Development of LAPPD^{TM}/MCP-PMT towards EIC application

Junqi Xie, E. May, R. Wagner, L. Xia

Argonne National Laboratory, Argonne, IL 60439

M. Hattawy

Old Dominion University, Norfolk, VA 23529

B. W. Adams, M. Aviles, Till Cremer, C. D. Ertley, M. R. Foley, C. Hamel, A. Lyashenko, M. J. Minot, M. A. Popecki, M. E. Stochaj, W. A. Worstell

Incom Inc, Charlton, MA 01507

Electron Ion Collider User Group Meeting 2018

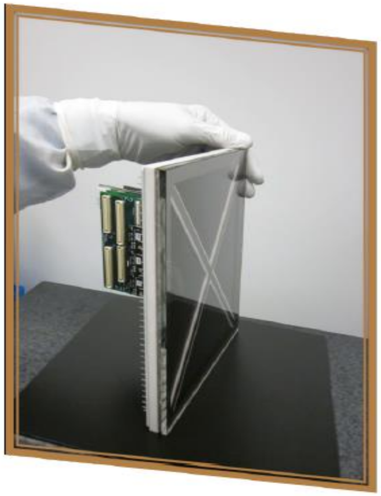
July 30 - August 2, 2018

Catholic University of America

Washington, DC

Background: Large Area Picosecond PhotoDetector (LAPPD)

- **LAPPD** is a photomultiplier based on new generation microchannel plate, reinvents photodetector using transformational technologies.
- Goals: low-cost, large-area (20 cm x 20 cm), picosecond-timing, mm-position
- Applications: picosecond timing, mm-spatial on large-area
  - ✓ Particle physics: optical TPC, TOF, RICH
  - ✓ Medical imaging: PET scanner, X-ray imaging devices
  - ✓ National security: Detection of neutron and radioactive materials
- Status: Incom, Inc. is routinely producing standard LAPPD on a pilot production basis for test and evaluation by "Early Adopters".



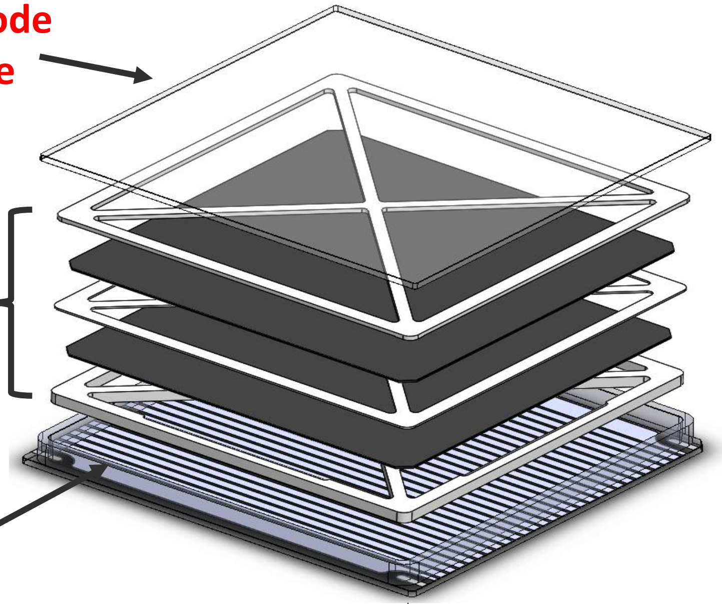
LAPPD Standard (Gen I) Design

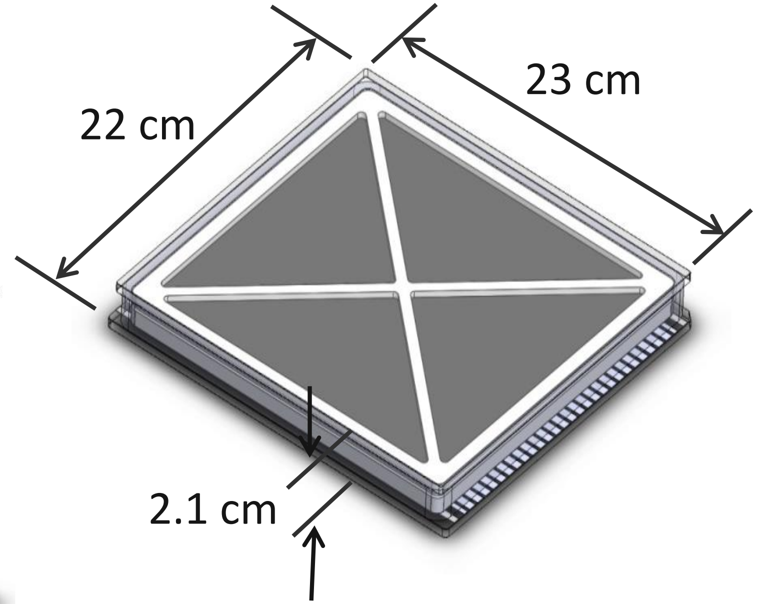
Fused silica window with **photocathode on inside surface**

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

Strip line anode and sidewall

Voltage tab at each corners 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 195mm²**

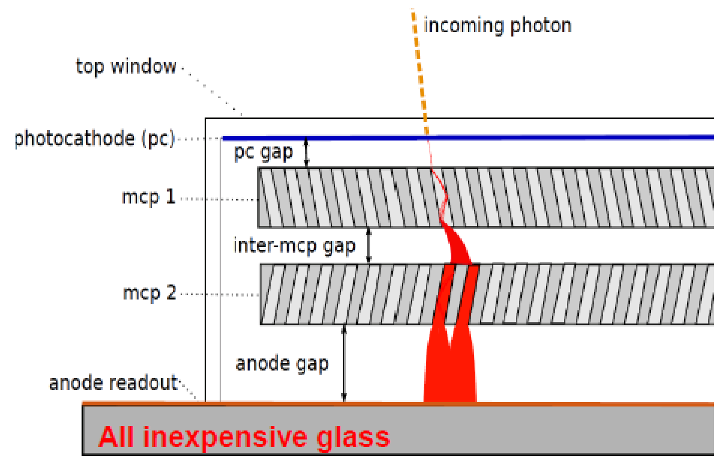
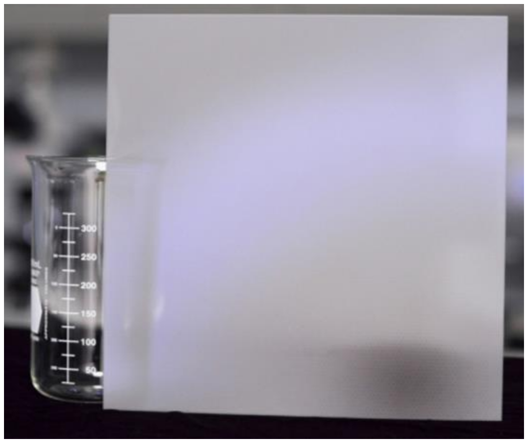


Illustration credit to Univ. of Chicago

Advantages of LAPPD™

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

Glass capillary array (GCA)



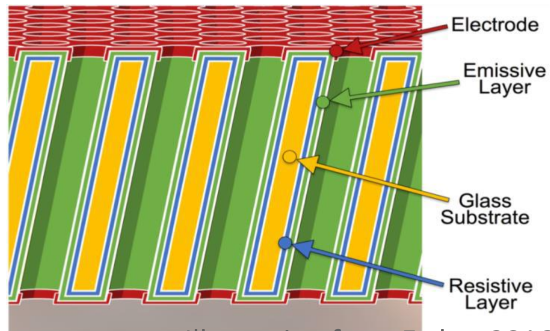


Illustration from Ertley, 2016

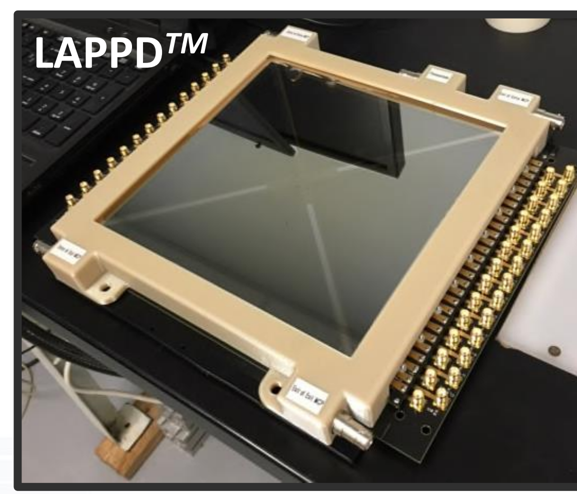
ALD coating

Licensed from Argonne to Incom

Functionalized MCP

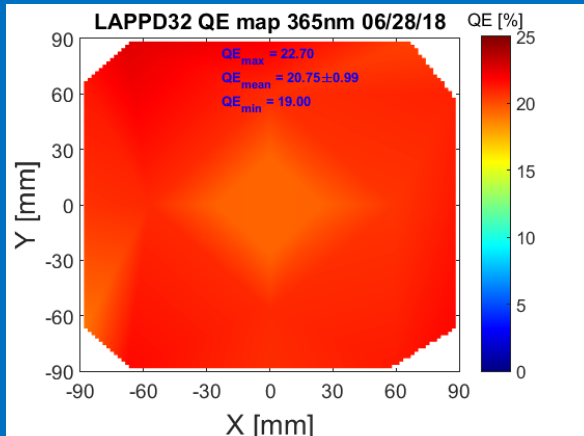
World largest MCP-PMT: Large Area Picosecond PhotoDetector (LAPPD™)

- **Large-area** (20 cm x 20 cm): world's only method for such large area MCPs, cheap B33 glass
- **Low-cost**: 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

Spectra response

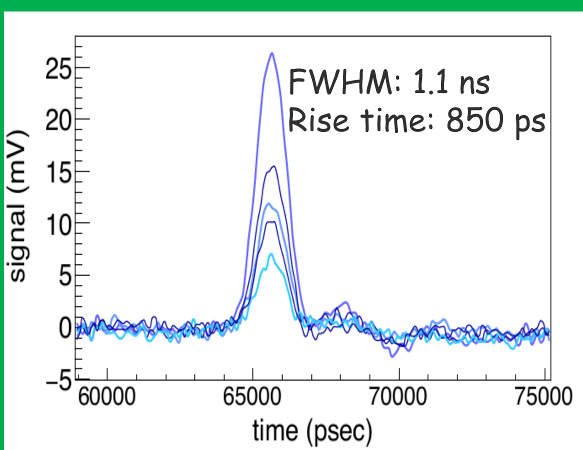


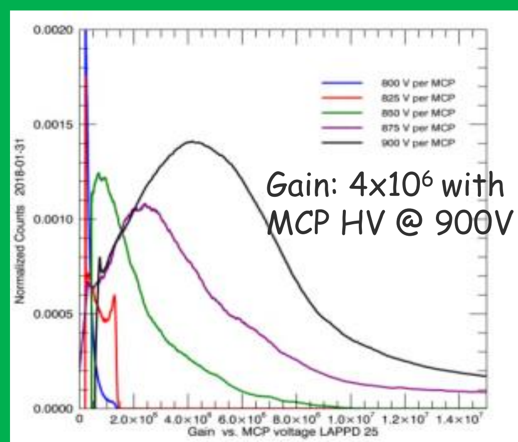
Large Area Photocathode production process is established
QE >20% demonstrated in sealed LAPPDs

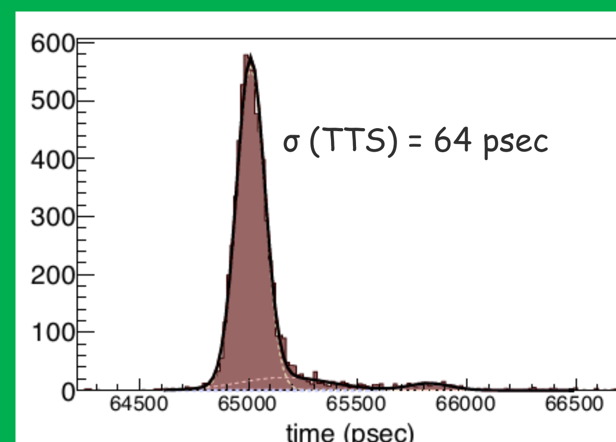
LAPPD S/N	Maximum %	Average %	Minimum %
LAPPD #13:	23.5	18.6±3.3	13.5
LAPPD #15:	25.8	22.3±3.0	15.7
LAPPD #22:	14.7	10.6	7.0
LAPPD #25:	10	7.1	5.0
LAPPD #29:	19.6	13.0±6.0	3
LAPPD #30:	22.9	17.2±2.5	13
LAPPD #31:	19.6	16.0±1.9	12.1
LAPPD #32:	22.7	20.8±1.0	19.0

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

Gain & Timing







Waveform and timing measurement credit to M. Westin at Iowa State Univ.

Applications in High Energy Physics

Current standard design is sufficient for HEP applications: water-based Cherenkov detector for Neutrino Physics, no emergency in further optimization.

Two working LAPPD^{TM}s have been **SOLD** and delivered to:

(1) The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) at Fermilab

New more orders are scheduled to be placed contingent to ANNIE Phase II funding

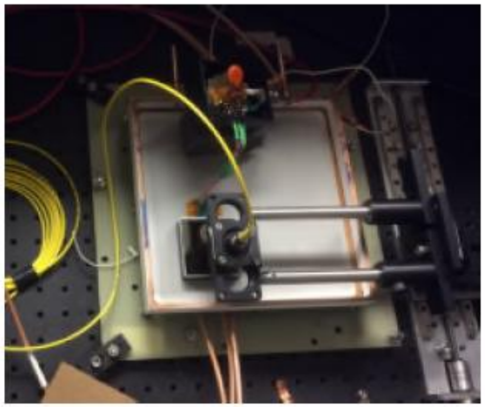
Credit to ANNIE collaboration

(2) Single-Volume Neutron Scatter Camera at Sandia National Laboratory

Gen II LAPPD^{TM} – *customizable readout*

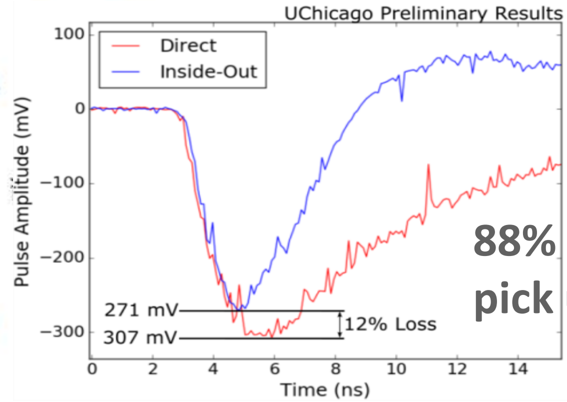
Under development (INCOM & U. Chicago)

GEN II Capacitive Coupling



A thin metal DC ground plane is deposited onto 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.

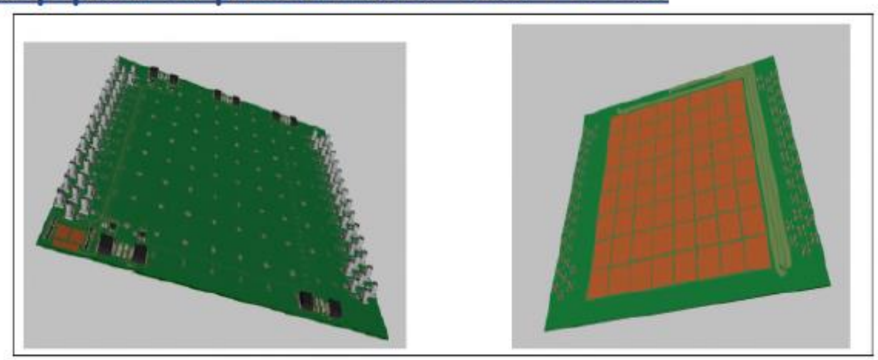


88% signal pick up

- 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

PCB with signal-pickup pads is placed under Gen-II tile

4-GHz amplifier over the back of each pad converts signals to a differentially signal that connects to the perimeter.

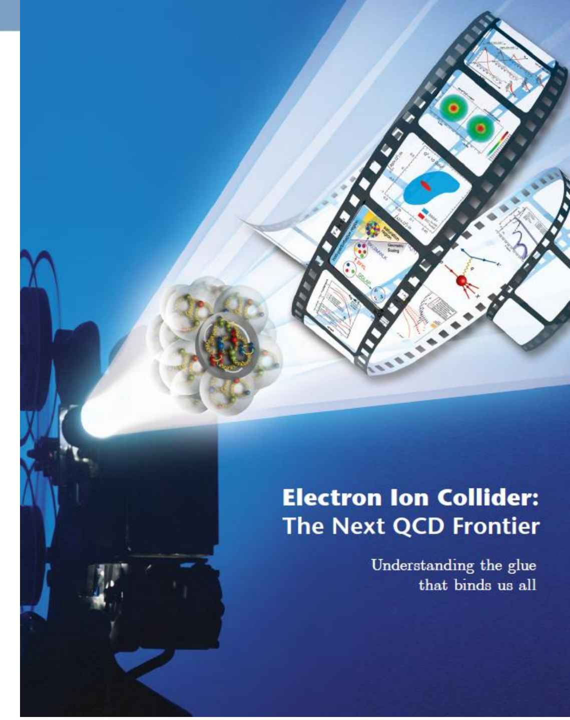


Slide from M. Minot, 14th Pisa Meeting on Advanced Detectors, La Biodola, Isola d'Elba (Italy) 2018

LAPPD^{TM} towards EIC Application

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

- ❑ EIC particle identification (PID) ($e/\pi/K/p$) calls for **low-cost, large-area Multi-channel Plate (MCP) type detector** with high time and spatial resolution, high rate capability, radiation tolerance and magnetic field tolerance.
- ❑ Within EIC PID consortium, we have coordinated a program including PID sub-system design, simulation, photosensor and electronics development towards the demonstration of EIC PID subsystems using low-cost LAPPD^{TM}s with specifications optimized for ECI applications.
- ❑ Optimization of current LAPPD^{TM} design, extensive characterization to address issues, and industrial mass production are critical to the success of EIC PID.



eRD14 - EIC PID Consortium

- An integrated program for particle identification (PID) for a future Electron-Ion Collider (EIC) detector.

M. Alfred[10], B. Azmoun[3], F. Barbosa[15], M. Boer[4], W. Brooks[20], T. Cao[24], M. Chiu[3], E. Cisbani[13,14], M. Contalbrigo[12], S. Danagoulian[17], A. Datta[23], A. Deldotto[13], M. Demarteau[2], A. Denisov[11], J.M. Durham[16], A. Durum[11], R. Dzhygadlo[9], D. Fields[23], Y. Furletova[15], C. Gleason[24], M. Grosse-Perdekamp[22], J. Harris[25], M. Hattawy[18], X. He[8], H. van Hecke[16], T. Horn[4], J. Huang[3], C. Hyde[18], Y. Ilieva[24], G. Kalicy[4], A. Kebede[17], B. Kim[5], E. Kistenev[3], M. Liu[16], R. Majka[25], J. McKisson[15], R. Mendez[20], I. Mostafanezhad[21], P. Nadel-Turonski[19], K. Peters[9], W. Roh[8], R. Pisani[3], P. Rossi[15], M. Sarsour[8], C. Schwarz[9], J. Schwiening[9], C.L. da Silva[16], N. Smirnov[25], J. Stevens[6], A. Sukhanov[3], X. Sun[8], S. Syed[8], R. Towell[1], G. Varner[21], R. Wagner[2], C. Woody[3], C.-P. Wong[8], J. Xie[2], Z.W. Zhao[7], B. Zihlmann[15], C. Zorn[15].

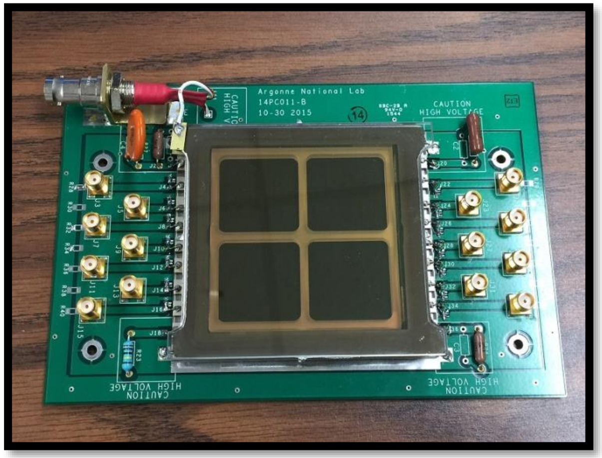
Contacts: P. Nadel-Turonski <turonski@jlab.org>, Y. Ilieva <jordanka@physics.sc.edu>

[1] Abilene Christian University, Abilene, TX 79601
[2] Argonne National Lab, Argonne, IL 60439
[3] Brookhaven National Lab, Upton, NY 11973
[4] Catholic University of America, Washington, DC 20064
[5] City College of New York, New York, NY 10031
[6] College of William & Mary, Williamsburg, VA 2318
[7] Duke University, Durham, NC 27708
[8] Georgia State University, Atlanta, GA 30303
[9] GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[10] Howard University, Washington, DC 20059
[11] Institute for High Energy Physics, Protvino, Russia
[12] INFN, Sezione di Ferrara, 44100 Ferrara, Italy
[13] INFN, Sezione di Roma, 00185 Rome, Italy
[14] Istituto Superiore di Sanità, 00161 Rome, Italy
[15] Jefferson Lab, Newport News, VA 23606
[16] Los Alamos National Lab, Los Alamos, NM 87545
[17] North Carolina A&T State University, Greensboro, NC 27411
[18] Old Dominion University, Norfolk, VA 23529
[19] Stony Brook University, Stony Brook, NY 11794
[20] Universidad Técnica Federico Santa María, Valparaíso, Chile
[21] University of Hawaii, Honolulu, HI 96822
[22] University of Illinois, Urbana-Champaign, IL 61801
[23] University of New Mexico, Albuquerque, NM 87131
[24] University of South Carolina, Columbia, SC 29208
[25] Yale University, New Haven, CT 06520

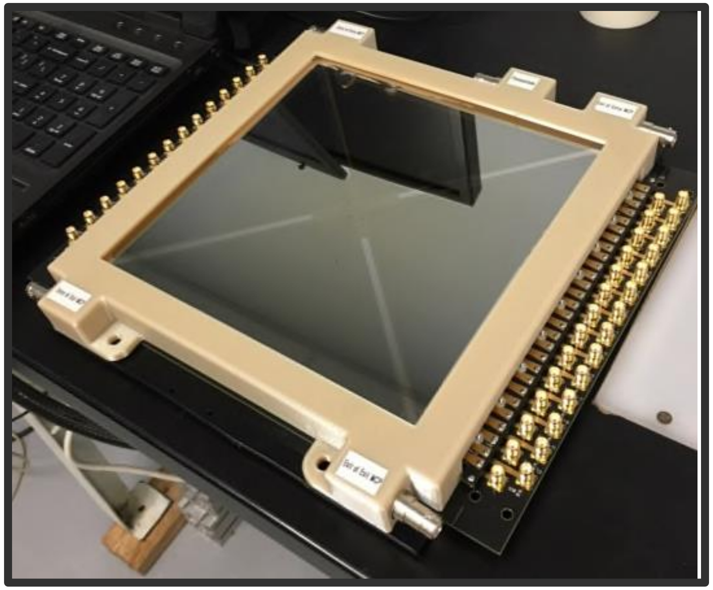
Argonne 6 cm MCP-PMT & LAPPD^{TM}

Small form factor LAPPD (6 cm MCP-PMT) was produced at Argonne for R&D.

R&D test bed: 6x6 cm^2



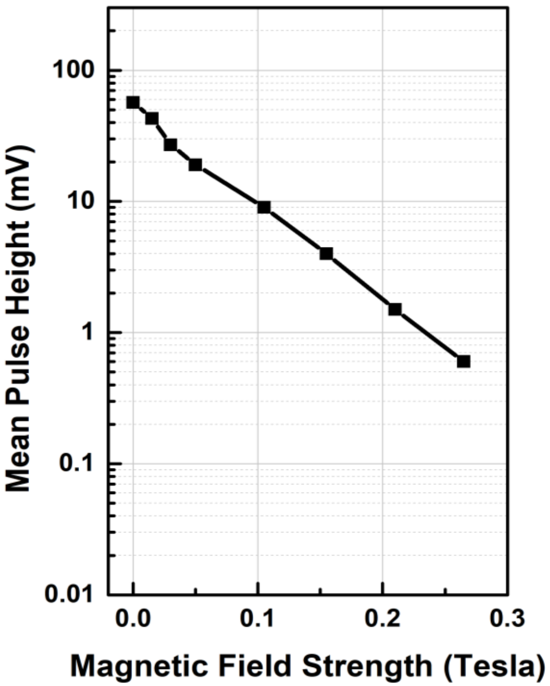
Commercialization: 20x20 cm^2



- The Argonne 6 cm MCP-PMT and INCOM 20 cm LAPPD^{TM} share the same MCPs and similar internal configuration and signal readout.
- The Argonne 6 cm MCP-PMT serves as R&D test bed for performance characterization and design optimization; INCOM 20 cm LAPPD^{TM} is the final commercialized product.
- Closed communication (bi-weekly meeting), optimized configurations are directly transferrable to INCOM production line for mass production.

Argonne 6 cm MCP-PMT in magnetic field

ANL version 1 design 20 µm

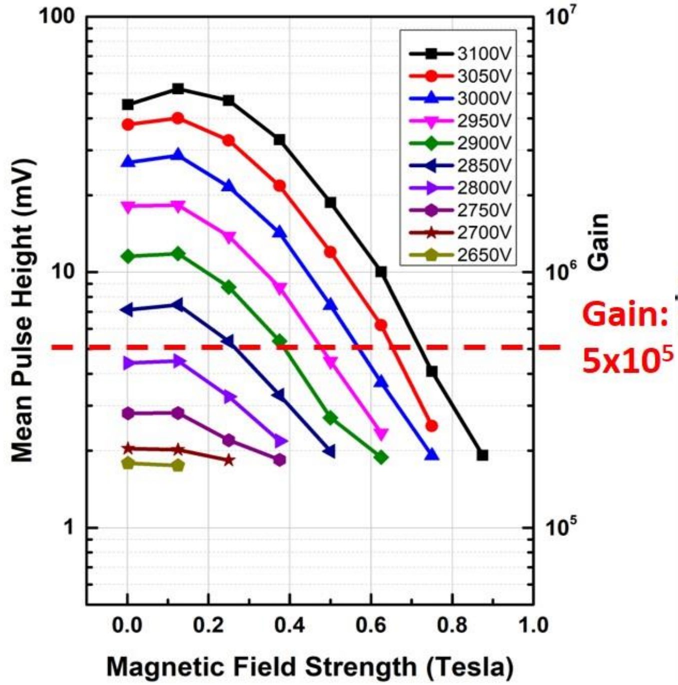


Internal resistor chain design

Gain drops quickly

0< B < 0.15 T

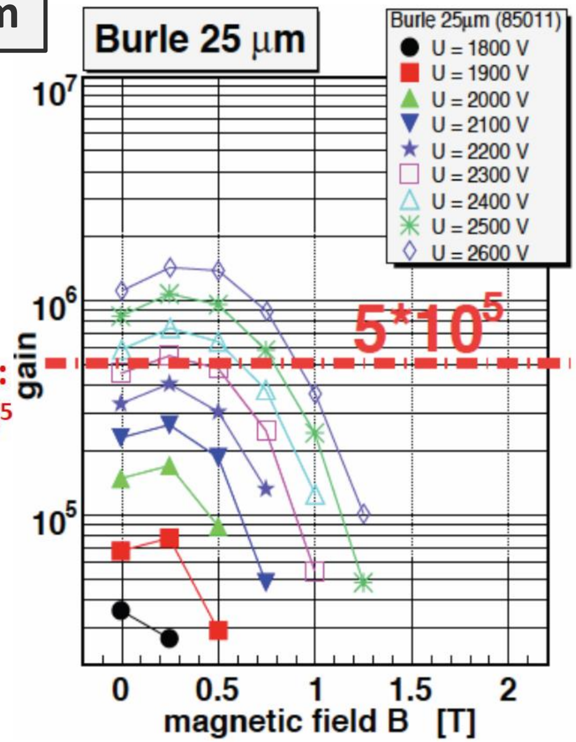
ANL version 2: IBD design 20 µm



Individual biased design

B field tolerance

0< B < 0.7 T



A. Lehmann NIMA 595 (2008) 173–176

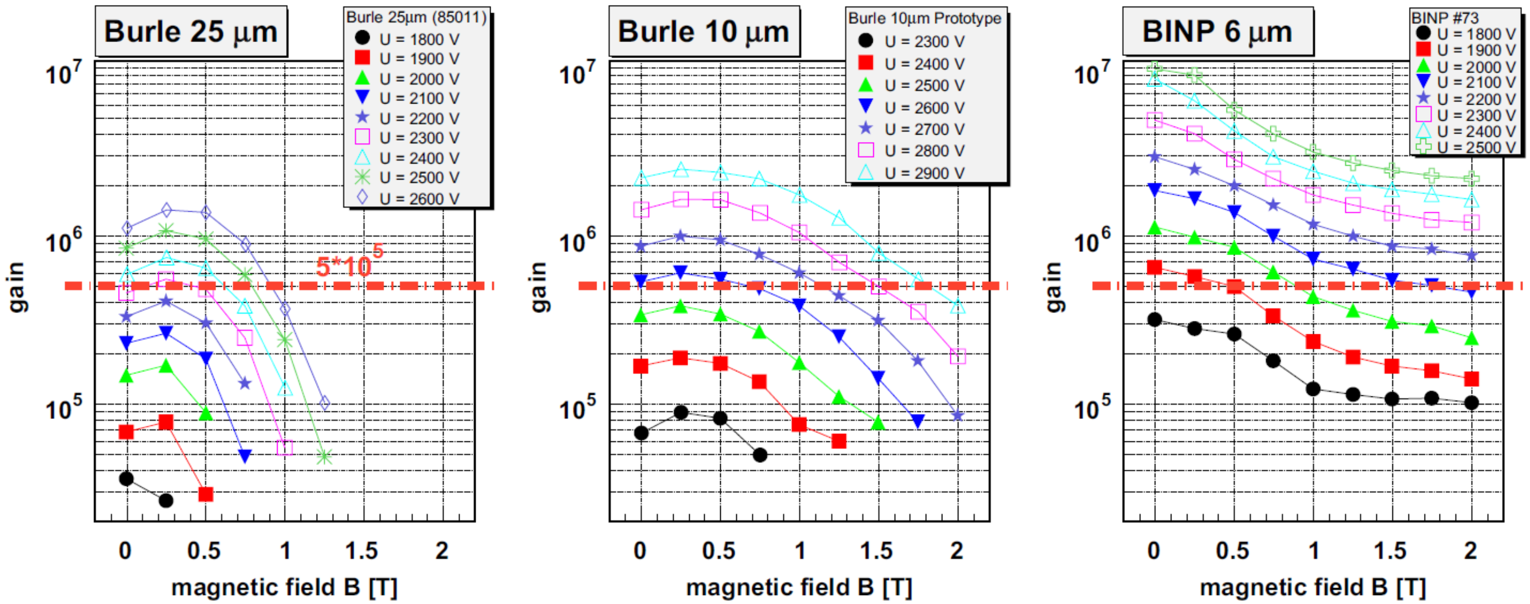
Photonis Planacon MCP-PMT

B field tolerance

0< B < 1.0 T

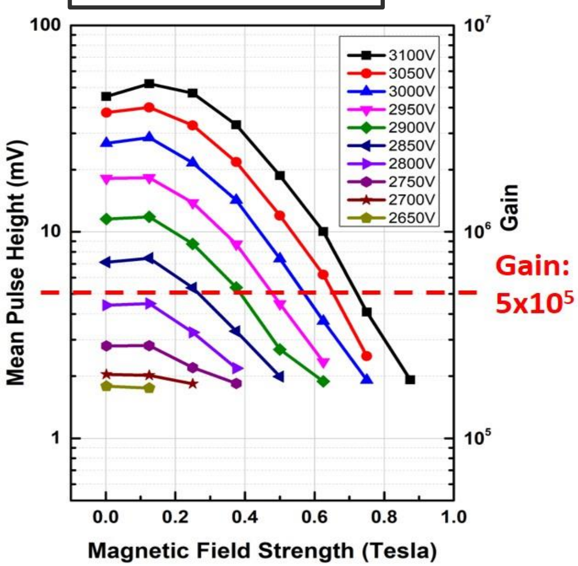
- Obvious improvement from internal resistor chain design to individual biased design, optimization of biased voltages for both MCP is important
- Comparable performance of LAPPD (Not optimize gaps yet) to Planacon in B field

Direction to enhance B field tolerance



PANDA collaboration, A. Lehmann NIMA 595 (2008) 173–176

Argonne 20 µm



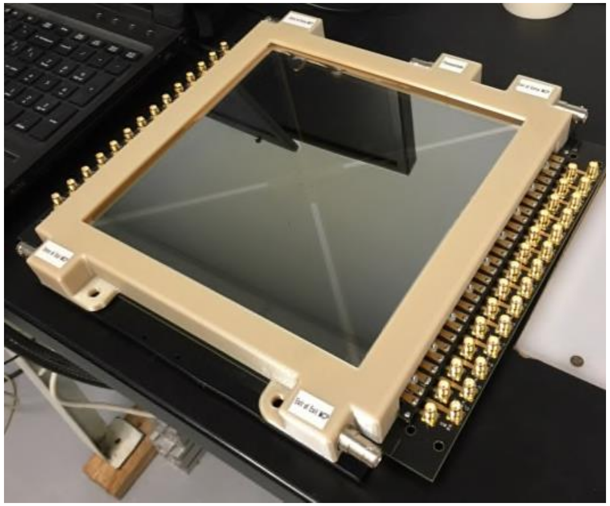
- **Smaller pore size**: 20 µm -> 10 µm -> 5 µm
- **Reduced spacing**: the minimum available spacing

With the encouraging results from Argonne small form factor LAPPD, an SBIR Phase I was awarded in April 2018 to develop magnetic field tolerant LAPPD™ (2.0 Tesla)

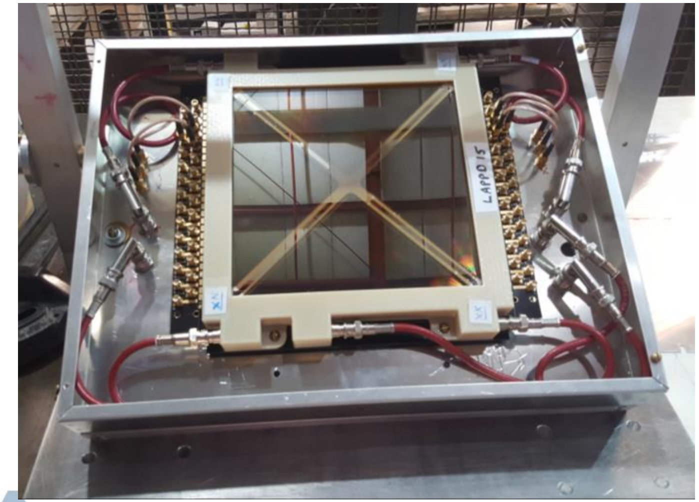
Phase I: baseline of LAPPD™, 10 µm MCP test at Argonne

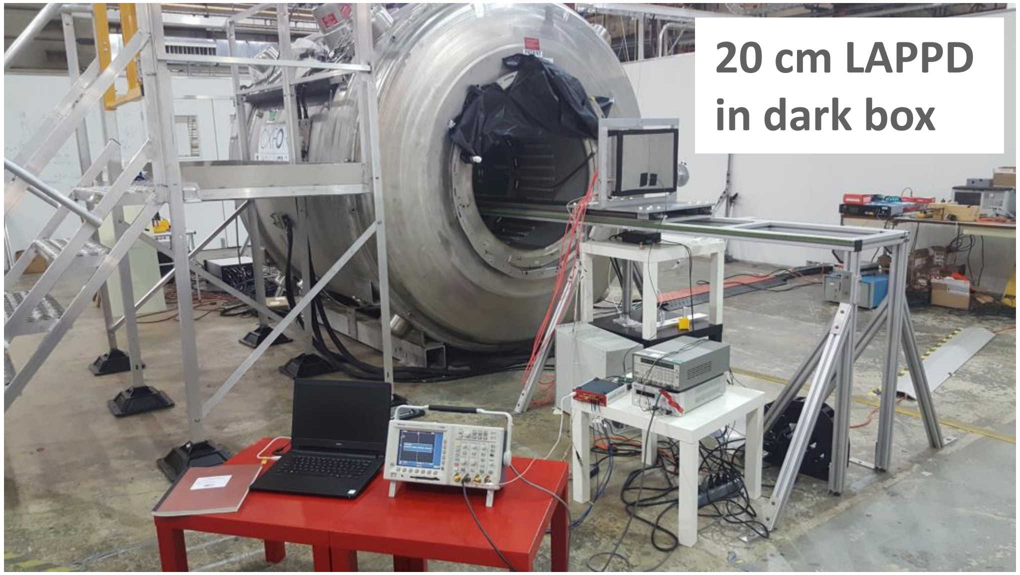
Phase II: design transfer to Incom, 5 µm MCP test at ANL

LAPPD^{TM} delivered and installed at Argonne



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

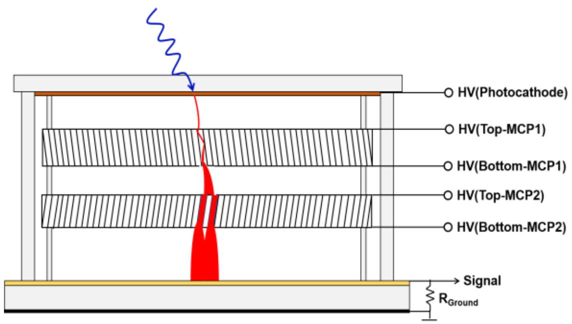


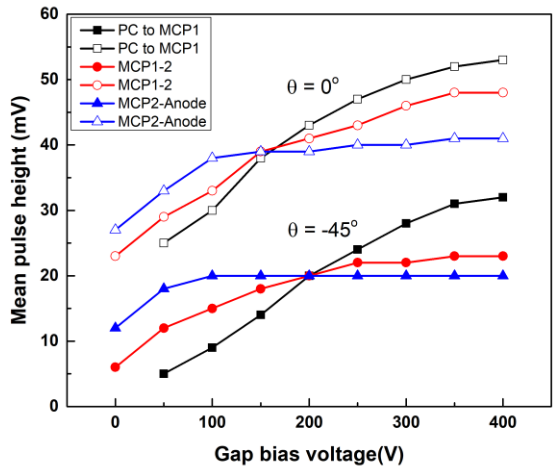


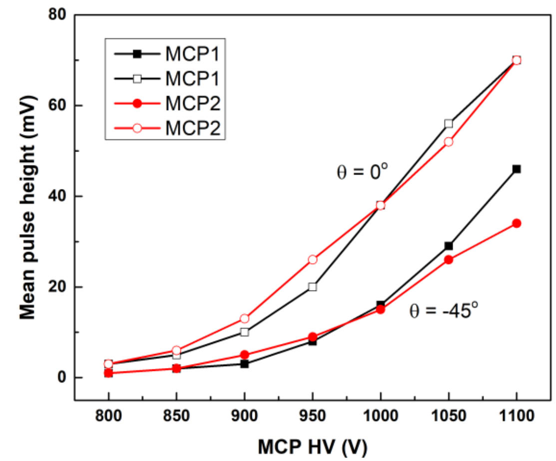
Baseline LAPPD^{TM} performance in magnetic field

Due to the magnetic sensitive components (Kovar nickel–cobalt ferrous alloy is used as shims in the current LAPPD^{TM}), we can not go to high magnet field test (fear to break it). **A new LAPPD^{TM} with non-magnet components is scheduled to be delivered and tested in Sep. 2018.** The results here demonstrate the test capability of the facility for 20 cm LAPPD^{TM}.

Gap and MCP ΔHV dependence







- HV applied to all three gaps affects the gain of the LAPPD in magnetic field.
- HV between the photocathode and MCP1 gap has the greatest slope, indicating the strongest effect.
- HV applied to MCPs seems to have NO preference, equally affects the LAPPD gain.

The B field tolerance can also be further enhanced by adjusting the HVs.

Address the requirement of 3x3 mm pixelated readout

Magnetic field tolerance is now on track, what about the pixelated readout?

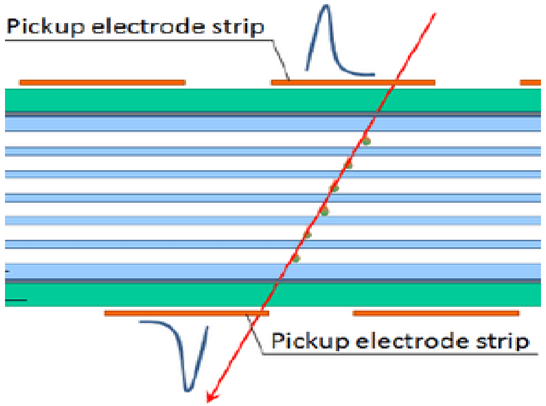
Gen II design is a very nice, ceramic is robust!

Personal opinions only:
Risk with Gen II ceramic base design: sealing is not easy.
Glass to ceramic seal process is not established at Incom, a number of technical strategies has being developed to address the challenge of Ceramic to glass sealing.
Smallest demonstrated pad size is 12.7x12.7 mm. No test on 3x3 mm yet.

R&D to address this requirement with an alternative and lower cost way:

INCOM has demonstrated great yield on recent whole glass body LAPPD production.

What about a capacitive coupled signal pickup with glass base?? Less robust, but cheaper, mRPC community experiences, and established sealing procedure!

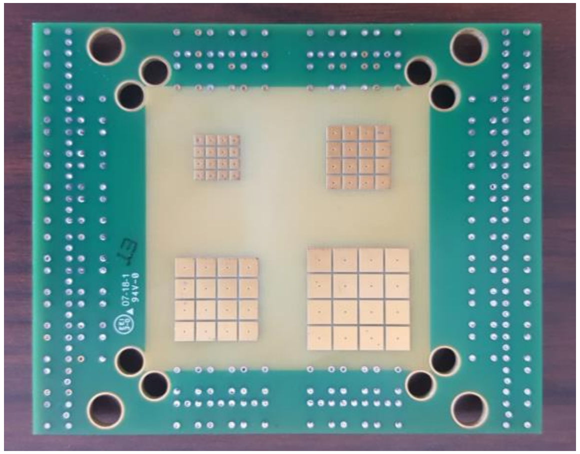


INCOM team also works towards this way now, expects very soon to fabricate Gen II LAPPD^{TM} with capacitive coupling initially using Borofloat glass, transitioning to robust fused silica and ultimately ceramic once those sealing issues are resolved.

Pixelated readout baseline

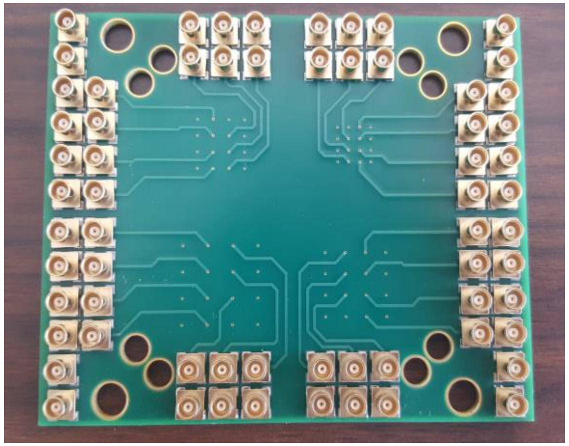
- without glass base for capacitive coupling yet

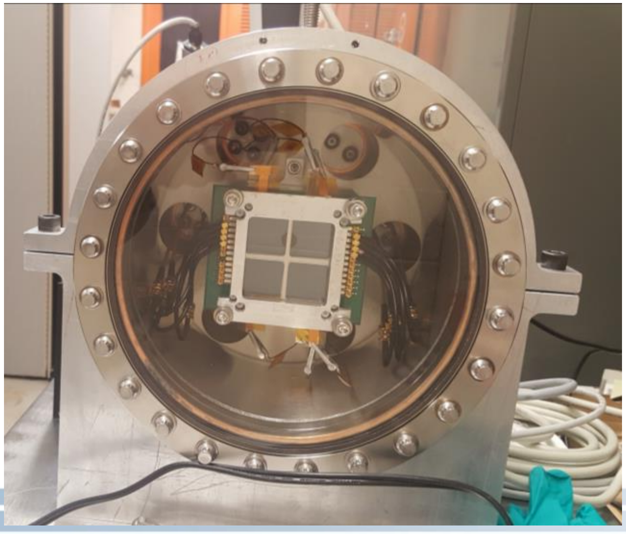
Demountable chamber installed on the stage of Fermilab Test Beam Facility MT6.2C

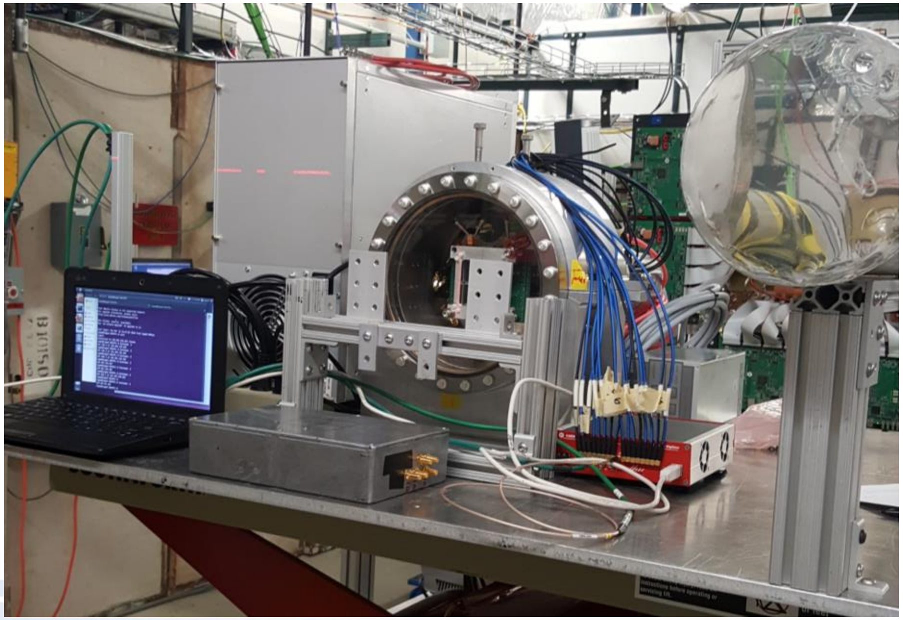


Pad sizes:
2mm x 2mm
3mm x 3mm
4mm x 4mm
5mm x 5mm

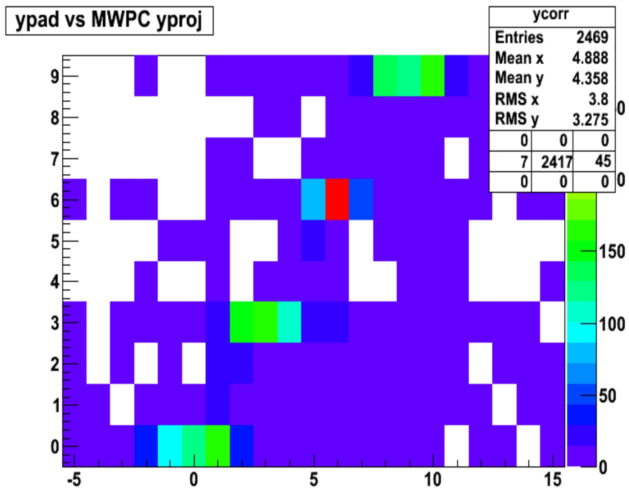
Spacing between pads:
0.5 mm

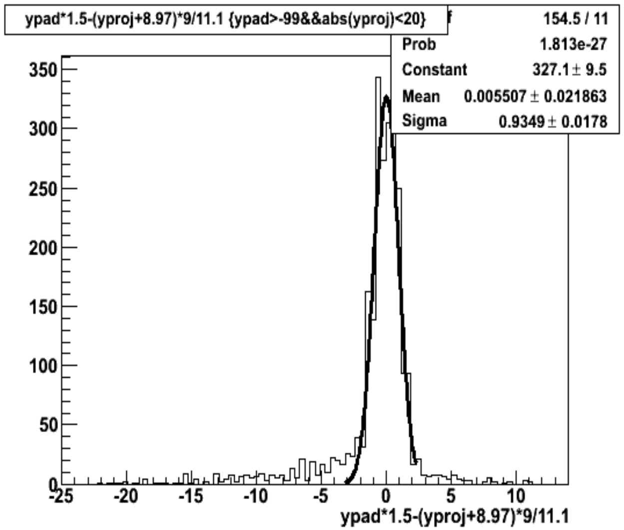






Pixelated readout baseline





Example correlation between the y-axis of a 3 mm x 3 mm pad and the MWPC projection

Pixel size	2 mm x 2 mm	3 mm x 3 mm	4 mm x 4 mm
σ (x)	-	1.01 mm	1.11 mm
σ (y)	0.73 mm	0.93 mm	1.43 mm
σ (expected) = pixel size/√12	0.6 mm	0.9 mm	1.2 mm

- Beamline experiment preliminary results show that experimental position resolutions are close to the expected position resolutions
- Further R&D with glass or fused silica coated with resistive layer to demonstrate signal pick up

Conclusion

- LAPPD collaboration successfully commercialized the LAPPD^{TM}.
- In close collaboration with INCOM, R&D on LAPPD towards EIC application is on going, focusing on design optimization for EIC PID:
  - Magnetic field tolerance
  - Pixelated readout

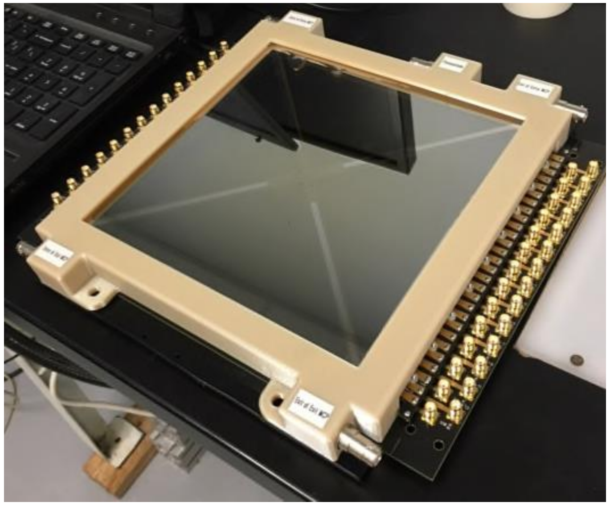
Dedicated R&D efforts are critical to identify the issues, demonstrate feasible solutions via prototype R&D to guide and ensure INCOM progressing towards the low-cost LAPPD^{TM} designated for EIC PID.

QE uniformity
Addressing by INCOM

After pulse

Rate capability

Stability (over time, temperature…)



Lifetime
Testing at Univ. Texas

Radiation hardness

…

…

We just started a challenging, but the most promising journey…

INCOM

Bright Ideas in Fiberoptics

LAPPD Measurement & Test Workshop

Schedule & Sample Agenda

Incom is hosting our second LAPPD Measurement & Test Workshop which will be held as follows:

1. **Three Day Workshop** - The Workshop will take place four times per year, typically Tuesday, Wednesday and Thursday. Testing will mostly focus on evaluating the performance of recently fabricated LAPPD tiles.
2. **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

A great team to work with, great opportunity for EIC members to get hands on with LAPPD^{TM}:

- 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.

MCP and LAPPD documents http://www.incomusa.com/mcp-and-lappd-documents/

Acknowledgments

W. Armstrong, J. Arrington, D. Blyth, K. Byrum, M. Demarteau, G. Drake, J. Elam, J. Gregar, K. Hafidi, M. Hattawy, S. Johnston, A. Mane, E. May, S. Magill, Z. Meziani, J. Repond, R. Wagner, D. Walters, L. Xia, H. Zhao
Argonne National Laboratory, Argonne, IL, 60439

K. Attenkofer, M. Chiu, Z. Ding, M. Gaowei, J. Sinsheimer, J. Smedley, J. Walsh
Brookhaven National Laboratory, Upton, NY, 11973

A. Camsonne, P. Nadel-Turonski, Y. Qiang, W. Xi, Z. Zhao, C. Zorn
Jefferson Lab, Newport News, VA, 23606

J. McPhate, O. Siegmund
University of California, Berkeley, CA, 94720

A. Elagin, H. Frisch
University of Chicago, Chicago, IL, 60637

Y. Ilieva
University of South Carolina, Columbia, SC, 29208

And many others …

The LAPPD collaboration, The EIC PID consortium, The Argonne EIC-LDRD program

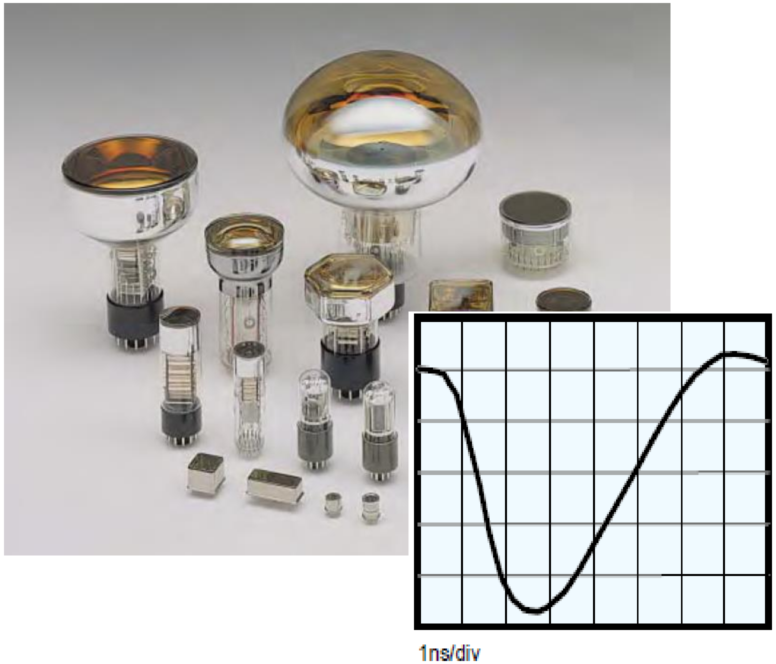
This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, Office of Nuclear Physics under contract number DE-AC02-06CH11357 and DE-SC0018445.

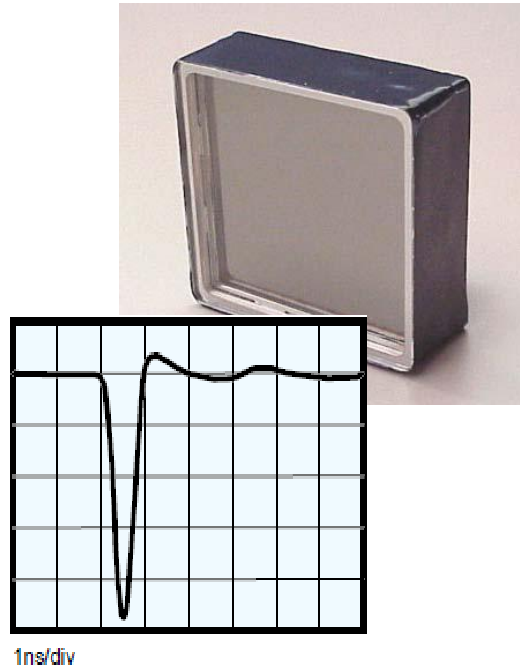
Thank you for your attention!

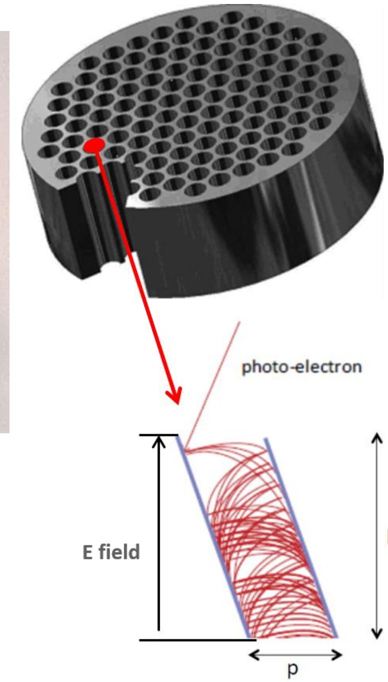
Questions?

Back up

Background: Standard PMT vs. MCP-PMT







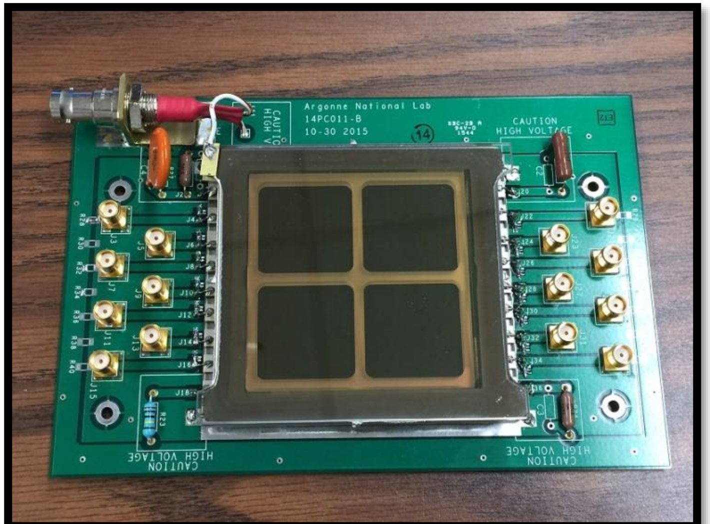
Standard photomultipliers

- ✓ Successful technology over decades
- ✓ Large area available at low cost
- ✓ Rather fast: ns timing
- ➢ But……
  - Bulky
  - Limited position resolution
  - Low magnetic field tolerance

MCP-based photomultipliers

- ✓ Compact design
- ✓ **Picosecond-level** time resolution
- ✓ **Micron-level** spatial resolution
- ✓ Good magnetic field tolerance
- ➢ But……
  - Few venders, high cost
  - Limited sizes

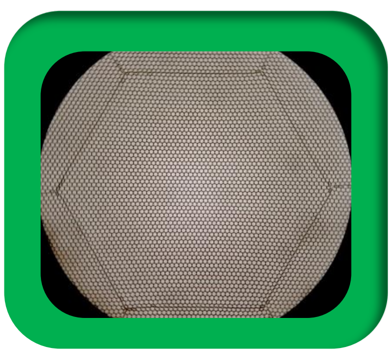
Argonne MCP-PMT program within LAPPD project



6 cm × 6 cm

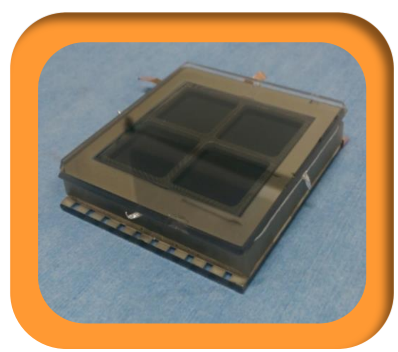
- Produce the first functional devices and provide them to the community for evaluation and incorporation into experiments
- Support the industry for commercialization of large-area devices
- Provide a flexible platform for further R&D efforts (VUV-UV-Vis response, B-field application, cryogenic application…)

ALD-MCP

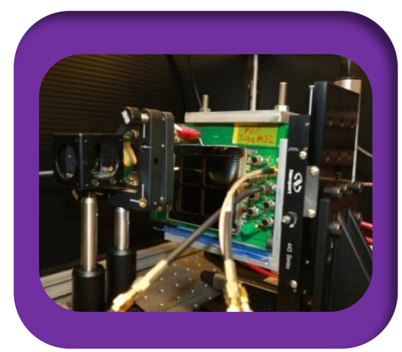


Photocathode

Packaging

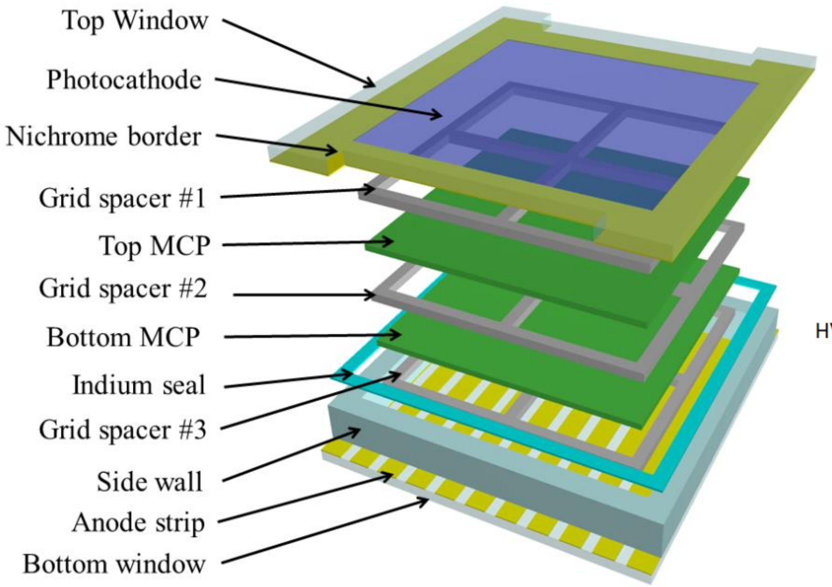


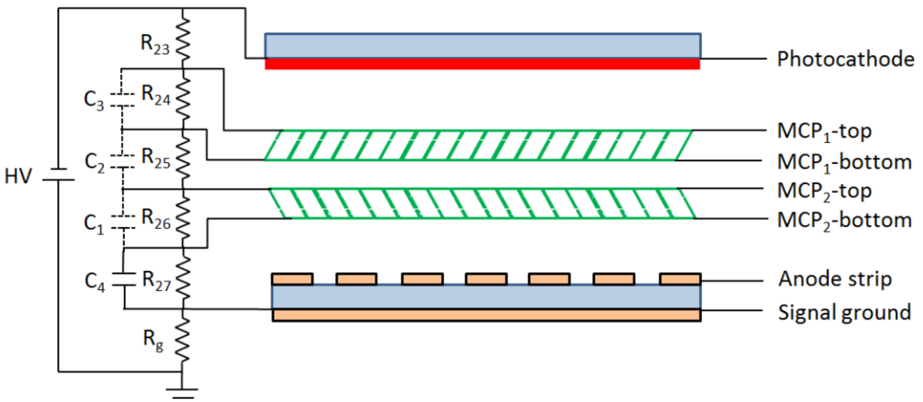
Testing



Argonne 6 cm × 6 cm MCP-PMT

- A glass bottom plate with stripline anode readout
- A glass side wall that is glass-frit bonded to the bottom plate
- A pair of MCPs (20µm pore) separated by a grid spacer.
- Three glass grid spacers.
- A glass top window with a bialkali (K, Cs) photocathode.
- An indium seal between the top window and the sidewall.

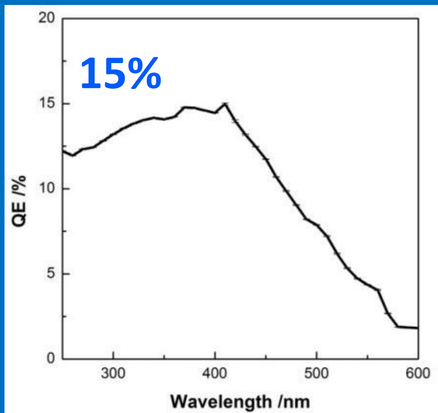


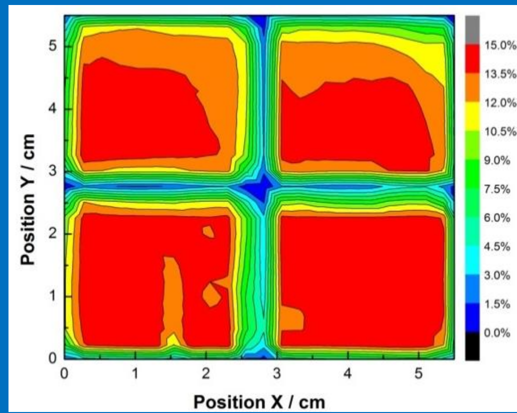


A very flexible platform for R&D efforts!

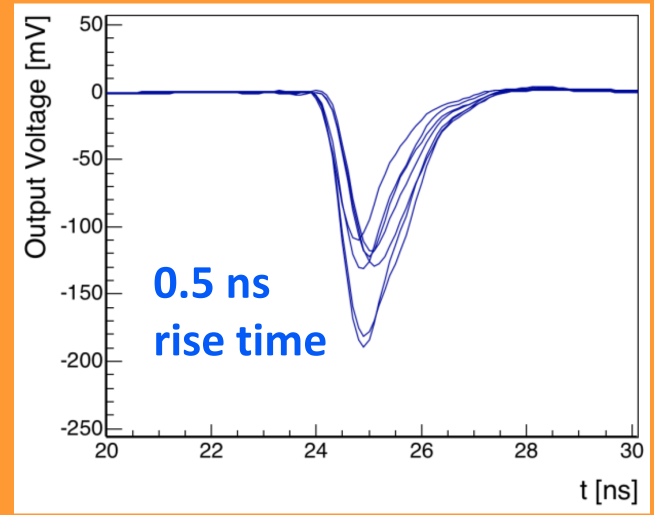
Argonne 6 cm × 6 cm MCP-PMT Key performances

Spectra response





Signal component

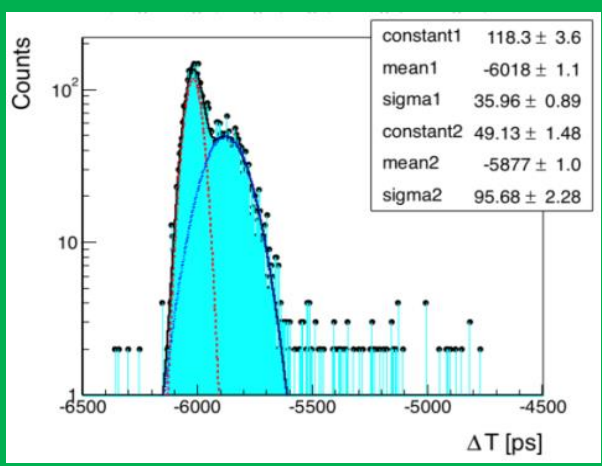


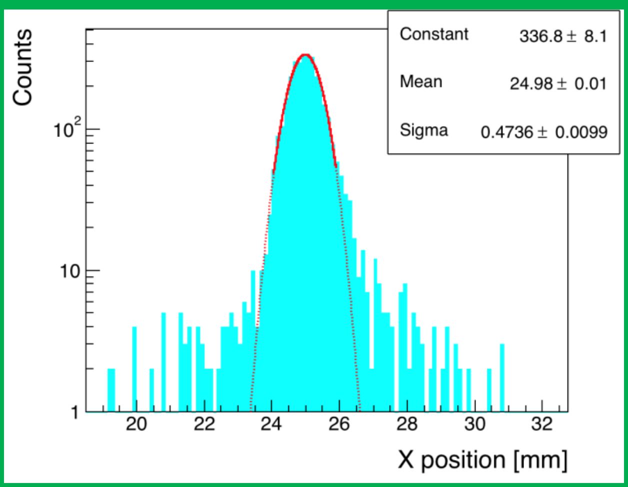
$$\sigma_{I.R.F.}{}^2 \sim \sigma_{.T_{MCP}}{}^2 + \sigma_{.T_{laser}}{}^2$$

σ_{IRF} ~ 35 ps for SPE

σ_{TTS} ~ 20 ps

Timing / position distributions



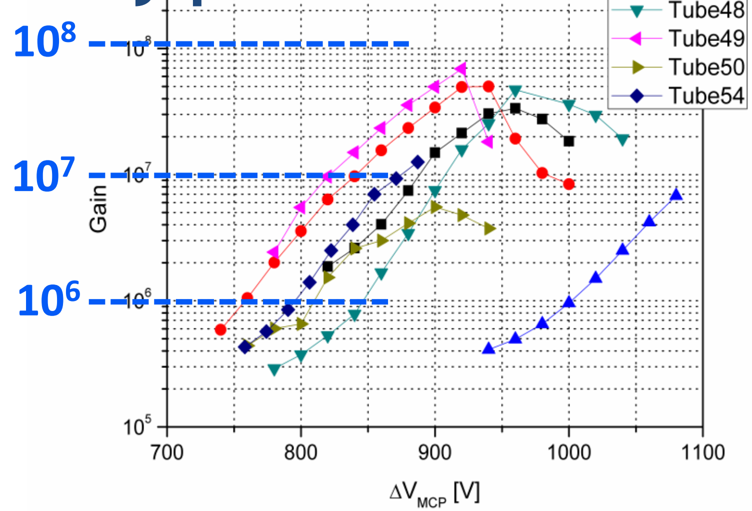


σ < 1 mm for SPE

Argonne 6 cm × 6 cm MCP-PMT Key performances

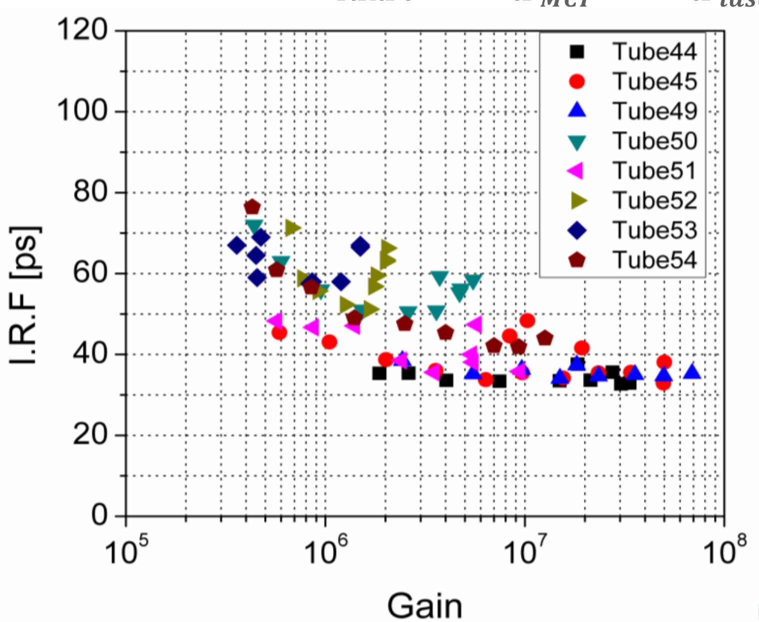
- Gain as high as **$7X10^7$**
- Time resolution **$\sigma_{overall}$ ~35 ps, TTS <20 ps**
- Laser start time jitter: **σ_{laser} ~30ps**
- Rate capability: **> 75KHz/cm^2**

Gain

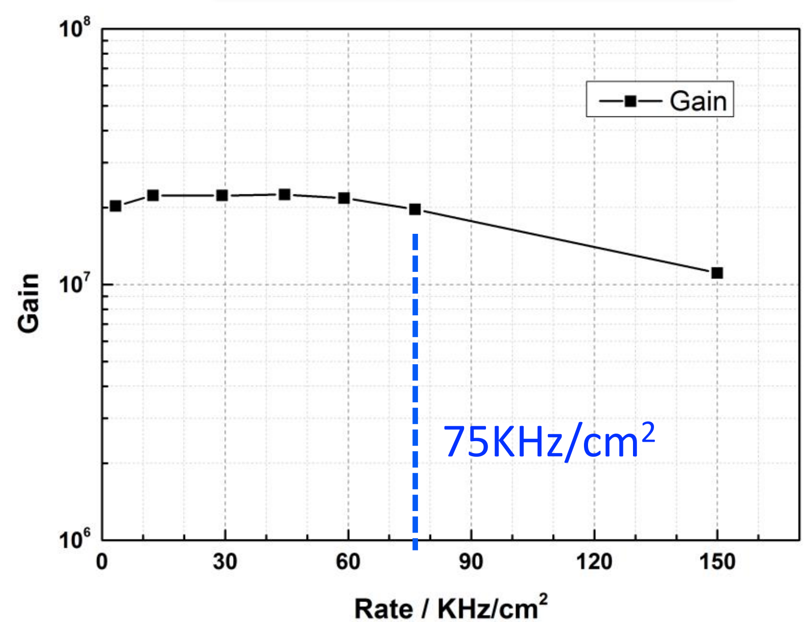


Overall time resolution

$$\sigma_{I.R.F.}{}^2 \sim \sigma_{.T_{MCP}}{}^2 + \sigma_{.T_{laser}}{}^2$$



Rate capability

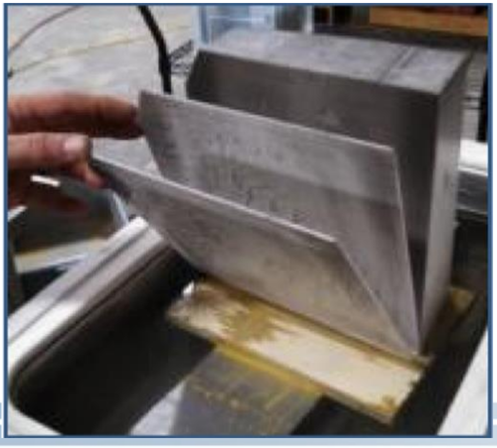


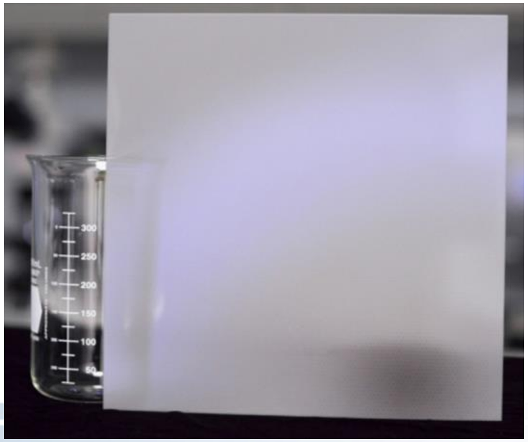
Next generation micro-channel plates – 1.GCAs

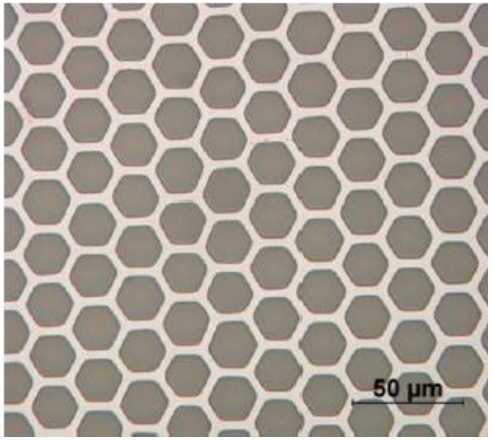
- **Conventional Pb-silicate glass MCP:** Based on optic fiber production, chemical etching and thermal processing
  - × Expensive lead-silicate glass
  - × Complex, labor consuming technology
  - × Large deviation of channel diameters within MCP
  - × Difficult to produce large area MCP, brittle after firing

- **"Next generation" MCPs - Break through 1: Production of large blocks of hollow, micron-sized glass capillary arrays (GCAs)** based on the use of hollow capillaries in the glass drawing process
  - ✓ Use considerably less expensive borosilicate glass (Pyrexs or similar)
  - ✓ Eliminate the need to later remove core material by chemical etching
  - ✓ Low alkali content for reduced background noise
  - ✓ World's largest MCP: 20 cm x 20 cm

*M. Minot et al., Nucl. Instr. Meth. A **787** (2015) 78-84*



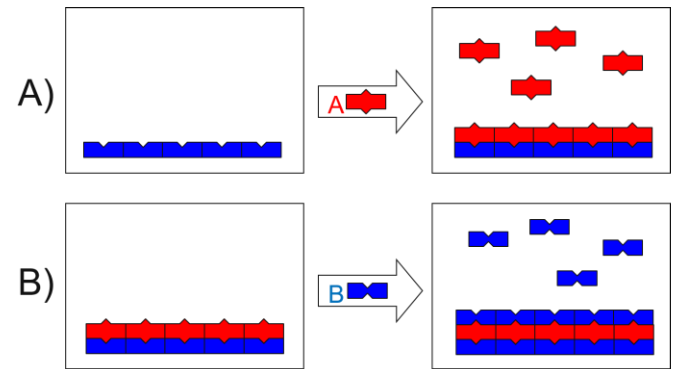




Next generation micro-channel plates - 2.ALD

- **"Next generation" MCPs - Break through 2:**
  Functionalization of the glass capillary arrays with atomic layer deposition (ALD) methods
  - ✓ Self-limiting thin film deposition technique
  - ✓ Controlled film thickness
  - ✓ Freedom to tune the capabilities:
  - ✓ Robust, good performance

Self-terminating surface reactions

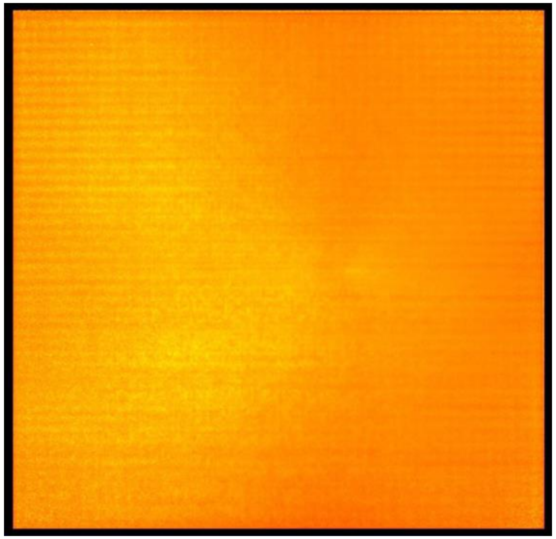


MCP after functionalization

MCP parameters

- Pore size: 20 µm
- Thickness: 1.2 mm
- L:D ratio: 60:1
- Open area ratio: 65%
- Average gain: 7×10^6
- Gain variation: <10%

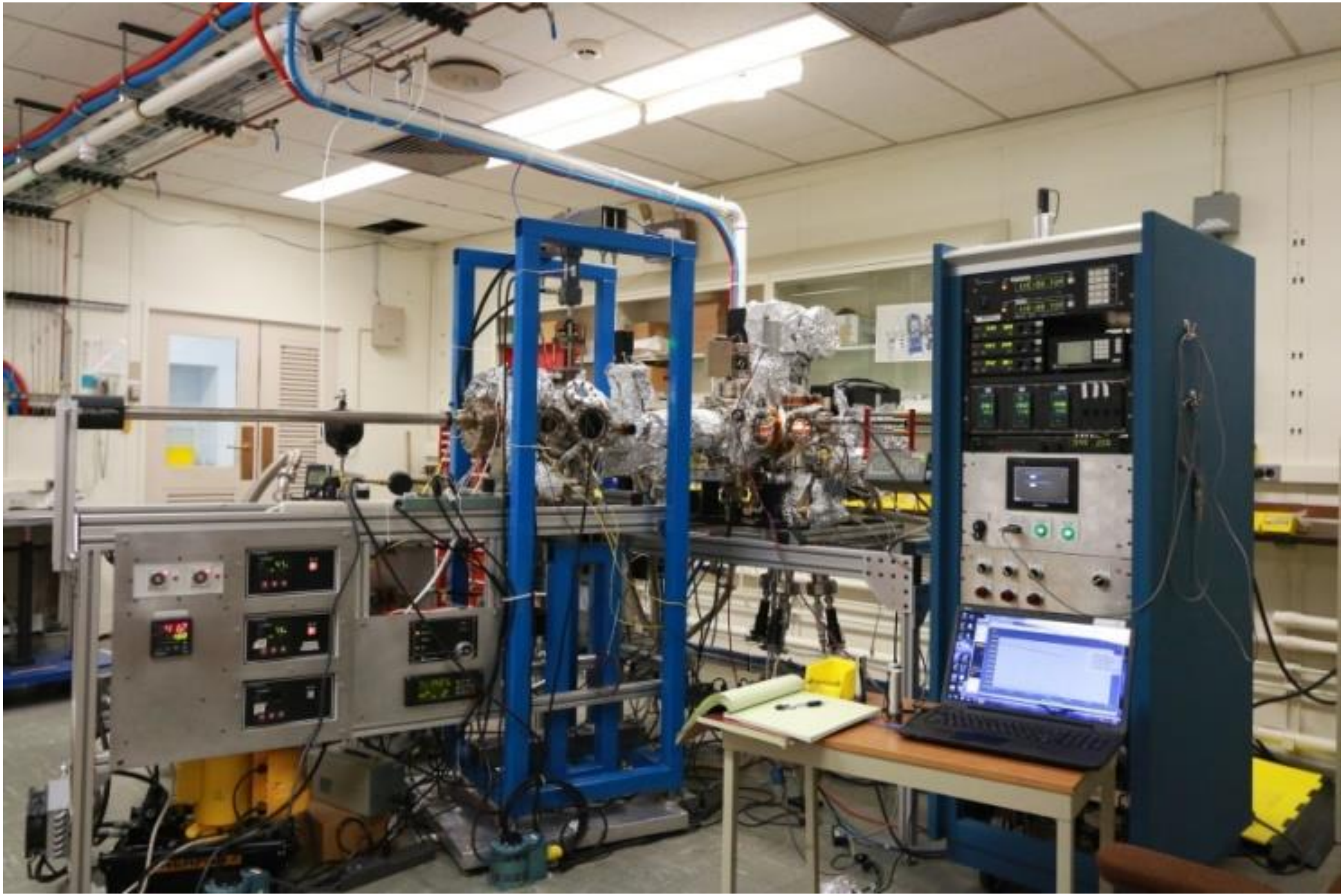
Average gain image "map"



*M. Minot et al., Nucl. Instr. Meth. A **787** (2015) 78-84*

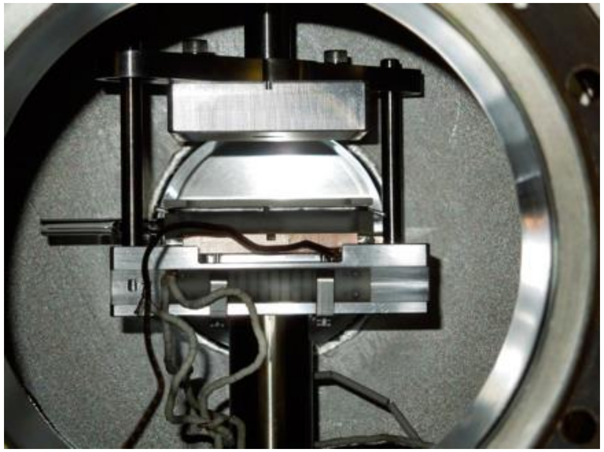
The Argonne ALD technique has been licensed to Incom, Inc. for commercialization.

Photodetector fabrication lab

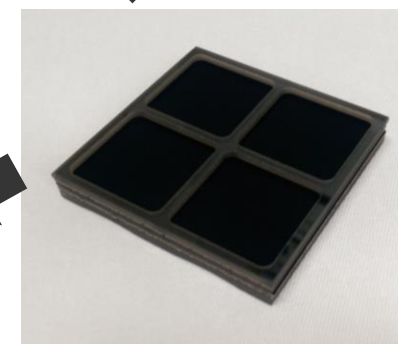


Hermetic packaging

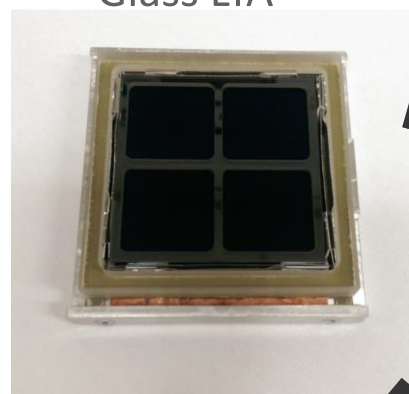
hydraulic driven platens



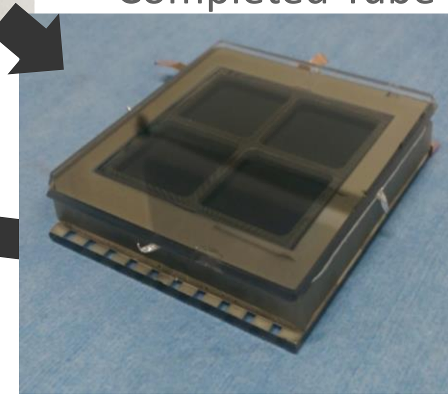
MCP & Resistive Grid Spacer Stack



Glass LTA



Completed Tube

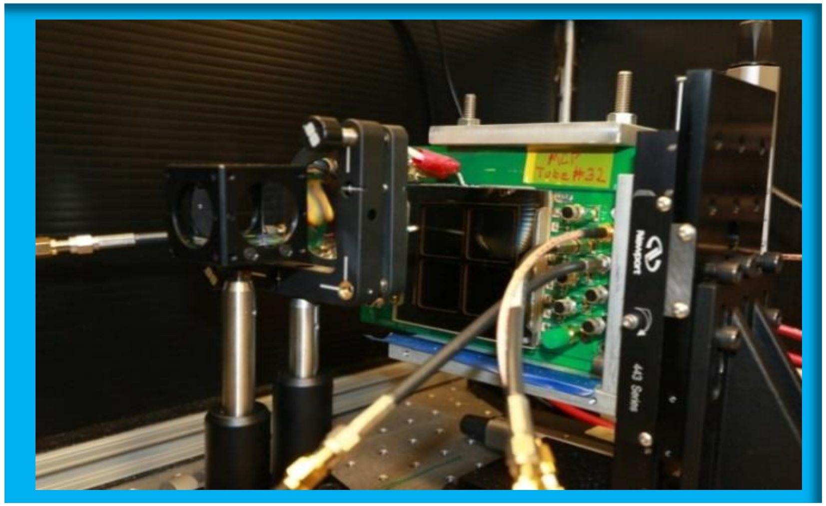


- **Tube processing is very challenging**
  - Baking, scrubbing, getter activation, compression sealing

Test facilities

Optical table for QE measurement

Blue laser facility: 70 ps pulse duration



Fermilab Test Beam Facility

ANL G-2 Magnetic Field Test Facility