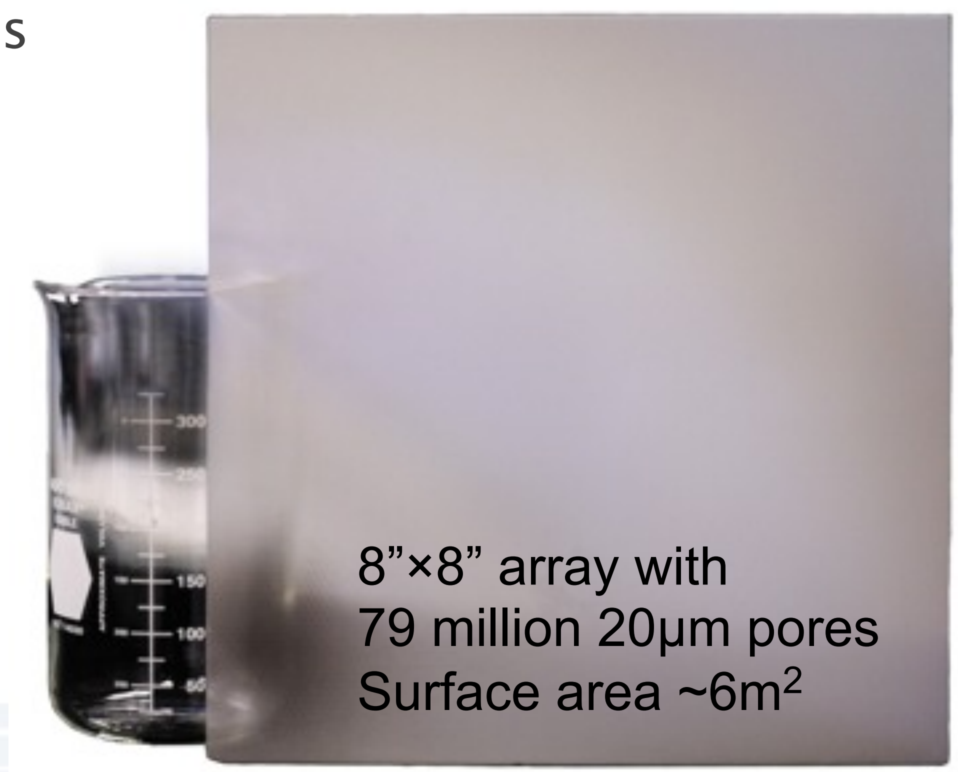
- Multifiber stacking
- Triple point gaps
- Pore crushing at multifiber boundaries

Capillary array quality dramatically improved during last 3.5 years

More recent block



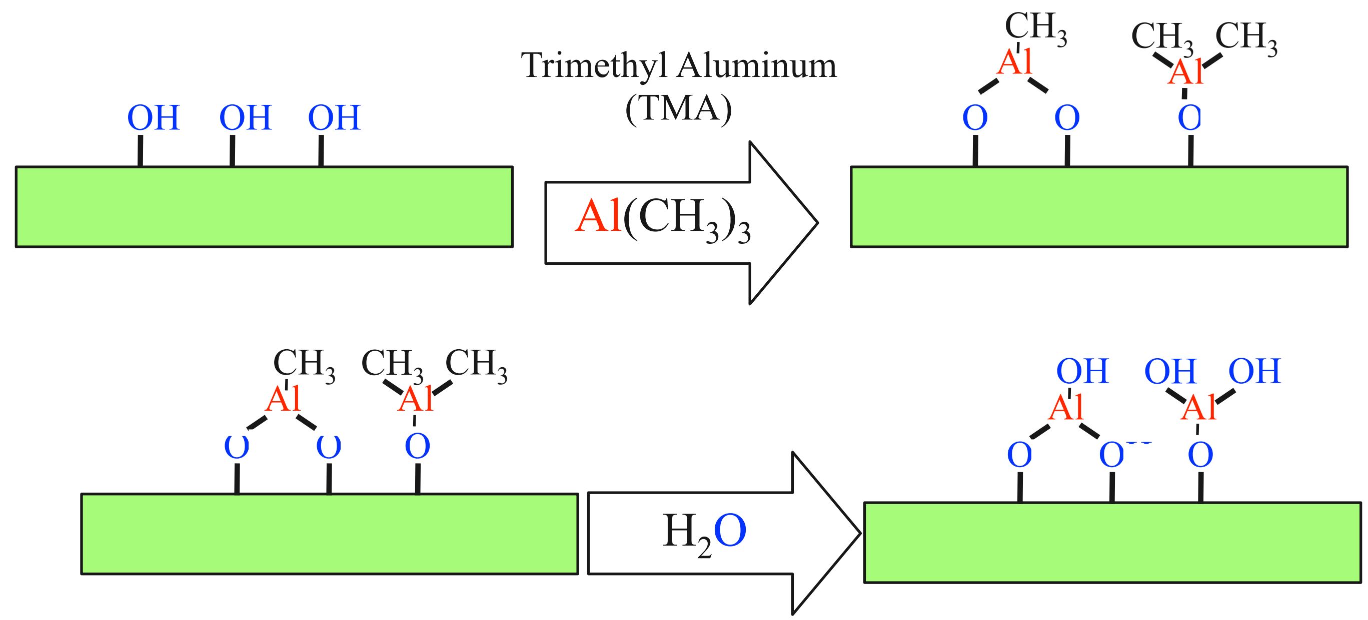
- Triple points eliminated
- Minimal boundary pore distortion

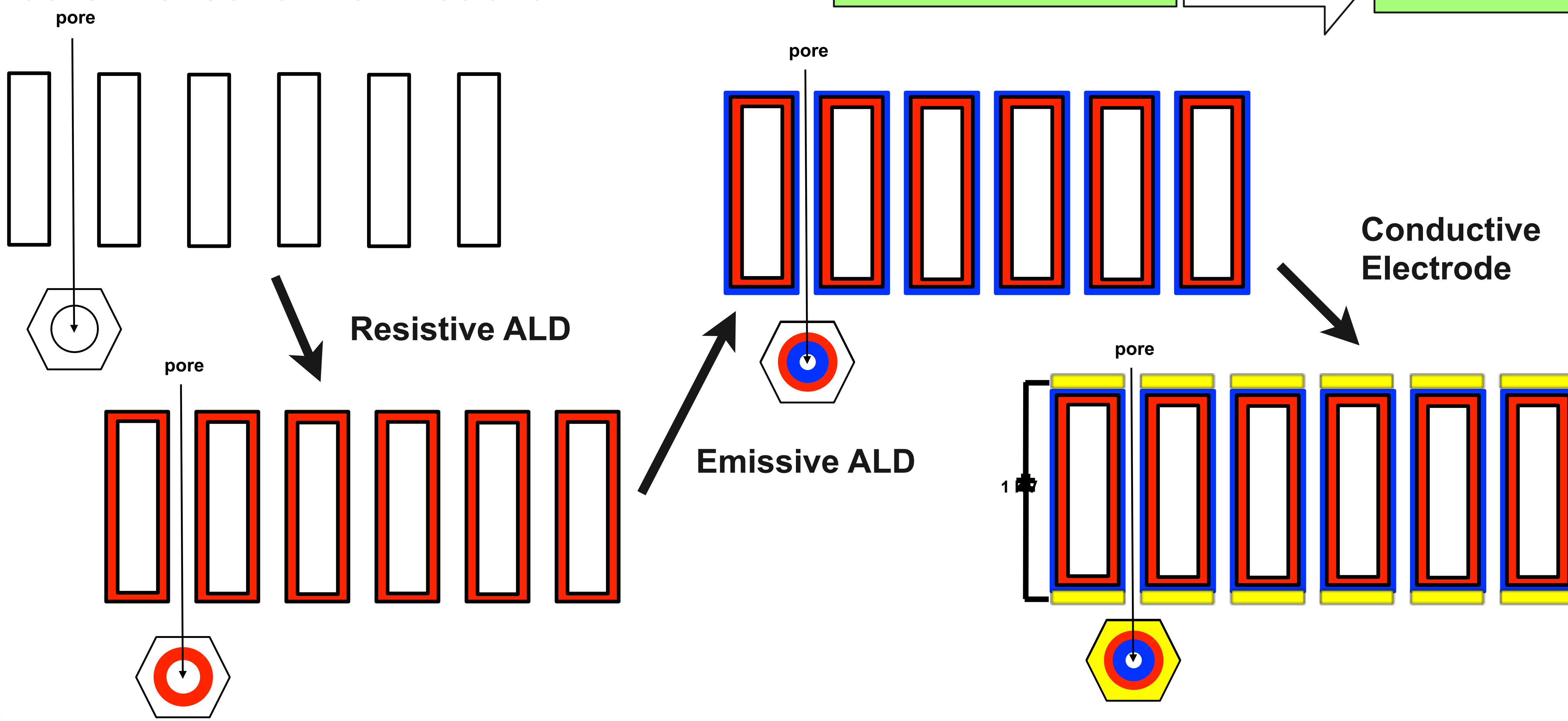


Pore Activation via Atomic Layer Deposition (ALD)

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

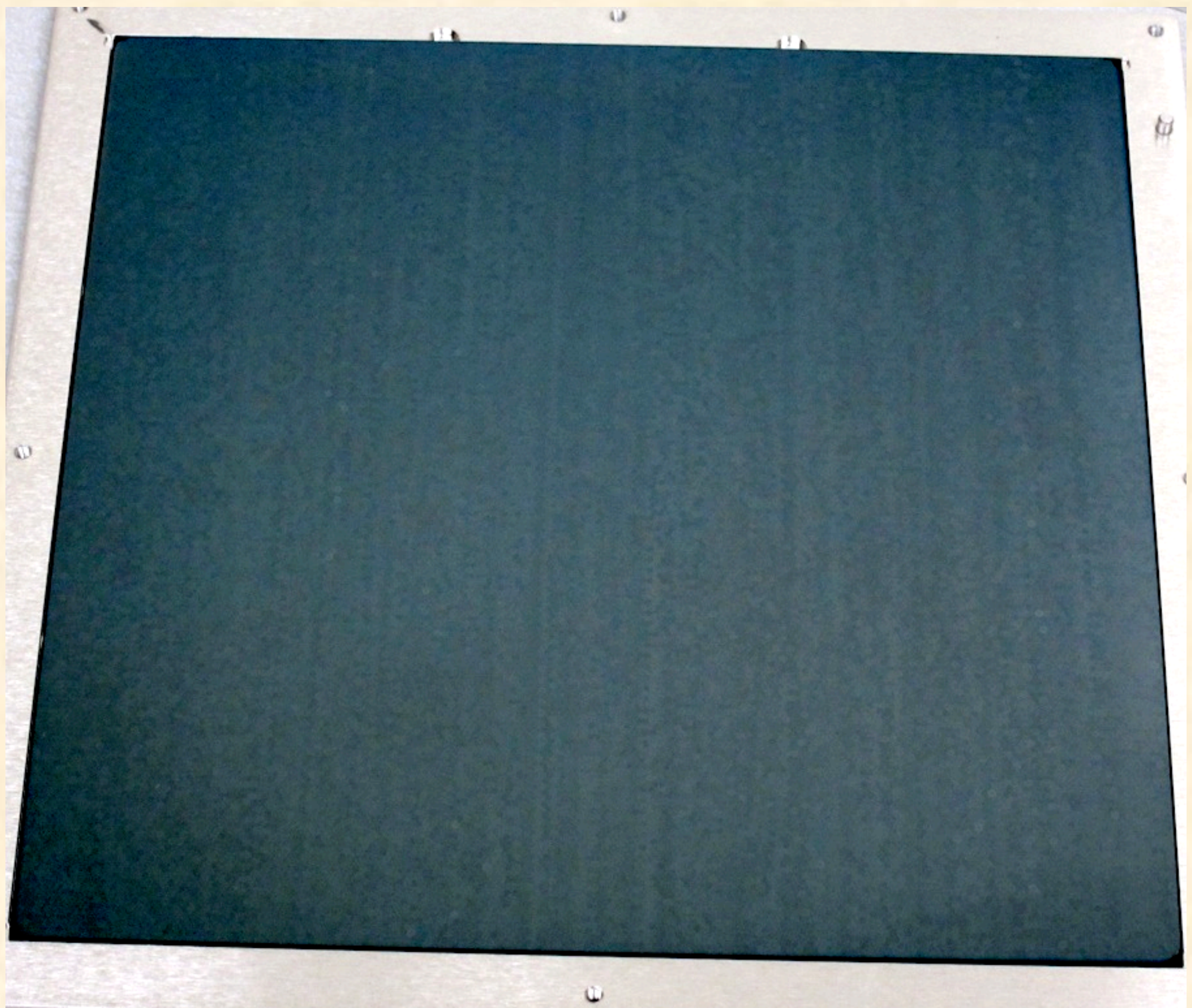




Tuesday, November 12, 2013

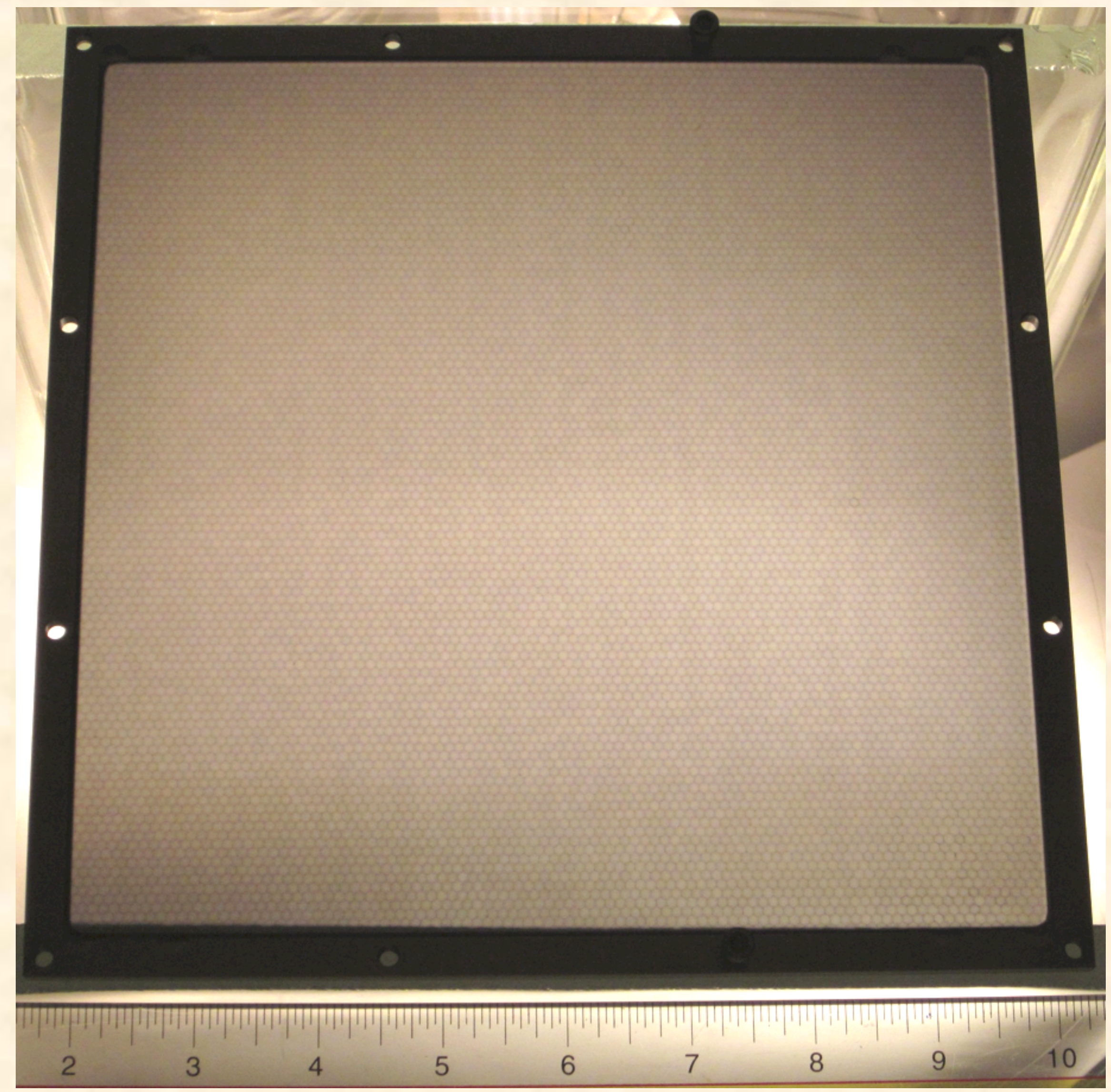
20cm × 20cm Microcapillary Array and Functionalization to MCP

ALD Functionalized Microchannel Plate



20cm ALD MCP photo showing the patterns of multifibers and stacking arrangement.

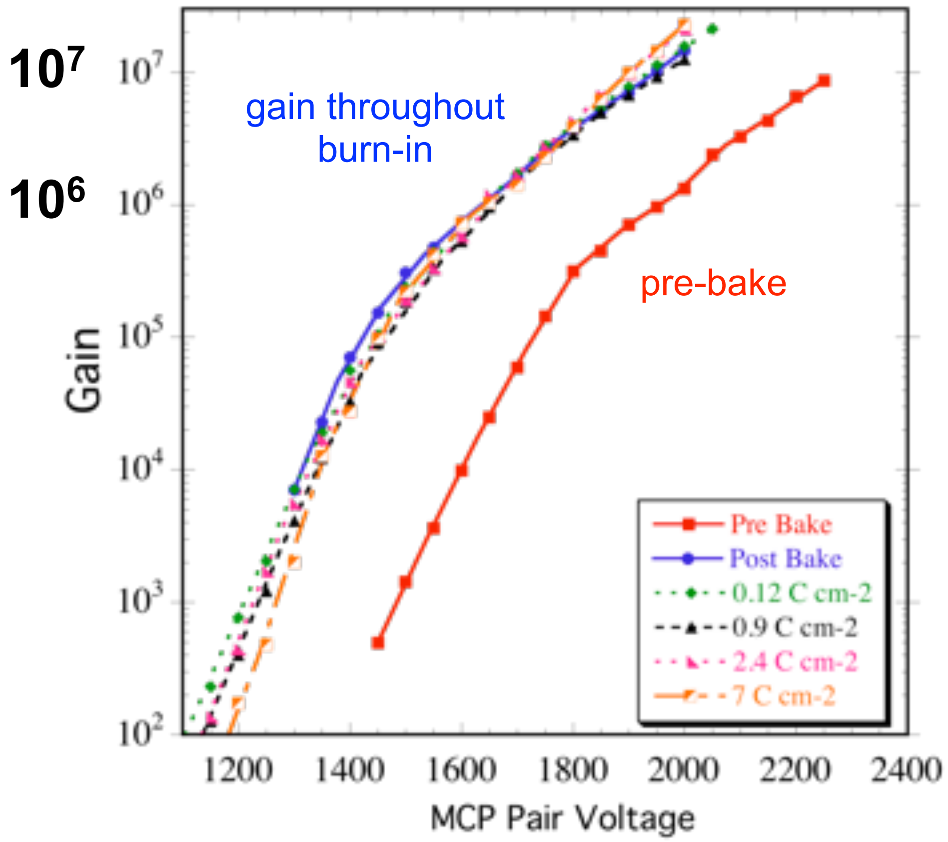
Bare Microcapillary Array Plate



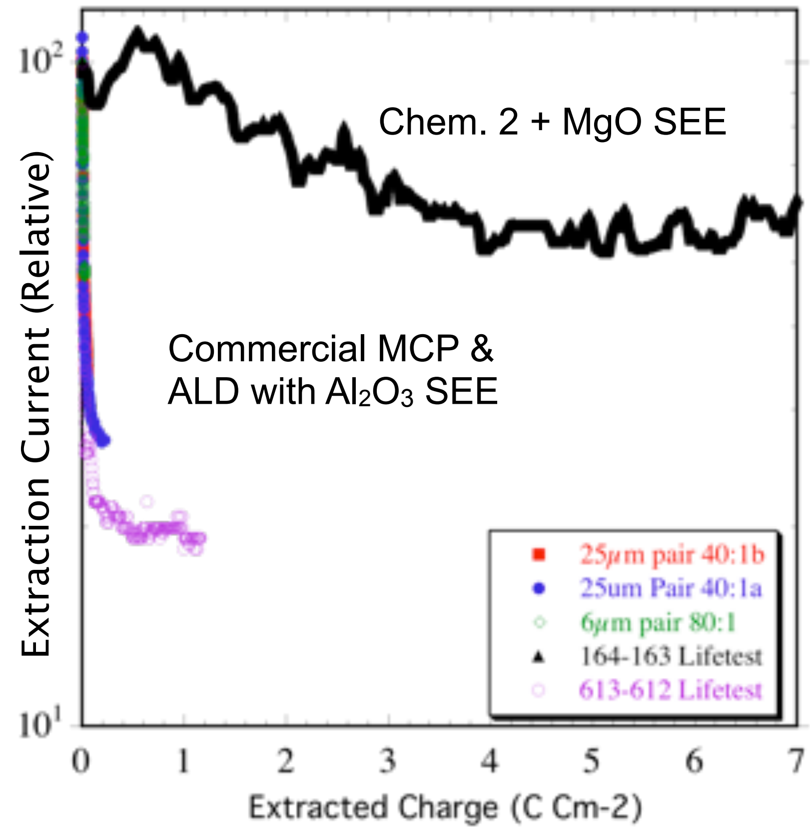
Backlit photo of a 20cm MCP showing the multifiber stacking arrangement.

MCP Development & Testing

MCP LIfetest:
350˚C bakeout then 1-3μA "burn-in" to 7C/cm²

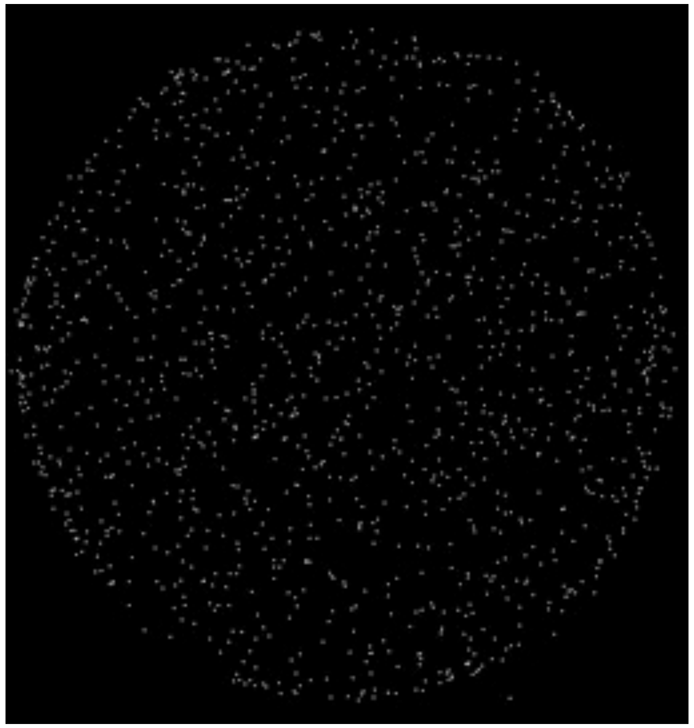


Gain curves of 33mm ALD MCP pair at stages during conditioning.



UV scrub of ALD MCP pair 164-163 compared with conventional MCPs. Outgas during burn-in < 4 x 10^{-10} torr H_2.

Background Noise Measurement (separate from lifetest)



3000s bkgd, counting
0.0845 events/cm²-s
7 x 10^6 gain
1025v bias per MCP
300V gap bias

Rate comparable to cosmic bkgd

Desirable MCP properties with MgO SEE:

- **Precipitous initial gain decrease seen in commercial MCPs absent in ALD-functionalized sample. Little or no aging up to 7C/cm².**
- **MgO SEE produces low-noise MCP**

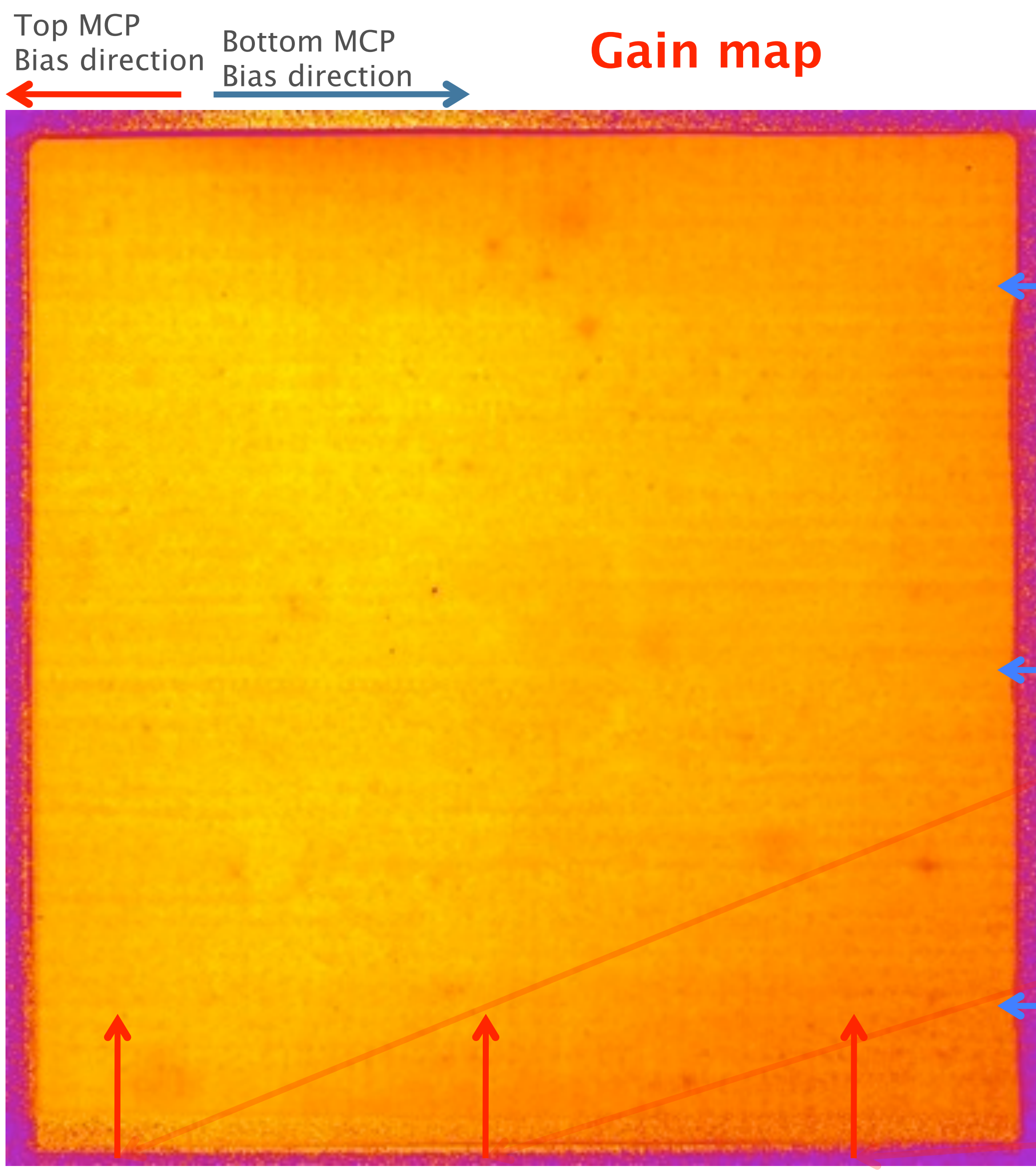
graphics: Ossy Siegmund & Jason McPhate, SSL

Uniformity of Gain Mapping 20cm × 20 cm Plates
Cross-Flow ALD Coating

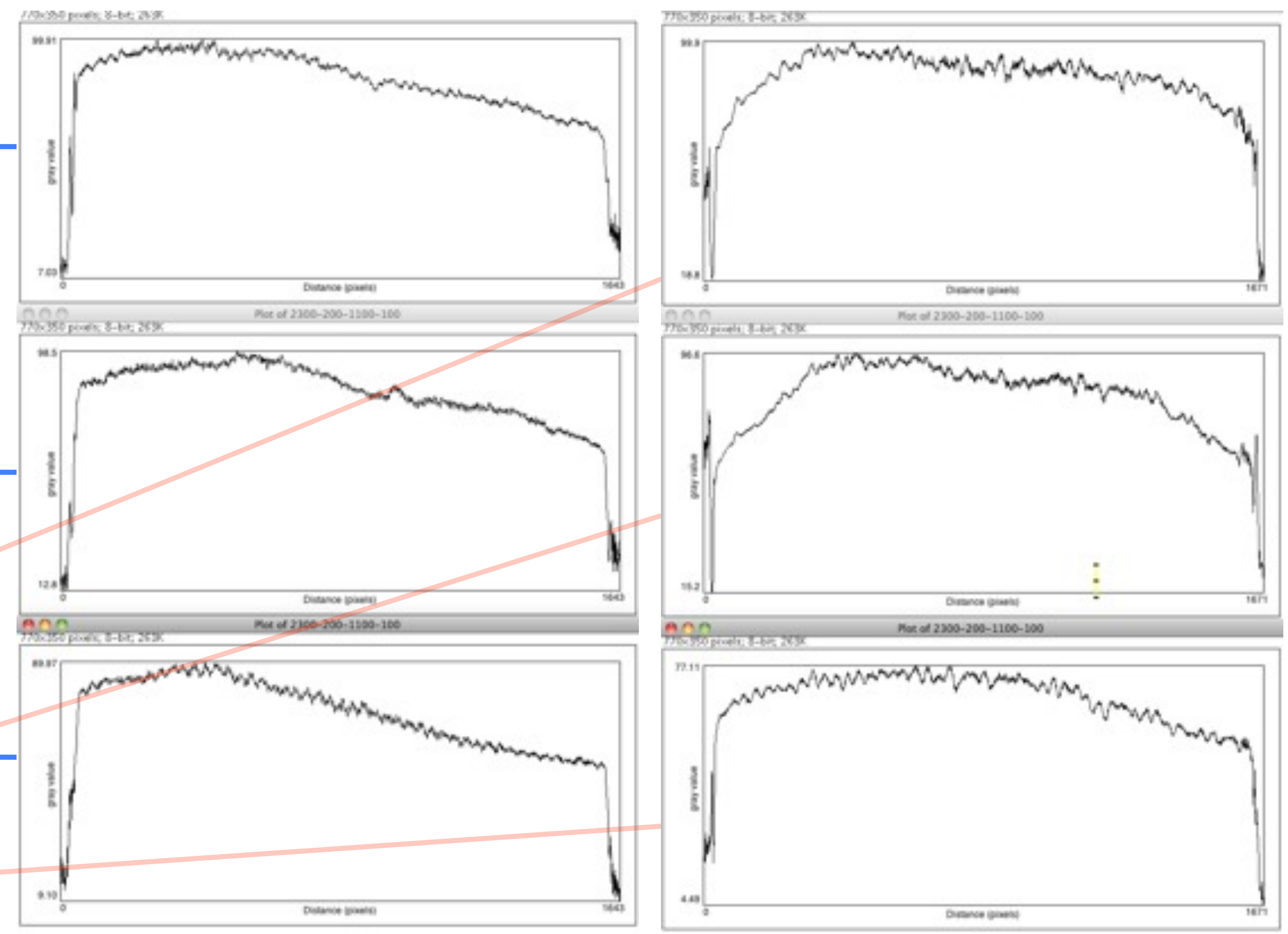
8” 20µm MCP Pair Gain Map

Gain map

MCP 13600-061 – 36MΩ – top
MCP 13600-081– 19MΩ – Bottom



Gain 50% lower at right edge



X gain slices

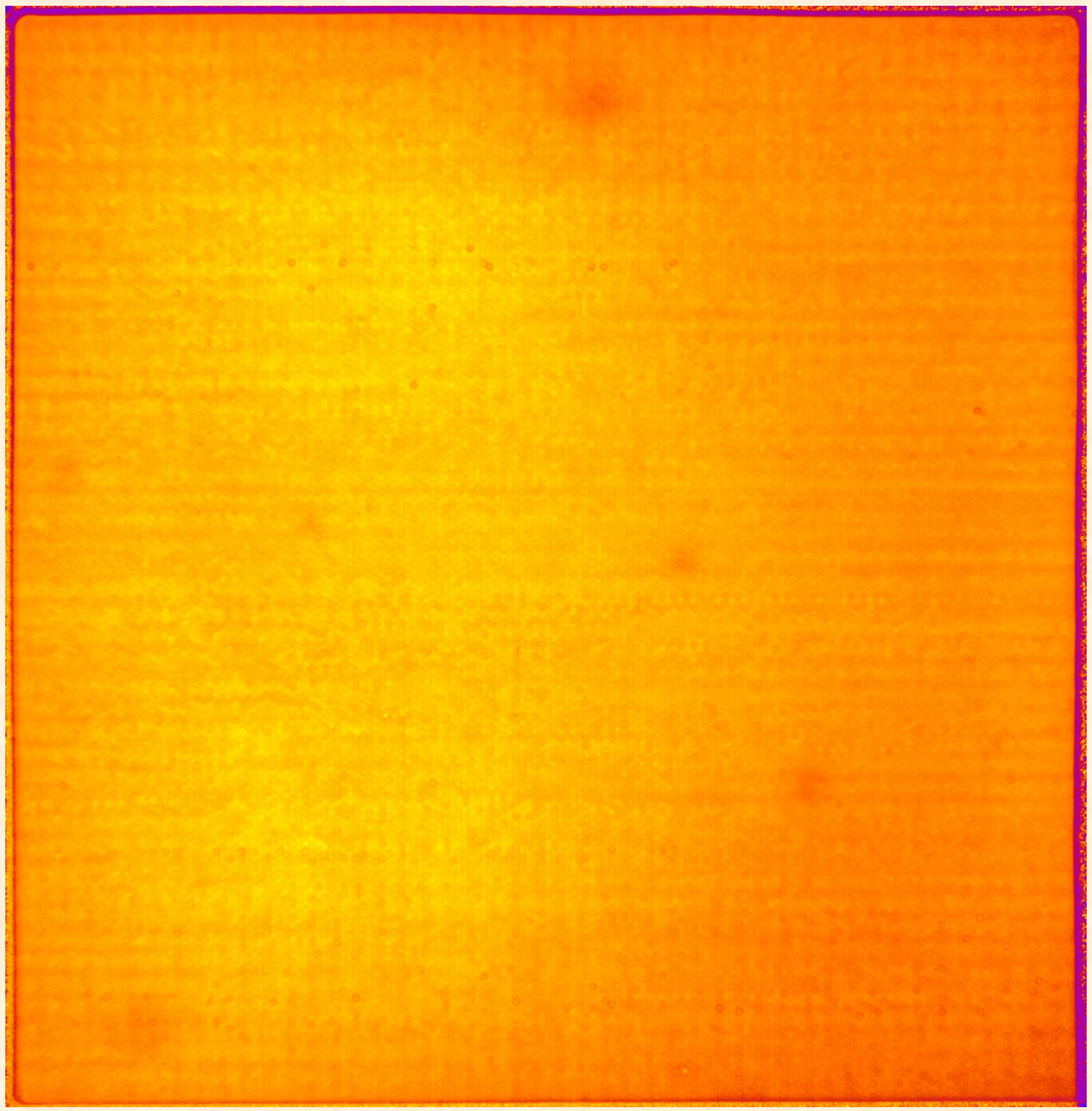
Y gain slices

graphics: Ossy Siegmund, SSL

Uniformity of Gain Mapping 20cm × 20 cm Plates Flow-Through ALD Coating

Testing of 20cm, 20μm pore ALD-MCP Gain

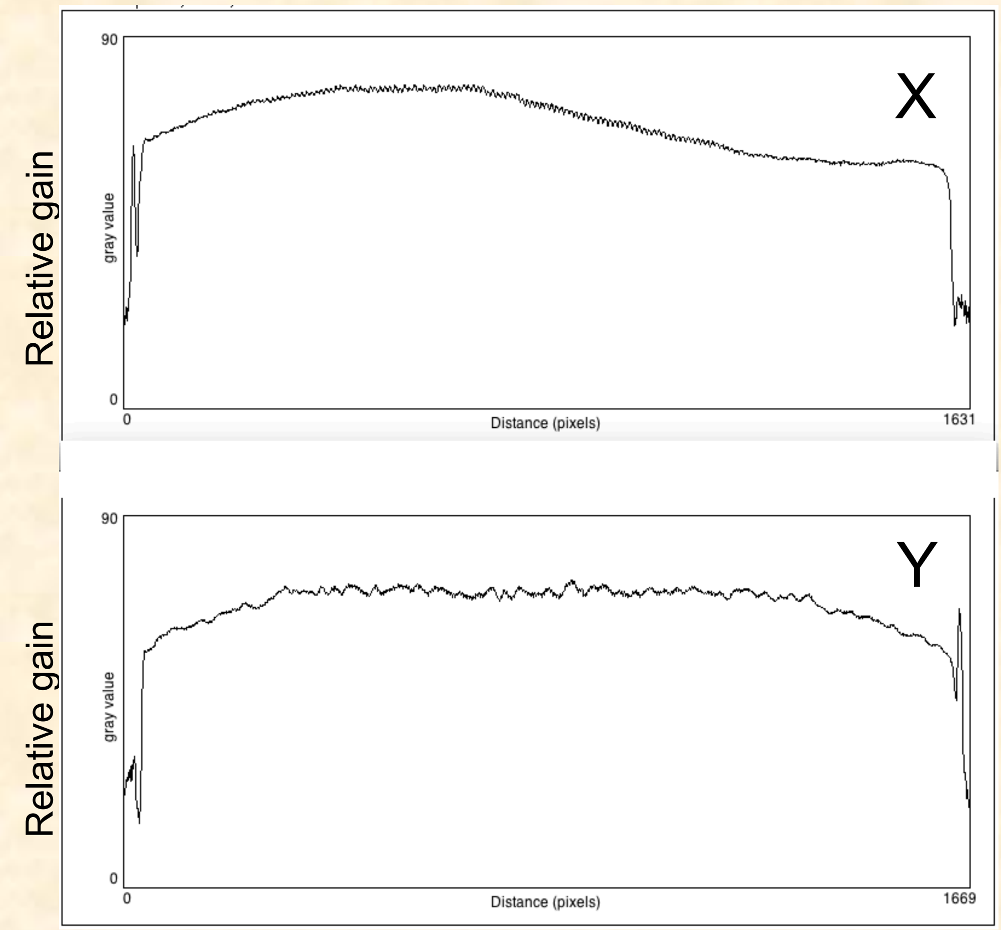
Mean gain ~7 x 10^6



8” MCP pair average gain map image

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.

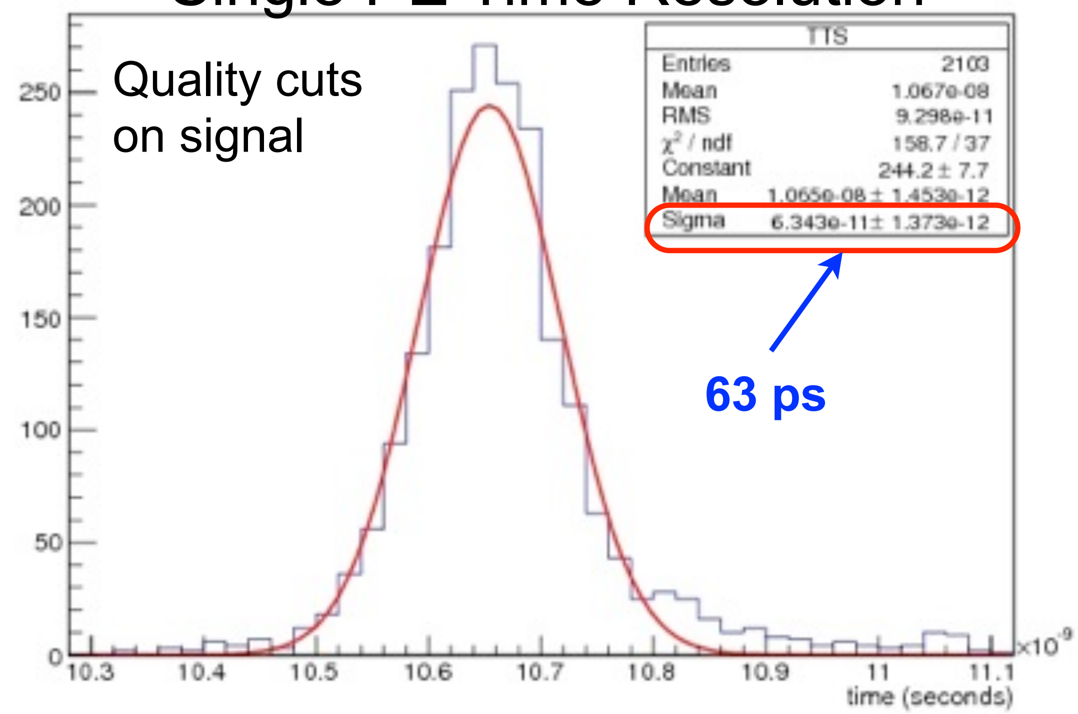


Histograms show the gain modest variation

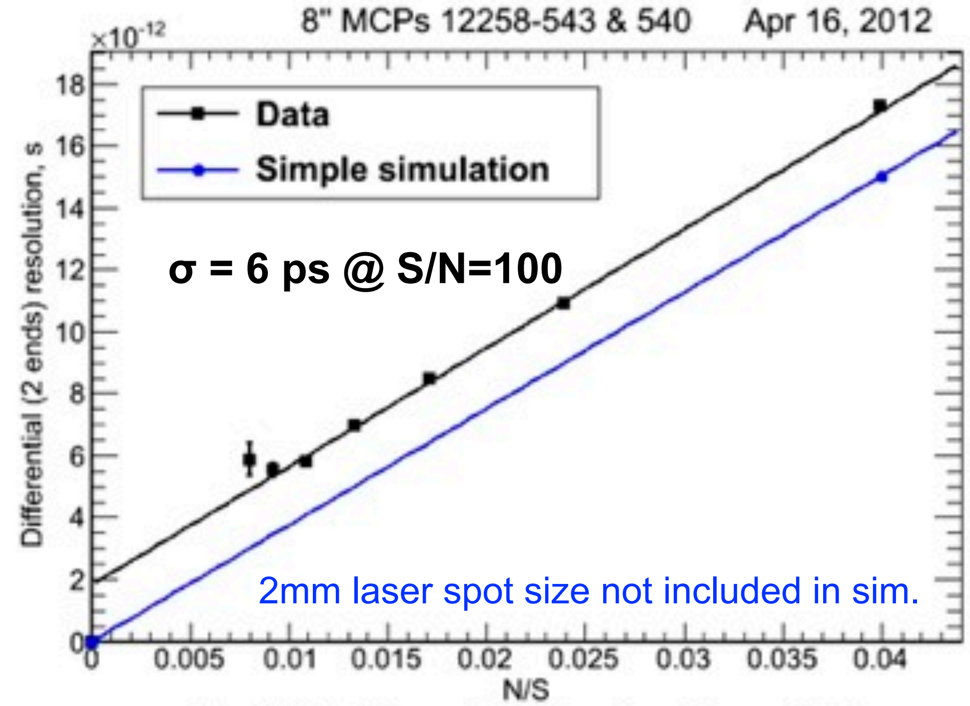
graphics: Ossy Siegmund, SSL

Strip Line Anode Performance with 8” MCP Pairs

Single PE Time Resolution



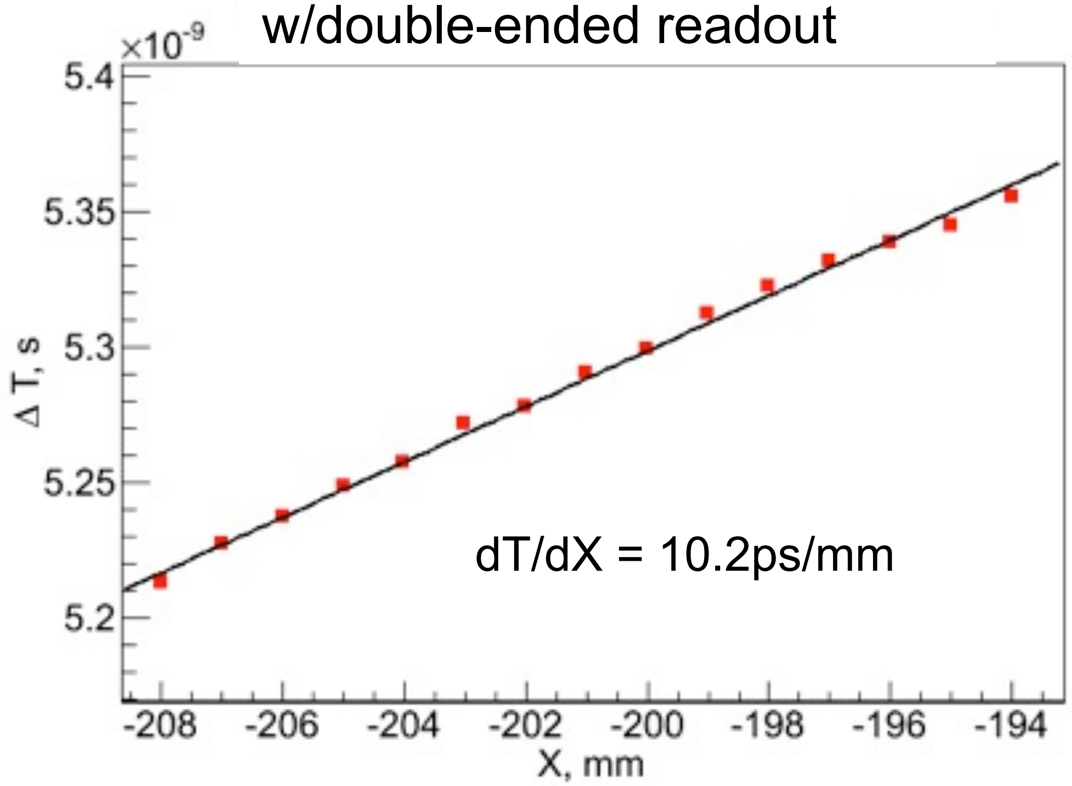
Differential Time Resolution vs. Noise



N = RMS of the noise; S = signal amplitude

Simulation has many more points than shown. All are very well consistent with the blue line.

Position scan along stripline
w/double-ended readout

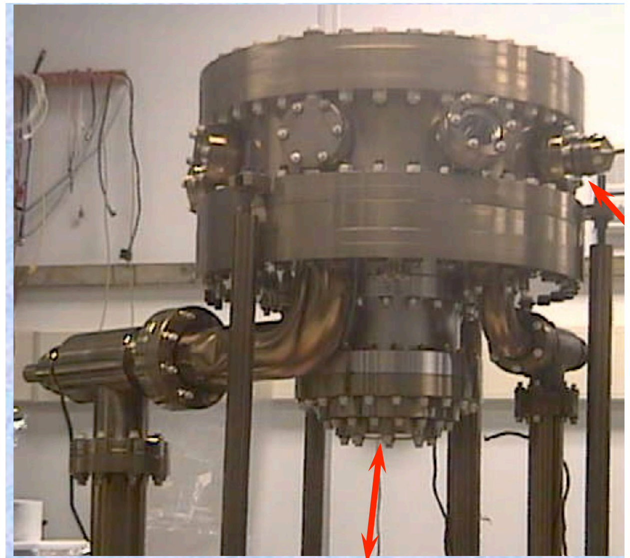


- Results from Argonne 8” Test Ch. w/UV laser excitation, fast scope readout (M.Wetstein, B. Adams, A. Elagin, R. Obaid, A. Vostrokov)
- Un-optimized Anode performance impressive and meets present needs
- Prospects for improvement to few ps resolution are good

8” Photocathode Development – SSL/Berkeley

Na_2KSb Photocathode Chosen for

- Resistivity
- Noise
- Temperature robustness
- Uniformity



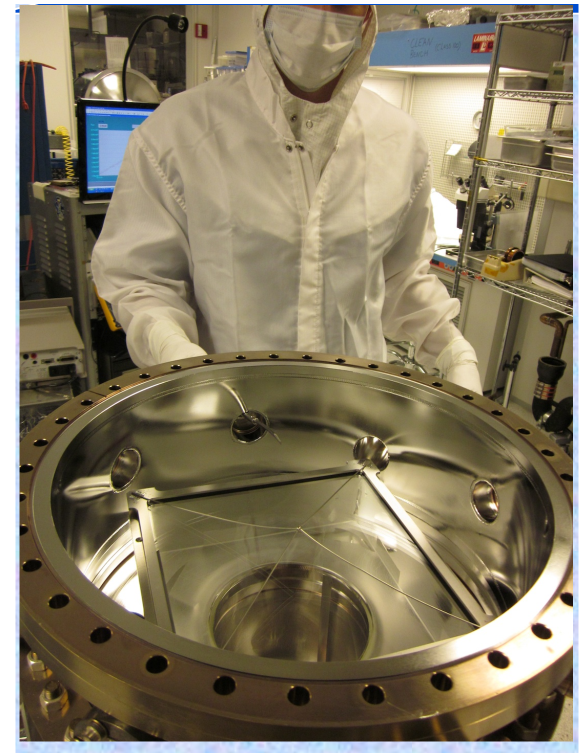
Alkali sources

Larger 16” flange tank, for testing

-Quantum efficiency

-QE Uniformity

-Seal tests

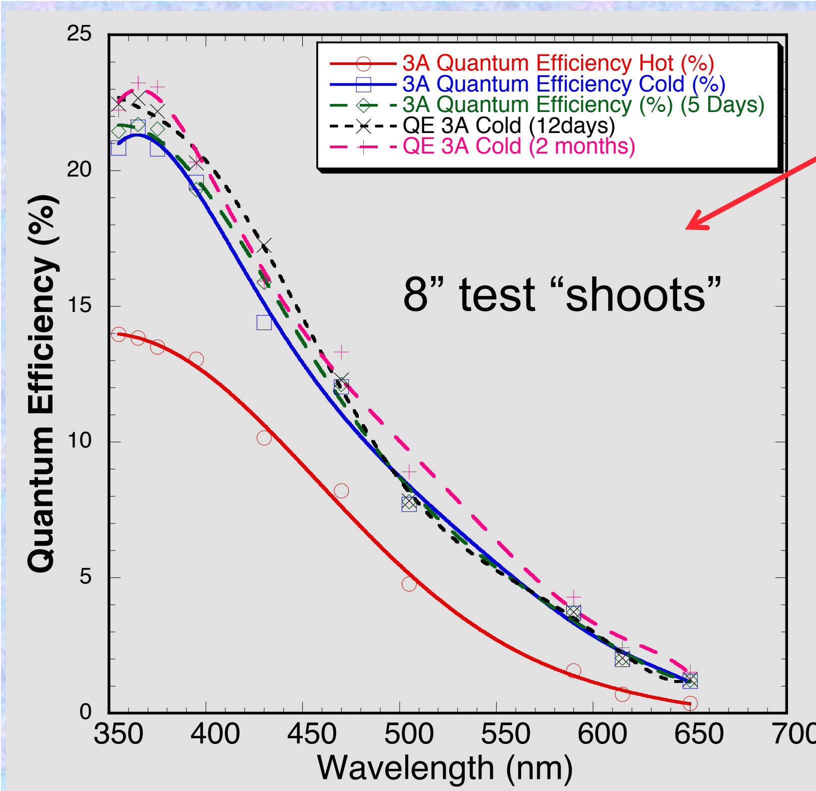


8.7” window loaded

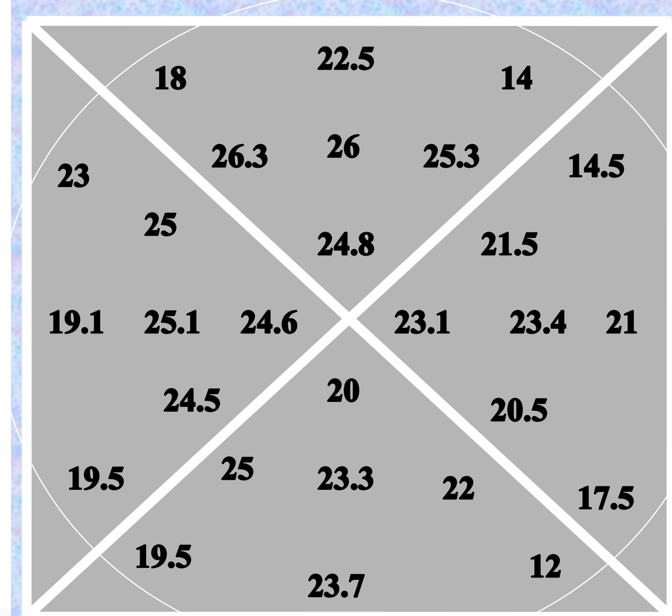
graphics: Ossy Siegmund & Jason McPhate, SSL

8” Photocathodes successfully produced at SSL

- **Cathodes in 8” test chamber with QE~22%**
- **Uniformity and stability meet MCP tube needs**
- **Technique has been transferred from 8” test ch. to large tube processing station.**

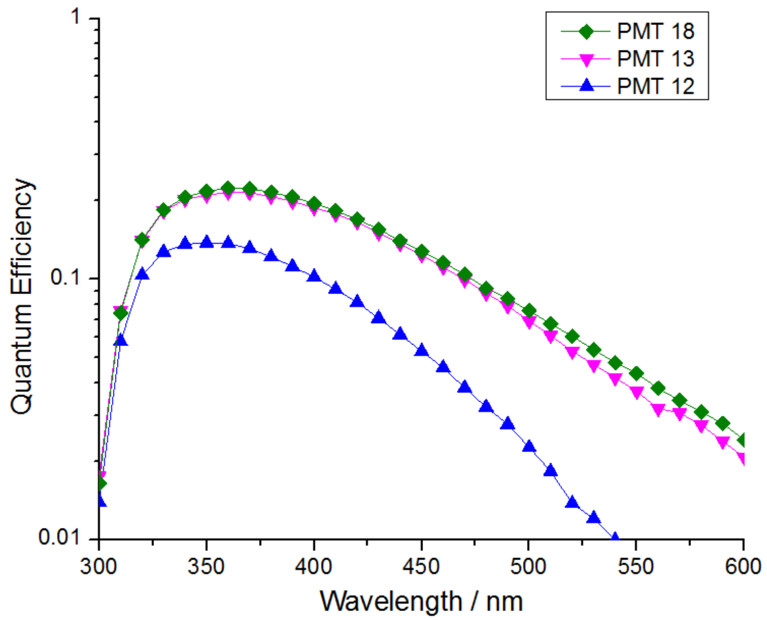


Basic process is a co-evap technique. We get an enhancement of the QE after cool-down. The QE has remained stable over the 2 months since deposition.

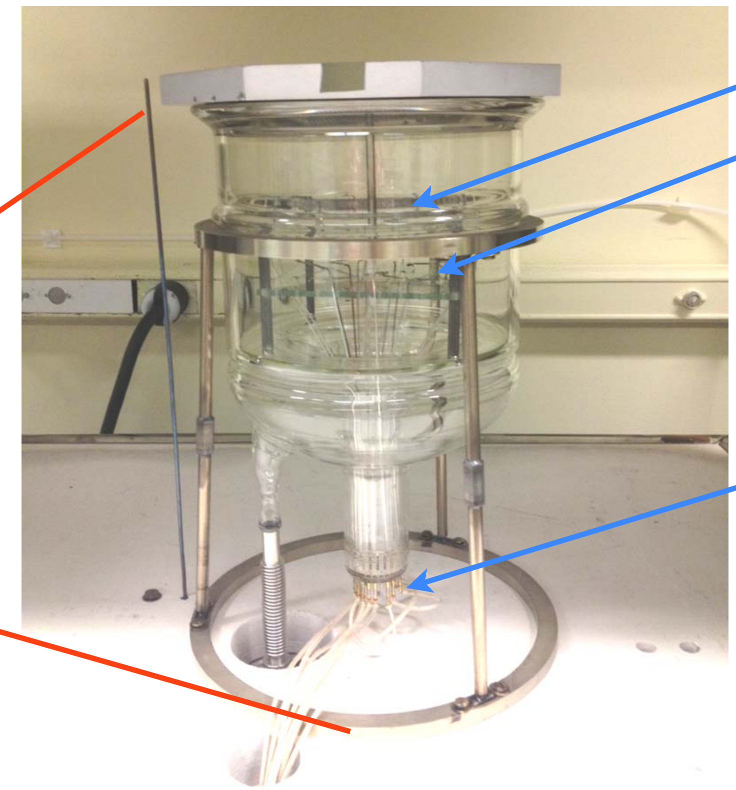


#3A photocathode uniformity

Photocathode Development — Argonne



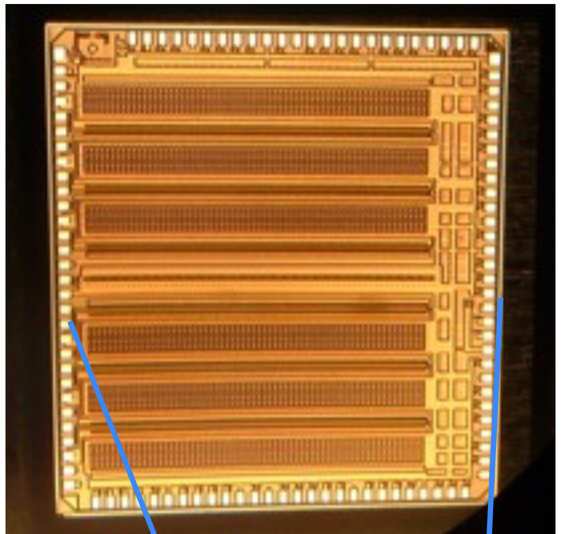
K_2CsSb Photocathode



Large glass vacuum vessel (**Chalice**) replaced small PMT manifold to produce 4” & 7” photocathodes

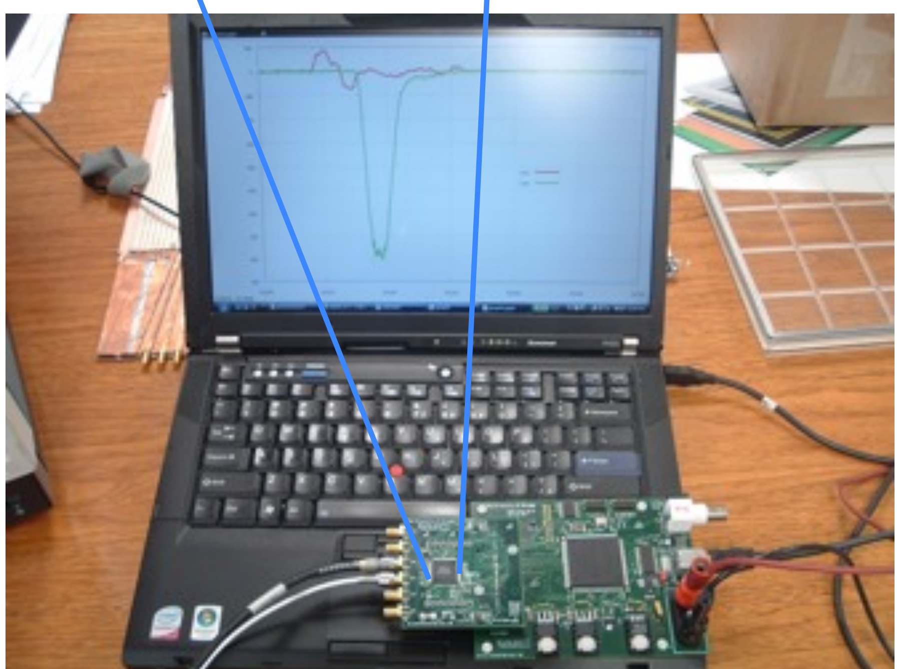
Learned photocathode fabrication techniques on phototube process system purchased from Burle/Photonis

Development & Testing of Front-end Electronics

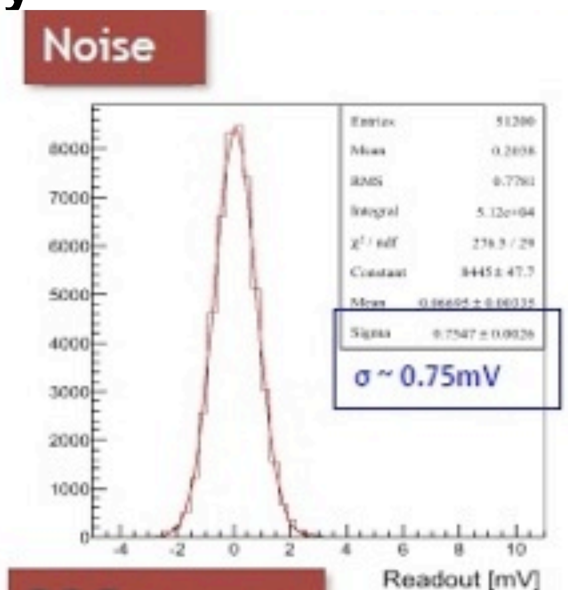


PSEC4 6-ch.
Waveform sampling switched capacitor array "scope-on-a-chip"
1.6 GHz BW, 10-15 GSa/s,
130nm technology

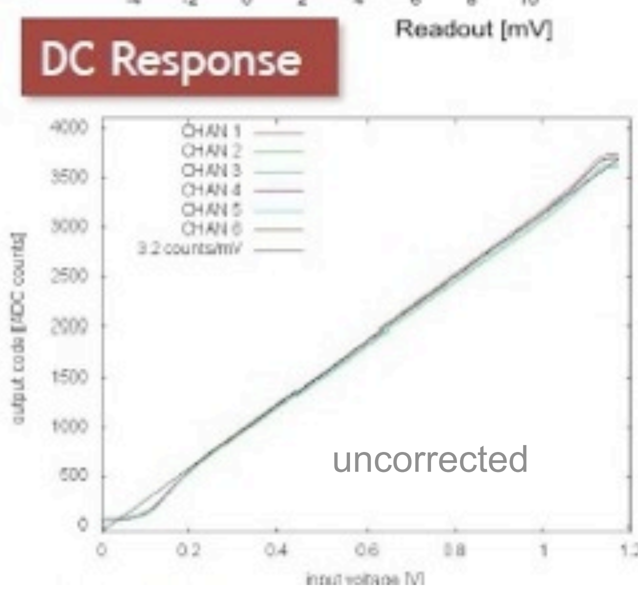
PSEC ASIC Design and Testing by
Univ. of Chicago & Univ. of Hawaii

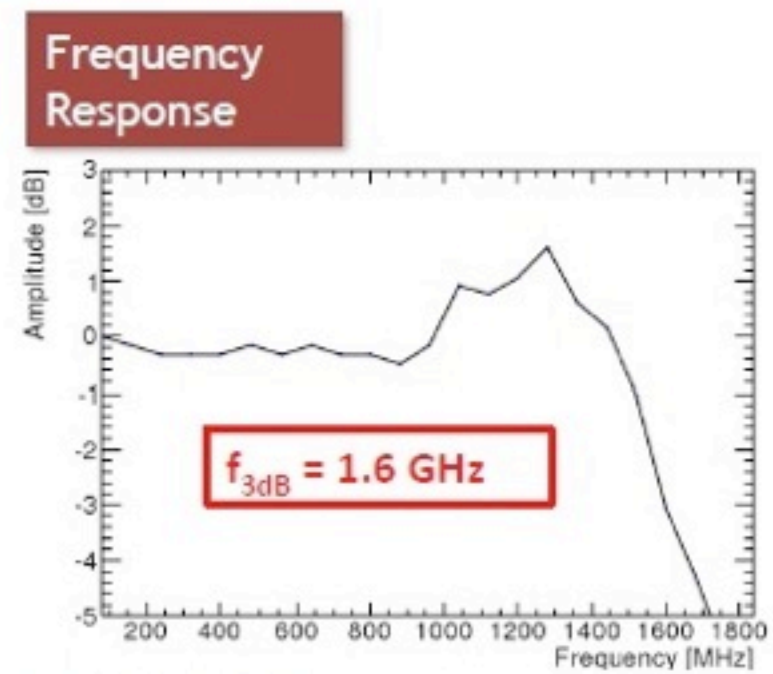


Evaluation board w/2.0 USB interface + PC DAQ software



- Low noise <1 mV
- ~1V dynamic range with excellent linearity
- Analog bandwidth of 1.6 GHz
- Sampling rates up to 15 GSa/s

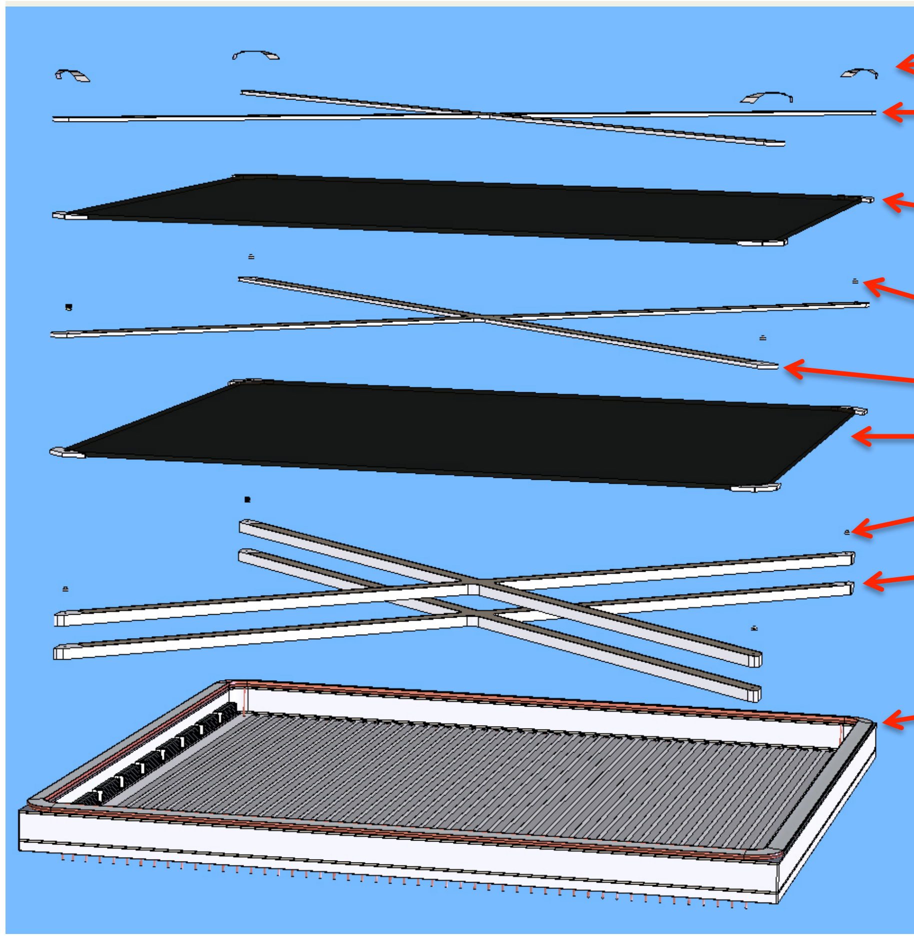




PSEC 4 design & test results: Eric Oberla & Hervé Grabas, Chicago

Development of Hermetic Packaging – Ceramic Tube

Components for SSL Ceramic Tube

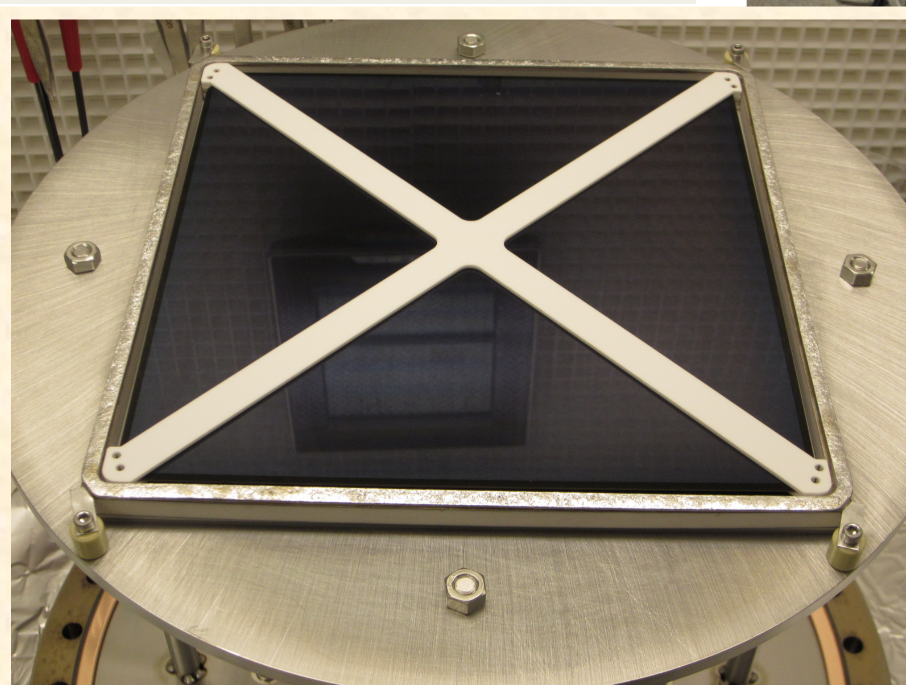


- Stack hold-down straps
- Top X-Grid – .060” thick plus ~.002” X-shim to adjust stack height
- Top MCP – with anti-rotation blocks at corners
- HV contacts
- Middle X-Grid – .060” thick
- Bottom MCP (w/ AR blocks)
- HV contacts
- Anode gap X-Grids - .060” ea plus ~.020” X-shim to adjust stack height
- Prepared BBA (indium and getters)

- Internal stack height .003”–.006” shorter than walls to ensure seal

1st complete 20cm×20cm functional tube stacked and ready for insertion into process tank

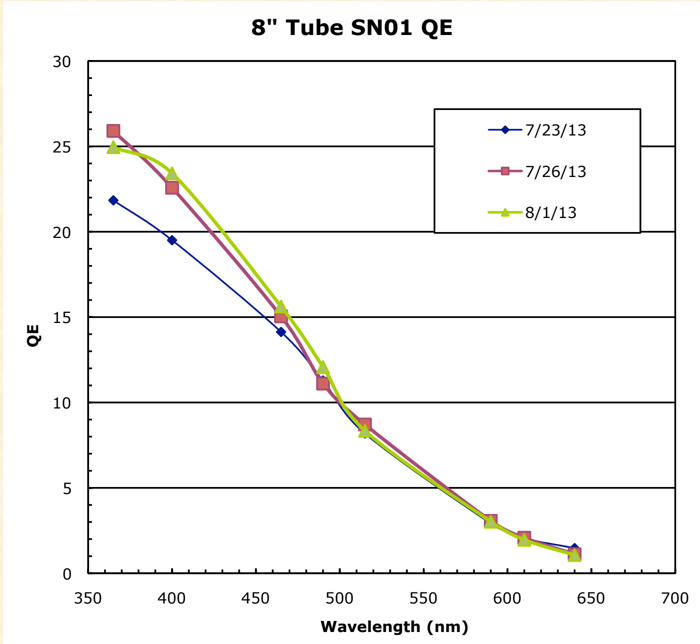
July 2013

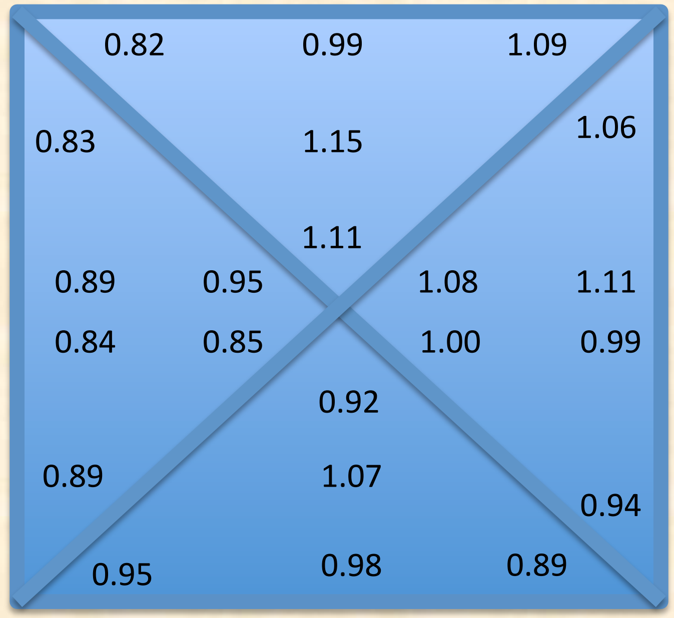


Tube #1 stackup showing top MCP and “X” spacer

Photocathode Fabrication and Sealing of First Ceramic Tube

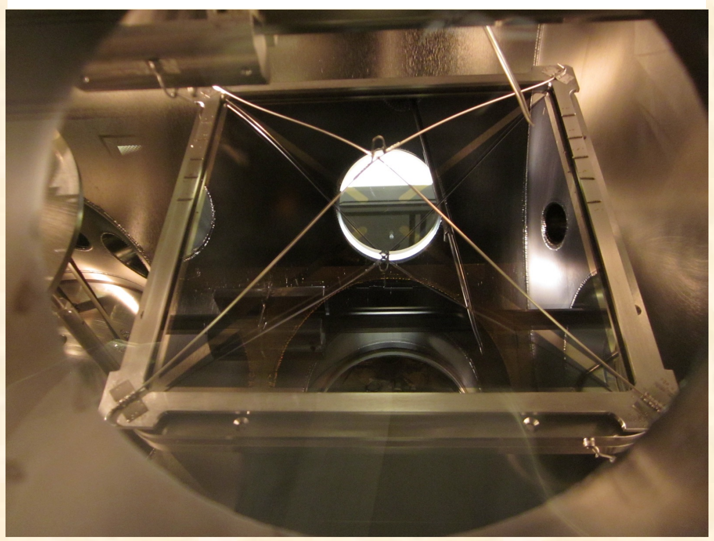
LAPPD Sealed Ceramic Tube #1



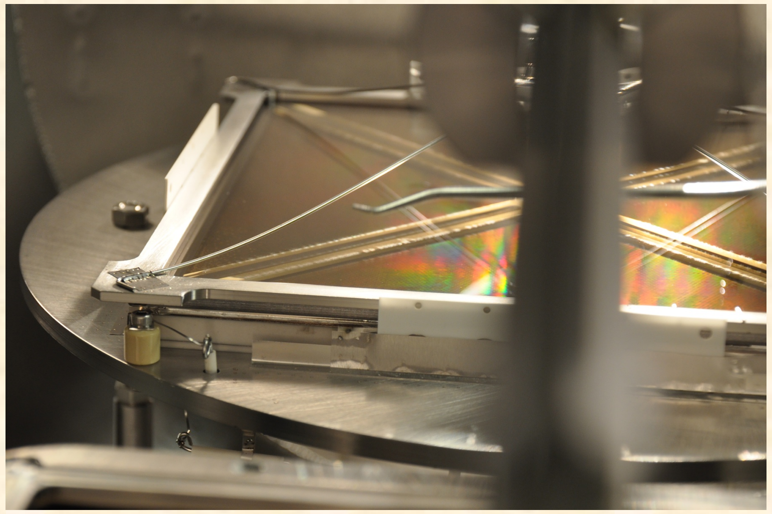


Cathode uniformity at 400nm - relative

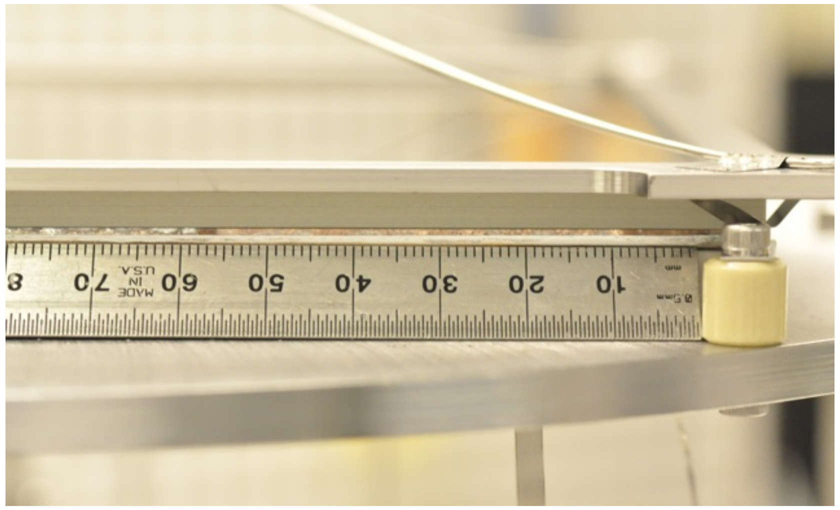
Tube was found to have not sealed along 15cm length around one corner. Problem with wicking of InBi to remaining perimeter



Completed cathode, dark brown shaded



Tube with window hot indium seal completed

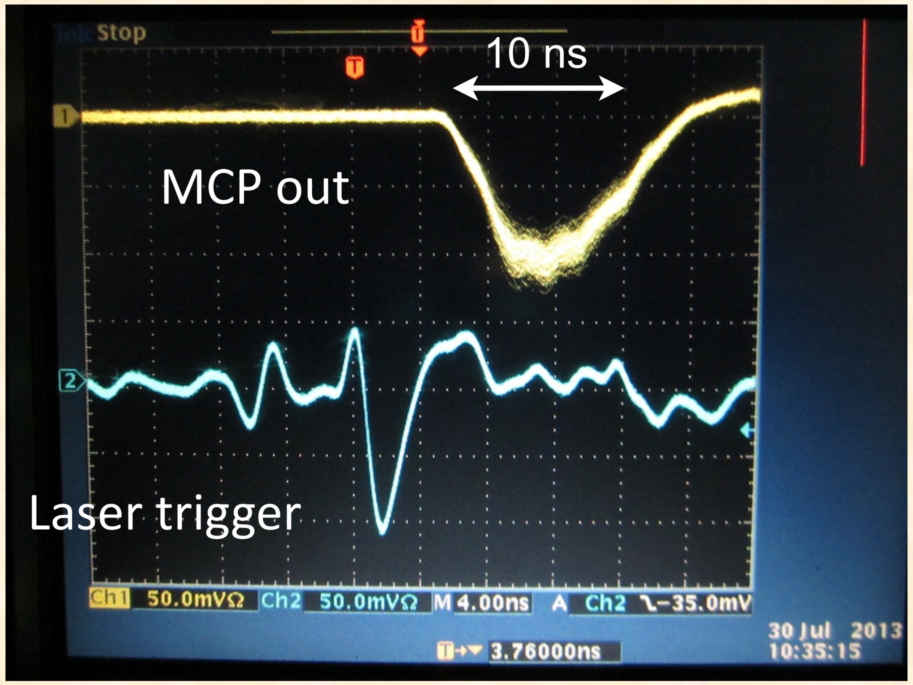


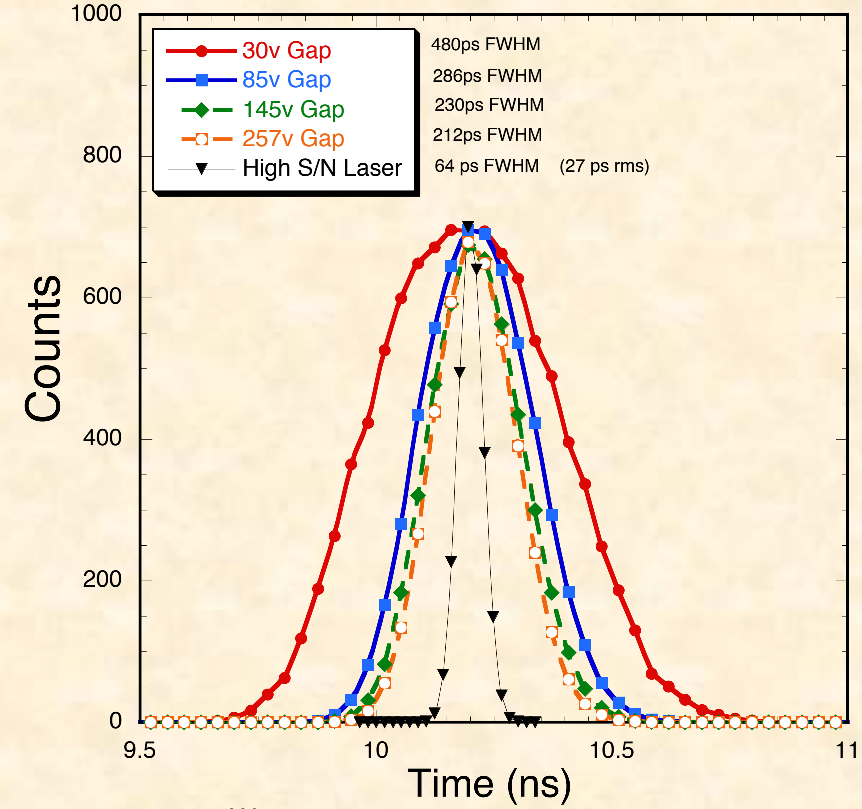
Corner indium deficit - RHS

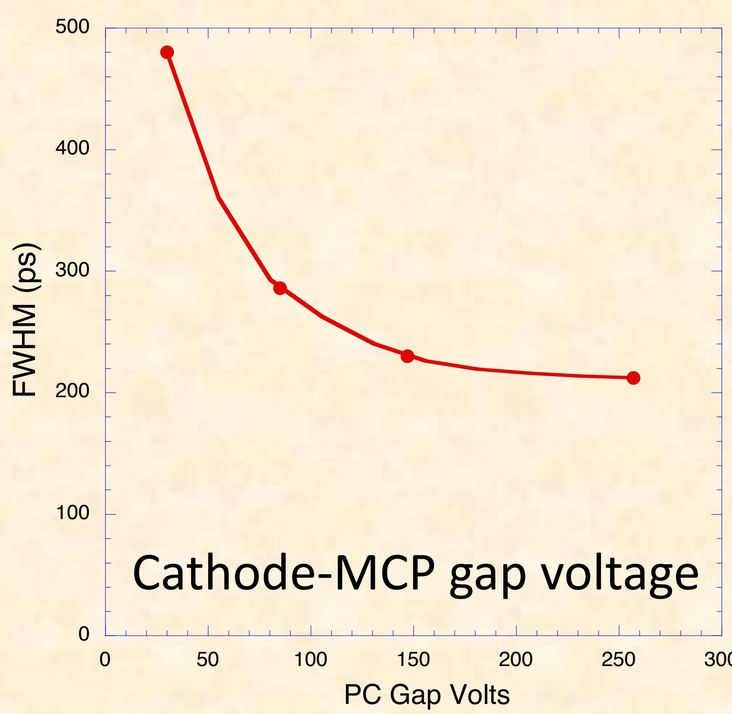
graphics: Ossy Siegmund & Jason McPhate, SSL

Testing of First Tube in Vacuum Tank

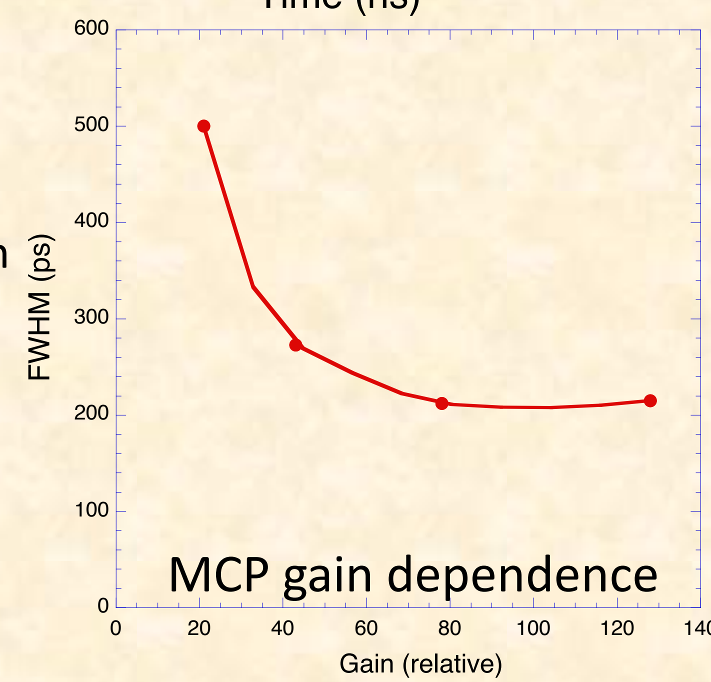
LAPPD Tube #1, Laser Pulse Transit Time Spread



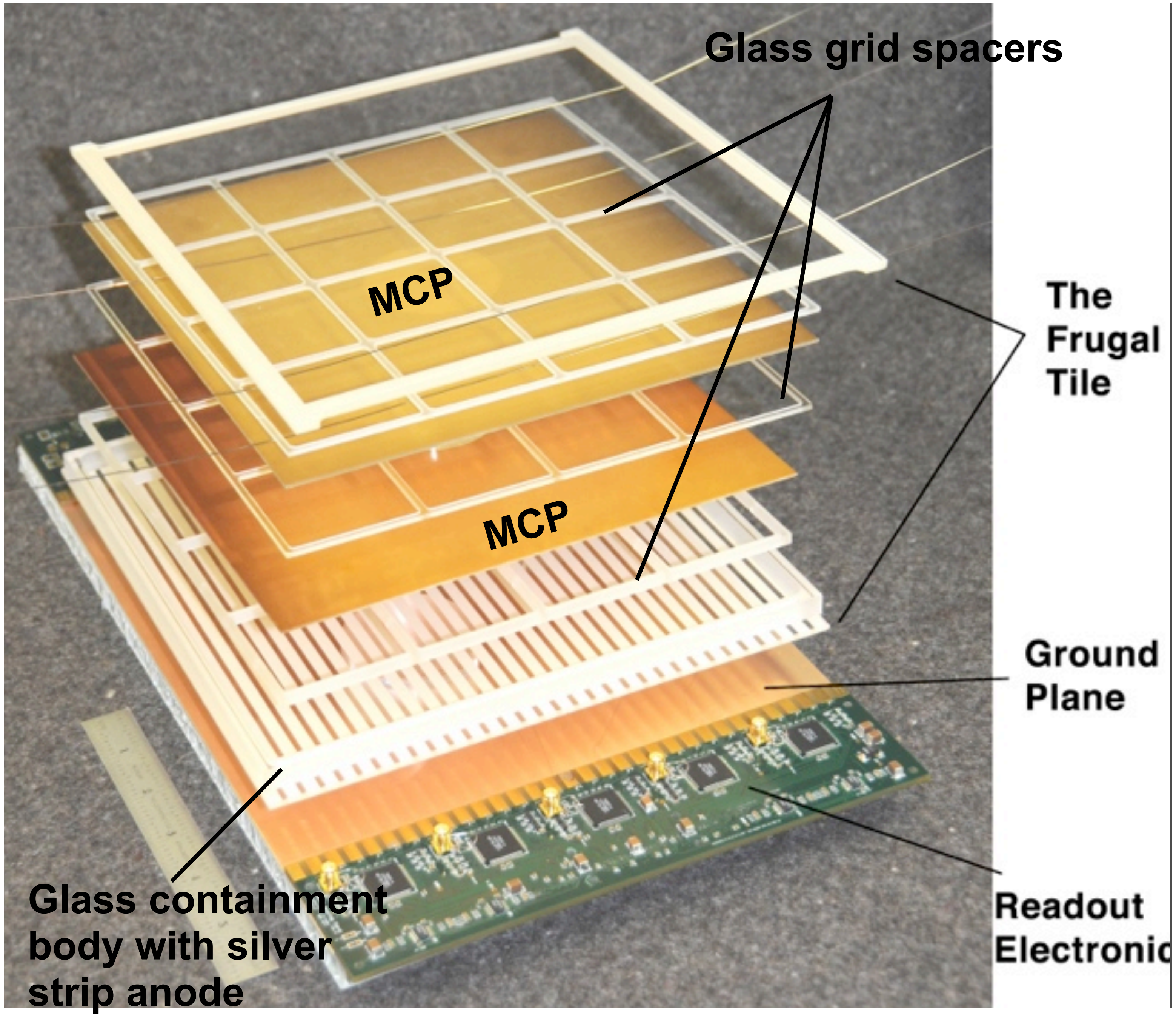




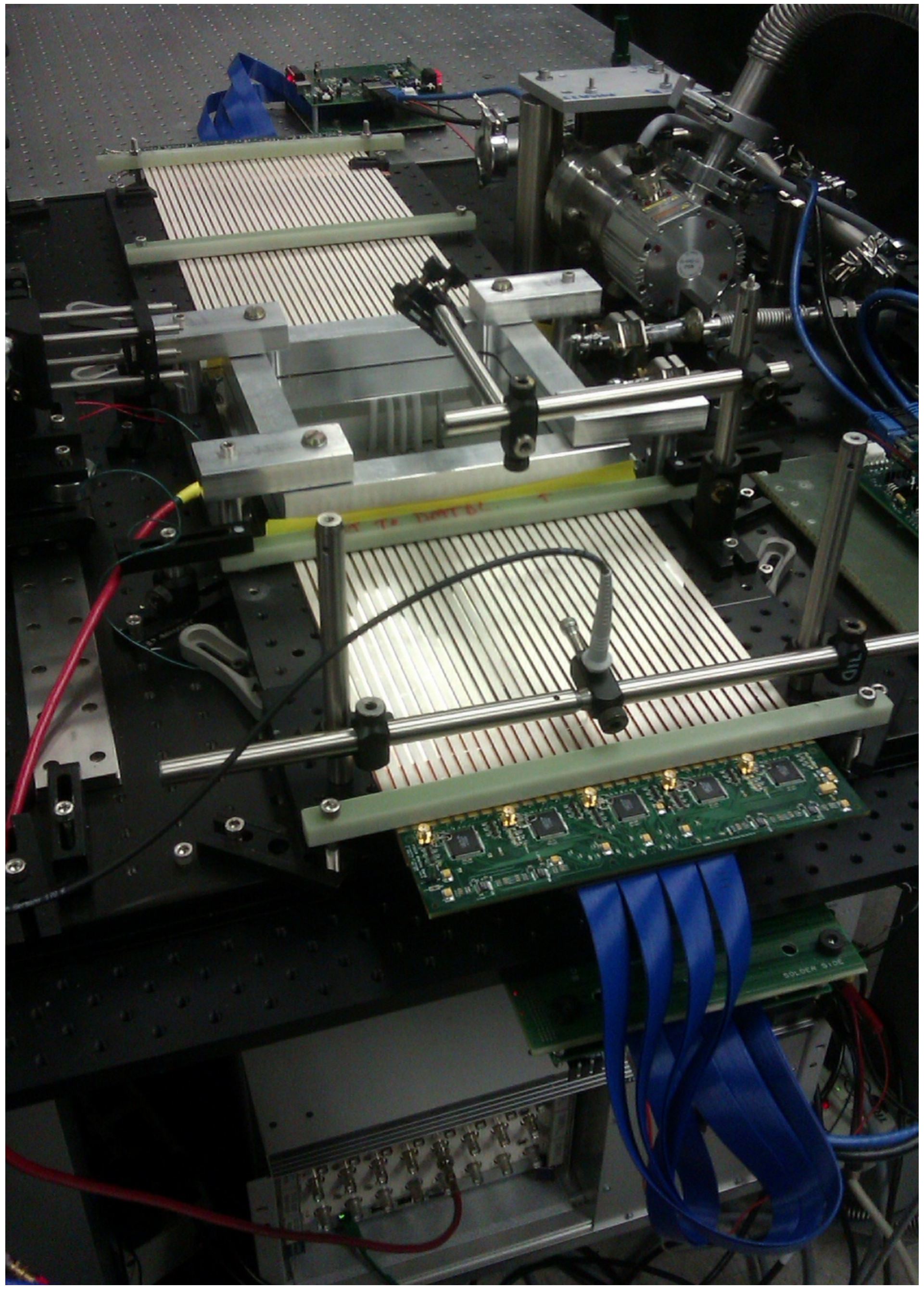
Transit time spread asymptote at ~200ps is due to poor matching and connections of the signals for the configuration inside the vacuum processing tank (confirmed with high S/N tests)



20cm x 20cm All-Glass Tile(≡Tube) Work at Argonne



Borosilicate Glass MCP PMT much less expensive than ceramic body tube.
No pins: HV via tabs on top window;
Resistive coated grid spacers provide bias for MCPs
signal through silver striplines



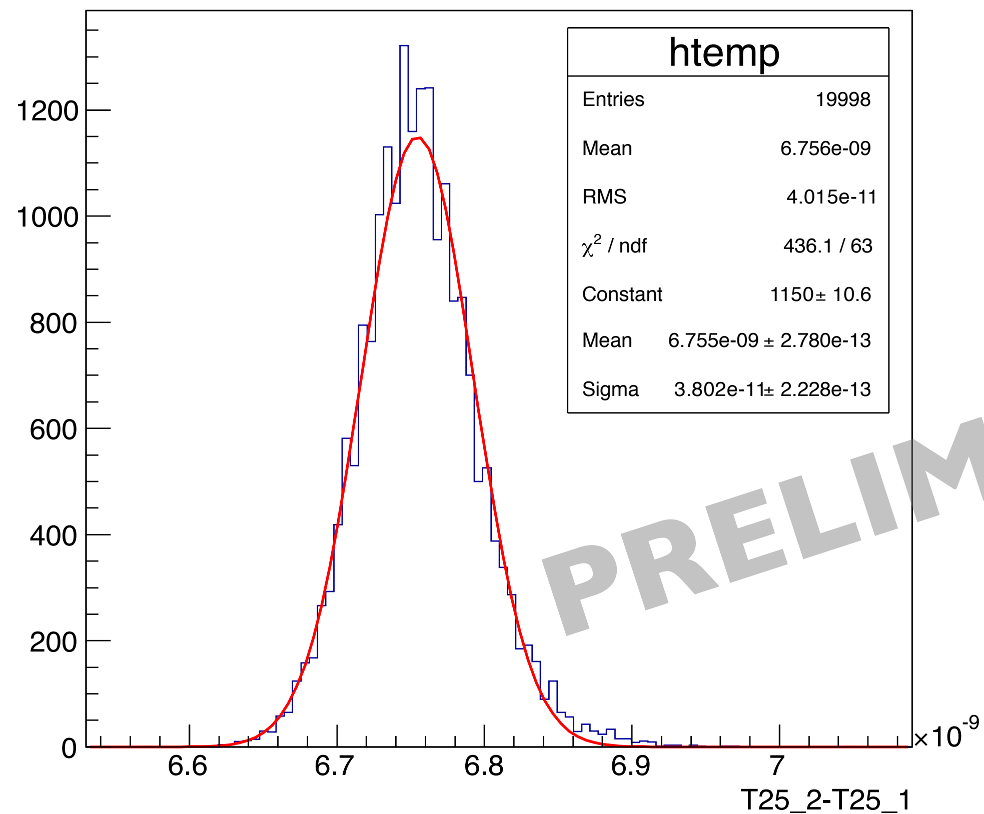
Demountable Tile

First deployment using aluminum photocathode and o-ring seal for top window
Input signal via UV pulsed laser

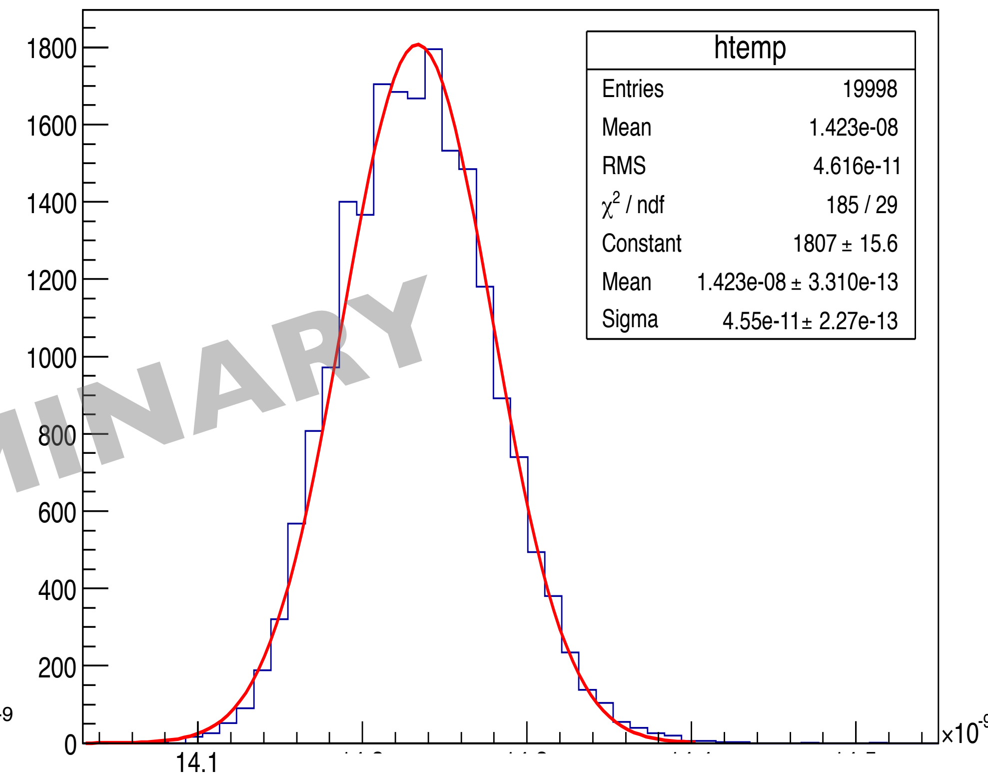
Time Resolution of Demountable All-Glass Tube

First results with 90 cm-long anode:

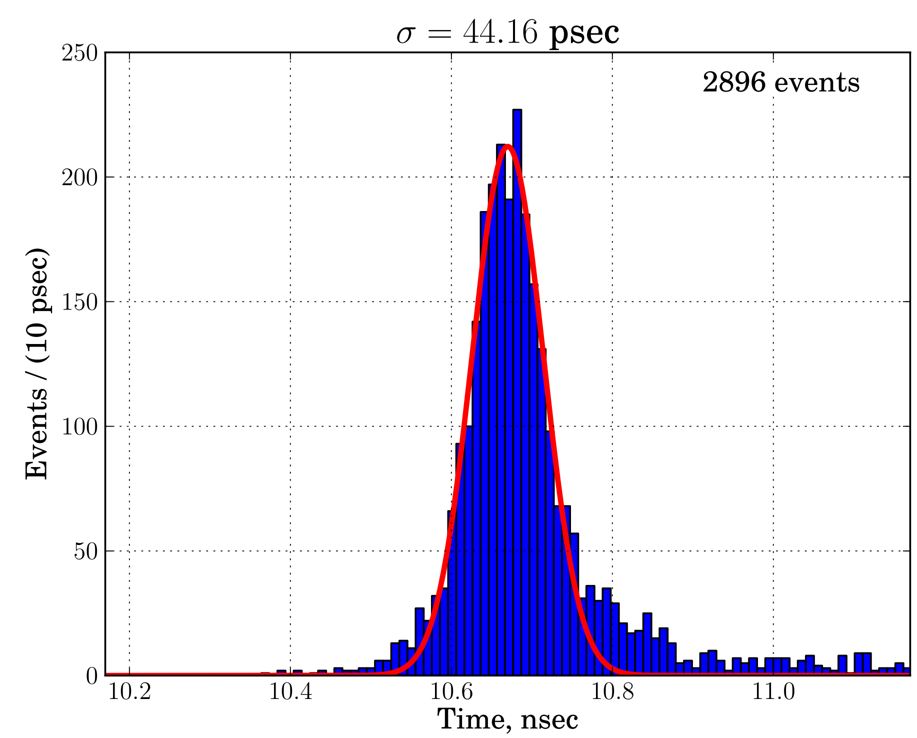
38 picosecond differential time resolution



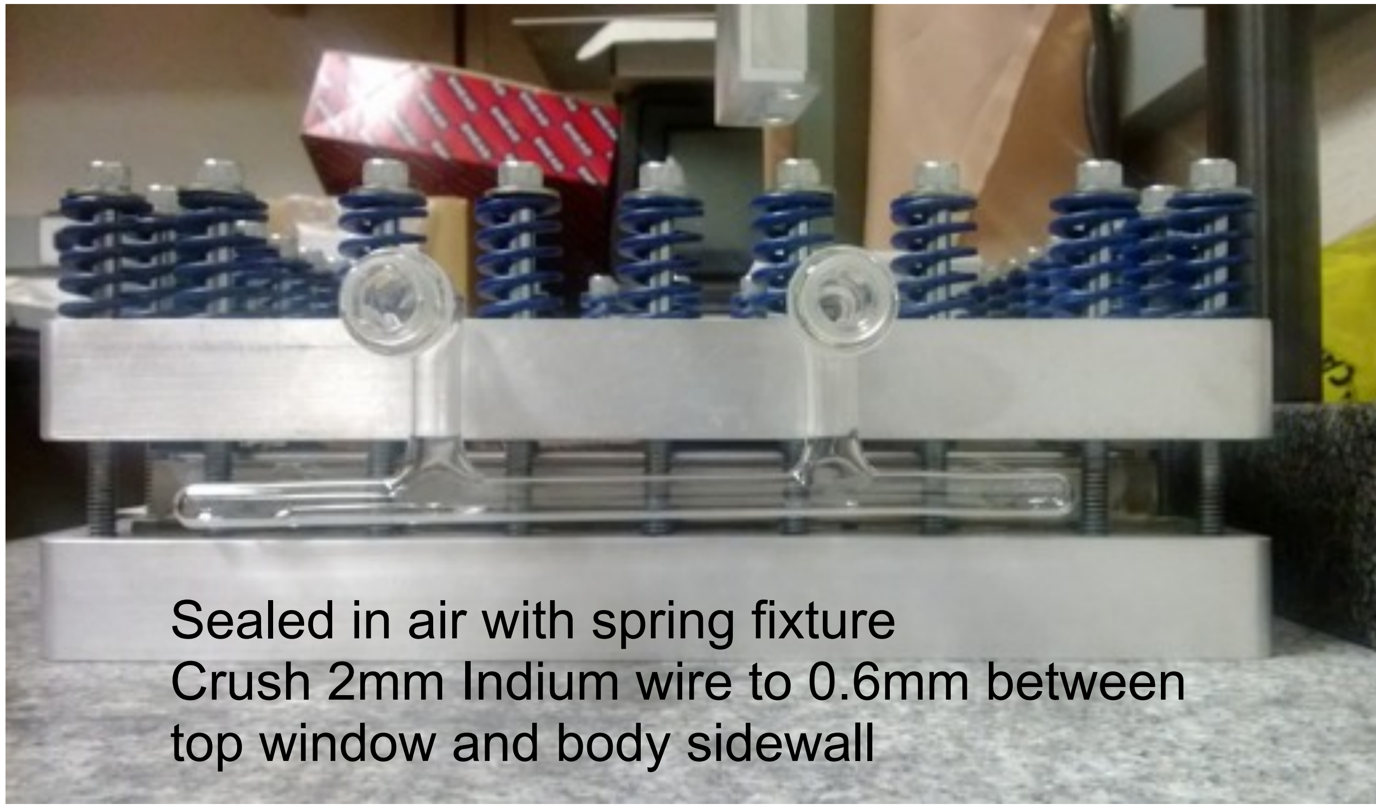
46 picosecond Transit Time Spread

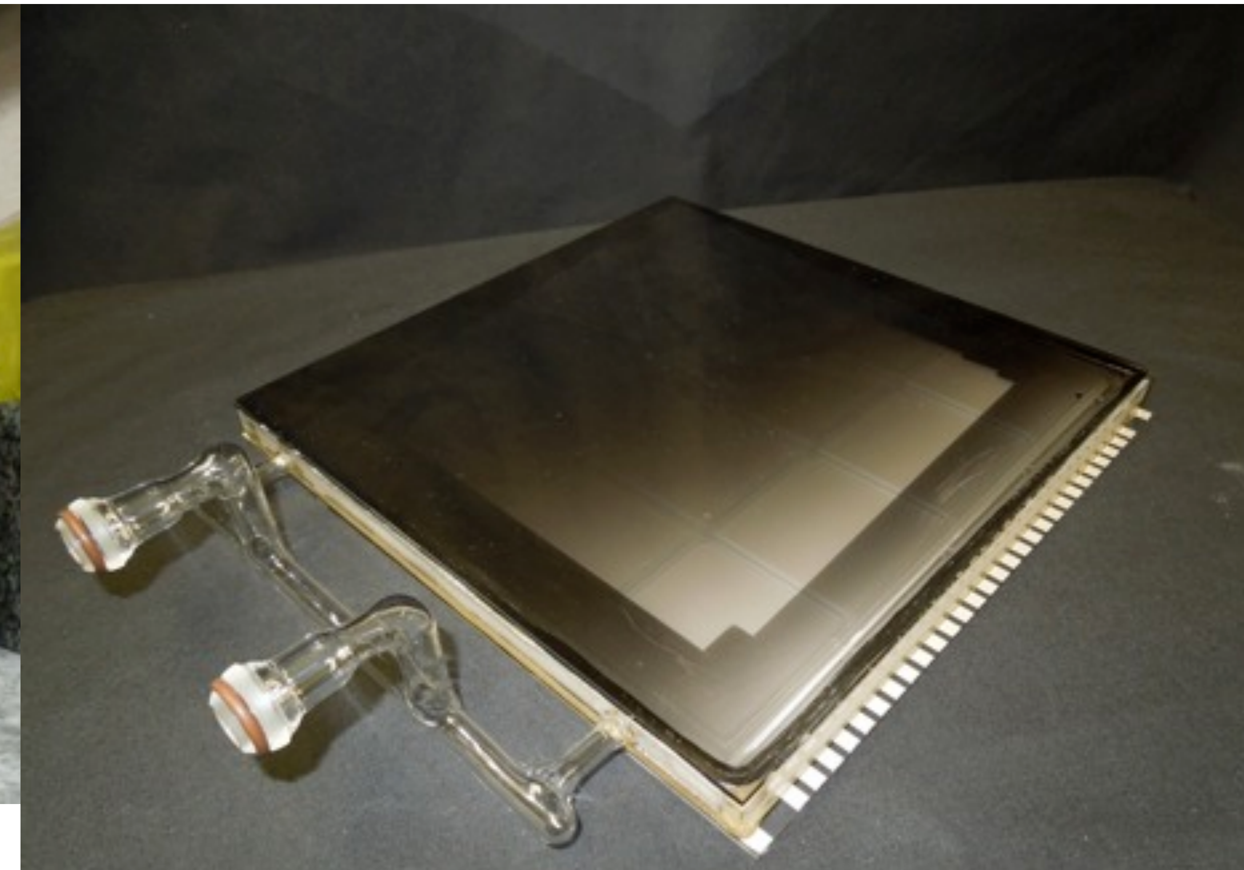


Most recent single PE result using improved analysis package: δt = 44 ps



First Pressure Indium Sealed All-Glass Package





Purpose is to demonstrate leak tight top window seal

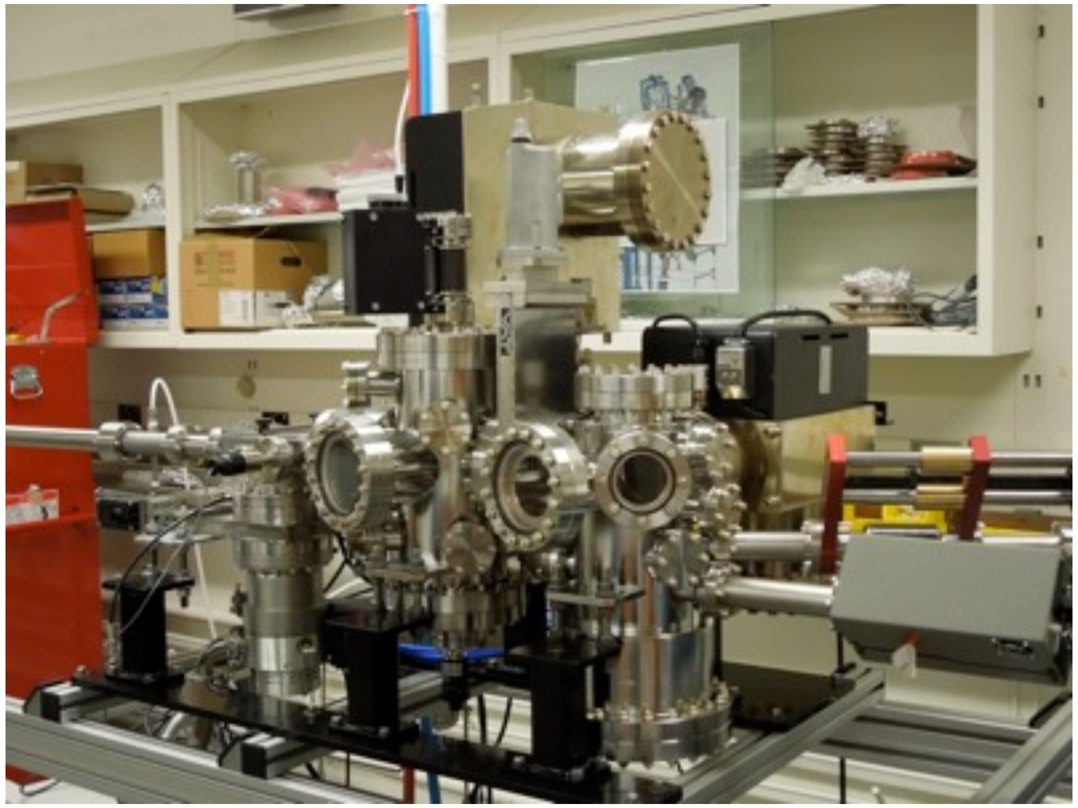
Package contains grid spacers & non-functional MCPs

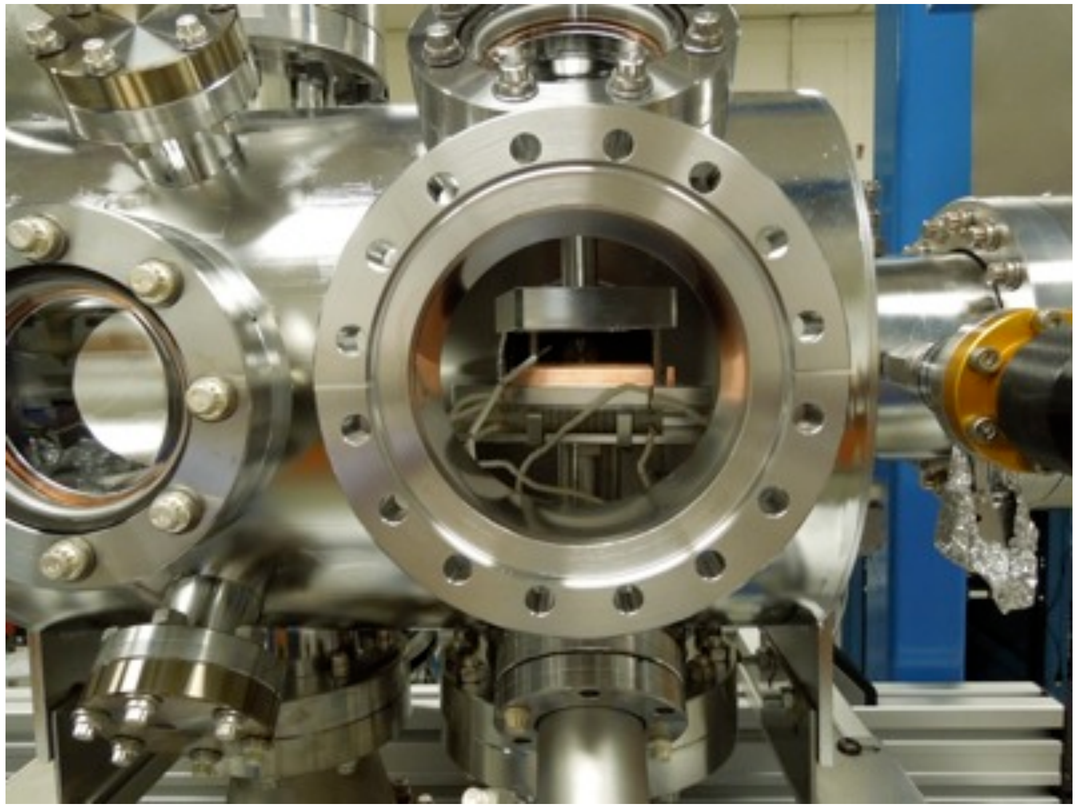
Leak tight under vacuum for 10 days.

No indication of degradation of Indium seal

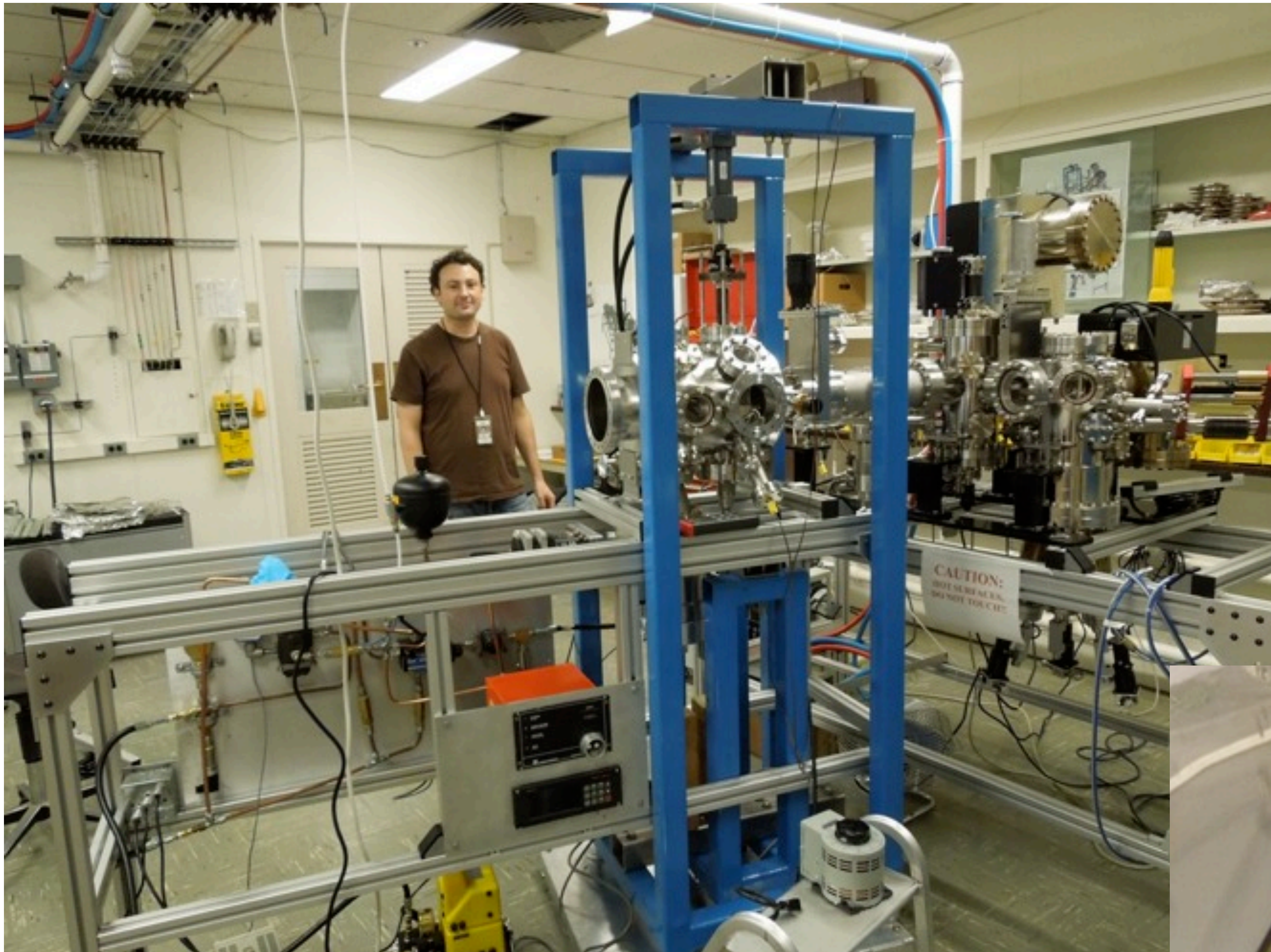
Argonne Small Single Tube Processing System (SmSTPS)

- Argonne design for MCP-PMT fabrication is ultra-high vacuum multi-chamber transfer system
  - Chambers specific to fabrication function
    - Load lock
    - Bake & scrub (pre-condition low voltage operation of MCP/grid spacer stack
    - Photocathode deposition
    - Top seal chamber (hydraulic compression system within UHV chamber)
- Initial system to produce 6cm × 6cm active area tube
- Expect first tubes sealed in vacuum next month (December)
  - Use top window with pre-deposited aluminum photocathode
  - First attempts for bialkali K_2CsSb in early 2014



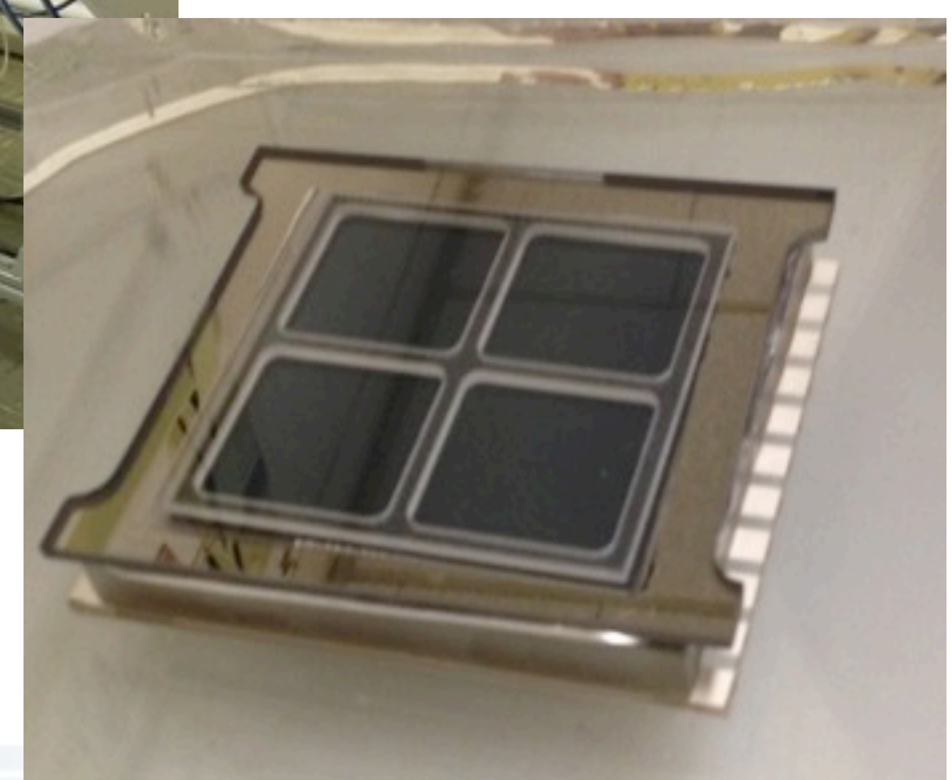


Assembled SmSTPS



First 6cm tube prototype sealed in chamber in air

Non-functional MCPs plus grid spacer supports



Summary & Outlook

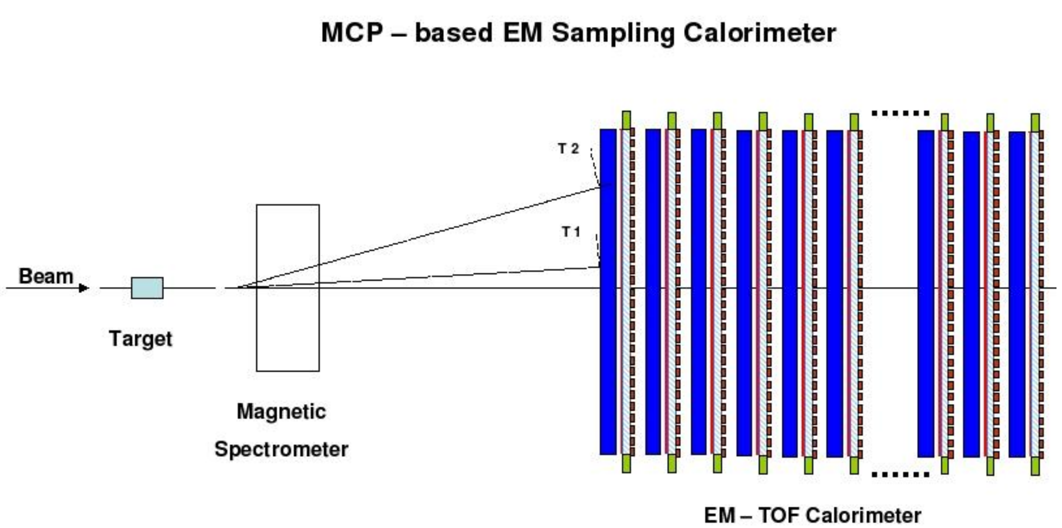
- 20cm × 20cm microcapillary arrays developed using borosilicate glass
- Have successfully functionalized many 20cm plates and 33mm disks into Microchannel Plates using 2 different resistive formulations and 2 different secondary electron emission coatings via ALD
- Fabrication of large area planar photocathodes with QE~25% accomplished
- Developed complete readout system based on 16 GS/s waveform sampling ASIC
- Hermetic packaging of large format tubes has proven difficult but recent successes
  - First ceramic body attempt at SSL in July, 2013 did not seal completely
  - Have modified ceramic body design and new bodies are being brazed
  - Working at SSL on all-glass body tube as part of Small Business technology transfer grant
  - First indium pressure seal on all-glass body successfully made in Oct, 2013
  - First indium seal in air in SmSTPS for 6cm tube made in Nov. 2013
- Plans for future
  - First functional 6cm tube with NiCr photocathode -- Dec. 2013
  - First functional 20cm tube with Al photocathode and Indium seal -- Dec. 2013
  - First 6cm tube with bialkali photocathode -- 2014
  - First commercially produced 20cm all-glass tubes -- 2015

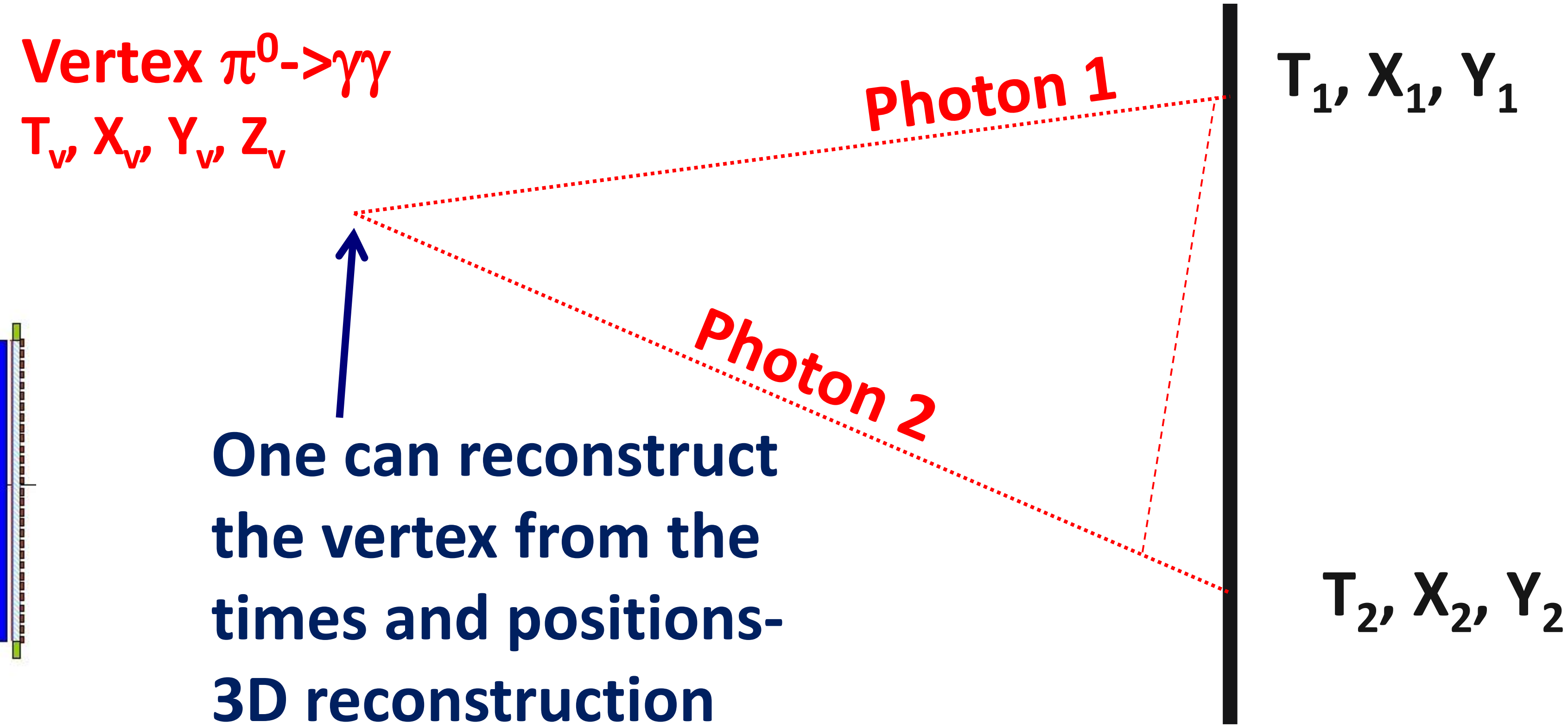
Backup Slides

Applications — Photon Vertexing

Rare Kaon Decays - $K_L \rightarrow \pi^o \nu \bar{\nu}$

Combination with precision energy resolution in calorimeter critical





One can reconstruct the vertex from the times and positions- 3D reconstruction

Reduce combinatoric background for π^o

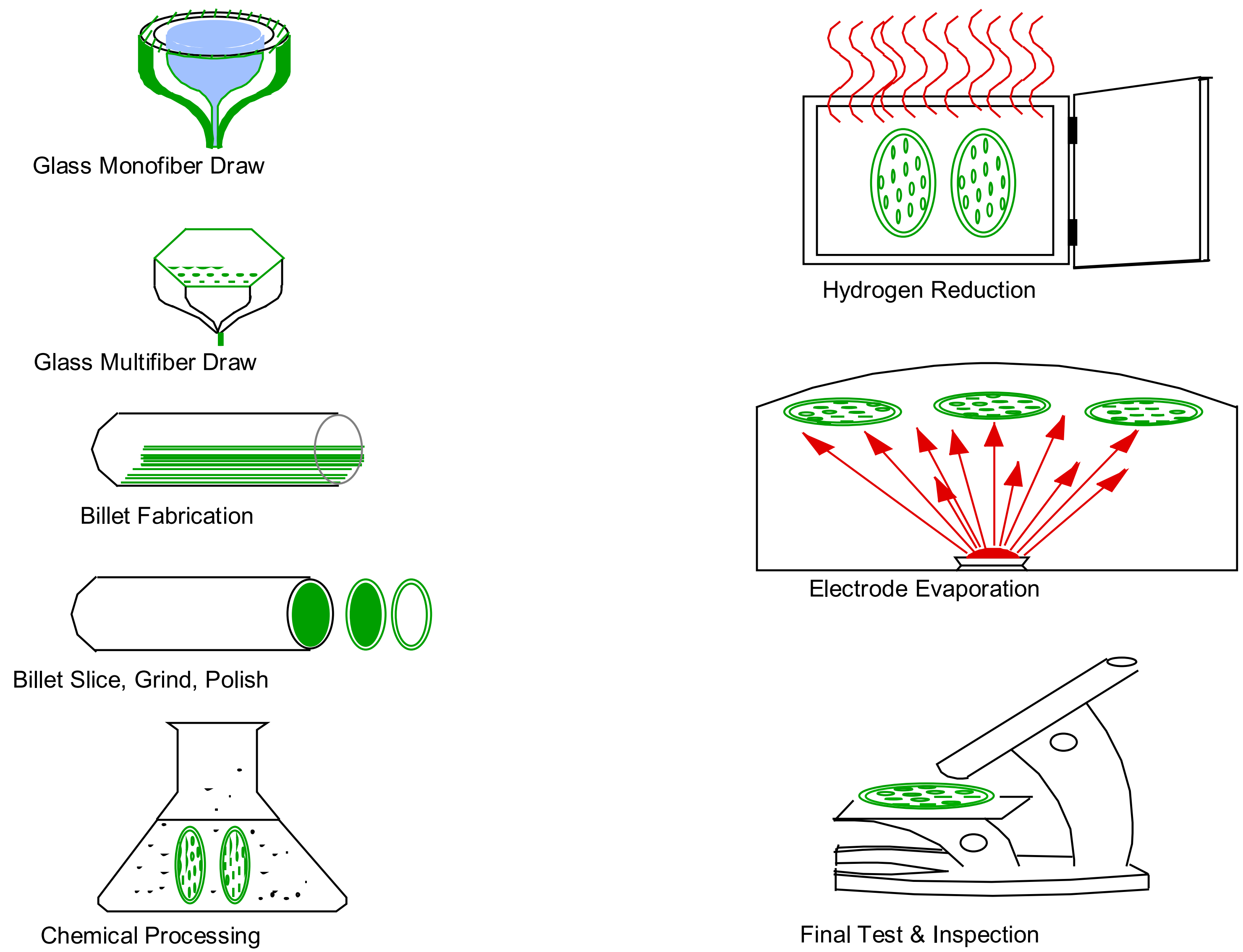
Industrial Microchannel Plate Fabrication

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

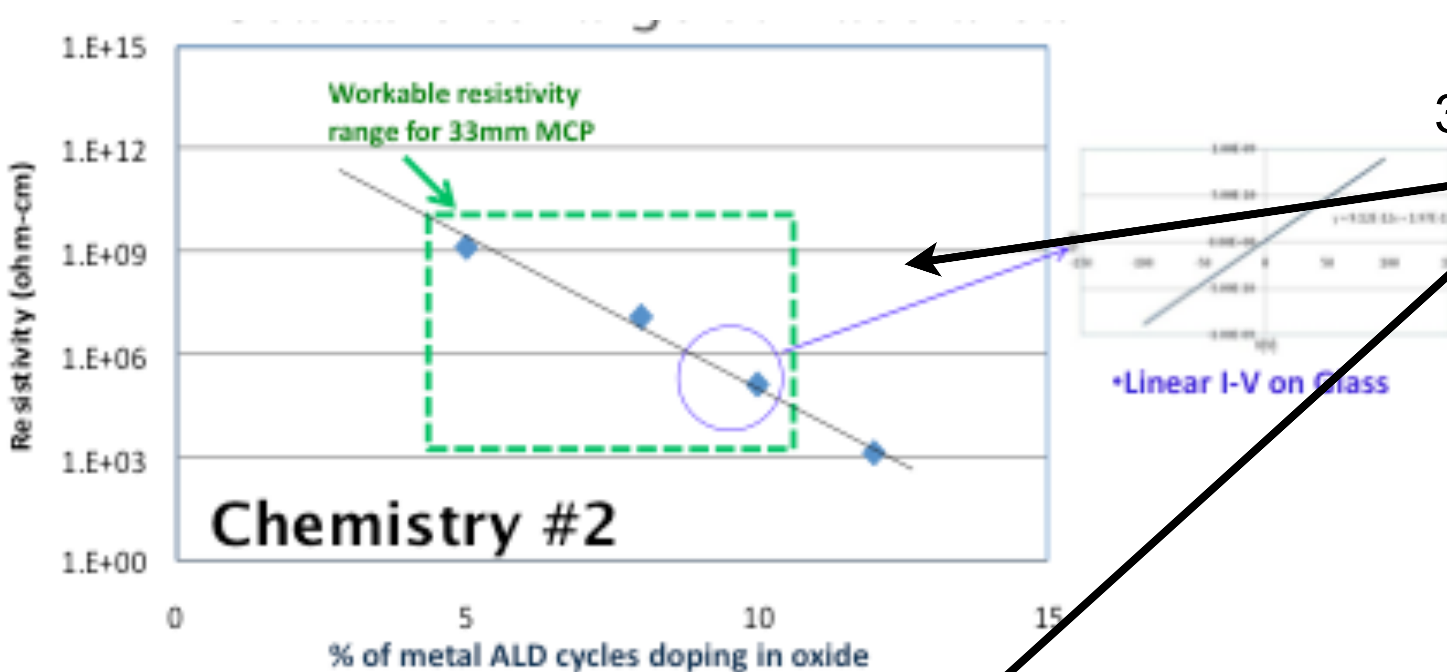


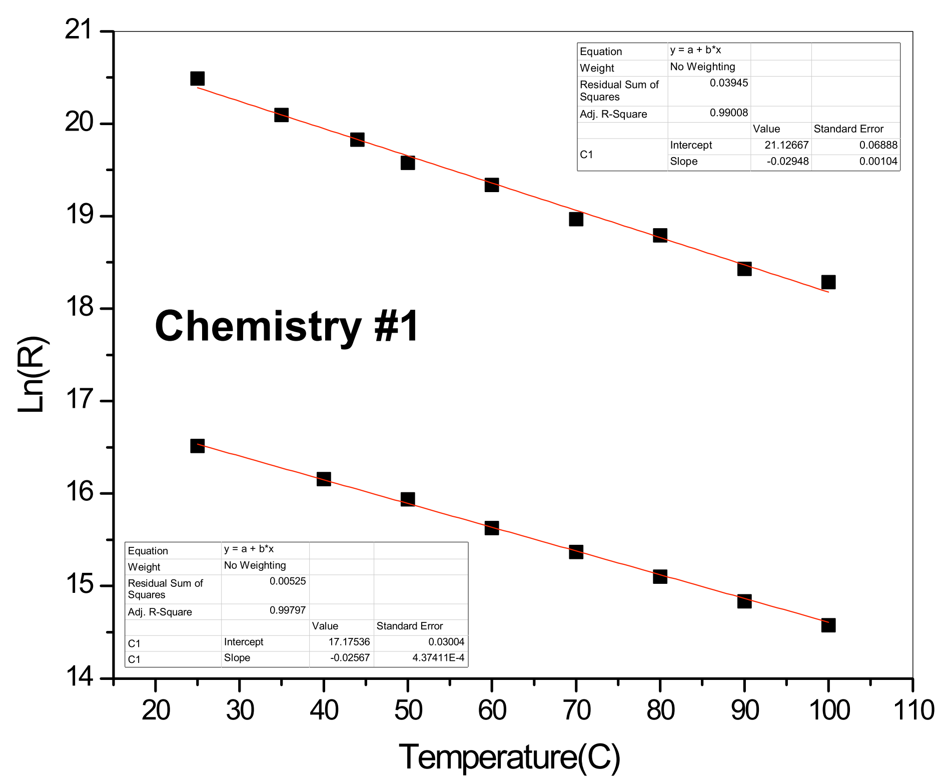
Before sealing in tube, plate must be subjected to prolonged exposure to electrons at low voltage to outgas H_2 and other material

ALD Materials Development

3 Resistive Chemistries invented by ANL ALD Group:

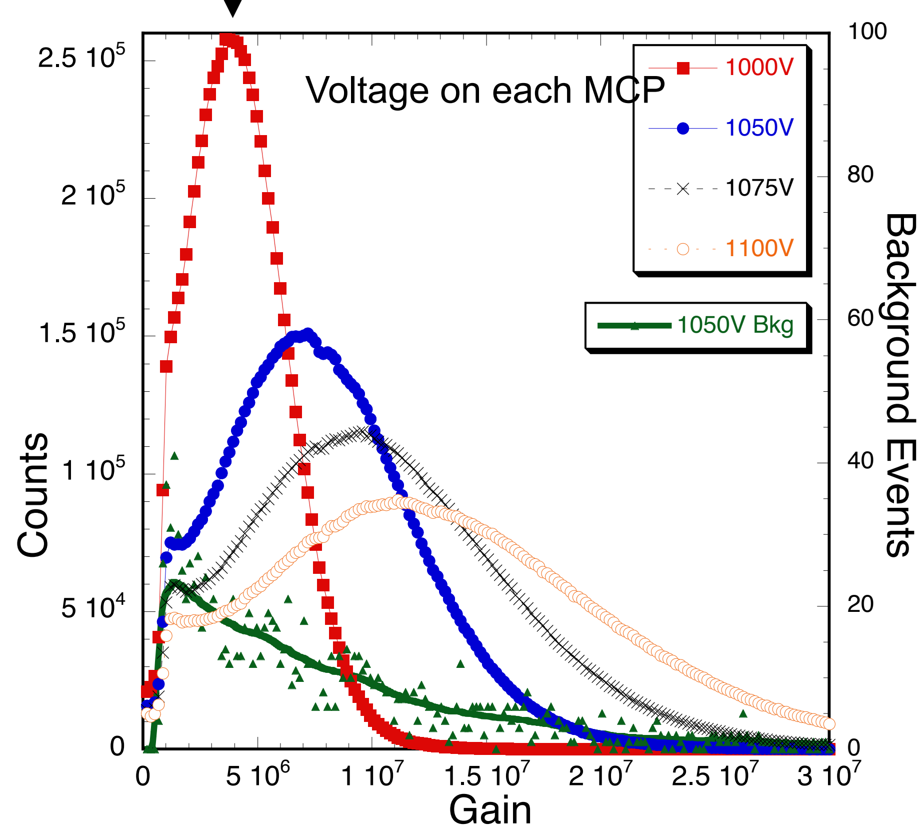
- **Tunable R over 6+ orders of mag.**
- **R vs. Temp. stable against thermal runaway**
- **Functionalized MCPs exhibit high gain**





ALD development: Anil Mane & Jeff Elam, Argonne ESD

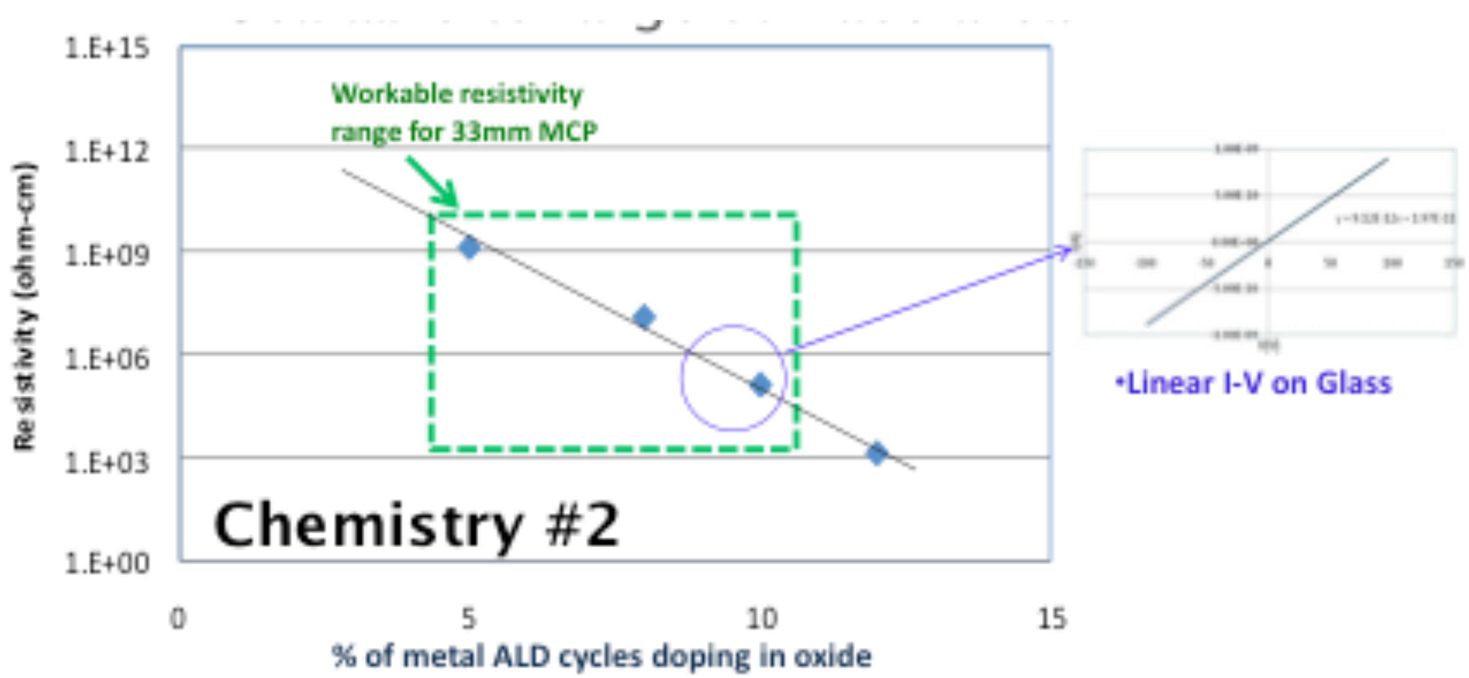
G=4×10^6 @ 1000V



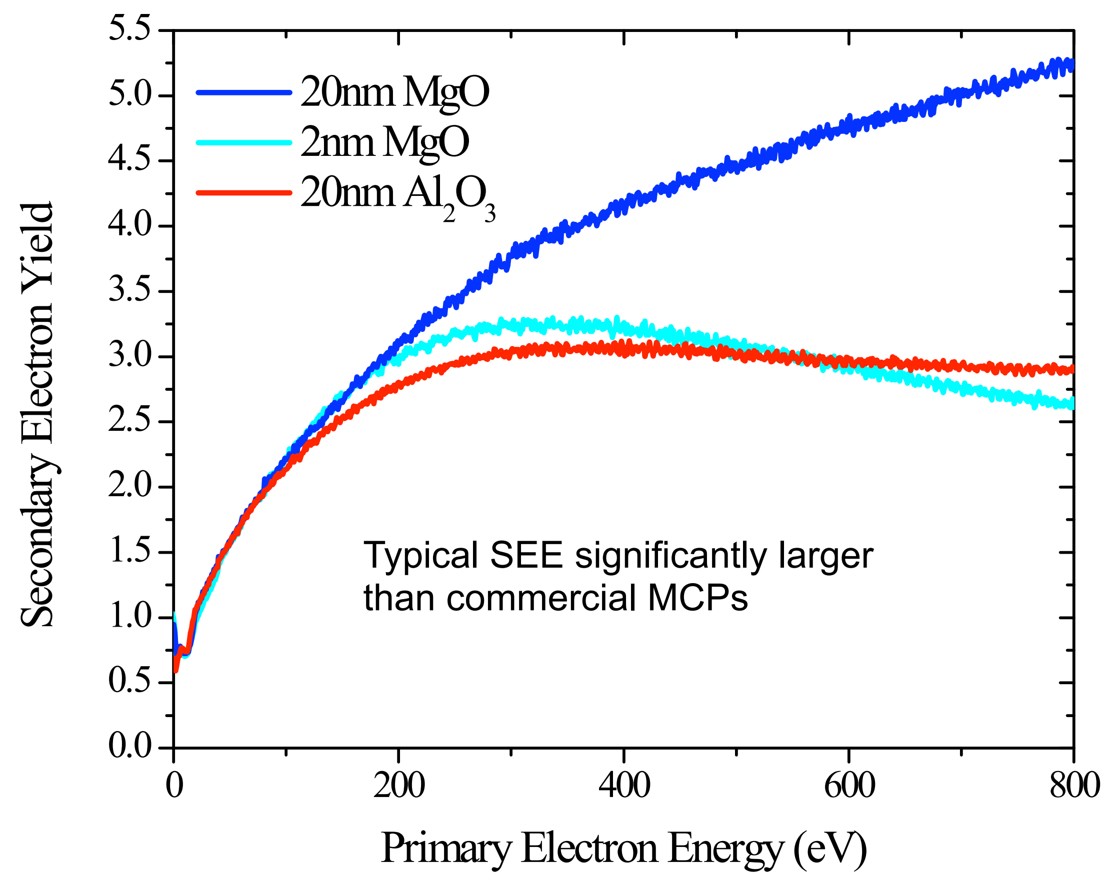
Pulse height amplitude distributions. MCP pair, 20µm pores, 8° bias, 60:1 L/d, 0.7mm pair gap with 300V bias. 3000 sec background.

graphic: Ossy Siegmund, SSL

Materials Characterization



Secondary Emissive Materials characterized
with Low Energy Electron Diffraction (LEED)



MCP Testing at Argonne and SSL — Facilities

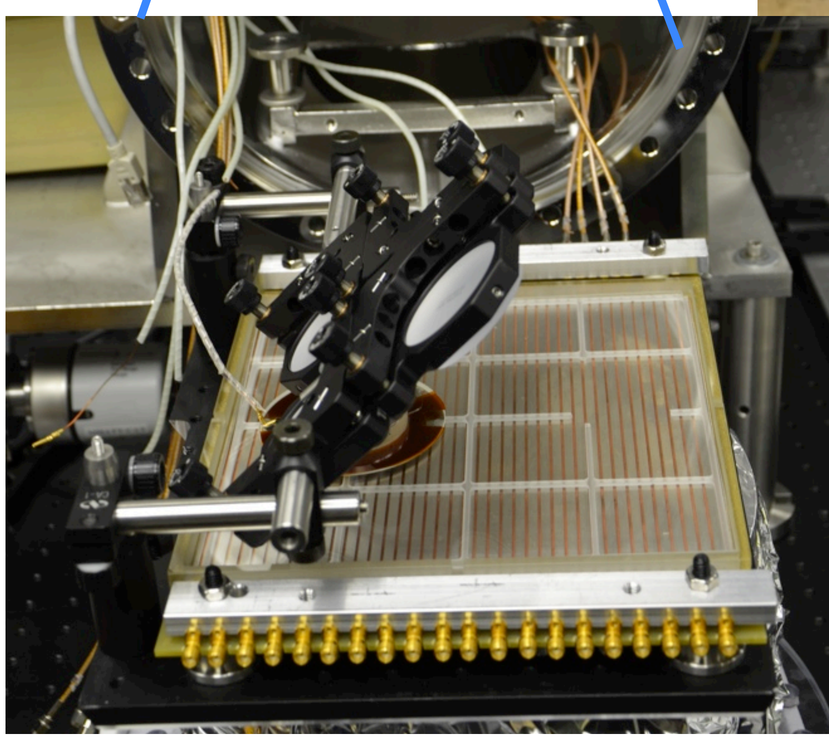
Argonne 33mm & 8” Test Chambers
with UV fs-pulse laser

SSL 33mm Test Chambers

Phosphor detector on left imaged with camera

Cross-strip delay line on right for gain mapping

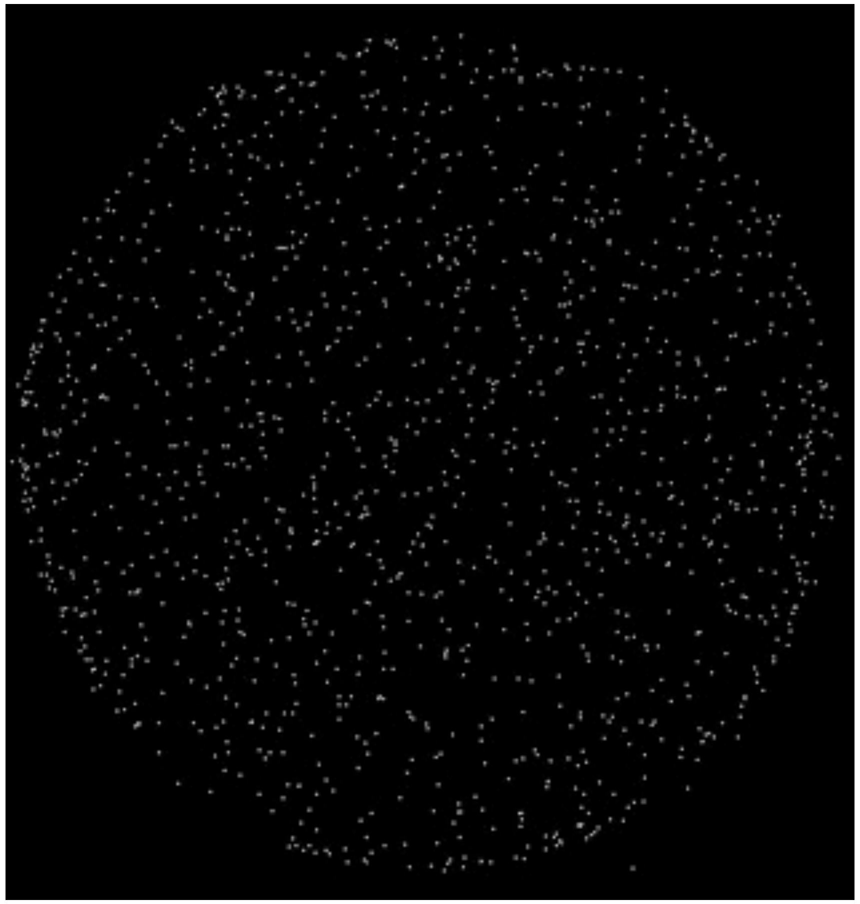
MCP on stripline anode ready for insertion into 8” chamber



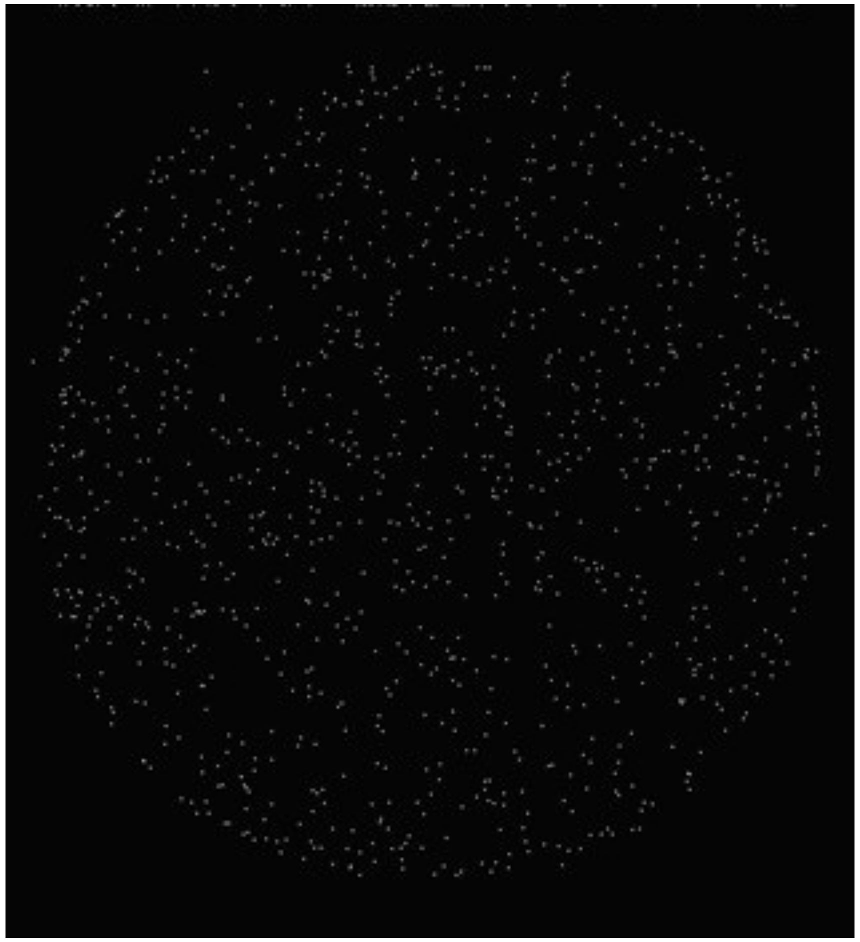
SSL 8” MCP Test Detector Vacuum System

Noise Characterization

MgO SEE Layer

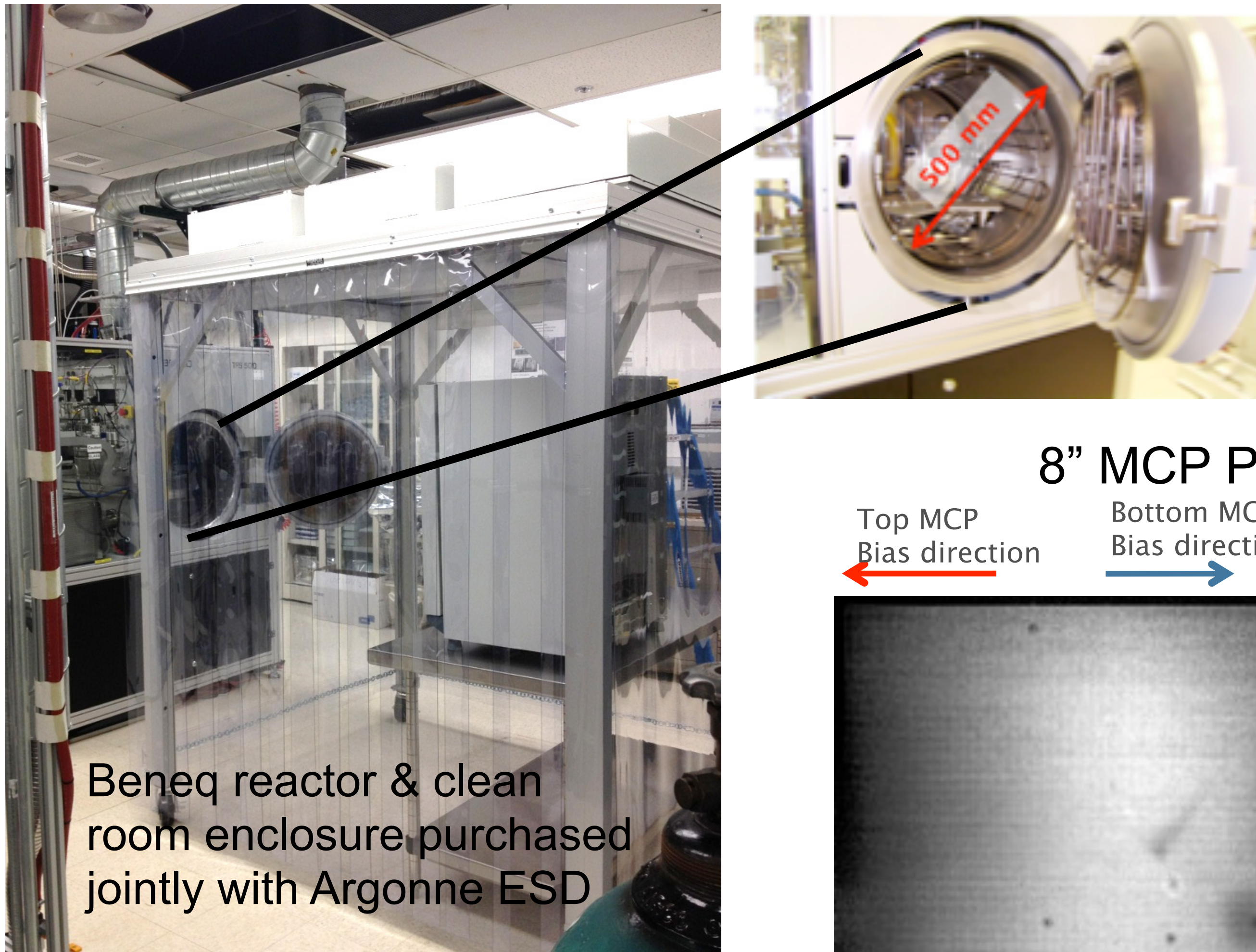


3000 sec background, 0.0845 events cm^{-2} sec^{-1} at 7 x 10^6 gain, 1025v bias on each MCP. Get same behavior for most of the current 20μm MCPs



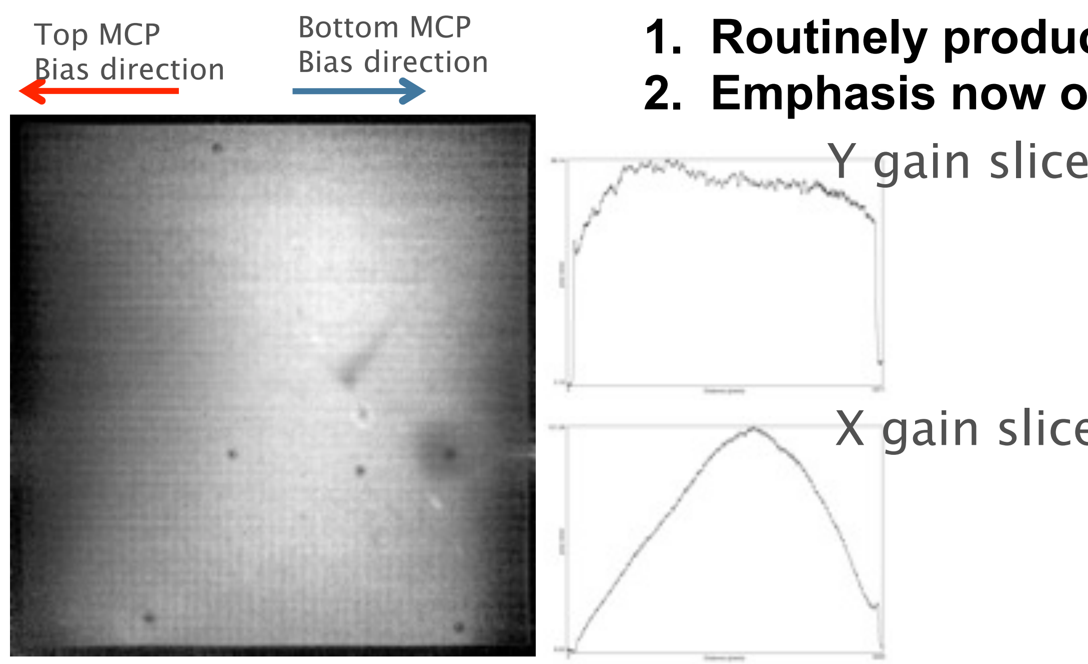
Post-bake –2000 sec
~0.1 events cm^{-2} sec^{-1}

MCP Development — Scaling to Large Area



In June, 2012, Project received an R&D 100 Award for cost-effective and robust route to fabricate large-area MCP detectors

8” MCP Pair test at SSL



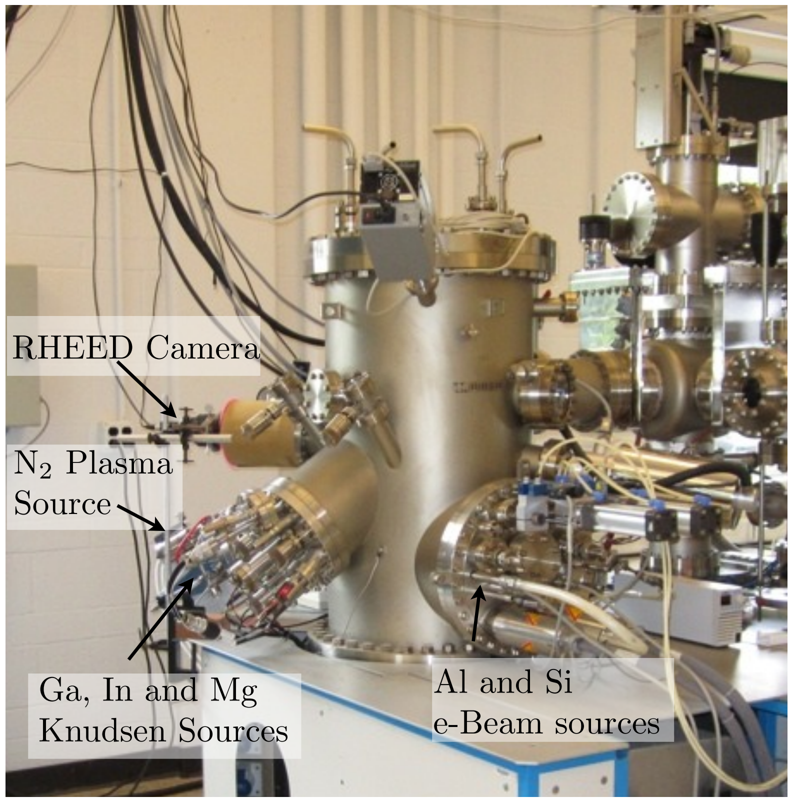
1. **Routinely producing targeted resistance**
2. **Emphasis now on SEE layer gain uniformity**

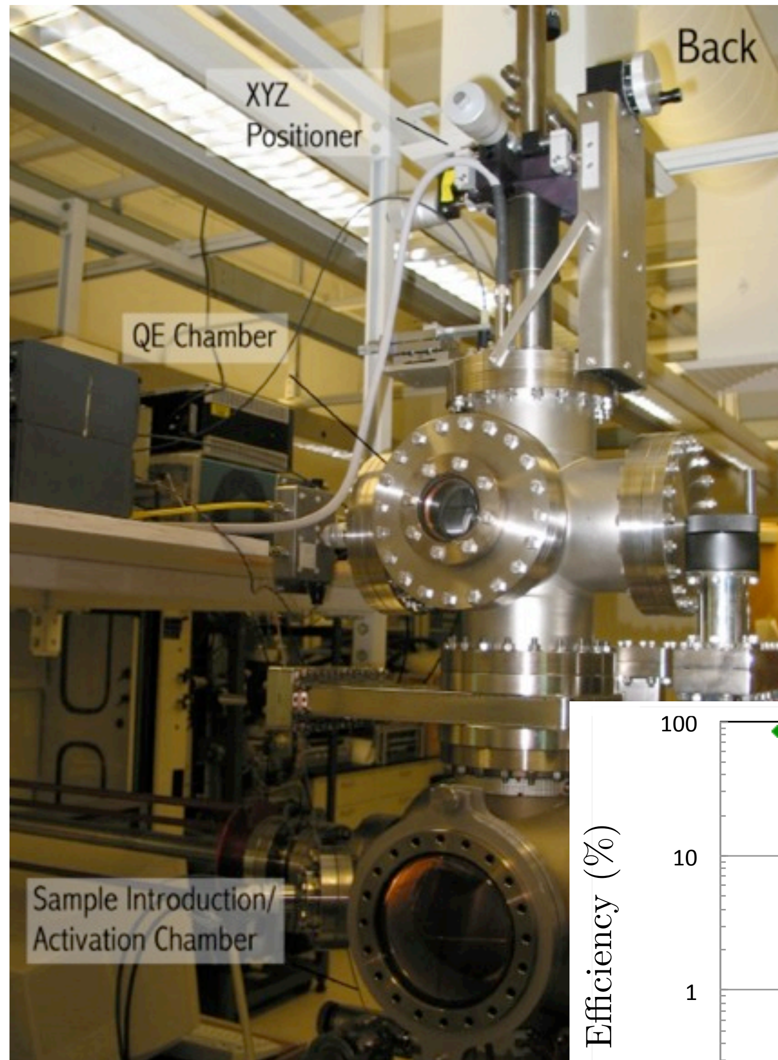
Areas of Future Focus for MCP Development

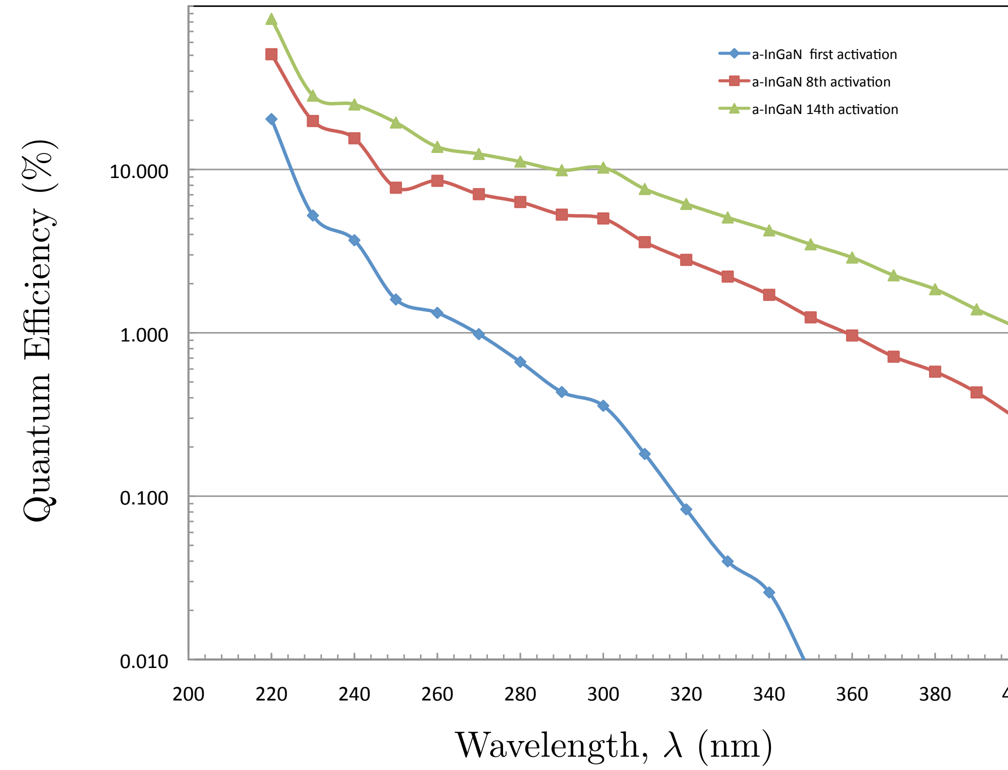
- **Near term:**
  - **Tune ALD processing for uniform gain**
  - **Continue capillary array quality improvement**
- **3 Year Plans:**
  - **Increase L/D, Open-Area-Ratio; decrease pore size for improved timing**
  - **Develop techniques to lower plate production cost, improve finish quality**
  - **Explore new ALD chemistries for lower cost, higher rate**

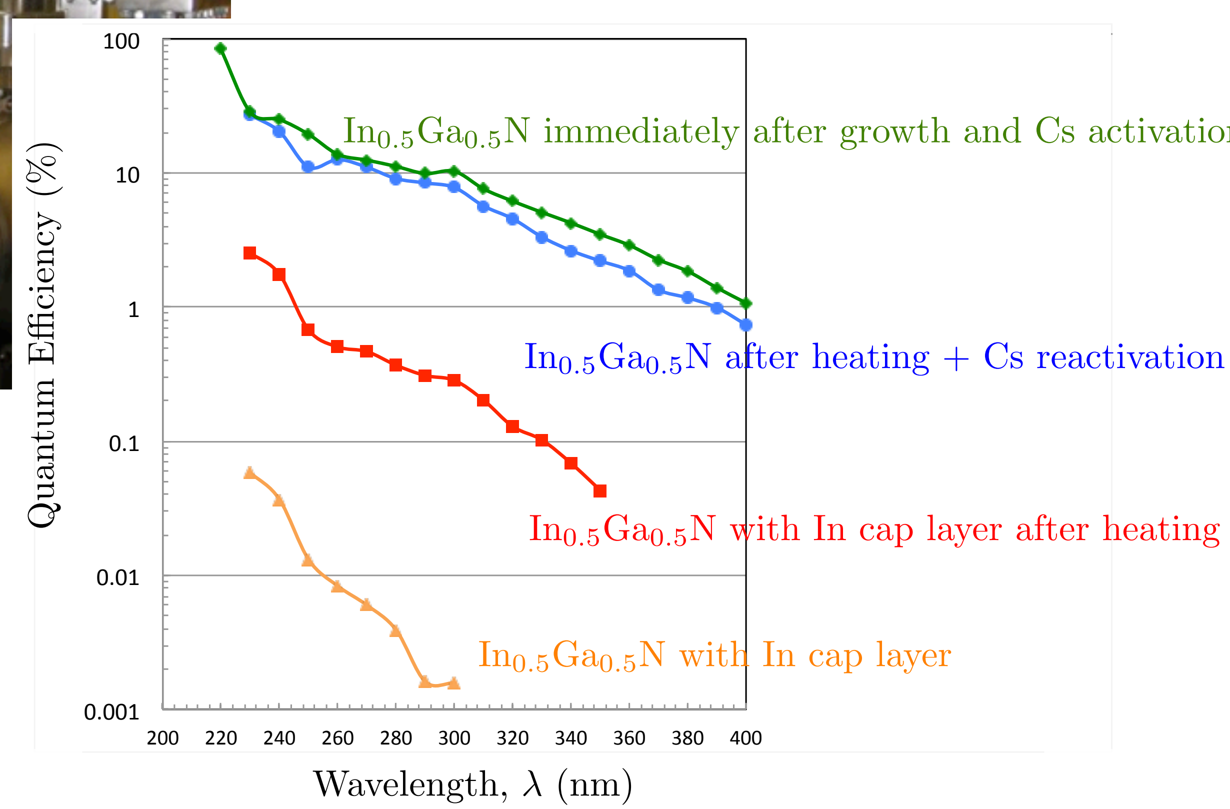
gain meas.: Ossy Siegmund & Jason McPhate, SSL

InGaN Photocathode Development — Washington University

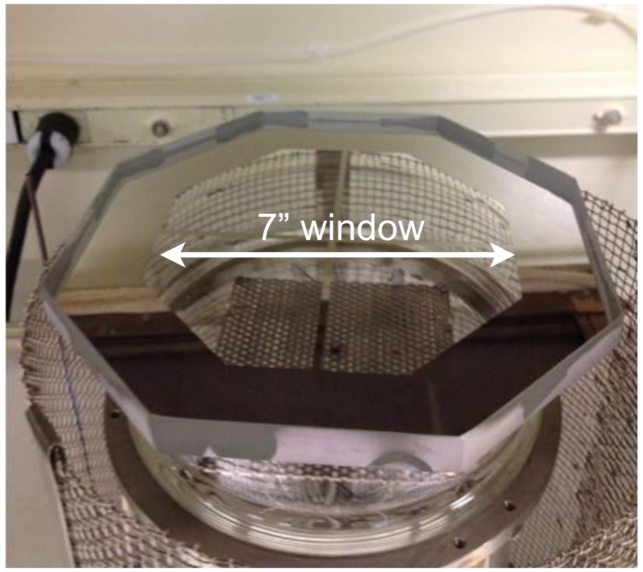








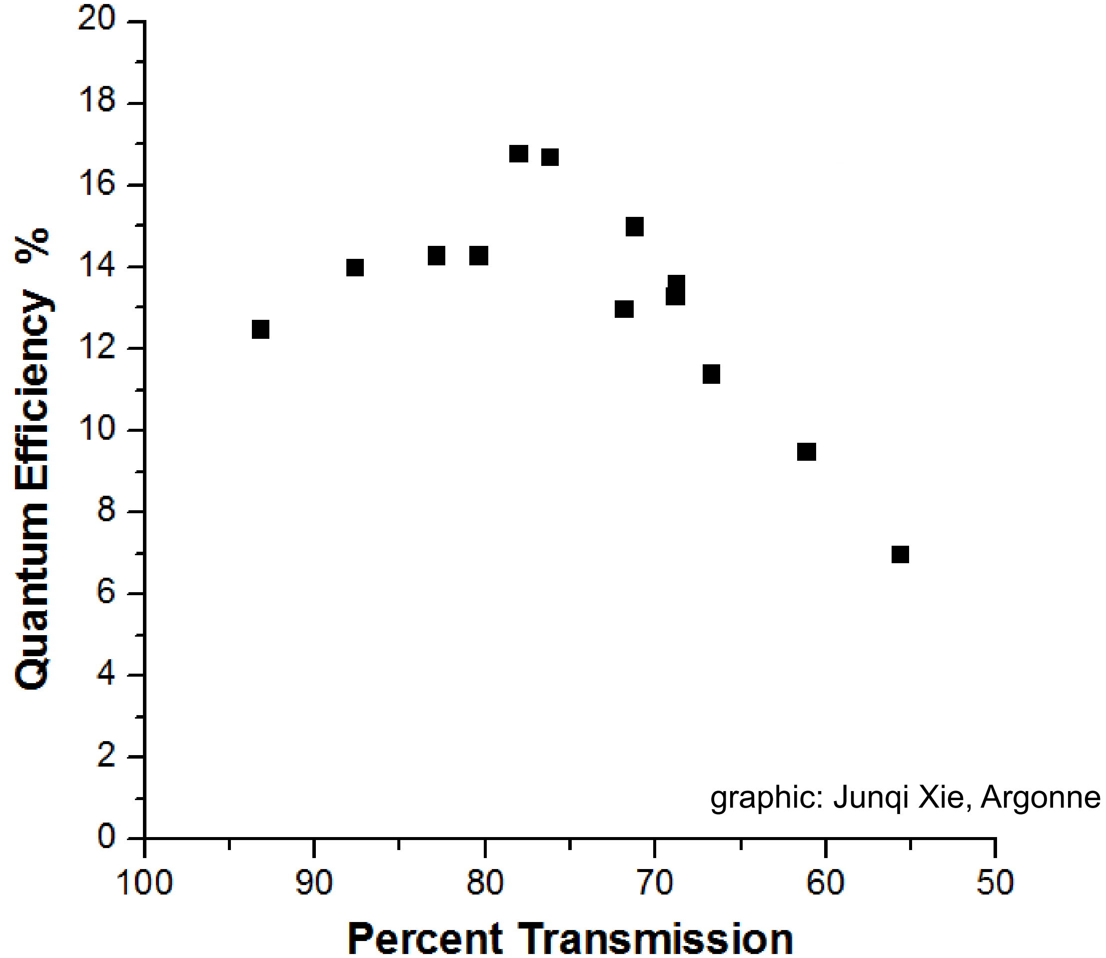
Scale-up to 7" Photocathodes at Argonne



10 Photocathode shoots on "erasable" glass window:

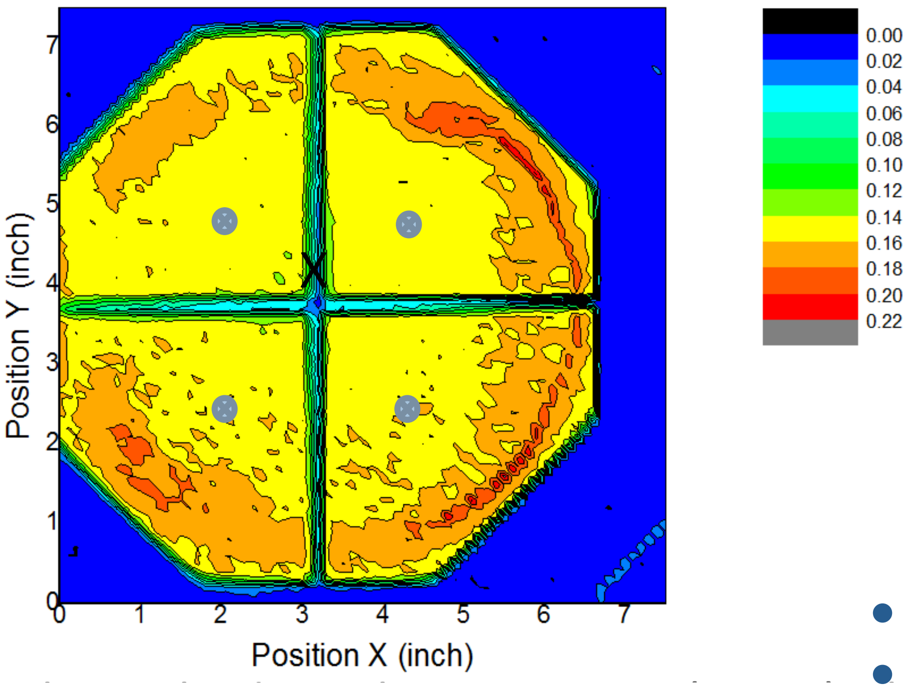
- Tune process parameters
- Optimal # and placement of Sb, K, Cs dispensers
- Improve QE and uniformity

KCs-Sb Photocathode



Optimization of QE w.r.t SB thickness
% transmission of Sb ⇒ thickness

QE Map



Chalice Photocathode #9

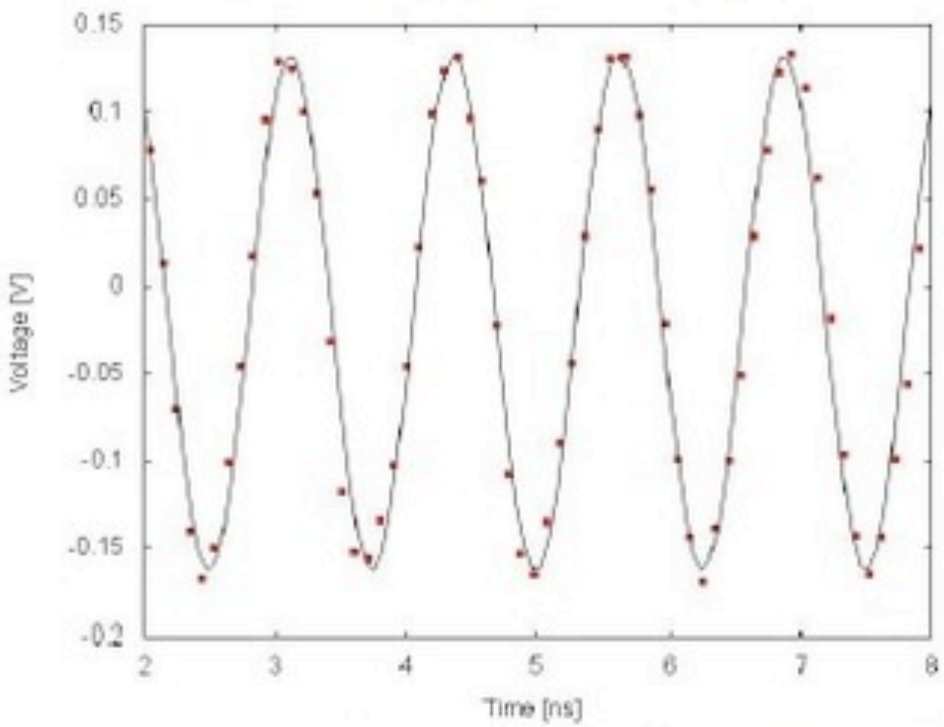
- **Photocathode fabrication established at Argonne**
- **Ongoing study for uniformity and QE>20%**
- **Future focus will be to transfer techniques from Chalice to design for 8" tube processing at Argonne**

PSEC4 Performance

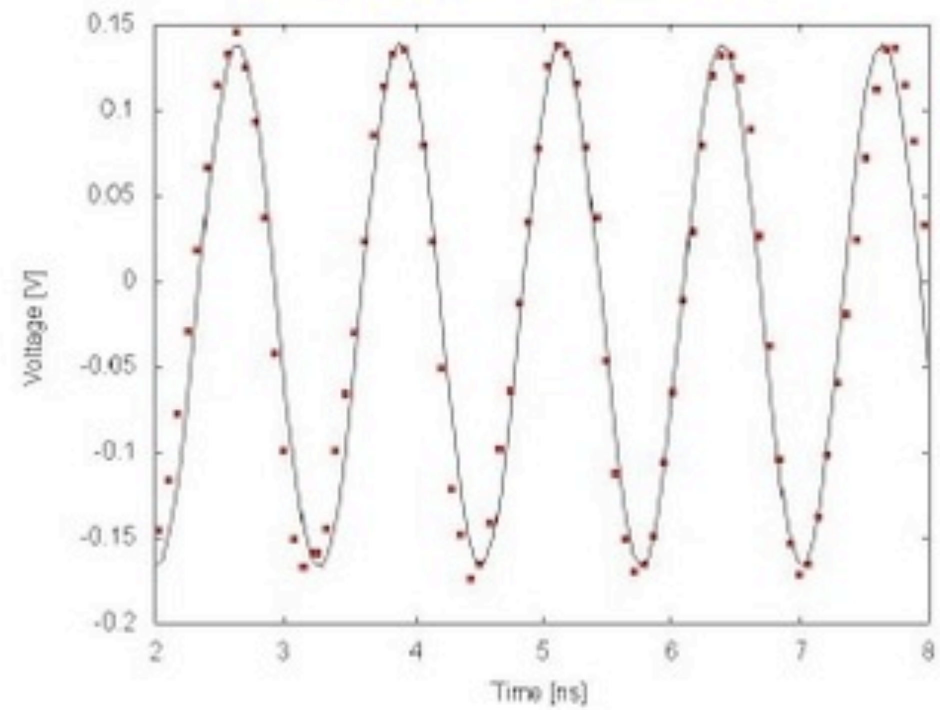
Digitized Waveforms

Input: 800MHz, 300 mV_{pp} sine

Sampling rate : 10 GSa/s

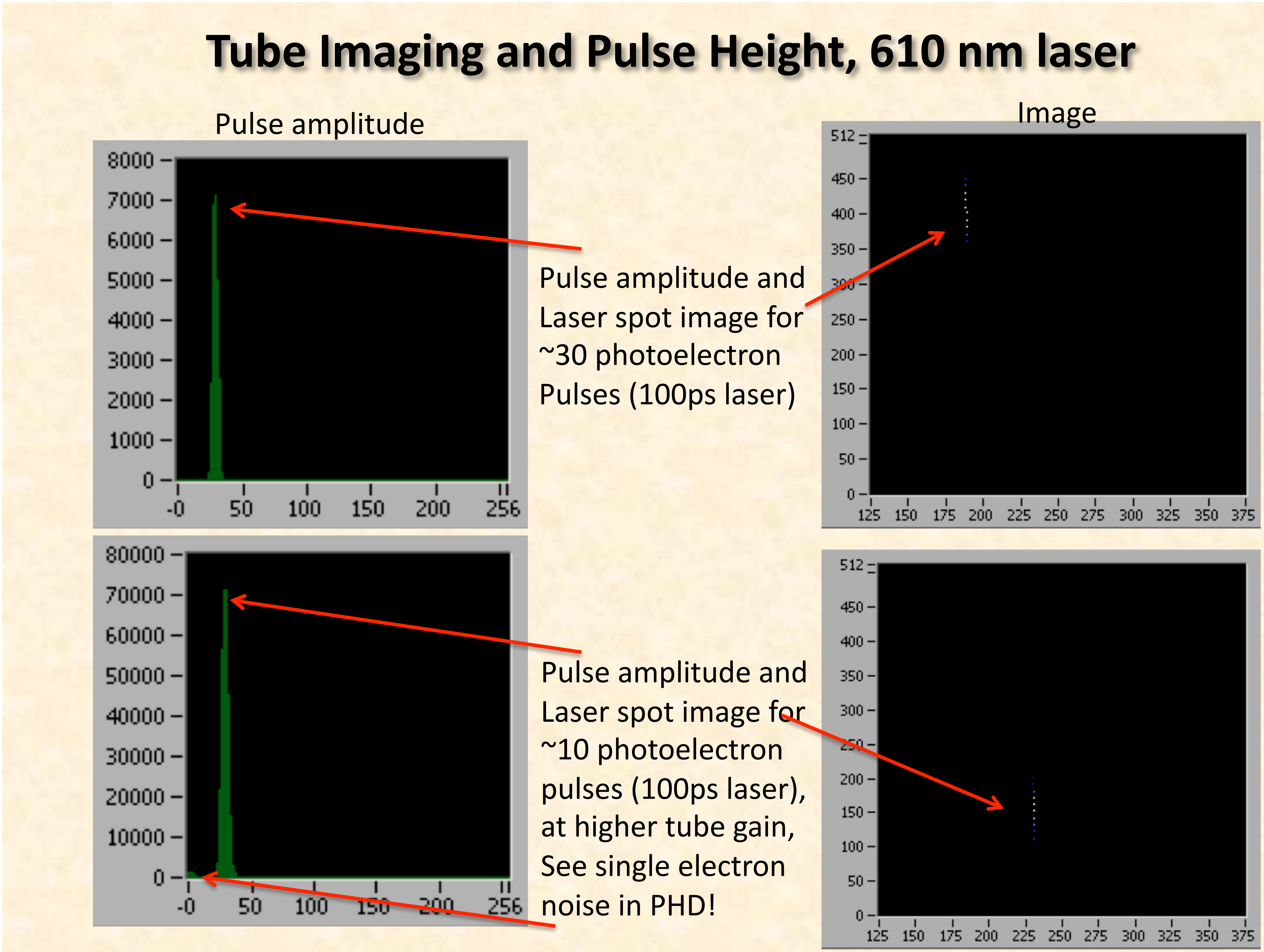


Sampling rate : 13.3 GSa/s

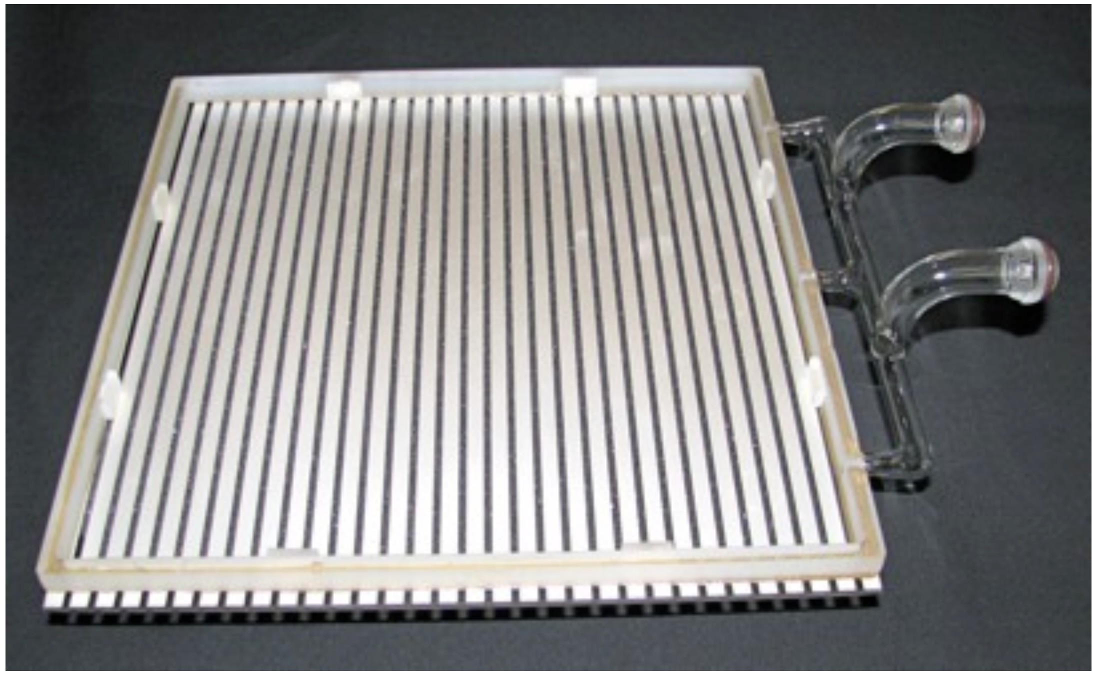


- Only simple pedestal correction to data
- As the sampling rate-to-input frequency ratio decreases, the need for time-base calibration becomes more apparent (depending on necessary timing resolution)

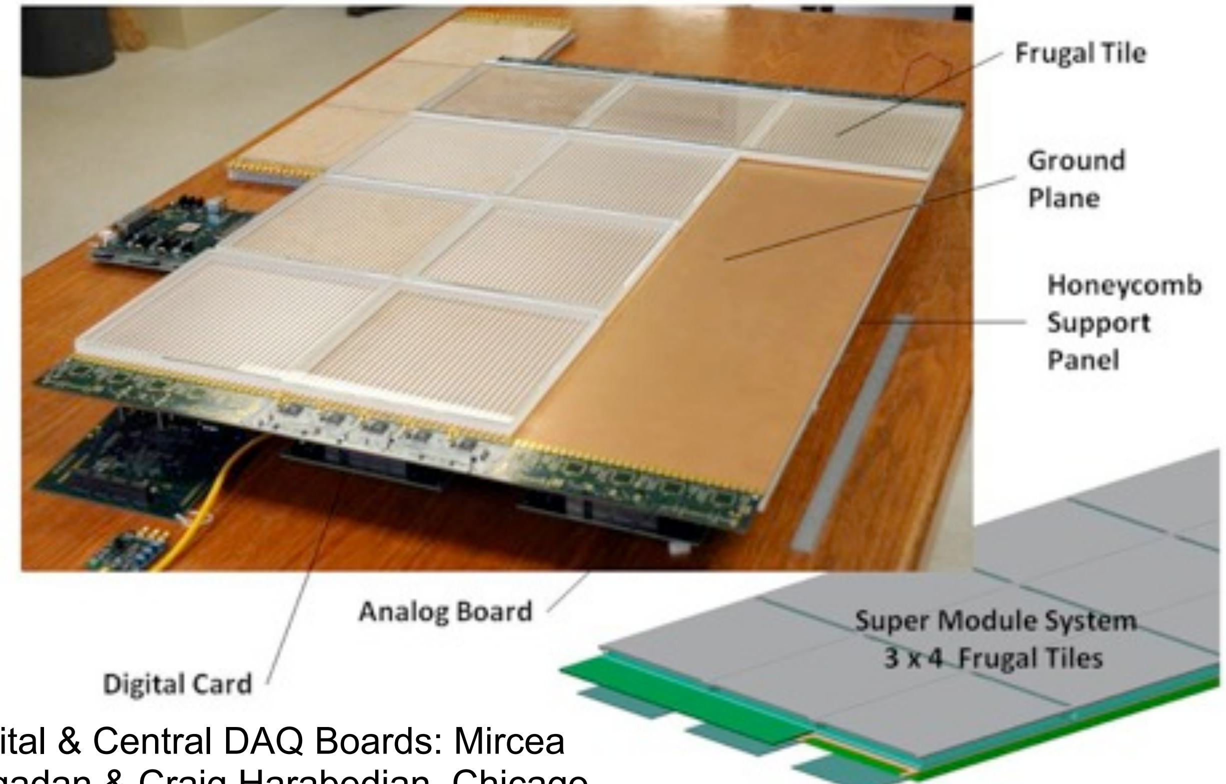
First Sealed Ceramic Body Tube -- Position Resolution



Glass MCP Phototube Strip Line Anode

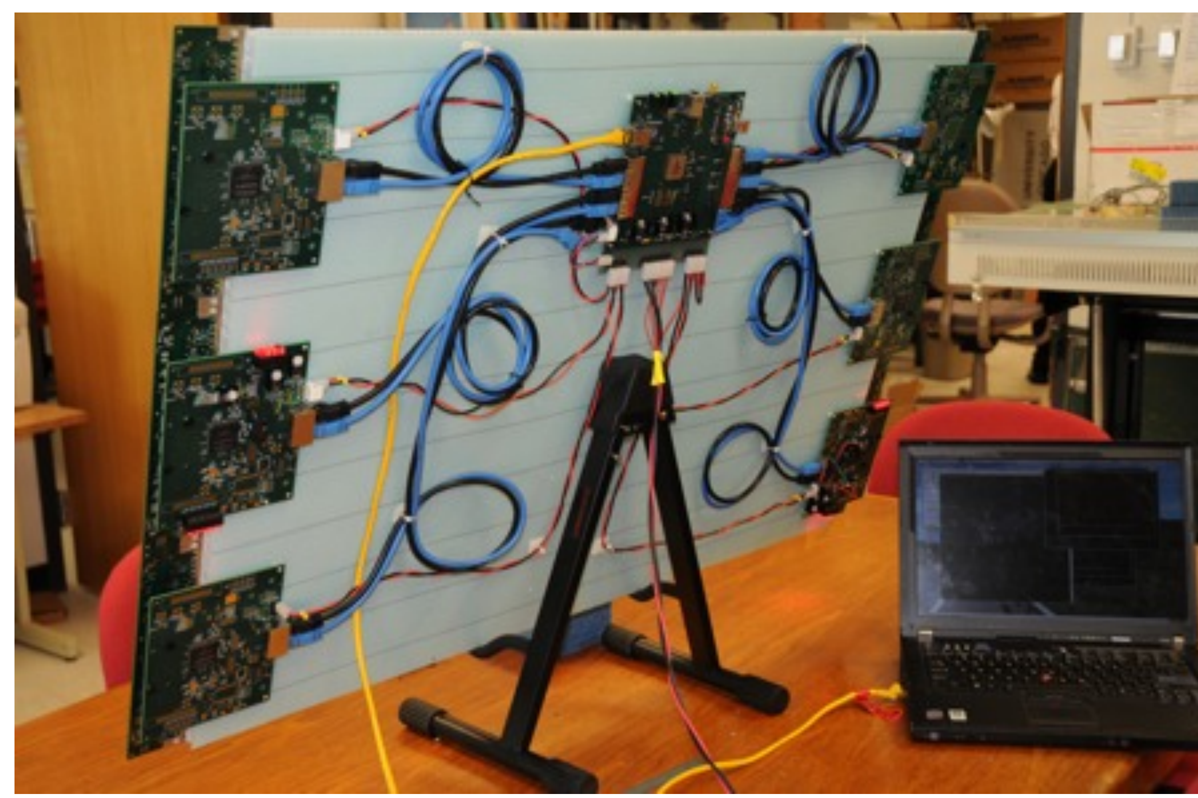


Tile base is 30 strip silk-screened anode



Digital & Central DAQ Boards: Mircea Bogadan & Craig Harabedian, Chicago

Tray and Tiles - The Super Module System



- One 8” MCP Glass PMT ≡ Tile
- Serial connection of tiles with common double-end readout minimally affects performance
- 4×3 array of tiles ≡ SuperModule Tray
- Complete readout chain from front-end waveform sampling ASIC through digital and central control cards to graphics processor PC has been integrated into SuperModule

Existing 4” Vacuum Transfer System at Argonne — System for Early Vetting of STF Process

Two chamber CsTe Photocathode Transfer System

Indium Top Seal Vacuum Test Chamber

Possible early STF demonstrator:

- Chambers can be coupled via existing 6” flanges to give PC process chamber and sealing chamber.
- Left system is operating now at 5×10^{-10} torr, right system is 10^{-8} torr

Summary of Accomplishments 2009-2012

- ☑ Developed large area capillary arrays (20μm pore, L/D=60) for MCP substrate
- Functionalized MCPs via separate Atomic Layer Deposition resistive and secondary emissive coatings
  - ☑ Demonstrated high gain (> 10^7) with little aging
- ☑ Characterization of SEE materials within Argonne MSD
- ☑ Established MCP test facilities at Argonne and SSL/UC-Berkeley
- ☑ Developed detector-to-computer DAQ based on PSEC4 ASIC with 1.6GHz BW, 10-15 GSa/s
- Timing resolution: 6ps differential, 63ps single pe
- ☑ 8" photocathodes (SSL) with QE~25% @ 350nm with good uniformity & stability
- Established photocathode lab at Argonne and made first 4"&7" photocathodes
- ☑ Demonstrated signals from o-ring sealed all-glass economical tile at Argonne
- ➡ Completing ceramic body braze at SSL and assembling working sealed tube
  - First attempt on 8" ceramic tube at SSL: good in vacuum; not complete InBi seal
- ☑ Development of 4×3 tile SuperModule tray with complete readout chain

☑ Original Proposal Milestone
➡ Milestone yet to be achieved

LAPPD Project Summary

Capability Gap

- Development of large area MCP-PMTs with few ps resolution would provide a transformational tool for HEP experiments, e.g.
  - Water Č tracking detector
  - Higher momentum Particle ID
  - Pile-up vertex separation/Photon vertexing
- Existing MCPs have small effective area, are expensive, and have all properties embodied in a single medium.

Benefit

- Cost-effective and robust technique for fabricating large-area MCPs recognized by R&D 100 award
- Potential for picosecond time and millimeter spatial resolution photodetection over large surface areas.
- Applications within and beyond HEP.
- Re-establish U.S. photodetector development and manufacturing.
- Potential large cost savings for detectors requiring 1000s of photodetectors.

Approach

- MCP substrate, resistive, and secondary emissive components separated into less expensive individually tunable materials.
- Functionalization of MCPs via ALD.
- Develop unique, less expensive borosilicate glass hermetic package using ALD coated grid spacers for support and voltage distribution.
- Manage package risk with parallel ceramic body approach using proven techniques and expertise.
- Develop integrated DAQ w/low-power multi-ch. 15GSa/s Waveform Sampling ASIC frontend.
- Enabled by unique multi-disciplinary expertise and cross-divisional infrastructure at Argonne

Results and Deliverables

- Signals from o-ring sealed complete all-glass MCP tile
- Diff. time resolution with 8” MCP pair < 6ps
- Complete DAQ system with PSEC4 ASIC;
  15 GSa/s; noise<1mV, bandwidth ~1.6GHz
- 8” Photocathode QE~25% @ 350nm & uniform & stable
- On track for sealed ceramic MCP-PMT by Fall
- Propose to construct MCP Tile Facility at Argonne to produce all-glass tiles for evaluation by HEP community
- Continue production of ceramic tiles at SSL
- PC research to achieve QE » 25%
- Seek industrialization of photodetector; in active discussion of tech transfer with companies