# Large Area Picosecond Microchannel Plate Photodetectors

Bob Wagner
Argonne HEP Division
Wednesday 25 July 2012
for the LAPPD Collaboration

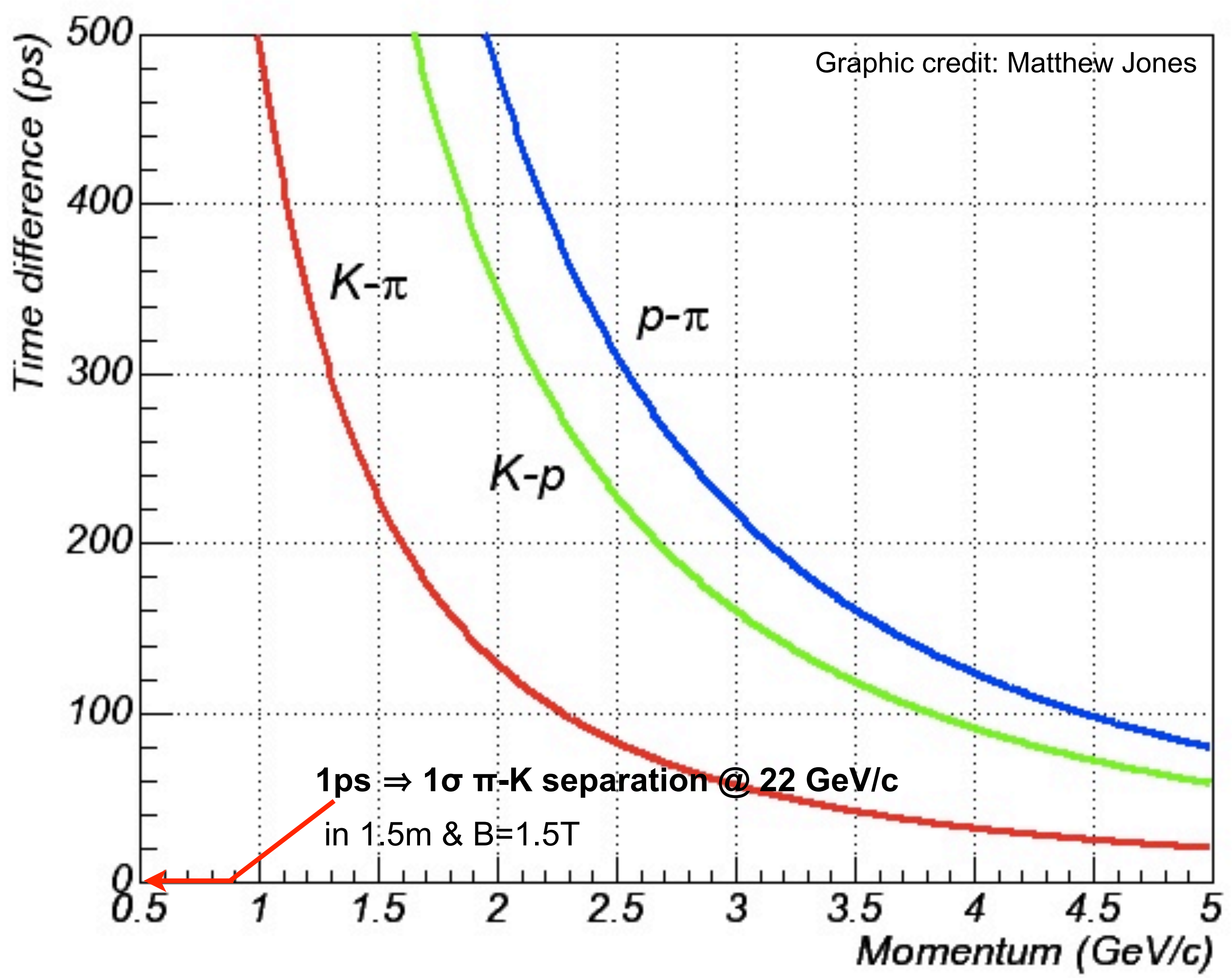
# The Large Area Picosecond Photodetector Participants During the First 3 Years

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

LAPPD is a multi-disciplinary/multi-institutional effort that draws on the unique expertise and infrastructure at Argonne and at our partner institutions

# Motivation — Pushing the Limits of Time Resolution

- Project evolved from LDRD to improve Particle ID in colliding beam experiments




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

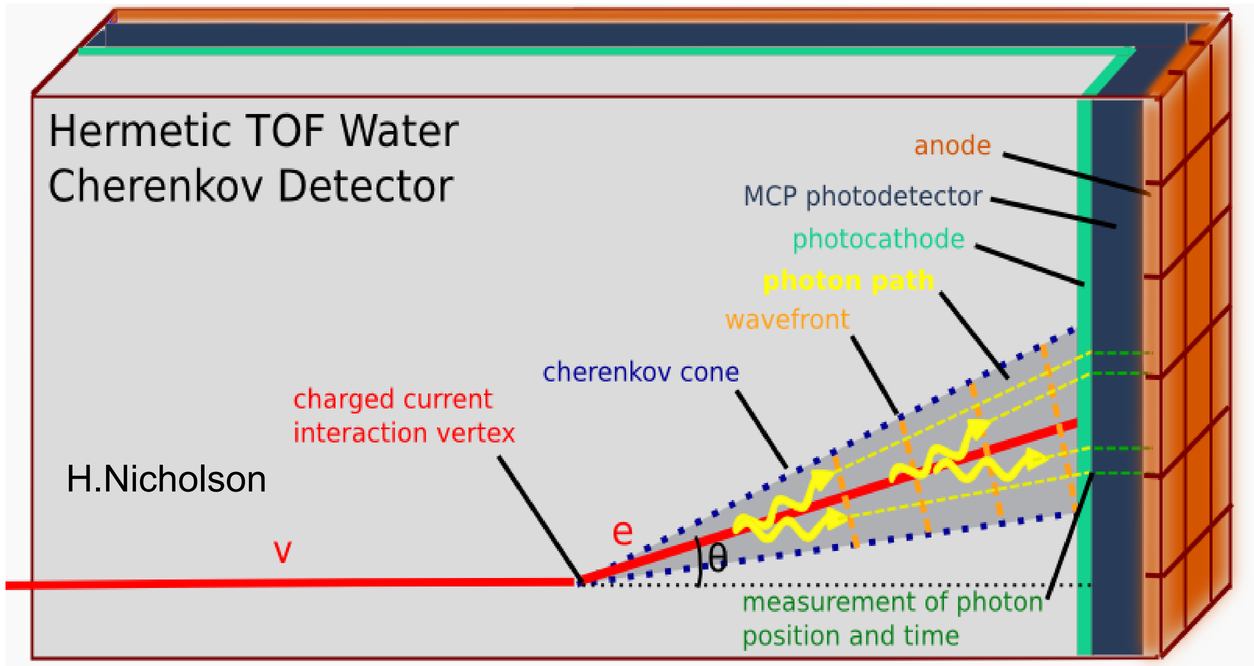
Several components contribute to time resolution limit:

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

Complete particle measurement: E, p + m(PID)
1ps time & 1mm space resolution

# Applications — Tracking Neutrino Water Cherenkov Detector

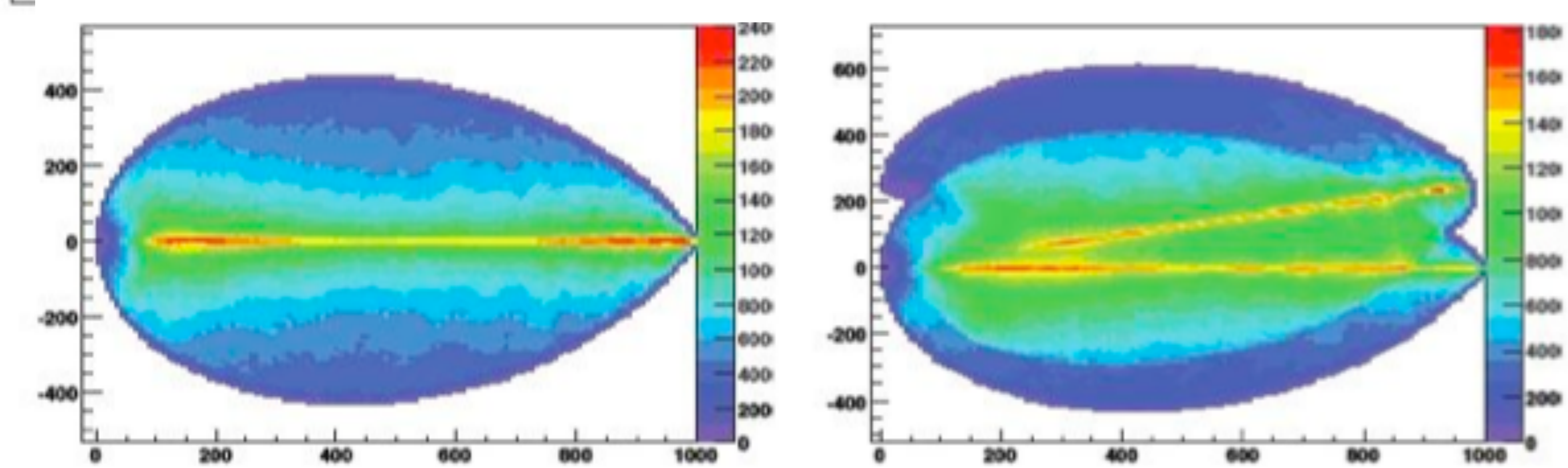
**Technique:** measure arrival time and position of photons and reconstruct tracks in water




Tesselation of detector with Large Area MCP-PMTs

Results of a toy Monte Carlo with perfect resolution

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



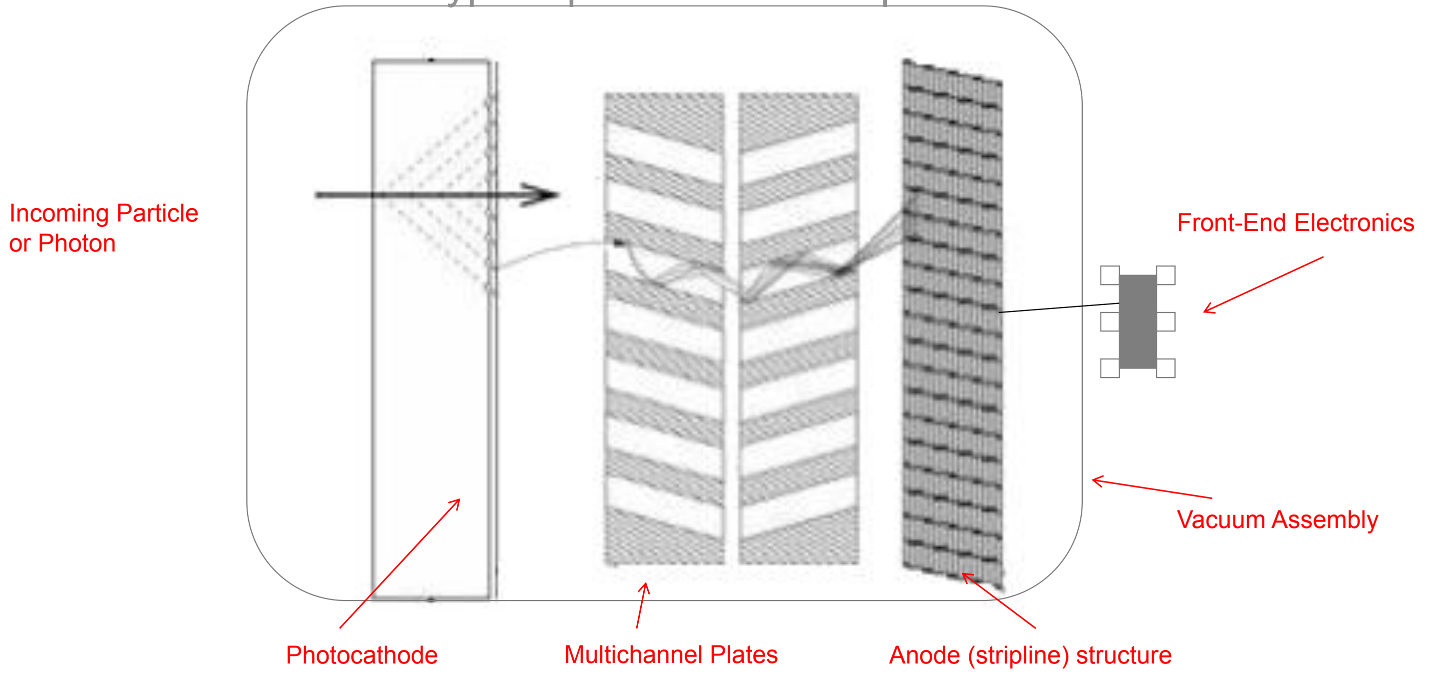
Single track

Two tracks displaced from a common vertex

graphic credit: Matt Wetstein

# Microchannel Plate Photomultipliers

Typical pore size is 6-40μm




## Existing commercial MCP-PMTs:

- MCP fabrication constrained by common material for substrate, resistive and emission layers
- ≤ ~25mm$^2$ active area
- Expensive
- Can be difficult to obtain/purchase

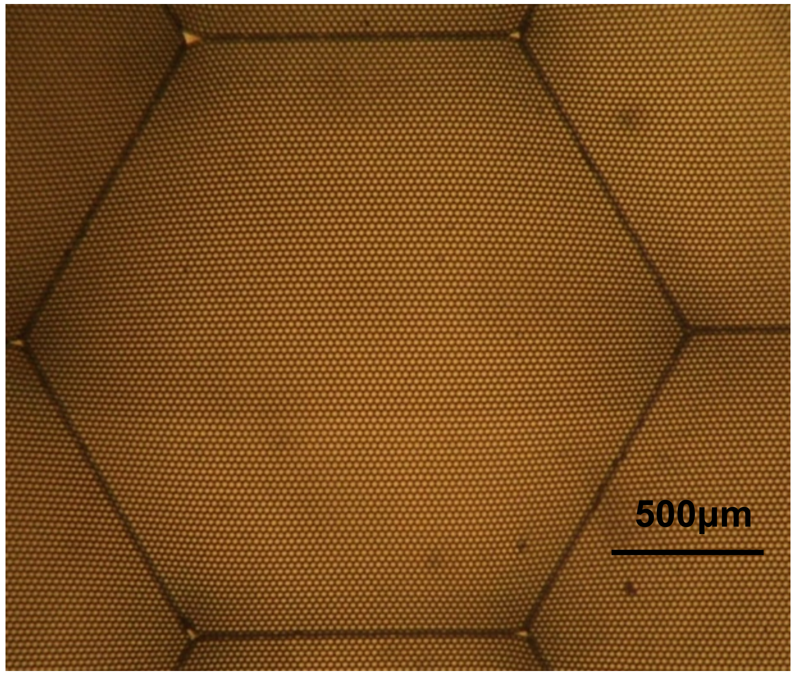
## Components of the Large Area Picosecond Photodetector Development:

- Transformational improvement of MCP fabrication and size
  - 8”×8” borosilicate glass w/20&40μm pore (33mm development disks)
  - Separate resistive & secondary emissive functions into 2 materials via ALD coating
- Development of planar, large-area photocathodes
- Waveform sampling 10GSa/s electronics readout for best time resolution
- Development of economical hermetic packaging
  - Standard ceramic package w/InBi hot seal & HV/signal pins feedthru — SSL/UC-Berkeley
  - Inexpensive borosilicate all-glass w/thermopressure seal, pinless — Argonne/UChicago

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

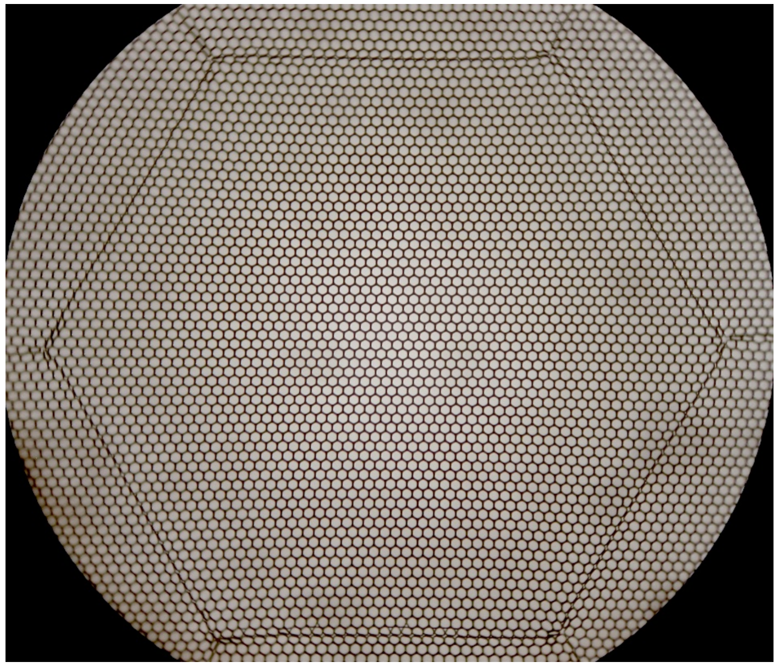
Fused block ready for slicing


First block

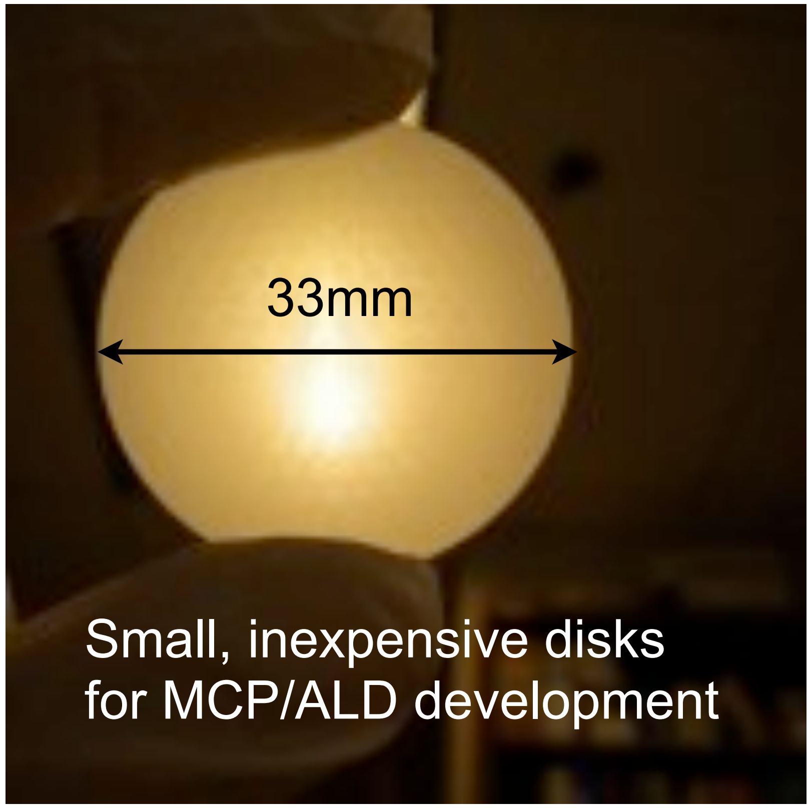



- Multifiber stacking
- Triple point gaps
- Pore crushing at multifiber boundaries

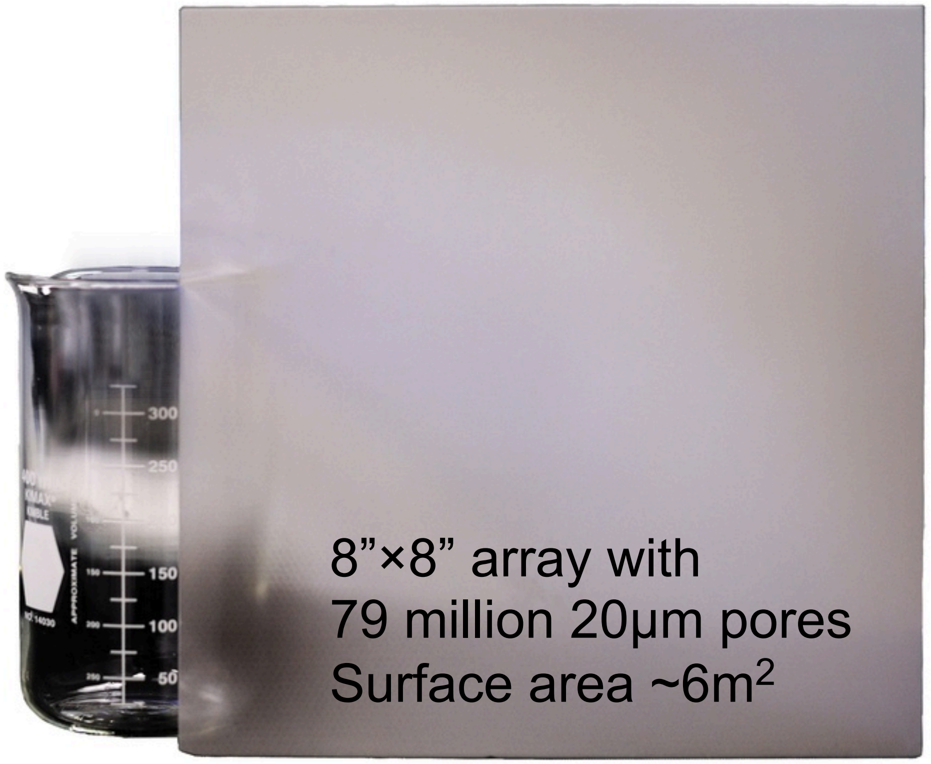
Most recent block



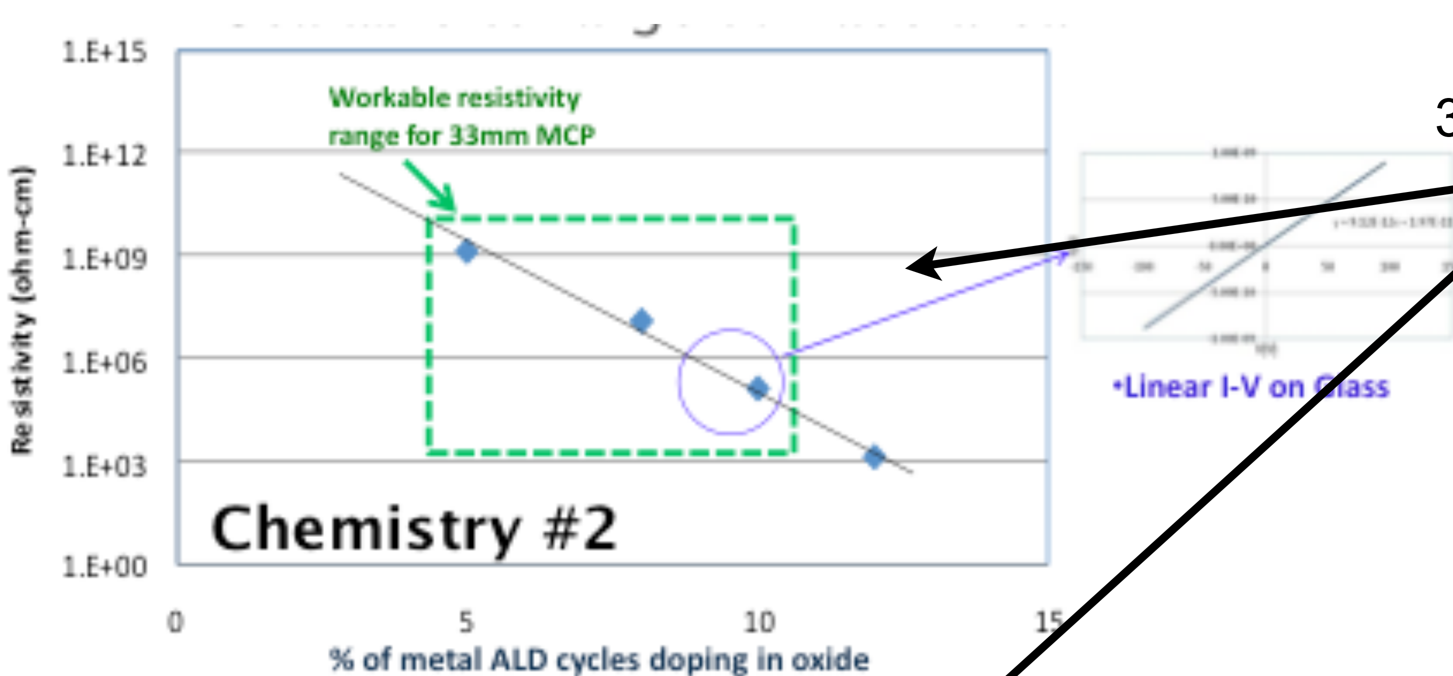
- Triple points eliminated
- Minimal boundary pore distortion




**Capillary array quality dramatically improved during last 2.5 years**



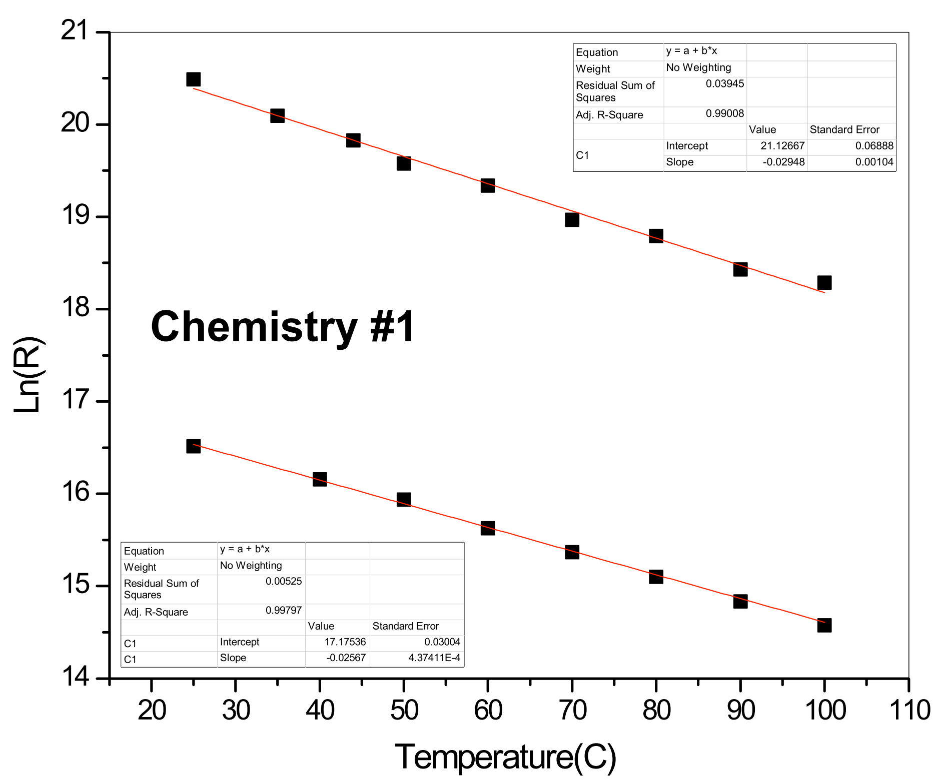
# ALD Materials Development

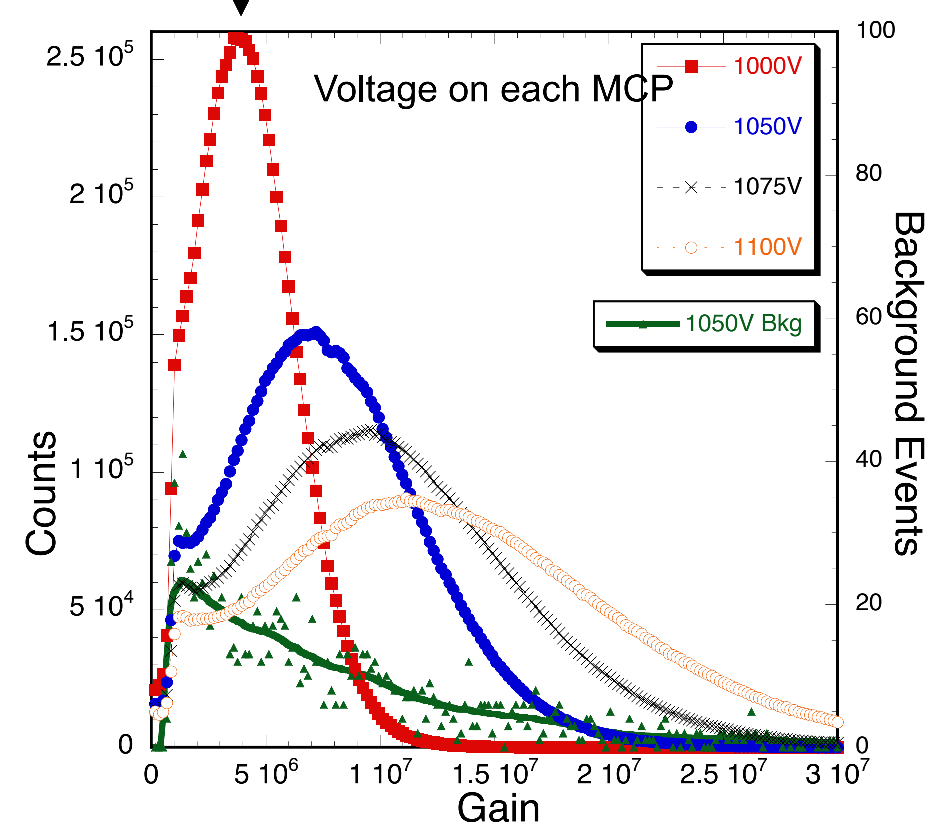



3 Resistive Chemistries invented by ANL ALD Group:

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

**G=4×10$^6$ @ 1000V**




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

ALD development: Anil Mane & Jeff Elam, Argonne ESD

graphic: Ossy Siegmund, SSL

# MCP Testing at Argonne and SSL — Facilities

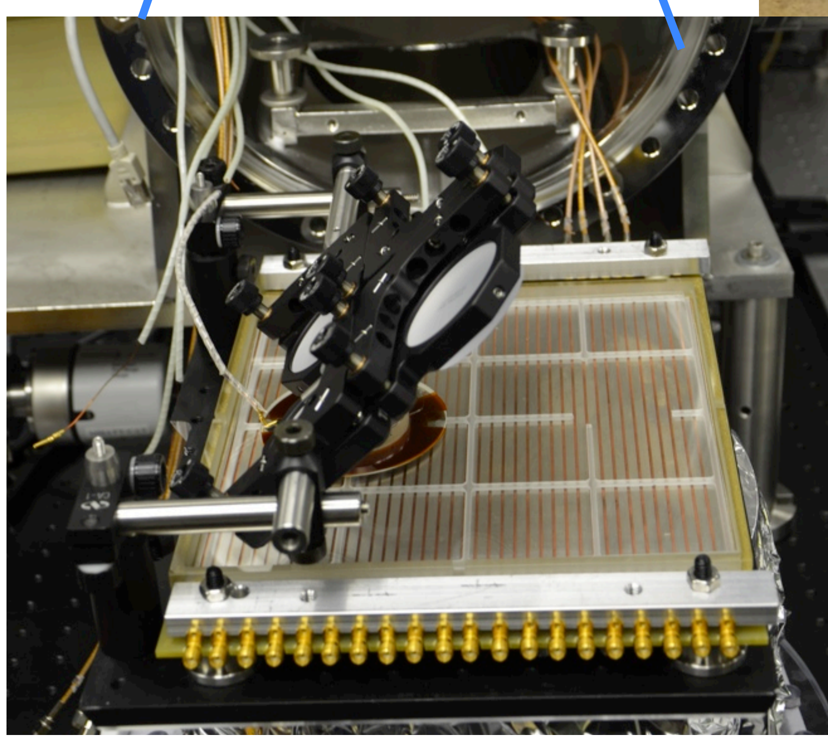
Argonne 33mm & 8” Test Chambers
with UV fs-pulse laser

SSL 33mm Test Chambers

Phosphor detector on left imaged with camera

Cross-strip delay line on right for gain mapping

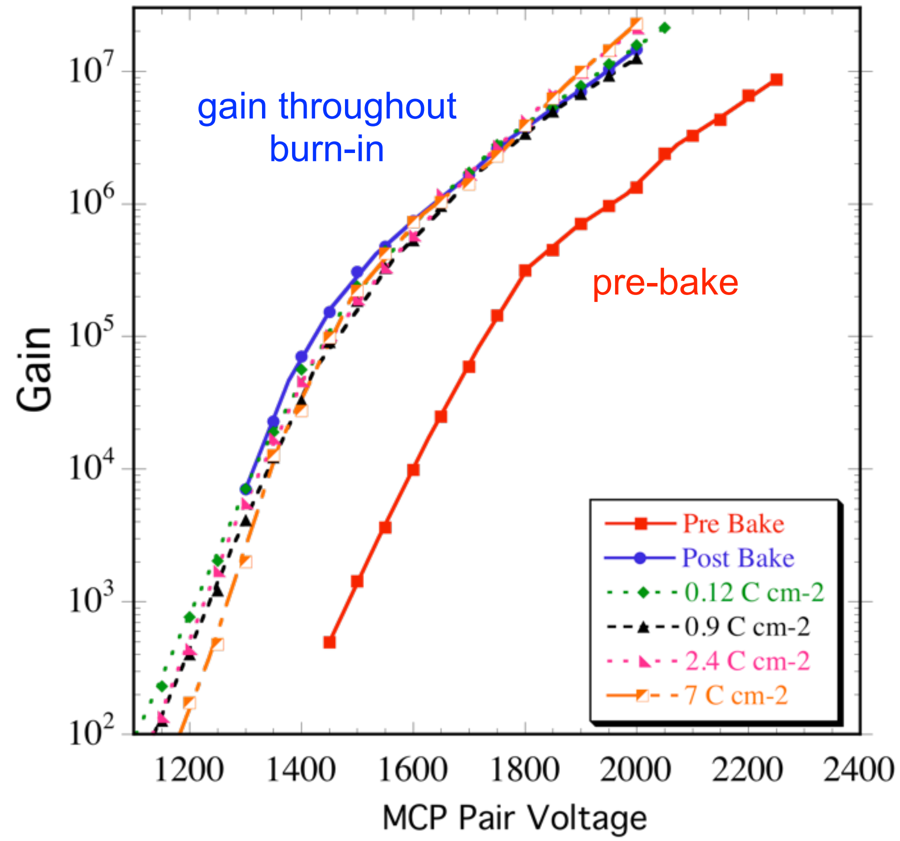
MCP on stripline anode ready for insertion into 8” chamber



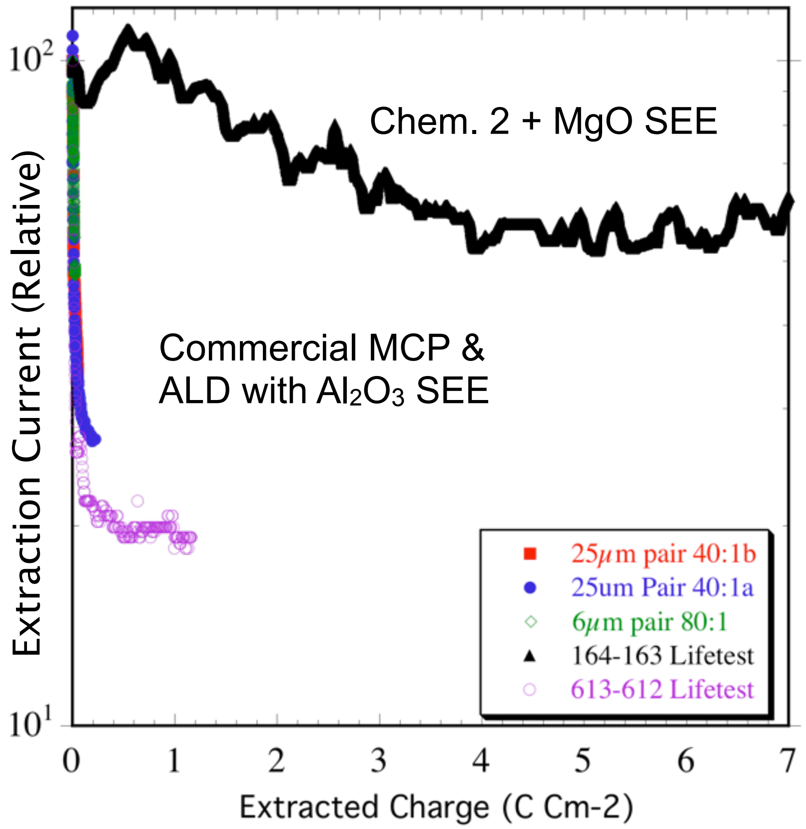
SSL 8” MCP Test
Detector Vacuum System

# MCP Development & Testing

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

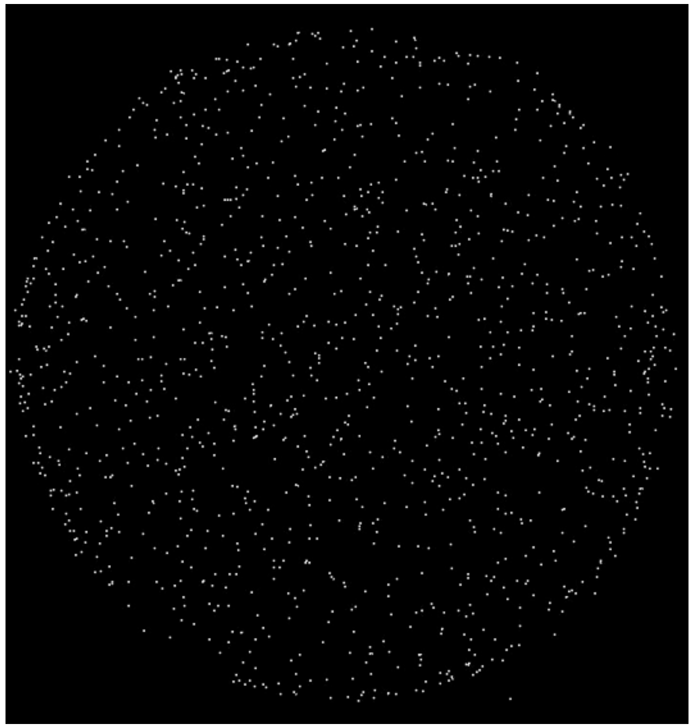



Gain curves of 33mm ALD MCP pair at stages during conditioning.




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

**Background Noise Measurement (separate from lifetest)**



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

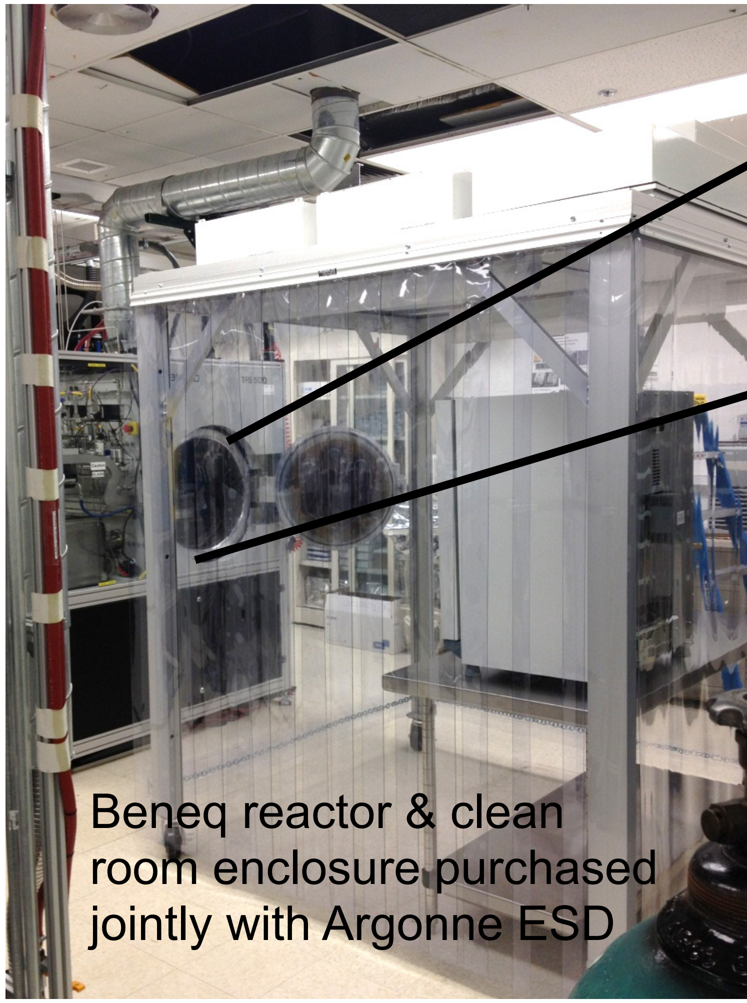
Rate comparable to cosmic bkgd

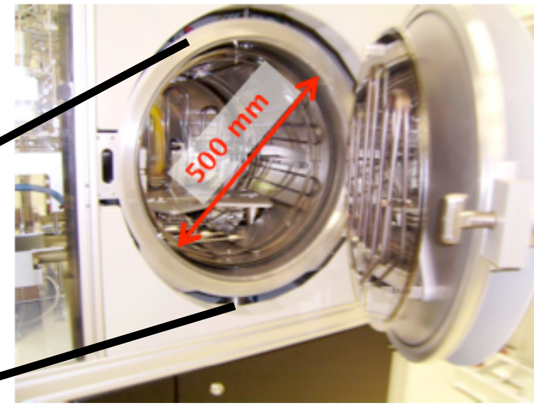
## Desirable MCP properties with MgO SEE:

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

graphics: Ossy Siegmund & Jason McPhate, SSL

# MCP Development — Scaling to Large Area



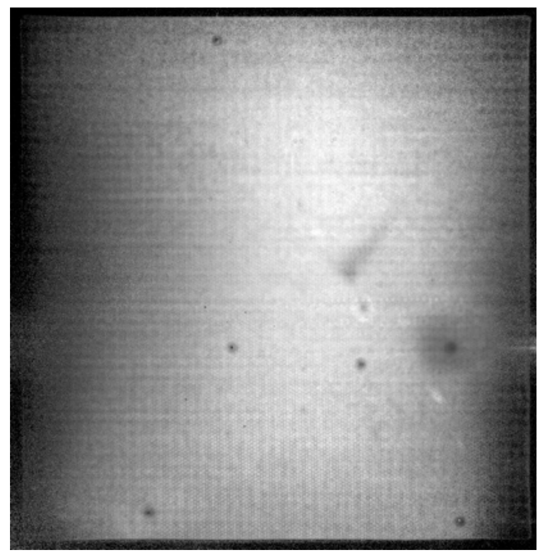




In June, 2012, Project received an R&D 100 Award for cost-effective and robust route to fabricate large-area MCP detectors

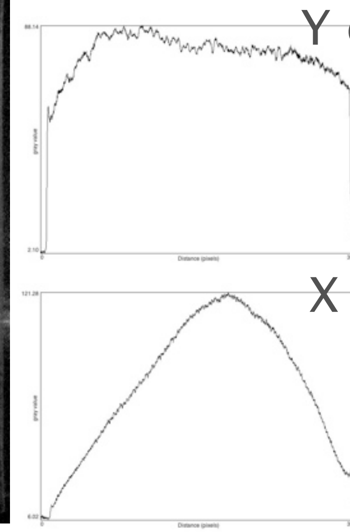
8” MCP Pair test at SSL

Top MCP Bias direction

Bottom MCP Bias direction



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



Y gain slice

X gain slice

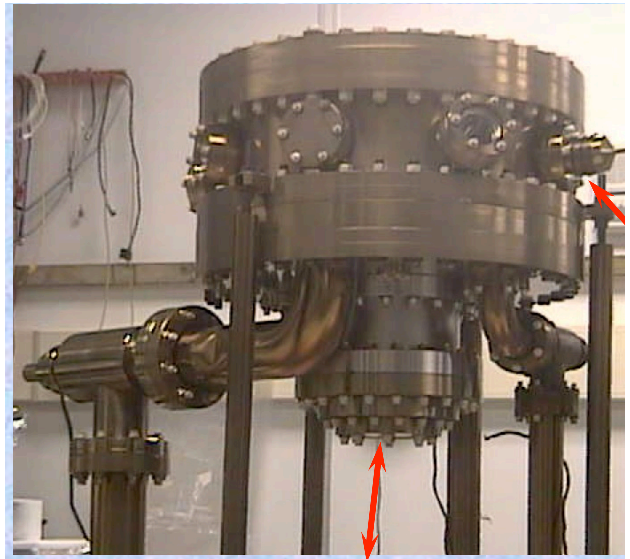
**Areas of Future Focus for MCP Development**

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

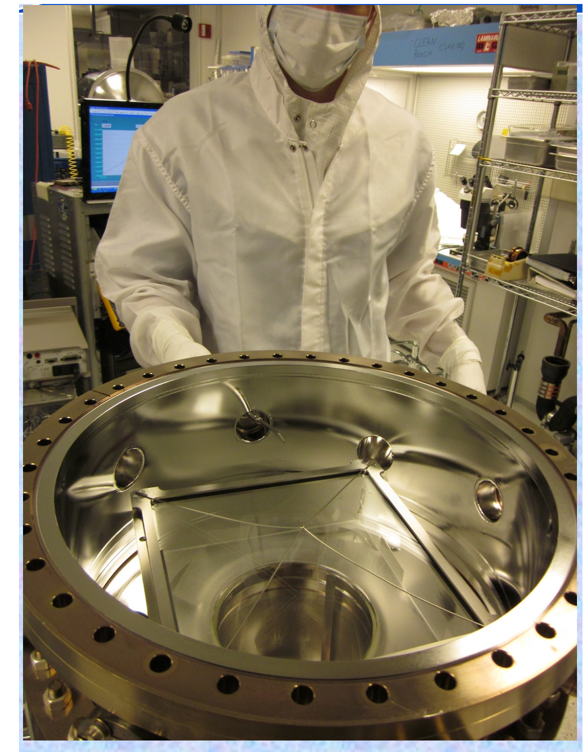
gain meas.: Ossy Siegmund & Jason McPhate, SSL

# 8" Photocathode Development — SSL/Berkeley

$Na_2KSb$ Photocathode Chosen for
- Resistivity
- Noise
- Temperature robustness
- Uniformity



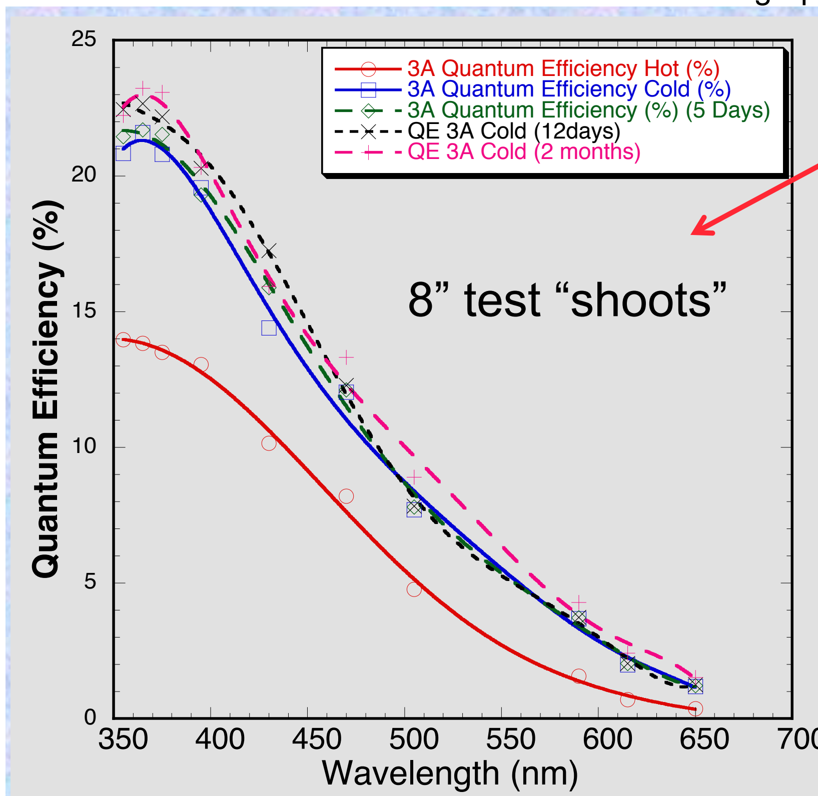

Larger 16" flange tank, for testing
- -Quantum efficiency
- -QE Uniformity
- -Seal tests



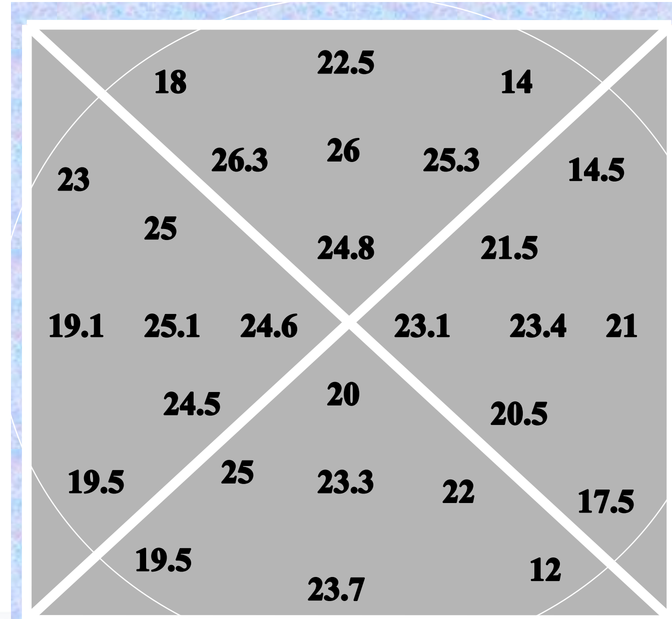
8.7" window loaded

graphics: Ossy Siegmund & Jason McPhate, SSL

**8" Photocathodes successfully produced at SSL**
- **Cathodes in 8" test chamber with QE~25%**
- **Uniformity and stability meet MCP tube needs**
- **Ready to transfer techniques from 8" test ch. to large tube processing station.**

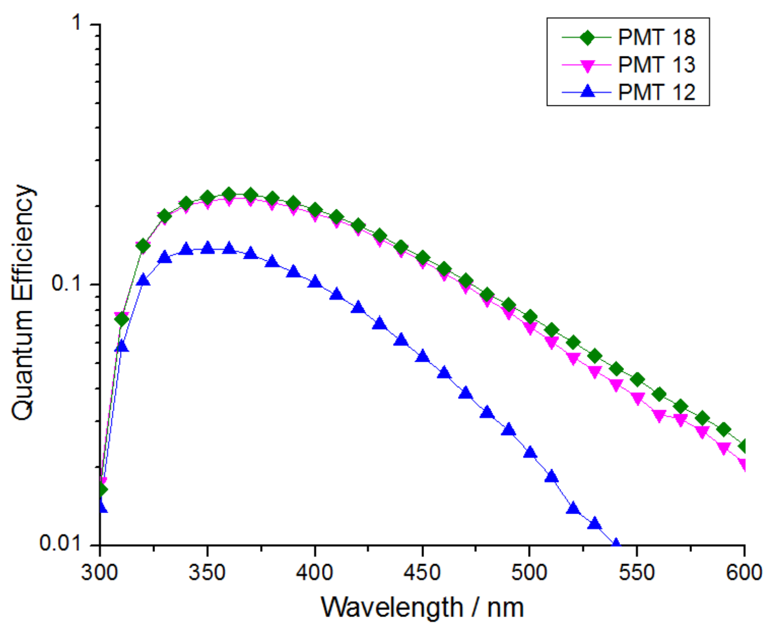


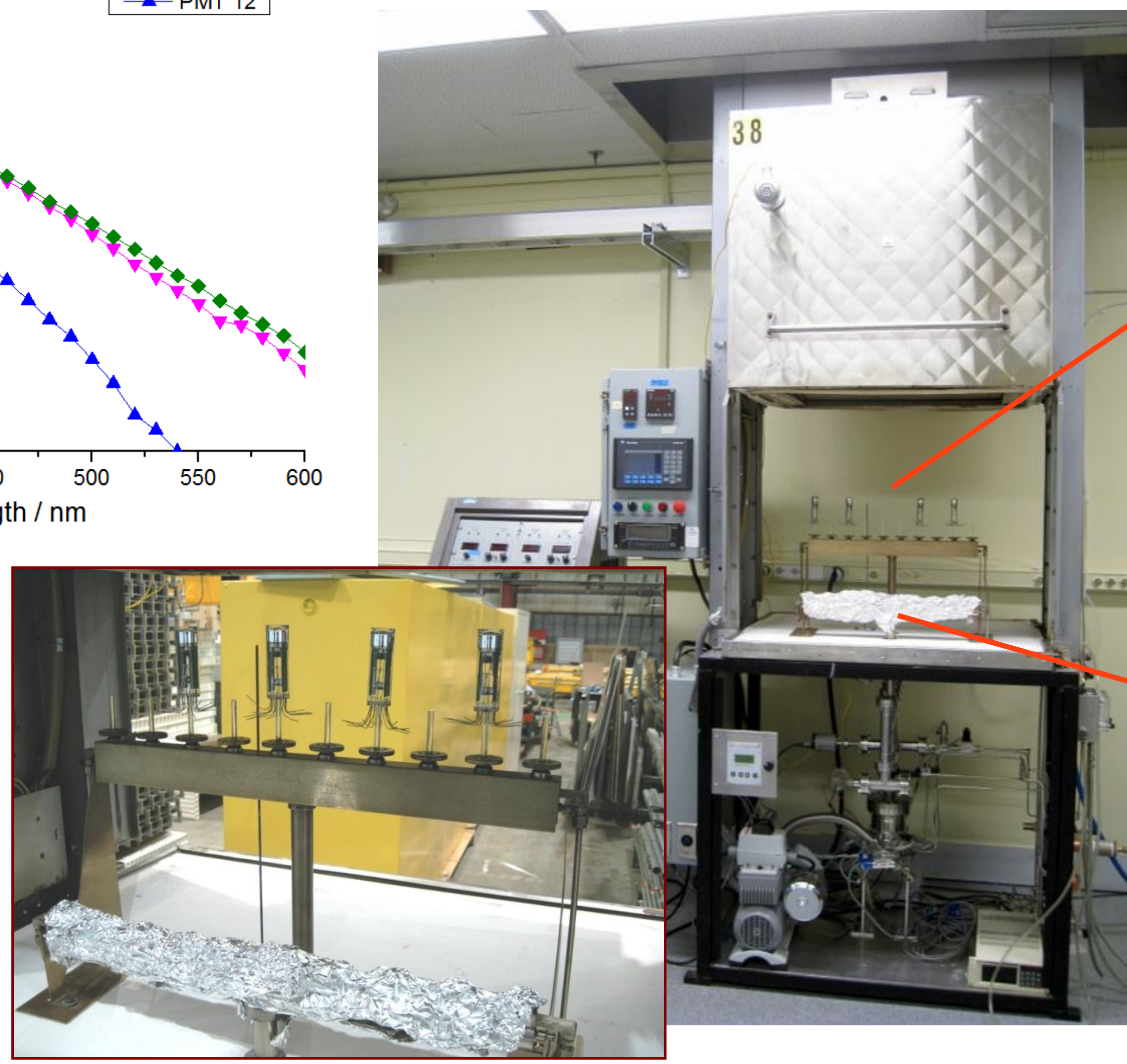

Basic process is a co-evap technique. We get an enhancement of the QE after cool-down. The QE has remained stable over the 2 months since deposition.

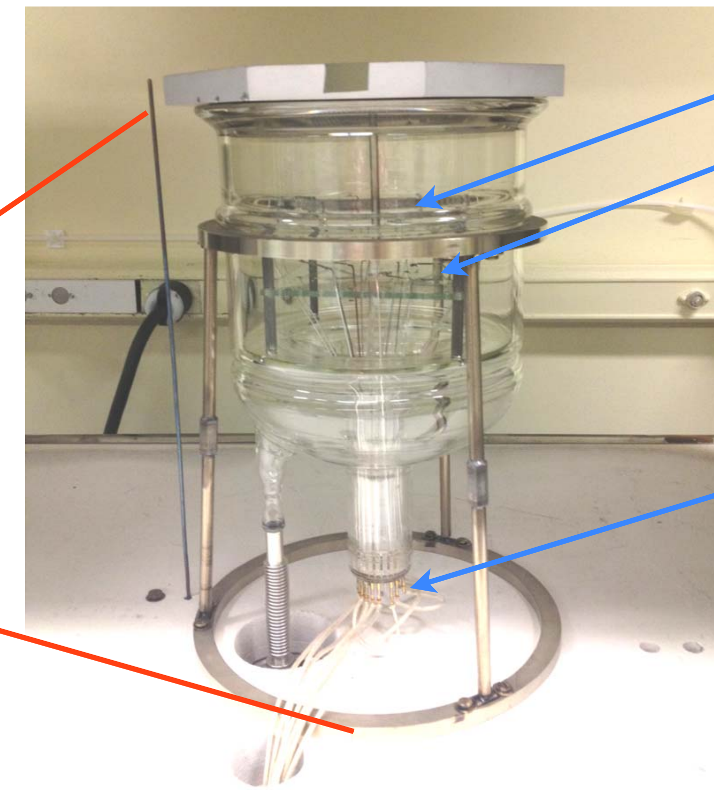



#3A photocathode uniformity

# Photocathode Development — Argonne



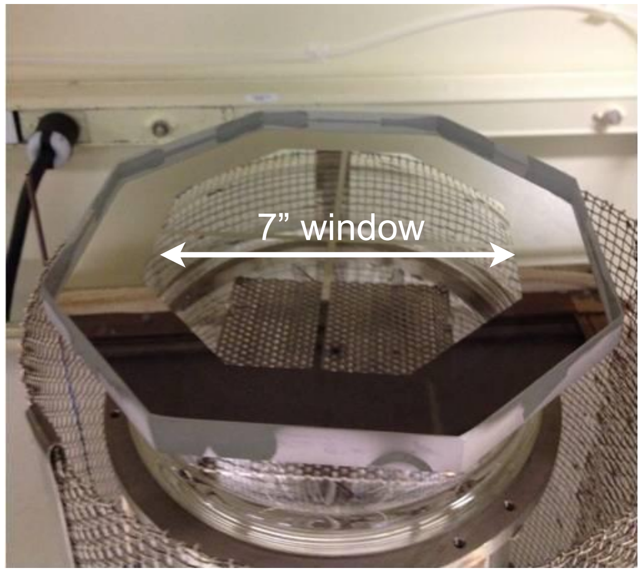



Large glass vacuum vessel (**Chalice**) replaced small PMT manifold to produce 4" & 7" photocathodes

Developing techniques to scale to 8" transfer cathode for Tile Facility at Argonne

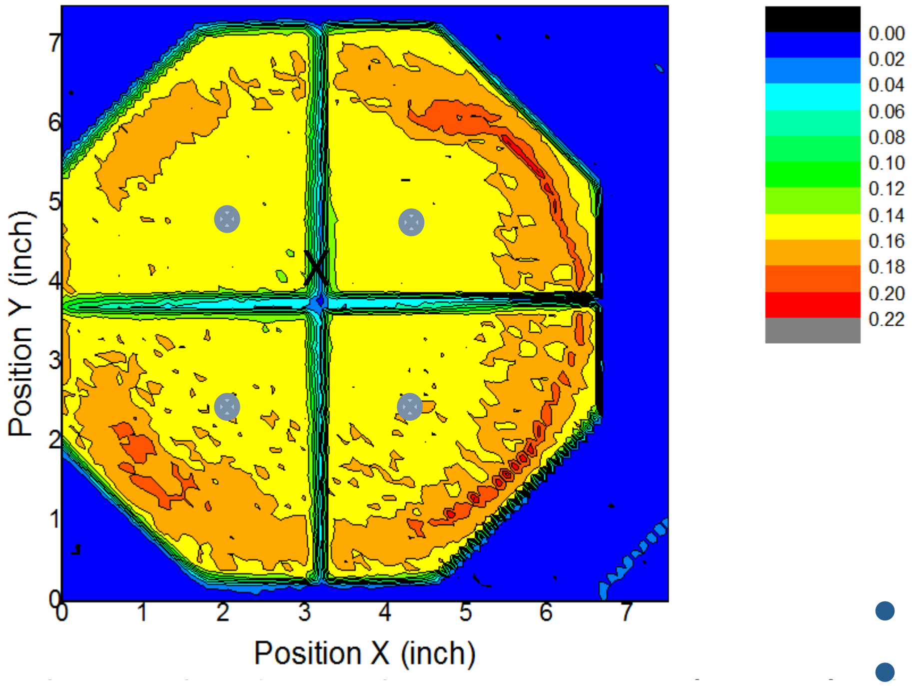
Learned photocathode fabrication techniques on phototube process system purchased from Burle

# Scale-up to 7” Photocathodes at Argonne



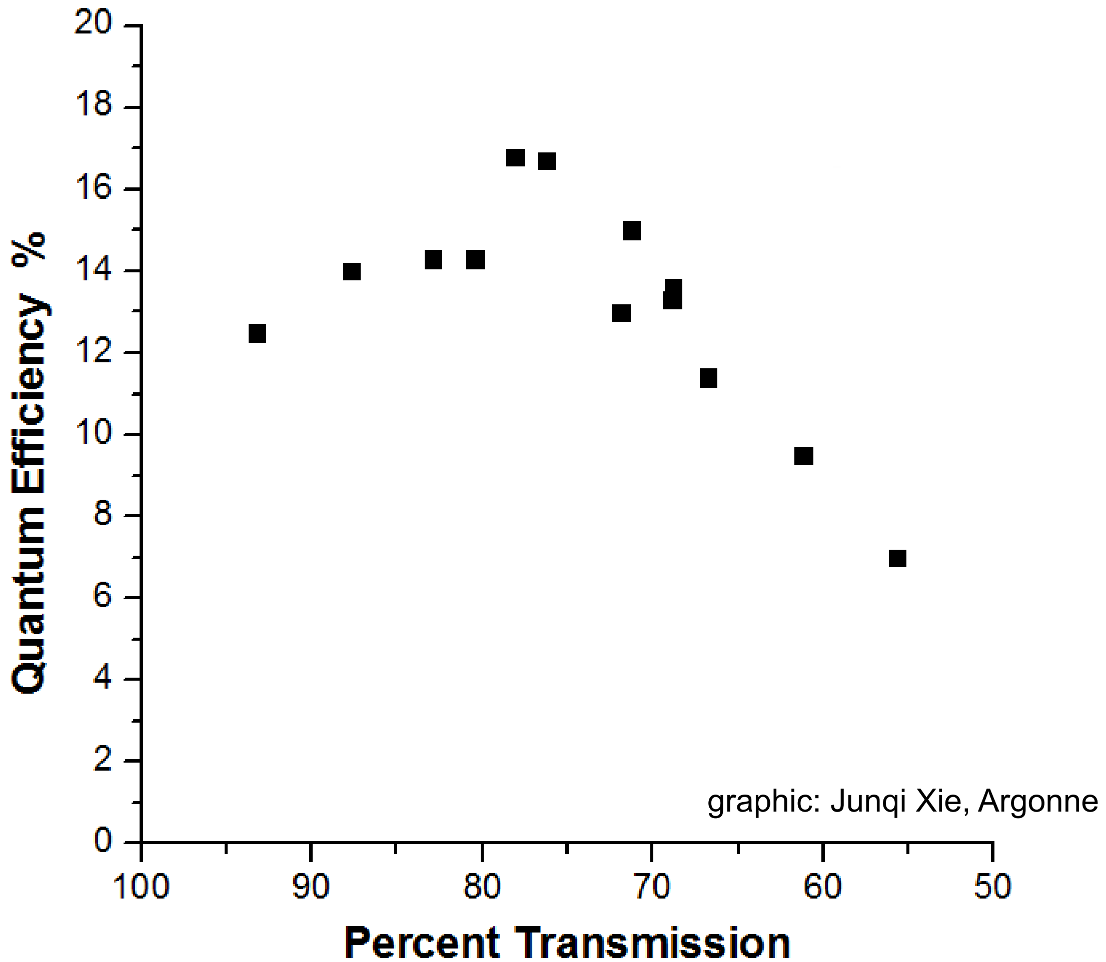

10 Photocathode shoots on “erasable” glass window:
- Tune process parameters
- Optimal # and placement of Sb, K, Cs dispensers
- Improve QE and uniformity

QE Map




Chalice Photocathode #9

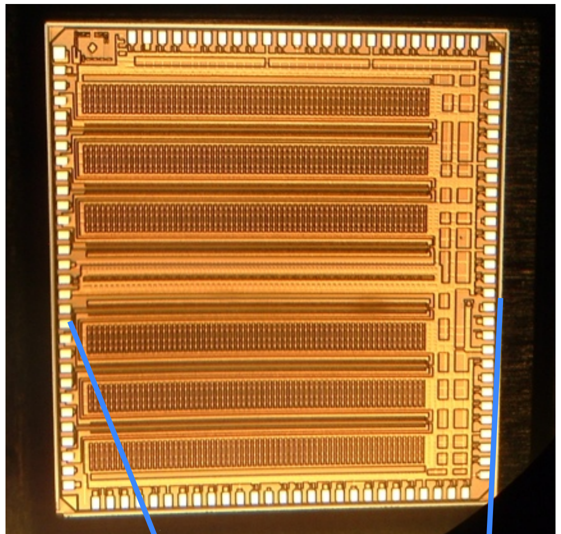
KCs-Sb Photocathode




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

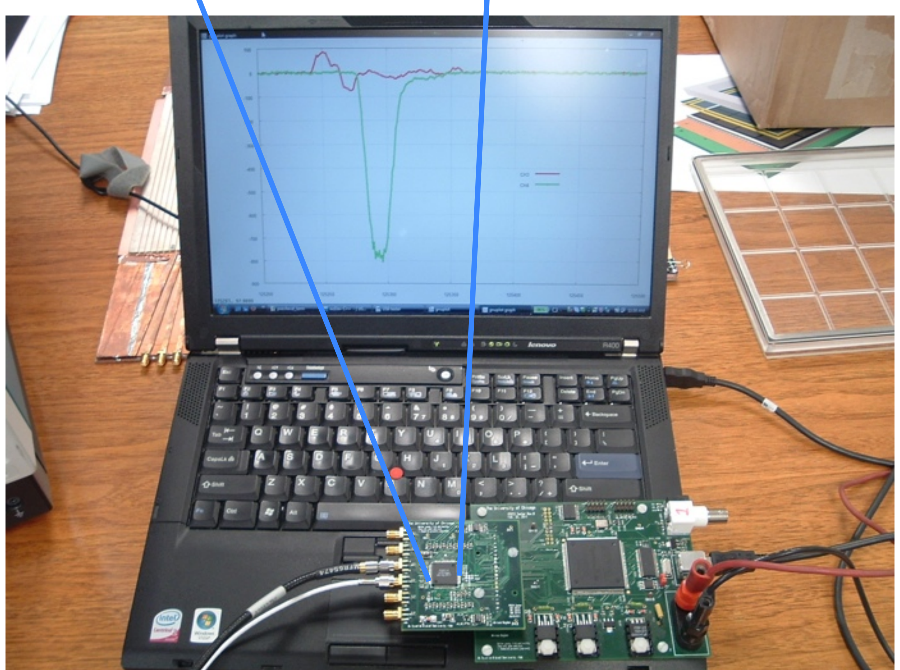
- **Photocathode fabrication established at Argonne**
- **Ongoing study for uniformity and QE>20%**
- **Future focus will be to transfer techniques from Chalice to design for 8” tube processing at Argonne**

# Development & Testing of Front-end Electronics



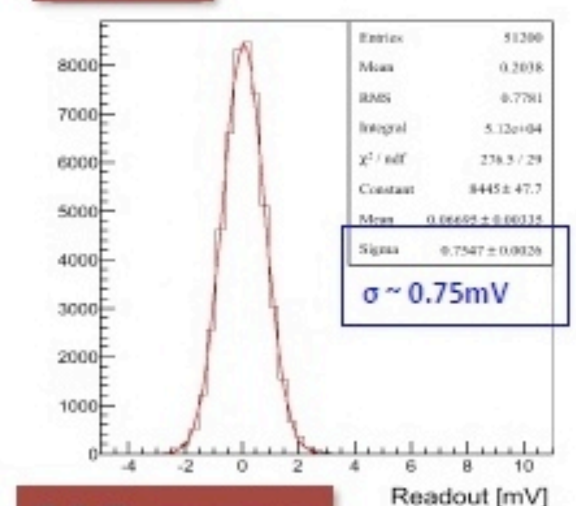
**PSEC4 6-ch.**
**"scope-on-a-chip"**
**1.6 GHz BW, 10-15 GSa/s,**
**130nm technology**

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

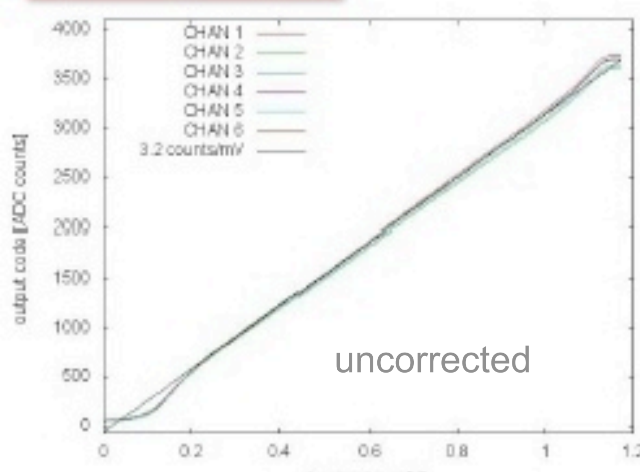


Evaluation board w/2.0 USB interface + PC DAQ software

Noise

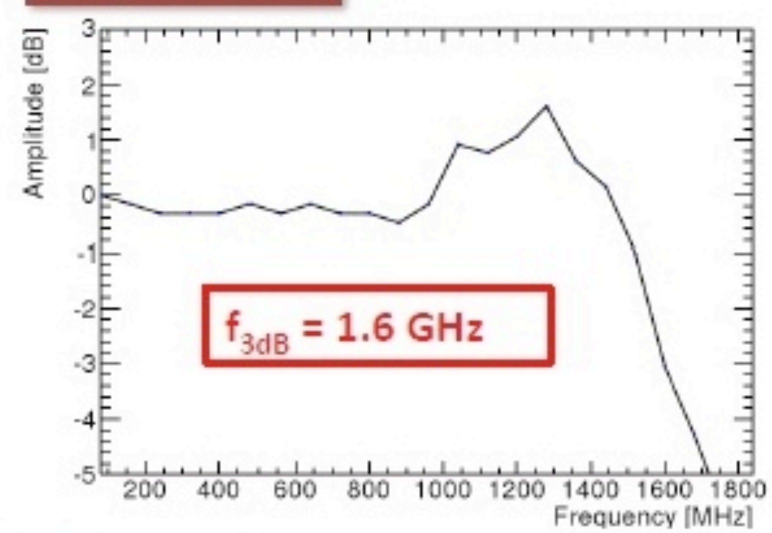



DC Response



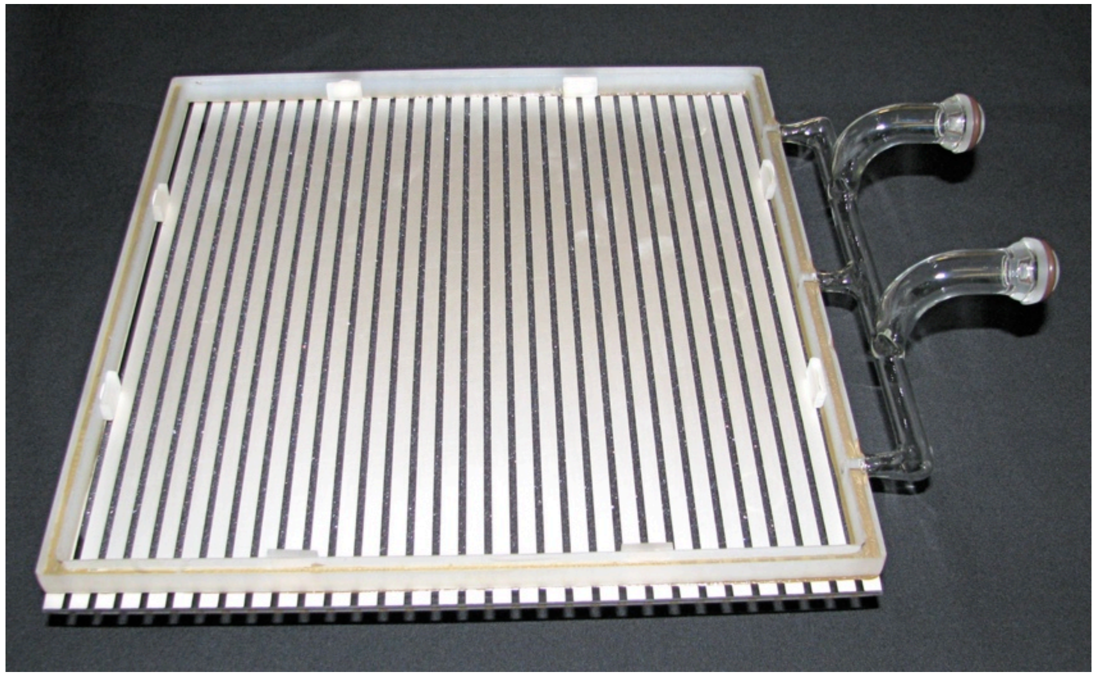

- Low noise <1 mV
- ~1V dynamic range with excellent linearity
- Analog bandwidth of 1.6 GHz
- Sampling rates up to 15 GSa/s

Frequency Response

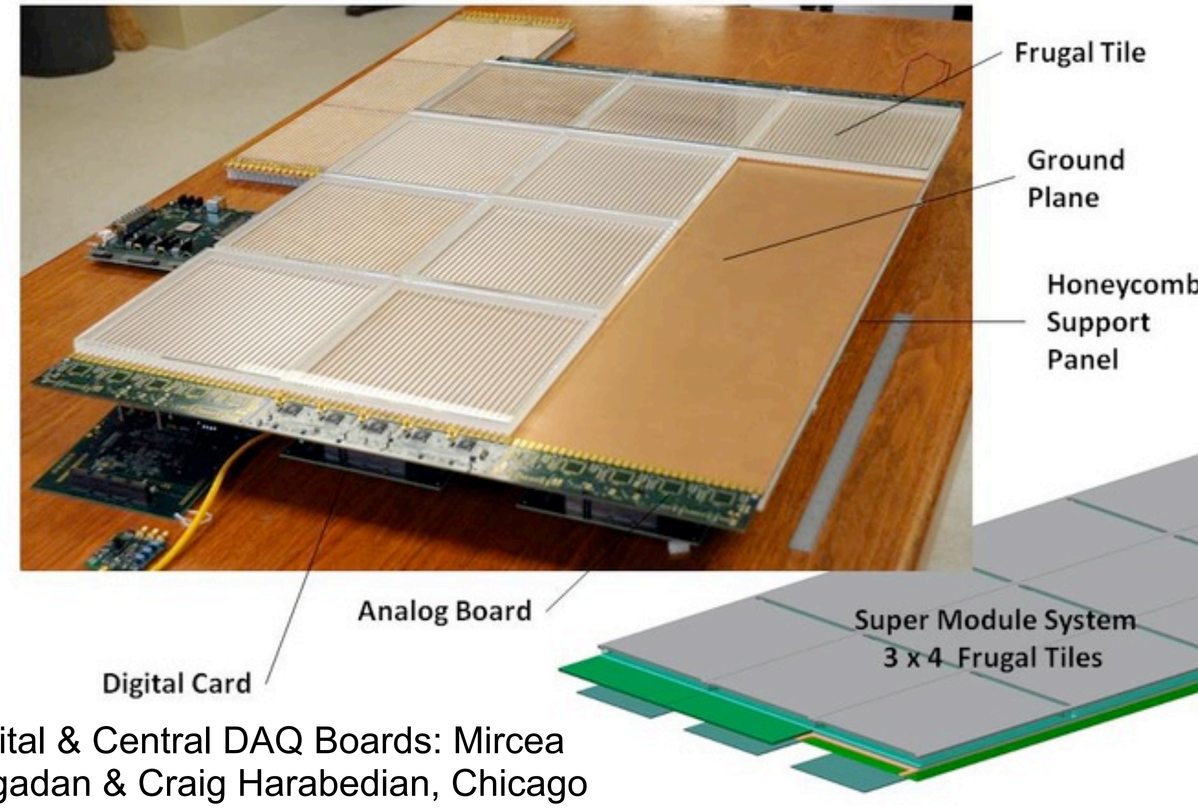



PSEC 4 design & test results: Eric Oberla & Hervé Grabas, Chicago

# Glass MCP Phototube Strip Line Anode



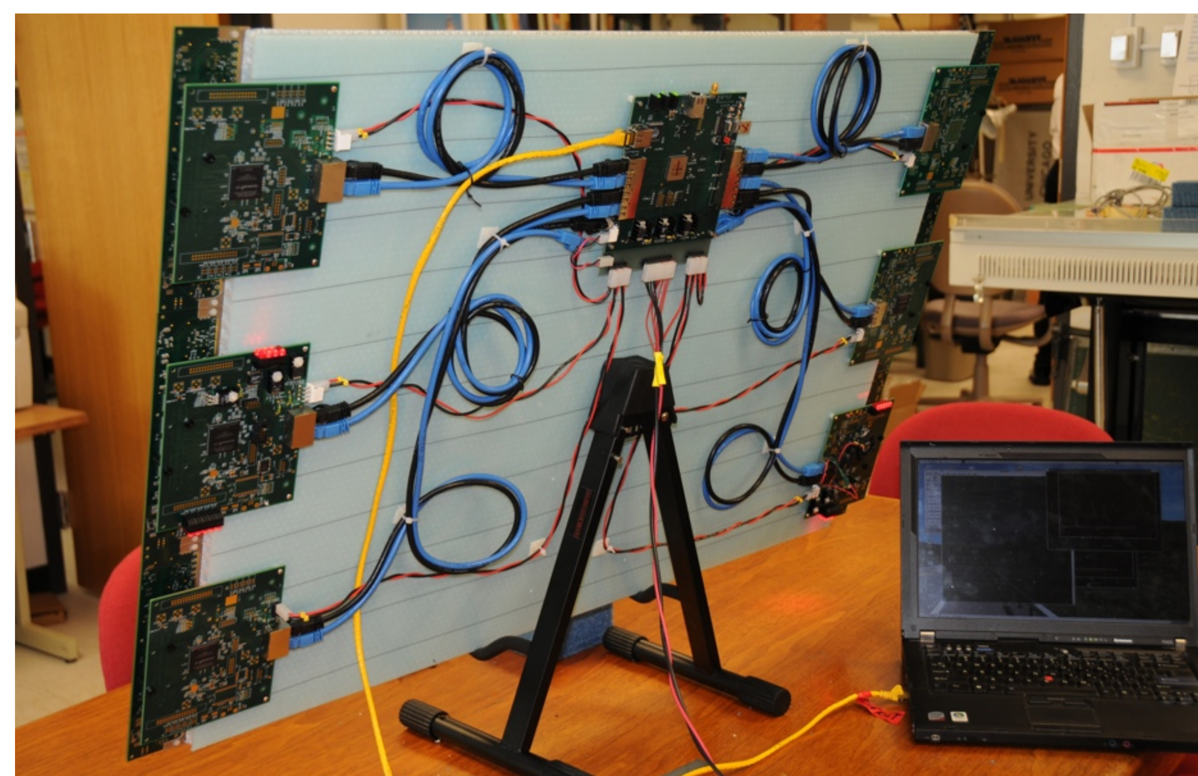
Tile base is 30 strip silk-screened anode




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

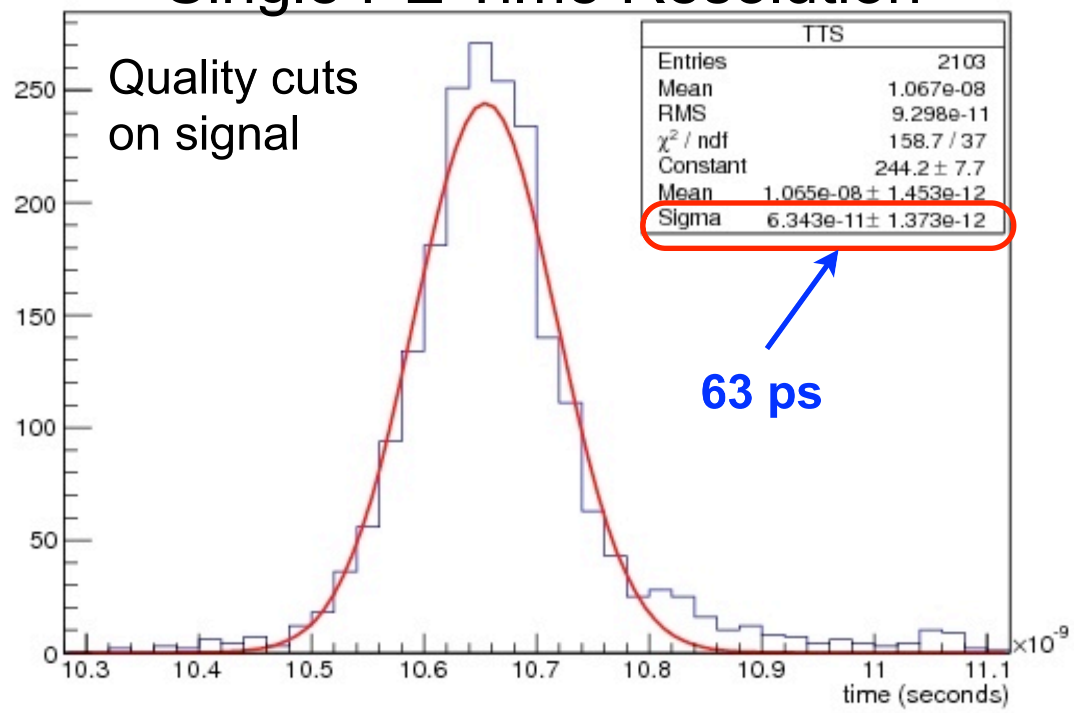
**Tray and Tiles - The Super Module System**

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

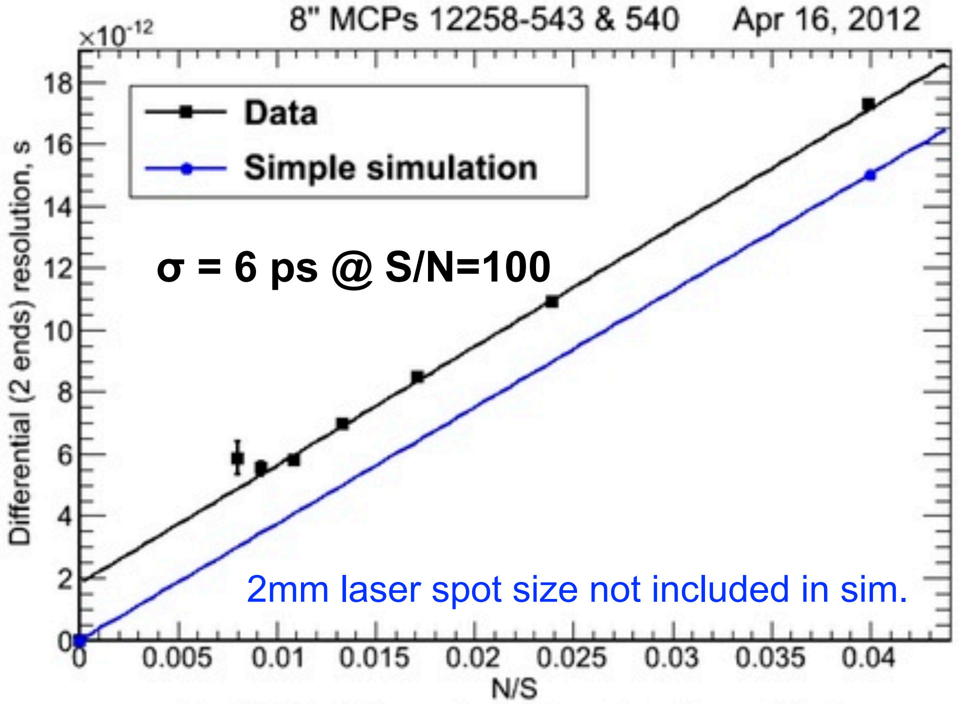


# Strip Line Anode Performance with 8” MCP Pairs

Single PE Time Resolution

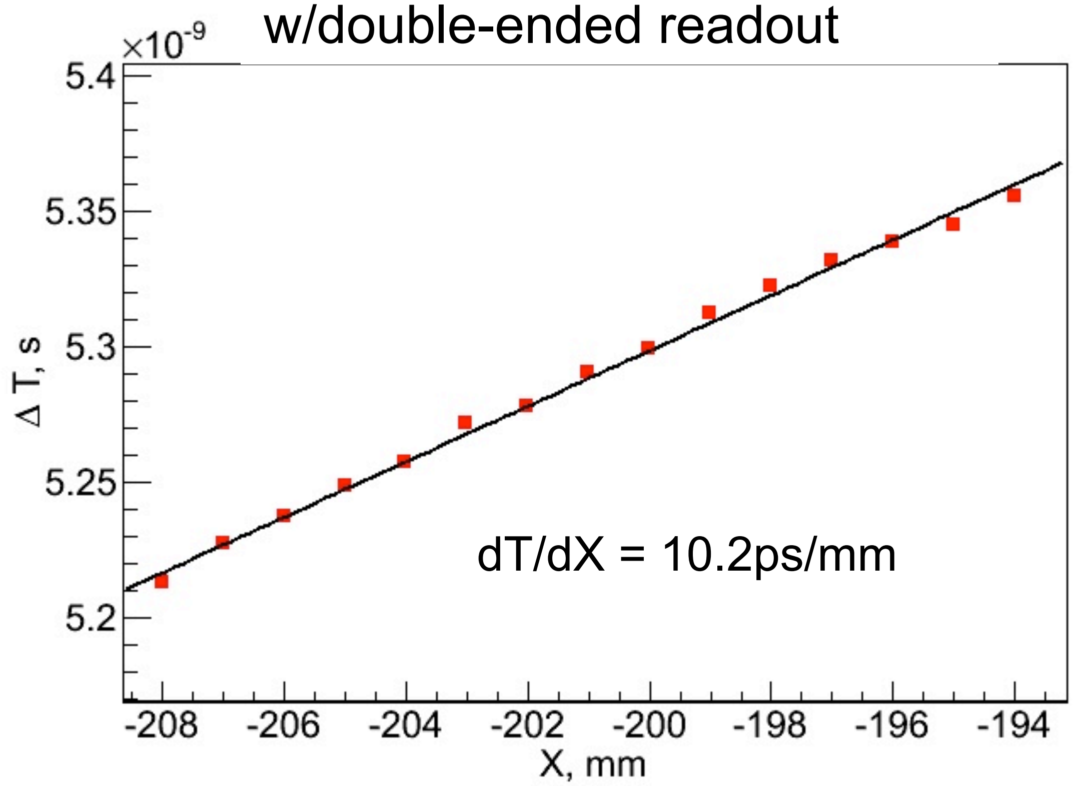



Differential Time Resolution vs. Noise




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

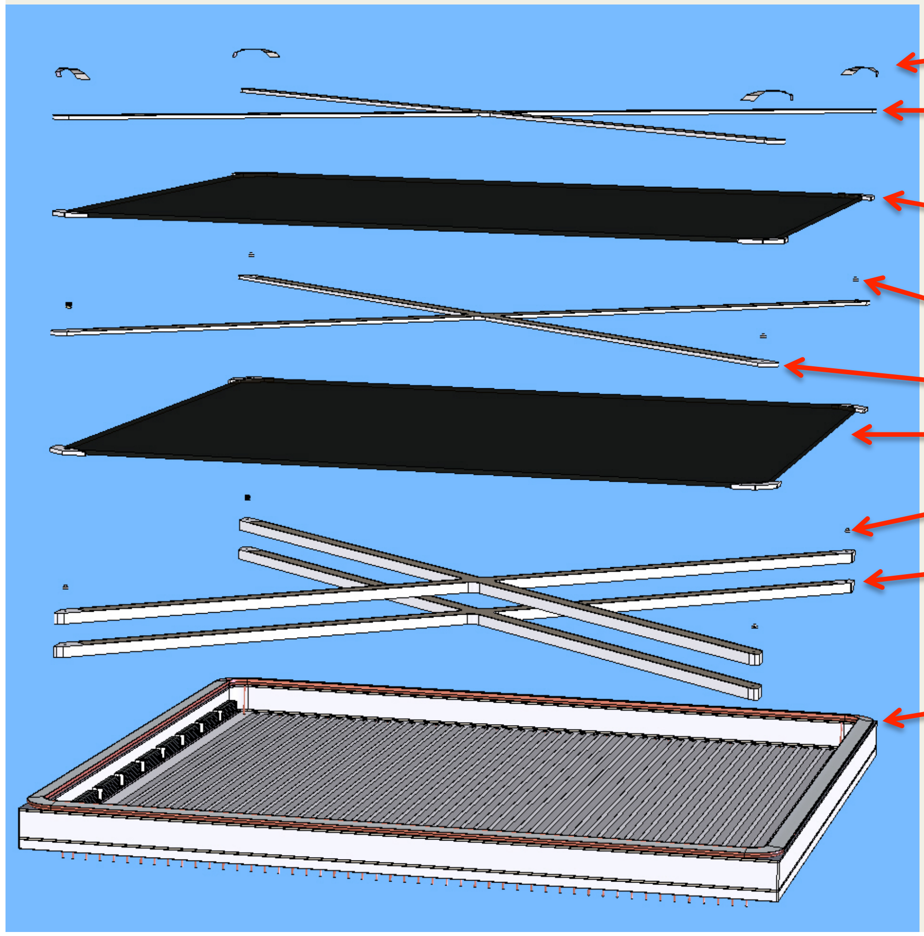
Position scan along stripline w/double-ended readout




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

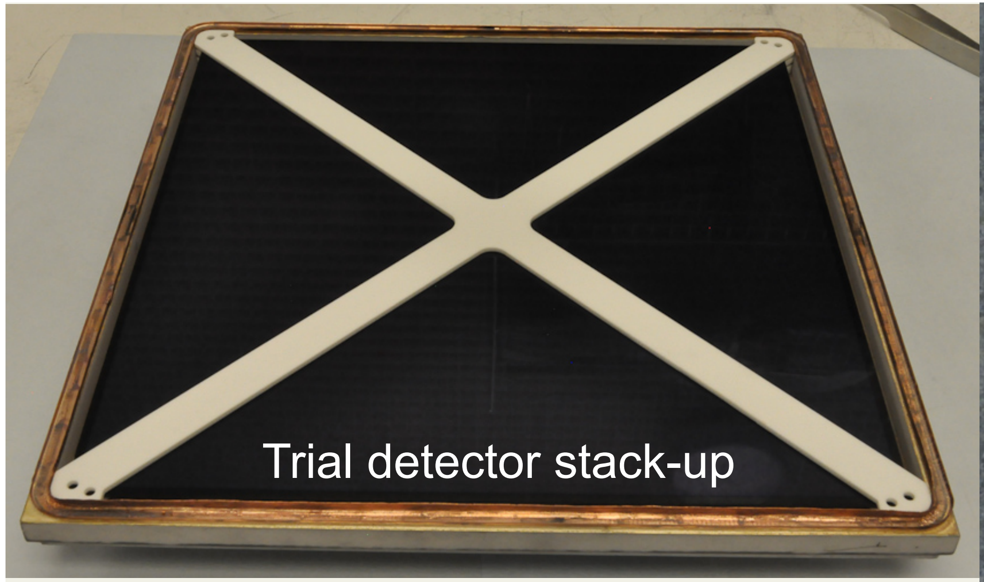
# Development of Hermetic Packaging — Ceramic Tube

## Components for SSL Ceramic Tube

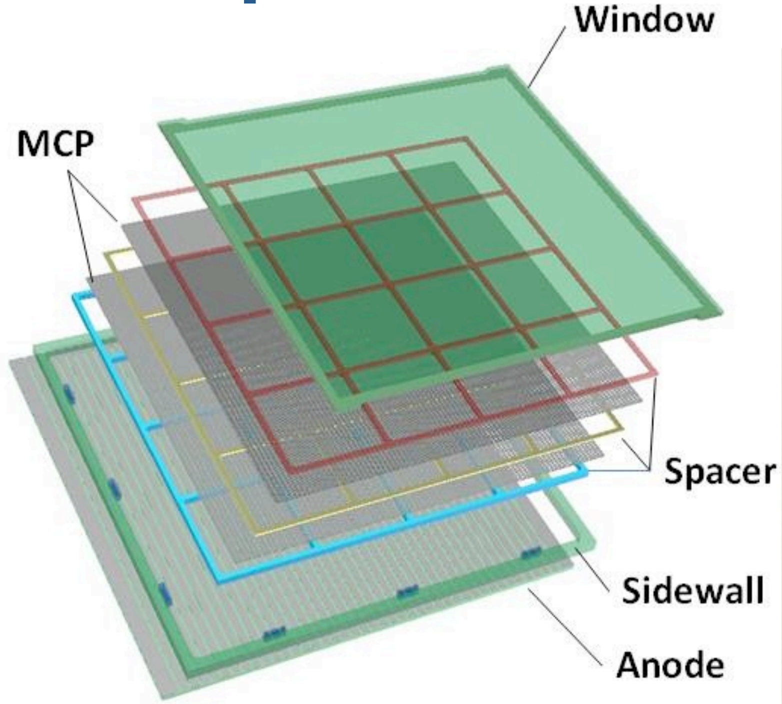


- Stack hold-down straps
- Top X-Grid – .060" thick plus ~.002" X-shim to adjust stack height
- Top MCP – with anti-rotation blocks at corners
- HV contacts
- Middle X-Grid – .060" thick
- Bottom MCP (w/ AR blocks)
- HV contacts
- Anode gap X-Grids - .060" ea plus ~.020" X-shim to adjust stack height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

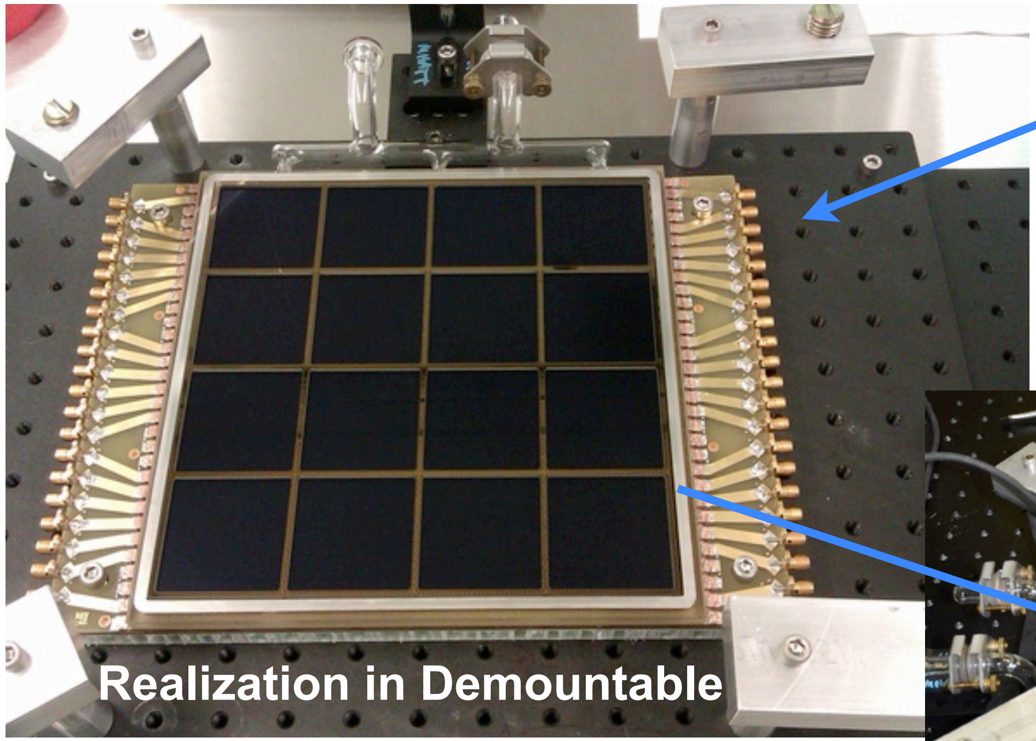
- Internal stack height .003"–.006" shorter than walls to ensure seal


# Development of Hermetic Package – All Glass Tile

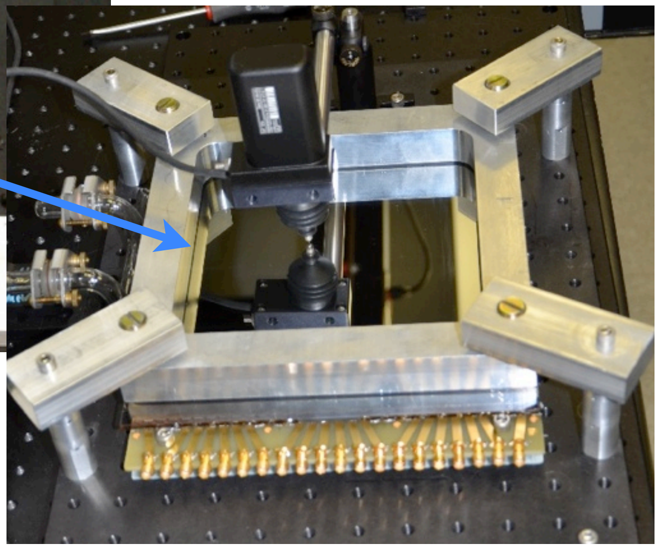



Design Drawing - September 2010



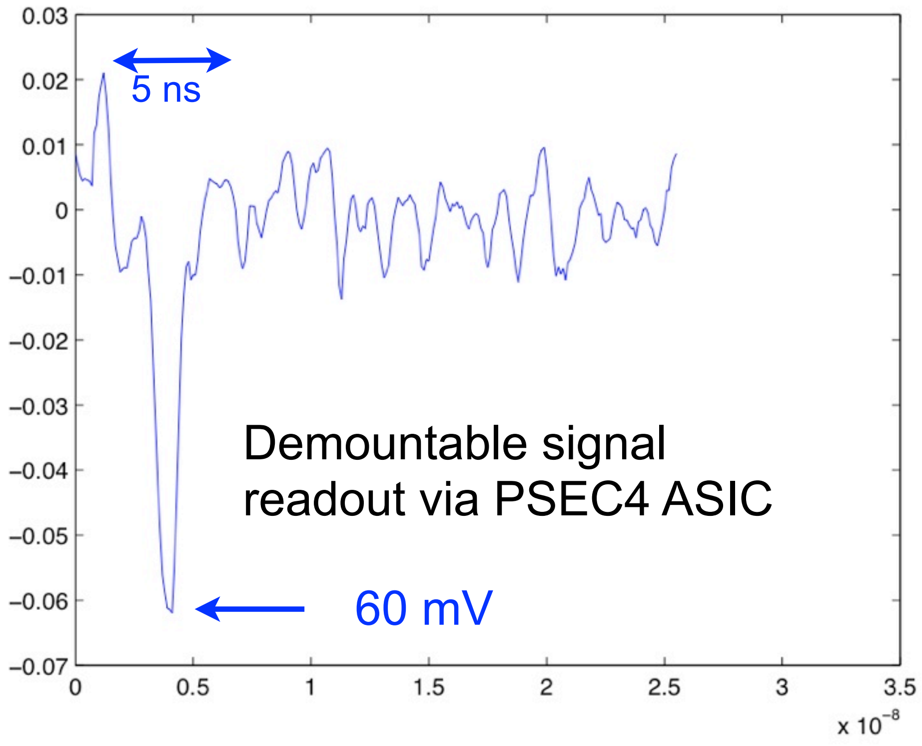

Assembled in ALD Lab Clean Room

Transported to APS UV Laser Test Setup



**Demountable is o-ring sealed tile:**

- Continuously pumped
- MCP pair: Chem. 2 + MgO SEE
- Al photocathode on quartz window
- ALD grid spacer for HV distribution
- 30-strip anode to fanout board



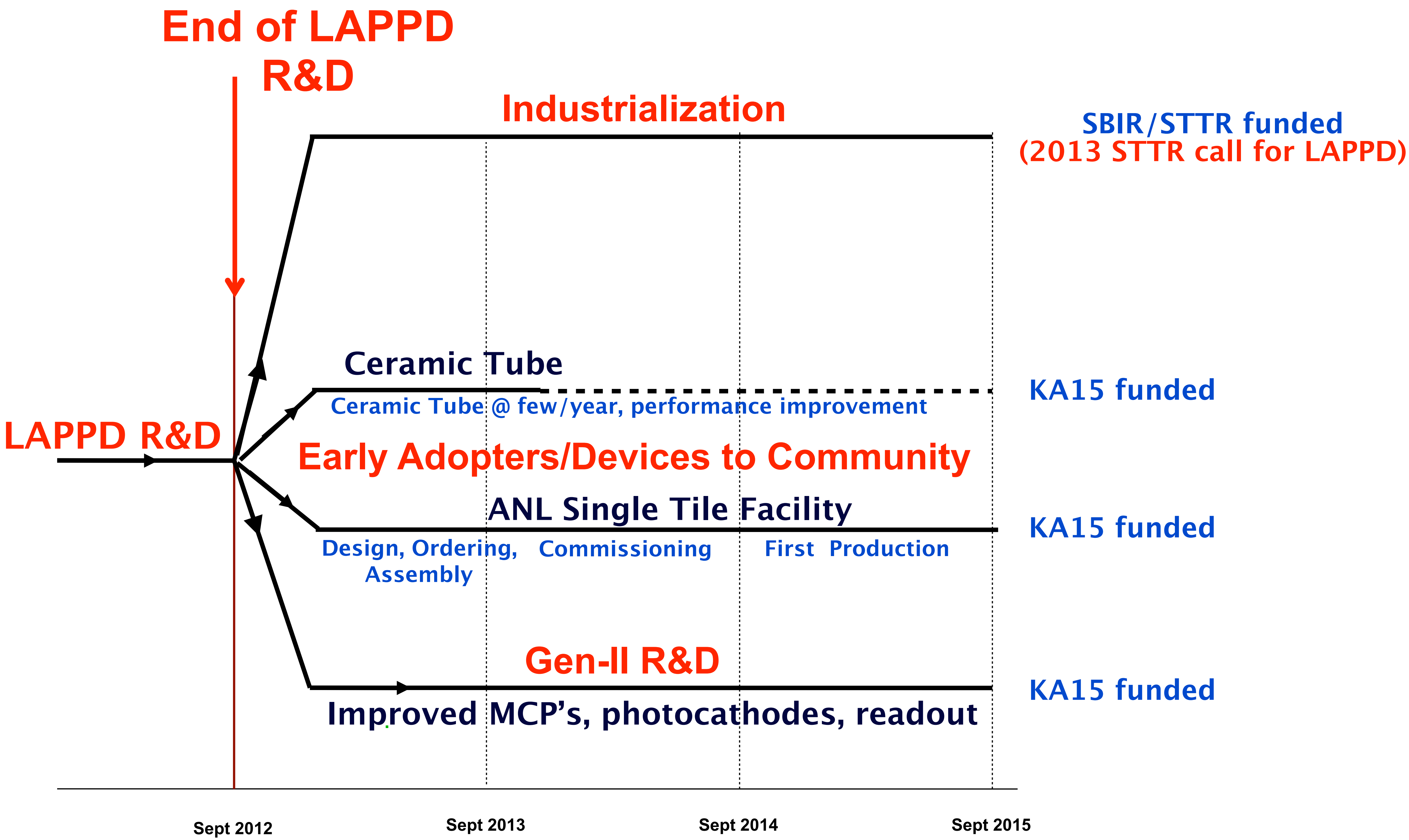

- **Concept of All-Glass Package demonstrated with signal acquisition in o-ring sealed "Demountable" Tile**
- **Future Work:**
  - **Complete work presently ongoing for Indium pressure seal for top window**
  - **Produce sealed tiles with bialkali PC in future Argonne Single Tile Processing System**

# Summary of Accomplishments 2009-2012

- ☑ Developed large area capillary arrays (20µm pore, L/D=60) for MCP substrate
- Functionalized MCPs via separate Atomic Layer Deposition resistive and secondary emissive coatings
  - ☑ Demonstrated high gain (> $10^7$) with little aging
  - Success recognized with R&D100 award 2012
- ☑ Characterization of SEE materials within Argonne MSD
- ☑ Established MCP test facilities at Argonne and SSL/UC-Berkeley
- ☑ Developed detector-to-computer DAQ based on PSEC4 ASIC with 1.6GHz BW, 10-15 GSa/s
- Timing resolution: 6ps differential, 63ps single pe
- ☑ 8" photocathodes (SSL) with QE~25% @ 350nm with good uniformity & stability
- Established photocathode lab at Argonne and made first 4"&7" photocathodes
- ☑ Demonstrated signals from o-ring sealed all-glass economical tile at Argonne
- Process tank for 8" ceramic tube at SSL ready for commissioning
- ➡ Completing ceramic body braze at SSL and on-track for working sealed tube in Fall 2012
- ☑ Development of 4×3 tile SuperModule tray with complete readout chain

☑ Original Proposal Milestone
➡ Milestone yet to be achieved

# LAPPD Future Directions



# STTR Call for LAPPD

**U.S. Department of Energy**

**Small Business Innovation Research (SBIR) and**
**Small Business Technology Transfer (STTR) Programs**

**Topics**

**FY 2013**
**Phase I**
**(Release 1)**

**Participating DOE Research Programs**

- Office of Advanced Scientific Computing Research
- Office of Basic Energy Sciences
- Office of Biological and Environmental Research
- Office of Defense Nuclear Nonproliferation
- Office of Fusion Energy Sciences
- Office of High Energy Physics
- Office of Nuclear Physics

**38. TECHNOLOGY TRANSFER OPPORTUNITY: DETECTORS ($450,000 PHASE I/ $3,000,000 PHASE II)**

*Applicants to Technology Transfer Opportunities should review the section describing Technology Transfer Opportunities on page 1 of this document prior to submitting applications.*

**Grant applications are sought in the following subtopics:**

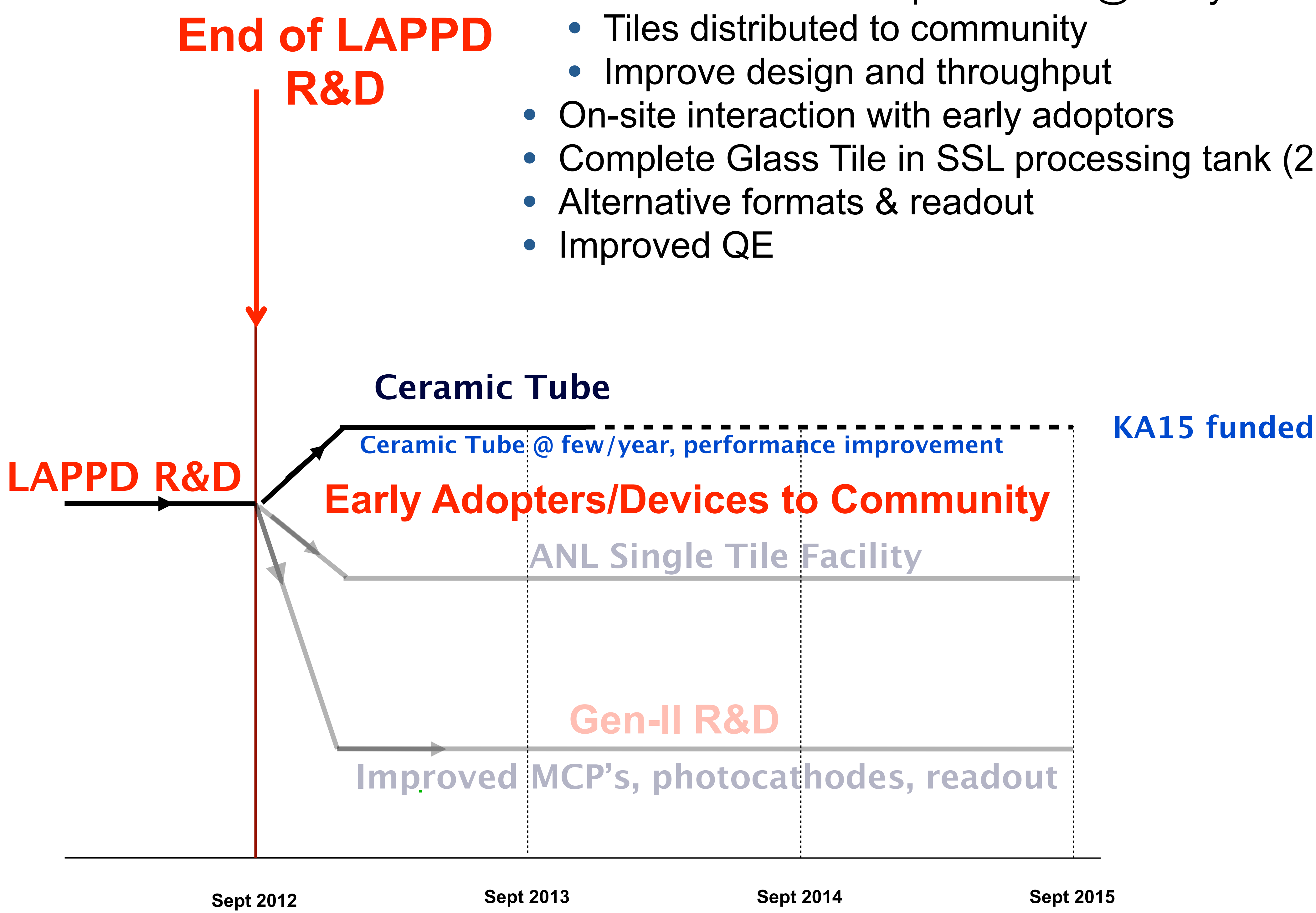
a. **Large Area Fast Photodetectors for Particle Detection (LAPPD)**
Patent Status: Two pending and unpublished patent applications and one published patent application

The LAPPD Collaboration, based at ANL, has been developing an innovative large-area (8” by 8”) photodetector for use in particle physics experiments. The detectors represent an alternative to multi-channel PMTs, possibly at lower cost and with several advanced features.

# LAPPD Future Directions — Ceramic Tube Production

**Tile Production at SSL/UC-Berkeley:**

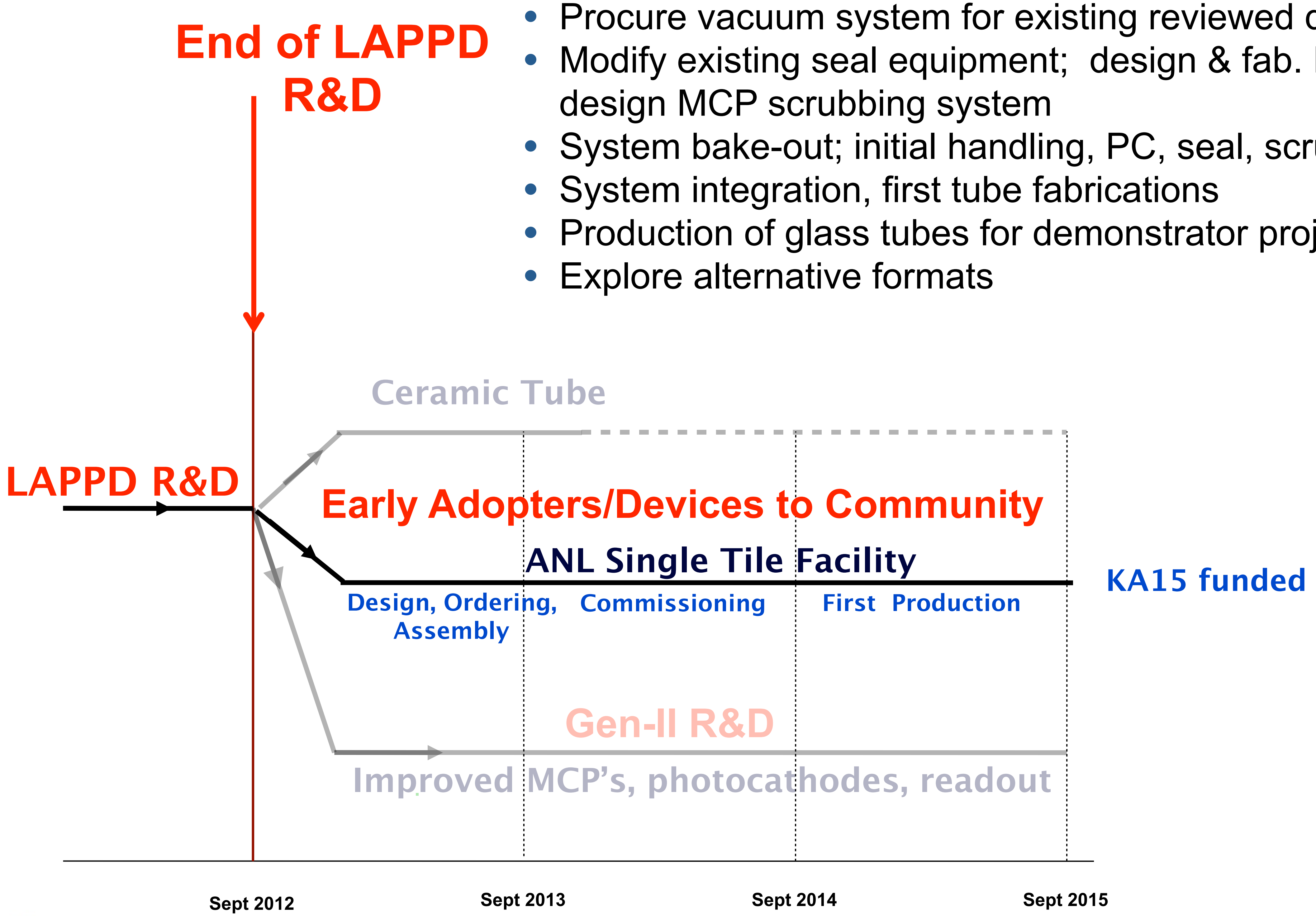
- Continue ceramic tile production @ few/year
  - Tiles distributed to community
  - Improve design and throughput
- On-site interaction with early adoptors
- Complete Glass Tile in SSL processing tank (2013)
- Alternative formats & readout
- Improved QE



# LAPPD Future Directions — Argonne Single Tile Facility

**Glass Tile Production at Argonne:**

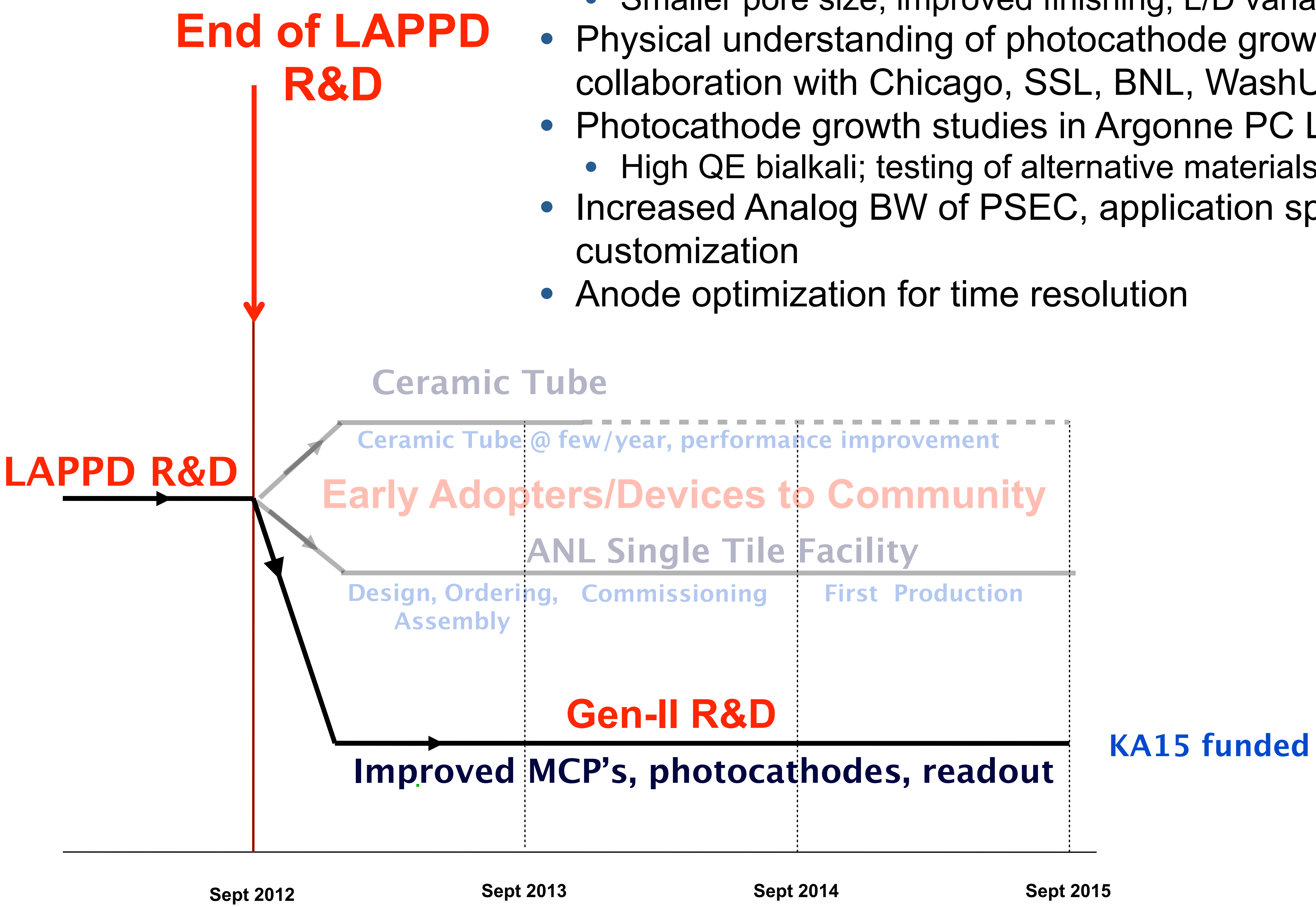
- Completion of indium seal technique
- Procure vacuum system for existing reviewed design
- Modify existing seal equipment; design & fab. PC system; design MCP scrubbing system
- System bake-out; initial handling, PC, seal, scrub tests
- System integration, first tube fabrications
- Production of glass tubes for demonstrator project
- Explore alternative formats



# LAPPD Future Directions — Generation-II R&D

**Gen-II R&D for Large-Area MCPs:**

- Block fabrication at Incom for continued quality improvement
  - Smaller pore size, improved finishing, L/D variation
- Physical understanding of photocathode growth; collaboration with Chicago, SSL, BNL, WashU, …
- Photocathode growth studies in Argonne PC Lab
  - High QE bialkali; testing of alternative materials, e.g. (In)GaN
- Increased Analog BW of PSEC, application specific customization
- Anode optimization for time resolution



# LAPPD Project Summary

## Capability Gap

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

## Benefit

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

## Approach

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

## Results and Deliverables

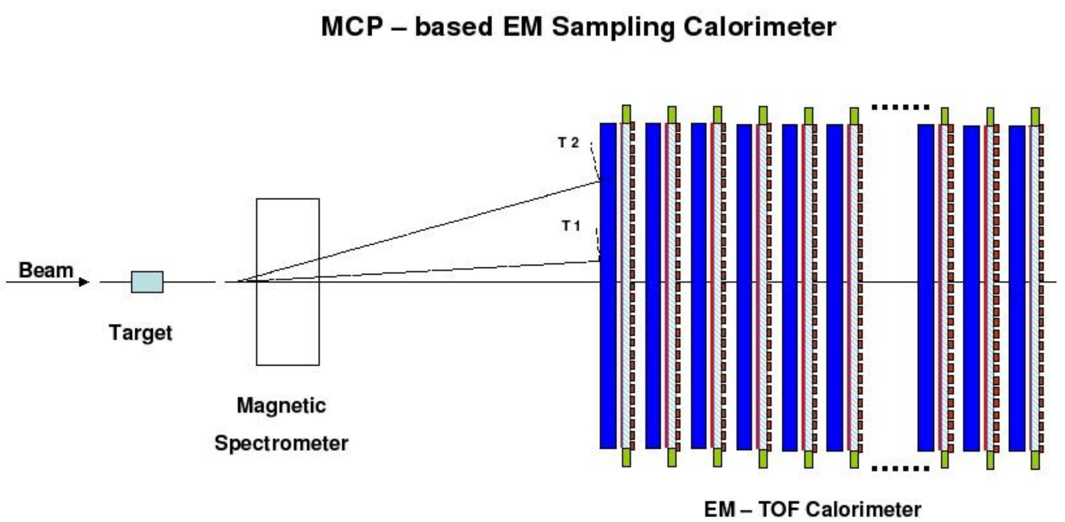
- Signals from o-ring sealed complete all-glass MCP tile
- Diff. time resolution with 8" MCP pair < 6ps
- Complete DAQ system with PSEC4 ASIC; 15 GSa/s; noise<1mV, bandwidth ~1.6GHz
- 8" Photocathode QE~25% @ 350nm & uniform & stable
- On track for sealed ceramic MCP-PMT by Fall
- Propose to construct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

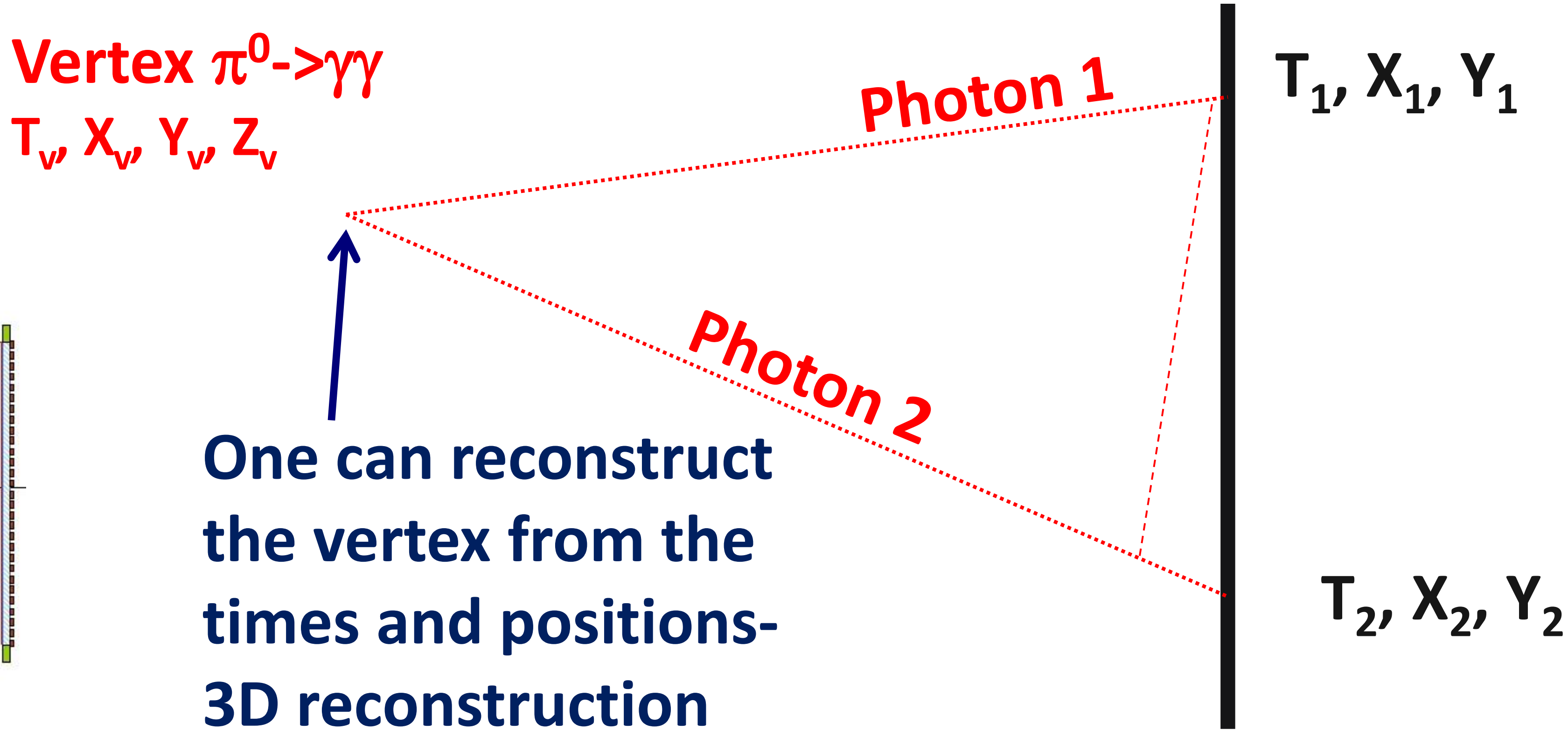
# Backup Slides

# Applications — Photon Vertexing

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

Combination with precision energy resolution in calorimeter critical




Reduce combinatoric background for $\pi^o$

Henry Frisch, DOE Presentation, 24 May 2012

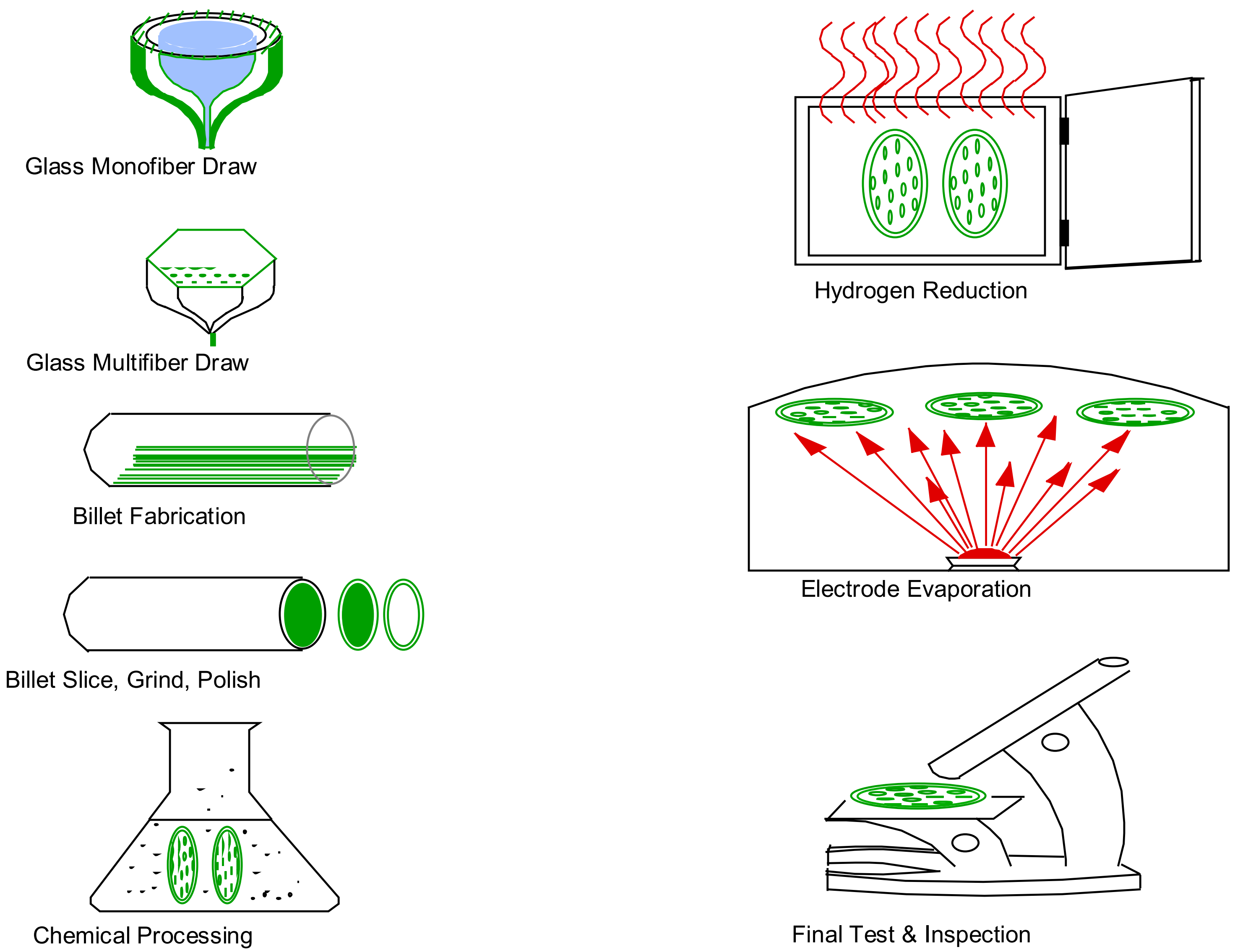
# Industrial Microchannel Plate Fabrication

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

Glass is gravity-fed via cylindrical furnace

Glass is typically lead glass tube with solid soft glass core

Chemical processing to remove soft core glass

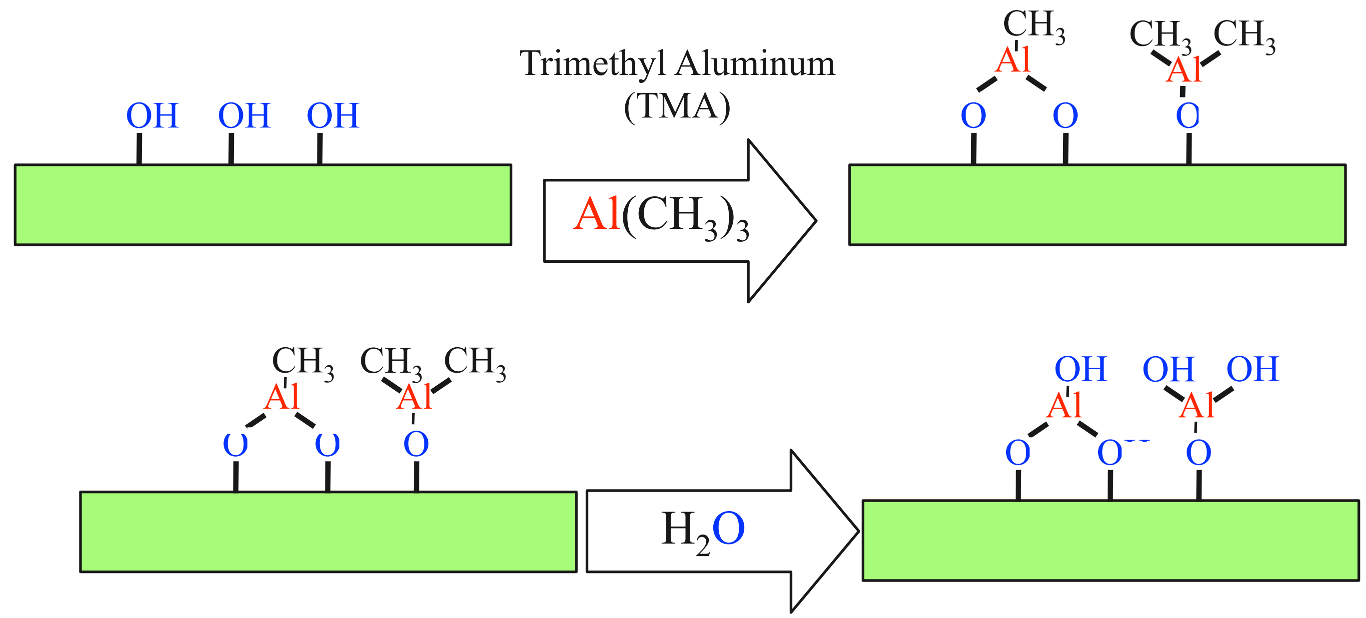


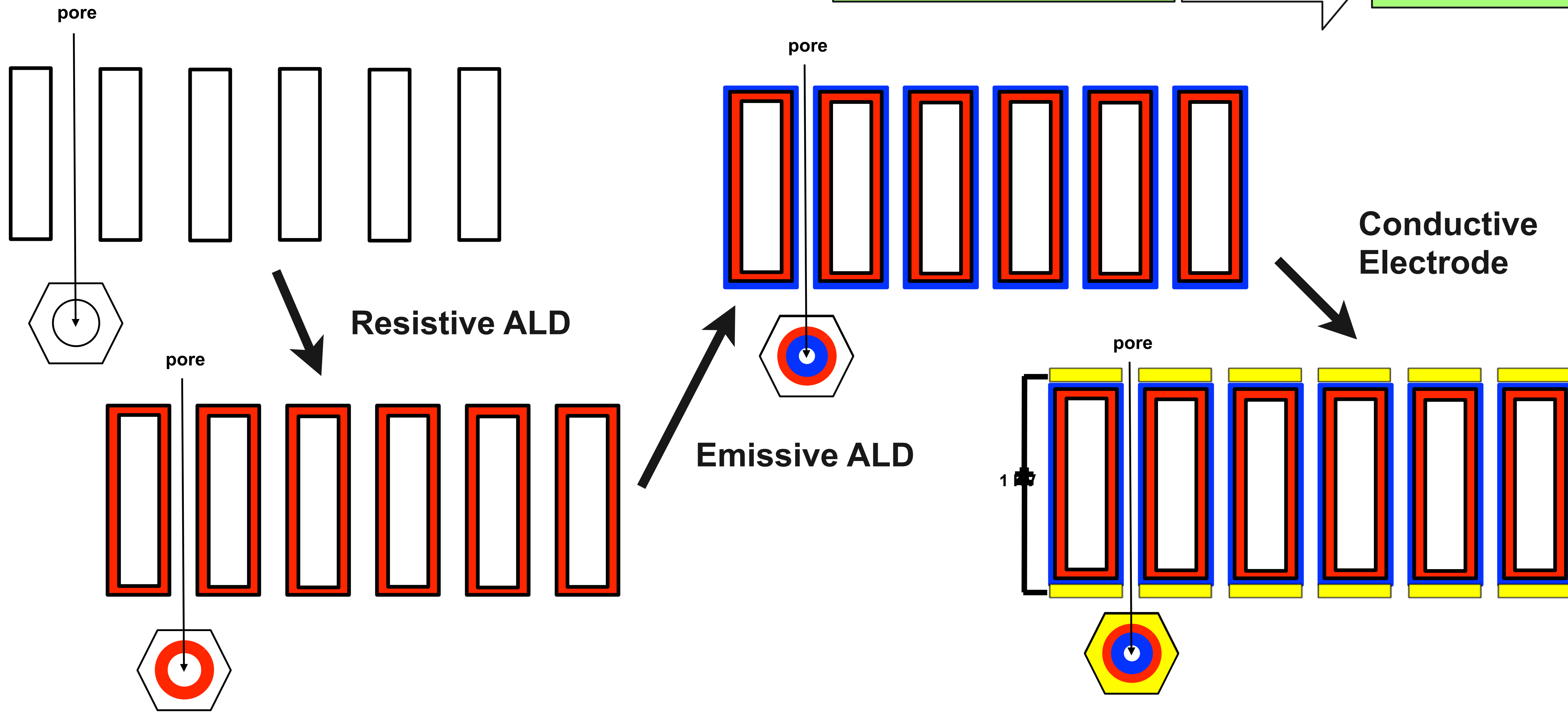

Before sealing in tube, plate must be subjected to prolonged exposure to electrons at low voltage to outgas $H_2$ and other material

# Pore Activation via Atomic Layer Deposition (ALD)

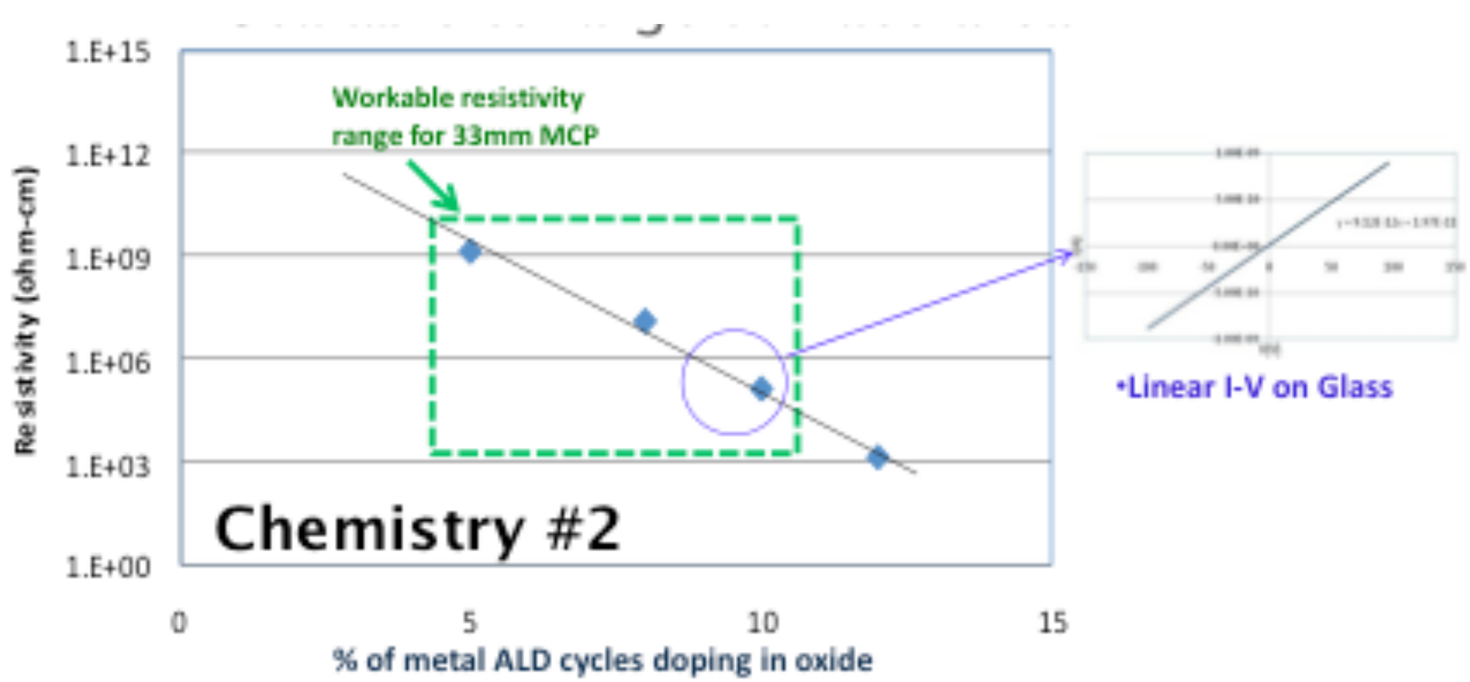
**Example:**

- 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

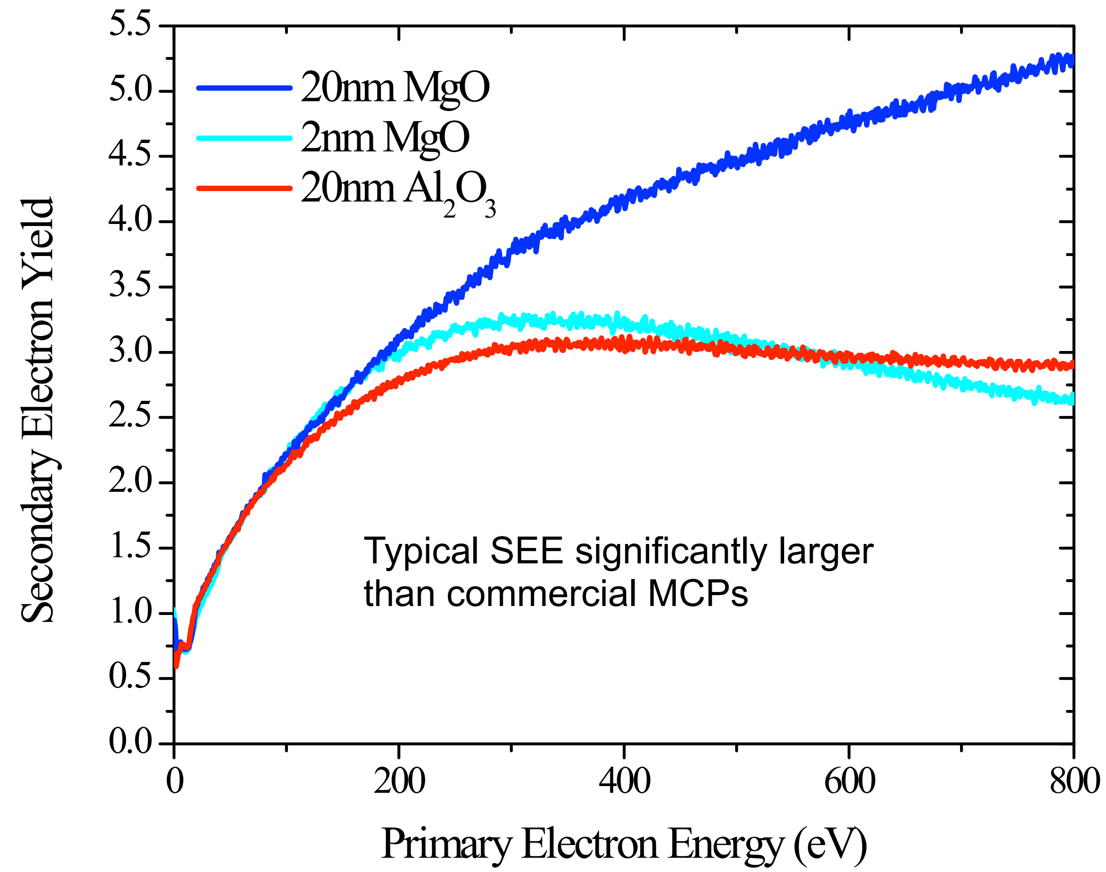


# Materials Characterization

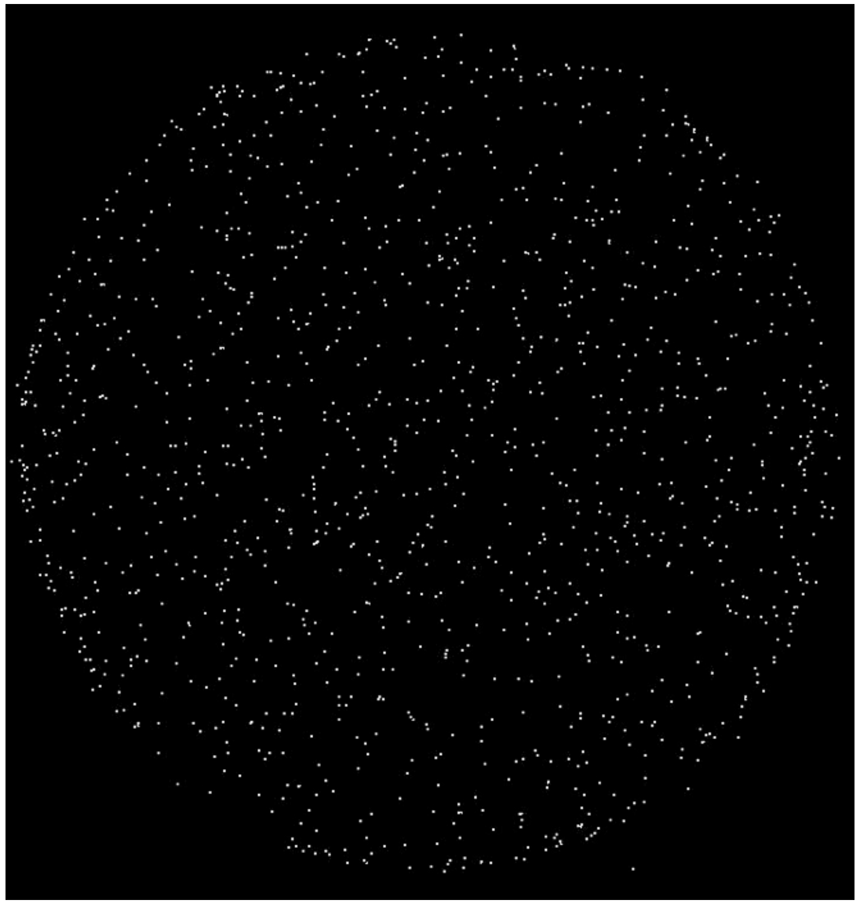



Secondary Emissive Materials characterized with Low Energy Electron Diffraction (LEED)

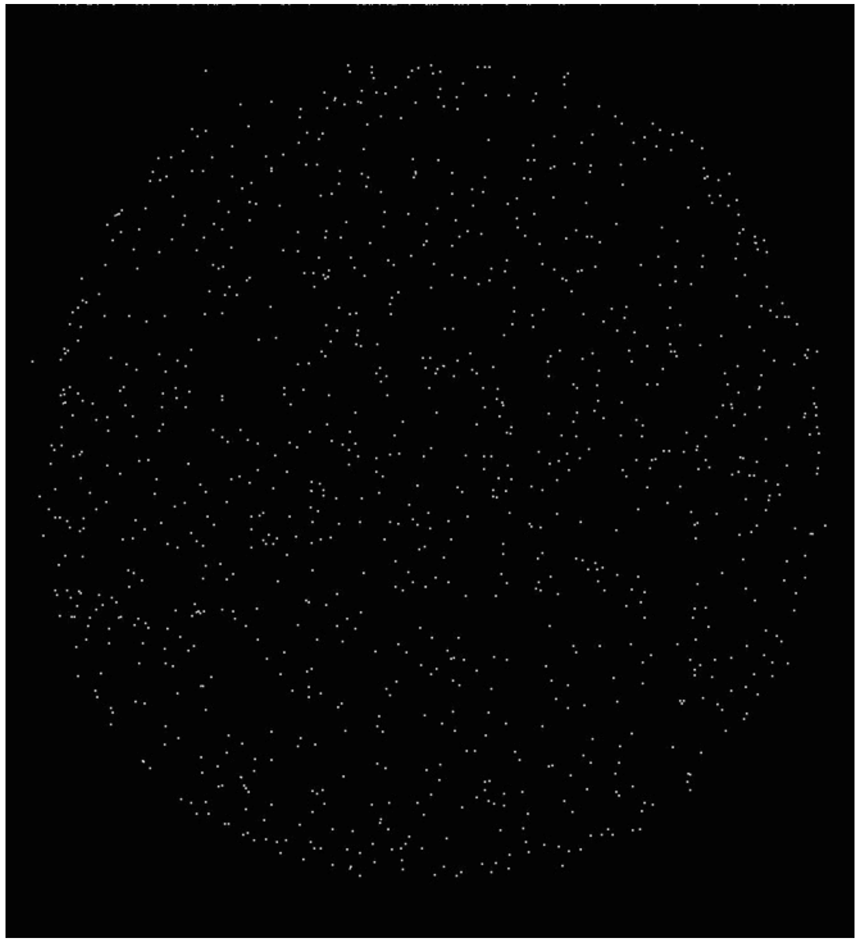


# Noise Characterization

MgO SEE Layer

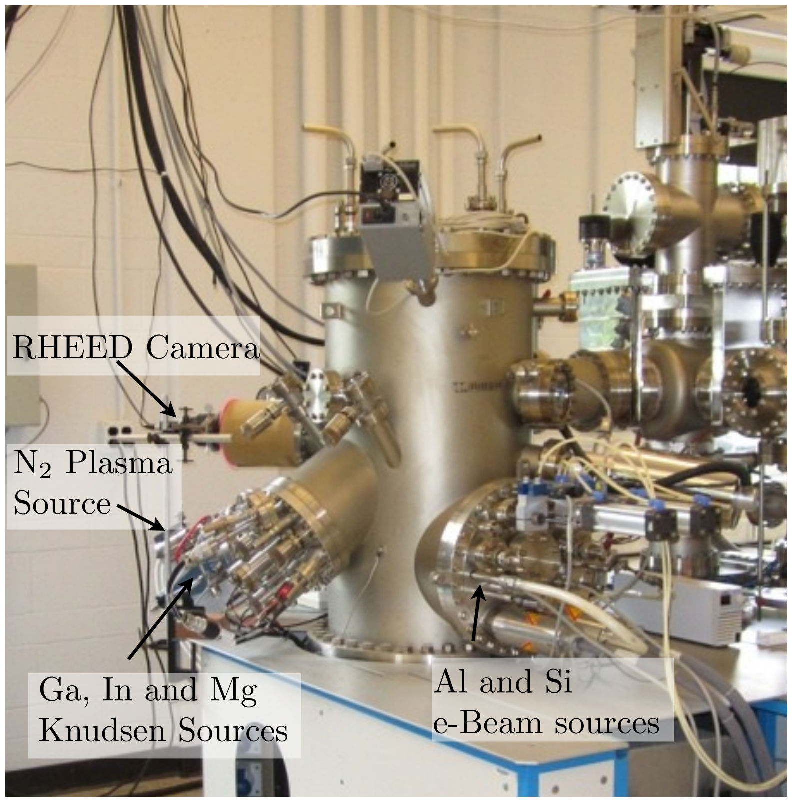


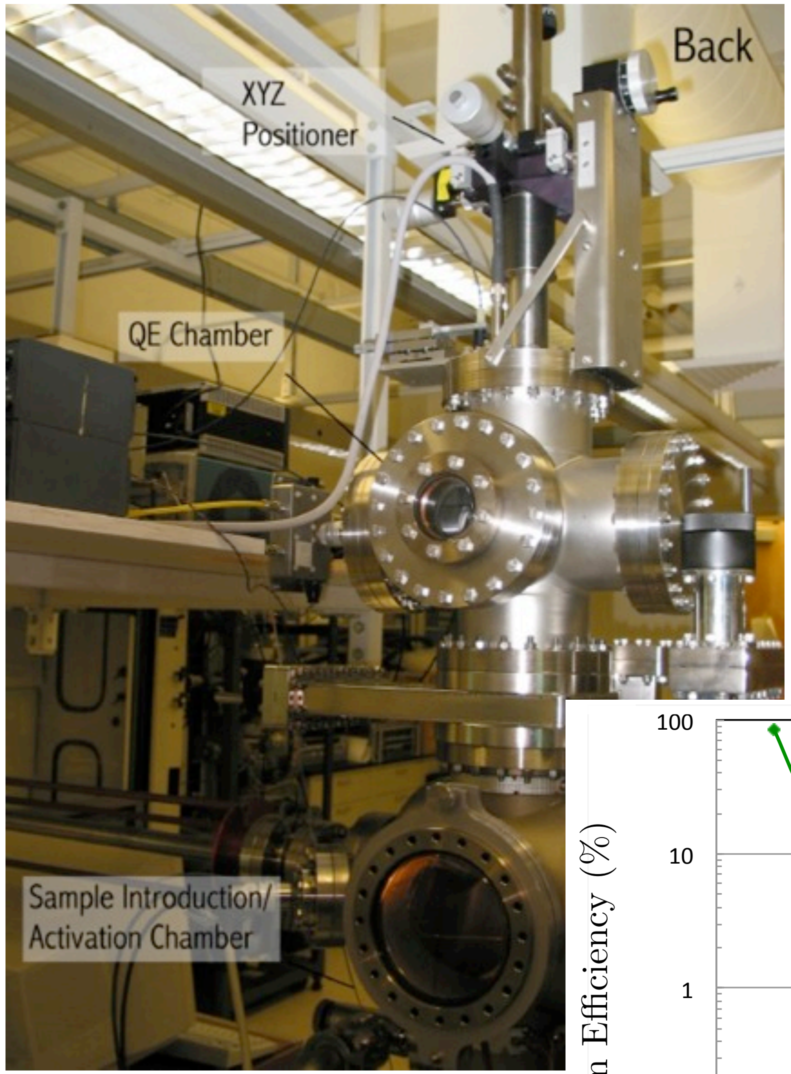
3000 sec background, 0.0845 events $cm^{-2}$ $sec^{-1}$ at 7 x $10^6$ gain, 1025v bias on each MCP. Get same behavior for most of the current 20µm MCPs

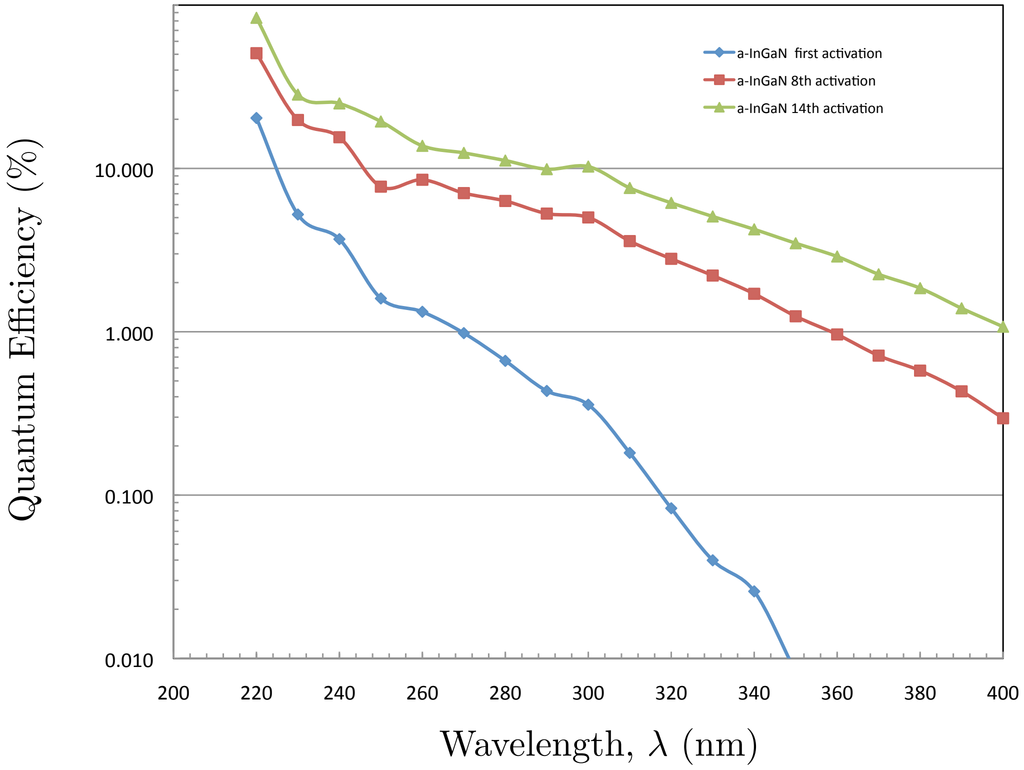


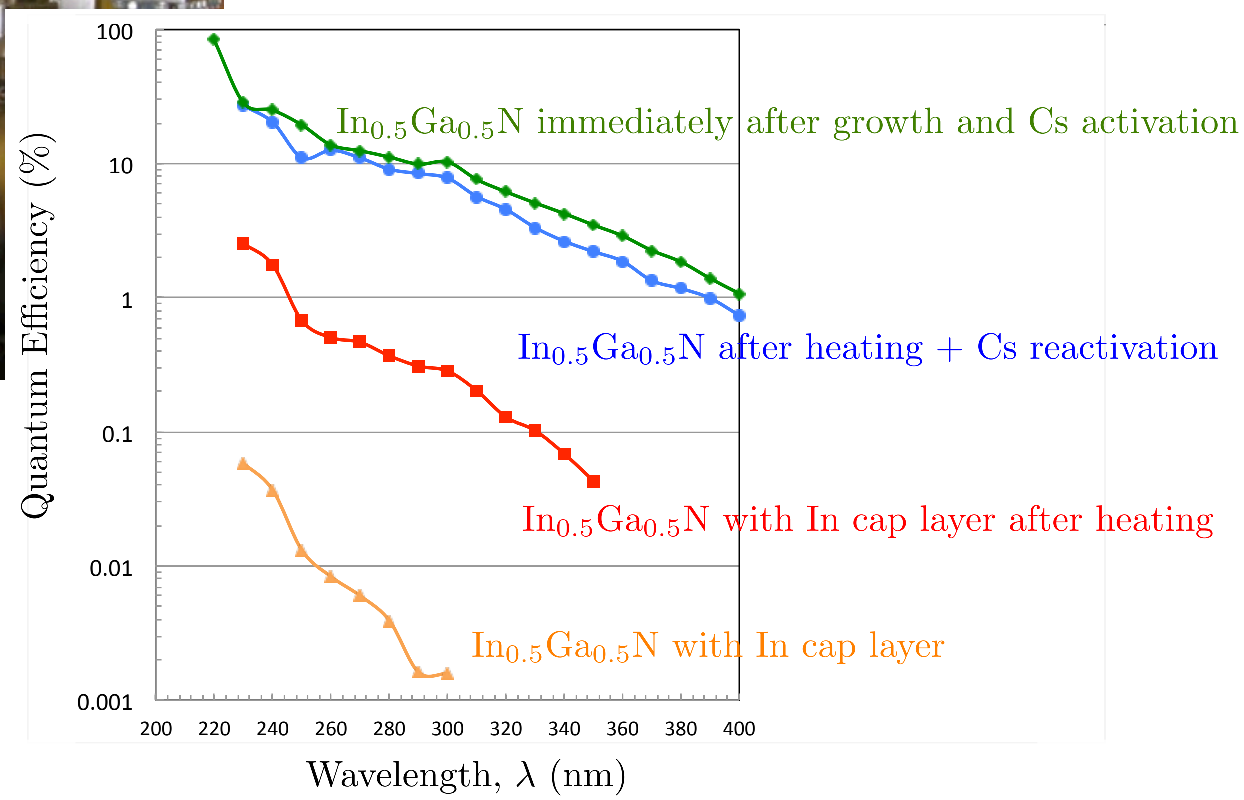
Post-bake –2000 sec
~0.1 events $cm^{-2}$ $sec^{-1}$

# InGaN Photocathode Development – Washington University



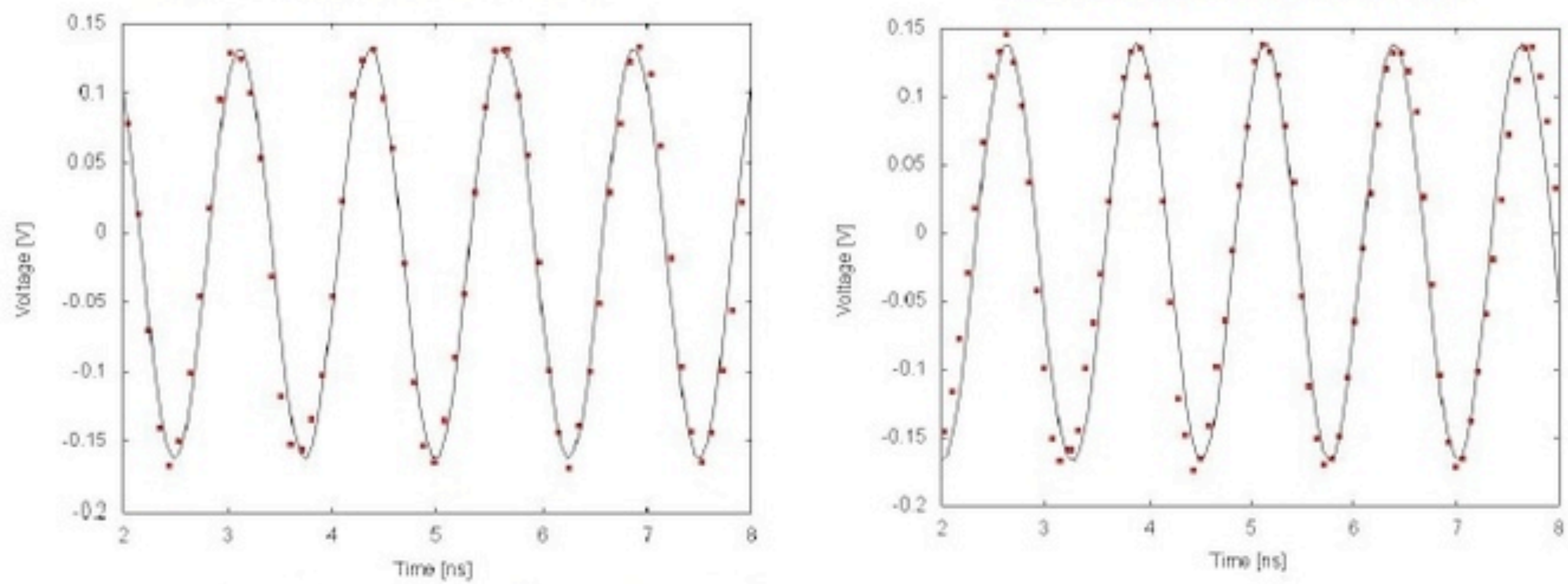



# PSEC4 Performance

**Digitized Waveforms**

Input: 800MHz, 300 $mV_{pp}$ sine

**Sampling rate : 10 GSa/s** **Sampling rate : 13.3 GSa/s**




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

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


Two chamber CsTe Photocathode Transfer System


Indium Top Seal Vacuum Test Chamber

**Possible early STF demonstrator:**

- Chambers can be coupled via existing 6” flanges to give PC process chamber and sealing chamber.
- Left system is operating now at $5\times10^{-10}$ torr, right system is $10^{-8}$ torr