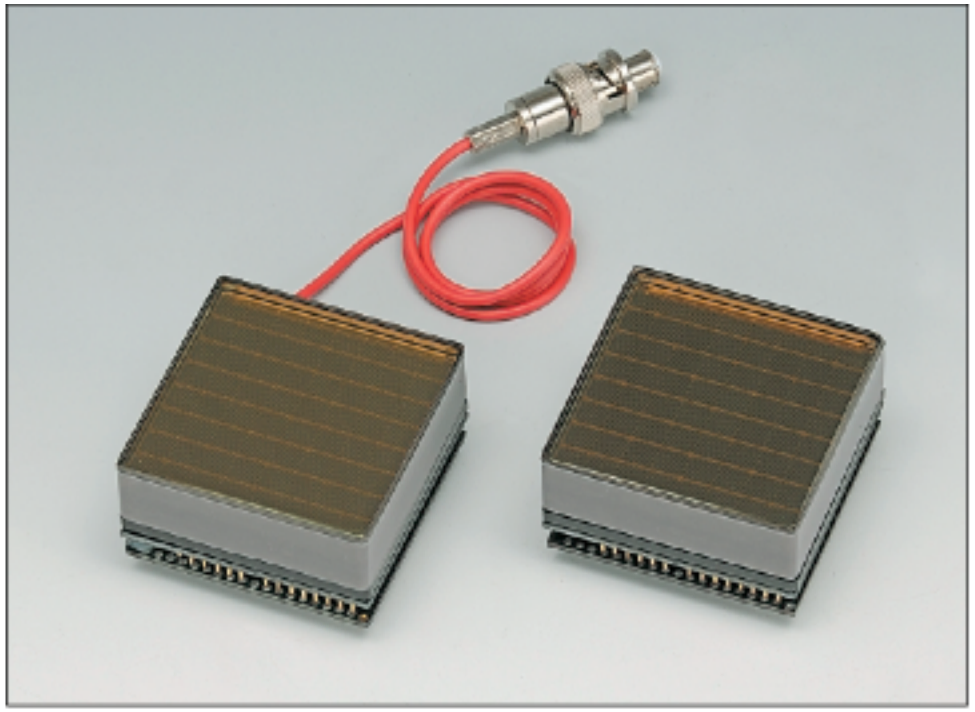
Development of New Photodetectors

Bob Wagner, Argonne National Laboratory
Fermilab Workshop on Detector R&D
Friday 08 October 2010

The Charge

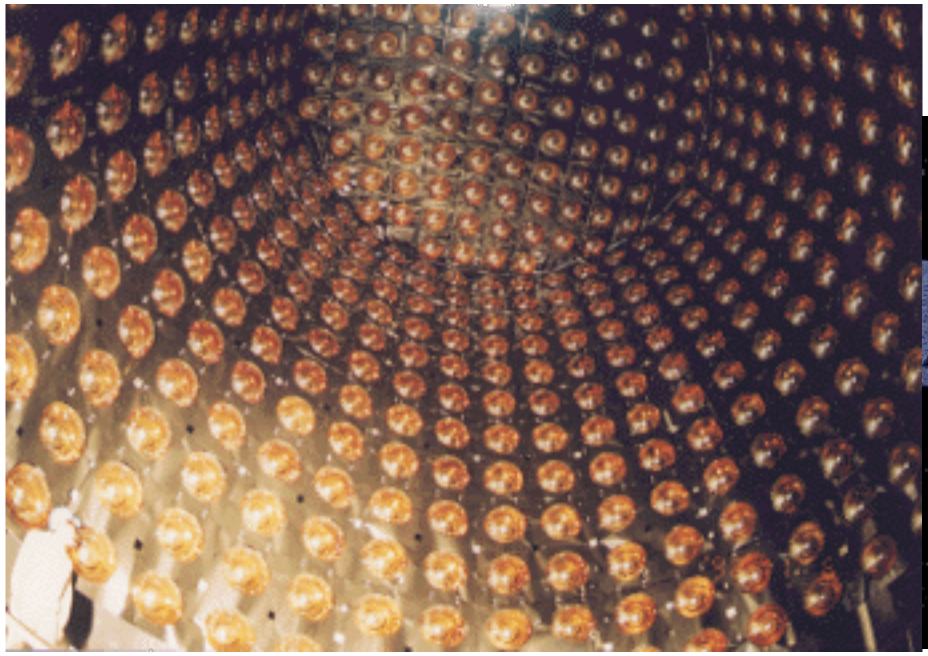
- State of Relevant Detectors Now -- Appropriate for Upgrades
  - Conventional PMTs
  - Hybrid Photodetectors
  - Geiger Mode Avalanche Photodetectors/Silicon Photomultipliers (J. Va'vra talk)
  - Microchannel Plate Photodetectors
- What Drives Upgrades (Improved Photodetectors)?
  - Lower Cost per Channel
  - Higher Photon Detection Efficiency
  - Improved Timing Precision
  - Finer Energy Resolution
  - Spatial Resolution
  - High Data Rate
- "Pie-in-the-Sky" Technology for Addressing New Physics
- "Cut-and-Dried" Technology
- Timescales
- Focus Now, Near Future, Far Future

Conventional Photomultiplier Tubes

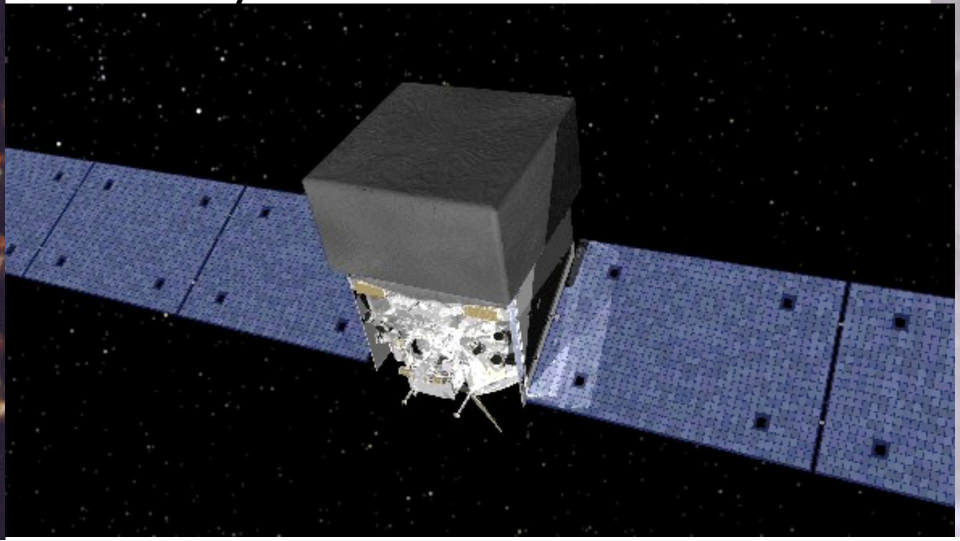


Left: H8500C (HV cable input type), Right: H8500D (HV pin input type)

- "Cut-and-Dried" Technology
  - has been in use for decades
  - robust, generally low noise
  - simple biasing
- Low Profile Multi-anode PMTs readily available
  - lower cost readout per channel - fiber
  - good spatial resolution for imaging

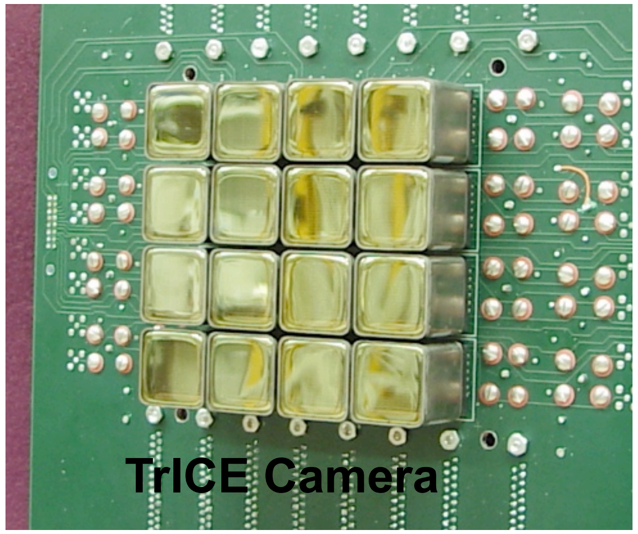


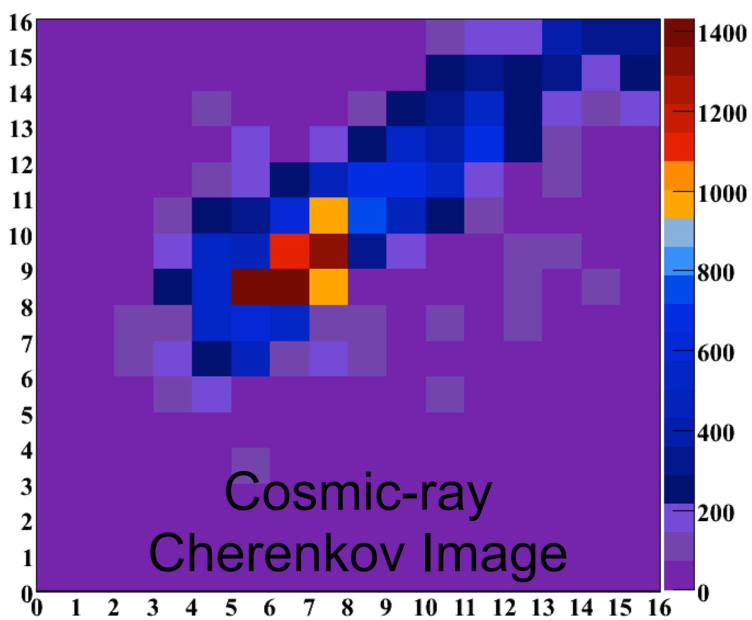
Photomultipliers operate in a variety of harsh environments



Imaging with Multi-Anode Phototubes

R8900 16 pixel (6×6mm^2) MAPMTs

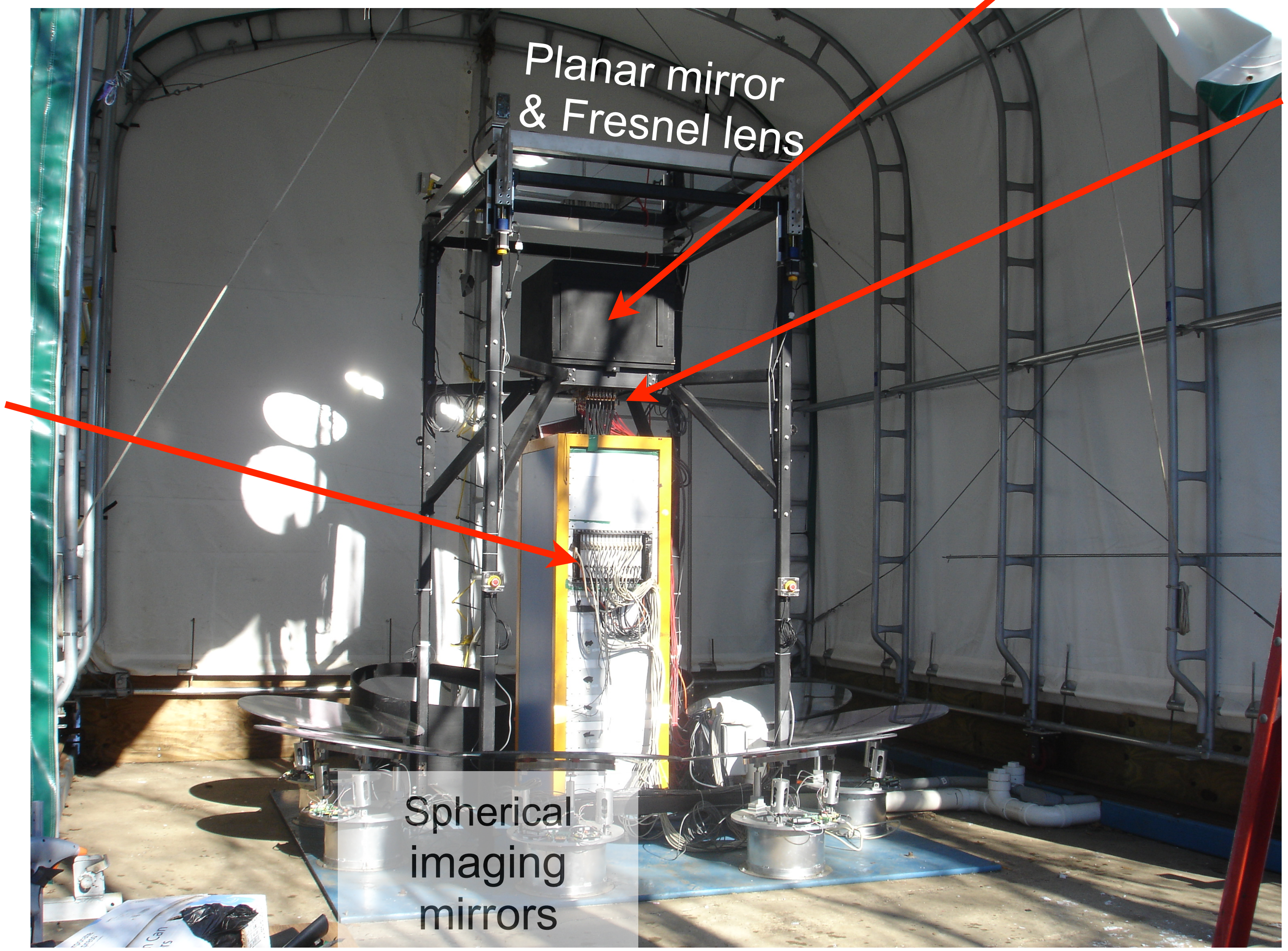




Camera located within baffle

HV and sign
connection

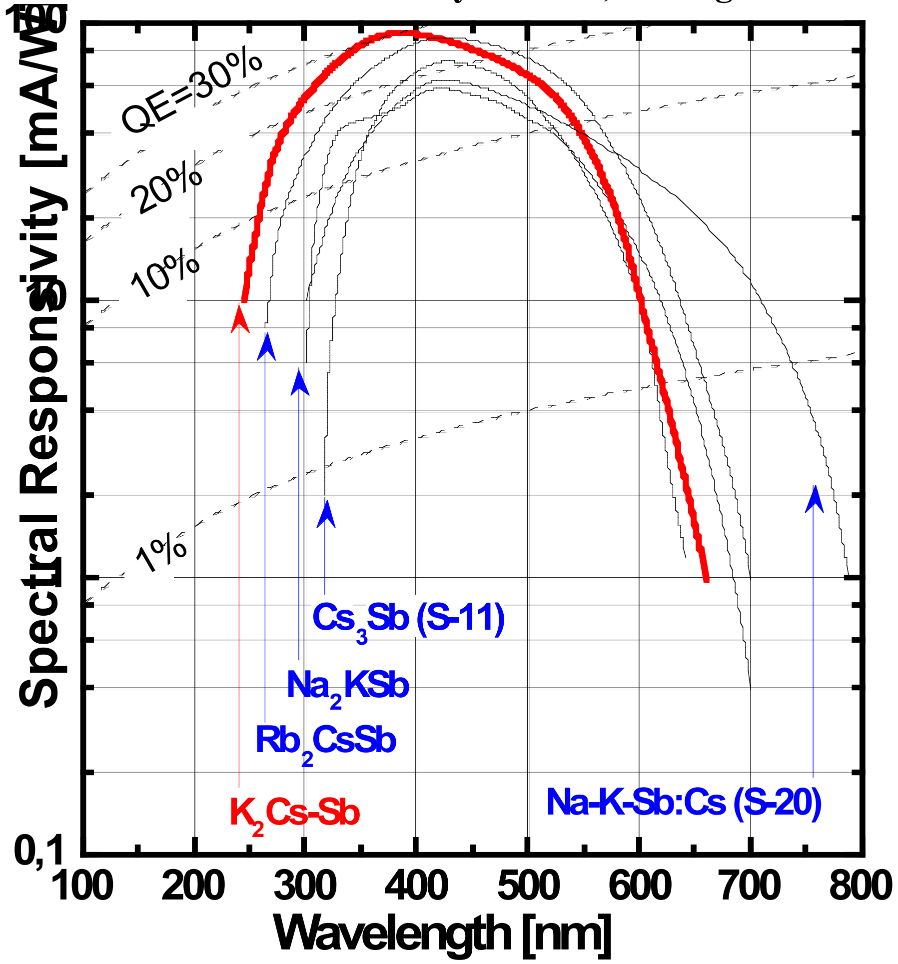
Digitization
electronics



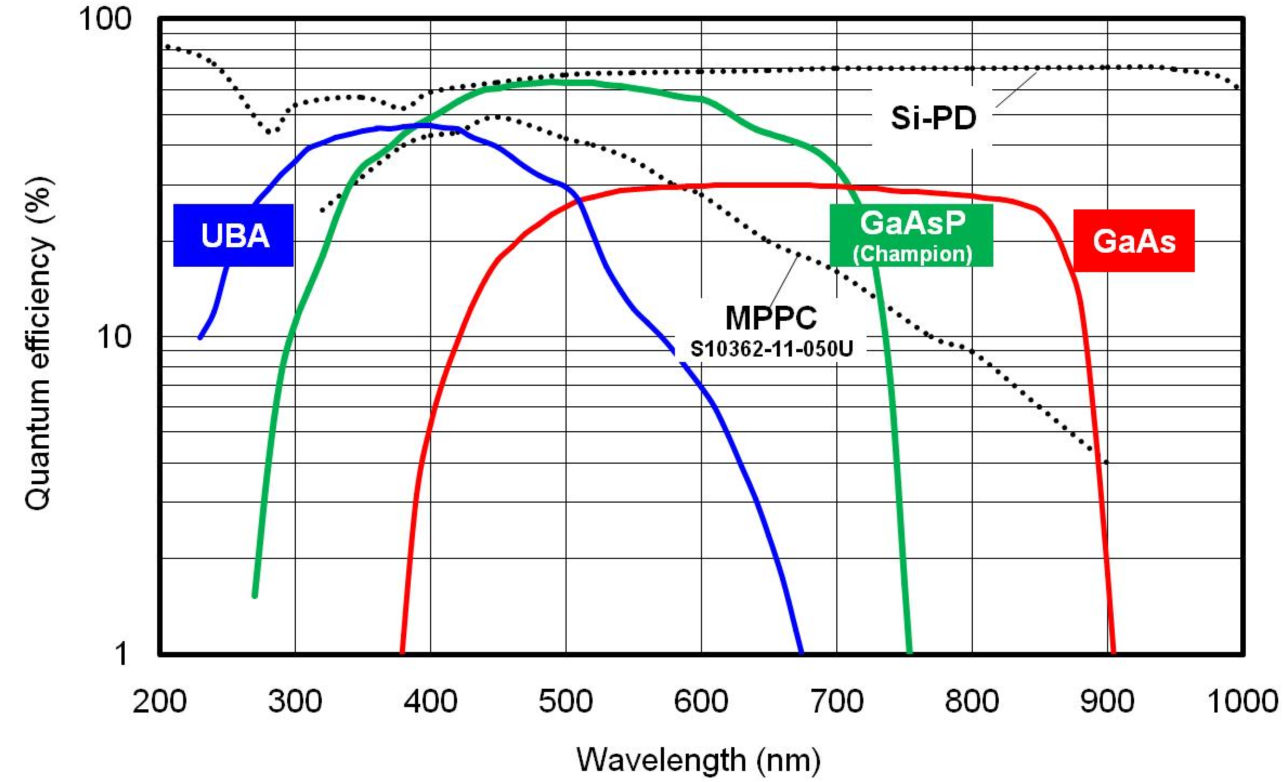
TrICE Telescope -- located at Argonne Natl. Lab.

Improving Conventional Photomultipliers -- QE

Lyashenko, Chicago 7/09

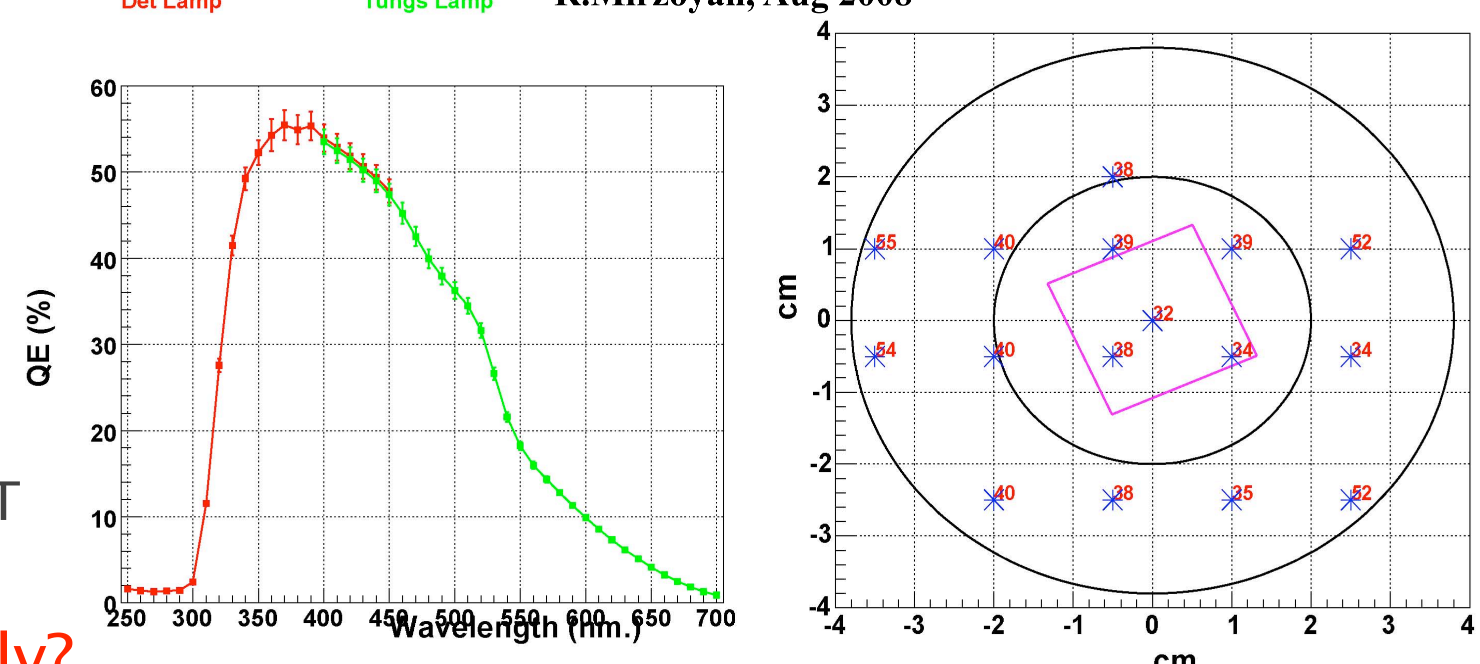


M. Suyama, HPK, PD09, Matsumoto, Japan



- Typical multi-alkali QE ~ 15-30%
- In past few years, Hamamatsu marketing super- & ultra-bialkali with QE 35-45%
- One of kind higher QE (~50%) PMT has been produced
  - Restricted to specific locations on PMT

R.Mirzoyan, Aug 2008



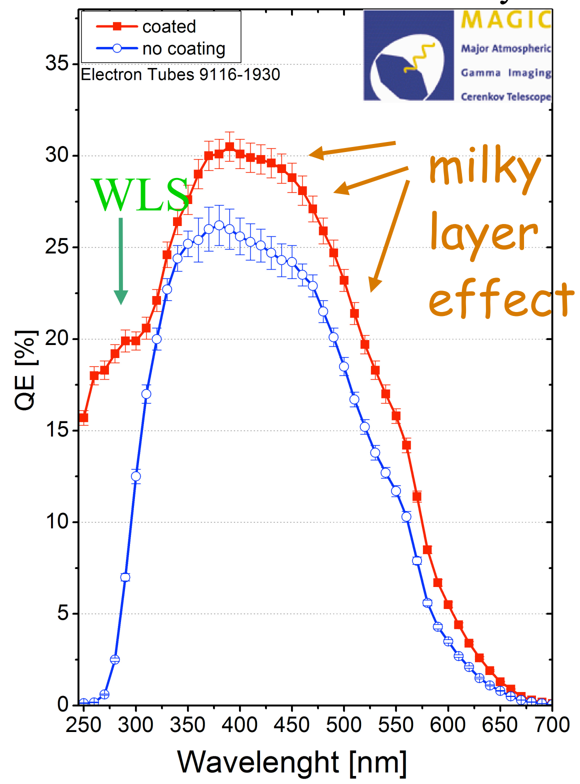
How to achieve high QE reproducibly?

“One-off” Commercial 3” PMT

Improving Photocathode QE

- High-purity materials
  - reduce scattering from impurities
- Anti-reflective coating
- Coating “tricks”
- Tune material composition
  - “adjust the recipe ingredients & proportions”
- Adjust material thickness
- Use of “under-coatings”
  - MgO
  - Indium-Tin-Oxide (ITO)
- Novel photocathode materials -- non-alkali metals
  - GaAs
  - GaN
  - GaAsP
  - InGaN

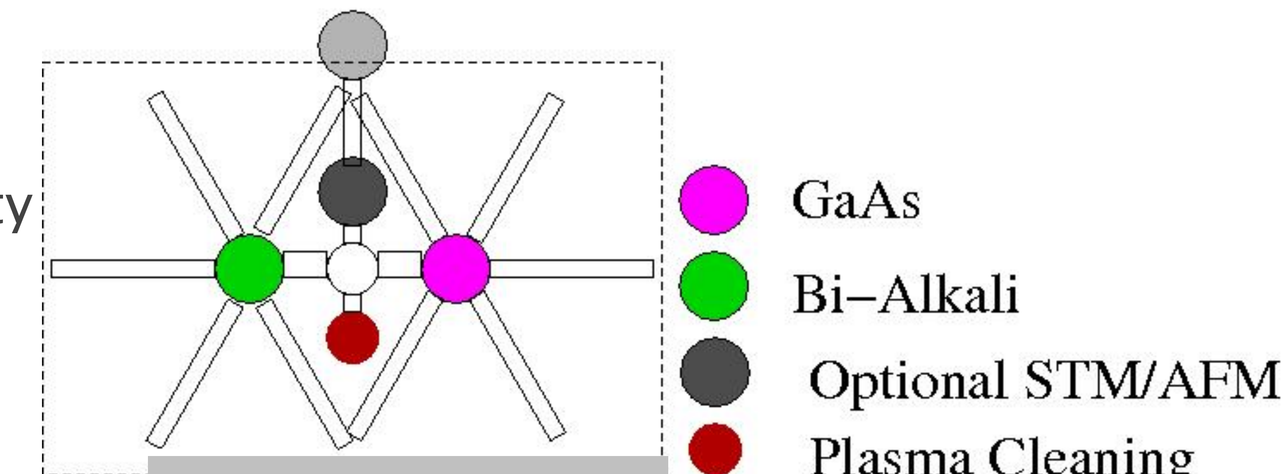
Photo & Plot Credit: R.Mirzoyan

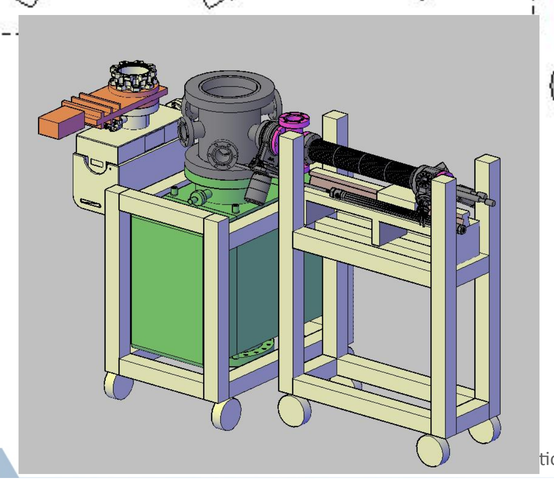


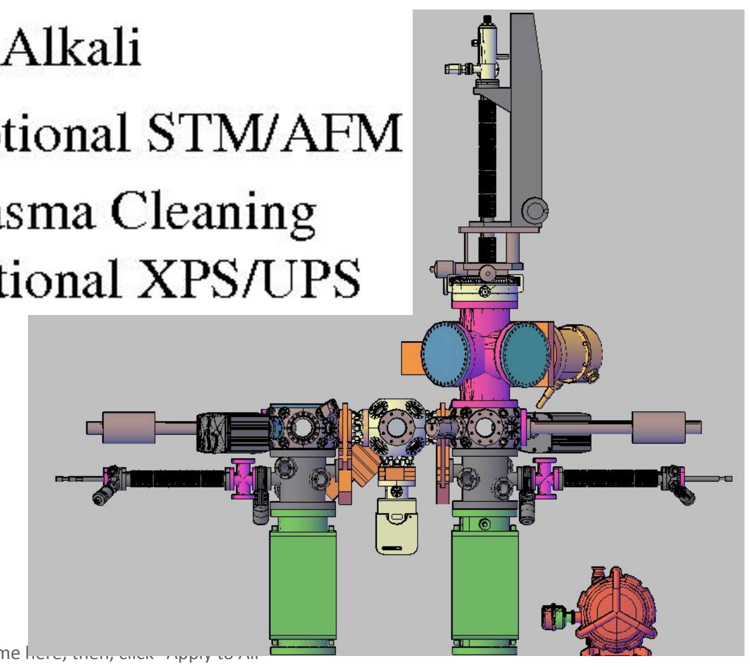
Can we do better than trial & error?

Proposed Argonne Photocathode Growth & Characterization Facility -- A Mid-Future Focus

- **Scientific Goals:**
  - Device physics – correlation between structure and functionality of PC
  - Materials Science – microscopic model of growth & activation process
  - Device engineering – reliable high yield growth procedures giving high QE (and low I_{dark})
- **Engineering Goals:**
  - Define process control parameters & acceptable variations
  - Test of process control units



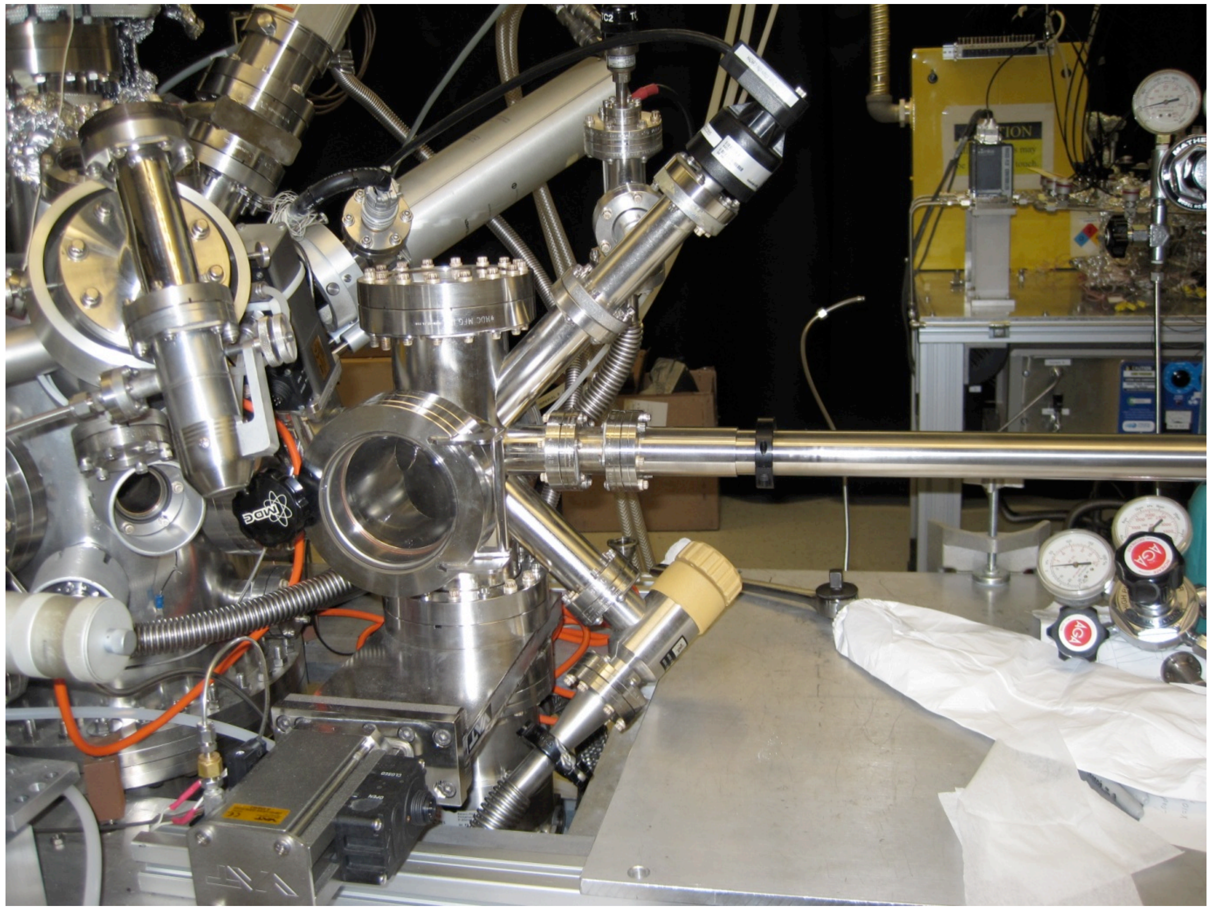




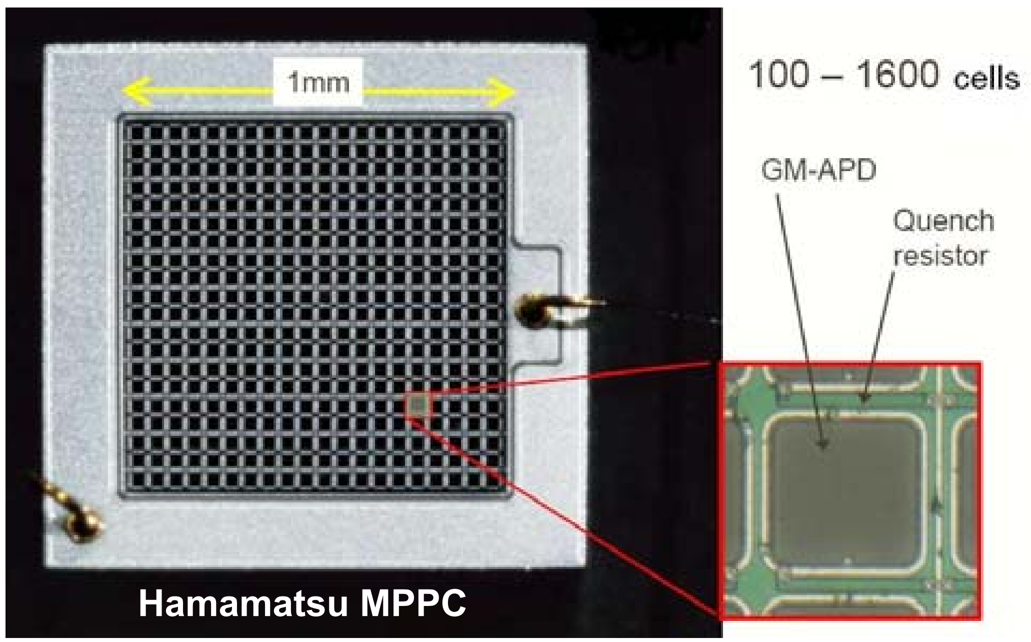
- **Science Questions:**
  - Film structure (chemical phases, crystal orientation, amorphous contribution) & Morphology (roughness, crystal size, surface composition)
  - Influence of substrate on growth characteristics and electronics properties
  - What is best film structure?

Argonne PC Characterization Facility

- Characterization Tools
  - X-ray Photoelectron Spectroscopy
  - UV Photoelectron Spectroscopy
  - Low Energy Electron Diffraction
  - Mass Spectrometer



Silicon Photomultipliers - G-APD, MPPC, PPD,...

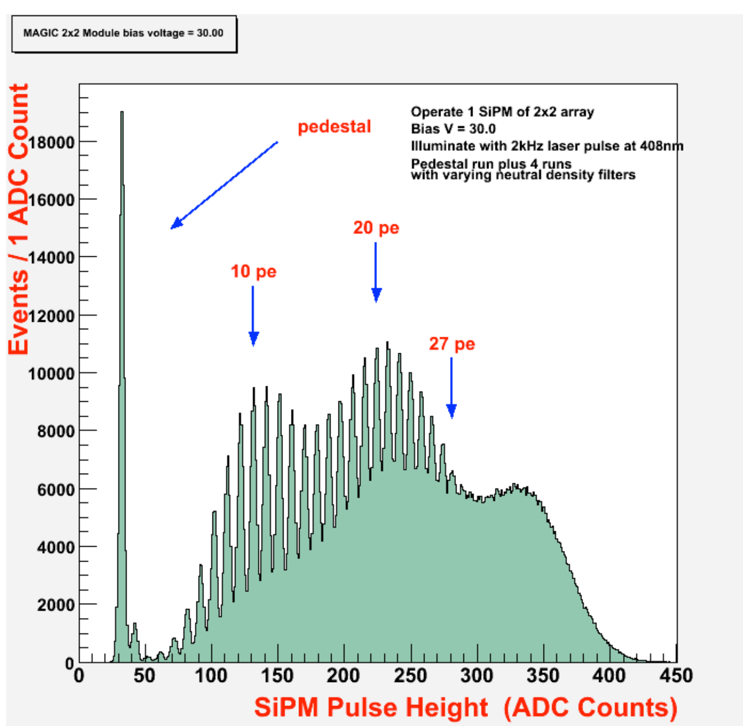


Advantages (compared to conventional photomultipliers:)

- $10^{5\text{-}7}$ gain for low bias voltage (~30-70V)
- Robust: mechanically & exposure to daylight illumination
- Simple biasing & readout -- two pin operation
- Extremely good single photon resolution
- High QE; potentially high overall PDE
- Insensitive to magnetic field
- Small size allows embedding in/on detector
- Good timing resolution (~50-150ps for single PE)

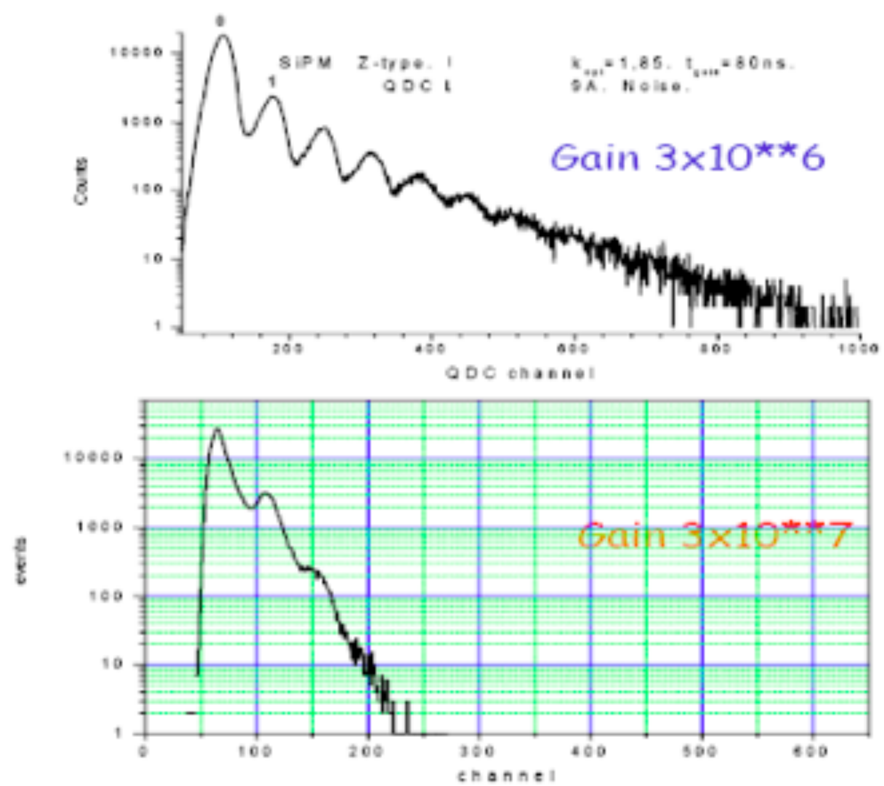
Disadvantages:

- Large noise rate ~few × 100kHz → 1 MHz per $1mm^2$
- High crosstalk - photons generated in avalanche
- Afterpulsing - charge traps
- Temperature sensitivity of breakdown voltage, noise
- Presently limited to small active area ($5{\times}5mm^2$ max.)
- Not particularly radiation hard
- Small operating voltage range

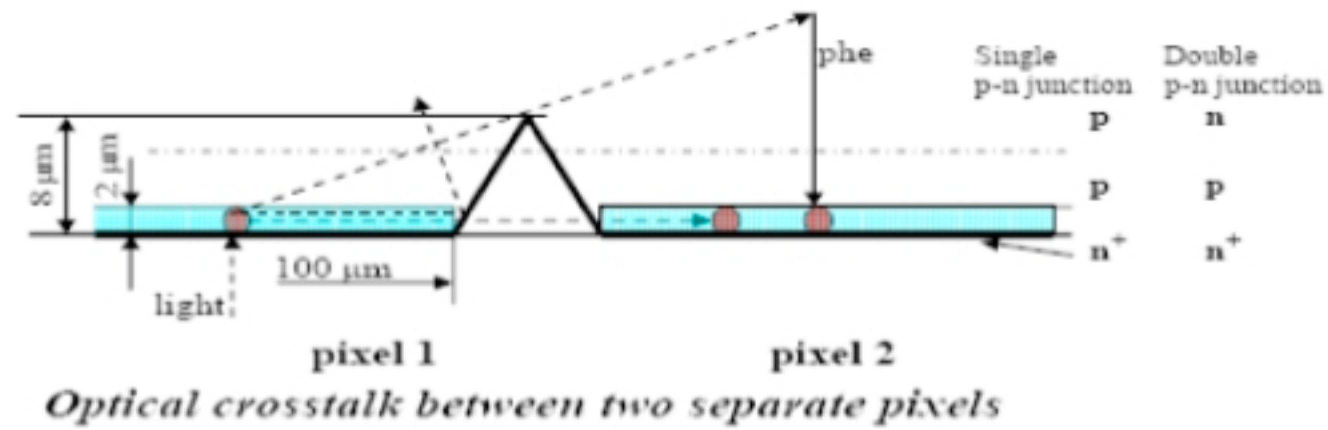


Improved MEPhI SiPM $5x5mm^2$
with ~1% crosstalk

Improving G-APDs



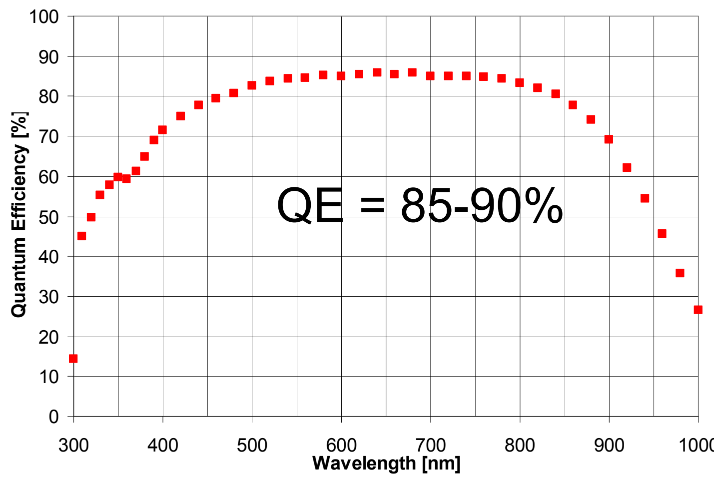
Plot credit: B. Dolgoshein LIGHT06 → R. Mirzoyan, Argonne 2008



B.Dolgoshein,SiPM review

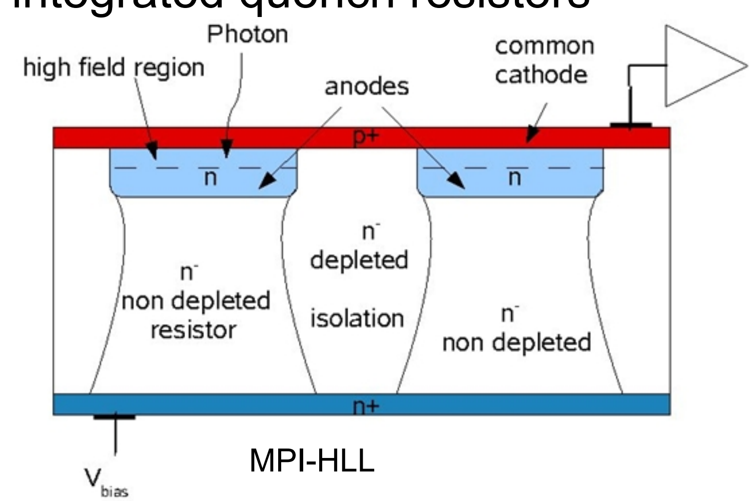
Reduction of crosstalk with trenching & double p-n junction

PDE = QE × Geom. Eff. × $P_{breakdown}$



Geom. Eff. = 30-70% depends on pixel size

Improved geometric eff. via integrated quench resistors



MPI-HLL

Future G-APD Improvements - Planned & Desired

- Larger dynamic range
  - smaller pixel size
  - Zecotek – 15–40k pixels/mm^2
- Larger PDE – improved design
- Reduced dark count rate – improved materials
- Larger active area
  - Needed Cherenkov telescope camera application
  - Medical imaging (PET)
- Improved radiation hardness – new fabrication materials
- Lower cost
  - We keep expecting this to happen
  - Competition is increasing
- Integration of G-APD with ASIC (see Ramburg talk)
  - active quenching, faster recovery
  - true digital photon counting; now digital→analog→digital

Large Area Picosecond Photodetector Collaboration

The Development of Large-Area Fast Photo-detectors

April 15, 2009

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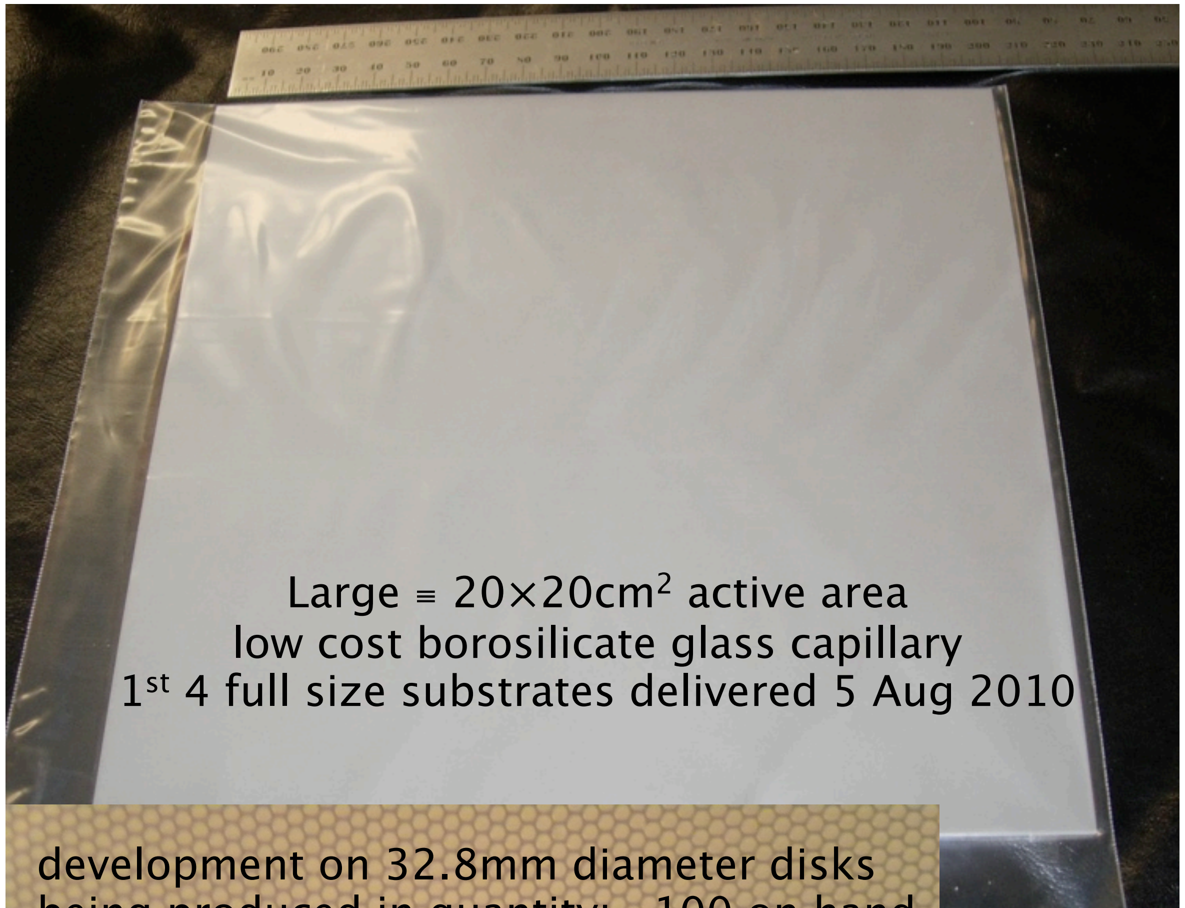
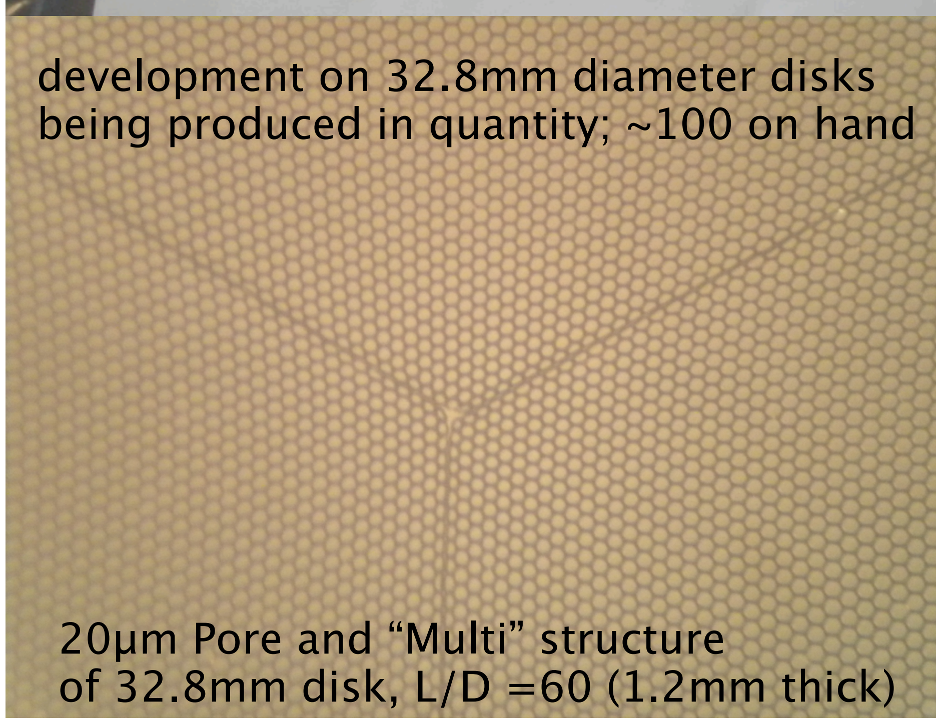
3 National Labs.
6+ Argonne divisions
3 universities
3 small companies

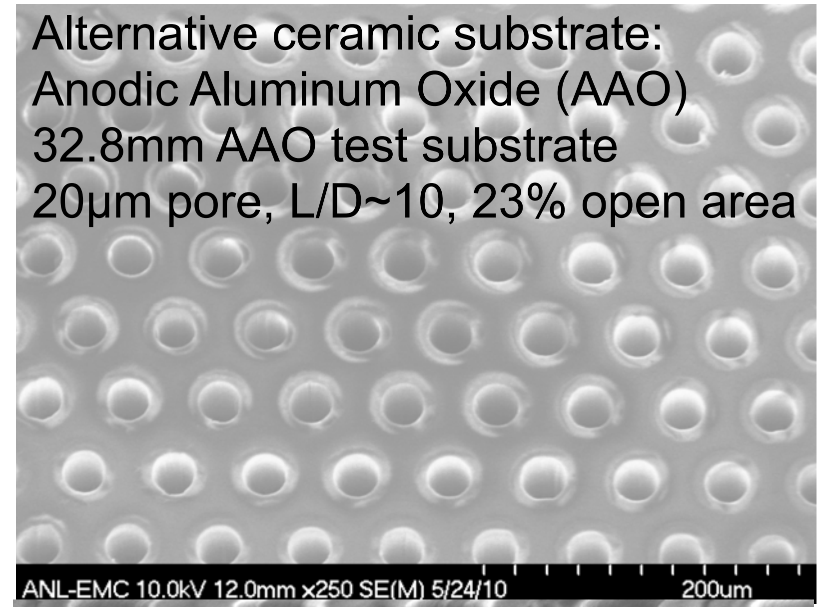
association with
3 universities
2 small companies

Large Area Picosecond Photodetector Development

Large, Cheap, Fast Microchannel Plate Photomultiplier





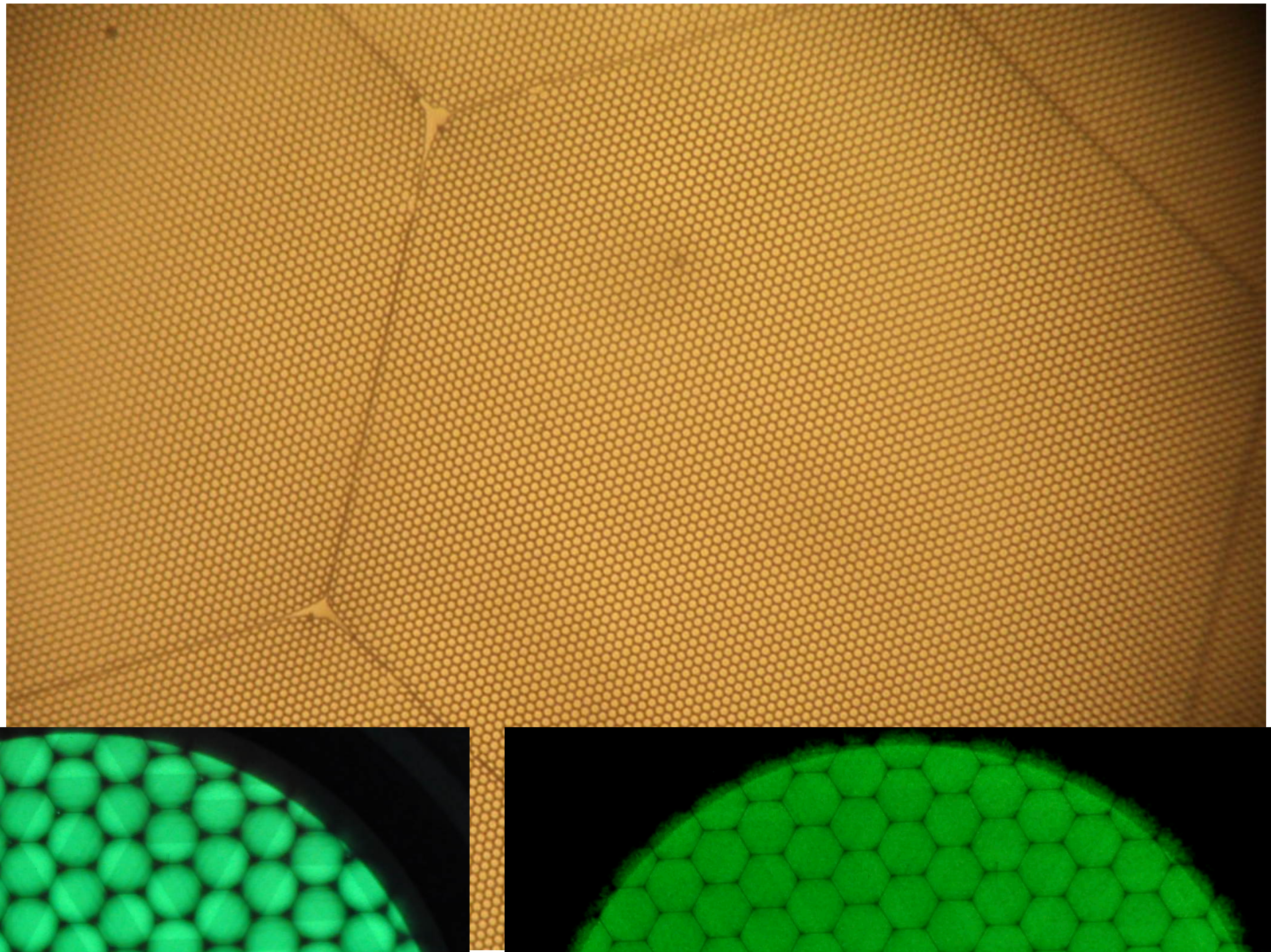


- Pore activation via Atomic Layer Deposition (ALD)
  - Separate material for resistive and secondary emission layers
  - Optimize resistive and emissive properties separately via study of range of materials

Tiling onto stripline PC board to construct 2×3 supermodule

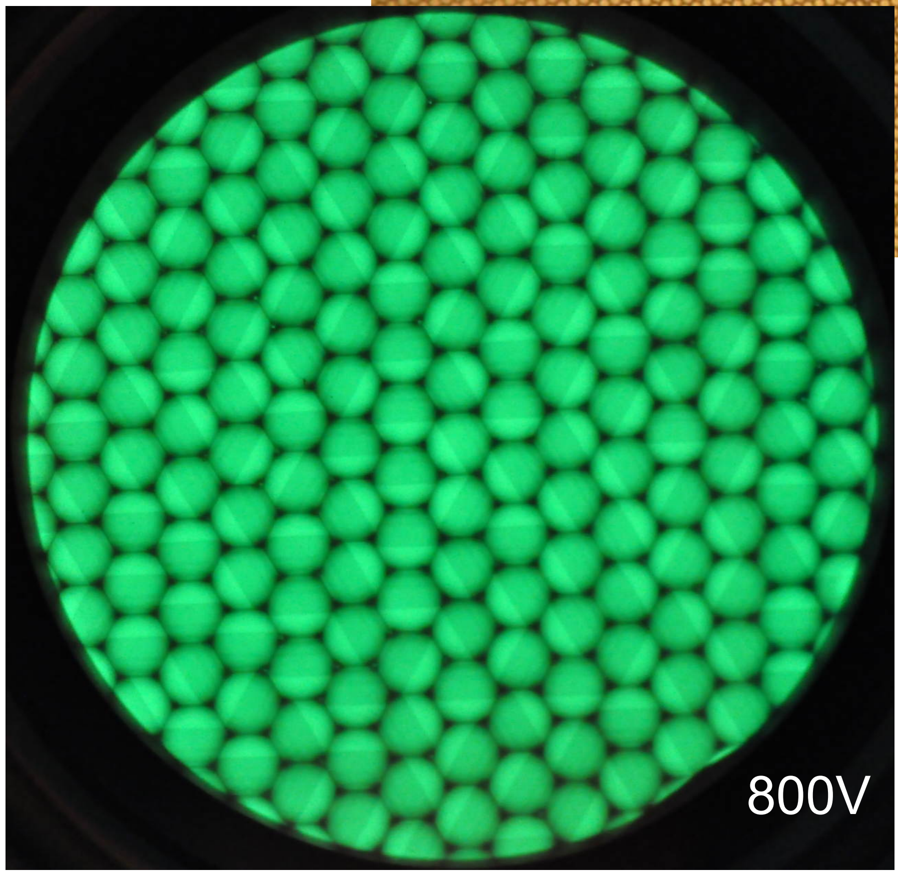
Development of Glass Capillary Arrays

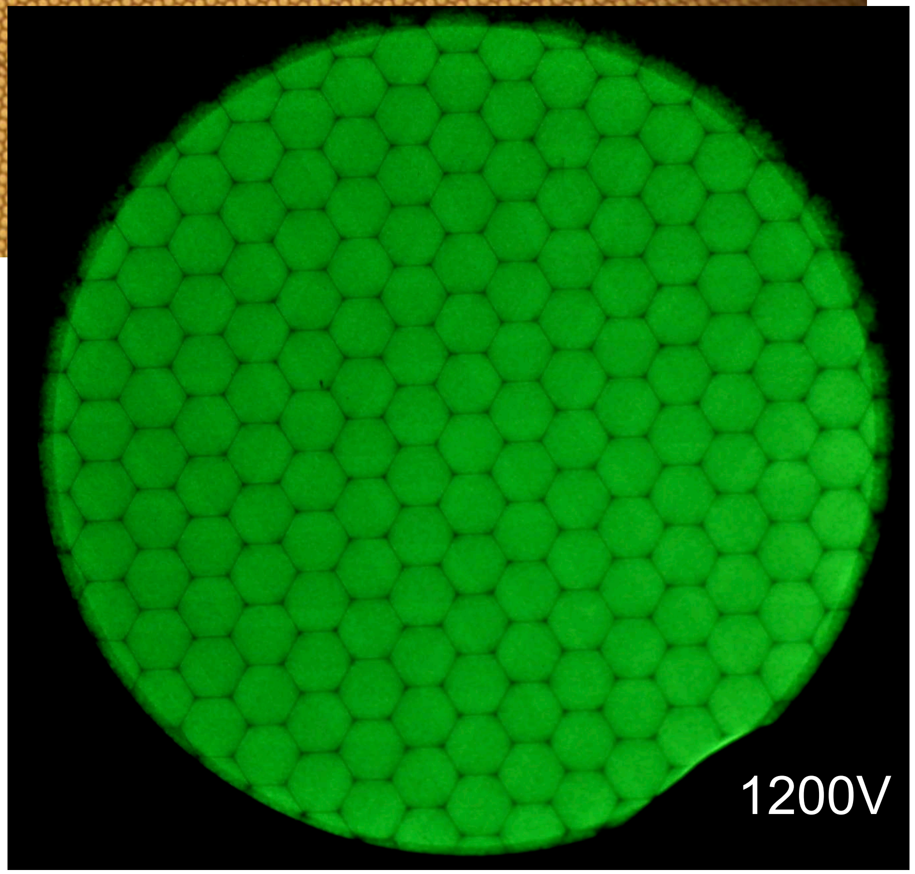
- Challenges in development of glass capillary arrays
  - drawing – gaps at triple pts.
    soln. – larger furnace
  - fusion – distortion of capillaries at “multi” boundaries
    soln. – solid core arrays??
  - slice & finish – blocked pores
    soln. – keep wet during processing, better post cleaning



GCA-MCP functionalized by Arradiance, Inc.
Illuminated with UV lamp and imaged with phosphor screen.

Multi boundaries and triple points apparent. Fade at increased voltage.

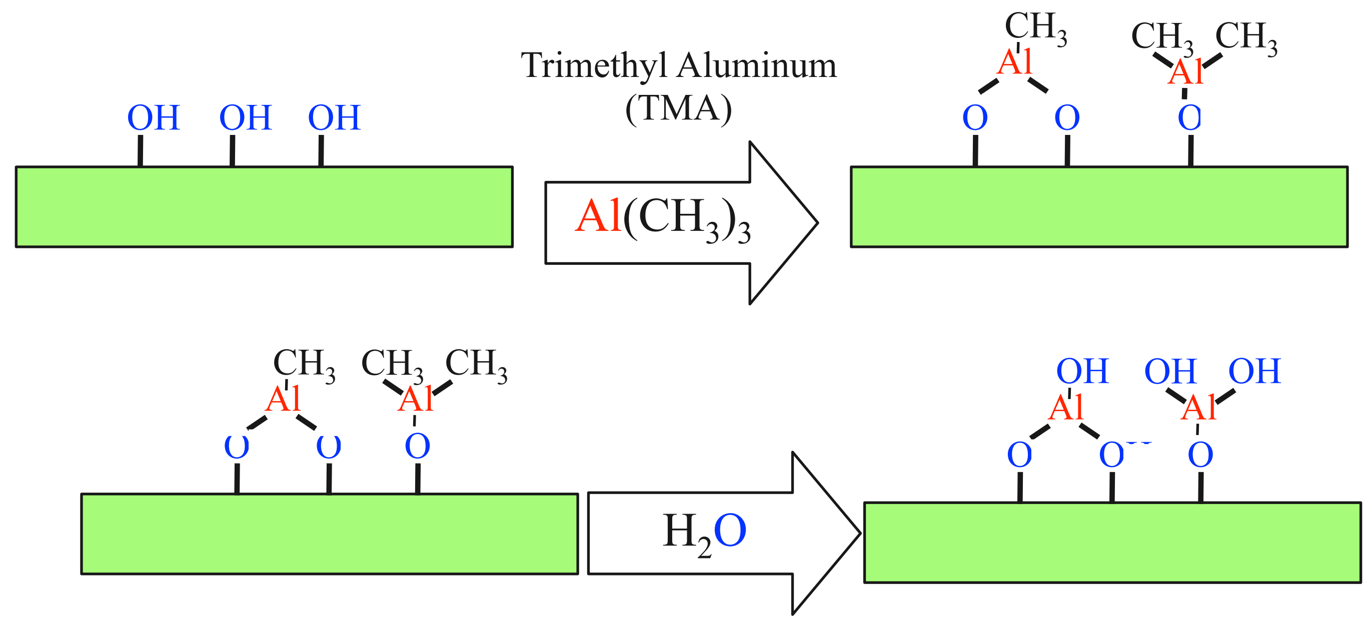


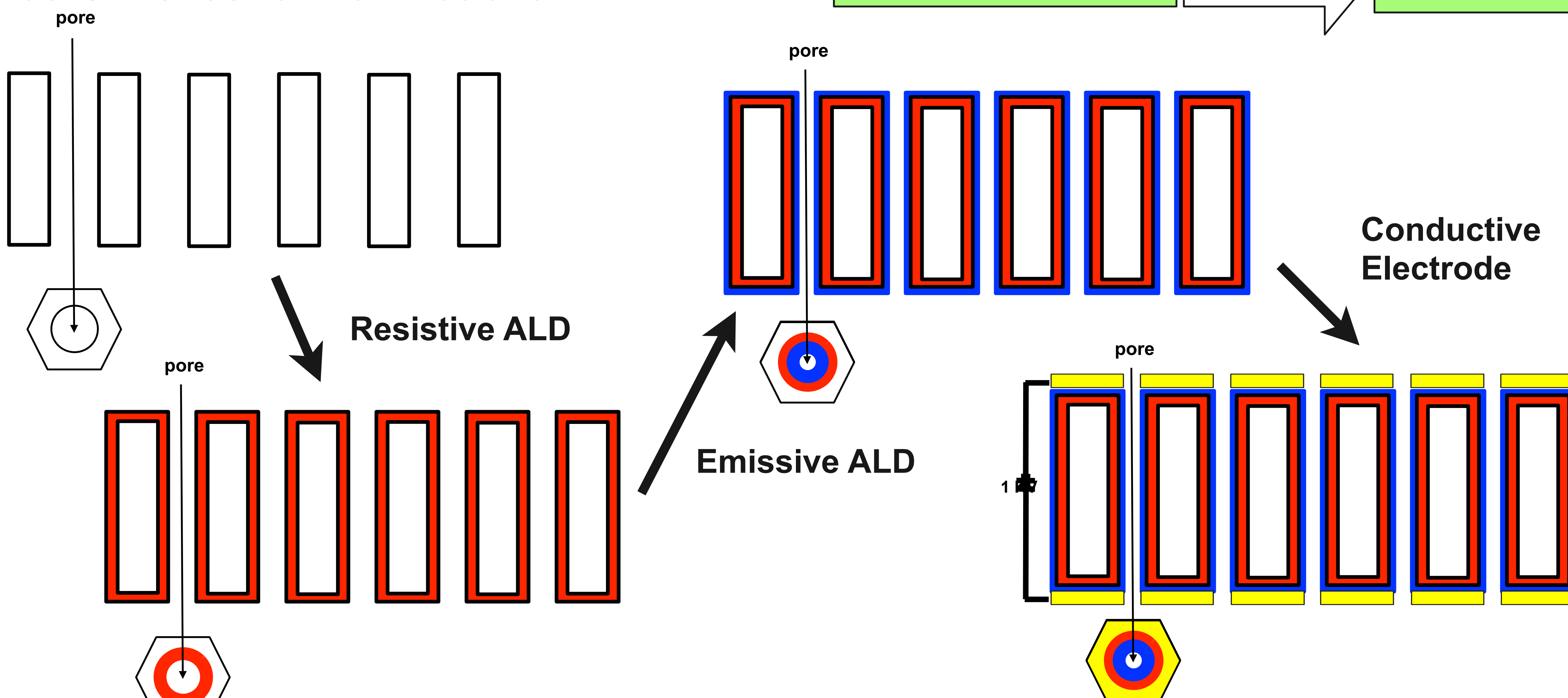


Pore Activation via Atomic Layer Deposition (ALD)

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



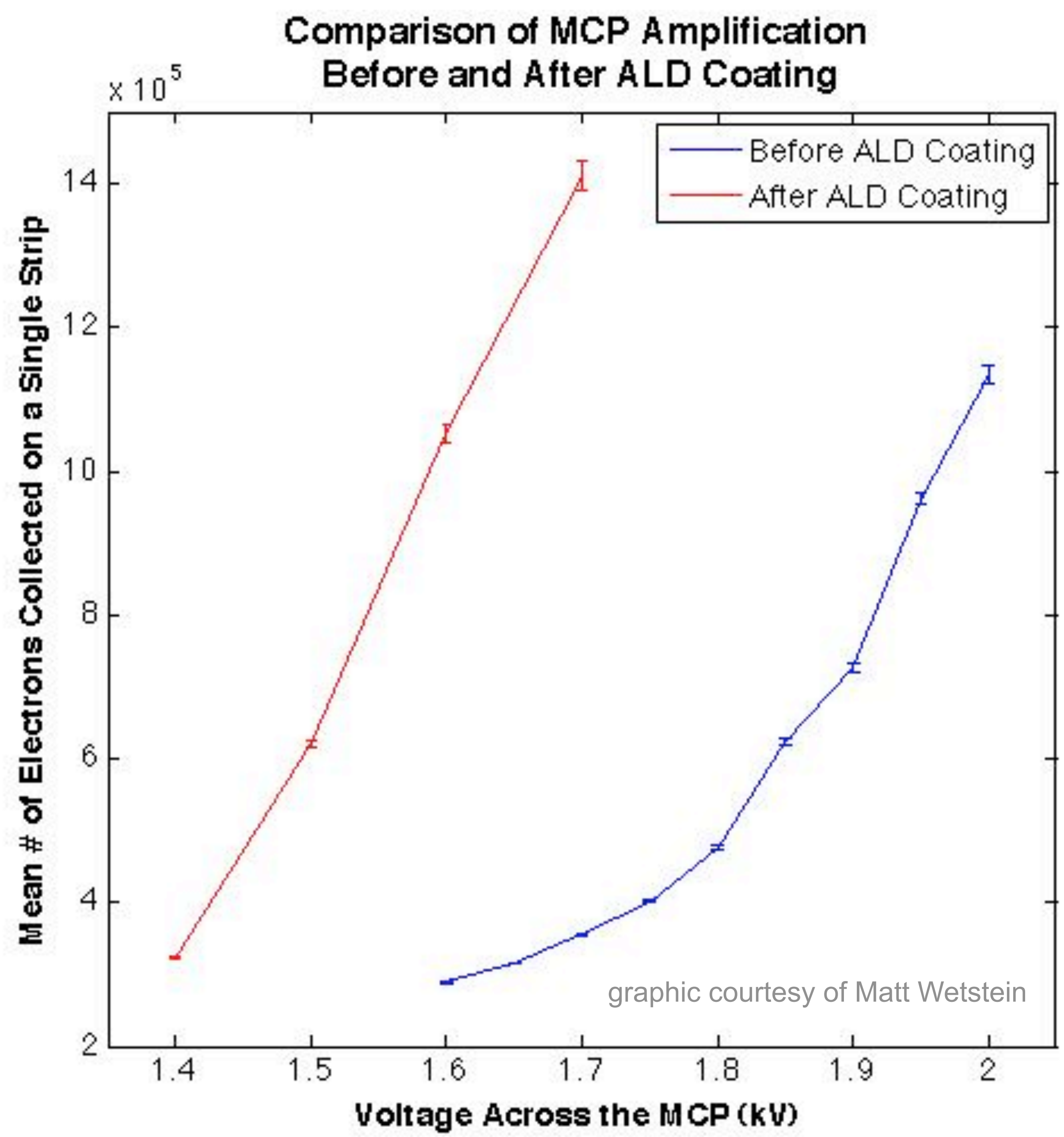


Functionalization of Commercial MCP

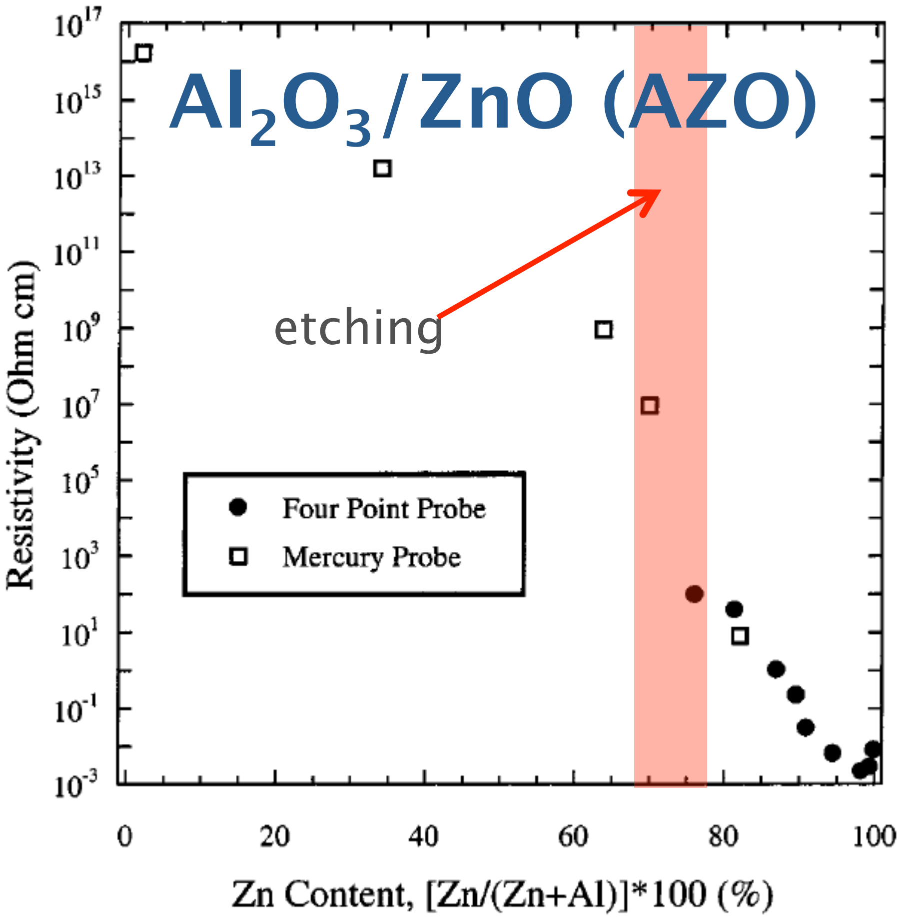
First test of ALD coating

Commercial Pb-Glass MCP with existing functionalization

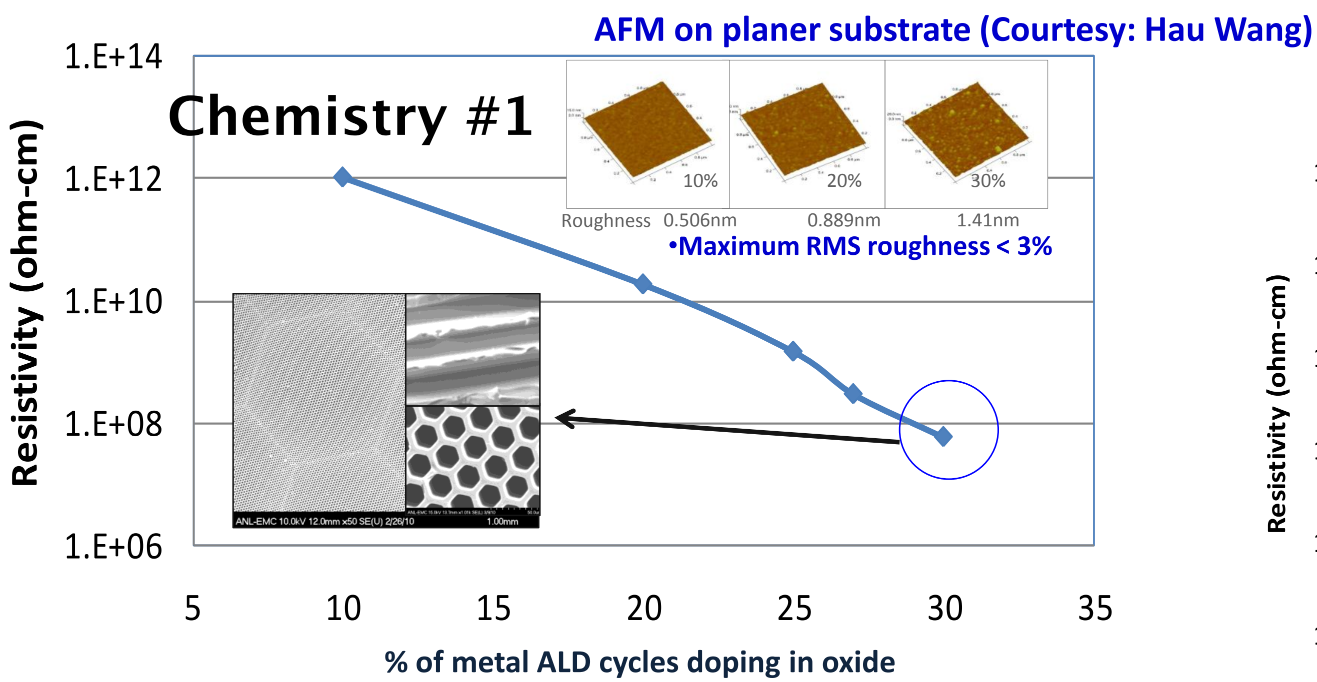
ALD of Al_2O_3 coating improves gain



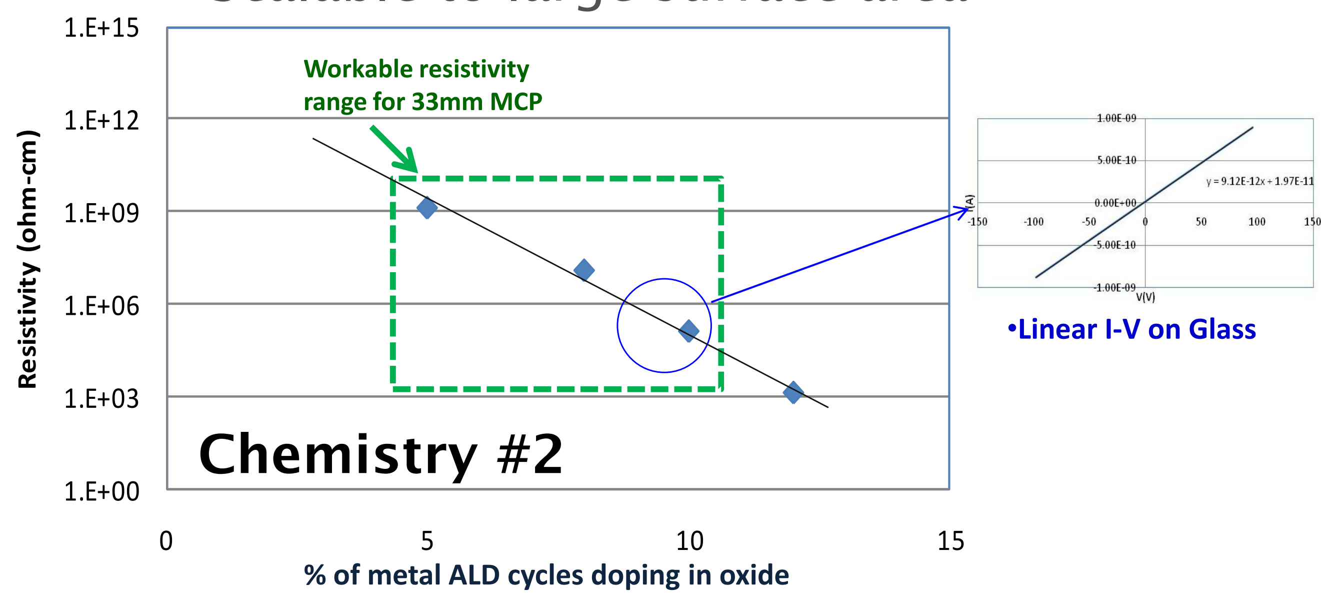
ALD Resistive Coating Development



- First resistive coating tested at Argonne
- Good:
  - Existing process
  - Functionalized MCPs exhibited high gain
- Bad:
  - etching of ZnO by trimethyl aluminum
  - 10^5 resistance change over 10% composition change



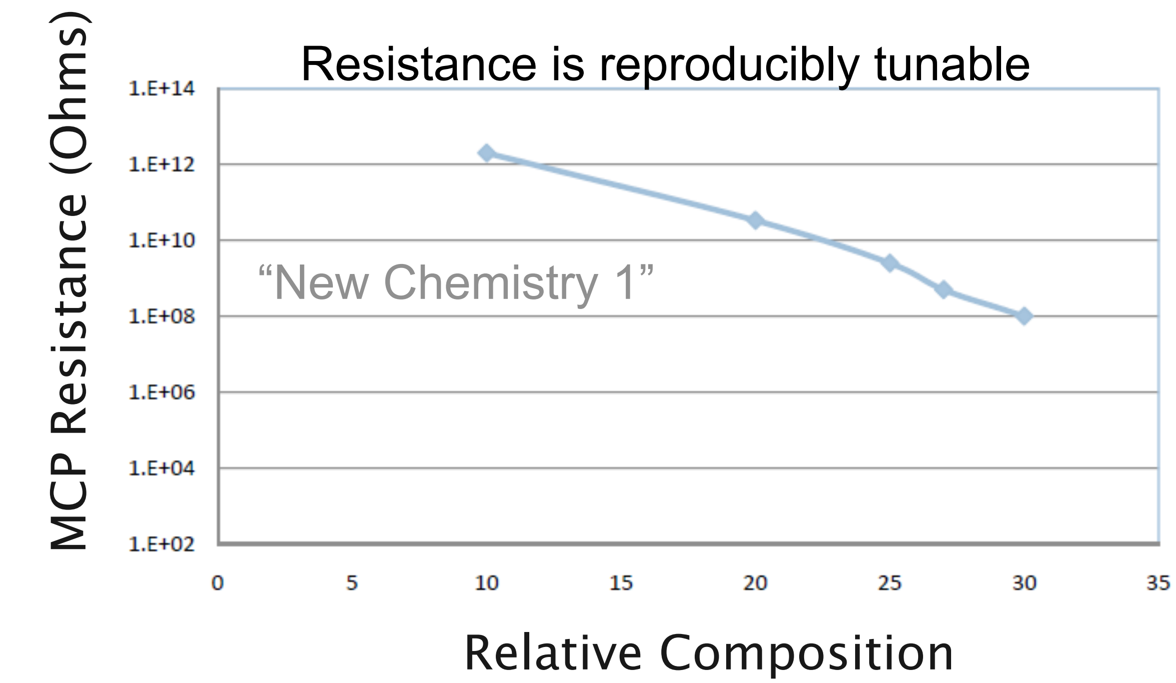
- **3 Alternative Resistive Chemistries developed by Argonne ALD group**
- Good:
  - Good control of resistivity
  - Uniform, smooth coating, no etching
  - Functionalized MCP pair exhibited high gain
  - Scalable to large surface area



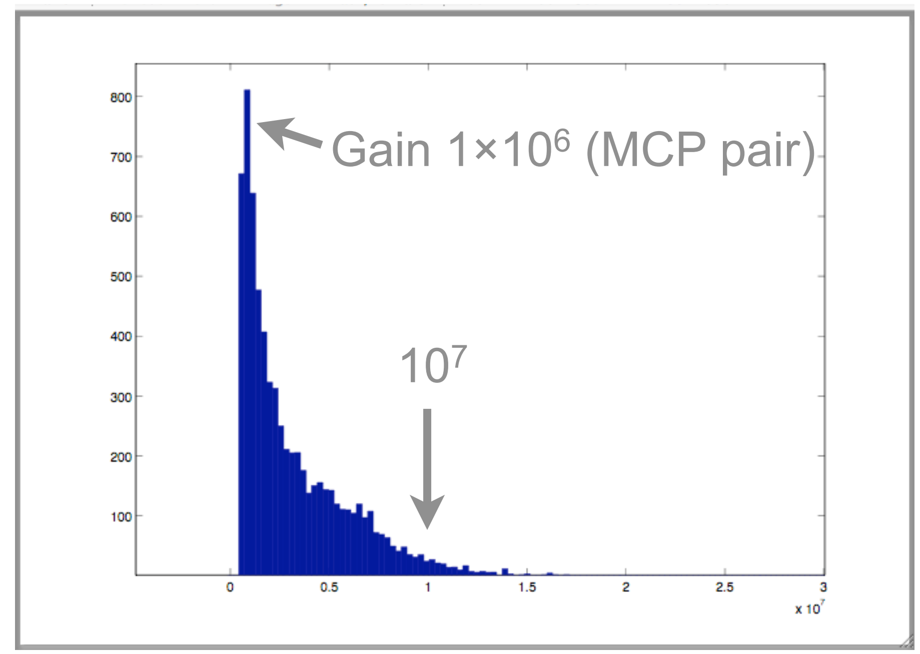
• **Uniform and smooth ALD coating pores of MCP**

ALD Functionalization of Micro-Channel Plates

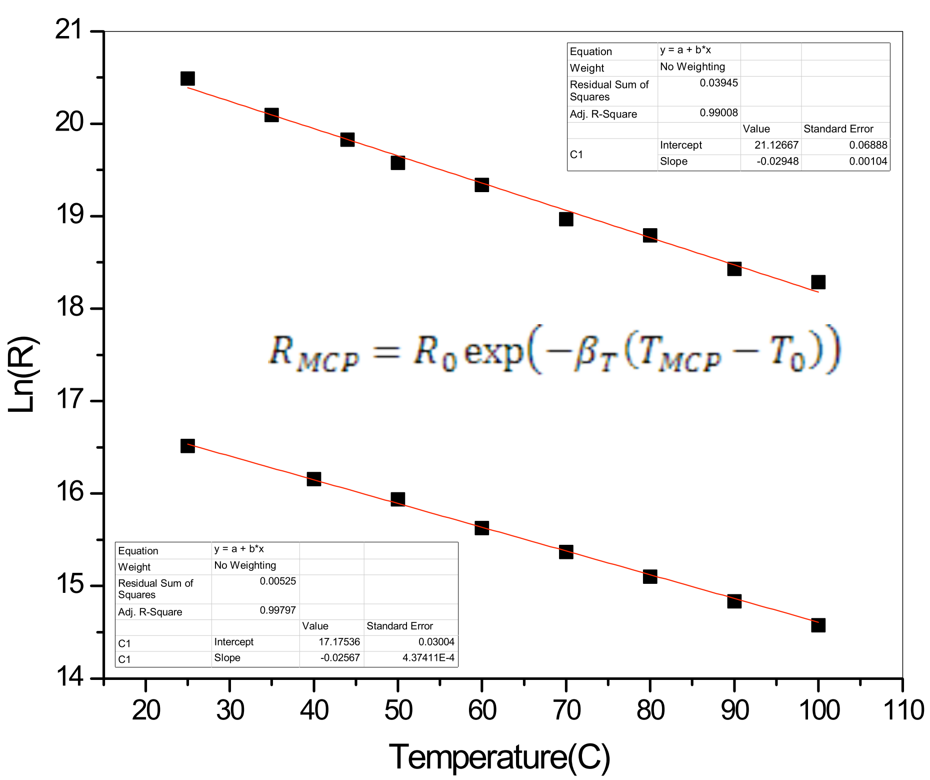
New ALD chemistries for resistive coating developed at Argonne



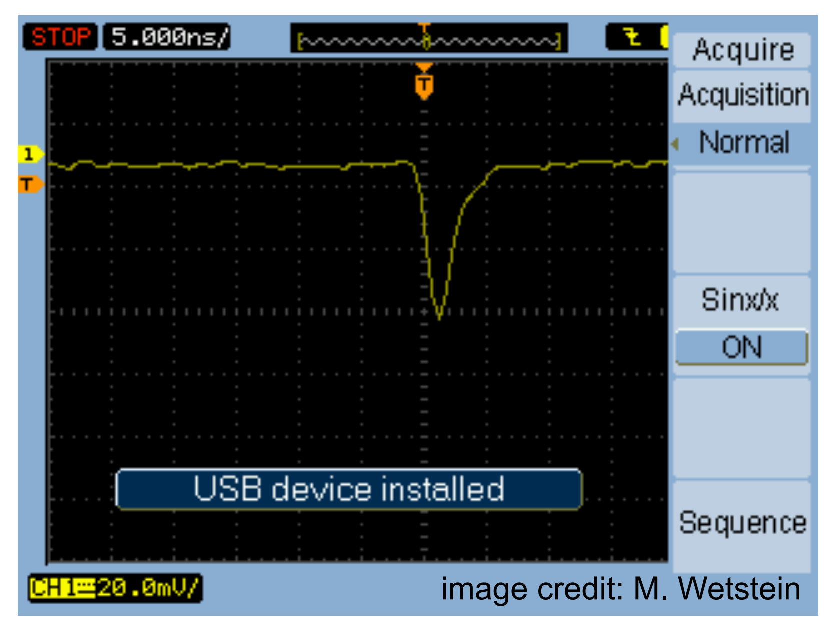
MCP 72/78 Amplification: 1.3/1.2 kV



Al_2O_3 Secondary Emission Layer



β_T = -0.02 for commercial MCP (literature)
= -0.027 "New Chemistry 1"



Signal from MCP pair coated with new resistive layer + Al_2O_3 emissive layer

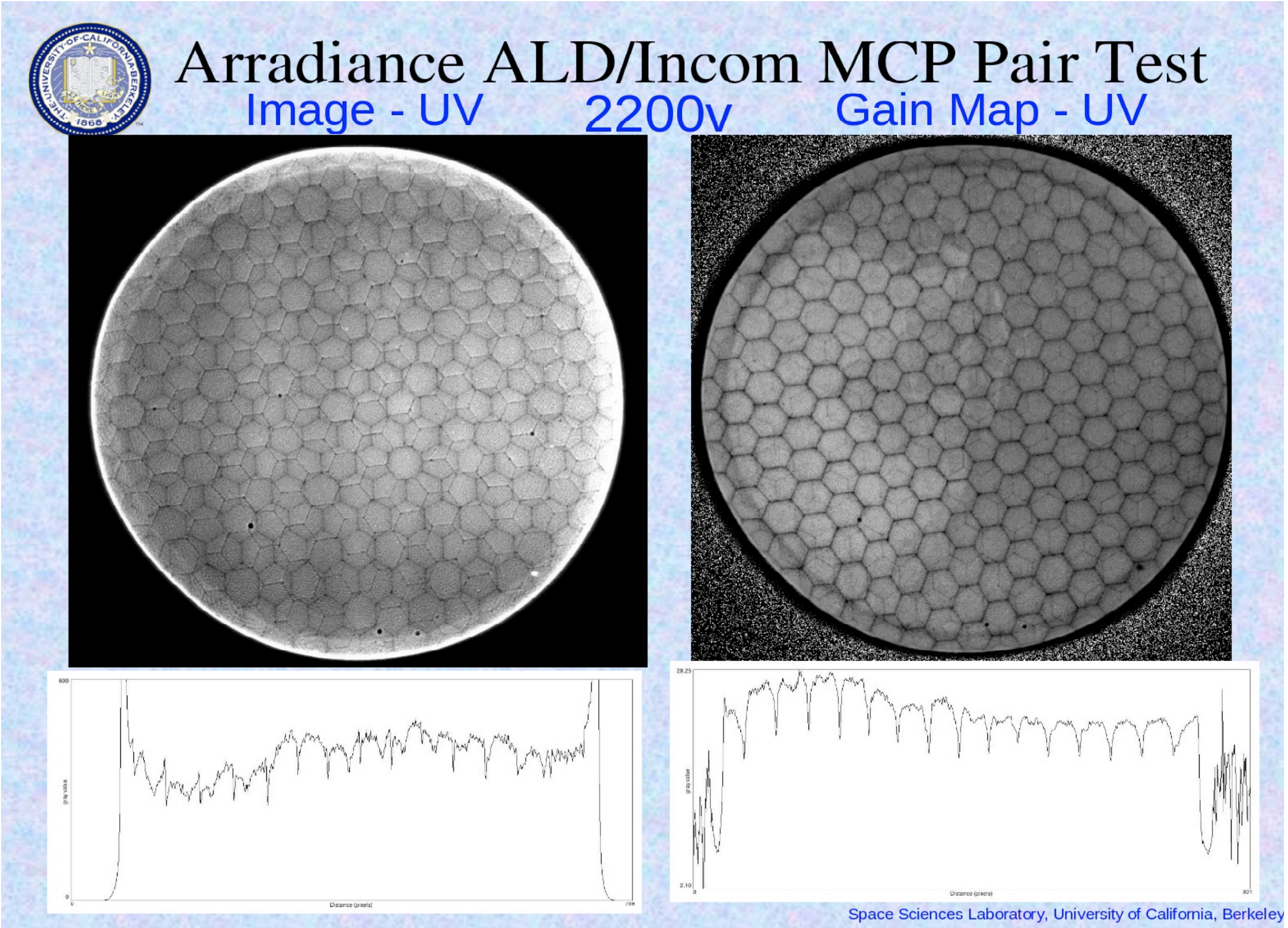
Visual Study of ALD Coated MCP

Glass capillaries coated by Arradiance, Inc.

Pair test at Space Sciences Lab/UC-Berkeley

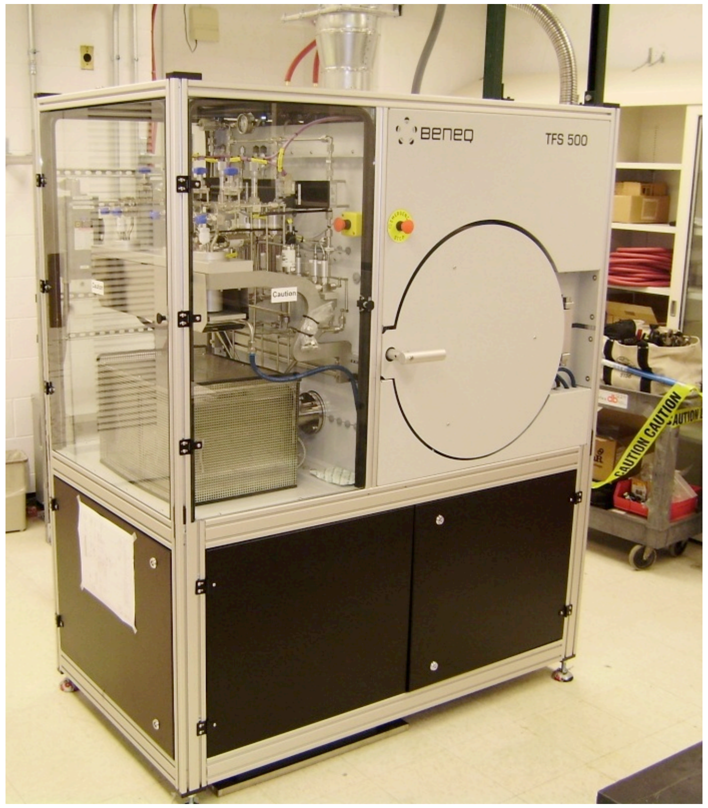
Electron map of MCP

“Multi” boundaries visible, fade at higher gain



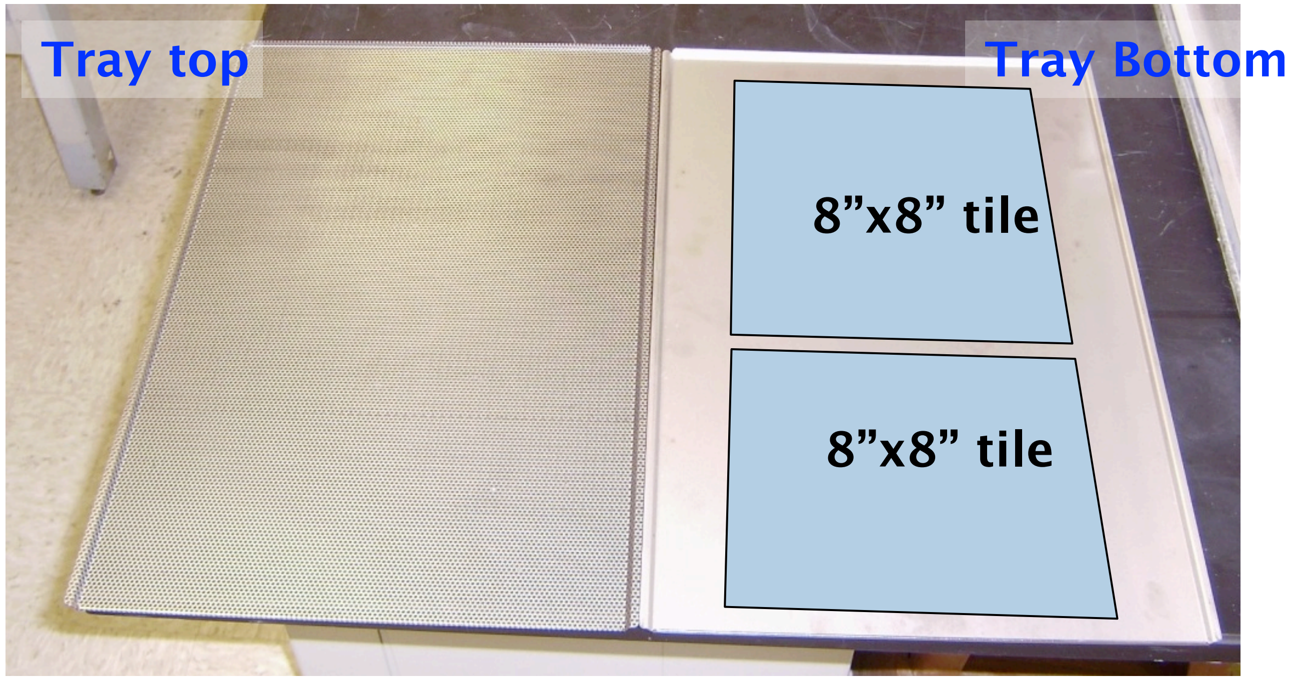
Scale-Up of ALD Processing -- Beneq Reactor

Arrived 18 May 2010



Studying ALD on Large Surface Areas

- 33mm disk surface area is $0.13m^2$
- 8”x8” surface area is $6.4m^2$
- 20 MCPs area is $129m^2$



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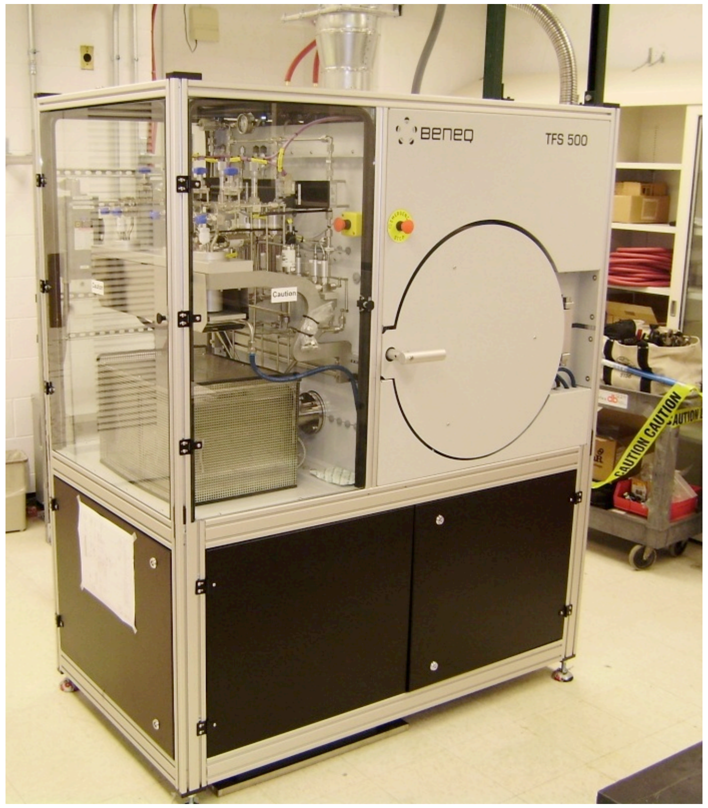

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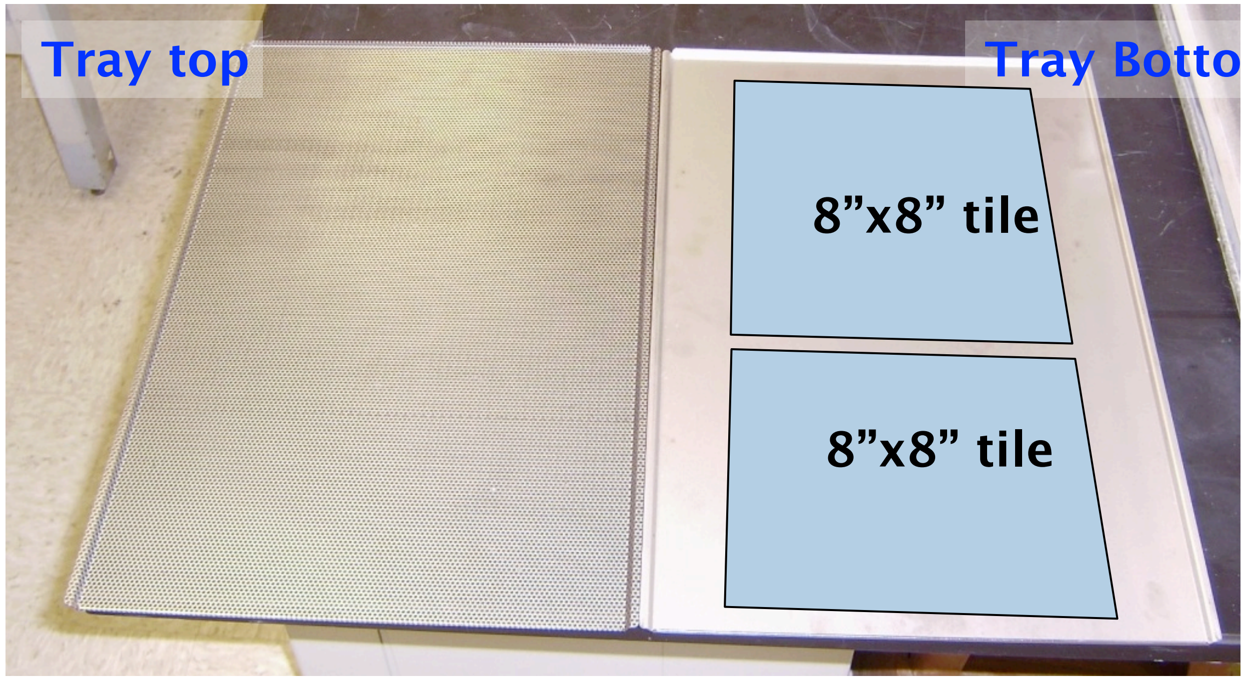
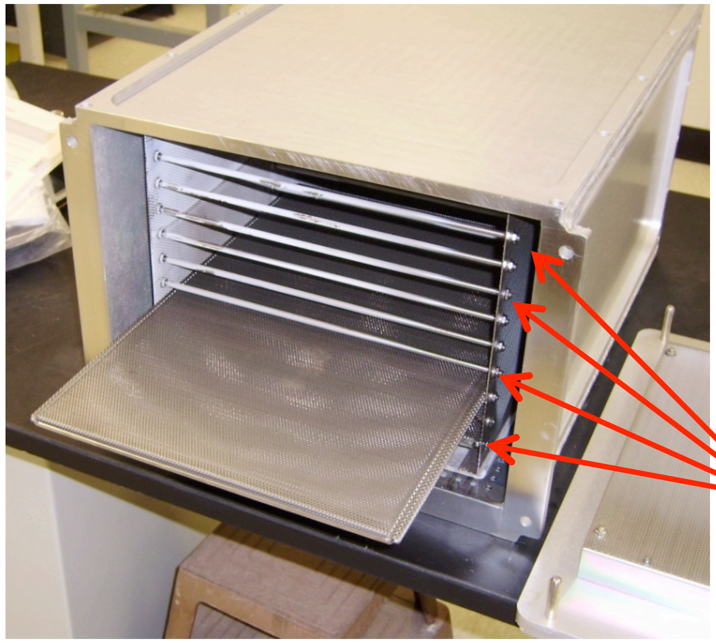
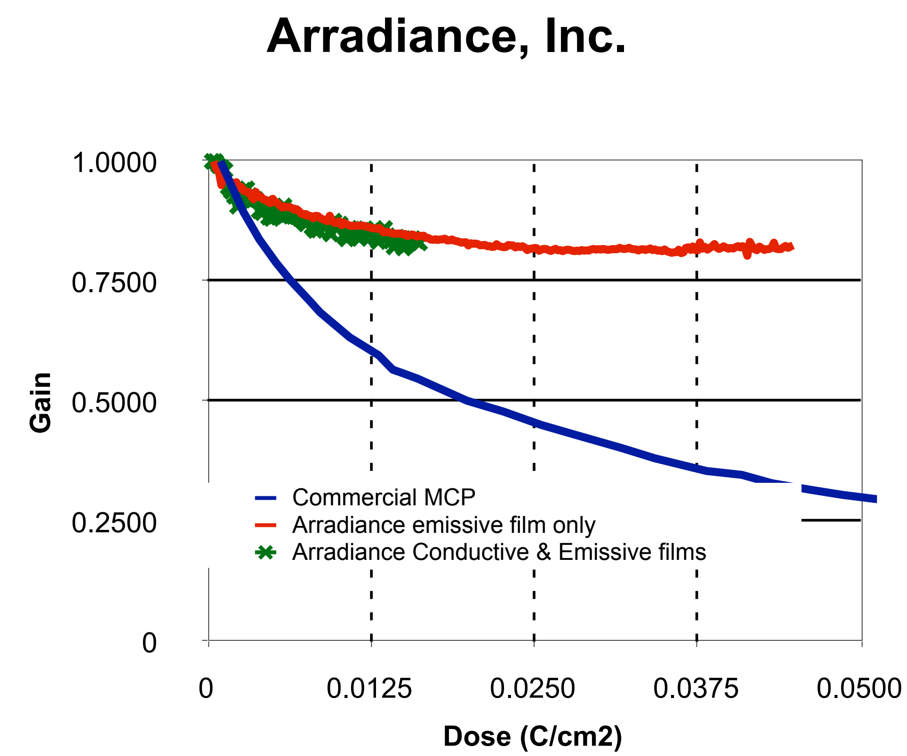
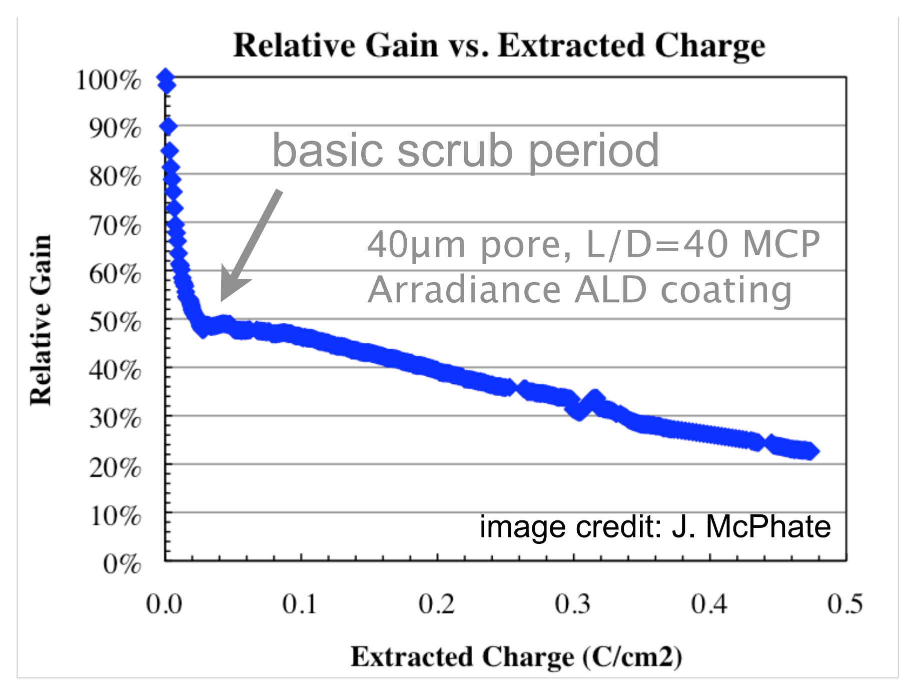




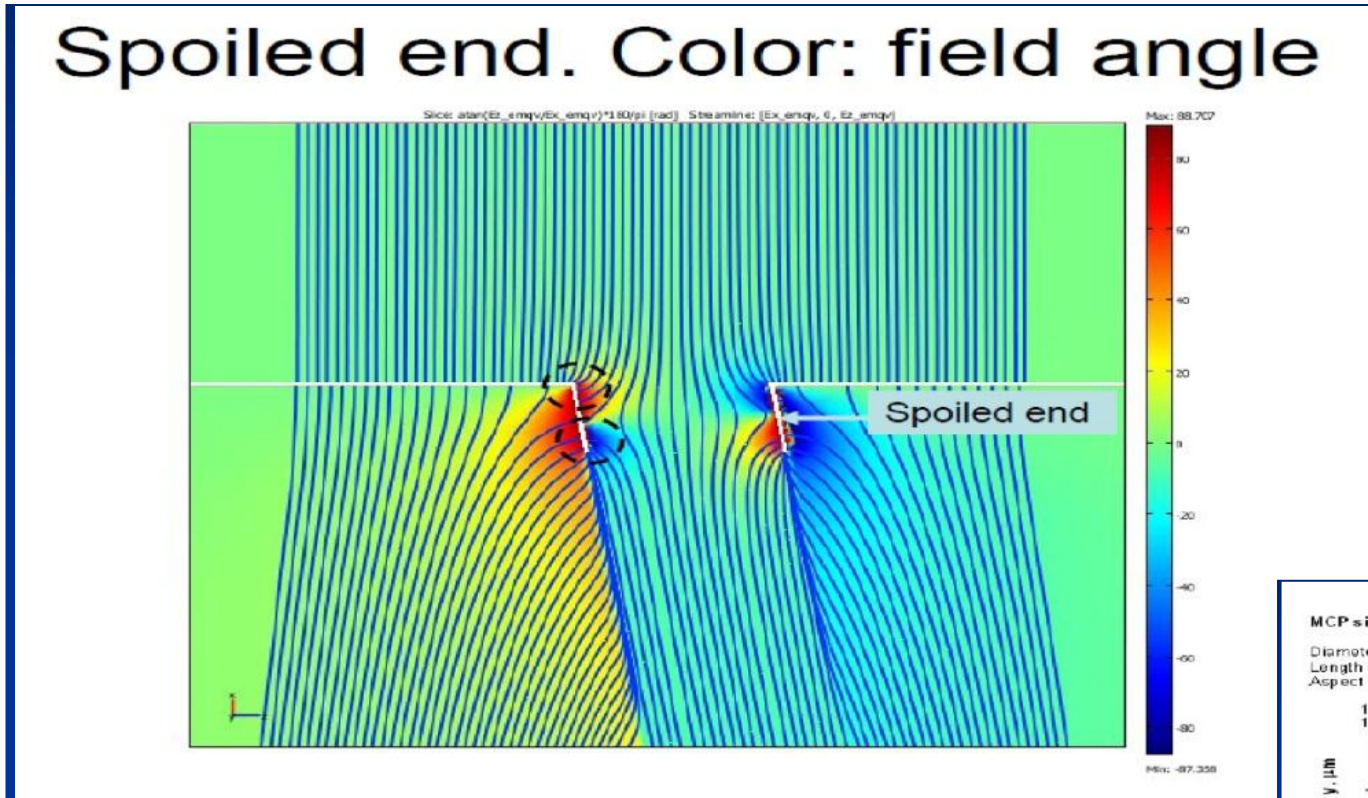
Advantages of ALD vs Conventional Pb Glass MCP

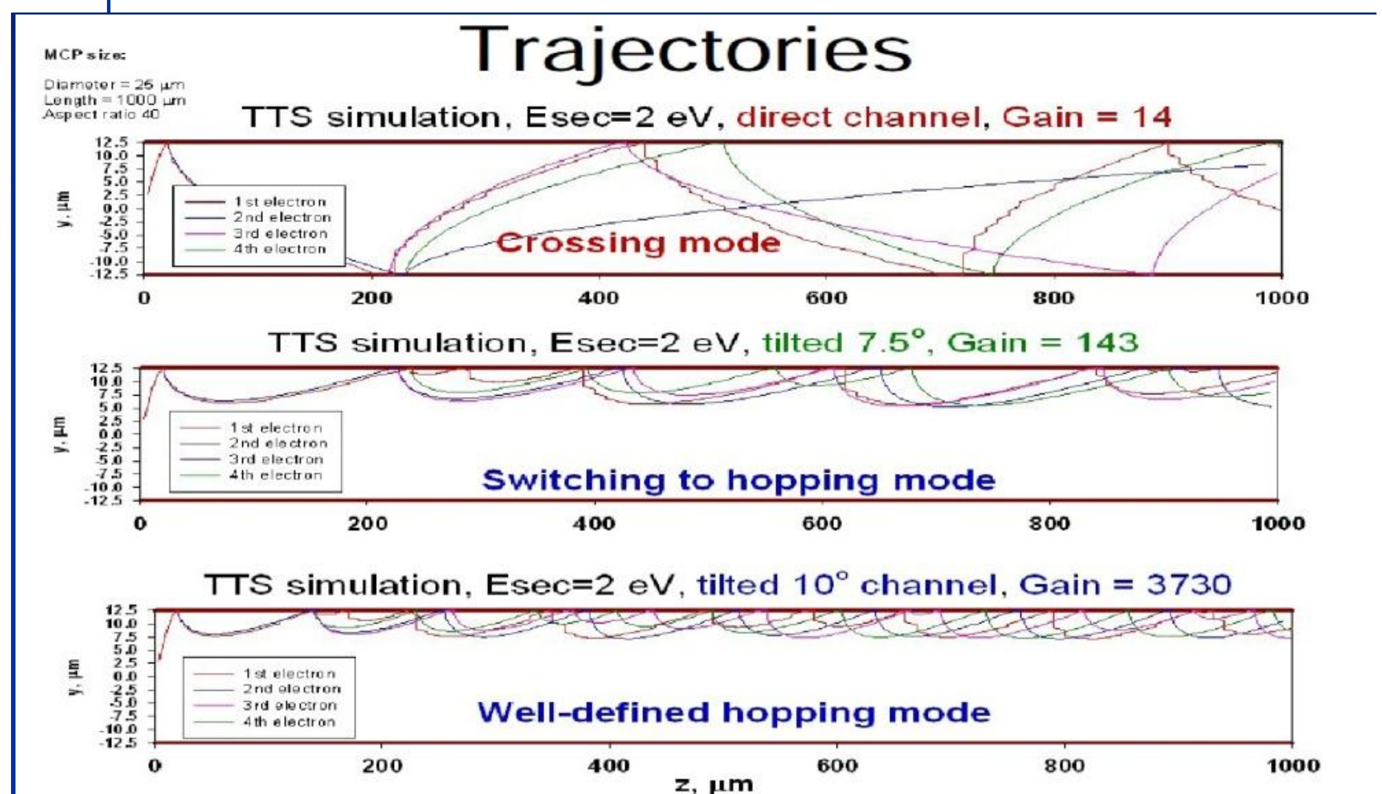
- Conventional lead-oxide MCPs have single composition for resistive/emissive material
  - Functionalized in H-furnace requiring long “scrubbing” time (removal of volatiles)
- ALD allows separate control of resistive and emissive layers
  - separately optimize each layer for best overall performance
  - Scrub time reduced by up to ×10



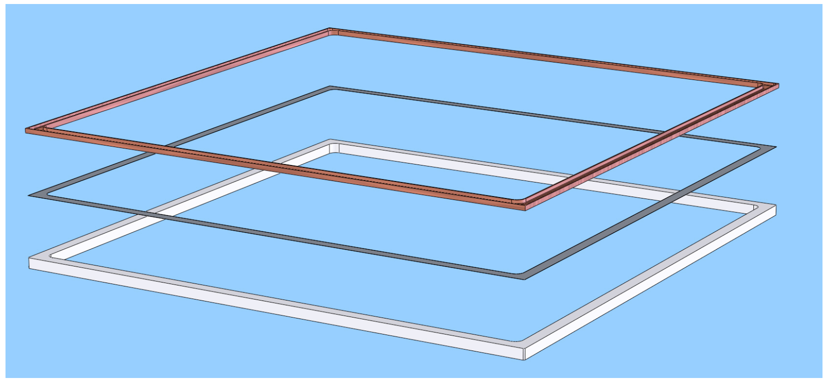


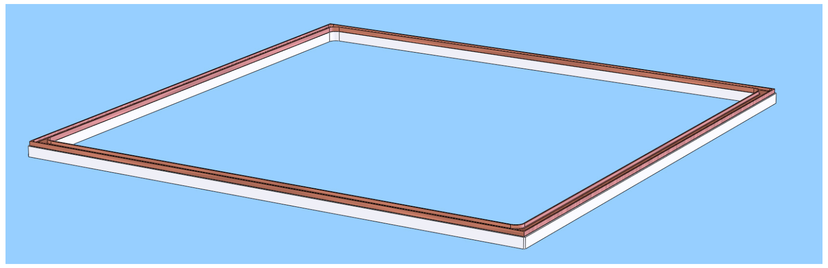
Simulation of MCP & Material Performance

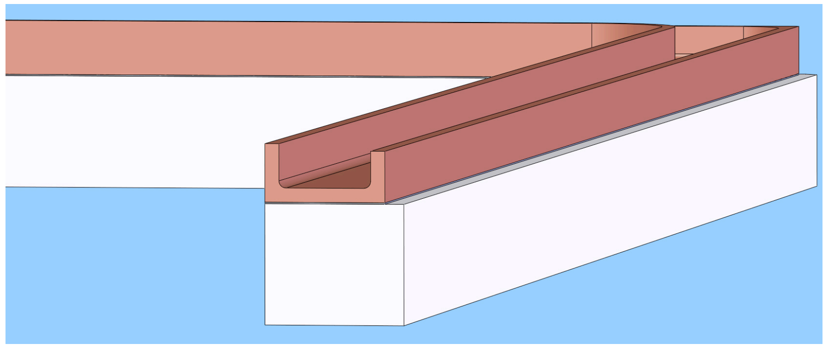




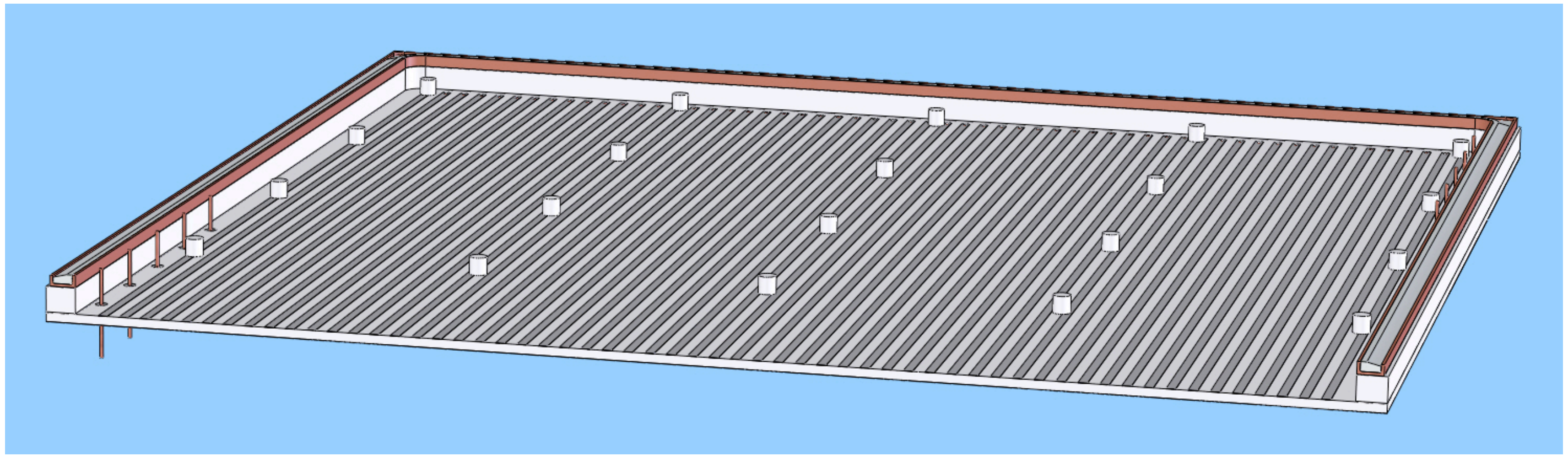
MCP Photomultiplier Packaging -- Ceramic Body (Space Science Laboratory/UC-Berkeley)



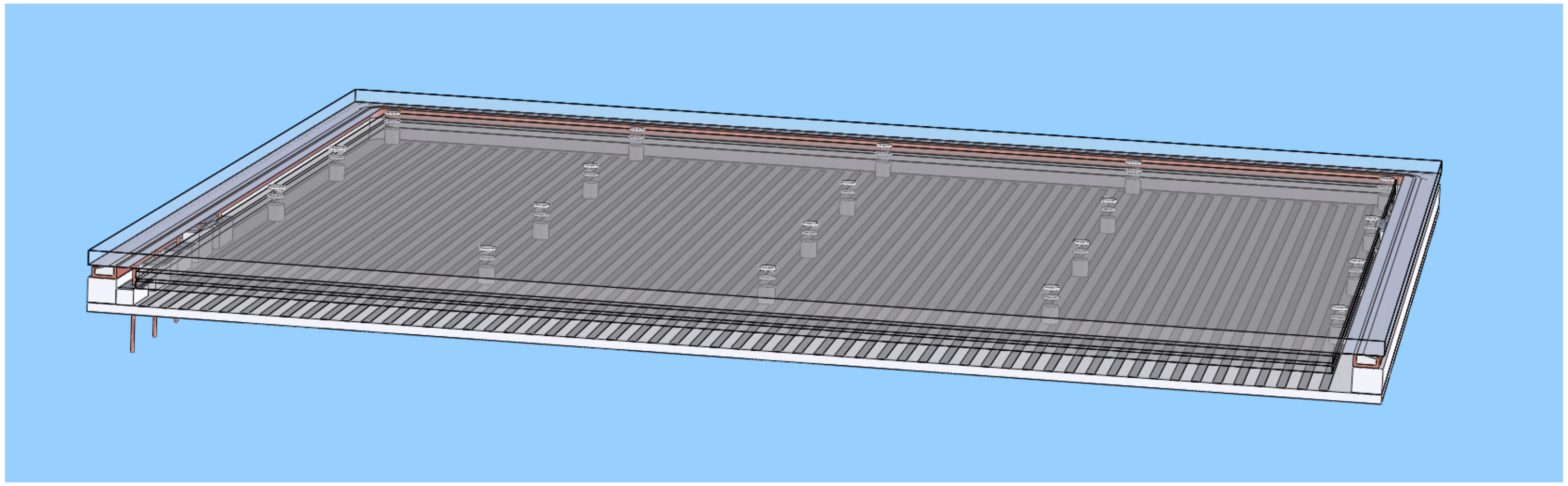




Single Joint Brazed Body
Tray for Indium top seal
- Kovar
- Ni plated/sintered
- Cu plated for Indium wetting



SSL/UC-Berkeley Ceramic Body Design

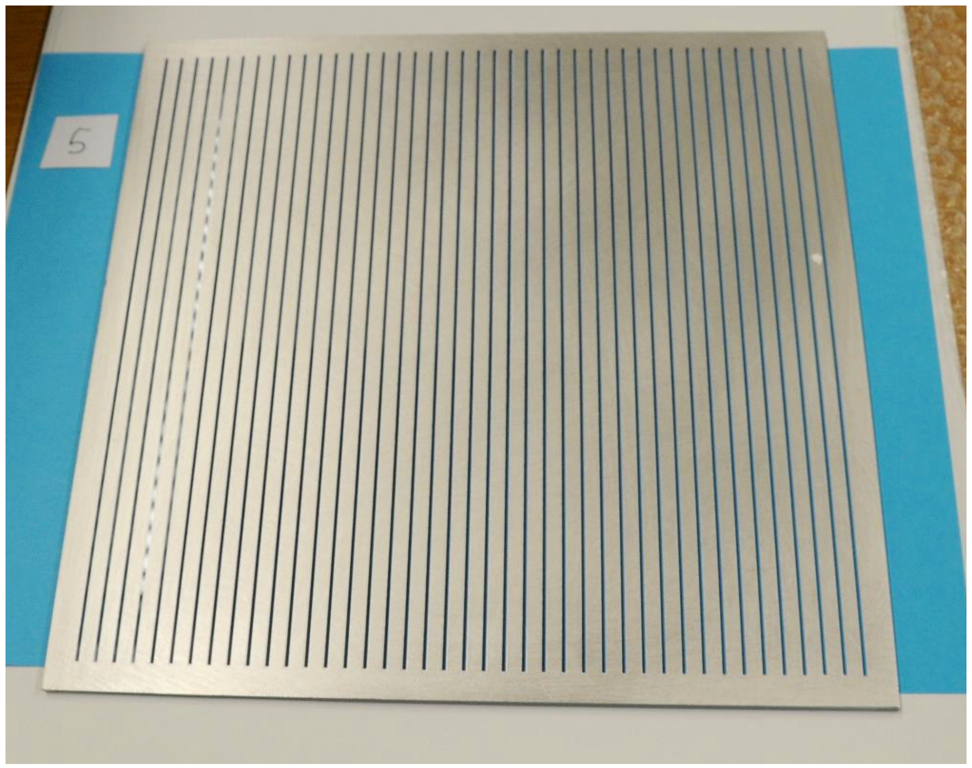


Final assembly with MCP, photocathode top plate, anode strip line, HV pins

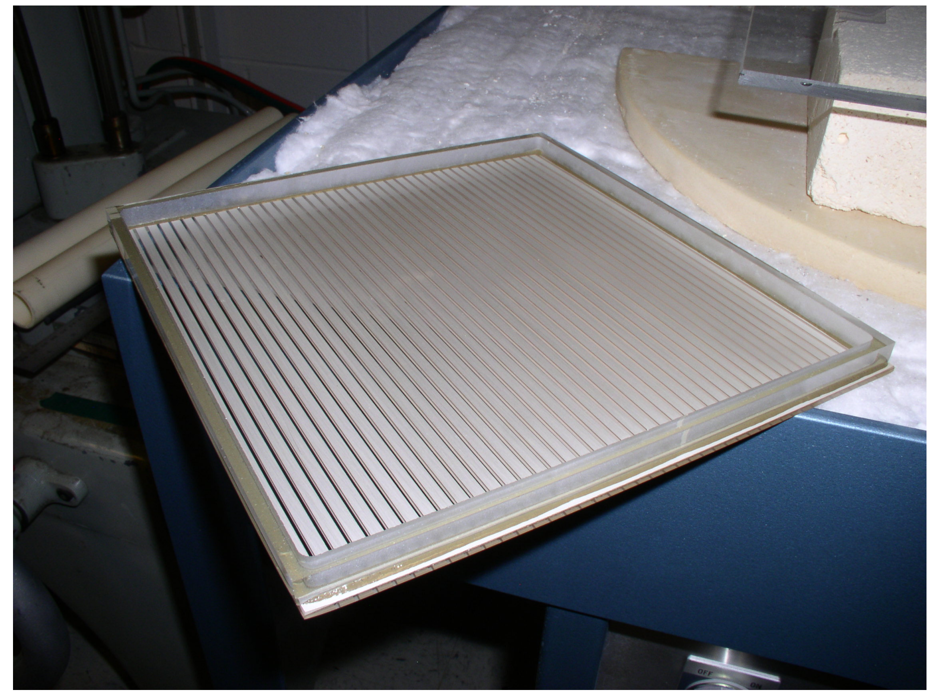
design drawings courtesy J. McPhate, SSL

MCP Photomultiplier Packaging -- Borofloat Glass Body (Univ. of Chicago/Argonne Natl. Lab.)

Ceramic body is proven method. Design by SSL group with years of experience.
Relatively expensive.
UC/Argonne alternative design with inexpensive glass & bonding methods. Untested.

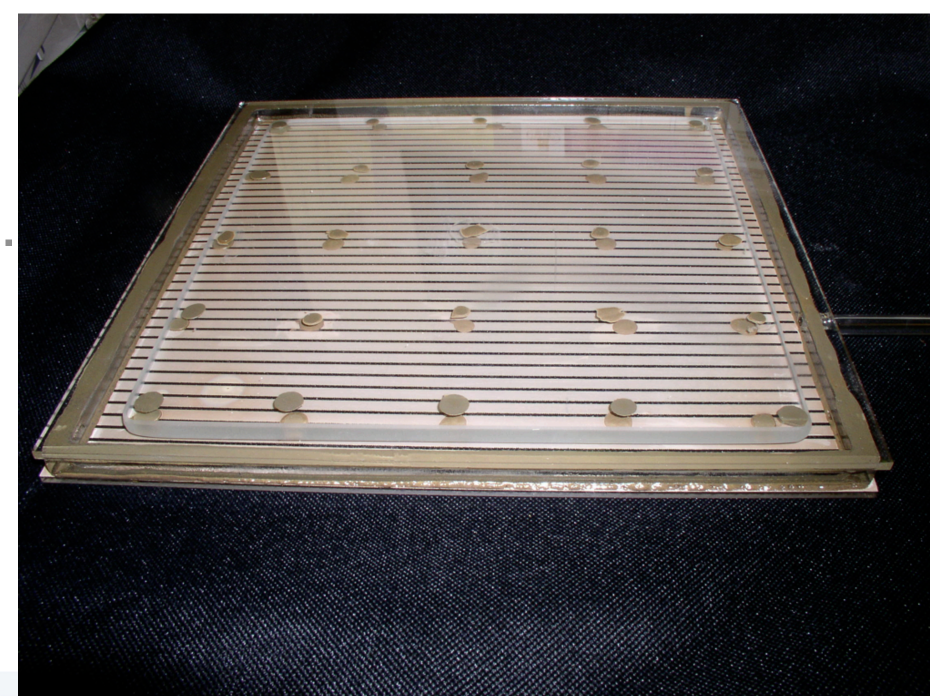


Silk-screen printing of anode ground plane on B33 glass

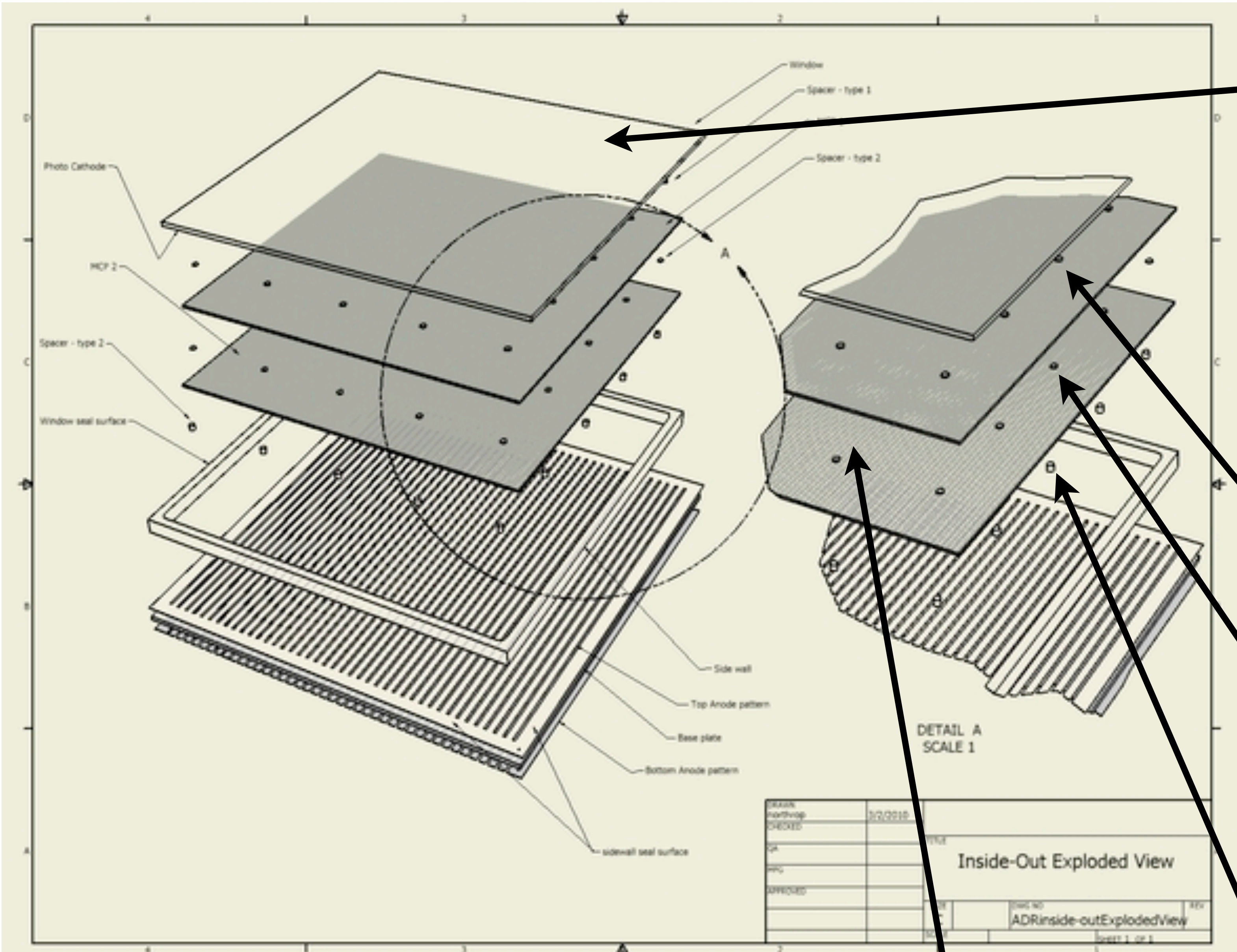


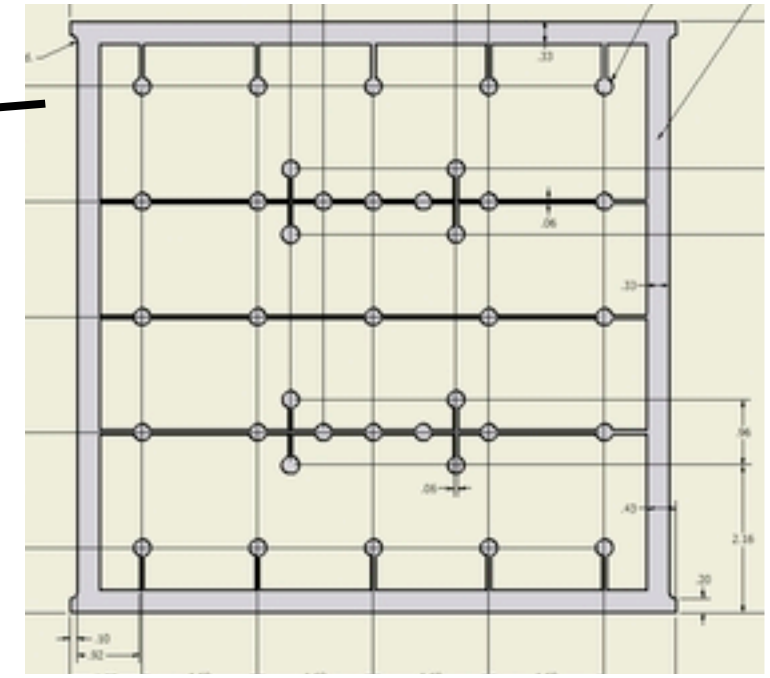
Sidewall bonded to bottom plate with glass frit

First “sealed box”. No internals.
Glass “drop piece” for internal support.
Top seal is glass frit in this test.
Will ultimately use Indium or Indium alloy

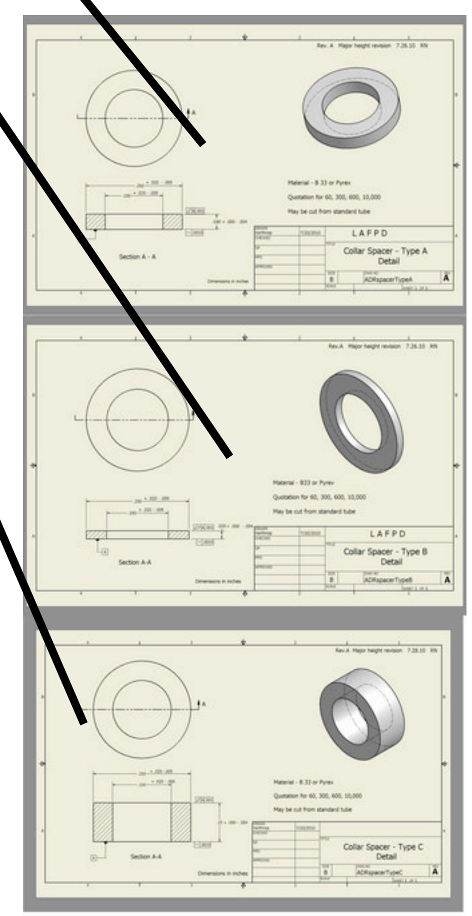


Mechanical Assembly of Tiles -- Overview

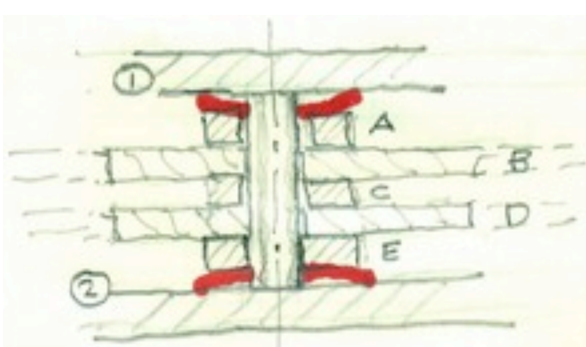




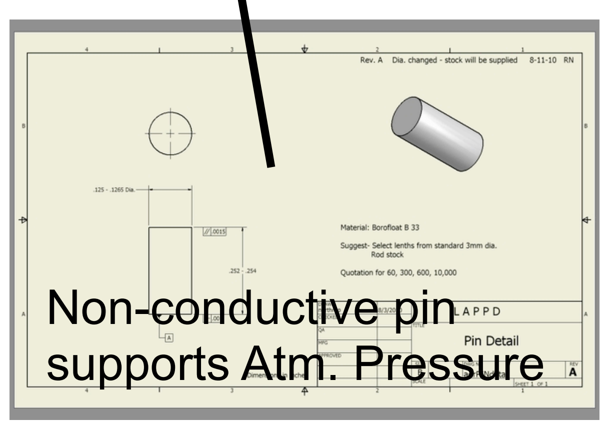
Photocathode Top Window
HV distribution through strip pattern



Conductive
spacer collars set
HV distribution
through MCPs &
to anode ground

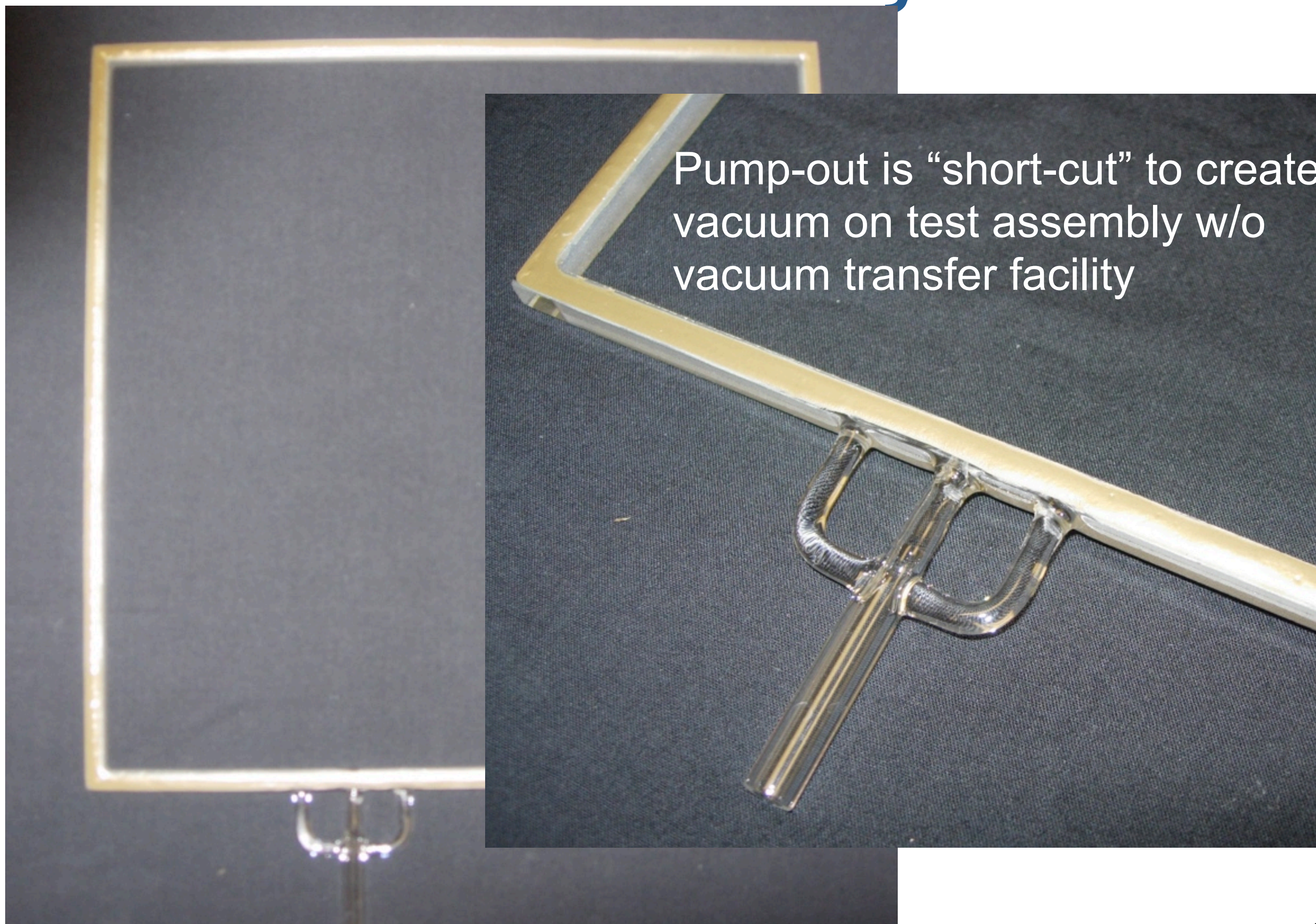


Spacer detail

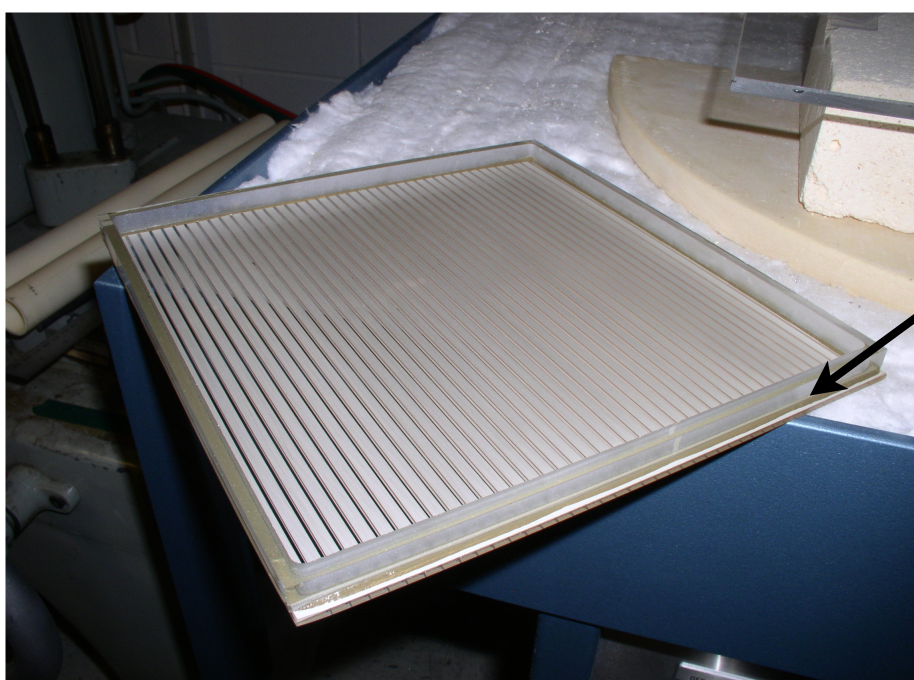


Non-conductive pin
supports Atm. Pressure

Tile Base Assembly -- Anode Bottom Plate & Sidewall



- **Develop technique to reproducibly bond sidewall to bottom anode plate**
  - Center sidewall frame w.r.t. bottom plate; 2 sides flush, equal overhang on anode ground strips



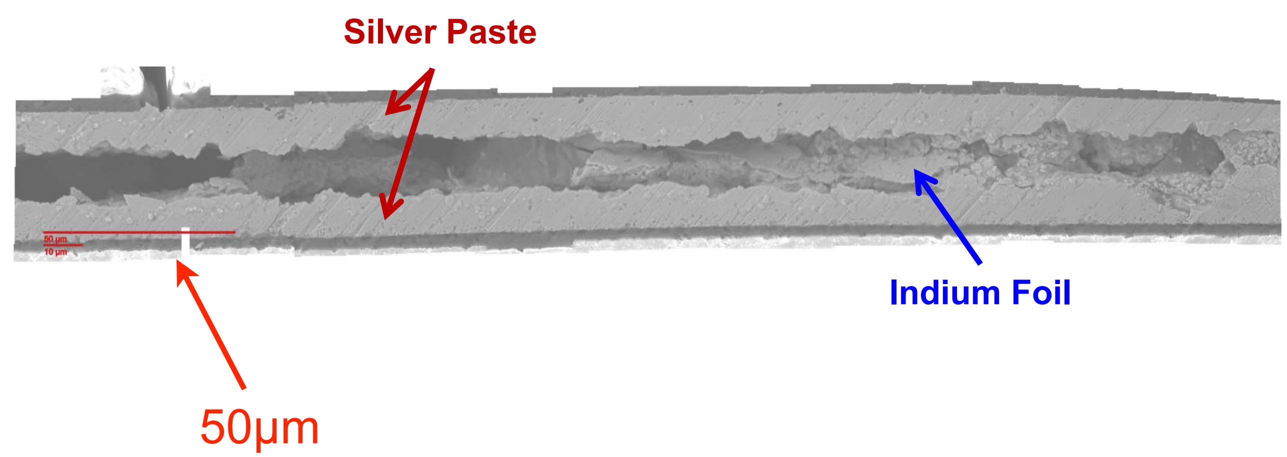
Sidewall bonds along thin silver strip
Extension of strip past sidewall for bridging grounds between tiles

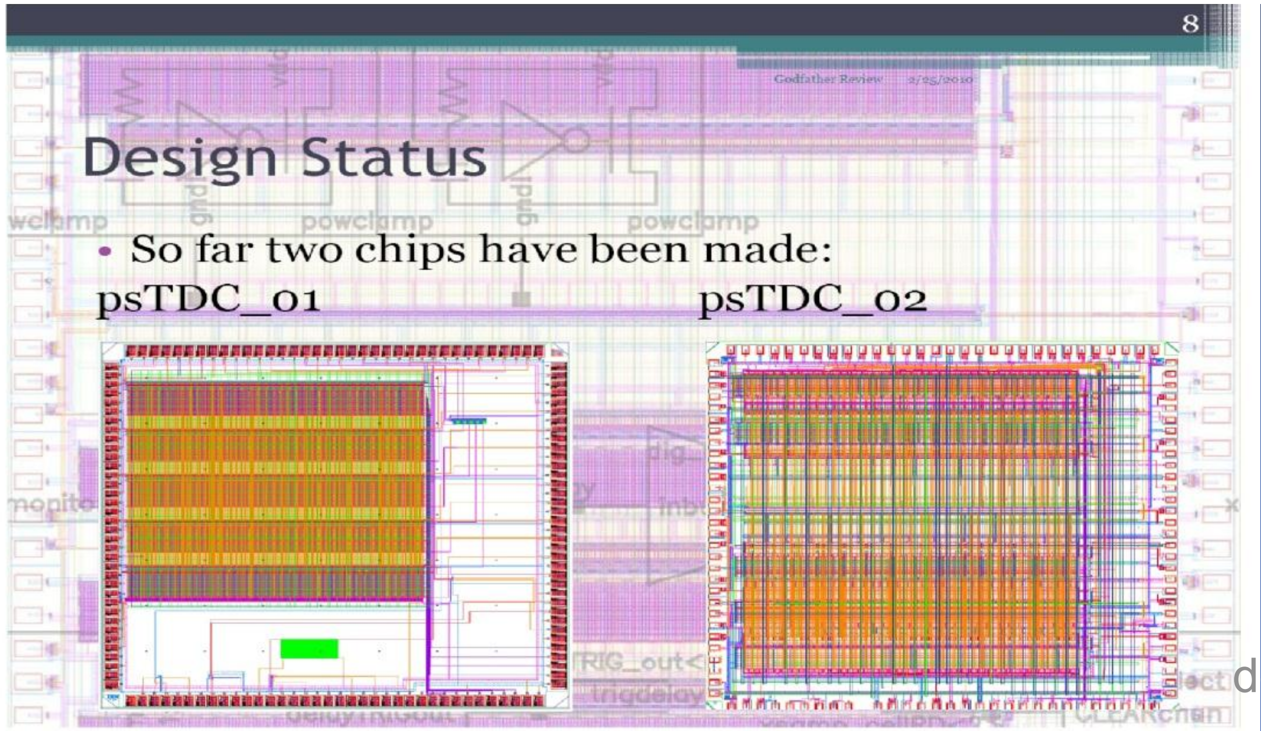
Indium Thermopressure Top Window Seal Development

- Collaborative effort with Univ. of Illinois- Chicago (Ernesto Indacochea, Alcides Raraz, Marc Kupfer)
- **Bonding of top plate to sidewall must be low temperature (≤150˚C) to avoid damage to photocathode**
  - Test indium cold/warm press seal to silver, chromium, or nichrome films on glass

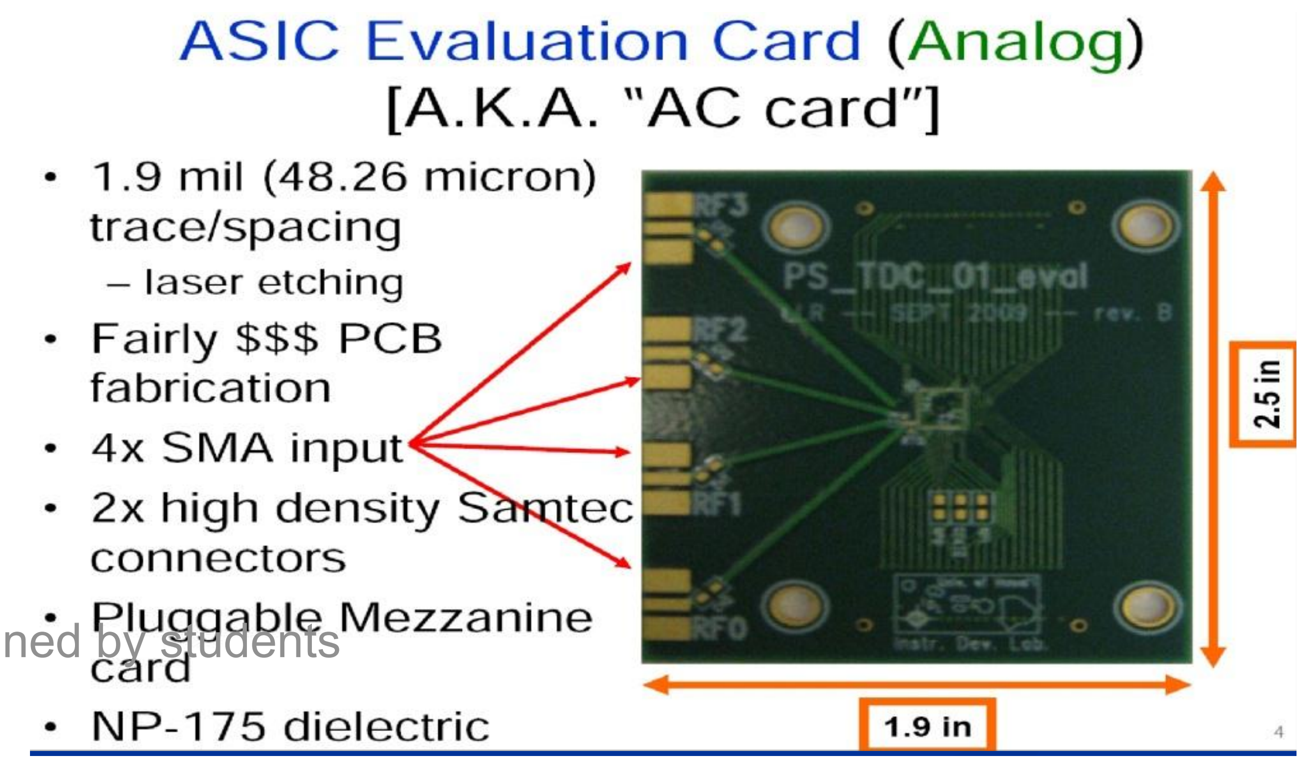
		5 Minutes			15 minutes		
	Temperature (ºC)	Pressure (psi)					
		800	1000	1200	800	1000	1200
Ag coated	25				*		
	100	✓	✓	✓		*	
	125					*	
	150	✓	✓			*	
Cr coated	25						
	100		✓			*	
	125						
	150						
Cr/In coated	25						
	100						
	125		✓				
	150						

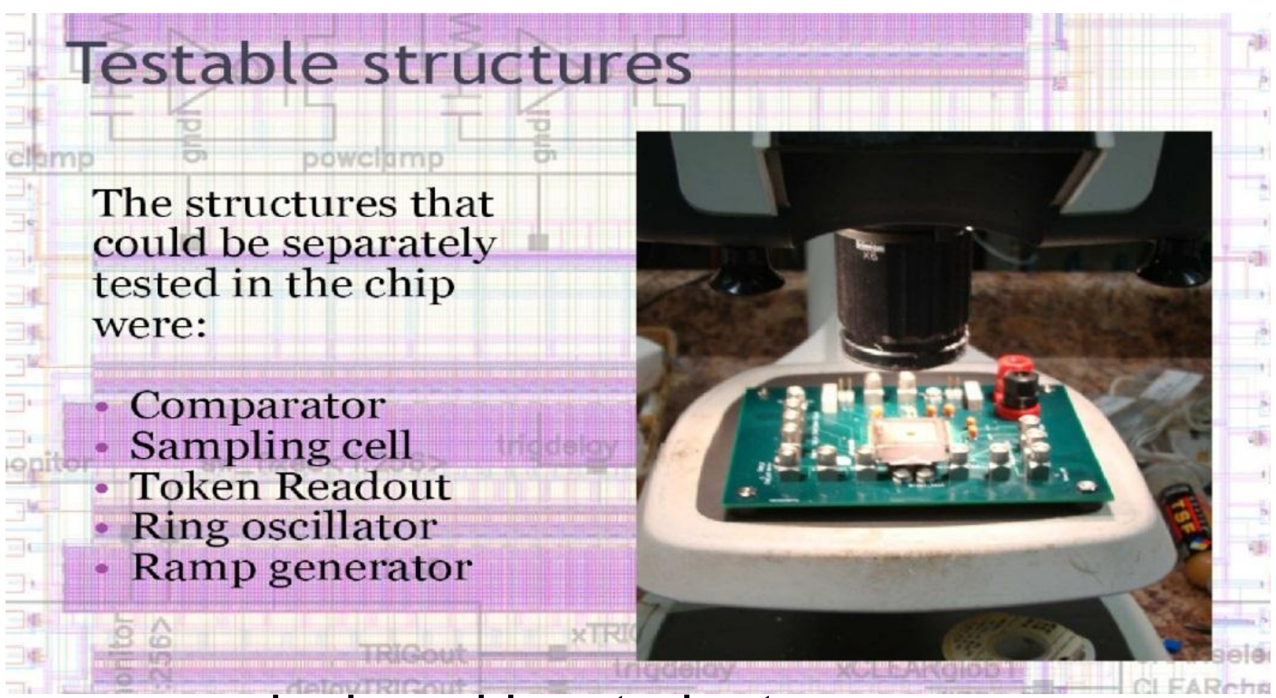
Successful Glass-Ag-In-Ag-Glass seal
1”×1” silver ink printed glass coupons
1000psi for 5 min., 160˚C





designed by students





designed by students

- 130nm IBM 8RF process
- 4 chs., 256 deep ring buffer
- 11 GS/s demonstrated
- ADC/ch – target 9 eff. bits
  - ADC on Psec2 non-func. due to leakage
  - Add ADC to test board
- Learning from Ritt, Breton, Delagnes, Genat*, Varner*   *-> collaborators

Summary - LAPPD

- Large Area Picosecond Photodetector Development collaboration completed 1+ year end having realized several initial goals.
- Glass capillaries look viable, working on improvements
- Atomic Layer Deposition coatings of 33mm glass capillary disks producing gain $>10^6$ for MCP pair
- Study of 3 ALD resistive + 2 ALD emissive chemistries
- Mechanical designs for hermetically sealed tube
  - Proven design in ceramic by SSL
  - Inexpensive glass design -- have demonstrated hermetic box; many other tests soon
- Developed alternative Anodic Aluminum Oxide substrate
- Design for photocathode growth and characterization facility at Argonne
- Vacuum transfer facility for 8”×8” photodetector near complete at SSL
- Photocathode fabrication and study in progress at SSL
- 8”×8” glass capillary arrays will be functionalized in next 1-2 months
- Proceeding with design & construction of tile fabrication facility at Argonne

BACKUP SLIDES

General procedures for Fabrication of MCPs

Pristine MCPs → Acetone sonication clean (30mins) → Air dry at 200C >2h (2 hrs) → Loading in Vacuum reactor → Ozone clean (2 hrs) → ALD coatings (10 hrs) → Baking at 400C under N2 (6 hrs) → Electrode coating (4 hrs) → Testing resistance (3 hrs) → Deliver for testing

For fabricating one pair MCPs:

~20-30hrs

if everything is right

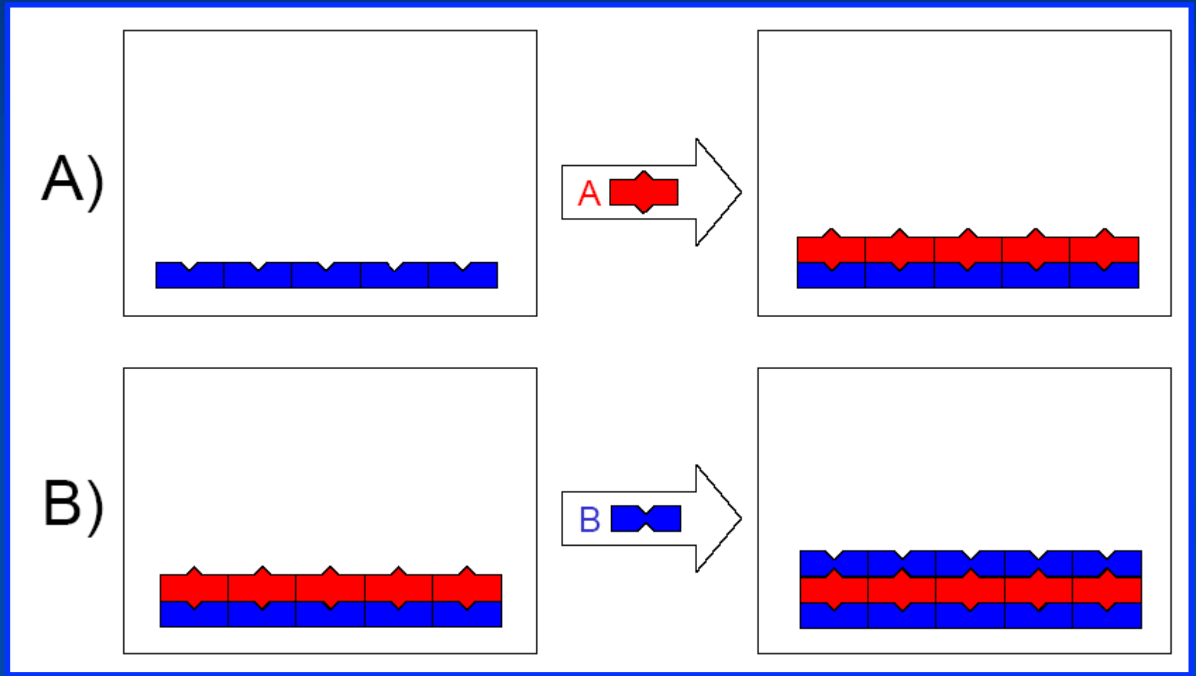
courtesy Qing Peng, Argonne ALD Group

Atomic Layer Deposition (ALD) Thin Film Coating Technology

•Lots of possible materials => much room for higher performance

Jeff Elam pictures

Atomic Layer Deposition (ALD) Thin Film Coating Technology

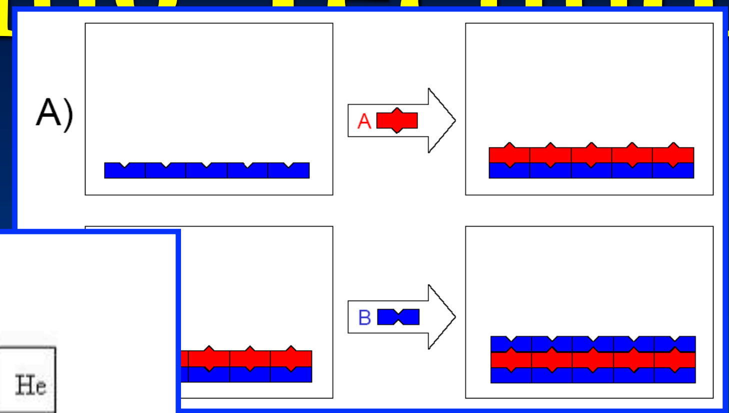


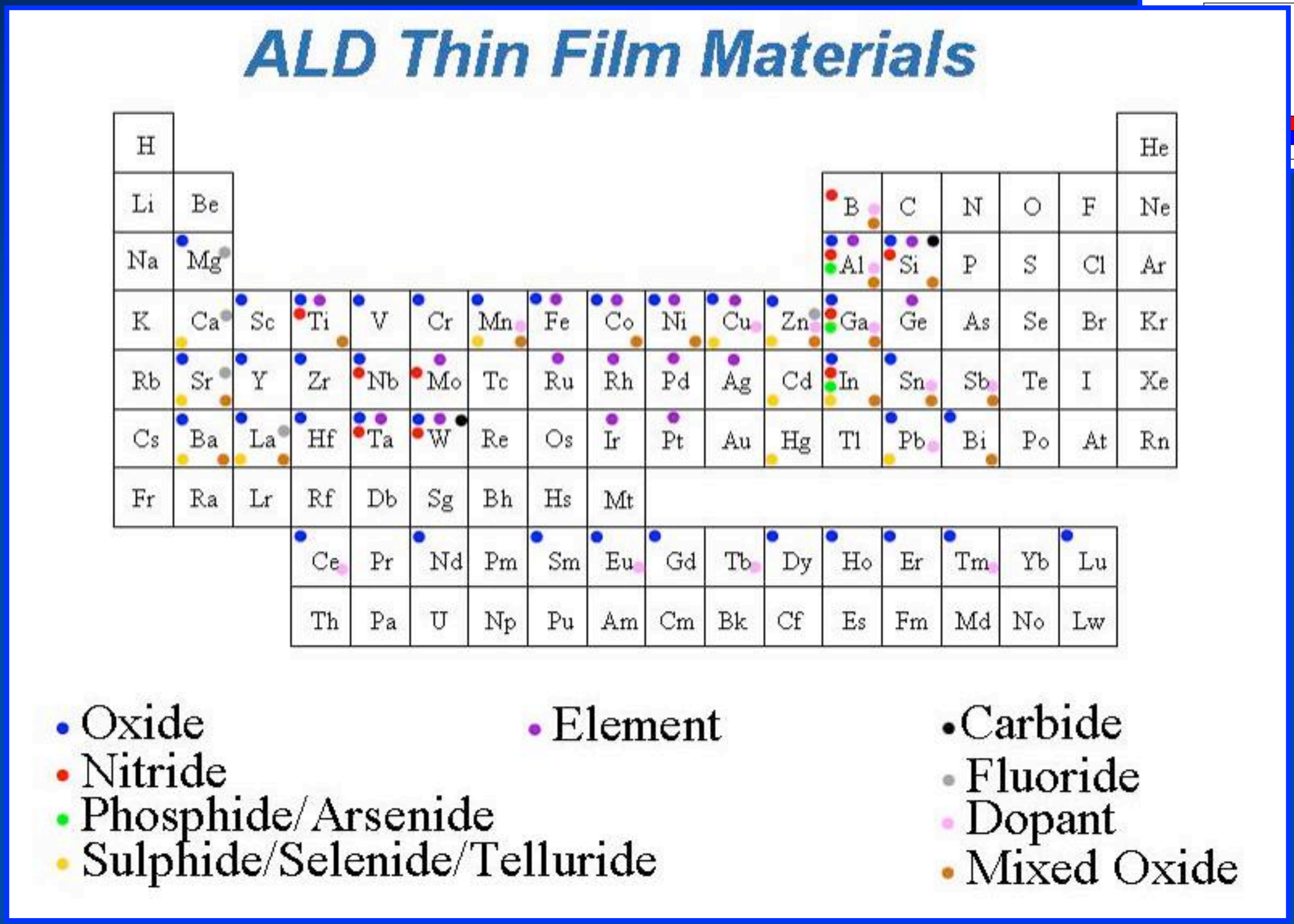
- Atomic level thickness control
- Deposit nearly any material
- Precise coatings on 3-D objects (JE)

•Lots of possible materials => much room for higher performance

Jeff Elam pictures

Atomic Layer Deposition (ALD) Thin Film Coating Technology





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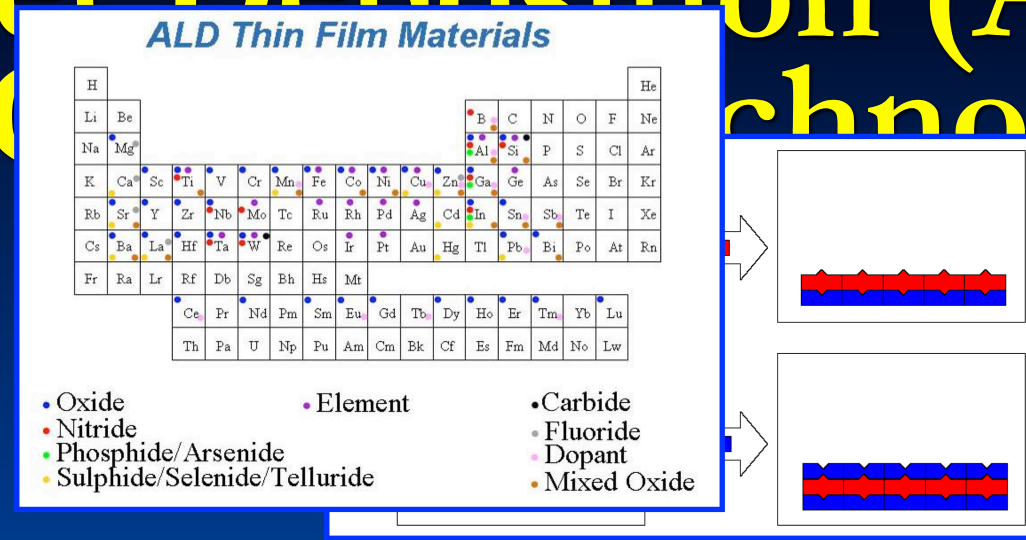
Atomic Layer Deposition (ALD) Thin Film C chnology



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Grid Spacer Alternative