Large Area Picosecond Photodetector (LAPPD™) Offers Fast Timing for NP and Medical Imaging

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Incom, Inc., Charlton Massachusetts, USA

FATA2019

FAst Timing Applications for Nuclear Physics and Medical Imaging

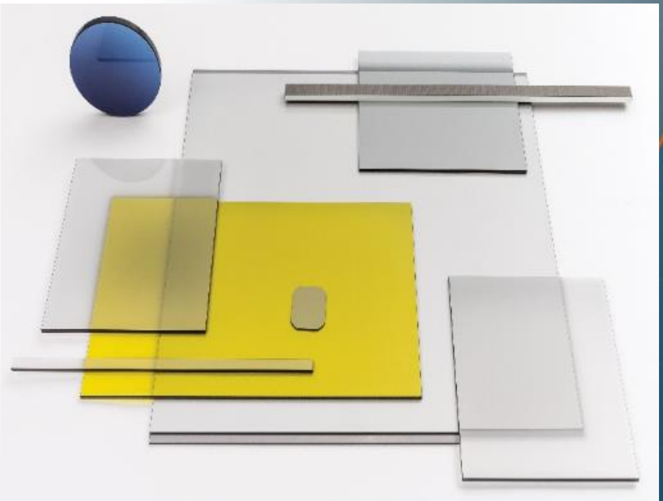
INCOM

BRIGHT IDEAS

Incom Inc. - Enabling the Vision of Tomorrow

Founded 1971 (Fused Fiber Optics)
Long history of Innovation
~220 Employees
Three facilities:

- Incom East (2) - Charlton, MA
  (includes R&D Pilot Production Facility)
- Incom West - Vancouver, WA



Incom Inc. – Enabling the Vision of Tomorrow

Medical

- Digital X-Ray
- Mammography
- Panoramic and Intra-oral X-Ray
- DNA sequencing
- Filtration

Display

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

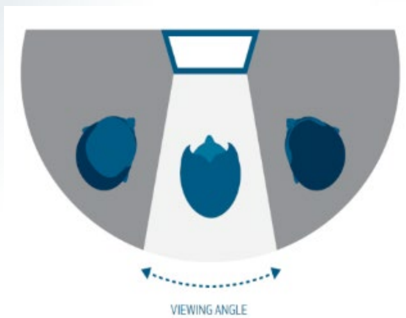
Defense

- Night Vision
- Biometrics
- Neutron Detection

Detector

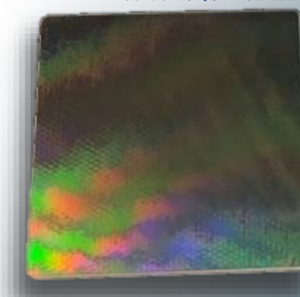
- Particle Identification
- Electron Spectroscopy
- Ion Spectrometry
- Space Flight Instrumentation

Large Fiberoptic Face Plate for medical diagnostics



DARC glass privacy filter

Night Vision



Plano MCP
53mm x 53mm

LAPPD (MCP-PMT)
200mm x 200mm

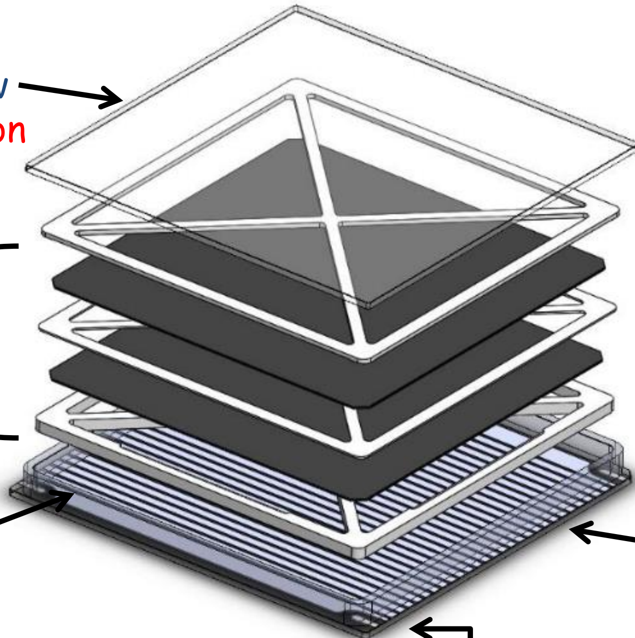
Curved MCP
25mm x 120mm

LAPPD™ Design

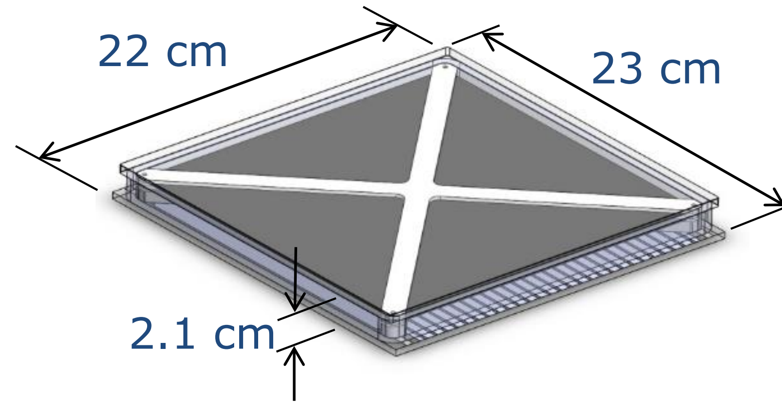
Fused silica or Borosilicate window with photocathode on inside surface

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

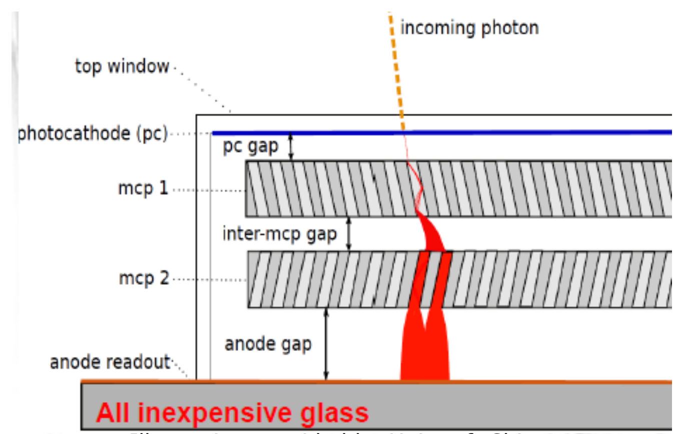
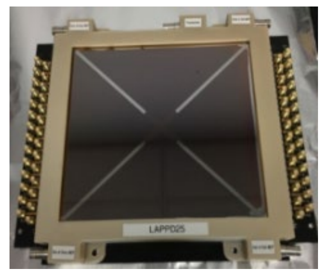
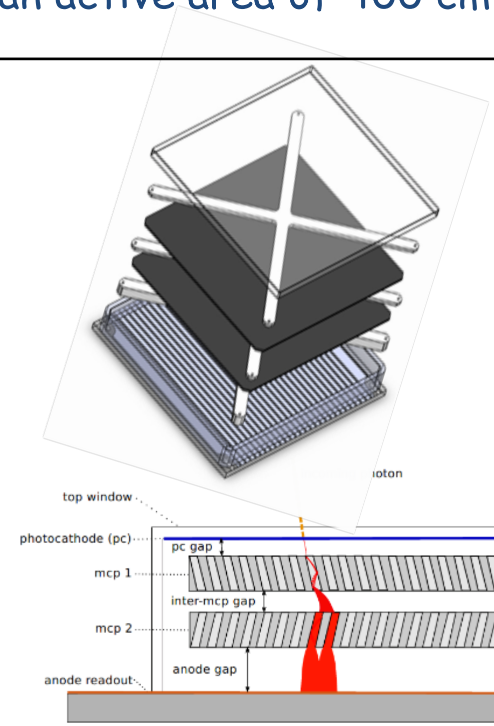


Illustration provided by Univ. of Chicago

LAPPD Advantages

LAPPD™ is an MCP based photodetector, capable of imaging with single-photon sensitivity at high spatial and temporal resolutions in a hermetic package with an active area of 400 cm^2.



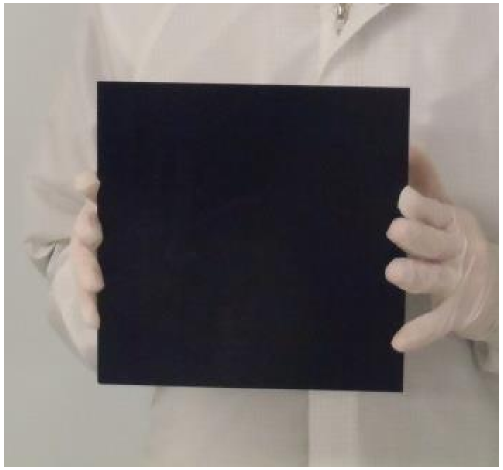


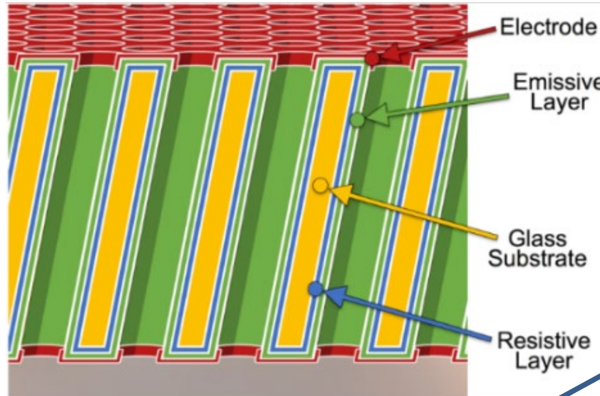
- Single Pixel
- Nanosecond resolution
- High background noise
- Sensitive to magnetic fields
- Small coverage
- Bulky

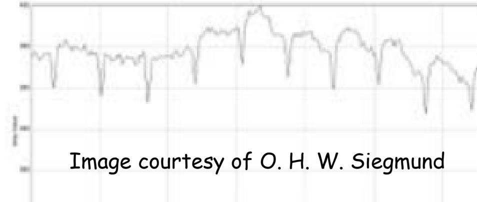
- Millimeter spatial resolution
- ≤50 picosecond (σ) TTS
- Very low noise
- Large Area (16X Planacon)
- Compact
- Operates in magnetic field

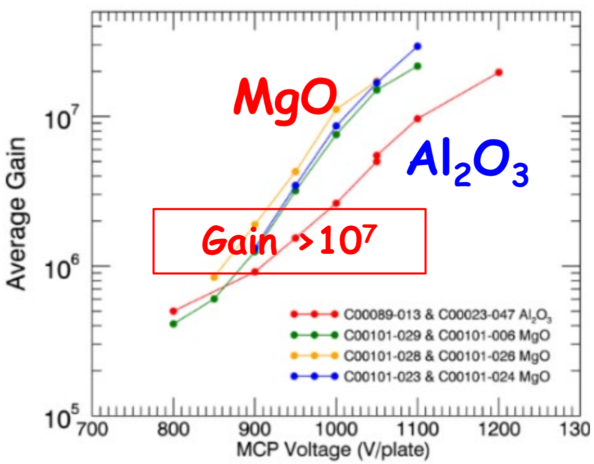
- 20μ Chevron Pair ALD-MCPs
- 28 silver strip Anode, 50 Ω
- Large Area, No Feedthroughs
- Borosilicate Glass Housing
- Fused Silica Glass Window

Incom ALD-GCA-MCP Performance









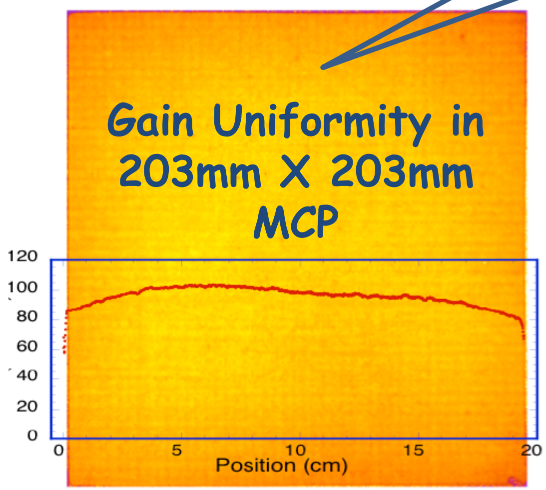


Fig. 8: Average gain image "map" (<15% overall variation). 8" MCP pair 20μm pore, 60:1 L/D ALD-MCP pair. ~7 × 10^6 gain, 0.7mm inter-MCP gap/200V.

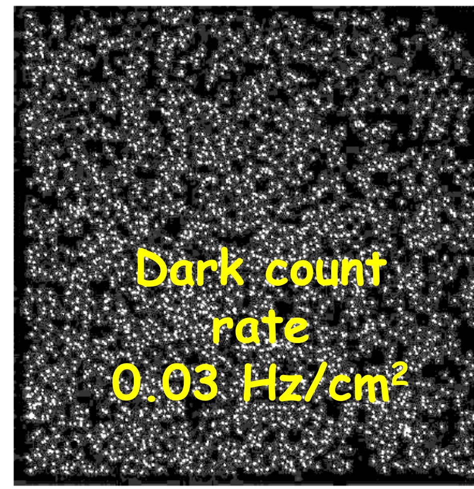
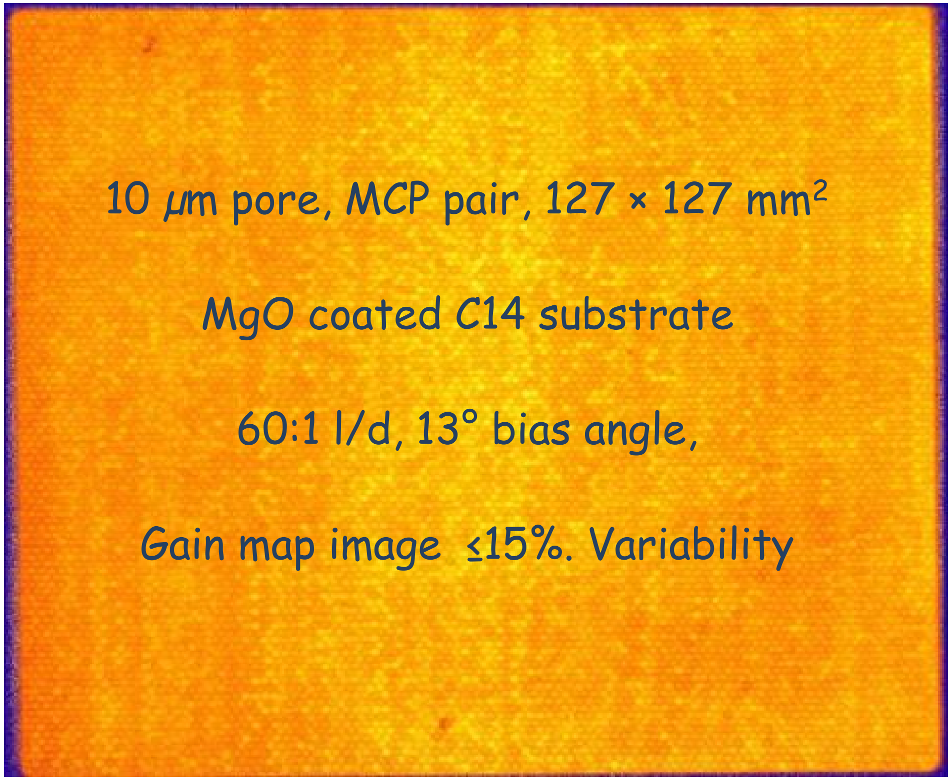
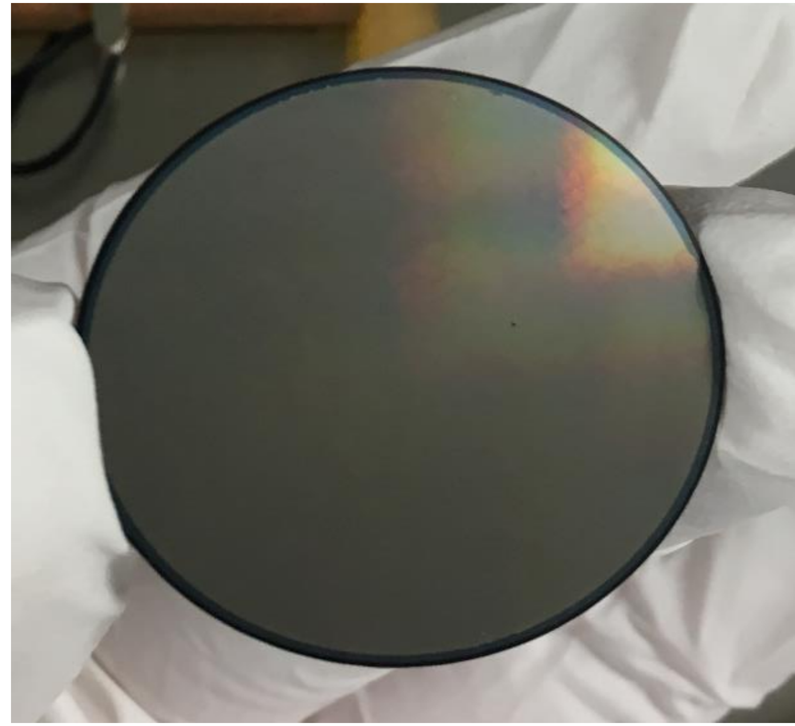


Fig. 9: 20 cm ALD MCP pair background, 500 sec, 0.03 events/cm²/sec[1]. Overall background ~8× better than standard glass MCPs (less K^{40}),

Incom's ALD-GCA MCPs are an enabling feature of LAPPD and are offered as a separate product line. Standard dimensions DIA33mm, SQ53mm, SQ60mm, SQ127mm, SQ200mm. Curved MCPs.

Incom's ALD-GCA-MCPs

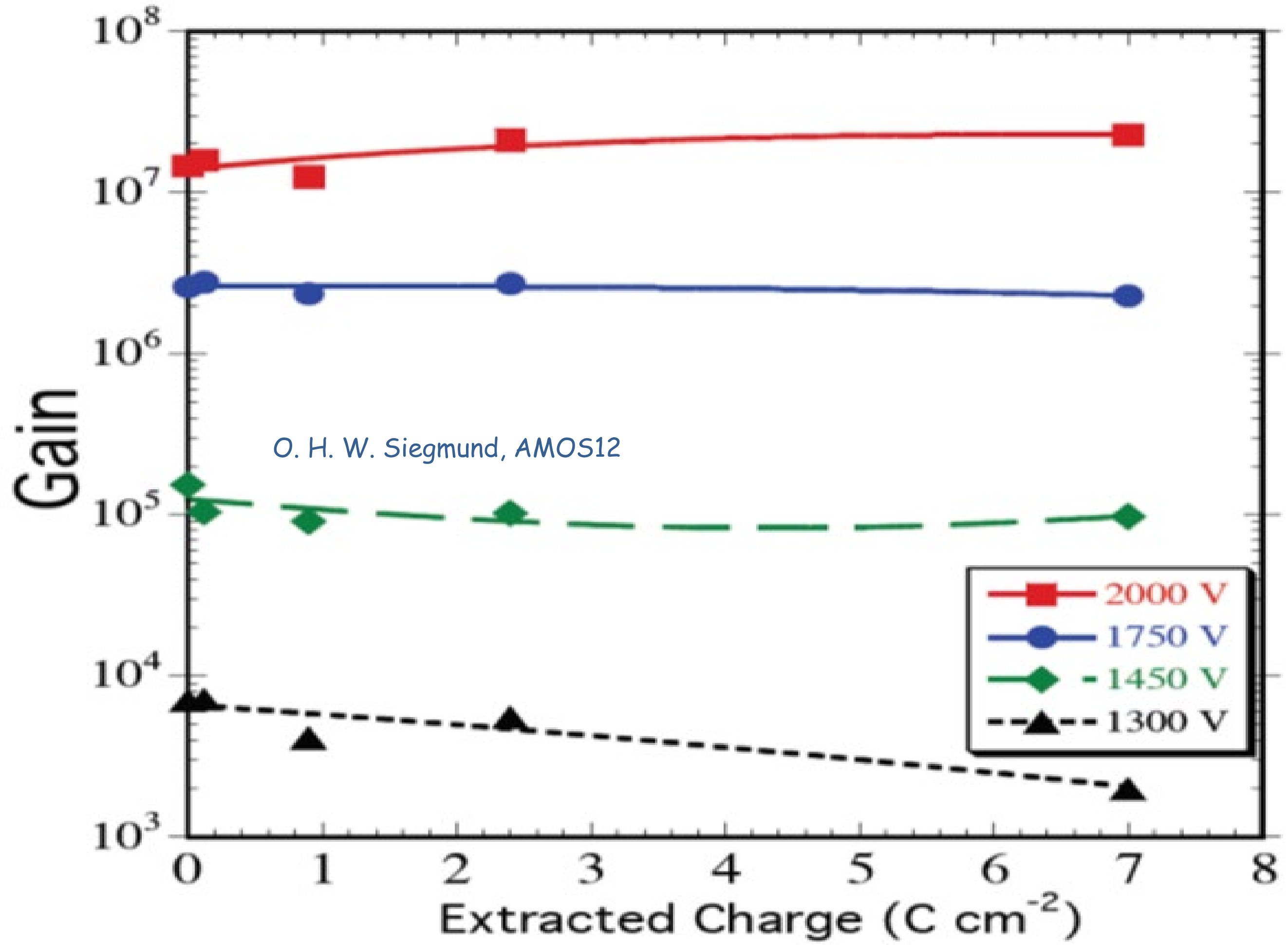




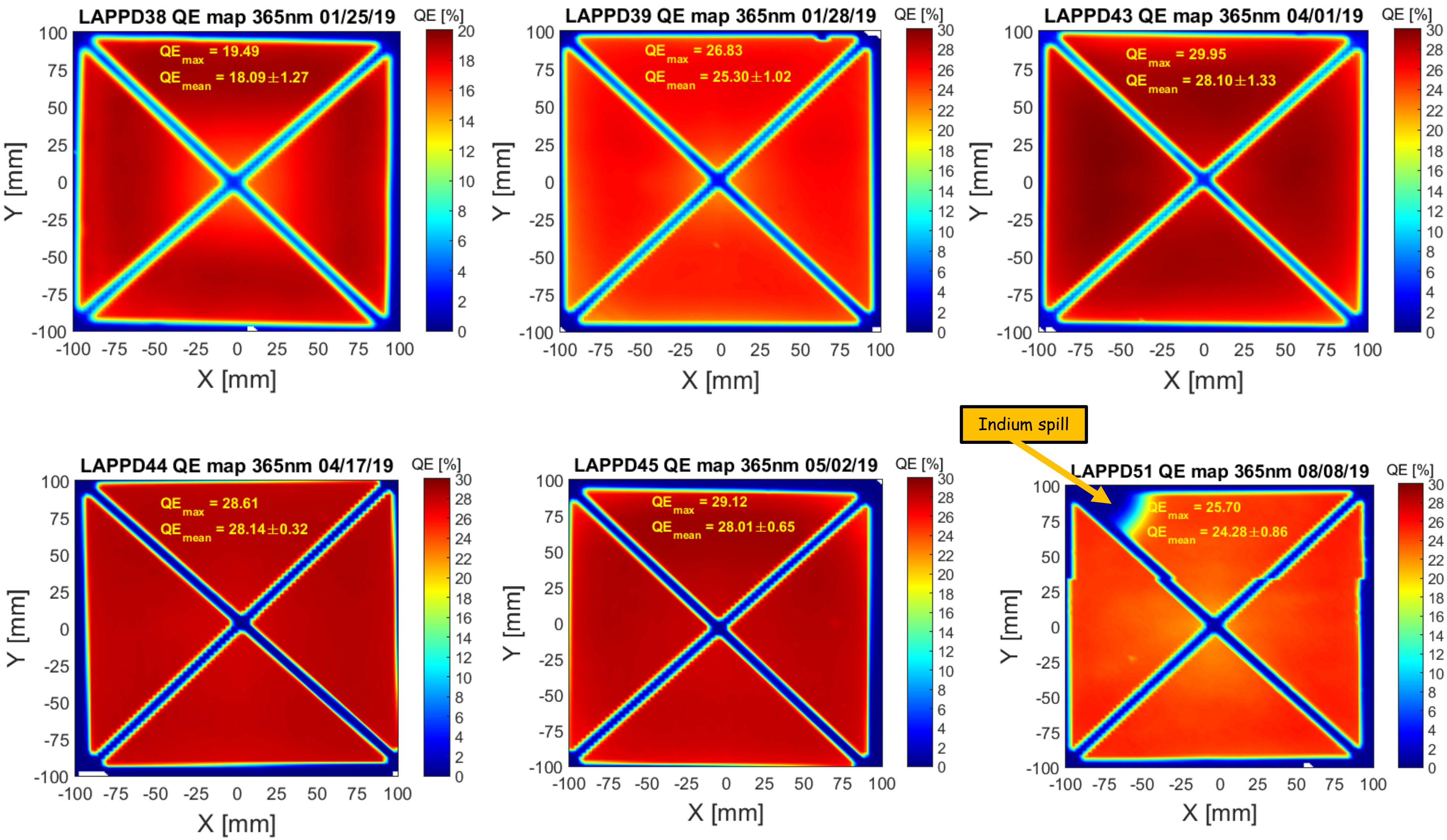
6 μm pore ALD-GCA-MCP, 63% open area, 60:1 L/d, C5 Substrate, March 1, 2019

Standard dimensions DIA33mm, SQ53mm, SQ60mm, SQ127mm, SQ200mm. Curved MCPs.

ALD-GCA-MCP Gain vs. Extracted Charge

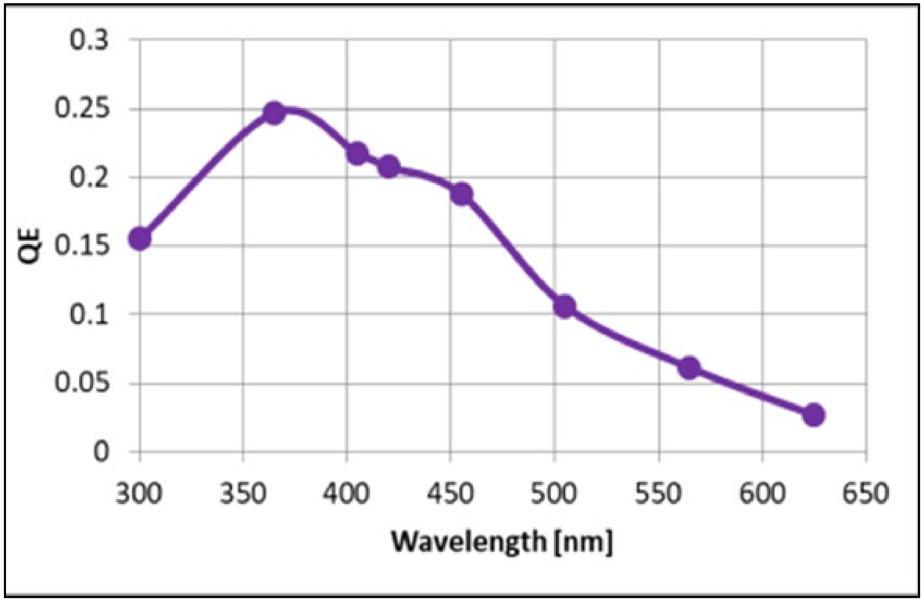


Photocathode QE and Uniformity

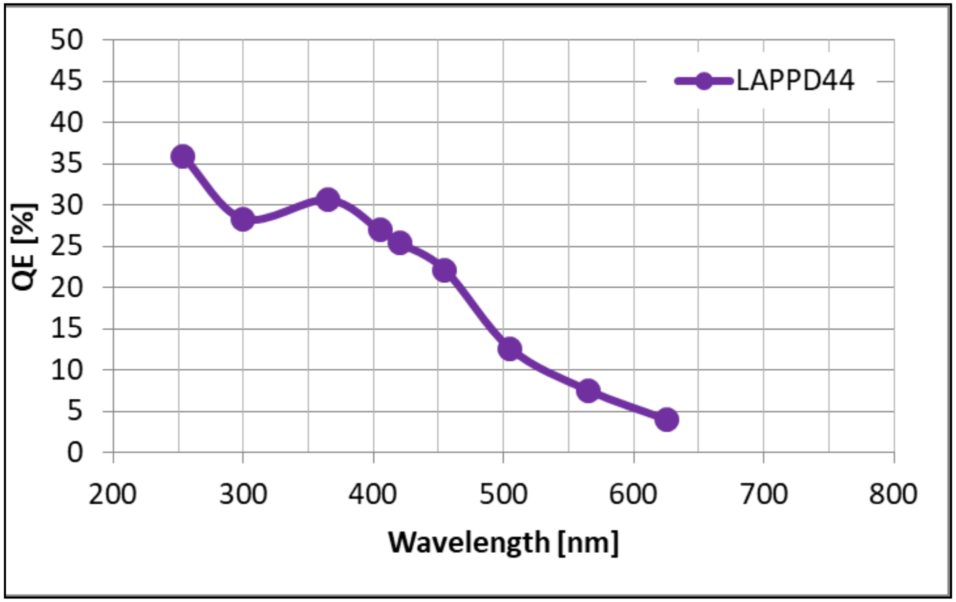


Large area PC process routinely yields QE ≥20%
with ≥ 90% uniformity demonstrated in recently sealed LAPPDs

LAPPD™ Photocathodes - Na_2KSb



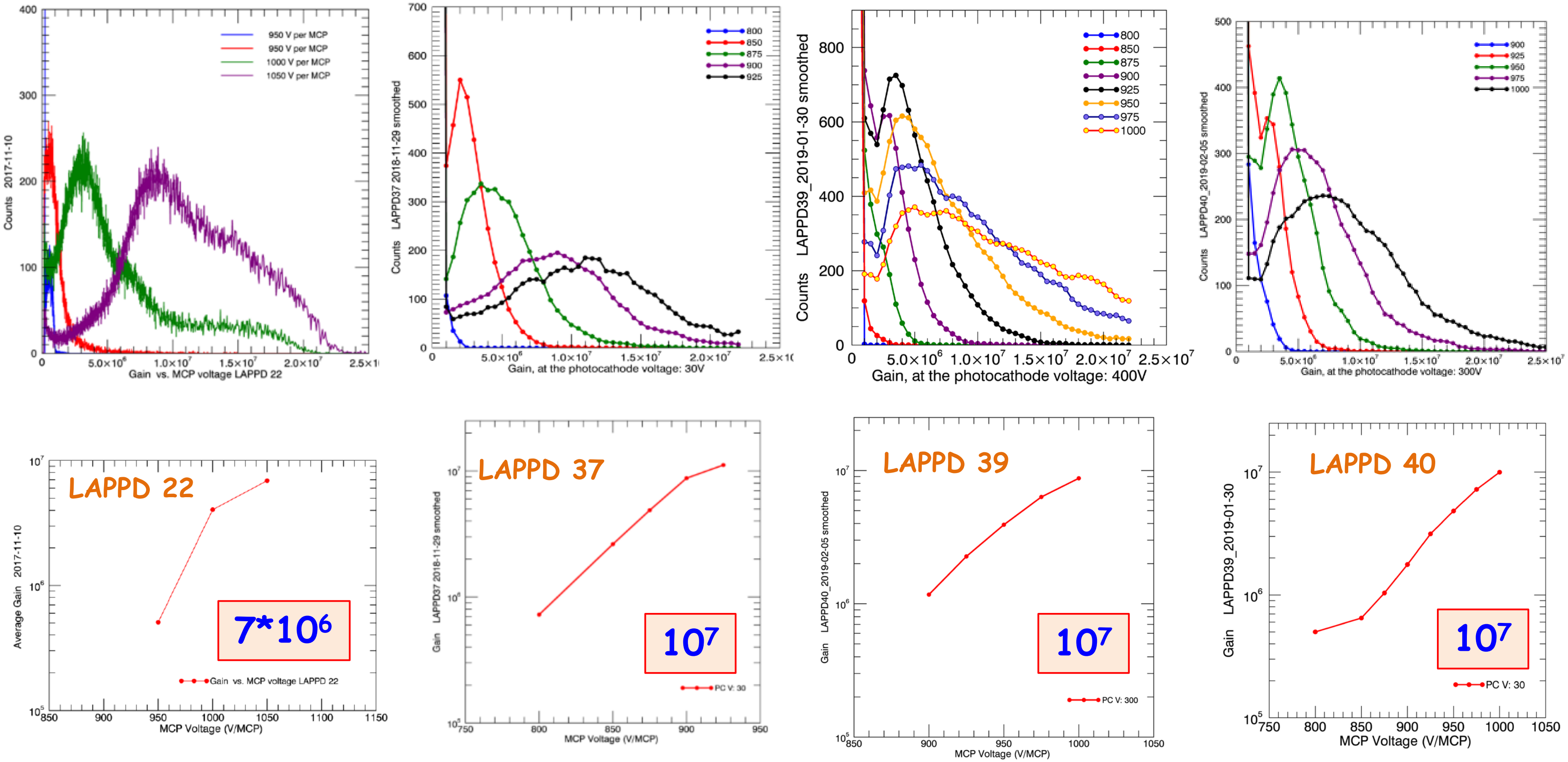
Borosilicate Window



Fused Silica Window

Higher QE at shorter wavelengths with UV grade fused silica Window

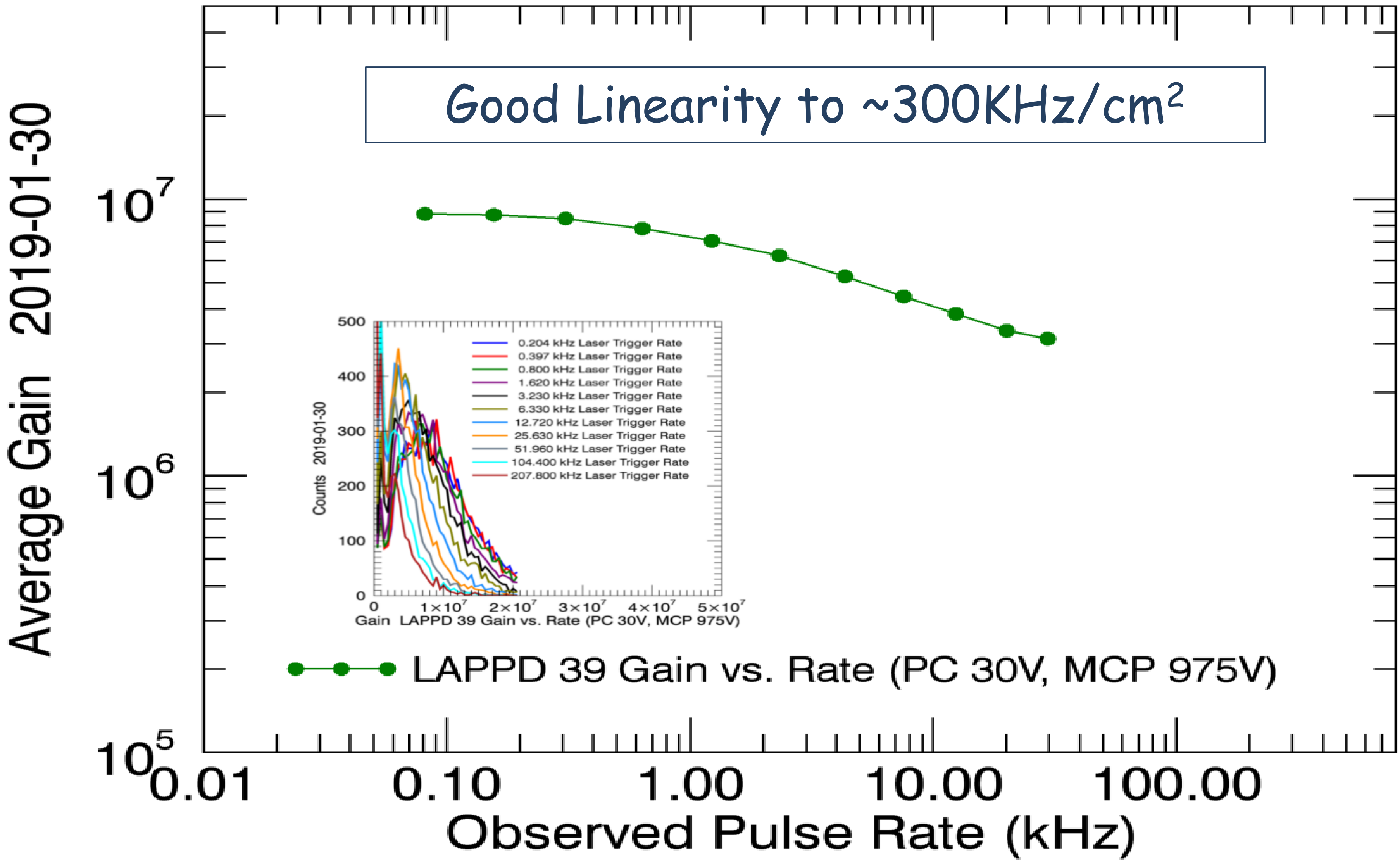
LAPPD Gain



Gain ~10^7 achieved at relatively low MCP voltage of 950V-1000V per plate

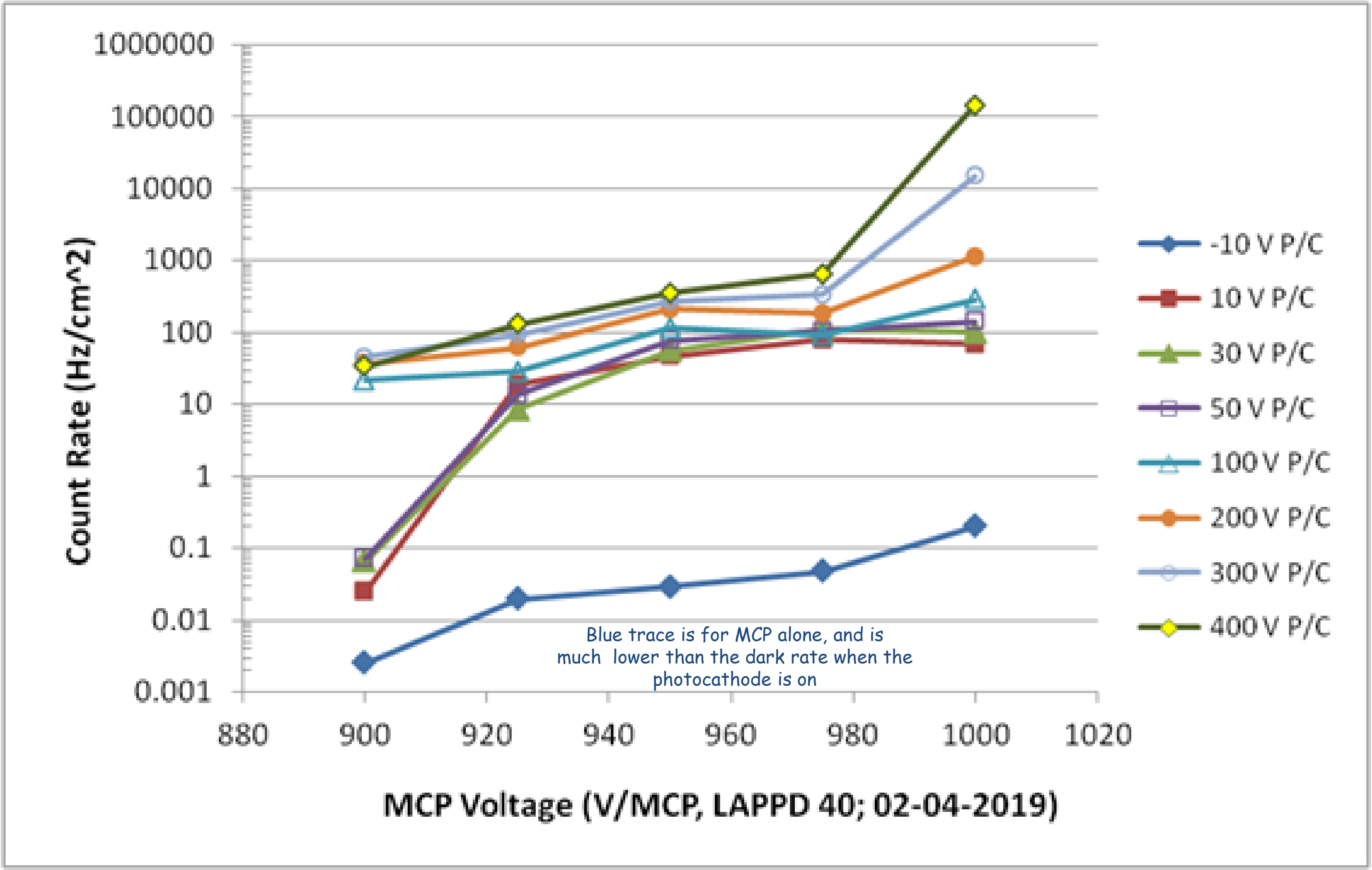
Read out with DRS4 evaluation board or CAEN waveform digitizers

Gain vs. Rate



Good Linearity to ~300KHz/cm²
Average Gain 2019-01-30
10⁷
10⁶
10⁵
0.01
0.10
1.00
10.00
100.00
Observed Pulse Rate (kHz)
LAPPD 39 Gain vs. Rate (PC 30V, MCP 975V)
Counts 2019-01-30
0.204 kHz Laser Trigger Rate
0.397 kHz Laser Trigger Rate
0.800 kHz Laser Trigger Rate
1.620 kHz Laser Trigger Rate
3.230 kHz Laser Trigger Rate
6.330 kHz Laser Trigger Rate
12.720 kHz Laser Trigger Rate
25.630 kHz Laser Trigger Rate
51.960 kHz Laser Trigger Rate
104.400 kHz Laser Trigger Rate
207.800 kHz Laser Trigger Rate
Gain LAPPD 39 Gain vs. Rate (PC 30V, MCP 975V)

Dark Count Rate



Dark count rate ~200 Hz/cm^2 @ 975V, gain 7*10^6, phe extraction voltage 200V

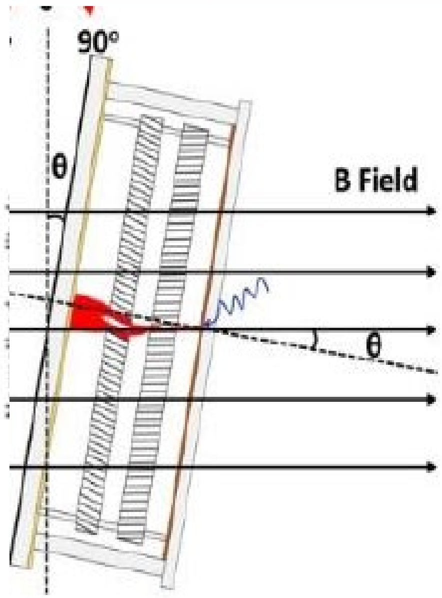
Dark count rate ~1000 Hz/cm^2 @ 1000V, gain 10^7, phe extraction voltage 200V

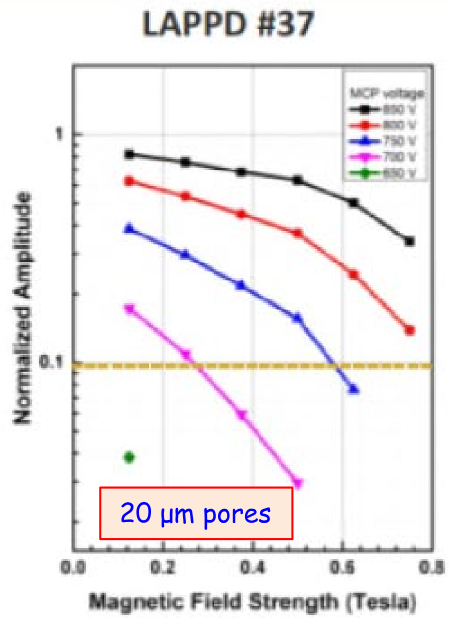
Preliminary LAPPD & Small Format Tile B-Field Testing

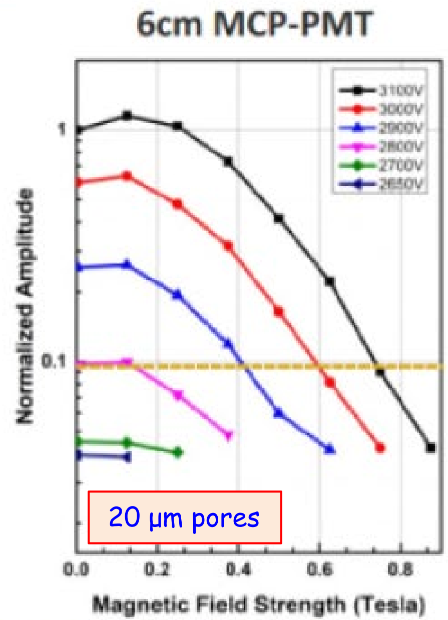
Bill Worstell (PI), Mark Popecki, Cole Hamel, Bernhard Adams, Bob Wagner, Junqi Xie, Ed May

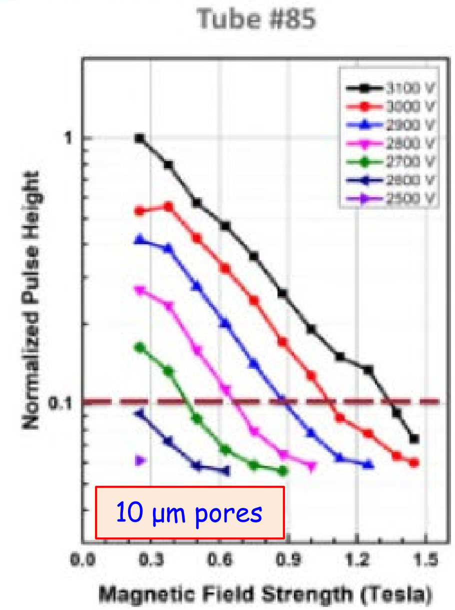
12/14/2018 B-Field Testing LAPPD #37

ANL 6cm Tile, 10 & 20μ MCPs

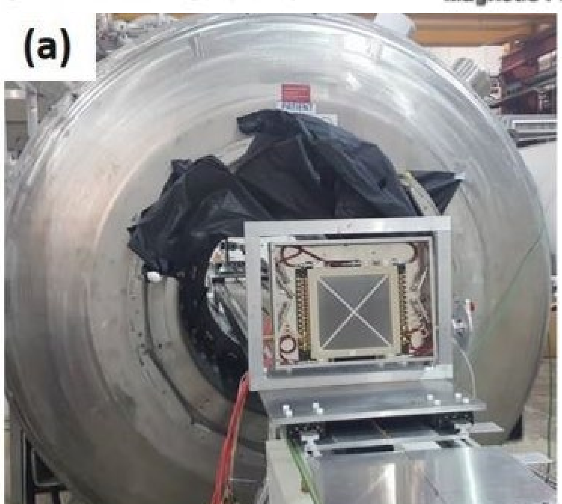








(a)



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

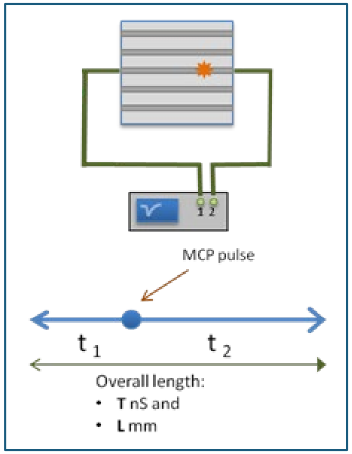
~1.3 T with 10 microns

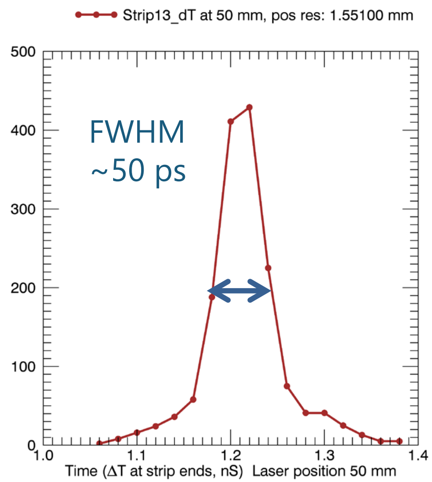
Further Analysis Pending

Phase II SBIR Targets Design Optimization

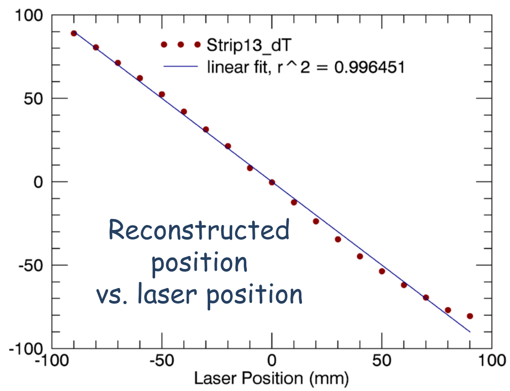
Gen-I LAPPD™ Spatial Resolution

ALONG STRIPS

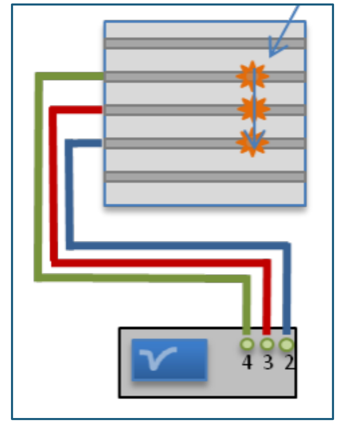


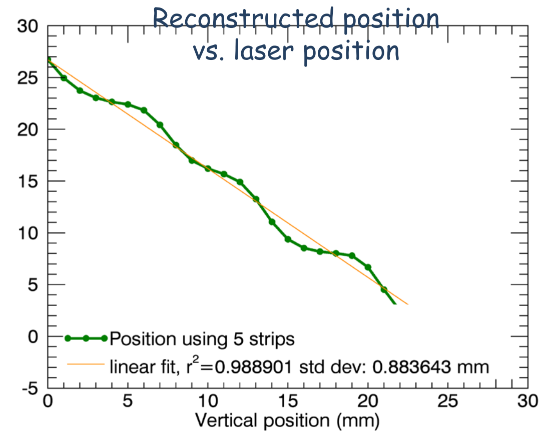


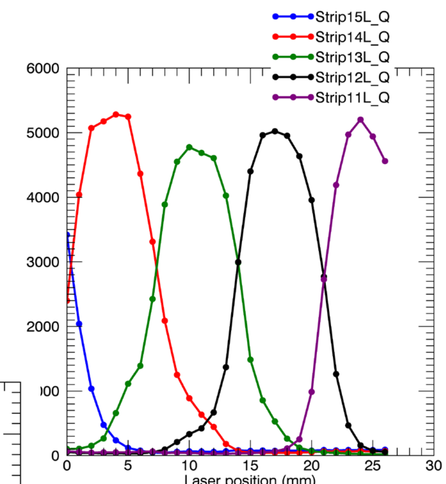
DRS4 waveform sampler:
Position by Δt for signal at both ends of single strip.



ACROSS STRIPS







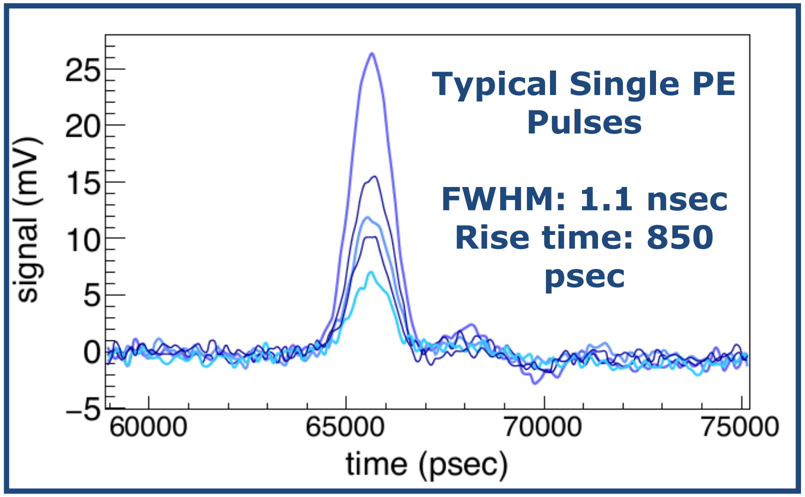
Center of mass for 5 adjacent strip signals.

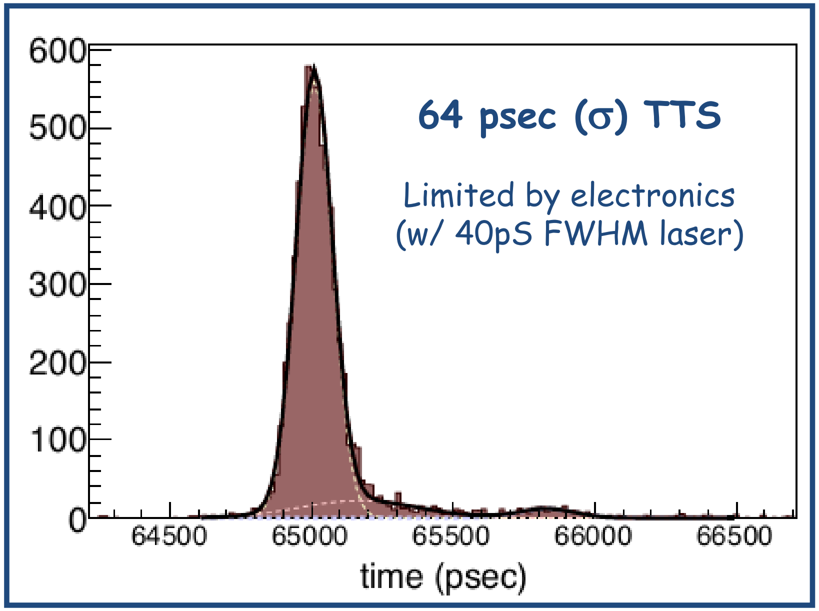
Resolution= 1.3 mm

Resolution= 0.76 mm

Time Resolution LAPPD #25

Testing at Iowa State University, Matt Wetstein, ANNIE Program





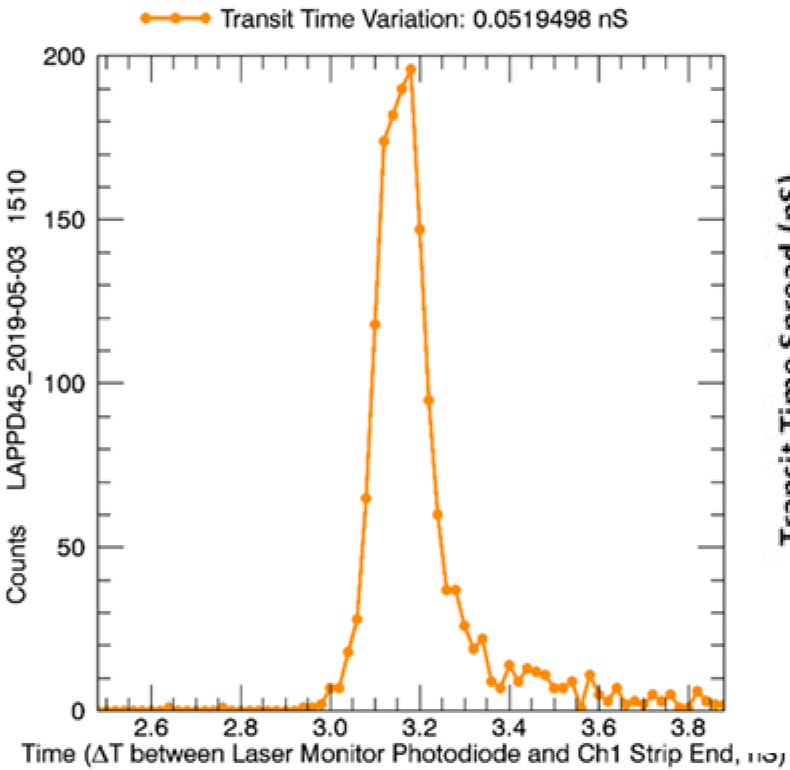
"Single PE time resolutions in the 50–60 ps (σ) are observed consistent with those of commercial MCPs with comparable pore structures.

Differential time resolutions are measured as low as 5.1 ps, with the large signal limit extrapolating below 2 ps".

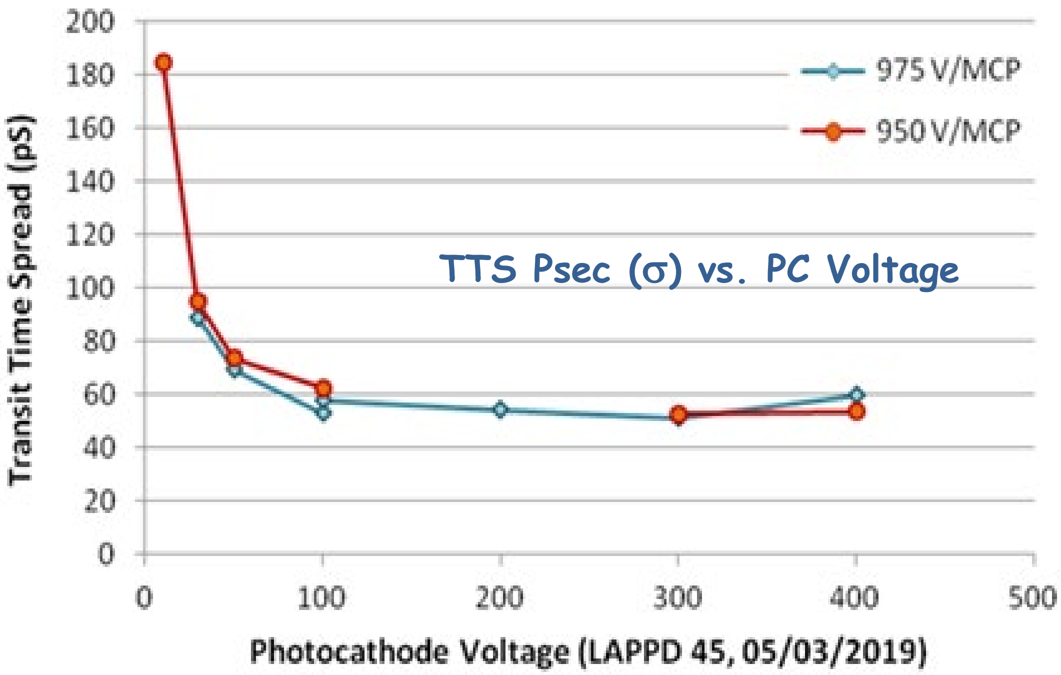
Nuclear Instruments and Methods in Physics Research A 795 (2015) 1–11

Time Resolution LAPPD #45

Testing at Incom Inc.



The transit time variation
Single PE, 975 V/mcp, 300 V on PC

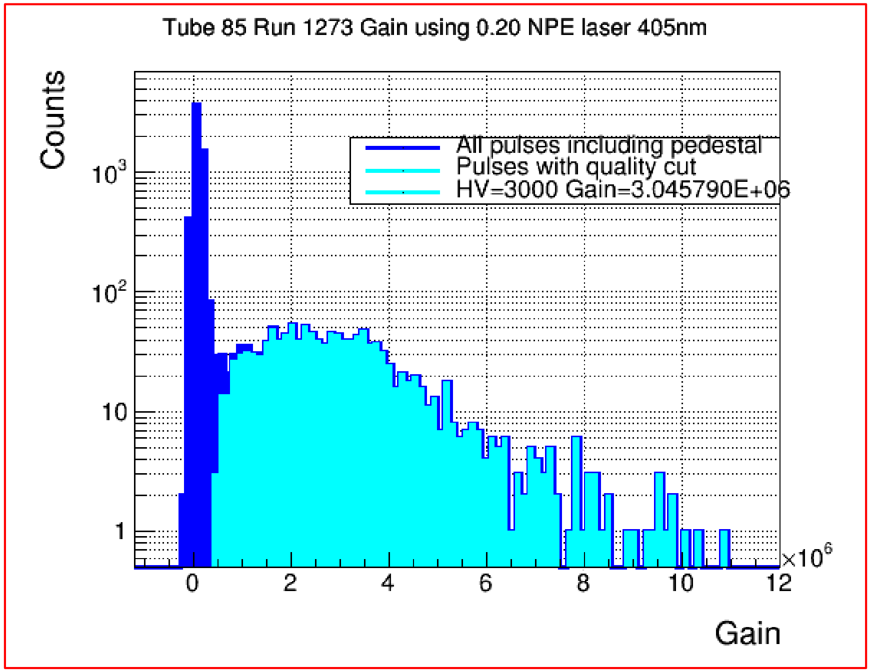


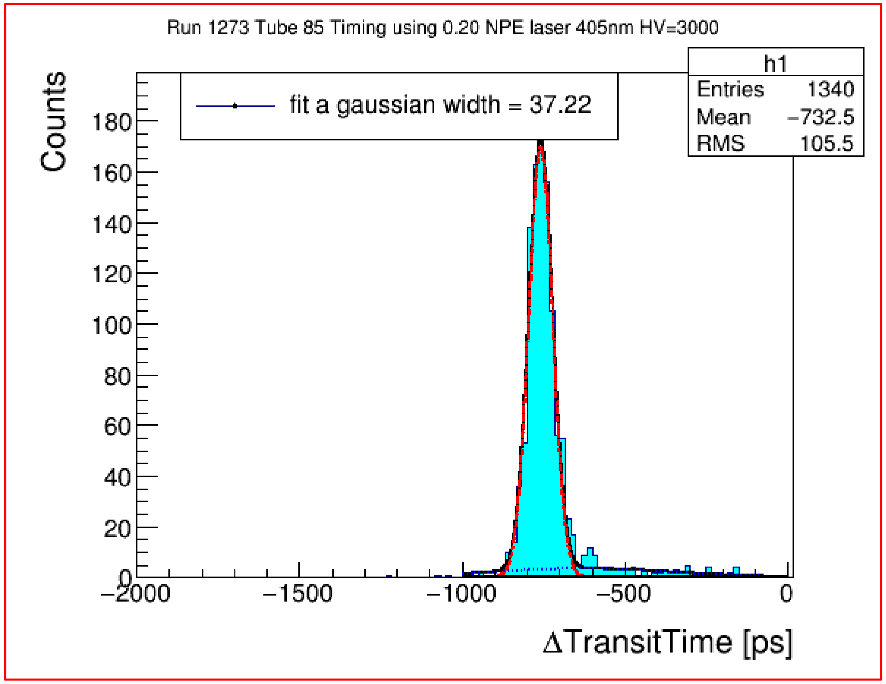
The transit time variation increased at 975 V/MCP and photocathode voltages above 300 V, where dark rates also increased.

Optimal Transit Time Variation = 52 pS (σ), single P/E

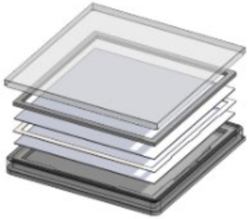
Argonne 6cm MCP-PMT with pair of INCOM 10 μm MCP
Smaller pore size, without gap optimization implemented

Greatly improved rise time and timing resolution as pore size reduced





Performance	20 um pore (tube #79)	10 um pore (tube #85)
Rise time	557 ps	457 ps
Gain	6.1×10^6	3.0×10^6
Timing resolution (SPE)	57 ps (σ)	37 ps (σ) (laser start jitter: σ_{laser} ~30ps)



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

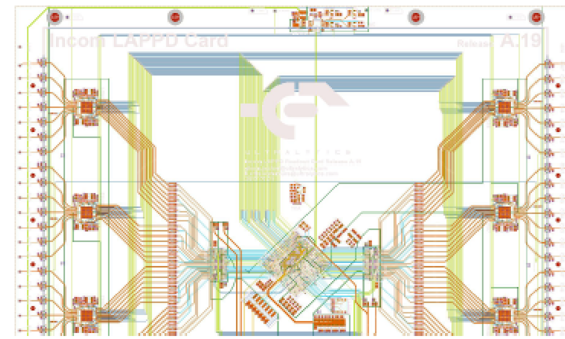
Ultralytics LAPPD Readout Card

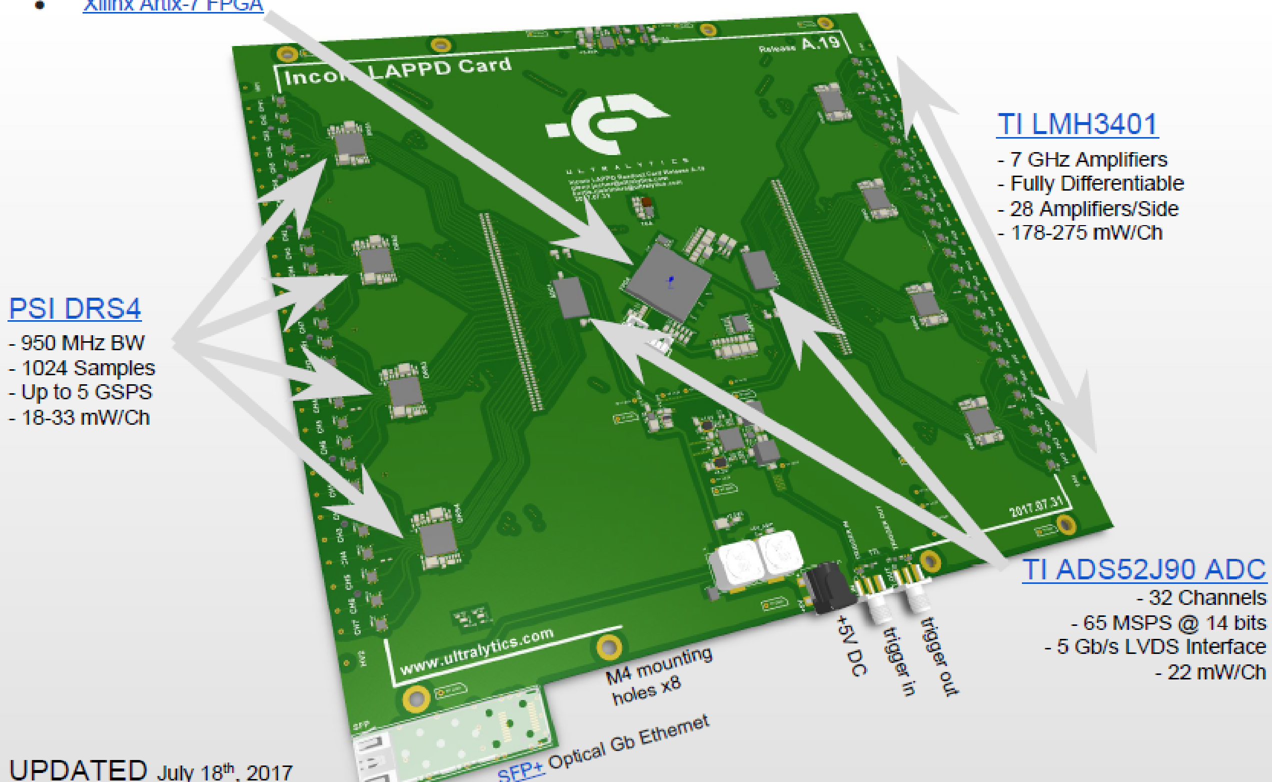
Designers are developing high speed readout boards for LAPPD

- 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

PERFORMANCE PARAMETERS

- Dual-sided, full waveform readout for all 28 LAPPD striplines
- 25 cm x 24 cm, form-factored to an Incom LAPPD
- 0.7 - 5 GSPS digitizing based on PSI DRS4 chips
- TI LMH3401 amplifiers for full 950 MHz DRS4 bandwidth
- 2x TI ADS52J90, 65 MSPS, 14 bit, 32 channel ADCs
- Parallel digitization of all channels at < 40 μs per event
- Reconfigurable triggering using DRS4 Transparent Mode
- Optically isolated gigabit Ethernet readout through SFP+
- Single 5V input for DC power
- Xilinx Artix-7 FPGA

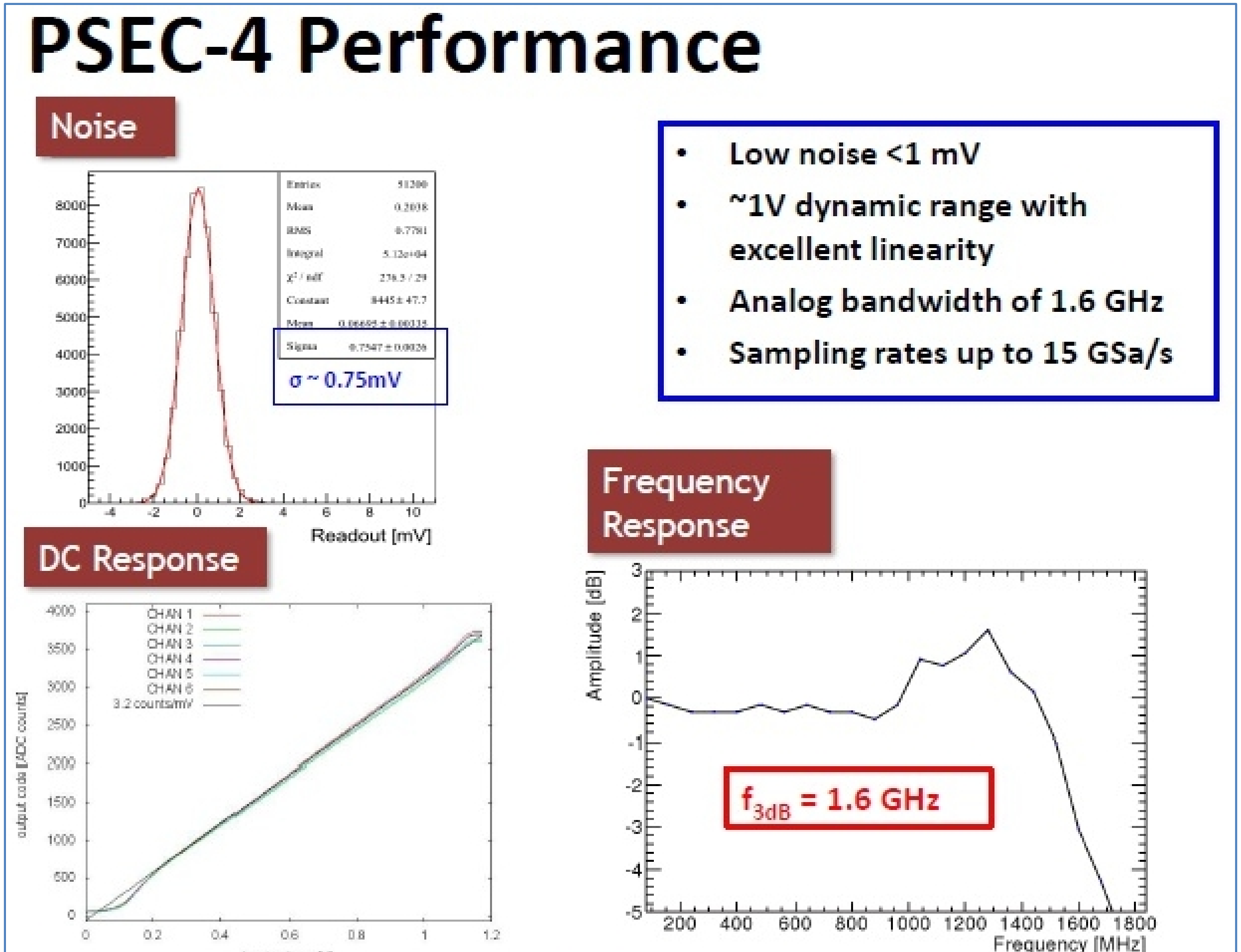


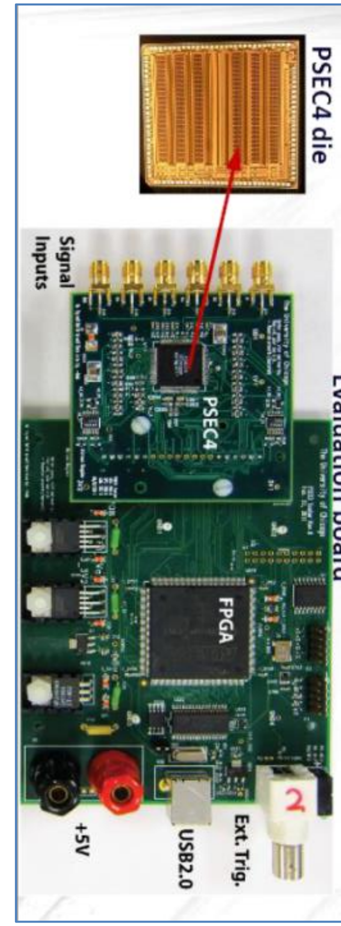


UPDATED July 18th, 2017

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

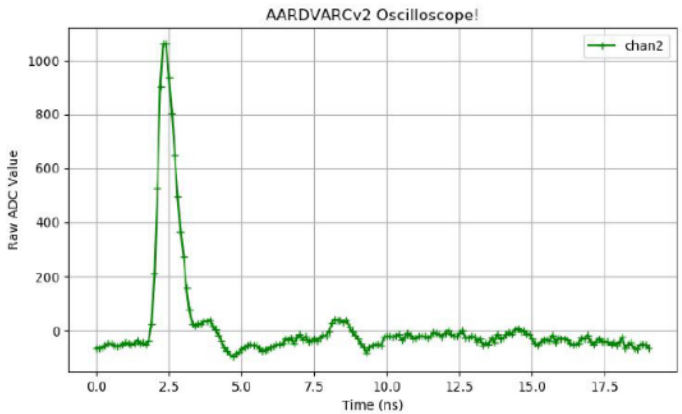
Picosecond timing resolution

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

On-chip digital control and signal processing

Low cost CMOS technology

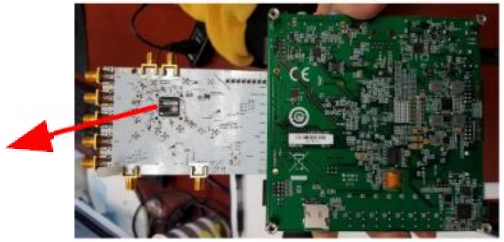
Applications include LAPPD



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

AARDVARC Test card

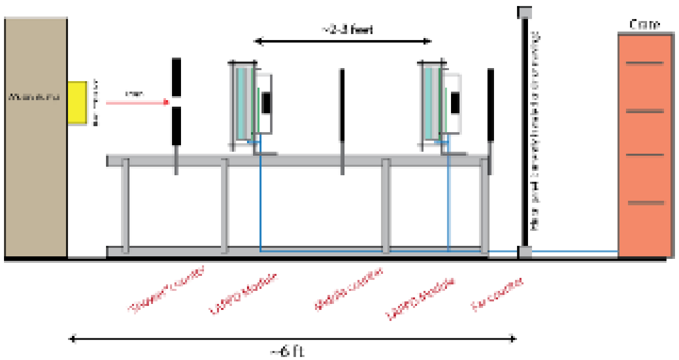
Xilinx A7 FPGA dev card

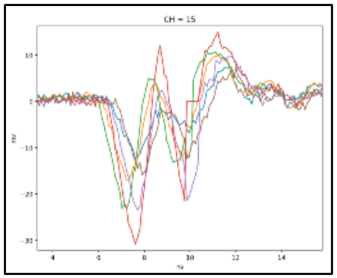


Fermilab Test Beam LAPPD Trials July 2-6, 2019

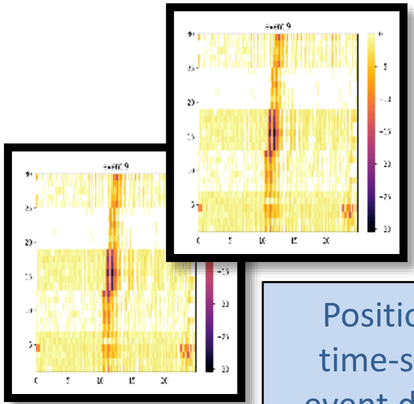
A Collaboration between U of Chicago, FNAL, Incom Inc., and the ANNIE Program

Test Beam trials of LAPPDs #42 and #43 during the week of July 2-6, 2019, prior to beam shutdown. Results still pending: testing resulted in measurement of ~1000s of charged particle events synchronized to beam spills with two LAPPD and 120 channels of PSEC4 readout.

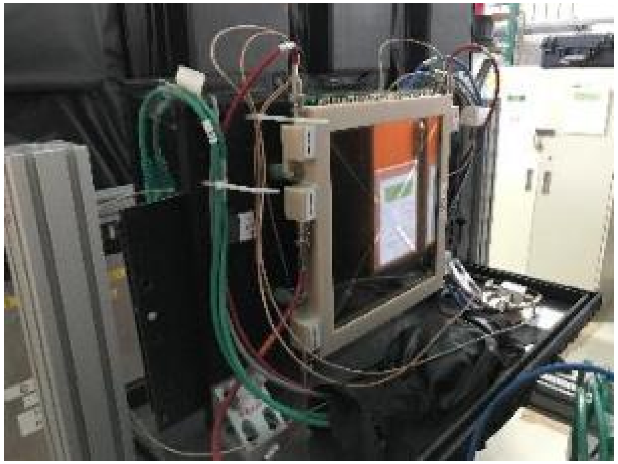




PSEC4 waveforms (UC Tile #31)



Position vs time-series event display



Goals:

- Provide particle ID for all particles in the test-beam facility as a permanent diagnostic tool
- Factor of >100 improvement on present TOF system
- Fully characterize LAPPD sensitivity/resolution to charged particles

With support of the DOE, Office of HEP, Dr. Helmut Marsiske

JLABs Telescope Light Gas Cherenkov for SoLID

Dr. Junqi Xie, Dr. Zein-Eddine Meziani (ANL), Alexandre Camsonne, Mark Jones (JLABs), Dr. Mark Popecki, Dr. Camden Ertley (Incom Inc)

Background:

Unprecedented luminosity for SoLID imposes new requirements on detector technology, trigger design and data acquisition.

Goals and objective:

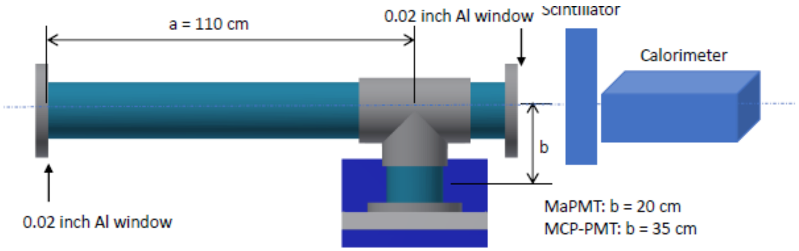
1. Investigate hit patterns for Cherenkov photons that belong to good particle tracks.
2. Understand how the MAPMTs and MCP-PMT/LAPPD behave in a very high-rate environment.
3. Evaluate DAQ electronics in such environment.

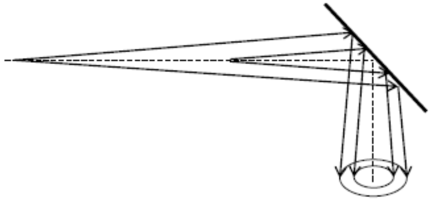
Setup:

1. LAPPD #41 – On Loan from Incom Inc.
2. Hall C "open" environment
3. Particles: scattered electrons, photons, neutrons
4. Radiator medium: CO_2
5. Trigger: scintillator & calorimeter
6. DAQ: FADC

Preliminary Indications:

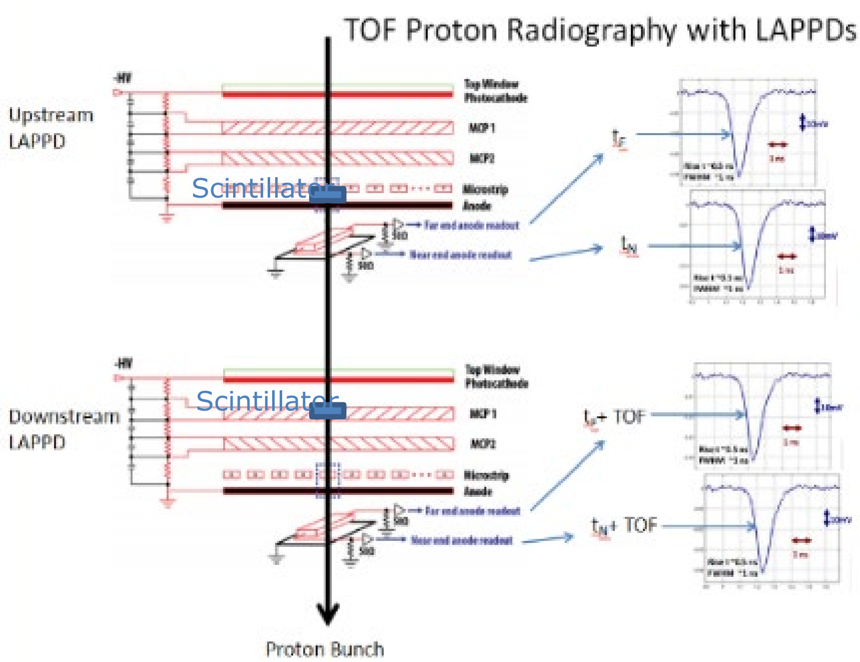
Confirmed Cherenkov event with multiple adjacent stripline readout (Nhit = 5 or 6)

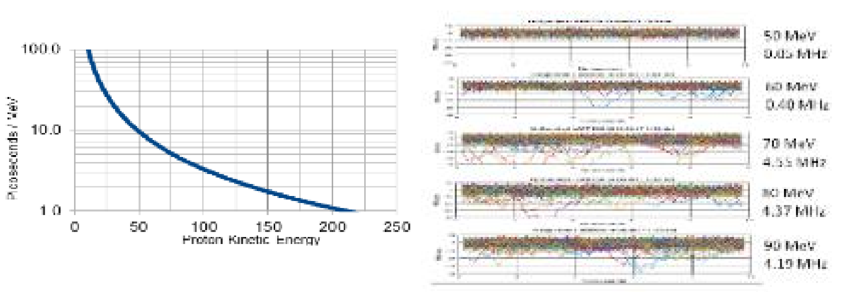




Medical Imaging Applications of LAPPDs

TOF Proton Radiography
Incom US Patent allowed 10/23/2018

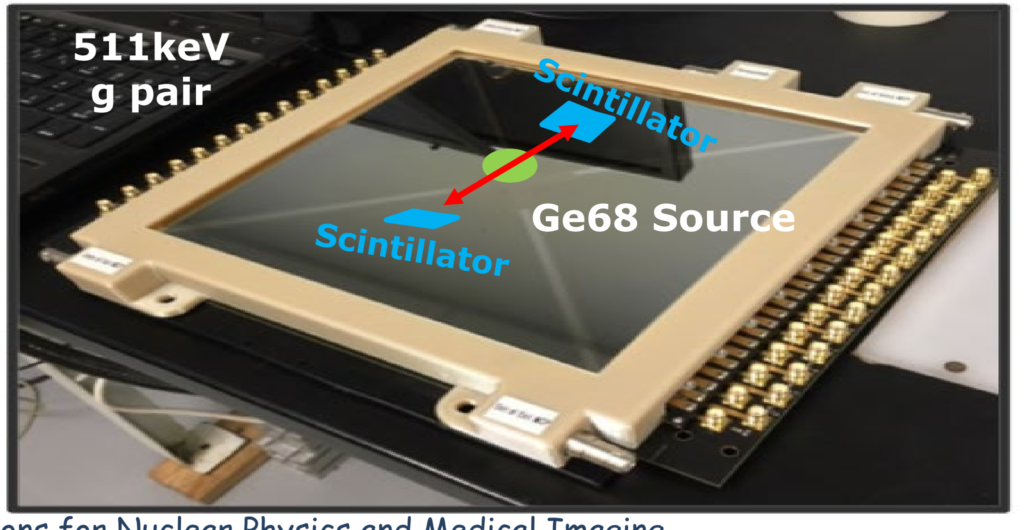




First Proton Waveforms

Portable LAPPD Telescope

Time-of-Flight PET Development



Time of Flight Positron Emission Tomography Detecting Prompt Cherenkov Luminescence

A basic science detector study focused on using the LAPPD to detect the prompt Cherenkov emissions from BGO and optimize timing performance.

Best avenue for improving performance of PET scanners is to increase timing resolution to spatially constrain events

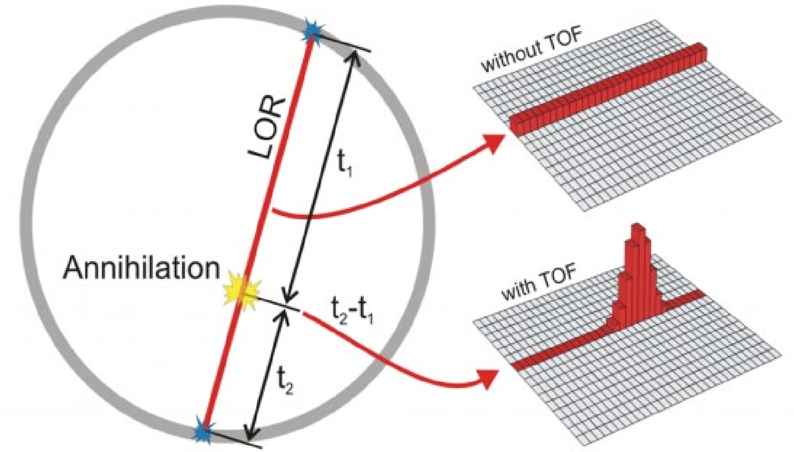


Image courtesy of Paul Lecoq, CERN

Detector material:
Good Cherenkov radiator
- high refractive index
- high transparency
High stopping power @511 keV

BGO

+

Very fast imaging photodetector **LAPPD**

BGO produces 10-15 prompt Cherenkov photons per 511 keV interaction – timing limited by photodetector

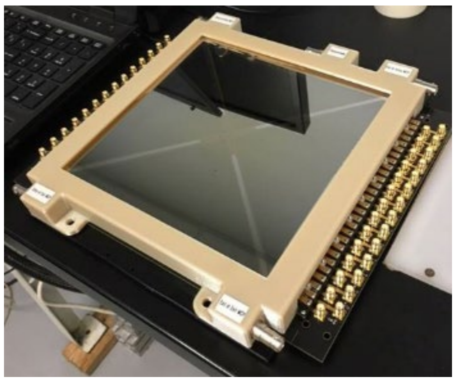
Stan Majewski, Sun Il Kwon, Simon Cherry, UC Davis, Bill Worstell, PicoRad Imaging LLC Michael Minot, Incom Inc.

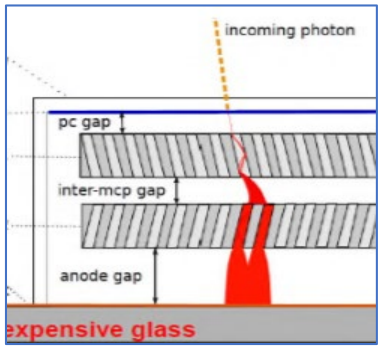
PicoRad Imaging NIH SBIR with UC Davis

Stan Majewski, Sun Il Kwon, Simon Cherry, UC Davis, Bill Worstell, PicoRad Imaging LLC Michael Minot, Incom Inc.

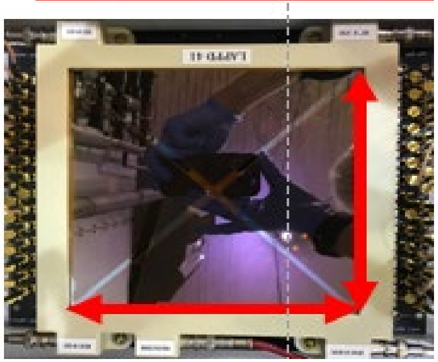
A pilot project with academic partner UC Davis to validate proof-of-concept

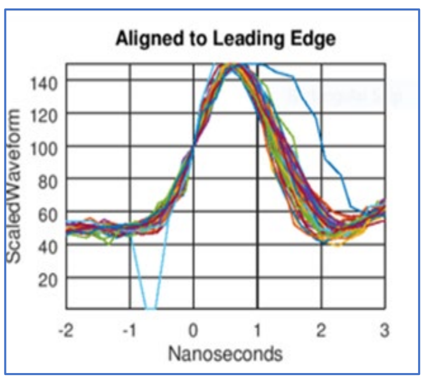
Target: ≤ 50ps FWHM TOF with DOI correction





195 mm x 195 mm





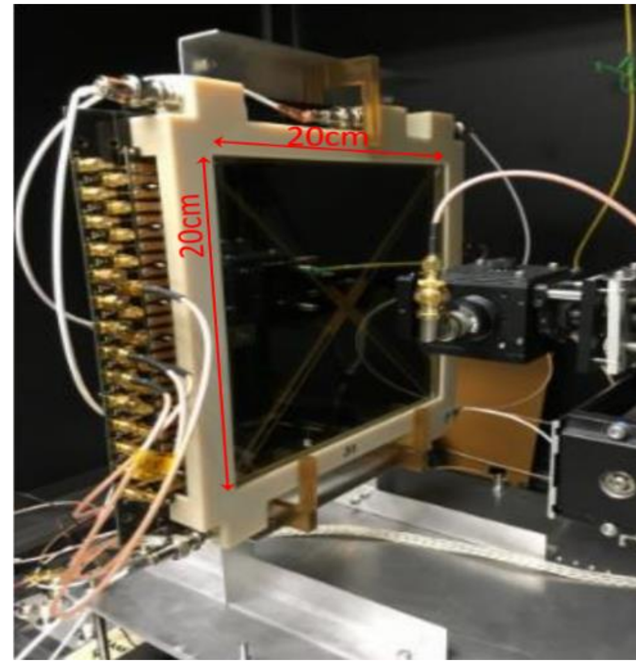
LAPPDs: large, super fast MCP PMT devices!

Characterize / Compare 3 Scintillators & Cherenkov Radiators

1. **LYSO: Fast bright scintillator**
   - Similar to SiPM TTS but faster
2. **PbF_2: Pure Cherenkov radiator**
   - Lower TTS and
   - Better SPE signal
3. **BGO: Good cost-effective Cherenkov radiator, high index, slow scintillator**
   - Lower TTS and
   - Better SPE signal

LAPPD DAQ for Positron EmissionTomography

1. LAPPD as low-cost, low noise Time of Flight photodetector
2. Reach beyond 100 ps FWHM coincidence timing resolution
3. Real-time feature extraction
   - ❖ Energy, timing and position
   - ❖ Dual-ended stripline readout offers new prospects for extraction strategies
   - ❖ Deal with pileup at standard PET rates
   - ❖ Real-time implemention for routine use (reduce saved data size)
   - ❖ Explore alternatives to waveform sampling



4. Share architecture with other high energy physics experiments

Marc-André Tétrault, Ph.D., Eng. In collaboration with PicoRad

MGH 1811
Gordon Center for Medical Imaging
UNIVERSITÉ DE SHERBROOKE
INCOM BRIGHT IDEAS

Summary & Conclusions

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

A. GEN I LAPPD - Available Today!
   - Artifacts are being resolved as production volume and experience increases.
   - Providing early adopters a means to explore potential of PSEC timing.

B. "Typical" performances meet early adopter needs:
   - Gain ~10^7
   - Mean QE ~ 26.1% @ ~80% uniformity
   - Time Resolution ≤52 Psec (σ), and mm spatial resolution

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

III. A good candidate for medical diagnostic including PET and Proton Therapy as well as use in collider, neutrino and rare decay experiments

IV. 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-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)
- **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 Phase I,** - Development of Advanced Photocathodes for LAPPDs
- **NASA Phase I,** - Improvement of GCA center to edge of high spatial/timing resolution applications
- **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.

BACK-UP SLIDES

For more information

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Grazie!

Special Thanks to Angelo Pagano for his support in making this presentation possible

Incom Measurement & Test Workshops

Next Workshop Dates Sep 10-12, 2019 Feb 11-13, 2020 May 12-14, 2020	Workshop #5, Feb 12-14, 2019 Jack McKisson, Electronical Eng. JLAB, Dr. Anatoli Arodzero, Director, Detection Division, RadiaBeam Technologies, 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)

Prototype Pricing - Available Now

- One price for all buyers.
- Provide program managers (PIs) with meaningful low volume (1-10 units) discounts.
- Encourages PIs to aggregate needs within their organization, department, or programs for tiles purchased, invoiced, billed 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.**

# Sold	Unit Price	Sales
1	$ 50,000	$ 50,000
2	$ 47,044	$ 94,088
3	$ 43,440	$ 130,319
4	$ 41,461	$ 165,842
5	$ 40,111	$ 200,557
6	$ 39,095	$ 234,571
7	$ 38,284	$ 267,988
8	$ 37,611	$ 300,890
9	$ 37,038	$ 333,343
10	$ 36,540	$ 365,398
20	$ 36,100	$ 721,995
50	$ 33,334	$ 1,666,694
75	$ 30,000	$ 2,250,007
100	$ 28,633	$ 2,863,335
300	$ 27,702	$ 8,310,468
500	$ 24,414	$ 12,206,898
750	$ 23,021	$ 17,265,691
1000	$ 21,972	$ 21,972,132