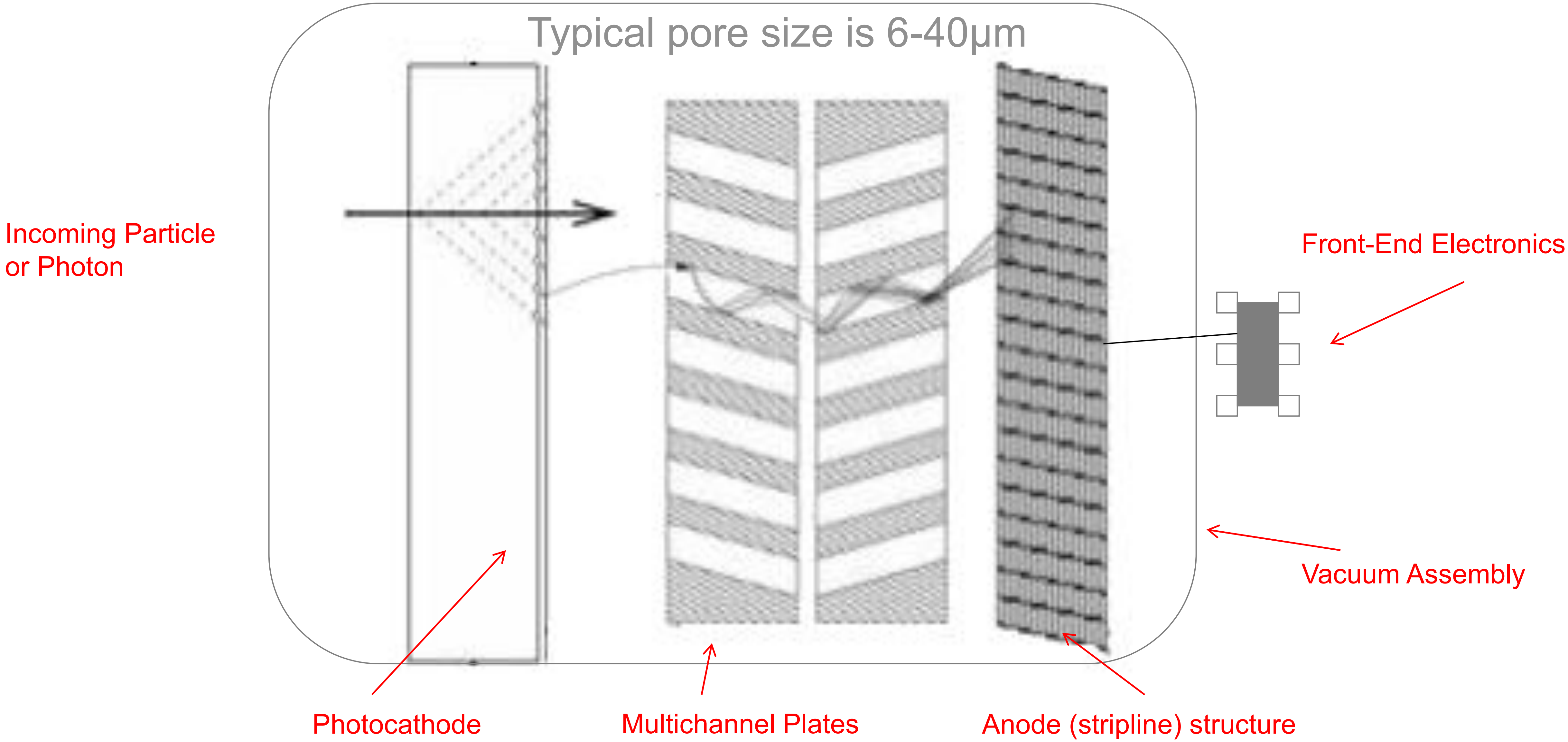
Development of Large Area Microchannel Plate Photodetectors

for the Large Area Picosecond Photodetector Development Collaboration
Bob Wagner, Argonne National Laboratory
Antiproton Physics at the Intensity Frontier
Fermilab
Friday 18 Nov 2011

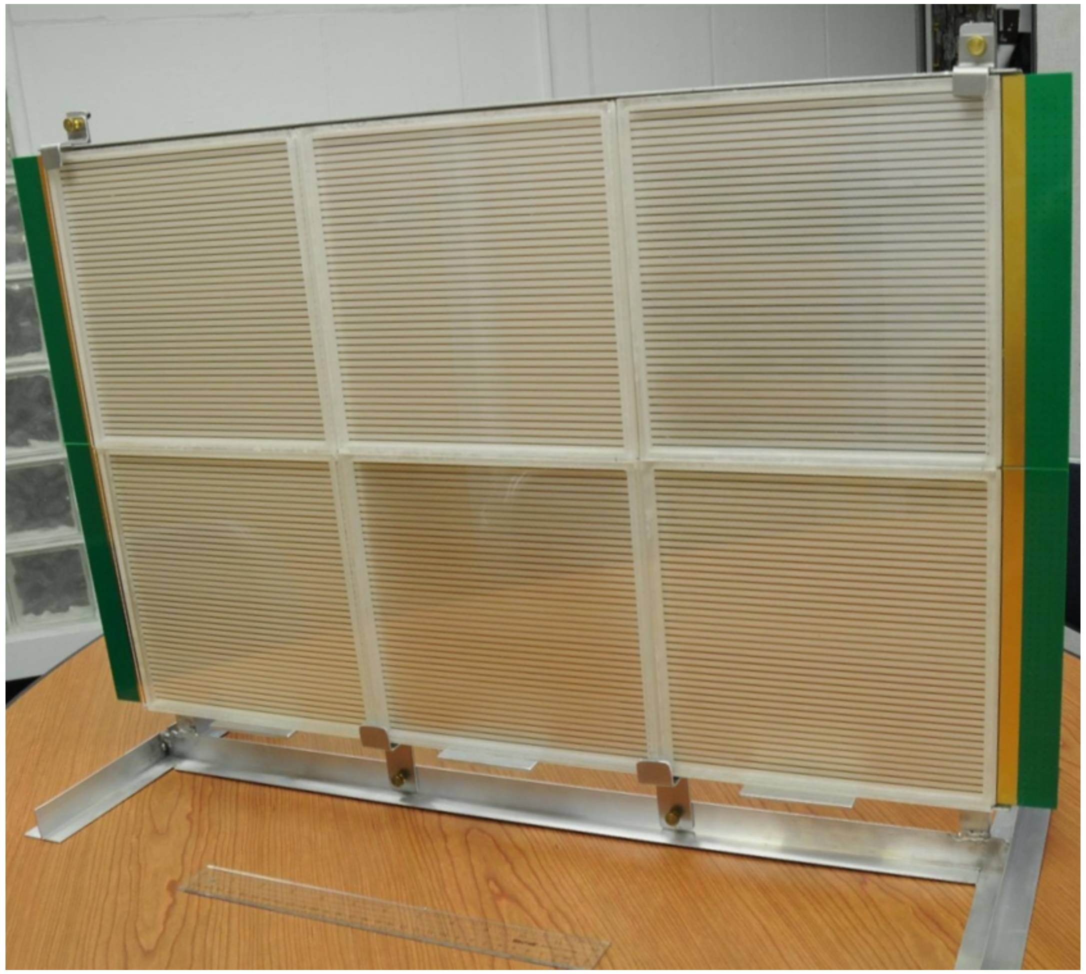
Microchannel Plate Photomultipliers



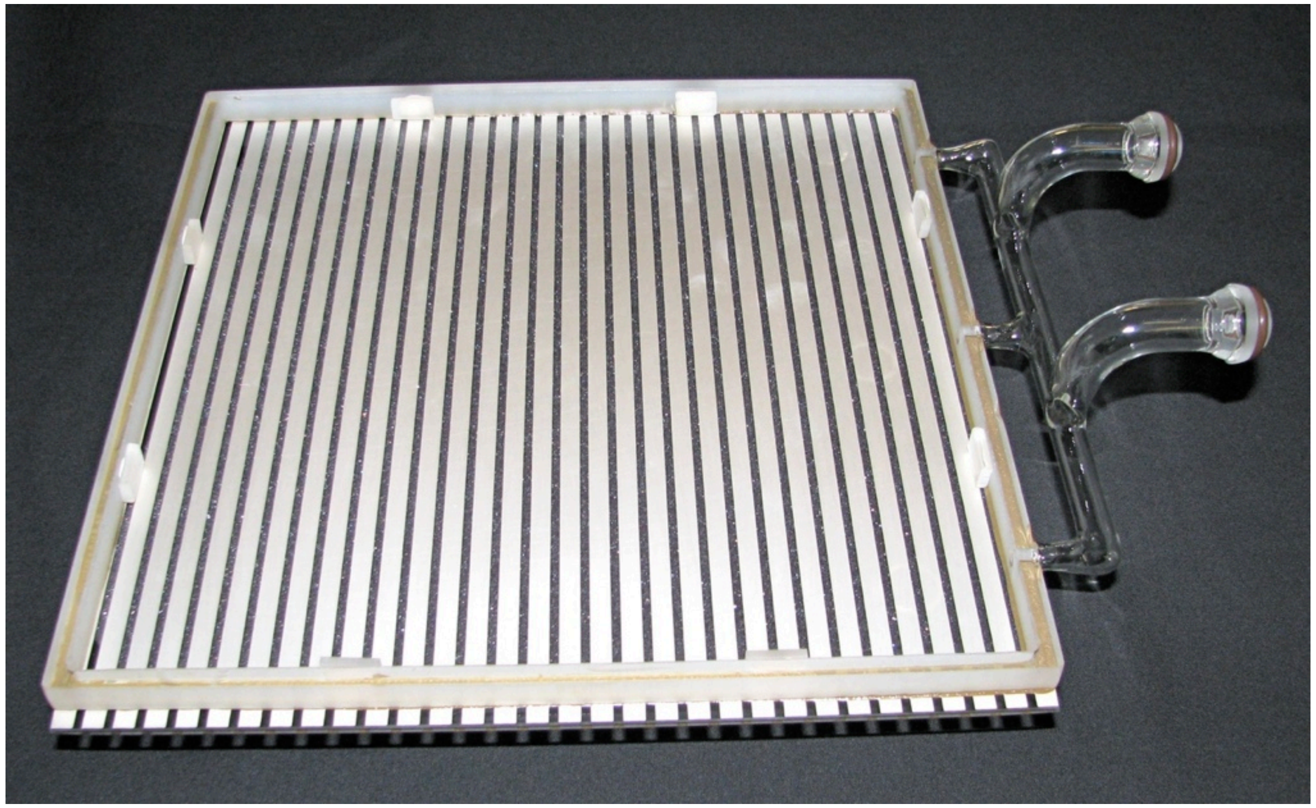
Multiple plates to increase gain

Chevron arrangement to inhibit positive ion freeback to photocathode

MCP-PMT Module & Readout Concept



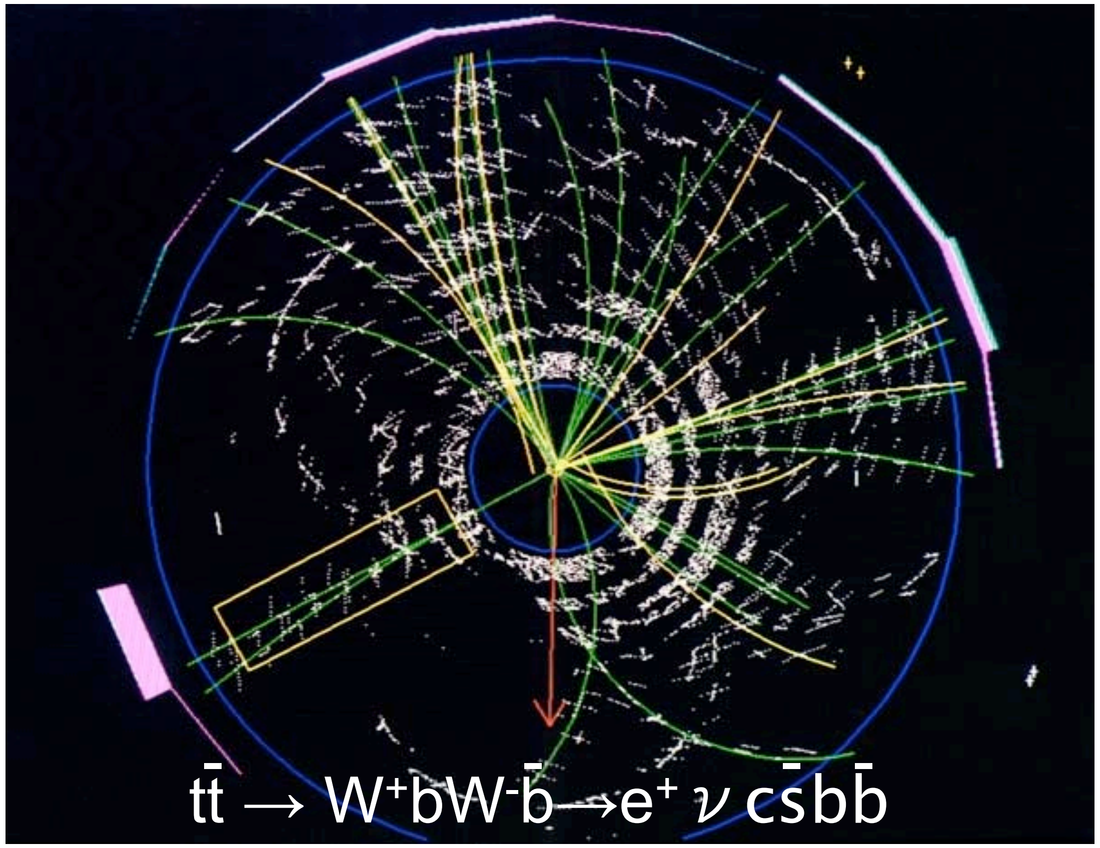
2×3 array of MCP Tiles for paneling detector, e.g. water Cherenkov tank



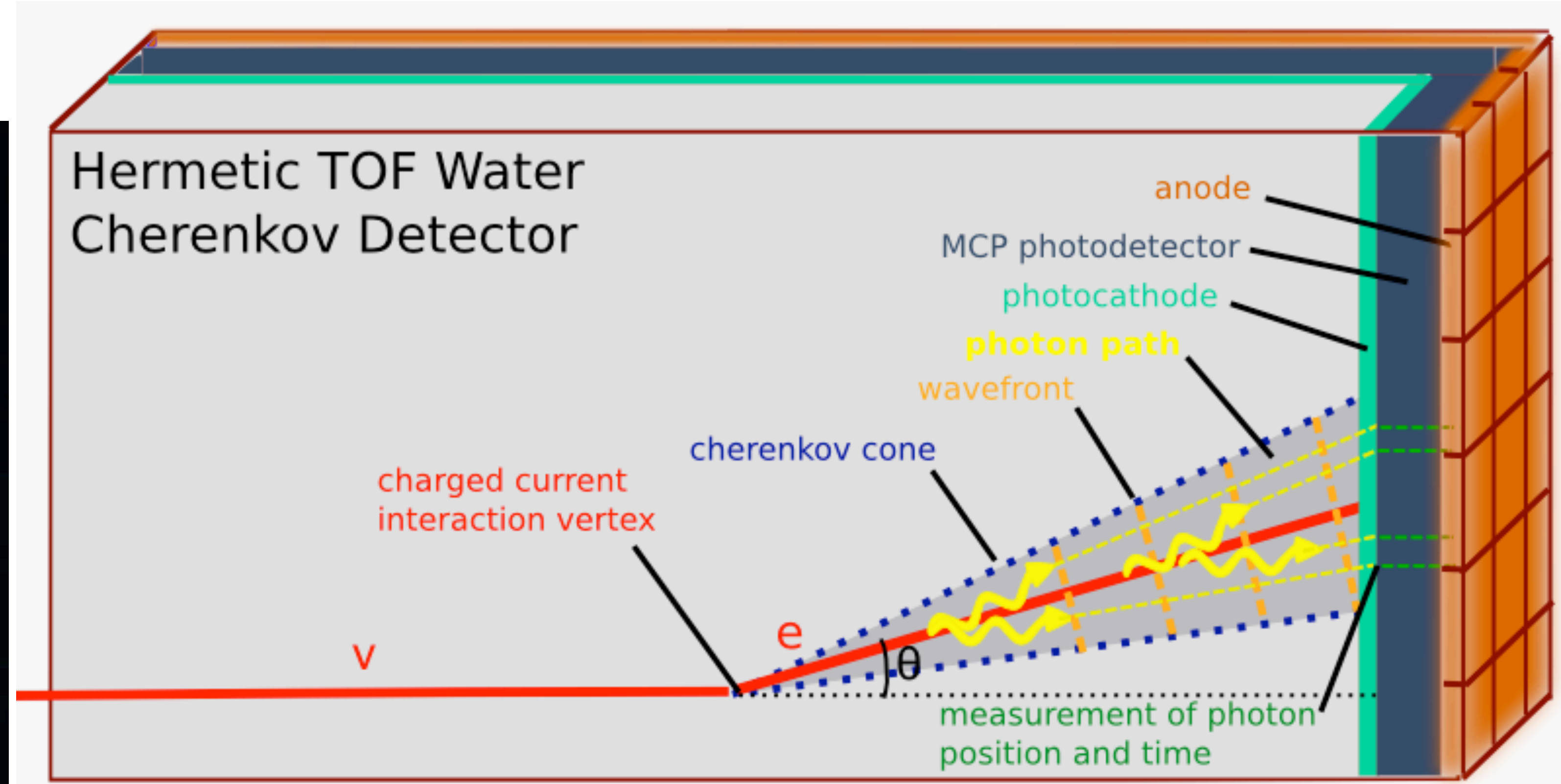
Strip readout pattern
3.8mm strips, 5mm pitch (40 strip anode)
4.6mm strips, 6.8mm pitch (30 strip anode)
Coordinate readout:

- Time difference along strip
- Charge division for ⊥ direction

Motivation



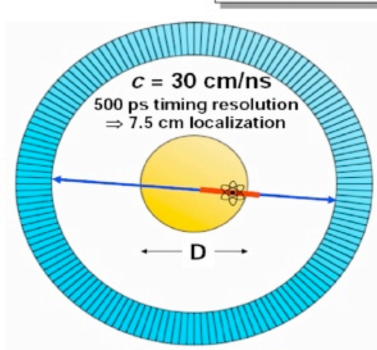
Complete particle measurement: E, p + m(PID)
1ps time & 1mm space resolution, \$100k/m²



Water Cherenkov neutrino detector (LBNE) ~80-90% coverage and 3-d photon vertex reconstruction
100ps time & 10mm space resolution, \$10k/m²

Bill Moses (LBNL)
Large Area Picosecond Photodetector Workshop, Clermont-Ferrand, Jan 2010

Time-of-Flight in PET



- Can localize source along line of flight.
- Time of flight information reduces noise in images.
- Variance reduction given by $2D/c\Delta t$.
- 500 ps timing resolution ⇒ 5x reduction in variance!

- Time of Flight Provides a *Huge* Performance Increase!
- Largest Improvement in Large Patients

TOF (Effective Efficiency) Gain for Whole-Body PET (35 cm)

Hardware	Δt (ps)	TOF Gain
BGO Block Detector	3000	0.8
LSO Block (non-TOF)	1400	1.7
LSO Block (TOF)	550	4.2
$LaBr_3$ Block	350	6.7
LSO Side Coupled	250	9.3
LSO Small Crystal	210	11.1
LuI_3 Small Crystal	125	18.7
$LaBr_3$ Small Crystal	70	33.3

- *Incredible* Gains Predicted
- *Nothing* Else Can Give Us Gains of This Size!

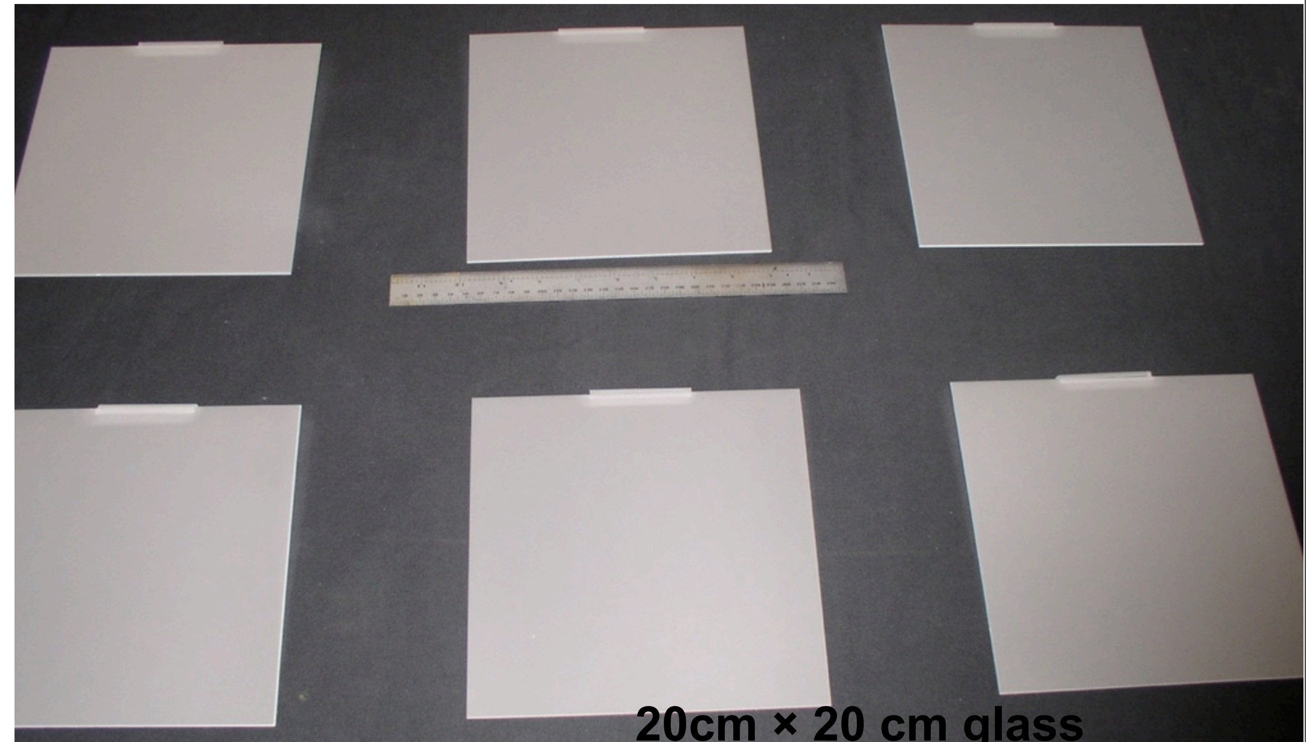
LAPPD Project Scope

Large, Cheap, Fast Microchannel Plate Photomultiplier

- 20×20 cm^2 active area (development on 3.3cm diam. disk)
- Novel, inexpensive MCP substrate
  - Borofloat glass capillary substrates (20-40μm pores, L/D ~60-40)
  - Anodic aluminum oxide (AAO) (research ended) -- ceramic
- Pore activation via Atomic Layer Deposition (ALD)
  - Separate material for resistive and secondary emission layers
  - Optimize resistive and emissive layers via study of range of materials
- Customized anode readout
  - Strip line double-ended readout for picosecond timing & water Cherenkov
  - Pad readout for energy and/or coarse spatial resolution -- gamma-ray telescope camera, dual readout calorimeters, medical imaging
- High quantum efficiency photocathode --- ≥25%
  - Bialkali (baseline), multialkali
  - "III-V" materials, e.g. GaAs, GaN
  - Systematic program of photocathode development and analysis
- Waveform sampling switched capacitor array ASIC for readout
- Use simulation to vet and tune design

Glass Capillary Substrate Development

- Borosilicate glass capillary substrates from Incom, Inc. (Charlton, MA, USA)
- Technology development on 32.8mm diameter disk substrates
  - 20μm (L/D=60) & 40μm (L/D=40) pore size
- 20cm × 20cm plates for working detector
  - (18) 40μm pore substrates delivered
  - (35) 20μm pore substrates delivered
  - Baseline is 20μm pore
- All substrate pores have 8° bias w.r.t axis ⊥ to substrate
  - Used in pair chevron configuration to reduce positive ion feedback damage to photocathode



20cm × 20 cm glass substrates October, 2011

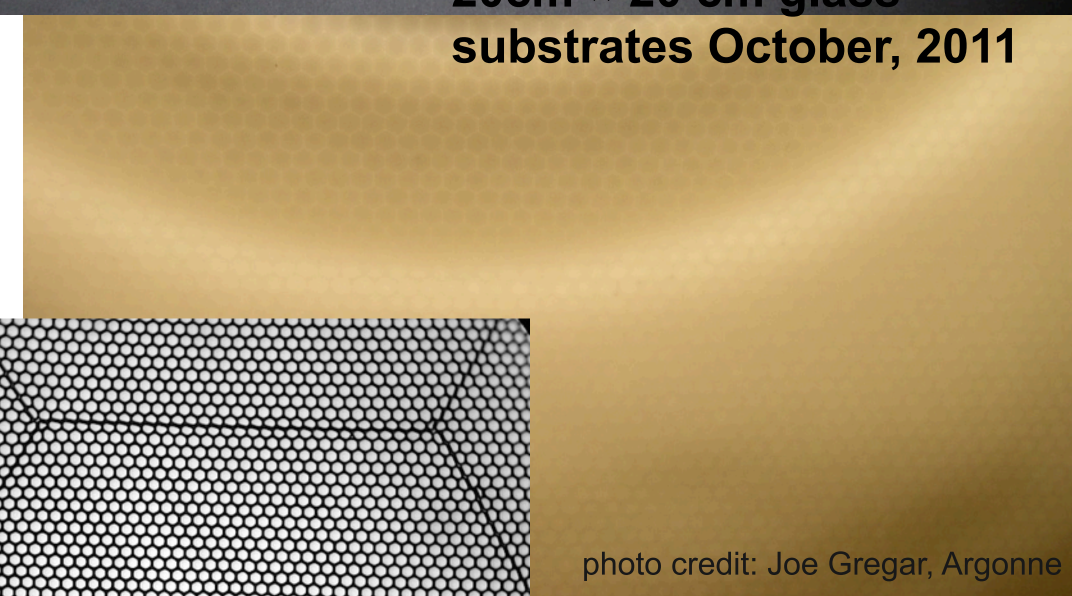
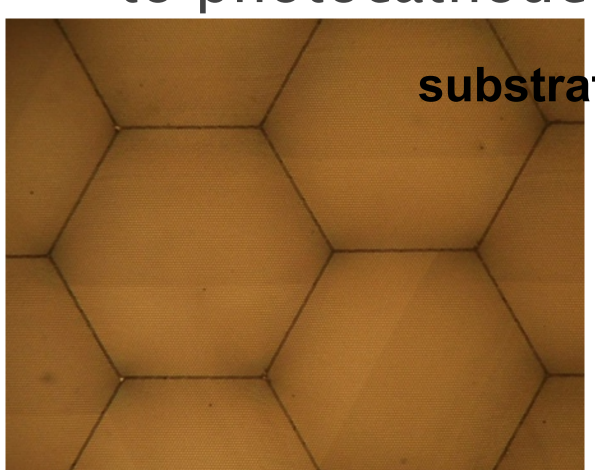
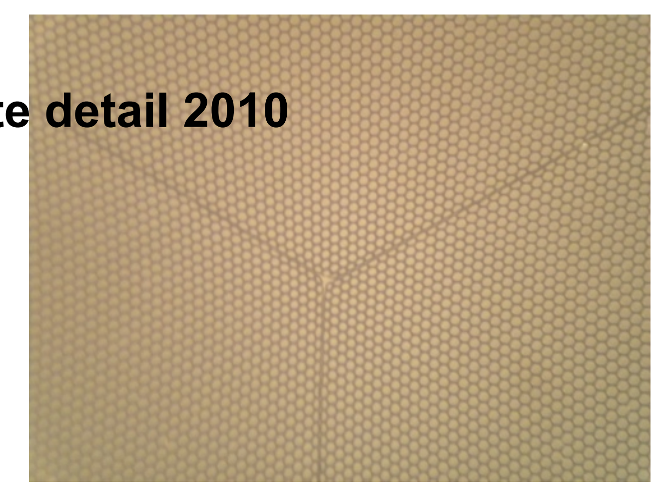
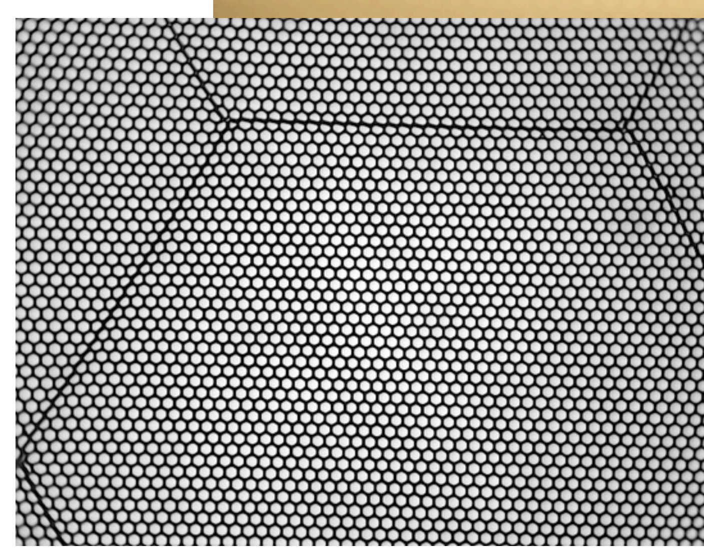


photo credit: Joe Gregar, Argonne





substrate detail 2010



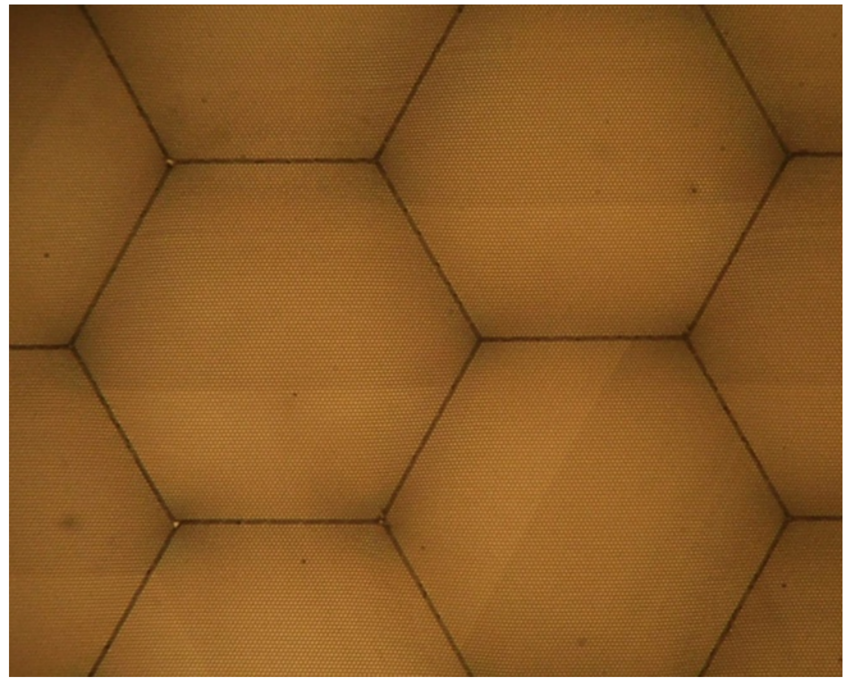
substrate detail August, 2011

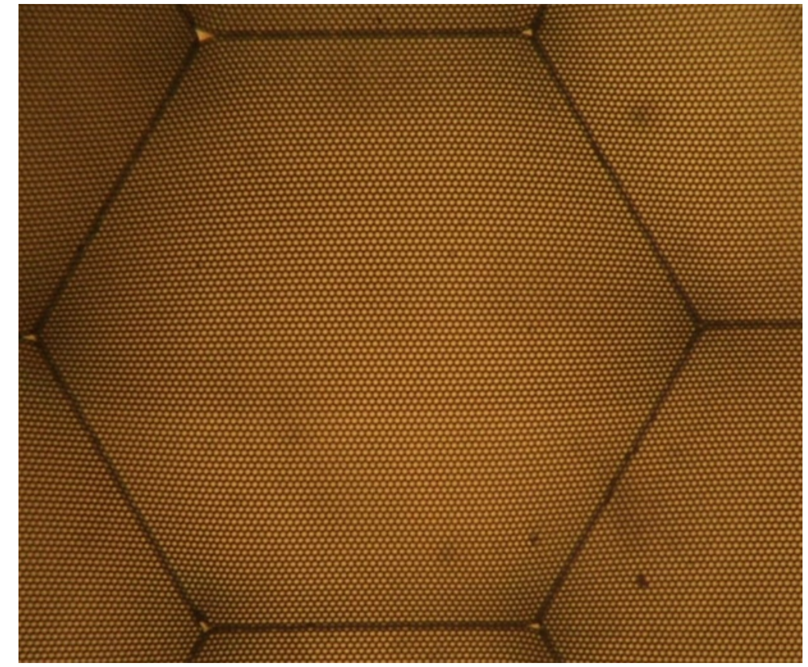
photo credit: Jason McPhate, SSL

Advances in Glass Capillary Array Development

1st Batch vs. Present Batch 20μm pores

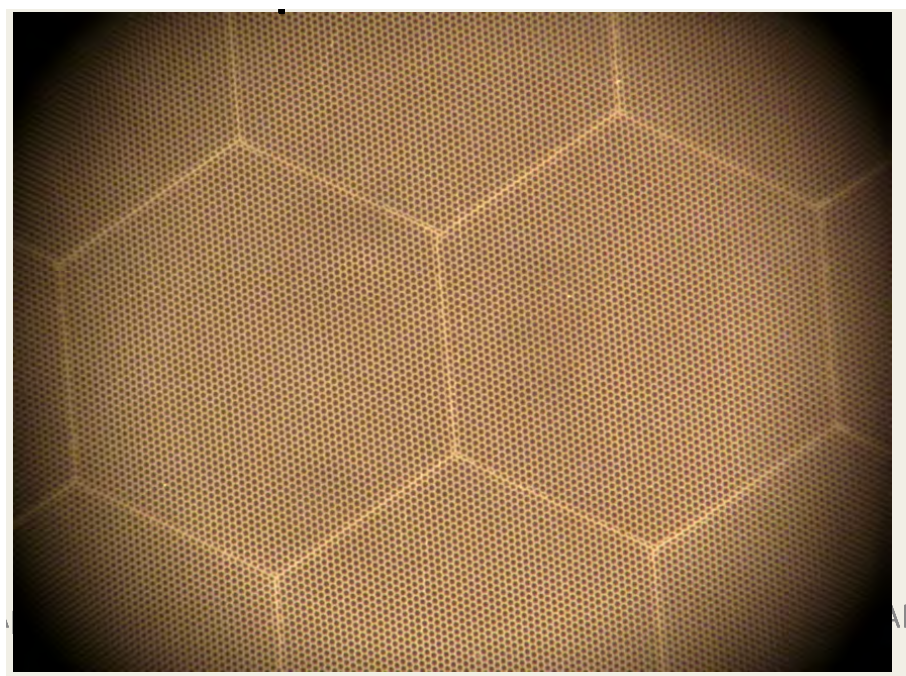
- Multifiber stacking evident
- Triple point gaps
- Pore crushing at multifiber boundaries

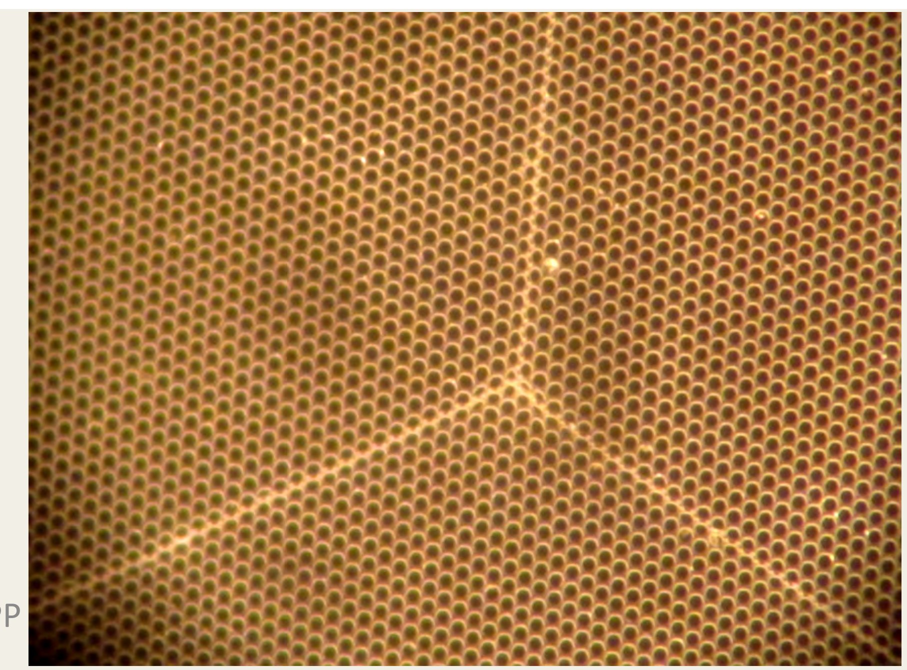




Batch 1

- Triple point gaps eliminated
- Minimal pore distortion
- Still some stacking issues





Batch 2

Commercial Microchannel Plate Fabrication

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

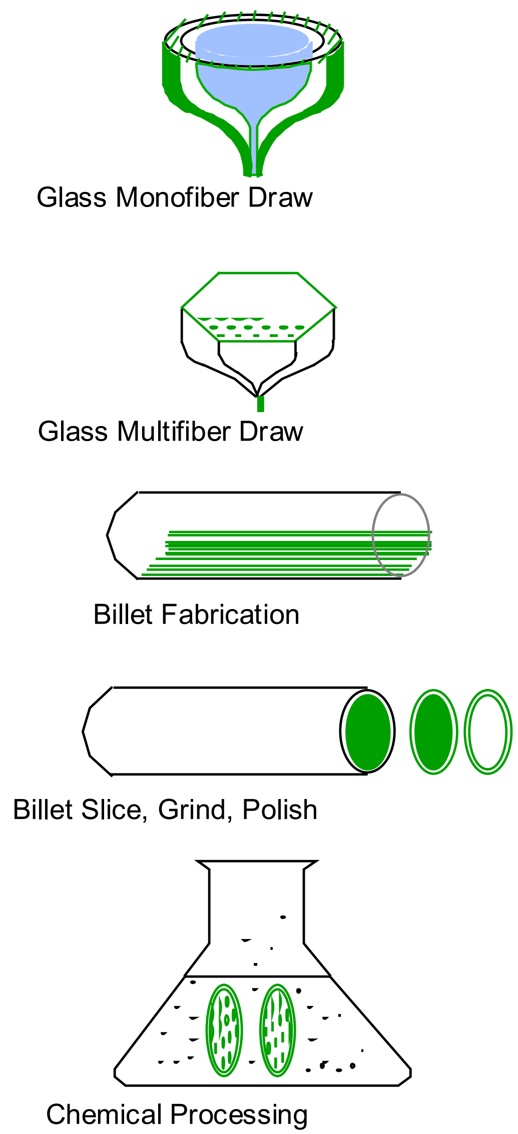
Glass is gravity-fed via cylindrical furnace

Glass is typically lead glass tube with solid soft glass core

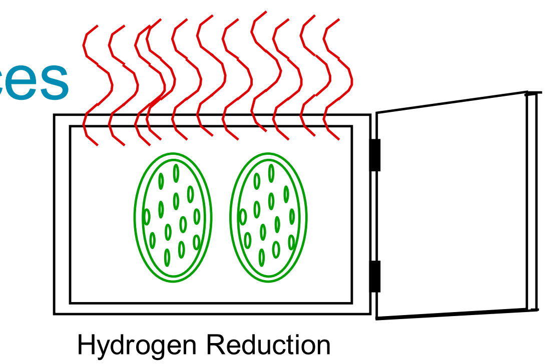
Borosilicate glass capillaries are hollow core

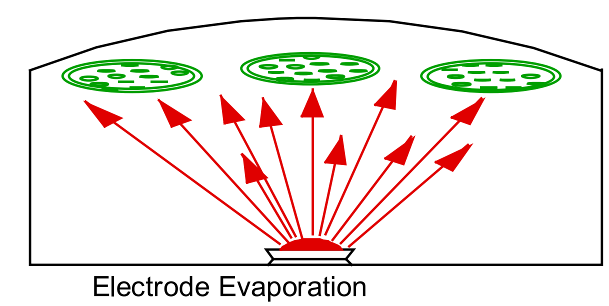
Chemical processing to remove soft core glass

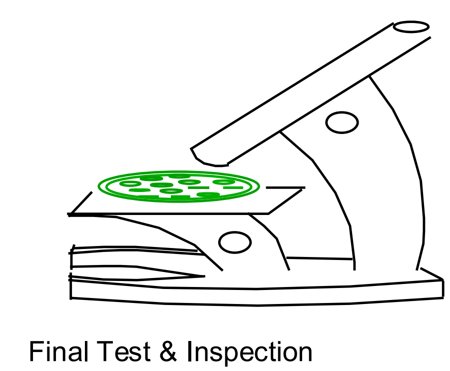
hollow core glass capillaries skip this step



ALD replaces this step



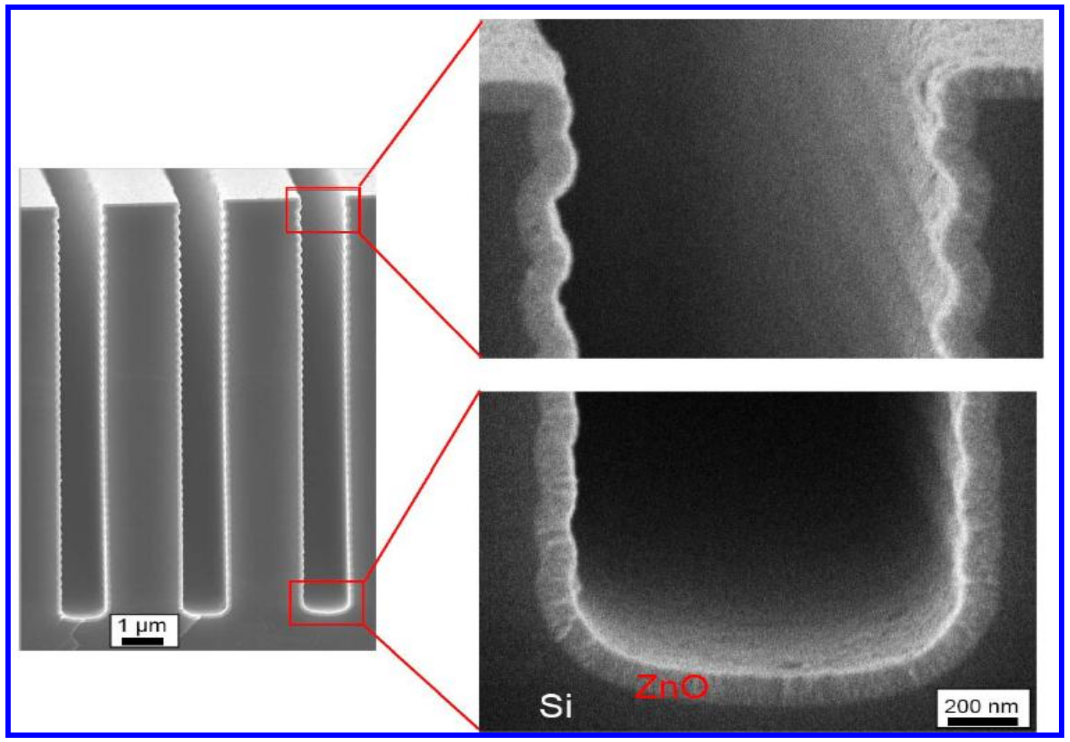


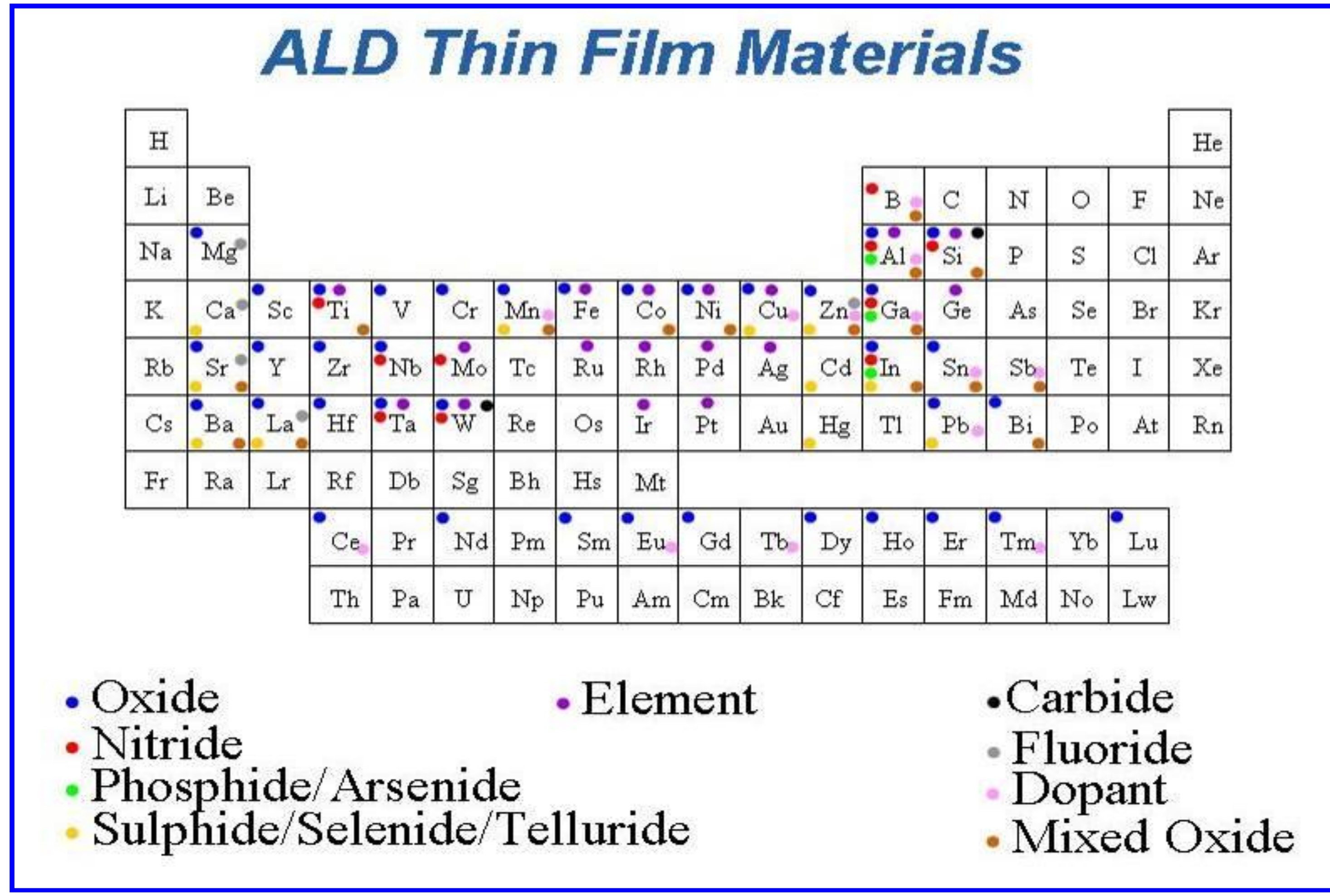


Before sealing in tube, plate must be subjected to prolonged exposure to electrons at low voltage to outgas H_2 and other material

ALD process greatly reduces scrub time (to zero?)

Pore Activation via Atomic Layer Deposition



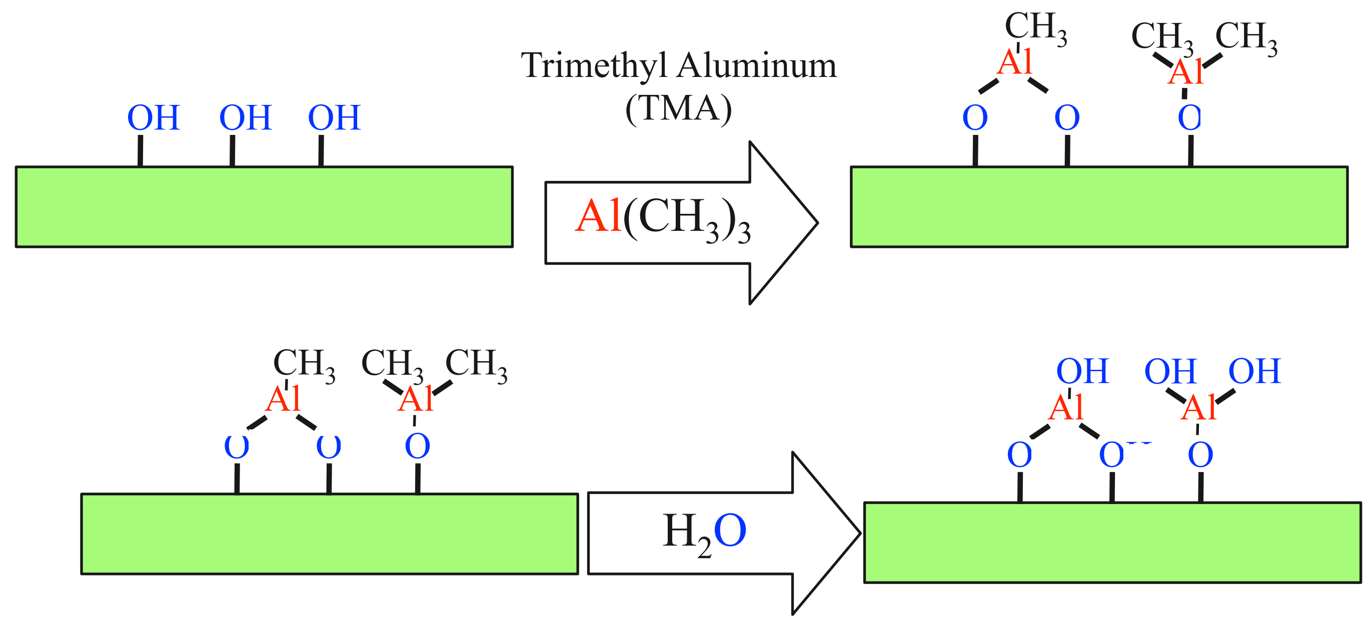


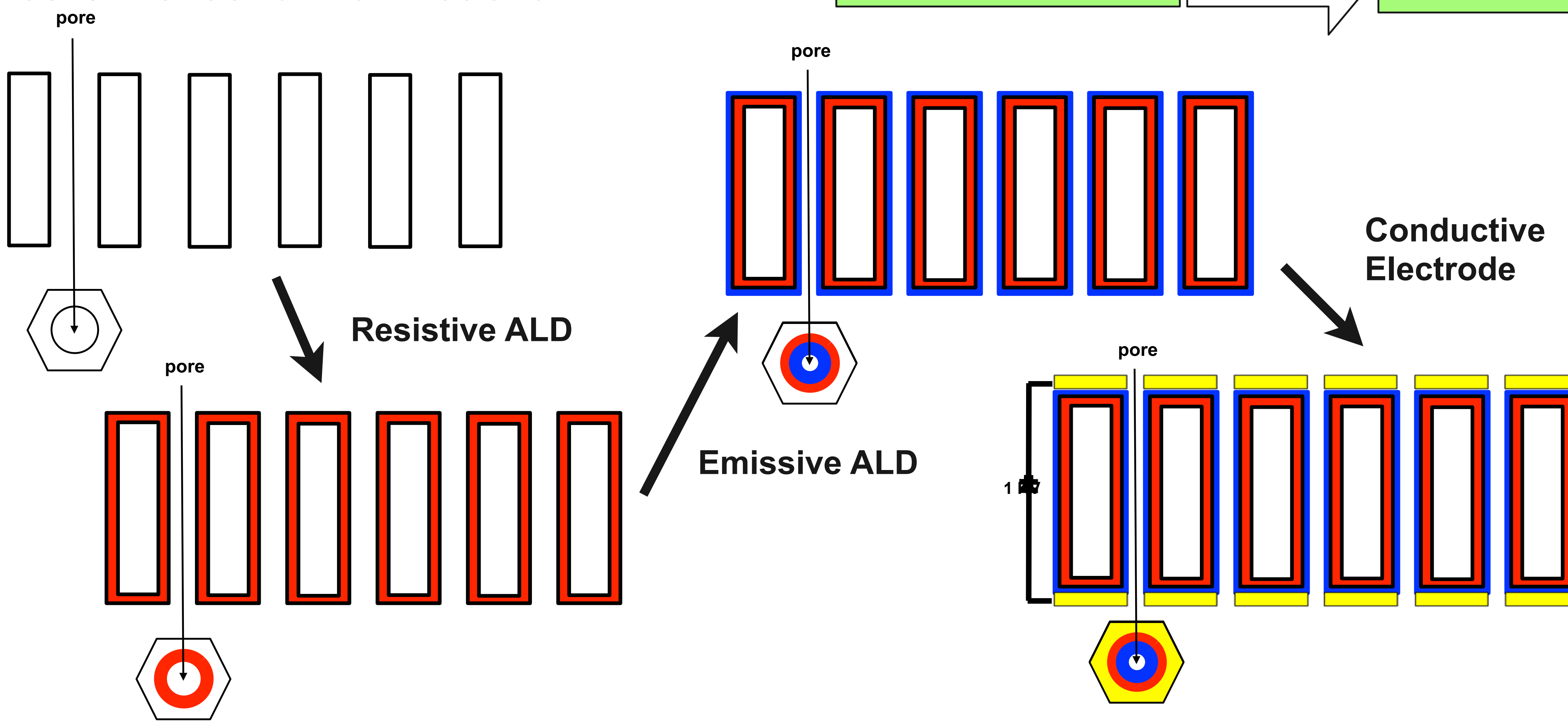
- Conformal, self-limiting process
- Molecular mono-layer thickness control
- Large variety of applicable materials

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

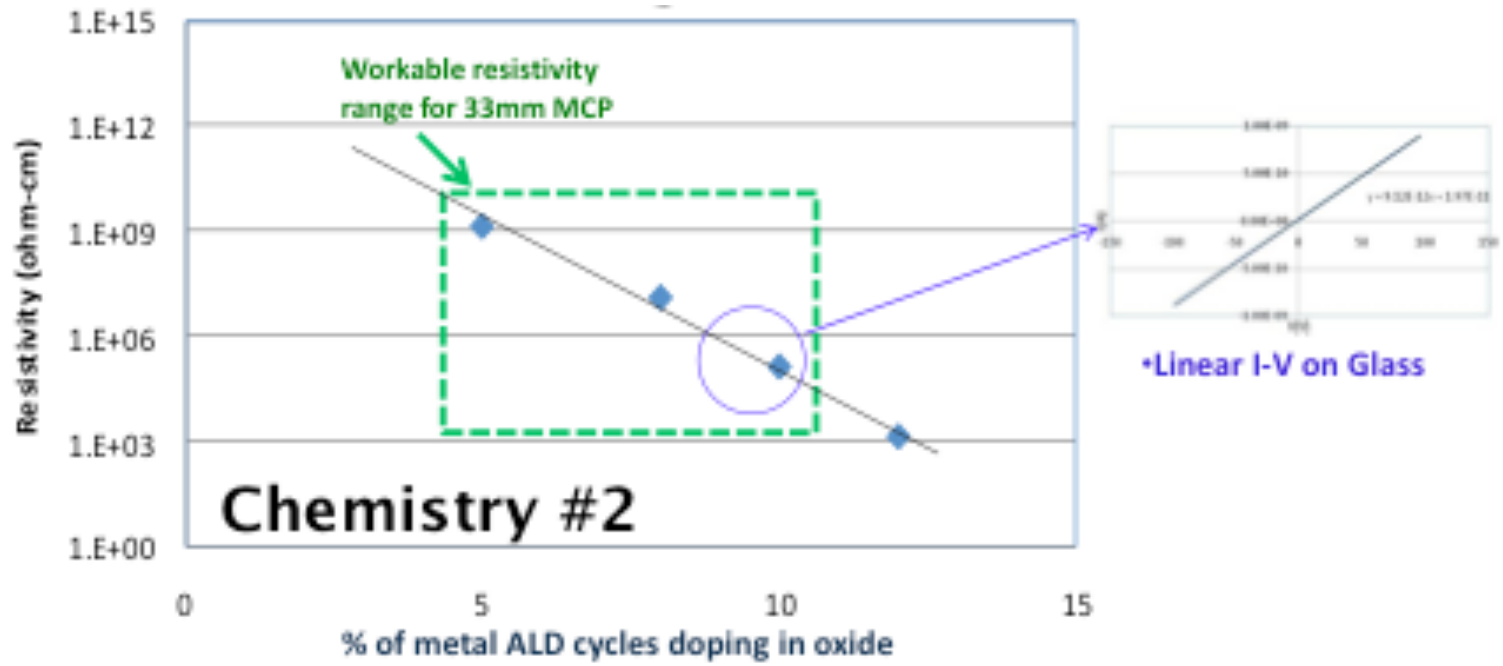


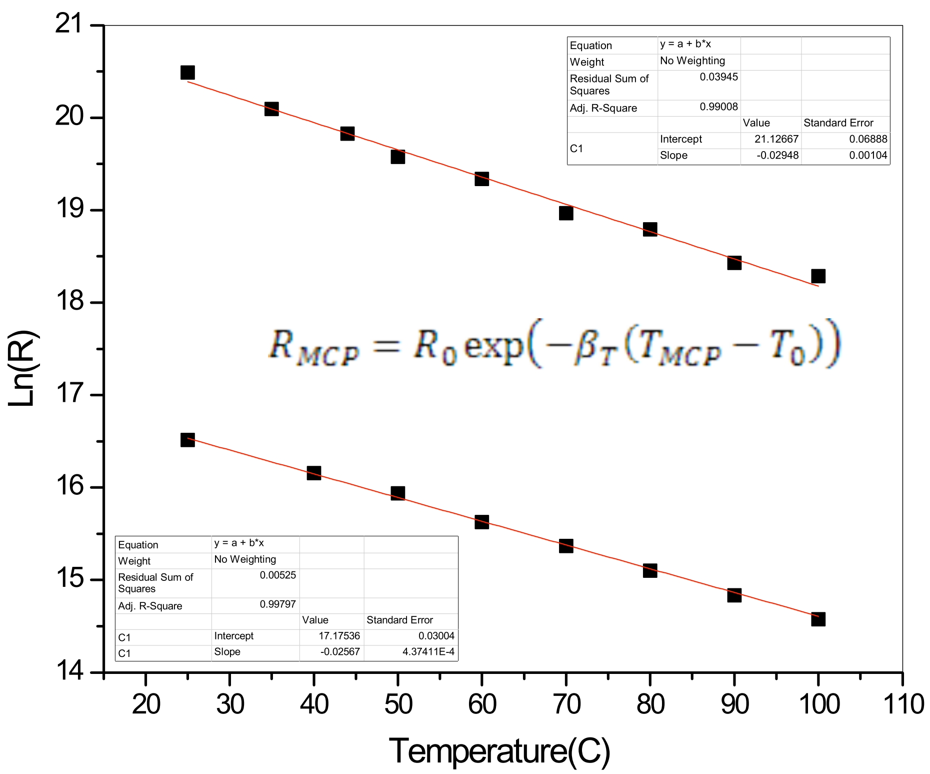


ALD Functionalization of Micro-Channel Plates

New ALD chemistries for resistive coating developed at Argonne

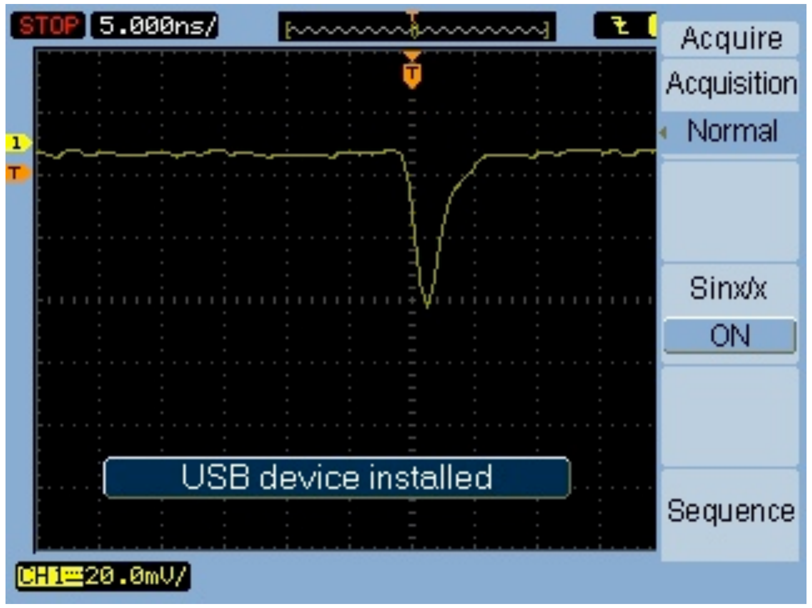
Resistance is reproducibly tunable





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

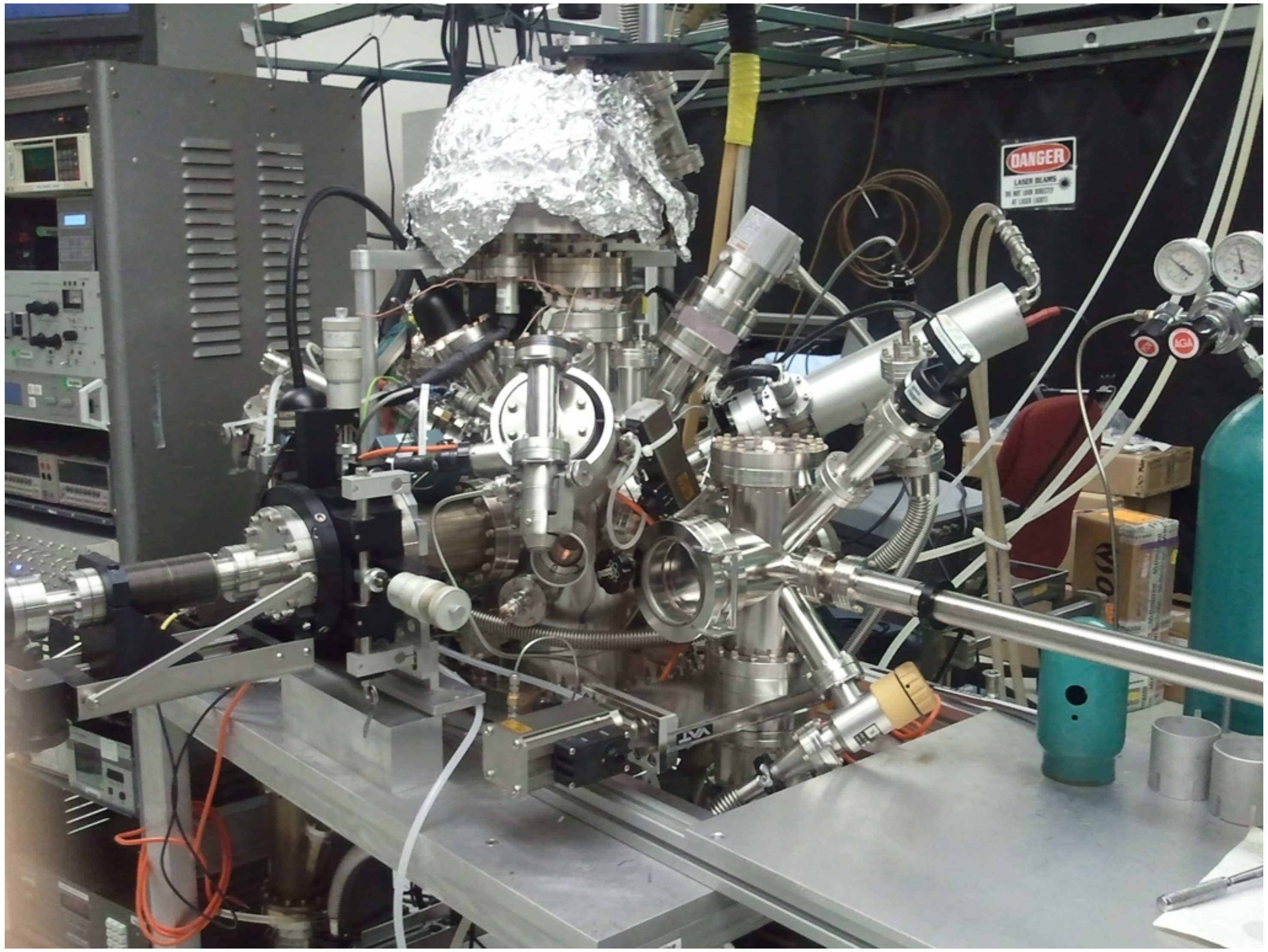
Al_2O_3 Secondary Emission Layer

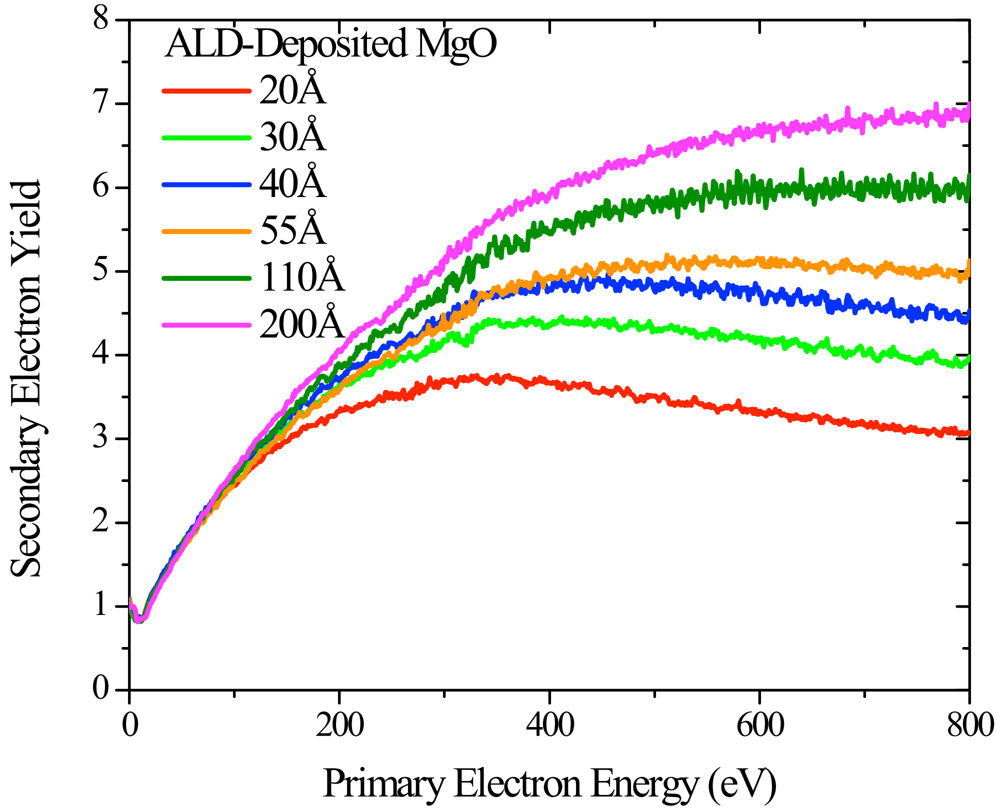


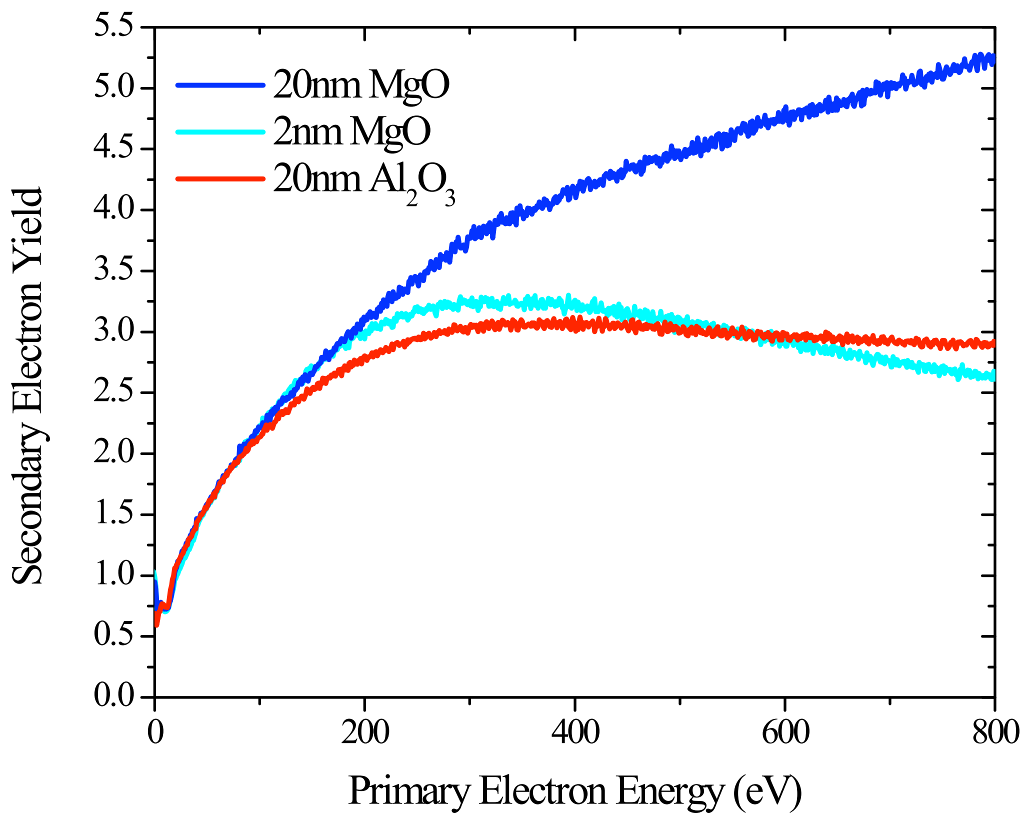
Signal from MCP pair coated with new resistive layer + Al_2O_3 emissive layer

image credit: M. Wetstein

Secondary Emissive Materials Characterization







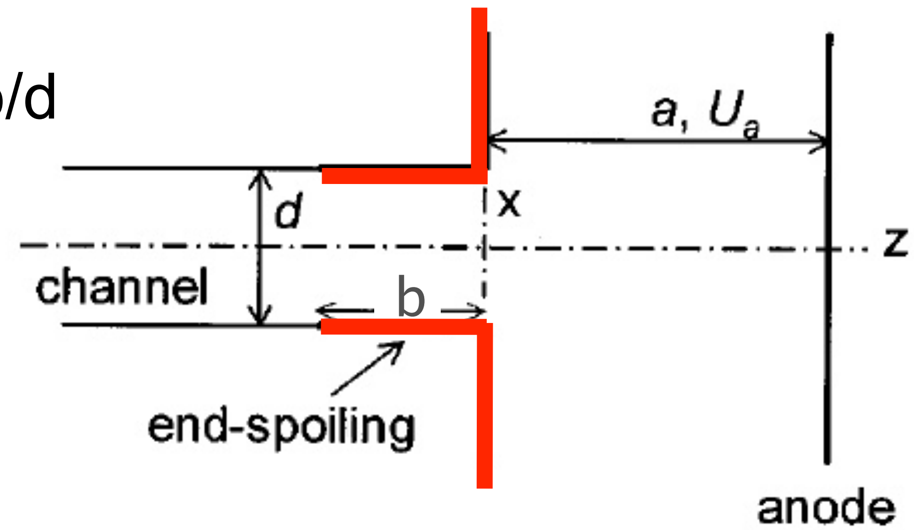
Characterization Chamber

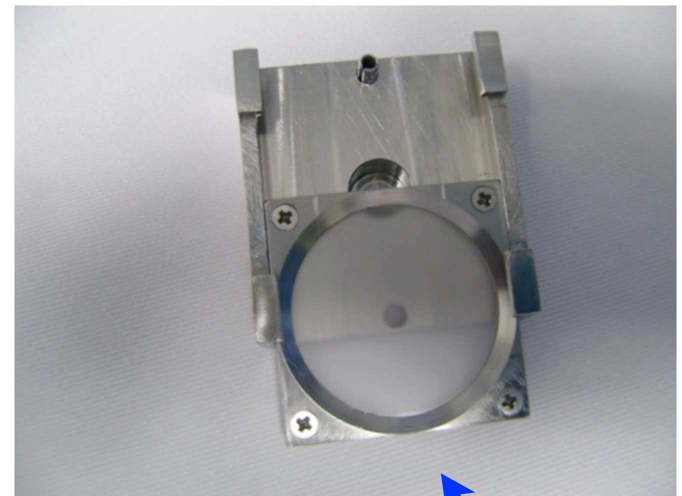
- UV Photoelectron Spectrometer
- X-ray Photoelectron Spectrometer
- Low Energy Electron Diffraction

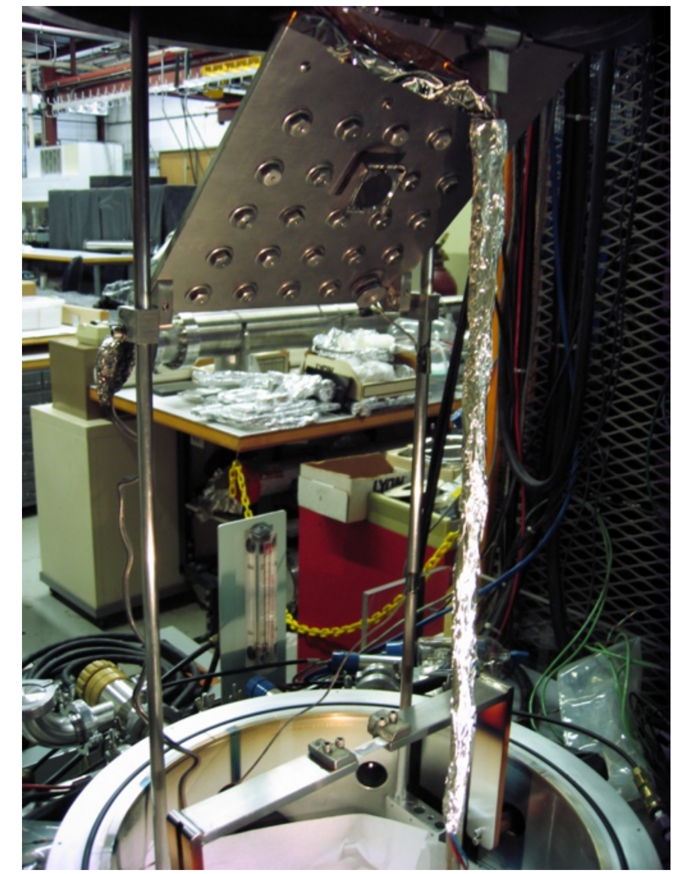
Electroding - End Spoiling

Electroding system at Fermilab for 33mm MCPs

$h = b/d$



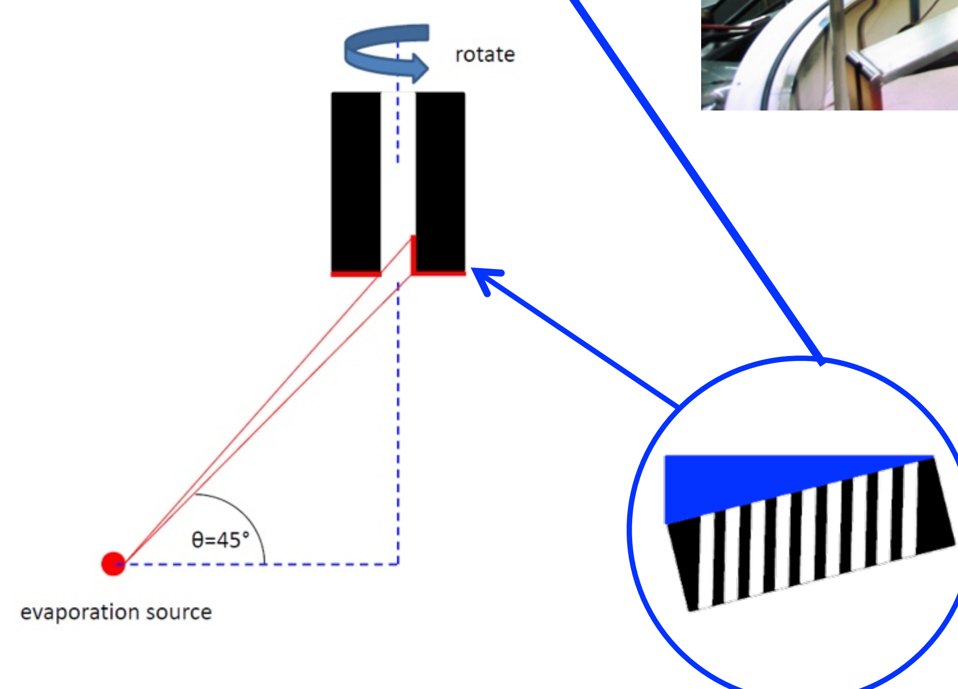




End-spoiling on output

- Increases spatial resolution
- Decreases gain
- Trade-off h = 1-2

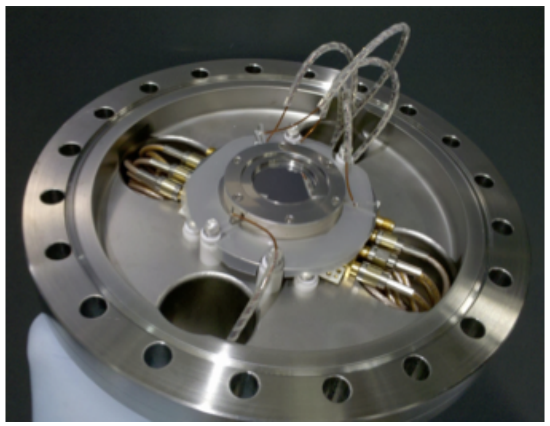
Line-of-sight evaporation

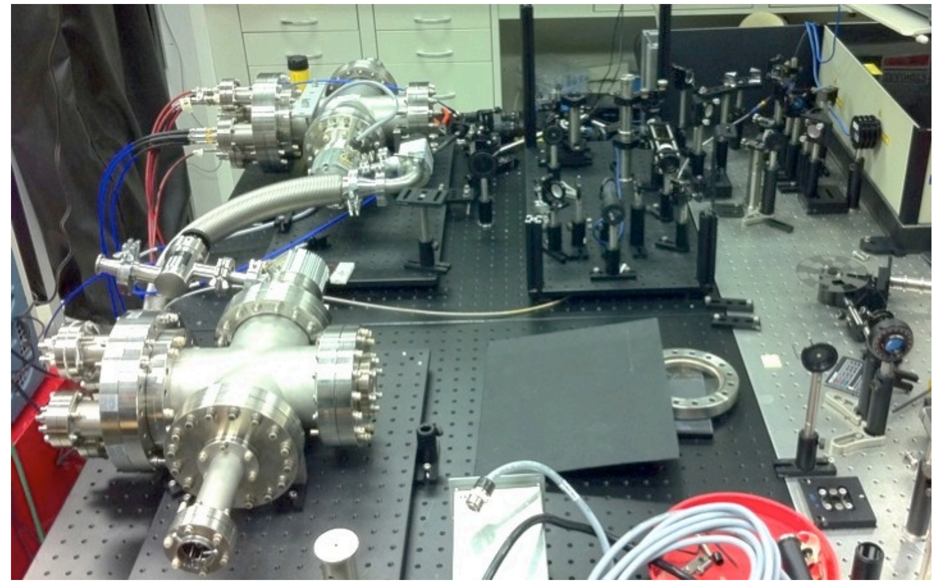


End-spoiling on input ~ h = 0.5-0.8

Electroding system for 8”×8” MCPs nearing completion

MCP Testing at Argonne -- APS UV Laser Facility

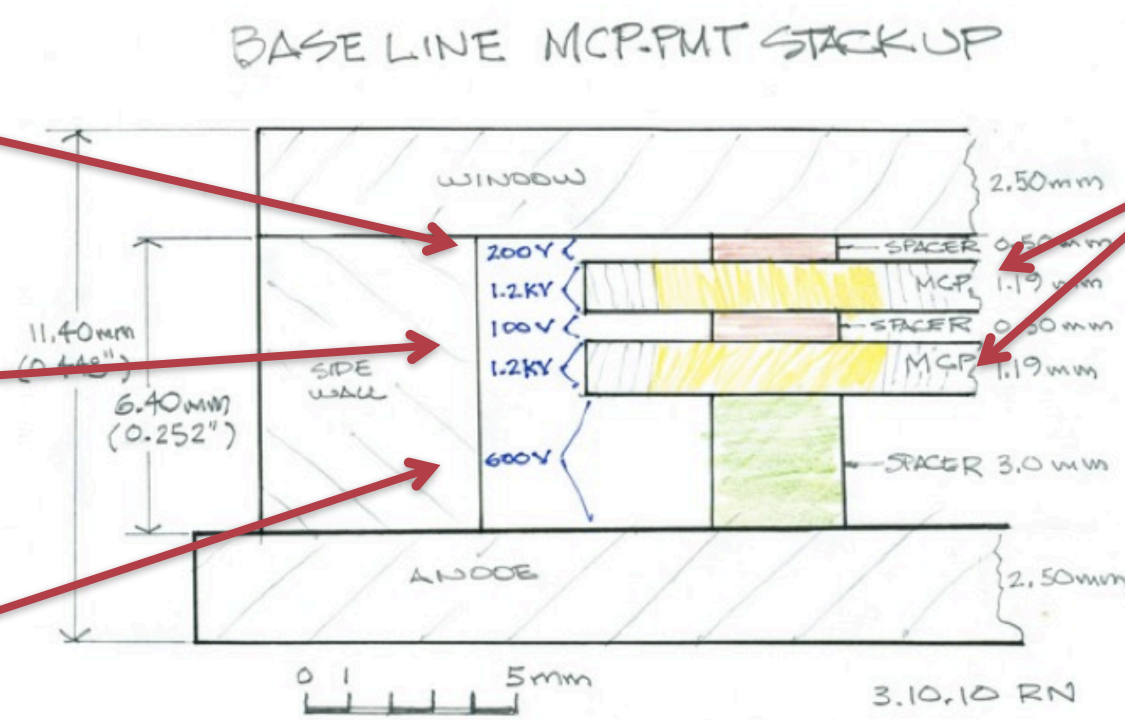




Gap 1: "first strike" Impacts on variability of transit time and amplification

Gap 2: Impact on saturation of MCP pair, spatial spread of signal

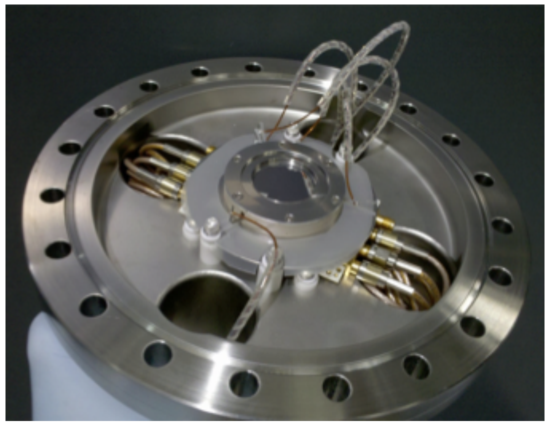
Gap 3:spatial and temporal spreading of the charge cloud. Space charge effects. Interface with anode.

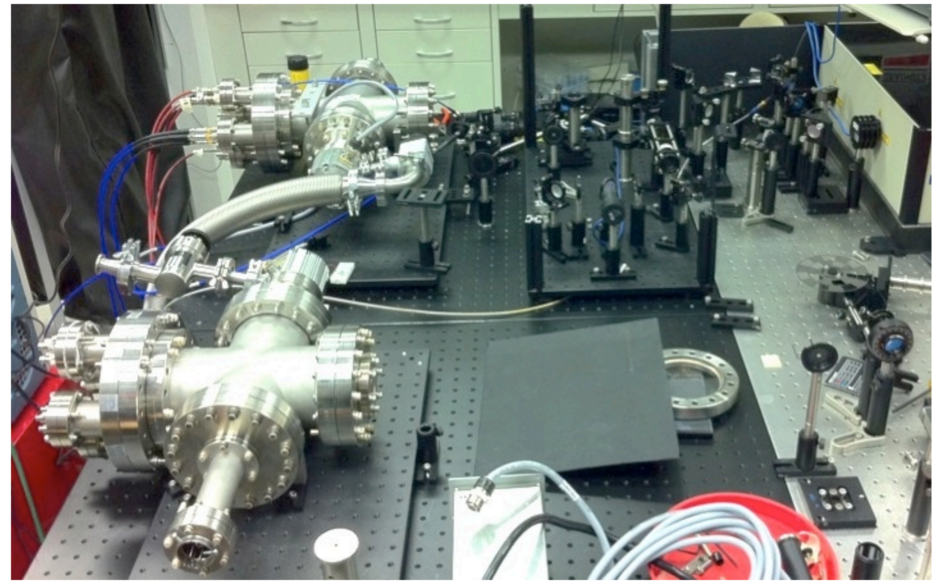


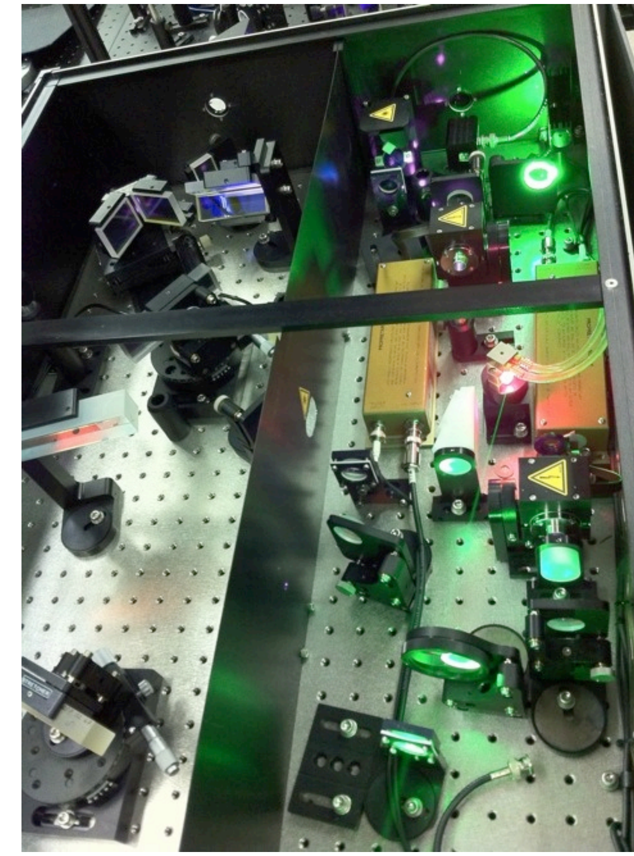
Operational voltages
Plate geometry (pore size, L/D)
Chemistry (SEE, resistive layer)
- Plate quality
- Uniformity
- Noise
- Stability

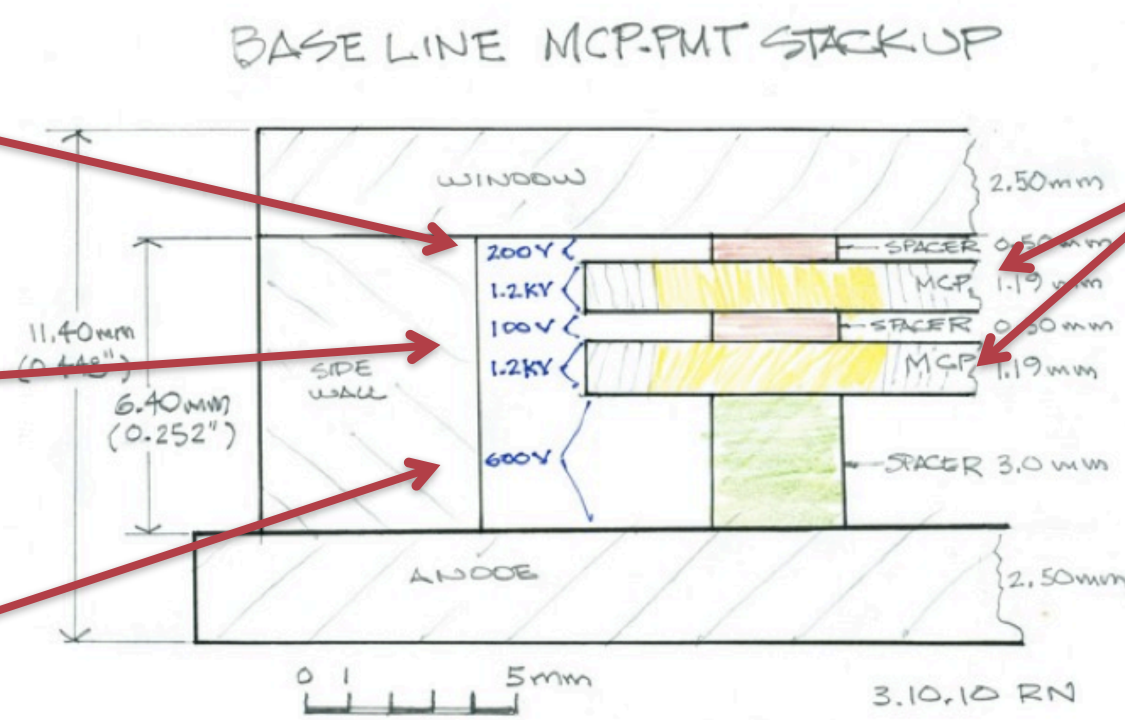
Plate resistance
- Saturation
- Relaxation time

MCP Testing at Argonne -- APS UV Laser Facility









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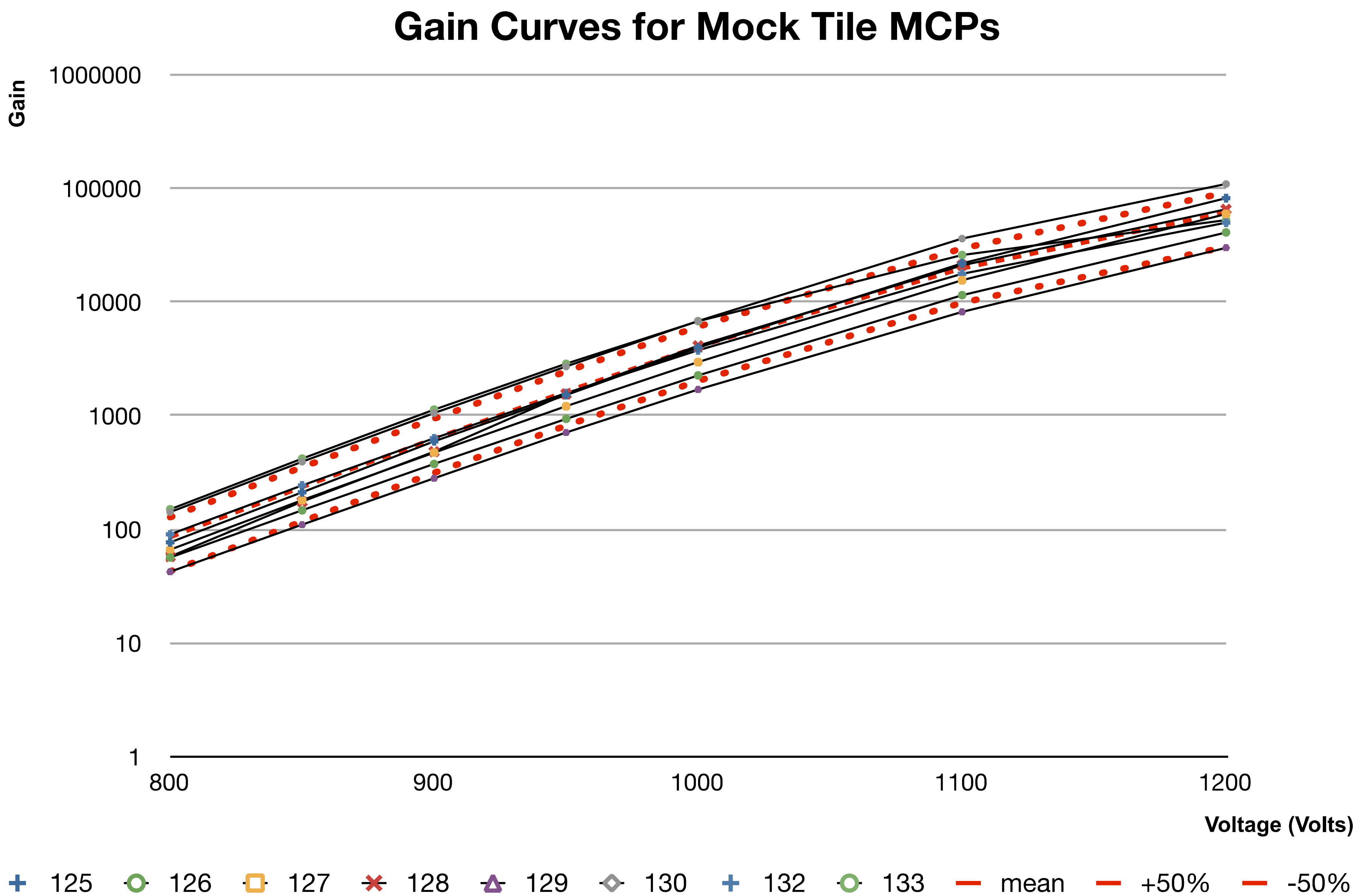
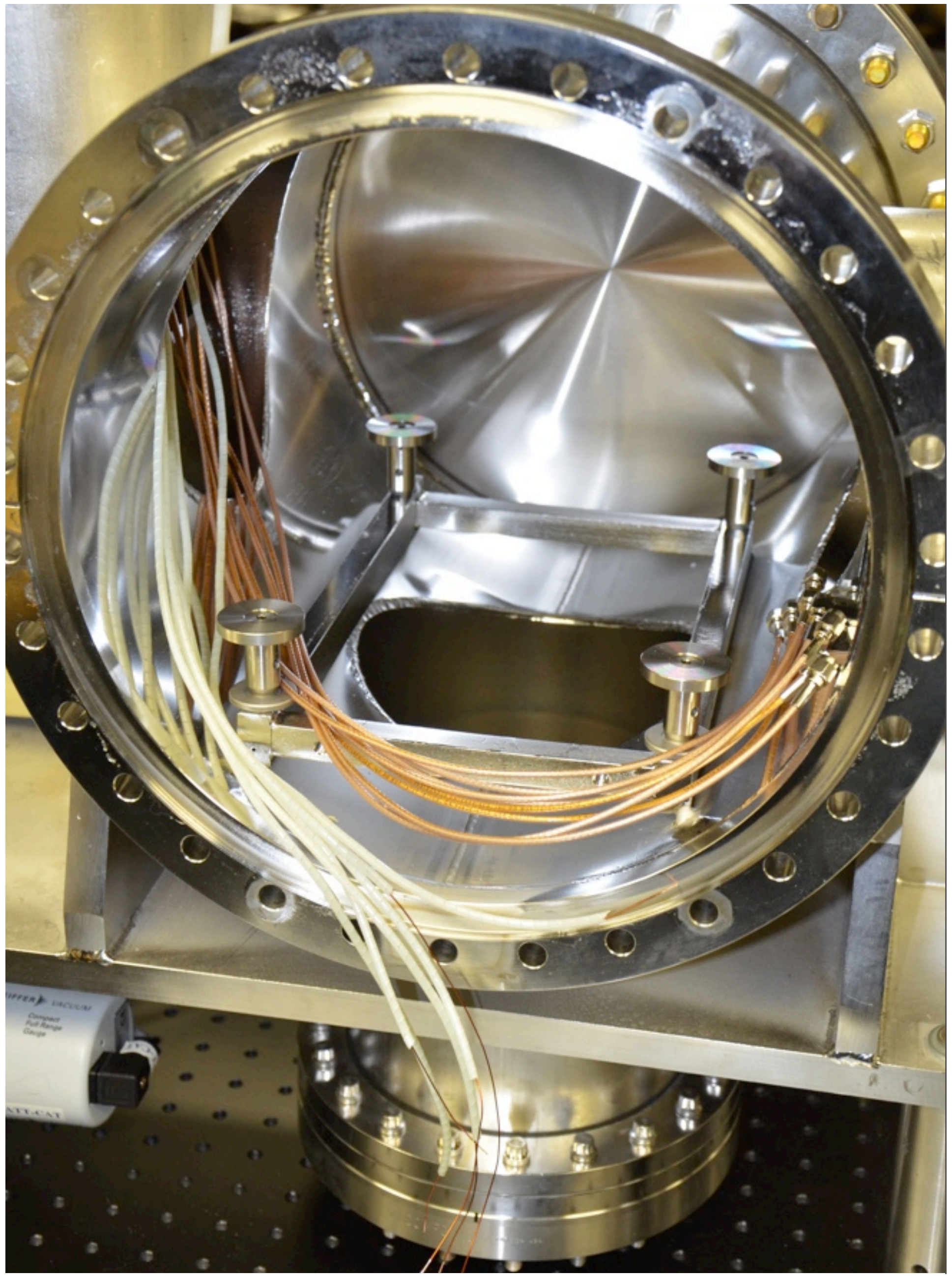
- Operational voltages
- Plate geometry (pore size, L/D)
- Chemistry (SEE, resistive layer)
  - Plate quality
  - Uniformity
  - Noise
  - Stability
- Plate resistance
  - Saturation
  - Relaxation time

MCP Testing at Argonne -- “Mock Tile” MCPs

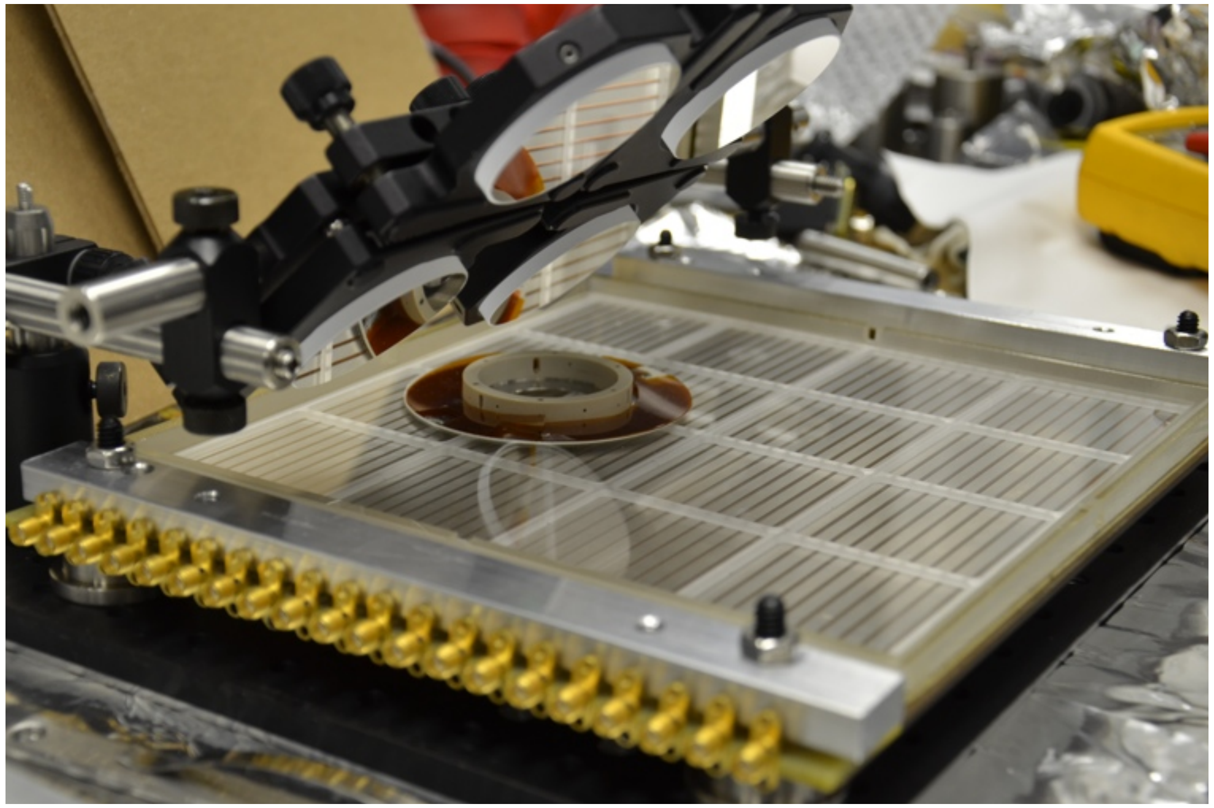


Eight 33mm MCP disks functionalized with identical “Chemistry 2” resistive coating and Al_2O_3 SEE layer

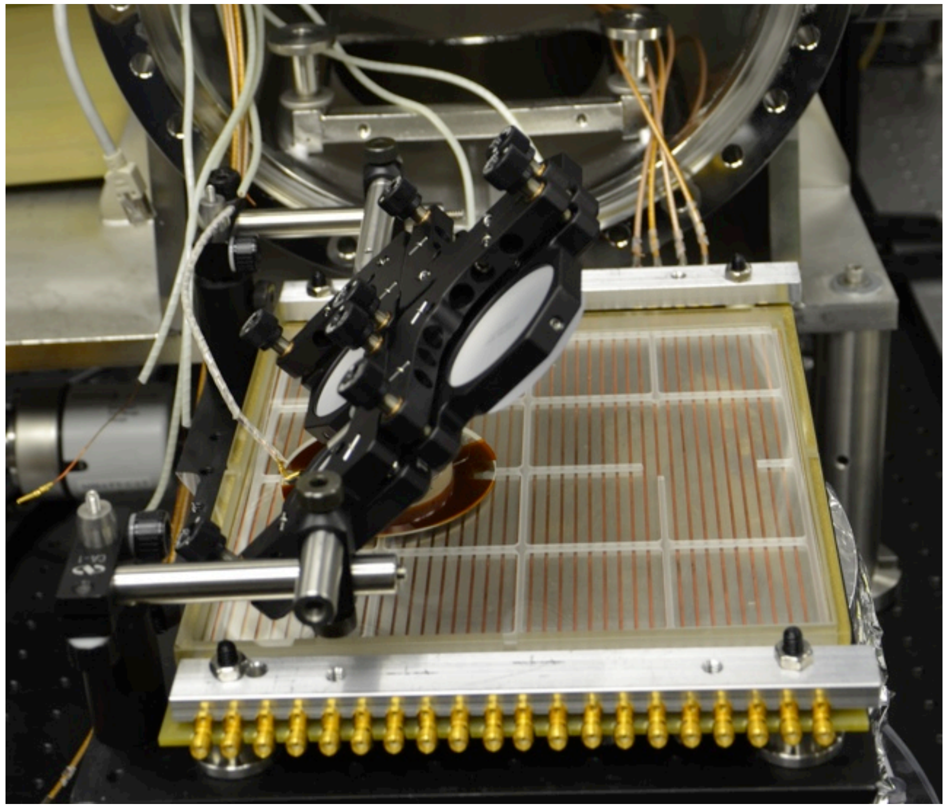
Commissioning of 8" Test Chamber at Argonne APS



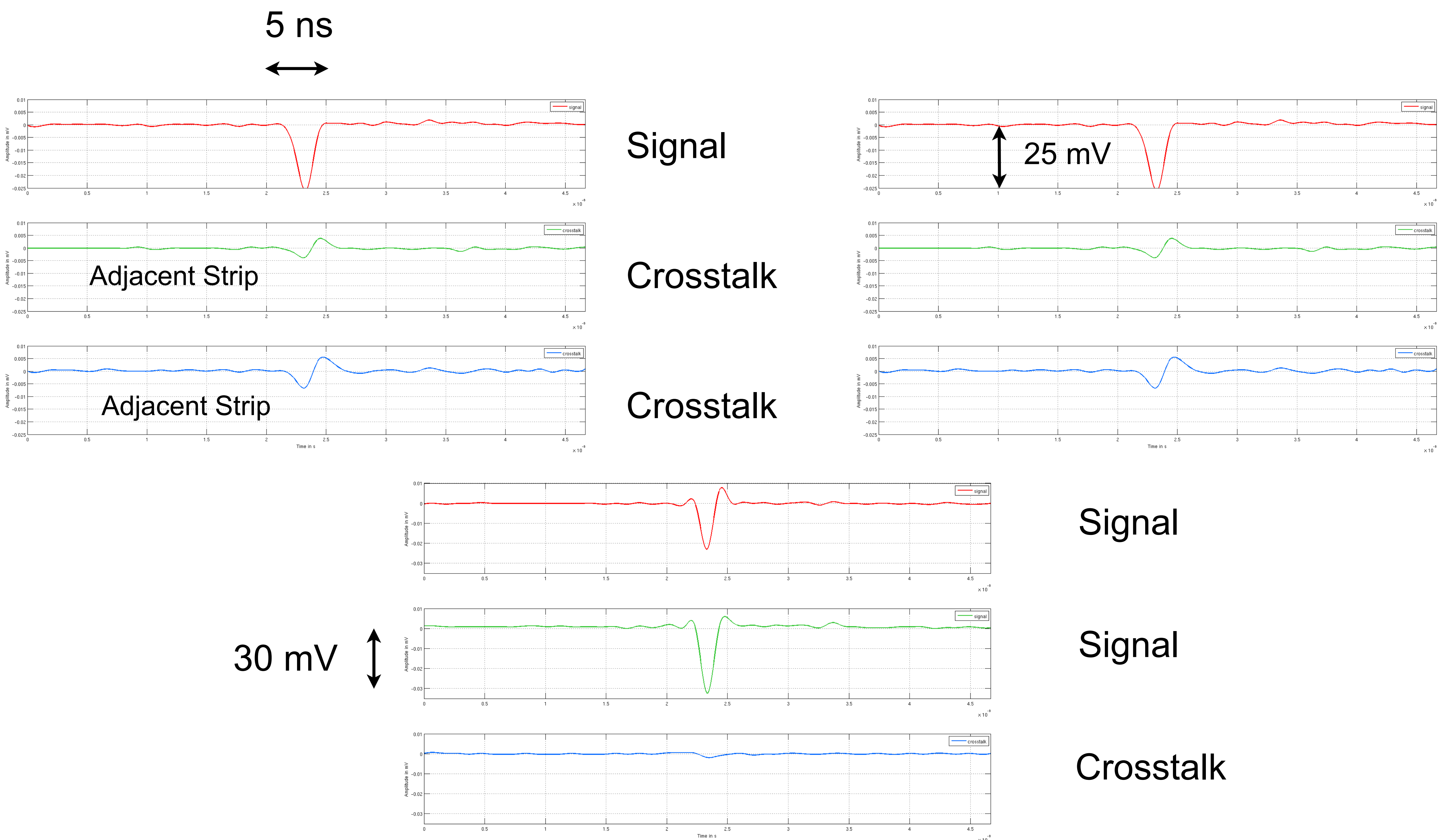
8" MCP Vacuum Test Assembly



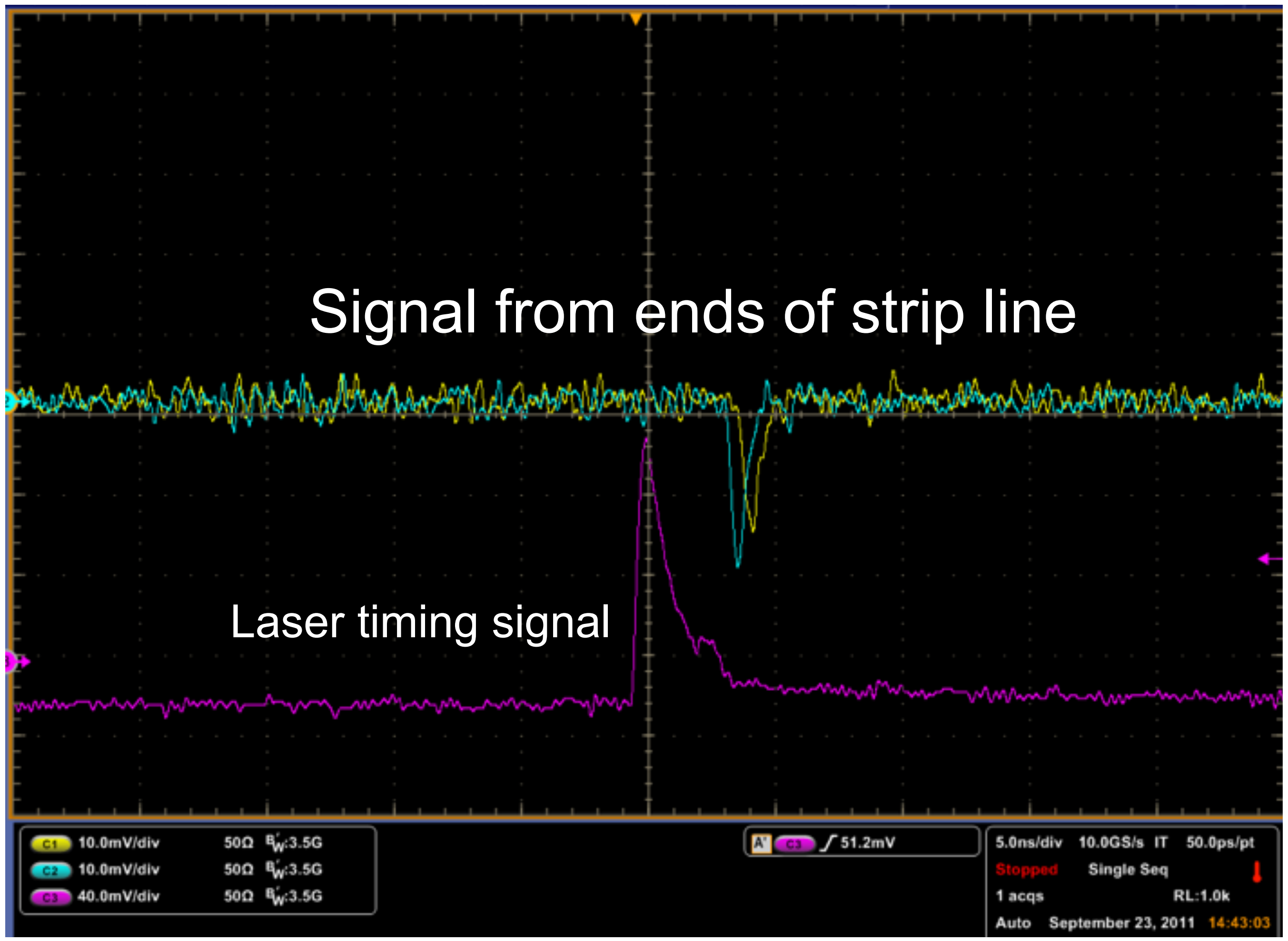
8" Tile base with 33mm MCP pair ready for insertion into chamber



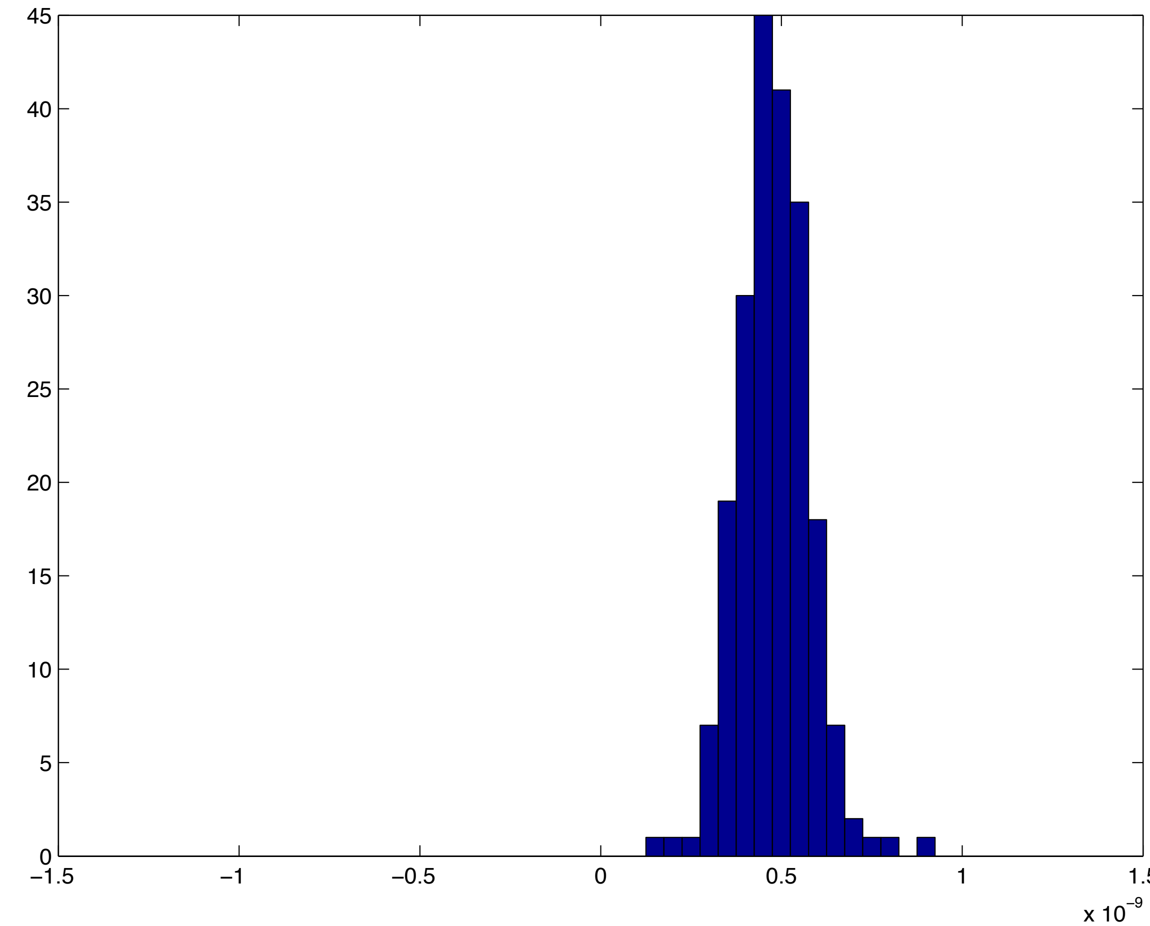
First Pulse Measurements with 8” Anode Strip Line



First Pulses on 20cm × 20cm MCP Plate



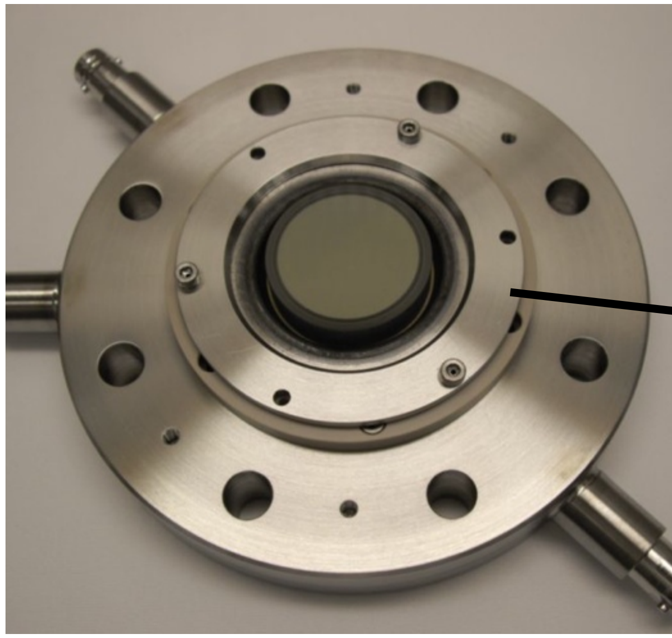
differential arrival time distribution



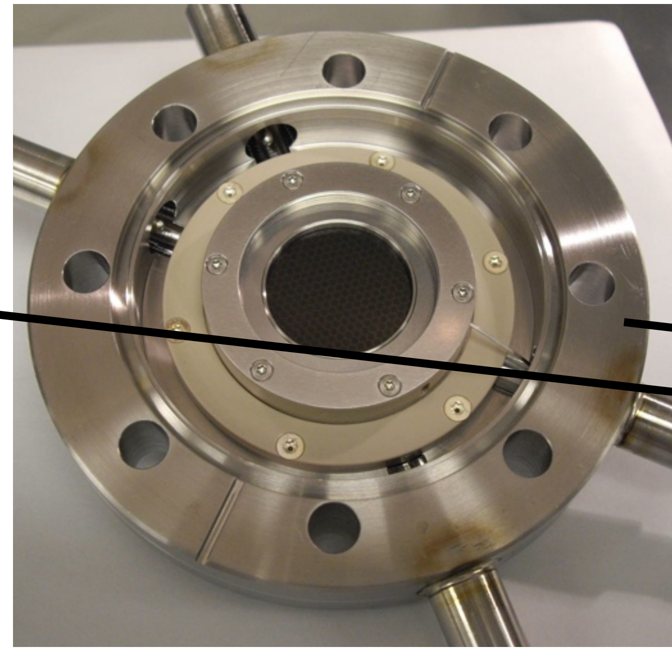
500 ps

Simple soldered wire connection to strip line
Readout and differential timing with fast scope

MCP Testing at Space Sciences Lab (SSL)/Berkeley

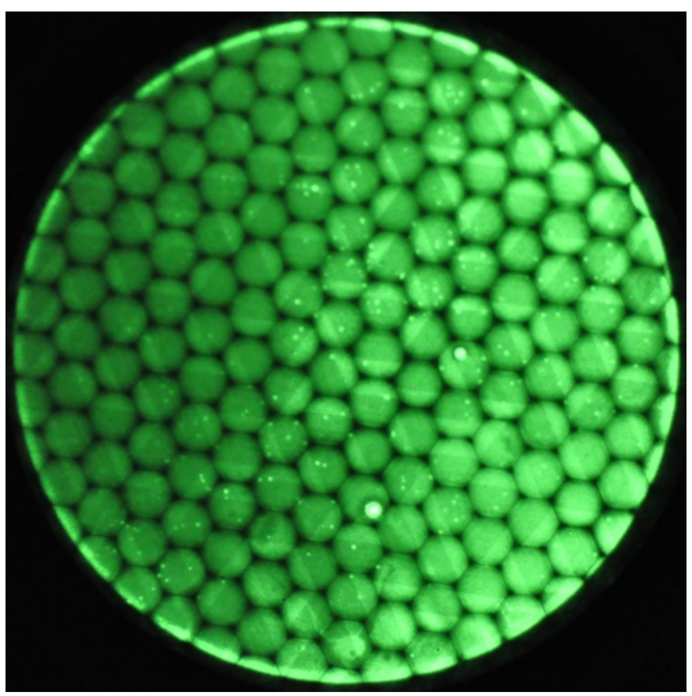


25mm Phosphor on
4.5” CF Flange

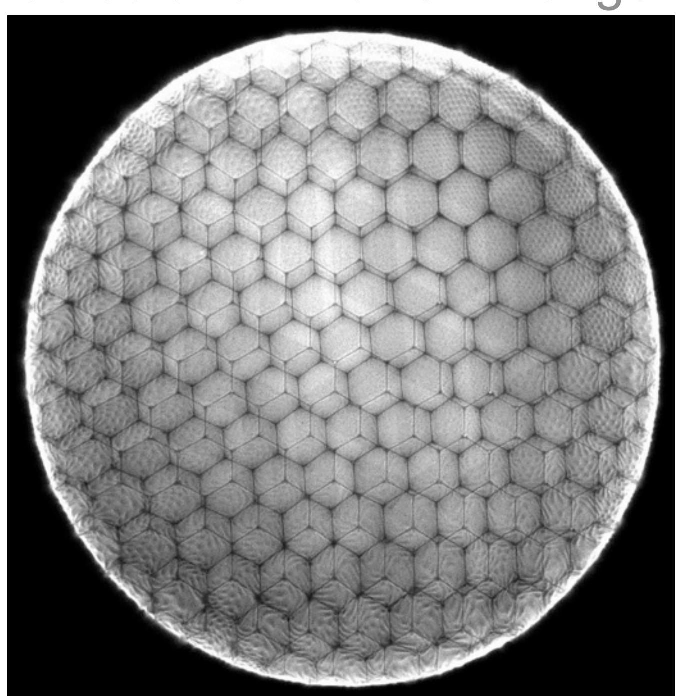


25mm Cross Strip Delay
Line photon counting
detector on 4.5” CF Flange

Double Chamber UHV Test Station



Single MCP Phosphor Image

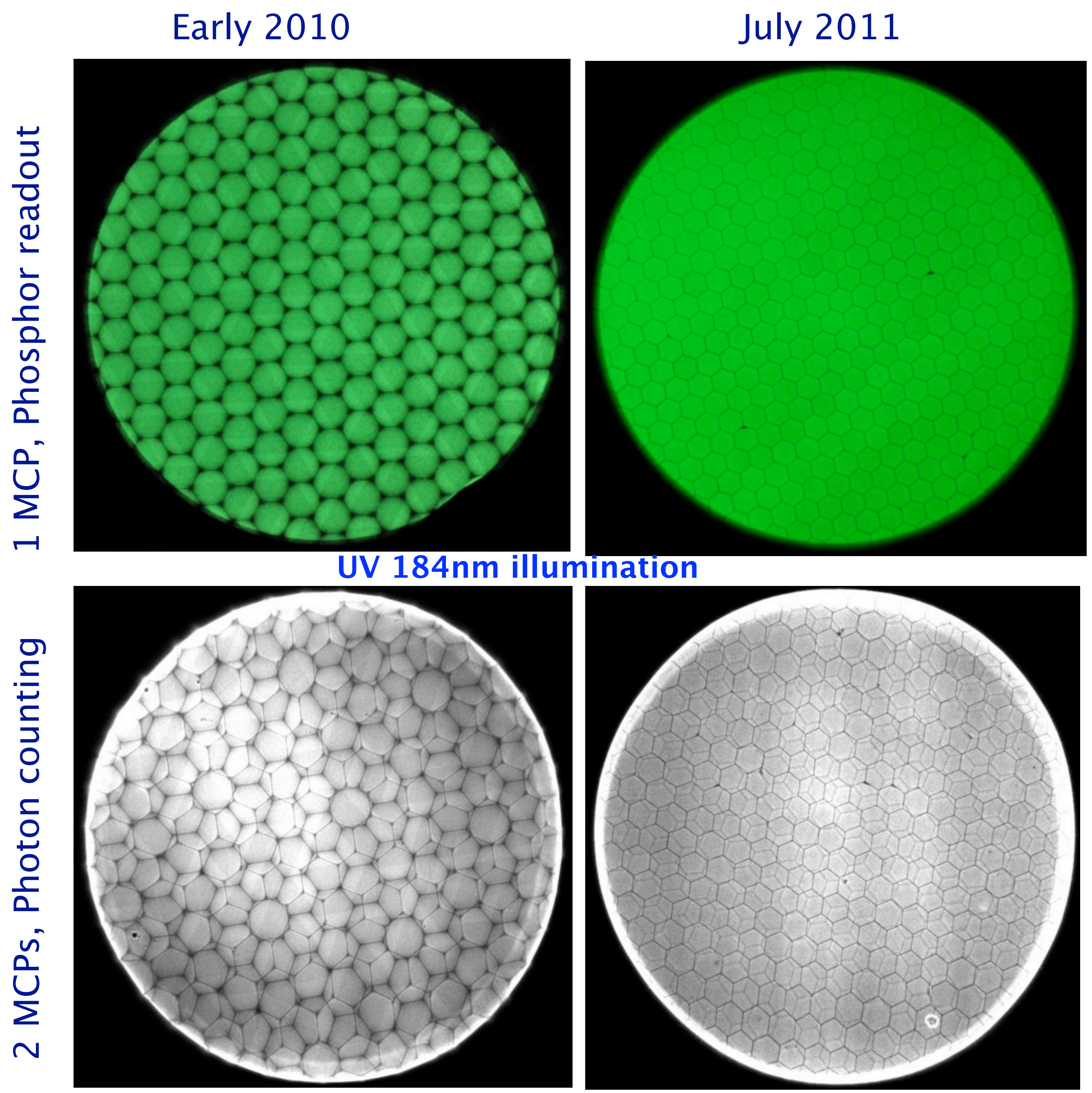


Pair MCP XDL Image

Amp/TDC and PC Acq/display for XDL

Nikon camera or electrometer for Phosphor

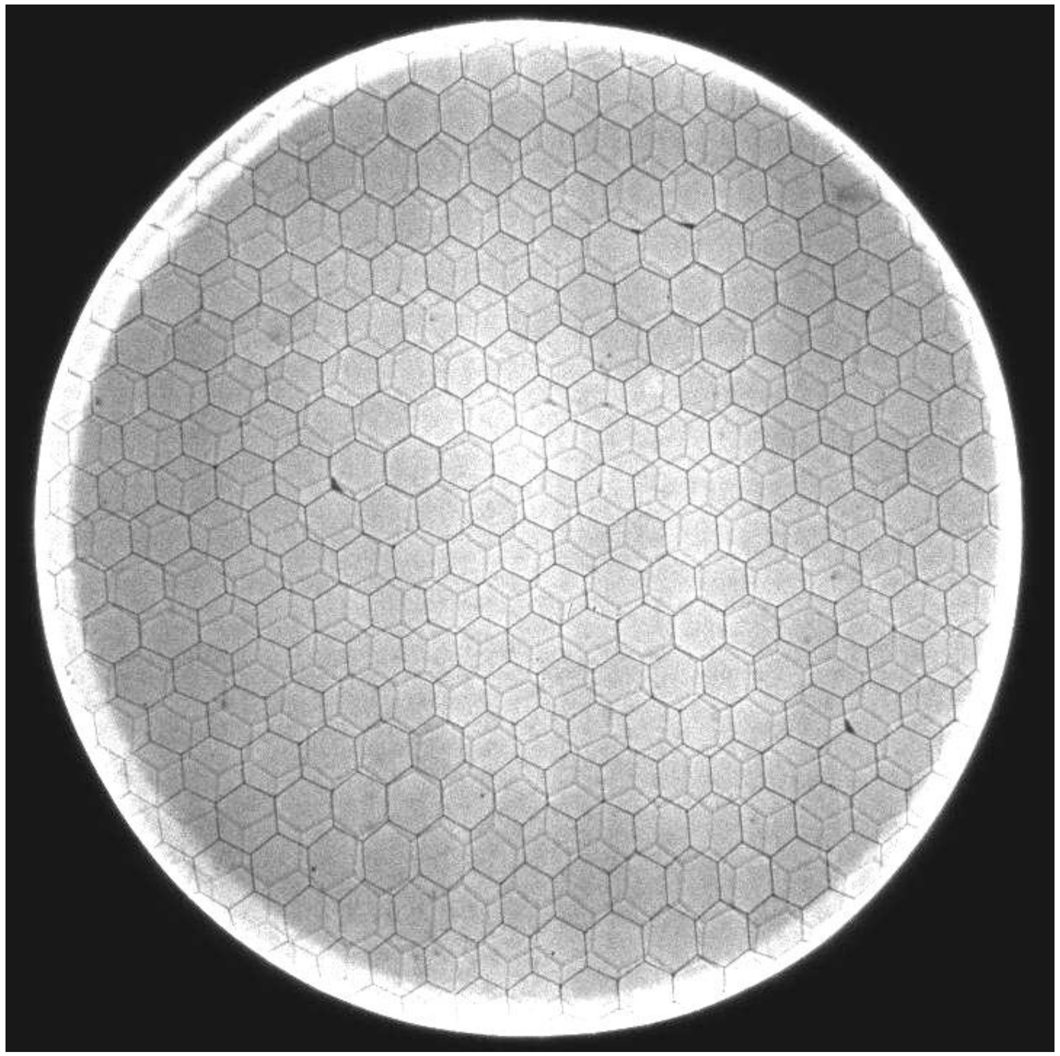
Improvement in Glass Capillary Array Fabrication



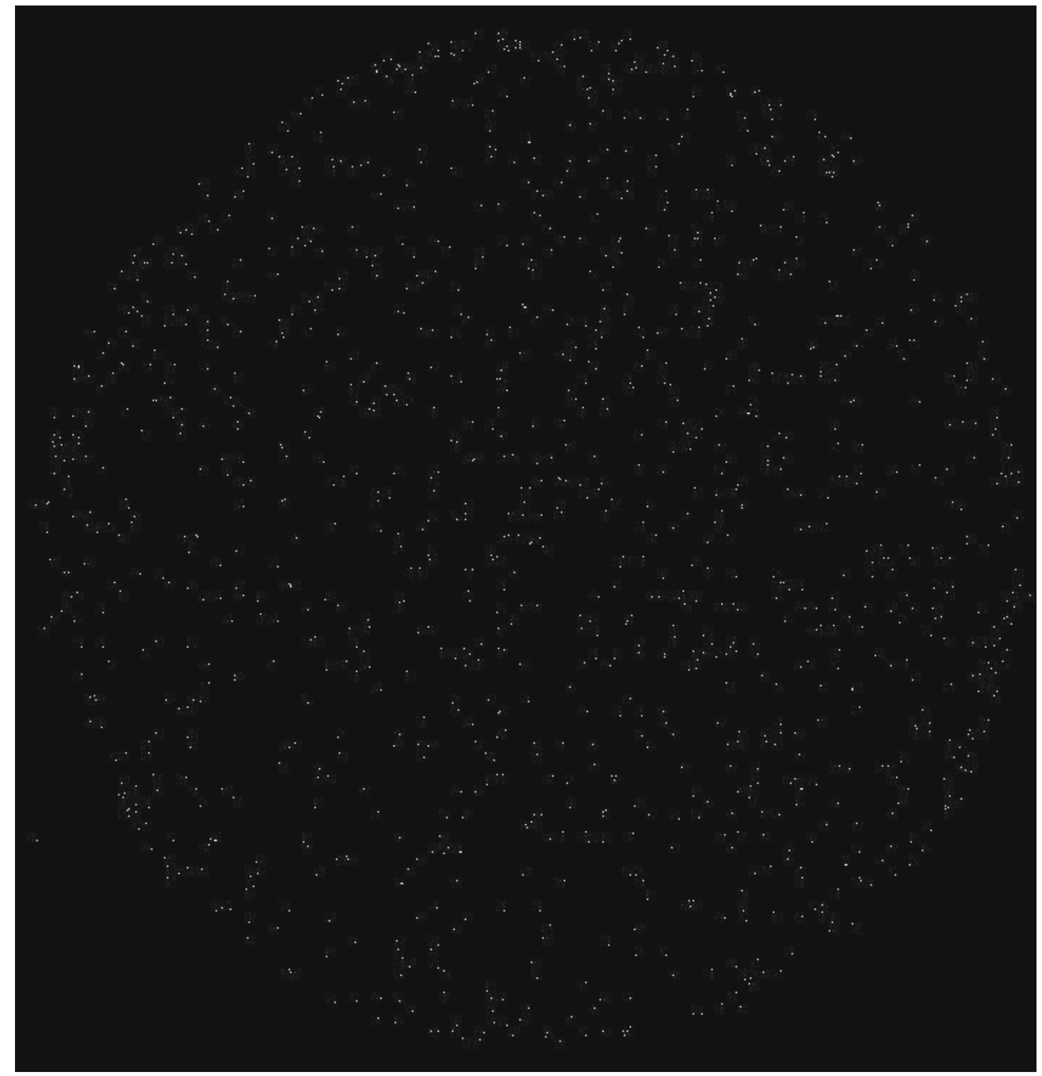
- 20 μm MCP, L/D = 60, 8˚ pore bias, 1000V applied to each MCP
- Imaging & gain comparable to commercial MCPs
- Sample performance shows dramatic improvement due to capillary process improvements

Argonne ALD MCP Pair Background Test

MCP pair, 20μm pores, 8° bias, 60:1 L/d, 0.7mm gap with 300V bias



185nm UV illumination. Top MCP hex modulation (sharp) and faint bottom MCP modulation

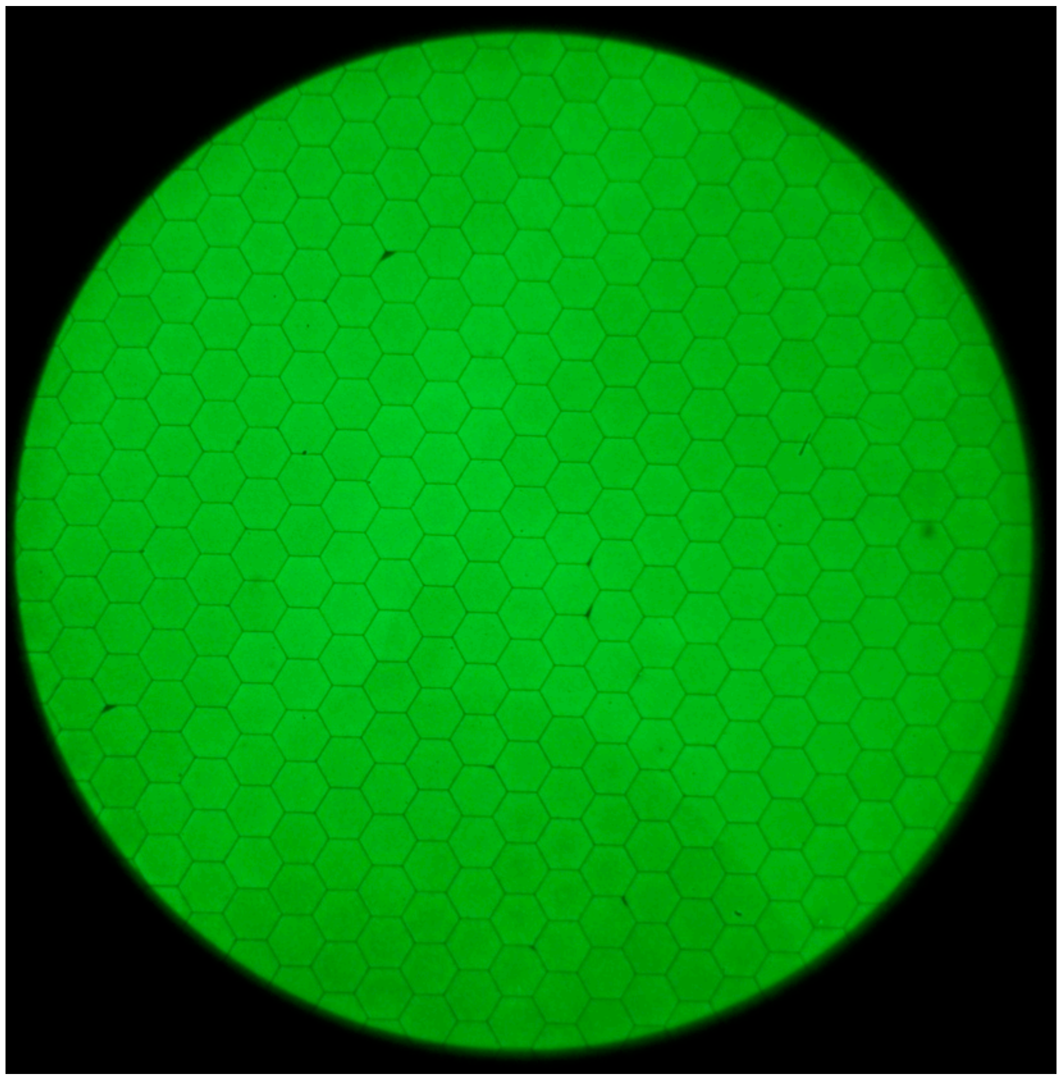


3000 sec background, 0.0845 events cm^{-2} sec^{-1} at 7×106 gain, 1050V bias on each MCP

Robustness

MCP 162, 2nd Batch MCPs, 20μm

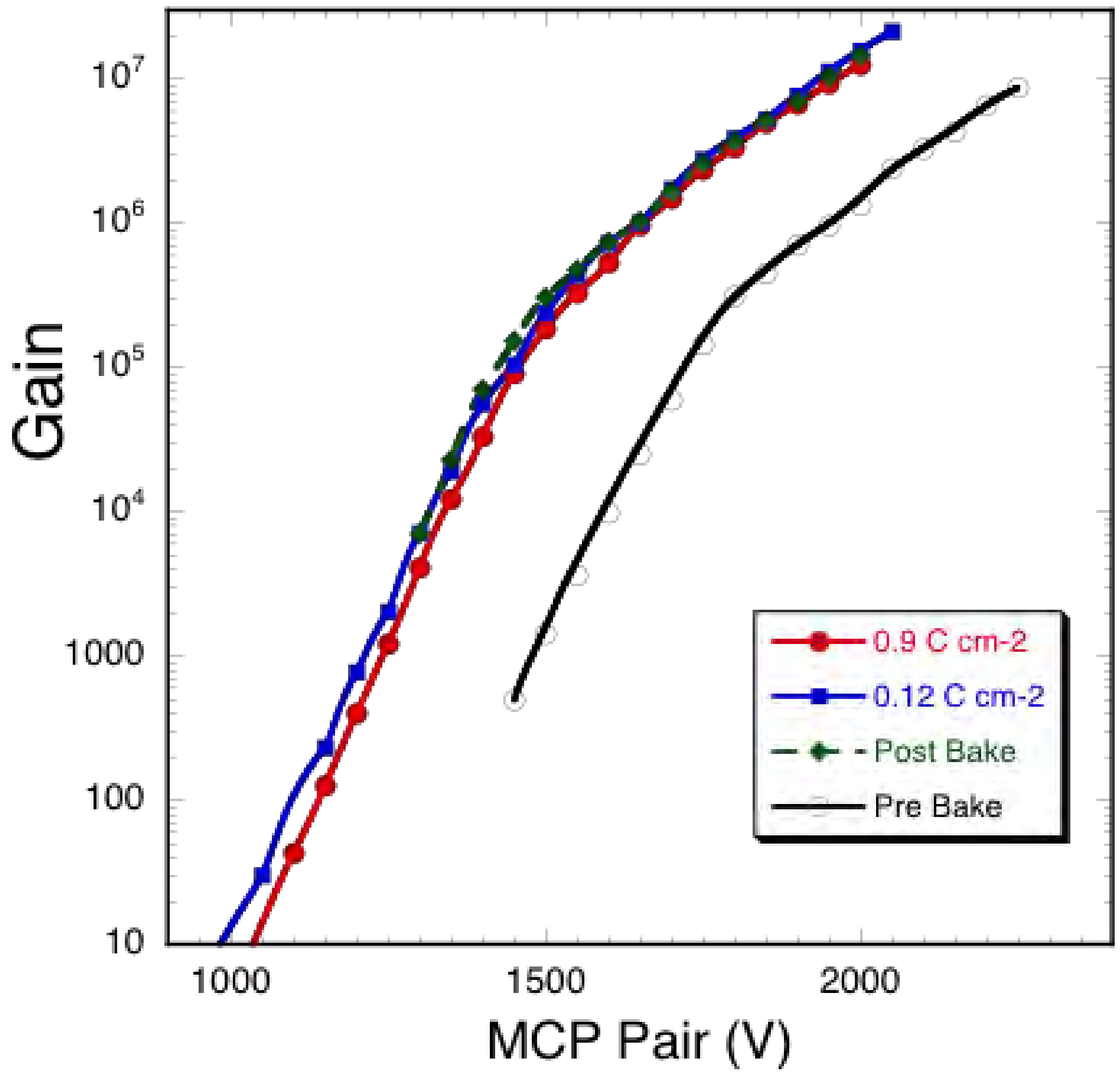
Breakdown event with a phosphor screen which essentially evaporated away the electrode on a part of MCP162.



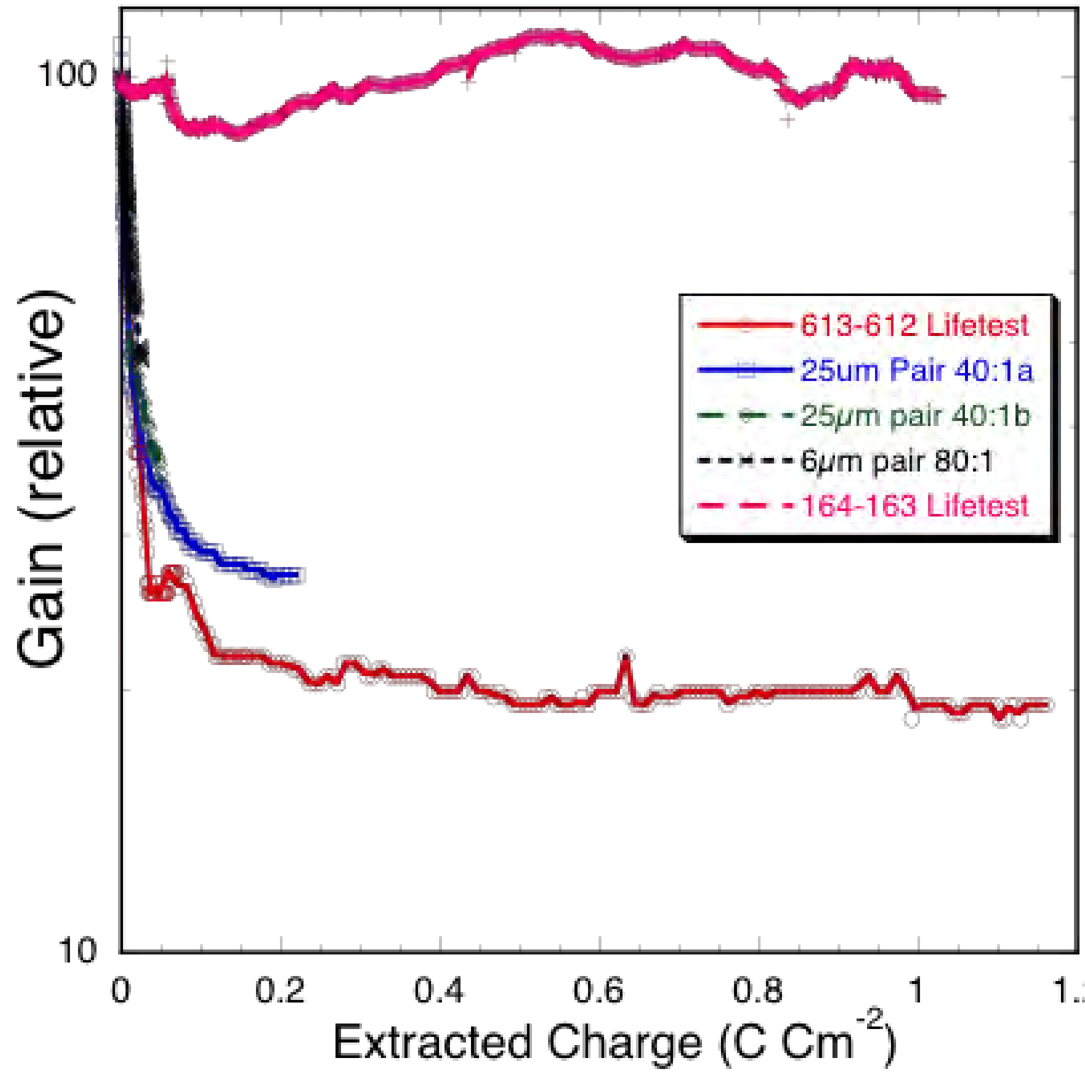
Inspection showed no melting of the pores.
Electroded on top of the damaged face and tested in phosphor detector – no sign of damage!
Any regular MCP would have been toast – melted!!!

33mm ALD MCP Pre-Conditioning Tests

Vacuum 350°C bakeout with RGA monitoring first, then UV flood low gain, then high current extraction "burn in" (1 – 3μA). Most recent ALD formulation:-
Gain increases by x10 during bake, after 1 C cm^{-2} only few % gain change!



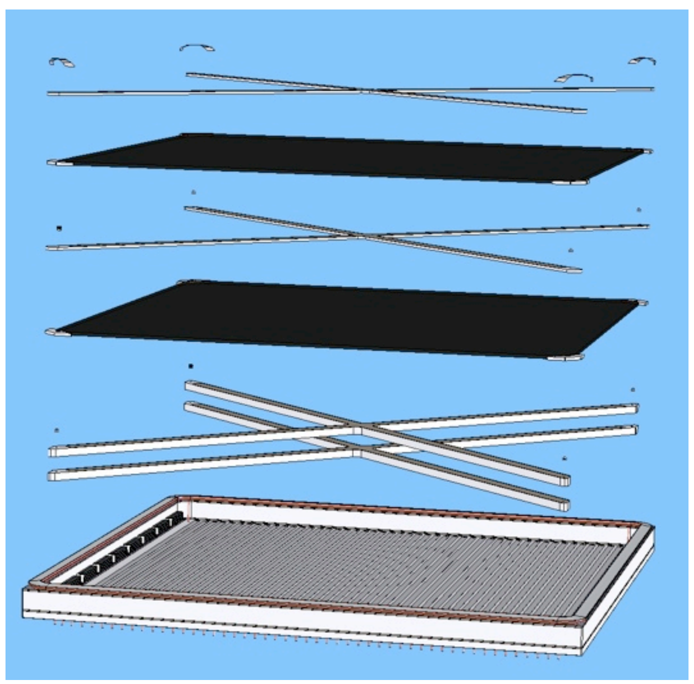
Gain curves of MCP pair (20μm pore, 60:1 L/d, 8° bias) at stages during preconditioning. Outgas during burn-in < 4 x 10^{-10} torr H_2.



UV scrub of ALD MCP pairs 613-613 & 164-163, (20μm pore, 60:1 L/d, 8° bias) compared with conventional MCPs.

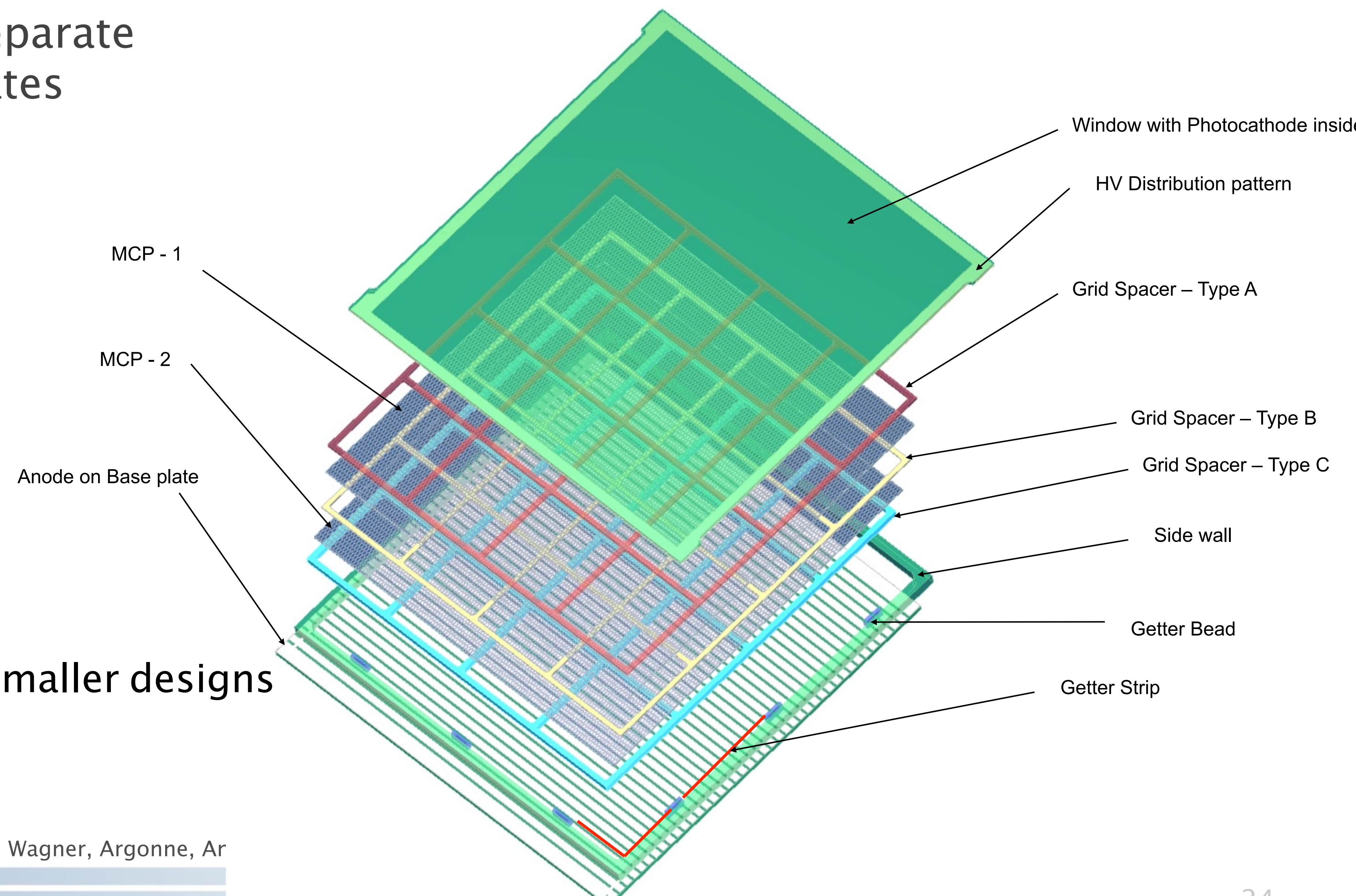
Hermetic Packaging

- For working MCP Photodetector, need to provide
  - Functionalized, Scrubbed MCP Plates
  - Vacuum tight housing
    - Bottom plate with anode strip lines
    - Sidewall
    - Top plate with photocathode
    - Getter strip for long term pumping
  - Support/Spacers to separate MCPs, bottom/top plates



Ceramic body:
Expensive, brazed ⇒ proven in smaller designs
HV & Signal via pins thru body
SSL Design

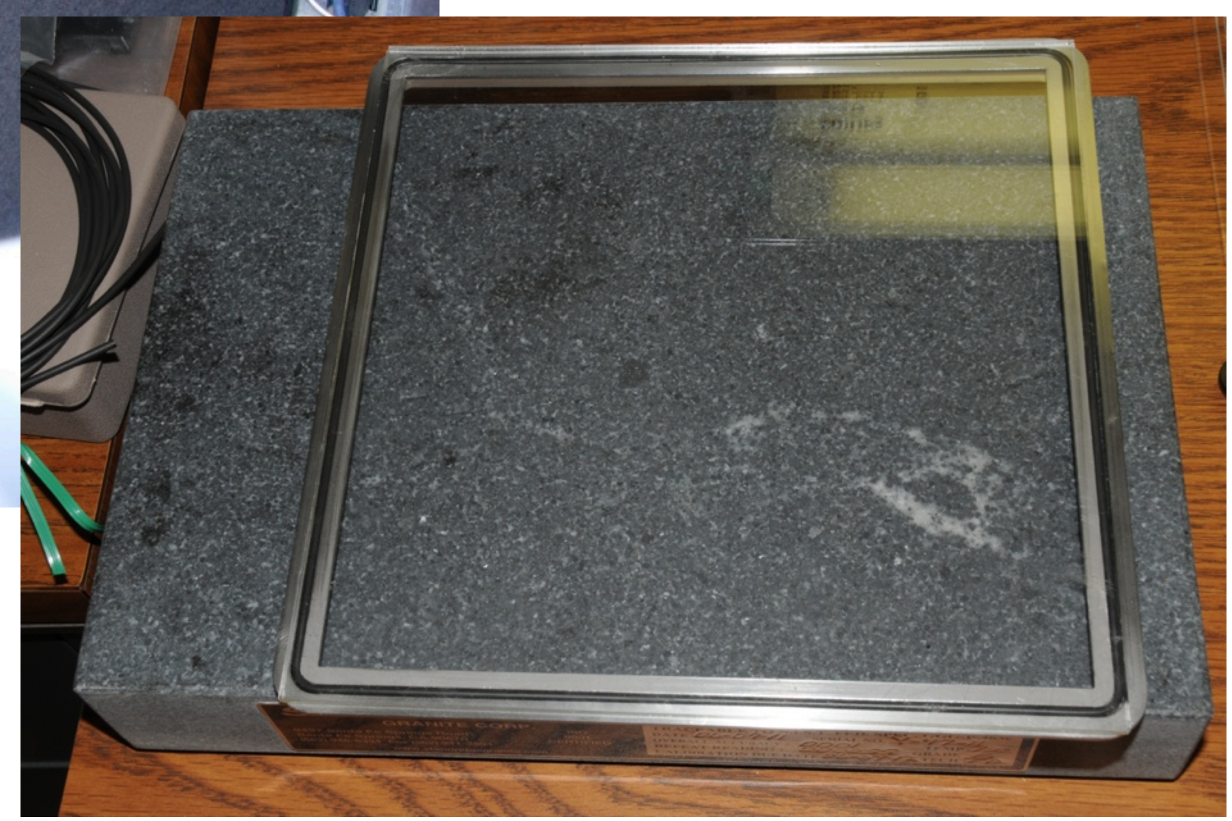
Borosilicate all glass design:
Frugal, innovative ⇒ higher risk
No pin penetration into housing
Under development at Argonne



Demountable 8" Tile Prototype

Inner, outer retainer rings for demountable O-ring seal

Inner, outer retainer rings for demountable O-ring seal

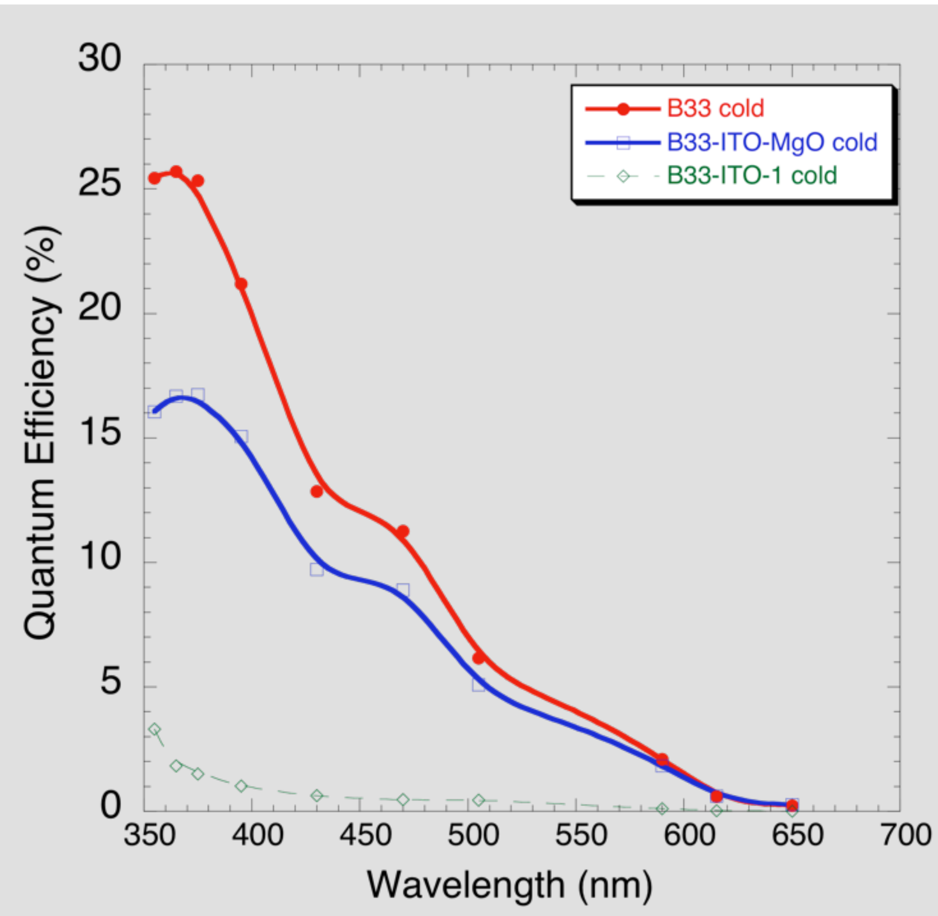


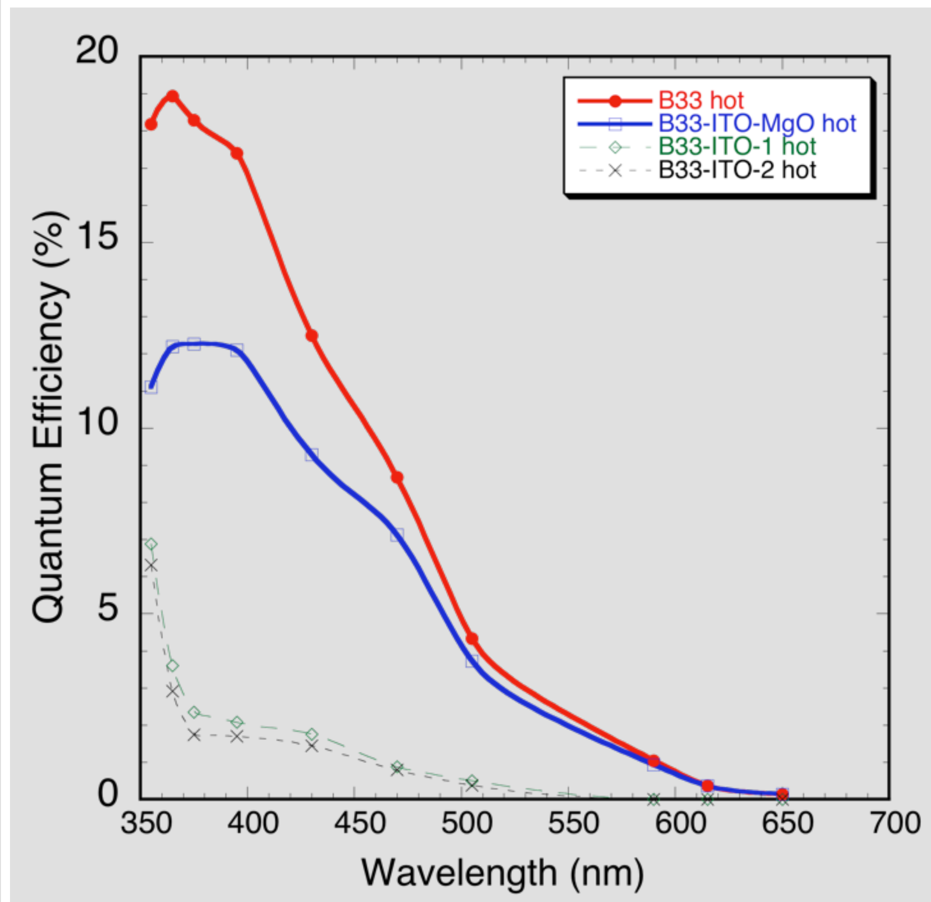
Leak checking of assembled demountable structure

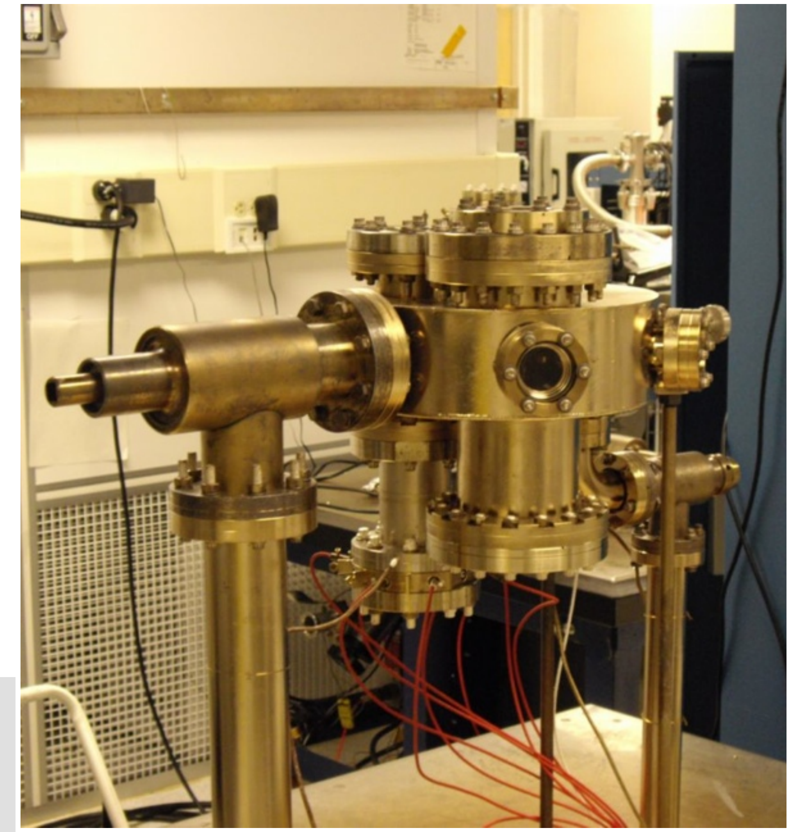
Photocathode Fabrication -- SSL

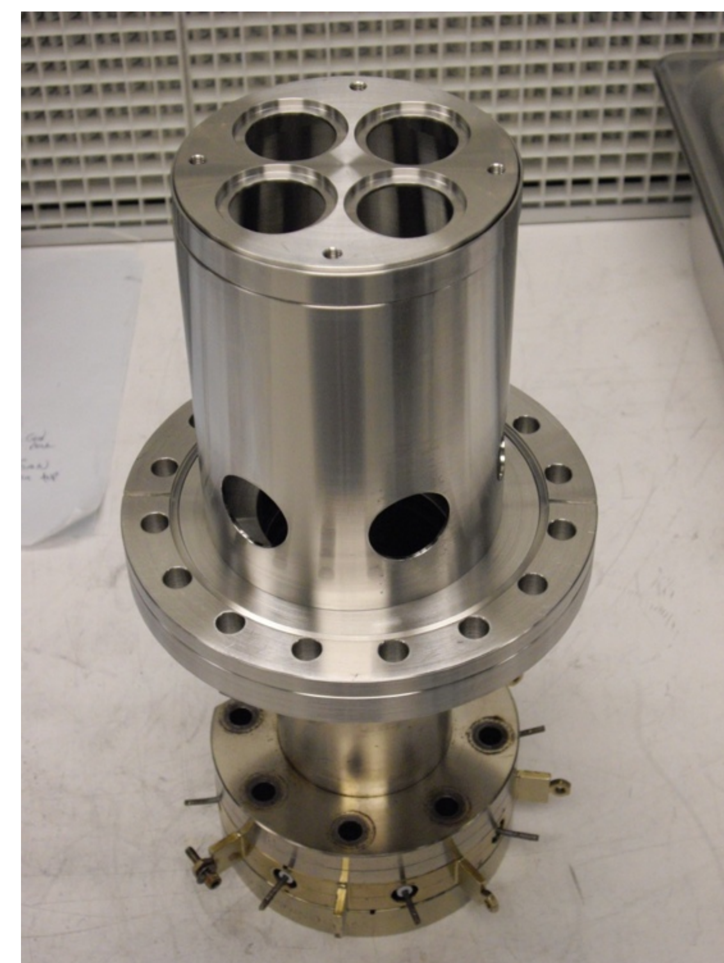
Cathode test run #6B, Na_2KSb cathode, Sb

B33, B33+ITO, B33+MgO/ITO substrates
Substrates with ITO are very bad, ITO-MgO better, but not great



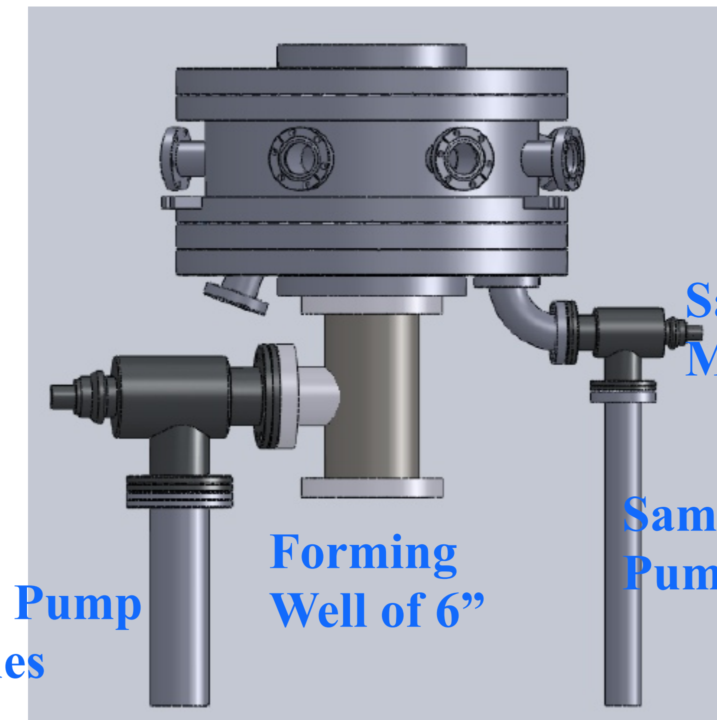




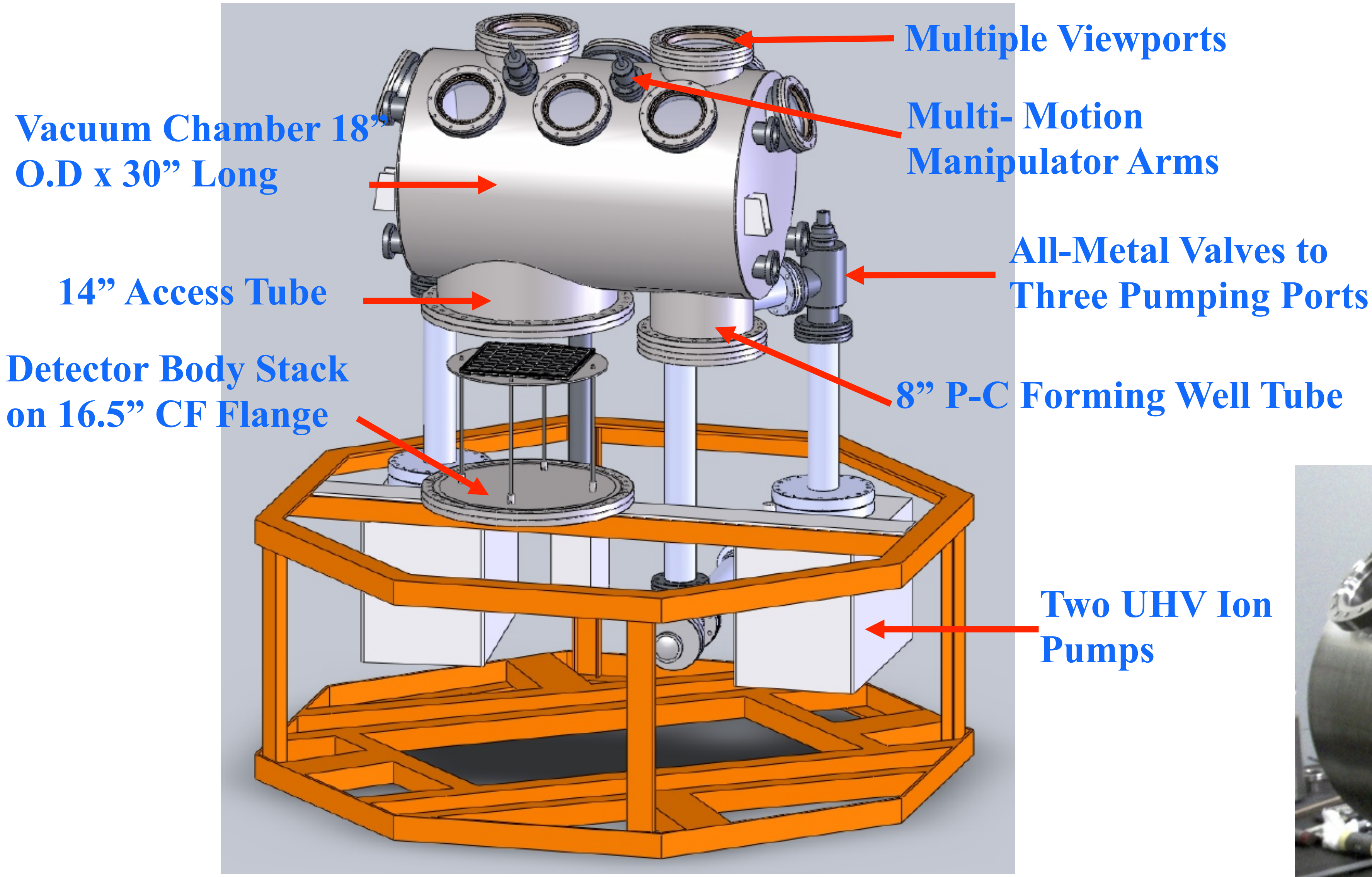


8.7” Photocathode & Seal Test Chamber

8.7” Photocathode/Seal Test Chamber

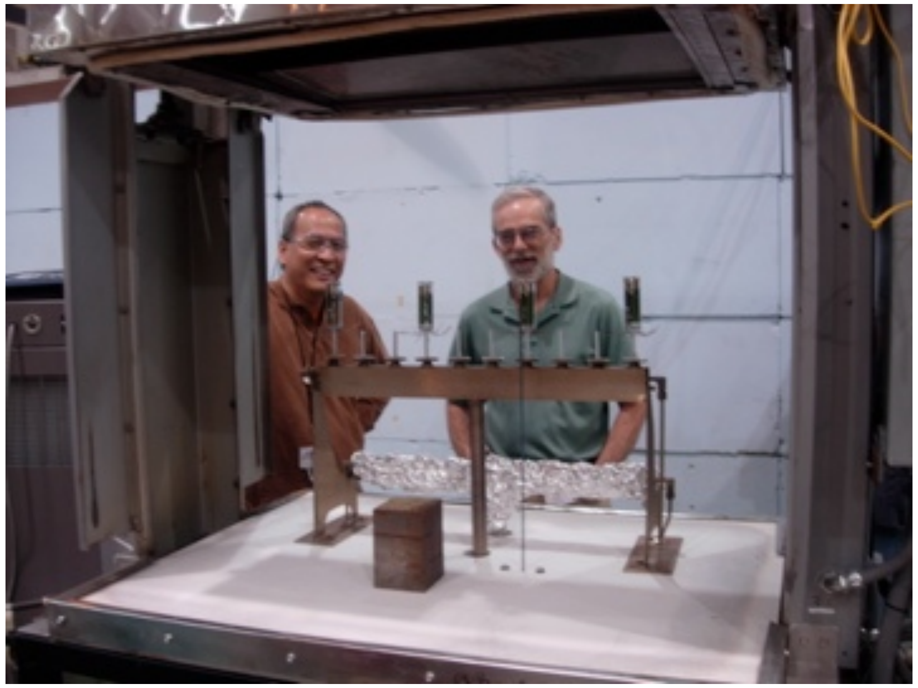


Large Process Chamber for Ceramic Tube Fabrication at SSL

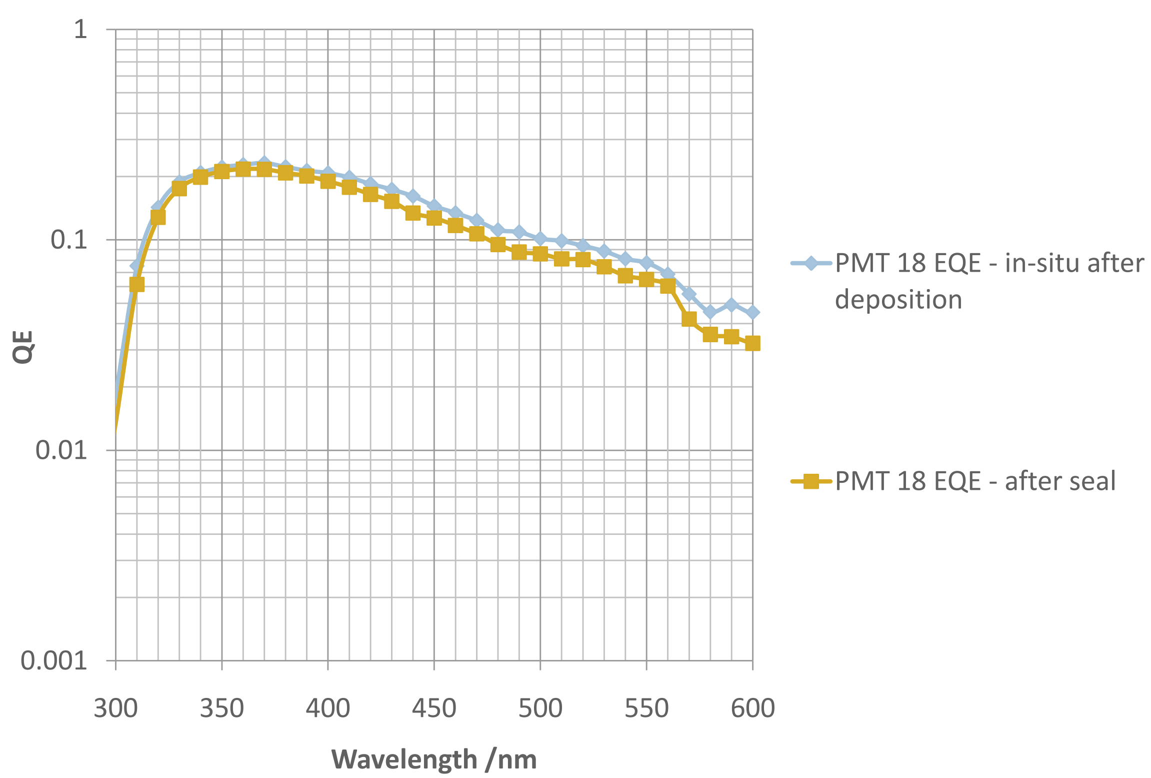


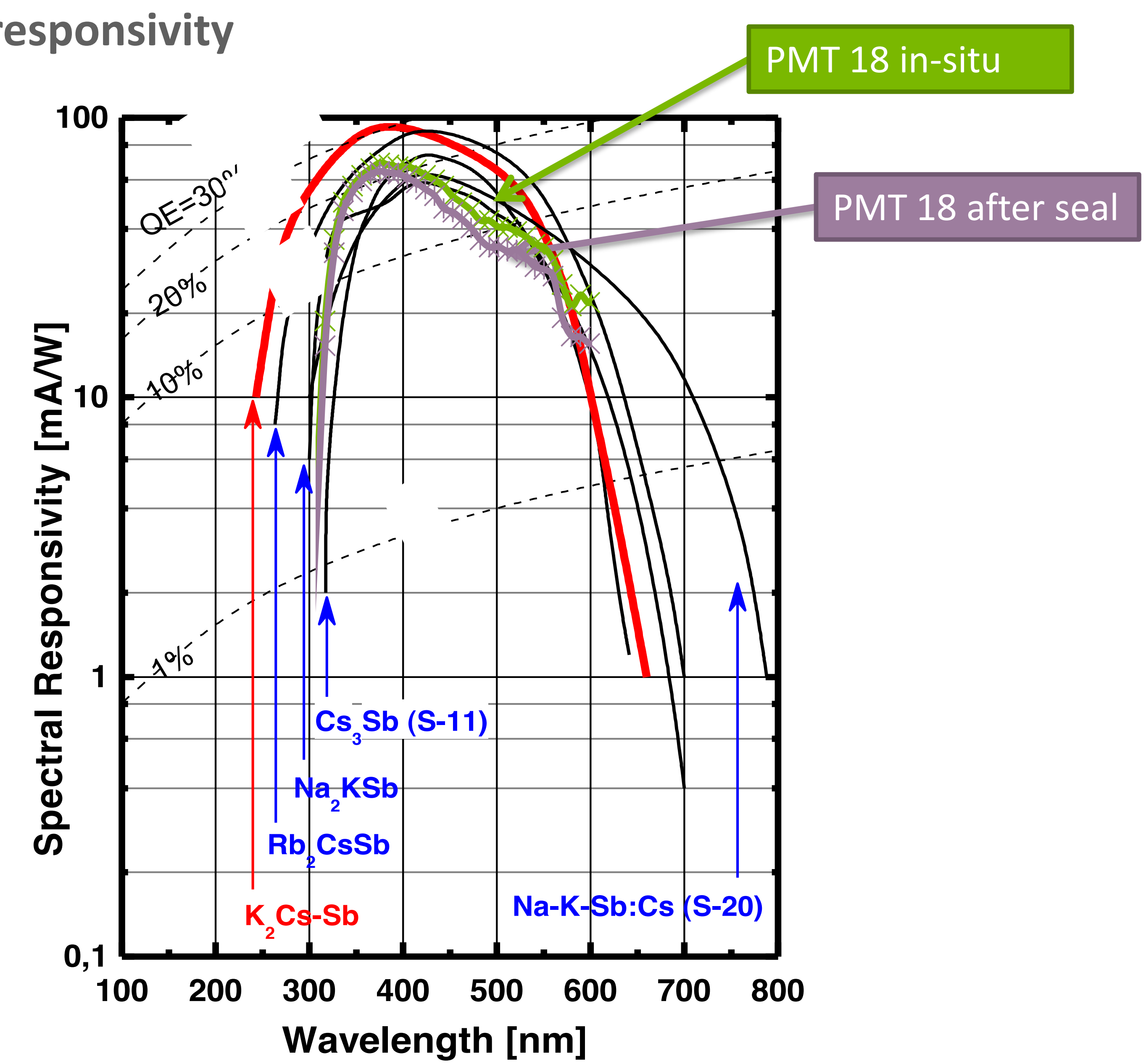
Bialkali Photocathode Development at Argonne

- Shoot photocathode similar to traditional PMT method
  - metal beads activated by current heating
- Use glass containment vessel with bead support structure & detachable top window
- Learn method by making photocathodes on small PMTs
  - PMT processing equipment obtained from Burle Industries

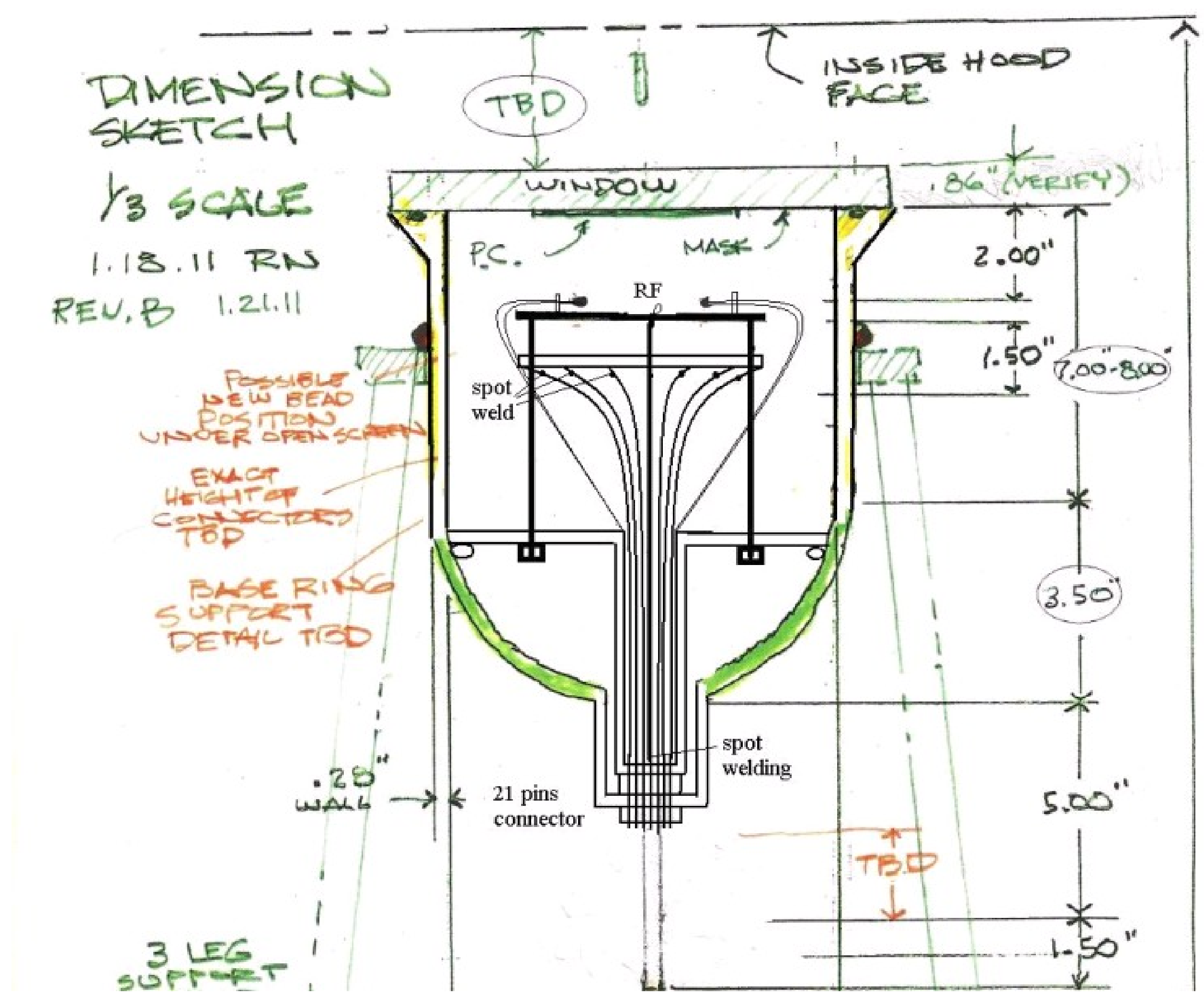


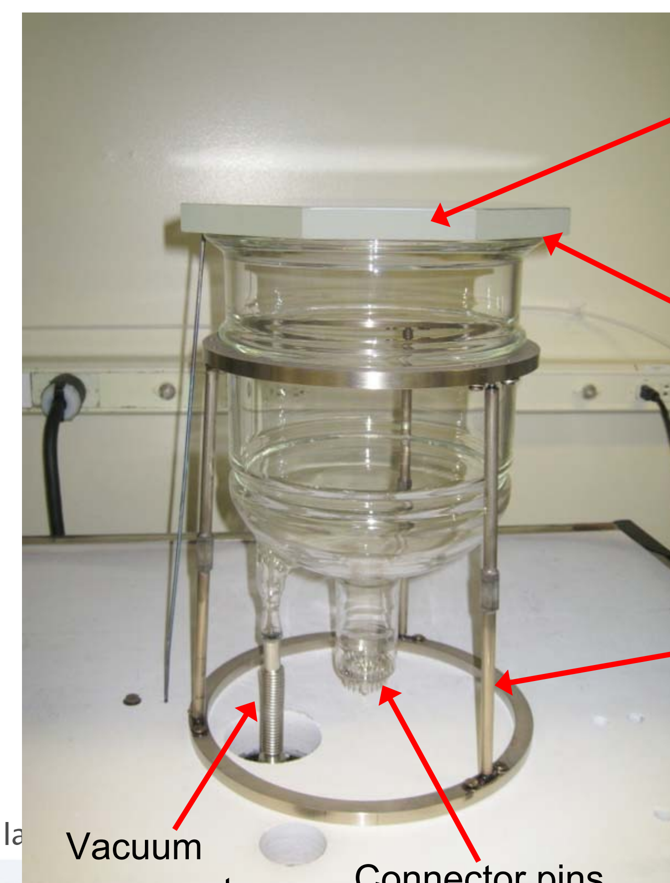
Results from Photocathode Growth in Burle Process Chamber





Bialkali Photocathode -- Scale-Up to 4” Photocathode





Summary

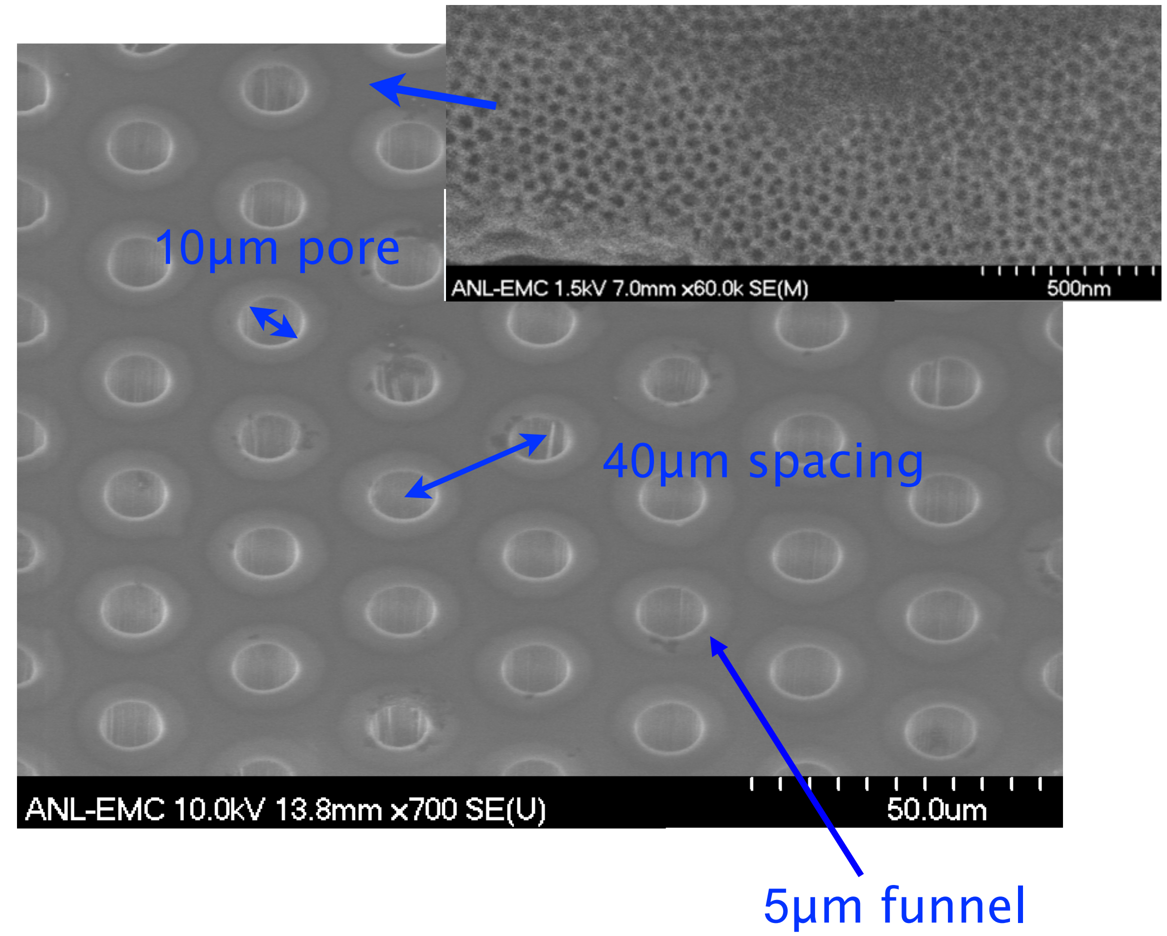
- Large Area Microchannel Plate Photodetector project has completed 2nd year
- Many critical milestones achieved for detector realization
  - Signals acquired from full-sized tile base with 33mm MCP pair in 8” test ch.
  - ALD coatings of 33mm glass capillary disks producing gain $>10^6$ for MCP pair
  - Observation of gain from 8”×8” MCP
  - Production of detector quality 8”×8” glass capillary arrays
  - Developed 3 ALD resistive + 2 ALD emissive chemistries
  - Low temperature (120 °C) In(52)Sn(48) seal made on 1” sidewall/window
  - Readout ASIC for picosecond resolution fabricated & tested (4th gen. chip due in October)
- Mature mechanical designs for hermetically sealed tube
  - Proven design in ceramic by SSL
  - Well-advanced inexpensive glass design -- hermetic prototypes
- Facility for 8”×8” photocathode fabrication and study near completion at SSL
  - Full-size process chamber installed, near commissioning
- Tile production facility for All-Glass MCP-PMT in design at Argonne

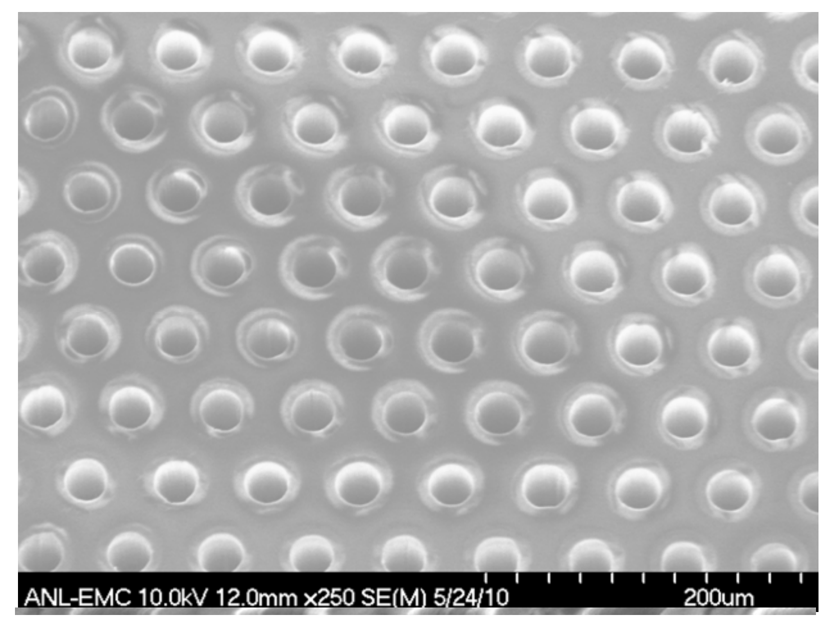
Visit our web site for more information:
http://psec.uchicago.edu
(“Blog” and “Library” links are a good starting place)

BACKUP SLIDES

Anodic Aluminum Oxide (AAO) Development

- Self-ordering fabrication of pore structure in aluminum by anodization
- Alternative to glass capillary MCP
- Argonne AAO fabrication is 2-step
  - Form 10nm pore matrix through anodization (more “natural” size for process)
  - Pattern and etch 2-10µm pore via photolithography
    - Initial 10nm pore structure enables uniform etch larger diameter pores
- Development at Argonne is very successful
  - Now producing pores with funneled pores
    - Potential for large effective open area ratio
    - Addresses first-strike problem
    - Possible future generation of MCP with Photocathode coated on funnel via ALD

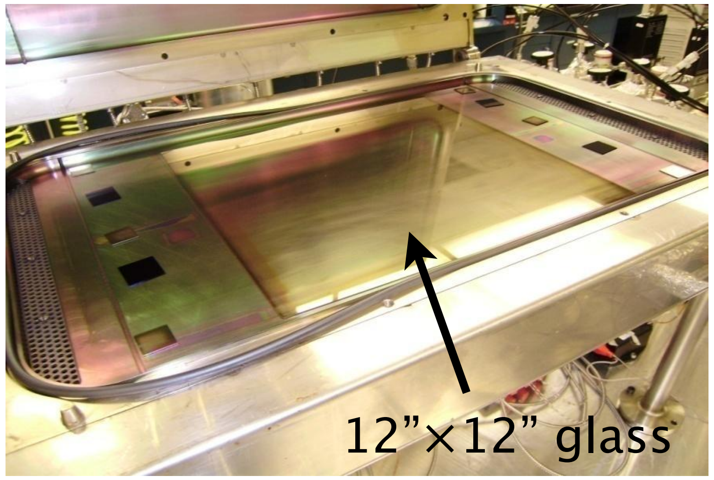


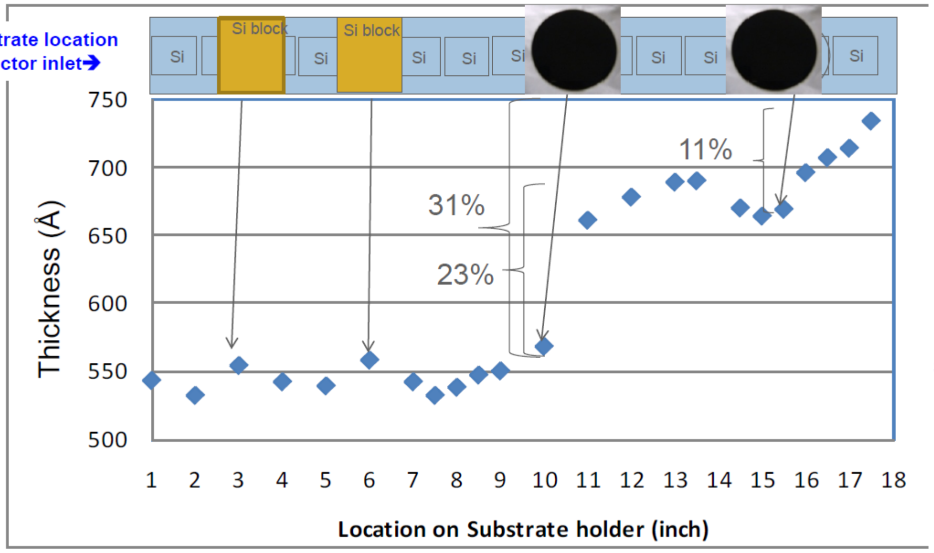


32.8mm AAO test substrate
20µm pore, L/D~10, 23% open area

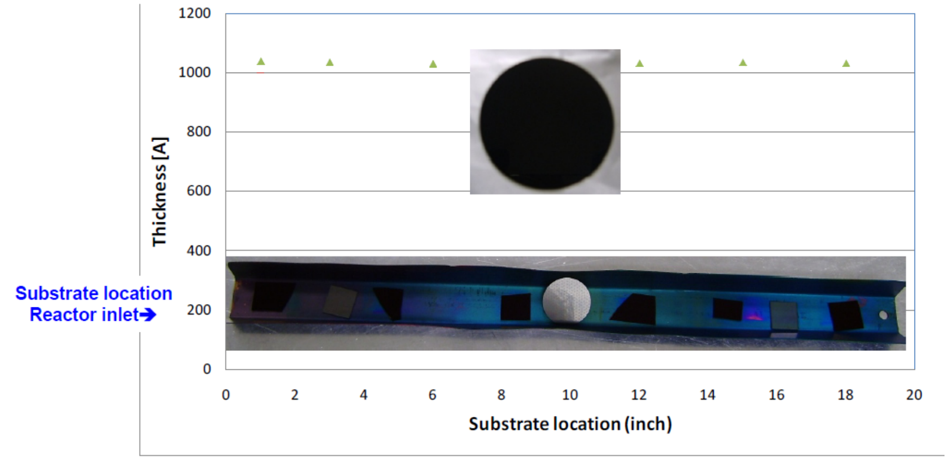
Scale-up to Large Surface Area

Process scale-up on large reactor

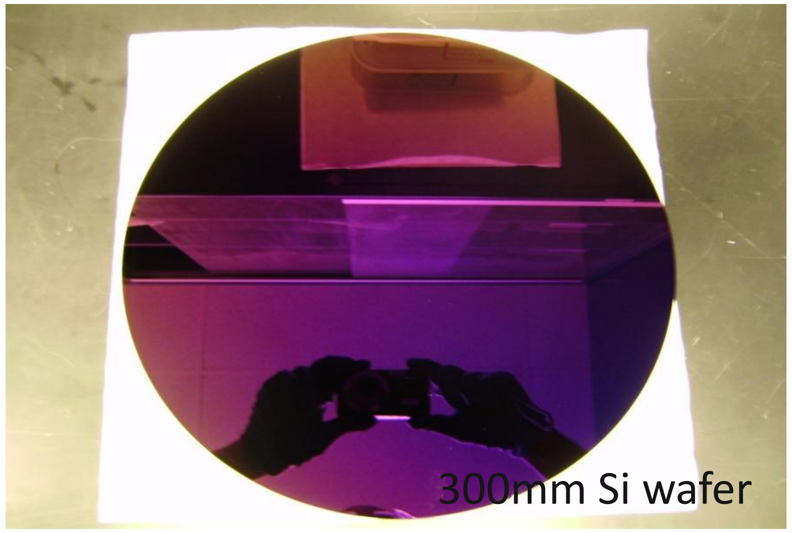




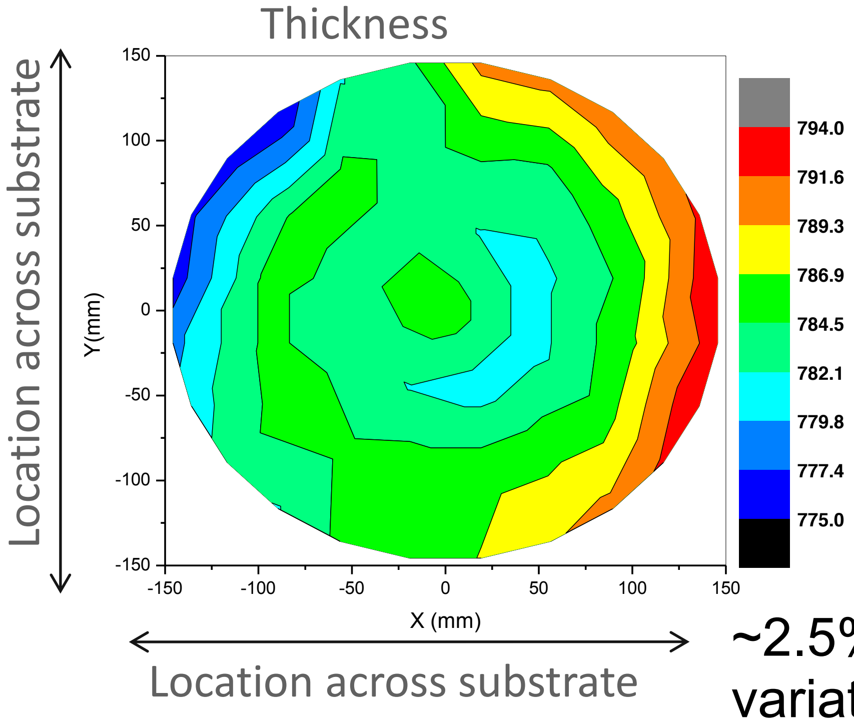
Chemistry #1:
1% thickness increase across Si wafers
Up to 30% increase after MCP locations



Chemistry #2:
No thickness increase near MCP
Uniformity, scaling ease in ALD are process dependent



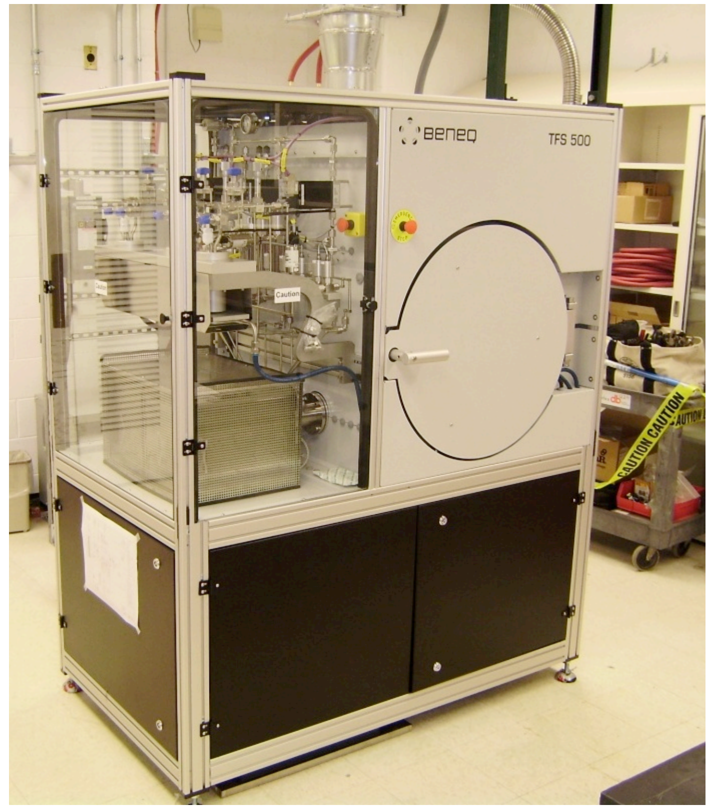
300mm Si wafer coated with Chemistry #2



~2.5% thickness variation across wafer

Scale-Up of ALD Processing -- Beneq Reactor

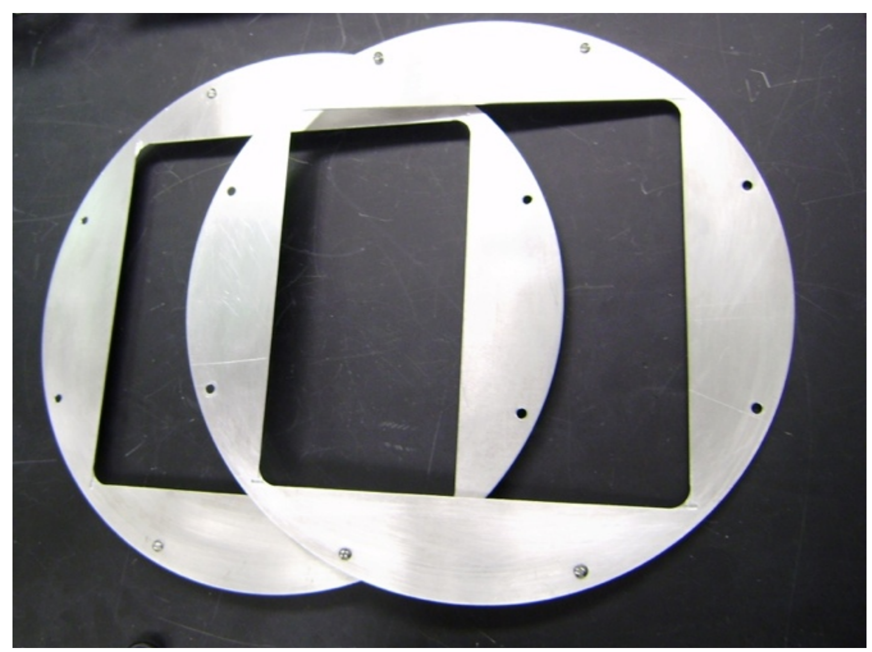
Arrived 18 May 2010



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 $129m^2$

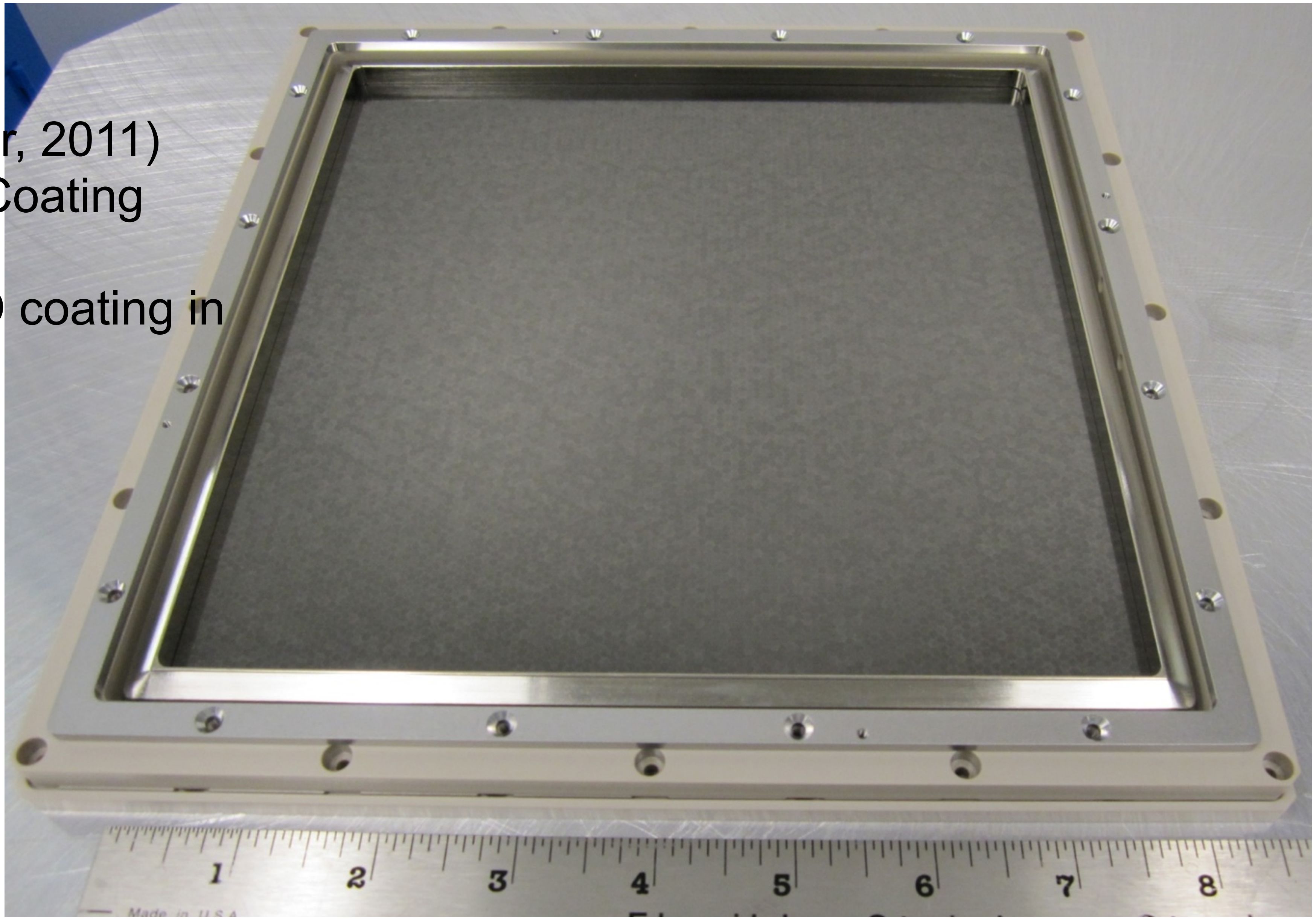
Stackable 20cm × 20cm plate holders for multiple plate coating in Beneq Reactor



8”×8” MCP Plate Testing at SSL

ALD Coated 8”×8” 20µm MCPs
1st production quality plates (Apr, 2011)
Develop process for Resistive Coating

Tuning parameters now for ALD coating in Beneq reactor



8” electroded MCP in the open face test detector.
MCP #3 and MCP #2 have been electroded on both sides with 1700Å inconel.
#2 is 31kΩ and #3 is 3MΩ in air - and vacuum (Needs to be ~10-30MΩ).

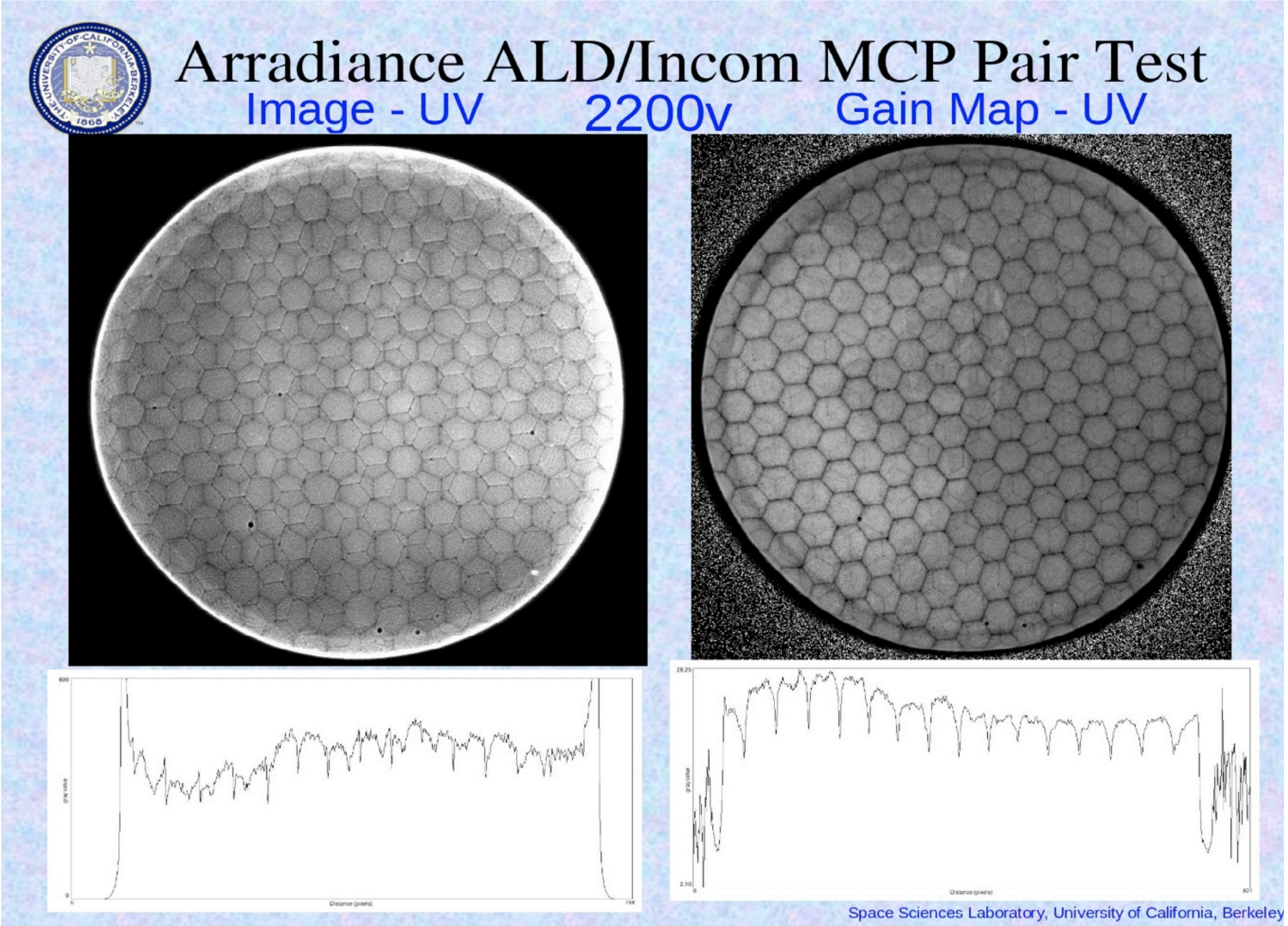
Visual Study of ALD Coated MCP at SSL

Glass capillaries coated by Arradiance, Inc.

Pair test at Space Sciences Lab/UC-Berkeley

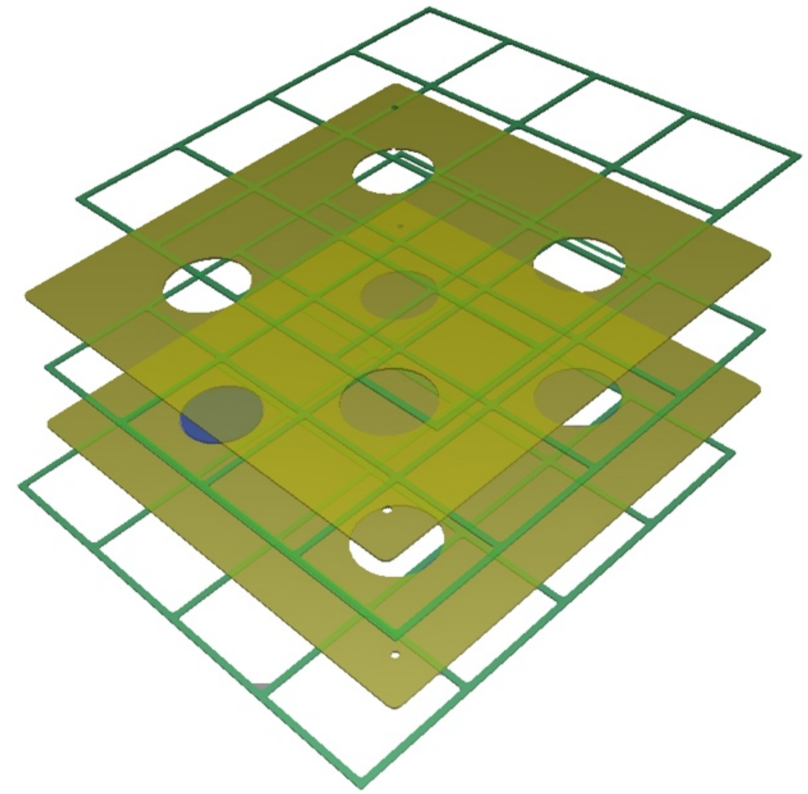
Electron map of MCP

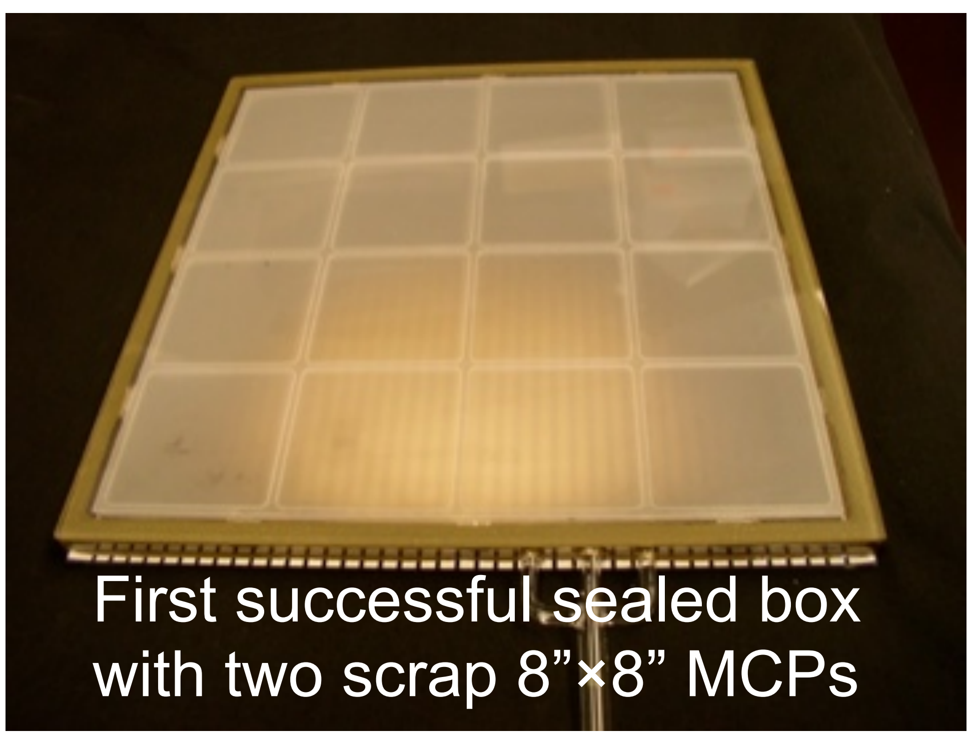
“Multi” boundaries visible, fade at higher gain



Mock Tile Fabrication

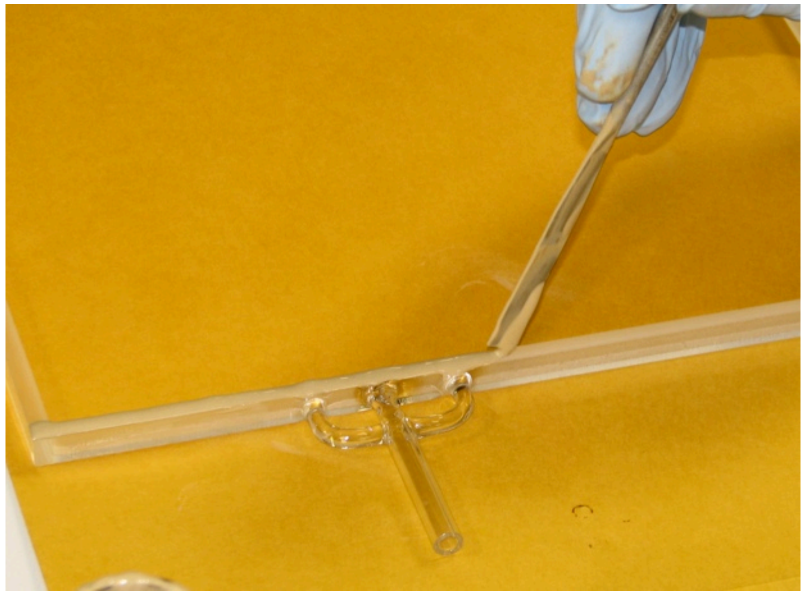
- Short-cut to testing full assembled large area MCP-PMT
- Glass 8”×8” Mock MCP w/4 holes for 33mm functional MCP pairs
- Use tile bases with pump-out port on sidewall & standard anode bottom plate
- Top window with Al photocathode
- Top seal with glass frit (like bottom seal)



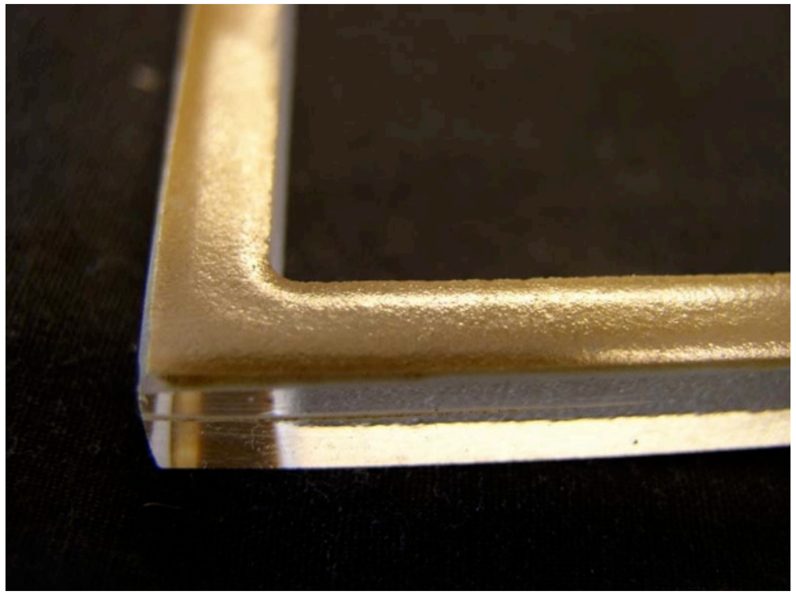


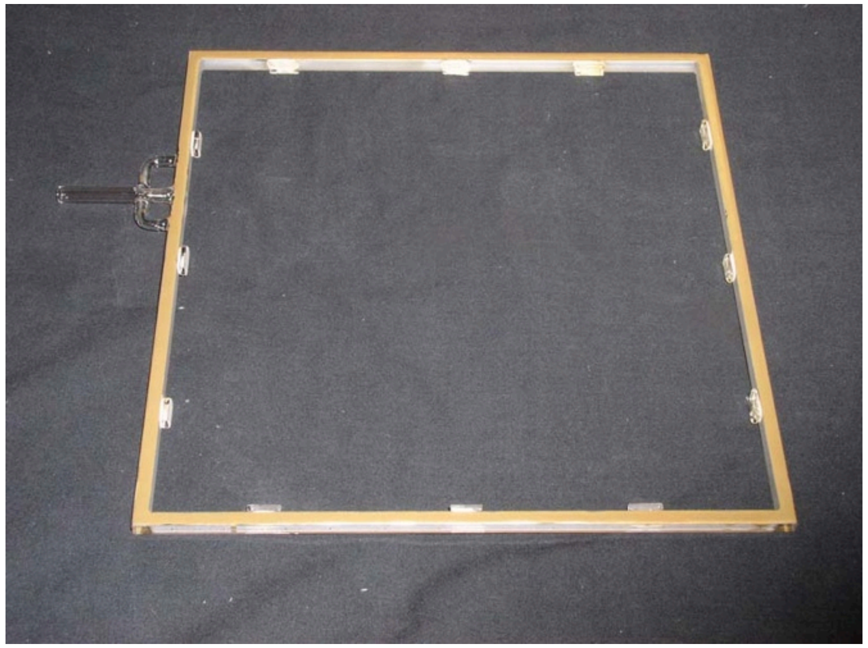
First successful sealed box with two scrap 8”×8” MCPs

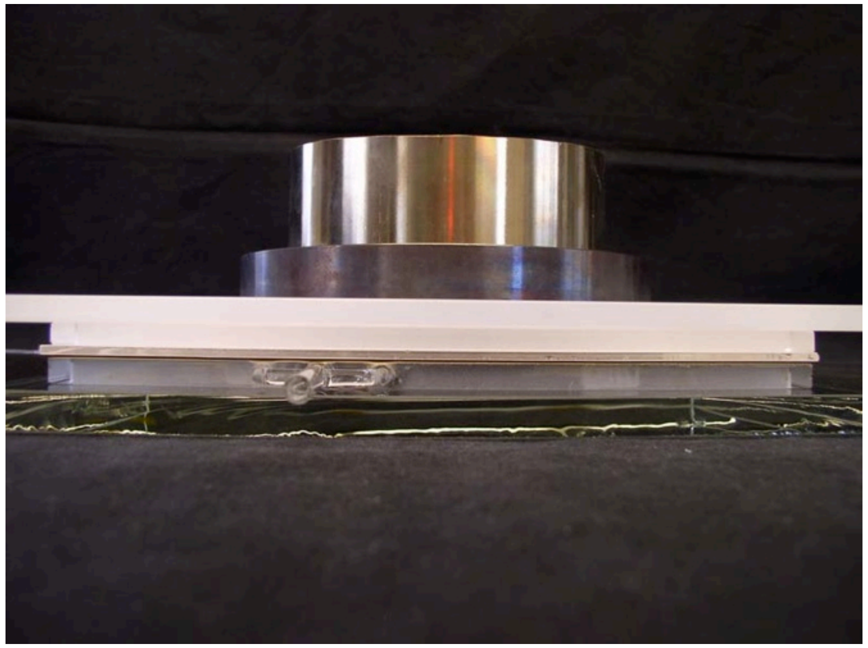
Mock Tile Fabrication -- Tile Base

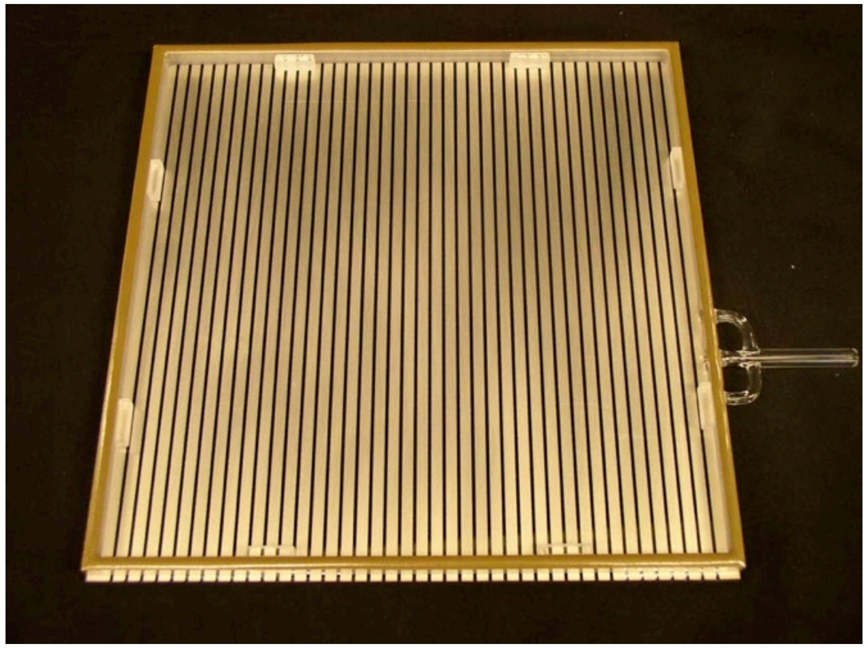

Apply Frit Paste to Sidewall


350˚C Fire to Dry Paste

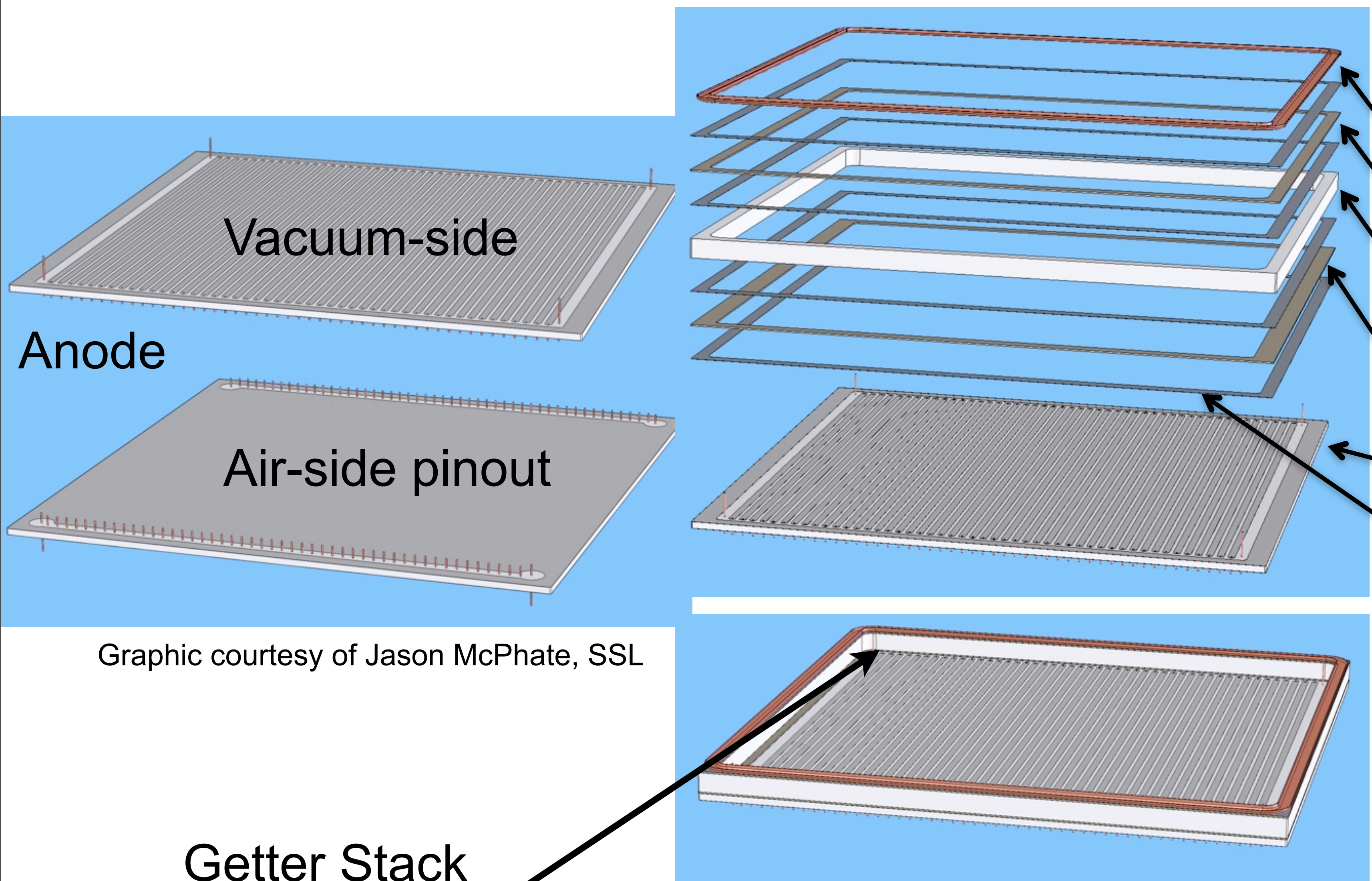

470˚C Fire to Glaze


Attach Getter Holders
Silver Ink Frit @ 350˚C


470˚C Fire to
Bond Anode Plate


Completed Tile Base
w/Vacuum Tight Bond

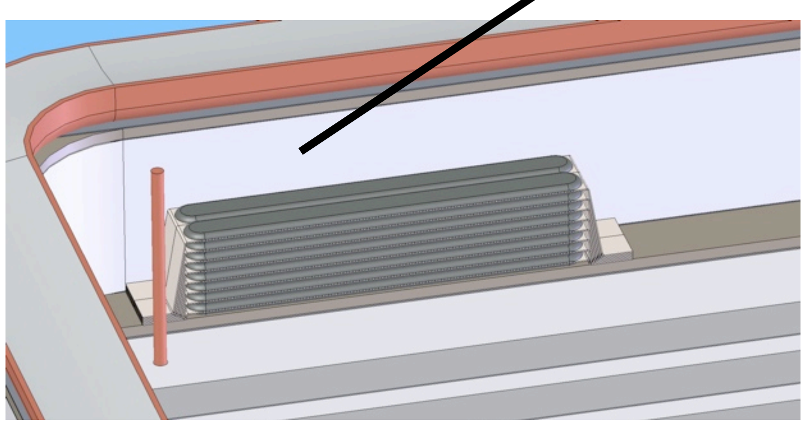
Ceramic Body Design -- SSL

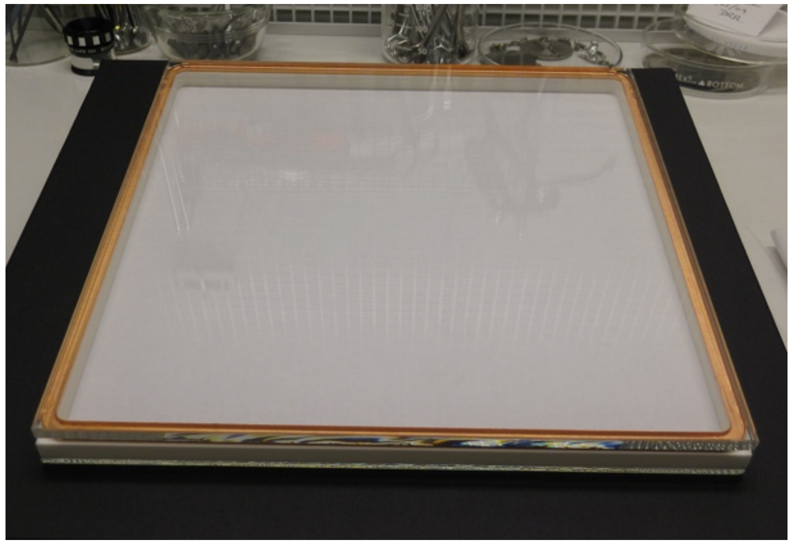


Graphic courtesy of Jason McPhate, SSL

- Single step braze
  - Stamped OFHC Cu or Kovar indium well
  - Kovar intermediary flange
  - Alumina wall
  - Kovar getter flange
  - HiTemp, CuSil brazed anode
- InCuSil braze alloy (750°C braze)
  - Avoids remelt of anode CuSil
- Four braze joints in final assembly

Getter Stack

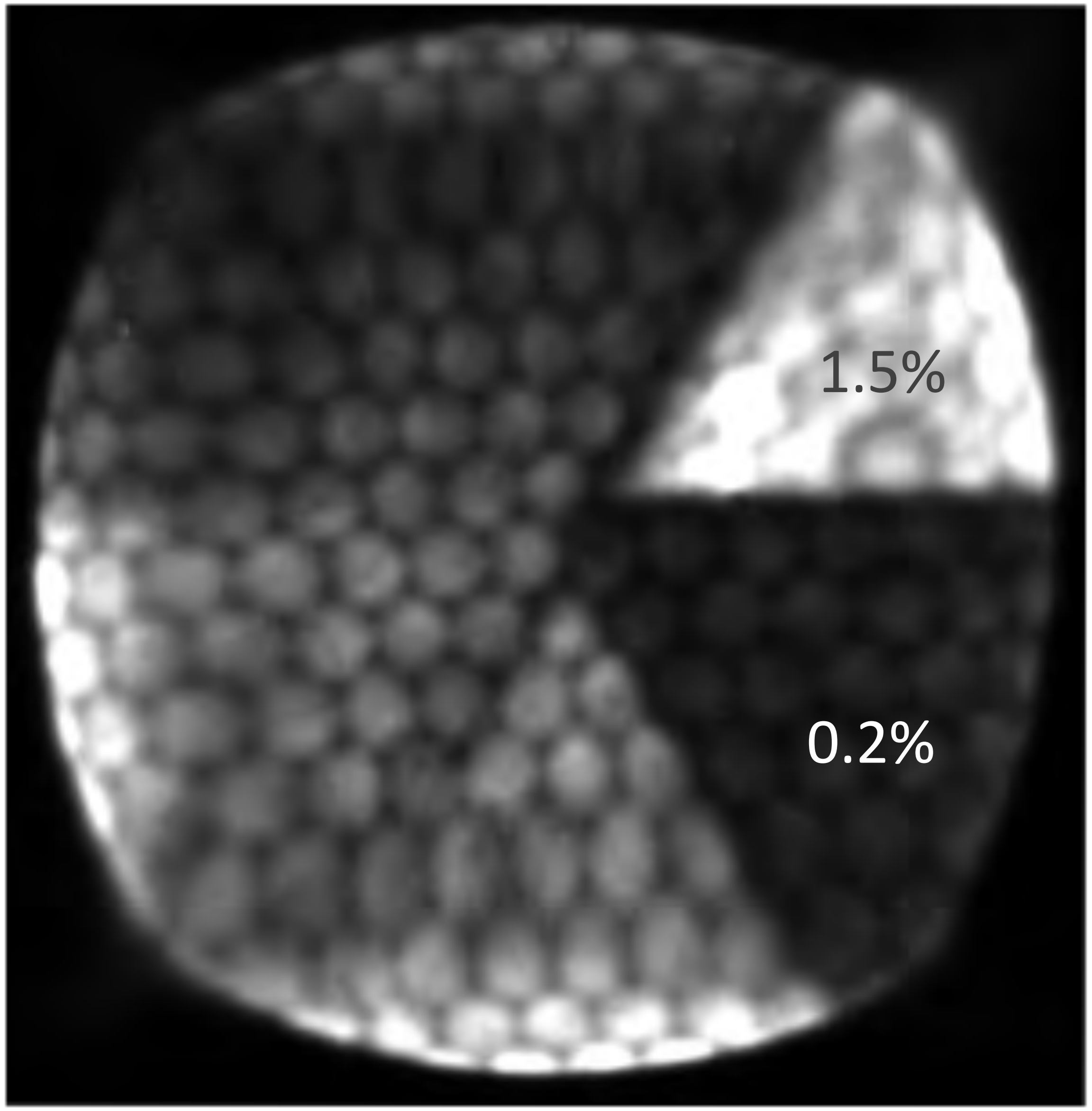




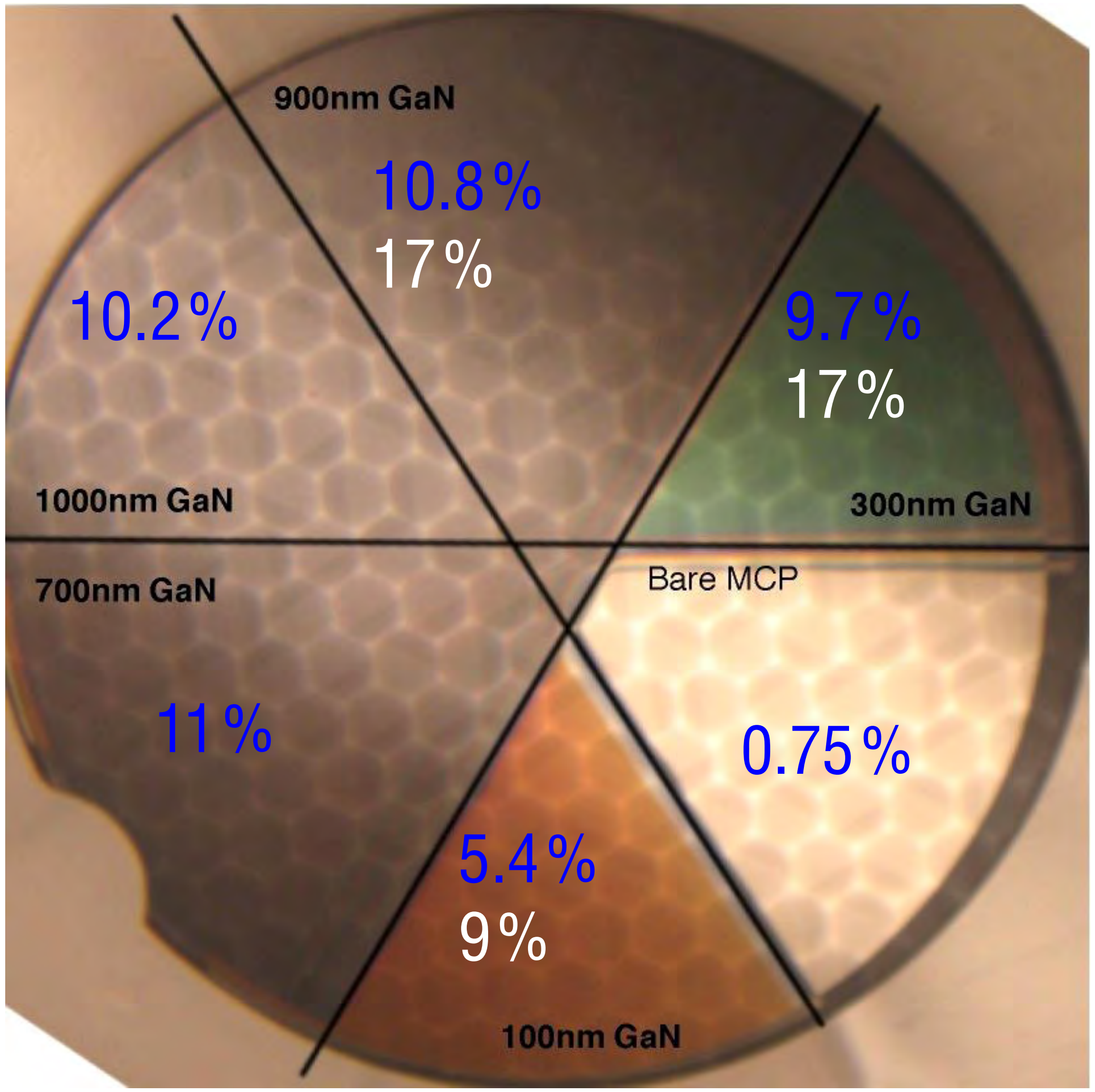
Illustrative Tube Stack

Opaque GaN Deposited on 33mm ALD MCP

Borosilicate/ALD MCP coated by MBE with P-doped GaN/AlN of various thicknesses (amorphous/polycrystalline) and tested in a photon counting imaging detector



Integrated photon counting image using 184 nm UV shows unprocessed GaN layer response vs bare MCP.



QEs (@214nm UV) measured after Cs. 10º (blue) or 45º (white) graze angle. Typical QE- thickness asymptote for opaque cathode.

General procedures for Fabrication of MCPs

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

For fabricating one pair MCPs:

~20-30hrs

if everything is right

courtesy Qing Peng, Argonne ALD Group