Development of Gen II LAPPD^{TM} (Large Area Picosecond Photo Detector) Systems for Nuclear Physics

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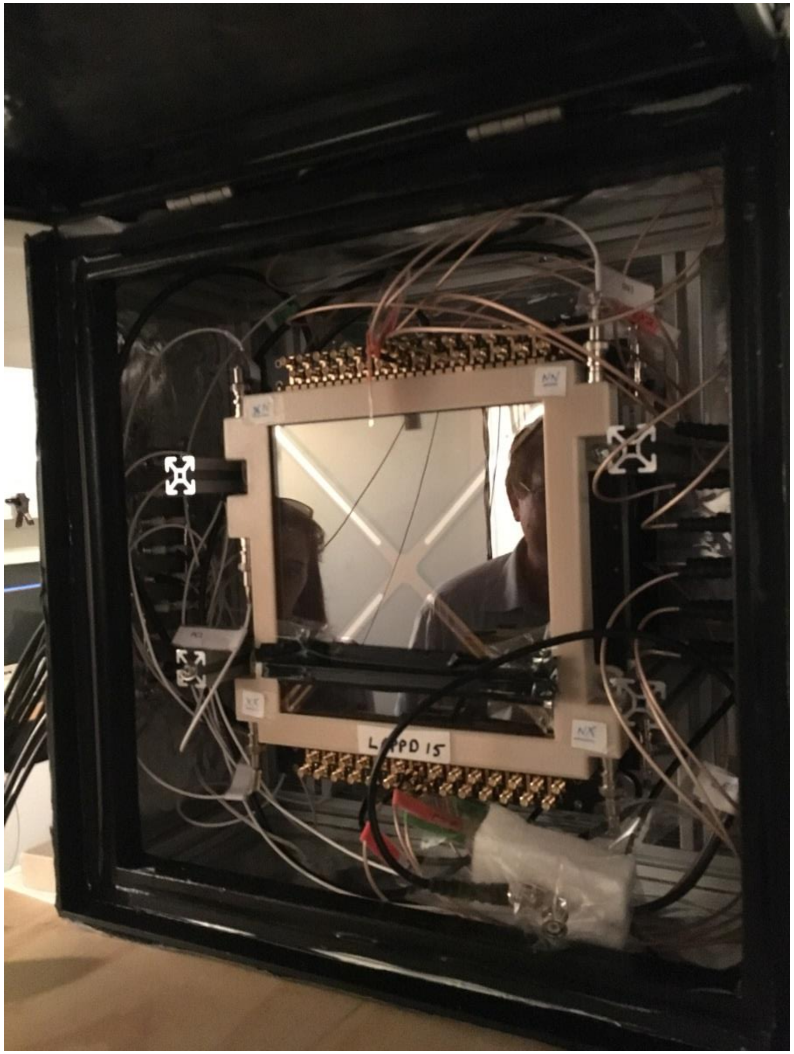
Outline

- Incom Inc. Corporate Overview
  - LAPPD Pilot Production Update
- Motivation for Nuclear Physics Program
- Phase II Project Objectives
- Gen I All-Glass LAPPD™ Design
  - LAPPD™ Performance
- Gen II LAPPD™ Year 1 Summary
  - Close Collaboration w/UChicago
  - New Innovations
  - Challenges
- Early Adopters/Programs
  - LAPPD Measurement & Test Workshops
  - Device awareness/Commercialization
- Year 2 Plans



Pair of LAPPDs at Massachusetts General Hospital for Proton Beam Testing

Incom Inc. Corporate Overview

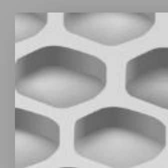
Celebrating 47 Years of New Technology Commercialization

1970s & 1980s | 1990s | 2000s ………… | 2014-2015 | 2016 – 2017 …………

- 1st fiber optic faceplate
- Fiber optic CRT product for photo type setting

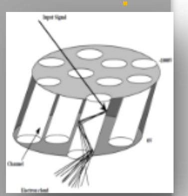
- 1985 – Distortion-free fiber optic night vision using INCOM's MEGAdraw

- Large area fiber optic tapers for medical & scientific digital imaging



Genomic analysis

- Glass capillary arrays (GCAs)
- Microchannel Plates (MCPs)
- LAPPDs



Pilot Production

- Glass tile components (INCOM)
- Develop pilot process for medium scale LAPPD production

Diverse Technology Development at Incom

Technologies

- Glass - including drawing, fusing, heat treatment & finishing
- Optics
- Polymer - including drawing, fusing, and finishing
- Coatings - Atomic Layer Deposition

Products

- Fused Fiber Optic Glass Products
- Polymer Fiber Optic Products
- Hollow Core Glass Capillary Array Products
  - Glass Capillary Arrays (GCAs) for Analytical & biological applications
  - X-Ray Optics
  - Microchannel Plates (MCPs)
- Large Area Photodetectors (LAPPDs)

Markets

- Nuclear Physics (Do; (Neutrinoless Double Beta decay, TOF at Colliders)
- High Energy Physics
- Medical Diagnostic / Life Sciences (PET, Proton Therapy, …)
- Material Science, Light Sources
- Defense & Homeland Security: (Reactor Monitoring, Watchman,,..)
- Display, Scientific

LAPPD Production Overview

- GCAs -Establish reliable GCA production at INCOM using Gen II Finishing
- MCPs - Resistive & Emissive ALD Coat,
- Tile Detector Kits - Manufacture component parts in the form of a “kit” ready for final integration and sealing step,
- Integration & Sealing - Establish UHV integration and sealing of component parts into a final detector tile,
- Demonstrate - Demonstrate multiple-per-month detector tile fabrication

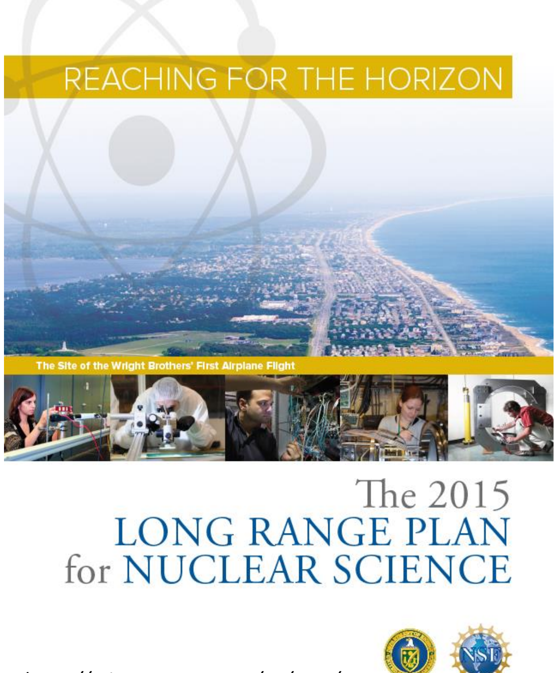
Motivation

- The world's first Electron Ion Collider (EIC) has been recommended in the 2015 Long Range Plan for Nuclear Science as the highest priority for a new facility construction in US.

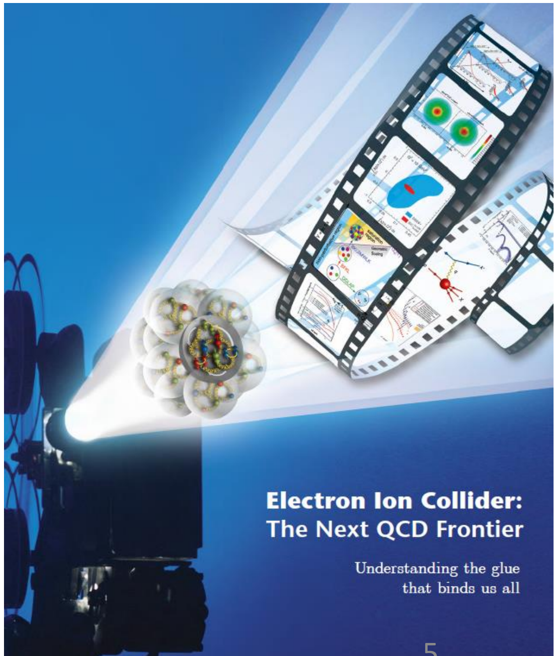
- Precise particle identification (PID) ($e/\pi/K/p$) over a wide range of momentum is essential for the proposed measurements, low cost large area Multi-Channel Plate (MCP) type detector with fast time (< 10psec) and spatial resolution, high rate capability, radiation tolerance and magnetic field tolerance

- Incom, Inc., the industrial partner of LAPPD collaboration, has successfully commercialized the PILOT production of LAPPD^{TM}. Optimization of current LAPPD^{TM} design, extensive characterization to address issues, and industrial mass production are critical to the success of EIC PID.

Ultimate GOAL: Achieve mass produced low-cost LAPPD^{TM} with specifications to fulfill EIC requirements



https://science.energy.gov/np/nsac/



arXiv:1212.1701

Large Area Picosecond Photo Detectors -LAPPDs

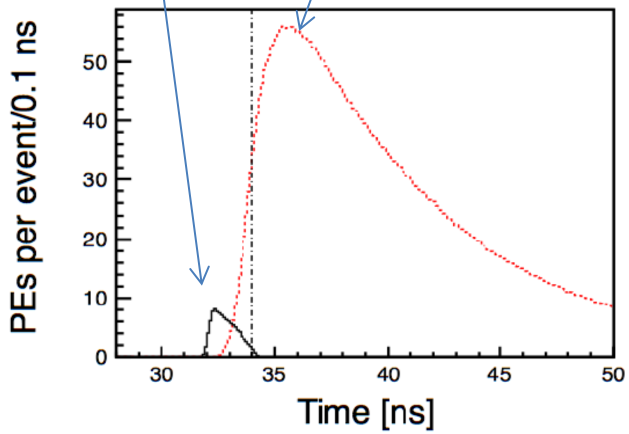
- Fast timing, high gain, single photon imaging
- Large Area: 200 x 200 mm^2
- Collider TOF – single digit psec
- Timing Resolution measured -
    - <64pS for Single Photo Electron (SPE)
- QE: ~20% w/bi-alkali photocathode
- Low Cost per Unit Area (in high volume prod)
- Sub-mm spatial resolution

Applications: NP, HEP and others

- Nuclear physics applications such as Electron Ion Collider (EIC), Neutrinoless double-beta decay (NuDoT)
- DOE-supported R&D
    - Accelerator Neutrino Neutron Interaction Experiment (ANNIE) and WATCHMAN
    - Deep Underground Neutrino Experiment (DUNE),
- homeland security sensors
- medical imaging: PET scanning, proton therapy beam targeting

- Prompt, brief Cherenkov light.
- Requires:
    - Fast timing
    - High gain

Long duration, bright scintillation light



References from:
UChicago (A.Elagin)
ANNIE (M. Wetstein),
WATCHMAN (M. Malek),
NuDot (J. Gruszko, L. Winslow)

JINST 9 (2014) P06012

What are the major goals for the Phase II Gen II LAPPD™

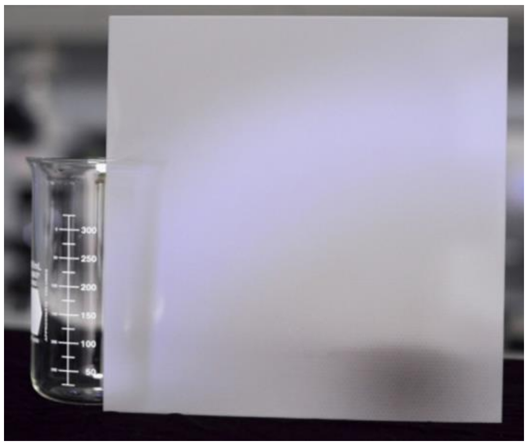
- Simplifying the **robust ceramic lower tile assembly**, including the thin film metallization processes to optimize electrical properties of the inside-out anode design.
  - **Capacitive signal coupling** to an external PCB anode below the tile
  - High fluence applications enabled by use of **pixelated anodes**
- Further **optimizing window-to-ceramic sealing process** for borofloat, fused silica, and other top window materials for detection of light in the visible and UV spectrum.
- Analyzing LAPPD™ pilot production processes to identify and implement measures for **reducing cost** and **maximizing yield** and throughput for **scale-up** to high-volume production.
- Incorporate the designs of the anode, lower tile assembly and top window sealing process, **fabricate working Gen-II LAPPD™s for both pad and microstrip applications**.
- Designing and fabricating **test and measurement stations** for the Gen-II LAPPD™ inside-out detector for use in the sealing tank and in the final inspection facility.
- Fabrication of a Gen-II LAPPD™ test station for long duration **life testing**.

- Subcontract collaboration contributions at the **University of Chicago**
  - Weekly/daily communication with Professor Henry Frisch's team (**Parallel efforts**)
  - **Monolithic piece lower tile with wall penetrations**
    - for HV contact and **In-situ photocathode deposition (air transfer process)**
  - Ceramic Metallization
  - Chemical/Physical Characterization Tools
  - External Signal PC-Board Pickup for Pad/Strip/Patterned Readout
  - Front-End Electronics and DAQ Systems

Advantages of LAPPD^{TM}

Completely different MCP manufacture technology, eliminated the etching and firing processes in old technology, using robust borofloat glass making low-cost, large area MCPs possible.

Glass capillary array (GCA)



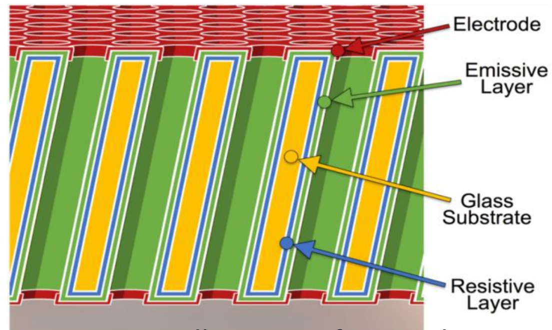


Illustration from Ertley, 2016

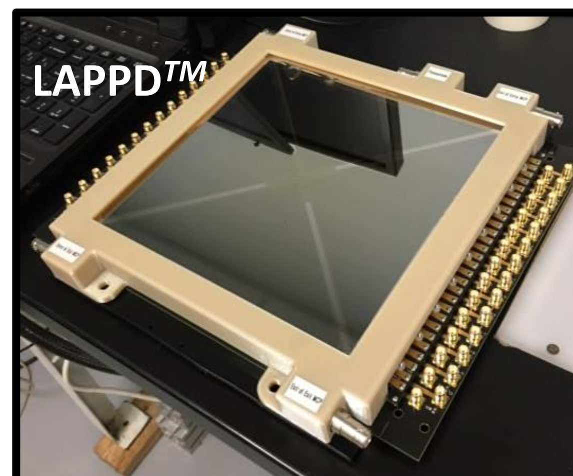
ALD coating

Licensed from Argonne to Incom

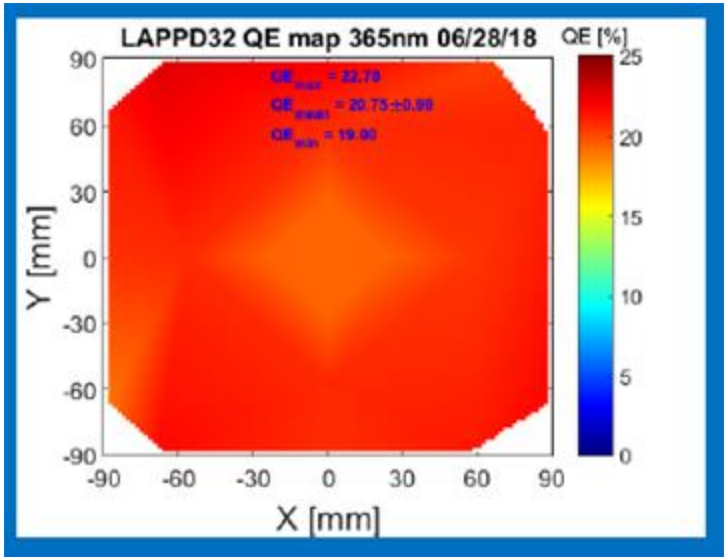
Functionalized MCP

World largest MCP-PMT: Large Area Picosecond PhotoDetector (LAPPD^{TM})

- **Large-area** (20 cm x 20 cm): world's only method for such large area MCPs, cheap B33 glass
- **Low-cost (in volume)**: labor cost is the same as making one small MCP-PMT, but area is 16 times larger
- **Comparable performance** compared to commercially available MCP-PMTs



LAPPD^{TM} Key performances

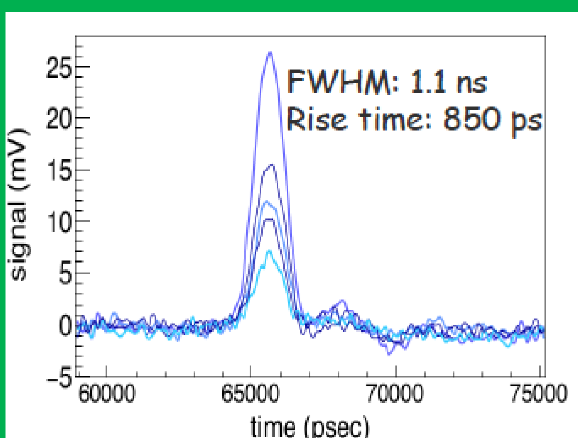


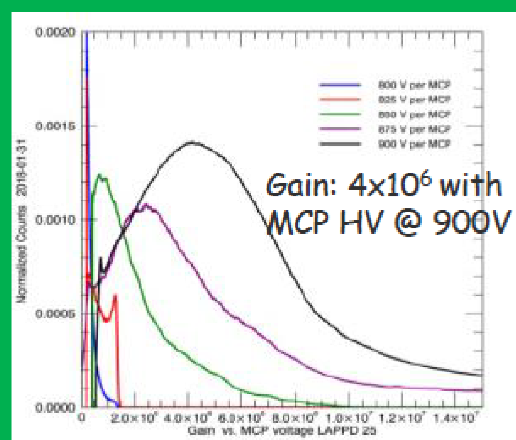
Large Area Photocathode production process is established
QE >20% demonstrated in sealed LAPPDs

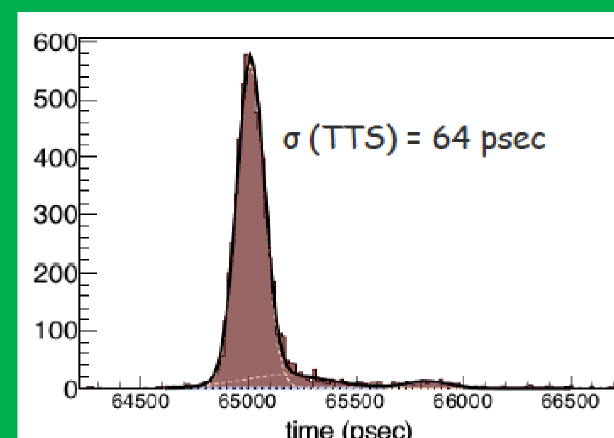
LAPPD S/N	Maximum %	Average %	Minimum %
LAPPD #13:	23.5	18.6±3.3	13.5
LAPPD #15:	25.8	22.3±3.0	15.7
LAPPD #22:	14.7	10.6	7.0
LAPPD #25:	10	7.1	5.0
LAPPD #29:	19.6	13.0±6.0	3
LAPPD #30:	22.9	17.2±2.5	13
LAPPD #31:	19.6	16.0±1.9	12.1
LAPPD #32:	22.7	20.8±1.0	19.0

Uniform QE at 20% average was achieved, but varies from run to run, addressing it now at INCOM

Gain & Timing



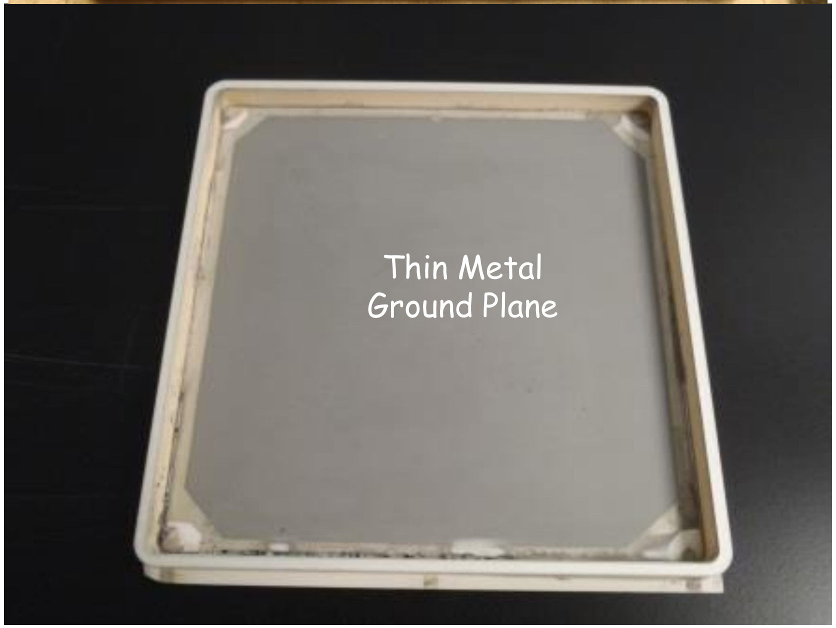




Note: Position measurement along and across anode strips show 2.2 mm and 0.95mm spatial uncertainty

Innovation (Incom)in the LAPPD design (Gen II)

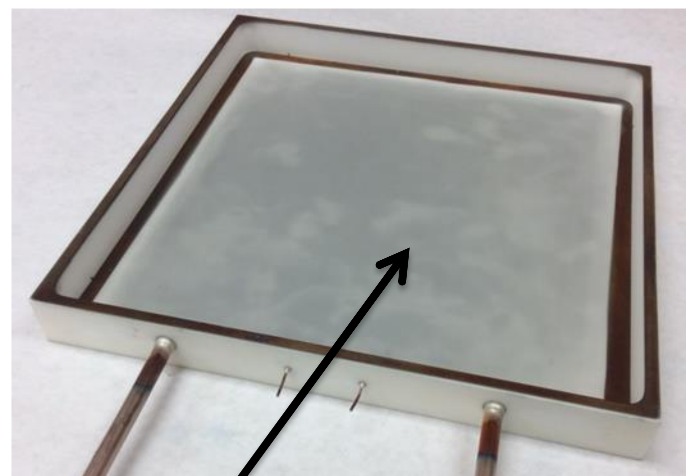
- Inside out anode
  - Capacitively coupled signals
  - Both striplines or user defined pixelated pattern
  - Outside of the package – easily changed
- Ruggedized Design Optimized for Capacitive Coupling
  - Rugged materials (toughness, strength)
    - Alumina ≥ fused silica/quartz ≥ Borofloat
    - Eliminate tile failures due to cracked LTA
    - Improved performance in portable field applications
  - Capacitive coupling is improved over B33
    - due to dielectric constant and low loss tangent
    - for temporal and spatial resolution



(UC) The Monolithic Ceramic Tile Base w. Capacitively-Coupled Anode/External Pickup

Sidewall and anode plane are green-trimmed and then ground to spec after full fire- no fritted or brazed large (long) joint

Ceramic tile bases from 4 vendors



10 nm-thick NiCr anode plane (DC ground)

Summary of Gen II Sealing commissioning trials from both Incom and UChicago.

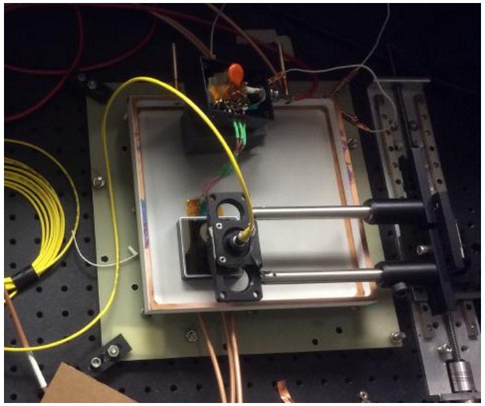
Seal Trial date	Side Wall Seal Surface	Window Transfer	PC QE @125-150C, @365 nm	Anode	MCP Function	Stack Height	Window deflection	Window Seal (Y/N)
1) Phase I Incom Nov 2016	Flat	Air	N/A	N/A	N/A	Low	Yes	Yes, but due to low internal stack height window cracked and vacuum was lost
2) Incom CLTA #1 Oct 2017	Flat	UHV	6%	metallized inside out ground plane only	N/A	low	Yes	Yes, but due to low internal stack height window cracked and vacuum seal maintained
3) Incom Tile #24 Nov 2017	Grooved	UHV	20%	Ag strips	Yes	Excellent	No	No, separated
4) Incom Tile #27 Jan 2018	Grooved	UHV	7%	Ag strips	Yes	Excellent	No	No, separated
5) UC Tile #17 July 2017	Flat	Air	N/A	metallized inside out ground plane	Yes	Excellent	Yes	Slow leak Unknown
6) UC Tile #21 Dec 2017	Flat	Air	N/A	metallized inside out ground plane	Yes	Excellent	Yes	Slow leak Unknown
7) Incom CLTA #2 Mar 2018 8) Incom CLTA #3 Apr 2018	Flat	UHV	6%	metallized inside out ground plane only	N/A	low	Yes	Slow leak in one corner
9) UC Tile #23 Mar 2018	Flat	Air	N/A	metallized inside out ground plane	Yes	Excellent	Yes	Slow leak Unknown
10-13) UC Tiles 24 -27 through July 2018	Flat	Air	N/A	metallized inside out ground plane	Yes	Excellent	Yes	Slow leak Unknown

NOTE: Tile numbering includes all previous glass LAPPD Tiles

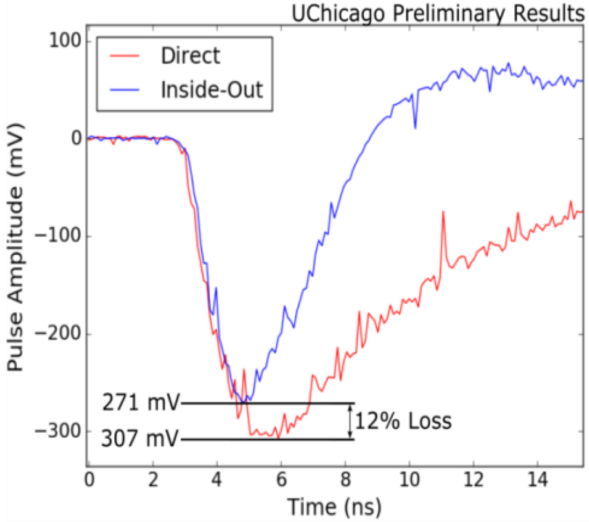
- GEN I LAPPD (All Glass Design) window to LTA sealing is well established with routine **success > 65%**
- Equivalent sealing to a ceramic body has proven to be very challenging. (1/6 Incom, 0/7 UC)
- The underlying cause is not fully established, but results to date point to **surface finish** of the ceramic, **effective thickness, coverage** and **bonding** of thin films. **Mechanical** tolerances and **stack height** are key as well.

GEN II Ceramic Package LAPPD™

DOE – NP Phase I SBIR, February 2016 in collaboration with U of Chicago



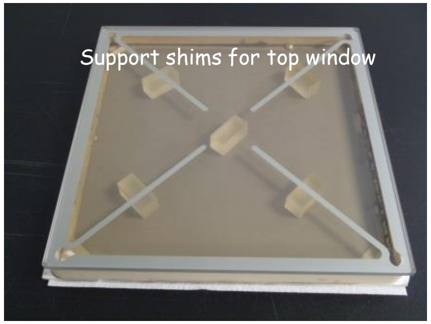
A thin metal layer anode serves as a DC ground on the inside of the detector. 88% of an MCP fast signal pulse was capacitively coupled through the ceramic, to strips or pads on the outside.

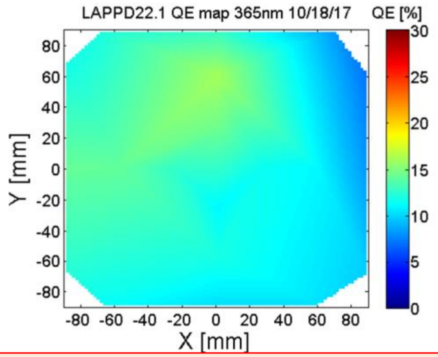


- B.W. Adams,et al, "An internal ALD-based high voltage divider and signal circuit for MCP-based photodetectors", Nucl. Instr. Meth. Phys. Res. A 780 (2015) 107-113
- Private Communication, Todd Seiss and Evan Angelico, University of Chicago. Inside-Out Tests of Incom Tiles, June 23, 2016
- Angelico,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

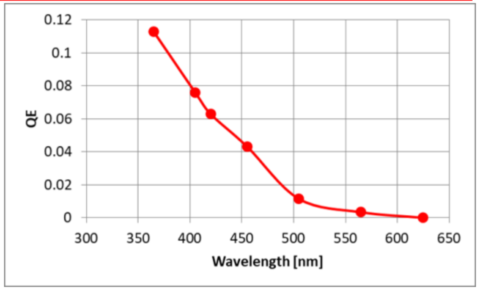
Incom UHV Transfer Process Ceramic LTA w/ Photocathode

DOE-NP Phase II SBIR, Oct 2017

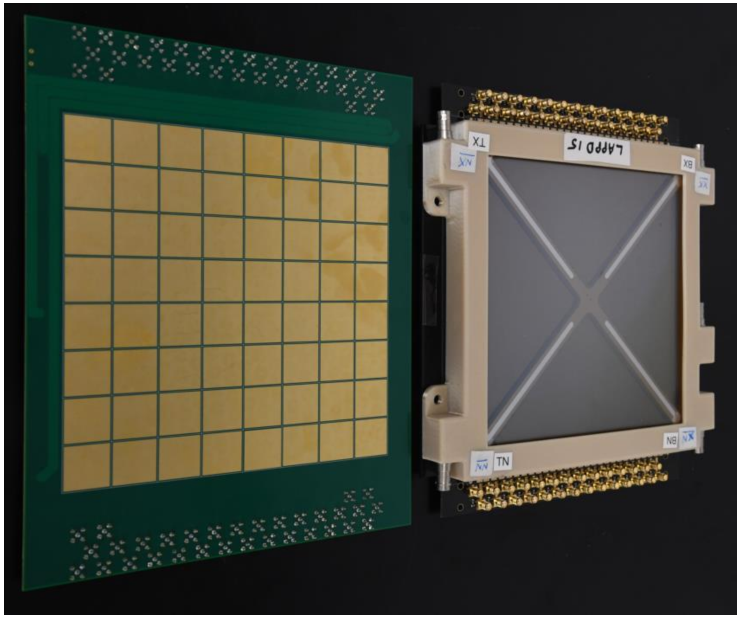




LAPPD22.1 QE (single point) of 12/12/17



Mean QE=11.6%
QE_{max}: 16.0%
QE_{min}: 7.0%



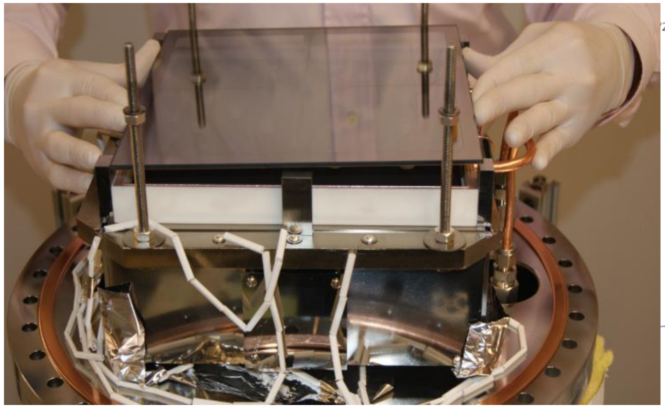
(L) PCB with the pixelated pads
(R) LAPPD with signal-pickup pads facing the tile

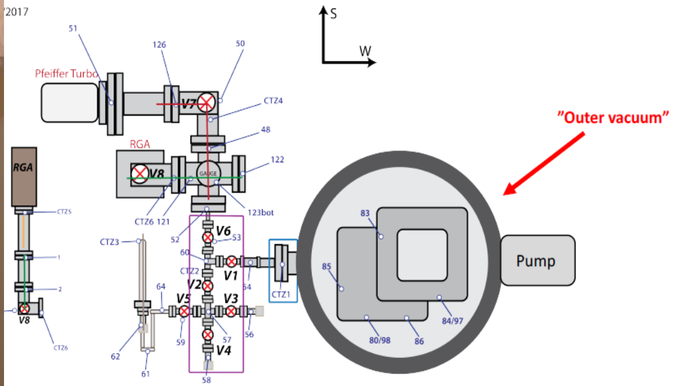
UC Air-Transfer Process

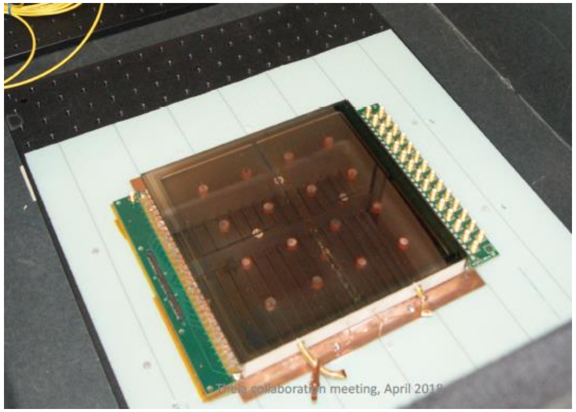
1. Window with pre-deposited Sb layer transferred in air

2. Dual vacuum bake-out & seal
3. Alkali vapors to form PC

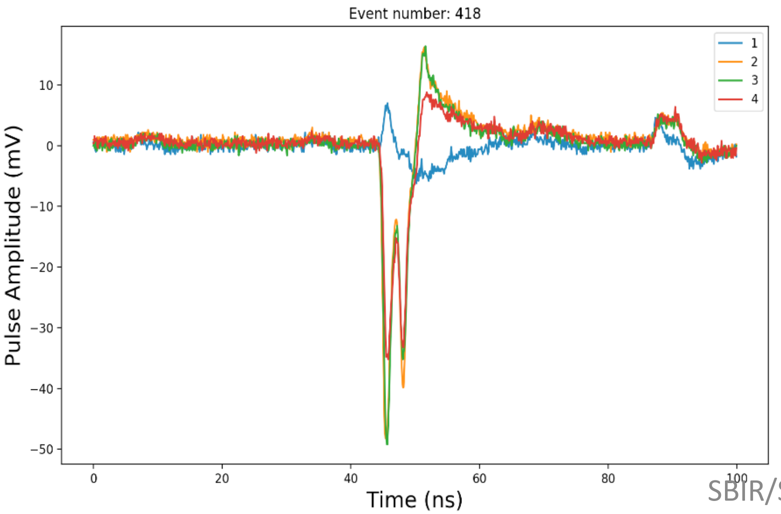
4. Seal copper tubes

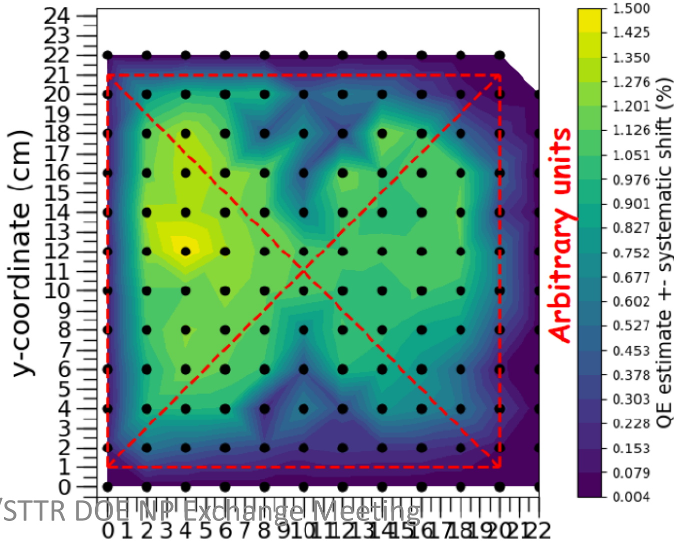






Pulses and photo-response map after complete processing in one of the first system commissioning trials





HV distribution is being upgraded to allow for absolute QE measurements

Surface Finish of Ceramic Sealing Edge(Incom & UC)

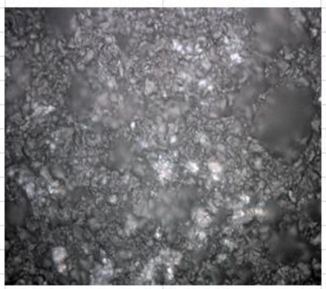
As rec'd (200 grit diamond tool)	
Ra	
µm	µin
1.683	66.3
1.229	48.4
1.625	64.0
1.599	63.0

after Incom CNC (600 grit diamond tool)	
Ra	
µm	µin
0.815	32.1
0.593	23.3
0.770	30.3
0.630	24.8

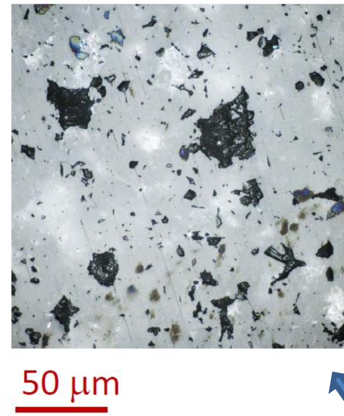
100x

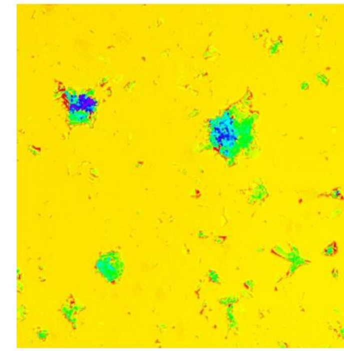
25x

500x

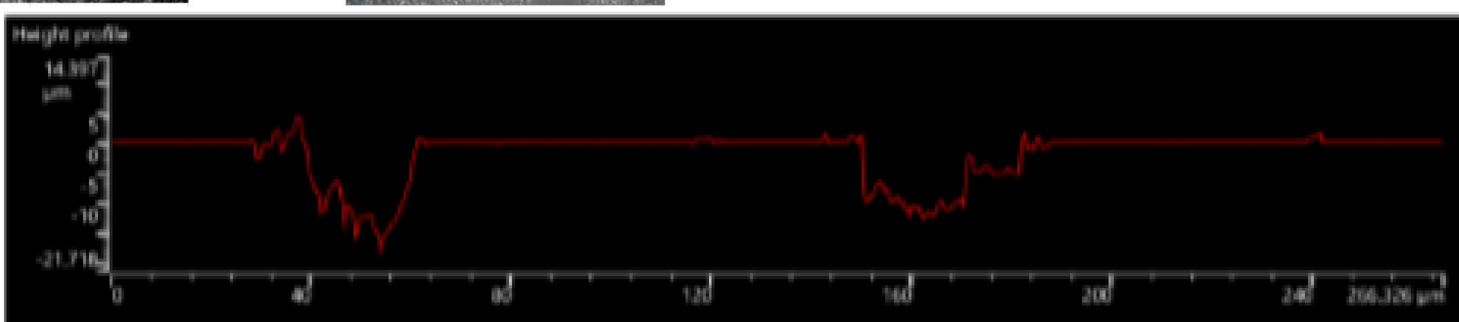


500 x

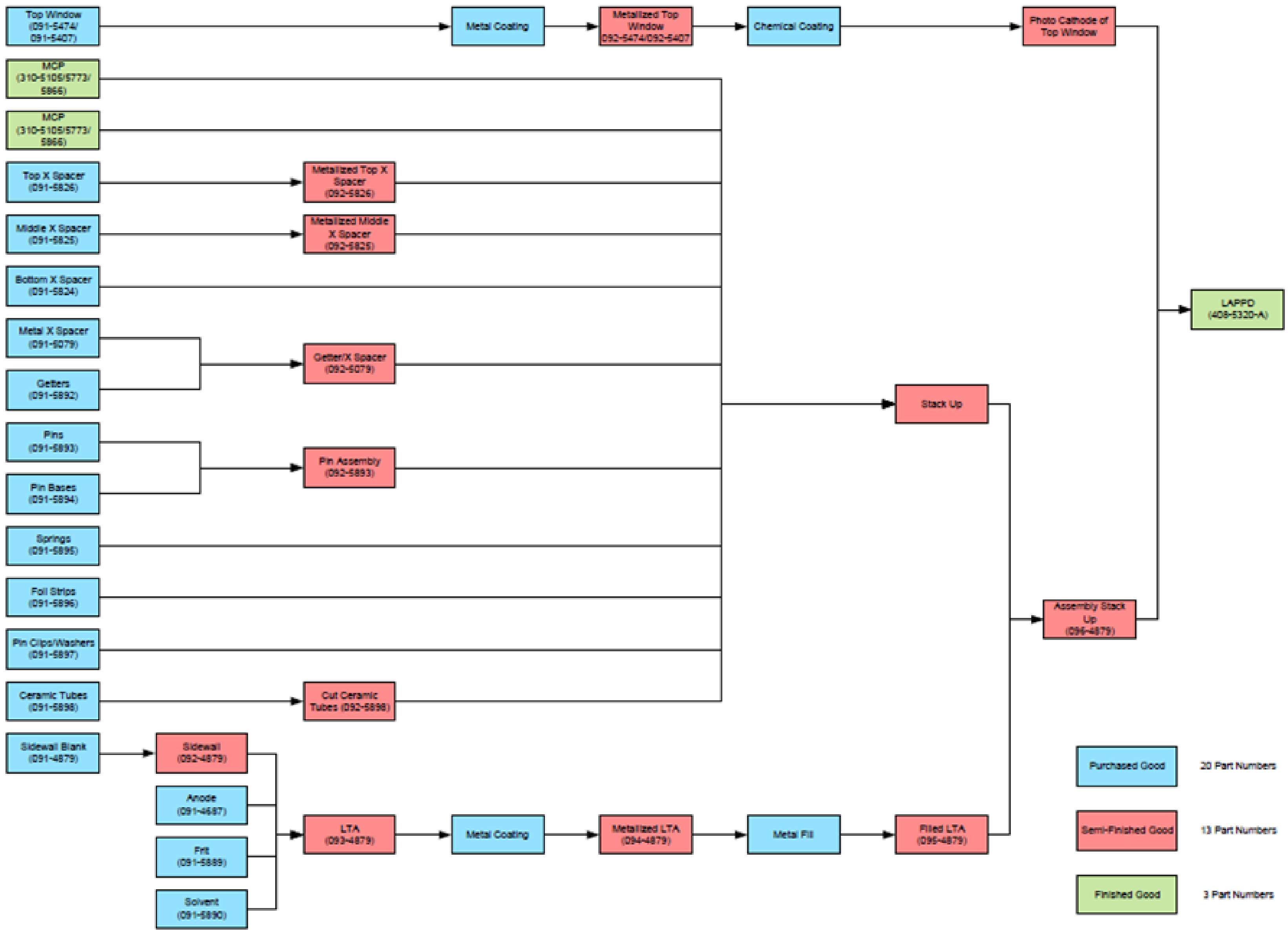




Surface viewed/measured using an Olympus Scope
(A. Elagin -UC)

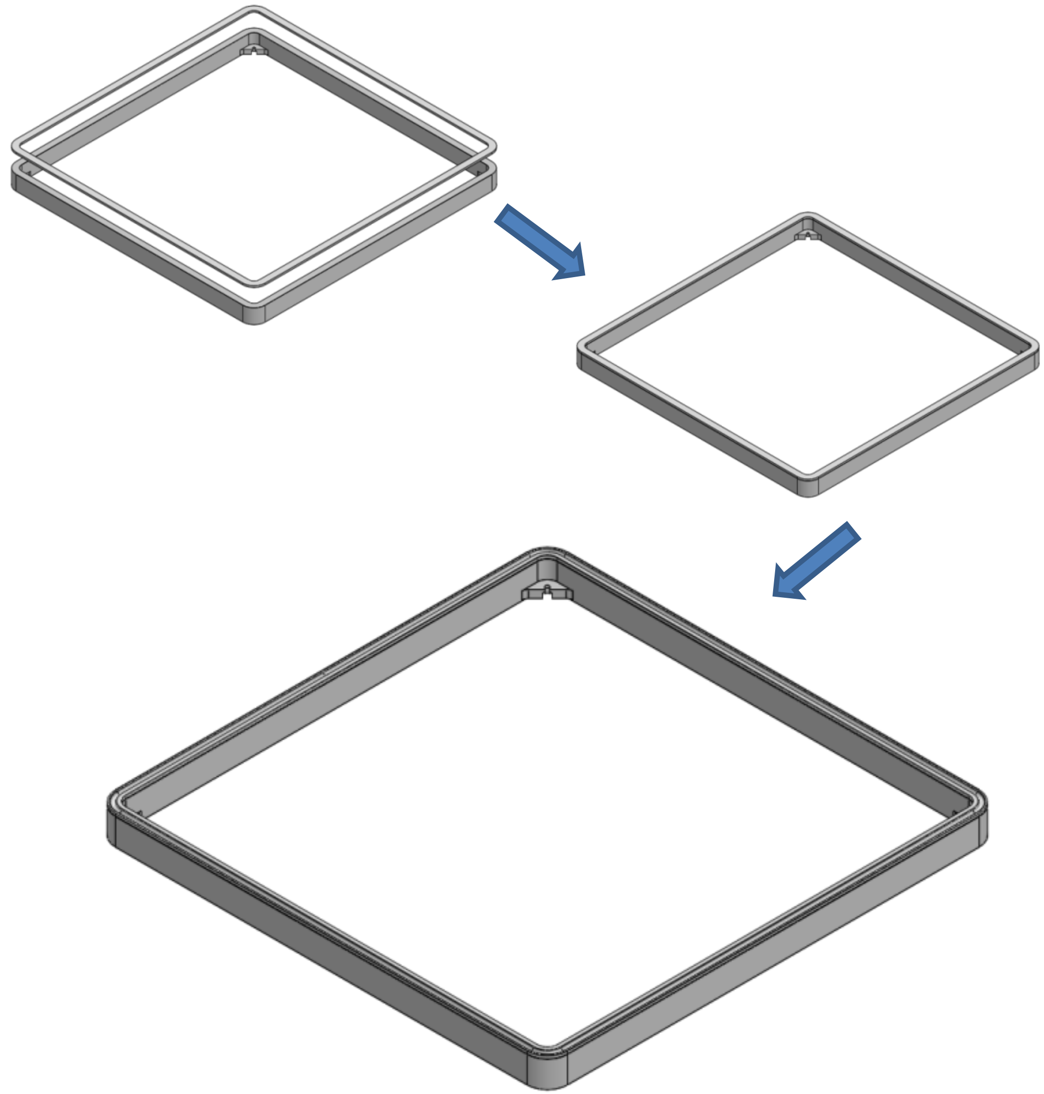


LAPPD Production Bill of Materials



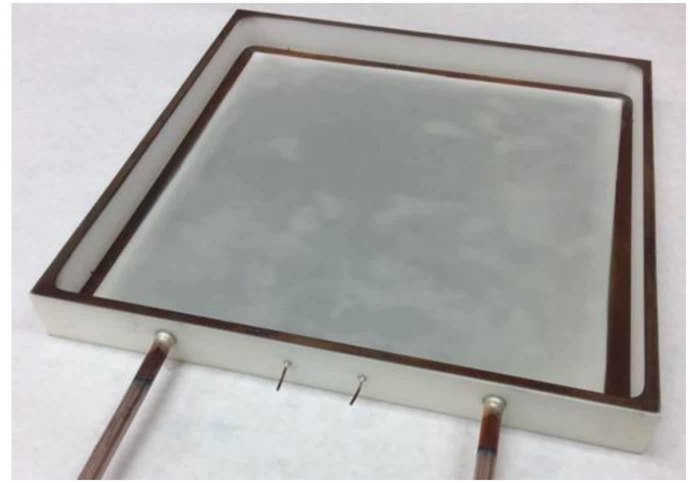
Near Term Trials to Address Sealing Issues @ Incom

- Bond alloy to sidewall
  - CTE matched alloy
    - CNC'd to size
  - Adhere to ceramic sealing edge using frit or metallization scheme
  - CNC top surface features analogous to the Gen I geometry for window sealing
- Use fused silica or Quartz LTAs

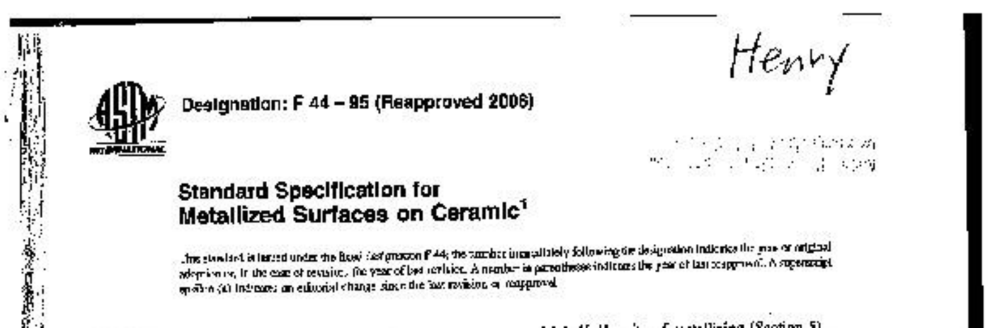


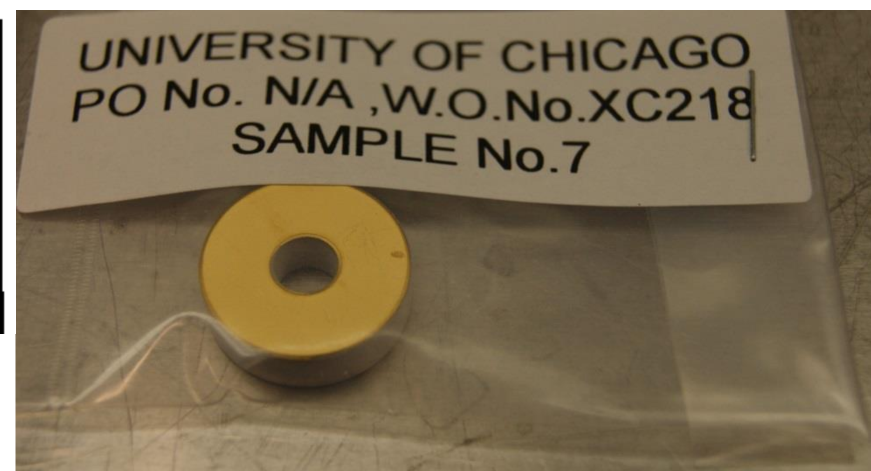
UC Metallization of Ceramic Sealing Surface

1. Ion-assisted Evaporation (2 vendors)- NiCr,Cu; SSL Gen-I inspired



2. Fired Moly-Manganese (W) –Ni-Au(2 vendors)-1450C





ASTM Standards on flatness, coverage, adhesion

LAPPD™ Early Adopter/Current Programs

PRINCIPAL INVESTIGATOR & SPONSOR	PROGRAM TITLE
Bill Worstell, Incom Inc. Phase II	TOF Proton Radiography for Proton Therapy
Fermilab / U Chicago Dmitri Denisov/Henry Frisch	• Two LAPPD for Fermilab beamline testing by January 2019
Mayly Sanchez and Matthew Wetstein, Iowa State	ANNIE - Atmospheric Neutrino Neutron Interaction Experiment • ANNIE funding has now been committed • LAPPD #25 Delivered February 2018 • LAPPD #31 – September 2018 • Three more before November
Andrey Elagin (U of Chicago)	Neutrino-less Double-Beta Decay
Mickey Chiu (BNL) -	Phenix Project - "eIC Fast TOF"
Erik Brubaker, Sandia National Lab/CA	Neutron Imaging Camera LAPPD #22 Delivered February 2018
John Learned, U. of Hawaii, and Virginia Tech	Short Baseline Neutrino (NuLat)
Lindley Winslow (MIT)	Search for Neutrino-less Double-Beta Decay (NuDot) Using Fast Timing Detectors
Bill Worstell, Incom Inc, Bob Wagner & Junqi Xie. ANL, Jefferson Laboratory	Magnetic Field Tolerant Large Area Picosecond Photon Detectors for Particle Identification
Andrew Brandt, University of Texas, Arlington	Life Testing of LAPPD
Dr Matthew Malek, The University of Sheffield	~10,000 LAPPDs for Hyper-Kamiokande (10 years)

LAPPD Measurement & Test Workshop

- Familiarize early adopters with the LAPPD, and provide early access.
- Provide researchers with raw data for their own evaluation and use, which might include using the data to evaluate LAPPD readiness for their program applications.
- Workshop Schedule / Dates:

Workshop #	Date
4	Oct 9-11, 2018
5	Feb 12-14, 2019
6	May 14-16, 2019
7	Sep 10-12, 2019
8	Feb 11-13, 2020
9	May 12-14, 2020

Ph II Gen II Summary

- The Gen I LAPPD is proven for:
  - Full size, fully integrated LAPPD are routinely sealing in pilot production with high yield
  - LARGE area MCP with high sustained gain and well-formed Pulse Height Distributions
  - Photocathode process with spatially uniform QE, moderately high QE and time stability
  - Positional accuracy shown to be < 3 x 1mm (0.7 x 0.7 mm with RF strips)
- Capacitive signal coupling to an external PCB anode below the tile is proven
  - Both pixelated and stripline PCBs designed, fabricated and in use
  - Low-Power Multichannel 10-15 GHz Waveform Sampling Electronics Systems designed, fabricated and in use
  - Stations for performance testing inside sealing tank and in the Dark Box Room are working well for both Gen I and Gen II style LAPPDs
- Early Adopters have attended our on-going LAPPD Measurement & Test workshops.
  - http://www.incomusa.com/mcp-and-lappd-documents/
- As Pilot Production processes are optimized the documented SOPs are updated.
- GEN II Sealing of Glass to Ceramic has proven to be more challenging than initially expected, but a focus on the fundamentals provides encouragement that this will be resolved shortly.

Year 2 Challenges and Plans

- #1 FOCUS: Continue to optimize the sealing process on the Gen II ceramic LTA to top window
- **Fabricate working detector tiles** while auditing tolerances on starting components and procedures to fine-tune the entire LAPPD fabrication process including photocathode synthesis. Equipment upgrades will be investigated as needed.
- Continuously **update document control** for bill of materials, standard operating procedures and developmental processes. This is a dynamic task and these are living documents that we will be updated constantly through Year 2.
- Finalize development of the testing electronics and measurement protocols for working Gen II LAPPDs
- Continue working with UTexas on **lifetime testing** while setting up Incom's own life test station
- **Supply Gen-II LAPPD™s** to specific NP, HEP or commercial applications that can be enabled by this technology. Customers may include TJNAL, BNL, Iowa State University (ANNIE), MIT (NuDot) and the beamline at Fermilab.

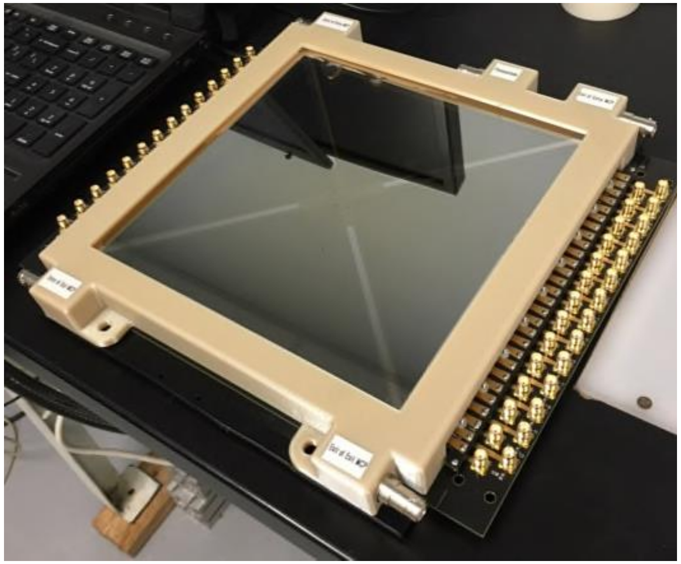
Current Funding & Personnel Acknowledgements for Incom Funding

- **DOE (NP, HEP, NNSA) Personnel**: Dr. Michelle Shinn, Dr. Manouchehr Farkhondeh, Dr. Elizabeth Bartosz, Dr. Alan L. Stone, Dr. Helmut Marsiske, Carl C. Hebron, Dr. Kenneth R. Marken Jr, Dr. Manny Oliver, Dr. Donald Hornback
- DOE, DE-SC0015267, NP Phase II – "Development of Gen-II LAPPD™ Systems For Nuclear Physics Experiments"
- DOE DE-SC0018445 NP Phase I "Magnetic Field Tolerant Large Area Picosecond Photon Detectors for Particle Identification"
- DOE, DE-SC0011262 Phase IIA - "Further Development of Large-Area Micro-channel Plates for a Broad Range of Commercial Applications"
- DOE DE-SC0017929, Phase II– "High Gain MCP ALD Film" (Alternative SEE Materials)
- NIH 1R43CA213581-01A Phase I – "Time-of-Flight Proton Radiography for Proton Therapy"
- DOE DE-SC0018778 Phase I "ALD-GCA-MCPs with Low Thermal Coefficient of Resistance"
- NASA 2018-I SBIR Proposal: S1.06-1093 Phase 1 "Curved Microchannel Plates and Collimators for Spaceflight Mass Spectrometers"

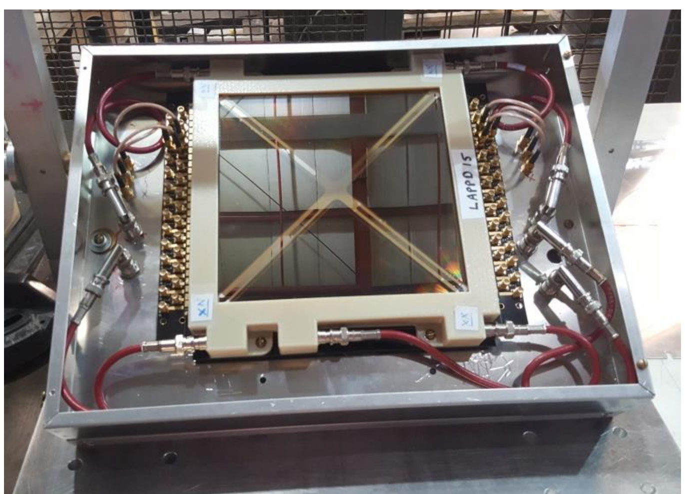
- Contact Information: Michael R. Foley: mrf@incomusa.com

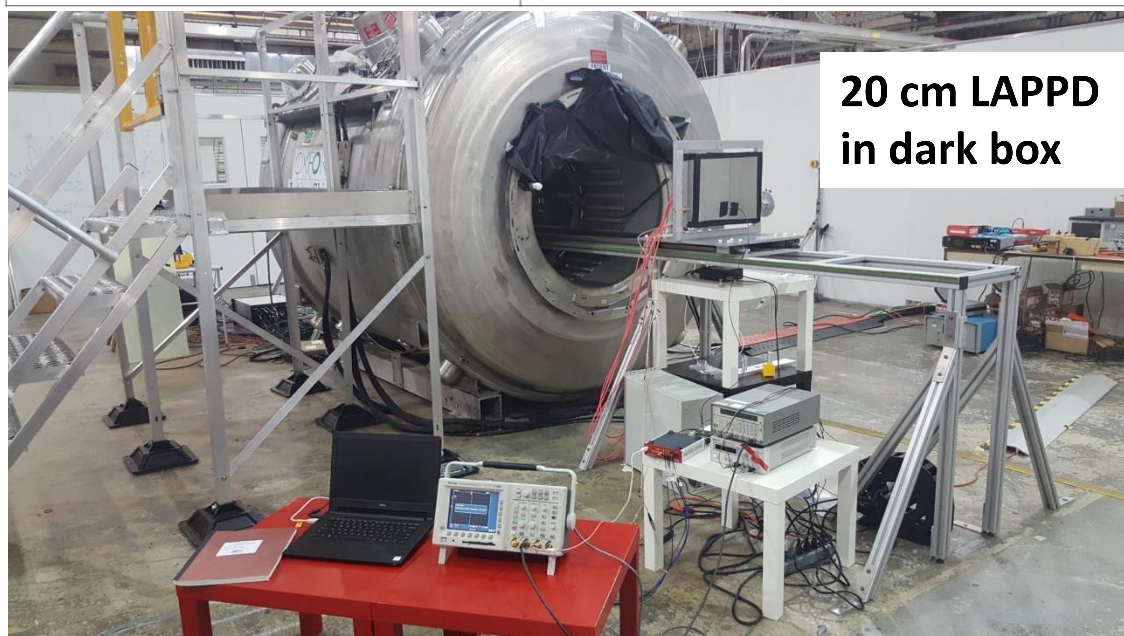
Back up slides

LAPPD^{TM} installed at magnetic field test facility



Feature	Parameter
Photodetector Material	Borosilicate Glass
Window Material	Fused Silica Glass
Photocathode Material	Multi-Alkali (K_2NaSb)
Spectral Response (nm)	160-850
Wavelength – Maximum Sensitivity (nm)	≤ 365 nm
Photodetector Active Area Dimensions	195mm X 195mm
• Minimum Effective Area	34,989 mm^2
• Active fraction with Edge Frame X-Spacers	92%
Anode Data Strip Configuration	28 silver strips, Width = 5.2 mm, gap 1.7 mm, nominal 50 Ω Impedance
Voltage Distribution	5 taps for independent control of voltage to the photocathode and entry and exit of MCP



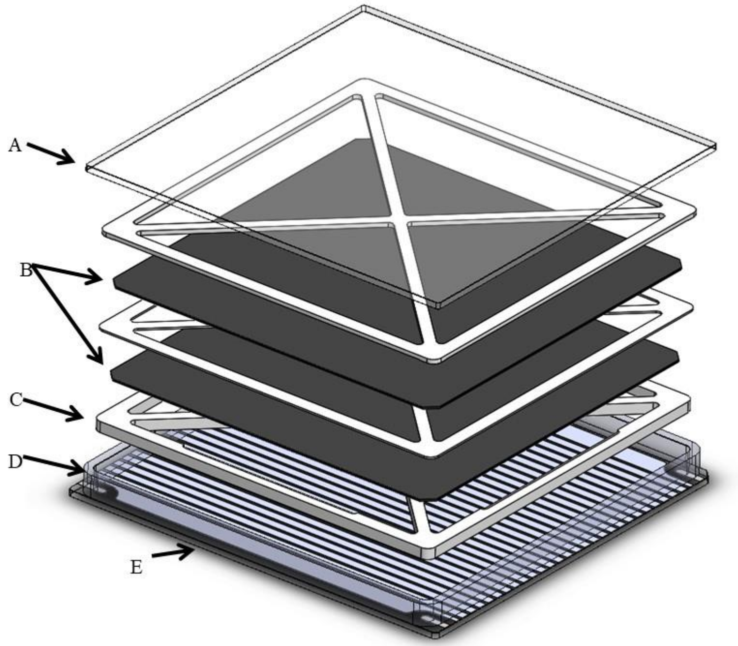


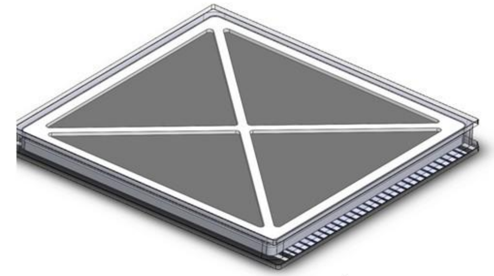
LAPPD Design

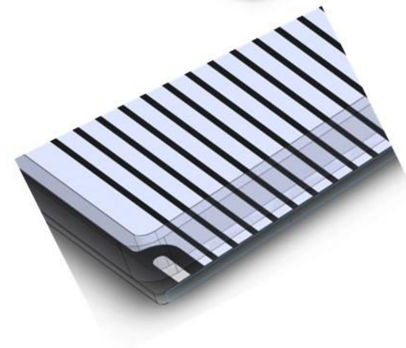
Fused silica window with **photocathode on inside surface**

20 cm x 20 cm **MCPs**, spacers

Strip line anode and sidewall







Signal readout, both ends of 28 strip lines

Voltage tab at each corner to **independently power MCPs**

- Signal and high voltage delivered on strips passing under a frit bond.
- **No wall or anode penetrations**.
- **Active area: 195 x 195mm** less the x-spacers
    - 34,989 mm^2, 350 cm^2
    - 92% active area

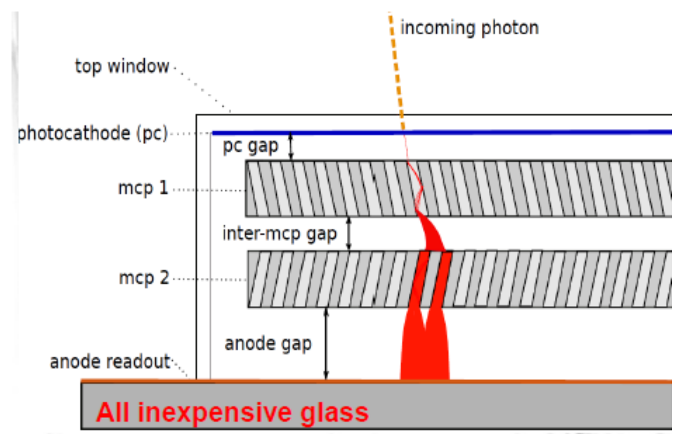


Illustration provided by Univ. of Chicago

Low-Power Multichannel 10-15 GHz Waveform Sampling Electronics Systems

Eric Oberla's Ph.D thesis; Mircea Bogdan, John Podczerwinski, Horatio Li, Evan Angelico;
John Porter of Sandia funded PSEC4A Mosis run; Jonathan Eisch, Miles Lucas,, .. (ANNIE)

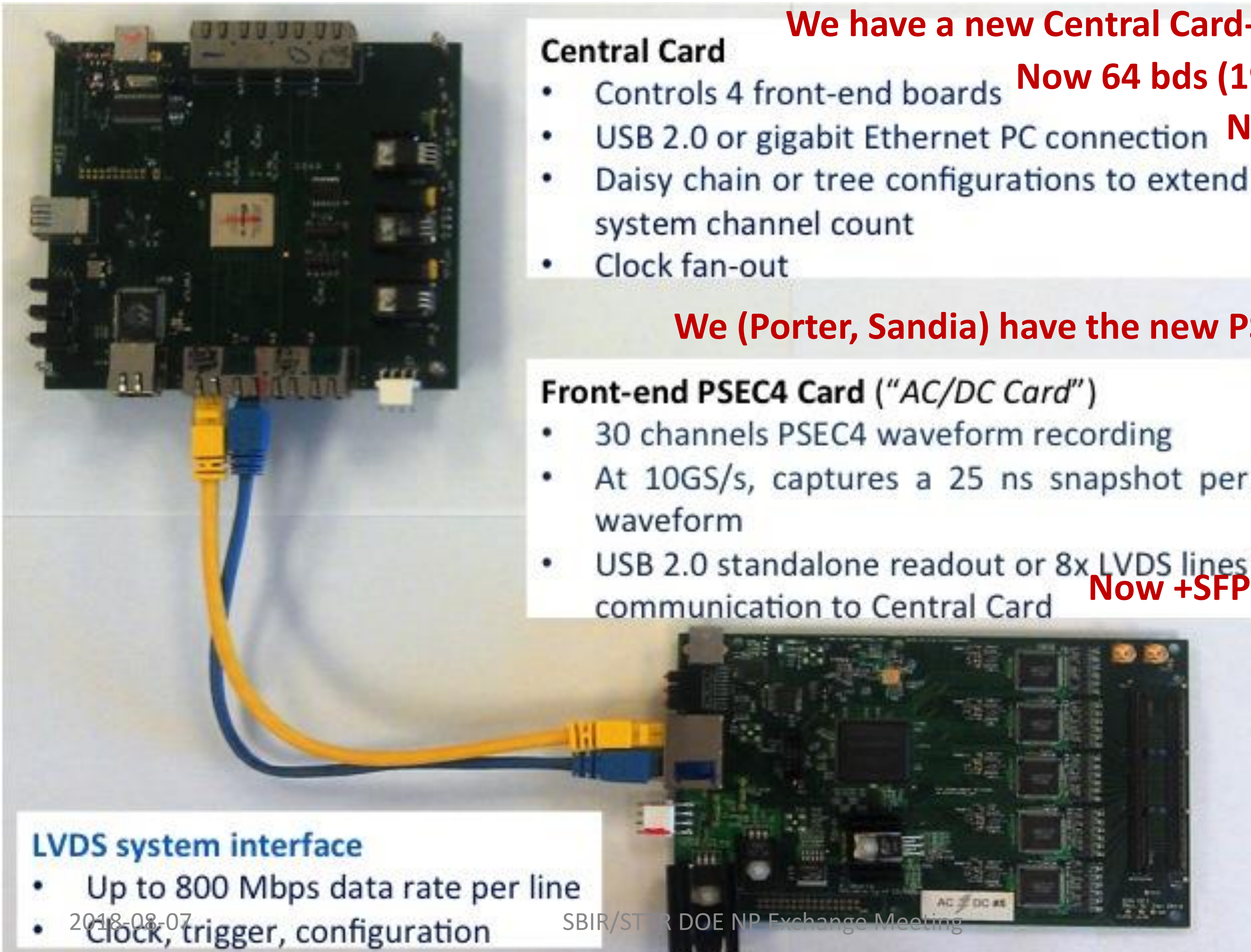
We have a new Central Card- Mircea Bogdan

Now 64 bds (1920 channels)

Now +SFP and VME

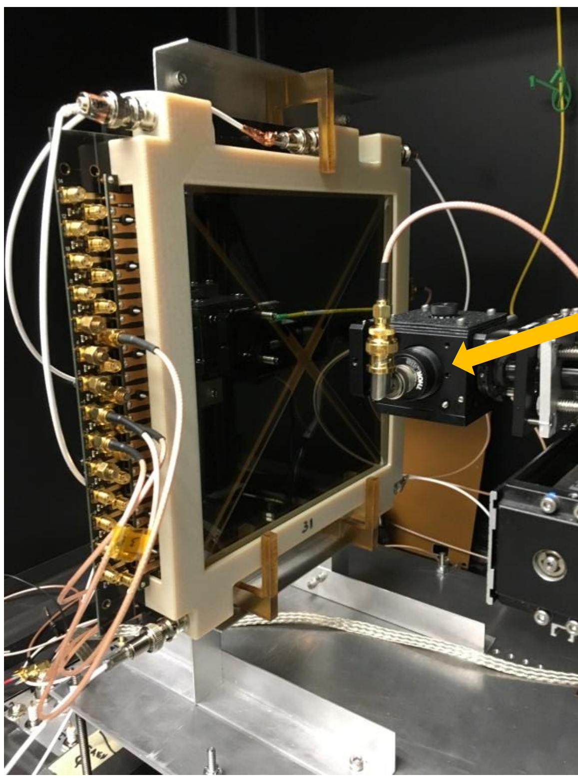
We (Porter, Sandia) have the new PSEC4A ASIC

Now +SFP and VME



Gain: LAPPD 25

- **Pulse height distributions** and **average gain** are shown vs. **MCP voltage for single photo electrons**
- Gain is as high as 6×10^6 at 900 V/MCP.



Light source: laser or LED