International Conference on High Energy Physics
August 5th, 2016 Detector: R&D and Performance

Pilot Production of Large Area Picosecond Photodetectors

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- A. U. Mane, J. W. Elam, **Argonne National Laboratory**
- O. H. W. Siegmund, C. Ertley, **University of California, Berkeley**
- H. J. Frisch, A. Elagin, **University of Chicago**

Outline:

Motivation - what is LAPPD, and why do we care (motivation)?

LAPPD Performance - The "Demountable"

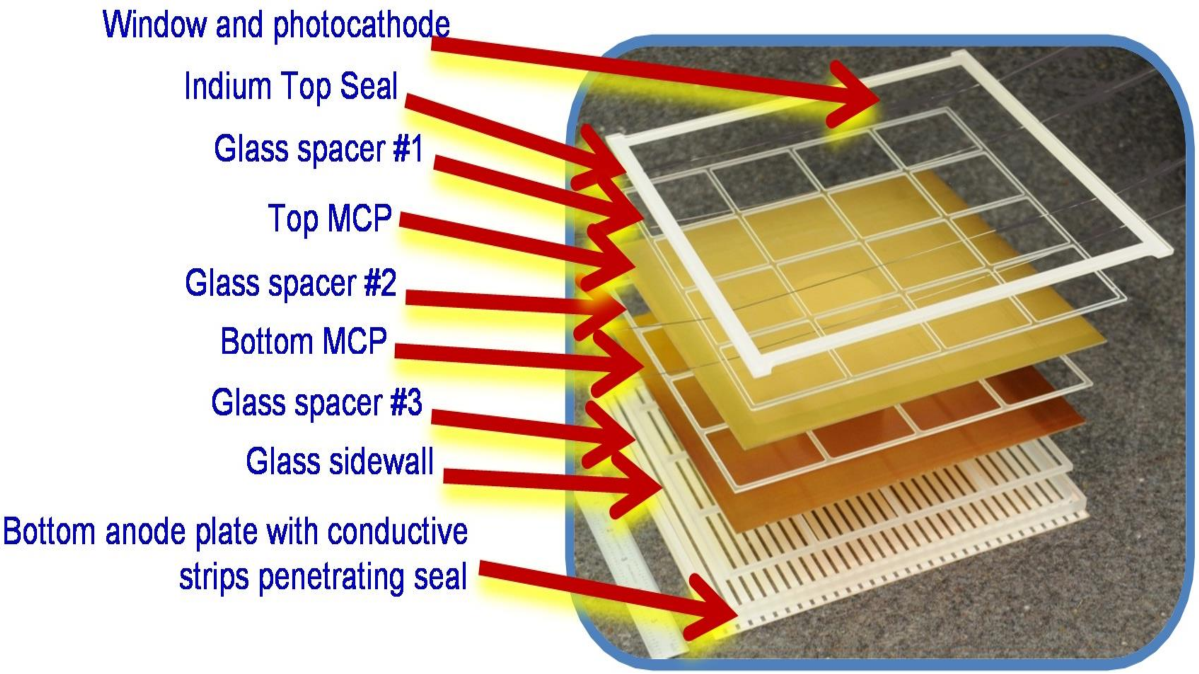
Objective – Produce fully functional free standing LAPPD

Incom Pilot Production Trials

- **Process & Hardware Overview**
- **LAPPD V2.0 Design Overview**
  - An all-glass borofloat hermetic package
  - 50 Ω strip-line anodes enter the LAPPD via pin-free hermetic frit seals.
  - X-spacers
  - Nano-engineered "ALD-GCA-MCPs"
  - A bi-alkali Na_2KSb photocathode,
- **LAPPD Trial #7**

Conclusions - Summary Results & Lessons Learned

LAPPD™ V1.0 – Motivation & Applications



LAPPD™

- MCP based photodetector,
- Capable of imaging
- Single-photon sensitivity
- High spatial and temporal resolutions
- Hermetic package
- 400 cm^2 active area

Motivation - MCP based detectors, despite their high speed, had not been considered for large-area HEP applications due to their small size (5 × 5 cm^2), high-cost per area, and poor lifetime due to ion feedback.

Applications: **HEP and others** [homeland security sensors, astronomy, electron microscopy, TOF mass spectrometry, molecular and atomic collision studies, fluorescence imaging, plenoptic and medical imaging (PET scanning) applications]

Henry J. Frisch, et. al., A Brief Technical History of the Large-Area Picosecond Photodetector (LAPPD) Collaboration, http://arxiv.org/abs/1603.01843 March 2016

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Timing characteristics of Large Area Picosecond Photodetectors

B.W. Adams [a], A. Elagin [b], H.J. Frisch [b], R. Obaid [c], E. Oberla [b], A. Vostrikov [b], R.G. Wagner [a], J. Wang [a], M. Wetstein [b,*]

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[b] Enrico Fermi Institute, University of Chicago, United States
[c] University of Connecticut, United States

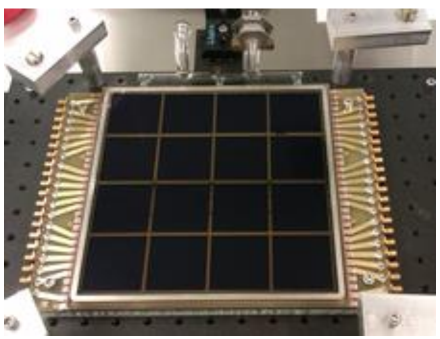
The performance of LAPPD is well established based upon testing of the "Demountable"

Absolute time resolutions

- Single-Pes: consistently < 100 ps, typically < 60 ps,
- Large pulses < 5 ps predicted

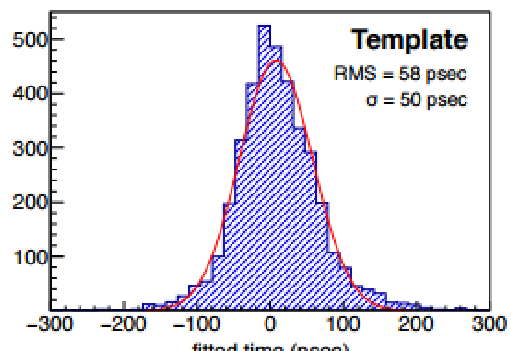
Spatial Resolutions

- Single-Pes: Several-mm
- Large pulses sub-millimeter



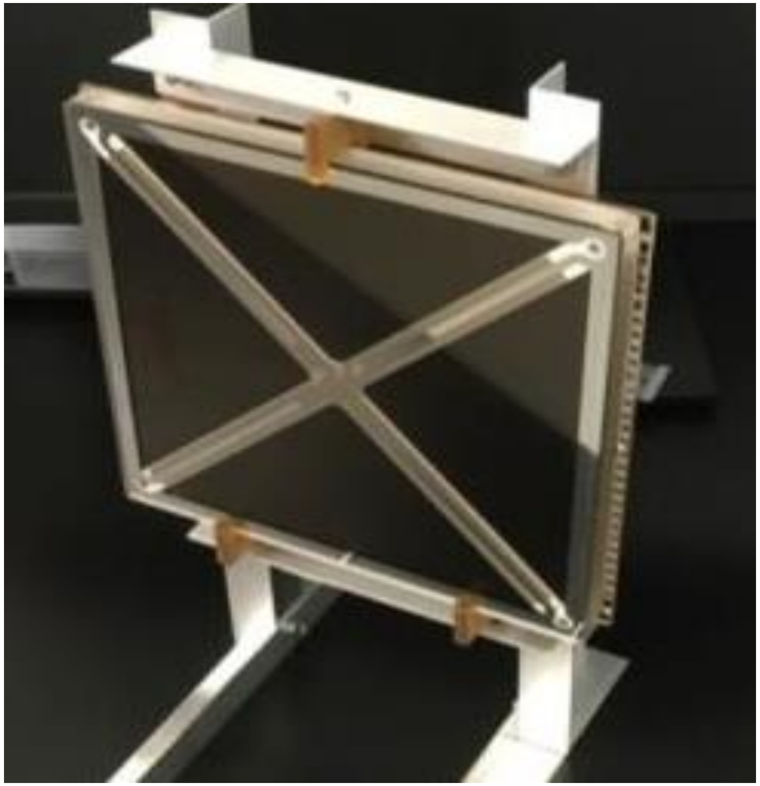
The Demountable LAPPD V1.0 (unsealed)

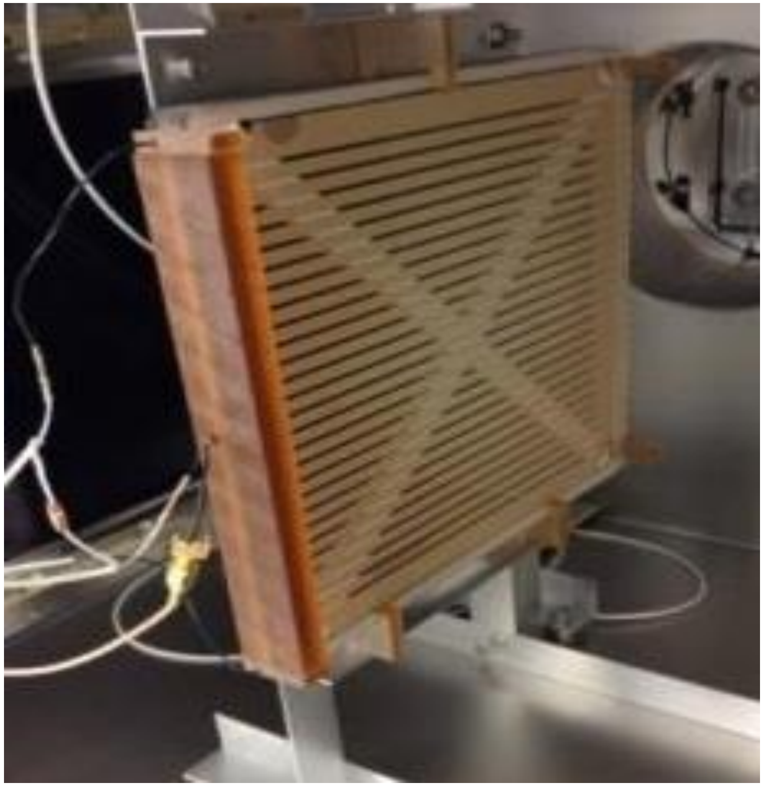
- **Dynamically pumped LAPPD Test Stand**
- Incorporates standard LAPPD components
- Aluminum photocathode
- O-ring Top seal and retainer



Measured 50psec Transit Time Variation for Single Photoelectron

Objective - Demonstrate routine production of fully functional, free standing, untethered LAPPD

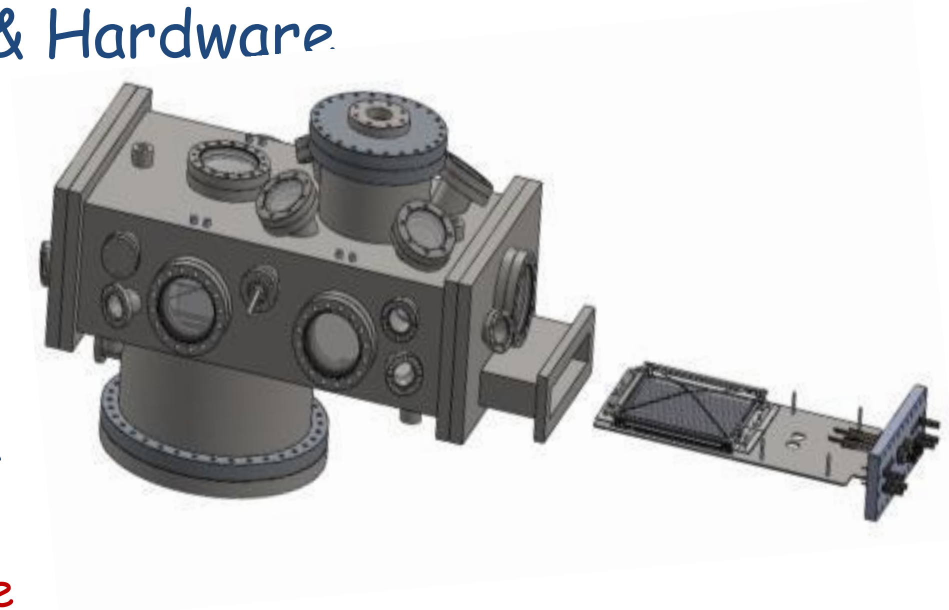




Incom LAPPD #1 – (L) Front, (R) Back Views
Successfully sealed 2/5/2016 but not fully functional due to electrical interconnect problems

Incom V2.0 LAPPD Integration & Sealing

Process & Hardware



Process:

- UHV – with Conflat seals, scroll, turbo and ion pump.
- Tile kit components pre-assembled & locked in place .
- Baked @ 350C to low 10^{-10} torr range
- In-tank scrubbing
- Window Transfer Process
- Na_2KSb Photocathode deposition @ 190C using SAES beads.
- Hot Indium Seal – with grooved sidewalls

Hardware:

- Single "Fully Bakeable" Chamber: 30"L X 16"W X 8"H
- Simple window transfer between photocathode deposition & sealing.
- Electrical interconnects for in-process monitoring
- Readily expandable for volume production

Incom Inc. LAPPD V2.0

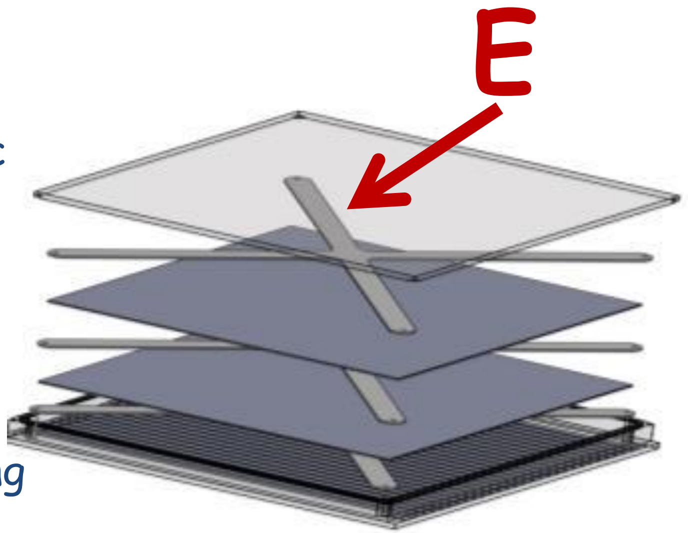
A. Lower Tile Assembly (LTA) – Borofloat glass sidewalls and bottom anode plate, hermetically sealed together,

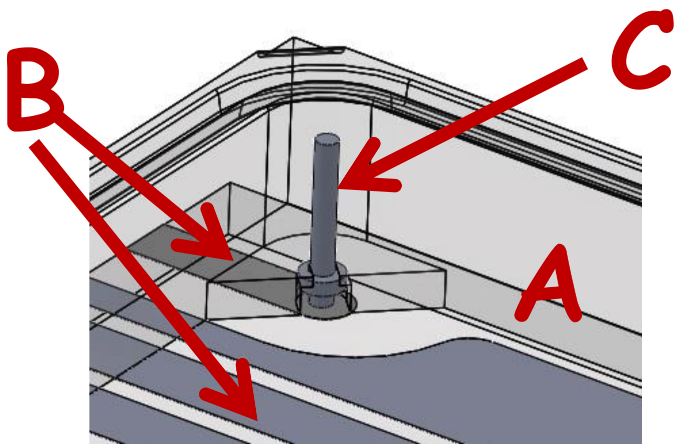
B. Power & Signal Anode Strips - pass under the hermetic seal providing a "penetration free" connection into and out of the tile.

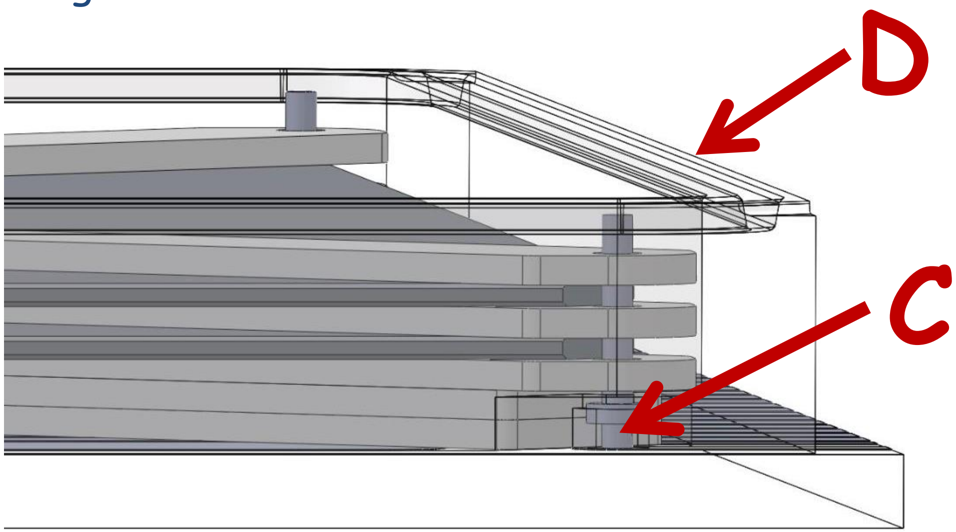
C. Internal Corner Pins - hold components and deliver voltage to the top and bottom of each MCP

D. Groove for Molten Indium Alloy - for top window sealing

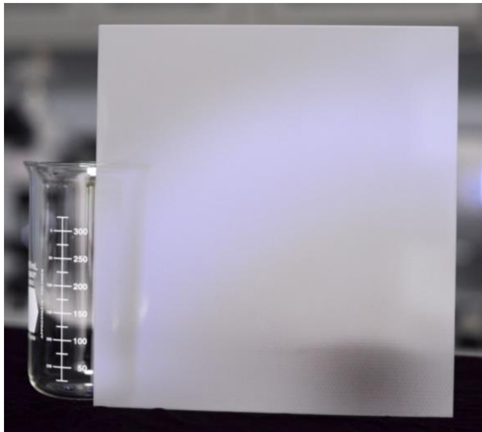
E. X-Spacers – restrain window deflection under atmospheric pressure, control critical spacing between components, support getters,

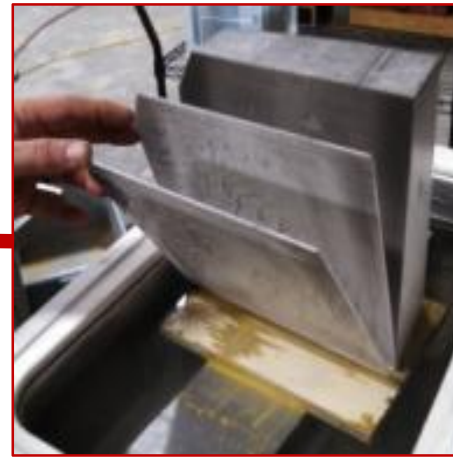


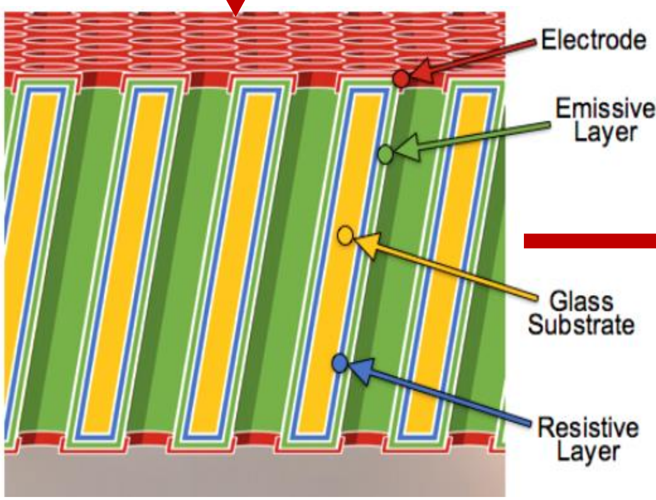


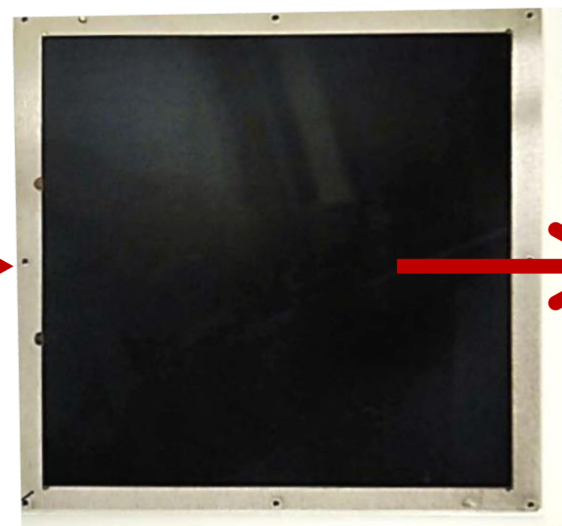


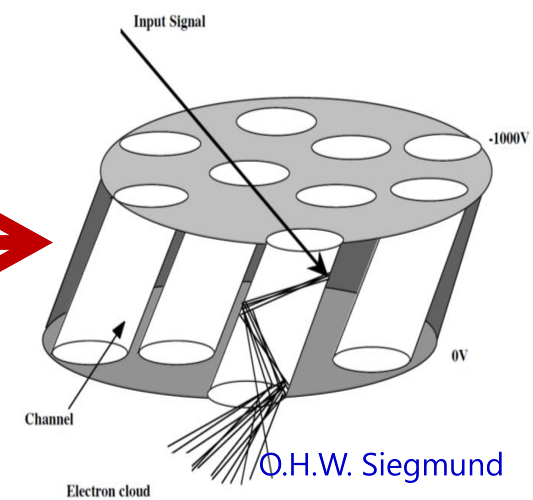
Enabling Technologies: ALD-GCA-MCP Manufacture:











Nanocomposite resistive layer and secondary electron emissive (SEE) layers

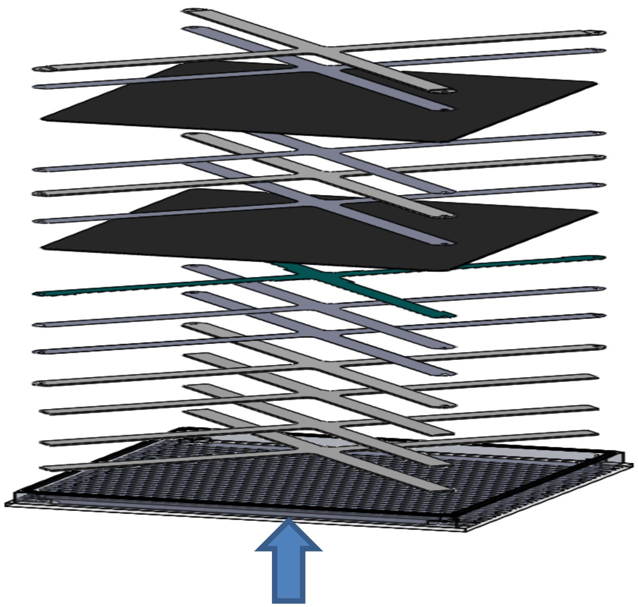
Resistive Layers: Chem1 = W/ Al_2O_3, Chem2=Mo/Al203

SEE = either Al_2O_3 or MgO are currently available

MCP Attribute	ALD-GCA-MCP Competitive Advantage
Tunable	Independent selection of glass substrate and tuning of resistive and emissive properties.
Gain Stability, Burn-in	High (10^5-10^7) overall gain, long-term temporal stability, minimal burn-in Vs. conventional MCPs that experience 10X gain drop and require extended (200 hrs) charge extraction. Helium free process, negligible ion feedback.
Low Dark Count (cm^{-2} s^{-1})	10-25 X Lower dark count (0.025-0.040 vs. 0.25-1.0) since for ALD-GCA-MCPs contain little or no radioactive isotopes, **Enhanced S/N.**
High SEY	~2.5 – 3.5 for conventional vs. ~2.5 to 3.0 and ~4 to 7 for Al_2O_3 and MgO SEE Layers. **Higher Gain Sensitivity**
Low X-ray Cross-Section	No lead, for **application in an X-ray background**.
TCR (K^{-1})	Semiconductor like behavior with TCR = ~-0.01 to -0.03 for conventional, and ~ -0.02 to -0.04 for ALD-GCA-MCPs
Pore Size & OAR	10 μm pores, with OARs up to 74% in large plate sizes for enhanced detection efficiency; and spatial and temporal resolution.
Large Size	203mm X 203mm MCPs wafers, **the world's largest**
Gain uniformity	Within 15% across 203mm x 203mm plates with 20 μm pores
Robust MCPs	No H_2 firing or acid etching, that make conventional lead silicate MCPs fragile, moisture sensitive and prone to shape distortions. **Chemically, thermally and mechanically stable.**
Curved Shape	Enhanced resolution for space and terrestrial TOF instrumentation, simplified design, reduced instrument volume, cost and mass.
Lower cost per area	Large area MCPs, diced to smaller sizes, low cost glass substrates with independently optimized resistive and emissive coatings results in enhanced performance with significant cost and design flexibility.

The Important Role of "Stack Height"

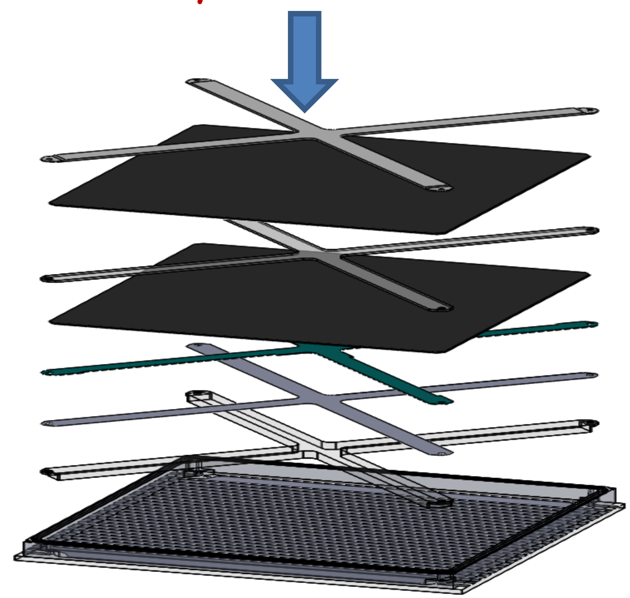
SH = Distance between compliant internal tile components & the sidewall sealing surface, in both the compressed and expanded situation



LAPPD #2 – 6
multiple layers with bow

Dagwood Bumstead

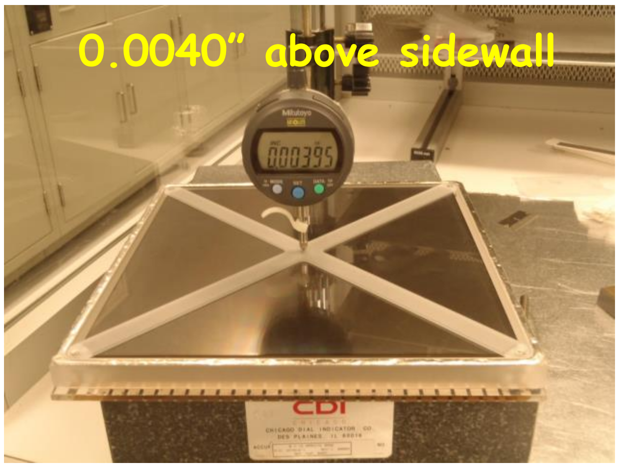
LAPPD #7
fewer layers, minimal bow



Stack Height - High	**Stack Height - Low**
Failed Seal	Cracked Window

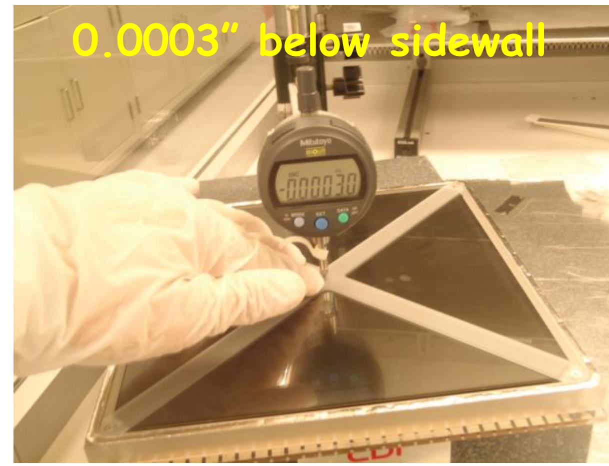
LAPPD #7: Predictable, Ideal Stack Height

SH = Distance between compliant internal tile components & the sidewall sealing surface, in both the compressed and expanded situation



"Expanded" height, Simulates when window is placed on sidewall

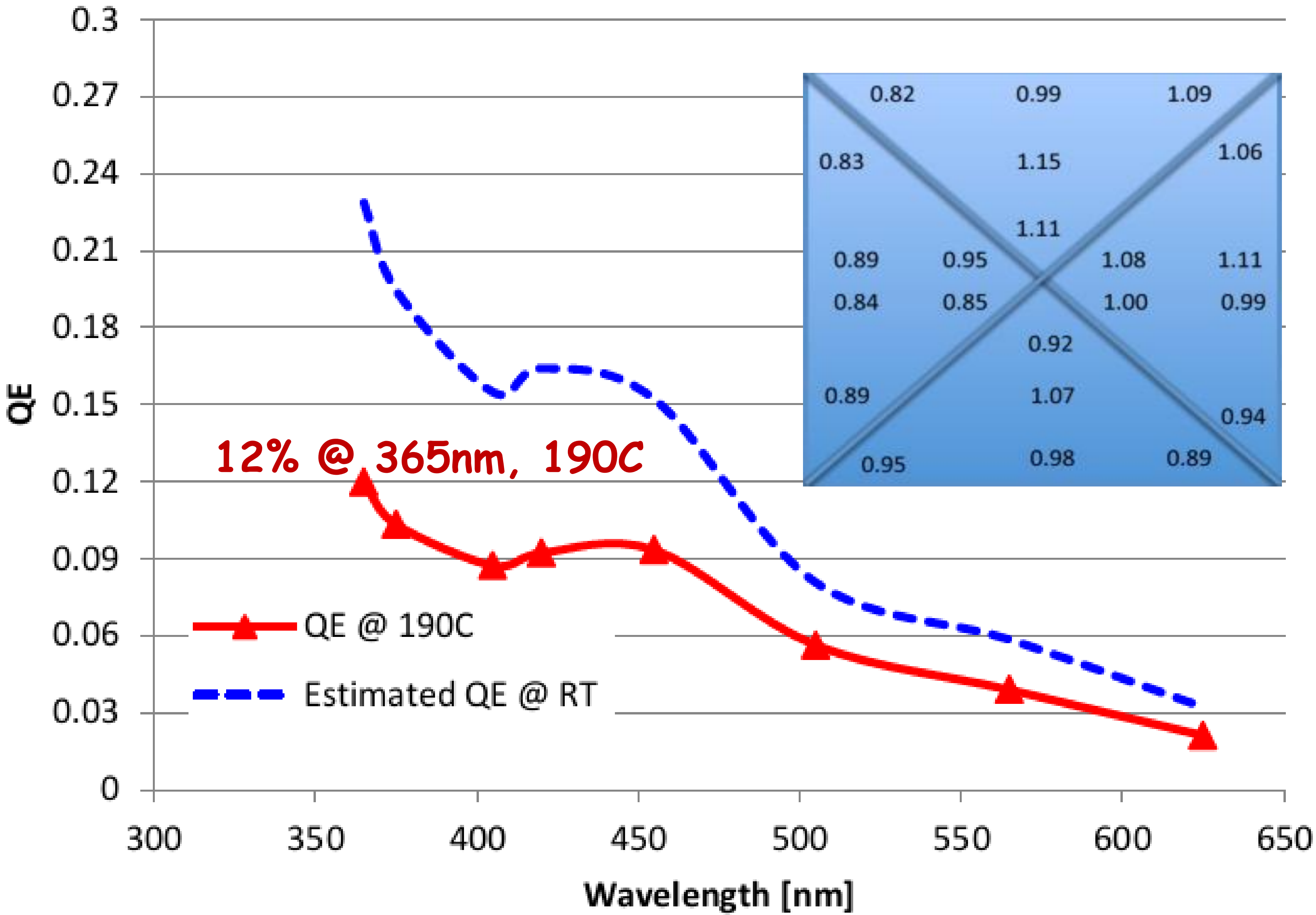
"Compressed", with window weight + 3X additional pressure applied with wobble stick during sealing



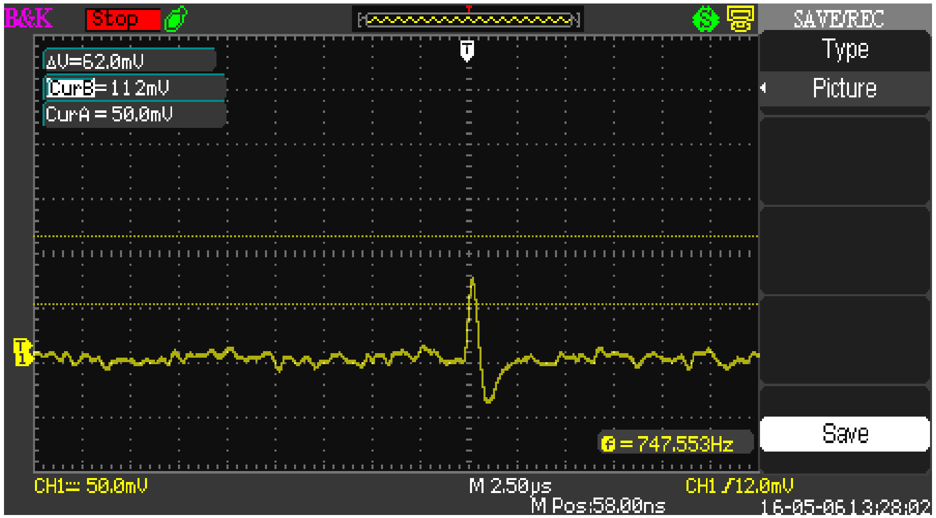
"Compressed", simulating full effect of atmospheric pressure (15 lbs/in^2)

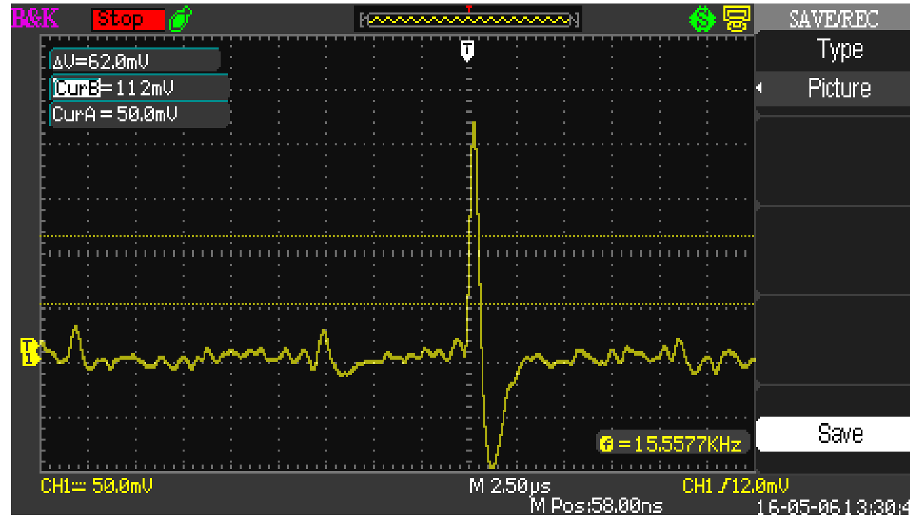
Molten indium alloy bead is 0.002"-0.004" above sidewall

QE – LAPPD #7


12% @ 365nm, 190C
QE
0.3
0.27
0.24
0.21
0.18
0.15
0.12
0.09
0.06
0.03
0
300
350
400
450
500
550
600
650
Wavelength [nm]
QE @ 190C
Estimated QE @ RT
0.82
0.99
1.09
0.83
1.15
1.06
1.11
0.89
0.95
1.08
1.11
0.84
0.85
1.00
0.99
0.92
0.89
1.07
0.94
0.95
0.98
0.89

Amplified oscilloscope plots of a background pulse in LAPPD #4





- (Left) **Not Illuminated**
  - 850V across MCPs, trigger set at 12mV,
  - **background rate ~750 Hz**
- (Right) **Illuminated**
  - 850V across MCPs, trigger set at 12mV,
  - **background rate increased to ~15 kHz**
- **Photocathode & MCPs were operational, in chamber under vacuum!**

Performance Metric	LAPPD#1	LAPPD#2	LAPPD#3	LAPPD#4	LAPPD#5	LAPPD#6	LAPPD#7
Seal date	02/05/2016	02/22/2016	03/10/2015	04/28/2015	5/20/2016	06/08/16	07/13/16.
Indium Seal	Excellent	Excellent	Excellent	Failed seal	Failed seal	Excellent	Failed seal
Vacuum Integrity	Excellent	Cracked window Low SH	Cracked window Low SH	High SH	High SH	Cracked window	Window Contamination
PC QE @190C, @365 nm	1%	4%	1%	6%	9.4%	4.5%	12%
Performance under Vacuum	Lost electrical connection to the top of entry MCP Contact failure	HV discharge problems Signal lost upon venting	☺ No HV problems Signal lost upon venting.	☺ No HV problems Dark pulses detected.	☺ No HV problems Dark pulses detected	☺ No HV problems Dark pulses detected	☺ No HV problems Dark pulses detected

Conclusions: Current Status of Pilot Production of LAPPD™s

- **Progress on infrastructure and process development has been steady:**
  - In the 2¼ years since beginning, a first-rate pilot production infrastructure, has been created, starting with nothing.
  - A talented, experienced team of scientists, engineers, and technicians has been assembled.
  - Tile processing was delayed awaiting delivery of custom designed and fabricated integration & sealing hardware.
- **No technical roadblocks** or insurmountable barriers encountered to date.
  - Eight leak tight indium top window seals were made achieving a major program goal.
  - Six K_2NaSb PCs were deposited on 8"X8" widows with QEs that varied from 1% to 12% @ 365 nm and 190C.
  - Five LAPPD™ tiles were assembled, sealed and tested, 2/5 through 5/20, demonstrating a pace of 2 tiles / month, with ample opportunity to improve.
  - Since beginning processing trials in February 2016, the focus has been addressing details to insure that everything works at the same time.
- **Evolutionary optimization –** Steady progress on identifying & resolving technical issues:
  - HV stability ☺
  - Indium Spilling ☺
  - Photocathode QE ☺
  - Stack height issues ☺
  - **UHV window transfer hardware -** down pressure application
- ***A reproducible pilot process is expected shortly as identified component and hardware improvements are implemented and process experience is gained!***

Funding & Personnel Acknowledgements:

DOE, NASA, and NGA Contracts

- DOE, DE-SC0009717 "LAPPD Commercialization – Fully Integrated Sealed Detector Devices"
- DOE, DE-SC0011262 Phase II - "Further Development of Large-Area Micro-channel Plates for a Broad Range of Commercial Applications"
- DOE, DESC0015267, Development of Gen-II LAPPD™ Systems For Nuclear Physics Experiments
- NASA: NNX15CG22P Curved Microchannel Plates for Space Flight Mass Spectrometers
- NGA-IV, NGA-V Next Generation Neutron Imager
- DOE, DESC0015729, Resistive coatings for high-performance, low-background MCPs operating across broad temperature ranges and at cryogenic temperatures
- DOE, DE-SC0009717 Phase IIA - LAPPD Commercialization – Fully Integrated Sealed Detector Devices

DOE Personnel: Dr. Alan L. Stone, Dr. Helmut Marsiske, Dr. Manouchehr Farkhondeh, Dr. Peter Kim, Carl C. Hebron, Dr. Kenneth R. Marken Jr, Dr. Manny Oliver, and many others.

NGA Personnel: Shawn Usman, Dr. Thomas J. Johnson, Dr. John Learned, Andrew Druetzler

For more information
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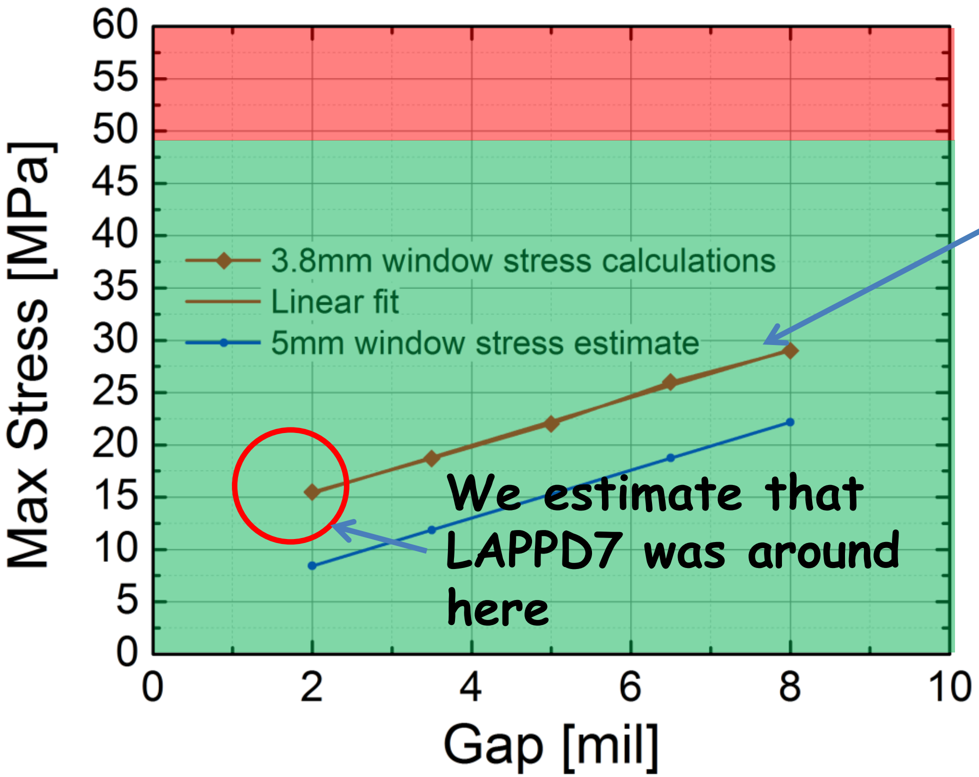
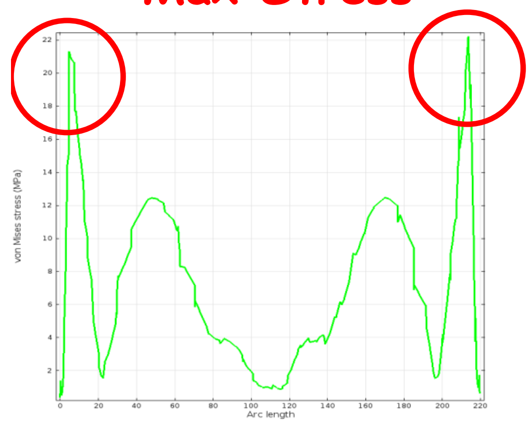
LAPPD # 7 Window Stress vs Gap width



Calculated stress for fracture, 3.8 mm thick fused silica

Max Stress



3.8 mil thick fused silica strength is ~ 2X that of borofloat, calculated stress for fracture is doubled

Early Adopter Programs with Expressed Interest in LAPPD™

PRINCIPAL INVESTIGATOR & SPONSOR	PROGRAM TITLE	Program Timing	INITIAL # TILES	TOTAL # TILES
Shawn Usman (NGA), John Learned (U. of Hawaii)	mini-TimeCube (mTC) collaboration*	Q-3 2016	4	104
Bill Worstell, Incom Inc., Henry Frisch, Enrico Fermi Institute	Large Area Detectors for PET Scanning	ASAP	2	6
Henry Frisch (U of Chicago)	LaRiaT (Liquid Argon Beam-line Experiment at Fermi Lab)	ASAP	5	5
	Sub-psec TOF for collider vertex and particle ID	ASAP	6	6
	Track reconstruction in a small water Cherenkov counter			
	Double-beta decay development			
	Calorimeter development			
Mayly Sanchez and Matthew Wetstein, Iowa State University (and collaborators)	Atmospheric Neutrino Neutron Interaction Experiment	Q-2 2016	2	20
Andrey Elagin (U of Chicago)	Neutrino-less Double-Beta Decay	Q2 - 2016	1	72
Artur Apresyan, Spiropulu , Newman, Bornheim (CalTech)	Precision timing detector for the CMS experiment at the Large Hadron Collider	2023	2	*10m^2
Vivek Nagarkar - Radiation Monitoring Devices	"Fast-Timing Large-Area Detector for Neutron Scattering"	2015	1	1
Anatoly Ronzhin & Pasha Murat (Fermi Lab)	Crystal calorimetry for the Mu2e experiment	2018	TBD	*2000
Mickey Chiu (BNL) -	Phenix Project - "eIC Fast TOF"		5	25
Nikolai Smirnov Dick Majka, J. W. Harris (Yale)	Barrel time of-flight for a future Electron-Ion collider	2018	TBD	*1,250
	Forward particle detection in ALICE at the LHC.	2018	TBD	*50
Erik Brubaker, Sandia National Lab/CA	Single-Volume Neutron Scatter Camera	Q2-2015	2	6
John Learned, University of Hawaii, and Virginia Tech	Search for Neutrino-less Double-Beta Decay (NuDot) Using Fast Timing Detectors		1	72
Bernhard Adams, Incom , Matt Wetstein, Iowa State University and Marcel Demarteau, ANL,	Plenoptic Acquisition Imaging Knowledge Experiment (PAIKE)			
	TOTAL =		30	317

Committed to Continuing Developments

Long Life ALD-GCA-MCPs

Incom's C-14 Glass has virtually no alkali elements. Dark count is 10-25 X Lower (0.025-0.040 vs. 0.25-1.0) compared to conventional MCPS, since for ALD-GCA-MCPs contain little or no radioactive isotopes, Further enhanced S/N.

GEN II Ceramic Package LAPPDTM

A thin metal layer anode serves as a DC ground on the inside of the detector. 88% of an MCP fast signal pulse was capacitively coupled through the ceramic, to strips or pads on the outside.

MCPs with reduced, near-zero TCR,

Allowing their use over very wide temperature ranges. Three process variables are being studied to evaluate their impact on TCR ; 1) Film thickness, 2) ALD metal chemistry and 3) ALD nanocomposite nanostructure.

Long Life ALD-GCA-MCPs

Alkali elements (e.g. potassium and sodium) present in conventional lead silicate MCPs diffuse under high extracted charge affecting the gain performance of the MCP [1]. Potassium (^{40}K) contributes to dark current in conventional MCPs.

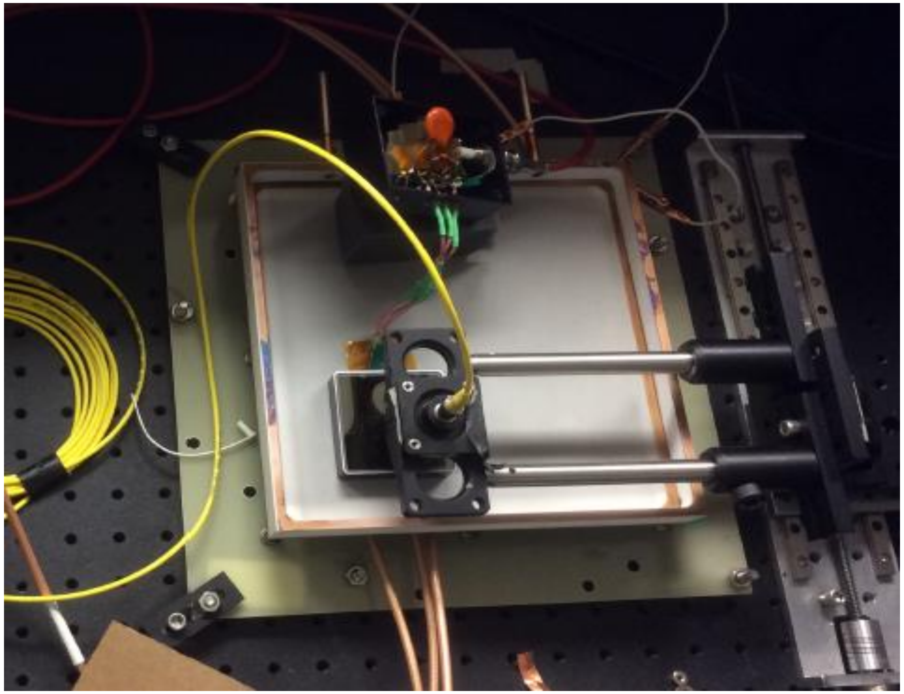
Incom's C5 glass is a Pyrex® like borosilicate material with reduced alkali content compared to conventional MCPs. It has less potassium content than conventional MCPs, which is why the dark current in Incom MCPs is substantially lower than in conventional MCPs [2, 3].

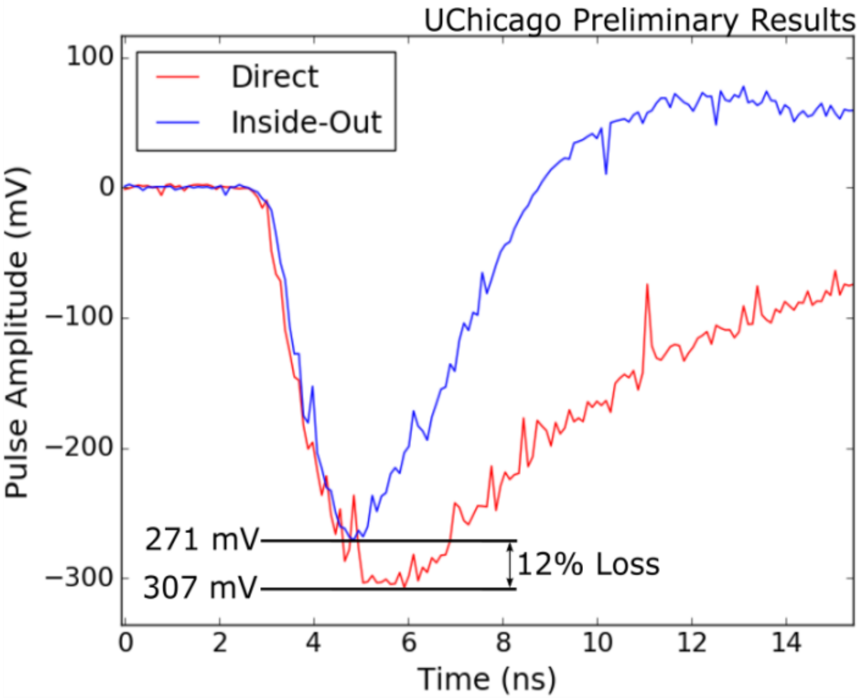
Incom's C-14 Glass has virtually no alkali elements except as impurities. Dark count is 10-25 X Lower (0.025-0.040 vs. 0.25-1.0) compared to conventional MCPS, since for ALD-GCA-MCPs contain little or no radioactive isotopes, Further enhanced S/N.

1. Then, A.M., and C.G. Pantano, "Formation and behavior of surface layers on electron emission glasses", Journal of Non-Crystalline Solids, 120, pp. 178-187, 1990.
2. O.H.W. Siegmund, N. Richner, G. Gunjala, J.B. McPhate, A.S. Tremsin, H.J. Frisch, J. Elam, A. Mane, R. Wagner, C.A. Craven, M.J. Minot, "Performance Characteristics of Atomic Layer Functionalized Microchannel Plates" Proc. SPIE 8859-34, in press (2013).
3. O.H.W. Siegmund, K. Fujiwara, R. Hemphill, S.R. Jelinsky, J.B. McPhate, A.S. Tremsin, J.V.Vallerga, H.J. Frisch, J. Elam, A. Mane, D.C. Bennis, C.A. Craven, M.A. Deterando, J.R.Escolas, M.J. Minot, and J.M. Renaud, "Advances in Microchannel Plates and Photocathodes for Ultraviolet Photon Counting Detectors," Proc. SPIE 8145, pp. 81450J-81450J-12 (2011).

GEN II Ceramic Package LAPPD™

DOE (Nuclear Division) Phase I SBIR, February 2016 in collaboration with U of Chicago



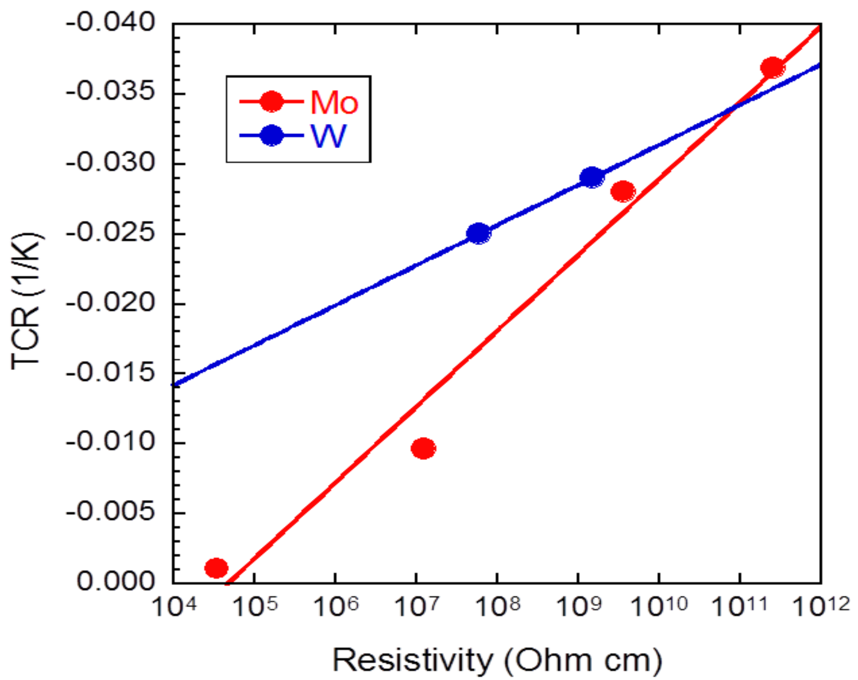


A thin metal layer anode serves as a DC ground on the inside of the detector. 88% of an MCP fast signal pulse was capacitively coupled through the ceramic, to strips or pads on the outside.

- B.W. Adams,et al, "An internal ALD-based high voltage divider and signal circuit for MCP-based photodetectors", Nuclear Instruments and Methods in Physics Research A 780 (2015) 107–113
- Private Communication, Todd Seiss and Evan Angelico, University of Chicago. Inside-Out Tests of Incom Tiles, June 23, 2016
- Angelico, Evan et al., "Development of an affordable, sub-pico second photo-detector", University of Chicago, Poster 2016

Low TCR ALD-GCA-MCPs

DOE HEP Phase I SBIR "Resistive coatings for high-performance, low-background MCPs operating across broad temperature ranges and at cryogenic temperatures"



- Resistivity vs. TCR for Chem1 (W:Al_2O_3) and Chem2 (Mo:Al_2O_3) nanocomposite material.
- Data points represent different film compositions (decreased metal content with increased resistance), and demonstrate that the TCR is material dependent

Three process variables are being studied to evaluate their impact on TCR
1) Film thickness,
2) ALD metal chemistry and
3) ALD nanocomposite nanostructure.