

Recent Advances in Lead-free MCPs Functionalized by ALD for Photomultiplier Tubes

Cole J. Hamel

Sr. Associate Research Scientist

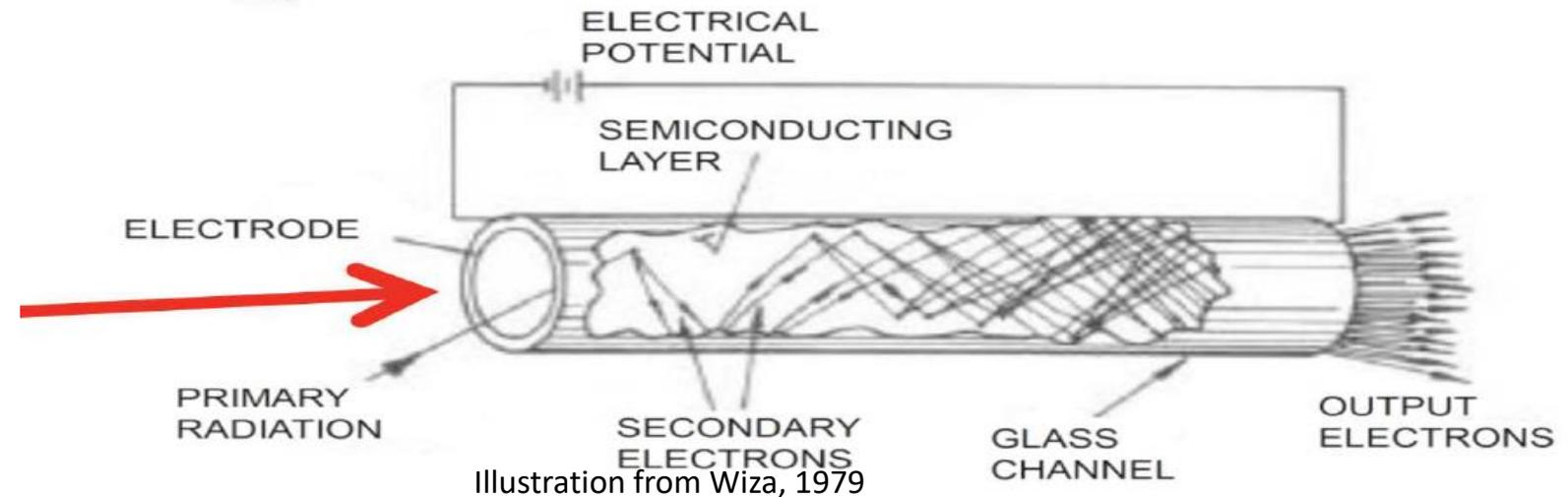
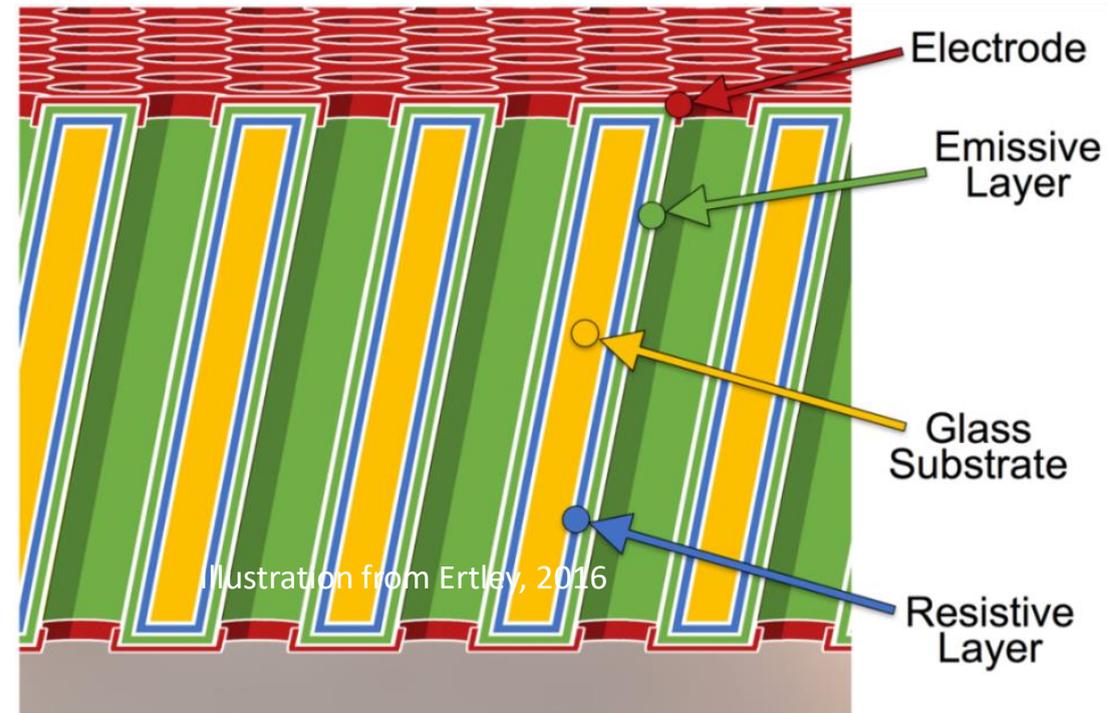
Incom, Inc. Charlton, MA

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Co-Authors: Melvin Aviles, Travis Curtis, Stefan Cwik, Jeffrey
Elam, Matt Grden, Alexey Lyashenko, Michael Minot, Mark
Popecki, Oswald Siegmund, Anton Tremsin

The Microchannel Plate

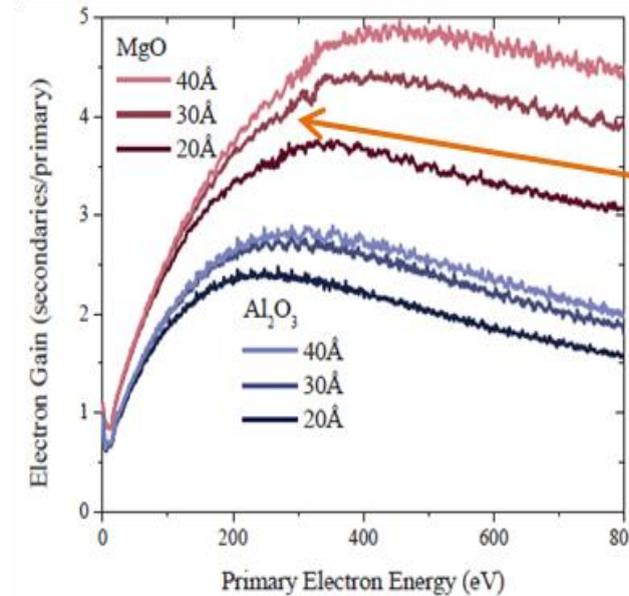
- Traditional Lead-Glass Microchannel Plates (MCPs)
 - PbO glass
 - Acid Etched
 - Hydrogen Fired
- Functional, but:
 - Brittle
 - Issues with gain stability
 - High afterpulse rates



Atomic Layer Deposition (ALD) Coating = GCAs \rightarrow MCPs



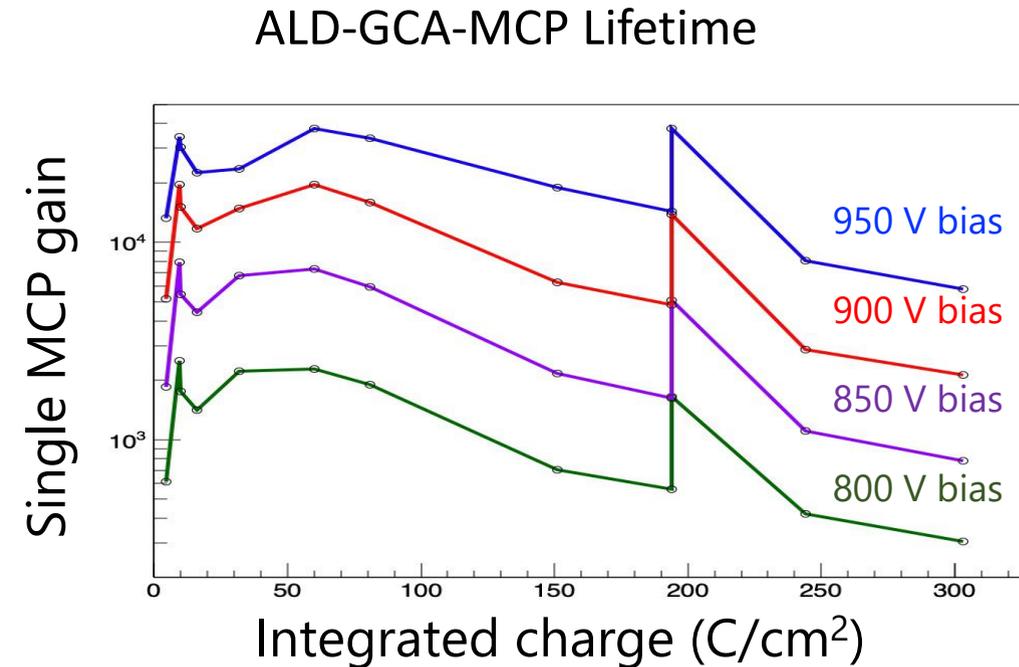
- Combination of Incom's Glass Capillary Array (GCA) technology and ALD technology developed at ANL
 - Made possible by DOE funding
- Resistance can be tuned to desired value
- Non-leaded glass as a substrate
- Resistance and secondary emission come from thin films
- Al_2O_3 or MgO SEE layer for high gain (Mane, et al., 2012)



MgO secondary electrons

Advantages of Incom ALD-GCA-MCPs

- Mechanical Robustness
 - Larger sizes
 - Unique form factors
 - Easier handling
 - No moisture-related breakages
- Gain
 - Higher gain than conventional MCPs
 - Lower operation voltages
- Longer Lifetime
 - Longer lifetimes than conventional MCPs
 - At 300 C/cm² extracted charge, the gain falls by a factor of 7
 - This can be accommodated with an increase in voltage of 100 V/MCP
- Higher Open Area Ratios (OAR)
 - 65-74 % depending on glass type
 - No funneling of the pore ends- preserve time resolution with high OAR
- Lower Intrinsic Dark Rate
 - Less 40K than conventional MCPs- background as low as 0.05 Hz/cm² achieved



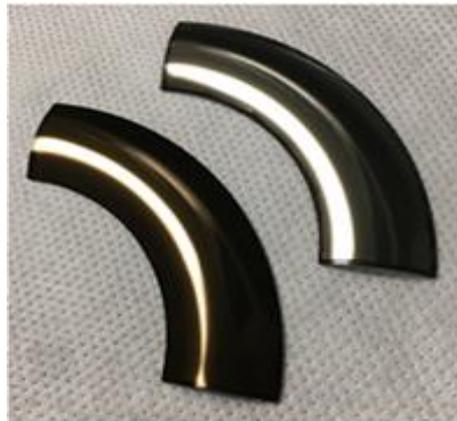
Standard MCP Sizes

Outer Dimensions (10 and 20 um pores)
203 mm x 203 mm
108 mm x 108 mm
53.47 mm x 53.47 mm
50 mm diameter
33 mm diameter
25 mm diameter

- L/D Ratio is 60:1, meaning that all MCPs with 20 um pores are 1.2 mm thick and all MCPs with 10 um pores are 0.6 um thick
- Curved substrates also available
- Custom Form Factors are available



Durability



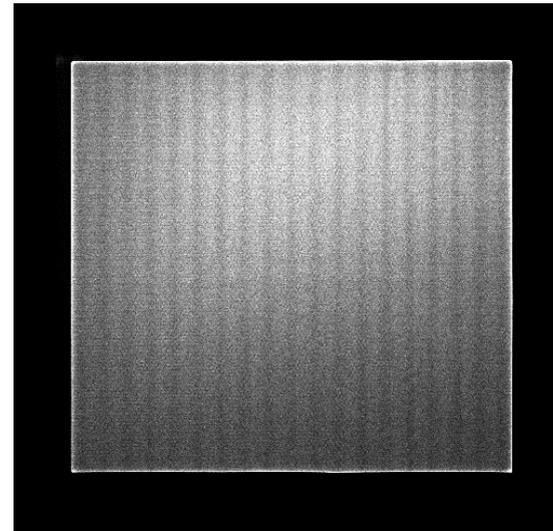
- ALD-GCA-MCPs can be curved based on customer specifications
- We can ALD coat virtually any substrate geometry- shape to the physics requirements of the measurement
- Up to 180 degree curve with a radius of curvature as low as 20 mm
- ALD-GCA-MCPs are hand-portable even at sizes up to 20 x 20 cm!



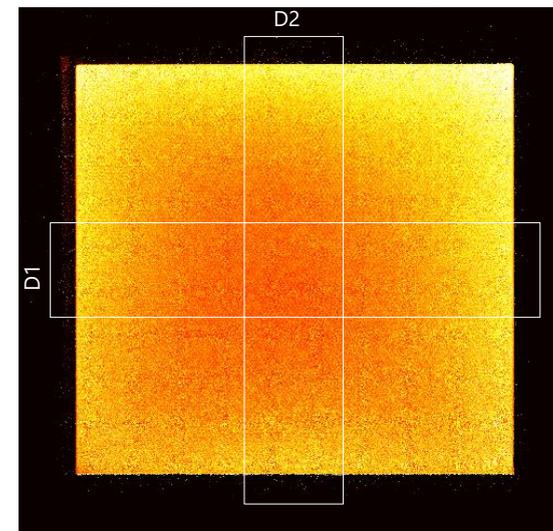
Large Size ALD-GCA-MCPs: 10 and 20 um pore size 203 mm sq.



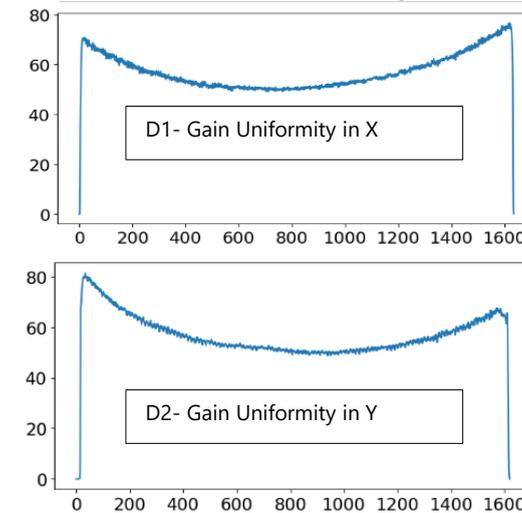
Photon Map



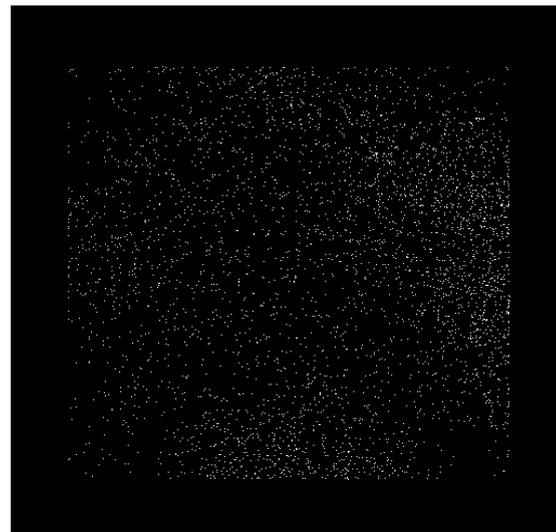
Gain Map



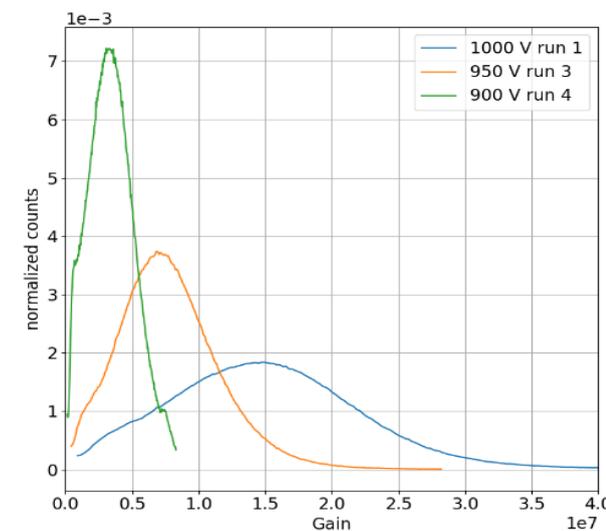
Gain Uniformity X-Y



Background Map



Pulse Height Distribution



Dimensions:

203 wide x 203 long x 1.2 mm thick

Pore size: 20 um

L/D = 60:1

Pore bias: 13 degree

MCP resistance: 1-5 MΩ

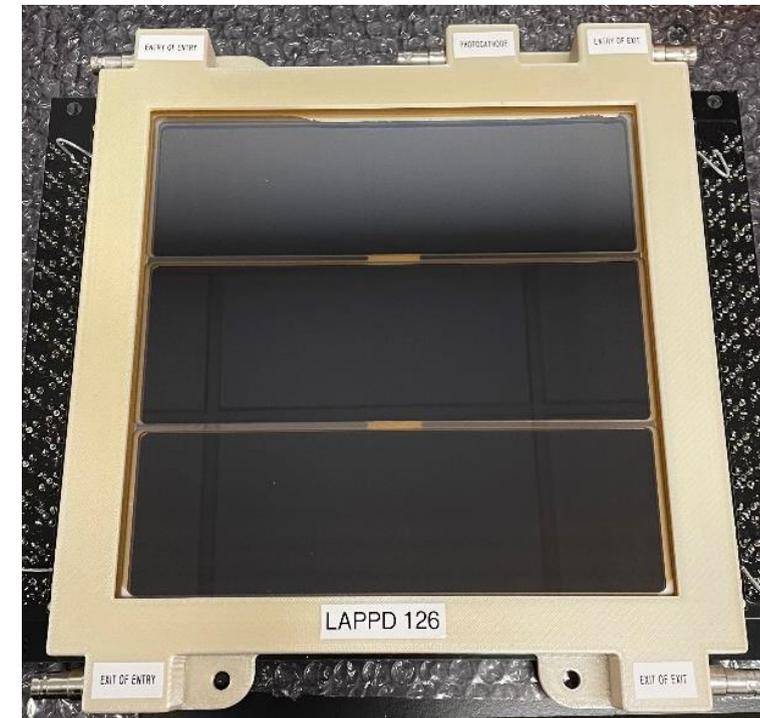
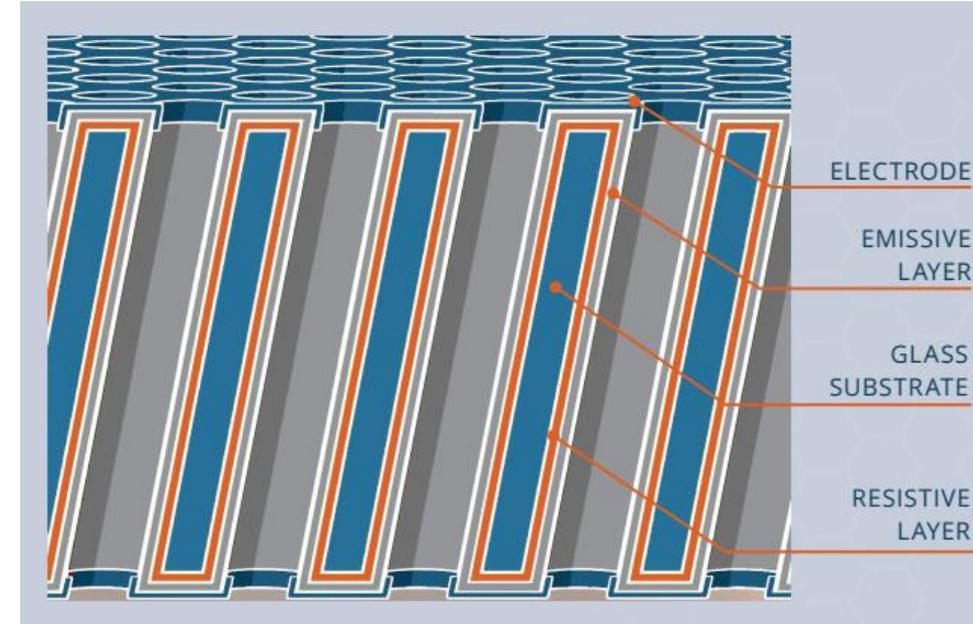
Peak gain: 1×10^7 @ 1000 V/MCP



Large Area Picosecond Photodetector (LAPPD™)

Technical Overview

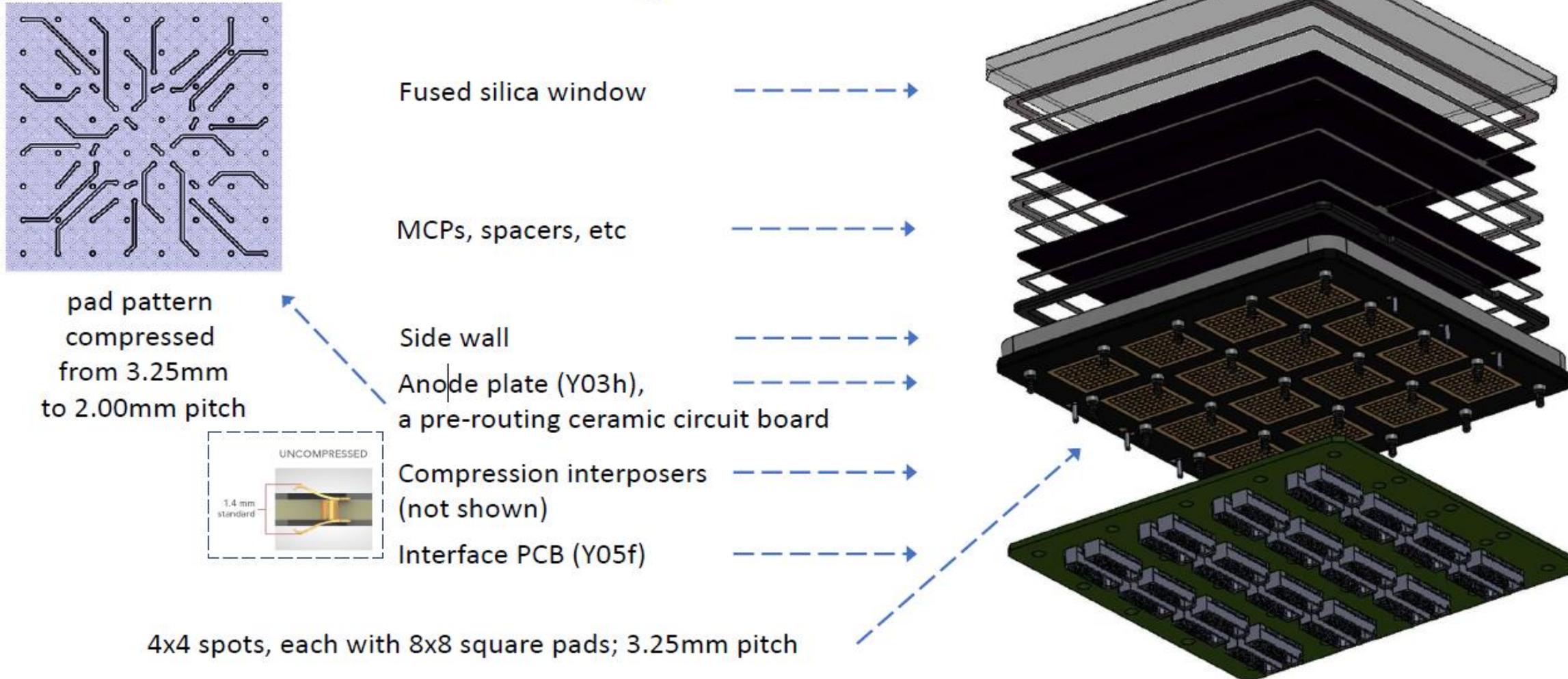
- **Developed with DOE Funding**
- **20 x 20 cm MCP-PMT**
 - Chevron pair of ALD-functionalized MCPs
 - (10 μm or 20 μm)
 - Glass/Ceramic package
 - 373 cm^2 effective area (97% open area)
- **High Gain ($\sim 10^7$)**
- **Alkali Photocathode**
 - Sodium-Potassium-Antimony Na_2KSb
 - >30% QE at 365 nm
 - >95% spatial uniformity
- **Timing Resolution**
 - SPE: ~ 48 ps (electronics limited), ~ 30 ps (Vagnoni, INFN)
 - 5 GeV EM Shower: ~ 15 ps (Vagnoni, INFN)
- **Position Resolution ~ 1 (mm)**



Incom's High Resolution Picosecond Photodetector (HRPPD)

- Currently being considered as the MCP-PMT for the pf-RICH detector of the Electron-Ion Collider

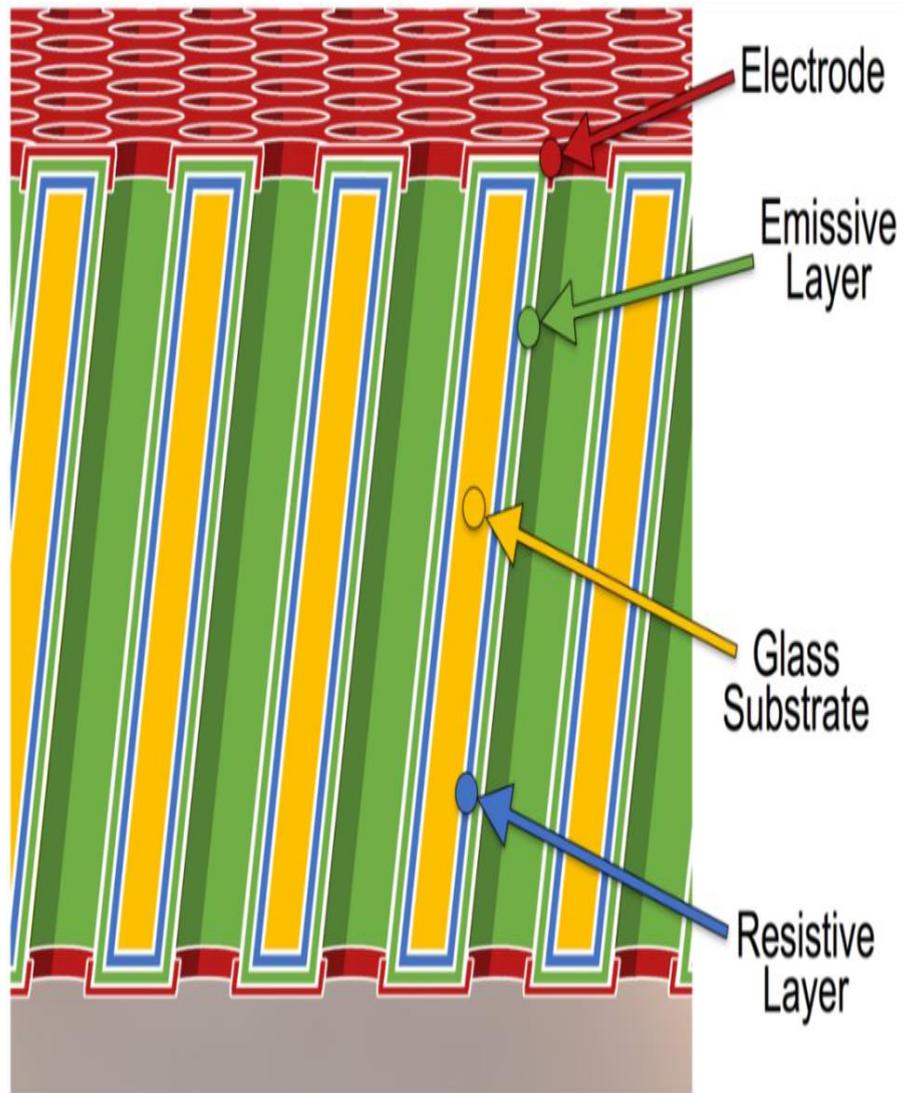
EIC HRPPD assembly



Charge path: (1) vacuum side anode pads -> anode plane stackup -> air side pads -> compression interposers -> (2) interface PCB -> MMCX adapter PCB -> pigtail RG-316 (?) cables -> 6" RG-174 cables -> V1742 digitizer



A Layered Approach



- Using the ALD-GCA approach, the Glass Substrate, Barrier Coating (not pictured) Resistive Layer, Emissive Layer and top Electrode can all be independently optimized.
- Understanding Interactions between
 - The glass chemistry
 - The ALD layers
 - The experimental environment
 - Is a key part of fabricating high-functioning ALD-GCA-MCPs for specific applications



Chemistries Optimized For Your Application

- Chem-1 / MgO
 - Developed by ANL, commercialized by Incom with DOE SBIR funding
 - High gain (1E7 at 1000 V / MCP)
 - Better environmental stability
 - Gain doesn't change much with air exposure
 - Good for use in exposed MCPs, for applications such as Mass Spectrometry or Neutron Detection.
- Chem-5 / MgO
 - Developed and commercialized by Incom using DOE SBIR funding
 - Very High gain (1E7 at 800 V/ MCP after bakeout)
 - Poor Environmental Stability
 - Gain drops to 1E7 at 1200 V / MCP after environmental exposure
 - Good for use in sealed MCP-PMTs



The Pull of the Customer

- What Customers tell us they would like
- Improved ALD-GCA-MCPs
 - MCPs with 6 um Pores
 - ALD Barrier Coatings
 - Next Generation ALD Resistive MCP Coatings
 - Environmentally Robust ALD-MCPs
 - ALD-MCPs for (Epithermal) Neutron Detection
- Improvements in Detectors with MCPs
 - Ion Counting Mass Spectrometry
 - MCP-PMTs optimized for High Rate Applications
 - Small Format MCP-PMTs with Glass or Single Crystal Scintillator Windows

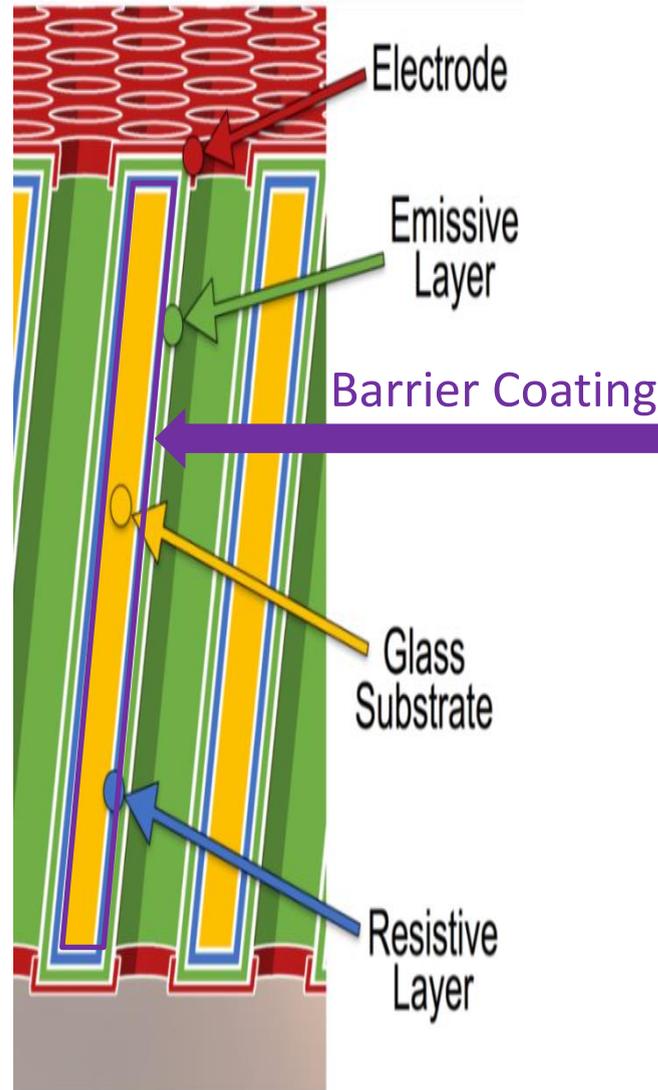


MCPs with 6 μm Pores

- Incom is developing MCPs with 6 μm pores
 - The first prototypes will be ALD coated this month
- 6 μm pores provide improved
 - Timing
 - High gain at high event rates
- With appropriate funding, can scale up from 33 mm diameter MCPs to 108 mm square MCPs and beyond



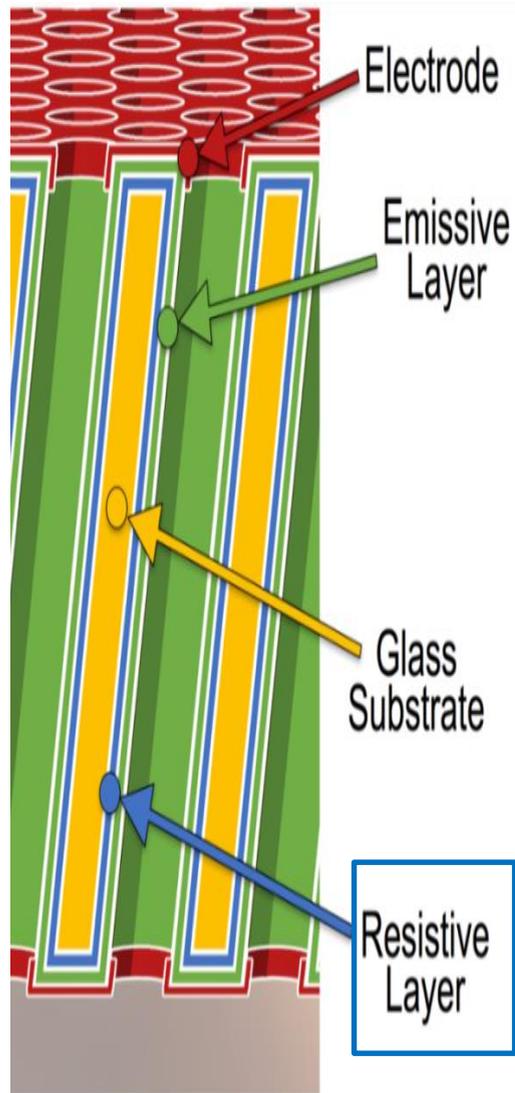
ALD Barrier Coatings



- Constituents of the glass substrate makes it easier to draw and form
- These same constituents can leach out of the glass and affect the gain and dark rates of an MCP.
- For conventional PbO MCPs, alkali atoms need to be kept at the surface of the pores to maintain gain. Migration of these alkalis is the cause of gain loss in the first 0.1 C/cm^2 of use for PbO MCPs
- For ALD-GCA-MCPs, we want all impurities to be kept away from the ALD layers.
- BC7 allows Incom to be relatively insensitive to the composition of the glass substrate, but other barrier coatings may work better
- Incom is working on alternative BC layers to improve lifetime and allow for a wider variety of glass substrates



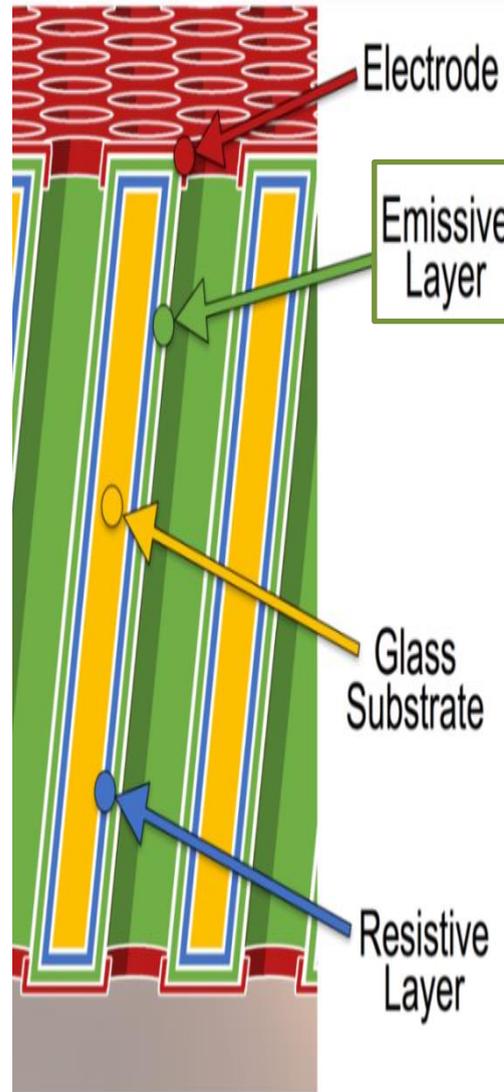
Next Generation ALD Resistive MCP Coatings



- The Resistive Layer maintains the MCP resistance and recharges the SEE layer with electrons
- The composition of the SEE layer can affect the TCR value of the MCP, or how much MCP resistance varies as a function of temperature
- Alternative resistive coatings are being developed to improve performance and provide strategic flexibility in light of recent supply chain friction



Environmentally Robust ALD-MCPs

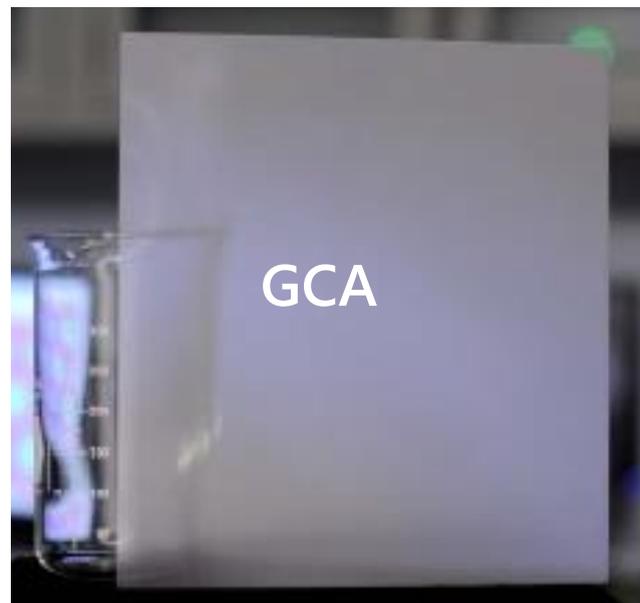


- MgO as an SEE layer offers the highest gain, but it is also hygroscopic
- This leads to variations in gain as a function of MCP cleanliness, and also higher afterpulse rates in sealed devices
- Incom is working with Argonne National Lab to develop next generation ALD coatings that will be immune to environmental exposure while maintaining high gain
- Decreased afterpulse rate in sealed detectors will prolong photocathode lifetimes for many applications



ALD-MCPs for (Epithermal) Neutron Detection

- Boron makes a good scintillator for epithermal neutrons
- Current patents disclose coating the surface of PbO MCPs with boron-doped coatings
- Incom's unique ALD-GCA-MCP approach allows us to make MCPs with high concentrations of Boron in the glass
- Incom already works with a number of proprietary Borosilicate Glasses, including Incom C5, C20, and C7 which have, respectively, 9.5%, 13% and 19% B₂O₃ content.
- Incom is working with Oak Ridge National Laboratory to use Incom MCPs to detect epithermal neutrons in the High Flux Isotope Reactor (HFIR).



Ion Counting Mass Spectrometry

- Traditionally, Mass Spectrometry instruments have measured output currents from ion beams rather than counting individual ions
- Incom is considering a program with Pacific Northwest National Laboratory to combine Incom's ALD-GCA-MCPs with TimePix4 electronic readout in order to count individual ions coming from an ion beam.

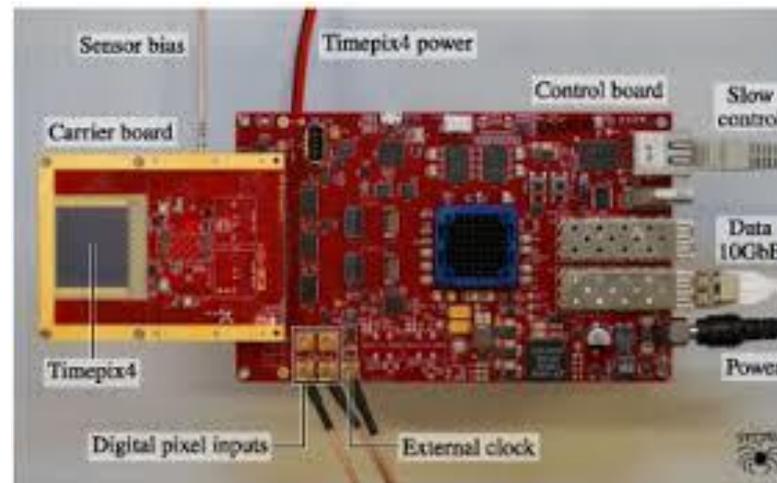
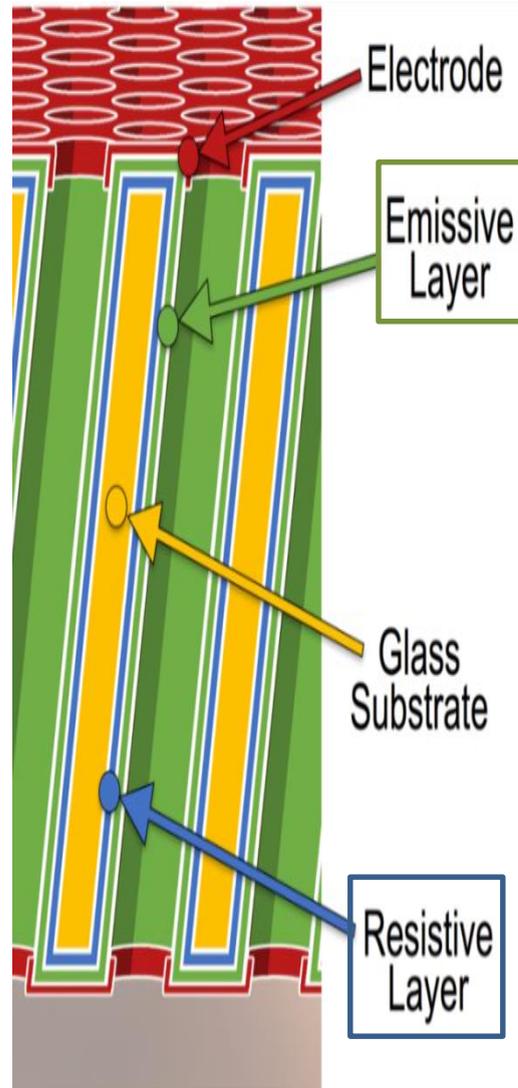


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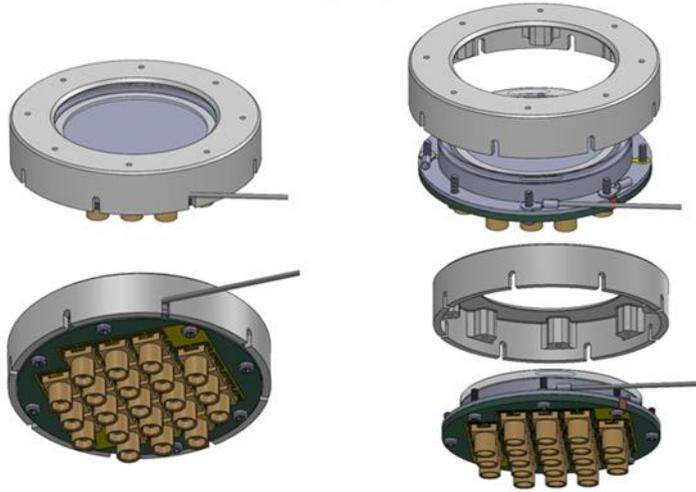
MCP-PMTs Optimized for High Rate Applications



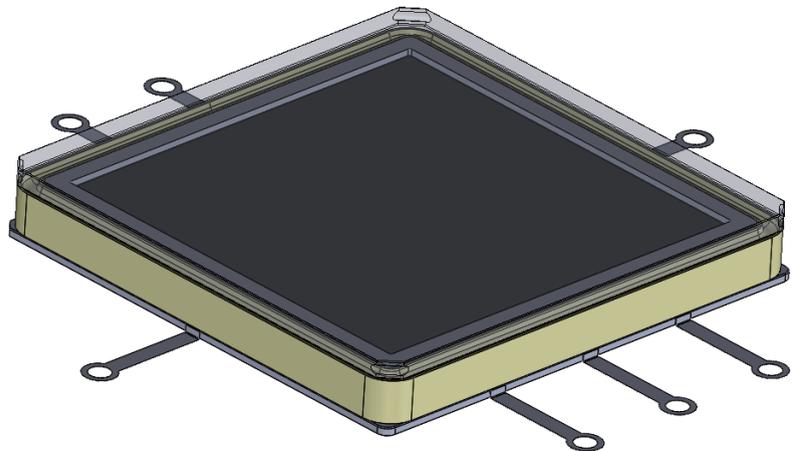
- Incom has measured an MCP pore recharge time of 15 ms for 20 um MCPs with a resistance of 10 MOhms and a size of 20 x 20 cm
- This slow recharge time is the driving force behind gain saturation in high rate environments for MCP-PMTs
- Pore Recharge Times can be improved in 3 ways
 1. Lower MCP Resistance
 2. Thinner SEE layer
 3. Conductive SEE layer
- With ALD-GCA-MCPs, these can all be optimized independently, enabling large improvements in high rate capability for Incom's MCP-PMTs



Small Format MCP-PMTs with Glass or Single Crystal Scintillator Windows



- Incom is developing smaller format MCP-PMTs- 43 mm diameter and 56 mm square
- These devices can be used for high throughput design testing to optimize MCP-PMTs for various markets, including PET
- Various iterations are already under development including
 - Lead Tungstate Single Crystal Windows with Clearmind
 - Alternative Single Crystal Windows with Crytur
 - Glass Scintillator Windows with Alfred University



Future Developments In Need of Funding

- Improved ALD-GCA-MCPs
 - MCPs with 6 um Pores
 - ALD Barrier Coatings
 - Next Generation ALD Resistive MCP Coatings
 - Environmentally Robust ALD-MCPs
 - ALD-MCPs for (Epithermal) Neutron Detection
- Improvements in Detectors with MCPs
 - Ion Counting Mass Spectrometry
 - MCP-PMTs optimized for High Rate Applications
 - Small Format MCP-PMTs with Glass or Single Crystal Scintillator Windows
- Incom is committed to working with our collaborators to develop our technology to meet their needs.
 - Continued support from DOE accelerates the pace of development!



Thank You!

Cole Hamel

chamel@incomusa.com

508-909-2345



Incom MCP Specifications

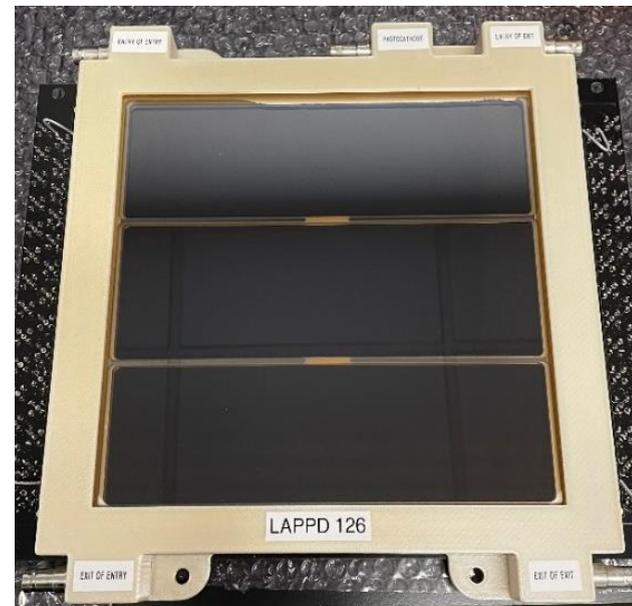
Parameter	20 μm Pores	10 μm Pores	Unit:
Maximum MCP Dimensions	203 x 203		mm
Form Factor	Flat or Curved		--
MCP Substrate Material	C5 / C14		--
Capillary Pore Diameter	20	10	μm
Center to Center Pitch	25	13	μm
Channel Length / Diameter	60:1		--
Substrate Thickness	1.2	0.6	mm
Substrate Flatness	± 50		μm
Bias Angle (From Normal)	13		degrees
Capillary Open Area Ratio	$\geq 65 / 72$		%
Electrode Penetration Depth	0.5-1.0		Pore Diameters
Electrode Material	Nichrome		--
Supply Voltage (Max)	1.4	1.2	kV
Recommended Vacuum	1E-7		Torr
Gain (Chevron Pair) (1000 V/ MCP)	1E7		--
Resistance ¹	1-100		M Ω
Maximum Linear Output	TBD	TBD	
Pulse Rise Time	0.75	0.5	ns
Dark Rate	≥ 0.25		Hz/cm ²
Spatial Gain Variation ²	± 20		%
Thermal Coefficient of Resistance	-0.02 to -0.03		K ⁻¹

1. Acceptable resistance is heavily dependent on MCP Size and operating temperature

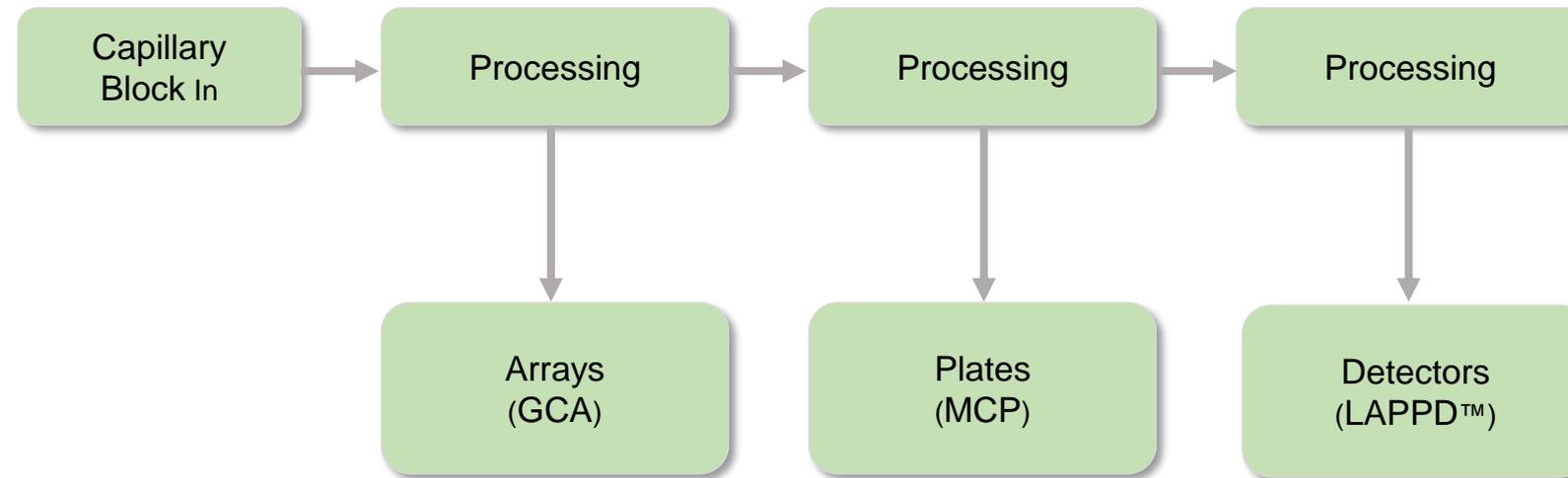
2. Spatial Gain Variation is defined as Std Dev / Mean

Summary

- ALD-GCA-MCPs superior performance
 - Mechanical robustness
 - Timing resolution
 - Custom form factors and non-planar shapes
 - 10 and 20 um pore diameters
 - Longer Lifetime
 - High Open Area Ratio
 - **Lead Free substrates**
 - Independent selection of:
 - Glass
 - Resistance
 - Secondary electron emission
- Incom MCP – PMTs for scintillator applications
 - LAPPD MCP-PMT
 - 20 cm square form factor- world's largest
 - Good timing resolution
 - High Quantum Efficiency
 - Spatial Sensitivity
 - HRPPD MCP-PMT
 - 10 cm form factor
 - Under Development for EIC program



Process Overview

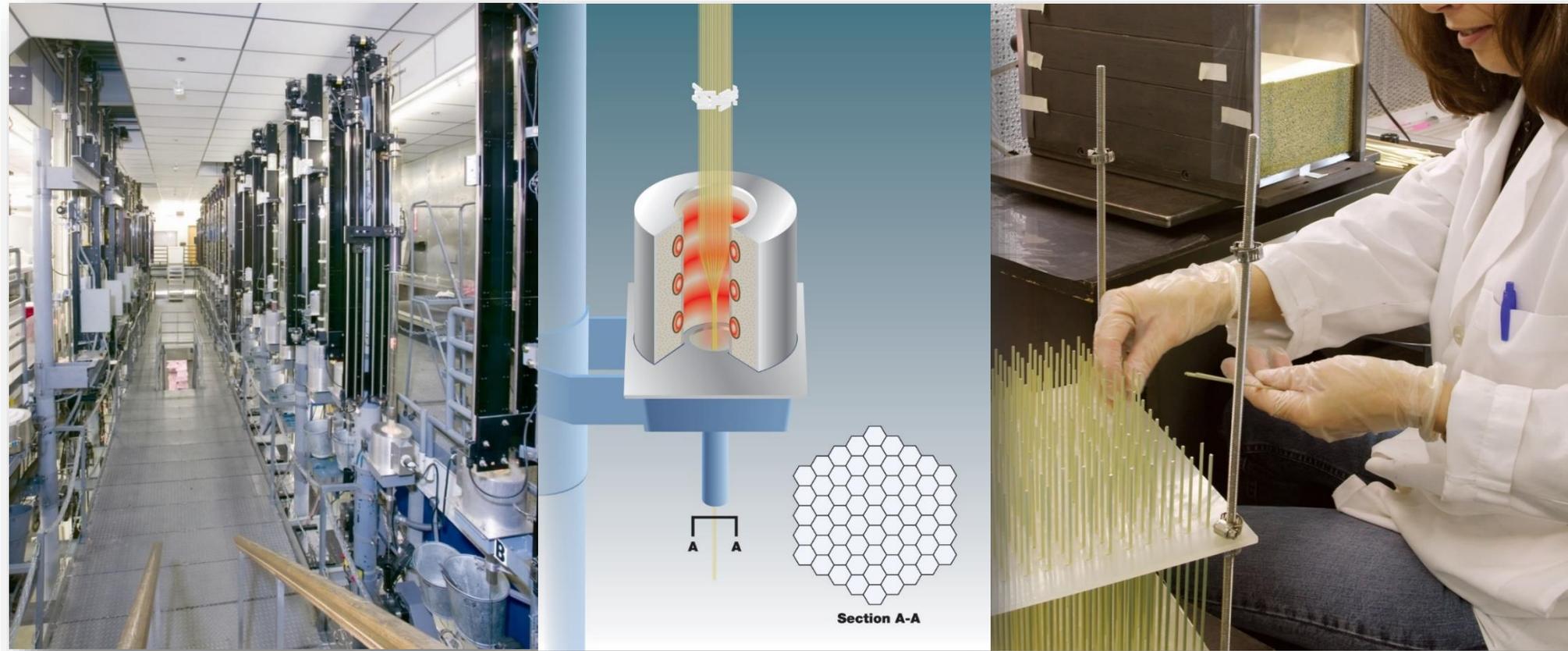


Incom's DBU offers three product lines

1. Incom's existing Glass Capillary Arrays (GCAs)
2. Microchannel Plates (ALD-GCA-MCPs)
 - GCAs functionalized with an Atomic Layer Deposition (ALD) process
3. The Large Area Picosecond Photodetector (LAPPD)
 - An MCP-PMT using Incom's MCPs



Capillary Draw & Block Fusion

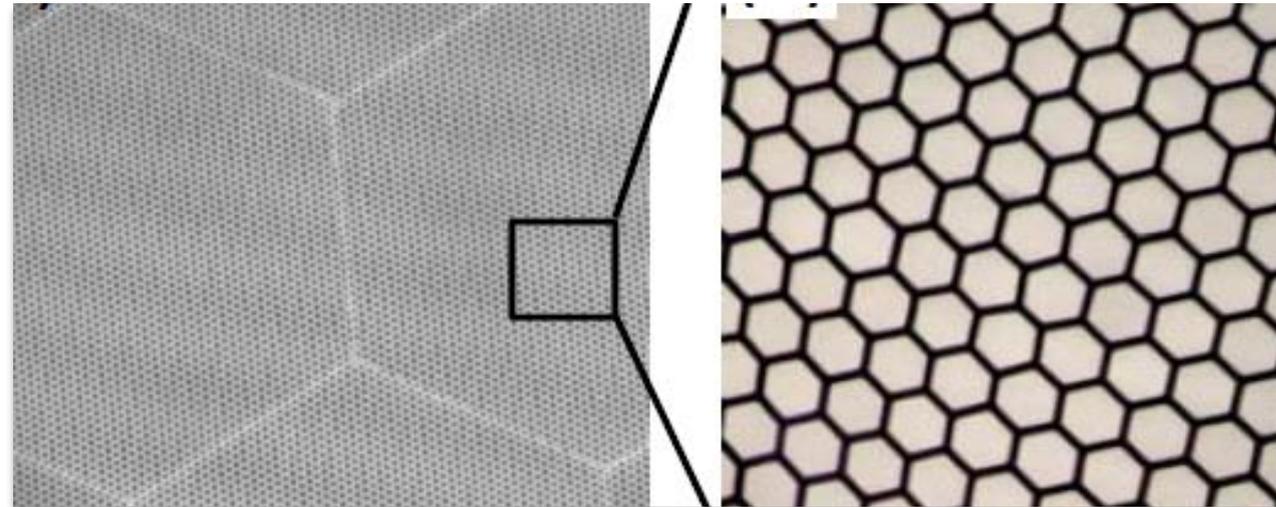


Incom's Hollow Core Drawing Process

Borosilicate Glass → Single Fibers → Multi Fiber Assembly → Glass Capillary Block

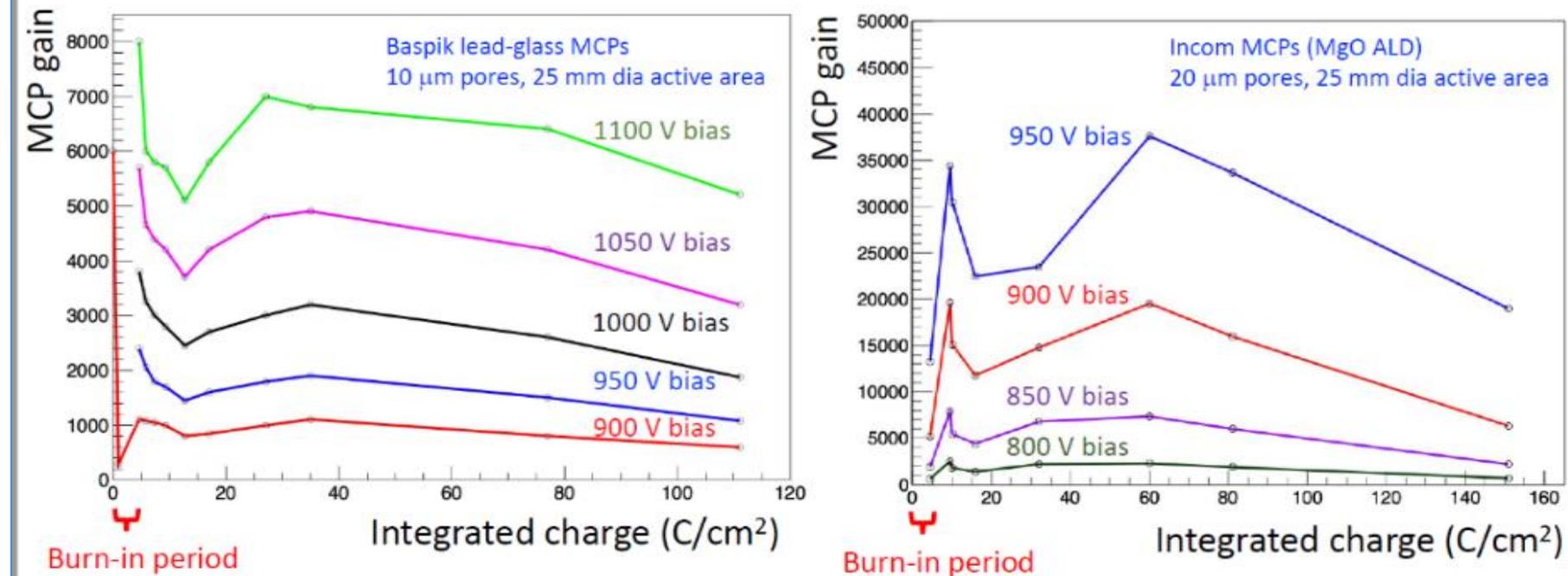
Glass Capillary Arrays

- INCOM's Custom Hollow Core Manufacturing Process
- Ability to create large blocks of Glass Capillary Arrays (GCAs) with 10 μm pores



ALD-GCA-MCP Superior Lifetime

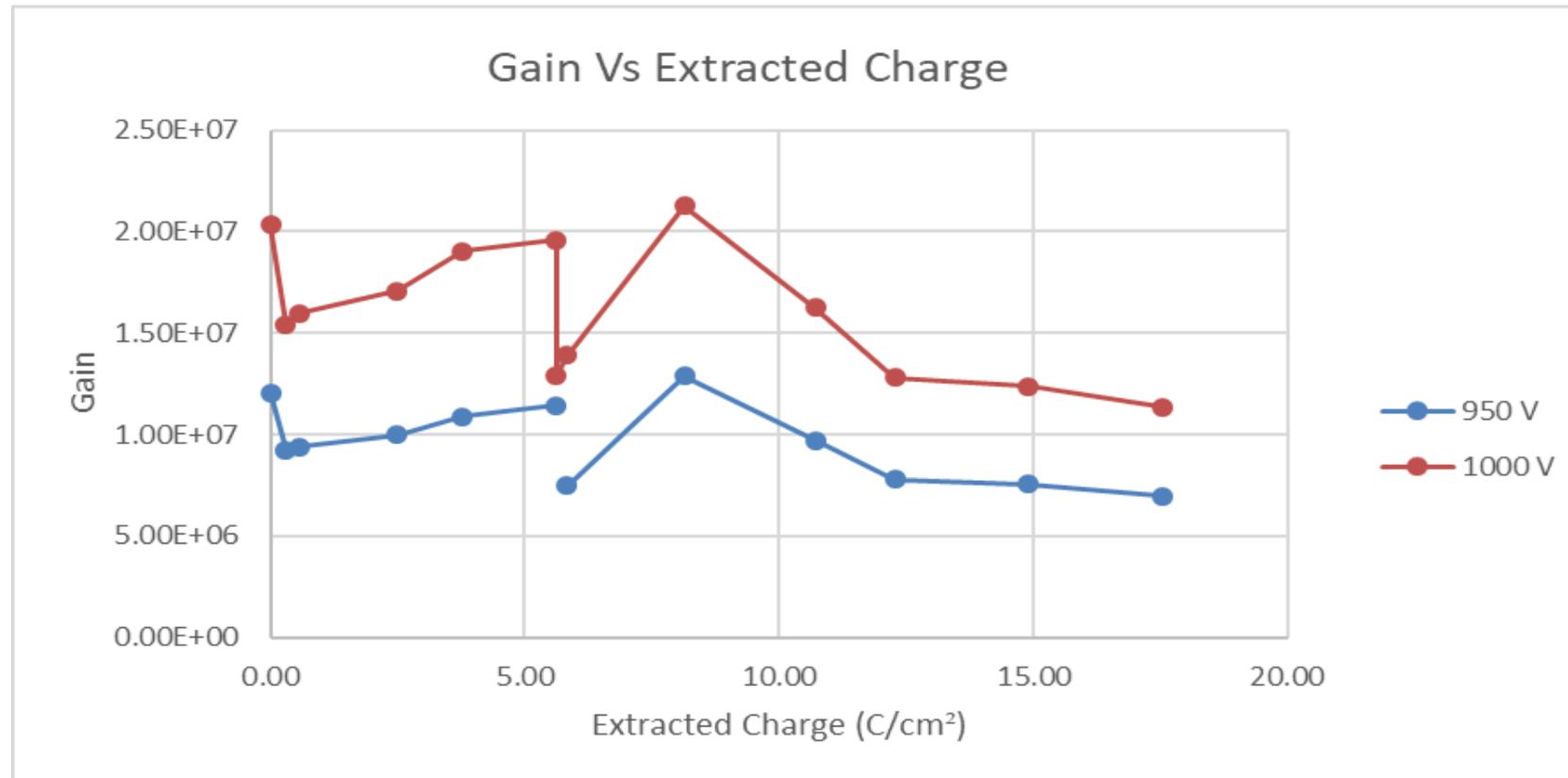
Baspik vs Incom: lifetime summary



- Vincenzo Vagnoni, INFN Bologna, compared Incom MCPs to conventional lead-based MCPs made by Baspik
- Incom's MCPs
 - Higher gain at the same voltage
 - Sustained gain at higher extracted charge (150 C/cm² vs 110 C/cm²)



Incom Life Testing

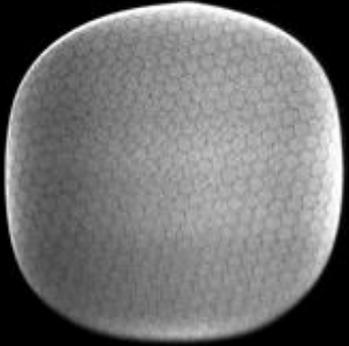
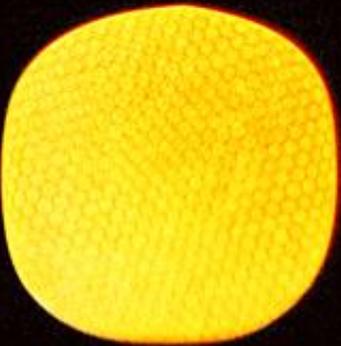
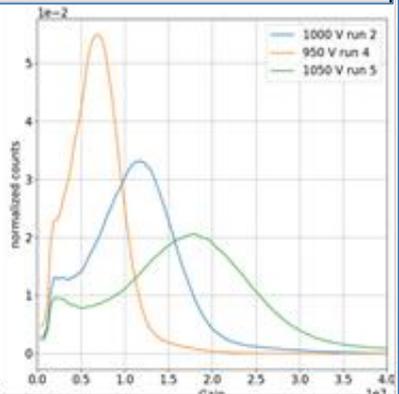


- Slower rate of charge extraction
 - few Amps vs. 100s of Amps
- No initial “burn-in” period typical of Incom MCPs



Incom ALD-GCA-MCP Performance

Imaging and Dark Rate

Total Extracted Charge (C/cm ²)	Comments	Intensity Image	Gain Image	Background image	PHD
-17.53	1000 V				

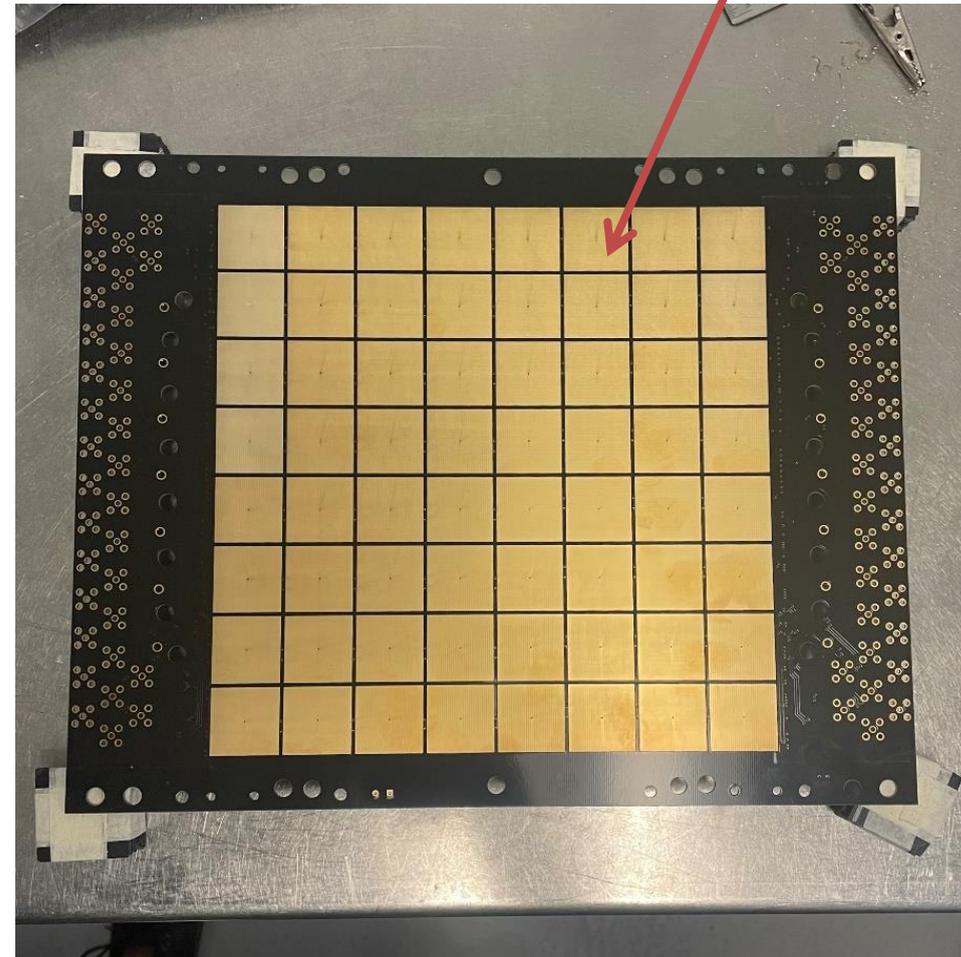
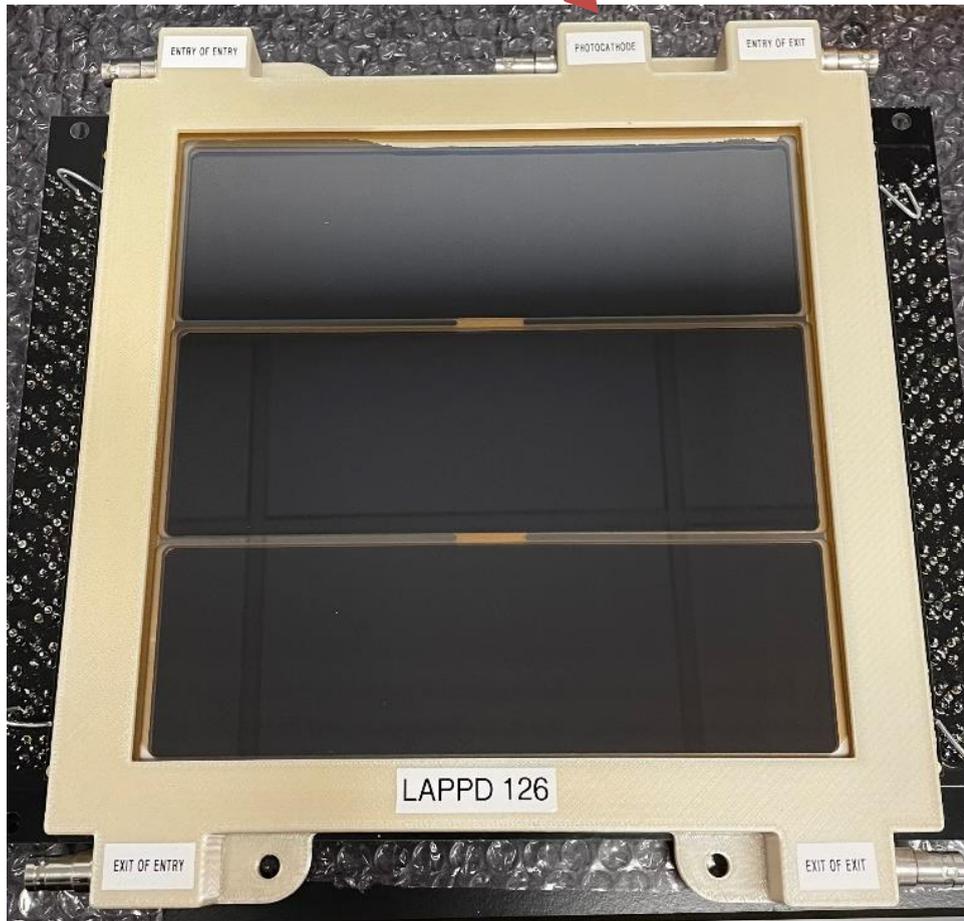
- Pair of 33 mm diameter MCPs
- Scrubbed to -17.5 C/cm² of extracted charge
- Performance has not degraded

Gen-II LAPPD

Photocathode HV

MCP HV

8 x 8 Pad Array
25 mm pixels



Ultem Housing



LAPPD Design

Fused Silica window
(**Photocathode inside**)

MCPs + Spacers

HV tabs at each corner
(**Independently power MCPs**)

User changeable signal board

Internal Resistive Anode

- **No wall or anode penetrations**
- **Active area: 195 mm x 195 mm**
 - **Grid Spacer leaves active area of 373 cm² (97%)**

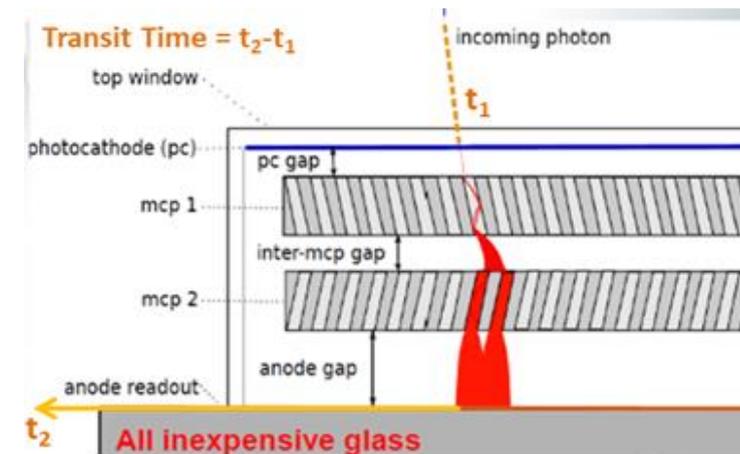
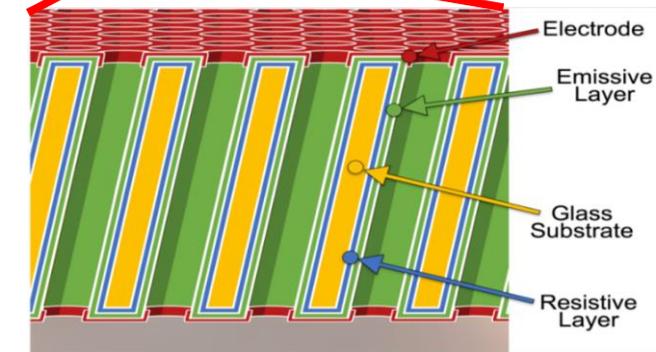


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