LAPPD™ and HRPPD: Next-Generation Photosensors for EIC

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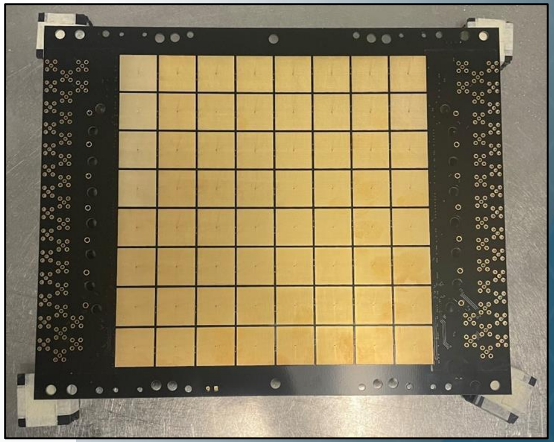
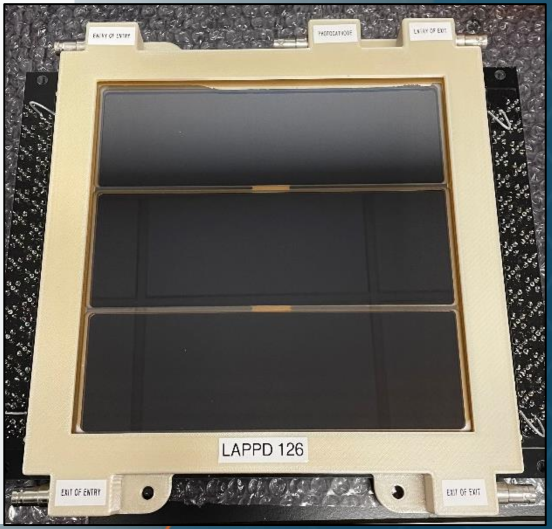
Five things you need to know about LAPPD / HRPPD for EIC DIRC & RICH

1) **The Sensors** - Incom offers both capacitively coupled and direct readout sensor solutions for EIC DIRC and RICH
2) **Manufacturing Scale-up** - Incom has the experience and infrastructure to fully support manufacturing scale-up to ensure high quality tile delivery well in time for EIC and related program needs.
3) **Frugal Price** - For EIC, \$20k / device is achievable (**\$52/cm^2**)
4) **Technical Specifications** - LAPPD / HRPPD already meet most EIC requirements
5) **EIC Critical Developments** - A Pending SBIR Application will address remaining EIC critical developments

The Sensors: LAPPD™ - Large Area Picosecond Photodetector Pixelated Capacitively Coupled Readout

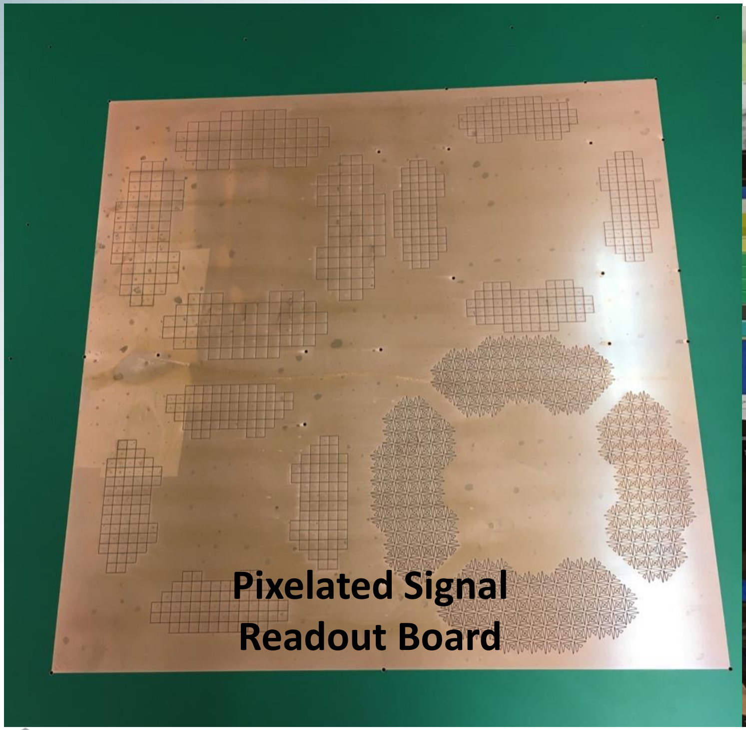
- **20 cm x 20 cm MCP-PMT**
  - Single photon sensitivity
  - Chevron pair of ALD-functionalized MCPs
    - **(20 µm pores)**
  - Glass/Ceramic package
  - **373 cm^2** effective area (97% open area)
- **High Gain (~10^7)**
- **Bialkali Antimonide Photocathode**
  - Sodium-Potassium-Antimony Na_2KSb
  - **>30%** QE at 365 nm
  - **>95%** spatial uniformity
- **Timing Resolution**
  - SPE: **~50 ps** (Vagnoni, INFN)
  - 150 GeV induced EM shower: **~8 ps** (Vagnoni, INFN)
- **Position Resolution**
  - **< 0.6 mm with 6 mm pixel**



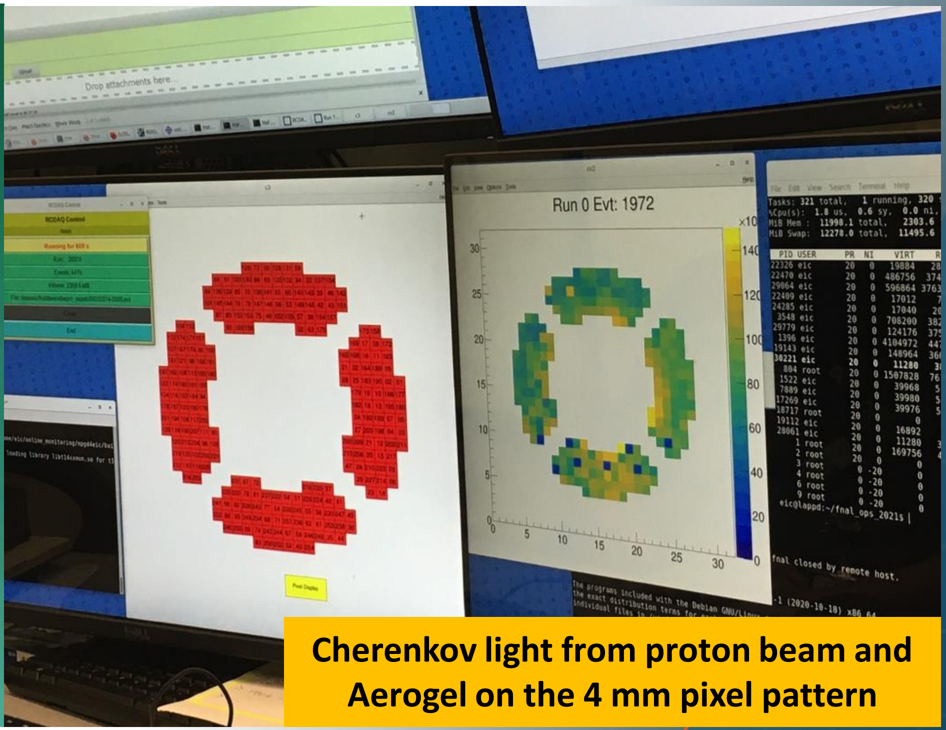


<u>The Sensors:</u> Customer Application

- Cherenkov Ring Imaging Board designed at Brookhaven National Laboratory
- Tested with CC LAPPD with 20 and 10 um pores at the Fermi Beamline
  - July 2021
  - June 2022



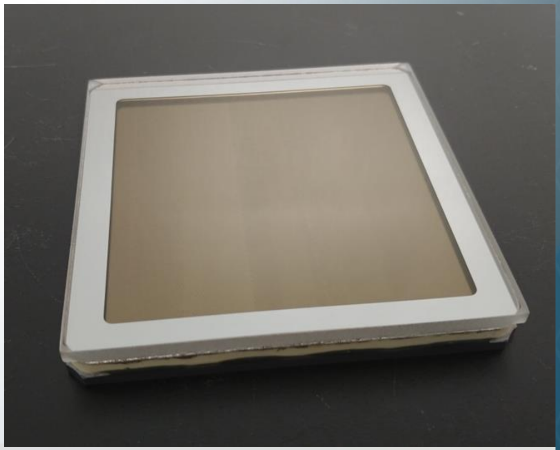
Pixelated Signal Readout Board



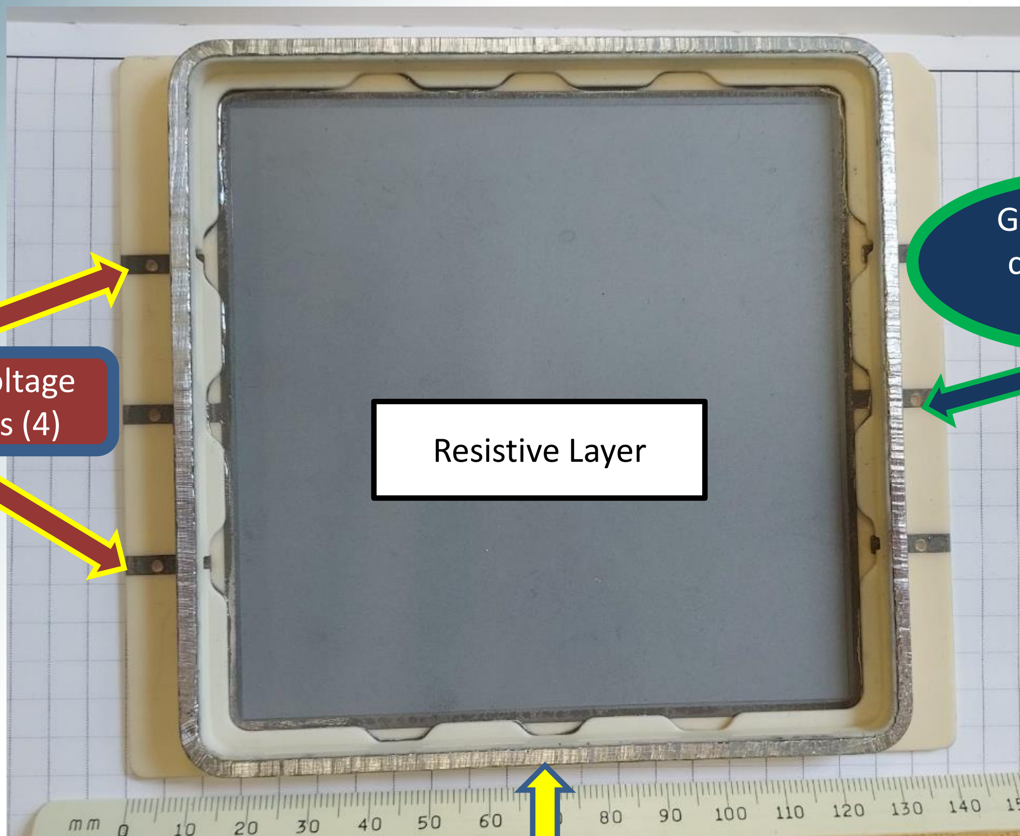
Cherenkov light from proton beam and Aerogel on the 4 mm pixel pattern

The Sensors: HRPPD - High Rate/Resolution Picosecond Photodetector Direct or Capacitively Coupled Readout

- **10 cm x 10 cm MCP-PMT**
  - Single photon sensitivity
  - Chevron pair of ALD-functionalized MCPs **(10 µm)**
  - Glass/Ceramic package
  - Capacitive (CC) or Direct (DC) Coupling
  - **100 cm²** active area (only spacers on edges)
- **High Gain (~10^7)**
- **Bialkali Antimonide Photocathode**
  - Sodium-Potassium-Antimony Na_2KSb
  - **>30%** QE at 365 nm
  - **>95%** spatial uniformity
- **Timing Resolution**
  - SPE: **~23 ps** (Vagnoni, INFN for 10 um pores)
- **Position Resolution**
  - **< 0.6 (mm)** (dependent on readout board)
  - DC version has 1024 2.5 x 2.5 mm pixels



The Sensors: Capacitively Coupled (CC) HRPPD



MCP high voltage connections (4)

Resistive Layer

Ground plane connections (2)

Metallization Layer

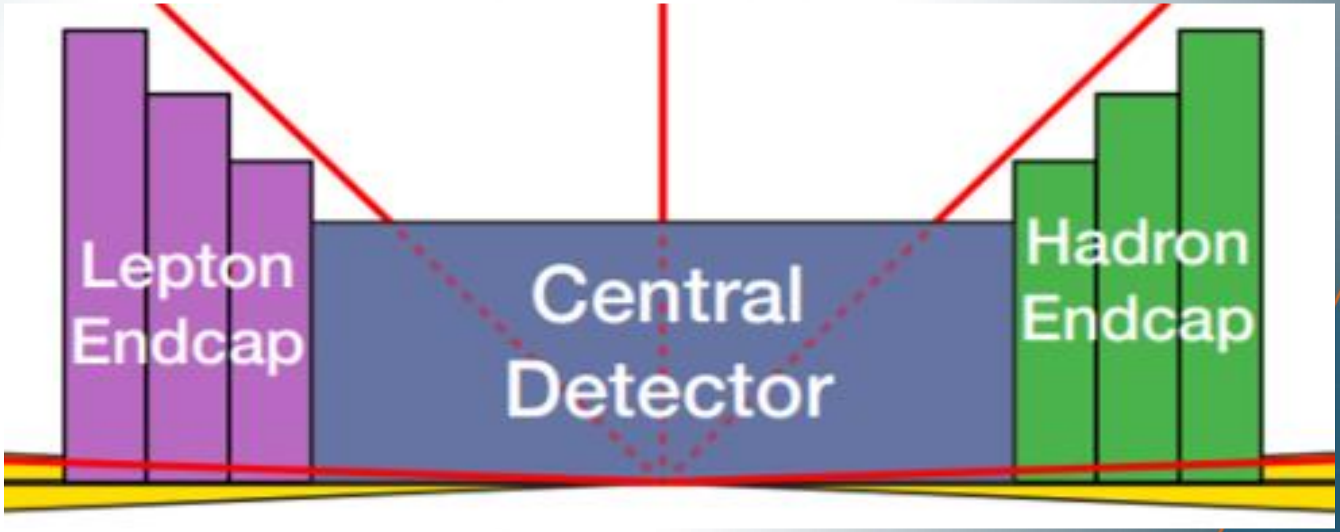
Sealed – ceramic CC HRPPD (#5)

Technical Specifications: LAPPD / HRPPD Requirements for EIC PID Detectors

Parameter	DIRC	mRICH	pf-RICH	dRICH	LAPPD / HRPPD
Gain	>1E6	>1E6	>1E6	>1E6	1.00E+07
SPE Timing Resolution	<100 ps	<800 ps	<100 ps	<800 ps	<50 ps
MPE Timing Resolution					8 ps
Pixel Size	3 mm	6 mm	6 mm	6 mm	Any / 2.5 mm X 1024
Spatial Resolution					<1 mm
Dark Noise	≤1 kHz/cm²	≤5 MHz/cm²	≤5 MHz/cm²	≤5 MHz/cm²	≤2 kHz/cm²
Radiation hardness	Yes	Yes	Yes	Yes	>1E15 15 MeV protons
Single-Photon readout	Yes	Yes	Yes	Yes	Yes
Magnetic Field Tolerance	<2.0 T	1.7-2.0 T	1.7-2.0 T	1.7-2.0 T	1.4 T demonstrated
@ Degrees from Normal		±20 deg	±10 deg	Wide variations	TBD
PC QE @365 nm					30%
PC QE @450 nm					>20%
PDE @450 nm	≥20%	≥20%	≥20%	≥20%	TBD (≥20% = 70% OAR X 30% QE)
Demonstrated Tile Life					TBD (> 5 C/cm²)

Technical Specifications:
LAPPD for EIC Detectors

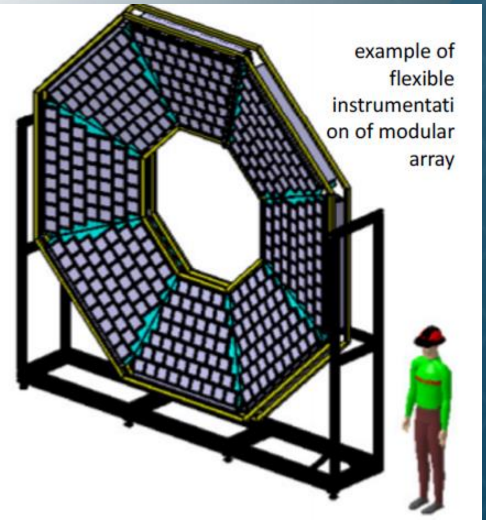
- There are 3 EIC Detectors
  - Lepton Endcap: mRICH or pf-RICH
  - Central Detector: DIRC
  - Hadron Endcap: dRICH
    - Each would require ~75 LAPPDs/ HRPPDs; 225 devices total



Source: Backward Cherenkov based PID for EIC Detector 1, meeting 6/13/22

Technical Specifications:
LAPPD vs SiPMs for Lepton Endcap

- Detection area
  - m-RICH ~3 m^2
  - pf-RICH ~1 m^2
- LAPPD is 20 cm x 20 cm (plus some outside edge)
  - With 6 mm CC pixels -> 1024 channels / LAPPD
    - Ways to minimize this
  - 75 LAPPDs for m-RICH:
    - @~$20k = $1.5 Million
    - @~$10k = $0.75 Million
  - Dark rates <2 kHz/cm^2 at room temperature
- SiPM is (26 mm x 26 mm)
  - 3mm pixels -> 64 Channels / SiPM
  - Need 4400 SiPM arrays for 3 m^2
  - Price: $0.5 Million / m^2 → $1.5 Million total
  - Need to be cooled to -25 C



Source: Backward Cherenkov based PID for EIC Detector 1, meeting 6/13/22

EIC Critical Developments: Pending SBIR Funding

Incom's Upcoming SBIR Proposal: Sensors

1) Red-shift photocathode QE
   - Comparable PDE to SiPMs at 450 nm
2) Life Testing
   - UV- PC → 5 C/cm^2 demonstrated @ UTA - validate & expand results
     - Run HRPPD in DIRC at 1E7 gain rather than 1E6?
   - Radiation- 1E16 protons → ~20% drop in gain (Vincenzo Vagnoni, INFN)
3) Electronic Readout
   - Electronics to read out 1024 channels or more
   - Evaluate NALU Scientific **DSA E10-96** readout with **96** channels
4) Form Factor & Timing
   - Close tiling of devices- higher Active Area per device

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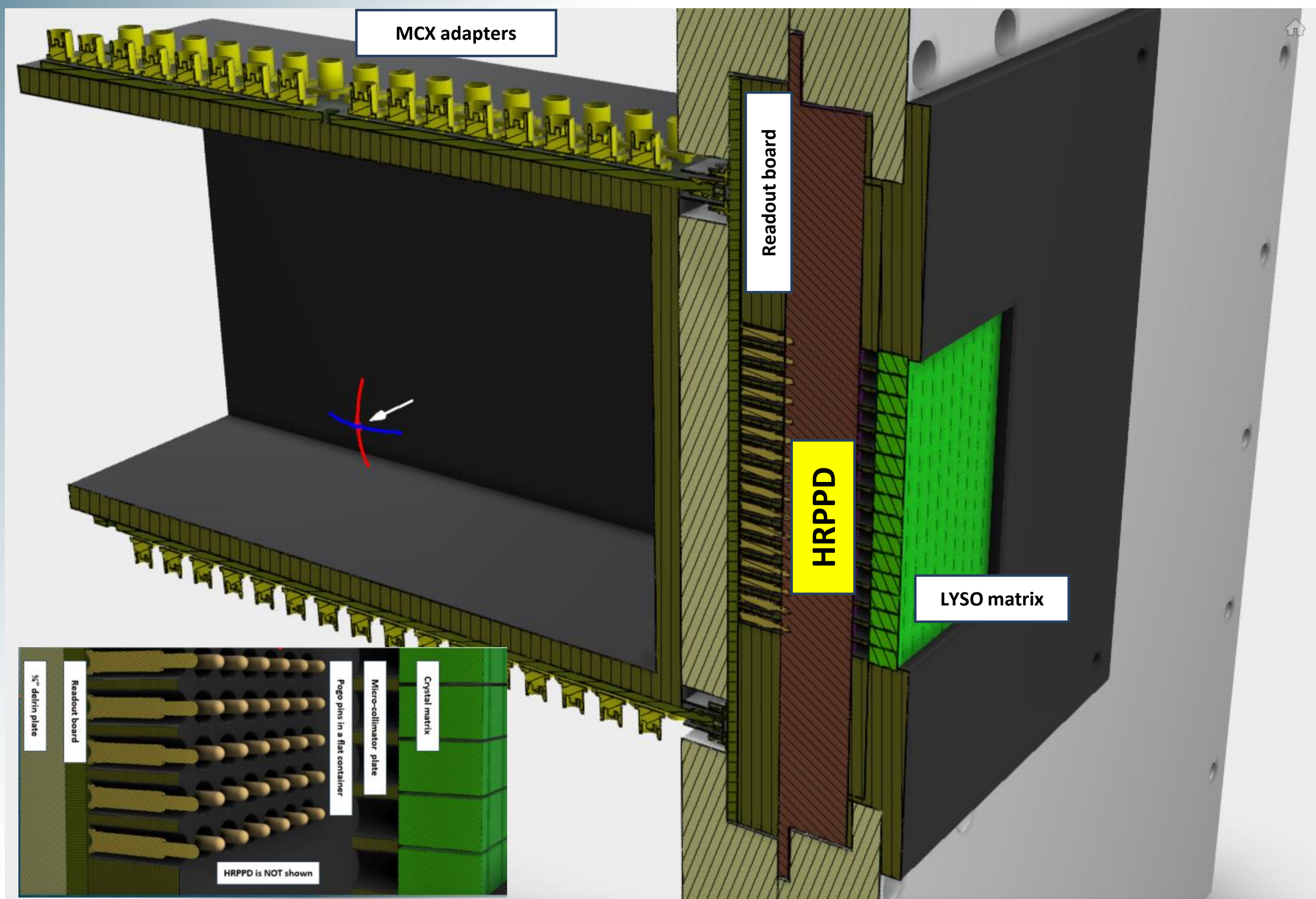
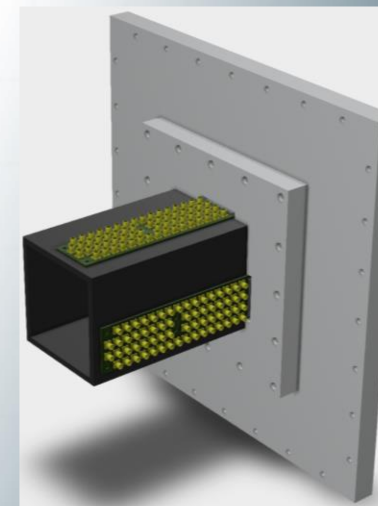
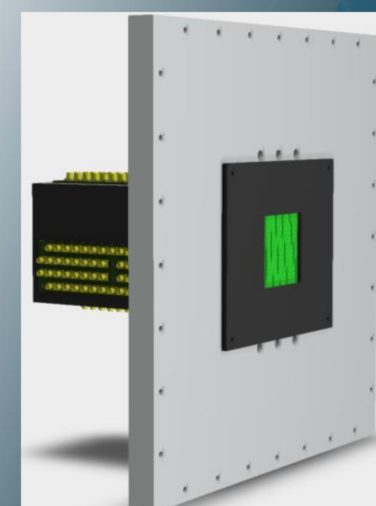
EIC Critical Developments - Electronics

Short-Term Electronic Readout Model

(Ref. A. Kiselev @ BNL/EIC) Reads out 256 channels -1/4 of the HRPPD!







EIC Critical Developments - Electronics

Nalu Scientific

Product Description DSA E10-96

Product Name: **DSA E10-96**

Product Description: 96 channel, 10 GSa/s digitizer

Dimensions: ~ 12” x 4” x 1”

Bandwidth: ~1.2 GHz

Digitizer Chip: UDC V1

Sample rate: 9-12 GSa/s

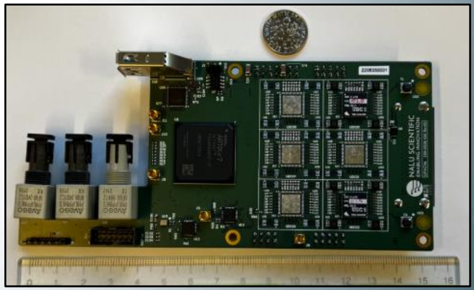
Power: Terminal

Data: USB 3/UART, future ethernet

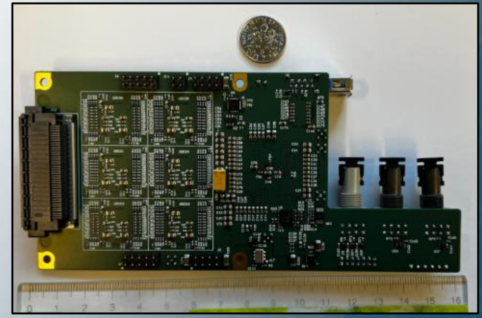
Integration: chip, FPGA, clock, regulators, comm, FW, SW

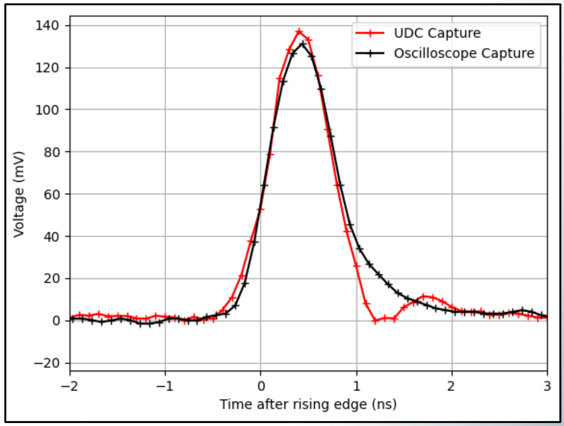
Trigger: Internal, External, Software

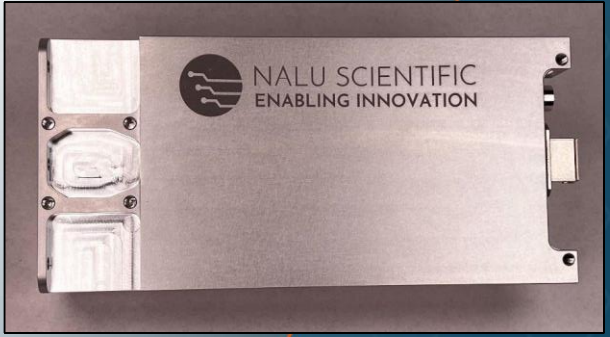
96 ch UFL breakout



PCB







Enclosure

Slides Courtesy of NALU Scientific

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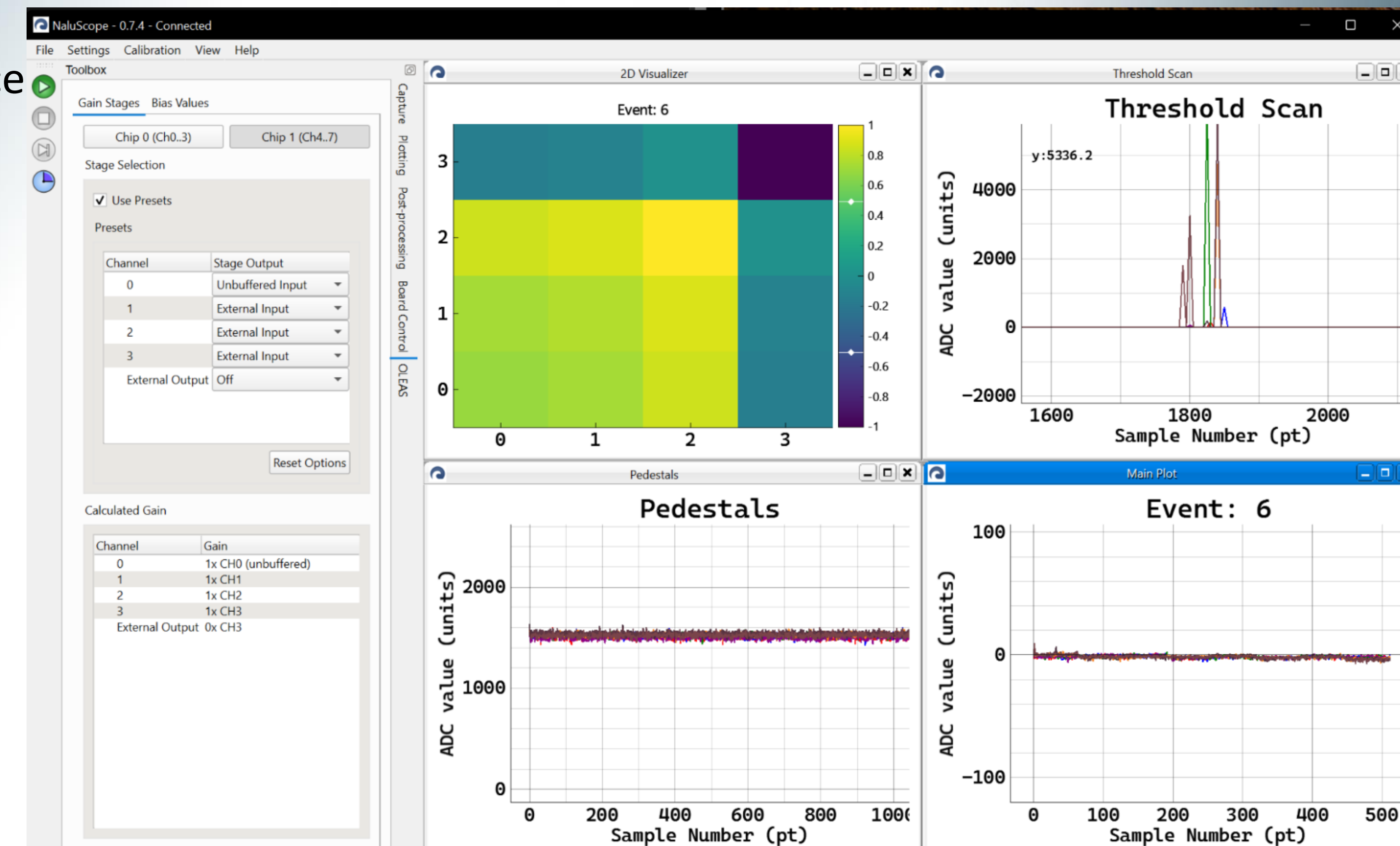
EIC Critical Developments - Electronics

Software

- Easy-to-use interface
  - Export mode
  - Easy mode
- Toolbox for quick access
- Real time visualization
- Flexible number of channels on display
- CSV/binary export



Slides Courtesy of NALU Scientific

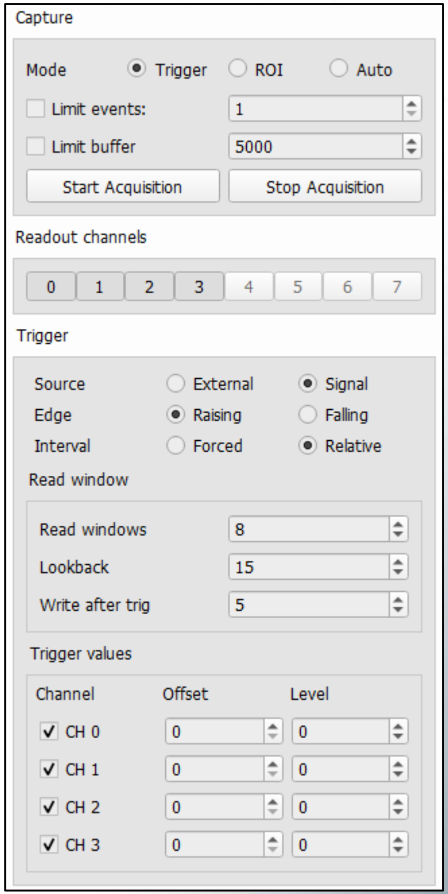
EIC Critical Developments - Electronics

Software Features

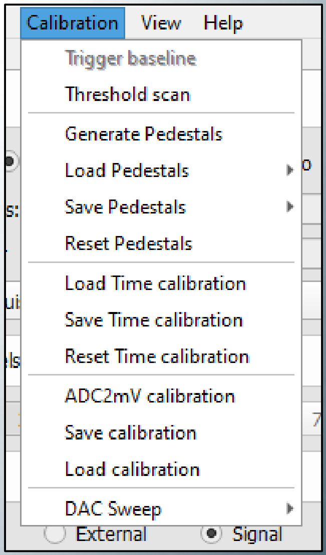
Straightforward readout configuration

- Tools for calibration generation and data correction
- Tools for data visualization and processing
- Automatically export data to disk while capturing

Captured data is stored with all calibration data and board parameters used for easy offline analysis.



Capture Toolbox



Calibration

Slides Courtesy of NALU Scientific

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5 Takeaways

1) **The Sensors** - DC HRPPD for DIRC, CC LAPPD/ HRPPD for RICH, **available today for rental or purchase**

2) **Manufacturing Scale-up** - If EIC needs 200+ devices, Incom can deliver 200+ devices

3) **Frugal Price** - Cost per unit area is competitive with existing technologies

4) **Technical Specifications** - LAPPD / HRPPD already meet most EIC requirements

5) **EIC Critical Developments** – With support of a pending SBIR program, Incom will develop critical LAPPD / HRPPD improvements for optimal, customized EIC performance, including readout.

Thank You For Listening!

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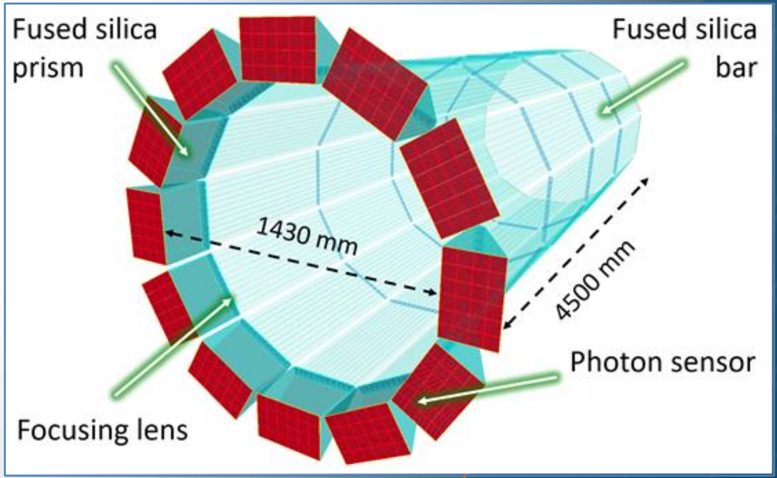
Technical Specifications:
HRPPD vs Photonis Planacon for DIRC

- For DIRC, there are 12 prisms, each 24 x 36 cm
- HRPPD is 10 cm x 10 cm (plus some outside edge)
  - With 2.5 mm DC pixels -> 1024 channels / HRPPD
  - ~75 HRPPDs for DIRC
  - Dark rates <2 kHz/cm^2 at room temperature
- Planacon is 5 cm x 5 cm
  - 6 mm pixels -> 256 Channels / Planacon
  - 300 Planacons for DIRC
    - @ $15k = $4.5 Million
    - Equivalent to $60k / HRPPD
    - But HRPPDs will be ~$20-$25k each



Thanks to Grzegorz Kalicy for the image of the proposed DIRC detector

Summary

Features

- **HRPPD->10 µm** MCPs , **100 cm^2** (100% active area)
- **LAPPD->20 µm** MCPs, **373 cm^2** (97% active area)
- **Capacitive Coupling** → flexible **pickup pattern modification**
- **Direct Coupling** → 2.5 mm pixels

Performance vs Other sensors

- **LAPPD Gain ≥ SiPM or Planacon Gain**
- **LAPPD TTS > SiPM TTS**
- **LAPPD Readout Channels ≤ SiPM or Planacon Channels**
- **LAPPD Dark Rates << SiPM Dark Rates** at room temperature
- **LAPPD PDE < SiPM PDE**
  - To be addressed in upcoming SBIR

LAPPD or HRPPD Price per unit area ≤ SiPM or Planacon

Frugal Price

Volume Price Discounts Available Today!

TILES ORDERED	TILE COST	LAPPD Cost / cm^2	CUSTOMER SERVICES	SELLING PRICE	TOTAL SALES
1	$35,000	$92.11	$15,000	$50,000	$ 50,000
3	$28,440	$74.84	$15,000	$43,440	$ 130,319
5	$25,111	$66.08	$15,000	$40,111	$ 200,557
7	$23,284	$61.27	$15,000	$38,284	$ 267,988
10	$21,540	$56.68	$15,000	$36,540	$ 365,398

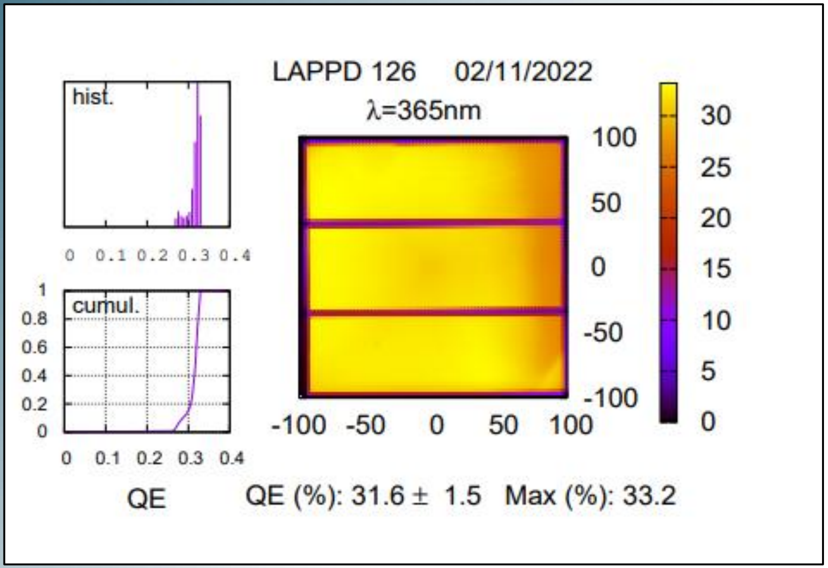
Full manufacturing (EIC Order) →

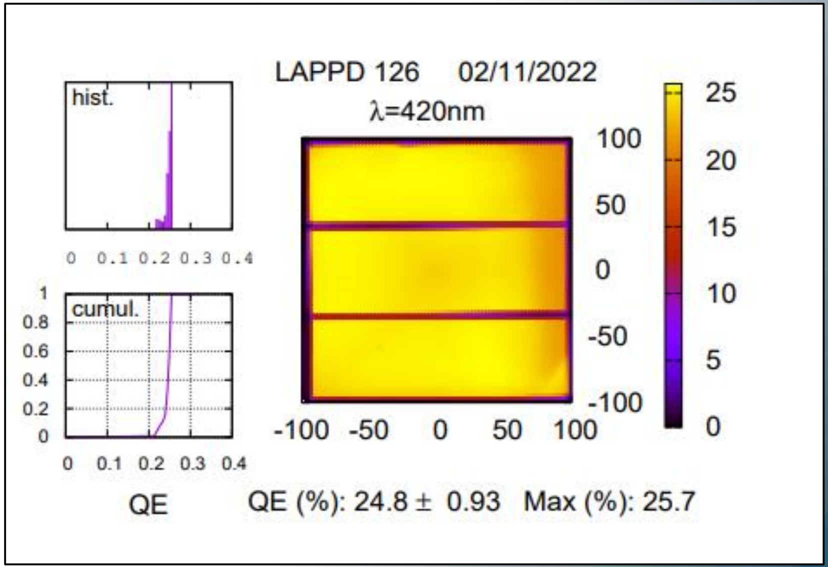
- **$30,000 to $20,000**
- **$78/cm² to $52/cm² for LAPPD**

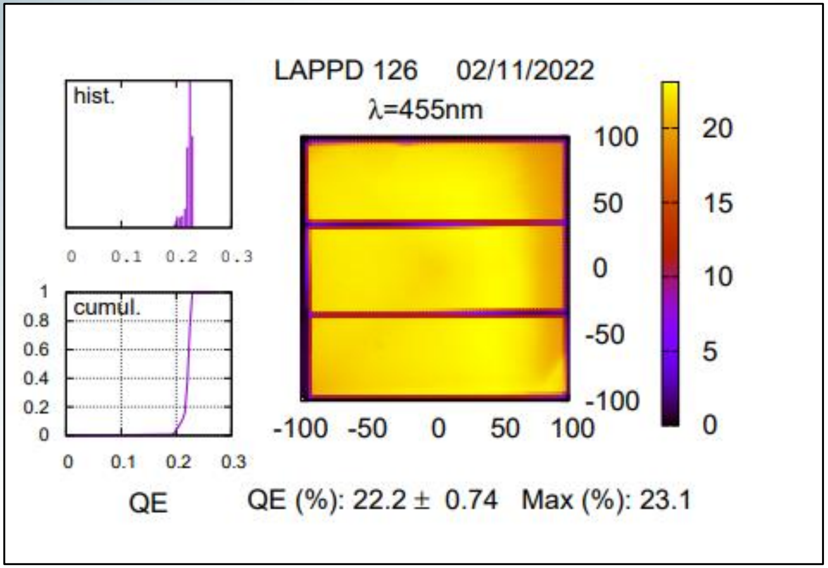
High-volume manufacture (Funded Scale-up)→

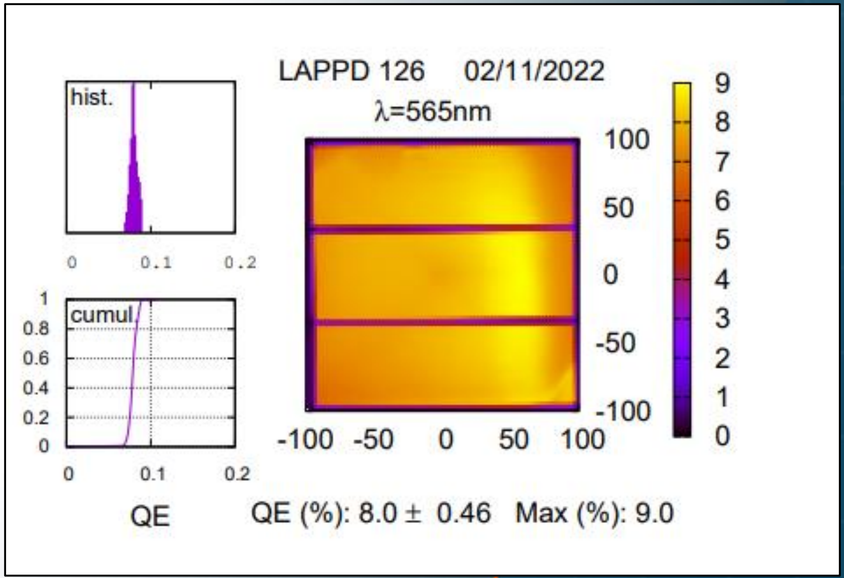
- **$10,000 should be achievable**
- **$26/cm² (M. J. Minot)**

Technical Specifications: Photocathode QE

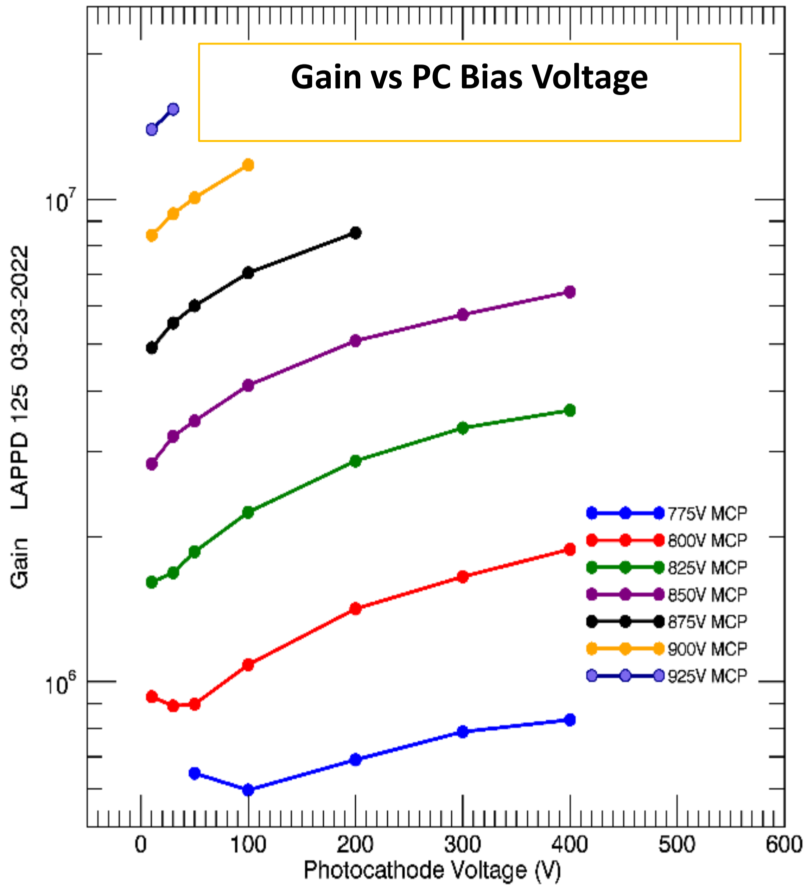


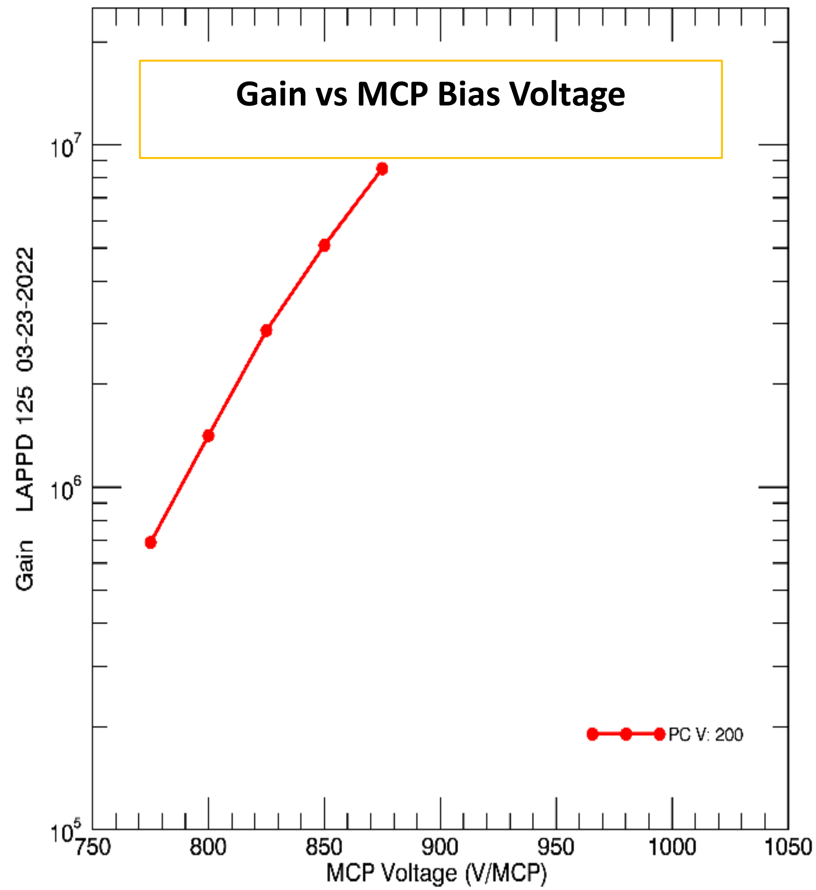




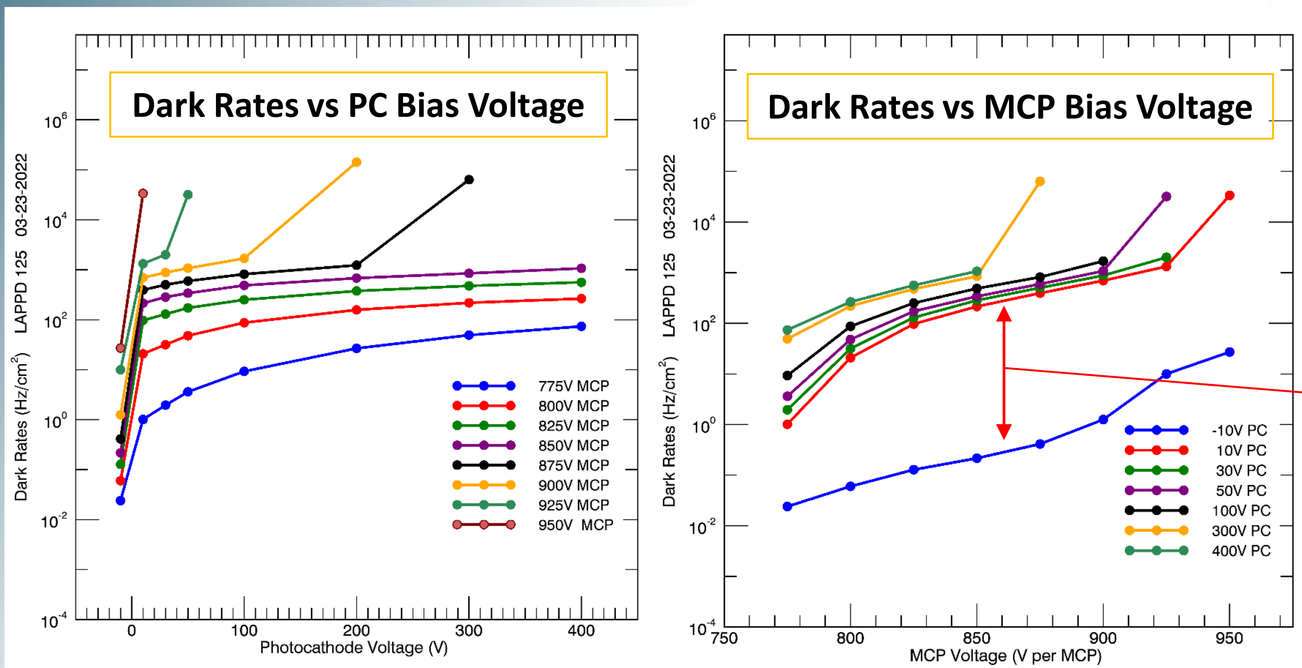


Technical Specifications: Gain vs Voltage





Technical Specifications: Dark Count Rate



- Observed MCP pulses in the absence of external light source
- Dominated by **thermionic emission** from photocathode

Example Recommended Operating Point

Gain ~$7 \cdot 10^6$, Dark rates <1 kHz/cm^2
@ 875V/MCP, 100V PC

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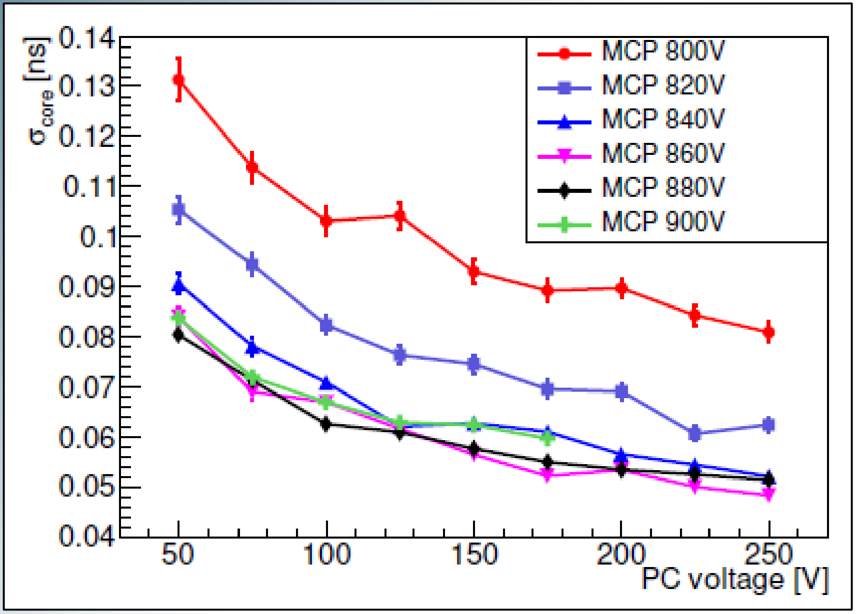
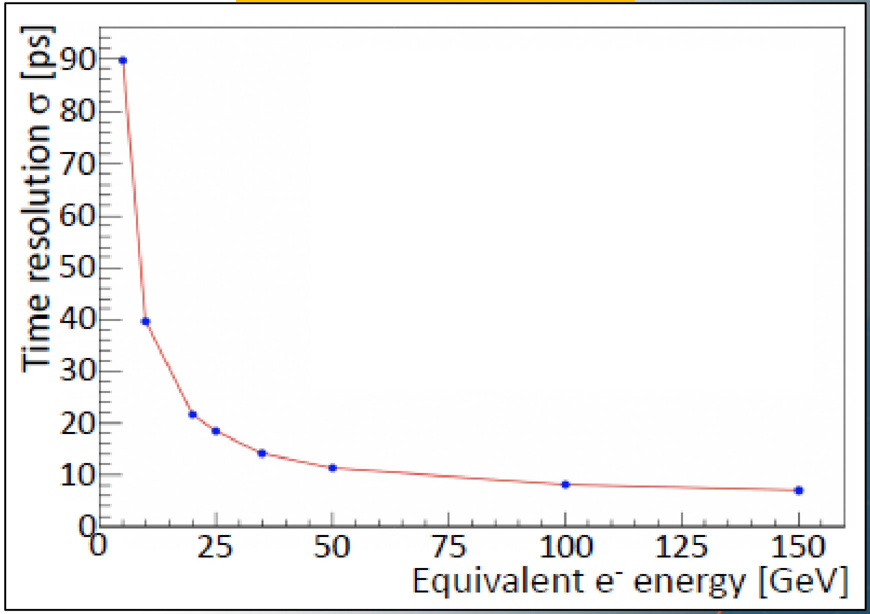
Technical Specifications: Core Timing Resolution

Single PE TTS vs PC Voltage



Multiple PE TTS
w/ 30 MHz/cm² Background



σ_{SPE} ~**50 ps**, σ_{MPE} ~**8 ps**
(Vagnoni, INFN)

- Estimating 4 charged particles per GeV of energy
- Multiple PEs decrease flight time variation of *"first one in"*

Stefano Perazzini, Fabio Ferrari, Vincenzo Maria Vagnoni and on behalf of the LHCb ECAL Upgrade-2 R&D Group, *Development of an MCP-Based Timing Layer for the LHCb ECAL Upgrade-2, Instruments 2022, 6, 7.*

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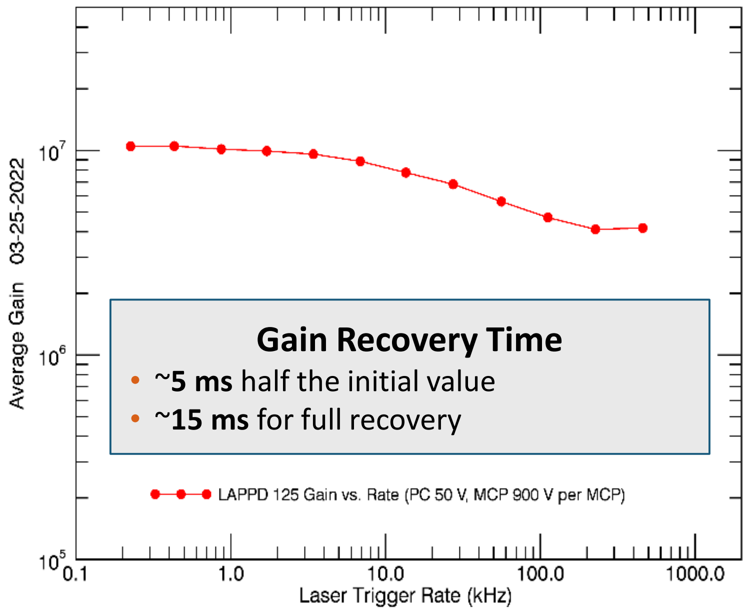
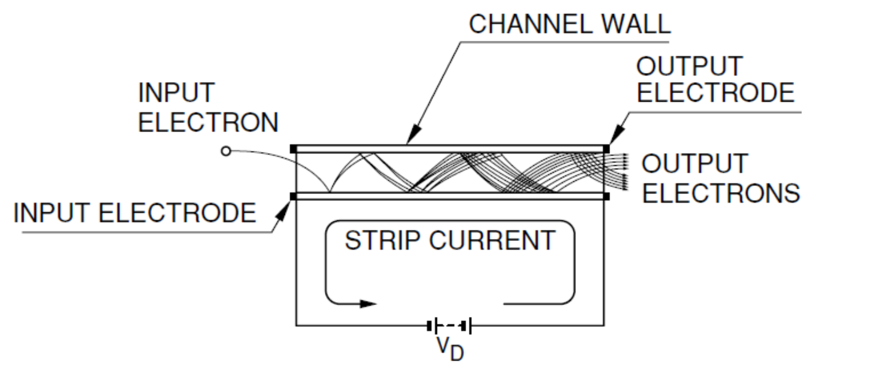
Technical Specifications: Gain vs Event Rate



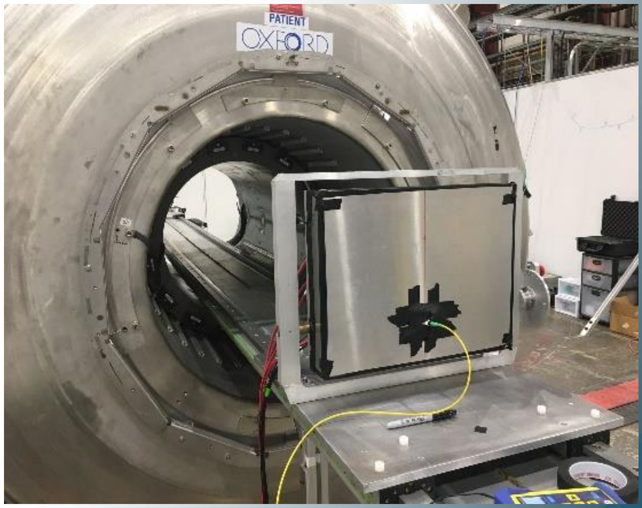


$$\tau_{dead} = \frac{Q_{out}}{I_{strip}}$$

- Gain retention is a function of *MCP resistance*
  - Lost electrons replenished by strip current
- Can be improved by using *smaller pore size* MCPs
  - Lowers probability of entering the same channel

Technical Specifications:
Gain vs. Magnetic Field Strength, B || P/C e-

- Testing at Argonne
- LAPPDs pushed toward solenoid increasing B-field in steps
- Gain decreased with increasing magnetic field.
- Gain recovered with a higher MCP voltage.
- Dark rates decreased even in the 0.02 T field
  - (200 Gauss, 400x Earth's field)



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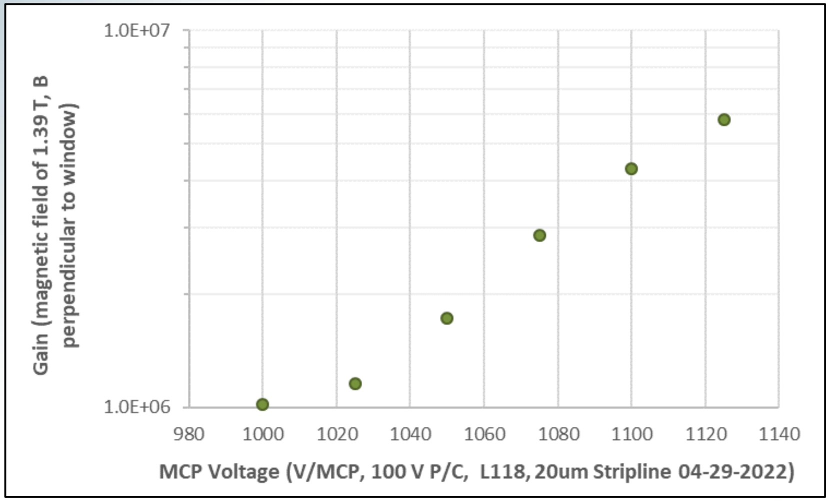

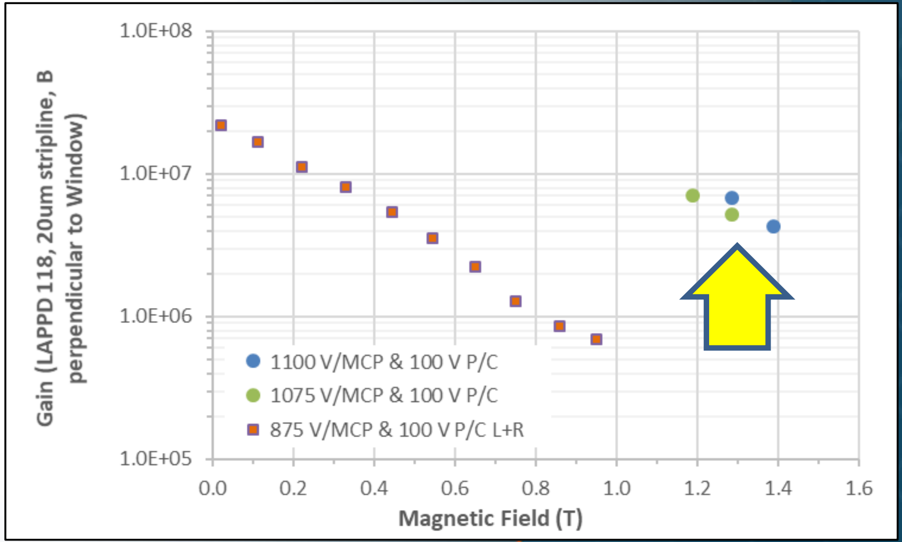

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Small Business name: **Incom Inc.**	Principal Investigator: **Cole Hamel** E-mail: chamel@Incomusa.com
Topic / subtopic: **C55-24. A2 Advances in Detector and Spectrometer Technology, 2. Cherenkov detectors** DOE Opportunity # **DE-FOA-0002783** Application Type: **Phase I SBIR**	

"LAPPD & HRPPD: Fast Photosensors for EIC and other Particle Physics Applications"

Critical LAPPD / HRPPD developments to optimize performance customized for EIC

1) **Photocathode and PDE Optimized for Aerogel Cherenkov Signals** – EIC RICH will use a silica aerogel Cherenkov radiator with a useable wavelength range above ~350 nm. The LAPPD PC will be modified to improve PDE in this range. Program objectives include PC QE ≥ 30% and PDE ≥ 20% for λ ≥400 nm, to be met as follows:
   a) **Photocathode Peak and QE** – 20% QE at 450 nm was previously (DE-SC0019821) achieved by modifying the chemistry of Incom's Na_2KSb bialkali photocathodes. This work will be extended to achieve ≥ 30% QE at >400nm.
   b) **Photon Detection Efficiency** – Incom will establish (for the first time) the ability to measure PDE. In addition to red shifting QE, PDE ≥ 20% for λ ≥400 nm, to be achieved by developing ALD-MCPs with higher OAR.
2) **Timing Optimization** - Optimize timing performance of LAPPD / HRPPD with regard to requirements for DIRC, which are more stringent than the RICH detectors.
3) **Sensor Readout** - Tests on LAPPD and HRPPD with fully populated readout to optimize pixel shape, size, and number, including for the availability, cost and performance of recommended electronics.
4) **Sensor Form Factor** - Modify LAPPD/ HRPPD dimensions for optimal lay out and tiling of sensors.
5) **Confirmation of Device Lifetime –** Measured 5 C/cm^2 extracted charge with no deterioration of gain. These results will be confirmed, extended, and validated replicating specific EIC RICH and DIRC conditions, and for the specific photocathode and tile configuration selected.
6) **Other suggestions from the EIC PID Community?**

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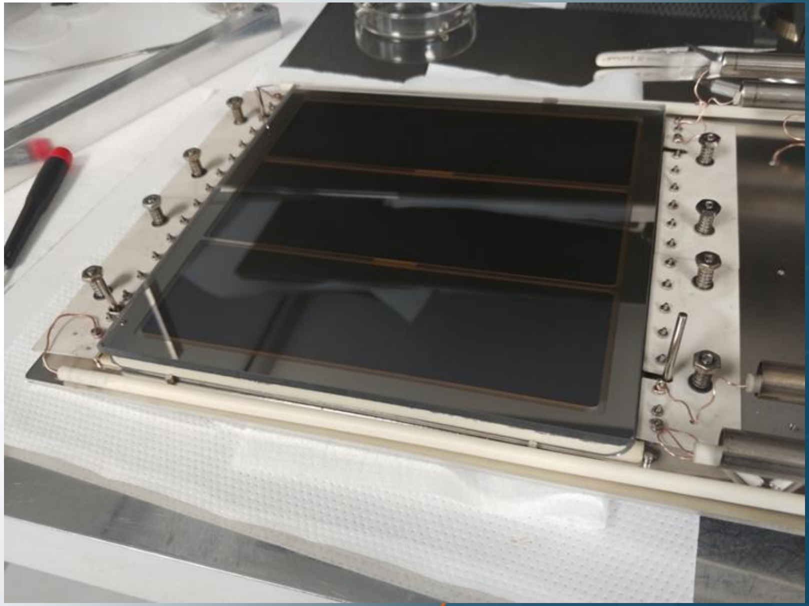
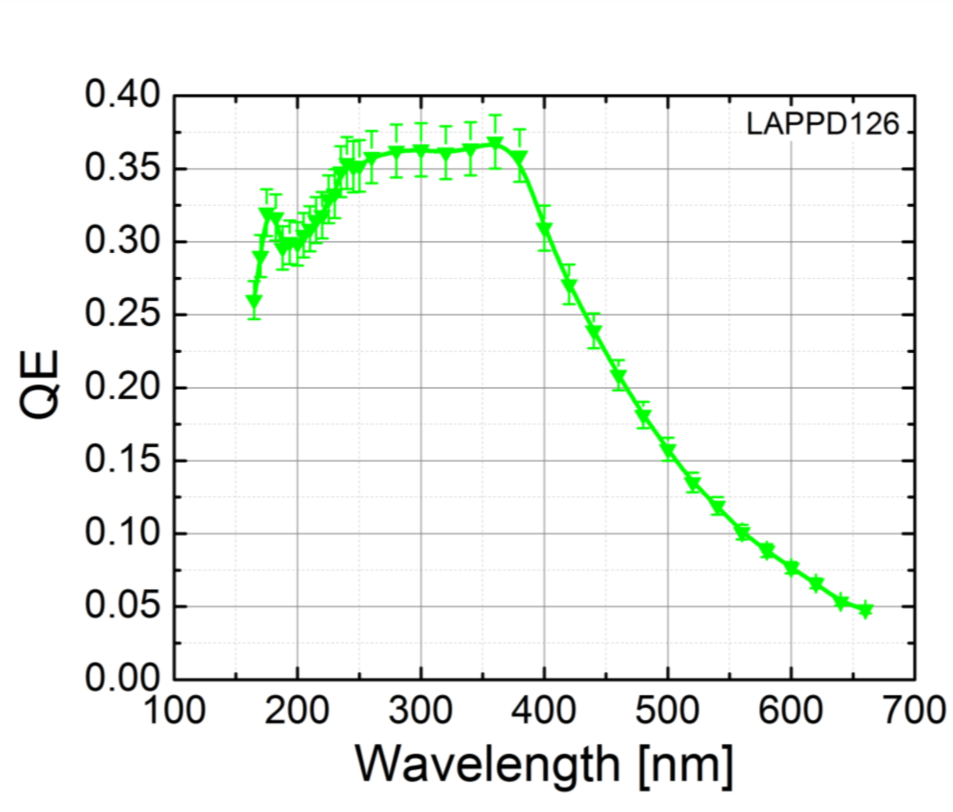
EIC Critical Developments: Currently Underway

Ongoing Developments

- 10 um pores for LAPPD- better TTS, faster pore recharge time, better B-field performance
- Ceramic Body- better durability, stronger capacitively coupled signal due to thinner anode plate and higher dielectric constant than glass
- B-field tolerance: Tests up to 1.4 T have been performed at ANL
  - 10 um and 20 um pores with Direct readout LAPPDs
  - Expand these tests for:
    - Capacitive Coupled LAPPDs
    - HRPPDs



EIC Critical Developments - QE vs Wavelength

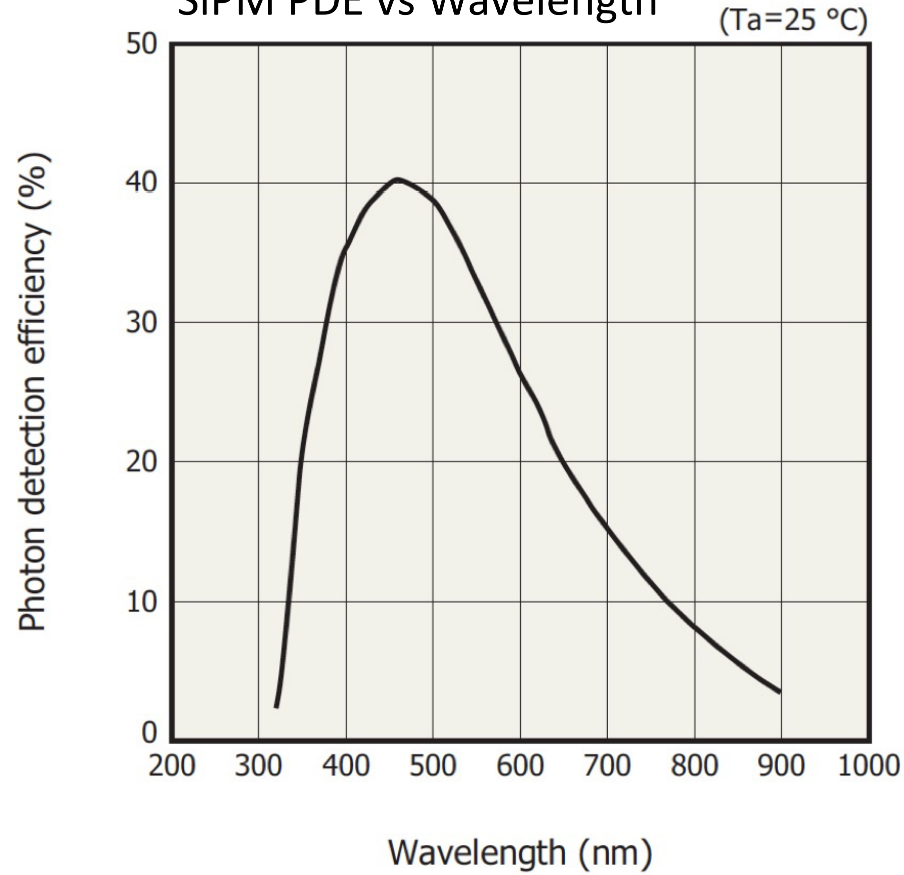


- UV grade Fused Silica glass window
  - Cutoff wavelength: **~160 nm**
- Peak at **~365 nm**
- Will Red-shift this spectrum
  - Make the peak wider using other alkali metals
  - Or red-shift the peak using alternate chemistries

EIC Critical Developments - Photon Detection Efficiency

- The Biggest Challenge for using the LAPPD/ HRPPD in EIC is the better photon detection efficiency of SiPMs
  - 40% PDE at 450 nm
- Best estimate for LAPPD
  - 14% PDE at 450 nm
  - 20% QE x 70% OAR
- This proposed SBIR would bring LAPPD PC QE to 30% at 450 nm
  - At best PDE=QE
  - Measure this value
- Steps to improve LAPPD PDE
  - Higher QE
  - Funnel-shaped MCP Pores
  - Electron Steering

SiPM PDE vs Wavelength



INCOM
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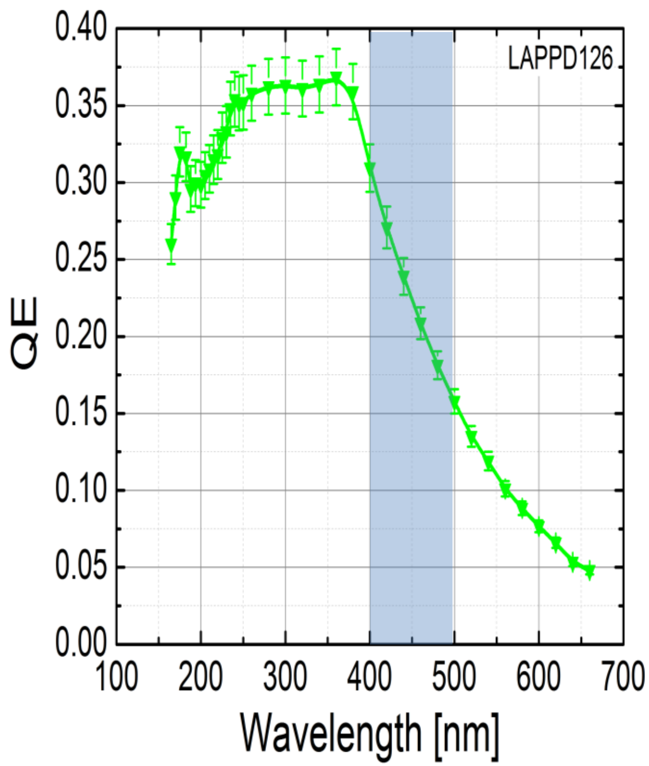
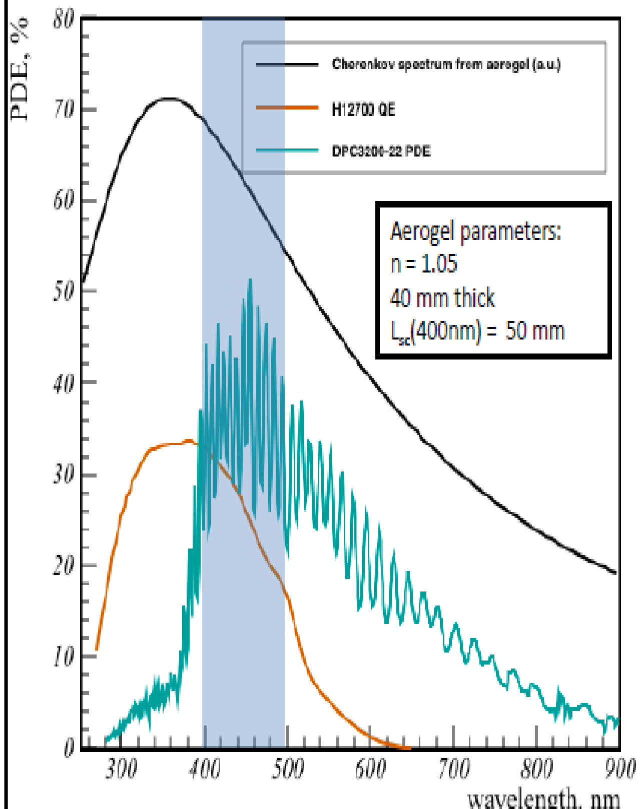
EIC Critical Developments:
Cherenkov Spectrum with Aerogel

LAPPD QE	Cherenkov Spectrum with Aerogel	SiPM PDE

LAPPD QE

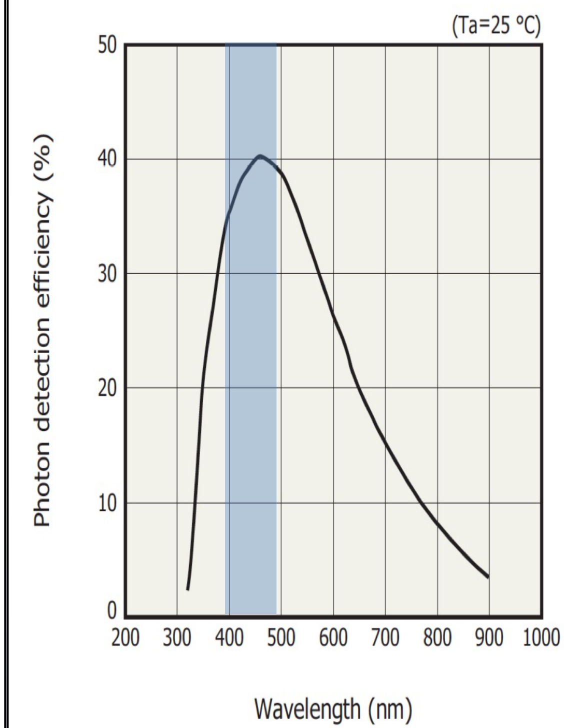


Cherenkov Spectrum with Aerogel



According to PANDA Forward RICH Detector

SiPM PDE



Frugal Price = Manufacturing Scale-up

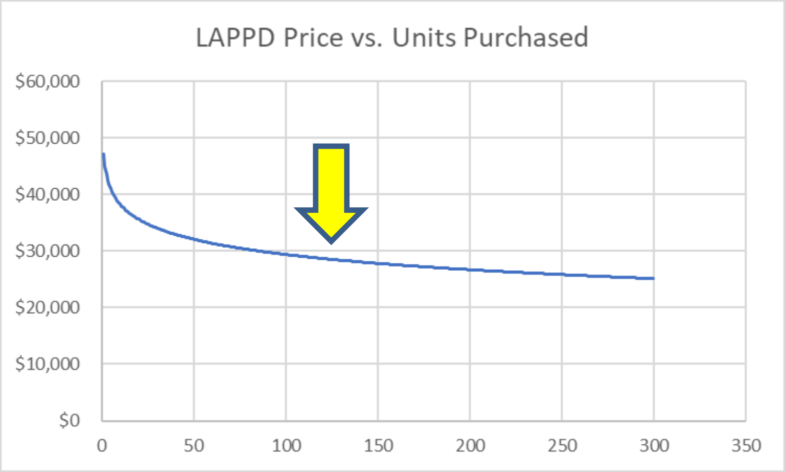
Incom, Inc. can readily meet EIC sensor requirements

- 51 Years in business, Founded 1971
- ~200 employees
- Yearly Sales of $30 MM
- Three facilities:
  - Incom West – Vancouver, WA
  - Incom East (2) – Charlton, MA
    - **LAPPD Pilot Production** by Detector Business Unit (**DBU**)
- Incom is a major supplier of glass products for the medical diagnostic market and numerous others
- Bottom line: **we've done scale-up before, and we can do it <u>for the LAPPD</u>**

Detector Pilot Production Facility

Manufacturing Scale-up:
Economies of Scale

- EIC is one customer, not three customers
- If orders are placed for DIRC and both endcap RICH detectors, volume discounts will be applied for the total order →~200 units
  - The price per unit drops down between $20k-$30k each
  - Now the LAPPD and HRPPD are easier to integrate, provide better performance, **and** are cheaper than SiPMs and Planacon
  - In very high volume, a unit price of $10,000, or $26/cm^2$ is achievable



INCOM
BRIGHT IDEAS

Frugal Price:

Engineering & Special Customer Services:

CUSTOMER SERVICES COSTS WILL BE DROPPED WHEN FULL PRODUCTION COMMENCES

1. **Technical Support** - Incom provides broad technical support to customers before and after they procure an LAPPD.
2. **Measurement & Test Workshops** - early adopters gain hands on experience operating and collecting data with LAPPD. This service is now offered both live and remotely with a virtual workshop and recorded videos.
3. **Measurement & Test Reports** – Full, comprehensive MCP and LAPPD / HRPPD test reports are prepared for each LAPPD / HRPPD and made available to the customer.
4. **SWAPS -** Incom offers to "swap" an early prototype, during the first year, with a later stage product that might be more suitable for their application. SWAPS are made at either full or partial value, depending on how the detector was maintained. Shipping costs apply.
5. **Proprietary Certificate** – To satisfy certain government agencies, universities or commercial firms that require competitive bids from other suppliers, Incom will provide a "proprietary certificate" indicating that LAPPD / HRPPD are novel, unique products not presently available from any other supplier in the world.
6. **Administrative Documentation, US Export Authorities** - customers are required to provide Incom with an End Use Statement, before product can be shipped. Incom will confirm the eligibility of all prospective customer to receive LAPPD or HRPPD.
7. **Administrative Documentation,** Customer Import Authorities - Incom will coordinate with the Massachusetts Export Center to provide guidance to prospective customers.