Development of Large-Area Fast Micro-channel Plate Photo-detectors

Marcel Demarteau
Argonne National Laboratory

for the LAPPD collaboration

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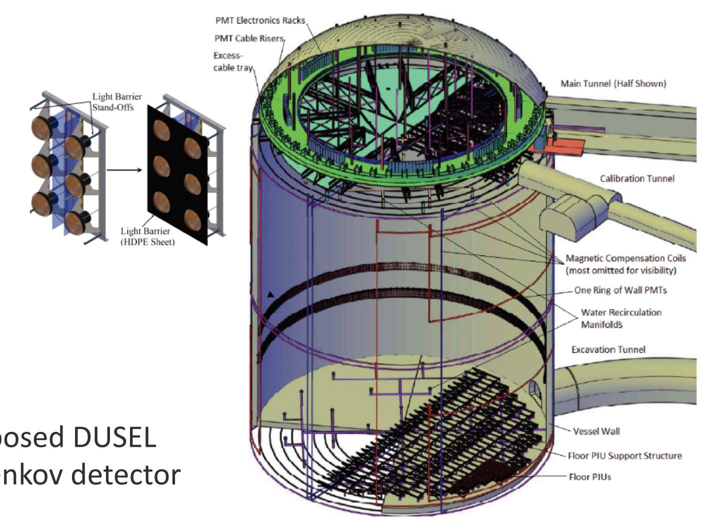
Outline

- Introduction
- Photo-Detector Development
  - Photo-cathodes
  - MCP
  - Anode and signal readout
  - Mechanical Design
- Simulations and Testing
- Concluding remarks

Photo Multiplier Tubes

- “Old” Technology
  - Used for decades
  - Robust, generally low noise
  - Simple biasing
- Time resolution ~2-3 nsec
- Spatial resolution limited by tube radius
- Total coverage offered is typically (much) less than 40%
- Typical photocathode efficiency ~25%
- Few vendors

- Can this technology address the challenges of the next generation of e.g. H_2O Čerenkov experiments?



Proposed DUSEL Čerenkov detector

Large-Area Photodetectors

Large-Area Pico-second Photo Detector (LAPPD)

- Newly funded by DOE and NSF (fall '09)
  - 4 National Labs
  - 5 Divisions at Argonne
  - 3 US small companies;
  - Electronics expertise at UofC and Hawaii
  - Photocathode expertise at Washington University, St. Louis and UIC
- Premise:
  - Apply advances in material science and nanotechnology to develop new, batch methods for producing cheap, large area photo-detectors
  - Improvement in at least one performance parameter by an order of magnitude
  - Develop path to a commercializable product
- Project currently in its third year
  - http://psec.uchicago.edu/

Large Area Picsecond Photodetector Collaboration

John Anderson, Karen Byrum, Gary Drake, Henry Frisch, Edward May, Alexander Paramonov, Mayly Sanchez, Robert Stanek, Robert G. Wagner, Hendrik Weerts, Matthew Wetstein, Zikri Zusof

High Energy Physics Division, Argonne National Laboratory, Argonne, IL

Bernhard Adams, Klaus Attenkofer, Mattieu Chollet

Advanced Photon Source Division, Argonne National Laboratory, Argonne, IL

Zeke Insepov

Mathematics and Computer Sciences Division, Argonne National Laboratory, Argonne, IL

Mane Anil, Jeffrey Elam, Joseph Libera, Qing Peng

Energy Systems Division, Argonne National Laboratory, Argonne, IL

Michael Pellin, Thomas Prolier, Igor Veryovkin, Hau Wang, Alexander Zinovev

Materials Science Division, Argonne National Laboratory, Argonne, IL

Dean Walters

Nuclear Engineering Division, Argonne National Laboratory, Argonne, IL

David Beaulieu, Neal Sullivan, Ken Stenton

Arradiance Inc., Sudbury, MA

Sam Asare, Michael Baumer, Mircea Bogdan, Henry Frisch, Jean-Francois Genat, Herve Grabas, Mary Heintz, Sam Meehan, Richard Northrop, Eric Oberla, Fukun Tang, Matthew Wetstein, Dai Zhongtian

Enrico Fermi Institute, University of Chicago, Chicago, IL

Erik Ramberg, Anatoly Ronzhin, Greg Sellberg

Fermi National Accelerator Laboratory, Batavia, IL

James Kennedy, Kurtis Nishimura, Marc Rosen, Larry Ruckman, Gary Varner

University of Hawaii, Honolulu, HI

Robert Abrams, valentin Ivanov, Thomas Roberts

Muons, Inc., Batavia, IL

Jerry Va'vra

SLAC National Accelerator Laboratory, Menlo Park, CA

Oswald Siegmund, Anton Tremsin

Space Sciences Laboratory, University of California, Berkeley, CA

Dimitri Routkevitch

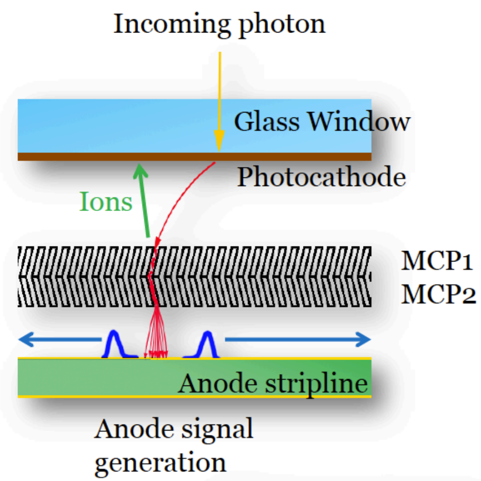
Synkera Technologies Inc., Longmont, CO

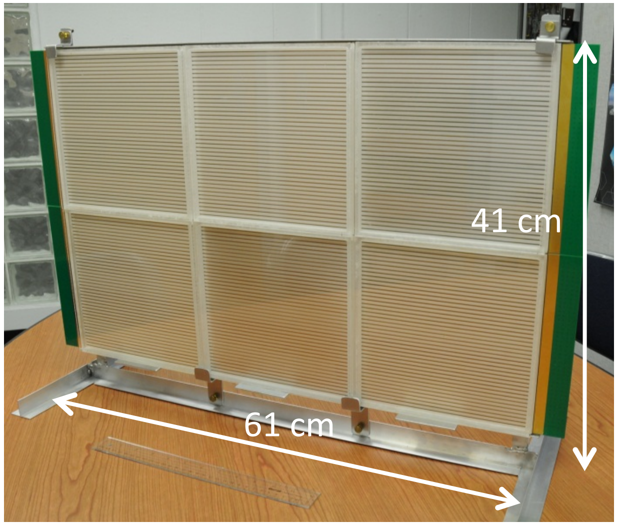
David Forbush, Tianchi Zhao

Department of Physics, University of Washington, Seattle, WA

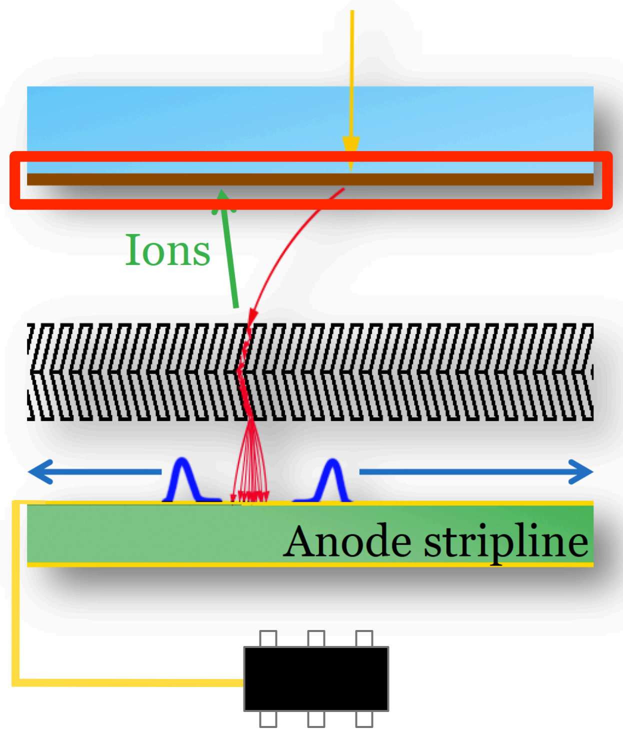
LAPPD: Approach

- Based on Existing Technology: Micro Channel Plate (MCP) photo-multiplier
- Fully integrate advances in material science and electronics to produce large-area MCP-PMTs:
  - Preserve and improve on time and space resolutions of conventional micro-channel plate detectors
  - At low enough cost per unit area





LAPPD Deconstructed



1. Photo-Cathode (PC)
   - Conversion of photons to electrons
   - Engineer III-V materials to develop robust high QE photo-cathodes
2. Micro-Channel Plates
   - Amplification of signal: two plates with tiny pores, held at high potential difference. Use Atomic Layer Deposition for emissive material on inert substrates to create avalanche
3. Electronics
   - Transmission line readout: 50Ω scalable strip line, silk-screen printed on glass ground plane
   - Readout at both ends with fast custom CMOS SCA chip with 10GHz waveform digitization
4. Hermetic Packaging
   - Maintain vacuum and provide support. No internal connections; no penetrations

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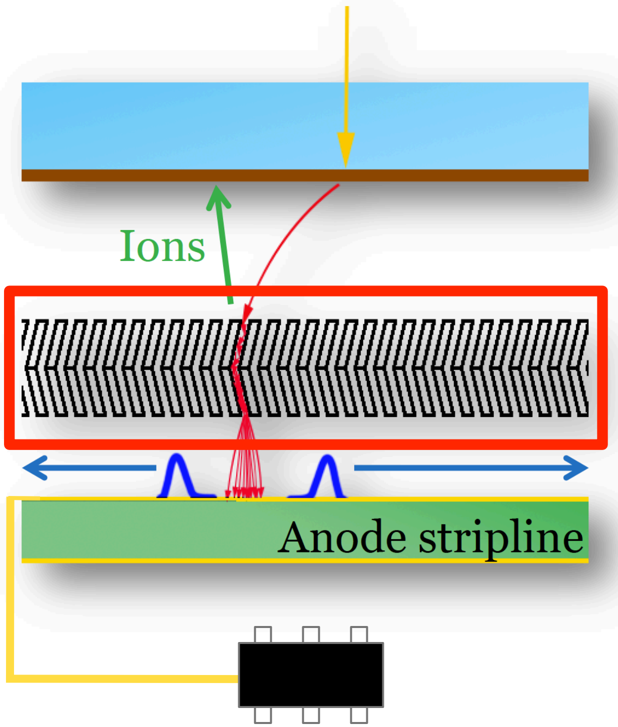

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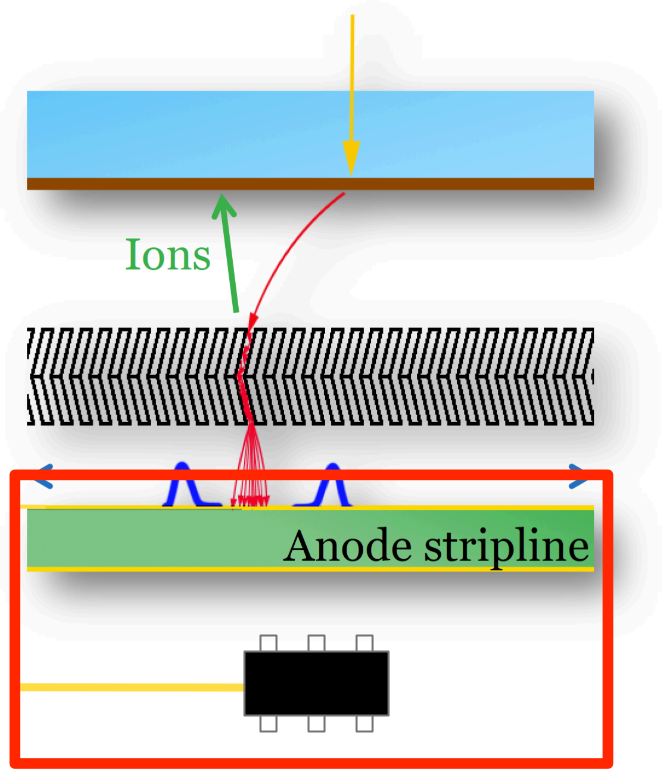

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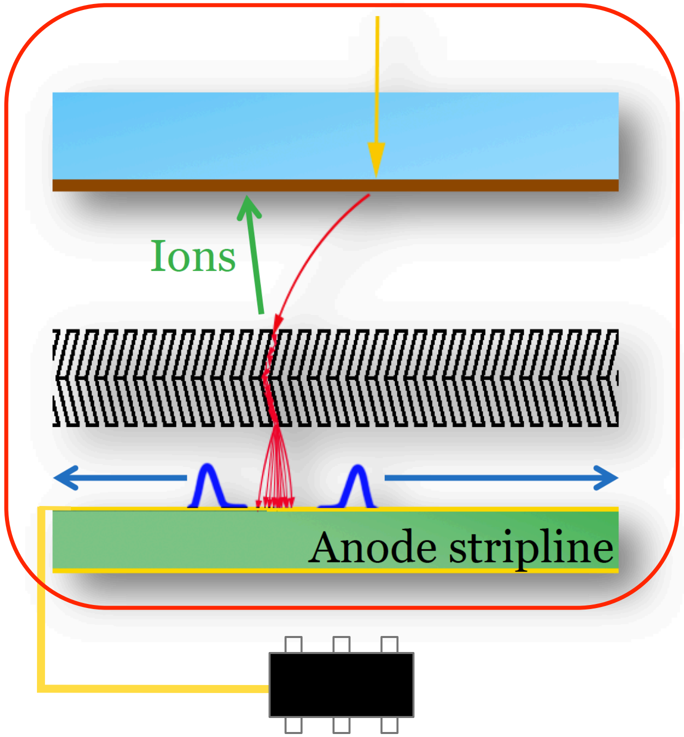

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Photo-Cathode Thrusts

- Space Science Laboratory, Berkeley:
  R&D focus on scaling up of traditional bi-alkali to larger area
- ANL/Wash U/UICU:
  R&D focus on theory inspired design
  - New novel photocathode technologies like nano-structured photocathodes
  - III-V have the potential for high QE, shifting toward the blue and robustness
  - Simulations, testing & characterization
- Argonne:
  R&D focus on design for industrial production of large-area photocathodes for a tile factory
  - In the process of setting up in-house photo-cathode production facility

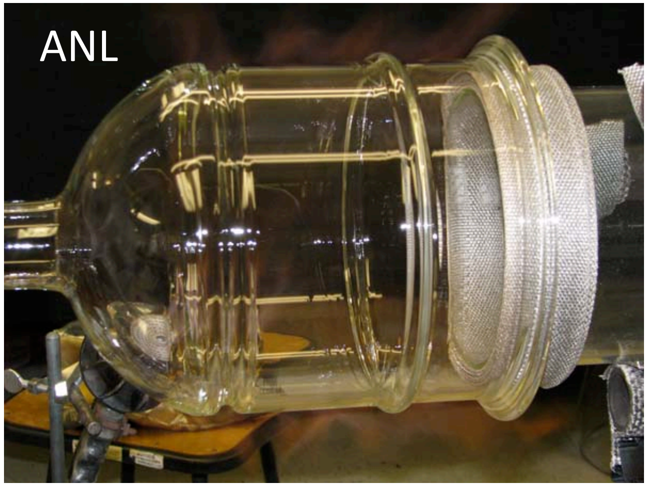
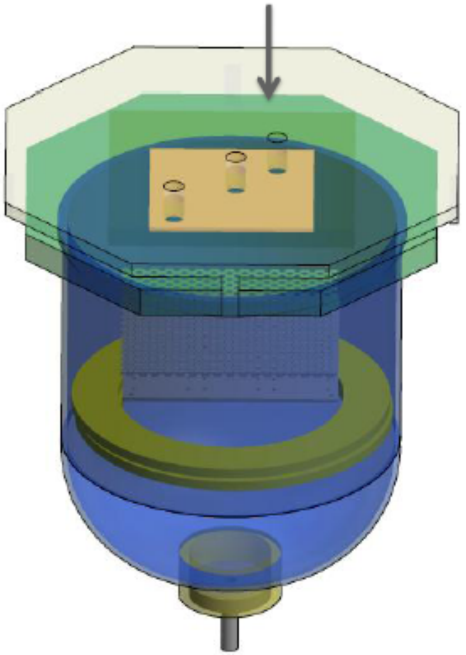


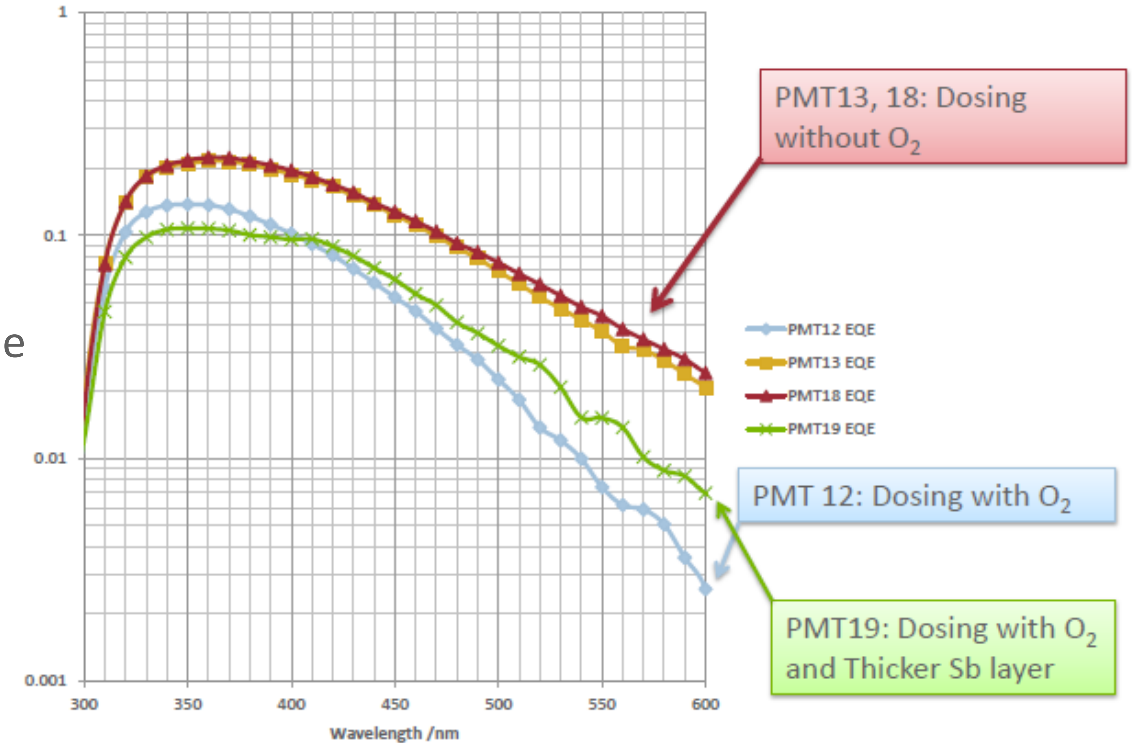
Photo-Cathode Growth at ANL

- Goal of the LAPPD project is to shoot photo-cathodes with 20-25% QE on 8"-square glass substrate
- Photocathode growth similar to traditional PMT method
  - Metal beads activated by current heating
  - Use evacuated glass containment vessel with bead support structure and detachable top window
- PMT processing equipment obtained from Burle Industries
- Process:
  - Grow photocathodes following Burle 'recipe' in evacuated tubes
  - Extend process to $10x10cm^2$ photocathodes in large evacuated glass vessel
  - Extend process to $20x20cm^2$ photocathodes for tile production

PMT Growth

- Multi-alkali (K, Sb, Cs) Photo-tubes grown at Argonne and characterized
- System calibrated with HPK reference tube
- Results cross-checked at Burle



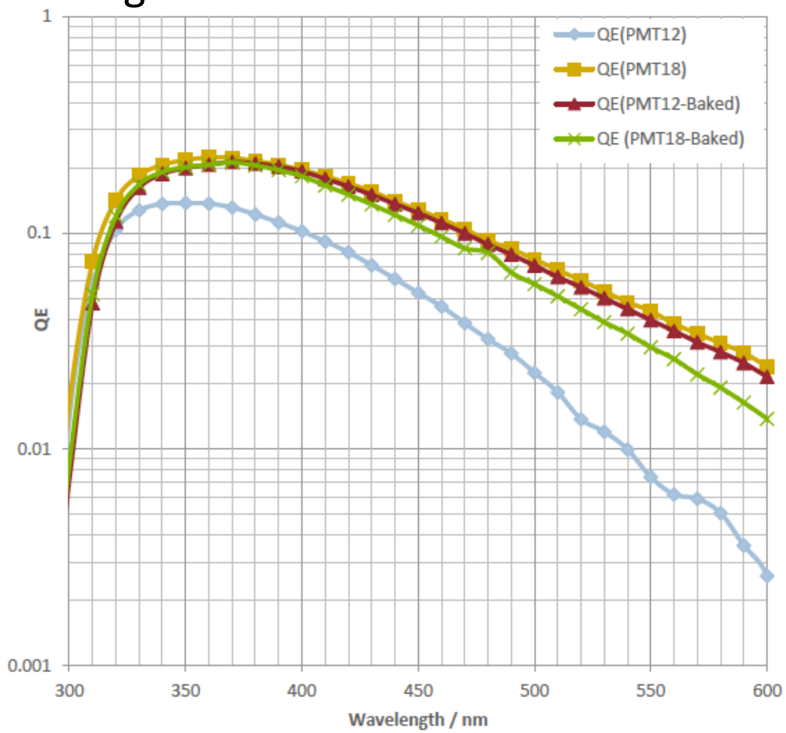


- In the process of transferring growth ‘recipe’ to 10x10cm^2 photocathodes on glass substrate, following same recipe
- Characterization in situ (not during growth)

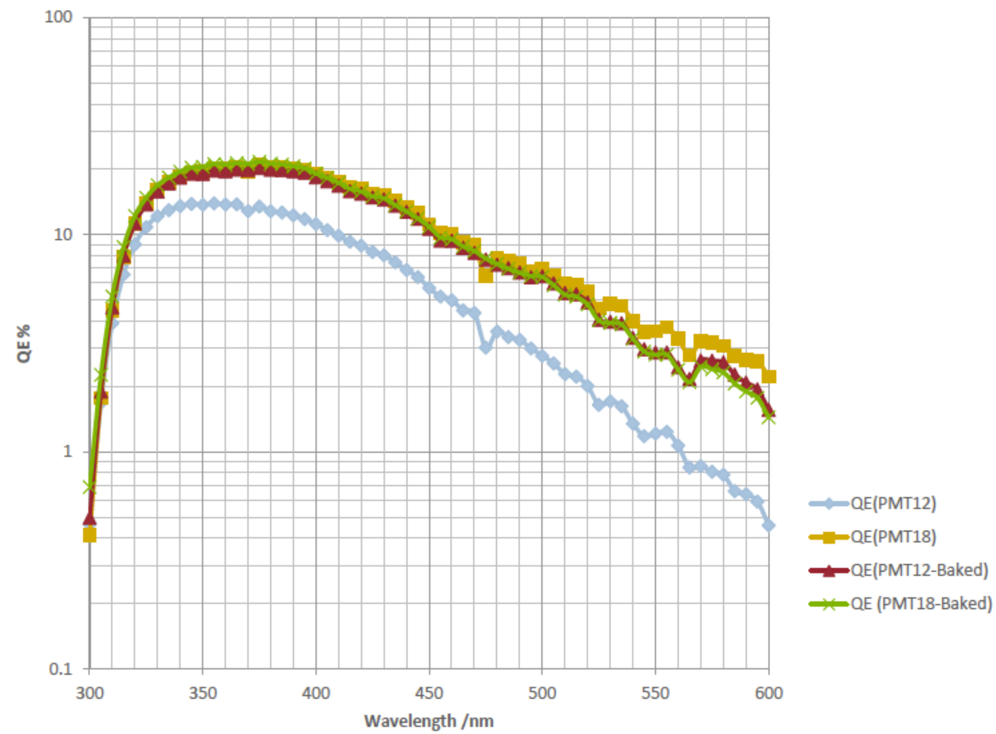
PMT Characterization Cross Check

- Tubes produced and measured at Argonne sent to Burle/Photonis for cross-check

Argonne Measurement

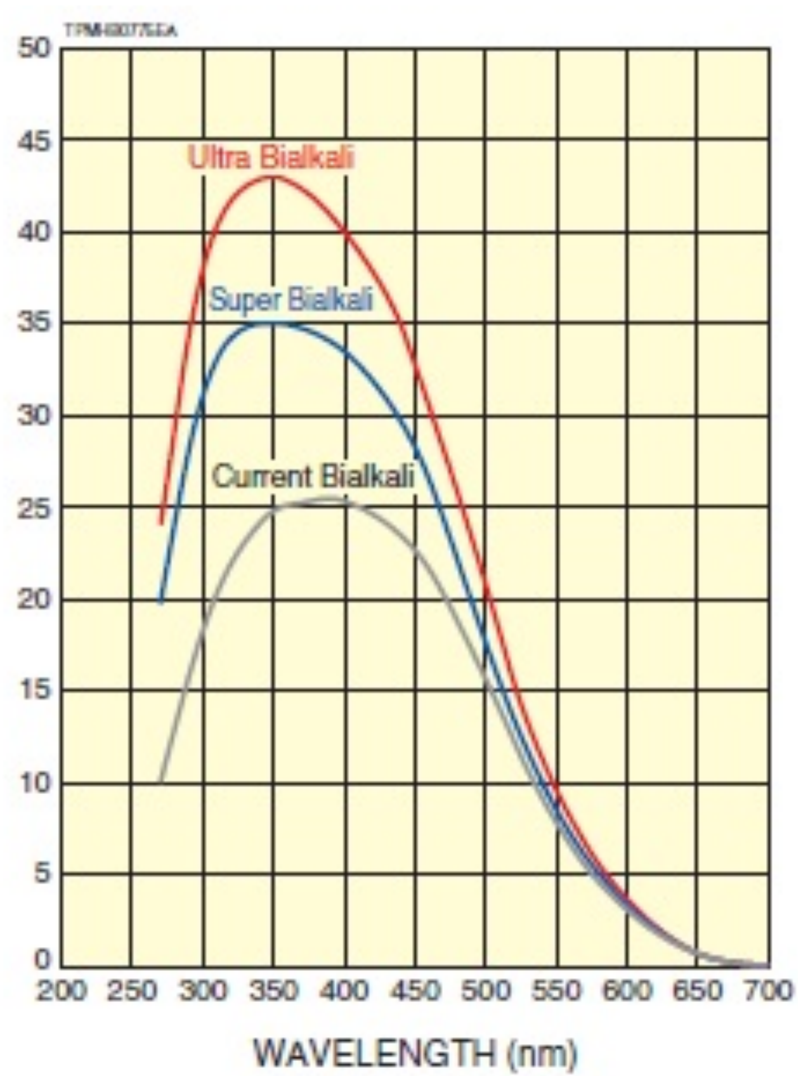


Photonis Measurement



- At Photonis, both phototubes wire cleaned (hot acid solutions), followed by oven bake 140 °C for 2 hrs
- ‘Feature’ at 475 nm an artifact from bad data point in the reference device

Photo-Cathode QE



- Three step model:
  - Absorption (reflection losses)
  - Transport to the surface
  - Emission through the surface barrier
- Ways to manipulate the material:
  - Absorption (band gap):
    - Band structure by composition variations
  - Transport (scattering):
    - Electron-electron scattering negligible (if not highly doped)
    - Electron-phonon scattering; very difficult to manipulate
    - Electron-impurity scattering; fully growth related
    - Symmetry break (electric fields)
  - Emission properties
    - Surface composition
    - morphology

Long Term Studies to Optimize Growth Recipe

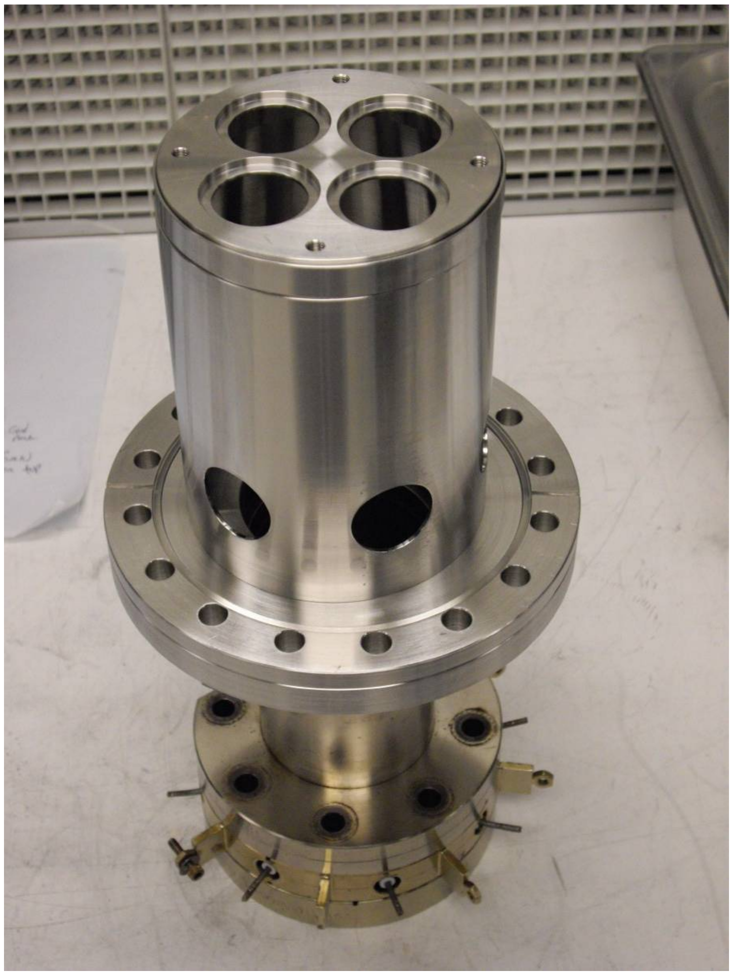
- **Correlation between functionality and structure**
  - The absorption of photons and generation of photoelectrons
  - The transport of the electrons from the point of generation to the surface
  - The escape from the surface

- **Correlation between Recipe and Structure**
  - Temperature / growth rate
  - Composition of materials
  - Grain size and thickness of the film

- **In-situ Visualization Tool of Microscopic Structure**
  - **X-ray Diffraction:** Crystallographic structure, chemical composition, grain size, crystalline orientation
  - **X-ray Reflectivity:** Control of thickness, various defects, surface roughness

Photo-Cathode Growth at SSL

- SSL has years of experience making bi-alkali photocathodes; backup solution for photocathode production



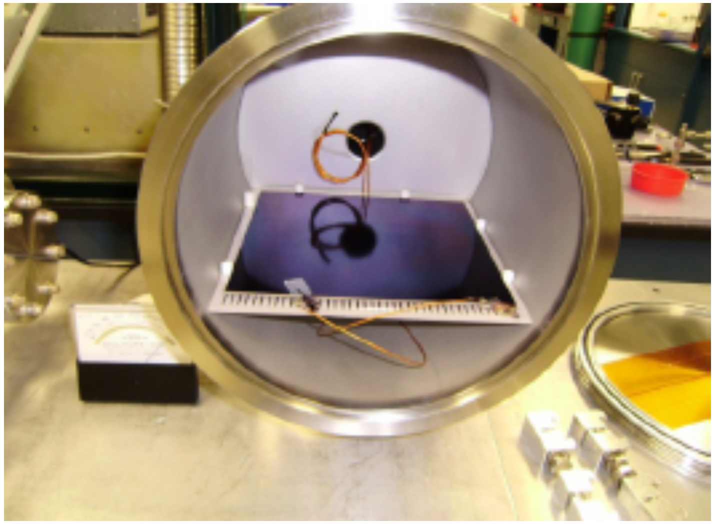
16" tank for full-sized 8.7" windows

Small tank for 1.22" test run samples
Test runs with Fused Silica, Borofloat glass

Micro-Channel Plate Thrusts

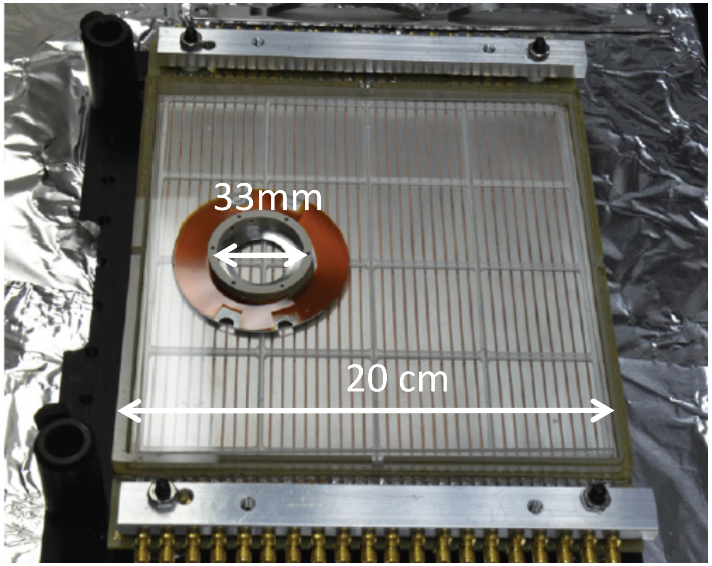
Argonne:

- Atomic Layer Deposition and characterization
  - thickness, uniformity, Resistance
- Gain map in UHV system
- Femto-second laser time/position measurement



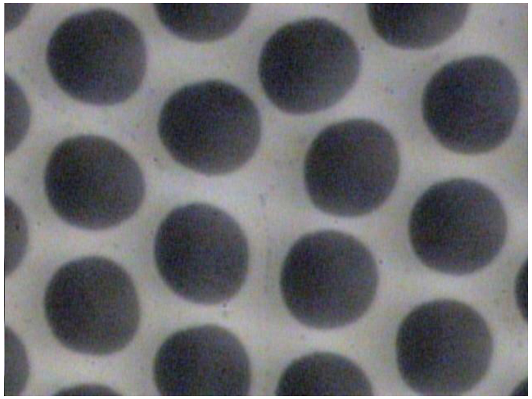
Space Sciences Lab (Berkeley)

- Image quality, gain and uniformity, scrub, spatial resolution

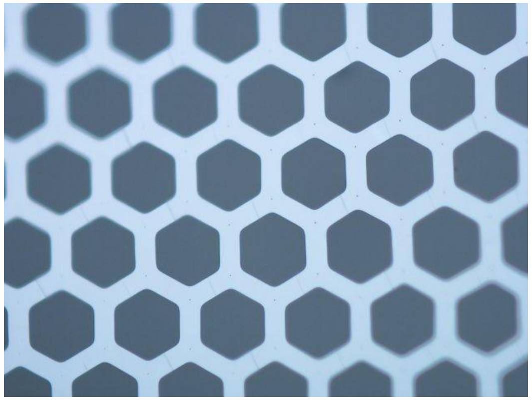


- Two working formats:
  - 33 mm arrays
  - 8”x8” `tile’

MCP Development: Simplifying Construction



Conventional Pb-glass MCP



Incom Glass Substrate

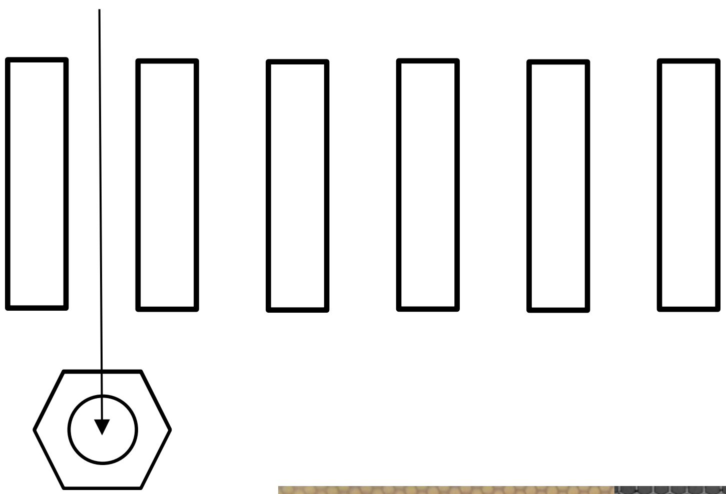
- Chemically produced and treated
- Pb-glass provides 3 functions:
  - Provides pores
  - Resistive layer supplies electric field in the pore
  - Pb-oxide layer provides secondary electron emission

- Separate the three functions:
  - Hard glass substrate provides pores
  - Separate Resistive and Emissive layer functions
  - Produce Tuned Resistive Layer (Atomic Layer Deposition, ALD) provides current for electric field
  - Specific Emitting layer provides secondary electron emission

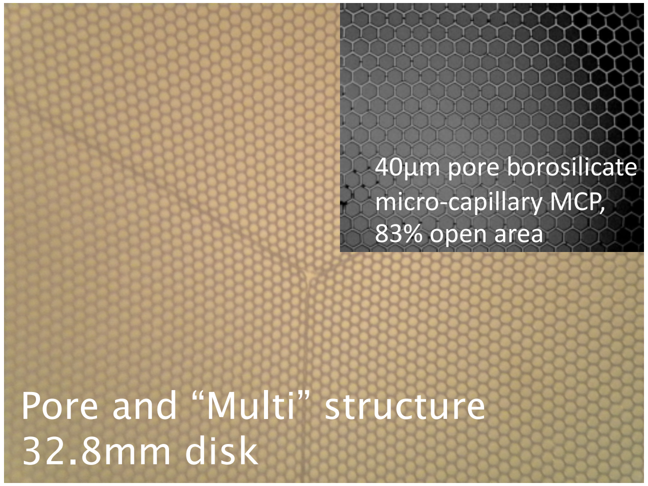
MCP Fabrication with ALD

- Start with glass capillary array (borosilicate), pulled to appropriate pore size; pore size 40, 20 μm, 8 degree bias angle


20 μm pores

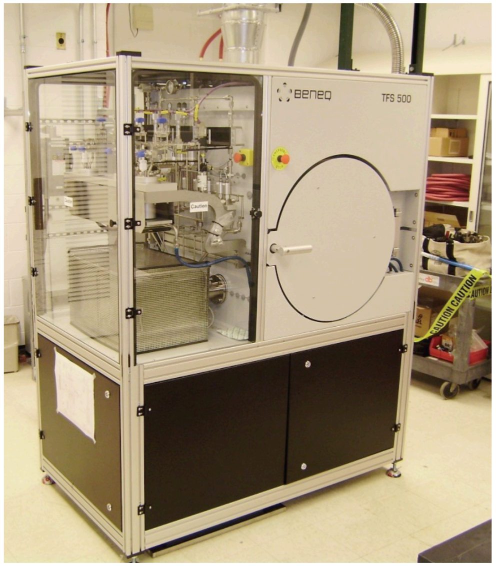


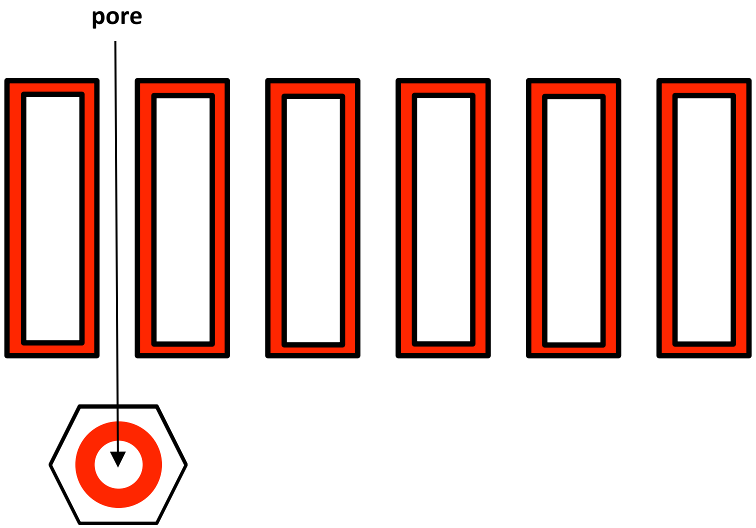
- L/d typically 60:1 but can be much larger.
- Open area ratios from 60% to 83%
- Two form factors: 33 mm circular arrays and 20x20 cm^2 “tiles”



MCP Fabrication with ALD

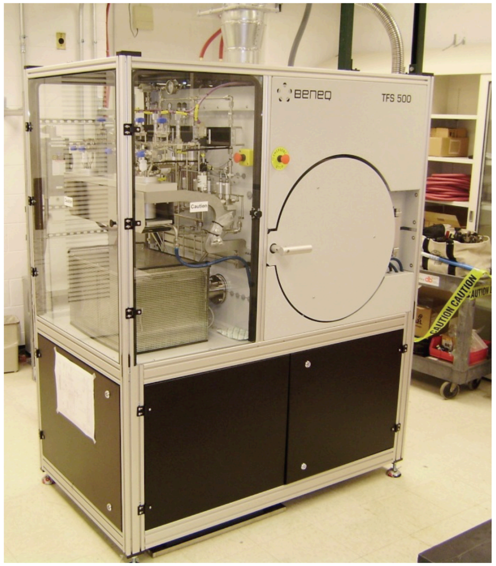
- Apply resistive coating, 17nm, using Atomic Layer Deposition, in Beneq reactor

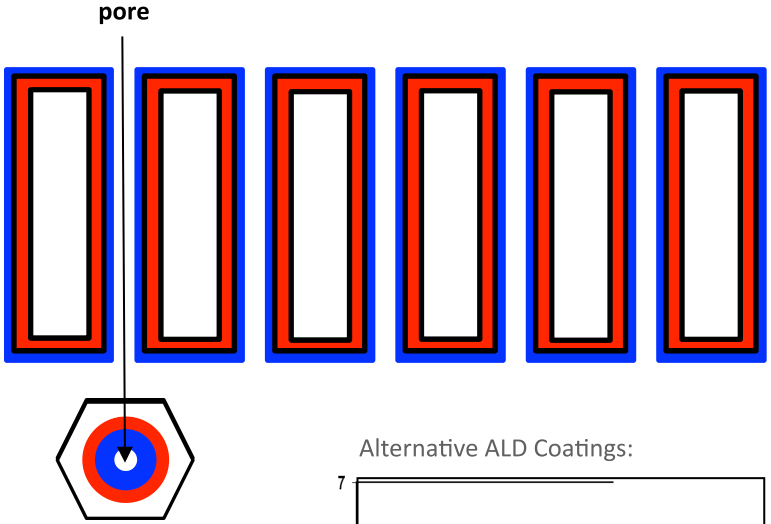




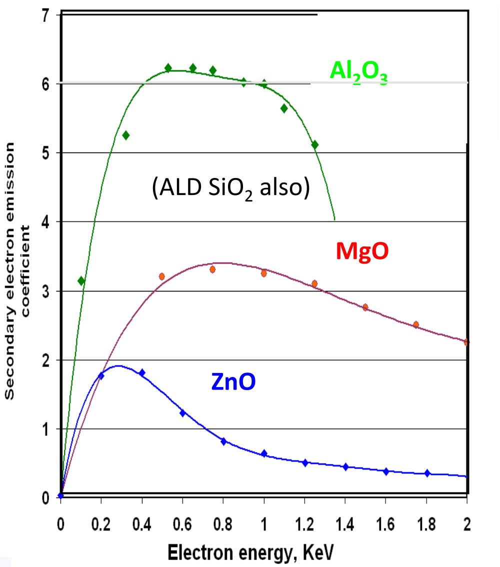
MCP Fabrication with ALD

- Apply emissive Al_2O_3 layer, using using Trimethyl Aluminum $Al(CH_3)_3$ and ALD





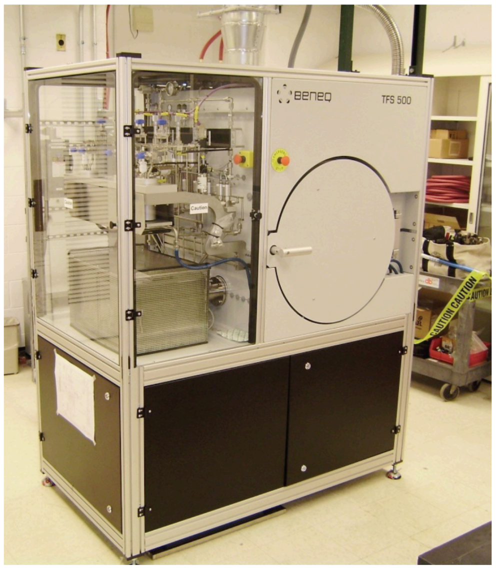
Alternative ALD Coatings:

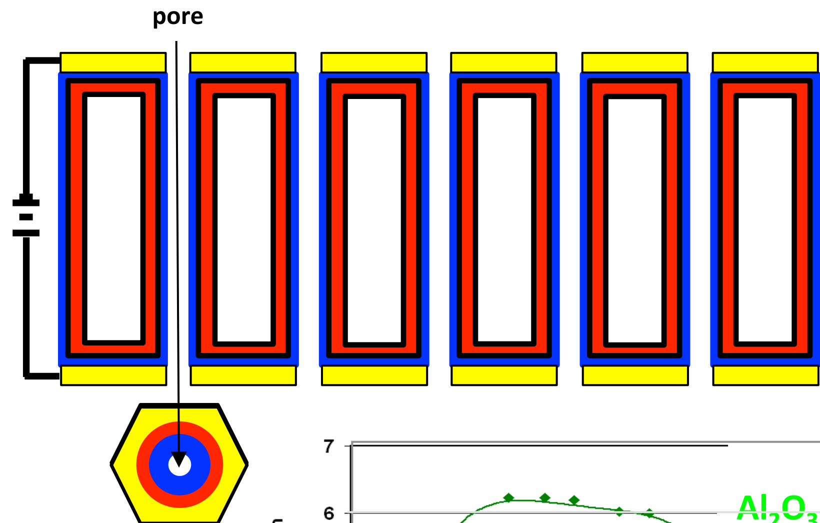


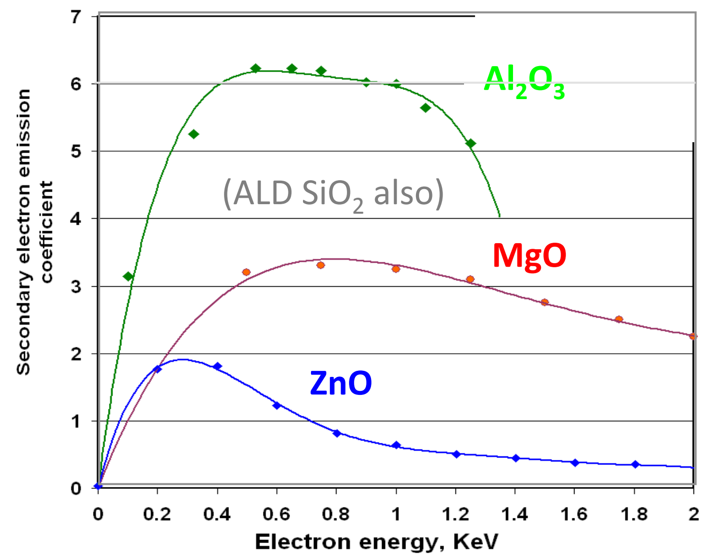
- Wide parameter space studied
  - Relative composition of materials
  - Temperature for ALD
  - Different materials and thicknesses
- Figure shows secondary electron emission coefficient as function of electron energy (keV)

MCP Fabrication with ALD

- Apply conductive coating for HV, using thermal evaporation or sputtering



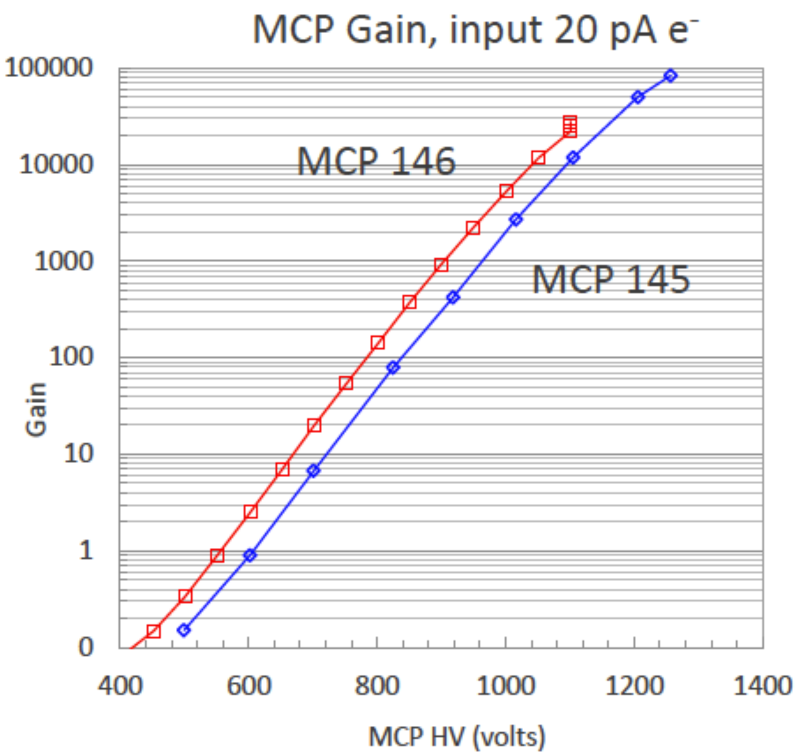




- First time applying new technology, a factor >5 improvement obtained in gain of ALD treated MCPs compared to commercial MCPs; area will be substantially increased

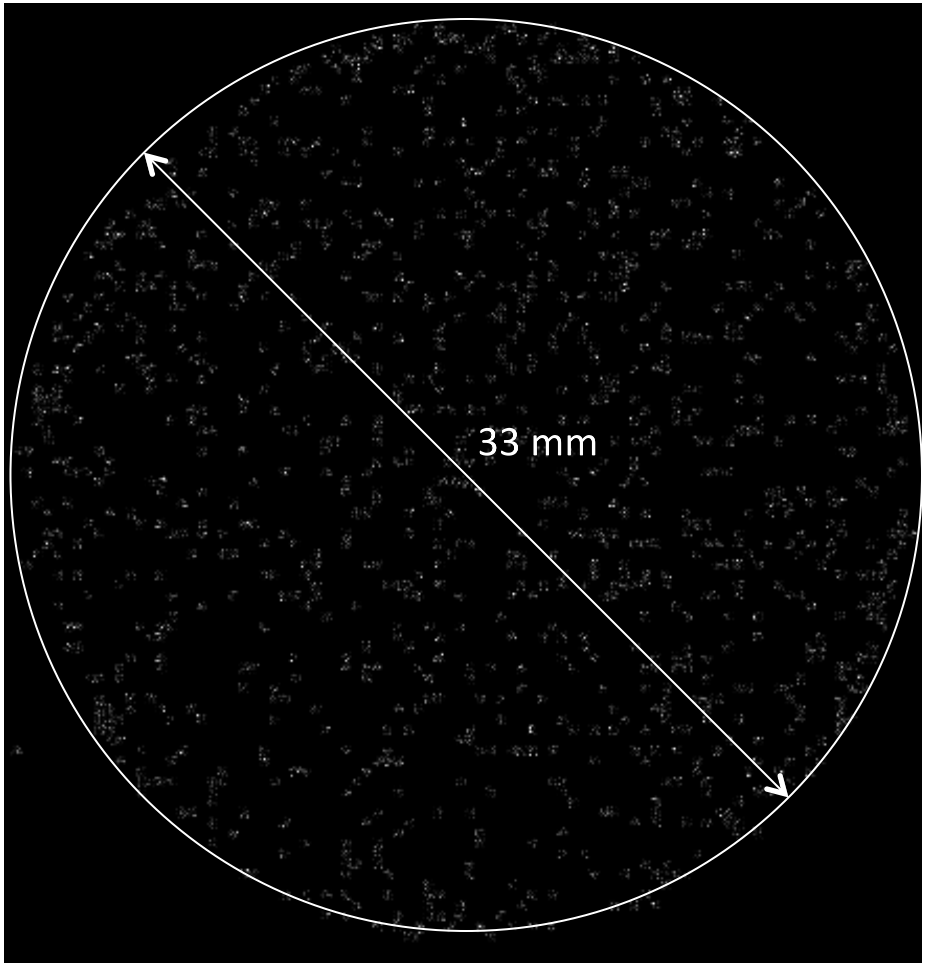
MCP Performance

- Single MCP, 33mm diameter, 20µm pore borosilicate MCP substrate, L:d = 60:1, 8 degree pore bias
- MCP disks functionalized with identical "Chemistry 2" resistive coating and Al_2O_3 SEE layer
- Single MCP tests in DC amplification mo[cut off] imaging and gain very similar to conventional MCPs.
- MCP pair gain of > 10^7 with > 10^5 in a single plate
  - Attractive for cost/simplicity



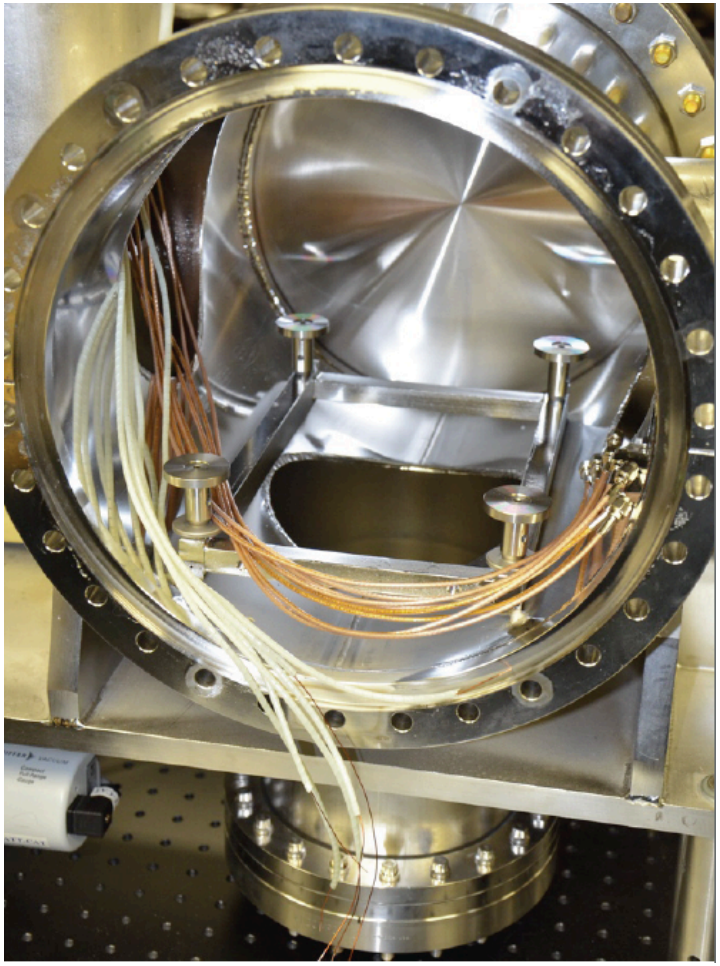
MCP Performance

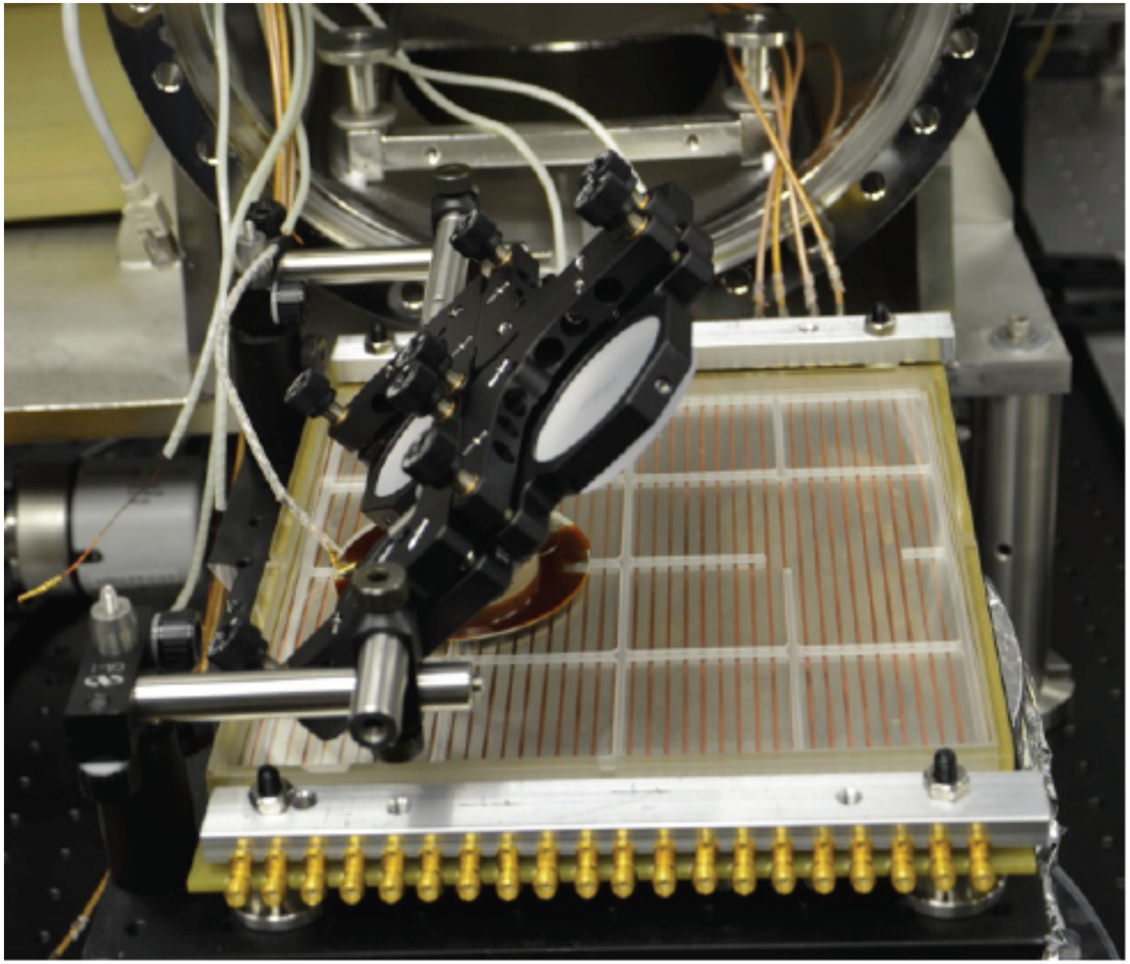
- MCP pair, 20µm pores, 8° bias, 60:1 L/d, 0.7mm pair gap with 300V bias
- 3000 seconds background image from SSL
- Background rate of 0.0845 events cm^{-2} sec^{-1} at 7 x 10^6 gain, 1050 V bias on each MCP
  - Rate compatible with cosmic rate
- Typical behavior
- First look at 8" plates show similar background rates (40µm pore, 40:1 L/d ALD-MCP pair, 0.7mm gap/400 V)



MCP Performance

- UHV Test Chamber setup and commissioned at ANL for testing 20cm MCP tiles



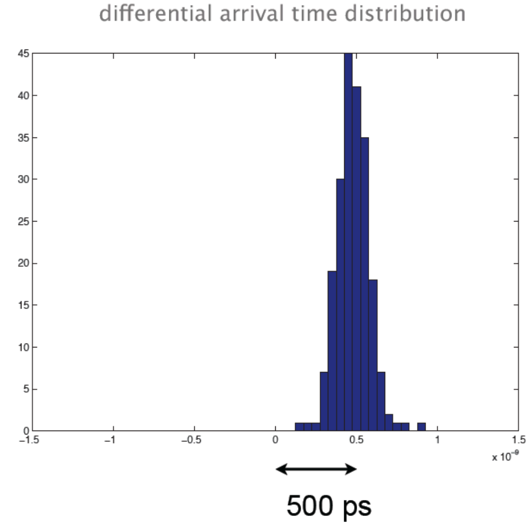


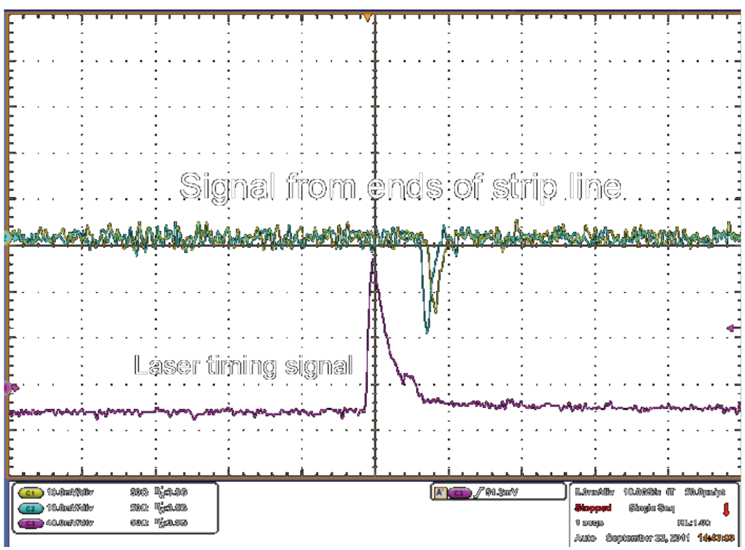
MCP Performance

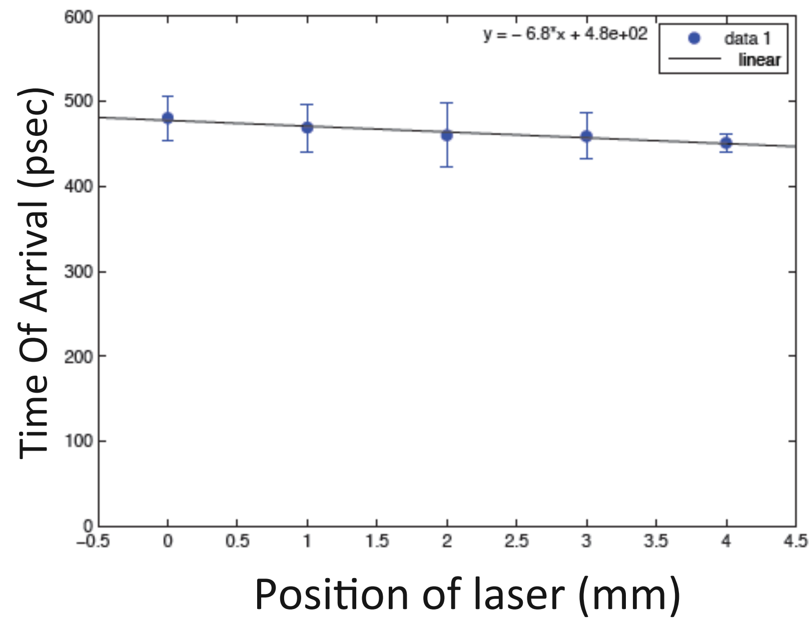
- Response of first single 20cm MCP to femto-second laser
  - Time difference of the 2 ends of the strip: longitudinal pos.
  - Average of the time at 2 ends: arrival time
  - Strip number: transverse position

c = 300 μm/ps

1/c = 3.3 psec/mm

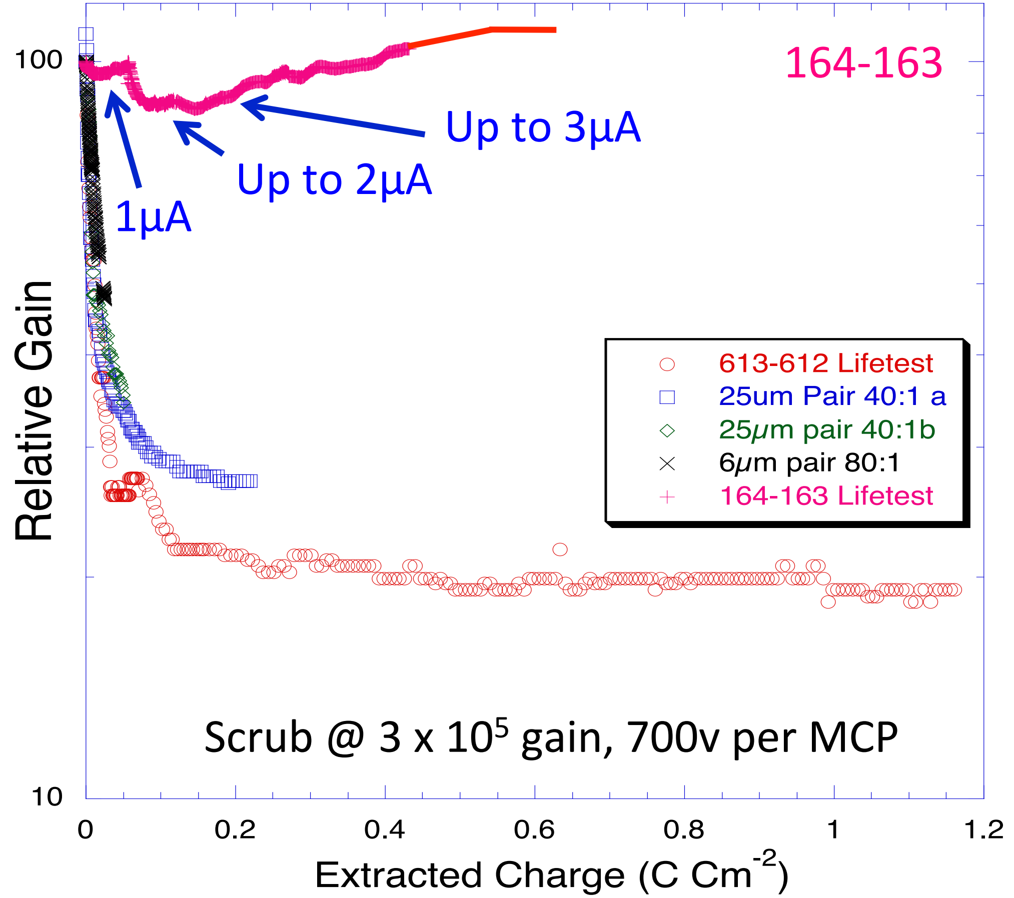






MCP Performance

- MCP pair, 20cm, 20μm, 60:1, 8° bias; Resistances 159MΩ, 138MΩ, NiCr, MCPs gapped by 0.001” spacer
- 350°C bake, with RGA scans
- Scrub at 1μA, 2μA and 3μA,
  - Minimal gain drop for 1 μA to 0.06 C/cm^2, some small H2 outgas (10^{-10} Torr)
  - Faster drop @ 2μA but stabilized quickly with some H2 outgas (4×10^{-10} Torr).
  - At 3μA small drop then recovery to >100% gain – leveling off
- Scrub ongoing at SSL!



MCP Testing Program

Gap 1:

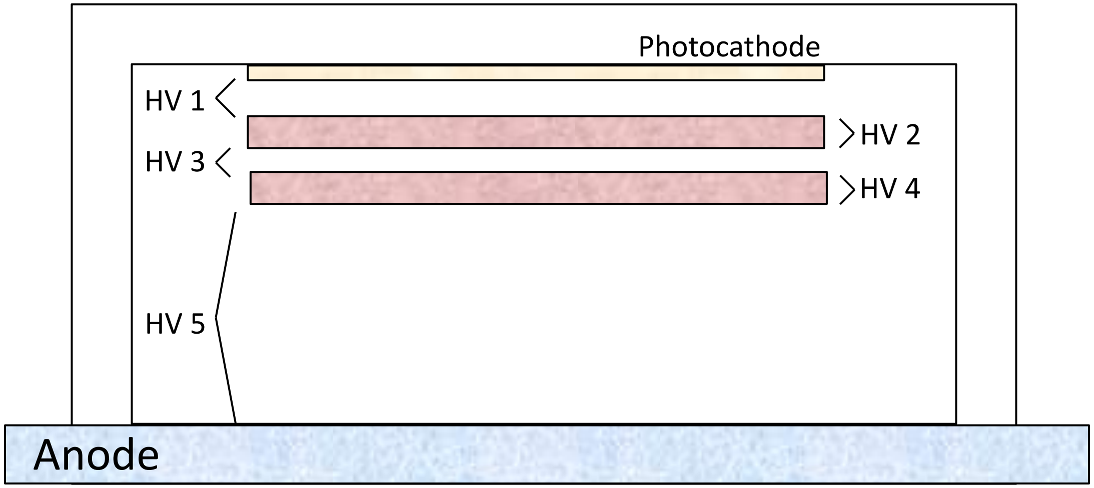
"first strike" impacts variability of transit time and amplification

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.



MCPs:

Operational voltages

Plate geometry: pore size, L/D

MCPs:

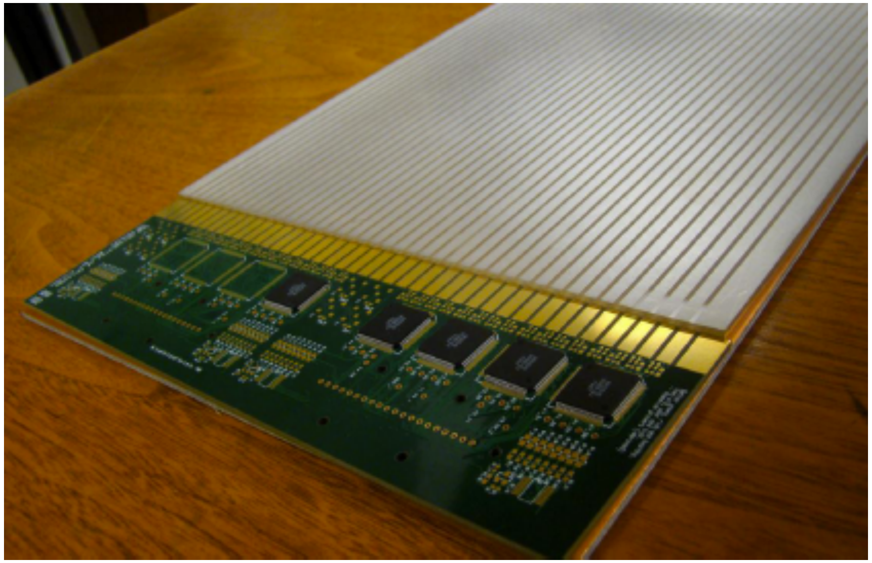
Chemistry: SEE, resistive layer,

Plate quality, Uniformity, Noise, Stability

MCPs:

Plate resistance: Saturation, Relaxation time

Electronics Thrusts



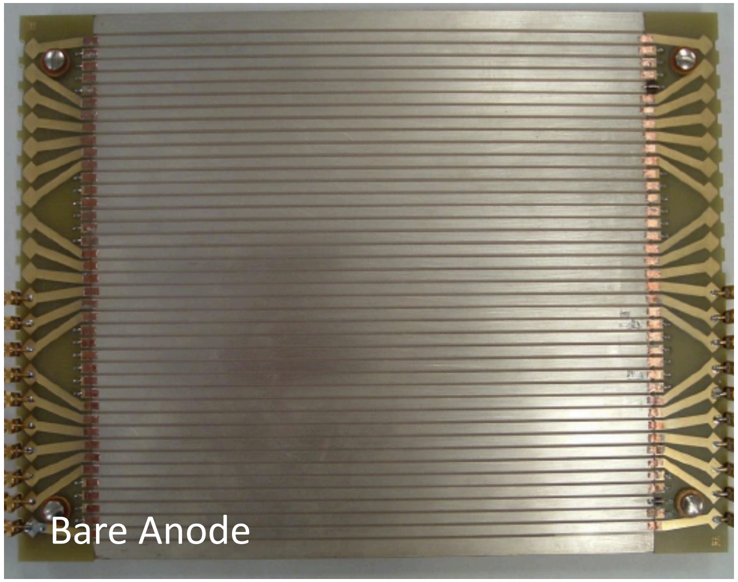
- LAPPD Anode: Transmission line readout
  - 30 microstrip transmission lines (Z_o=50Ω)
  - 0.108” thick glass substrate, 0.182” strip width
- Front-end: Gigahertz waveform digitizing ASICs
  - PSEC4 6-channel ASIC in IBM-8RF 0.13µm process with fast (>10 GSa/s), low-power waveform digitization
- Data Acquisition System
  - Analog Card: 5 PSEC4 ASICs (4 Analog Cards per module)--flexibility allows for integration of alternative front-end ASIC
  - Digital Card: control, trigger handling and calibration

Anode

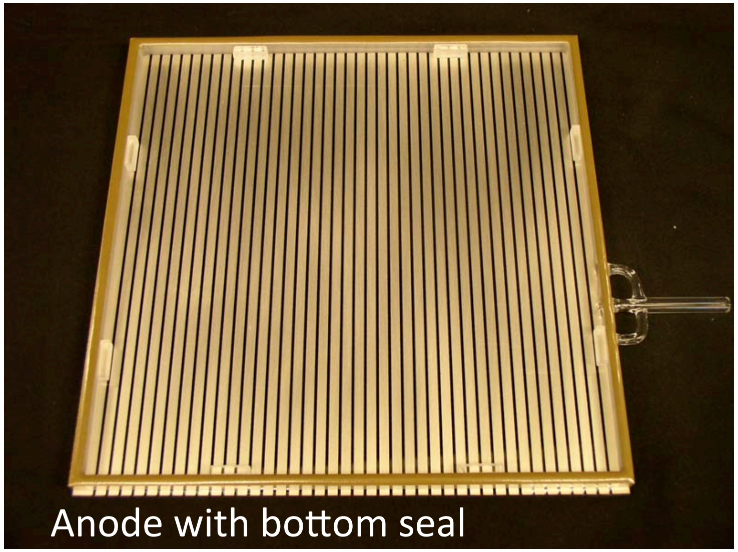
- Anode:
  - Silk-screened, no pins, penetrations, no internal connections
  - Transmission line readout both ends → gets position and time
  - Signal is differential between ground (inside, top), and PC traces (outside)
  - Simulations indicate that these transmission lines could be scalable to large detectors without severe degradation of resolution.

- Cover large areas with much reduced channel count

- Bottom glass seal of edge directly onto strip lines: no penetrations



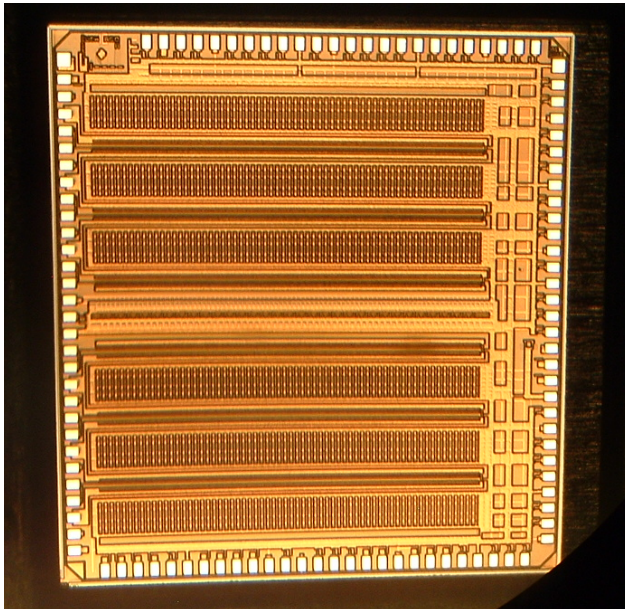
Bare Anode



Anode with bottom seal

PSEC-4

- PSEC-4: 6-channel "oscilloscope on a chip", analog bandwidth of 1.6 GHz, 10-15 GS/s
  - Buffer depth of 256 analog samples on each channel
  - Parallel 1.5 GHz Wilkinson ADC
  - Serial data readout that includes the capability of region-of-interest windowing
  - A switch capacitor array architecture
  - Measured jitter of better than 15ps
  - Sampling rates up to 17 GSa/s
  - RMS noise less than 1mV
- Evaluation board uses USB 2.0 interface and PC data acquisition software



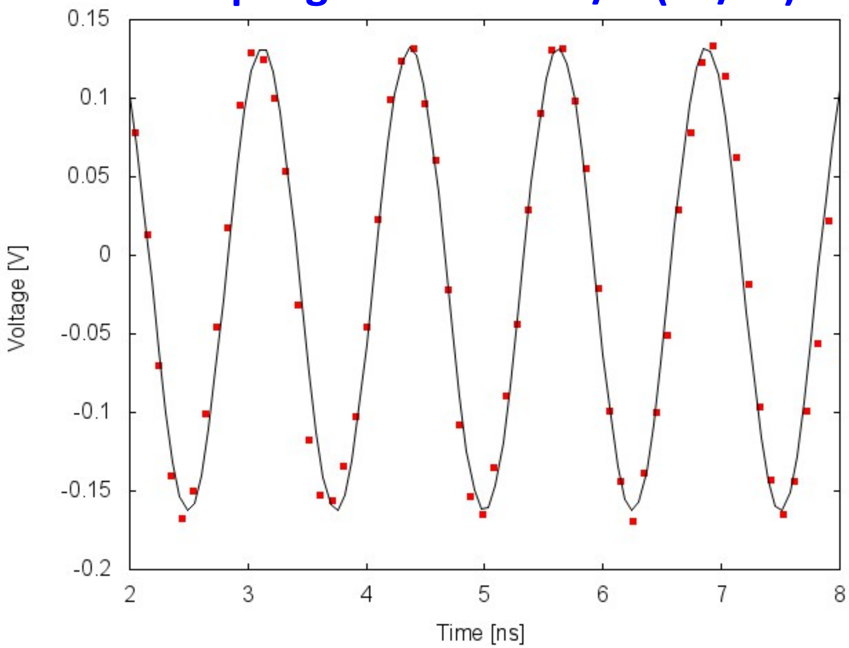
PSEC-4 ASIC

	ACTUAL PERFORMANCE
Sampling Rate	2.5-15 GSa/s
# Channels	6 (or 2)
Sampling Depth	256 (or 768) points
Sampling Window	Depth*(Sampling Rate)$^{-1}$
Input Noise	<1 mV RMS
Analog Bandwidth	1.5 GHz
ADC conversion	Up to 12 bit @ 1.5 GHz
Dynamic Range	0.1-1.1 V
Latency	2 μs (min) – 16 μs (max)
Internal Trigger	yes

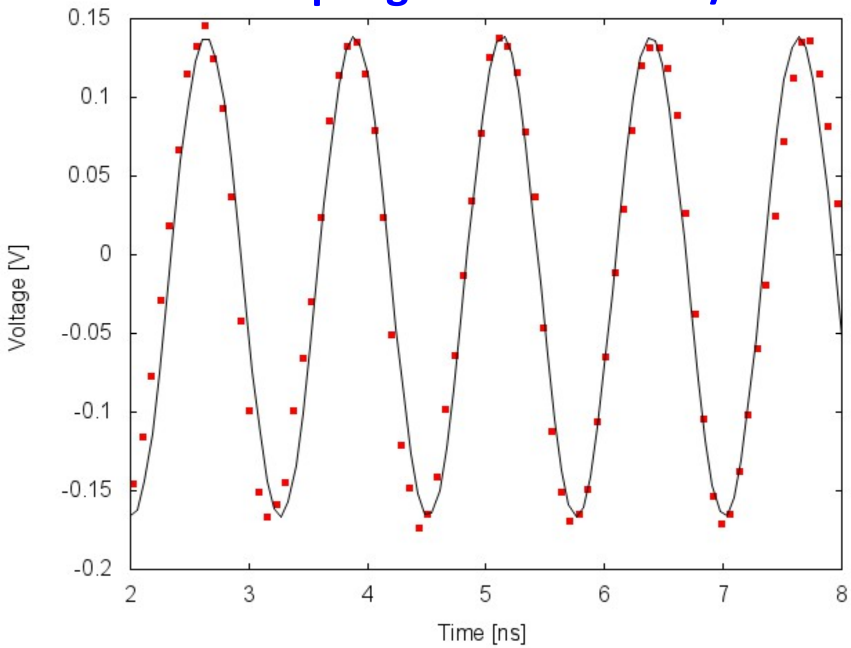
PSEC-4

- Performance with 800 MHz input sine-wave, 300 mV peak-to-peak; digitized waveforms

Sampling rate : 10 GSa/s (10/ns)



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)

DAQ

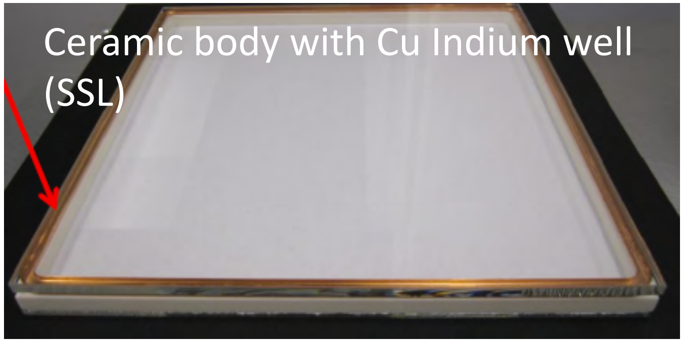
- The DAQ system is targeted towards a module, which is six tiles (large area applications)

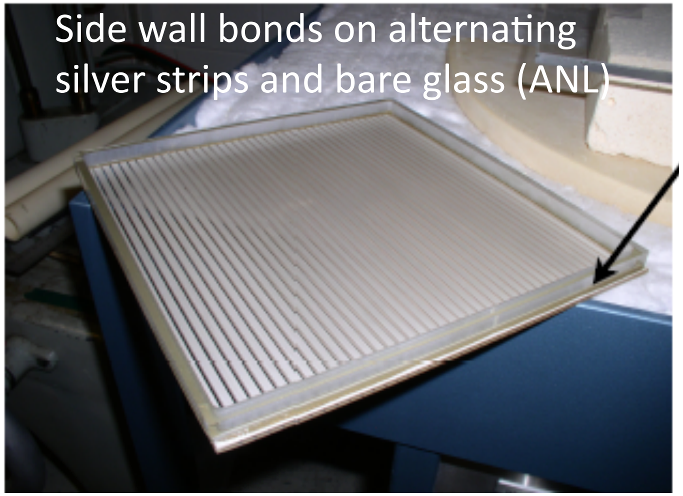
Hermetic Packaging Thrusts

- Two parallel paths: ceramic package at Space Science Lab (Berkeley) and all glass package at ANL

- SSL
  - Ceramic assembly
  - Alumina / Kovar brazing
  - Top seal is hot

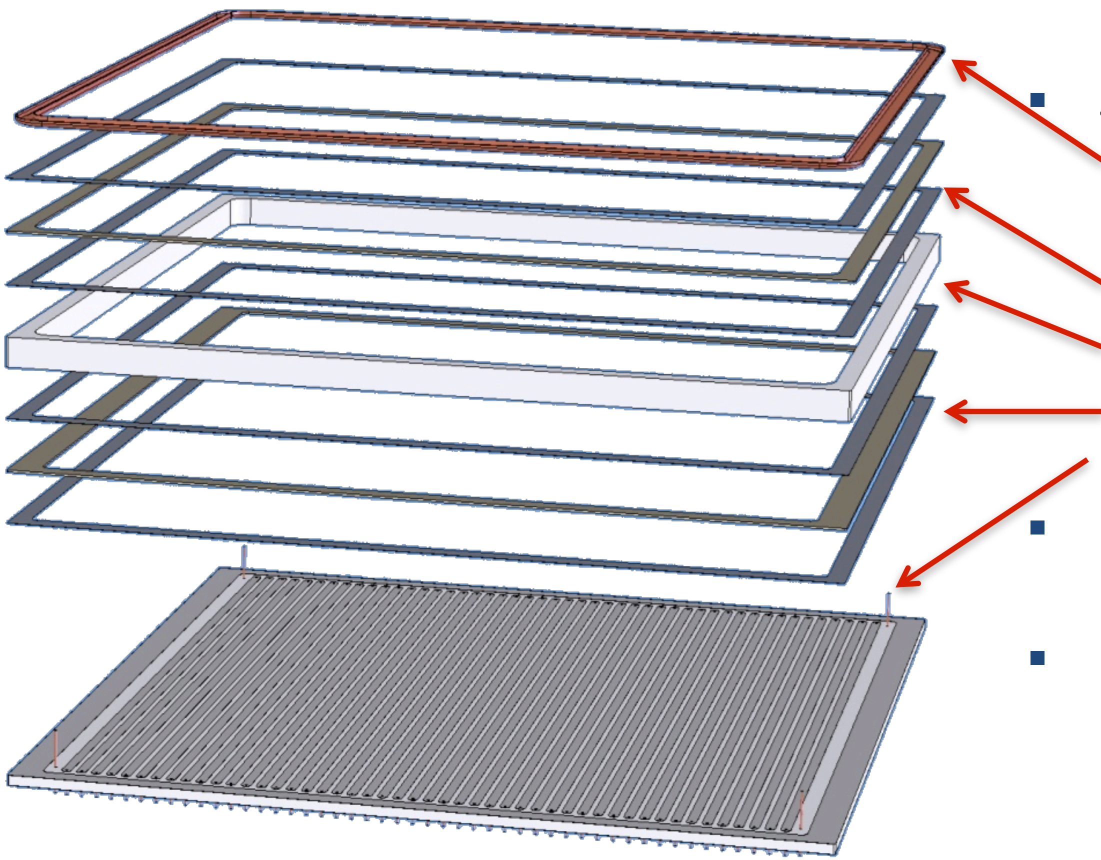
- ANL
  - All inexpensive borosilicate glass for containment vessel
  - No pins penetrating glass for HV and signal
  - Top seal is cold





Ceramic Hermetic Package

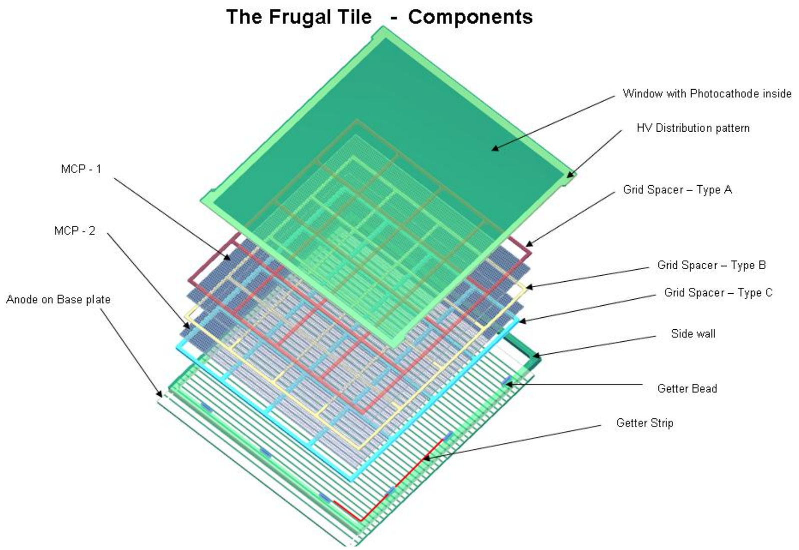
- Use ceramic assemblies, similar to those used by conventional MCPs.
- Well developed technology, know-how available at Space Sciences Lab, Berkeley



- 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

All Glass Hermetic Packaging

- All glass hermetic package:
  - Use inexpensive borosilicate glass for containment vessel
  - Avoid use of pins penetrating glass for HV and signal
  - Cheap, reliable, reproducible containment vessel fabrication



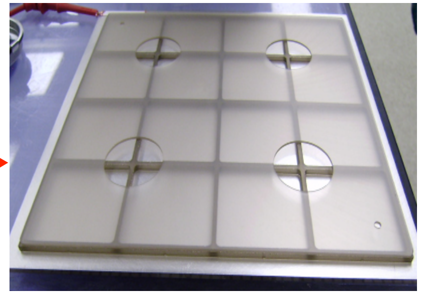
- Constraints:
  - Support vessel against implosive atmospheric pressure
  - Top photocathode window seal at low temp. (<120 C)
  - ~10 yr stability for seal with small leak rate
  - Minimum handling steps in fabrication
  - Avoid particulates in vacuum space
  - Materials chemically compatible with alkali metal photocathode

20cm ALD MCP, with spacer, side wall bonded to base

Construction of (Mock) Tile

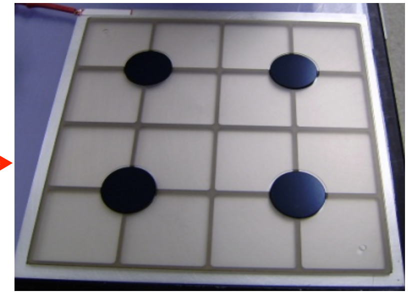
2.97mm bottom Grid Spacer

→



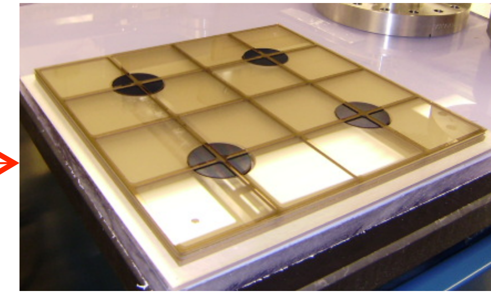
add Mock MCP

→



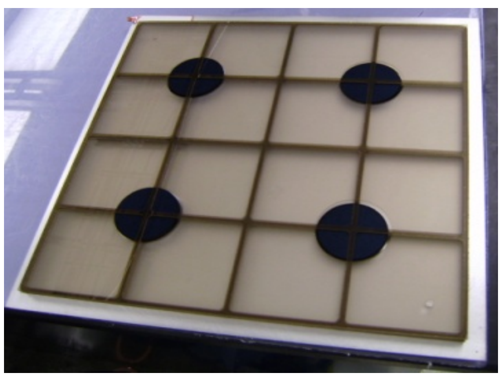
add functionalized MCPs

→



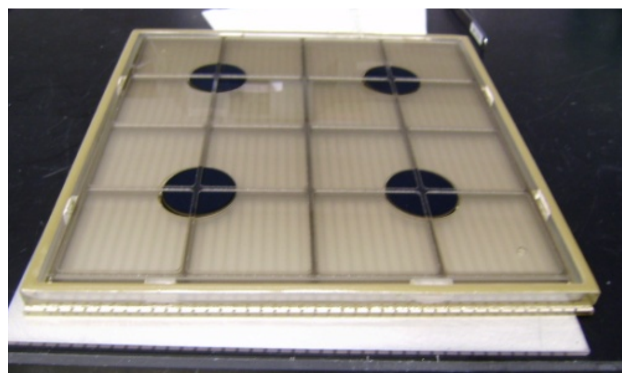
add 1.1mm Grid spacer

→



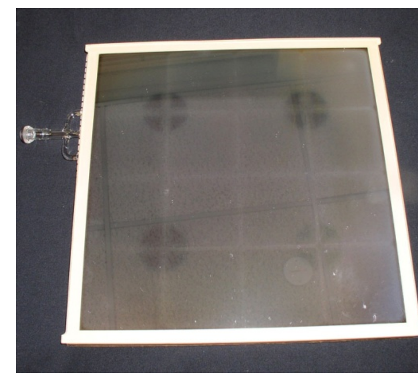
Add mock MCPs, 33mm functionalized MCPs & top 1.1mm Grid spacer

→



full stack in mock tile

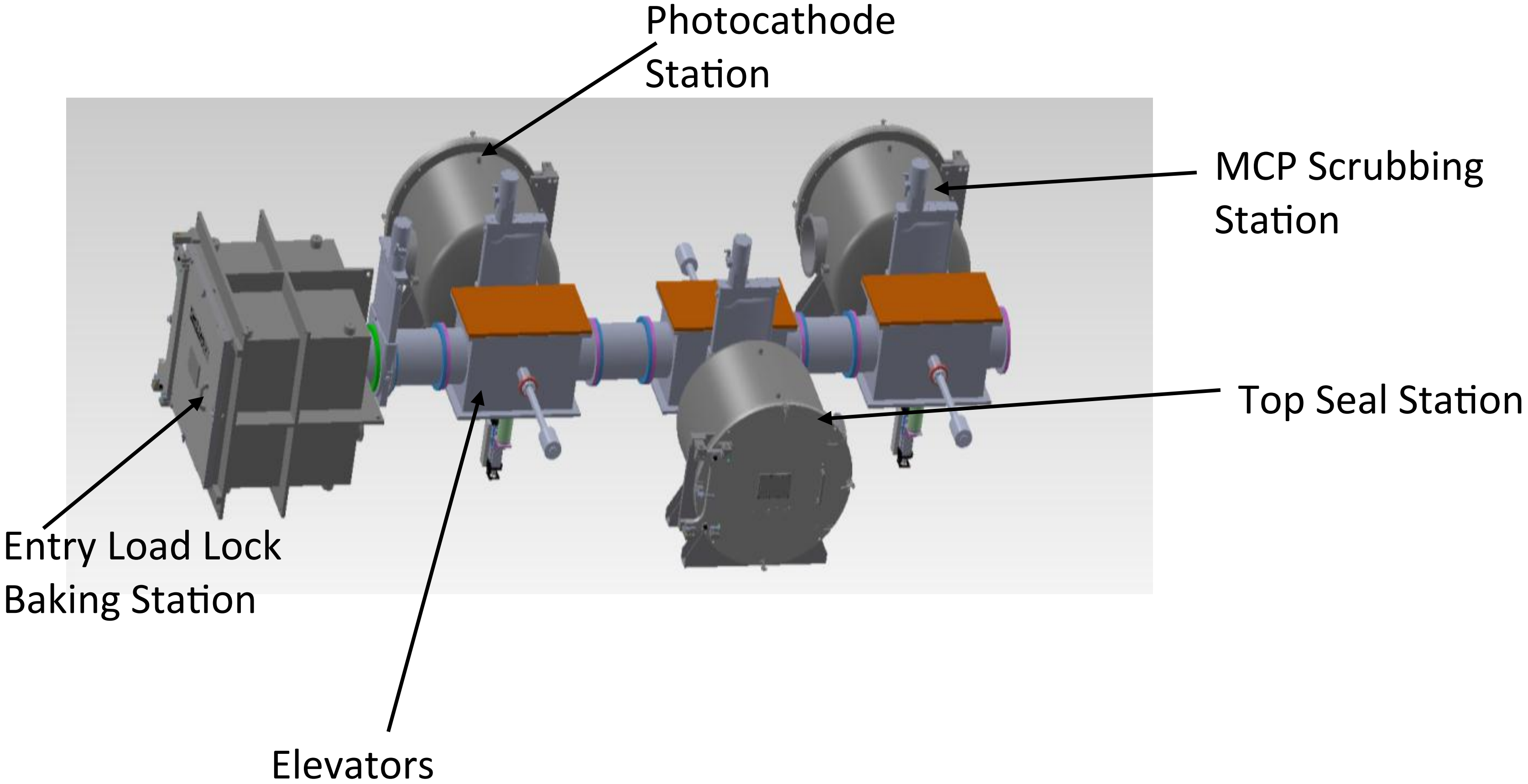
→



Mock tile after sealing and evacuation

Single Tile Production Facility

- Plans are being developed for an all-glass, low temperature, single tile production facility
- Tentative design:



Simulation and Testing

Microscopic/Materials-Level

Material Science Division, ANL

Constructing dedicated setup for low-energy SEE and PE measurements of ALD materials/photocathodes.

parts-per-trillion capability for characterizing material composition.

Berkeley SSL

Decades of experience.

Wide array of equipment for testing individual and pairs of channel plates.

Infrastructure to produce and characterize a variety of conventional photocathodes.

Macroscopic/Device-Level

HEP Laser Test Stand, ANL

Fast, low-power laser, with fast scope.

Built to characterize sealed tube detectors, and front-end electronics.

Highly Automated

Advanced Photon Source, ANL

Fast femto-second laser, variety of optical resources, and fast-electronics expertise.

Study MCP-photocathode-stripline systems close to device-level. Timing characteristics amplification etc.

Concluding Remarks

- ANL is moving towards development of new sensors and detectors going back to basic underlying physics principle using advances in other disciplines. Other technologies being pursued

- LAPPD based on this philosophy and has met 1st and 2nd year milestones
  - Innovation in lots of areas- detectors, wave-form sampling, ALD, material science, photocathodes, …
  - Ultimate goal is to transfer technology to industry.

- Project currently in its third year of funding and transitioning to a project stage

- Lots of interesting applications in (and interest from) many areas of science: TOF at colliders, PET, Reactor Monitoring, HEP neutrino detectors, ……

- We always welcome new collaborators

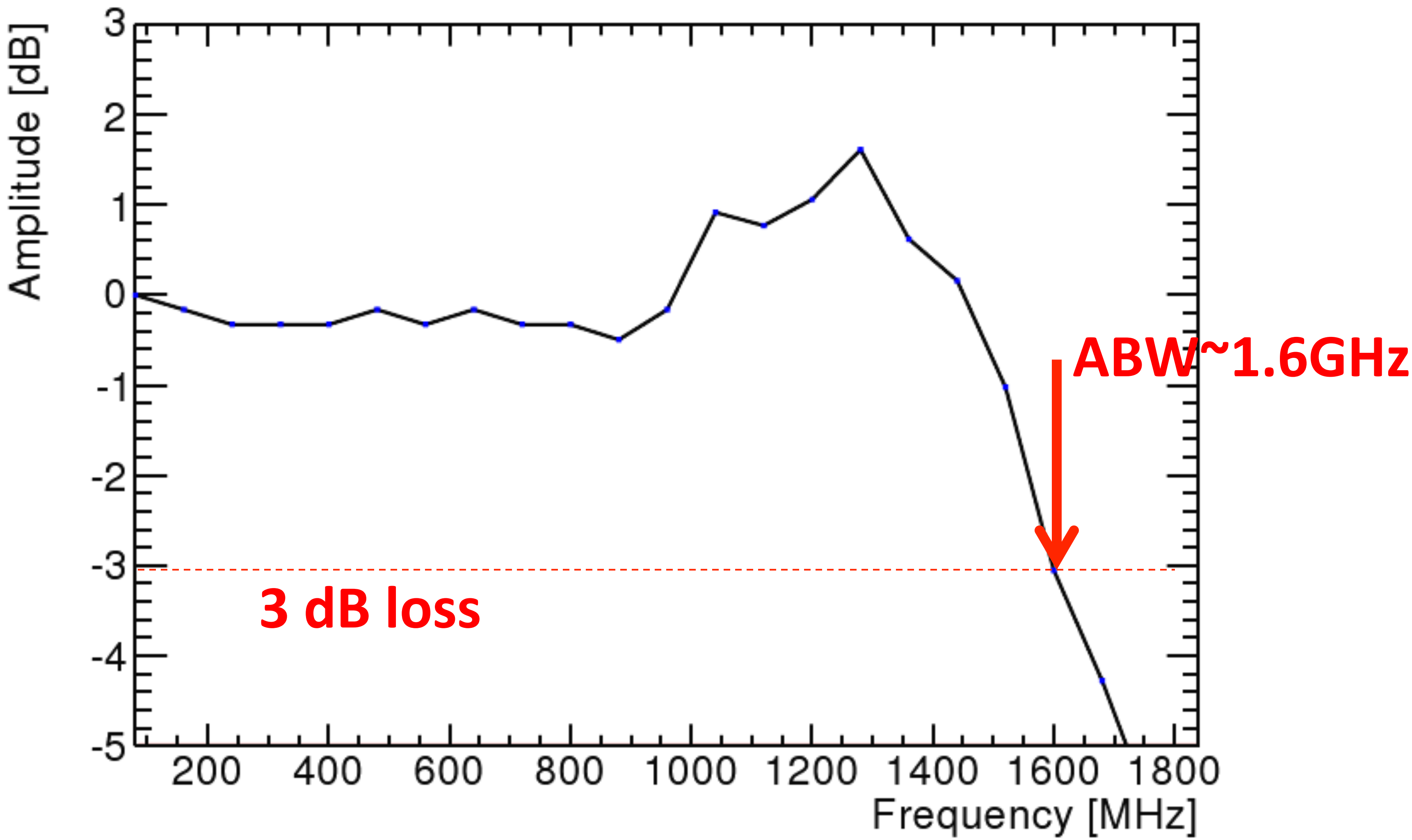
References

- 12 submissions of the LAPPD Project to the TIPP 2011 conference, Photodetector session
  http://conferences.fnal.gov/tipp11/

- 4 talks at ANT11 conference
  http://www.physics.drexel.edu/~neutrinoweb/ANT11/
  - Henry Frisch
  - Matt Wetstein
  - Klaus Attenkofer
  - Eric Oberla

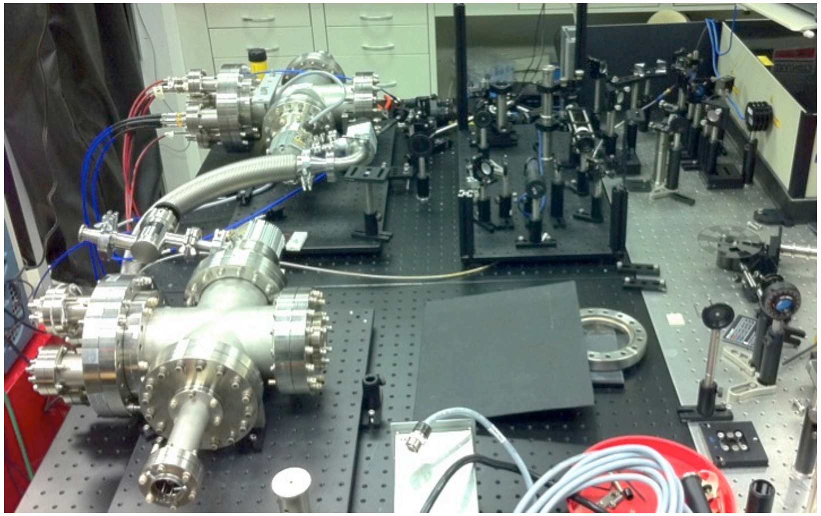
- 4 talks at Light11 Conference, Ringberg Castle (Ringberg11)
  http://conference.mppmu.mpg.de/light2011/
  http://indico.mppmu.mpg.de/indico/conferenceDisplay.py?confId=1407
  - Henry Frisch
  - Bob Wagner
  - Klaus Attenkofer
  - Oswald Siegmund

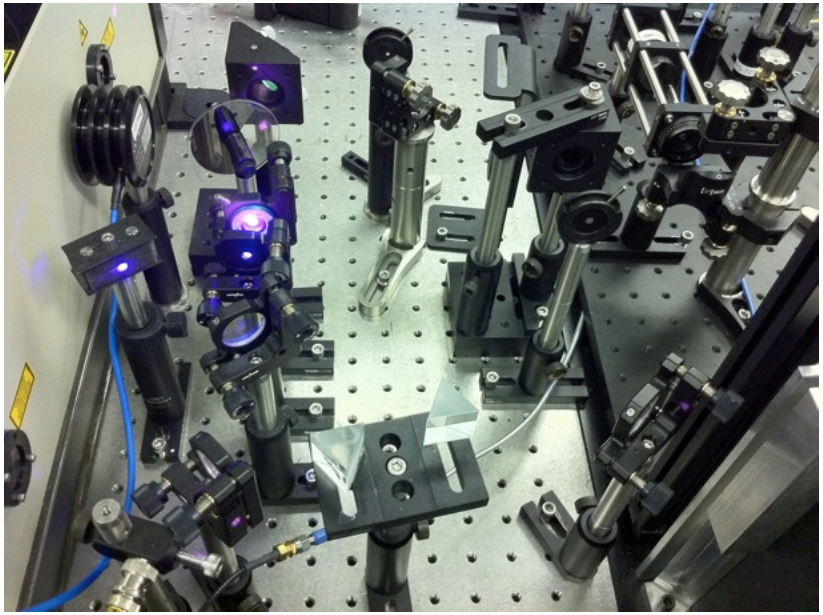
Analog Bandwidth

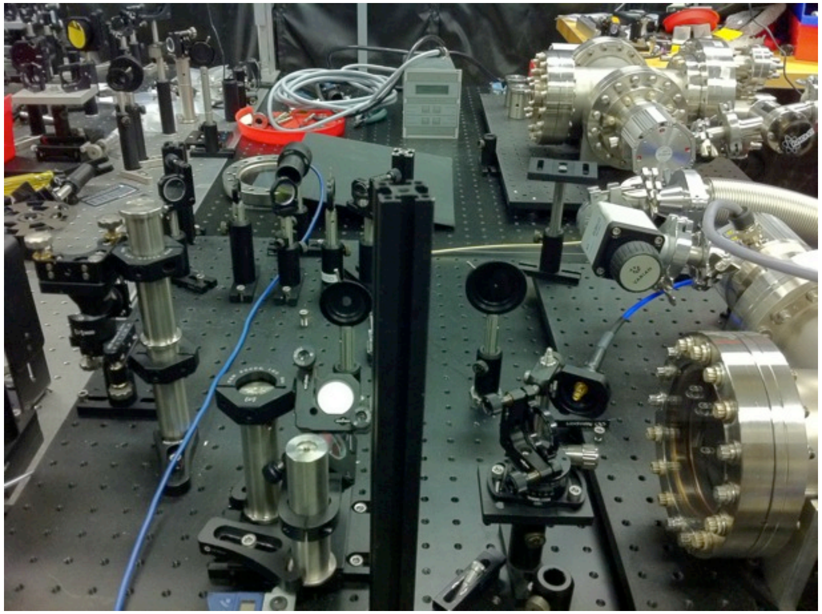


MCP Testing

- Full laser test setup with fs laser at APS
  - Clean UV beam
  - Laser power monitoring
  - Position scan
  - Absolute laser arrival time on MCP (in progress)
- Results compared with simulation



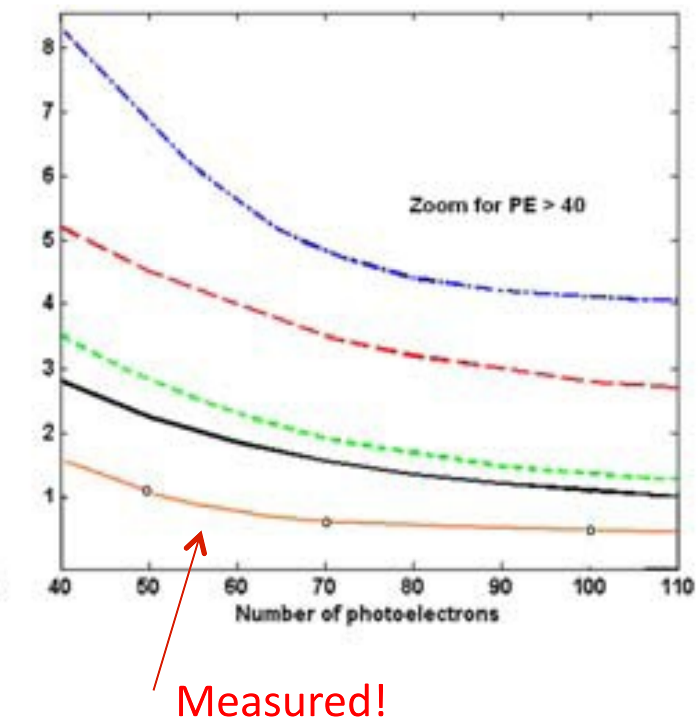


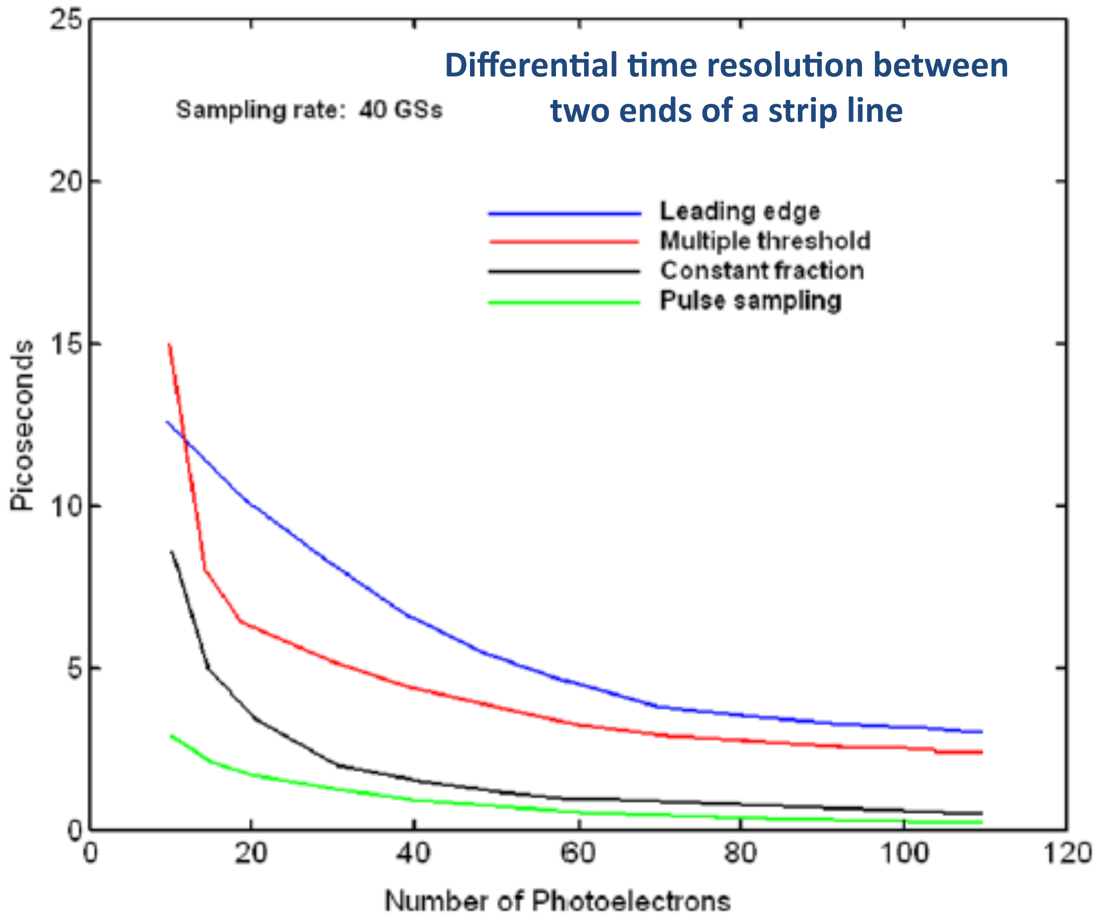


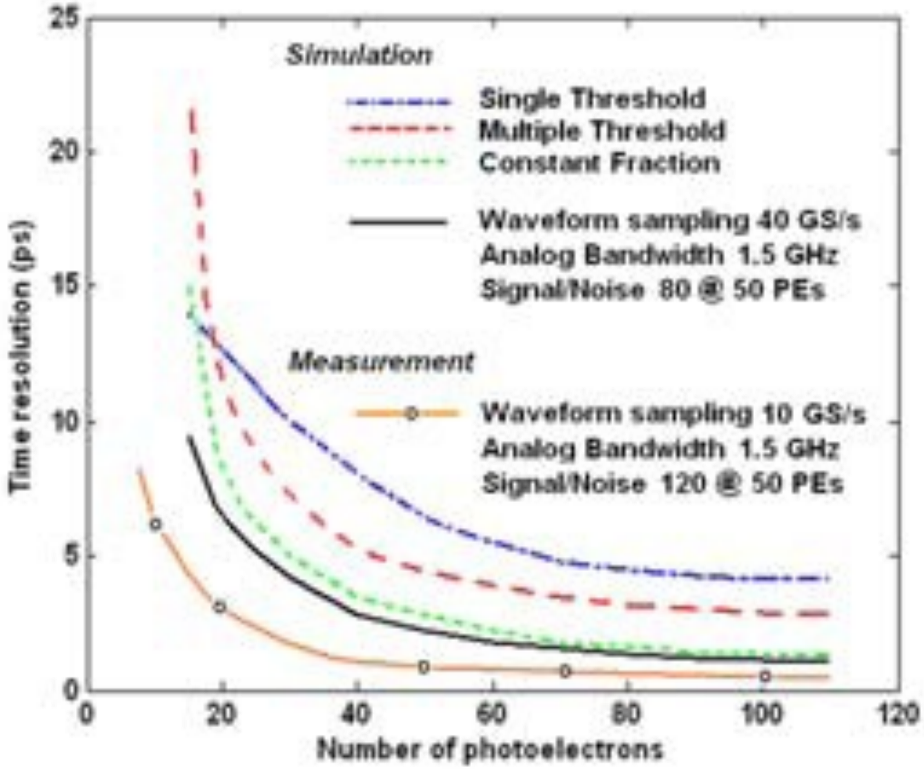
PSEC4 Waveform Sampling ASIC

- Resolution depends on # photoelectrons, analog bandwidth, and signal-to-noise.

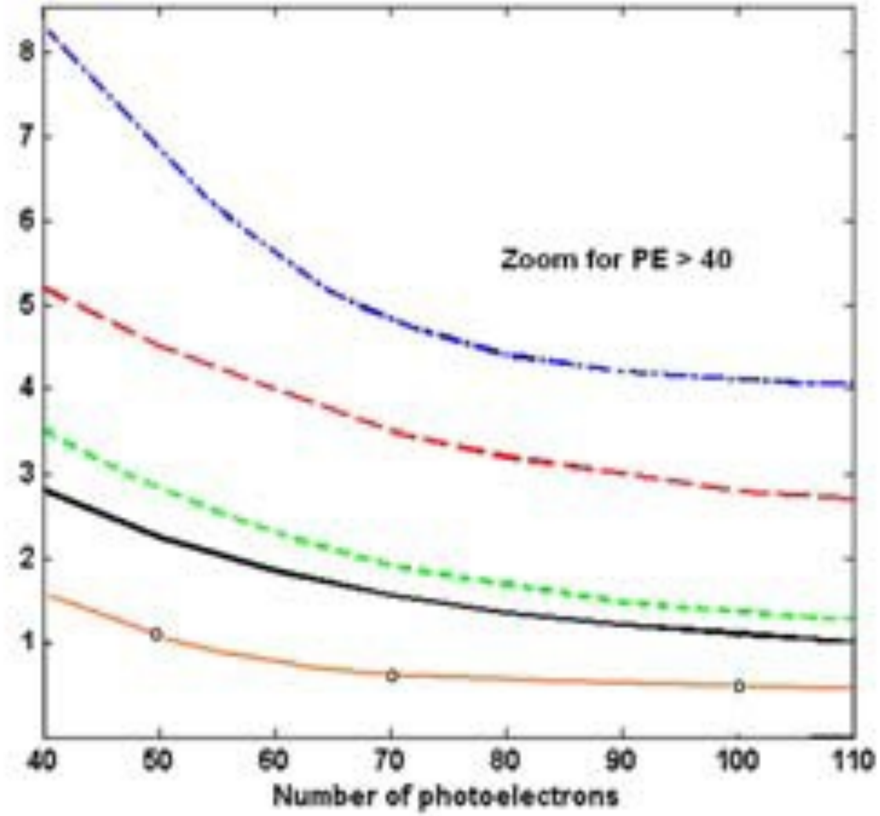
- Simulations showed "pulse sampling" to give the best results







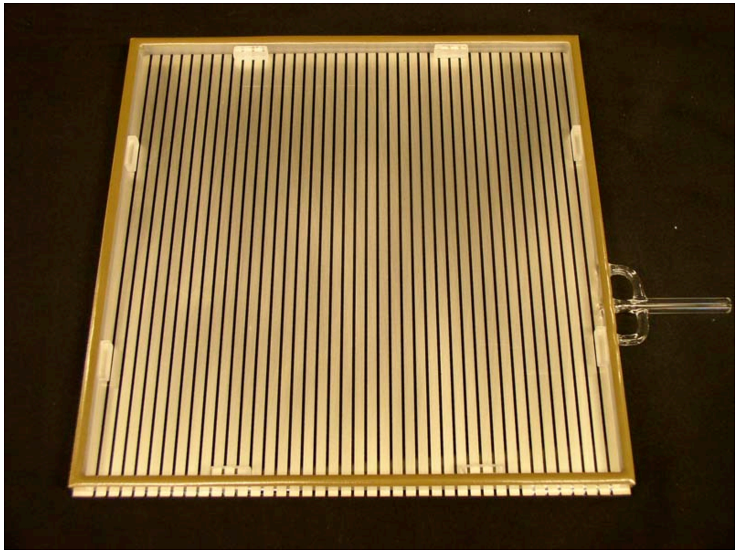
Time resolution (ps)
Simulation
Single Threshold
Multiple Threshold
Constant Fraction
Waveform sampling 40 GS/s
Analog Bandwidth 1.5 GHz
Signal/Noise 80 @ 50 PEs
Measurement
Waveform sampling 10 GS/s
Analog Bandwidth 1.5 GHz
Signal/Noise 120 @ 50 PEs
Number of photoelectrons

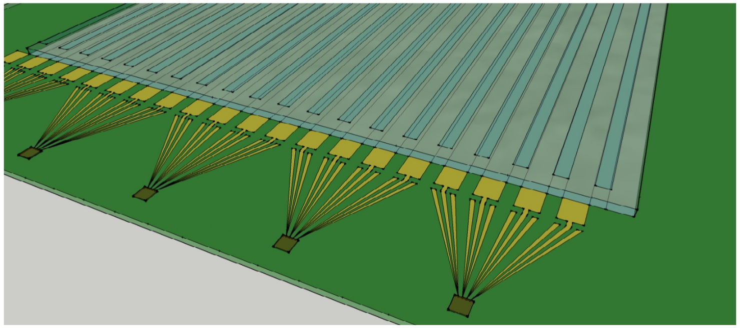


Zoom for PE > 40
Number of photoelectrons

Anode and Signal Readout

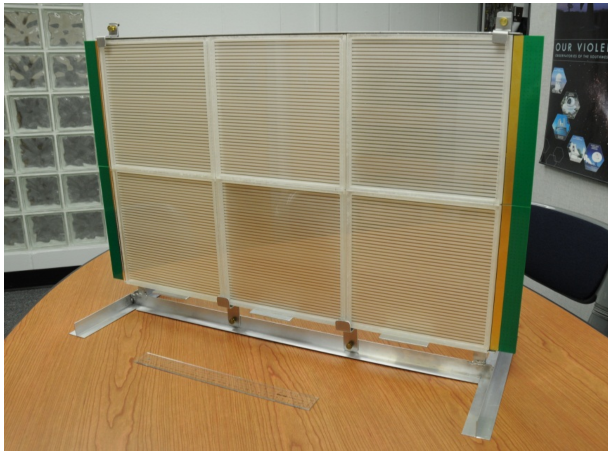
- Sealed tile construction: all glass
- Anode:
  - Silk-screened, no pins, penetrations, no internal connections
  - Transmission line readout both ends → gets position and time
  - Signal is differential between ground (inside, top), and PC traces (outside)
  - Simulations indicate that these transmission lines could be scalable to large detectors without severe degradation of resolution.
- Cover large areas with much reduced channel count





Future

- Construction of 8”x8” planar photo-detector imminent.
- Establishes the proof of principle; to be followed by construction of 3x2 array (not part of the DOE approved project)



- Exploring wide array of applications to bring technology into the field as quickly as possible through intermediate steps

- Large area H_2O Čerenkov detectors
- Pico-second timing resolution allows for π^0/e rejection
  - 100 ps time resolution corresponds to about 1 cm space resolution
  - Vertex separation many cm