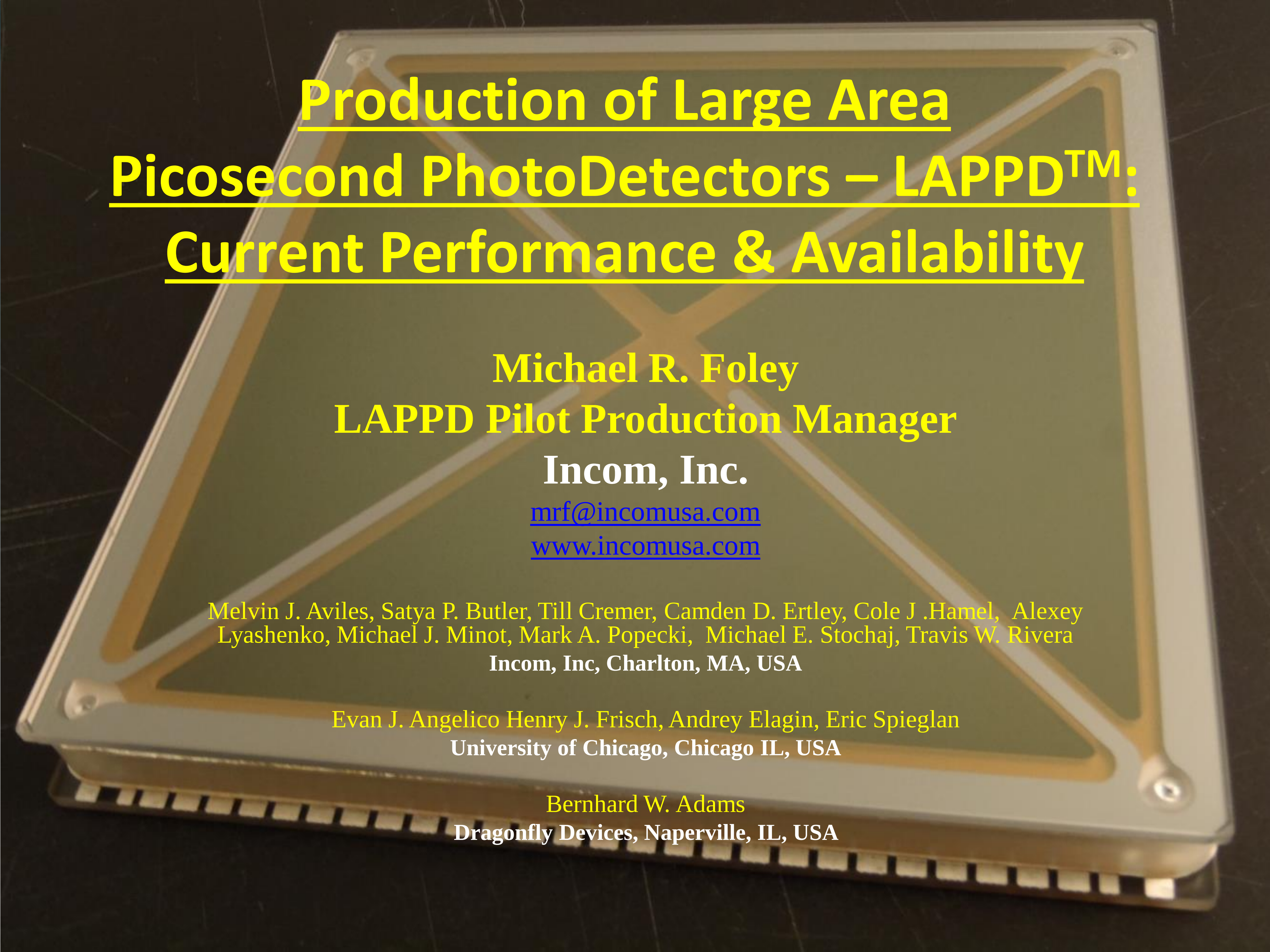

Production of Large Area Picosecond PhotoDetectors – LAPPD™: Current Performance & Availability

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Bernhard W. Adams
Dragonfly Devices, Naperville, IL, USA

Outline

- **LAPPD**
  - what is the detector?
  - where can LAPPD be used?
  - how does the device work?
- **Latest Performance Data**
  - Photocathode QE, Gain, Dark rates
  - Timing and Position Resolution
- **Recent Device Developments**
  - Capacitively Coupled LAPPD
  - 10 cm HRPPD
- **Availability, Current Applications/Collaborations**
- **Summary**

Large Area Picosecond Photodetector (LAPPD™)

- **MCP photomultiplier**
  - Good timing resolution
  - Position sensitivity
  - High gain
- **200 x 200 mm (8 x 8") : active area ~350 cm², 92% open area**
- **High gain: mid-10^6 or higher for single photoelectrons**
- **Blue-sensitive photocathode: Potassium-Sodium-Antimony (K_2NaSb)**
  - QE is 20-30% at 365 nm
- **Position resolution: 3x3 mm or better**
- **Time resolution: ~55 pS or better**

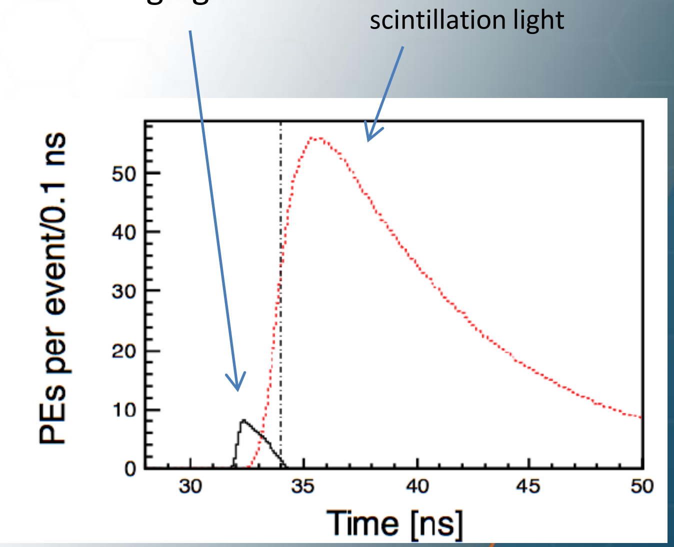
➔ **Time and position measurement for:**
- o Photons, with single or multiple photoelectrons
- o Penetrating energetic particles

Large Area Picosecond Photo Detectors -LAPPDs

Applications: HEP, NP and others

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

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



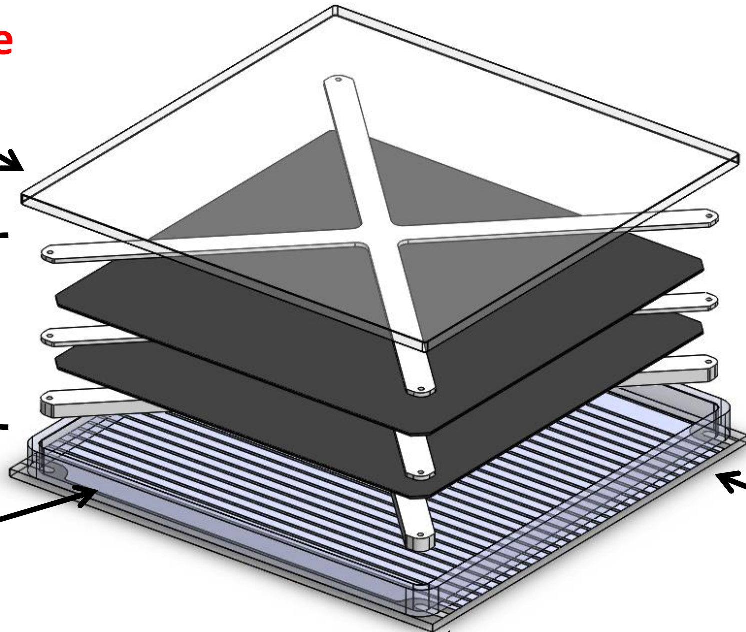
References from:
ANNIE (M. Wetstein),
WATCHMAN (M. Malek),
NuDot (J. Gruszko, L. Winslow)

JINST 9 (2014) P06012

INCOM BRIGHT IDEAS

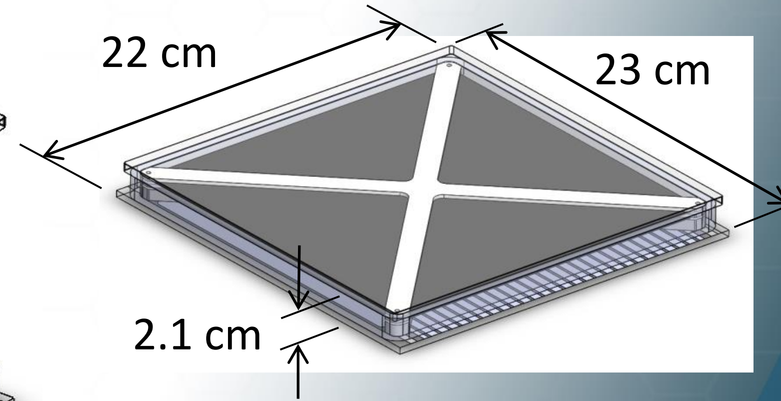
LAPPD Design

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

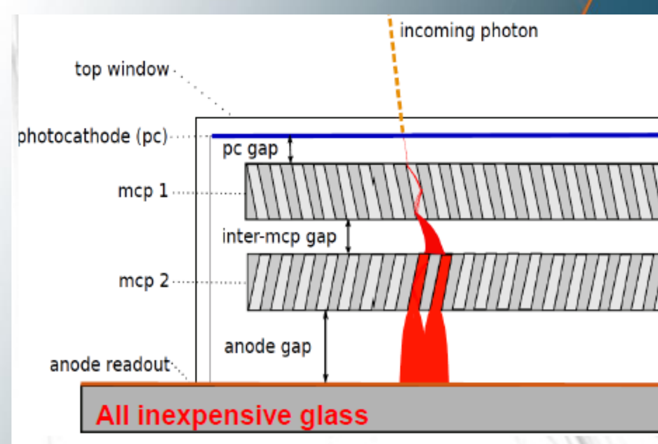


Illustration provided by Univ. of Chicago

INCOM BRIGHT IDEAS

Atomic Layer Deposition Coating: Convert Glass Capillary Arrays into MCPs (GCA-ALD-MCPs)

- 203 mm **robust glass substrates** are made with ~20 micron diameter microchannels.

Only available technique for this size MCP

- Many choices for the glass substrate, including non-leaded or low potassium glass.
- **Resistive film** is applied with ALD
  - Resistance can be tuned to desired value .
- Al_2O_3 or MgO **S**econdary **E**lectron **E**missive film is applied over the resistive film for **high gain**. (Mane, et al., 2012)

ALD+ glass substrate MCP: cross section

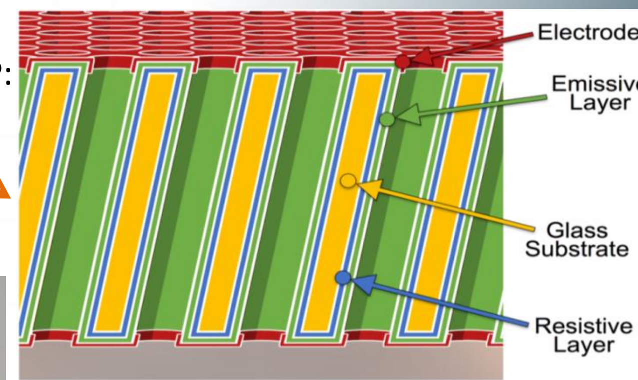


Illustration from Ertley, 2016

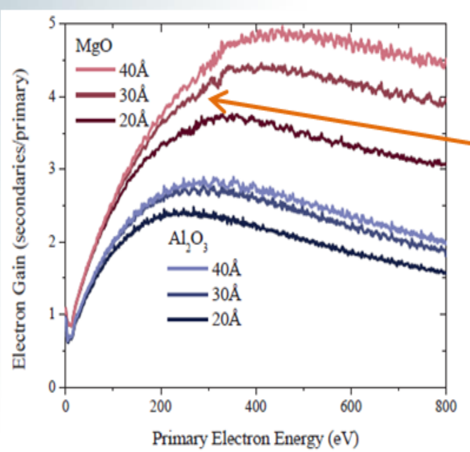
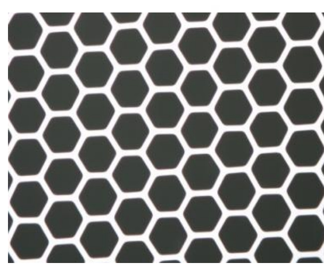


Figure 2. Secondary electron yield from select thicknesses of ALD MgO and Al_2O_3. See Figure 3 for the entire data set.

MgO secondary electrons



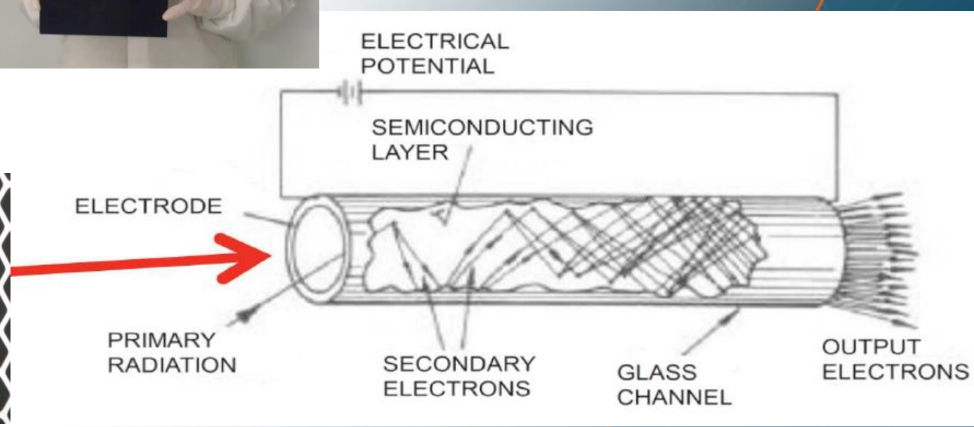
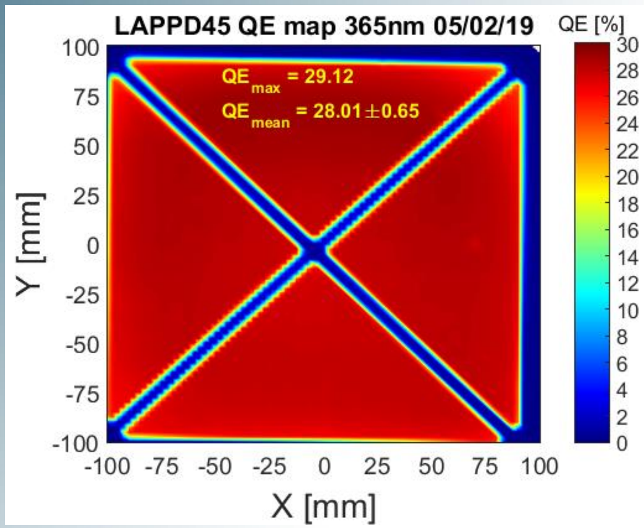


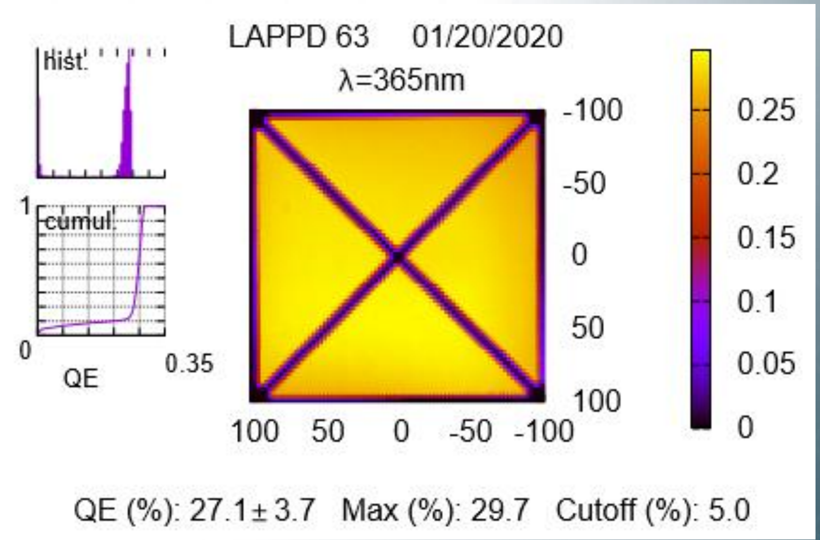
Illustration from Wiza, 1979

INCOM BRIGHT IDEAS

Photocathode Quantum Efficiency & Uniformity

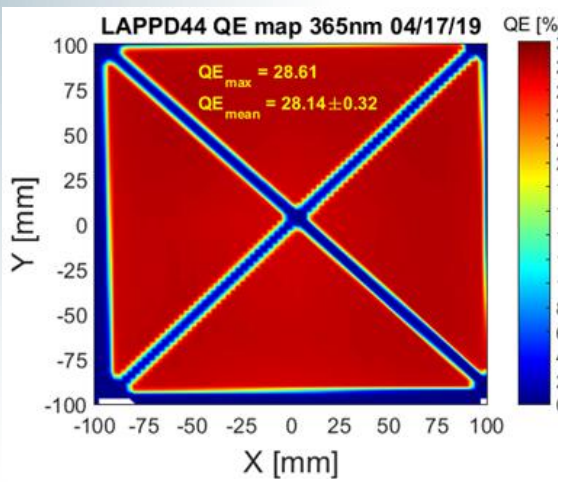
Typical QE and Uniformity

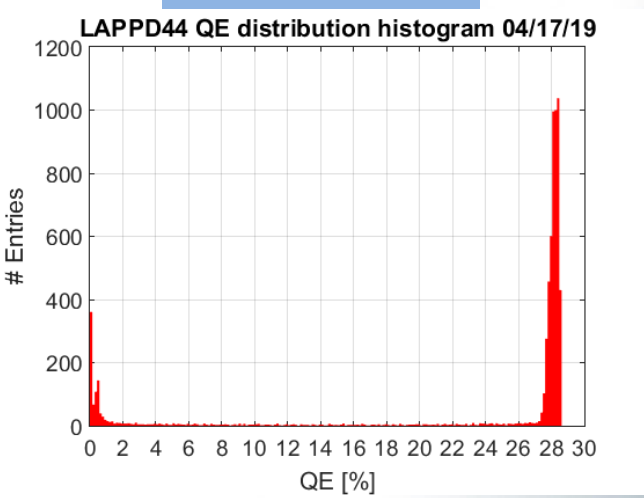


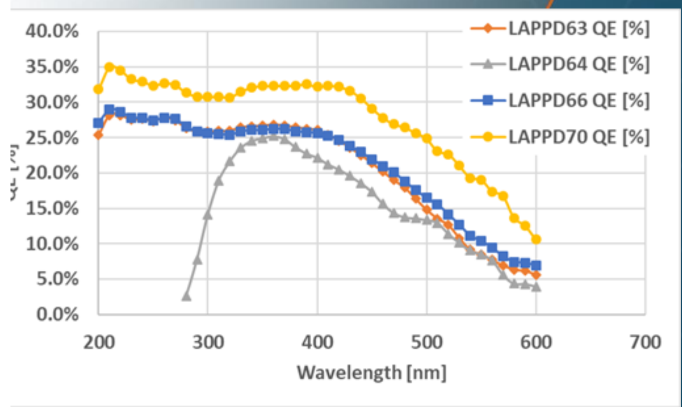


QE Uniformity

QE spectra



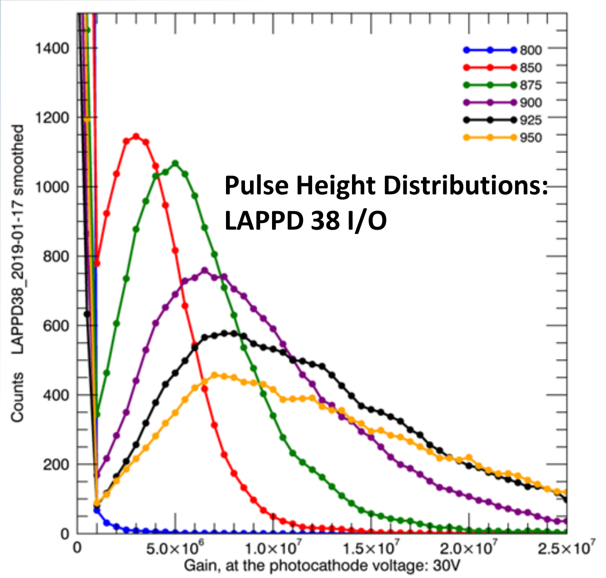


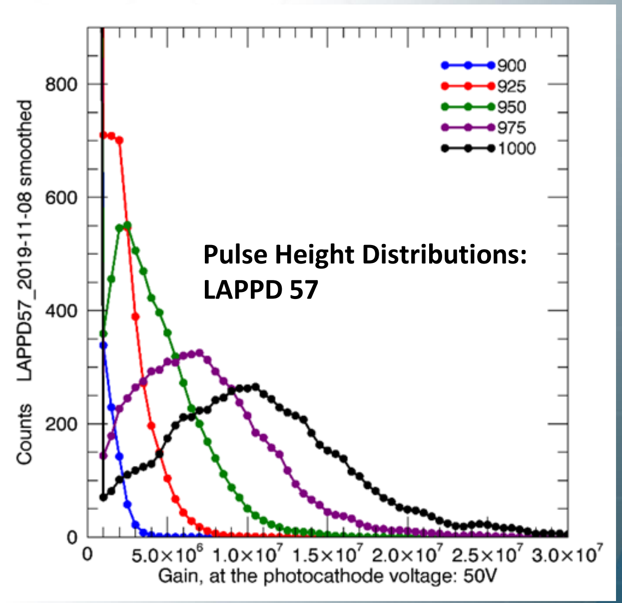


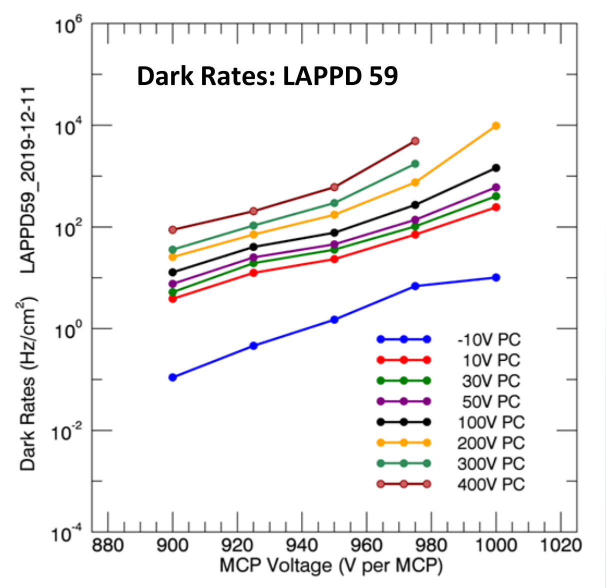
35% demonstrated

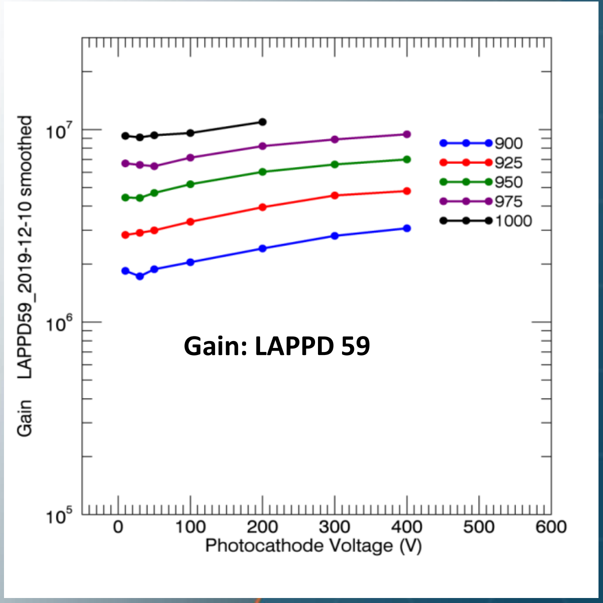
Gain & Dark count performance

- Gain of mid-10^6 is readily achievable with single photoelectrons.
- Pulse height distributions well-separated from threshold
- Dark rates are $10^3/cm^2$ in the mid-10^6 gain range.







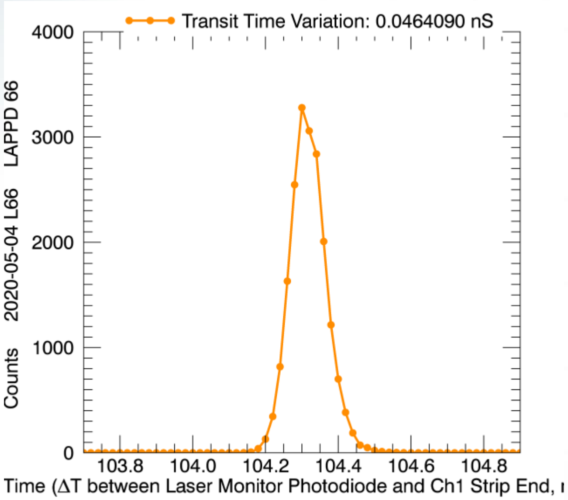


Timing

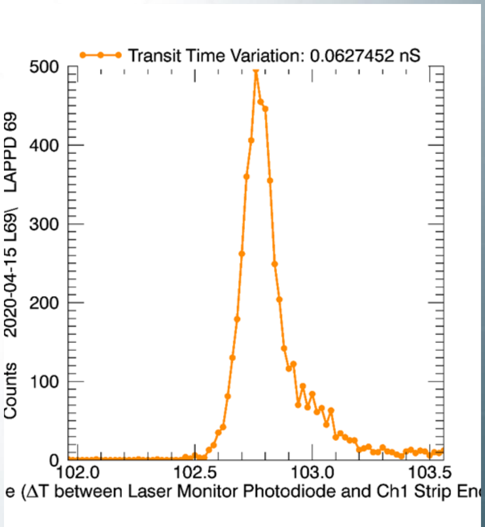
Single photoelectron timing, 20 μm channels:
- ~50-80 pS
- Capacitively-coupled models are similar to internal stripline models.

TTS with multiple photoelectrons:
- 46 pS
- Capacitively-coupled

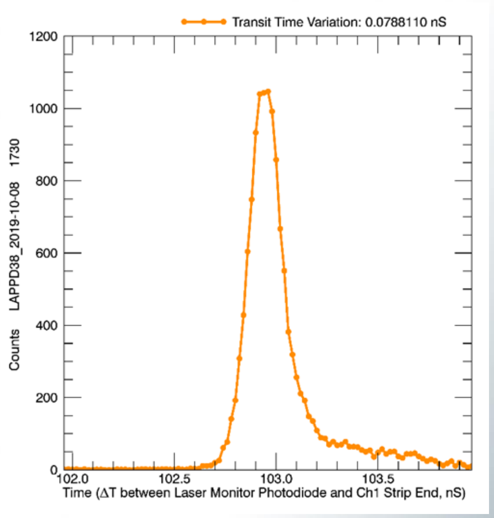
TTS is affected by:
- Signal to noise ratio (gain)
- Photocathode voltage (production of secondary electrons in the channel)
- MCP bias angle
- Channel diameter



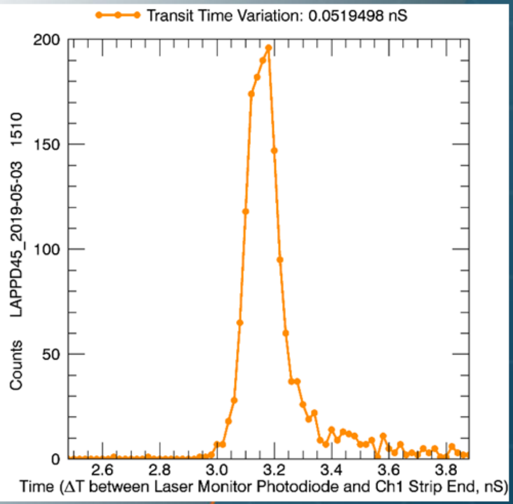
LAPPD 66, 46 pS multiple P/E Capacitively-coupled



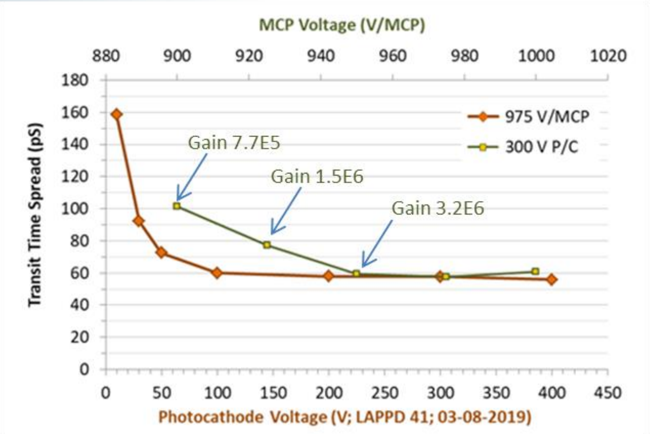
LAPPD 69, 62 pS single P/E Internal stripline



LAPPD 38, 78 pS single P/E Capacitively-coupled



LAPPD 45, 51 pS single P/E Internal stripline

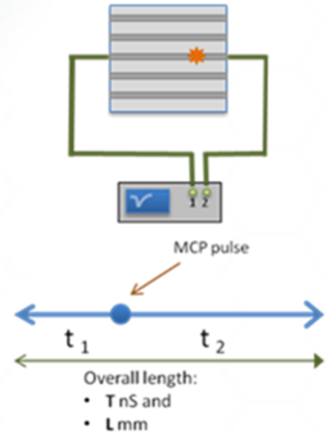


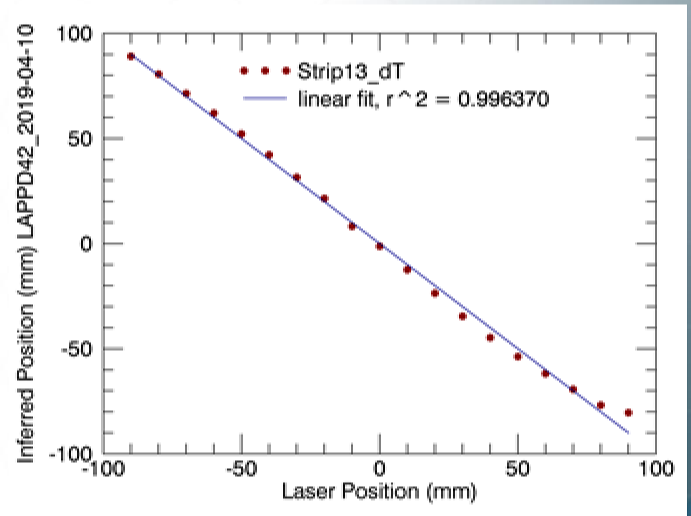
INCOM BRIGHT IDEAS

Measuring Position with the LAPPD Anode

Position measurement along an anode strip:

- Position is inferred from relative time of arrival of pulses at each end.
- Linear response; position uncertainty derived from spread in relative arrival times.
- **1.4 mm uncertainty**

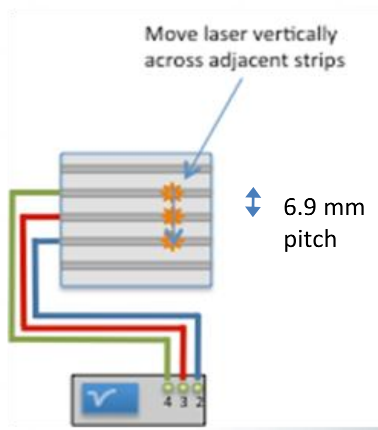


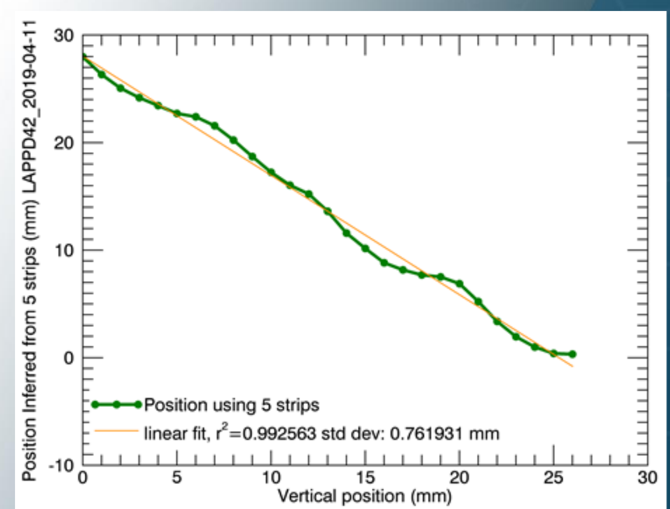


LAPPD 42

Position measurement across anode strips:

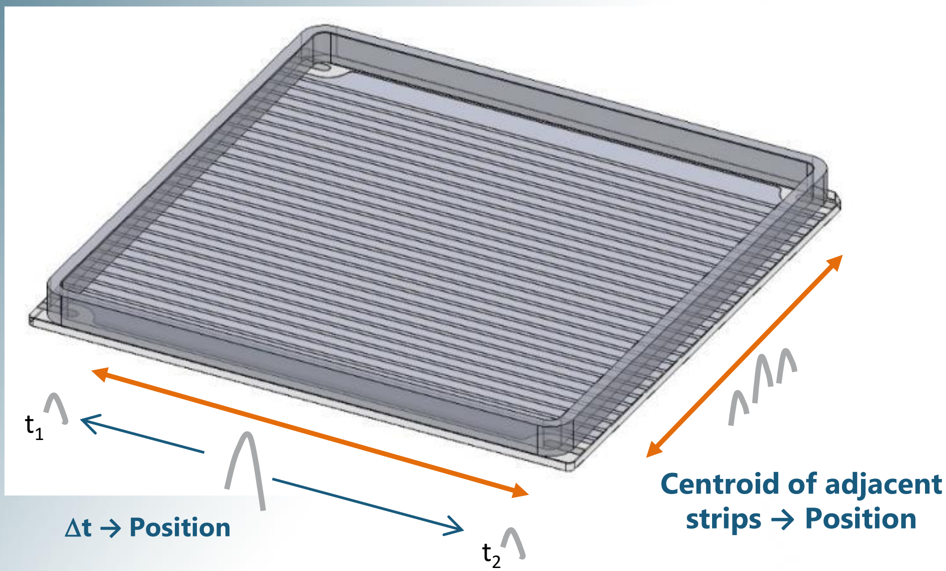
- Position calculated by centroiding five adjacent strip signals using charge.
- **0.76 mm standard deviation from linearity.**





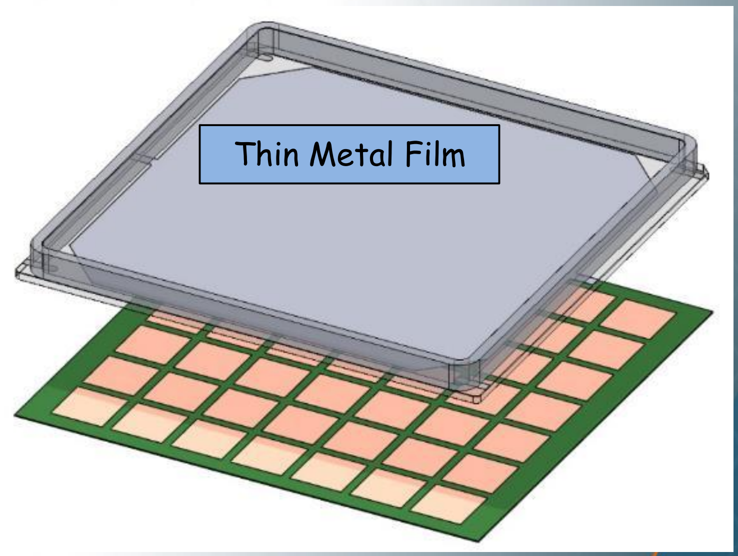
Gen-I vs Gen-II LAPPD™ Design

Gen-I Strip Line Anode



- Optimized for fast timing applications.
- ~1 mm spatial resolution, ~50 ps TTS
- Good compromise between the number of electronics channels and spatial coverage.

Gen-II Resistive Anode with Coupled Patterned Anode

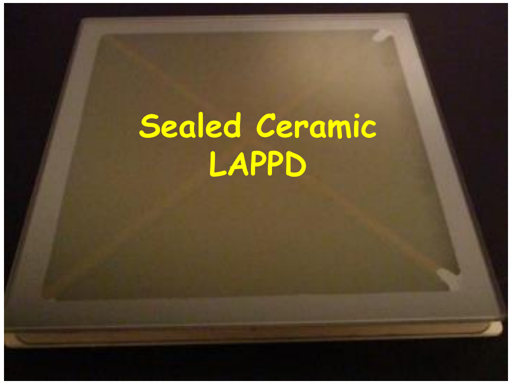


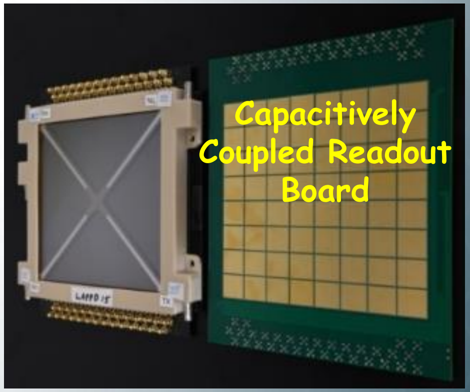
- Customizable anode pattern, user-changeable.
- Good detection of multiple, simultaneously-arriving photons.
- Flexibility in anode design allows a balance between rate, spatial resolution and the number of electronics channels.

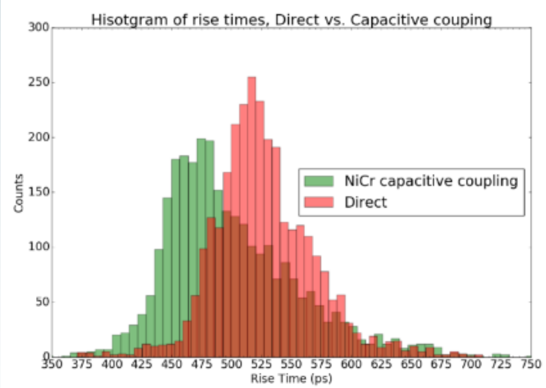
F. Tang et al., TWEPP 2008, Naxos, Greece, September 15-18, 2008
H. Grabas et al., Nuclear Instruments and Methods in Physics Research A 711 (2013) 124–131
B. Adams et al., Nuclear Instruments and Methods in Physics Research A 846 (2017) 75–80

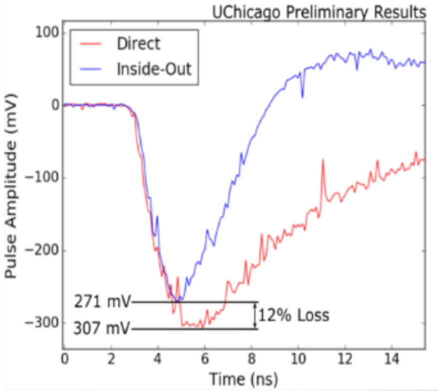
Gen II LAPPD

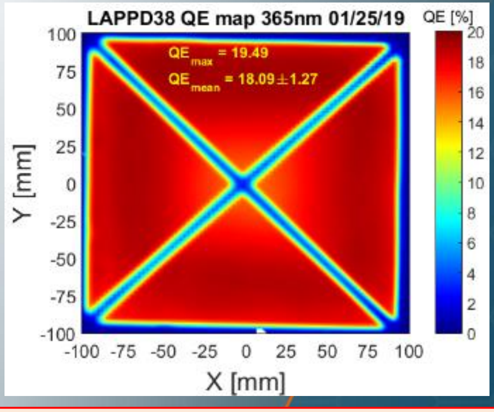
- **Capacitive signal coupling:** to an external PCB anode
- A **robust ceramic body**: for durability and dielectric properties
- **Pixelated anodes:** to enable high fluence applications











The capacitive readout scheme preserves rise-time of pulses (rise time is a key factor in timing resolution)
For pad pattern: 80% of the directly coupled amplitude

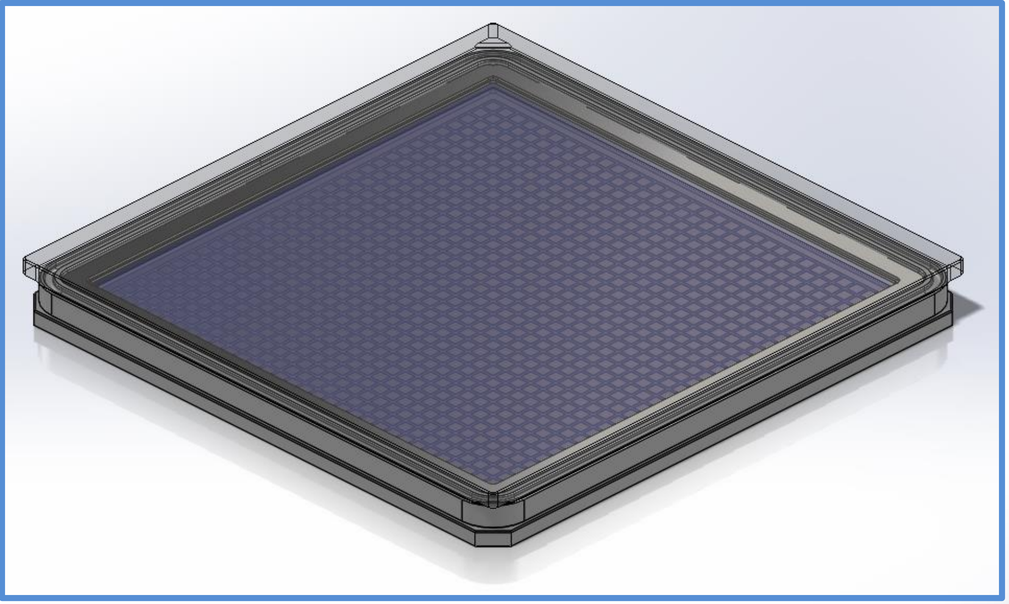
Sealing process established, high QE demonstrated.
Inner design optimization on-going

E. Angelico et al., Nuclear Instruments and Methods in Physics Research A 846 (2017) 75–80

10 cm HRPPD Detector Design

The 10 cm detector is the newest development of Incom's large area picosecond photodetectors, incorporating innovations from our full size Gen I & II LAPPDs.

- Taking advantage of the 10 µm pore MCPs
  - **(timing and B-field)**
- Reduced gap spacing
  - **for improved spatial resolution, and B-Field tolerance**
- An unobstructed Field of View (no window support)



Glass (B33) or Ceramic (Al_2O_3) Bodies
Several window options

- Fused Silica, B33, Sapphire, or MgF_2 (115 nm cutoff)
- Unsupported window with no obstruction
- 10 cm × 10 cm field of view

Reduced gap spacing and small pore MCPs (10 µm) for B-field tolerance

- MCP Stack clamped into sidewall
- 1.75 mm PC-MCP (drop face window option to reduce this)
- Small gap between MCPs
- 2 mm MCP-Anode

Several readout schemes possible

- Gen-I Strip-Line
- Gen-II Capacitive Coupling
- Gen-III Pixelated Cofired Anode

Narrow Sidewall and spacers for reduced dead space in Gen-III Design

- Dimensions: 142.12 cm2
- Active Area: 103.23 cm2
- HV and anode connections on bottom (4-side abuttable)

LAPPD^{TM} Availability

1) Routine "pilot production" supported by our R&D team, is now underway,
   a) In 2020, Incom will again double the output from 2019
      a) **Present capacity is 4 LAPPDs/month – plans to go to 6/month by late 2020**.
   b) Capacity can be rapidly and significantly increased when full production is implemented.
2) Prototypes are available for **purchase or rent** by customers that wish to qualify LAPPD for their applications.

❖ Minimum renewable term per month: (mrf@incomusa.com)

❖ Qualified prospects that don't presently have a budget or the ability to either rent or purchase an LAPPD, may qualify for special negotiated terms.

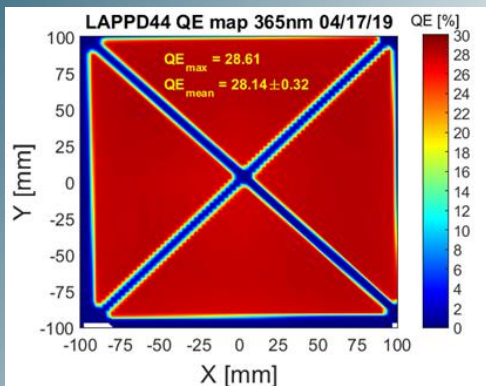
3) Incom Inc. hosts quarterly **Measurement & Test Workshops**
   a) familiarize potential users with the LAPPD,
   b) facilitate direct participation with the Incom team,
   c) hands on, characterizing an LAPPD,
   d) accept customer input on applications to improve future LAPPD designs
   e) and at no charge for attendance.

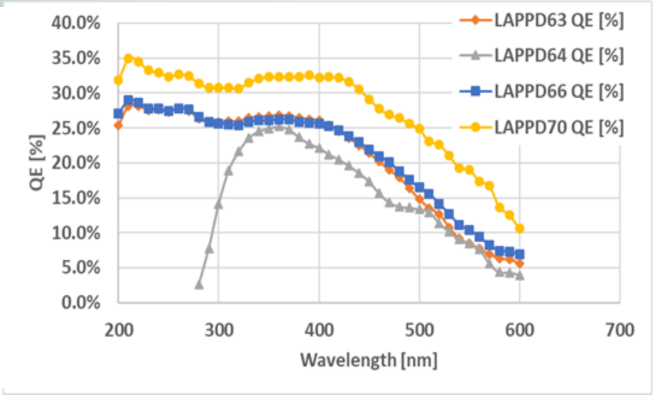
INCOM BRIGHT IDEAS

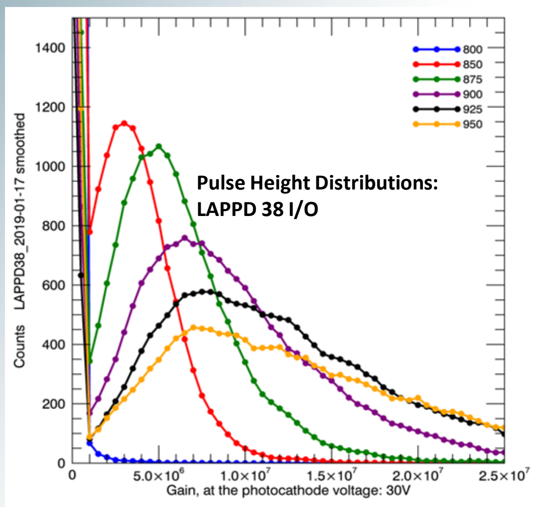
LAPPD Applications

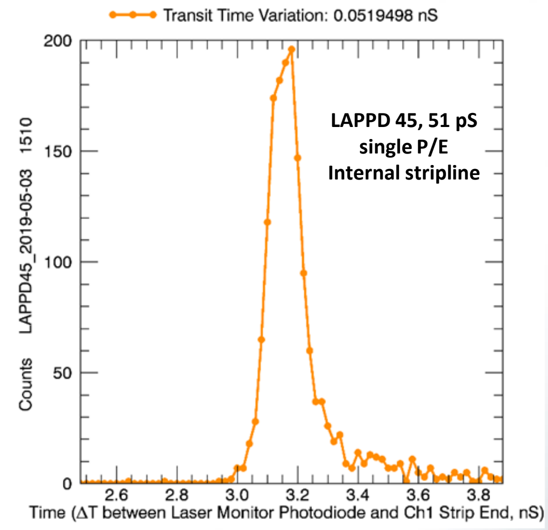
PROGRAM	AFFILIATIONS	2020 – 2021 STATUS
ANNIE - Atmospheric Neutrino Neutron Interaction Experiment	Iowa State	**Five LAPPDs** delivered;
Neutron Imaging Camera, Nanoguide scintillating polymer	Sandia National Lab (CA), U of Hawaii	LAPPD #22 being evaluated
Fermilab Test Beam Facility, IOTA KOTO	U of Chicago, Fermilab	Demonstrate achievable LAPPD TOF resolution and particle identification in a working beamline setting **(3 delivered)**
WATCHMAN, UK STFC	U. of Sheffield, The University of Edinburgh	**Two-Three LAPPDs planned** for 2020 delivery
CHESS, WATCHMAN, THEIA	Lawrence Berkeley National Laboratory	LAPPD under evaluation Possible tile upgrade in 2020
SoLID (Solenoidal Large Intensity Device)	ANL, J-LABS	**Gen II LAPPD #38** for testing at J-Labs Delayed due to COVID19
Neutrino-less Double-Beta Decay	U of Chicago	TBD
EIC PID - eRD14	BNL, ANL, J-LABS, Stony Brook, INFN	FermiLab Beamline Trials delayed due to COVID19, **2 LAPPDs waiting to ship**
CERN LHCb RICH phase-2 upgrade	The U. of Edinburgh, U. of Ferrara & INFN	CERN LHCb RICH phase-2 upgrade
i-MCPs for ECAL upgrade II (CERN LHCb)	Vincenzo Vagnoni INFN, Sezione di Bologna	Testing of MCP and **LAPPD #69** for precision timing of electromagnetic showers in a calorimeter.
LAPPD based Time of Flight PET (TOF-PET) Sensor	UC Davis, MGH – Harvard, PicoRad Imaging, Université de Sherbrooke	Measurements of the energy spectra produced by 511 keV photons and spatial resolution are being made. **(LAPPD #57)**
LAPPD Femtosecond Timing Trials	PicoRad Imaging, MA., & MGH - Harvard	TTS timing trials underway at MGH, using a femtosecond laser, and 4-ch 4GHz bandwidth Tektronix MSO64 scope with 25GSPS per channel.
Neutron Radiography System using Incom Nanoguide, and LAPPD	Starfire Industries LLC.	Portable x-ray/fast neutron radiography system **Planned September delivery**
LAPPD Read-out Board	Nalu Scientific, LLC, and University of Hawaii	Fully integrated, high channel count signal processing read-out board using NSL's AARDVARC ASIC.
Life Testing of LAPPD, Role of ion feedback.	UT Arlington	**Life Testing LAPPD #64 underway**
Neutron Beam Line testing	Los Alamos National Laboratory	GEN II LAPPD **planned September delivery**

Key Takeaways









- Performance summary
  - Gain: mid-10^6 and above
  - Dark rate: $10^3/cm^2$ in the mid-10^6 gain range.
  - TTS: ~55 pS or better
  - QE: 20-30% @ 365 nm
- Two LAPPD Types
  - Stripline model – Gen I
  - Capacitively coupled model – Gen II
    - user changeable pixelated signal board
  - Future model - 10 cm HRPPD
- LAPPDs delivered and pending
  - Several on-going tests w/collaborators
  - More on the way (production at 4/month)
- Available to purchase or rent
  - Volume pricing
  - Monthly rental
  - Technical Support & LAPPD Workshops

Current Funding & Personnel Acknowledgements

DOE (HEP, NP, NNSA, SBIR) Personnel: Dr. Alan L. Stone, Dr. Helmut Marsiske, Dr. Kenneth R. Marken Jr. Dr. Manouchehr Farkhondeh, Dr. Michelle Shinn, Dr. Elizabeth Bartosz, Dr. Gulshan Rai, Dr. Donald Hornback, Dr. Manny Oliver, Dr. Claudia Cantoni, Carl C. Hebron.

DOE, DE-SC0015267, NP Phase IIA – "Development of Gen-II LAPPD™ Systems For Nuclear Physics Experiments"

DOE DE-SC0017929, Phase II– "High Gain MCP ALD Film" (Alternative SEE Materials)

DOE DE-SC0018778, Phase II "ALD-GCA-MCPs with Low Thermal Coefficient of Resistance"

NASA 80NSSC19C0156, Phase II "Curved Microchannel Plates and Collimators for Spaceflight Mass Spectrometers"

DOE DE-SC0019821 Phase I- Development of Advanced Photocathodes for LAPPDs

DOE Award No. DE-SC0020578, Phase I - High Rate Picosecond Photodetector (HRPPD) being developed for Nuclear Physics

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Thank you

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www.incomusa.com

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BRIGHT IDEAS

Back up slides

GEN I LAPPD Pilot Production Implemented

Five LAPPD Shipped since 1/1/2020

Feature	GEN I LAPPD™
Availability	Available from stock
Anode	Direct readout of conductive microstrips
Outside Dimensions	22.0 cm × 23.0 cm
Active Area	19.7 cm × 19.7 cm (368 cm^2)
UHV Package Design	X-Spacer support window
Detector Package	B33 Glass, Alumina Ceramic
Window	Fused Silica, B33 Glass
λ Sensitivity	200 nm Fused Silica, 300 nm for B33 to 600 nm
Photocathode	Na_2KSb bi-alkali
Chevron pair, ALD-GCA-MCPs MCPs	203 mm × 203 mm × 1.2 mm thick, 20 µm pores
MCP resistance @975 V,	2 MΩ to 20 MΩ
Spatial resolution, typical	Along strips = 2.4 mm Across strips = 0.76 mm

INCOM
BRIGHT IDEAS

Typical performance for GEN I LAPPD
Specific performances achieved from recent prototypes

Parameter	Typical Performance	64	63	59	58	57
Window	FS or B33	B33	FS	B33	B33	FS
Mean QE% @365nm:	25±2	24.7±3.6	27.1±3.6	9.2	26,4	21.9
Max QE % @365nm:	30	28.1	29.7	10.7	29.1	25
QE Spatial % Variability	± 8	3.8	3.7	0.66	3.3	2.3
Gain @ROP	≥ 10^6 to 10^7	1.26E7	2.4E6	4.4E6	7.0E6	8.3E6
Dark Count @ ROP Hz/cm^2	≤ 500	24,644	7,800	174	107	100
Pulse Rate vs. Gain (KHz/cm^2) 10% gain drop =	500	163	69	375	182	305
Pulse Rate vs. Gain (KHz/cm^2) 50% gain drop =	3000	2,670	1,250	6,063	4,830	4,177
Single P/E (s) TTS, ps	50-70	82.5	66.1	86.8	84.9	65

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