Large Area Picosecond Photodetector (LAPPD™) Performance Update

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Incom, Inc., Charlton Massachusetts, USA

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- ~205 Employees
- Three facilities:
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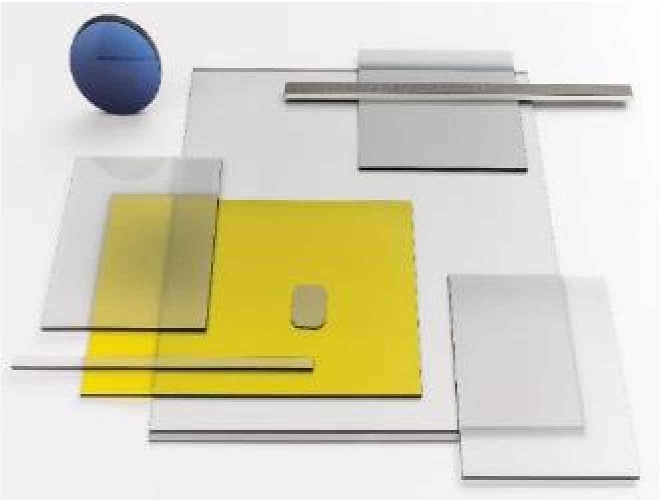
    - Headquarters / Main Plant
    - R&D Pilot Production Facility
  - Incom West - Vancouver, WA



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- Digital X-Ray
- Mammography
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- DNA sequencing
- Filtration

Display

- Gaming
- Automotive
- Audio/Video Editing
- VR/AR
- Holographic Imaging
- Light Field Technology

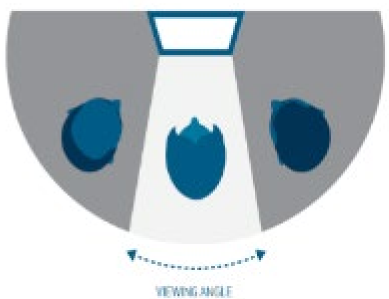
Defense

- Night Vision
- Biometrics
- Neutron Detection

Detector

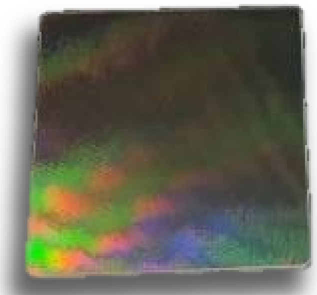
- Particle Identification
- Electron Spectroscopy
- Ion Spectrometry
- Space Flight Instrumentation

Large Fiberoptic Face Plate for medical diagnostics



DARC glass privacy filter

Night Vision



Plano MCP 53mm x 53mm

LAPPD (MCP-PMT) 200mm x 200mm

Curved MCP 25mm x 120mm

Large Area Picosecond Photodetector (LAPPD)

- MCP photomultiplier
  - Good timing resolution
  - Position sensitivity
  - High gain
- 8" x 8" : active area 34,989 mm^2, 92% open area
- High gain: mid-106 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: ~50 pS or better

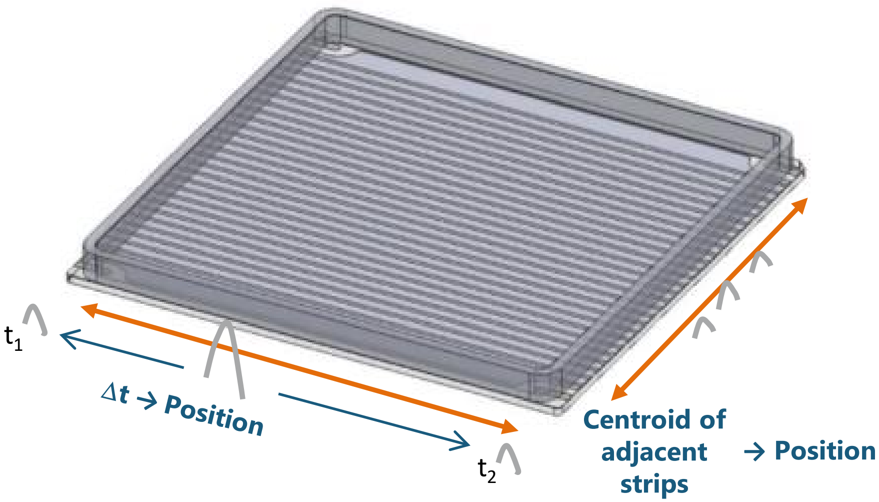
➔ Time and position measurement for:

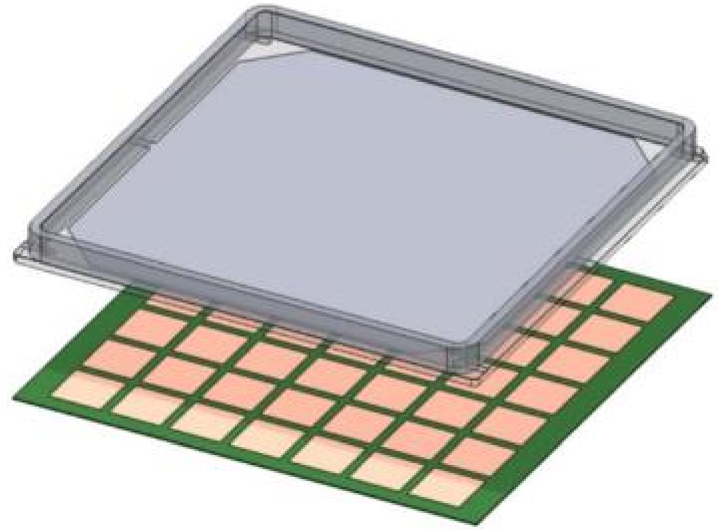
- **Photons, with Single or multiple photoelectrons**
- **Penetrating energetic particles**

Two LAPPD™ Design Versions

Gen-I Direct Read-out
Strip Line Anode

Gen-II Resistive Interior Anode with
Capacitive Coupled Patterned Signal Board





Optimized for fast timing applications.
~1 mm spatial resolution
50-70 ps TTS for SPE

Standard Pilot Production

Customizable anode pattern.
Maintains performance for most applications.

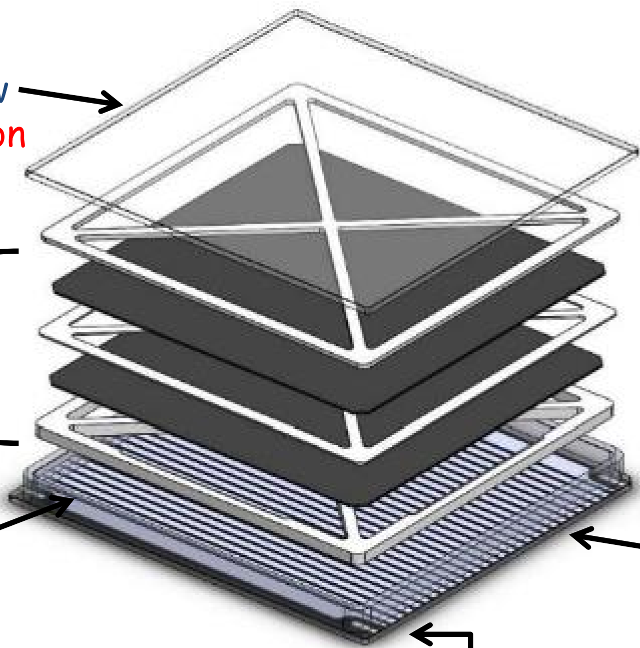
Development: Prototypes Available

GEN I LAPPD™ Design Features

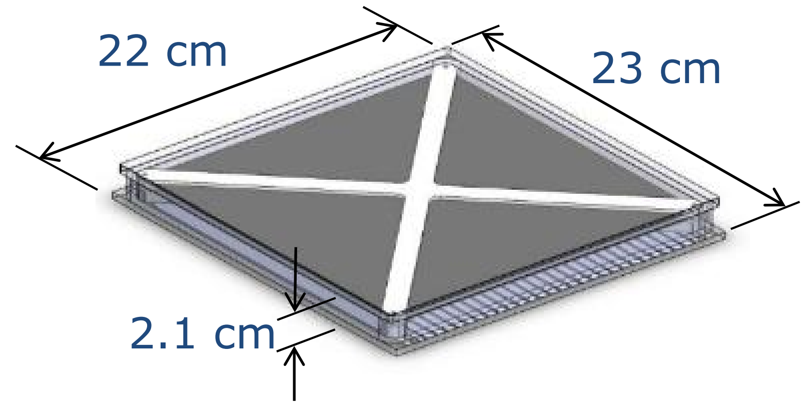
Fused silica or Borosilicate window with photocathode on inside surface

20 cm x 20 cm MCPs, spacers

Micro-strip anode and sidewall



HV Tabs to power MCPs



Signal readout, both ends of 28 micro-strip lines

- Pin Free
- Signal & HV pass under frit bonded side walls.
- Active area: 195 x 195mm =34,989 mm^2, 350 cm^2 , 92% active area

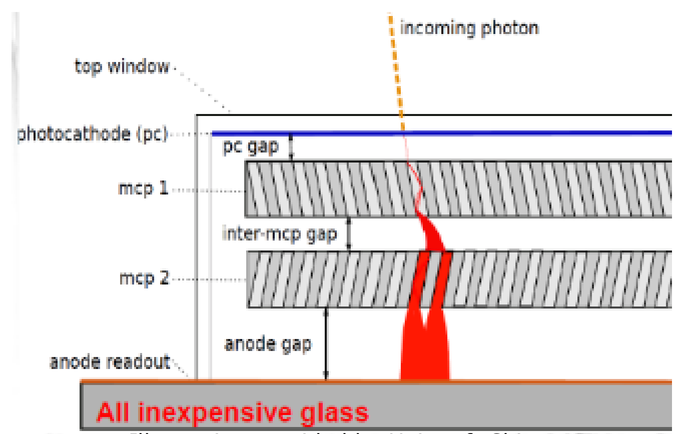
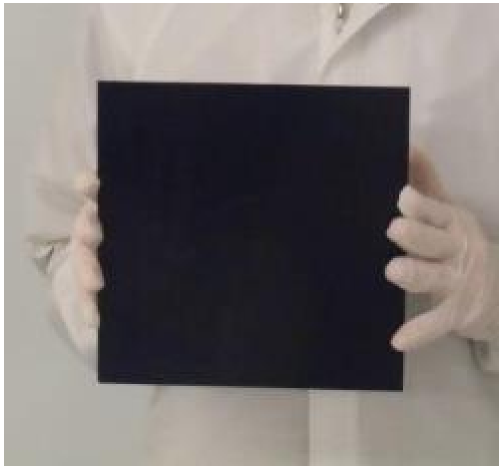
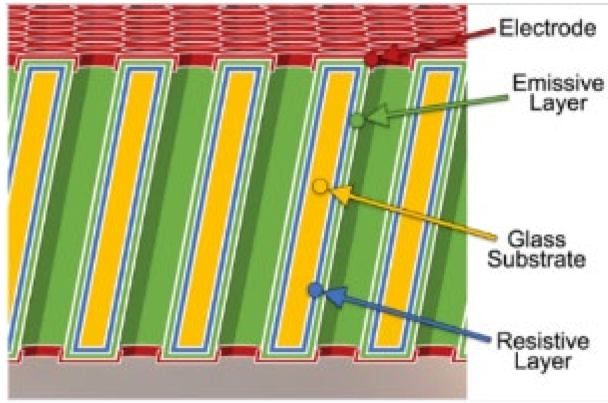
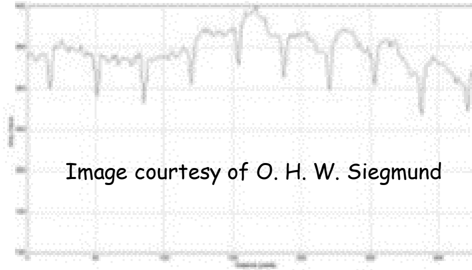


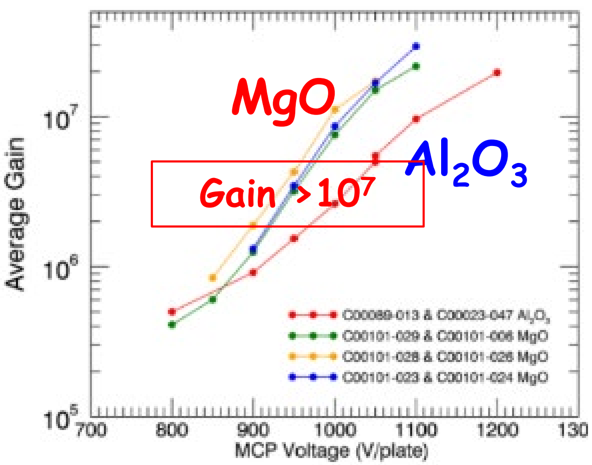
Illustration provided by Univ. of Chicago

Incom's ALD-GCA-MCP's
the enabling technology









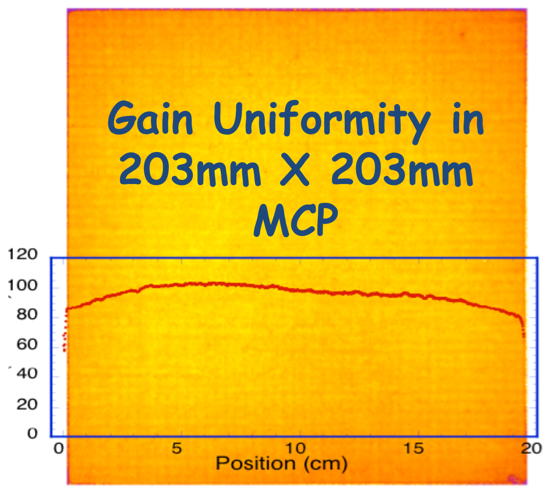


Fig. 8: Average gain image "map" (<15% overall variation). 8" MCP pair 20μm pore, 60:1 L/D ALD-MCP pair. ~7×10^6 gain, 0.7mm inter-MCP gap/200V.

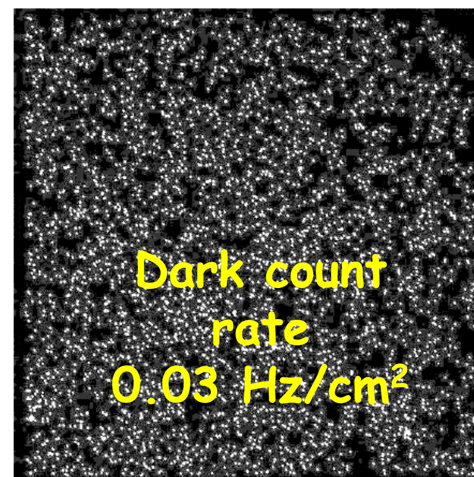
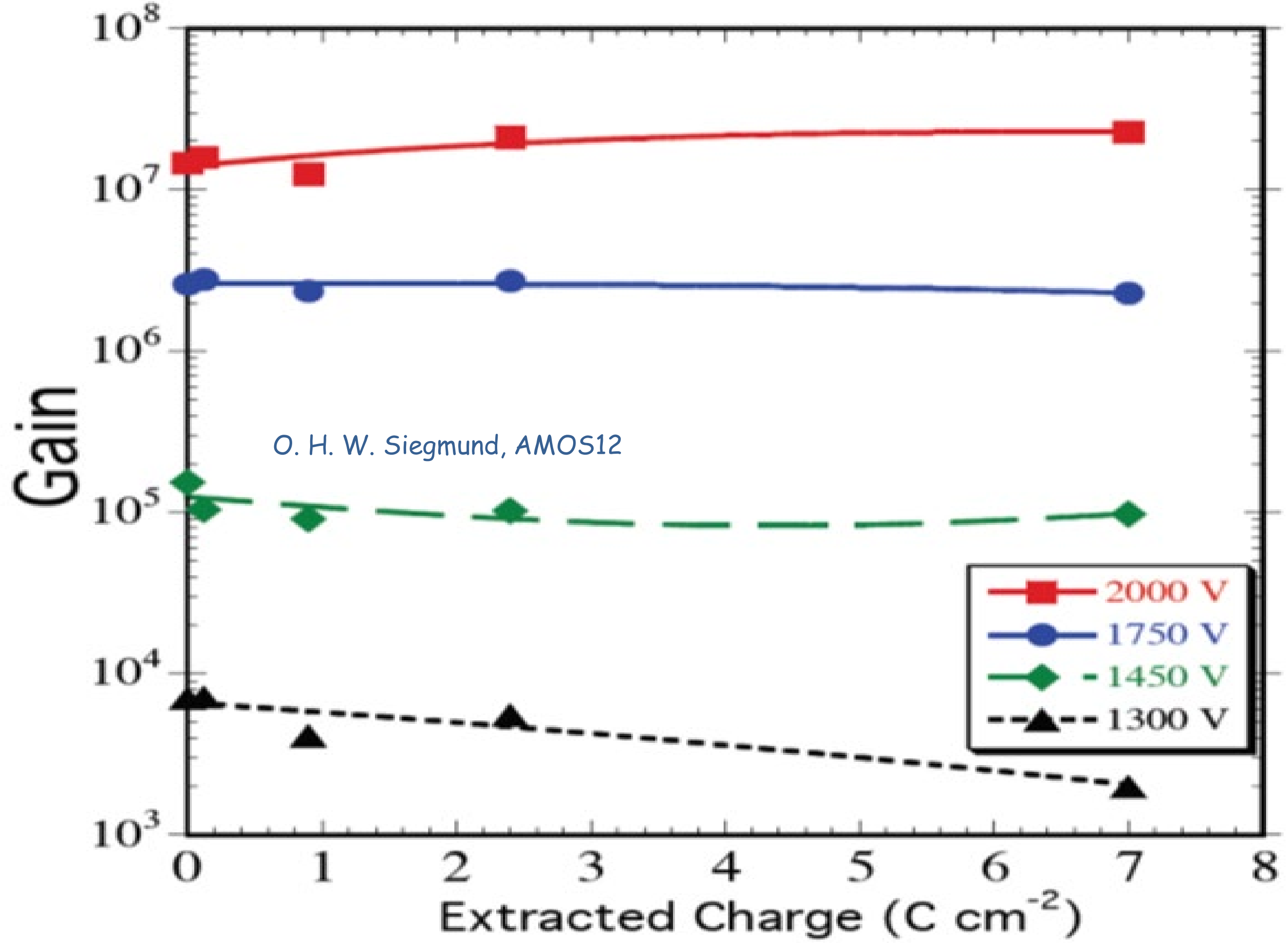


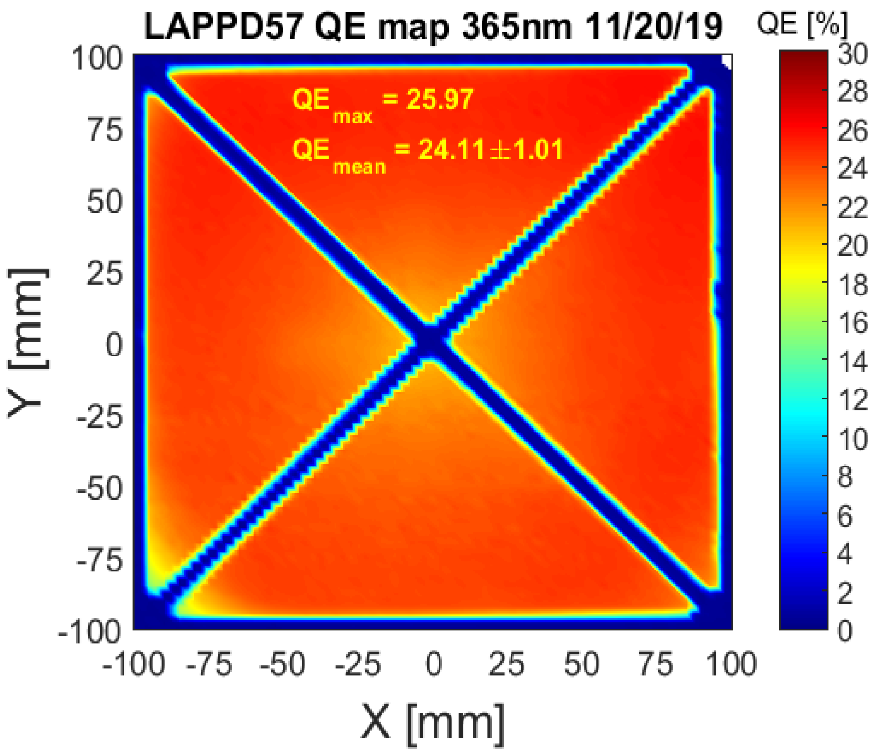
Fig. 9: 20 cm ALD MCP pair background, 500 sec, 0.03 events/cm²/sec[1]. Overall background ~8× better than standard glass MCPs (less K^{40}),

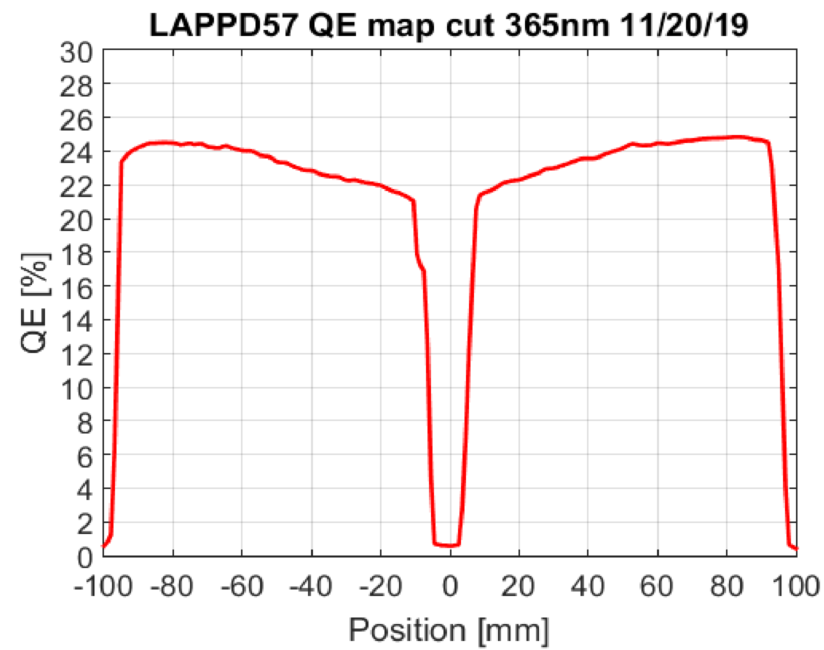
Incom's ALD-GCA MCPs: an enabling technology for LAPPD performance vs. conventional MCP-PMTs

ALD-GCA-MCP Gain vs. Extracted Charge



Typical Photocathode Quantum Efficiency @ 365nm



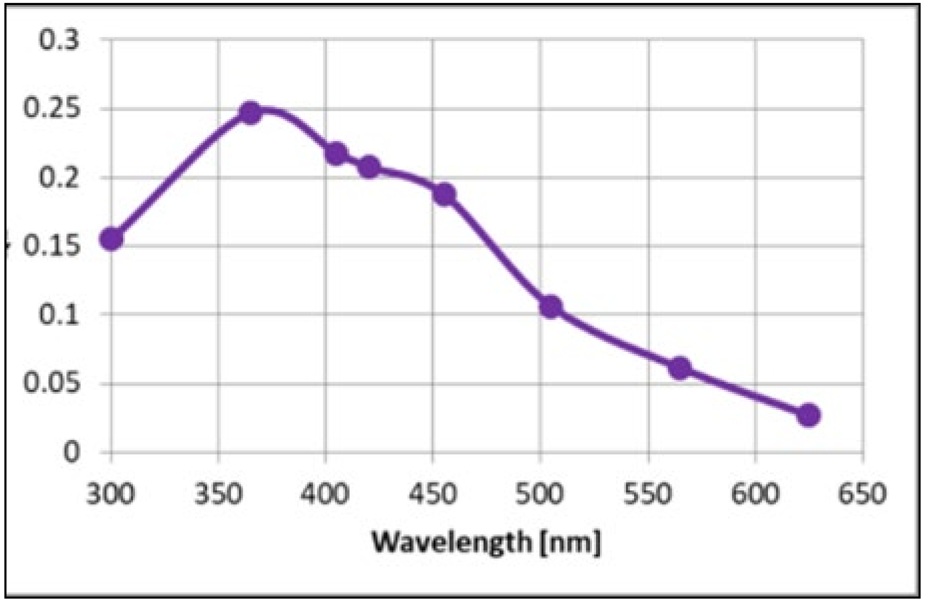


LAPPD #57:
Mean QE = 24.11 ±1.01%.
Maximum QE = 25.97%

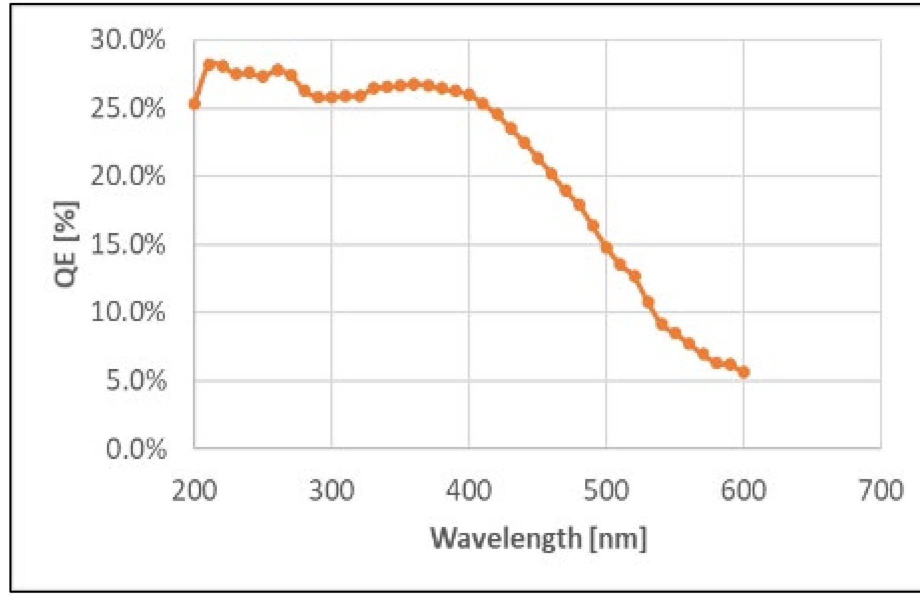
Spatial variation is ≈±4% outside regions obscured by X-spacers.

Average pilot production LAPPD QE is routinely ≥ 20% and often ≥25%, with ≥ 90% uniformity

PC QE vs Wavelength between 200nm and 600nm



Borosilicate 3.8mm Window



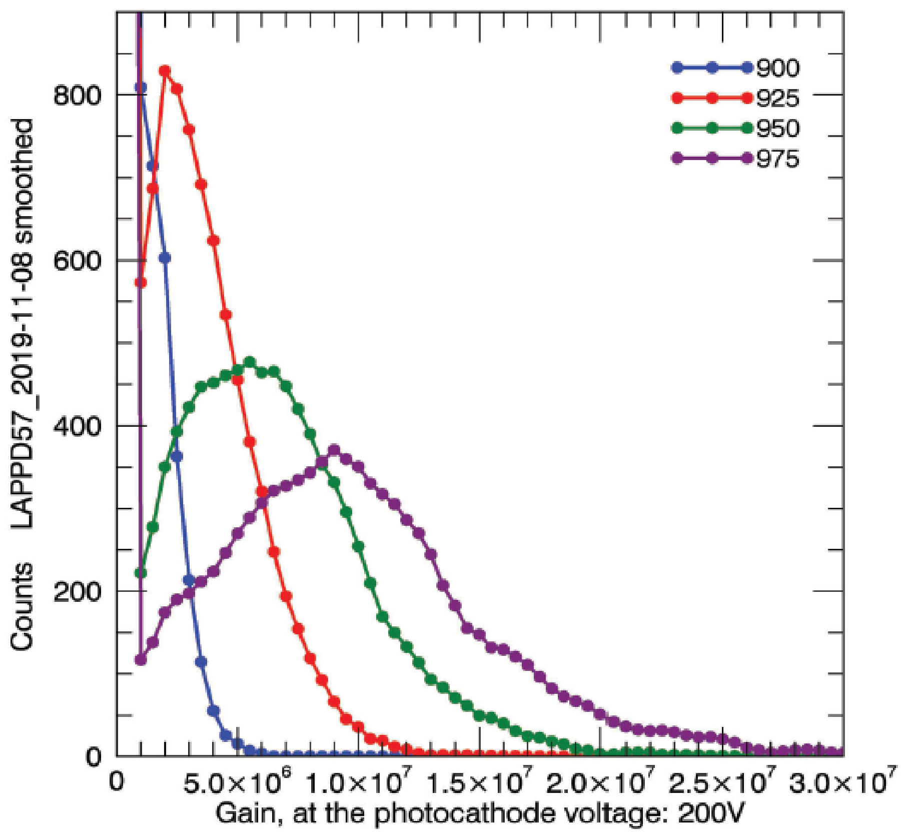
Fused Silica 3.8mm Window (LAPPD #63)

LAPPD™ Photocathodes - Na_2KSb

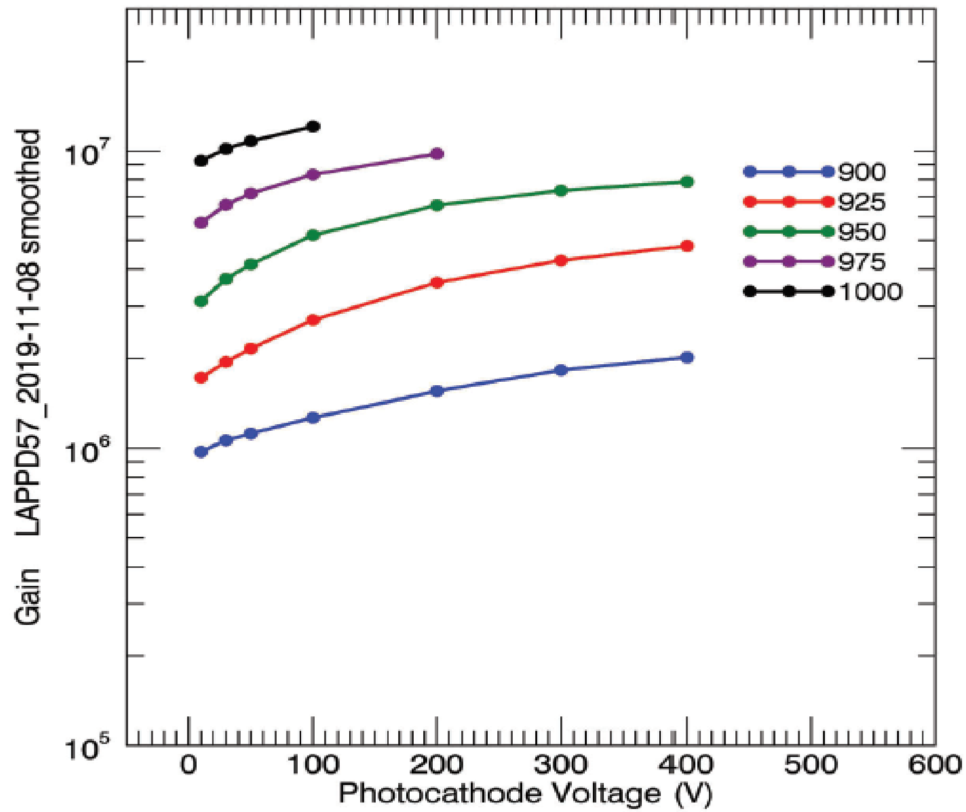
Higher QE at shorter wavelengths with UV grade fused silica Window

SPE Gain vs. MCP & PC Voltage,

LAPPD #57



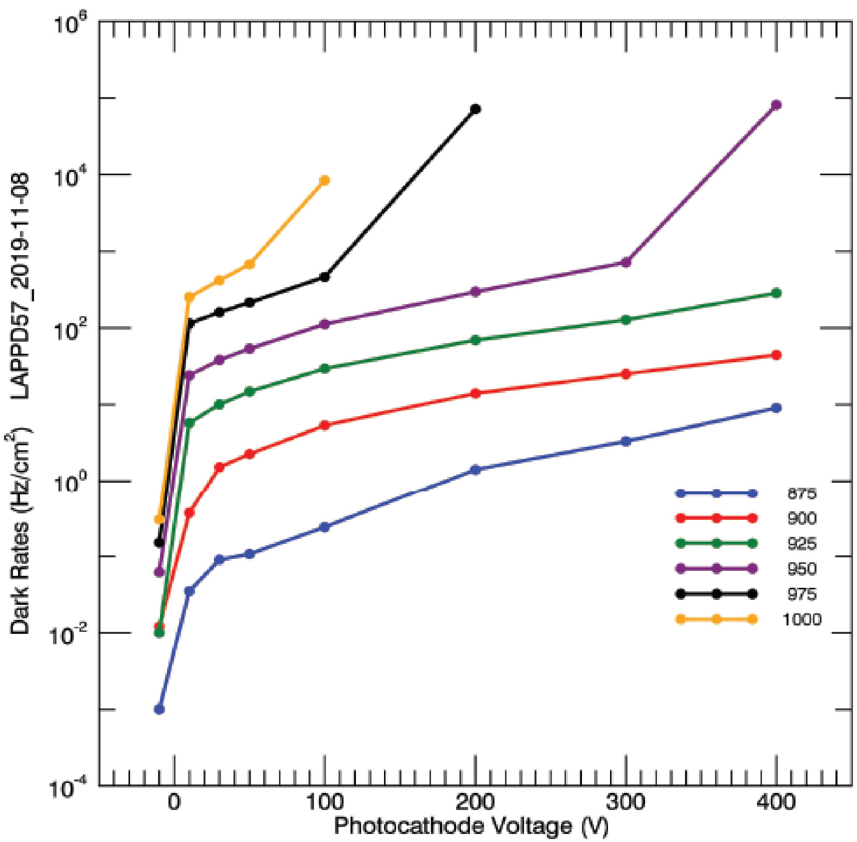
SPE Gain vs MCP voltage, with 200 V at the PC

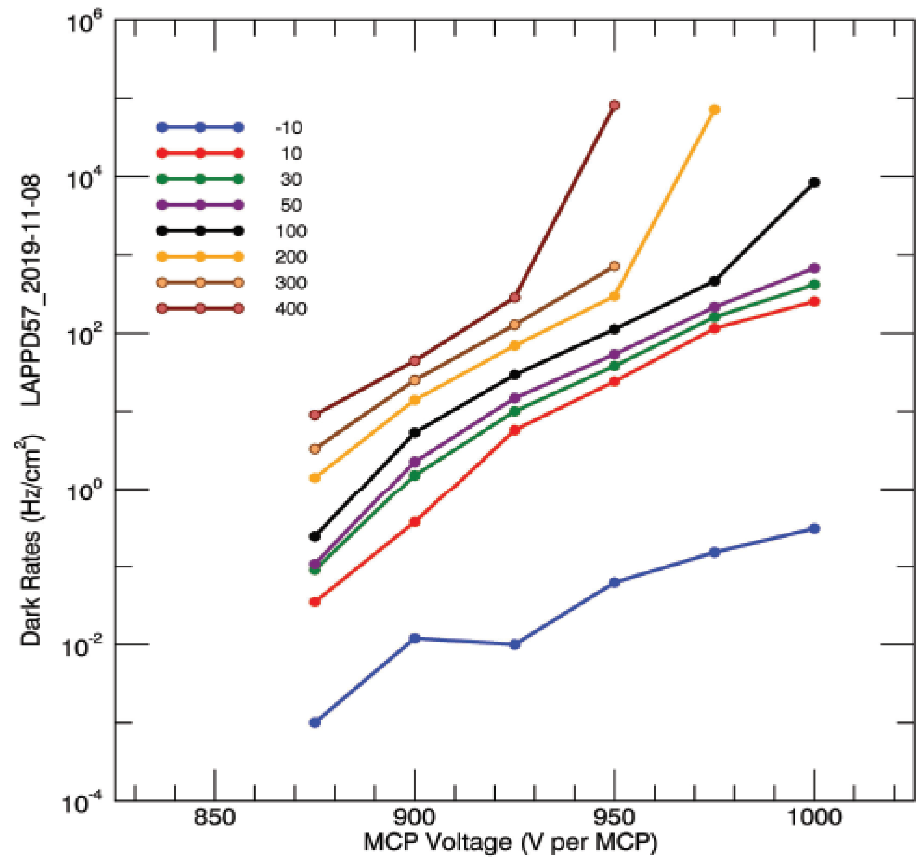


Average SPE gain vs. PC Voltage at different MCP voltages.

Dark Rate vs PC & MCP Voltage

LAPPD #57

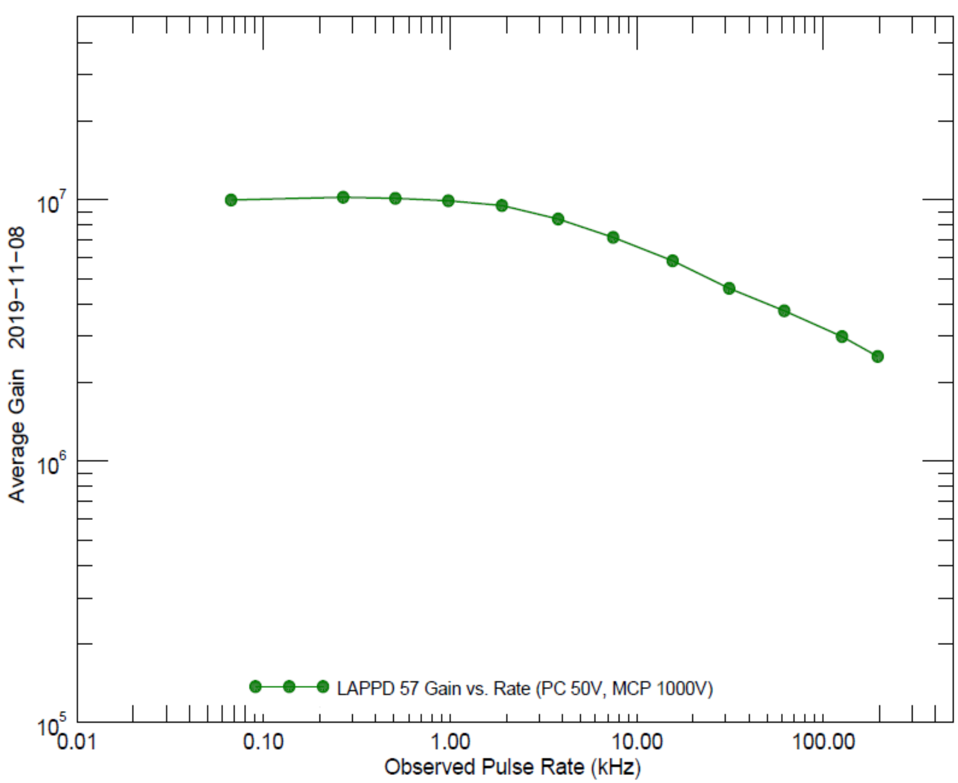




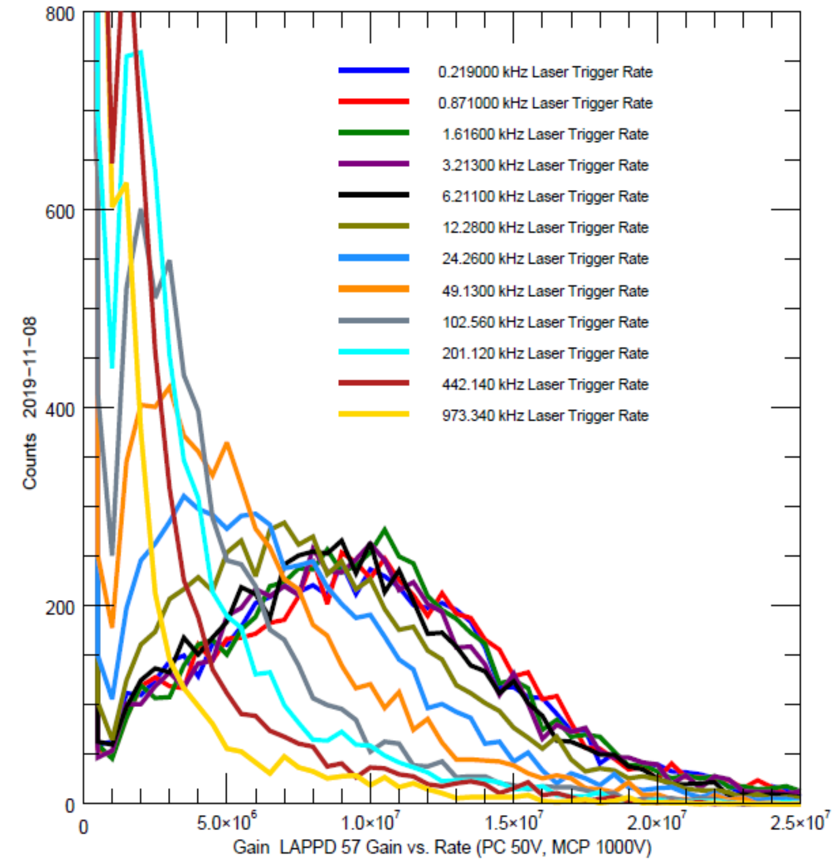
Despite its large size, the GEN I baseline LAPPD has predictable dark rates of only a few 100Hz/cm^2 at gains of ~5x10^6 ensuring lowest TTS and several 100Hz/cm^2 at gains of ~10^7

SPE Gain vs. observed pulse rate

LAPPD #57



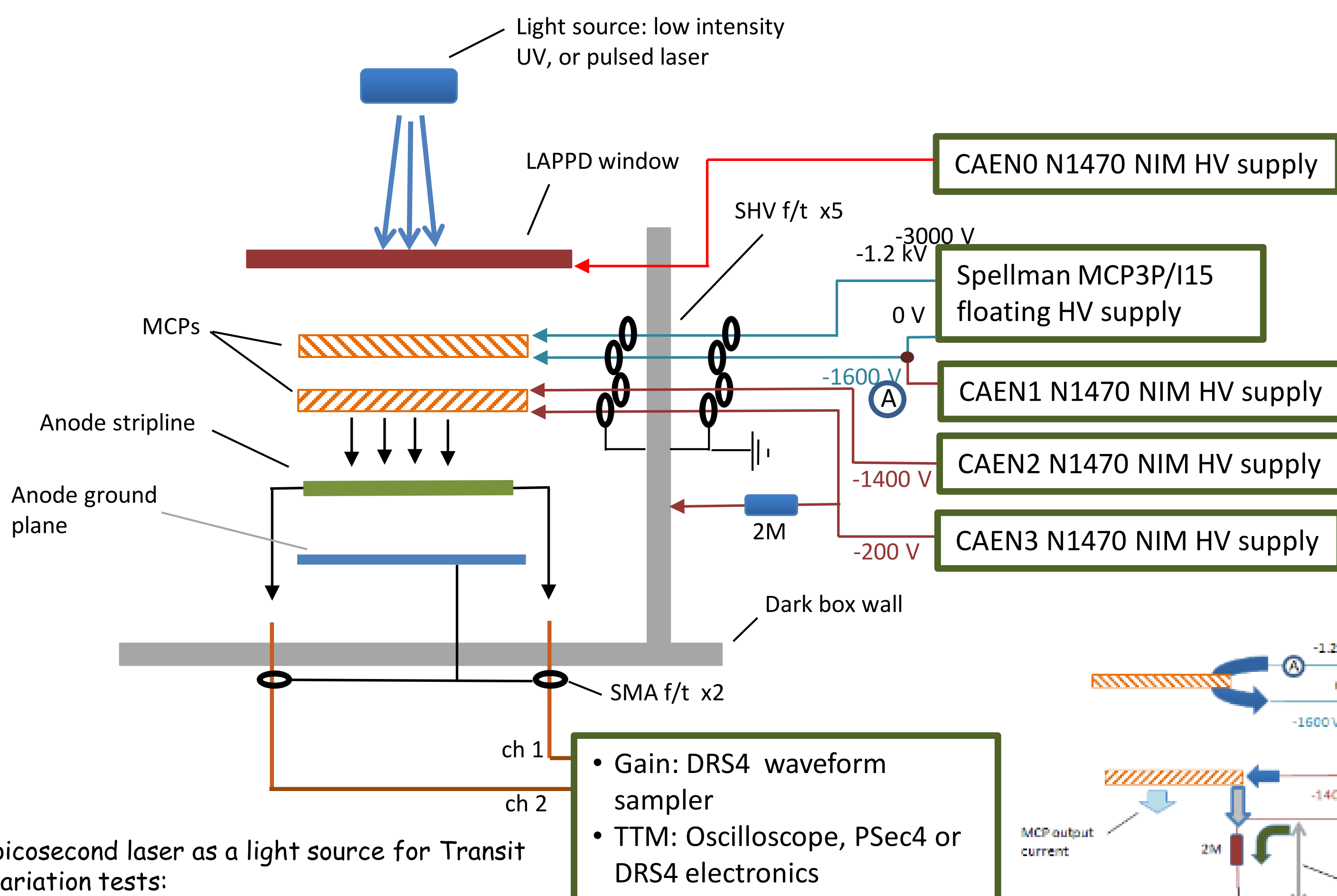
SPE Gain vs. observed pulse rate

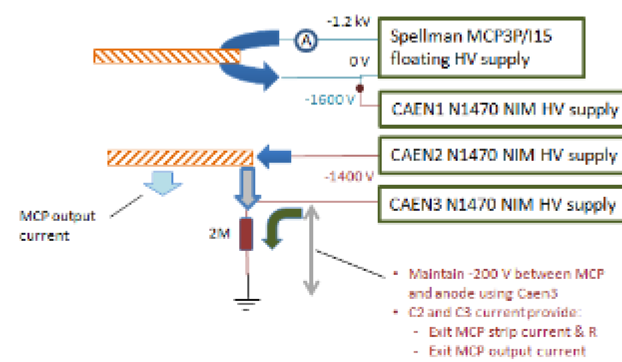


Pulse distributions vs. laser trigger rate

A 10% gain decrease occurs at an observed rate of about 400 kHz/cm^2.

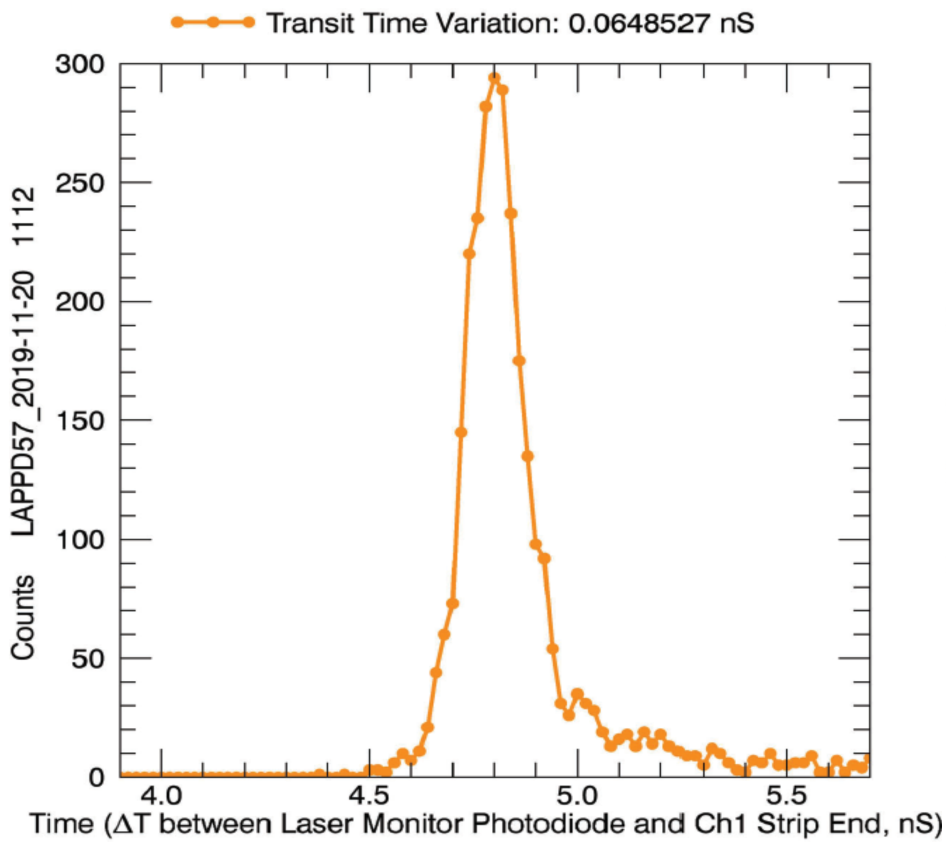
Single-P/E Gain & Transit Time Measurements

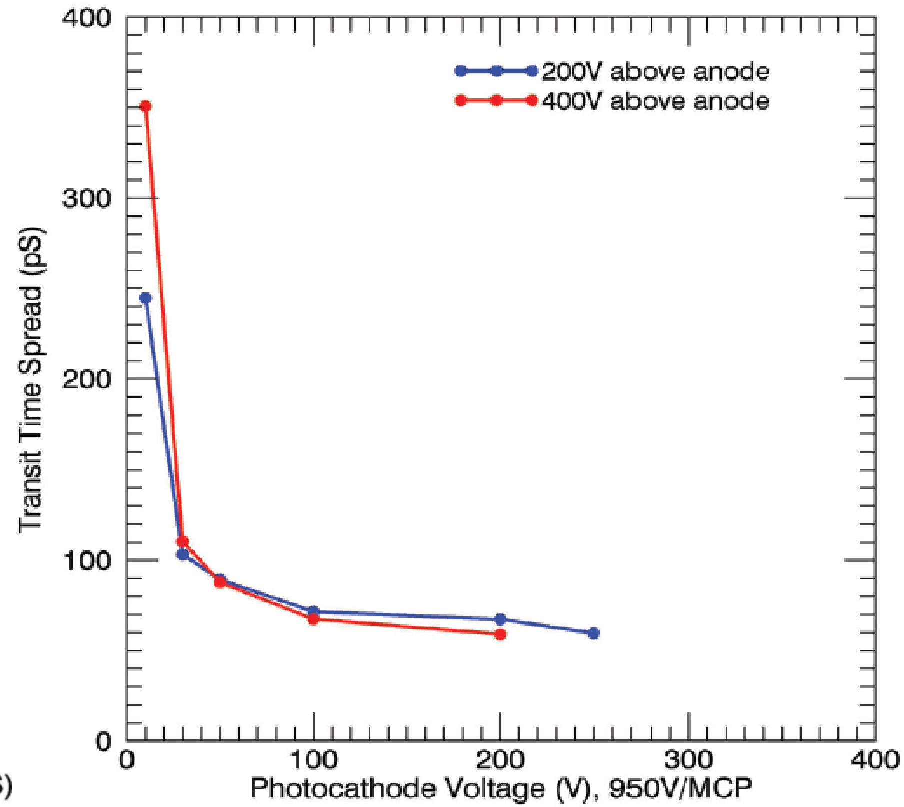




- Use a picosecond laser as a light source for Transit Time Variation tests:
  - Edinburgh Instruments EPL-GT-405 or Pilas laser.
- Initiate time measurement with laser monitor pulse.
- Attenuate light source for gain tests using neutral density filters, e.g. Thorlabs filters.

Transit Time Spread





Distribution σ= 64.8 pS. Corrected for laser variation TTS = 64.2 pS.

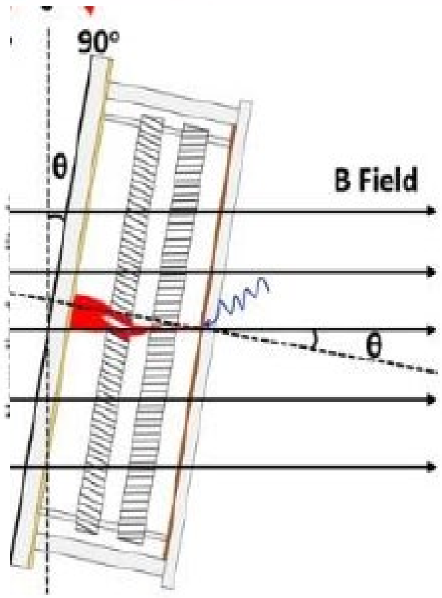
TTS vs. PC Voltage with 950 V/MCP and 200 vs. 400 Volts between Exit MCP and anode.

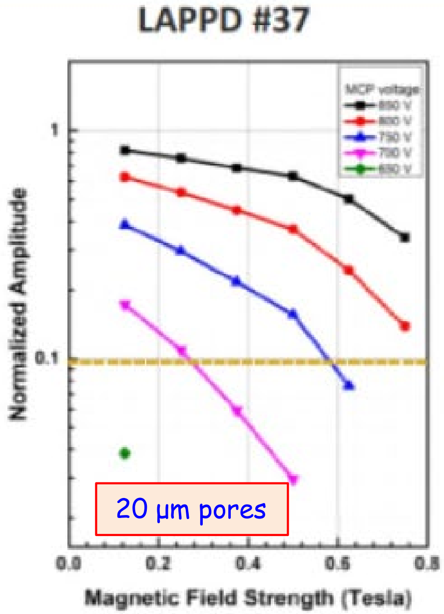
Preliminary LAPPD & Small Format Tile B-Field Testing

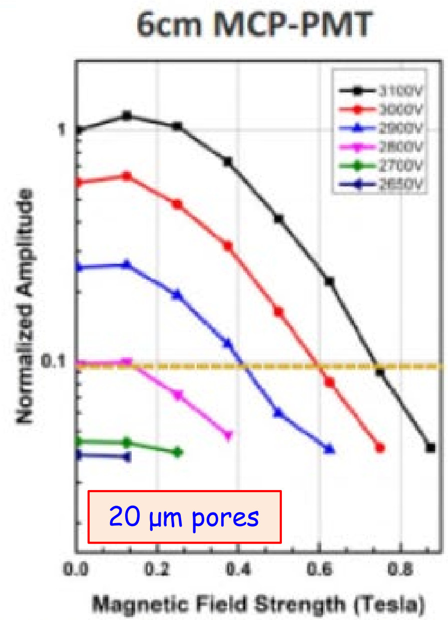
Bill Worstell (PI), Mark Popecki, Cole Hamel, Bernhard Adams, Bob Wagner, Junqi Xie, Ed May

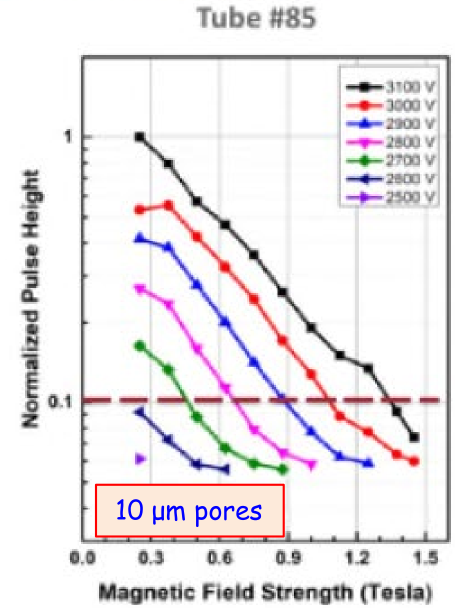
12/14/2018 B-Field Testing LAPPD #37

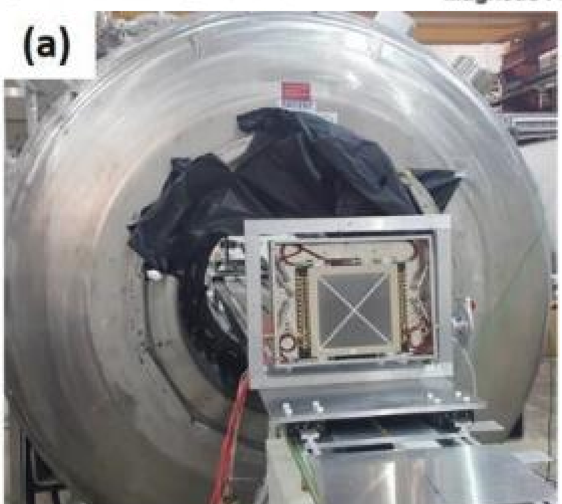
ANL 6cm Tile, 10 & 20μ MCPs











Phase I SBIR Preliminary Results: B field limit

Gain decreases with increasing field

Max with field aligned with MCP pore

~0.7 T with 20 microns

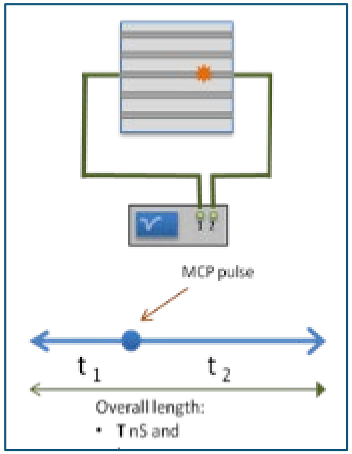
~1.3 T with 10 microns

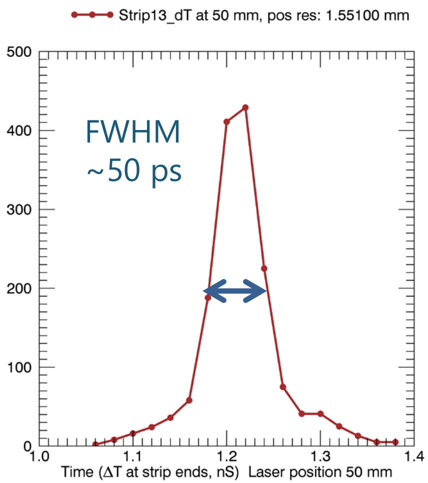
Further Analysis Pending

Phase II SBIR Targets Design Optimization

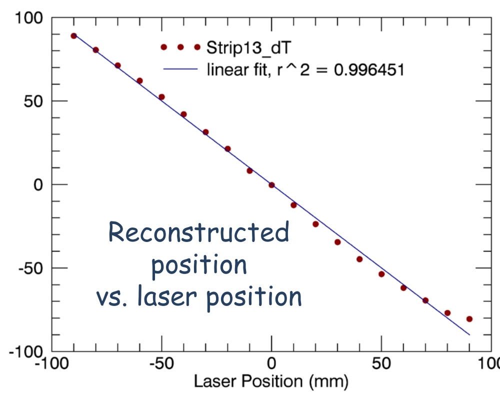
Gen-I LAPPD™ Spatial Resolution

ALONG STRIPS



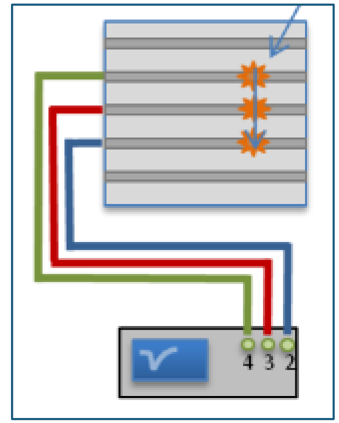


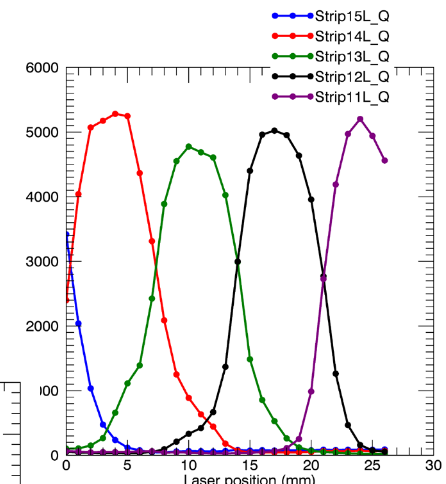
DRS4 waveform sampler:
Position by Δt for signal at both ends of single strip.

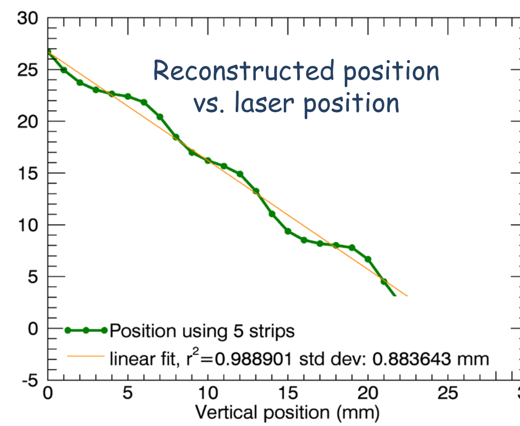


Resolution= 2.4 mm

ACROSS STRIPS





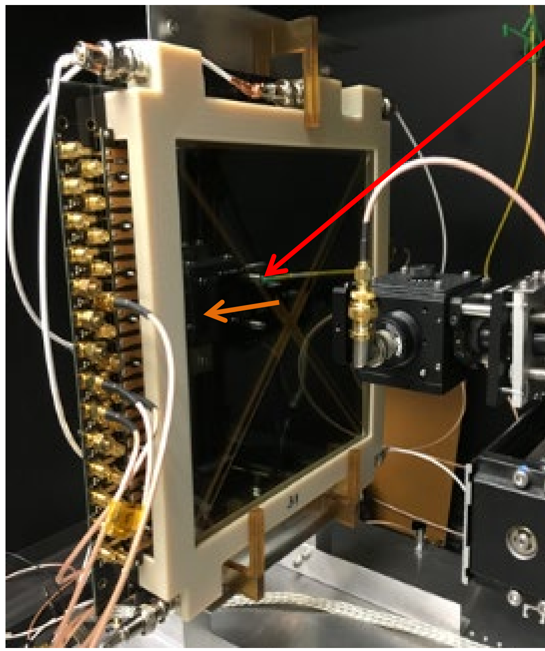


Center of mass for 5 adjacent strip signals.

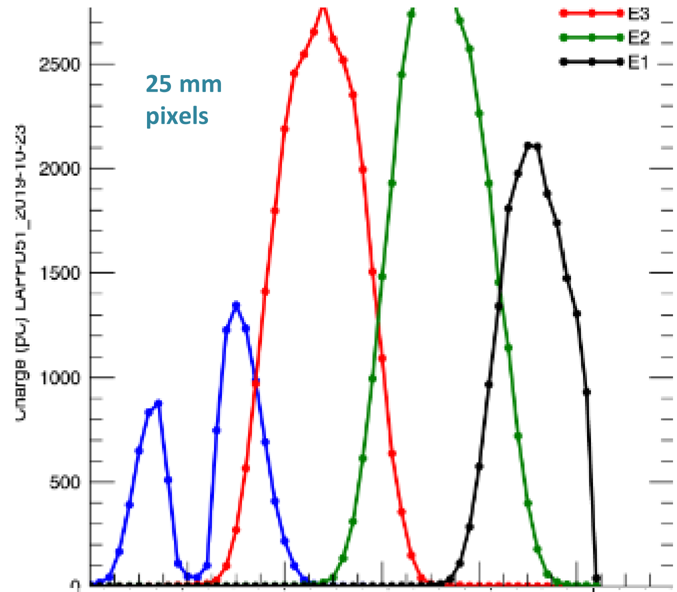
Resolution= 0.76 mm

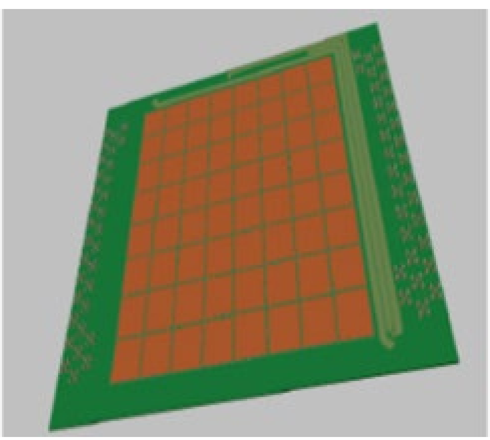
Position Resolution with an External Pixelated Anode

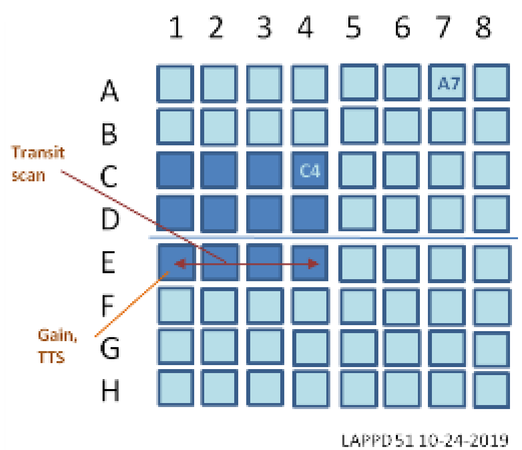
- Internal resistive anode: grounded
- 25 mm external pixels
- Capacitive coupling
- Position determined to better than 25 mm pixel size by centroiding.
- Left edge of position plot cut off by X spacer.

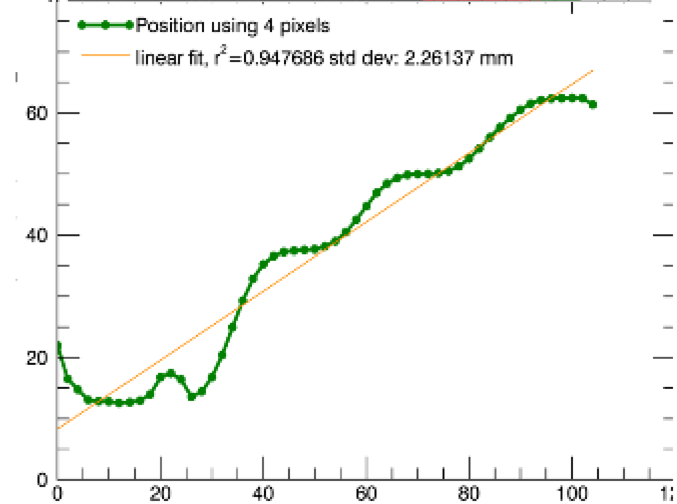


Laser obscured in this region (~15 mm)









Capacitive Coupling: MCP Pulses Observed Inside and Outside

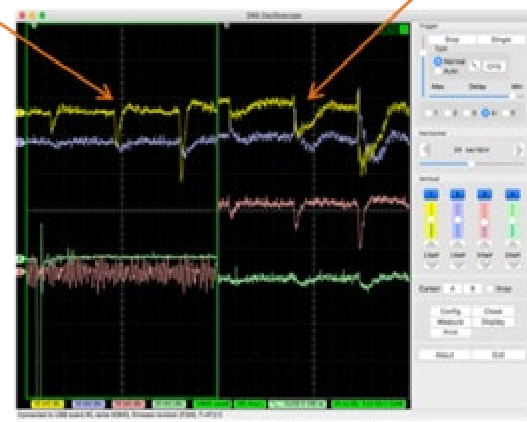
- MCP pulses observed from the resistive anode **interior** plane have a relatively fast rise time, but a typically slow fall time, as charge diffuses across the anode to the ground points.

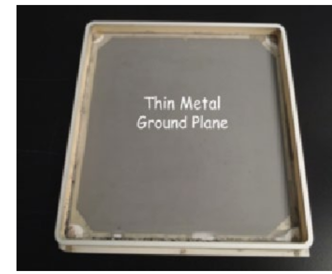
- Resistive anode pulses may begin with an inverted polarity as the charge migrates out.

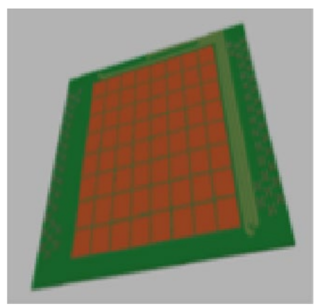
- **External pulses have a fast profile.**

Outside pixel: laser on adjacent pixel

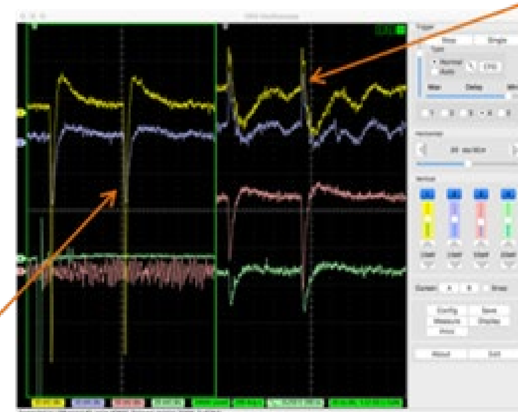
Inside anode



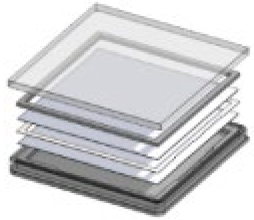




Inside anode



Outside pixel: laser on pixel



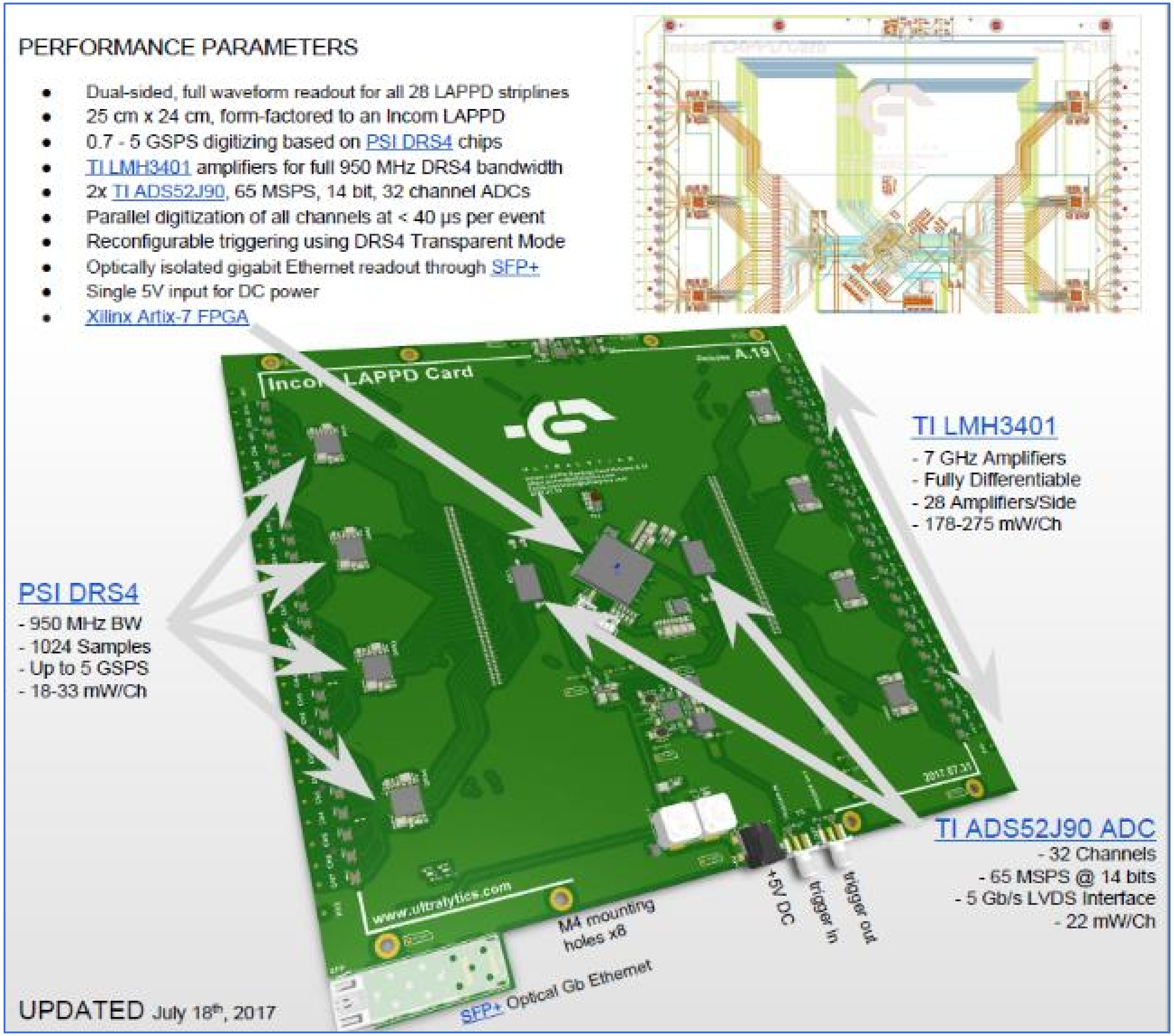
Development of New 10 cm × 10 cm Detector
"High-Rate Picosecond Photodetector" (HRPPD)
First prototypes QIII 2020

Feature	Large Area Picosecond Photodetector (LAPPD™)	High-Rate Picosecond Photodetector (HRPPD)
Application	Picosecond TOF	PET, TOF, UV Imaging
Detector Size	20 cm × 20 cm	10 cm × 10 cm
UHV Package Design	X-Spacer support window -> create dead zones	X-Spacer free -> large effective area
Detector Package	B33 Glass, Alumina Ceramic	Alumina Ceramic
Window	Fused Silica, B33 Glass	UV Fused Silica, MgF_2
λ Sensitivity	200 (300 for B33) - 600 nm	115 - 400 nm
Photocathode	Bialkali	UV optimized Bialkali
MCP Pore Size	20 μm & 10 μm	10 μm
Spacings	B-Field Optimized	B-Field Optimized
Anode	Direct readout of conductive microstrips, or capacitive readout of pixelated anodes	High density pixelated anode with direct or capacitive readout
Lower Tile Assembly	Side walls hermetically sealed to Anode	Side walls hermetically sealed to Anode
Connections	Under sidewall -> 2 side abuttable	Through Anode -> 4 side abuttable with minimum dead space

Ultralytics LAPPD Readout Card

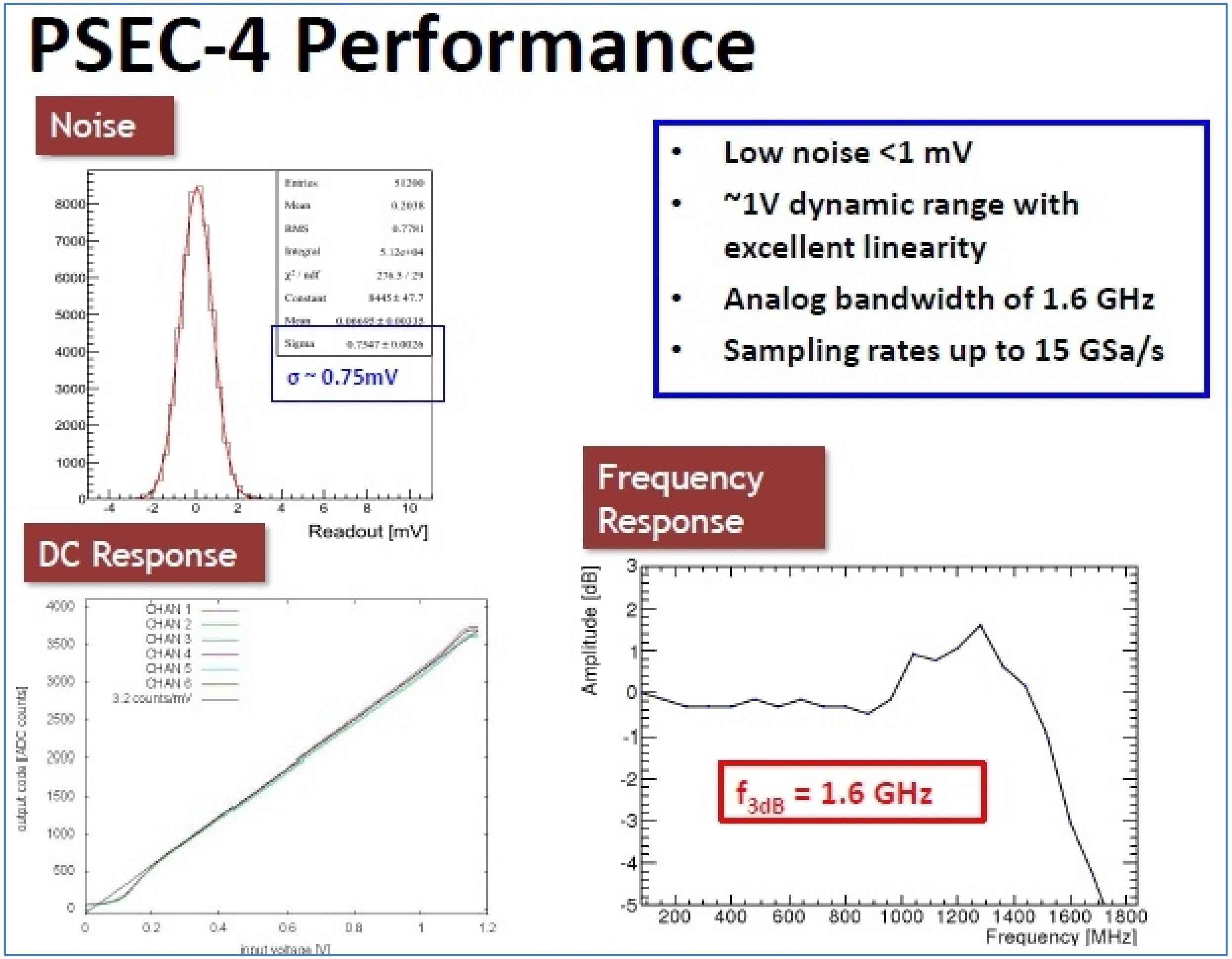
Designers are developing high speed readout boards for LAPPD

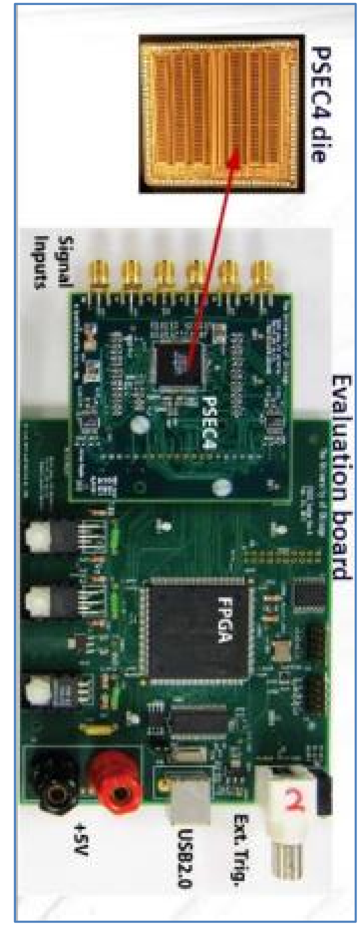
- PSI DRS4-Based Readout solution for Incom LAPPD
- High bandwidth amplifiers coupled to DRS4 to sample pulses at each end of Anode Strips.
- Xilinx Artix7 FPGA provides reconfigurable triggering and control of the DRS4 samples
- Readout of 1024-sample full waveforms on all strip ends,
- 28 strip ends per side, 56 total
- Up to 5 GSPS
- 6-20 Watts not including FPGA



PSEC-4: 15 Gsa/s Sampling Rate

Developed by U of Chicago for LAPPD





Nalu Scientific
Data Acquisition Systems
info@naluscientific.com

High Speed Waveform Digitizer "AARDVARC"

AARDVARC Parameter	Specification (measured)
Process node	130 nm
Channels	4
Sampling Rate	10-14.5GSa/s*
Storage Samples/ch	32768
Analog BW	>1GHz**
Dynamic Range	1.0 V**
Time accuracy	<5 ps***
Readout	Parallel/Fast Serial
ADC bits	12
Power/ch	80 mW*

High performance waveform digitizer at 10-14GSa/s

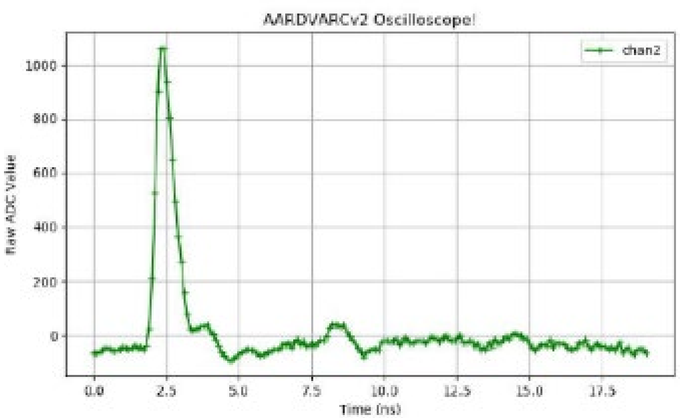
Picosecond timing resolution

Long analog buffer for large experiments (3-5 μs)

On-chip digital control and signal processing

Low cost CMOS technology

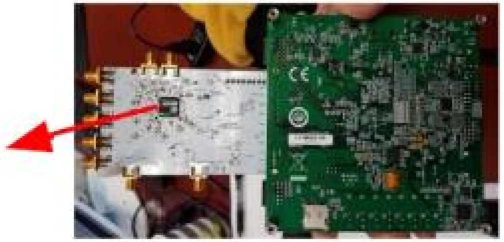
Applications include LAPPD



Sampling a ~500ps pulse at ~10 GSa/s

AARDVARC Test card

Xilinx A7 FPGA dev card



Summary of current and pending LAPPD trials.

PROGRAM TITLE & DESCRIPTION	AFFILIATIONS	2020 – 2021 STATUS
ANNIE - Atmospheric Neutrino Neutron Interaction Experiment	Iowa State	Five delivered; no-cost upgrades pending for tiles delivered in 2018. 5-15 additional tile purchases projected
Neutron Imaging Camera, Nanoguide scintillating polymer	Sandia National Lab (CA), U of Hawaii	Tile #22 Purchased (2018) being evaluated
Fermilab Test Beam Facility, IOTA (Integrable Optics test Accelerator), KOTO (Rare Decays)	U of Chicago, Fermilab	FermiLab Beamline Trials to demonstrate achievable LAPPD TOF resolution and particle identification in a working beamline setting using 10 Gsample/sec PSEC4 waveform sampling electronics system.
WATCHMAN, UK STFC	U. of Sheffield, The University of Edinburgh	Two LAPPD pending delivery for March 2020 delivery
CHESS, WATCHMAN, THEIA	UC Berkeley	Tile #22 being evaluated on loan from Sandia to UC Berkeley. Possible tile upgrade in 2020
SoLID (Solenoidal Large Intensity Device) High rate threshold Cherenkov Light Detection, CD0 mid-2020,	ANL, J-LABS	Testing at J-Labs February 2020, 10-30 LAPPD projected if results are promising.
Neutrino-less Double-Beta Decay	U of Chicago	TBD
EIC PID - eRD14	BNL, ANL, J-LABS, Stony Brook, INFN	FermiLab Beamline Trials proposed for 5/1/2020 using BNL signal readout board and related electronics. Demonstrate high resolution timing and coordinate measurement for correlated Cerenkov photons on event-per-event basis, in the same setup. - Two tiles requested for testing
ESS linac Lund, Sweden (https://essnusb.eu/).	Uppsala University	High power measurement of neutrino oscillation at the second maximum with a underground Megaton Water Cherenkov detector located in a mine some 500 km away from ESS. Several 100,000 LAPPD 20x20 cm2 detectors will be required for 30% coverage.
CERN LHCb RICH phase-2 upgrade	The University of Edinburgh, University of Ferrara & INFN	LAPPD pilot production performance update will be presented by U of Edinburgh at the upcoming CERN LHCb RICH phase-2 upgrade meeting, February 5th 2020
i-MCPs for ECAL upgrade II (CERN LHCb)	Vincenzo Vagnoni Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Bologna	Use of MCP or sealed LAPPD for precision timing of electromagnetic showers in a calorimeter. Secondary EM shower particles are detected by an MCP with signal proportional to the number of secondaries. MCPs are intrinsically very fast and can make a calorimeter with very good timing capabilities
LAPPD based Time of Flight PET (TOF-PET) Sensor	UC Davis PicoRad Imaging, MA Université de Sherbrooke	Preliminary measurements of the energy spectra produced by 511 keV photons and spatial resolution were made at Incom. Good energy resolution was observed that also confirmed for the first time that the device can handle large numbers of scintillation photons within each scintillation pulse without signal saturation. Excellent spatial resolution under 1 mm FWHM was measured in both coordinates. Further testing is underway which will form the basis for NIH R01 or SBIR funding
LAPPD Femtosecond Timing Trials	PicoRad Imaging, MA., & Massachusetts General Hospital (MGH)	LAPPD transit time spread (TTS) timing trials will be conducted 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 using the nGen®-400 platform incorporating Incom's fast neutron sensitive (proton-recoil) Nanoguide™ fiber array and subsequent testing with a conventional flat panel and LAPPD. Pending Phase I SBIR,
LAPPD Read-out Board	Nalu Scientific, LLC, and University of Hawaii	Design and commercialize a fully integrated and high channel count electronic and readout signal processing read-out board suitable for direct connection to LAPPD, targeting very high timing resolution based on NSL's AARDVARC ASIC. Pending SBIR funding
Life Testing of LAPPD, Role of ion feedback.	UT Arlington	1 GEN II on loan, testing underway

LAPPD Features & Typical Baseline Performance

Parameter	Feature / Target Performance	LAPPD #57
Lower Tile Assembly, Body	Borosilicate Glass	
Window	Borosilicate or Fused Silica Glass	
Photocathode (PC) Material	Na_2KSb bi-alkali	
PC Mean QE% @365nm:	**25±2**	24.11 ±1.01
PC Mean QE Spatial Variability, %	± 8	± 4
MCPs	Chevron pair of 203mm X 203mm X 1.2mm thick ALD-GCA-MCPs with 20μ pores	
MCP resistance, typical @975 V, Entry/Exit; MΩ	2 to 20	13.7 / 6.9 MΩ
Position resolution (mm) Along & across strips,	2.4 & 0.76 (Typical, not measured for every tile)	
LAPPD Gain (900-1,000 Volts on MCPs)	**≥ 10^6 to 10^7**	$8.6X10^6$ @975 V/MCP, 100 V on PC
Tile Dark Count Rate	**a few 100Hz/cm² at gains of ~$5X10^6$** and several 100Hz/cm² at gains of ~10^7 at a threshold of $8X10^5$ gain (134 fC)	100 Hz/cm² @950 V/MCP, 100 V on photocathode
Gain Linearity vs. Pulse Rate (KHz/cm²) — 10% decrease in gain =	500	400
Gain Linearity vs. Pulse Rate (KHz/cm²) — 50% decrease in gain =	3000	3900
Single P/E (σ) TTS, picoseconds	**50-70**	65

LAPPD™ Availability

1) Routine "pilot production" supported by our R&D team, is now underway,
    a) LAPPD fabrication doubled in 2019 from the prior years.
    b) Delivery commitments to key programs were completed.
    c) In 2020, Incom will again double the output from 2019.
    d) Capacity can be rapidly and significantly increased when full production is implemented.
2) Prototypes are available for rent or purchase by customers that wish to qualify LAPPD for their applications.

❖ Minimum 12-month renewable term @ (email: mjm@incomusa.com) per month

❖ 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) no cost early LAPPD access to large numbers of early adopters.

LAPPD Procurement: Purchase or Rent

Applies to GEN I LAPPD (direct read-out), GEN II LAPPD (capacitively coupled read-out) and new 10cm² "High-Rate Picosecond Photodetector" (HRPPD),

RENTAL

- Minimum 12-month renewable term @ (email: mjm@incomusa.com) per month.
- 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.

PURCHASE

- Volume discounts for tiles invoiced, and delivered to the same address.
- Provide visibility toward future high volume pricing (hundreds of units, for example).
- **Full Manufacturing High Volume Price Target = $10,000 / LAPPD ($26/cm²)**
- Compare: Photonis Planacon @ $428/cm2

# Sold	LAPPD Unit Price (380 cm² area)	Cost / cm²
1	$ 50,000	$ 131.58
2	$ 47,044	$ 123.80
3	$ 43,440	$ 114.31
4	$ 41,461	$ 109.11
5	$ 40,111	$ 105.56
6	$ 39,095	$ 102.88
7	$ 38,284	$ 100.75
8	$ 37,611	$ 98.98
9	$ 37,038	$ 97.47
10	$ 36,540	$ 96.16
20	$ 36,100	$ 95.00
50	$ 33,334	$ 87.72
75	$ 30,000	$ 78.95
100	$ 28,633	$ 75.35
300	$ 27,702	$ 72.90
500	$ 24,414	$ 64.25
750	$ 23,021	$ 60.58
1000	$ 21,972	$ 57.82

Incom Measurement & Test Workshops

Next Workshop Dates May 12-14, 2020

Workshop #9, Feb. 11-13 2020 • Bob Azmoun, BNL • Junqi Xie, ANL • Brian Jurczyk, Starfire Ind. • Hamid Sabet, MGH • William A. Worstell, PicoRad	Workshop #8, "Stony Brook University" Workshop – November 26, 2019 • Sanghwa Park • Roli Esha • Ross Corliss • Ciprian Gal • Thomas Hemmick • Jinlong Zhang • Mriganka Mouli Mondal	Workshop #7, Sept. 10-12, 2019 • Xianfei Wen, University. of Tennessee, Knoxville • Sun Il Kwon, UC Davis, • Marc-Andre Tetreault, Gordon Center, MGH • Bill Worstell, PicoRad Imaging • Yordanka Ilieva, Jefferson Laboratory
Workshop #6, Feb 12-14, 2019 • Internal Workshop • GEN I Pulse coupling • Incom Personnel Only	Workshop #5, Feb 12-14, 2019 • Jack McKisson, Electronical Eng. JLAB, • Dr. Anatoli Arodzero, Director, Detection Division, RadiaBeam Tech. LLC • Evan Angelico, University of Chicago	Workshop #4, October 9 – 11th, 2018 • Mitaire Ojaruega (NGA-DOD) • Kevin Richard Jackman (NGA-DOD) • Varghese Anto Chirayath, (Physics, UTA)
Workshop #3, May 15-17th, 2018 • Junqi Xie (ANL) • Mickey Chiu, (BNL) • Carl Zorn, (Jefferson Lab) • Wenze Xi, (Jefferson Lab) • Camden Ertley(UC B, now Incom)	Workshop #2, January 24-26, 2018 • Matthew Malek (University of Sheffield) • Matt Wetstein (ISU – ANNIE Program) • Lindley Winslow, Julieta Gruszko (MIT, NuDot) • Albert Stebbins (Fermilab, Cosmology Group) • Andrew Brandt, Varghese Chirayath (UTA) • Klaus Attenkofer (BNL, now Scientific Director at ALBA Synchrotron)	Workshop #1, November 13 – 16th, 2017 • Kurtis Nishimura (U of Hawaii / Sandia) • Josh Brown (Sandia) • Julieta Gruszko (MIT)

Summary & Conclusions

I. GEN I - Incom LAPPD Pilot Production is now underway

   A. GEN I direct read-out strip line anode - available today!
   B. Gen-II with resistive interior anode and capacitive coupled patterned signal board – Under development, prototypes available.
   C. "Typical" performances meet early adopter needs:
      - **Gain ~10^7**
      - **Mean QE ~ 25±2** @ ~90% uniformity
      - Time Resolution **50-70 Psec (σ),** and
      - **2.4 & 0.76 mm** spatial resolution (GEN I or GEN II!)

II. Design optimization is underway for lower TTS, and enhanced B-field tolerance includes 10-micron ALD-GCA-MCPs, and MCP gap spacing.

III. We support early adopters to make LAPPD available for test & evaluation.

Current Funding & Personnel Acknowledgements

- **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
- **NASA 80NSSC19C0486**, Phase I- Improvement of GCA center to edge of high spatial/timing resolution applications
- **DOE Award No. DE-SC0020578**, Phase I - High Rate Picosecond Photodetector (HRPPD) being developed for Nuclear Physics
- **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.

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