Performance of Large Area Picosecond Photo-Detectors (LAPPD™)

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LAPPD development group:

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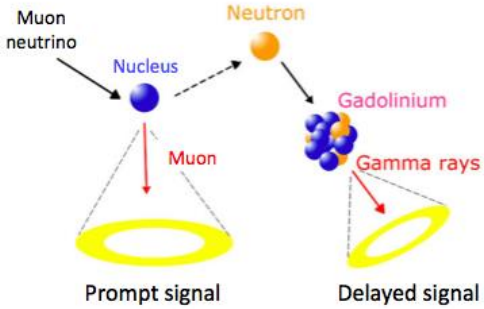
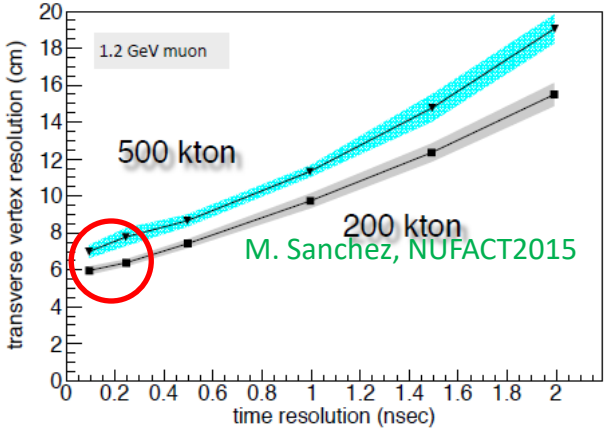
- A. U. Mane, J. W. Elam, **Argonne National Laboratory**
- O. H. W. Siegmund, **University of California, Berkeley**
- Prof. H. J. Frisch's group (E. Angelico, A. Elagin, E. Spieglan), **University of Chicago**
- Prof. M. Wetstein's group, **Iowa State University**
- R. Wagner, J. Xie, **Argonne National Laboratory**

Benefits of fast timing

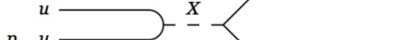
Neutrino: More efficient background rejection

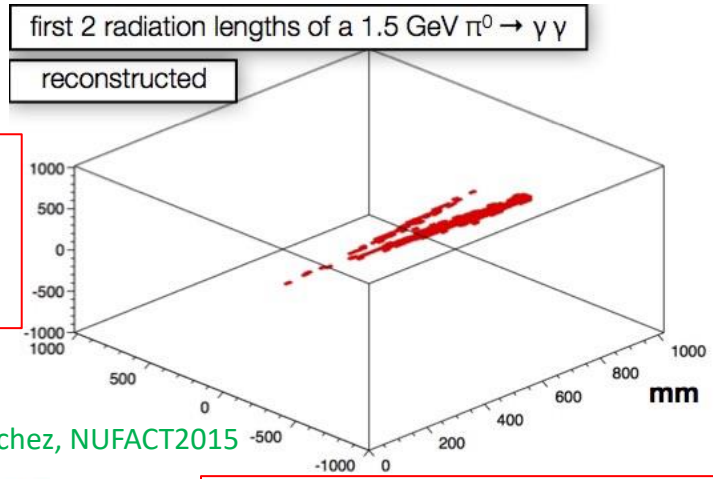




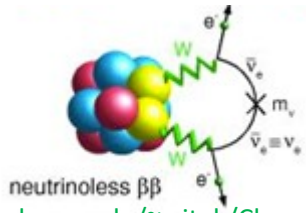
M. Sanchez, NUFACT2015

HEP applications: Precise TOF & PID





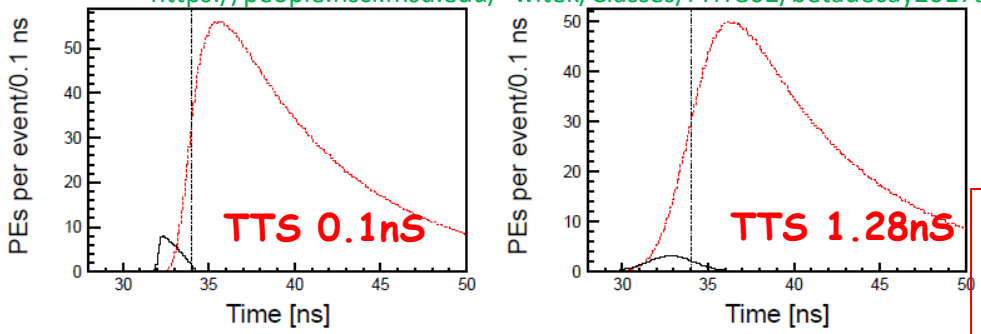
M. Sanchez, NUFACT2015



https://people.nscl.msu.edu/~witek/Classes/PHY802/betadecay2017a.pdf

Neutrino, rare decay : Precise track reconstruction

Neutrino: High vertex resolution in large scale experiments



(a) Default simulation. (b) Increased TTS (1.28 ns).

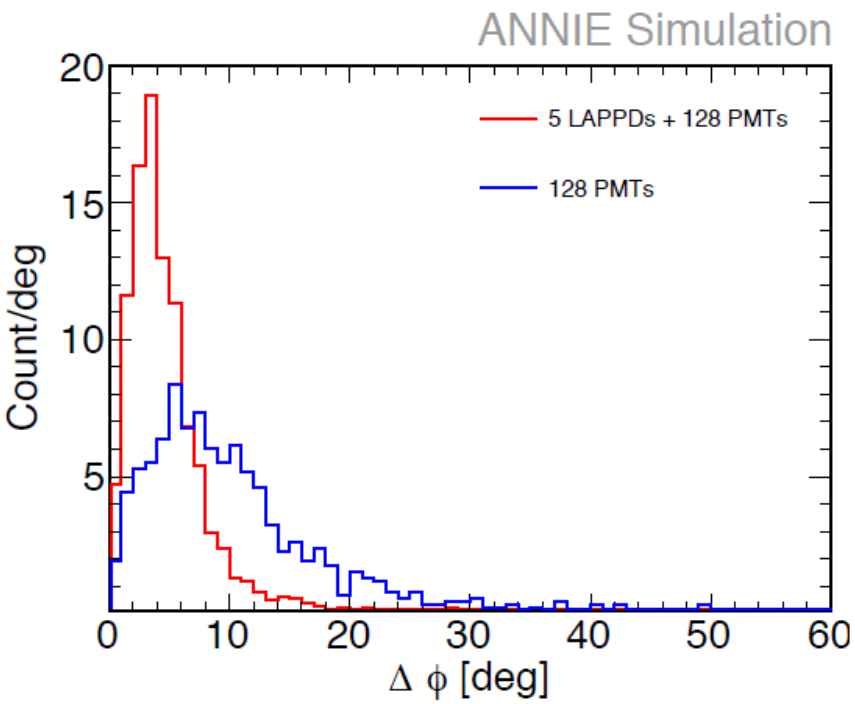
C. Aberle et al., JINST 9 (2014), **arXiv:1307.5813**

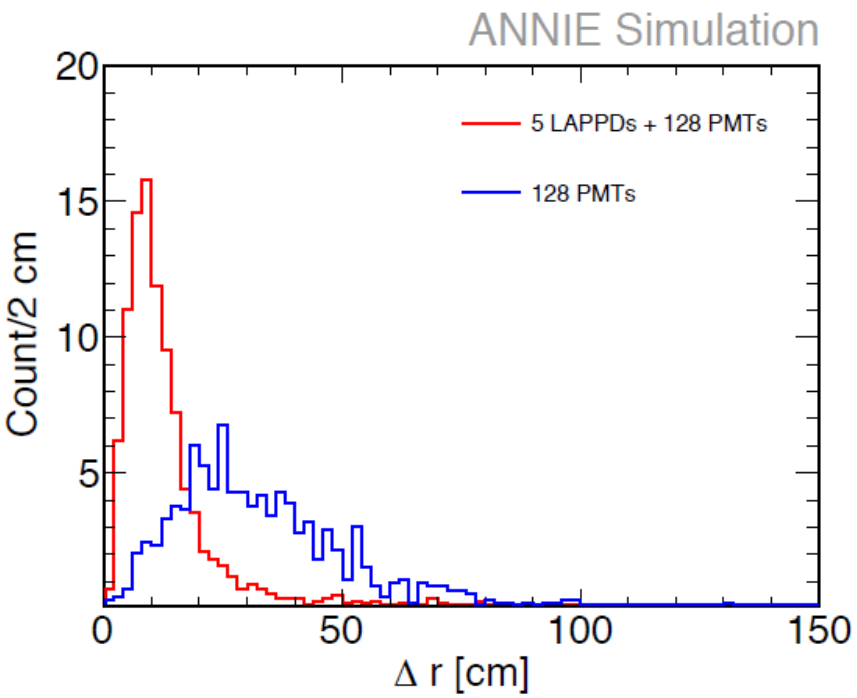
Obb decay: Directionality information

LAPPD applicability **ANNIE Experiment**

5 LAPPDs are being installed

- Even a small number of LAPPDs can make a big difference in the right context





- In ANNIE, the addition of 5 LAPPDs greatly improves reconstruction of muon track parameters

Details: http://annie.fnal.gov

LAPPD Pilot Production Timeline

- DOE Funding to create infrastructure and demonstrate a pathway toward pilot production (April 2014)
- Facility operational (November 2015)
- LAPPD Commissioning trials initiated (December 2015)

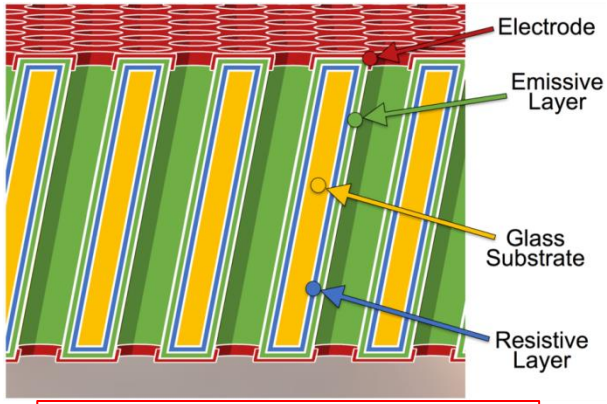
  #9 – 9/14/2016, First Sealed Tile – Aluminum Photocathode
  #15 – 03/31/2017, QE >20% demonstrated
  #22 – 10/10/2017, moderate QE, High Gain MCPs, Peaked SPE PHD,
  #31 – 5/25/2018 Functional Tiles with "Personality"
  #36 - 10/16/2018 – First GEN II, Ceramic Body LAPPD
  #37 – 11/13/2018 – High QE ~24% and high gain ~10^7 in the same tile
  #39 – 01/23/2019 – High QE ~25%, low noise @ high gain ~ 10^7

- Exploitation (2018-)

  Currently Producing prototypes for early adopters
  Process Optimization

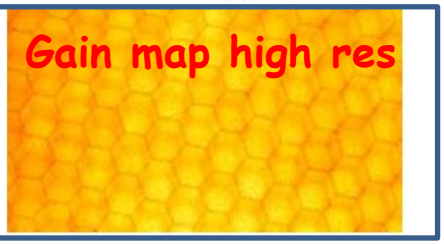
Incom MCPs

Glass capillary arrays functionalized in-house with ALD

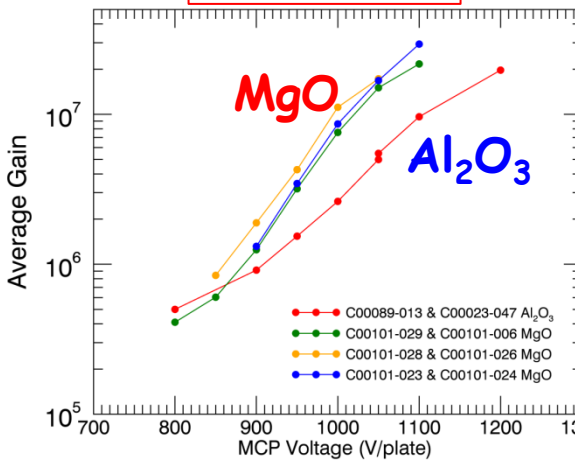


O. H. W. Siegmund et. al., SPIE Proc. 10397

Gain Uniformity in 203mm X 203mm MCP



Gain >10^7



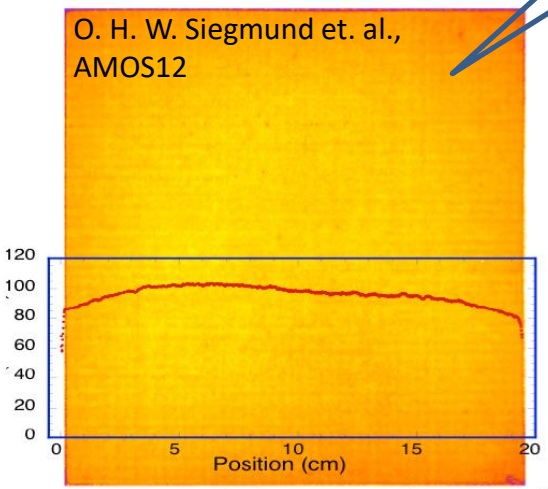


Fig. 8: Average gain image "map" (<15% overall variation). 8" MCP pair 20μm pore, 60:1 L/D ALD-MCP pair. ~7 × 10^6 gain, 0.7mm inter-MCP gap/200V.

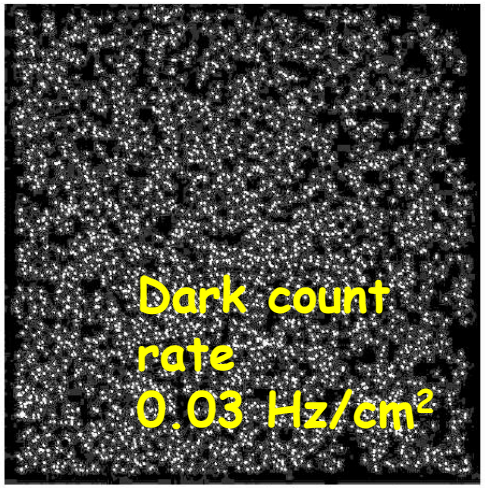
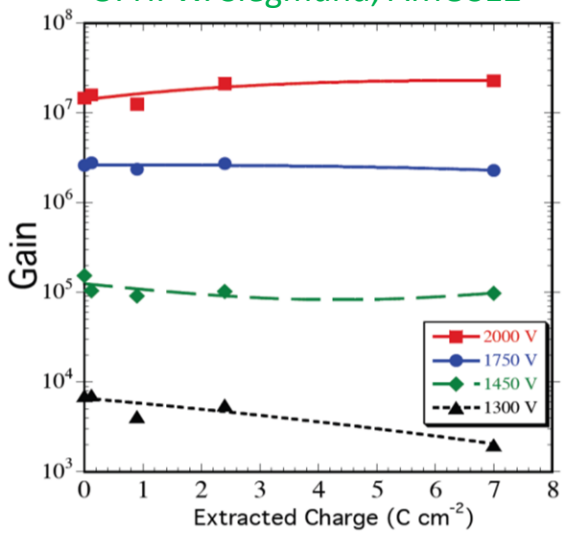


Fig. 9: 20 cm ALD MCP pair background, 500 sec, 0.03 events/cm²/sec¹. Overall background ~8× better than standard glass MCPs (less K^{40}),

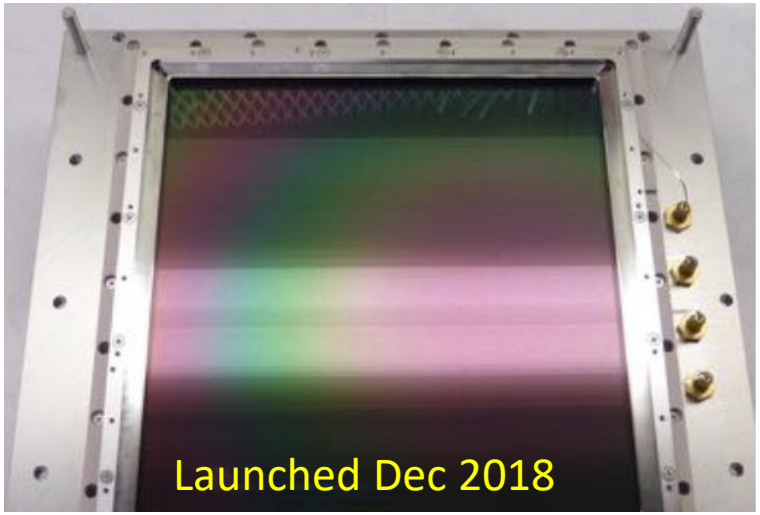
MCPs are marketed as a separate product line.
Standard dimensions DIA33mm, SQ53mm, SQ60mm, SQ127mm, SQ200mm. Curved MCPs.

Incom MCPs

O. H. W. Siegmund, AMOS12



O. H. W. Siegmund et. al., SPIE Proc. 10397



200 x 200mm XDL spectroscopy detector (DEUCE rocket, James Green, PI, Colorado) with KBr photocathode on ALD MCPs.

O. H. W. Siegmund, AMOS12

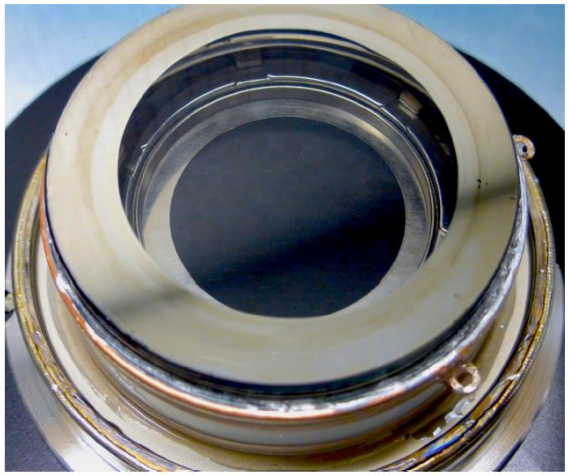
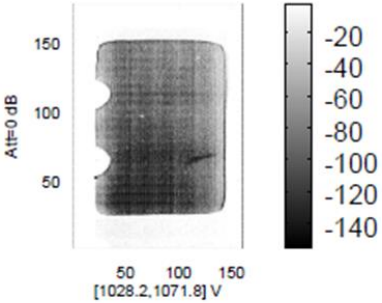
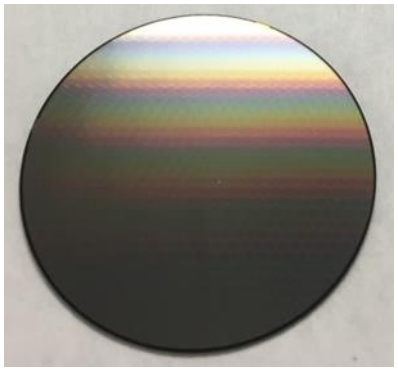
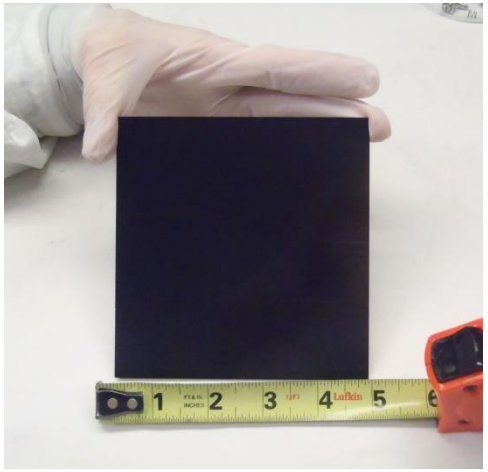


Fig. 17. 25 mm sealed tube with a GaN photocathode directly deposited onto a pair of borosilicate substrate ALD coated MCPs (20μm pore, 60:1 l/d). XDL readout.

Intensity image at ~1050V/MCP

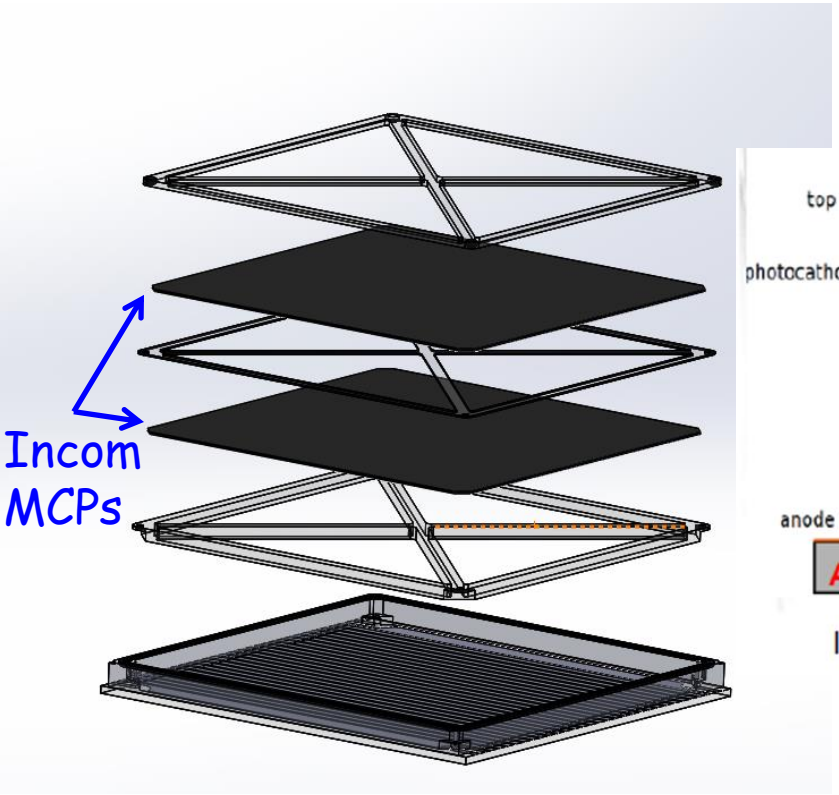






MCPs are marketed as a separate product line.
Standard dimensions DIA33mm, SQ53mm, SQ60mm, SQ127mm, SQ200mm. Curved MCPs.

LAPPD features



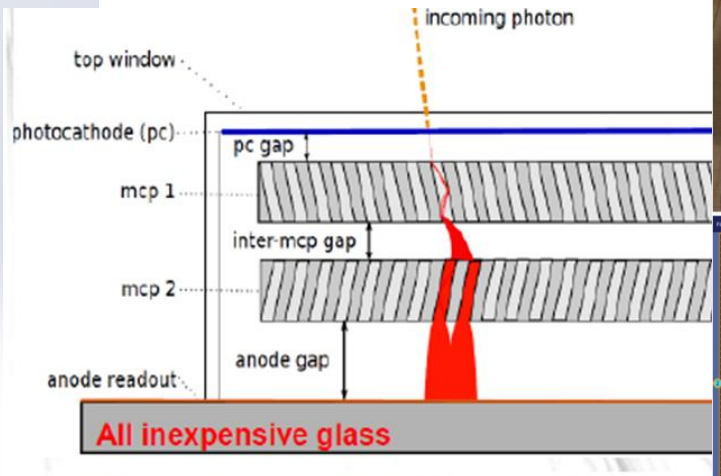
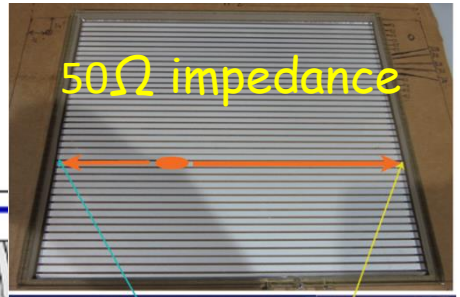
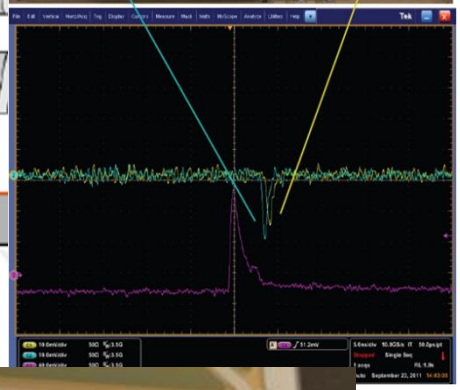
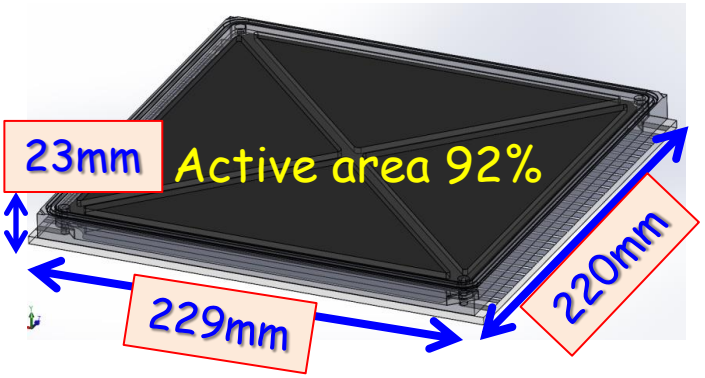


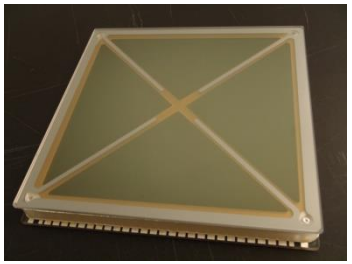
Illustration provided by Univ. of Chicago



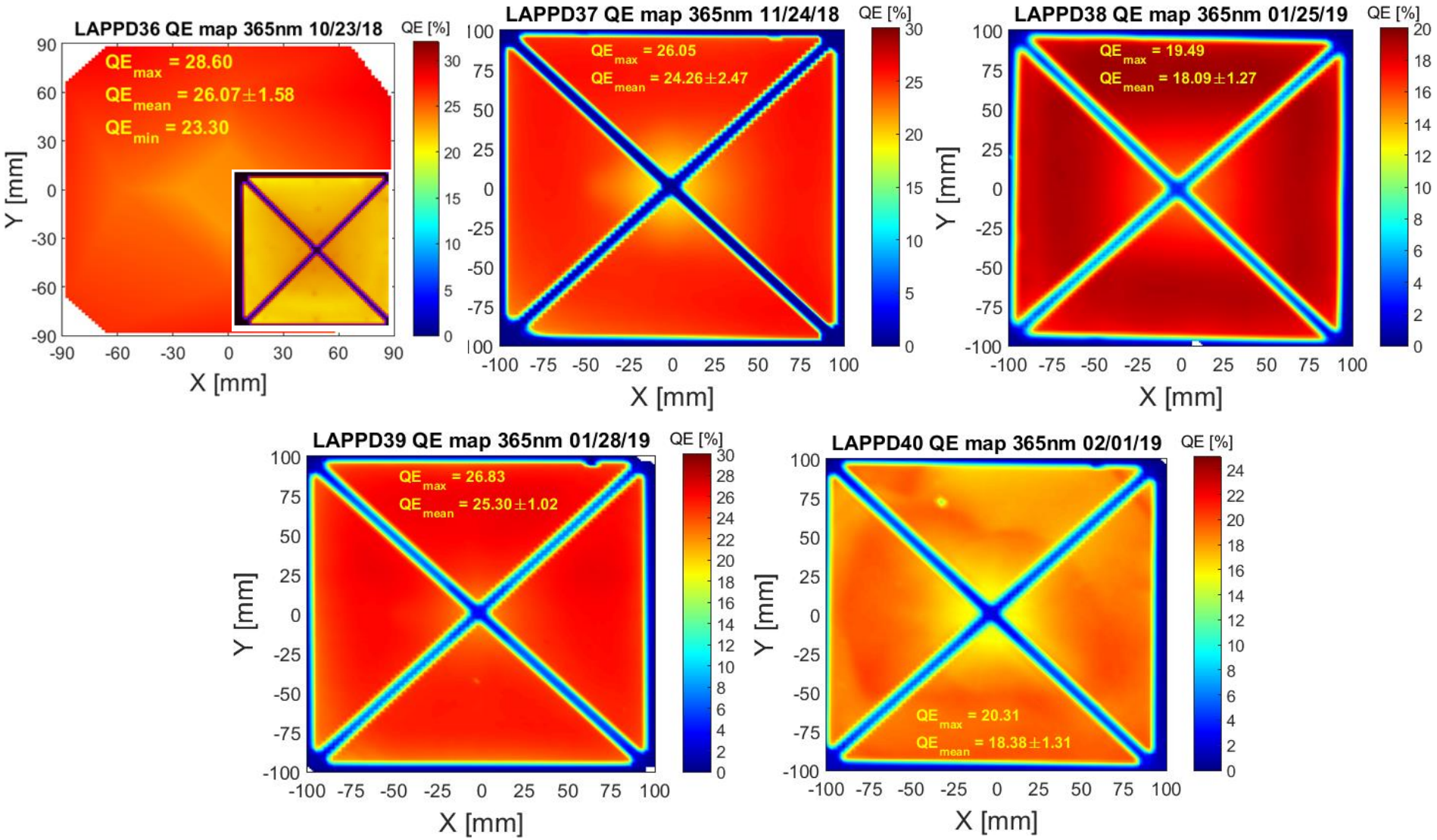




- Glass/ceramic body
- Large Active Area: 195 x 195 mm^2
- Picosecond timing resolution
- mm spatial resolution
- QE >20% w/bi-alkali photocathode
- Fused Silica/Borosilicate window
- Flat square geometry, high filling factor
- Lower Cost per Unit Area

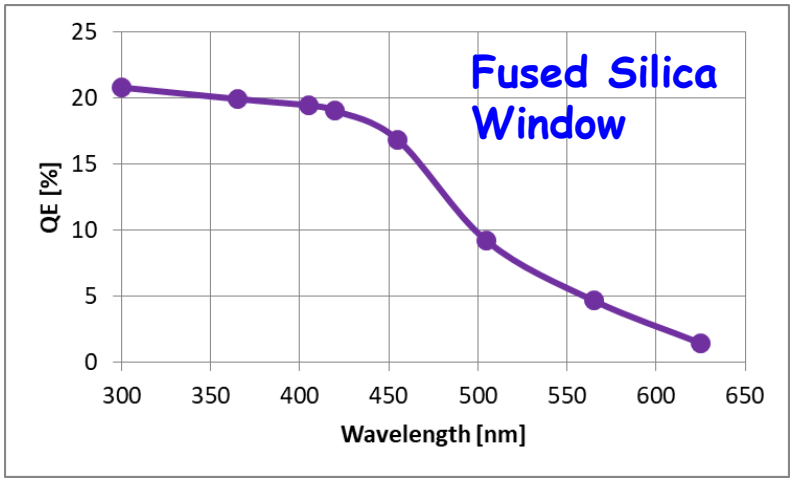


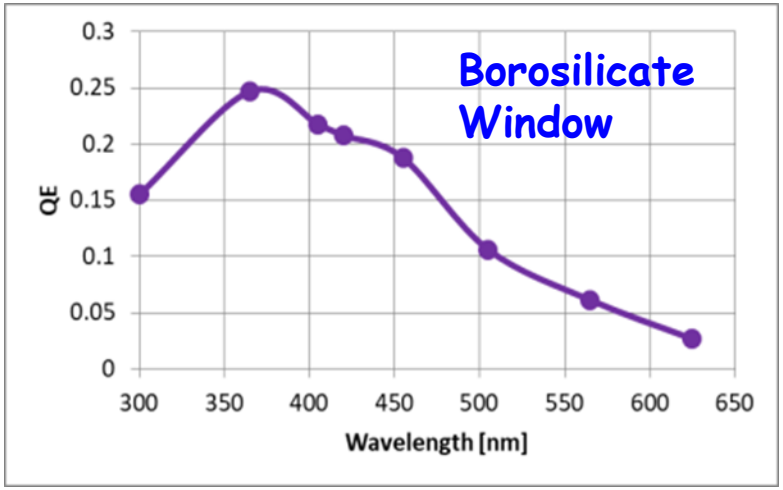
Photocathode (five most recent tiles)

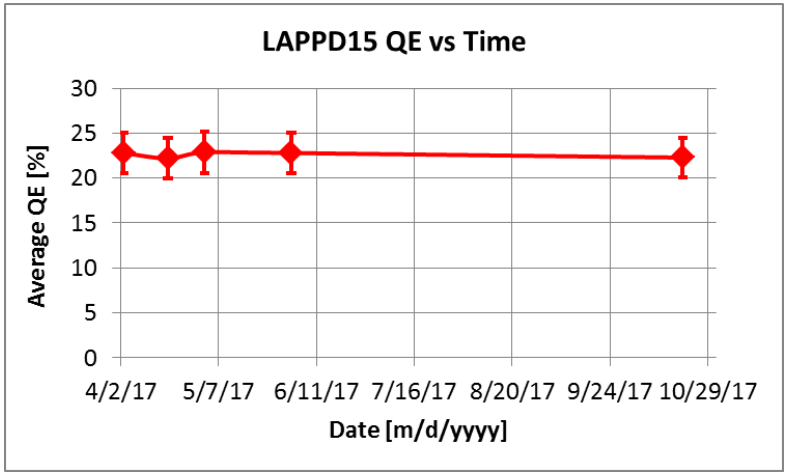


Large Area Photocathode production process is established
QE >20% and 90% uniformity demonstrated in sealed LAPPDs (five recent tiles shown)

Photocathode

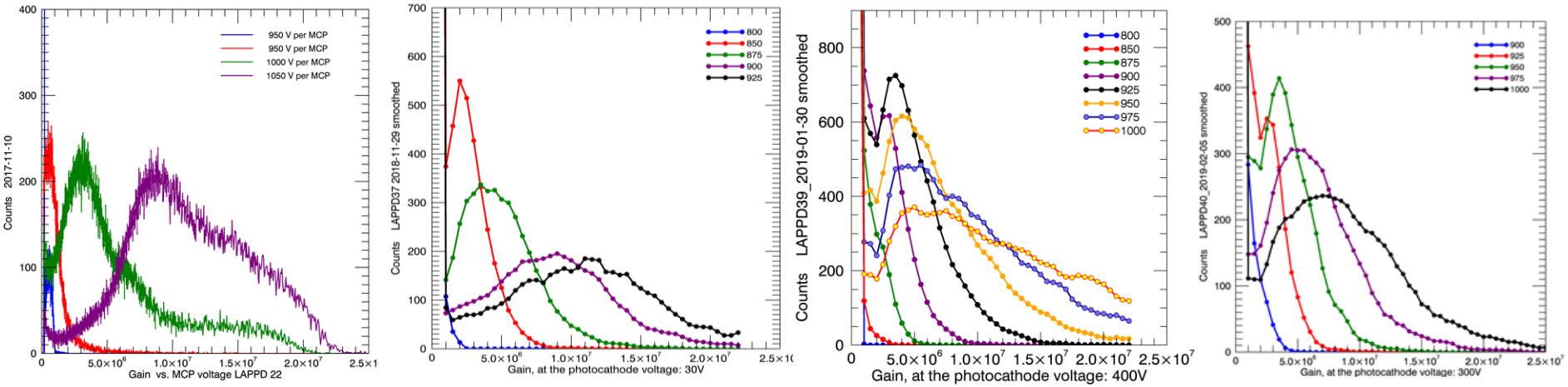


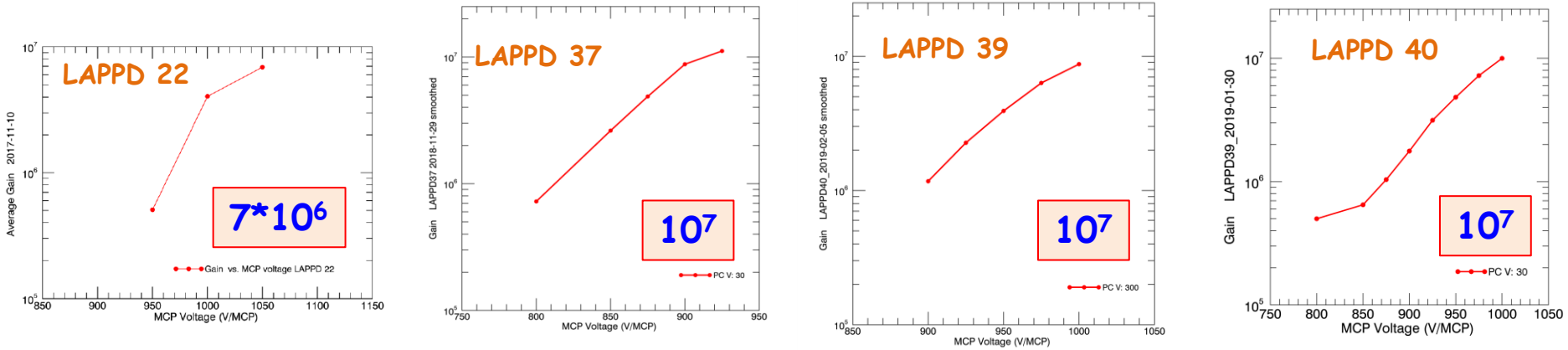




Stable for 6.5 month and counting

LAPPD Gain





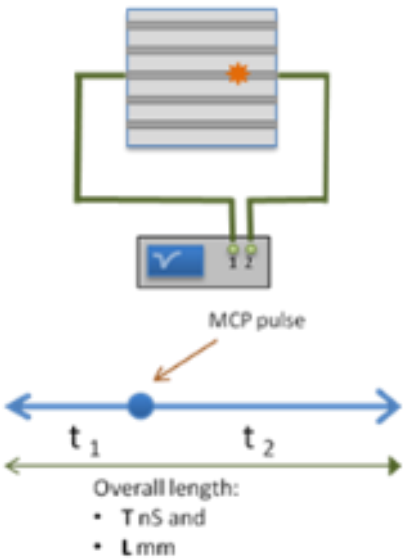
Gain ~10^7 achieved at relatively low MCP voltage of 950V-1000V per plate

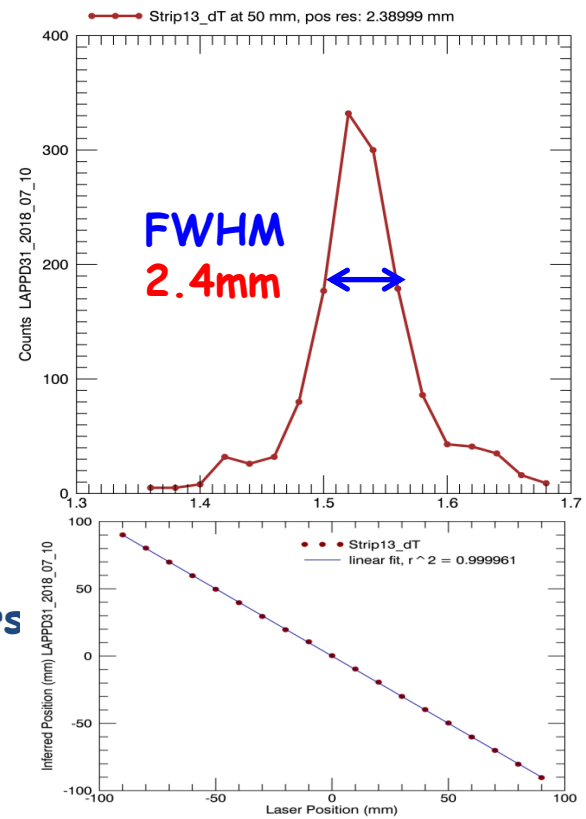
Read out with DRS4 eval. or CAEN waveform digitizers

Spatial Resolution

Along a Strip

Jitter in Δt for a fixed laser position





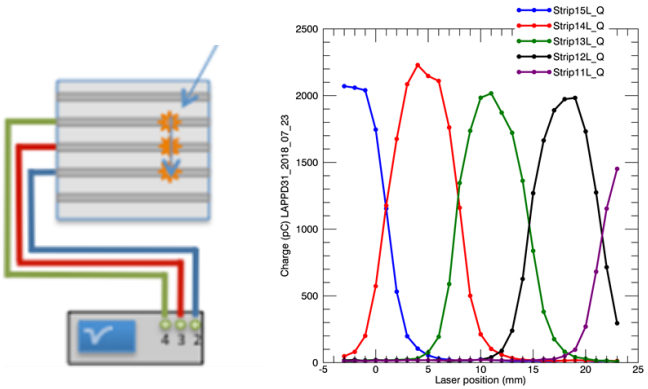
DRS4 waveform samplers

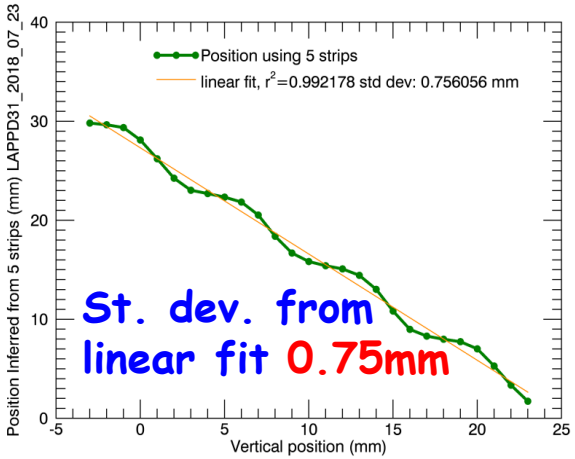
Pulses observed at both ends of a strip.

Reconstructed position vs laser position

Across Strips

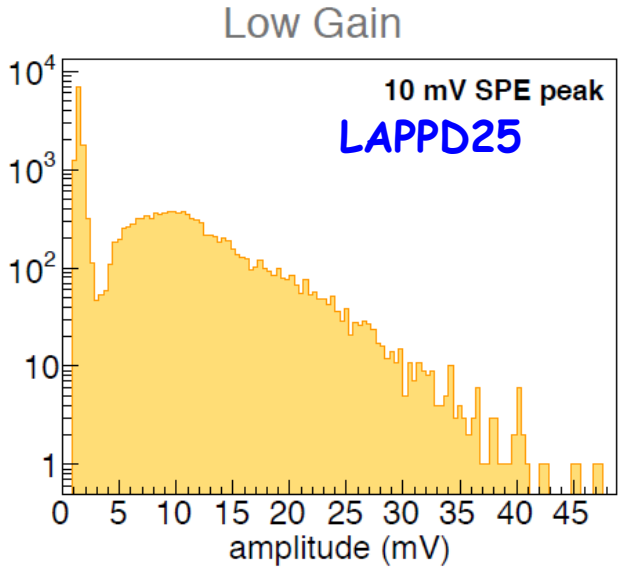
Center of Mass of five adjacent strip signals

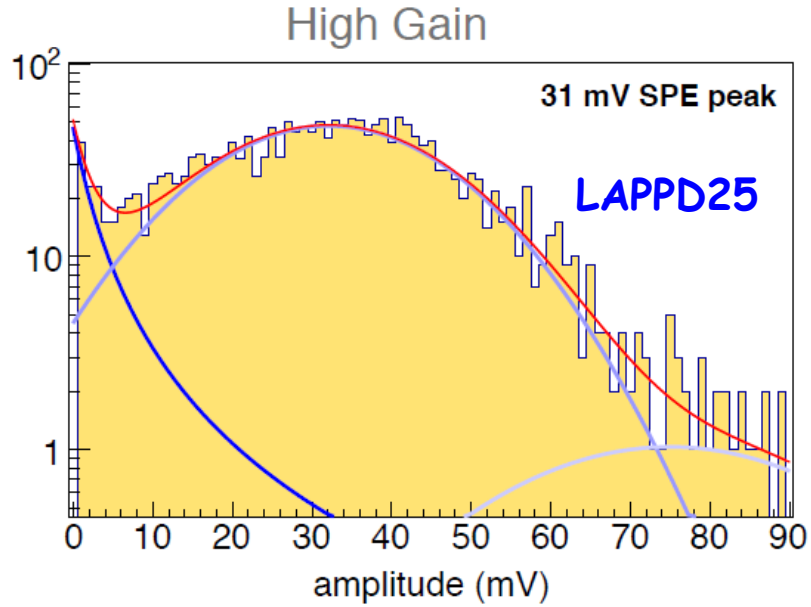


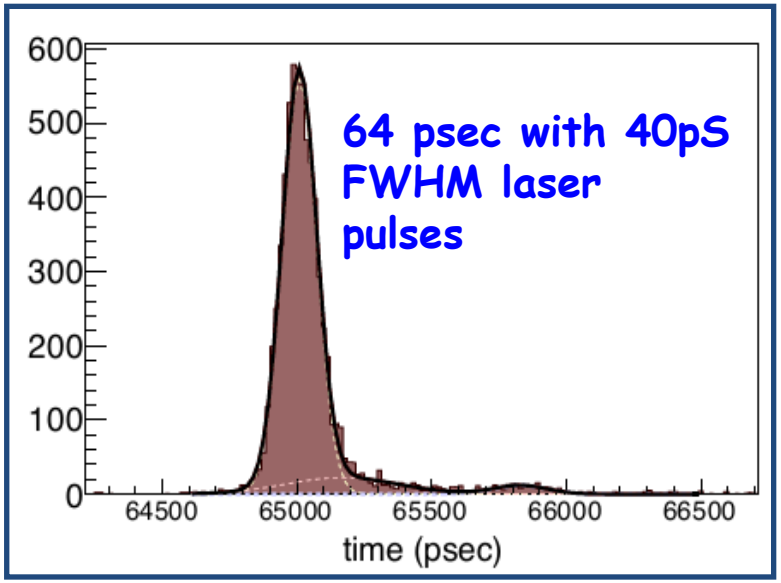


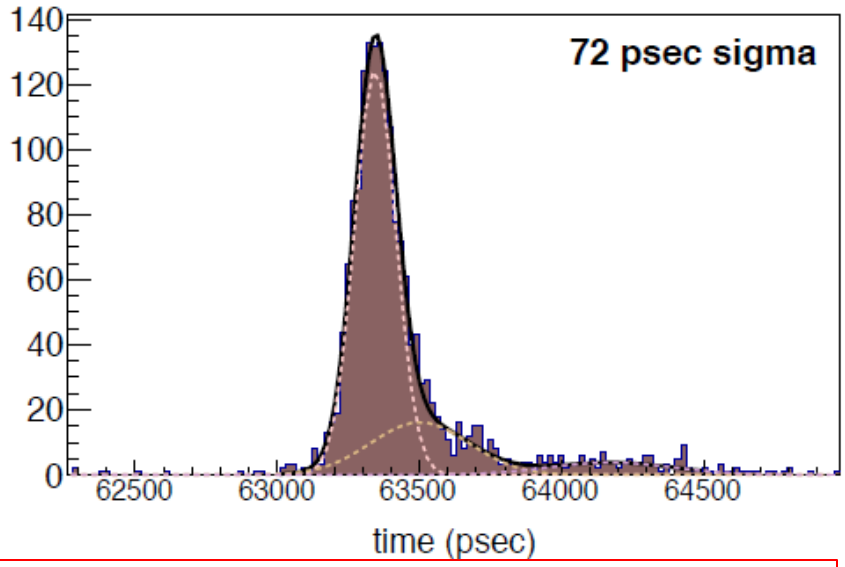
Time Resolution

Testing at Iowa State University, Matt Wetstein, ANNIE Program









Assuming $\sigma_{Meas}^2 = \sigma_{LAPPD}^2 + \sigma_{LaserWidth}^2$ the extracted TTS is 50pS

Time Resolution

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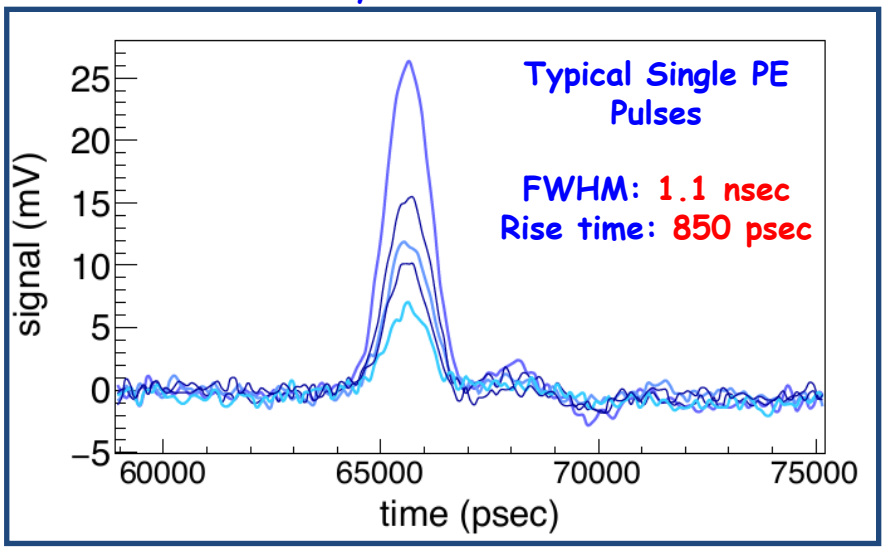
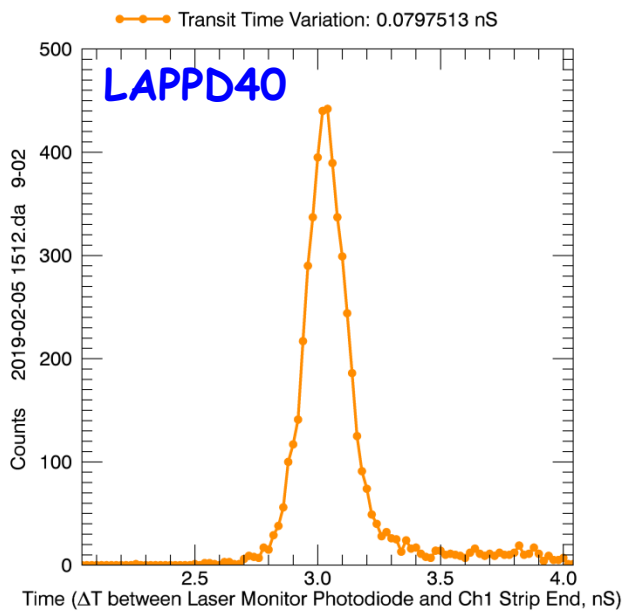


Transit Time Spread

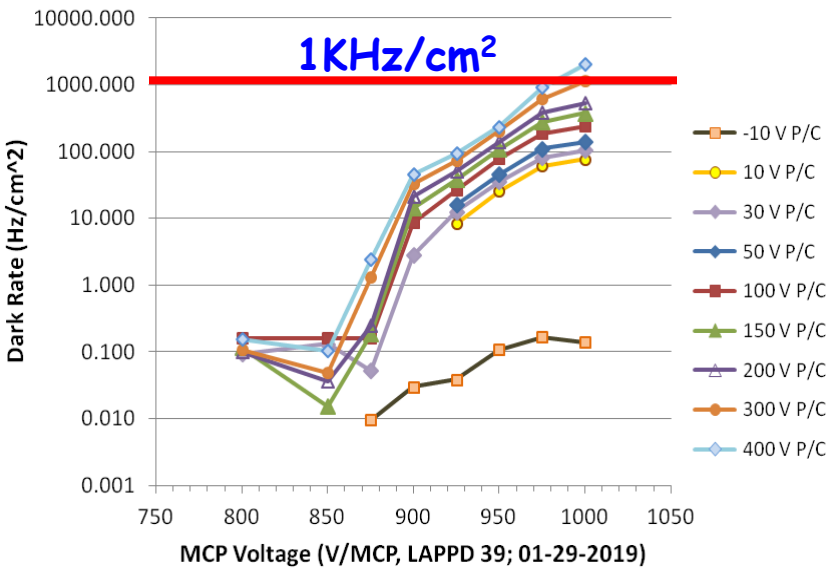
80pS with 63pS FWHM laser pulses



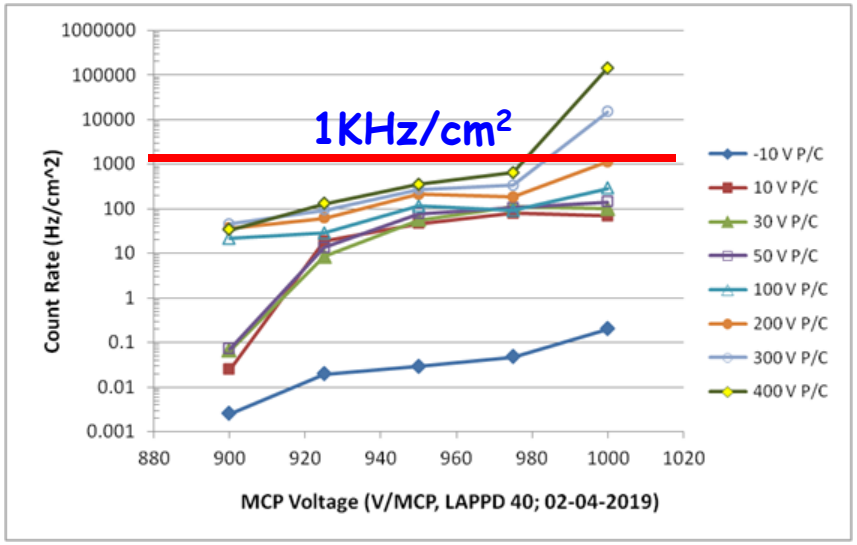
Assuming $\sigma_{Meas}^2 = \sigma_{LAPPD}^2 + \sigma_{LaserWidth}^2$ the extracted TTS is 49pS

Dark Count Rate

LAPPD39 (QE =25.3%)

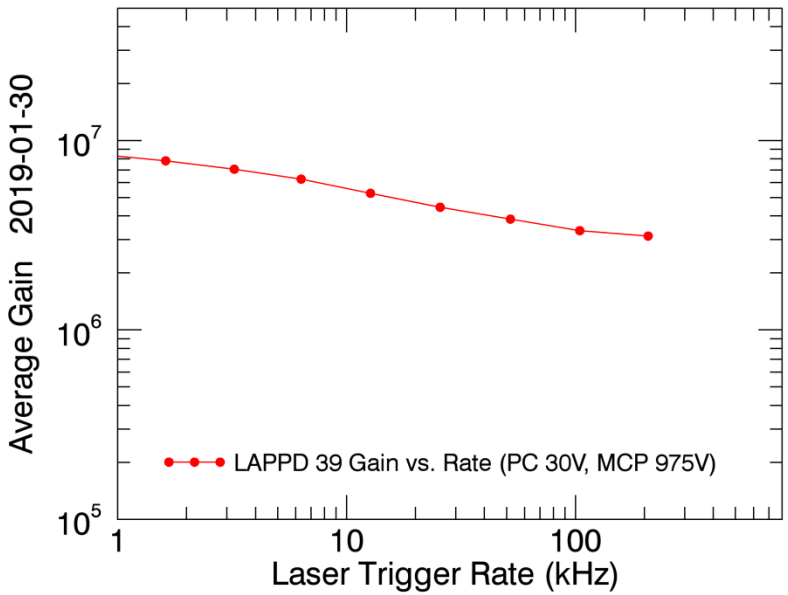


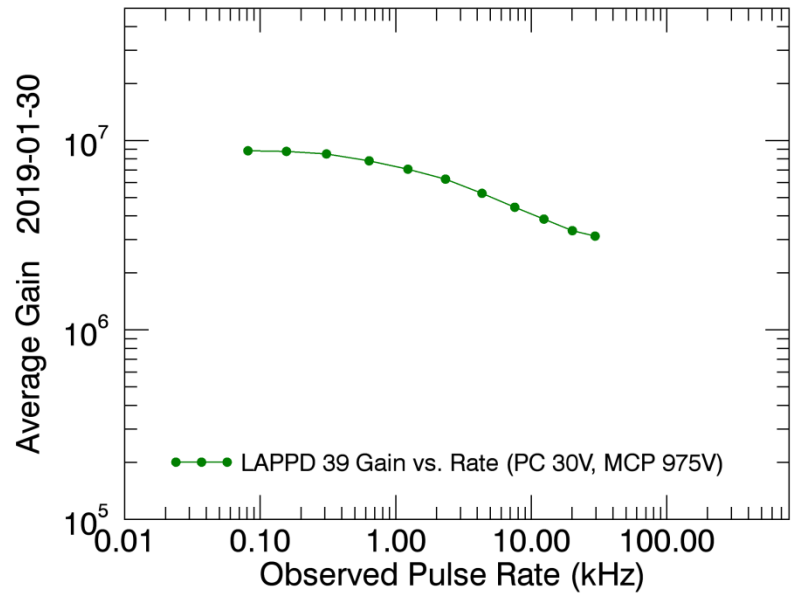
LAPPD40 (QE=18.4%)

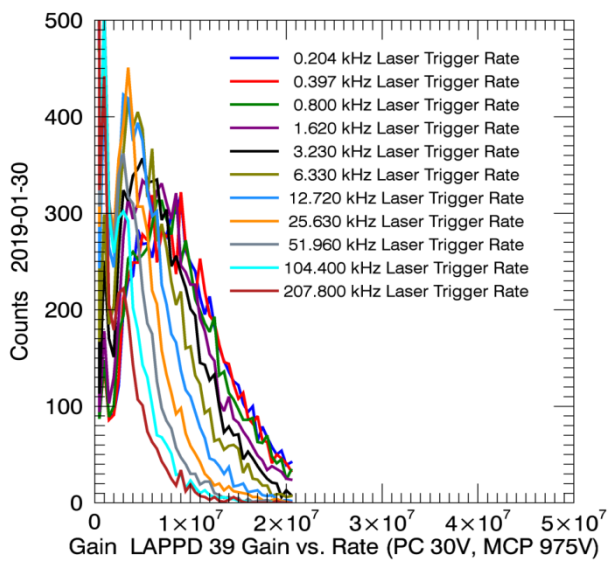


PC Voltage [V]	MCP Voltage [V]	Gain	Dark rate [Hz/cm^2]
200 (800V/cm)	925	$3*10^6$	50-70
200	975	$7*10^6$	200-300
200	1000	10^7	700-1000

Linearity

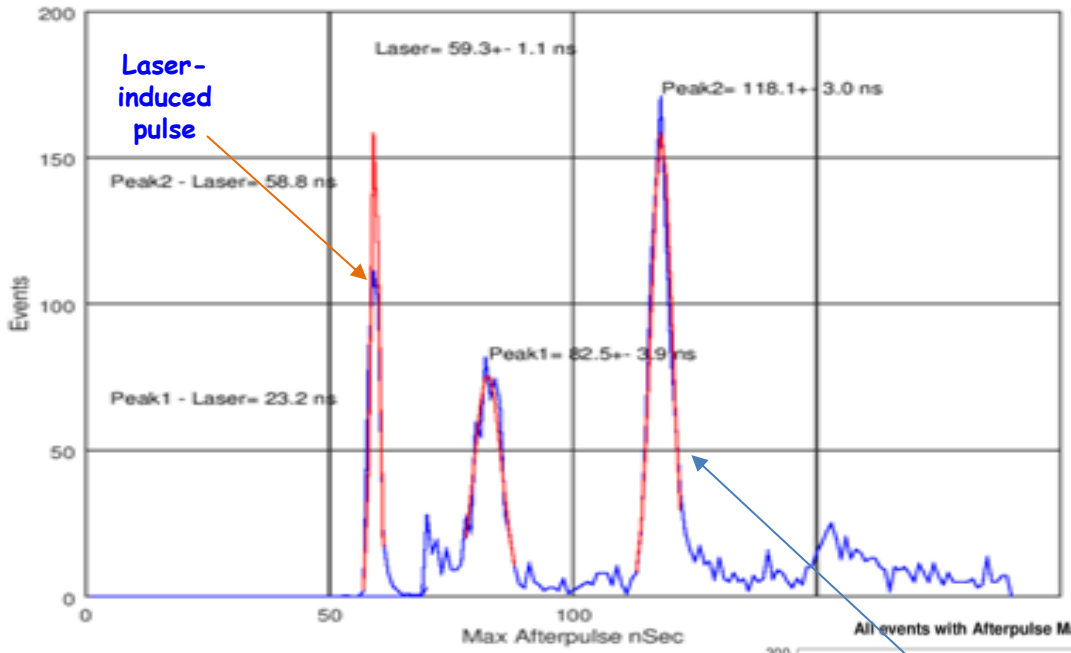


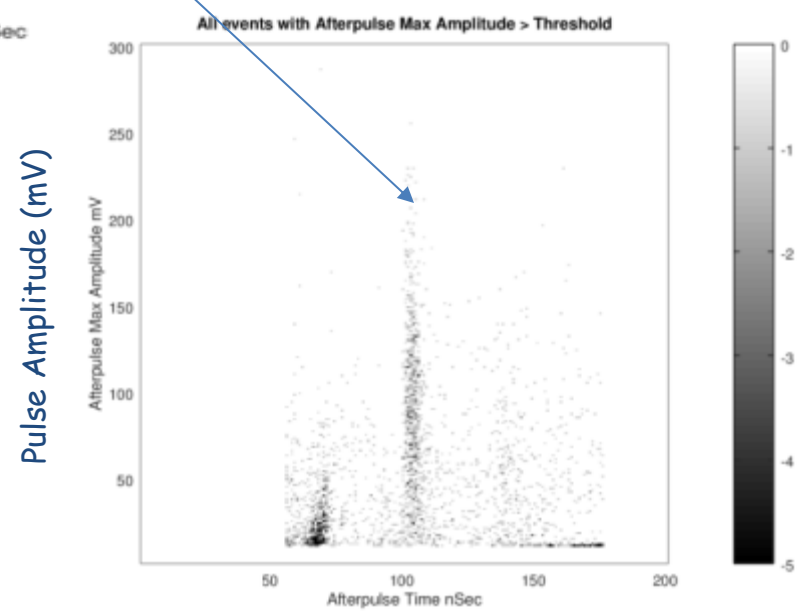




Good Linearity to ~300KHz/cm2

Afterpulses (worst case scenario)





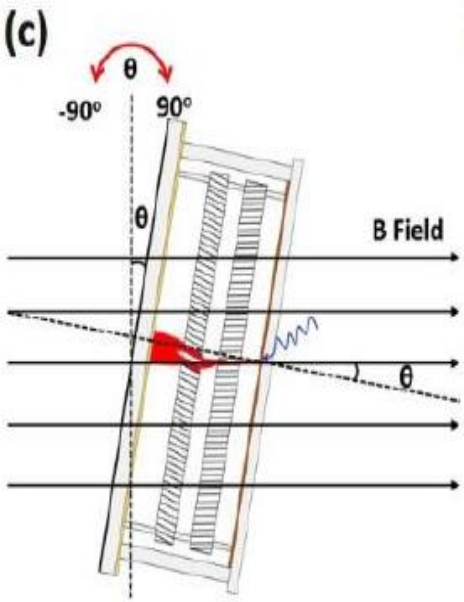
- Laser pulse downscaled to fit on histogram
- 3.5% afterpulse ratio
- With K_2CsSb photocathode

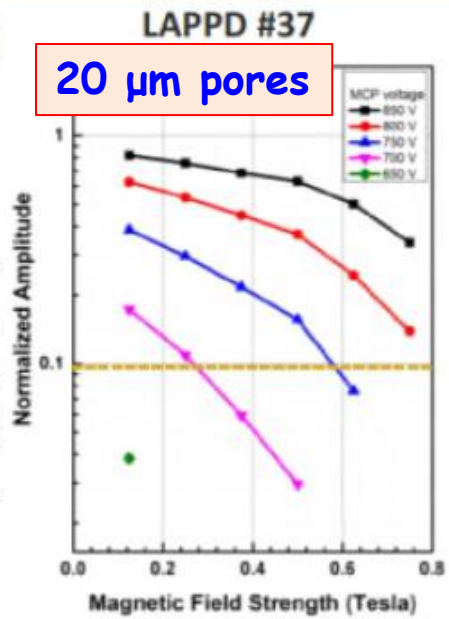
Preliminary LAPPD & Small Format Tile B-Field Testing

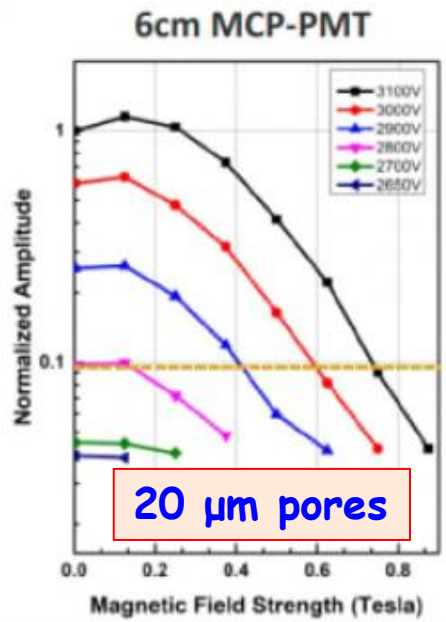
Bill Worstell (PI), Mark Popecki, Cole Hamel, Bernhard Adams, Bob Wagner, Junqi Xie, Ed May

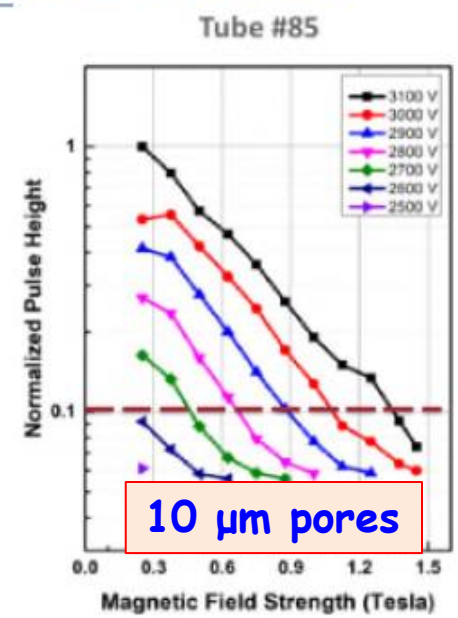
12/14/2018 B-Field Testing LAPPD #37

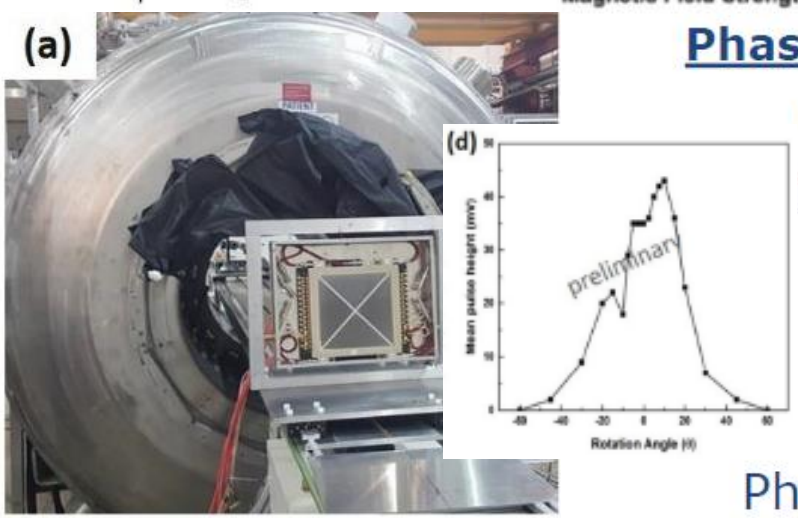
ANL 6cm Tile, 10 & 20μ MCPs











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

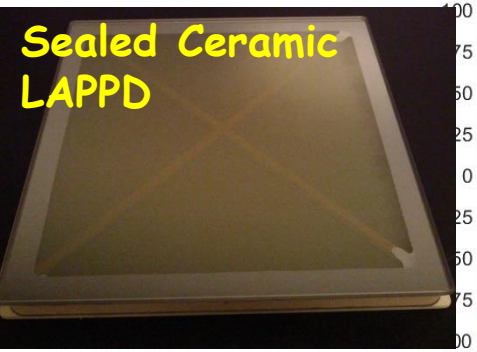
Conservative

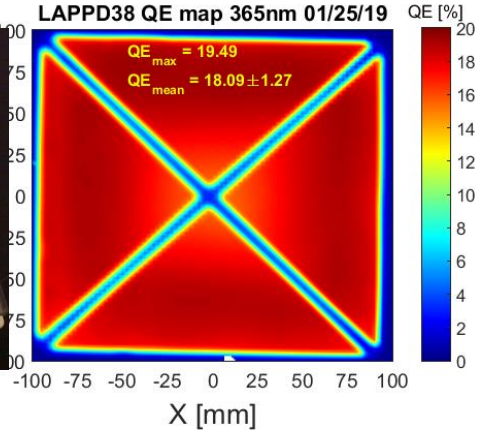
Further Analysis Pending

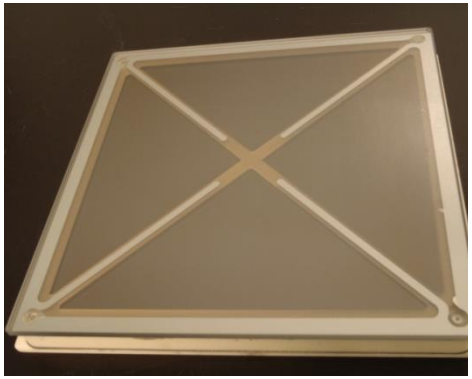
Phase II SBIR Targets Design Optimization

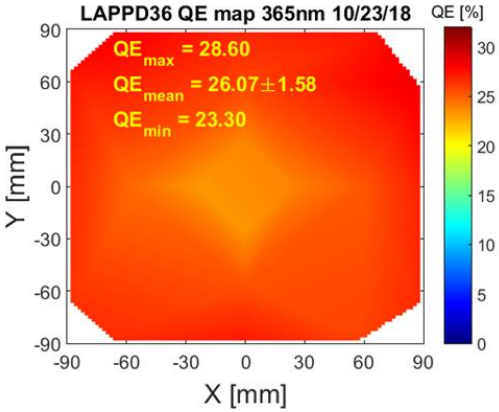
GEN II LAPPD

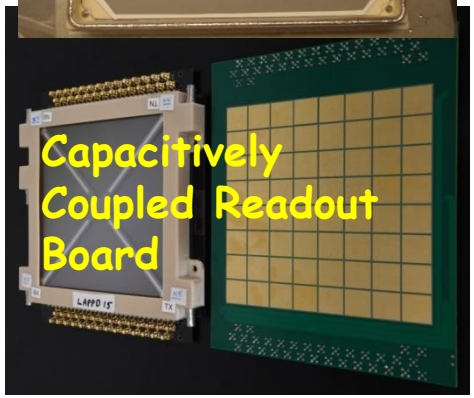
- A robust ceramic body
- Capacitive signal coupling: to an external PCB anode
- Pixelated anodes: to enable high fluence applications

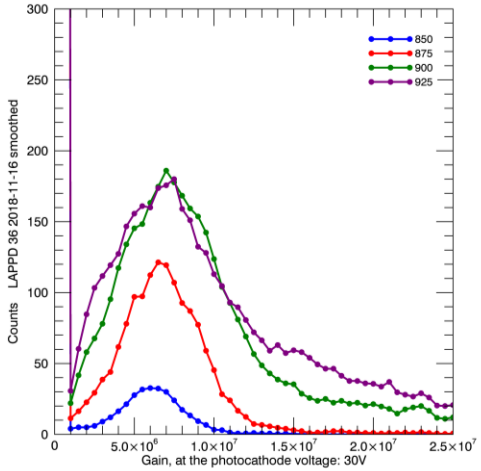


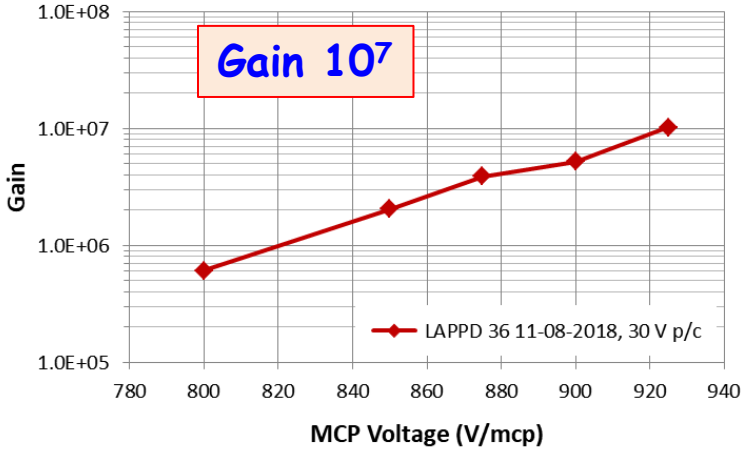












Sealing process established, high QE demonstrated, inner design optimization on-going

Early Adopters

- Opinion leaders able to influence the adoption of LAPPD for established or future technical programs.
- Collaborators that have access to special facilities: magnetic fields, neutron beam, Cherenkov light, Fermi Lab Particle Beams, Neutrino-less Double-Beta Decay, life testing, etc.
- Incom works with early adopters to insure that LAPPD are available to be evaluated for appropriate applications.
  - Measurement & Test Workshop
  - Discounted pricing to Early Adopters with DOE funded programs.
  - Swaps & Warranty
  - Options for Short term loan of LAPPD
- Discussions underway to explore joining end user programs as a **collaborator or sub-contractor** rather than just a vendor.

Incom Measurement & Test Workshops

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

Workshop #6, **May 14 – 16th, 2019** **Participants:** • Everybody is welcome	**Workshop #5,** **February 11 – 13th, 2019** **Participants:** • Anatoli Arodzero (RadiaBeam Technologies LLC) • Jack McKisson (JLAB) • Evan Angelico (UChicago)	**Workshop #4,** **October 9 – 11th, 2018** **Participants:** • Mitaire Ojaruega (NGA-DOD) • Kevin Richard Jackman (NGA-DOD) • Varghese Anto Chirayath, (Physics, UTA)
Workshop #3, **May 15-17th, 2018** **Participants:** • Junqi Xie (ANL) • Mickey Chiu, (BNL) • Carl Zorn, (Jefferson Lab) • Wenze Xi, (Jefferson Lab) • Camden Ertley(UC B, now Incom Inc.)	**Workshop #2,** **January 24-26, 2018** **Participants:** • Matthew Malek (The 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	**Workshop #1,** **November 13 – 16th, 2018** **Participants:** • Kurtis Nishimura (U of Hawaii / Sandia) • Josh Brown (Sandia) • Julieta Gruszko (MIT)

LAPPD™ Early Adopter Programs

PI & SPONSOR	PROGRAM TITLE
Mayly Sanchez and Matthew Wetstein, Iowa State	ANNIE - Atmospheric Neutrino Neutron Interaction Experiment
Erik Brubaker, Sandia National Lab/CA	Neutron Imaging Camera
Graham Smith, Klaus Attenkofer (BNL)	Gamma & Neutron Detectors
Henry Frisch (U of Chicago) , Dmitri Denisov (Fermilab)	Precision Time-of-Flight with Commercial Photodetectors at the Fermilab Testbeam Facility
Matthew Malek,(u of Sheffield)	WATCHMAN, UK STFC
Josh Klein, U of Penn	Spectrally Sorting of Photons, using Dichroic Films and Winston Cones, WATCHMAN, THEIA
Gabrial D. Orebi Gann (UC Berkeley)	WATCHMAN, THEIA
Zein-eddine Meziani	High Rate Trials at Jefferson Labs, EIC
Andrey Elagin (U of Chicago)	Neutrino-less Double-Beta Decay
Mickey Chiu (BNL) -	Phenix Project - "eIC Fast TOF"
John Learned, U. of Hawaii, and Virginia Tech	Short Baseline Neutrino (NuLat)
Lindley Winslow (MIT)	Neutrino-less Double-Beta Decay (NuDot) Using Fast Timing Detectors
Andrew Brandt, (UT Arlington)	Life Testing of LAPPD
J. Xie	PID, EIC

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.
- Life Testing is on-going
- Providing early adopters a means to explore potential of PSEC timing.

B. "Typical" performances meet early adopter needs:
- **Gain ~10^7**
- **Mean QE ~ 25% @ >80% uniformity**
- **Time Resolution < 70 Picoseconds, and mm Spatial Resolution**
- **Dark rate 50-70 Hz/cm^2 @ gain 3*10^6**

II. GEN II - Capacitive coupling works, **ceramic package demonstrated, high QE demonstrated**.

III. A good candidate for the use in collider, neutrino and rare decay experiments

IV. We will work with you to make LAPPD available for test & evaluation.

Current Funding & Personnel Acknowledgements

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

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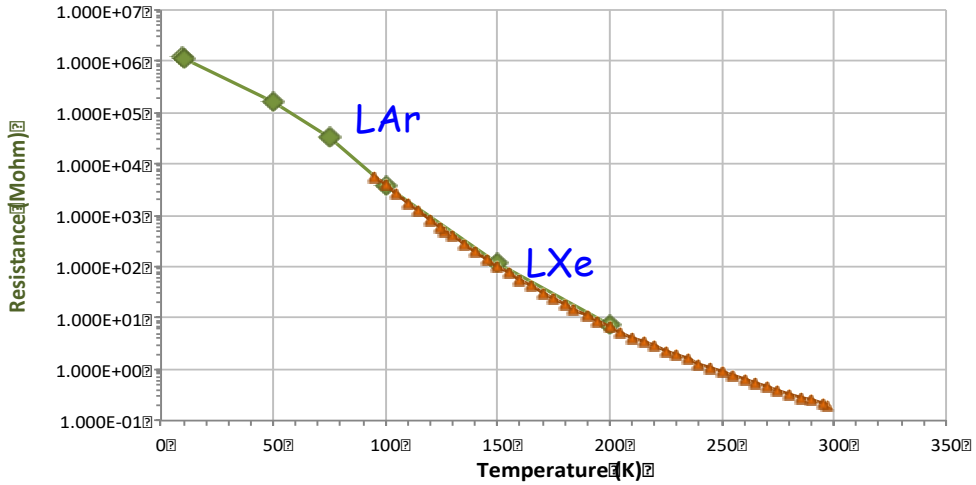
Thank you!

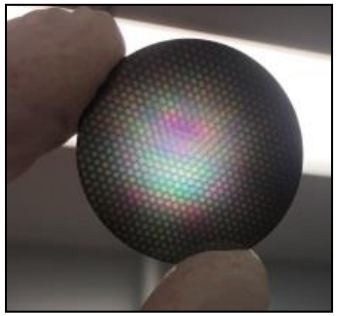
Selected LAPPD References & Links

- **http://www.incomusa.com/mcp-and-lappd-documents/**
- Craven, Christopher A. et al - **"Recent Advances in Large Area Micro-Channel Plates and LAPPD™"** TIPP'17 International Conference on Technology and Instrumentation in Particle Physics, Beijing, People's Republic of China, May 22-26, 2017
- Lyashenko, Alexey et al "**Further progress in pilot production of Large Area Picosecond Photo-Detectors (LAPPD™)"** New Technologies for Discovery III: The 2017 CPAD Instrumentation Frontier Workshop, University of New Mexico, Albuquerque, NM October 12-14, 2017
- Angelico, E. et al, "**Capacitively coupled pickup in MCP-based photodetectors using a conductive metallic anode"**, Nuclear Instruments and Methods in Physics Research A 846 (2017) 75–80
- Ertley, Camden et al, "**Microchannel Plate Imaging Detectors for High Dynamic Range Applications"**, IEEE Transactions on Nuclear Science, 2017.
- Siegmund, Oswald et al, "**Microchannel plate detector technology potential for LUVOIR and HabEx"**, Proceedings of the SPIE, Volume 10397, id. 1039711 14 pp. (2017)
- Siegmund, Oswald et al, "**Single Photon Counting Large Format Imaging Sensors with High Spatial and Temporal Resolution"**, Proceedings of the Advanced Maui Optical and Space Surveillance (AMOS) Technologies Conference, 2017.
- Michael J. Minot, et. al., **"Pilot production and advanced development of large-area picosecond photodetectors**" SPIE 9968, Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XVIII, 99680X (30 September 2016); doi: 10.1117/12.2237331
- Adams, B.W et al. "**A Brief Technical History of the large-Area Picosecond Photodetector (LAPPD) Collaboration"** - Submitted to: JINST arXiv:1603.01843 [physics.ins-det] FERMILAB-PUB-16-142-PPD, March, 2016
- M.J. Minot, et al., **Pilot production & commercialization of LAPPD™**, Nuclear Instruments and Methods in Physics Research A 787 (2015) 78–84

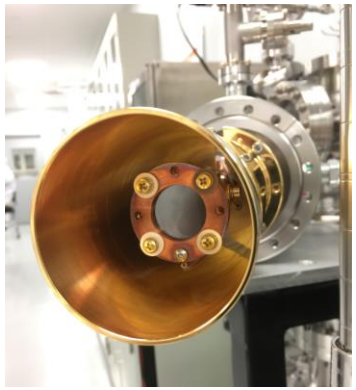
INCOM MCPs at cryogenic temperatures

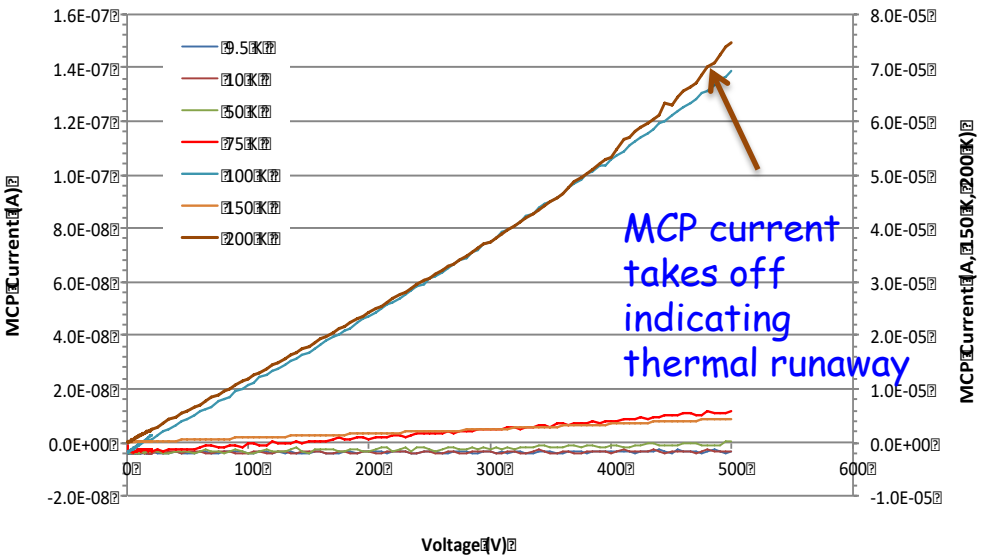
I-V curves for cryogenic temperatures

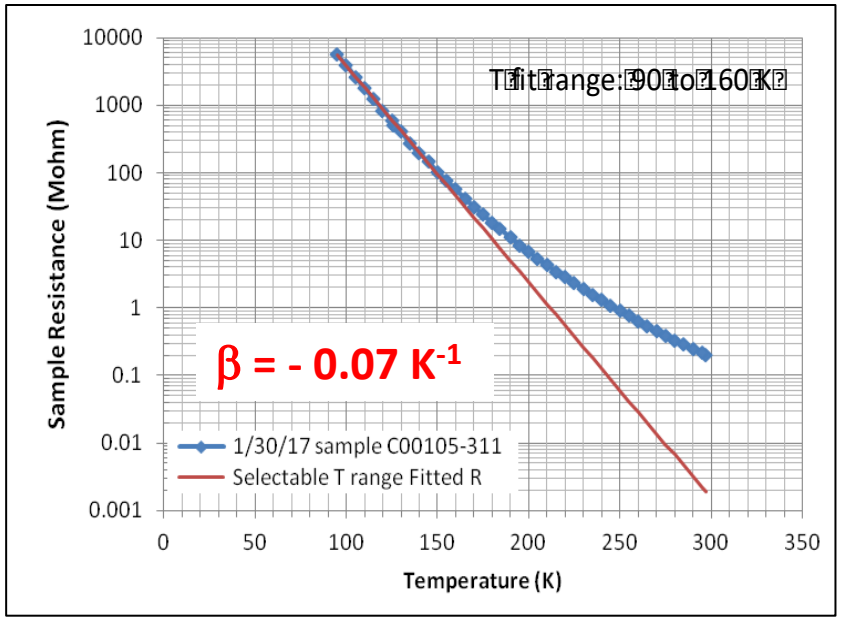




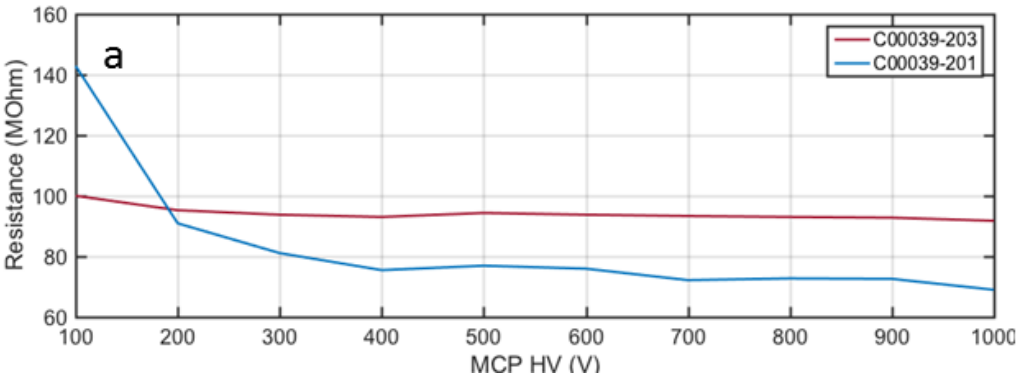
R_{RT} = 200 KΩ



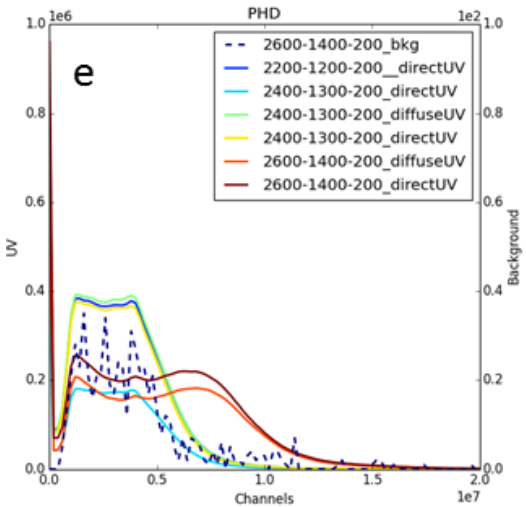




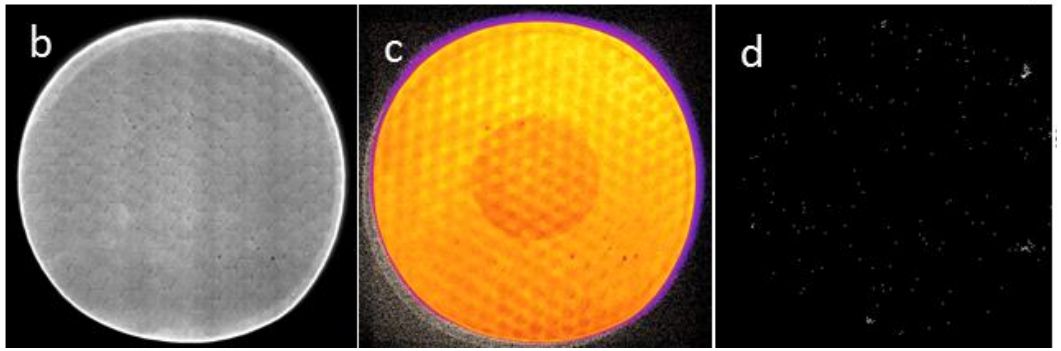
MCP chevron pair detector in cooled environment



1200 V across each MCP,
Stack resistance : 126 M
Background rates: 0.35 cnts/sec/cm^2 .

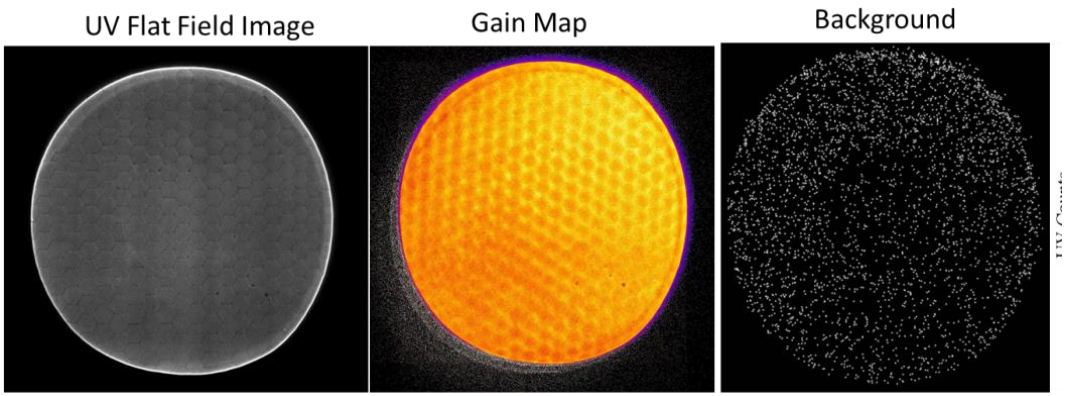


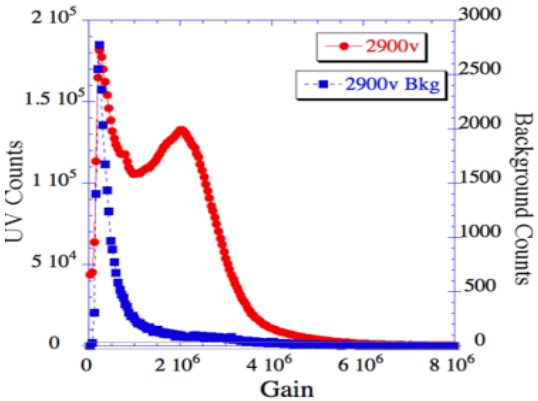
T = -50°C



1300/1400V across each MCP;
stack resistance: 1 GΩ

T = -100°C





LAPPD Price Projections

- Current costs are driven by overhead rates, non-reimbursed R&D Costs, and low volume
- **Costs drop rapidly, as demand and volume increases.**
- Incom projects price to drop from current levels as follows:

Timing	Cmrcl Price	DOE Price	Cum Vol.	Annual Capacity
Current	$ 75,000	$ 50,000	48	48
1	$ 56,250	$ 37,688	58	82
2	$ 45,000	$ 30,150	144	120
3	$ 36,900	$ 24,723	268	204
4	$ 31,365	$ 21,015	502	264
5	$ 30,032	$ 20,121	1,000	278

With full scale production, and cumulative volumes of product produced approaching 10,000 units, a price of $10,000 or less, for a full size LAPPD, is entirely plausible.