Development of Gen II LAPPD™
(Large Area Picosecond Photo Detector)
Systems for Nuclear Physics

(DE-SC0015267)

Michael R. Foley, Bernhard W. Adams, Melvin J. Aviles, Satya Butler,, Camden D. Ertley, Till Cremer, Cole J. Hamel, Alexey Lyashenko, Michael J. Minot, Mark A. Popecki, Travis W. Rivera, Michael E. Stochaj

Incom, Inc.

Collaborators:
Evan J. Angelico, Andrey Elagin, Henry J. Frisch, Eric Spieglan
University of Chicago

2019 Nuclear Physics SBIR/STTR Exchange Meeting
Gaithersburg, MD

INCOM
BRIGHT IDEAS

Gen II LAPPD™ Year 2 Review

- Incom background
- Where we were a year ago and challenges
- Ceramic Seal success for Gen I and Gen II style
  - LAPPD Yield
    - Incom
    - UChicago
- Incom LAPPD performance results
- UChicago collaboration
  - Fermilab LAPPD tests
- Summary, conclusions and Ph IIA plans
  - Early Adopters
    - UTexas Arlington (#38 Gen II)
    - JLab (#41 – CLTA Gen I)

Incom Inc. – Enabling the Vision of Tomorrow

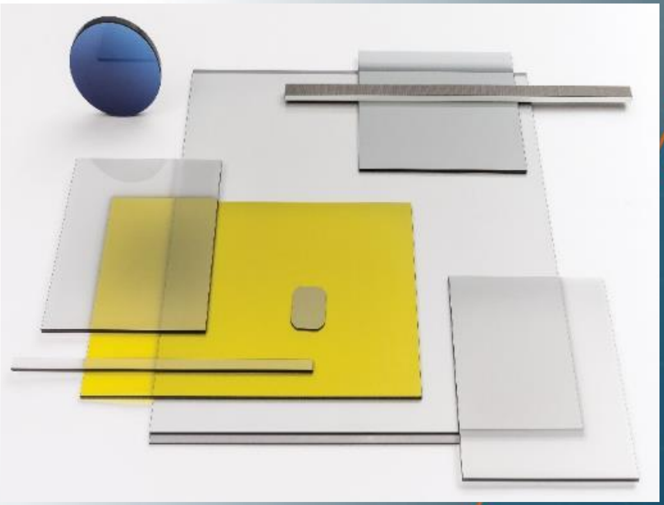
Founded 1971 (Fused Fiber Optics)

Long history of Innovation

~220 Employees

Three facilities:

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



INCOM BRIGHT IDEAS

Incom Inc. – Enabling the Vision of Tomorrow

Medical

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

Display

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

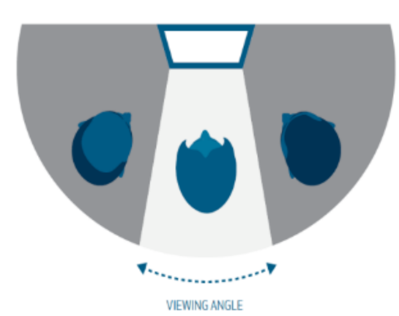
Defense

- Night Vision
- Biometrics
- Neutron Detection

Detector

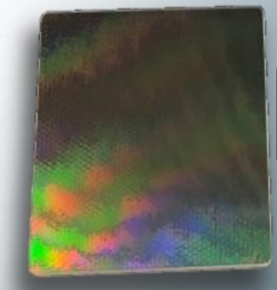
- Particle Identification
- Electron Spectroscopy
- Ion Spectrometry
- Space Flight Instrumentation

Large Fiberoptic Face Plate for medical diagnostics



DARC glass privacy filter

Night Vision



Plano MCP 53mm x 53mm

Curved MCP 25mm x 120mm

LAPPD (MCP-PMT) 200mm x 200mm

Major goals/tasks for the Phase II Gen II LAPPD™

(Original Proposal: '17)

- **Simplifying** the ceramic lower tile assembly
- **Optimize glass-to-ceramic sidewall sealing process**
- **Fabricate working Gen-II LAPPD™s** for both pad and stripline applications.
- **Optimize electrical properties** of the inside-out capacitively coupled anode design.
- **Document** LAPPD™ pilot production processes
- Build Test and measurement stations for **performance and life testing**.
- Work closely with **University of Chicago**

    Characterization, batch production techniques and applications

(Year 2 Challenges: Aug '18)

- Solve the Indium **sealing process** on the Gen II ceramic LTA to top window
- **Fabricate** working detector tiles
- Fine-tune the entire **LAPPD fabrication process**
- **Document control** for bill of materials, standard operating procedures
- Finalize **development** of the **testing electronics and measurement protocols** for working Gen II LAPPDs
- Collaborate with **UTexas at Arlington on lifetime testing** while setting up Incom's own life test station
- **Supply Gen-II LAPPD™s** to specific NP, HEP or commercial applications

LAPPD™ Design

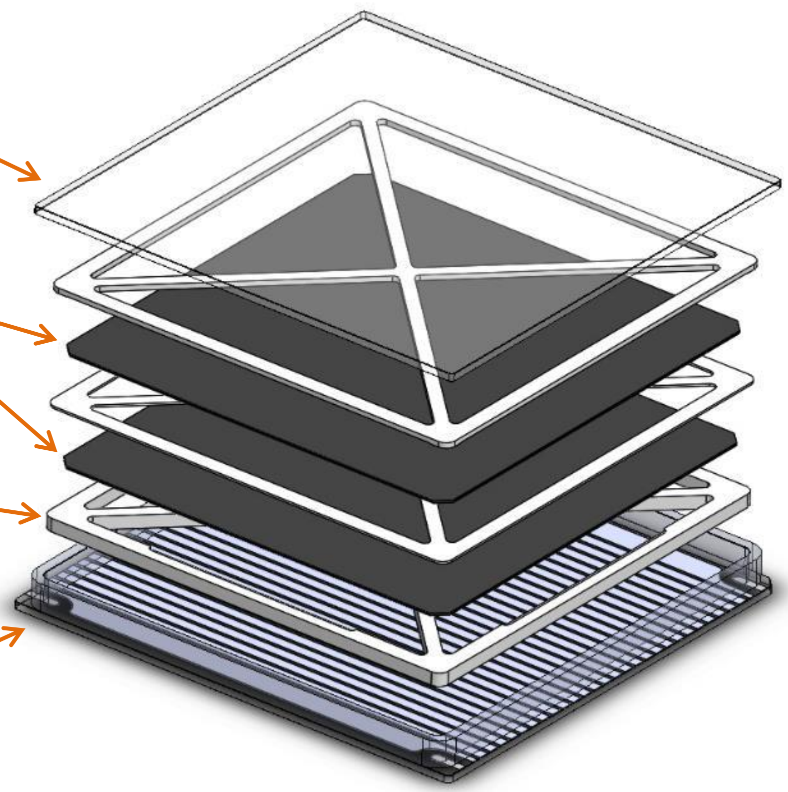
- **Two-part Glass or Alumina** packaging (Lower Tile Assembly)
- Signal and high voltage delivered on strips **passing under a frit bond** (i.e. no wall or anode penetrations)
- Active area: 195 x 195mm

Semi-Transparent Photocathode
Photon → electron

Pair of 20 × 20 cm ALD-GCA-MCP
1 electron → 10^7 electrons

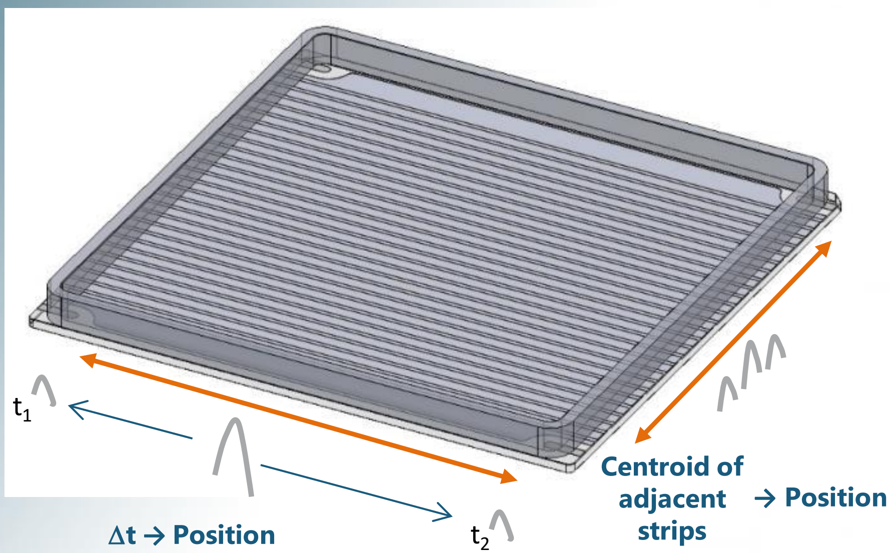
Glass Spacers (3)
Provides window support

Patterned Anode
Collect electron signal

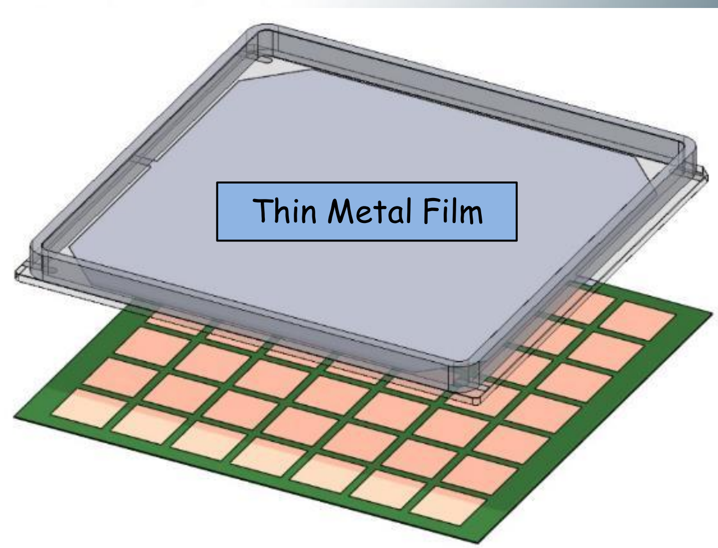


Gen-I vs Gen-II LAPPD™ Design

Gen-I Strip Line Anode



Gen-II Resistive Anode with Coupled Patterned Anode



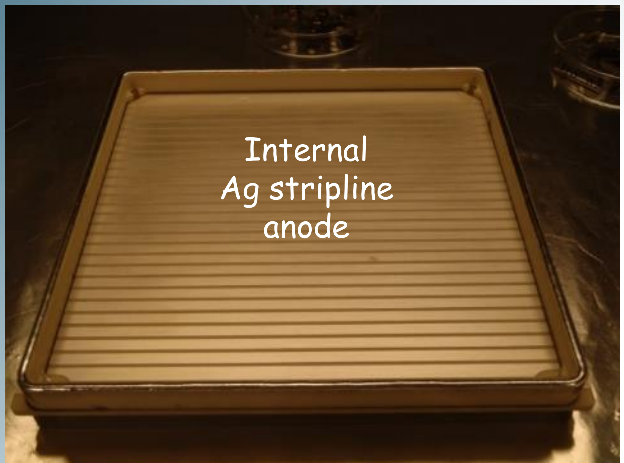
Optimized for fast timing applications.
~1 mm spatial resolution, ~50 ps TTS

⟹

Customizable anode pattern.
Maintains performance for most applications.

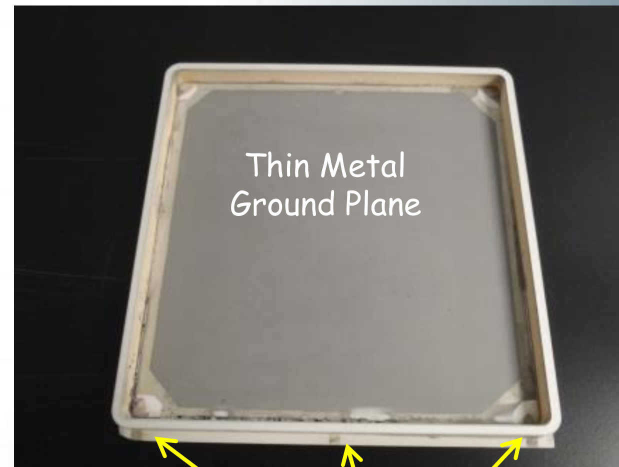
F. Tang et al., TWEPP 2008, Naxos, Greece, September 15-18, 2008
H. Grabas et al., Nuclear Instruments and Methods in Physics Research A 711 (2013) 124–131
B. Adams et al., Nuclear Instruments and Methods in Physics Research A 846 (2017) 75–80

Gen-II LTA (ceramic lower tile assembly)



Incom Inc.
Two–part design

- Vacuum Transfer
- Capacitively coupled signals
- User defined device using stripline or ground plane pattern
- Easily changed external pickup board

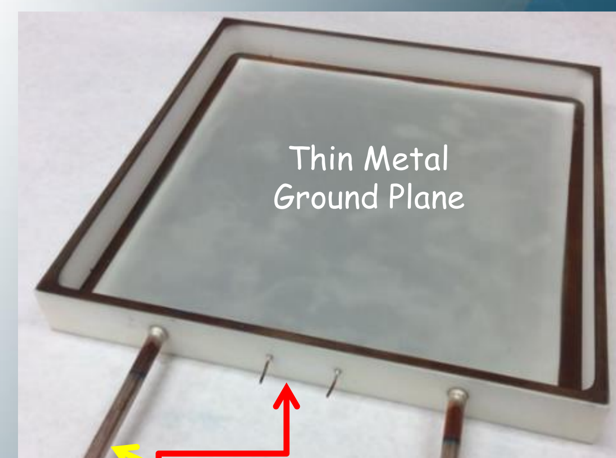


HV and ground tabs

Alumina Ceramic Bodies

UChicago
In-Situ design

- Mono base design
- Air transfer
- Pins and tubes brazed in for PMT-like batch production
- Easily changed external pickup board



HV pins and cesiation tubes

Window to Ceramic Sealing (X-ray @ UC)

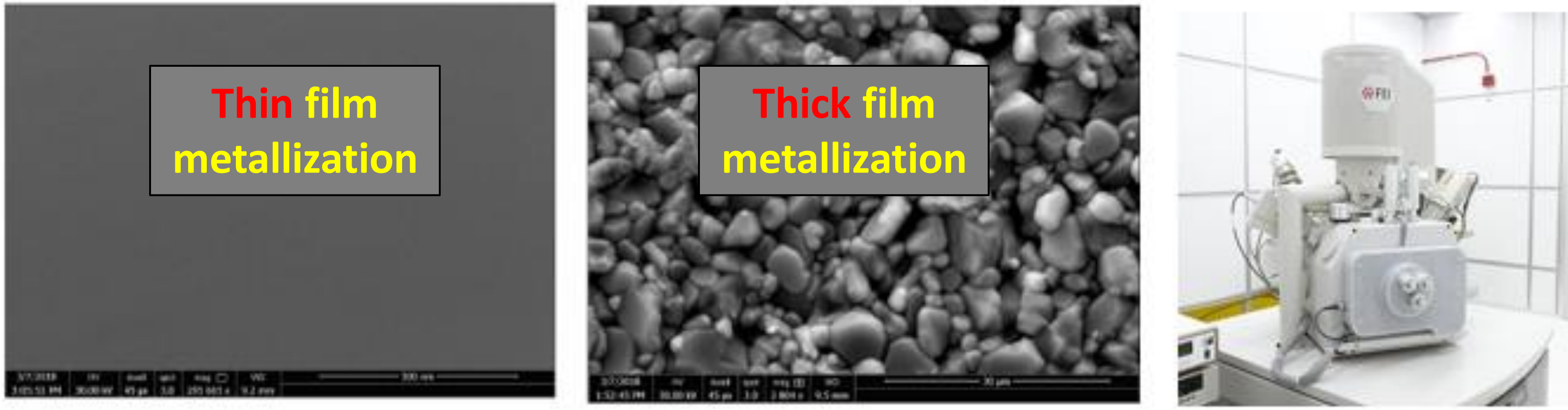


Figure 1: Shows the smooth surface of amorphous glass (Gen-I LAPPD) and the granular structure of the ceramic viewed in the FEI Quanta 650 FEG SEM.

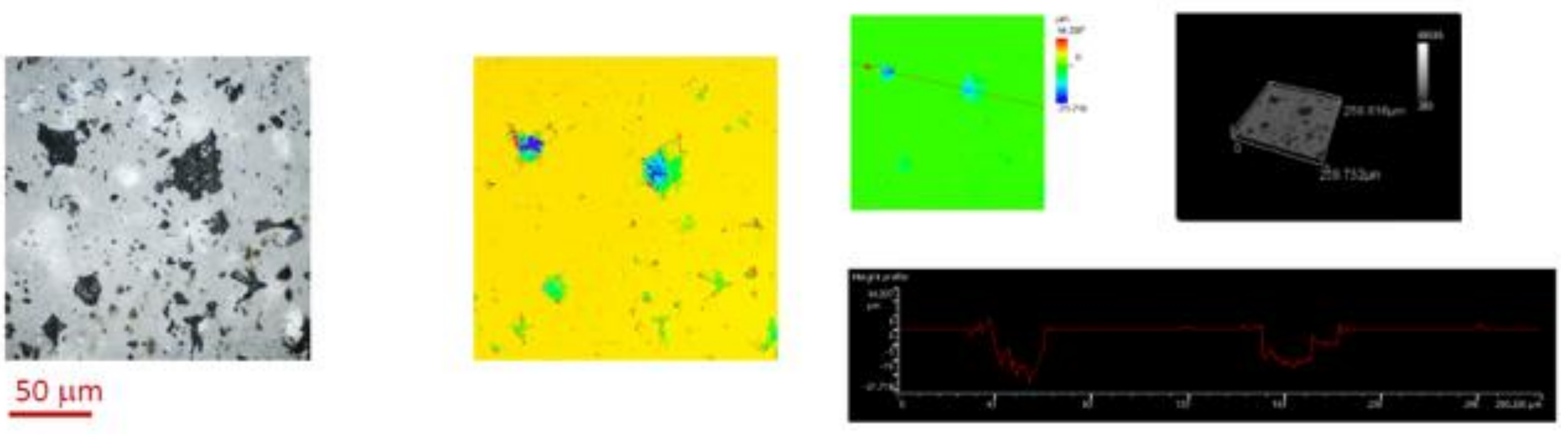
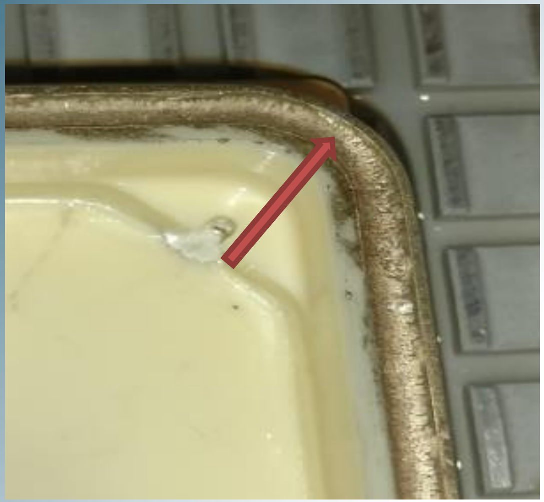
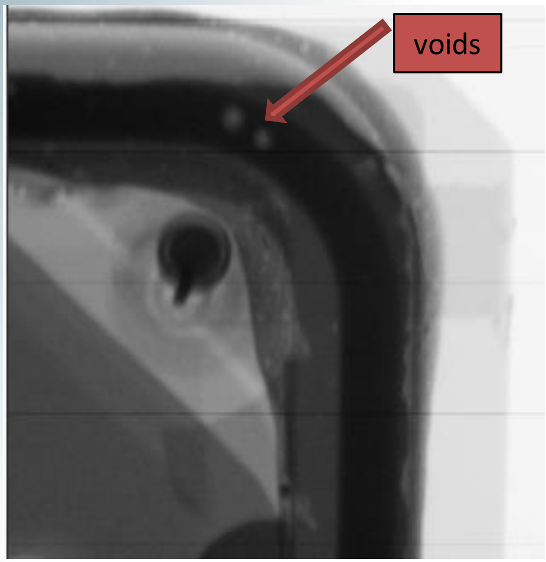


Figure 2: pores or grain pullout as deep as 20-25 µm on the machined ceramic surface

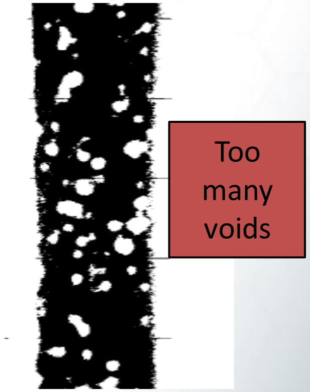
Window to Ceramic Sealing (Incom)



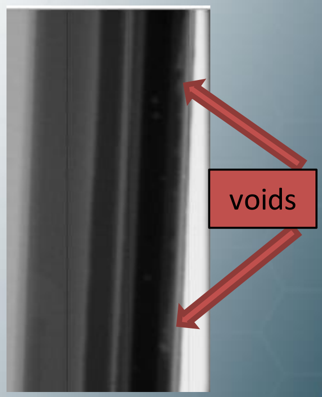
- Metallization of ceramic lower tile assembly sealing surface



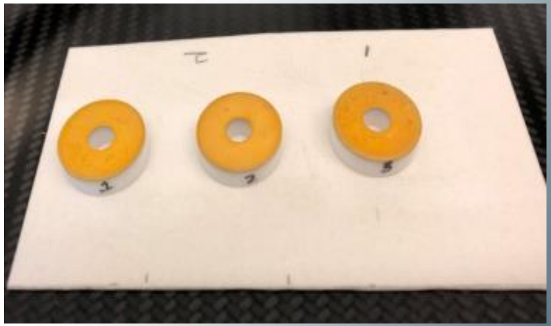
- X-ray inspection of corner and length of sealing surface



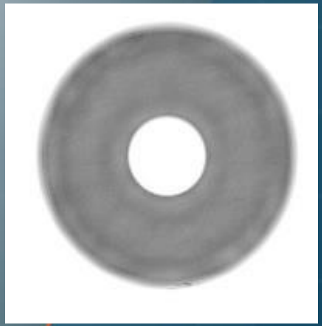
X-ray of early metallization



X-ray of Current processing



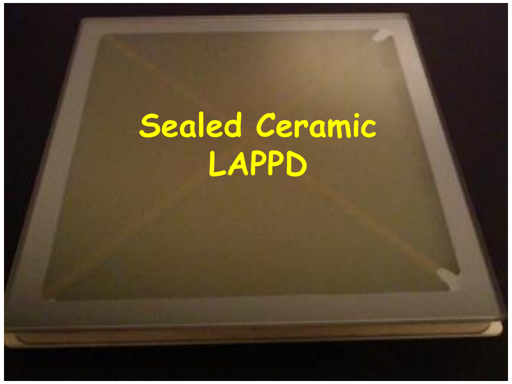
Vendor metallization

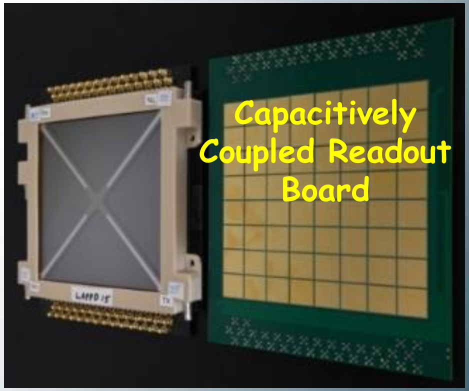


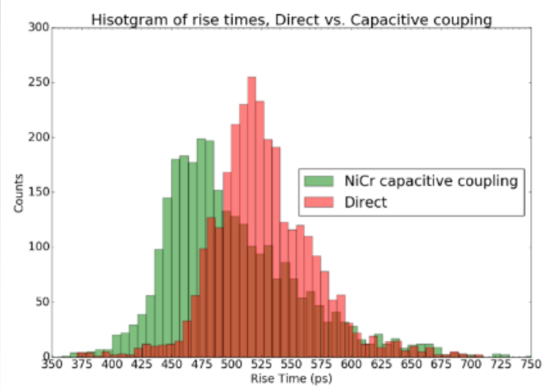
X-ray of vendor metallization

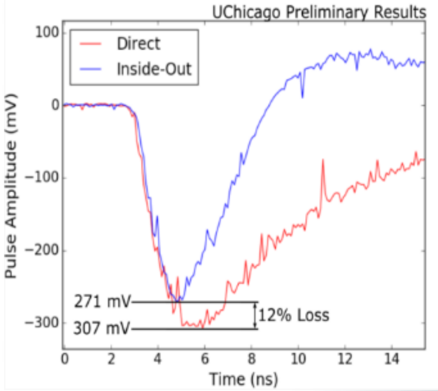
GEN II LAPPD

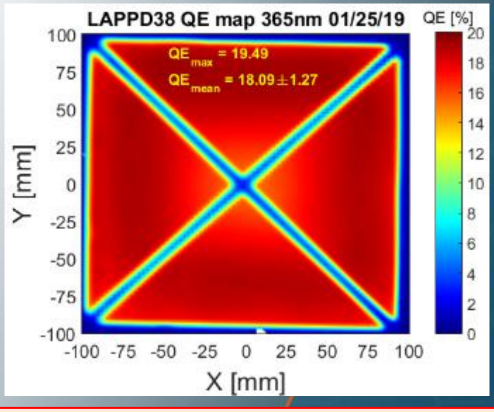
- **Capacitive signal coupling:** to an external PCB anode
- A **robust ceramic body**: for durability and dielectric properties
- **Pixelated anodes:** to enable high fluence applications









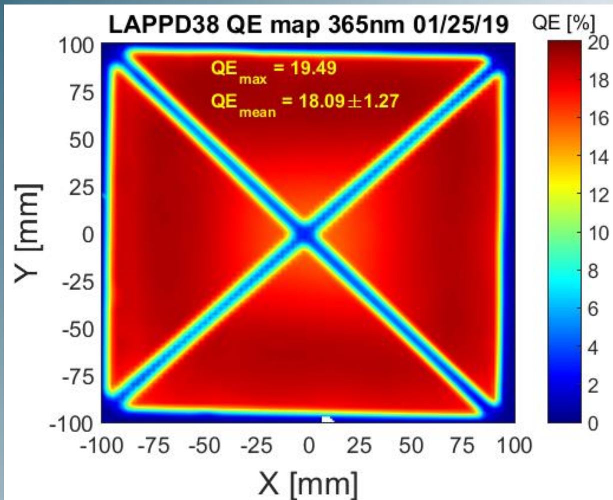


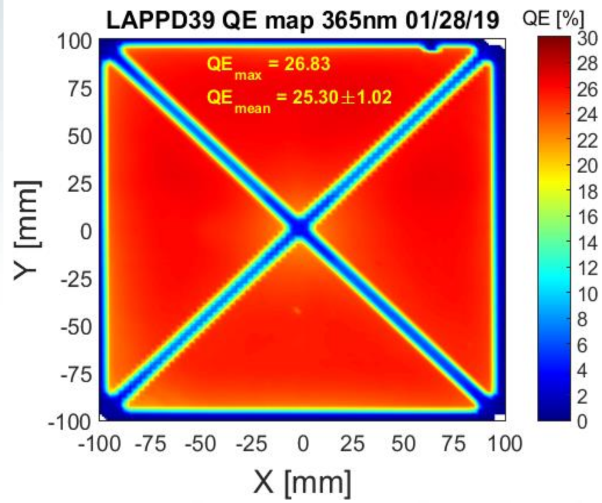
The capacitive readout scheme preserves rise-time of pulses (rise time is a key factor in timing resolution)
For pad pattern: 80% of the directly coupled amplitude

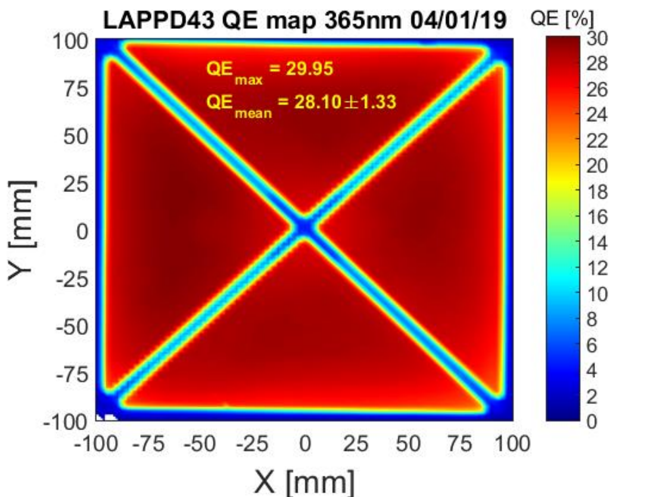
Sealing process established, high QE demonstrated.
Inner design optimization on-going

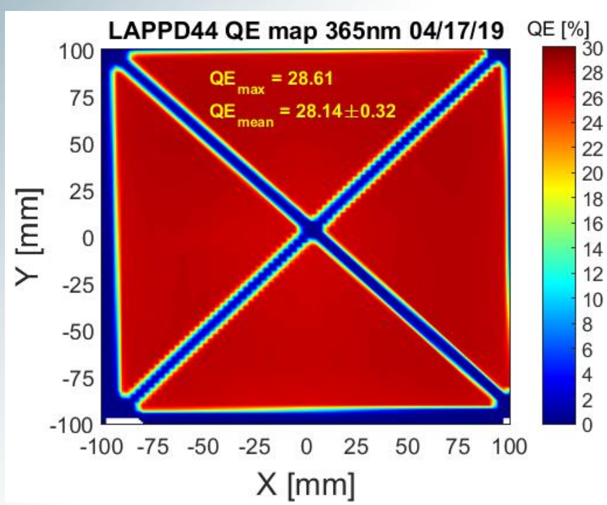
E. Angelico et al., Nuclear Instruments and Methods in Physics Research A 846 (2017) 75–80

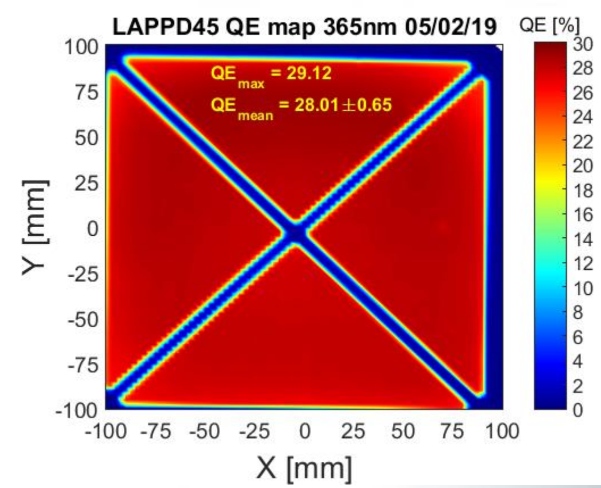
Photocathode (most recent tiles)

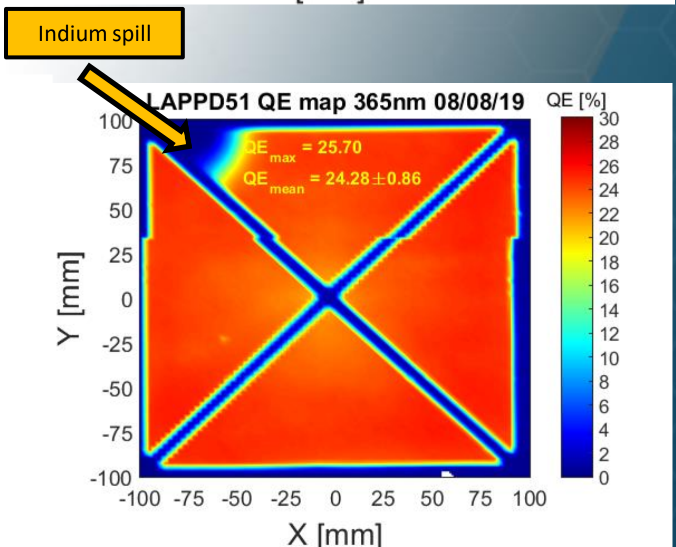












Large Area Photocathode production process is established **(independent of LAPPD type)**
QE ~20% and higher and 90% uniformity demonstrated in recently sealed LAPPDs

INCOM BRIGHT IDEAS

Incom LAPPD Sealing Yield

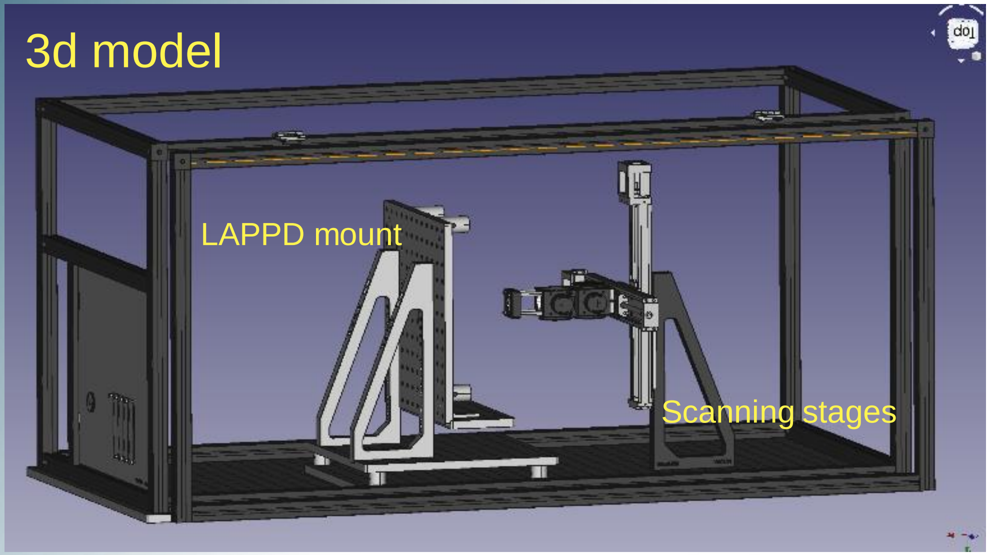
- From onset: photocathode deposition and sealing (glass) was in question.
  - Since 2016: A total of **51 LAPPDs** have been "started
    - Since Aug 2018 (while bringing on a 2nd IST):
      - **19 LAPPD (starts up 50% from one start/month**)

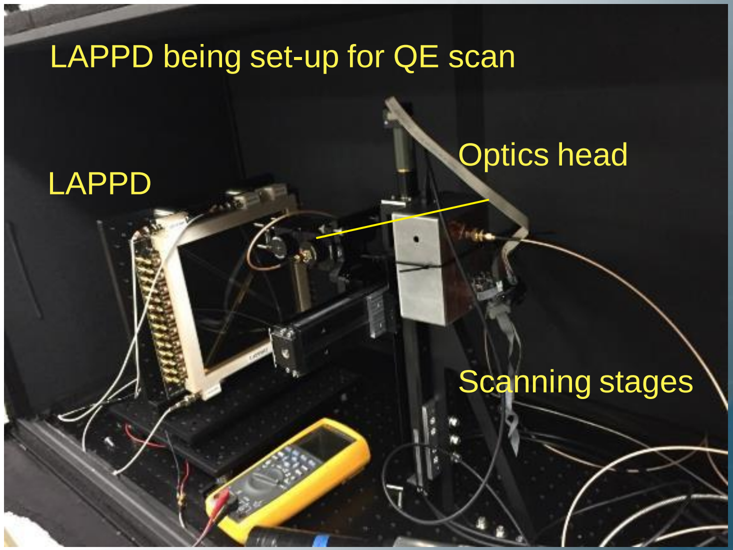
- Sealed Tile Yield in the last year **(~80%)**
  - **15 in a row sealed Integration & Sealing Tank #1**
    - PC deposition, **check!**
    - Sealing of glass tile, **check!**
    - Fabricating LAPPDs is now a **Routine Process**
  - **NOW, SIX out of SIX** ceramic to window seals, **check!**
    - FOUR are capacitively coupled Gen II, TWO with Gen I striplines
      - Five are **Incom** thick film metallization process
      - One is a **vendor** thick film metallization process
  - NINE glass Gen I thin film metallization sealed

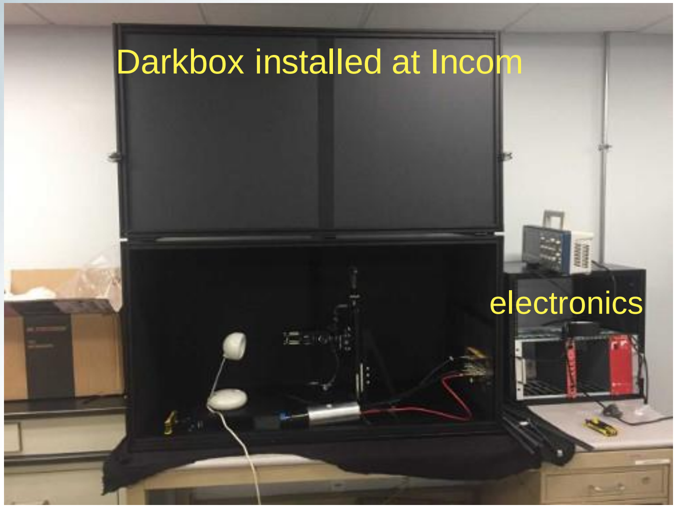
- The failed seals were:
  - Thin film metallization error, cracked anode
  - First trials in our 2nd Integration & Sealing Tank (#47 & 50)

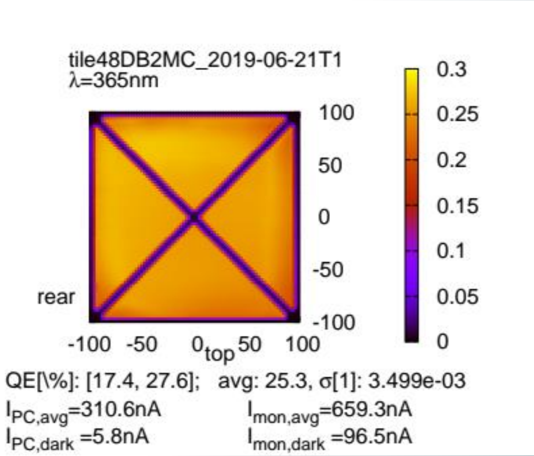
INCOM BRIGHT IDEAS

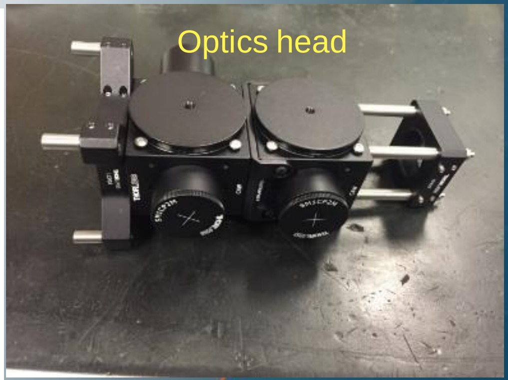
Gen-II LAPPD Darkbox for Measurement & Testing





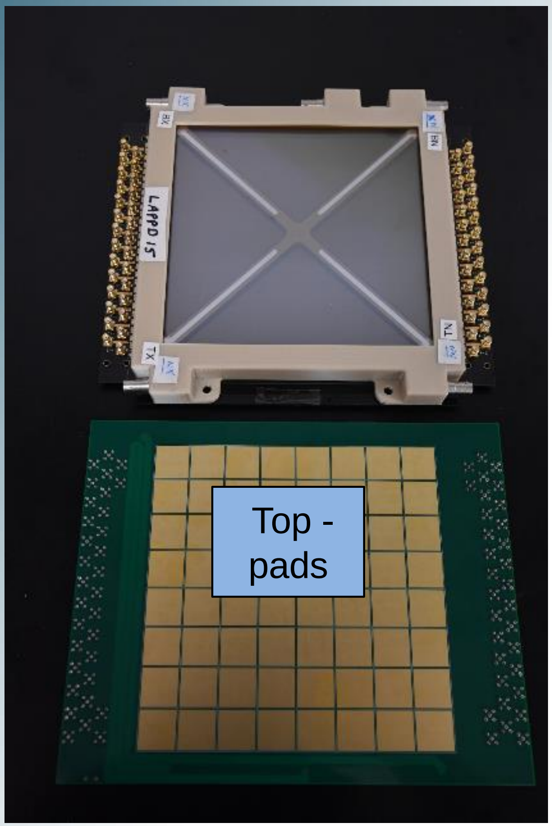


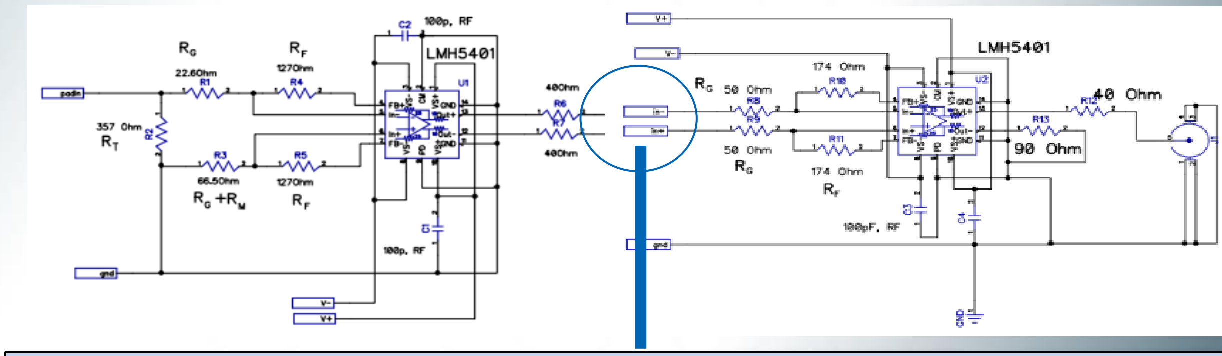




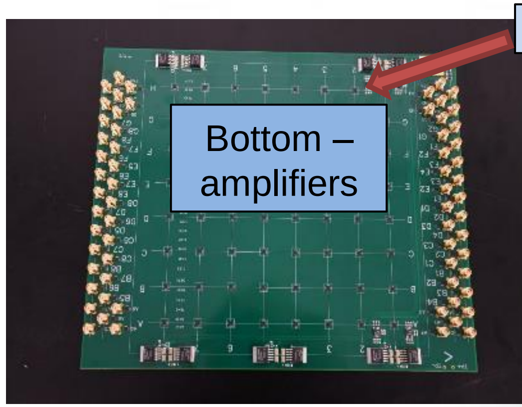
Construction plans are being disseminated to users.
A near-complete duplicate already at FNAL.

Gen II Capacitive Coupling



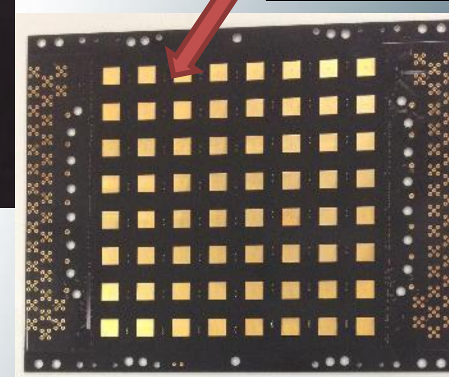


- Schematic showing two internal circuits.
- Each pad has an amplifier mounted on it. The amplifier output is differential, to minimize unwanted signal pickup.
- Another amplifier is mounted near the SMA connector to receive the differential signal. It converts to a single-ended signal for the output cable.



64 channels, 4GHz bandwidth, 50W

A passive (0W) and/or low-power board with ~0.8GHz bandwidth is being assembled.

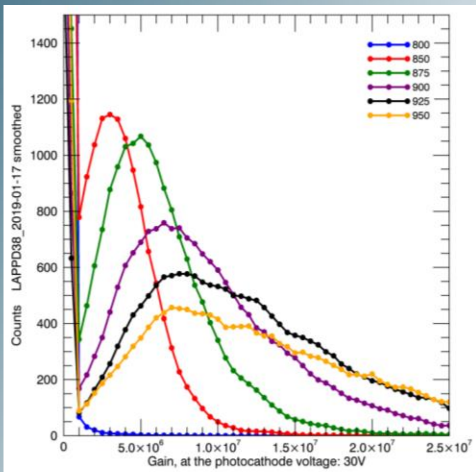


- Low-power
- Less expensive
- Quick turnaround for different pad and pixel patterns

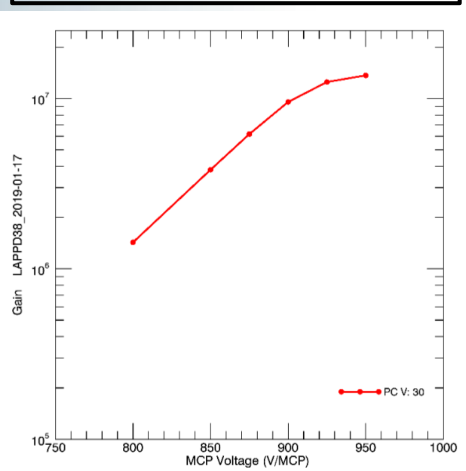
This board has been used for tests of capacitive coupling temporal and spatial resolution.

E. Angelico, T. Seiss, B. Adams, A. Elagin, H. Frisch, E. Spieglan
Capacitively coupled pickup in MCP-based photodetectors using a conductive metallic anode
Nucl. Instrum. Meth. A 846, 75-80 (2017)

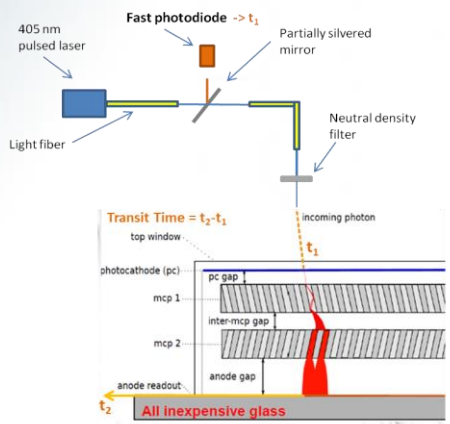
Gen-II readouts for PHDs, transit time (**SPE**) and spatial resolution

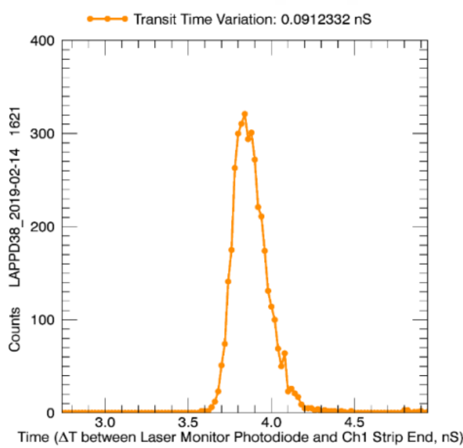


Amplified signals show PHDs nicely separated from noise and gain as high as 10^7

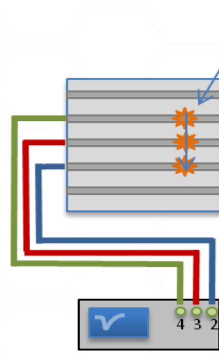


How is transit time variation/spread measured



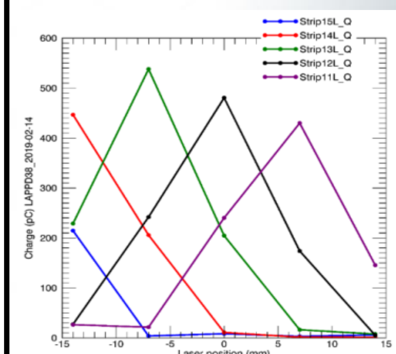


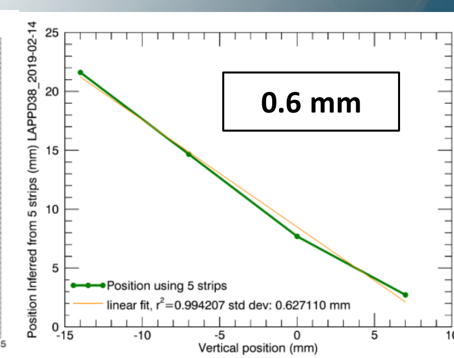
TTS measured : 91pS (FWHM)



Outline of experiment to measure spatial resolution.

A strip line circuit board was capacitively coupled to the back of the LAPPD.





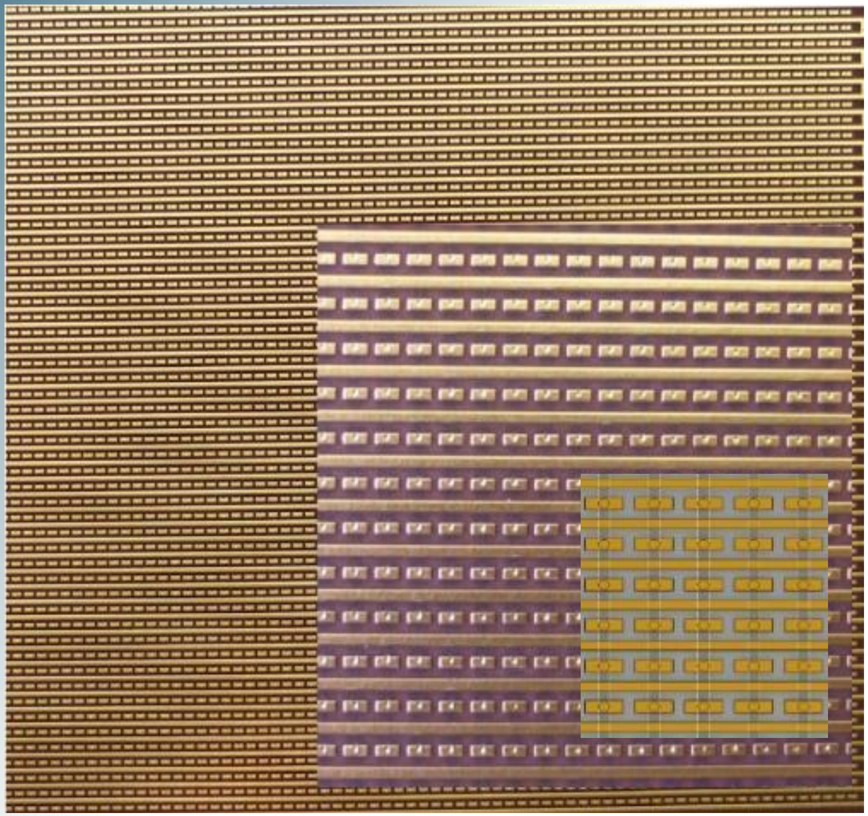
Charge is concentrated on the strip closest to where the charge cloud made contact but can still be observed on adjacent strips, enabling centroiding. This allows for mm and even sub mm spatial resolutions **(0.6 mm for Gen II)**

Gen I Resolution:

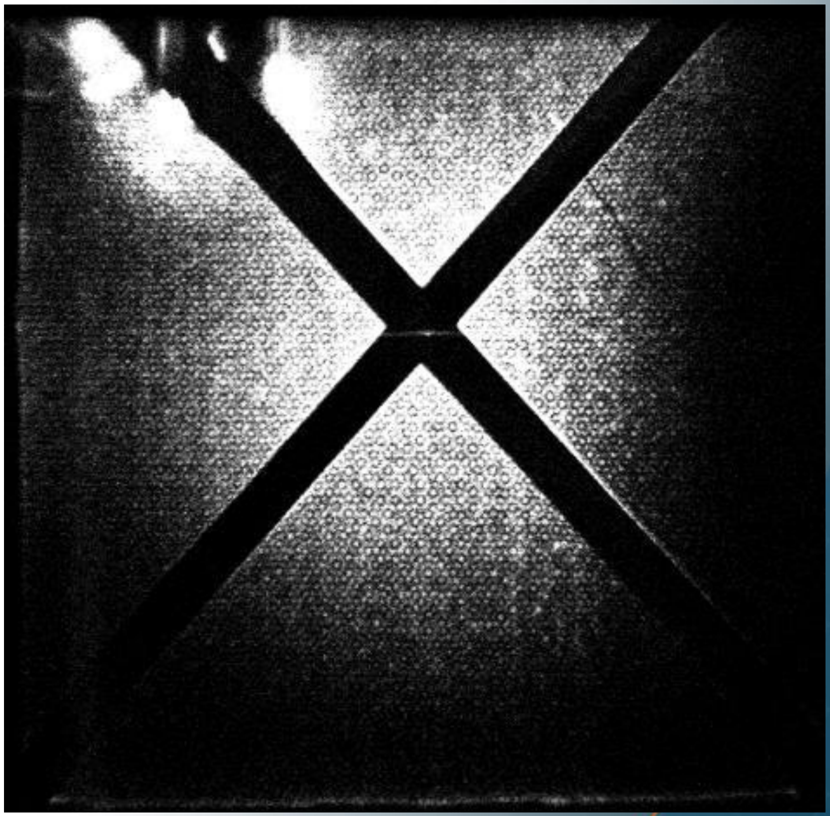
- along strip is 1.3mm
- across strip is 0.76 mm

INCOM BRIGHT IDEAS

High Resolution Imaging using GEN II LAPPD Capacitively Coupled to a Cross Delay Line Anode



200 mm square cross delay line anode. X serpentine on surface and Y serpentine connected by through-hole-via to surface pads. (UC Berkeley)



Preliminary high resolution image formed using a cross delay line anode capacitively coupled to GEN II LAPPD #44.

Preliminary results suggest spatial resolution in the 100-200 µm range.

"Margherita" Batch Production Chamber

Evan Angelico, Andrey Elagin, Henry J. Frisch, Eric Spieglan (University of Chicago)

Goal: Develop a batch production process for LAPPDs capable of >50/week (>2000/year)

Three key technological challenges:

- Hermetic seal

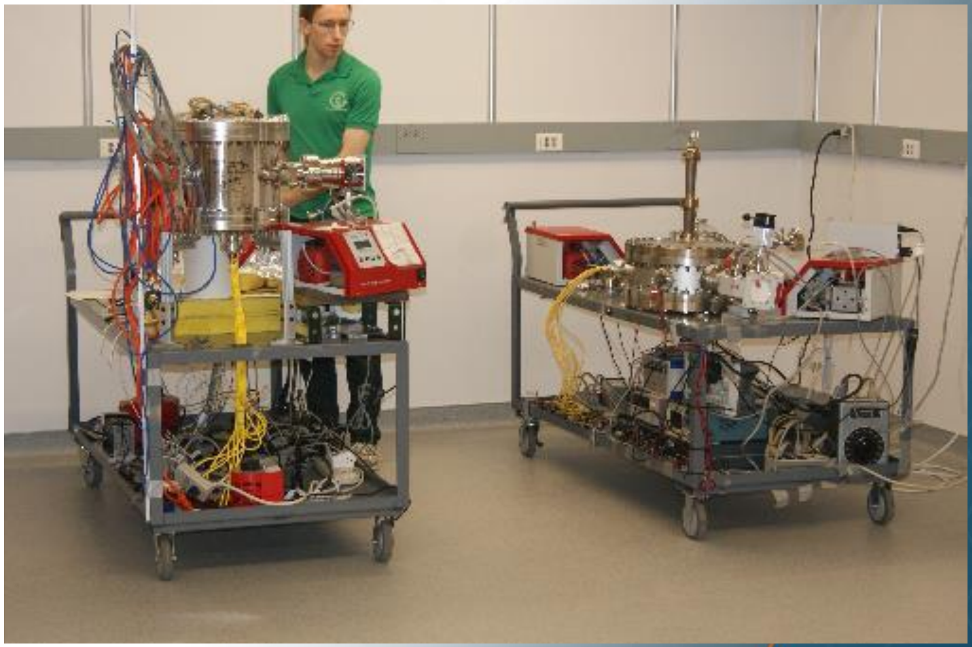
Challenges: indium oxide, metallization quality, surface quality

- Air-transfer photocathode method

Challenges: purity of Cs source, quality and thickness of antimony precursor, optimization of temperatures and rates

- Recovery of MCP after cesiation

Challenges: pre-scrubbing, baking after cesiation



Margherita version 2 (left) and 1 (right). Eric Spieglan behind Margherita 2

We believe that this process is close to a commercialization stage, with the goal of a prototype commercial batch production facility

Future Scale-up: Three key technological challenges

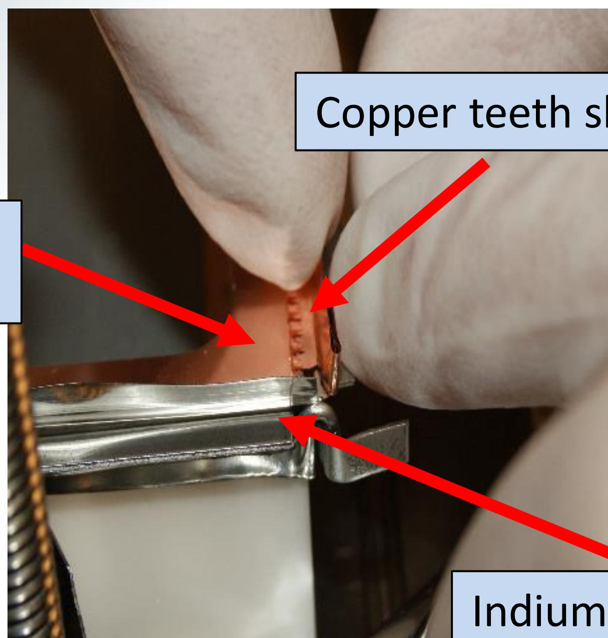
Eric Spieglan, Evan Angelico, Andrey Elagin, Henry J. Frisch, (University of Chicago)

1. **Hermetic seal** (patent applied for)

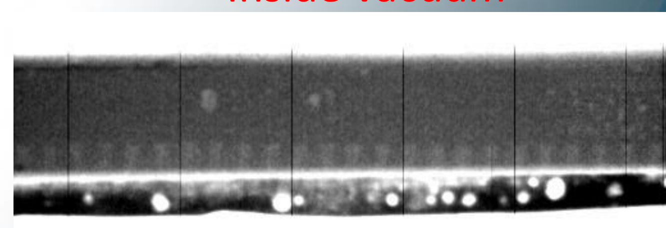
Big steps were:

- No oxide in sealing area, using capillary action to wick solder into the gap
- Diagnostics and process QC with large format X-ray

2 out of 2 ceramic to glass seals have succeeded using capillary action method. Margherita chambers allow for in-situ helium leak checking. Both are hermetic to 10^-12 Torr L/s



X-ray showing continuity and quality of indium in capillary seal



INCOM BRIGHT IDEAS

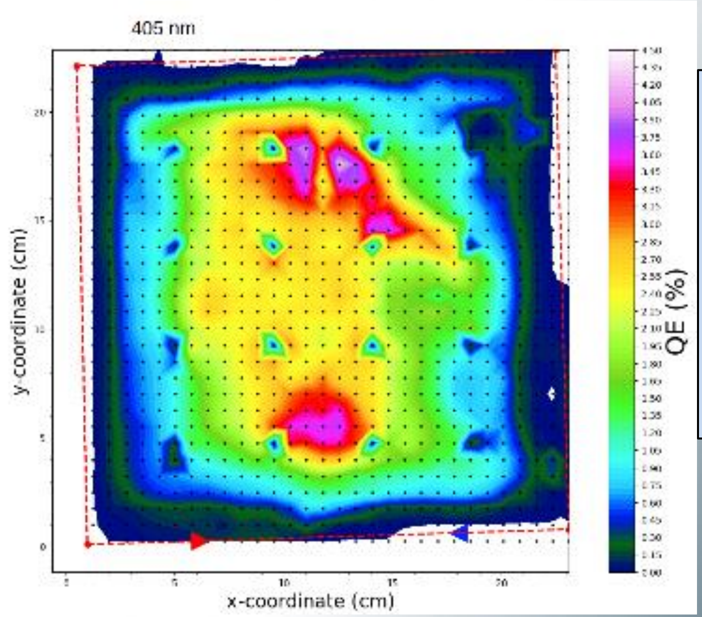
Future Scale-up: Three key technological challenges

Evan Angelico, Andrey Elagin, Henry J. Frisch, Eric Spieglan (University of Chicago)

2. Air-transfer photocathode method

a) Demonstration in-situ with Tile 31 (~3% Cs-Sb)
b) Optical monitoring of Cs quality
c) Air-transfer method used by commercial photo-multiplier manufacturer, MELZ
d) Barois paper (below) suggests bi-alkali can and should be formed via thermal equilibration process practiced in Margherita chambers

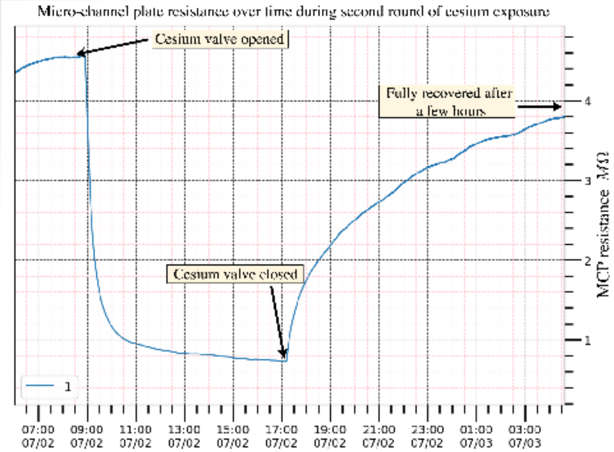
B. Tanguy, J. M. Barois, M. Onillon. *Experimental study of the equilibria of cesium potassium antimonides with alkali vapours.* Materials Chemistry and Physics, 30 (1991) 7-12

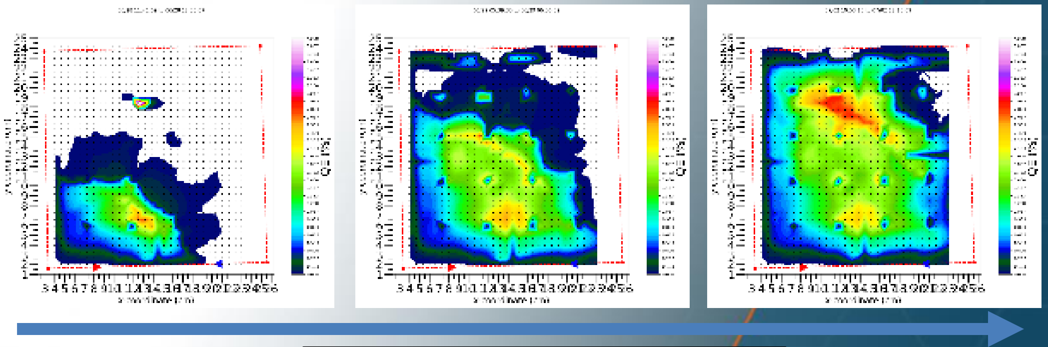


QE Monitoring while internals are still on the pump

3. MCP Recovery following cesiation

a) MCP resistance drops while cesium valve was open, but recovers to original resistance when closed
b) Single photo-electron pulses are observed after the entire cesiation process. High voltage is stable when MCPs are in gain mode.



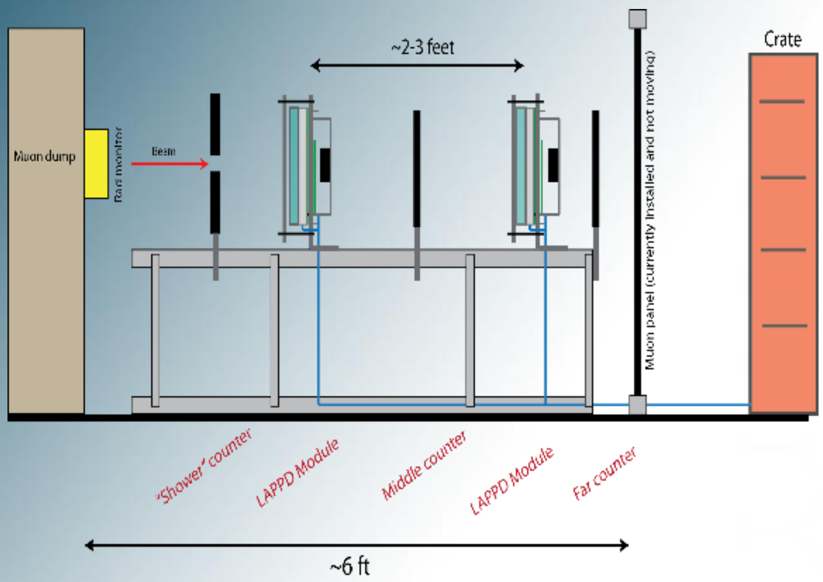


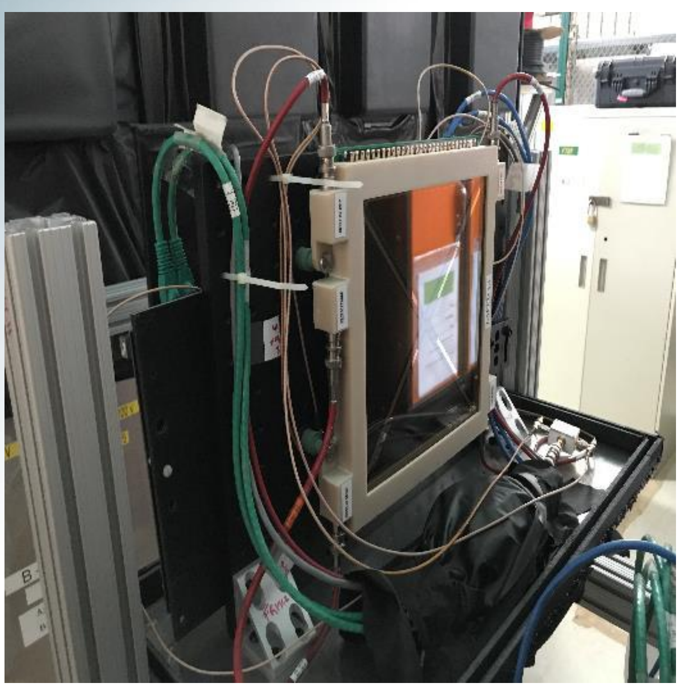
Cs-transport over time

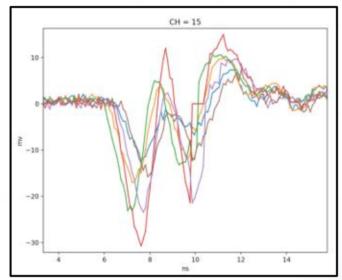
LAPPDs at the Fermilab Test Beam Facility

Thank you to Helmut Marsiske, Michelle Shinn, and offices of DOE HEP and NP.

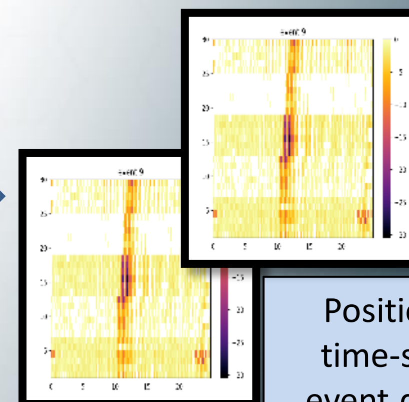
Status: have measured ~1000s of charged particle events synchronized to beam spills with 2-LAPPDs, 120 channels of PSEC4 readout







PSEC4 waveforms **(UC Tile #31)**



Position vs time-series event display

Goals:

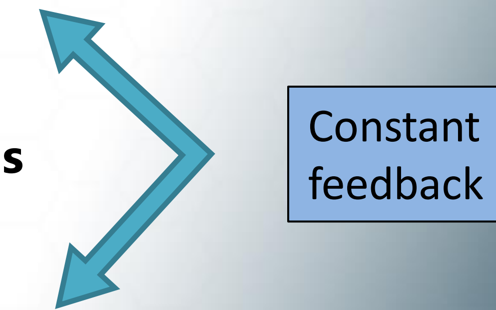
- Factor of 100 improvement for TOF resolution
- Optimize LAPPD temporal resolution for charged particles at the psec level
- Collaboration with Incom Inc., FNAL personnel, and ANNIE
- **PhD Thesis for E. J. Angelico**

Summary & Conclusions

- Current Pilot Production **Sales**
  - Seven - ANNIE, Sandia, Fermilab
  - Three Pending sales
    - UChicago, USheffield (2)
    - Four **loaned** out for testing and validation
- Ceramic to PC window **vacuum-transfer sealing process** has been **solved**
  - Incom, UC and Vendor
  - **Transition from glass to ceramic** body for Gen I striplines or Gen II capacitive coupling
- Two Incom Measurement & Test Stations running
  - **"Typical" performances** meet early adopter needs:
    - **Either Gen – I or Gen – II**
      - Gain ~10^7
      - Mean QE ~ 20 - 25% @ >90% uniformity
    - **Gen – I (Gen – II TBD)**
      - Time Resolution < 70 Picoseconds, and mm Spatial Resolution
      - Dark rate 50-70 Hz/cm2 @ gain $3*10^6$
- The UChicago **air-transfer fabrication process** is close to a commercialization stage, with the goal of a prototype commercial batch production facility
- Early adopters are **currently testing** Gen I and Gen II LAPPDs in **beamlines** and **lifetime** test stations
  - Fermilab (UChicago & ANNIE), UTA, JLab
  - Others (B-Field tests (ANL), Medical (PET), CHESS, Neutron camera)

Phase IIA Gen II Plans

- **Optimize Gen-II tile design/window seal/component stack**
  - Tighter component tolerances and internal design optimization
  - Pre-sealing test station: shorter sealing cycle
  - Automation: frit, metallization, indium
  - HV instability sources: internal free surfaces/edges/corners
- **Address outstanding performance issues and goals**
  - Reduce high voltage instabilities and high dark rates
  - Assess unwanted pulse coupling to pads
  - Minimize photocathode damage and after pulsing
  - Demonstrate high rate capability with pixelated signal boards
  - Perform life testing



- **Beamline testing at Fermilab**
  - Demonstrate high speed capabilities
  - Optimize LAPPD temporal resolution for charged particles at the psec level
  - Permanent set up @ FNAL for PID
- **Business Development and Commercialization**
  - Coordinate with early adopters: Incom workshops, validation, feedback
  - Test Gen-II devices for collider and double-beta decay applications
  - Cost models, yields, and SOPs with support from MassMEP (NIST partner)
  - UChicago in-situ PMT-like batch process for industrial viability

Current Funding & Personnel Acknowledgements

THANK YOU!

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 Phase I - Development of Advanced Photocathodes for LAPPDs

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

NASA DE-SC0017929 Phase II "Curved Microchannel Plates and Collimators for Spaceflight Mass Spectrometers"

NASA Phase I - Improvement of GCA center to edge of high spatial/timing resolution applications

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

INCOM BRIGHT IDEAS

Back up slides

III. LAPPD™ Early Adopters

PI & SPONSOR	PROGRAM TITLE
Mayly Sanchez and Matthew Wetstein, Iowa State	ANNIE: Atmospheric Neutrino Neutron Interaction Exp.
Henry Frisch, Evan Angelico (U of Chicago) , Sergei Nagaitsev, Petra Merkel (Fermilab)	FERMILAB TEST BEAM IOTA (Integrable Optics Test Accelerator) KOTO (Rare Decays)
Andrey Elagin (U of Chicago)	Neutrino-less Double-Beta Decay
Mickey Chiu (BNL) -	Phoenix Project - eIC Fast TOF
Lindley Winslow (MIT)	Neutrino-less Double-Beta Decay (NuDot)
Erik Brubaker, Sandia National Lab/CA	NEUTRON IMAGING CAMERA NanoGuide Scintillating Polymer with Incom West
John Learned, U. of Hawaii, and Virginia Tech	Short Baseline Neutrino (NuLat) NanoGuide Scintillating Polymer with Incom West
Andrew Brandt, Varghese Anto Chirayath (UT Arlington)	LAPPD LIFE TESTING, ROLE OF ION FEEDBACK
Silvia Dalla Torre (INFN Sezione di Trieste)	Confidential / TBD
Robert Wagner (ANL), J. Xie, E. May, F. Skrzecz, F. Cao	LAPPD B-Field Testing
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)	CHESS, WATCHMAN, THEIA
Zein-eddine Meziani	high rate threshold CHERENKOV LIGHT DETECTION Jefferson Labs, SoLID
Simon Cherry, Stan Majewski (UC Davis), William A. Worstell (PicoRad Imaging)	LAPPD based Time-of-Flight PET Sensor

I. 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	Workshop #1, November 13 – 16th, 2017 • Kurtis Nishimura (U of Hawaii / Sandia) • Josh Brown (Sandia) • Julieta Gruszko (MIT)

II. Active & Pending SBIR Development programs:

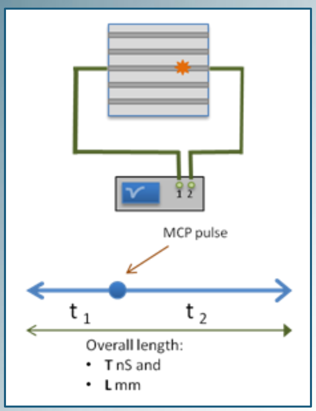
1. “GEN II LAPPD" - Gen-II LAPPD™ Systems For Nuclear Physics Experiments (Phase IIA, SBIR DOE, Michelle Shinn)
2. “ALD-GCA-MCPs with Low Thermal Coefficient of Resistance” (Phase II SBIR, DOE, NNSA, Donny Hornback)
3. "High Gain MCP ALD Films", SEE layer development (Phase II SBIR DOE, Helmut Marsiske)
4. “Development of Advanced Photocathodes for LAPPDs” (Phase I SBIR DOE HEP, Helmut Marsiske)
5. “Further Development of Large-Area Micro-channel Plates for a Broad Range of Commercial Applications” (PHASE IIA SBIR DOE HEP, Helmut Marsiske, Contract Ended: 07/30/2019)
6. “Improvement of GCA center to edge of high spatial/timing resolution applications” (Phase I SBIR, NASA)
7. “Curved MCPs and Collimators for Spaceflight Mass Spectrometers: (Phase II SBIR, NASA, Edward Sittler)
8. DOE Phase I Release 1 NP Submission: “Large Area Multi-Anode MCP-PMT” LOI due September 3d, Applications due October 15th

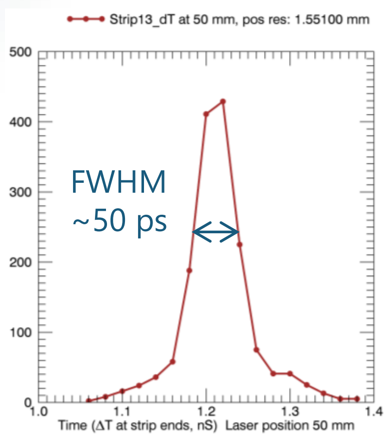
INCOM
BRIGHT IDEAS

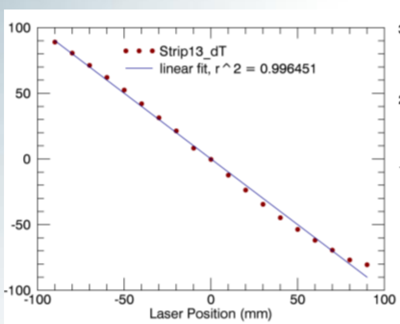
Gen-I LAPPD™ Spatial Resolution

ALONG STRIPS

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





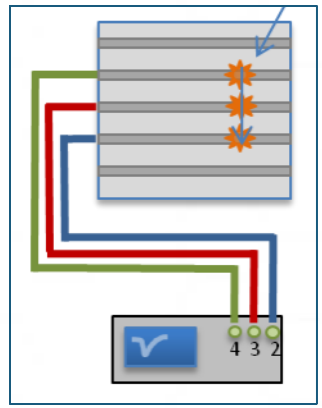


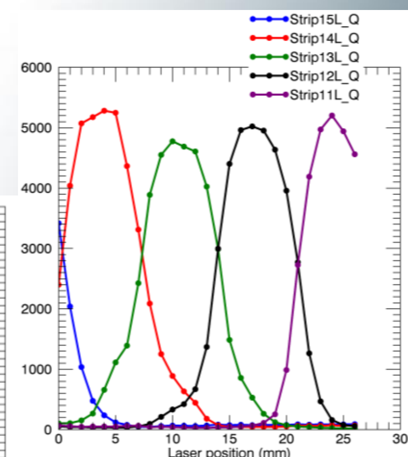
Resolution= 1.3 mm

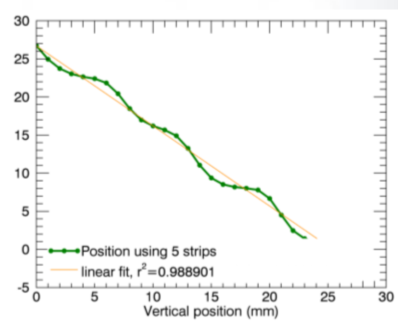
Reconstructed position vs. laser position

ACROSS STRIPS

DRS4 waveform sampler: Position by center of mass for 5 adjacent strip signals.







Resolution= 0.76 mm

Reconstructed position vs. laser position

INCOM BRIGHT IDEAS