Status of LAPPD technology

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EPIC GD/I Meeting, October 24, 2022

Resources

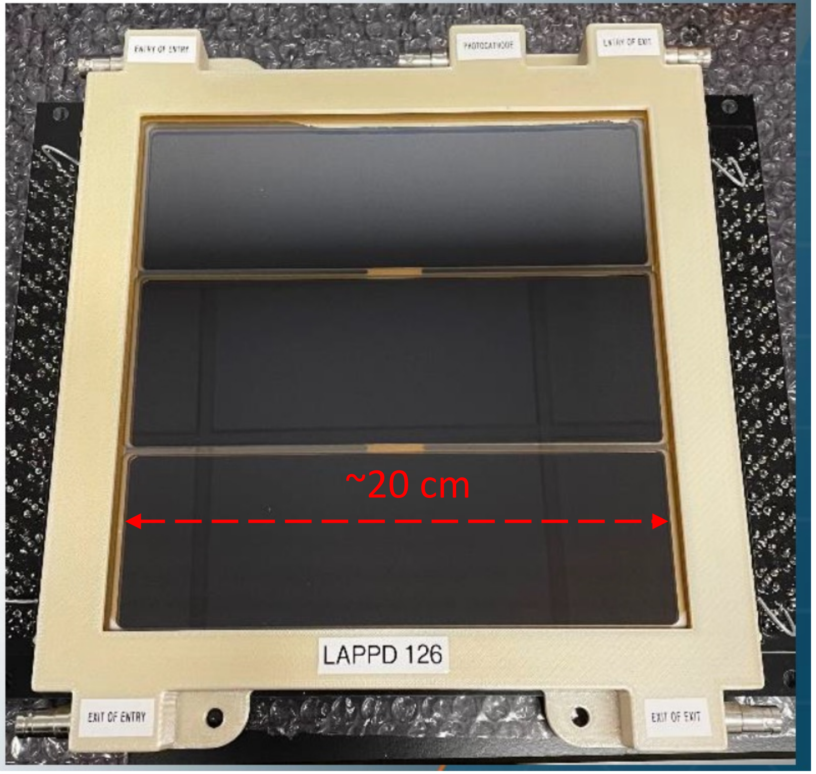
- Incom’s presentation for EIC by C. Hamel on 09/26/2022
- Our own studies (ANL, BNL, INFN & friends) within the old EIC R&D Program & eRD110
- Results by other R&D groups (in particular, V. Vagnoni INFN Bologna)

See also LAPPD Workshop #1 materials: https://indico.bnl.gov/event/15059/

Workshop #2 this week: https://indico.bnl.gov/event/17475/

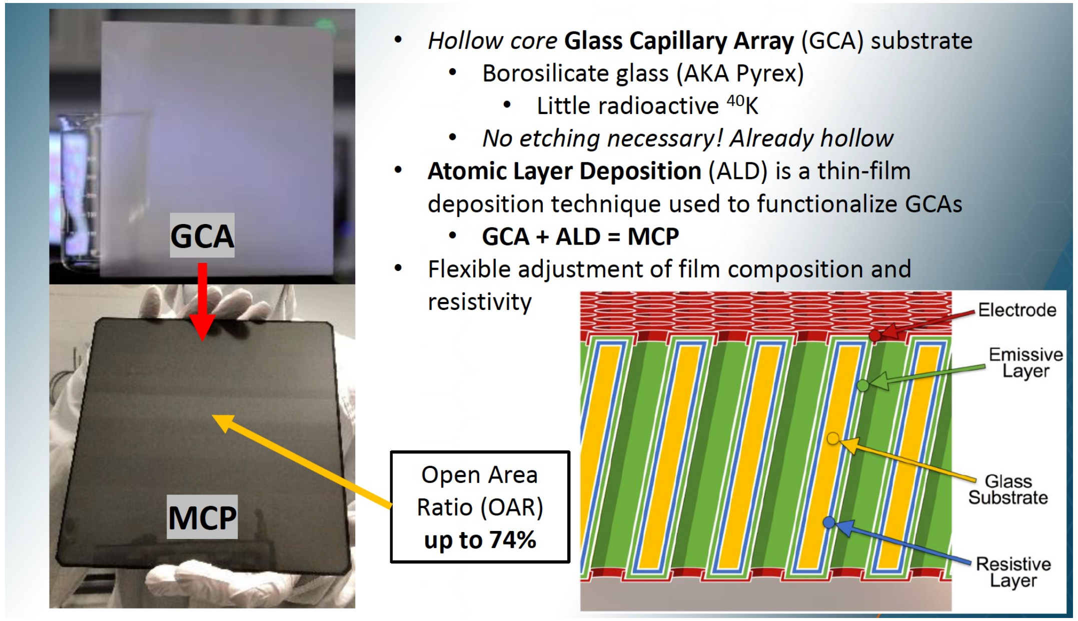
History & notation

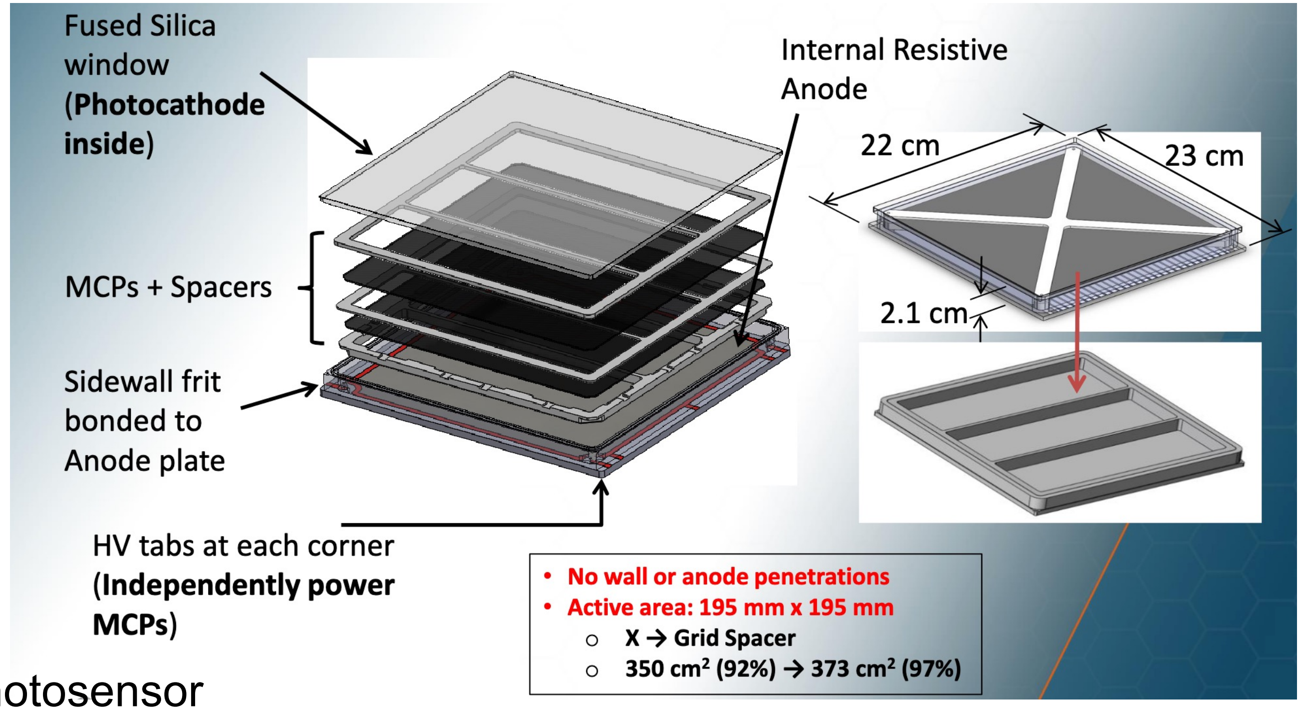
- **2009**: LAPPD Collaboration founded by Prof. Henry Frisch (U Chicago)
  - Motivation: Low cost, large detection coverage with picosecond timing
- **2015**: Early commissioning trials at Incom, Inc.
- **2018**: Demonstrated pilot production of LAPPDs
- **2022**:
  - 141 LAPPDs starts all time
  - 6 HRPPDs starts in 2022
  - Current capability of 36 LAPPDs / year
  - Current max capacity of 96 LAPPDs / year
- **Future**:
  - Improved performance
  - Commercial production



LAPPD (20cm): Large Area Picosecond Photon Detector
HRPPD (10cm): High Resolution Picosecond Photon Detector

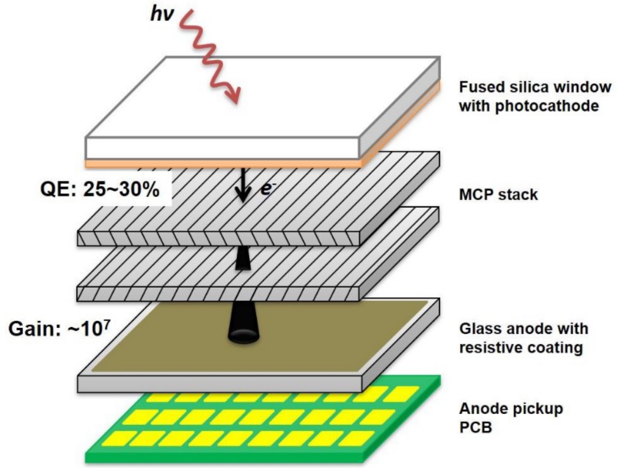
LAPPDs / HRPPDs by Incom Inc.





- An affordable large area (finely pixelated) vacuum photosensor
- 10x10 cm^2 or 20x20 cm^2 active area
- DC- (Gen I) or capacitively (Gen II) coupled species
- DC-coupled strips or 2D pixellation
- Expected to be (very) cost efficient in mass production
- High enough quantum efficiency and uniform high gain up to ~10^7
- Sub-mm spatial resolution for finely pixelated tiles
- Single-photon timing resolution on a ~50ps level or higher

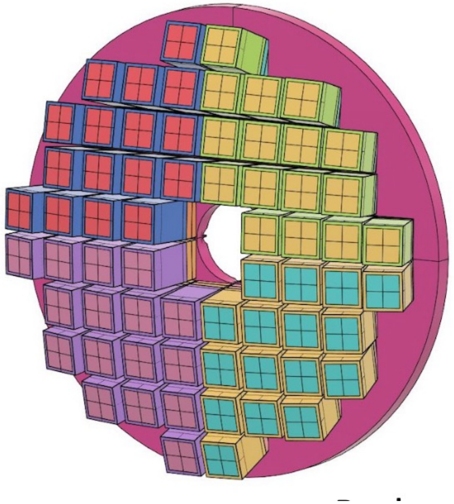
Gen II variety

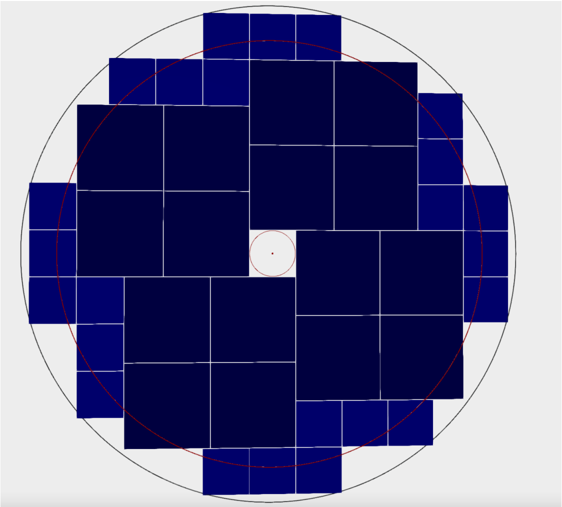


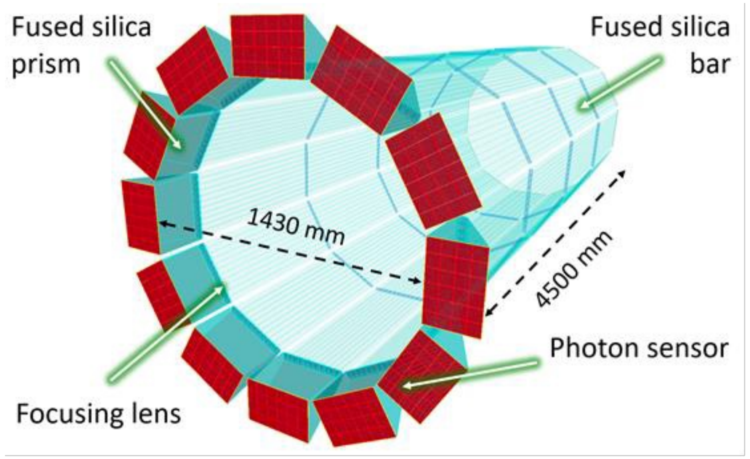
Possible applications for the EIC

- mRICH / pfRICH: low dark noise, Time of Flight capability (vs SiPMs)
- DIRC: expected to be more cost-efficient (vs other MCP-PMTs)
- dRICH: problematic, because of the magnetic field orientation
- Preferred variety:

mRICH	either DC-coupled or Gen II, 10cm formfactor
pfRICH	Gen II, either 10cm or 20cm
DIRC	DC-coupled, 10cm

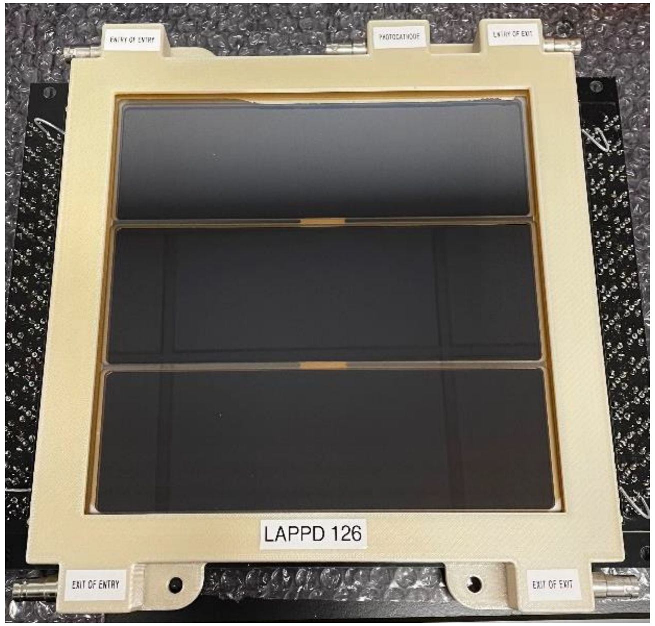

mRICH: 64 tiles total


pfRICH sensor plane: 40 tiles total

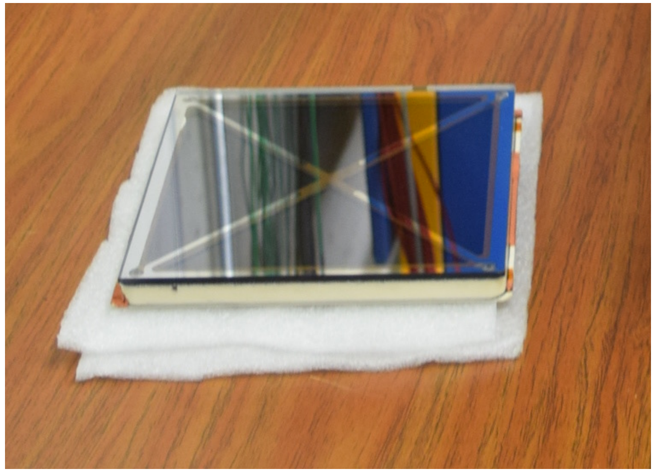


DIRC: 12*3*2 = 72 HRPPDs total

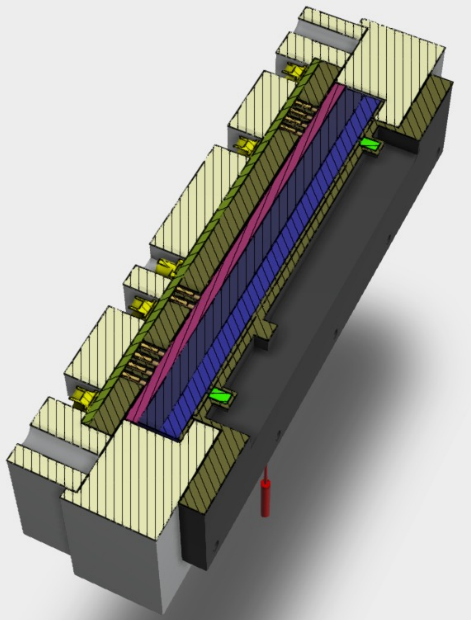
Formfactor & geometric acceptance

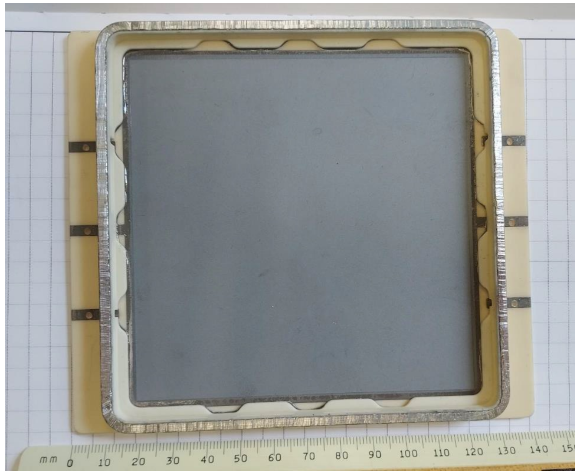


Capacitively coupled 20cm LAPPD



DC-coupled 10cm HRPPD

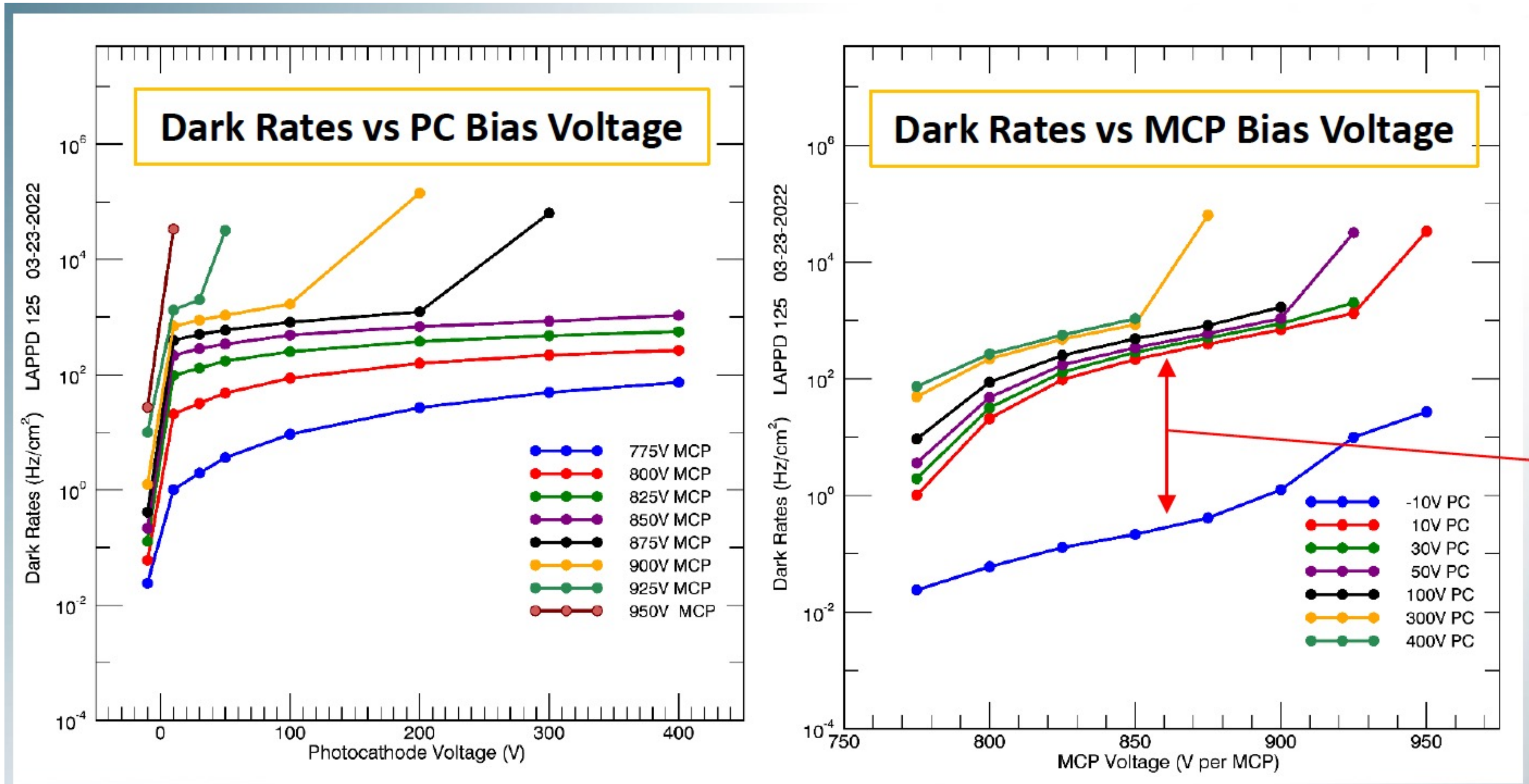




Capacitively coupled 10cm HRPPD

- None of them was initially designed for high geometric acceptance efficiency
- Can be fixed of course (meeting with Incom on this particular topic today)

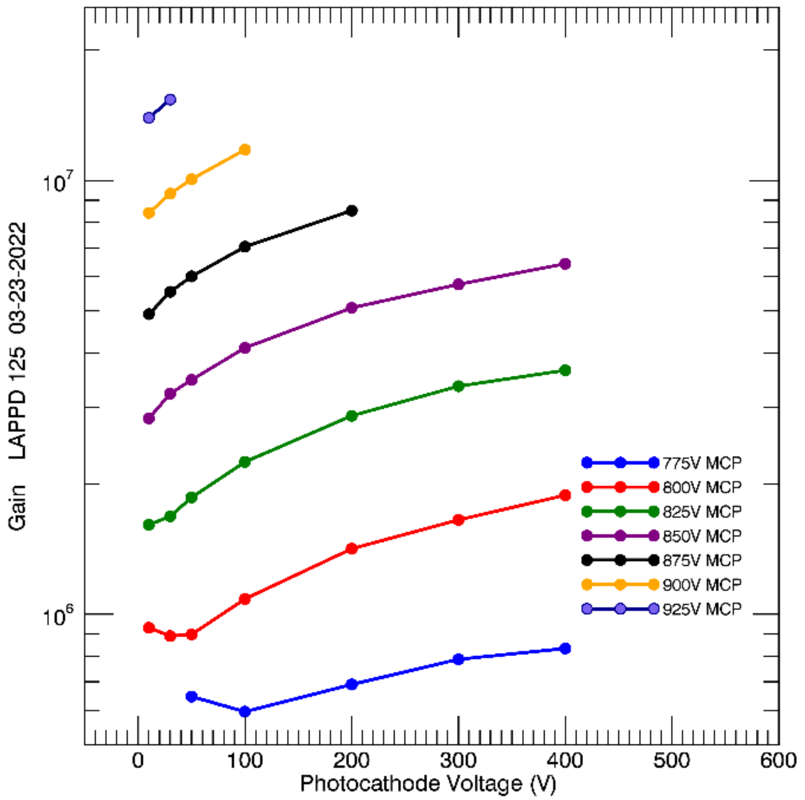
Dark count rate

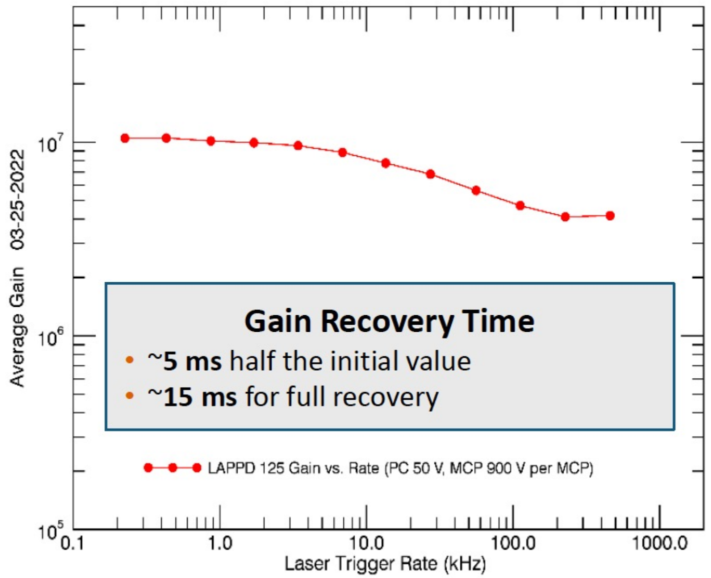


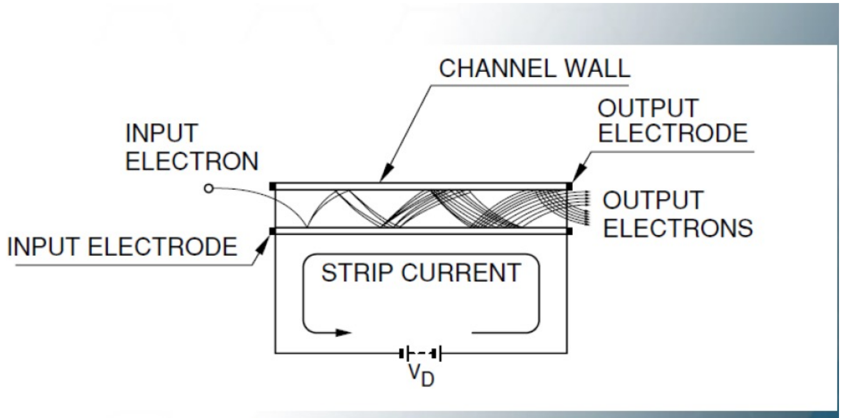
- Observed MCP pulses in the absence of external light source
- Dominated by **thermionic emission** from photocathode

- Dark rates are small, even that they go up with the PC and MCP voltages
- There are indications they get strongly suppressed even in a small magnetic field

Gain & pre-amplification







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

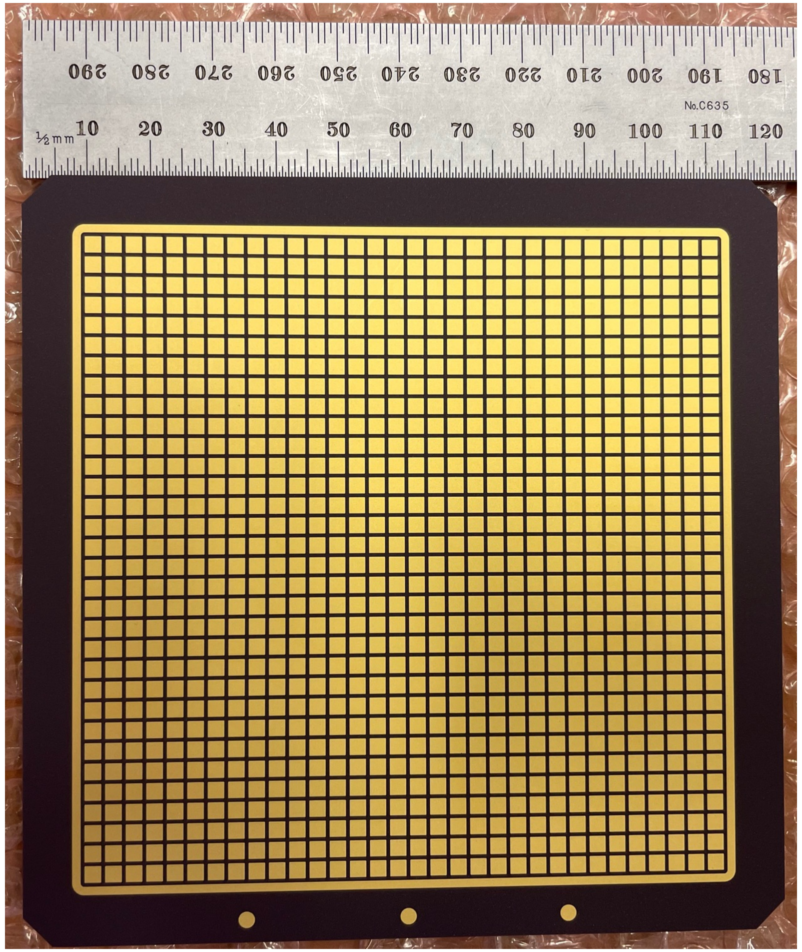
- Can reach gain ~10^7
- Recovery time may be of a concern
- In general, it looks like pre-amplification is a safe choice

Gain ~$7 \cdot 10^6$, Dark rates <1 kHz/cm^2

@ 875V/MCP, 100V PC

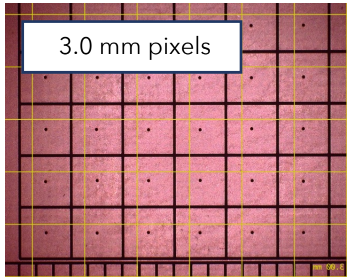
Pixellation

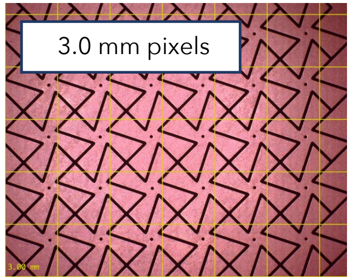
DC-coupled HRPPD

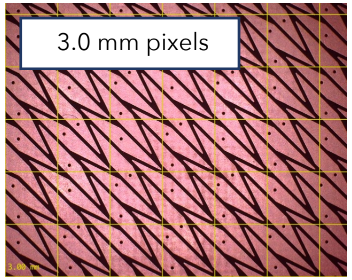


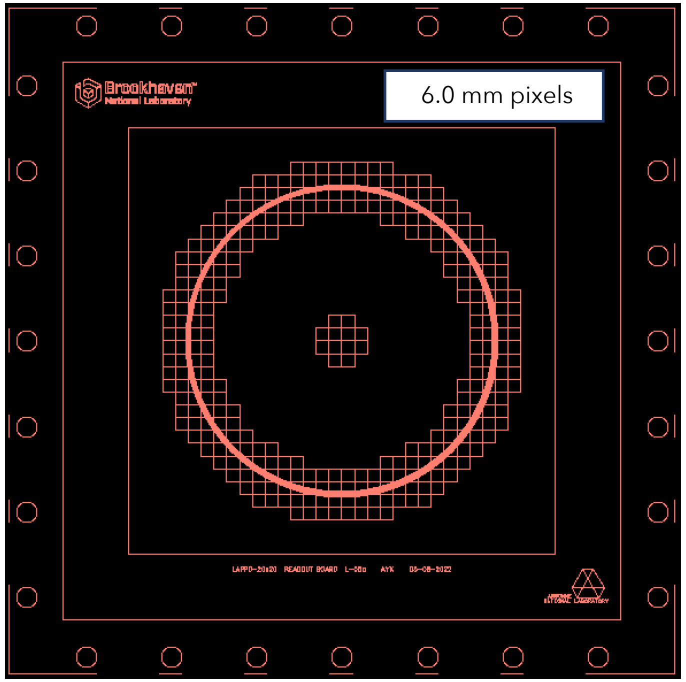
- ~100x100 mm^2 active area
- 1024 pads, 1/8" (~3.2 mm) pitch

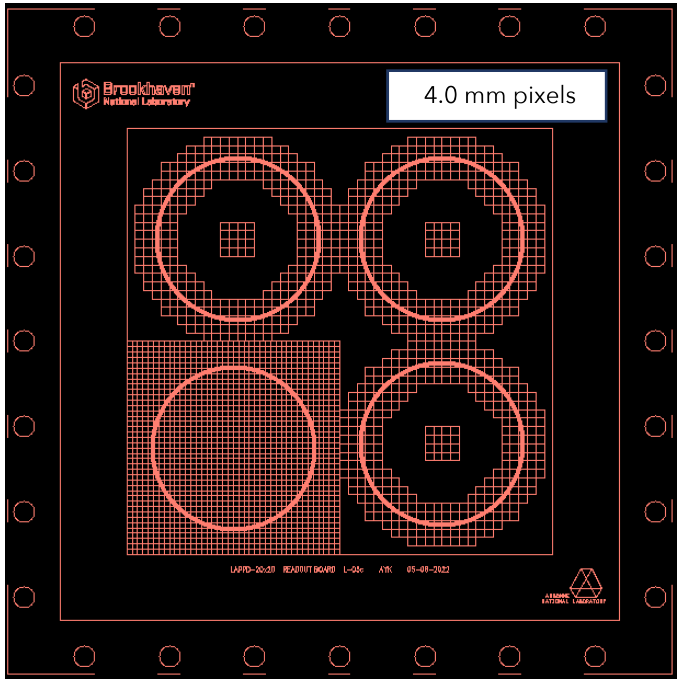
Capacitively coupled LAPPD / HRPPD





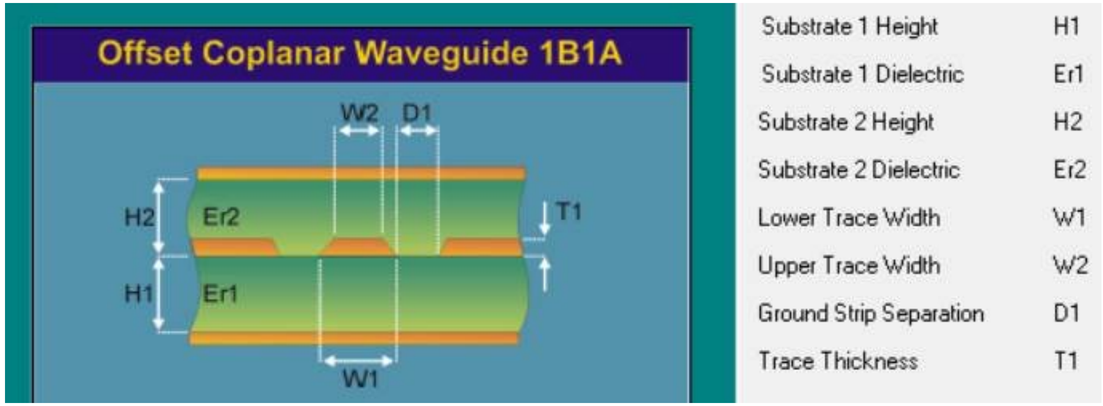


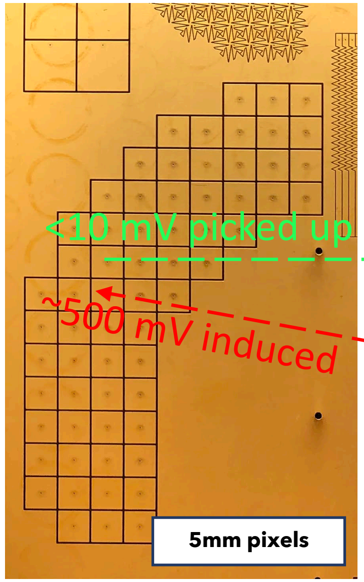


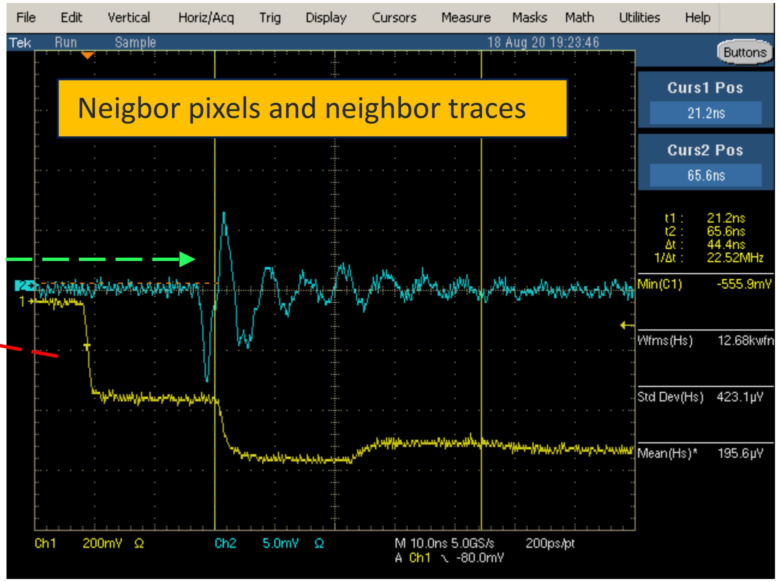


- Pixellation is defined by the user

PCB design, cross-talk, single photon cluster size

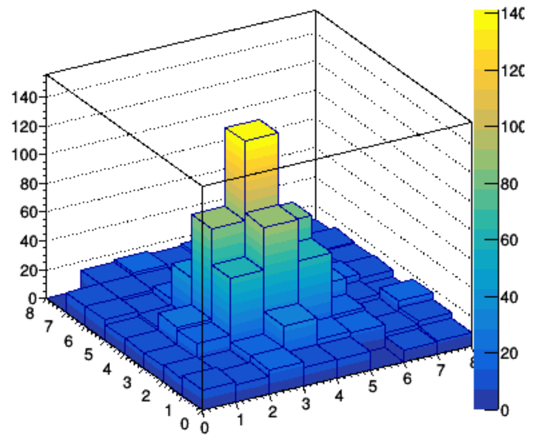




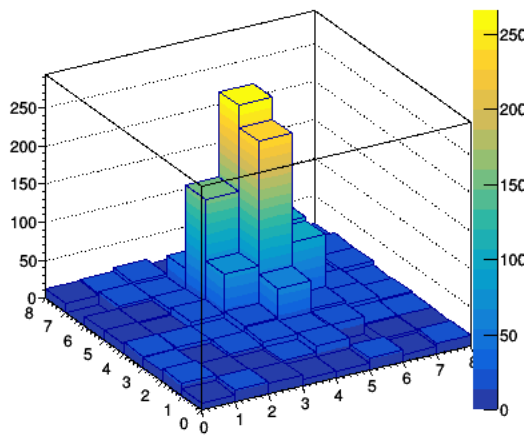


- Multi-layer stack-up; through vias; isolated traces
- Worst case X-talk ~few % level

3mm pixels



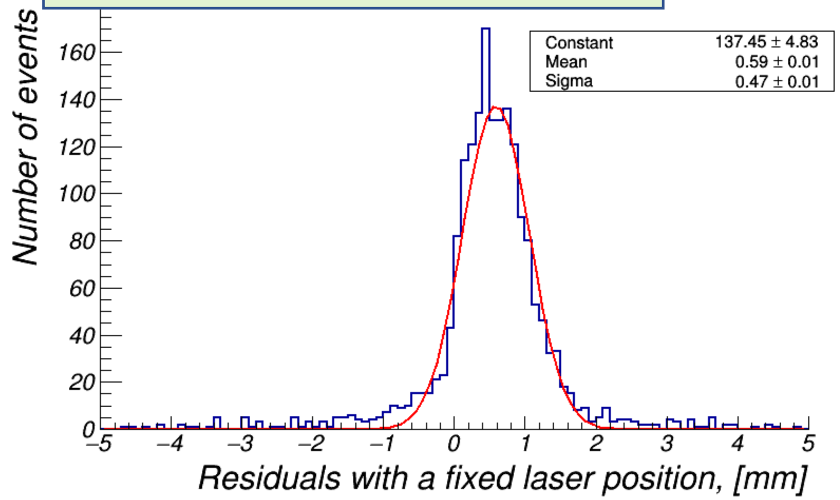
6mm pixels



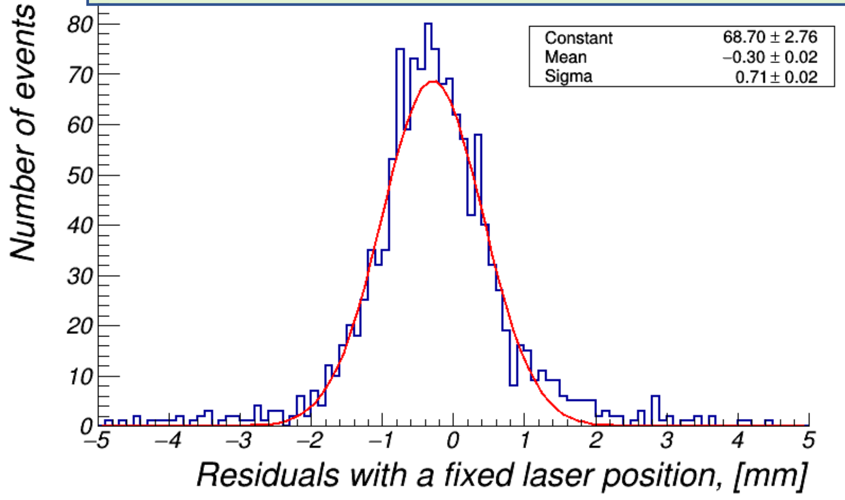
- For a capacitively coupled LAPPD with a “standard” stack and 2mm thick anode base cluster size RMS ~3.5mm
- Will be certainly smaller in a “short” stack configuration
- No data for DC-coupled tiles yet

Spatial resolution

3mm square pixels: σ ~500 μm

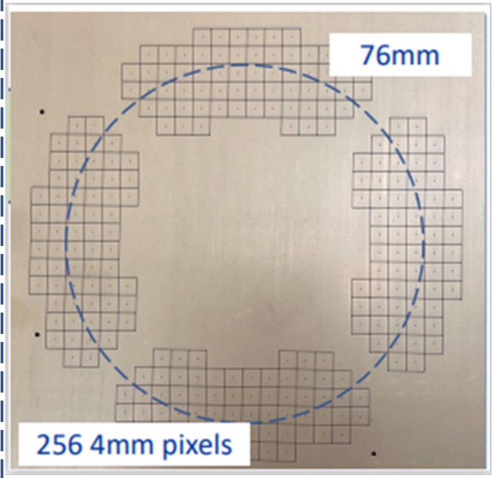


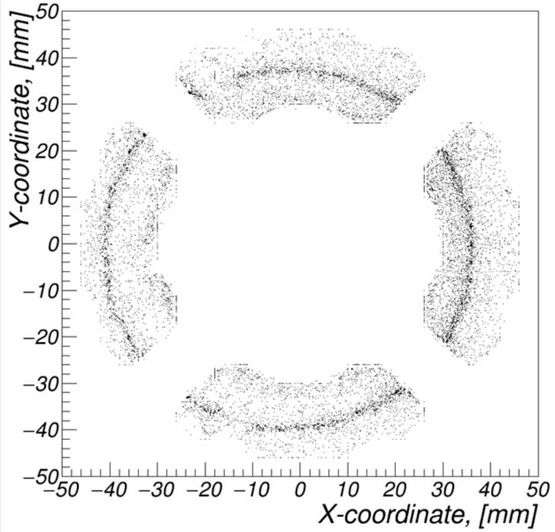
6mm segmented pixels: σ ~700-800 μm

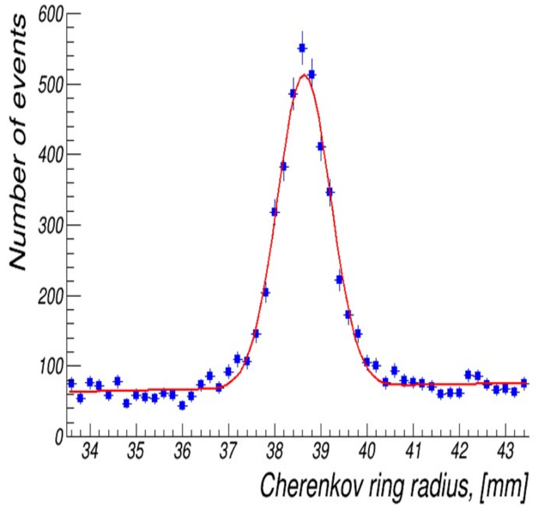


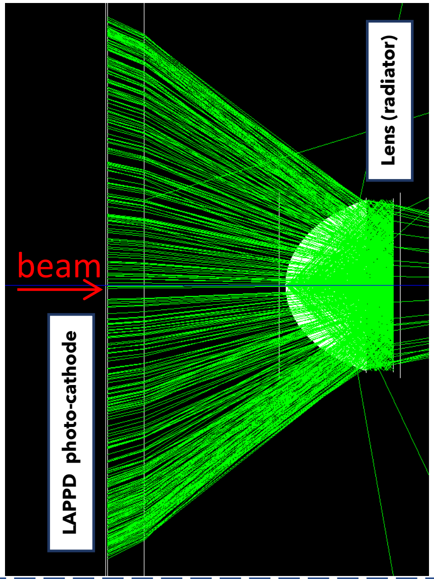
Lab results with a laser

$$X \sim \frac{\sum_i^n q_i x_i}{\sum_i^n q_i}$$





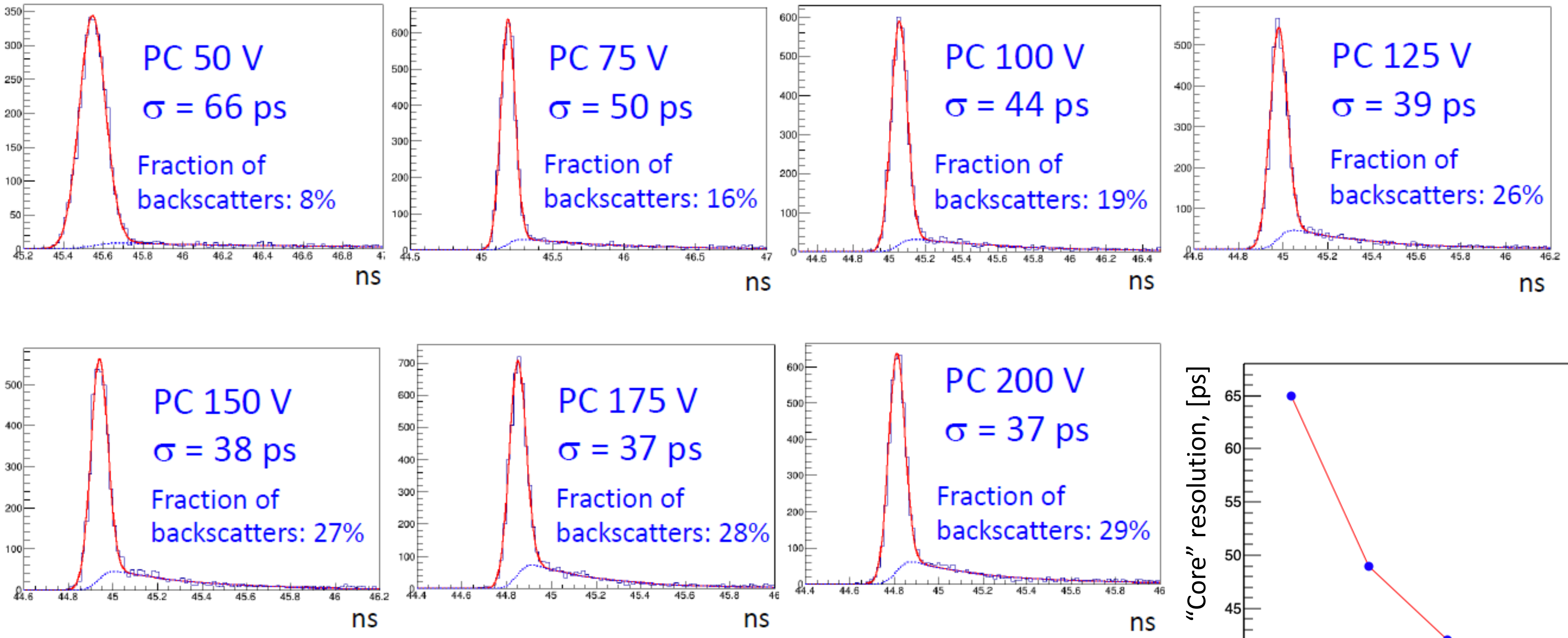




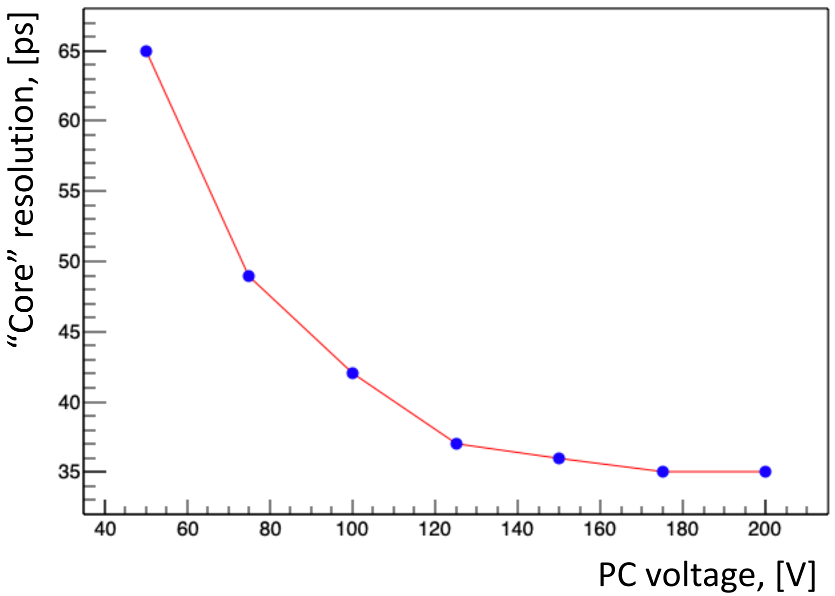
Beam data

Sub-mm resolution, even without pre-amplification

Single photon timing resolution



Data: V. Vagnoni (INFN Bologna)



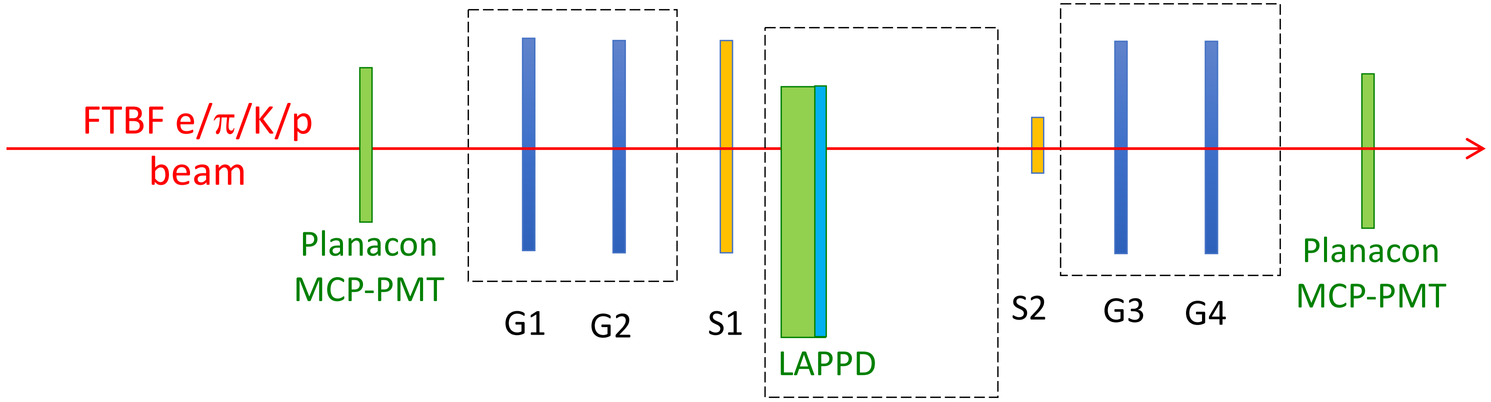
- Remember: EIC requirement is "<100 ps"
- Tail is of course a concern for the DIRC
- We are collecting our own beam data on this (INFN, BNL)

Data: V. Vagnoni (INFN Bologna)

Timing resolution for Time-of-Flight purposes

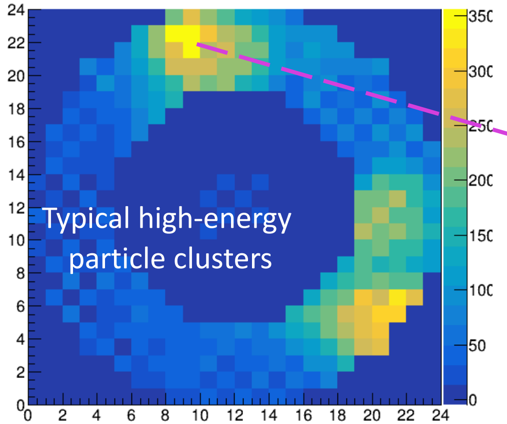
- G1 .. G4 – COMPASS GEM reference tracker
- S1 .. S2 – trigger scintillator counters

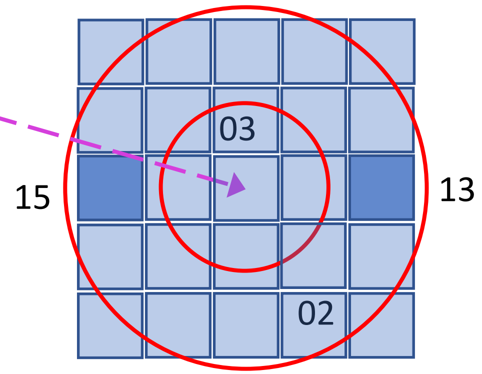
Our June 2022 FTBF data

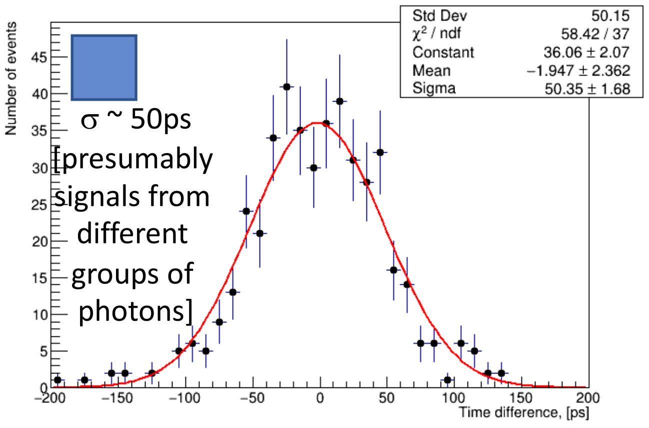


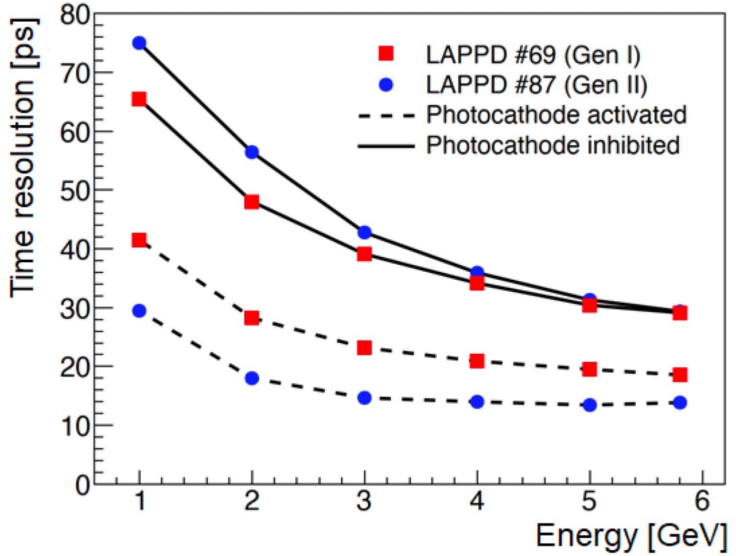
LAPPD quartz window as a Cherenkov radiator

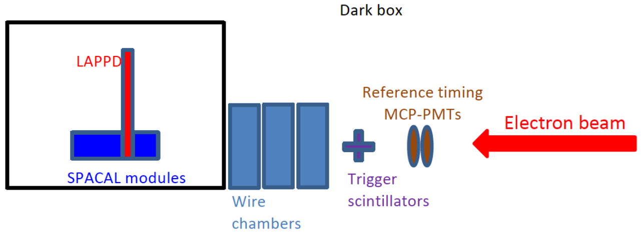
- *Single* photon TTS ~50 ps
- UV grade quartz window: a 120 GeV proton produces a **blob of ~100 p.e.'s**







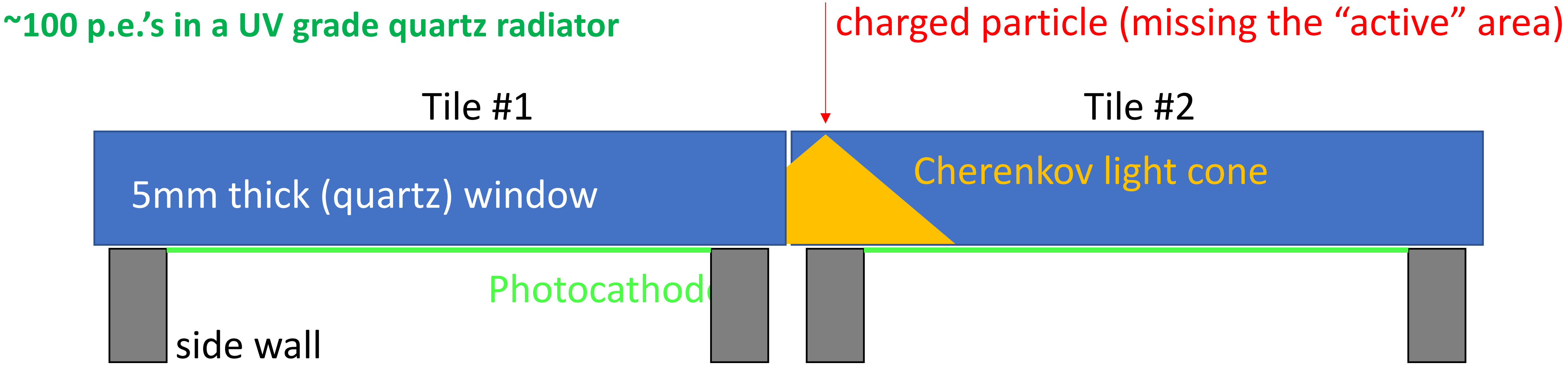




LHCb spacal tests at DESY

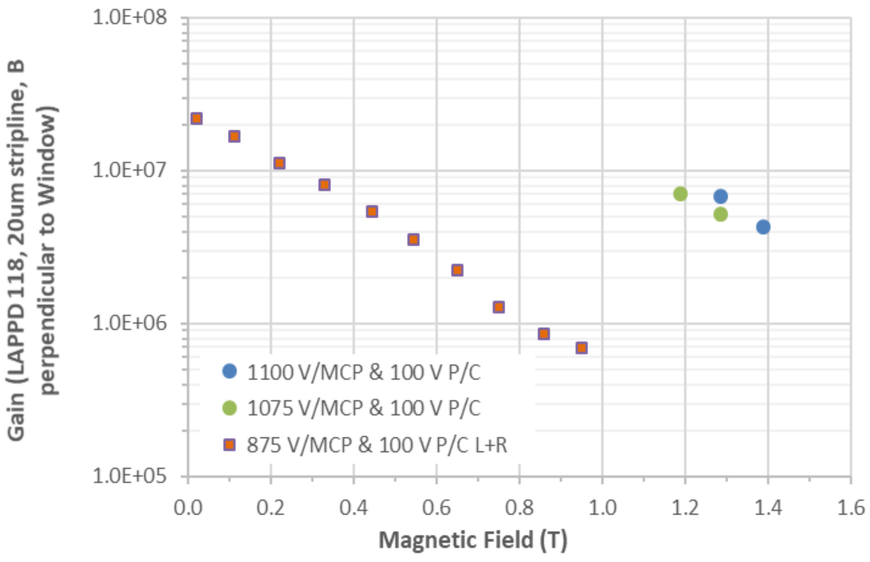
- Expect resolution σ < 15-20 ps in the mRICH / pfRICH configuration

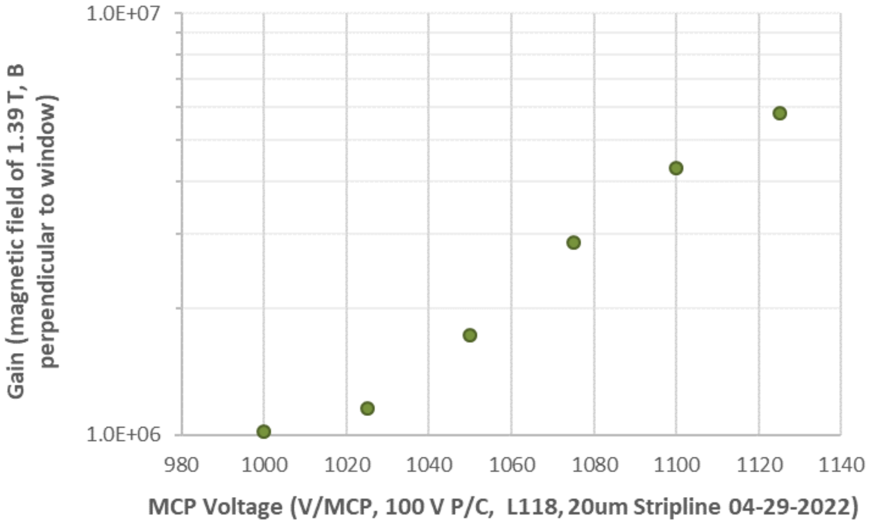
Geometric efficiency for Time-of-Flight purposes



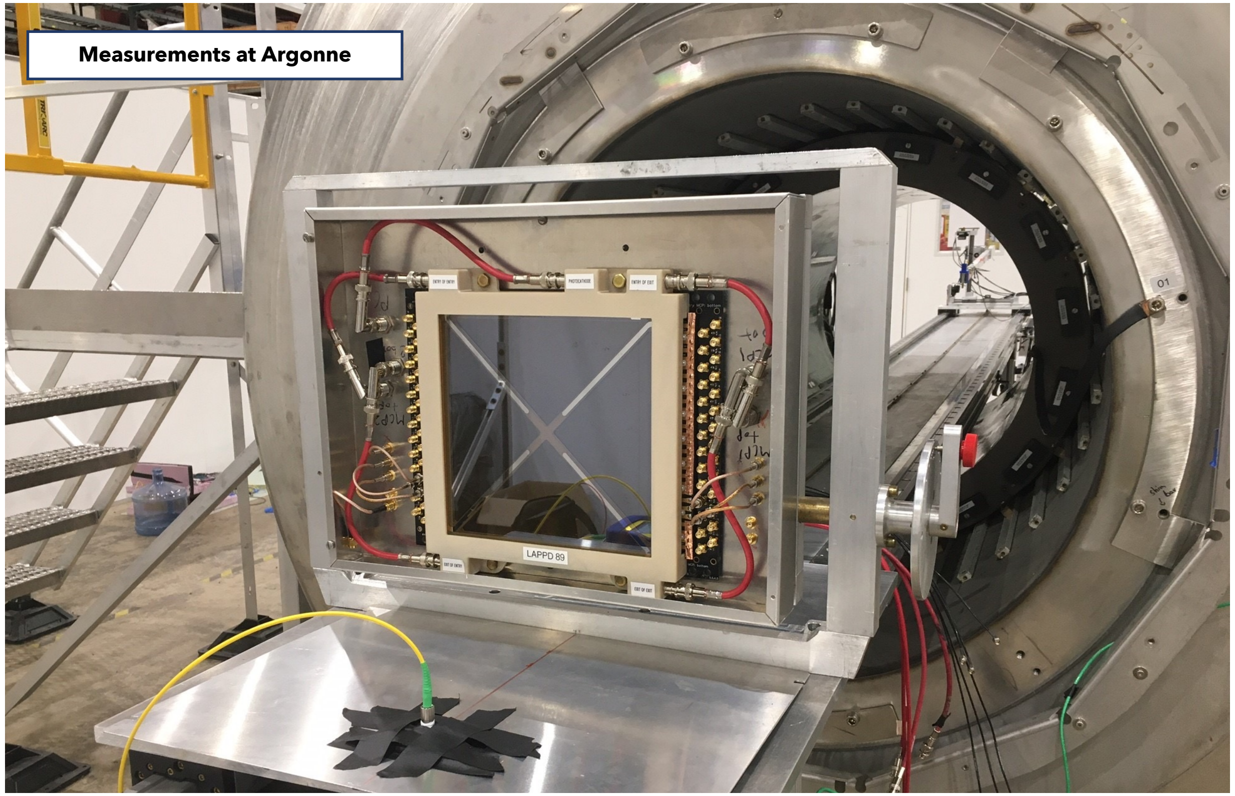
- Even that the HRPPD active area (the photocathode and the MCP stack) is much smaller than the tile footprint, the Cherenkov light cone spot in a 5 mm thick quartz window has a base of ~11 mm diameter
    - By making the edge area reflective (or perhaps just relying on a TIR) one should be able to gain timing performance over the whole surface, even though with a degraded resolution towards the tile edges, apparently

Magnetic field tolerance





Gen I LAPPD; magnetic field normal to the sensor surface

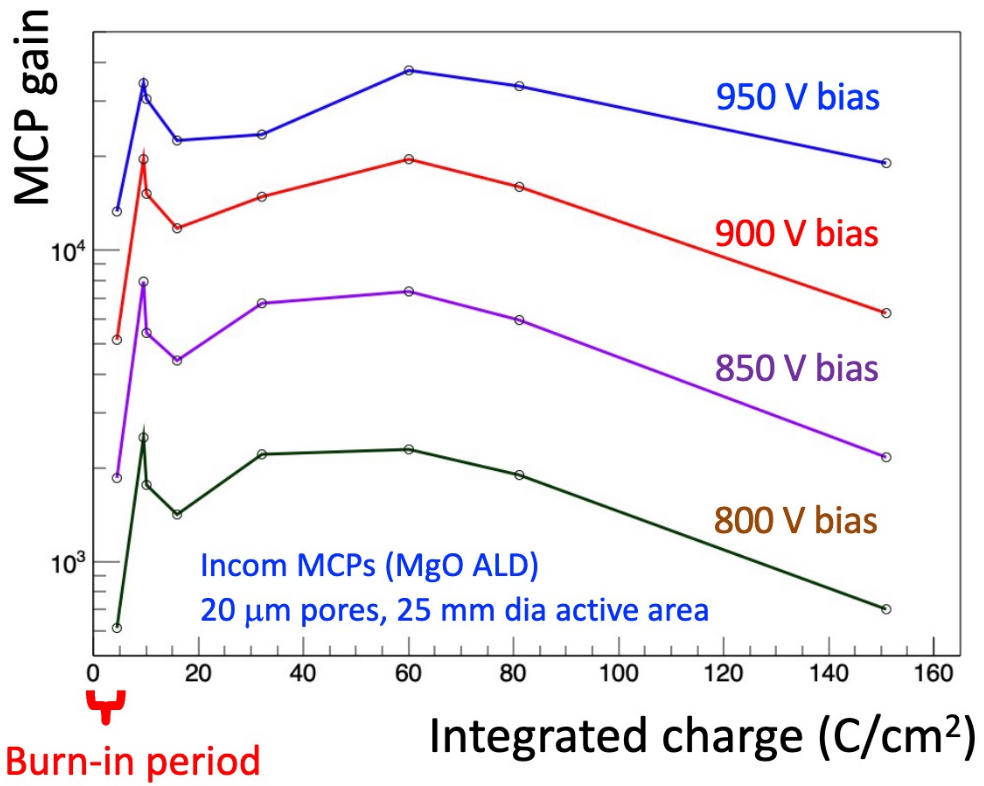


- LAPPD shows similar behavior trends as R&D MCP-PMT
  - Gain went down from over $2x10^7$ to ~$7x10^5$ as the field strength was increased from 0.02 T to ~0.9 T.
- At a field strength of 1.39 T, the gain was recovered to $6x10^6$ by significantly increasing the MCP voltages.

Need to verify up to ~2T and at (reasonable) non-zero angles

Radiation hardness

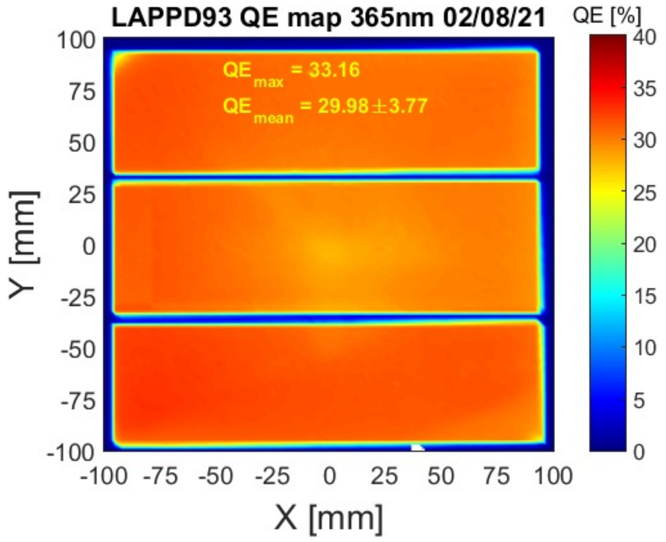
- MCP gain degradation

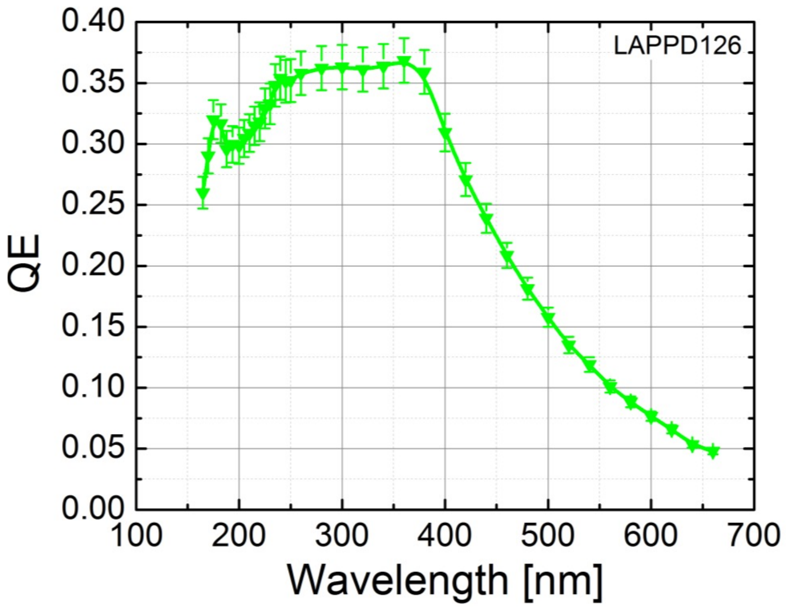


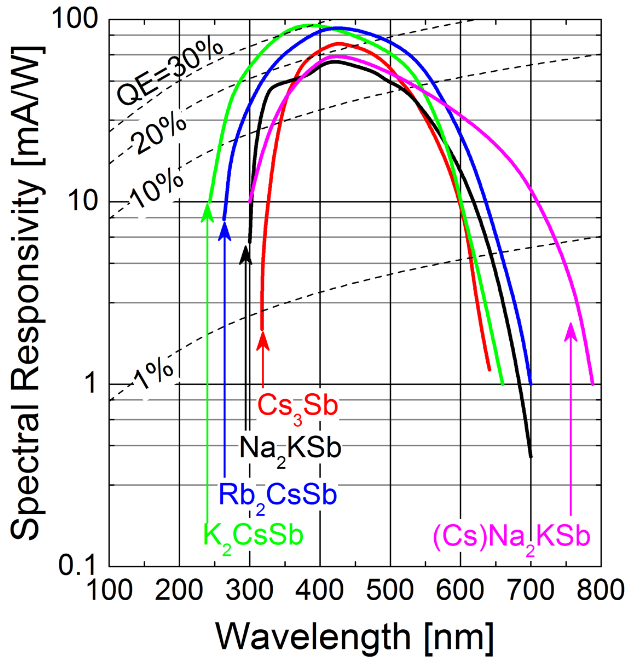
data by V. Vagnoni (INFN Bologna)

- Photocathode degradation requires further studies, but lifetimes of up to several C/cm^2 expected
- Talk by V. Chirayath on Wednesday
- Surprisingly enough, in mRICH / pfRICH we may reach ~C/cm^2 at η ~ -3
- May want to give up idea of using UV grade quartz window
- Yet another argument for using preamps

Quantum Efficiency & PDE







- QE is high enough, but peaked at ~300 nm
- As such, the wavelength range is not optimized for aerogel
- Besides this, the actual PDE was not yet measured

This is a concern, but Incom is making an effort to fix the problem for EIC (see SBIR topics)

- 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

Cost

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) →

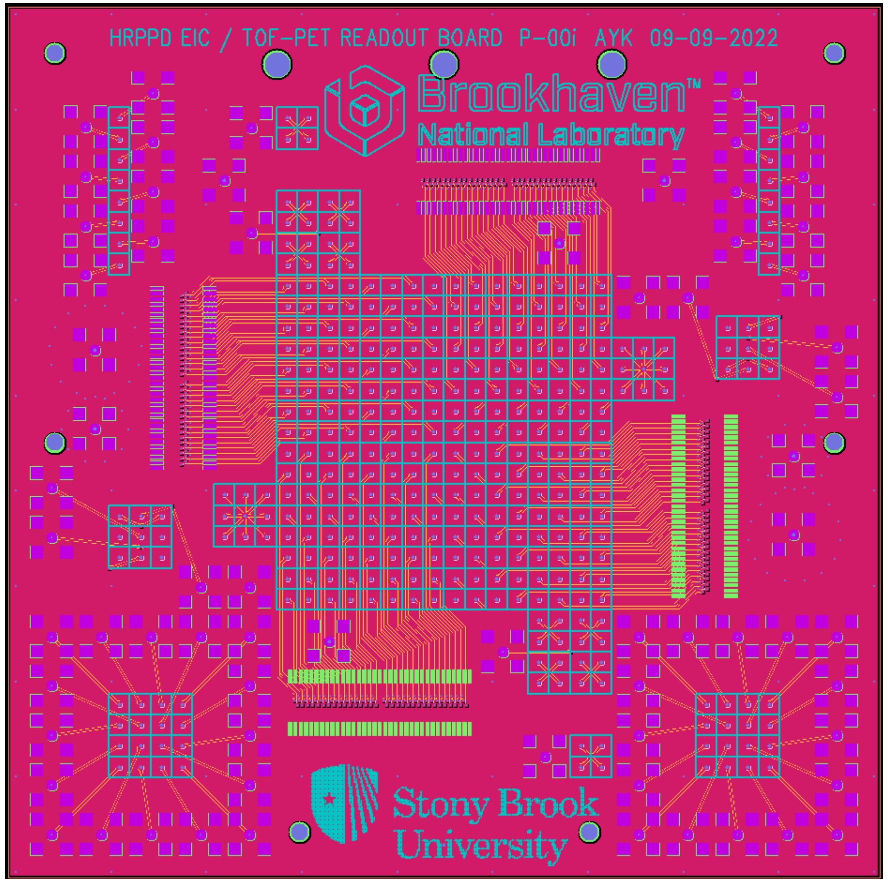
- **$30,000 to $20,000**
- **$78/cm² to $52/cm² for LAPPD**

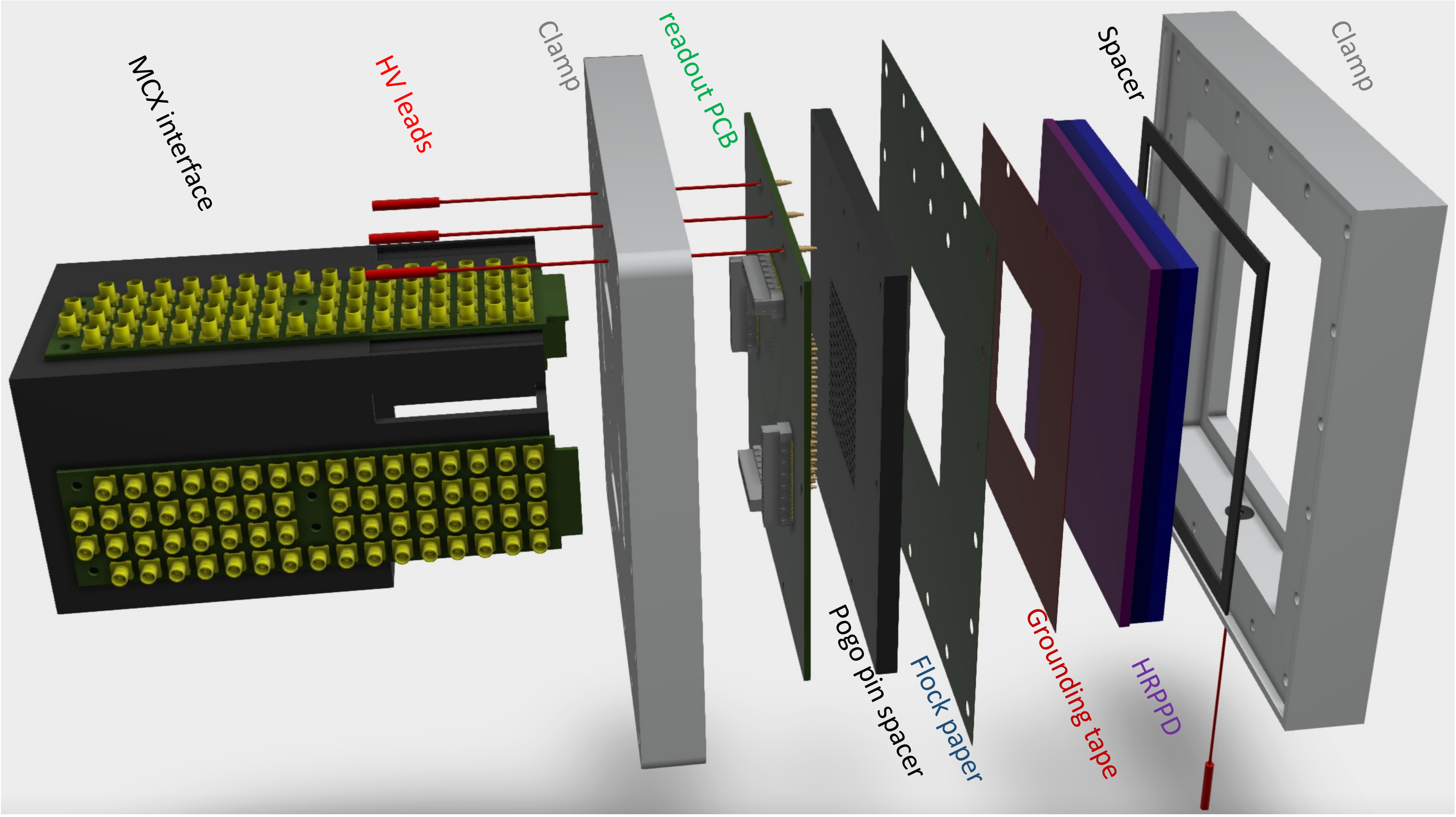
High-volume manufacture (Funded Scale-up)→

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

Source: presentation for EIC by C. Hamel 09/26/2022

DC-coupled HRPPD evaluation

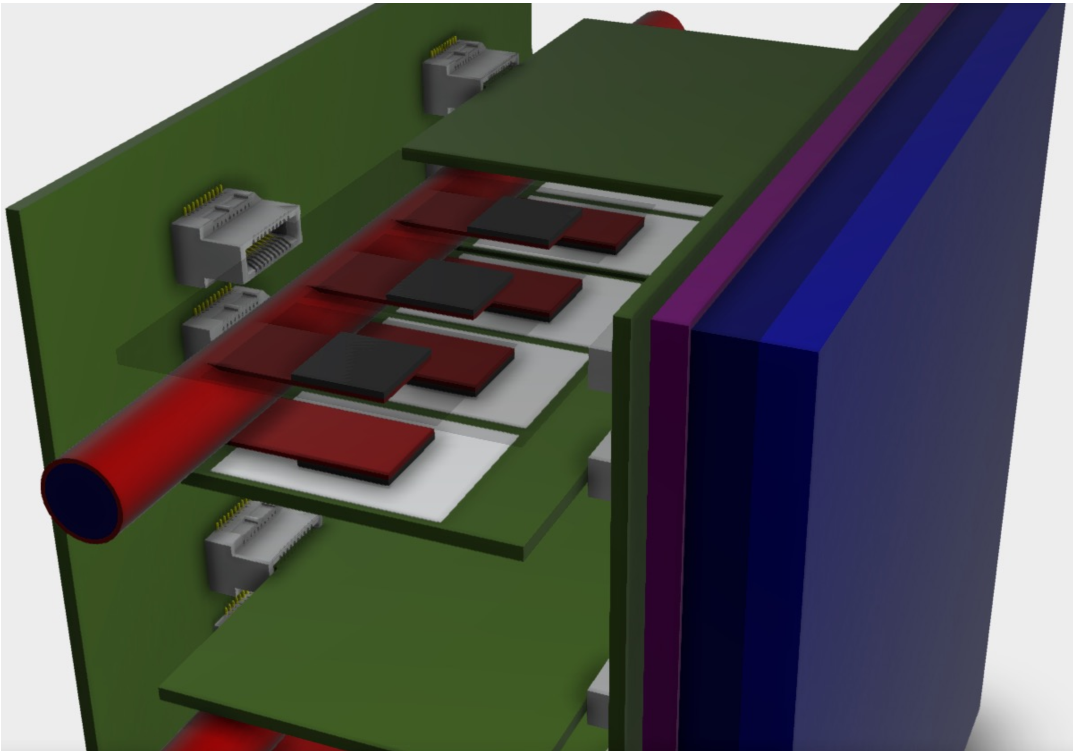


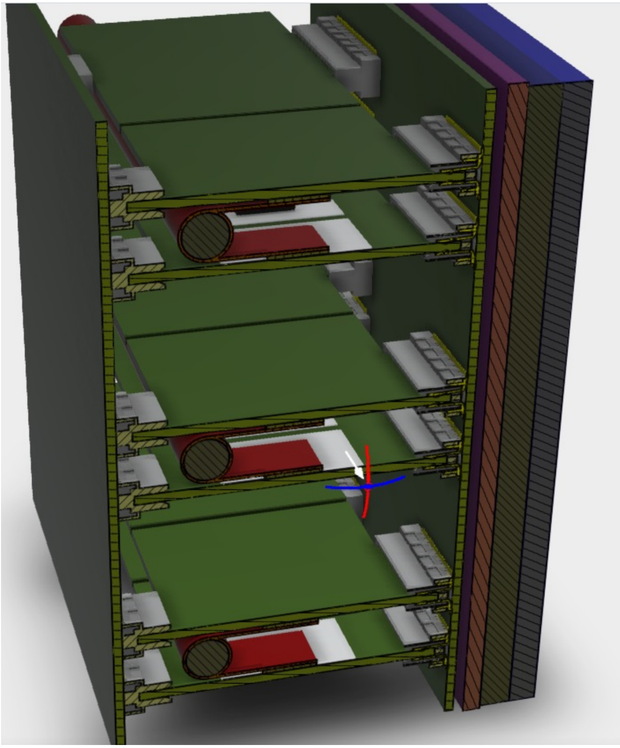


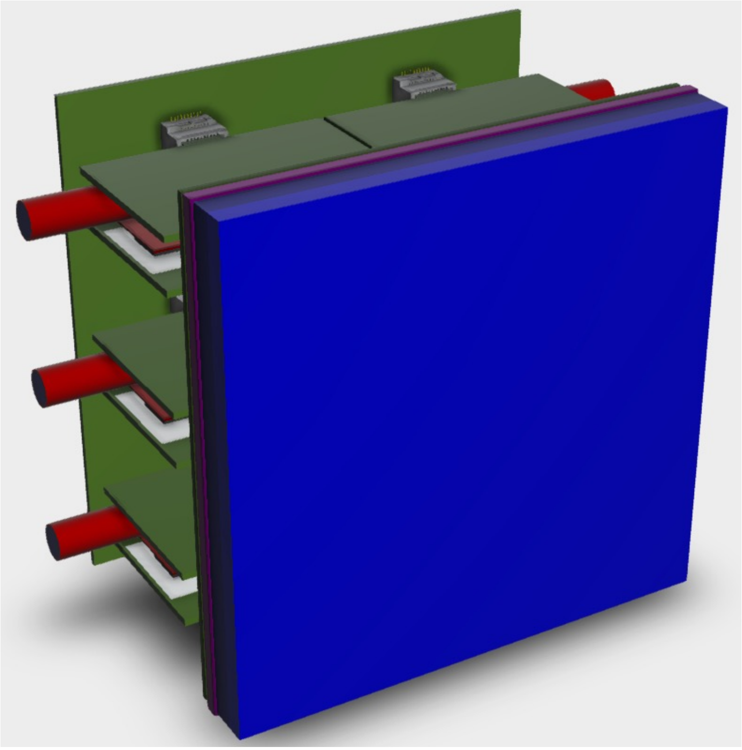
- Readout boards are ordered **(shipped to BNL already)**
- Parts are being machined and 3D printed **(to be ready first half of November)**
- The “final” integration design (LGA or ZIF sockets, dead area minimization) will require more work

Backup

Integration, electronics, etc.







- Assume 24x24 HRPPD pixellation suffices (~4.2mm pads) -> 576 pixels per 12x12 cm^2 footprint
- A hybrid of Nalu Scientific UDC and AARDVARC v4 chips assumed as a "reference ASIC"
  - 16-channel ASICs (would be better to have 32- or 64-channel ones, of course)
  - ~10GS/s digitizer, ~2GHz ABW, feature extraction, streaming capability (whatever it means), etc.
  - 0dB buffer amplifier (12 mW/ch) available in ARRDVARC V4 -> need a similar solution for a ~20dB preamp
  - Few kW of power dissipation for the whole pfRICH-like system seems to be a real-life estimate

LAPPD tuning for EIC purposes

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.

eRD110: FY23 R&D plan & proposed milestones

Task	Details	Timeline
LAPPD / HRPPD characterization in the magnetic field	At least one state of the art Gen II and one DC-coupled tile, as pre-selected by the spatial and timing resolution studies; gain dependency on the field-to-normal angle and feasibility of gain recovery by the HV settings tuning	September 2023
DC-coupled HRPPD interface feasibility study	Limitations of the DC-coupled interface in terms of the tile footprint increase, and pad density per cm^2 unless using custom low insertion force sockets	May 2023
Report on a simultaneous spatial and timing performance optimization for a selected subset of Gen II and DC-coupled tiles	Cluster size, spatial and timing single photon resolution evaluation for pixel sizes anticipated for ePIC mRICH/pfRICH and DIRC detectors	September 2023
Report on a “routine” Q&A characterization of a selected subset of tiles	Gain and QE uniformity	September 2023

eRD110: open R&D questions before CD-3

- In brief, we need to come up with a detailed assessment of the current state of the art and projected LAPPD photosensor performance, evaluate their potential use in various EIC PID detector subsystems, and assist Incom in modifying their existing product line to meet EIC requirements
  - Spatial resolution for Cherenkov imaging applications in a variety of fine pixellation schemes
  - Timing resolution in a single photon mode, for a selected subset of pixellation scenarios
  - Timing resolution for Time-of-Flight purposes
  - Performance in a strong (inhomogeneous) magnetic field

  - QE spectrum tuning and evaluation for ePIC detectors
  - Overall PDE and gain uniformity tuning and measurement
  - Geometric formfactor optimization

  - Prospects of integration in particular ePIC detector subsystems (together with the respective groups and / or consortia), as well as the on-board electronics integration (together with eRD109 and ASIC manufacturer candidates)