# Development of Gen-II (Capacitively Coupled) LAPPD™ Systems For Nuclear Physics Experiments


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# Incom Inc. – Enabling the Vision of Tomorrow

Founded 1971 (Fused Fiber Optics)

Long history of Innovation

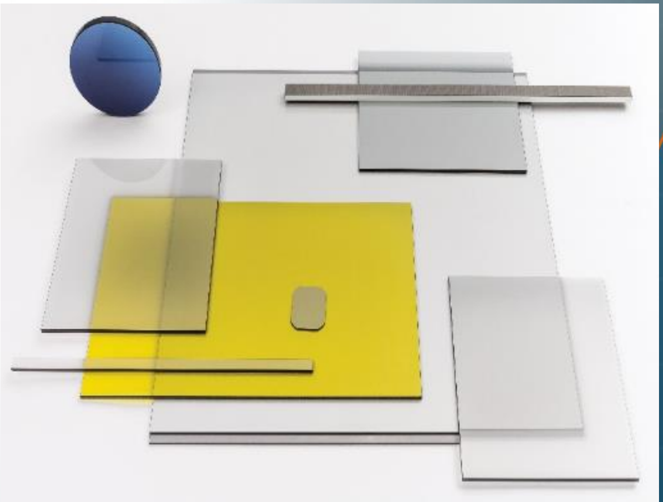
~200 Employees

Three facilities:

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

Three Business Units:

- Glass, Polymer & **Detectors**



INCOM BRIGHT IDEAS

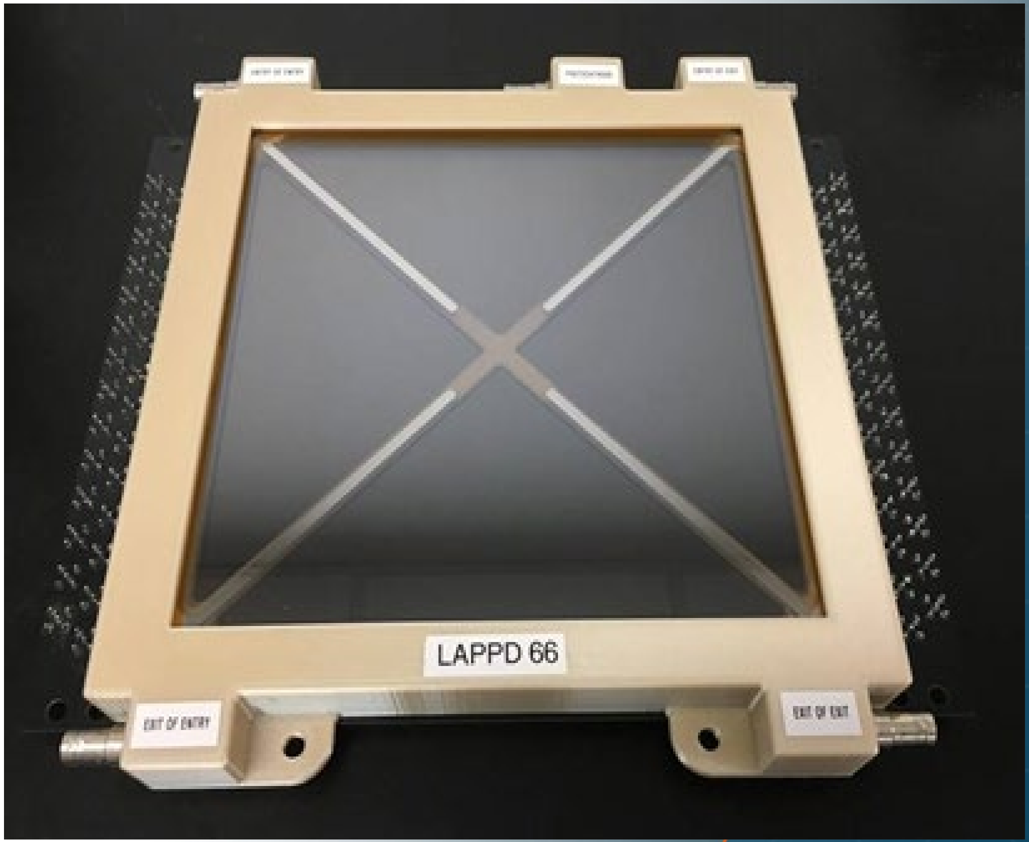
# Outline

- **LAPPD**
  - What is the detector?
  - Where can it be used?
  - How does it work?
  - Stripline (Gen I) vs Capacitively Coupled (Gen II)
- **Capacitively Coupled Performance Data**
  - Photocathode QE, Gain, Dark Counts
  - Timing and Position Resolution
  - Pixel pad size comparison
- **Recent Developments**
  - Crosstalk and modeling
  - 10 cm HRPPD device
- **Availability, Current Applications/Collaborations**
  - LAPPDs
  - Electronics and readout cards
    - UChicago, Nalu, Ultralytics, Alphacore, Pacific Microchip
- **Summary**

# Large Area Picosecond Photodetector (LAPPD™)
# What is it?

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

➔ **Time and position measurement for:**
- Photons, with **Single** or **Multiple** photoelectrons
- Penetrating energetic particles

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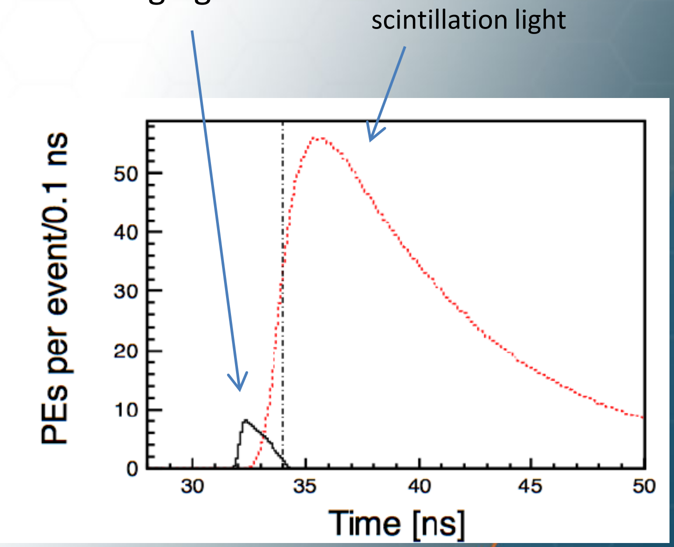
# Large Area Picosecond Photo Detectors –LAPPDs
# Where can it be used?

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

**Applications:** NP, HEP and others

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




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

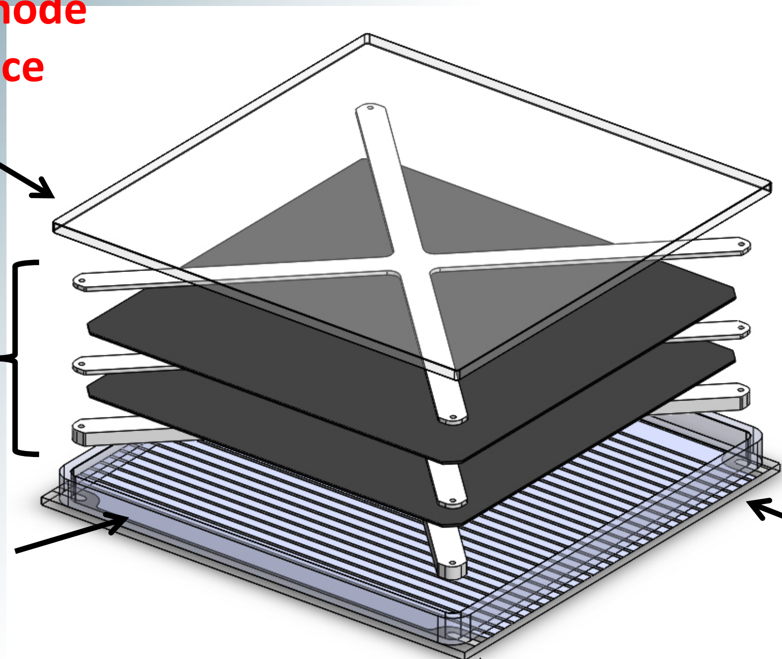
JINST 9 (2014) P06012

# LAPPD Design – How does it work?

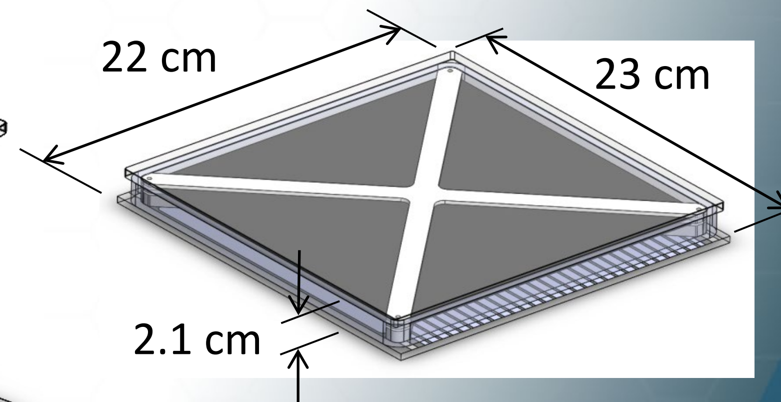
Fused silica window with **photocathode on inside surface**

20 cm x 20 cm **MCPs**, spacers

Strip line anode and sidewall



Signal readout, both ends of 28 strip lines




Voltage tab at each corner to **independently power MCPs**

- Signal and high voltage delivered on strips passing under a frit bond.
- **No wall or anode penetrations**.
- **Active area: 195 x 195mm** less the x-spacers
  - 34,989 mm$^2$, 350 cm$^2$
  - 92% active area

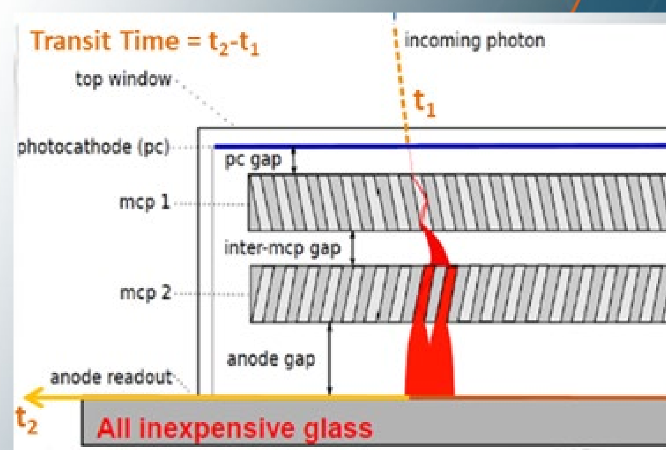



Illustration provided by Univ. of Chicago

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

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

**Only available technique for this size MCP**

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

ALD+ glass substrate MCP: cross section

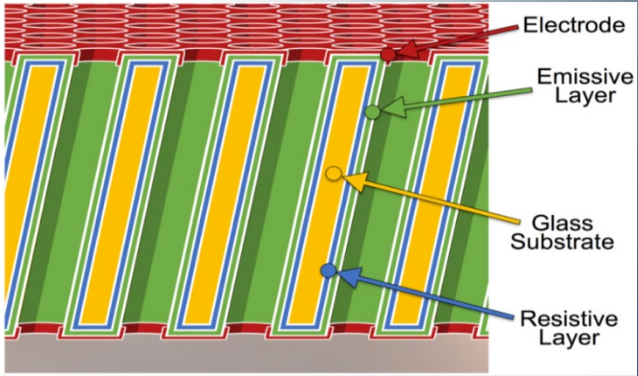



Illustration from Ertley, 2016

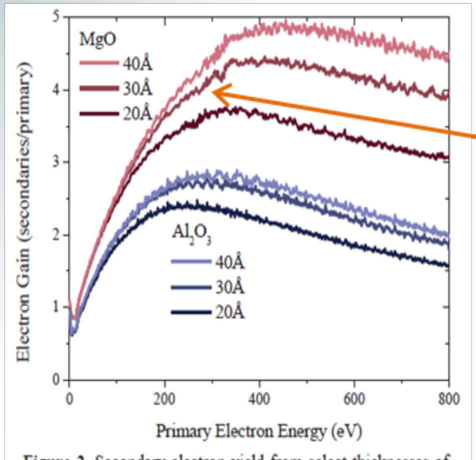
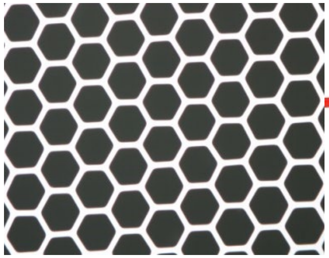



**Figure 2.** Secondary electron yield from select thicknesses of ALD MgO and $Al_2O_3$. See Figure 3 for the entire data set.

MgO secondary electrons



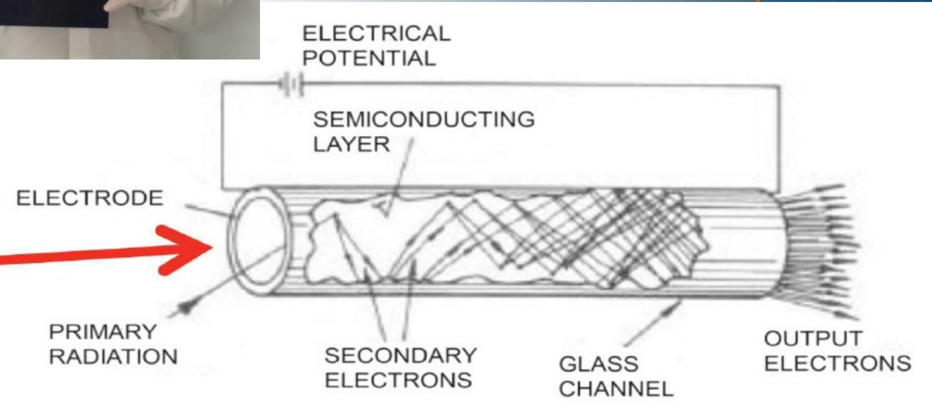
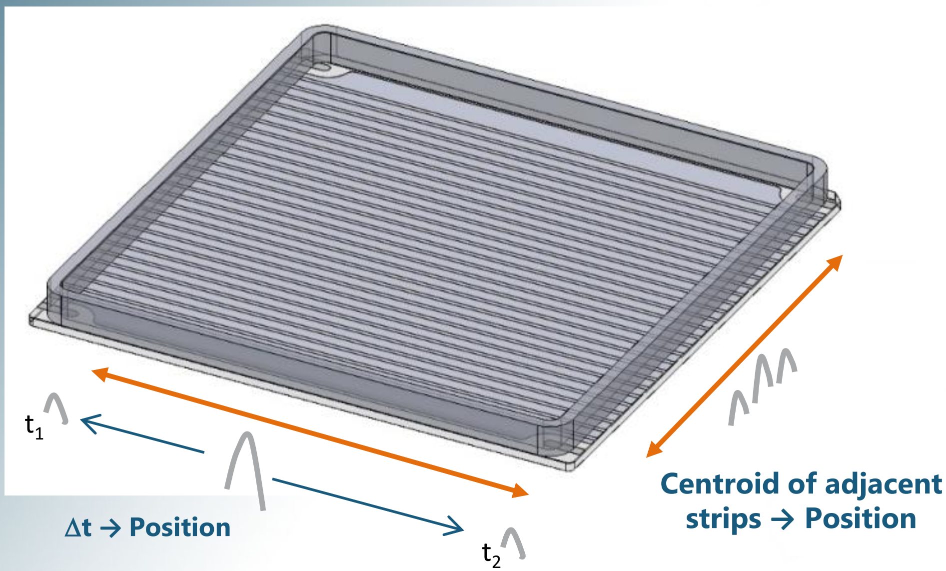



Illustration from Wiza, 1979

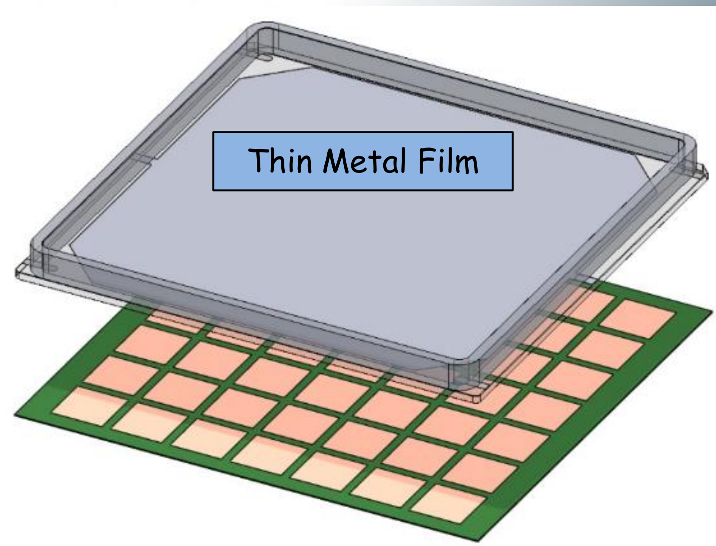
# Gen-I vs Gen-II LAPPD™ Design

## Gen-I Strip Line Anode




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

## Gen-II Resistive Layer with Capacitively Coupled Anode



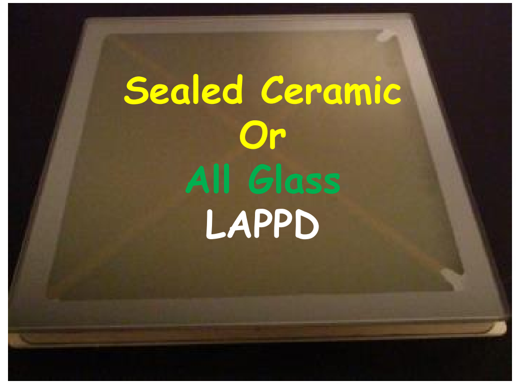

- Customizable anode pattern, user-changeable.
- Good detection of multiple, simultaneously-arriving photons.
- Flexibility in anode design allows a balance between rate, spatial resolution and the number of electronics channels.

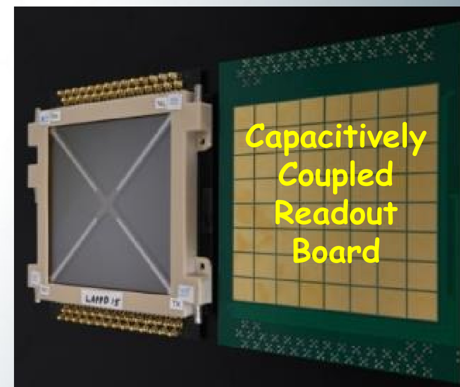

F. Tang et al., TWEPP 2008, Naxos, Greece, September 15-18, 2008
H. Grabas et al., Nuclear Instruments and Methods in Physics Research A 711 (2013) 124–131
B. Adams et al., Nuclear Instruments and Methods in Physics Research A 846 (2017) 75–80

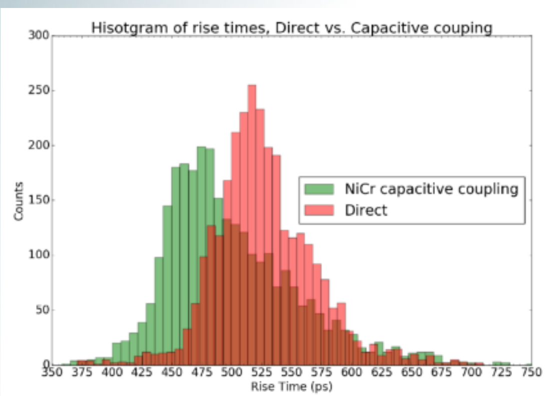

- Ongoing Anode Design & Characterization: Efficient Pulse Detection
  - Performed in a vacuum chamber for quick turnaround
  - Choose optimal resistive material for internal ground plane.
  - Select best anode material and thickness.

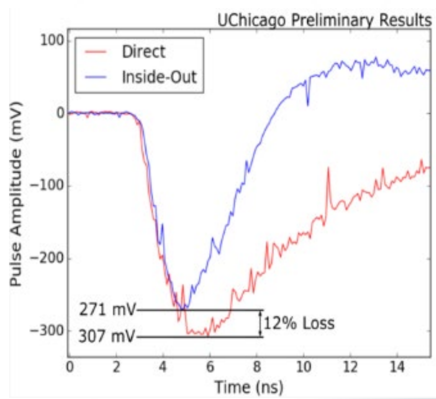
# Gen II LAPPD

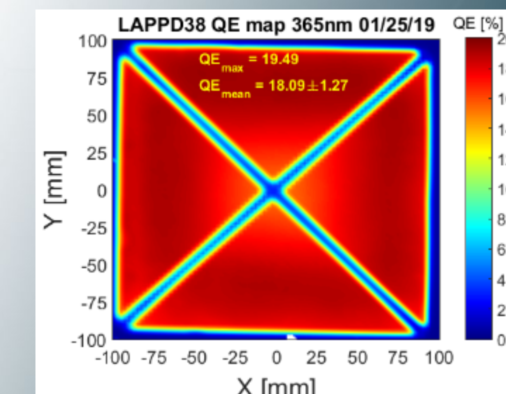
- **Capacitive signal coupling:** to an external PCB anode
- A **robust ceramic body**: for durability and dielectric properties
- **Pixelated anodes:** to enable high fluence applications

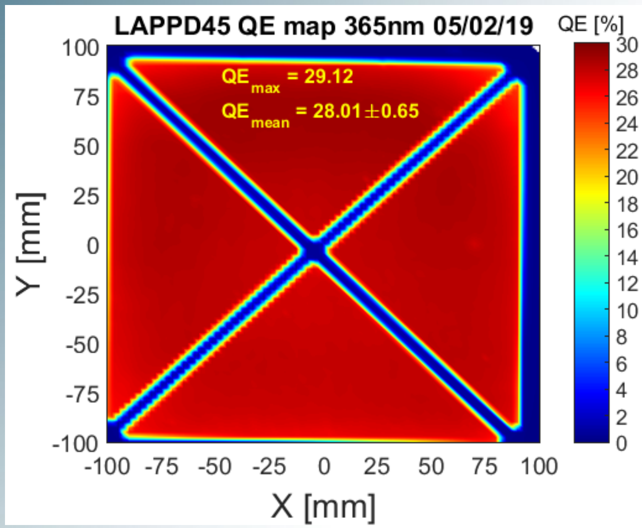

**The capacitive readout scheme preserves rise-time of pulses (rise time is a key factor in timing resolution)**
**For pad pattern: 80% of the directly coupled amplitude**

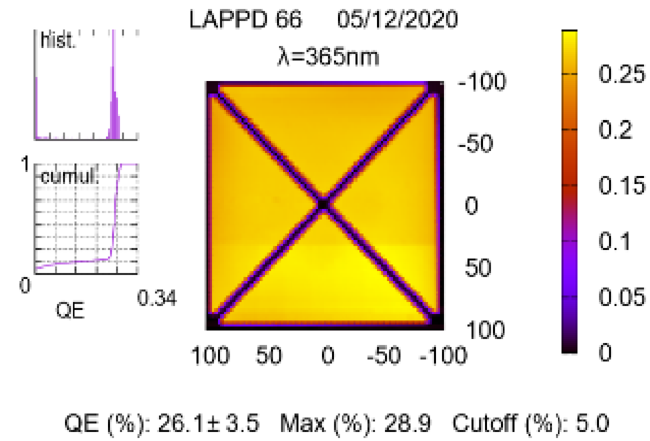
**Sealing process established, high QE demonstrated.**
**Inner design optimization on-going**

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

# Photocathode Quantum Efficiency & Uniformity

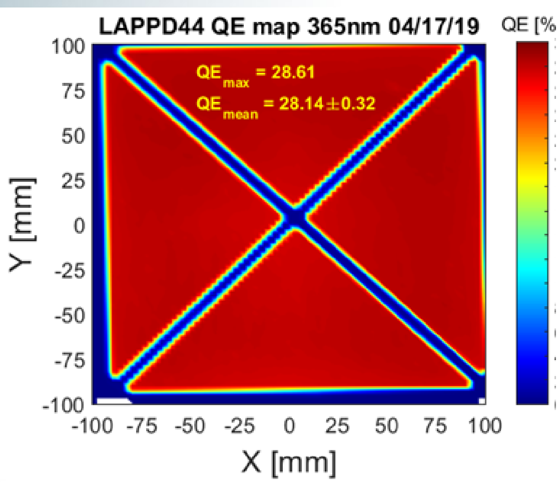
## Typical QE and Uniformity

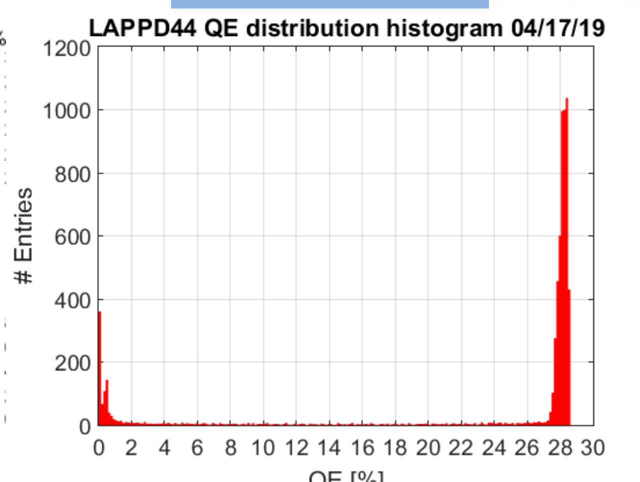


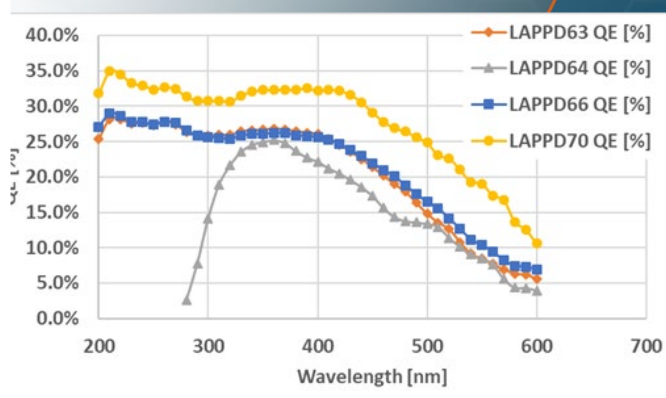




QE Uniformity

QE spectra



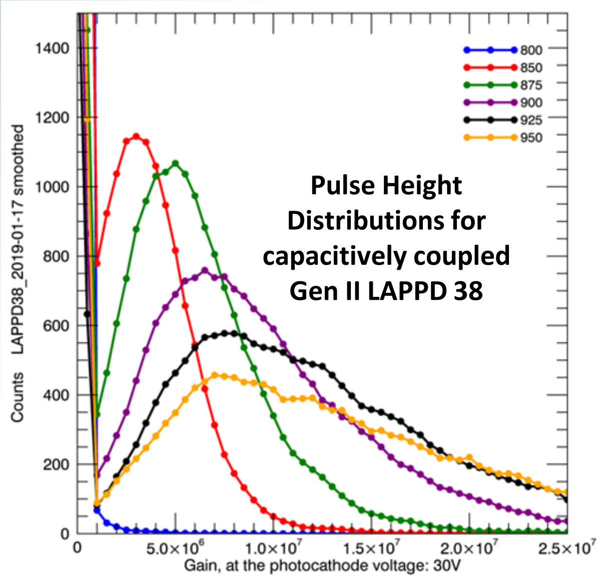



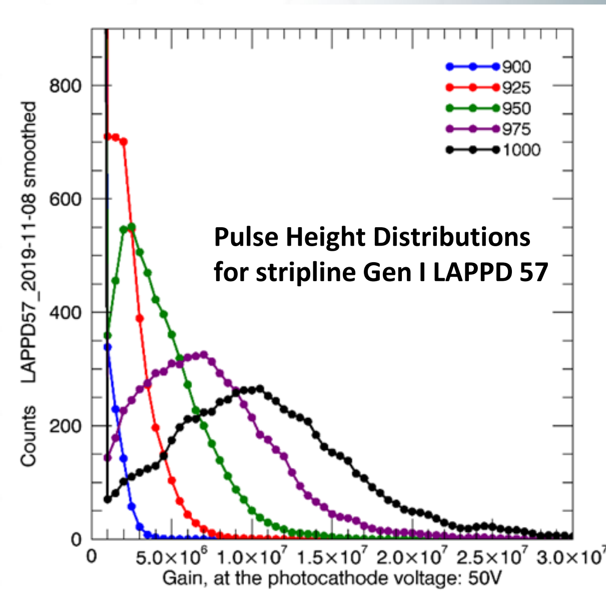



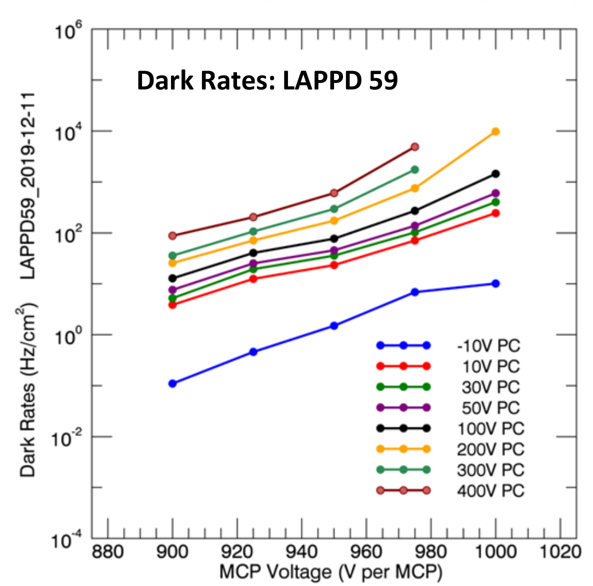

35% demonstrated

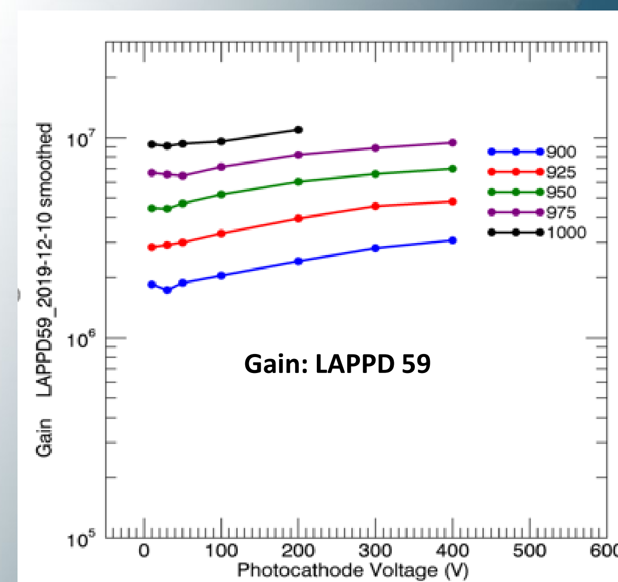
# Gain & Dark count performance

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

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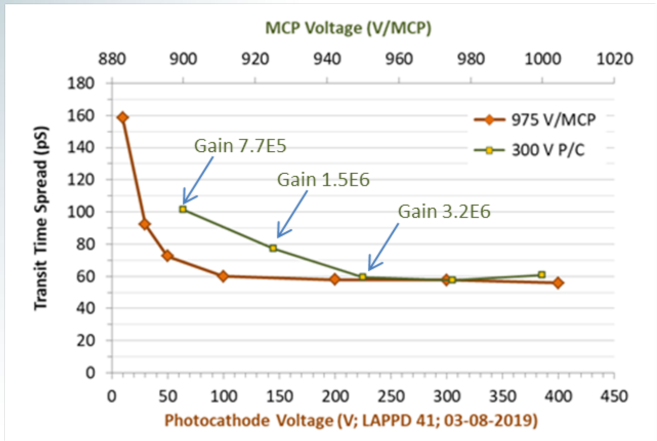
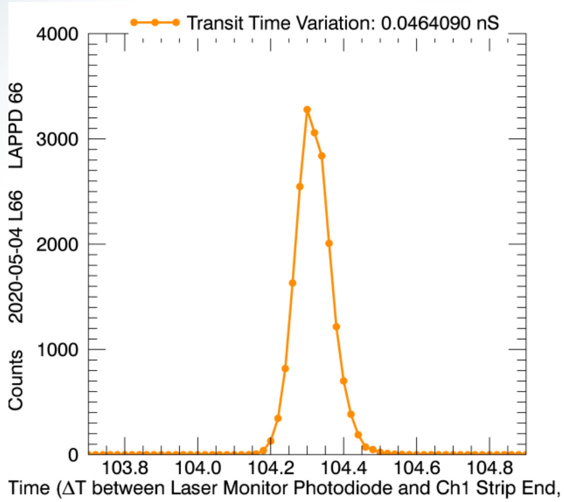
# Timing

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

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

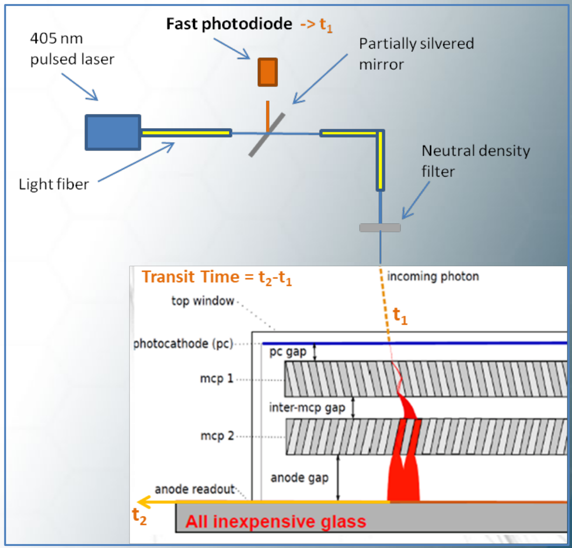
TTS is affected by:
- Signal to noise ratio (gain)
- Photocathode voltage (production of secondary electrons in the channel)
- MCP bias angle
- Channel diameter

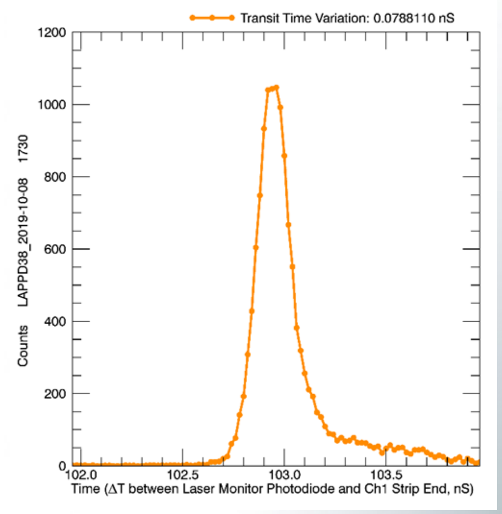


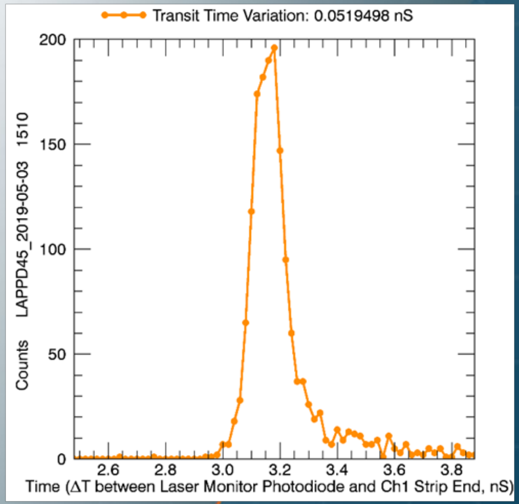

**LAPPD 66, 46 pS multiple P/E**
**Capacitively-coupled**

How is transit time variation/spread measured




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




**LAPPD 45, 51 pS single P/E**
**Internal stripline**

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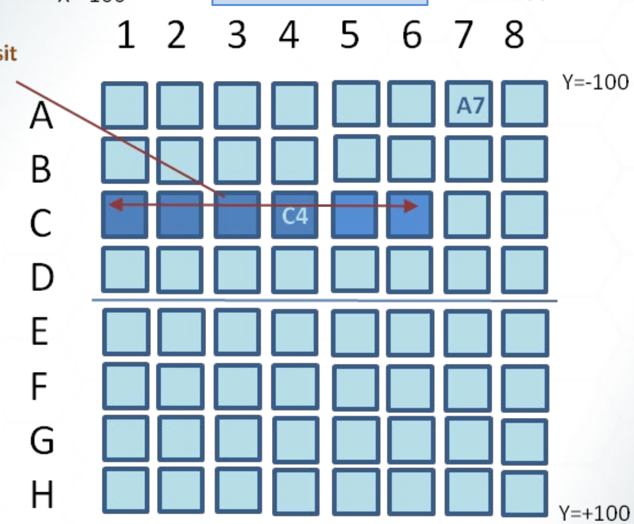
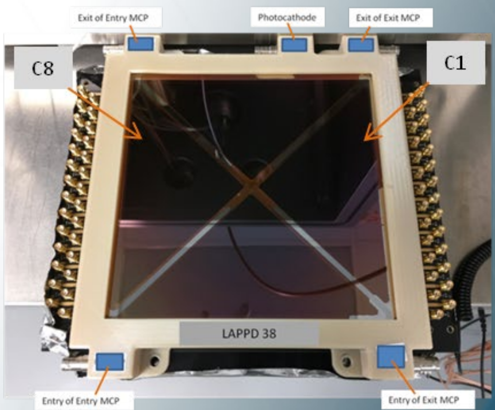
# Spatial Response: 25 mm Pixels

- A position scan was performed by moving a **laser spot of ~1 mm** dia. across the window.
- The **25 mm** pixelated board was used.
- Deviations from linearity are **~2.7 mm.**
- The response of a 25 mm pixel is essentially discrete when the laser is in the center of a pixel.

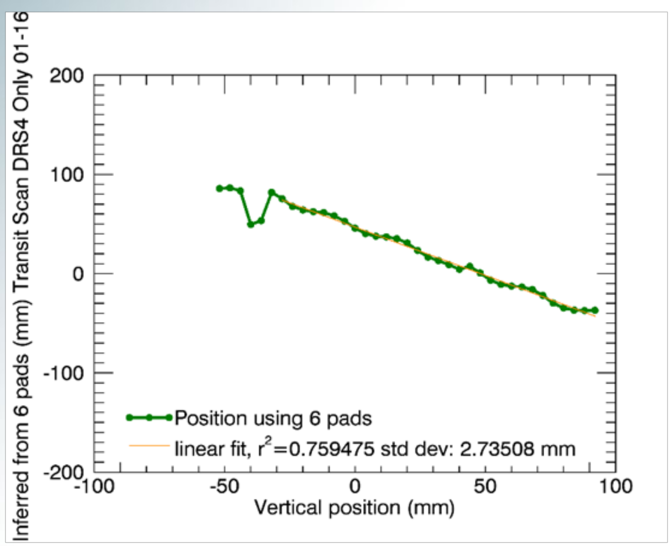
Rear view



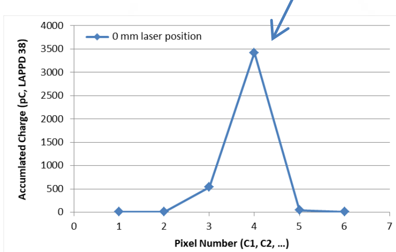

Front view



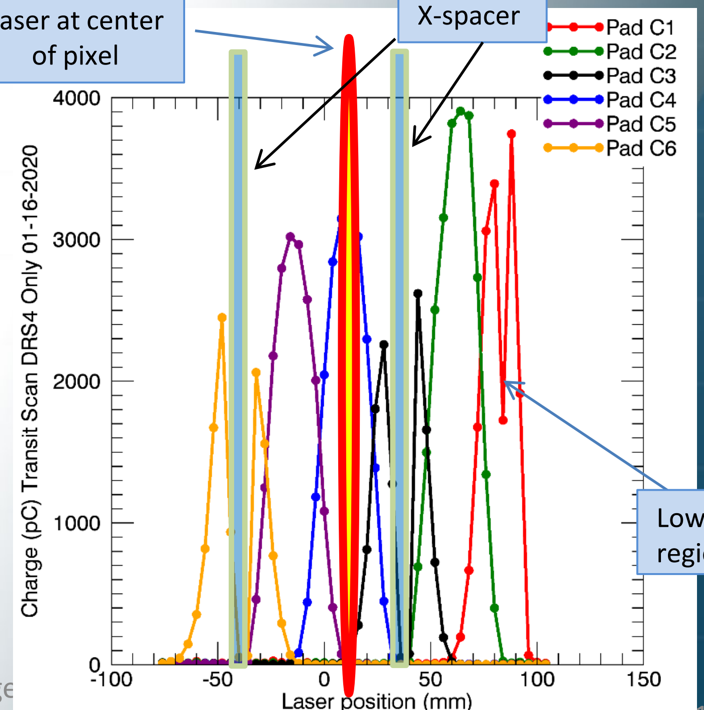

LAPPD 38 10-08-2019




Laser at center of pixel



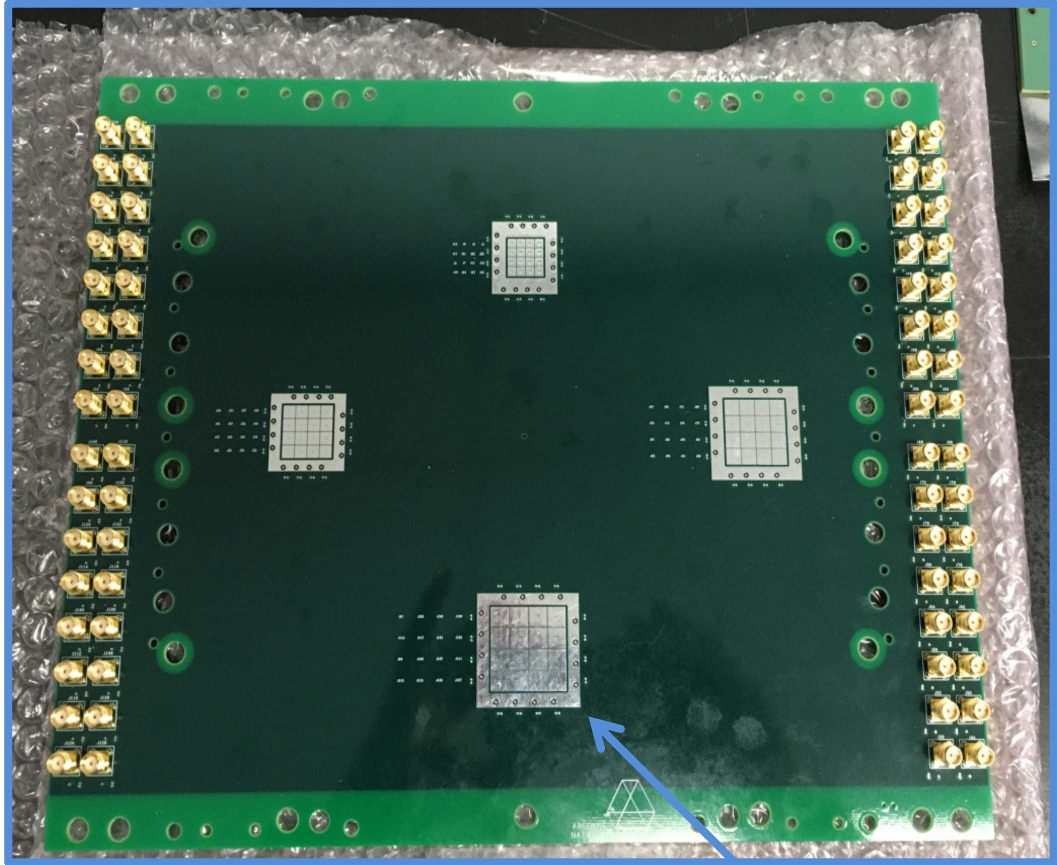

X-spacer




Lower gain region

# 4x4 Pixel Capacitively-Coupled Signal Board

- Argonne National Lab fabricated a signal board for the LAPPD with four 4x4 arrays of pixels.
- The board was installed under the LAPPD 38 ceramic anode.
- Pixel sizes:
  - 3 mm
  - 4 mm
  - 5 mm
  - 6 mm
- Transit scans and gain measurements were performed in each group
- Observe:
  - Adjacent pixel signal size
  - Unwanted crosstalk elsewhere on the board



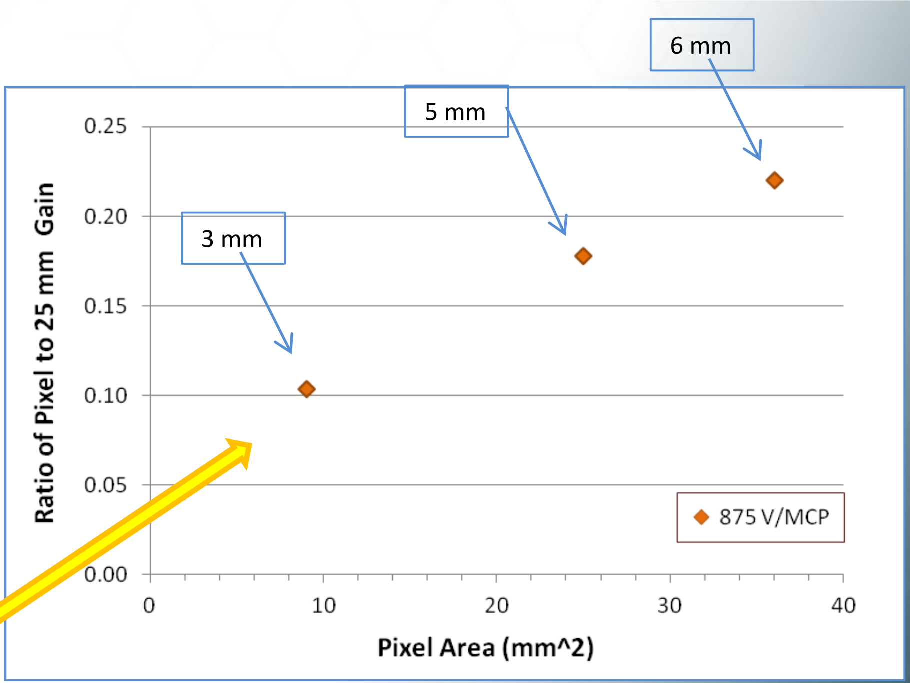
6 mm pixels

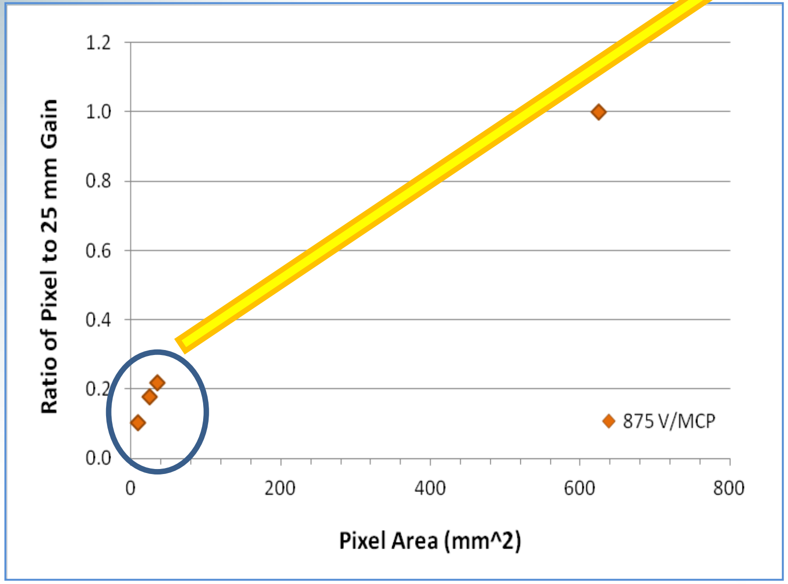
| Pixel size (mm) | Qty |
|---|---|
| 25 mm | 64 |
| 6 mm | 1,111 |
| 5 mm | 1,600 |
| 4 mm | 2,500 |
| 3 mm | 4,400 |

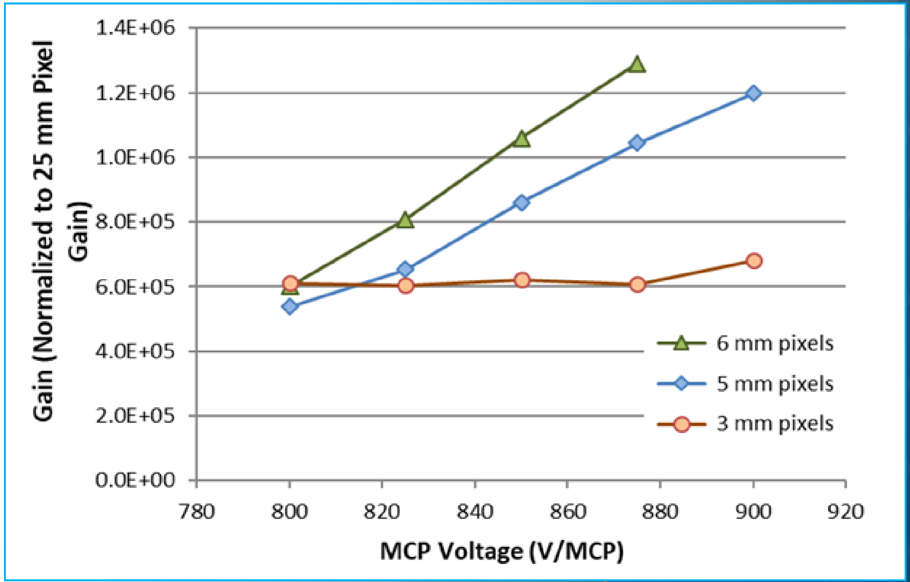
α electronics cost $

# Gain vs. Pixel Size

1) Gain was measured on three sizes of capacitively-coupled pixels
    - 3 mm
    - 5 mm
    - 6 mm
2) Gain was highest on the 6 mm pixels.
3) Gain was relatively low on the 3 mm pixels, and spread over adjacent pixels.
    - The ~1 mm laser spot size is significant with respect to the 3 mm pixel width.
    - Gain decreased with smaller pixel size: non-linearly with pixel area.

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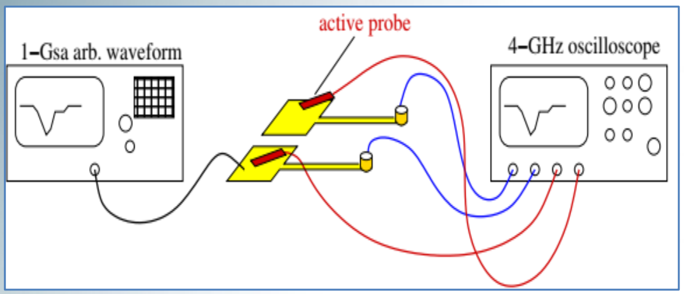
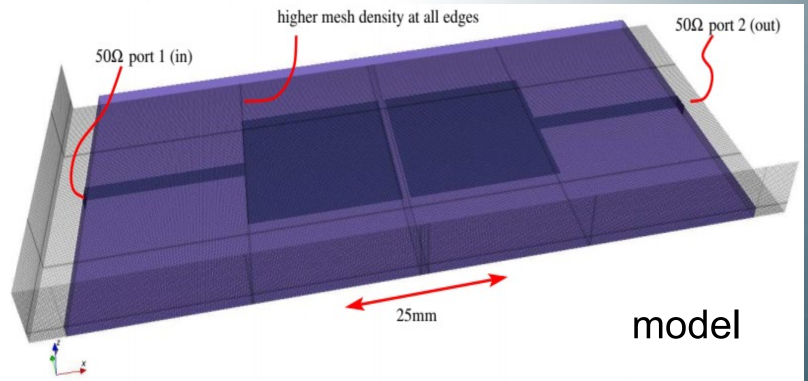
# Crosstalk simulation & measurement

- Simulate and verify experimentally to understand cross-talk and its role in interpolation for spatial resolution (also improve time res.)
- Vary parameters and simulate to find optimum pixel configuration

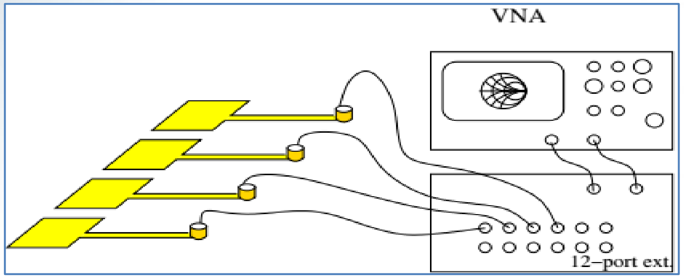
measurement in time domain



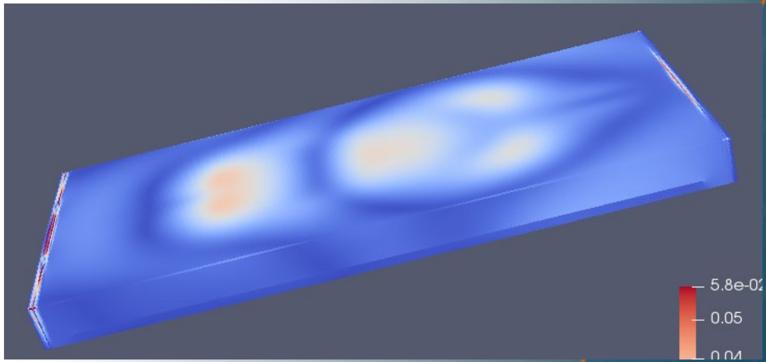

Replicates pulses acquired in LAPPD operation




measurement in frequency domain




Gives insights into origin of coupling



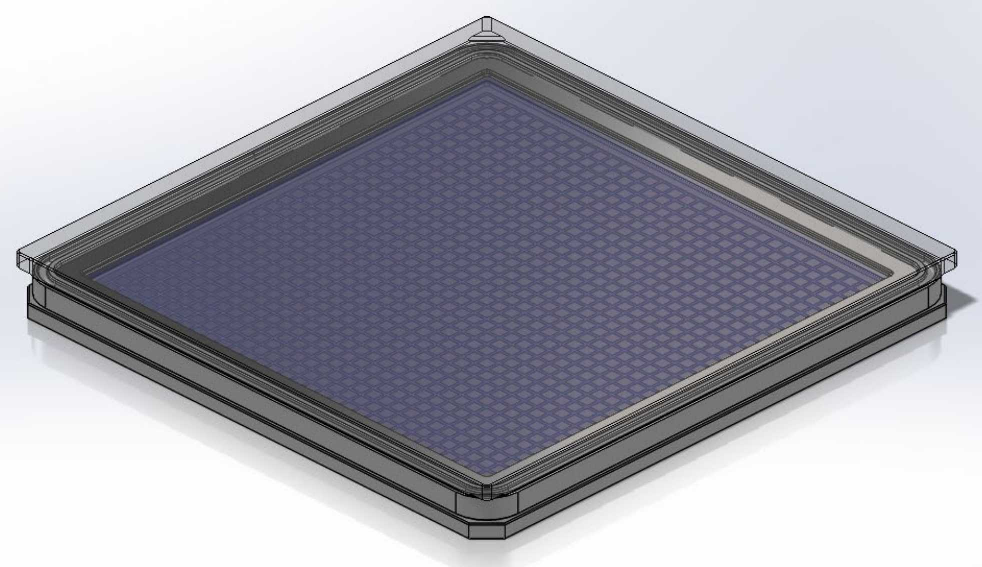

Visualization of E-field helps design pad structure

**Simulation results should agree with both TD and FD measurements**

# 10 cm HRPPD Detector Design

**The HRPPD 10 cm detector is the newest development of Incom's large area picosecond photodetectors, incorporating innovations made developing full size GEN I & II LAPPD.**

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



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

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

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

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

**Several readout schemes possible**

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

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

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

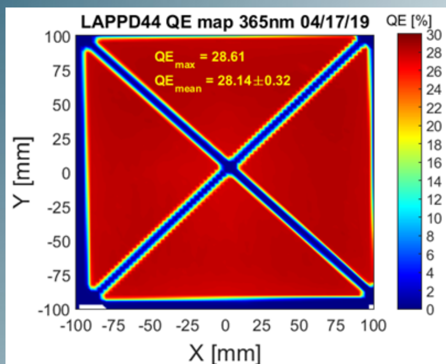
# LAPPD™ Availability

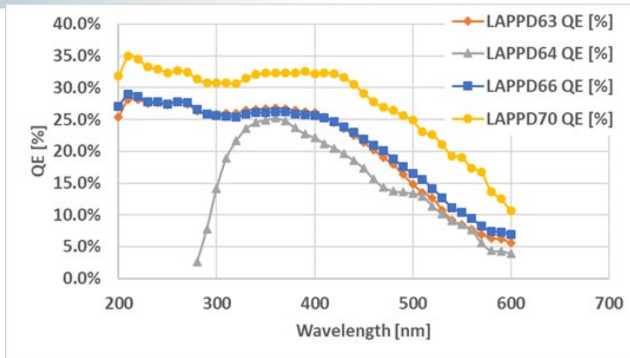
1) Routine "pilot production" supported by our R&D team, is now underway,
    a) In 2020, Incom will again double the output from 2019
        a) **Present capacity is 4 LAPPDs/month – plans to go to 6/month by late 2020**.
    b) Capacity can be rapidly and significantly increased when full production is implemented.
2) Prototypes are available for **rent or purchase** by customers that wish to qualify LAPPD for their applications.
    - Minimum renewable term per month: (mrf@incomusa.com)
    - Qualified prospects that don't presently have a budget or the ability to either rent or purchase an LAPPD, may qualify for special negotiated terms.
3) Incom Inc. hosts quarterly **Measurement & Test Workshops**
    a) familiarize potential users with the LAPPD,
    b) facilitate direct participation with the Incom team,
    c) hands on, characterizing an LAPPD,
    d) no cost early LAPPD access to large numbers of early adopters.

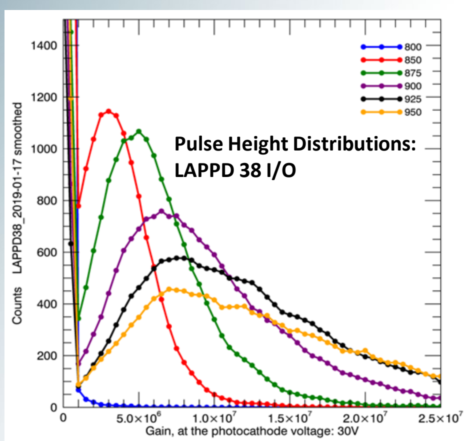
# LAPPD Applications

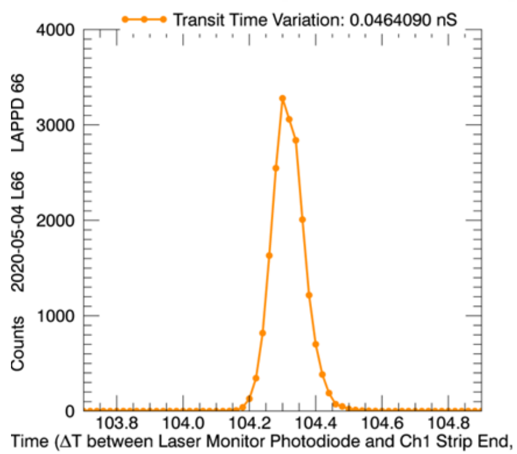
| PROGRAM | AFFILIATIONS | 2020 – 2021 STATUS |
|---|---|---|
| ANNIE - Atmospheric Neutrino Neutron Interaction Experiment | Iowa State | **Five LAPPDs** delivered; |
| Neutron Imaging Camera, Nanoguide scintillating polymer | Sandia National Lab (CA), U of Hawaii | LAPPD #22 being evaluated |
| Fermilab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

# Key Takeaways




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

- Performance summary
  - Gain: mid-$10^6$ and above
  - Dark rate: $10^3/cm^2$ in the mid-$10^6$ gain range.
  - TTS: ~55 pS or better
  - QE: 20-30% @ 365 nm
- Two LAPPD Types
  - Capacitively coupled model – Gen II
    - user changeable pixelated signal board
  - Stripline model – Gen I
  - Future model - 10 cm HRPPD
- LAPPDs delivered and pending
  - Lots of interest in capacitive coupled LAPPD
  - Several on-going tests w/collaborators
    - Including electronics/readout cards
  - More on the way (production at 4/month)
- Available to purchase or rent
  - Volume pricing
  - Monthly rental
  - Technical Support & LAPPD Workshops
- Project Going Forward
  - Fabricate all glass Gen II LAPPDs – define baseline
  - Model/Test pixel size, crosstalk, charge sharing and coupling
  - Work on ceramic to glass window seal
  - Get LAPPDs to collaborators/customers

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

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

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

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

DOE DE-SC0020578, Phase I - High Rate Picosecond Photodetector (HRPPD) being developed for Nuclear Physics

# Thank you

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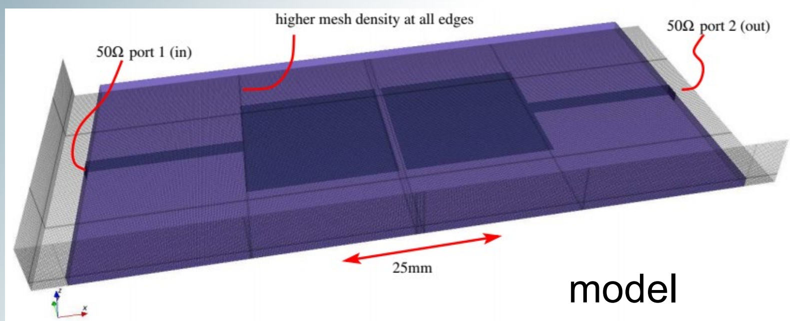
# Back up slides

# Crosstalk simulation & measurement

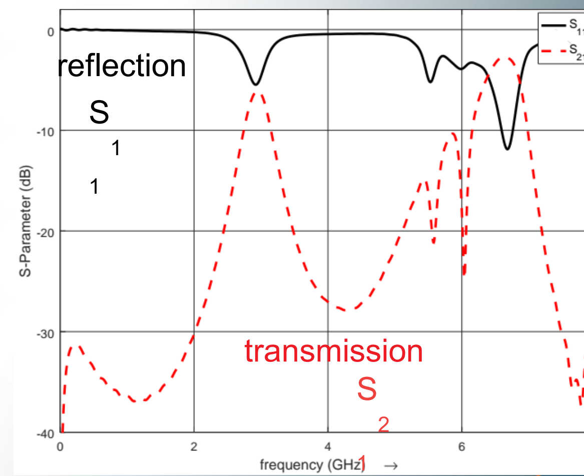
Interpolation for sub-pad resolution: signal ratio due to both charge sharing and coupling
Understand and design coupling through EM-field simulations verified with measurements

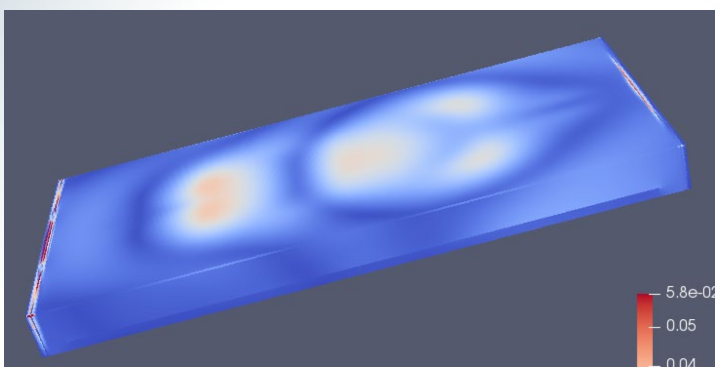
Method: Finite Difference Time Domain (FDTD),
Software: openEMS




model

Calculate
S-parameters




Visualization of E-field helps design pad structure

Verify with VNA

INCOM
BRIGHT IDEAS

# GEN I LAPPD Pilot Production Implemented

## Five LAPPD Shipped since 1/1/2020

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