HRPPD Photosensors for HEP and NP

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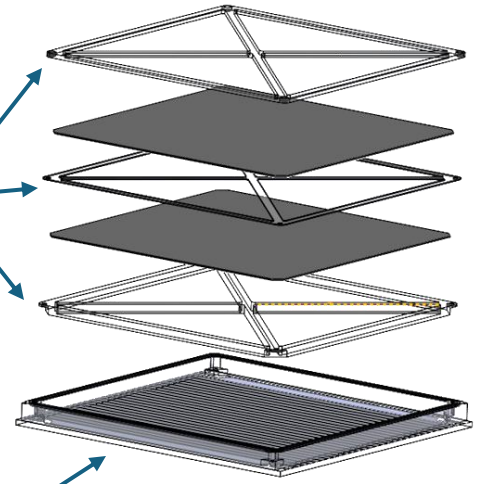
Outline

- HRPPD Features
- Mechanics
- Basic performance Specs
- QE Studies
- Single Photon Detection Efficiency
- Timing Studies
- Performance in Magnetic Field
- Initial Results from CERN beam test
- Summary

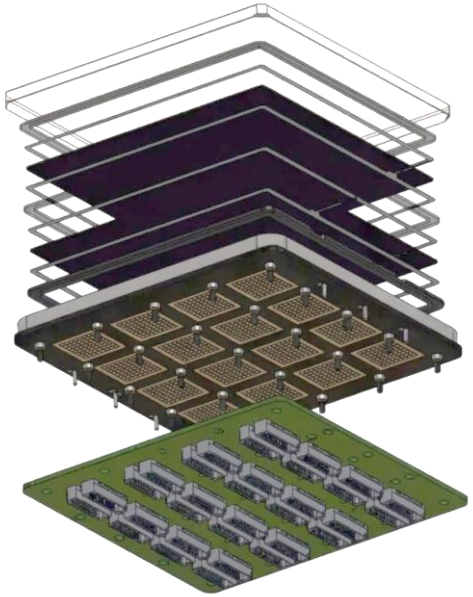
HRPPD Lineage

- **H**ight **R**ate **P**icosecond **P**hoto-**D**etectors (HRPPDs) are the latest microchannel-based vacuum photomultiplier tubes developed by Incom, Inc. in MA, USA
- Based on the earlier, ~general-purpose, **L**arge **A**rea **P**icosecond **P**hoto-**D**etector (LAPPD), which feature a large active area (195mm x 195mm), “standard yield" MCP pore diameters (20μm), and the use of window supporting ribs in the acceptance (91% geom. eff.)
- “EIC-HRPPDs” are designed specifically **for high rate capability and Tesla-scale magnetic field tolerance** at the Electron Ion Collider (EIC) at BNL with an active area: 104mm x 104mm (75% geom. eff.)



- DC-coupled strip-line readout
- **Or** AC-coupled to readout pads w/ Resistive layer anode

LAPPD
220mm x 230mm x 22mm



HRPPD
120mm x 120mm x 13.5mm

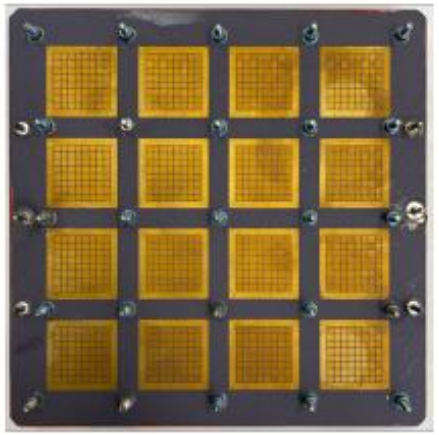
New Design Features of HRPPD

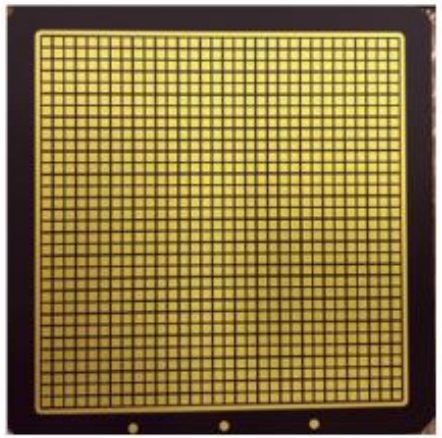
- Tesla-scale B-field tolerant MCPs
- Specialized ALD treatment
  - Functionalized emission layer → high gain
  - Resistive layer → high rate
- DC-coupled pixel array
  - Fewer parasitic effects
  - Avoid charge pileup and baseline shifts
- **Clear aperture** without supporting ribs and a robust casing design
- Smaller size → Greater detector tile-ability

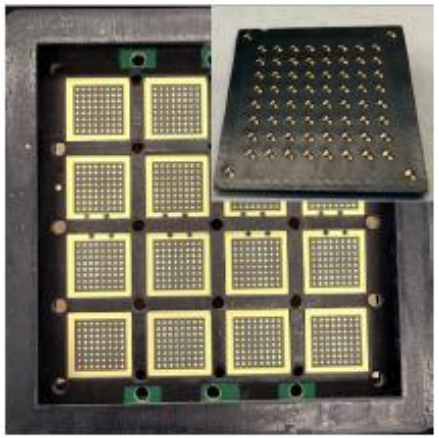
EIC-HRPPD Assembly

Fused Silica Window

Ceramic R/O Plate
signal pads







32 x 32 pad array
(3.25mm pitch)

Intermediate Readout PCB
(w/ compression interposer contact)

HRPPD Stack-up

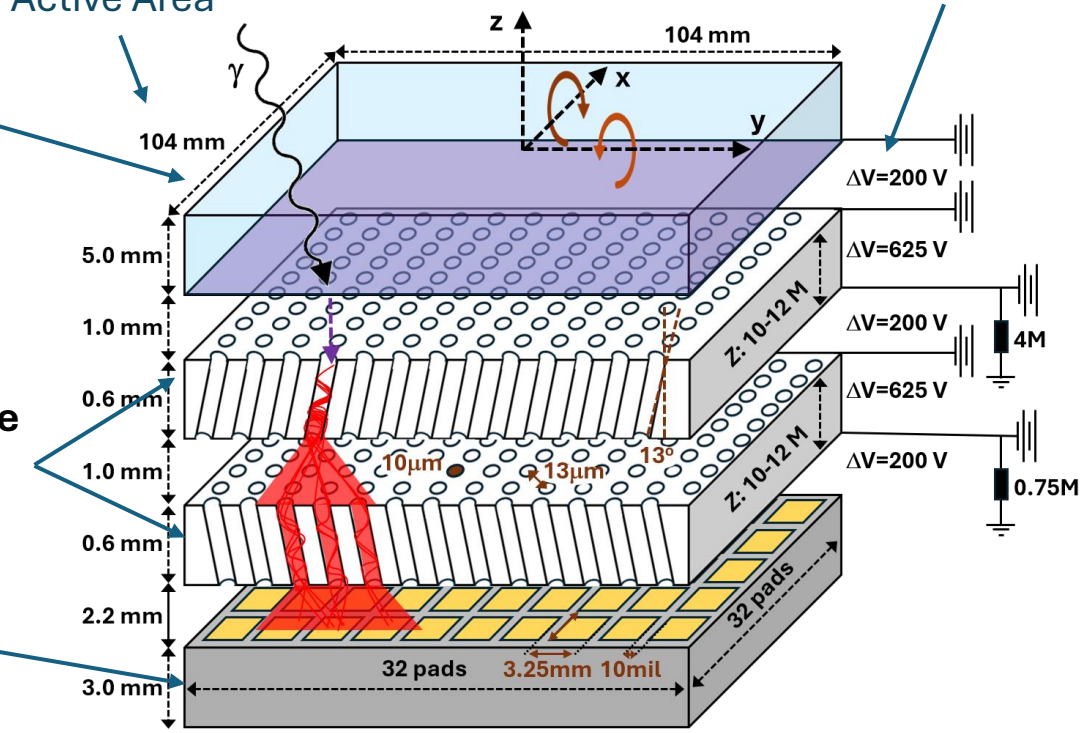
Typ. applied potentials

Active Area

Semi-transparent multi-alkali photocathode on a quartz window

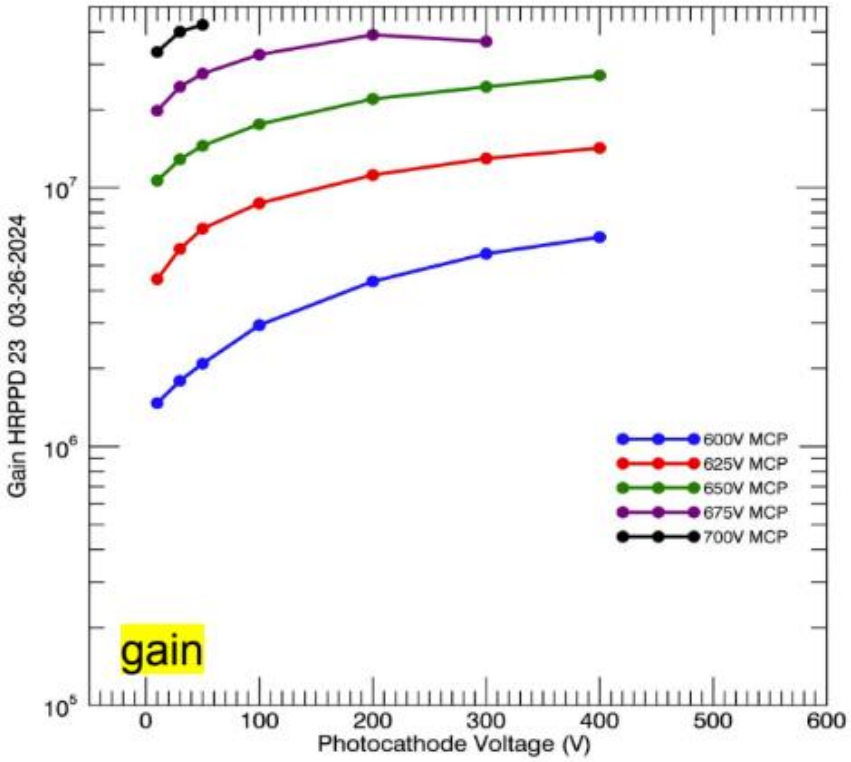
Micro-channel plate Gain stages

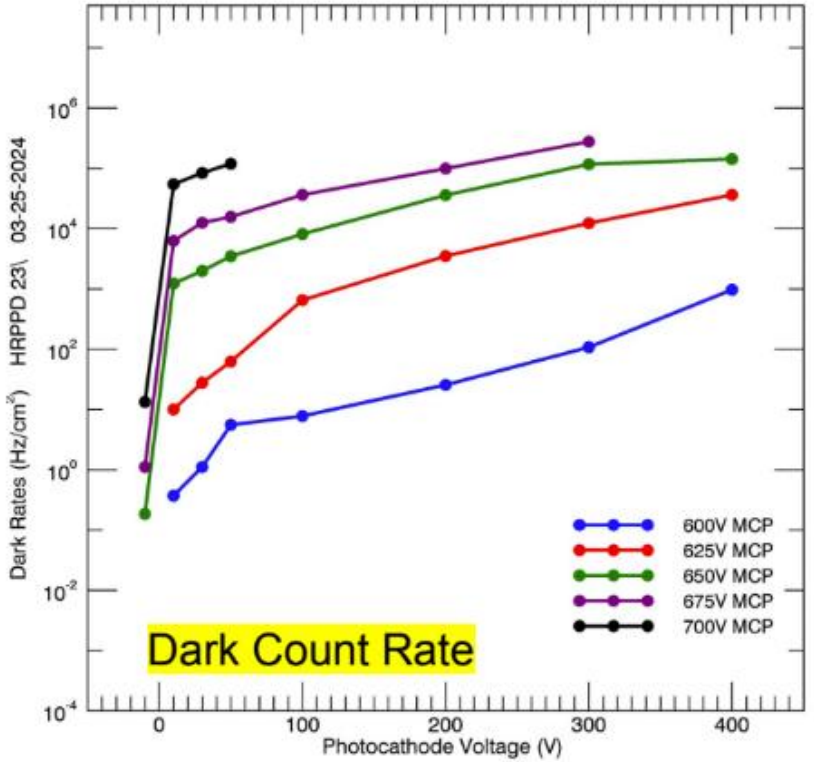
Hi-Temp Co-fired Ceramic R/O plate

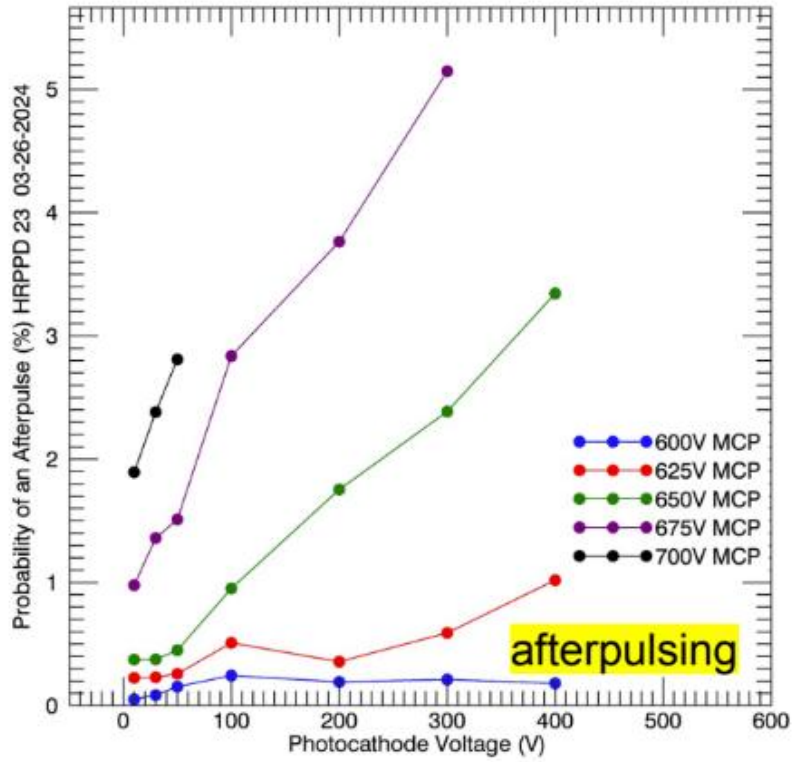


- MCPs: chevron config. (13°), 10 μm pore diam.
- Narrower inter-electrode gaps

Incom Test Report : DCR, Gain, Afterpulsing







- Newly developed ALD process allows for high gain at remarkably low bias voltage
- HRPPD #23: dark rates at mid-10^6 gain are below 1 kHz/cm^2, with afterpulsing on at the ~1% level

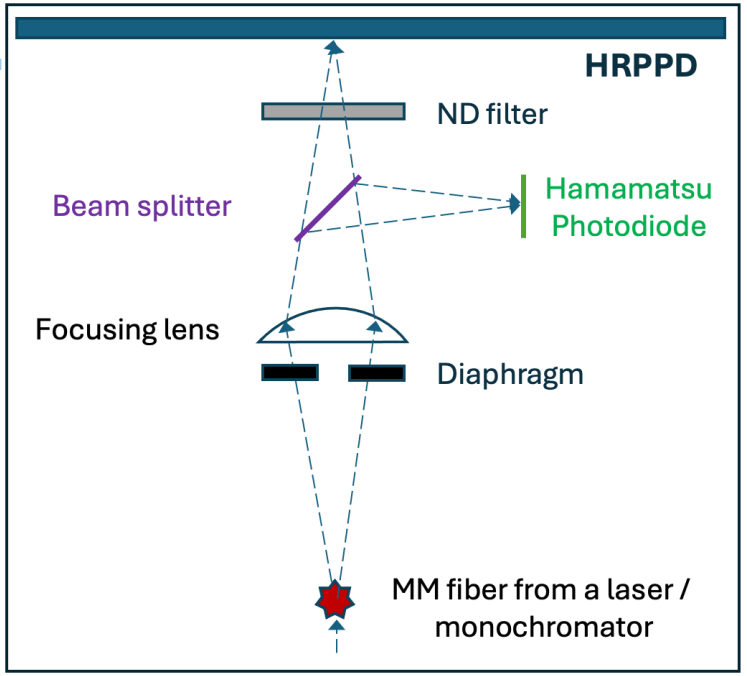
HRPPD QA at BNL

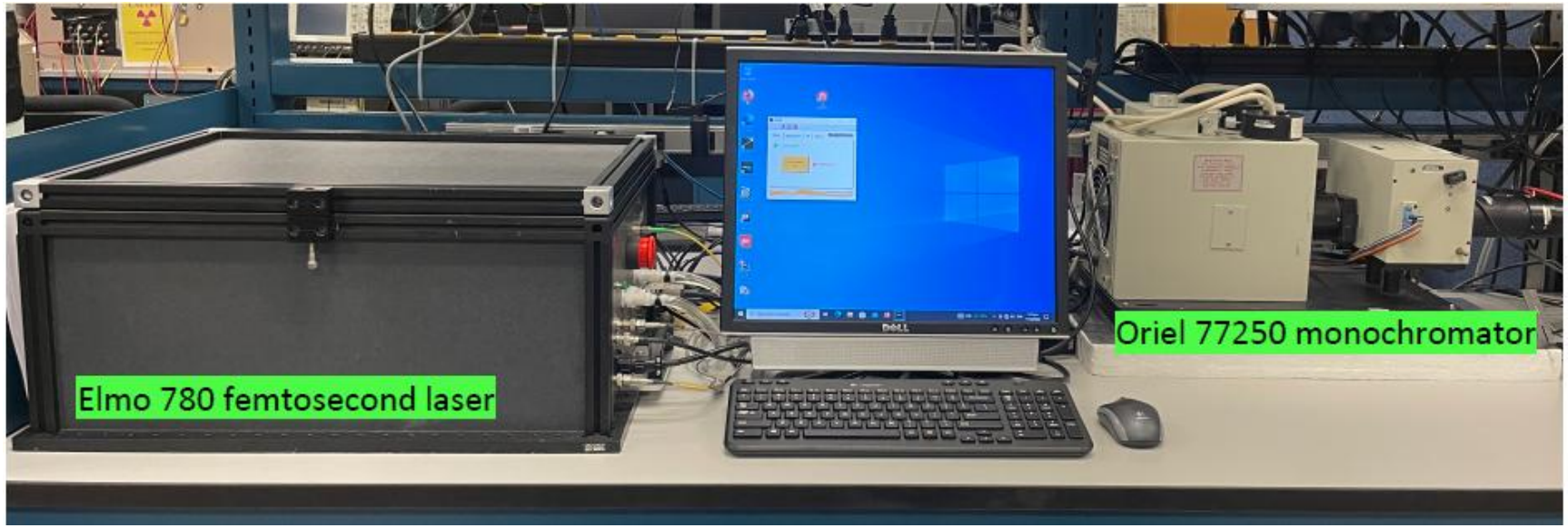
Initial test batch of HRPPDs from Incom: 10 produced, 7 evaluated

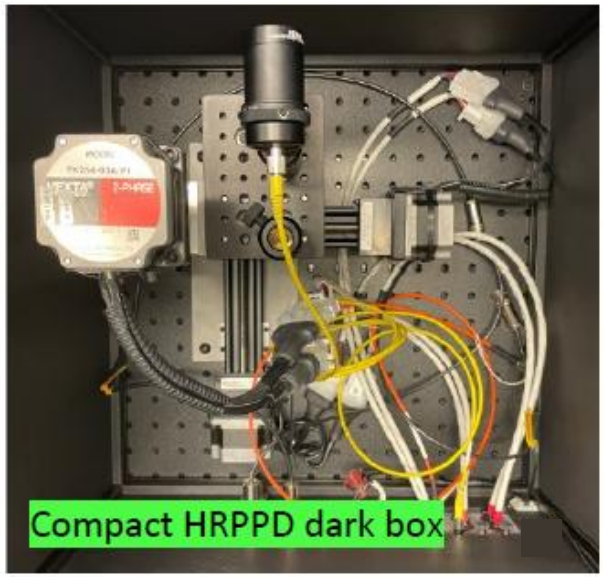
- ➢ Demonstrate production capability and reproducibility of key performance parameters
- • Gain, QE, Photon Detection Efficiency (PDE), Dark Count rates (DCR), timing res.
- • QA test stands at BNL, JLAB, INFN Trieste, Glasgow, and Yale

BNL

- • Dark box with 6” travel Velmex translation stages
- • PiLas (picosecond) and Elmo (femtosecond) lasers
- • Oriel monochromator (fiber coupled)
- • 50 GS/s Tektronix scope (8 GHz bandwidth)
- • CAEN V1742 digitizers (5 GS/s)
- • DAQ PC, NIM & VME crates

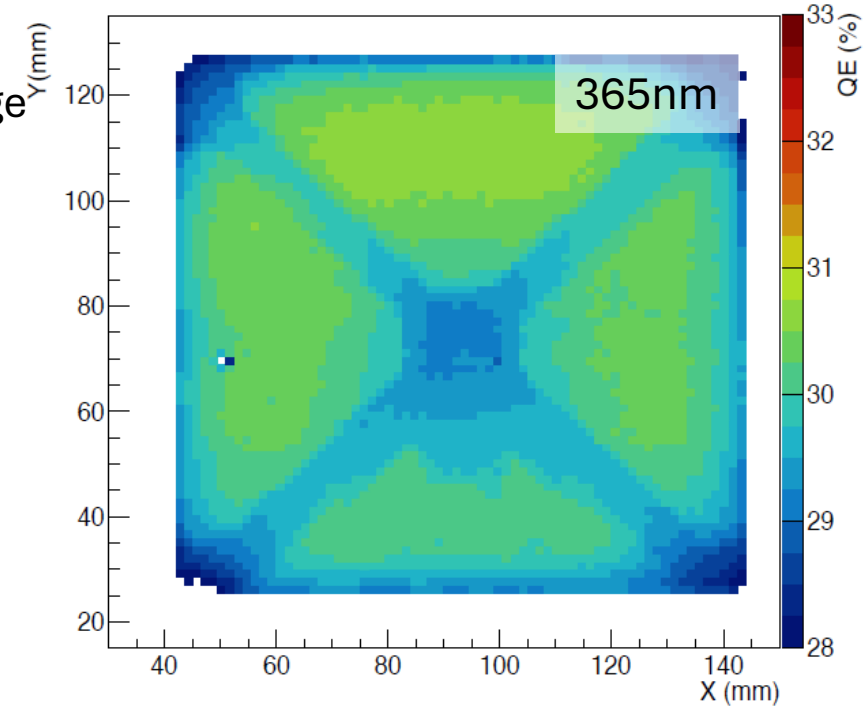




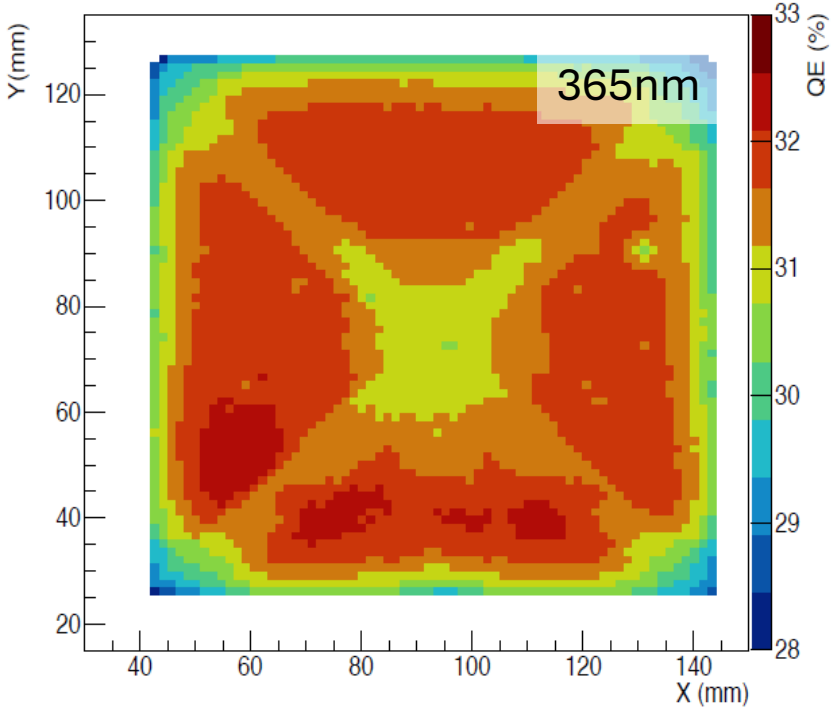


QE Uniformity Scans

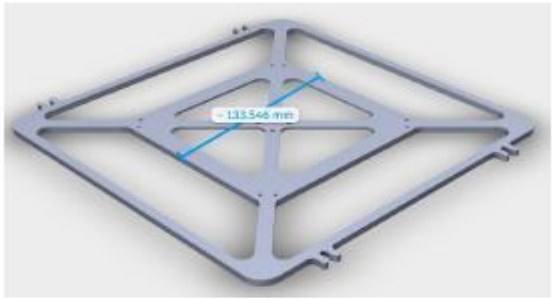
- QE uniformity at 365nm within a range of a few % (RMS) with peak value typically exceeding 30%
- X-shape is an optical artifact related to window handling during assembly in vacuum using support structure
- Artifact will be absent from new HRPPD batches, which should substantially improve the uniformity
- The wavelength dependence exhibits 33% peaks at 365nm and 255nm
- 1 tile showed markedly degraded QE (25% @ 365nm)



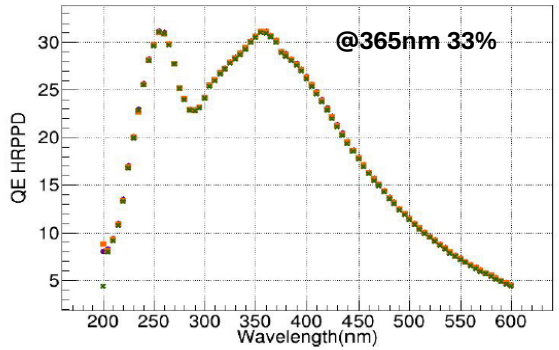
HRPPD 15 (sealing tank #2)



HRPPD 16 (sealing tank #2)



Window support used during assembly



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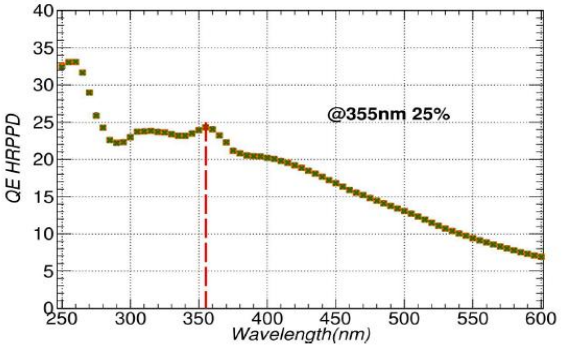
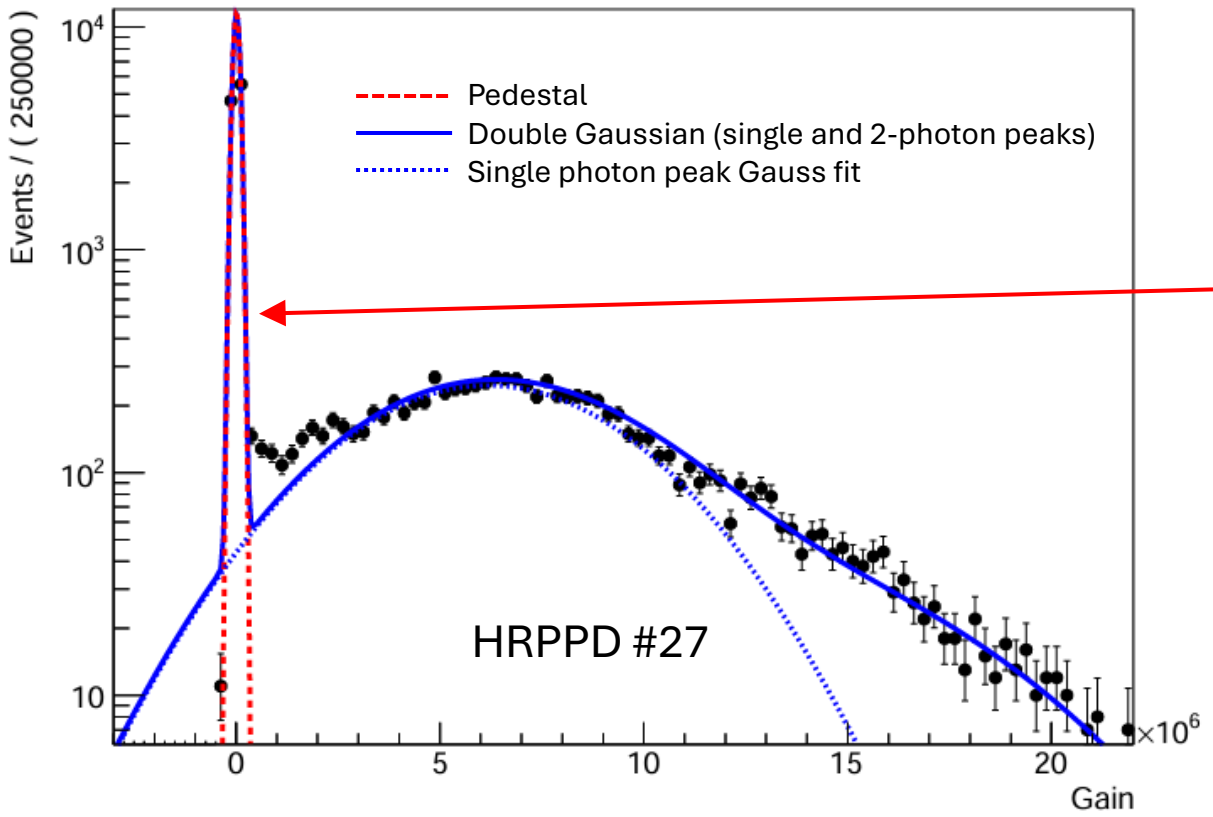


HRPPD 23 (sealing tank #1)

Photon Detection Efficiency (PDE)

- A zero-counting method was adopted in contrast to a traditional spectral fit method to avoid relatively large systematics associated with the fit



$$P(\text{no signal}) = \sum_{n=0}^{\infty} P(n)(1-p)^n$$

where $P(n) = \frac{\lambda^n e^{-\lambda}}{n!}$.

$$P(\text{no signal}) = \sum_{n=0}^{\infty} \frac{(\lambda(1-p))^n e^{-\lambda}}{n!} = e^{\lambda(1-p)} \times e^{-\lambda} = e^{-\lambda p}$$

$$PDE \sim p = \frac{ln(P(\text{no signal}))}{-\lambda}$$

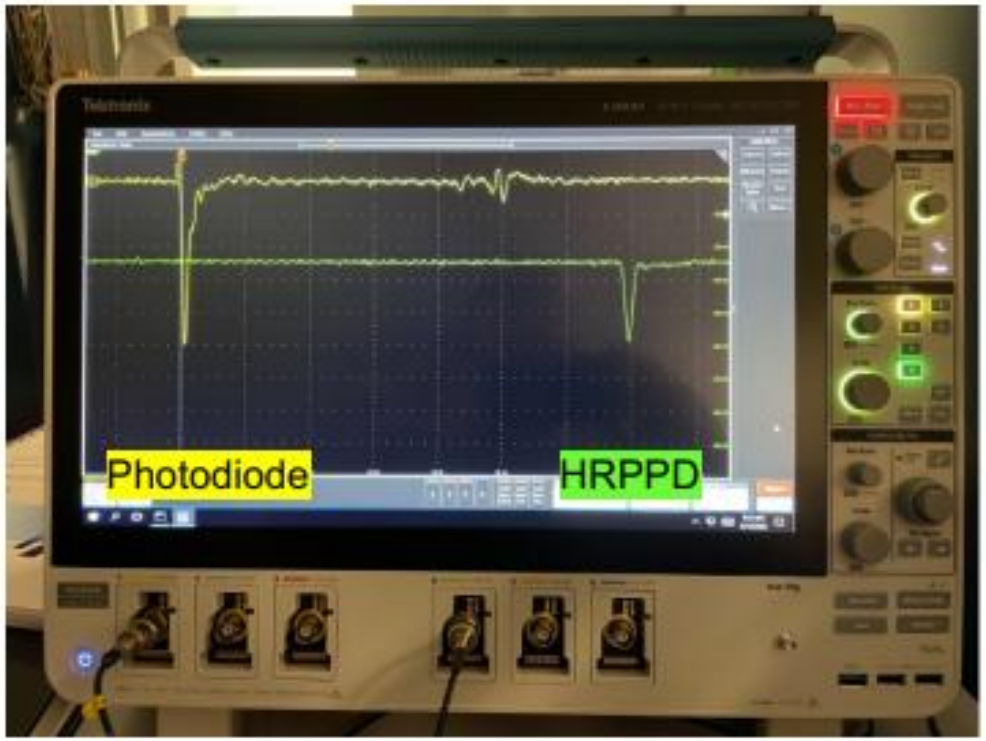
$$\lambda = \frac{I \cdot R}{e \cdot QE \cdot f \cdot A}$$

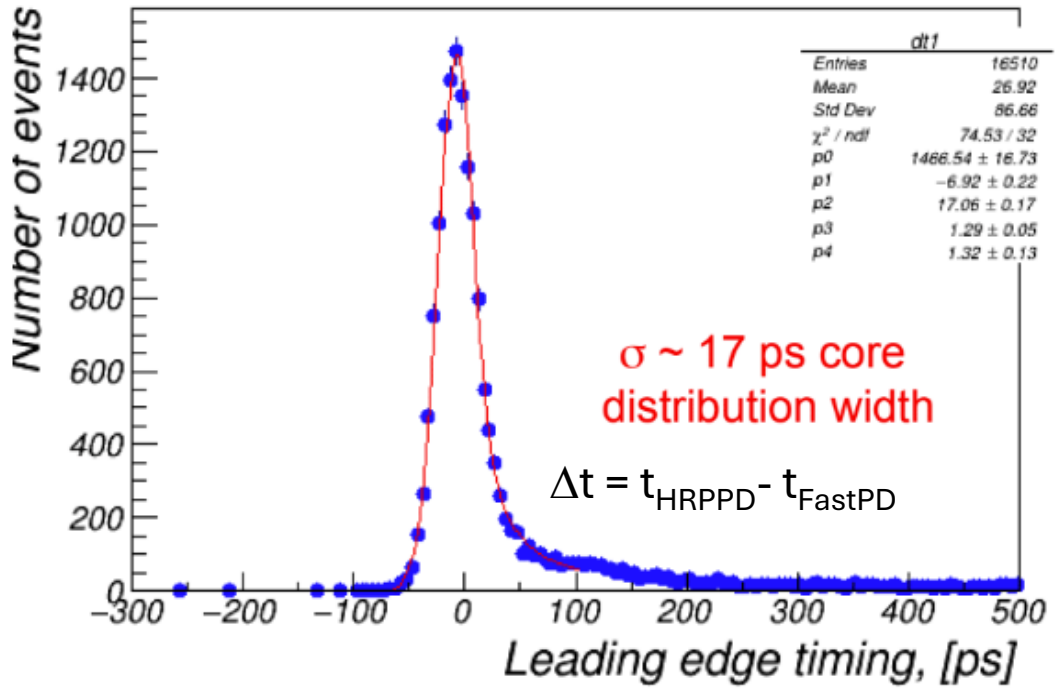
λ = mean number of photons/pulse
I = current measured by ref. PD
R = beam splitter ratio (trans./reflected)
e = elementary charge
QE = PC quantum eff.
f = laser rep. rate
A = ND filter attenuation

- Result: *PDE* = ***17.1*** ± 0.1 [stat] ± 0.3 [sys]%
- *PDE = QE*CE* (*CE* = HRPPD charge collection efficiency)
- *QE* for HRPPD 23 = *24.4% (low, outlier)*
- ***CE is better figure of merit***
- ***CE = 70.3% (Intrinsic to EIC HRPPD stack-up)***
- *Typical PDE = QE*CE = 30% * 70.3% = 21.1%*

Single Photon Timing Resolution

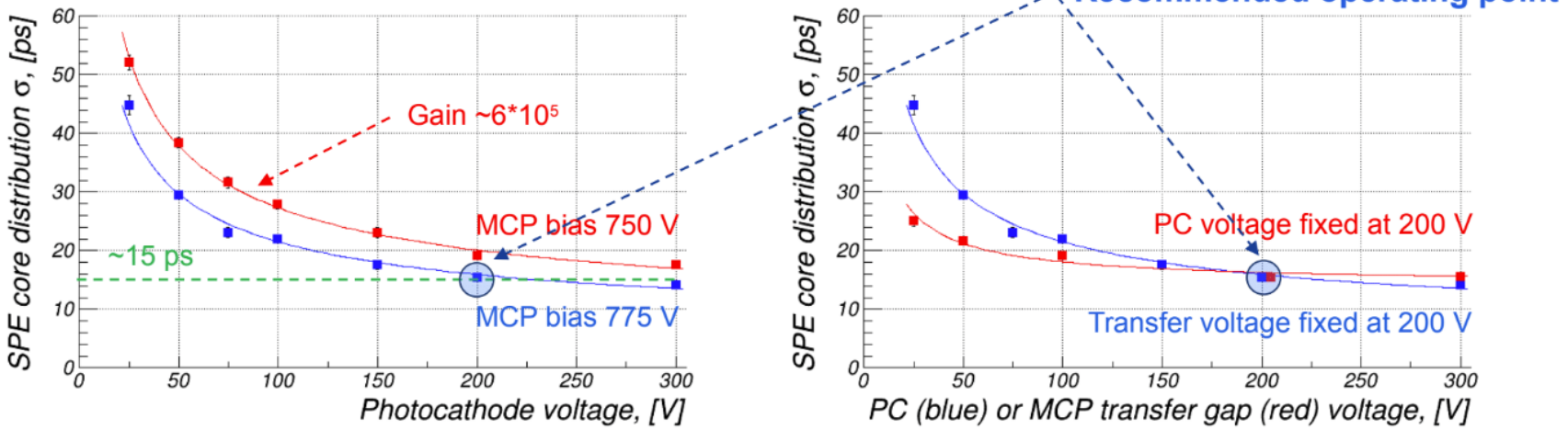
- **Femto-second laser** beam focused on a single HRPPD pad center
- Intensity tuned down to >90% empty events → SPE regime
- Fast IR photodiode signal used for triggering
- Signal waveform data taken with a Tektronix MSO66B scope (50 GS/s, 8 GHz BW)
- Leading edge fit; performed offline; timing estimate is independent of amplitude
- Δt spectrum: Crystal Ball fit of a Gaussian+tail in a range [-3σ.. +4σ] for all HV settings

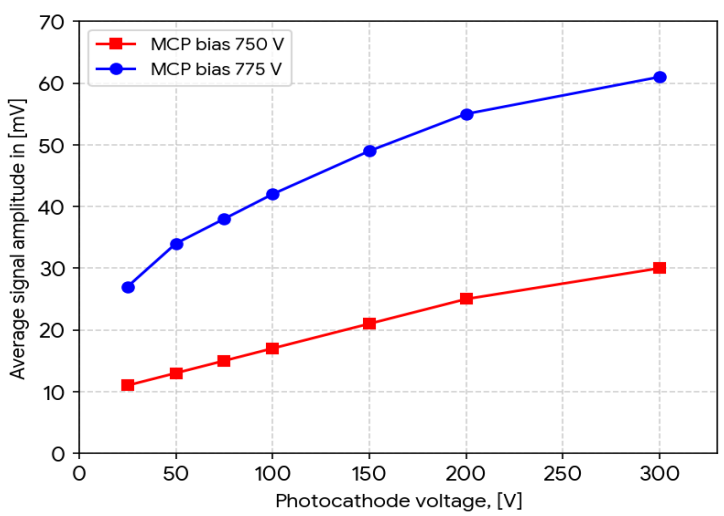


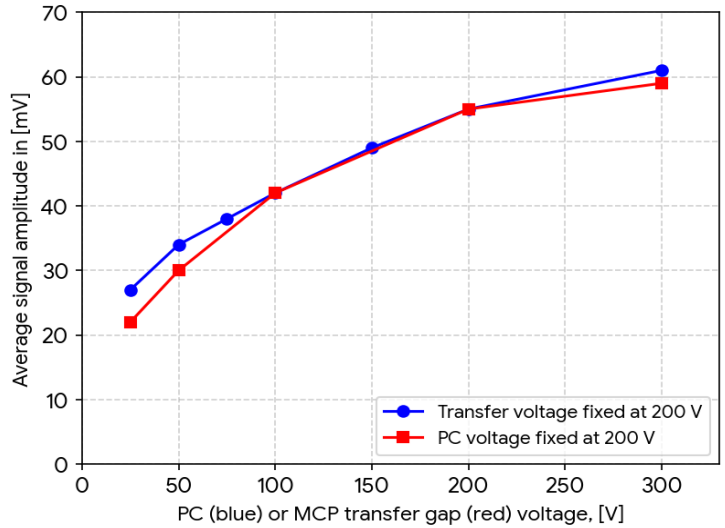


Single Photon Timing Resolution, cont…

- SPE timing resolution is <20 ps for nominal HRPPD HV settings (bias 775 V, PC & transfer 200 V)
  - Res. Depends on S/N, as expected (fcn of ASIC used, ie, oscilloscope)
- For Similar Gains, PhotoCathode voltage dependency present, beyond just varying S/N ratio (PC should be > 200V to preserve timing)
- Much less pronounced dependency on MCP1& MCP2 transfer voltage



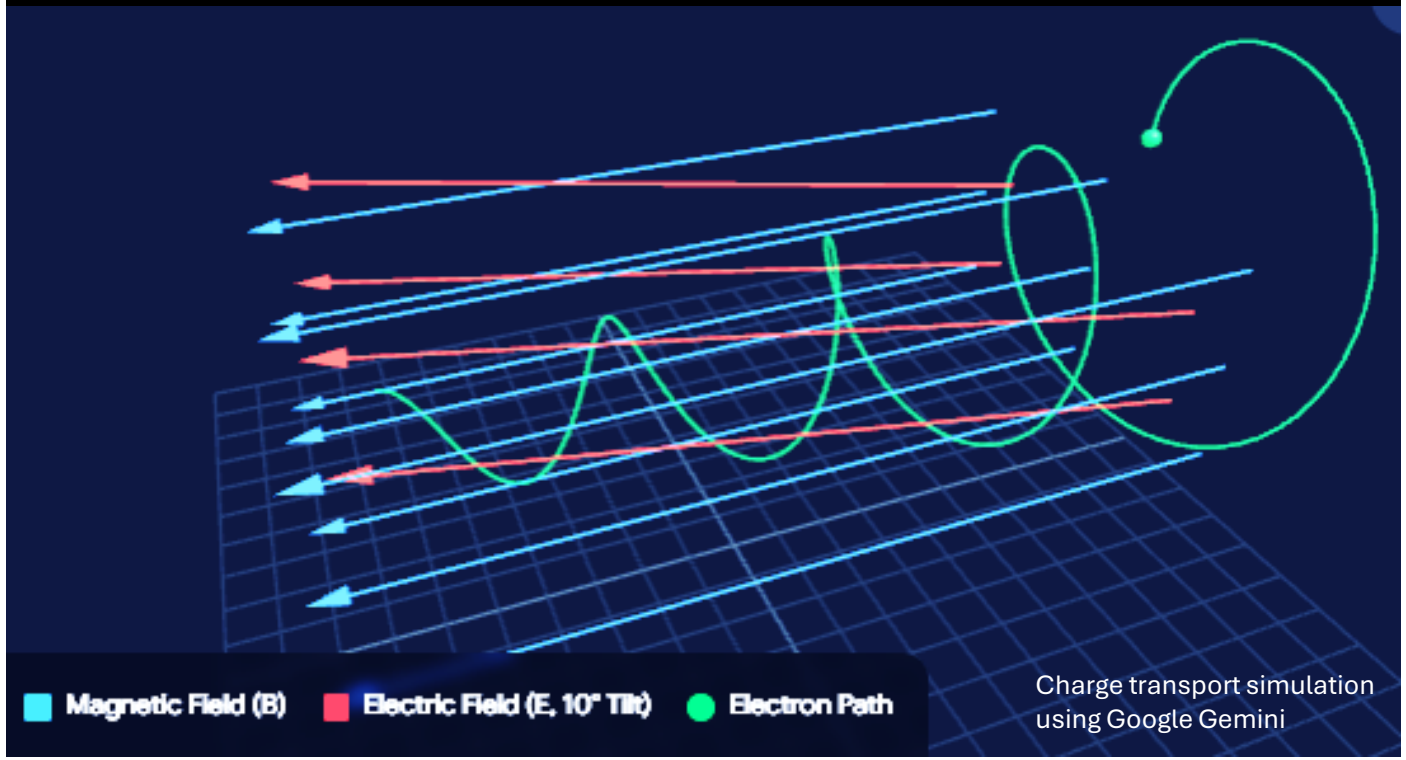




e- Motion in High Magnetic Field

- Transport of electrons in an MCP capillary experience:
  - Helical gyration
  - Parallel acceleration
  - E × B drift
- Resulting in:
  - Significant reductions in gain
  - Broadening of the transit time spread
  - Lateral displacement
  - Focusing effect on the charge cloud

Motion of an electron in non-parallel Tesla-scale B-field and E-field



The axis of the helical motion is aligned with the direction of the magnetic field

→ Fewer interactions with the capillary surface

→ Release of fewer secondaries

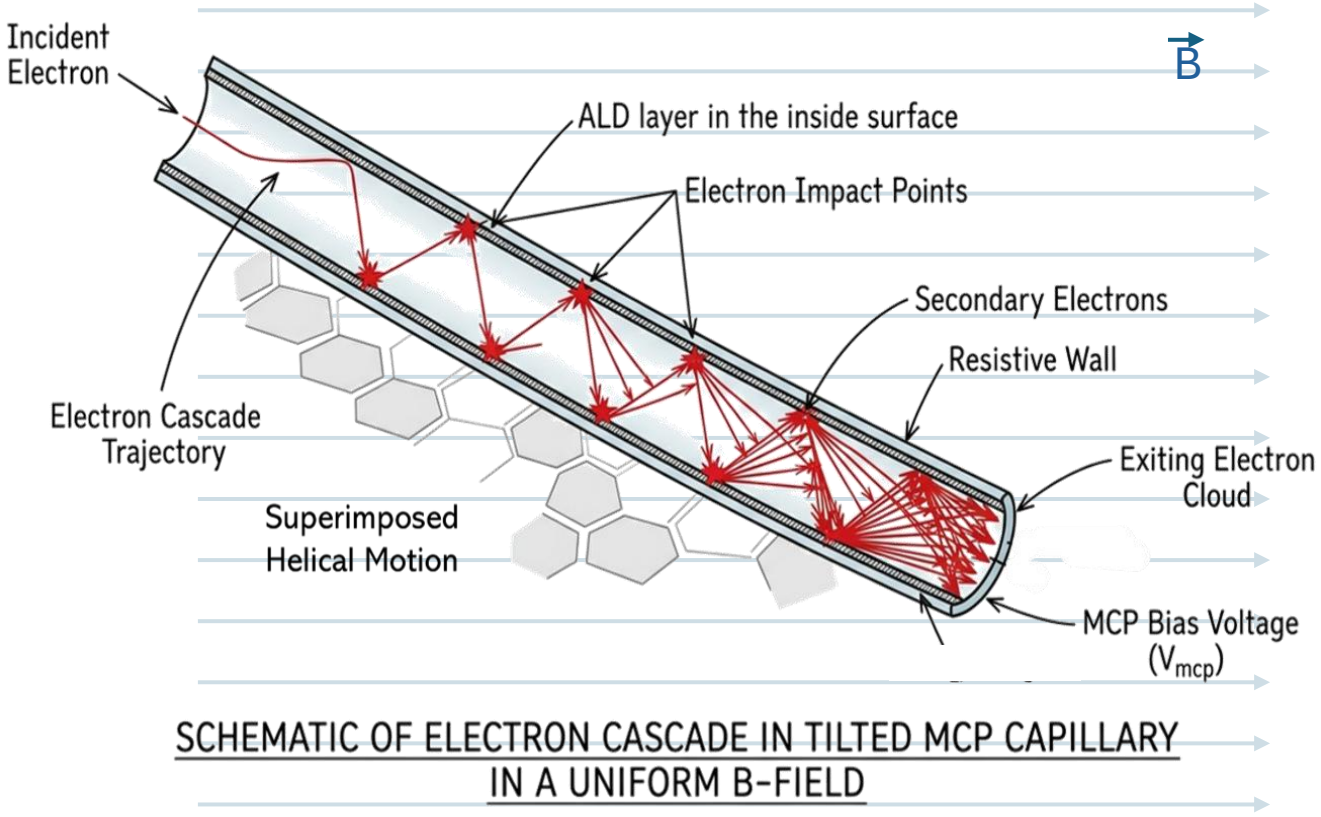
Features for Tesla-scale Tolerance

➢ **Smaller capillary pores**

- Improved probability for e- interaction with ALD surface (maintain gain)
- More constrained electron trajectories resulting in reduced transit time spread (improved timing res.)

➢ **Smaller transfer gaps**

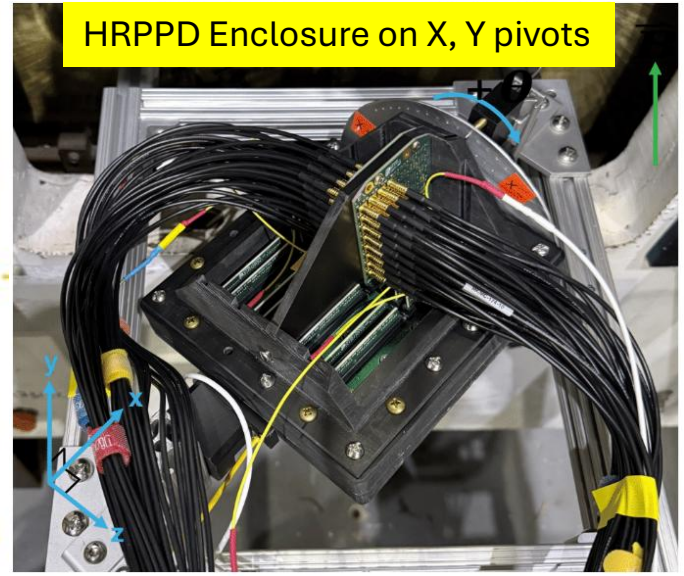
- Less susceptible to magnetic deflection (improved lateral displacement)
- Reduced transit time spread and charge cloud broadening

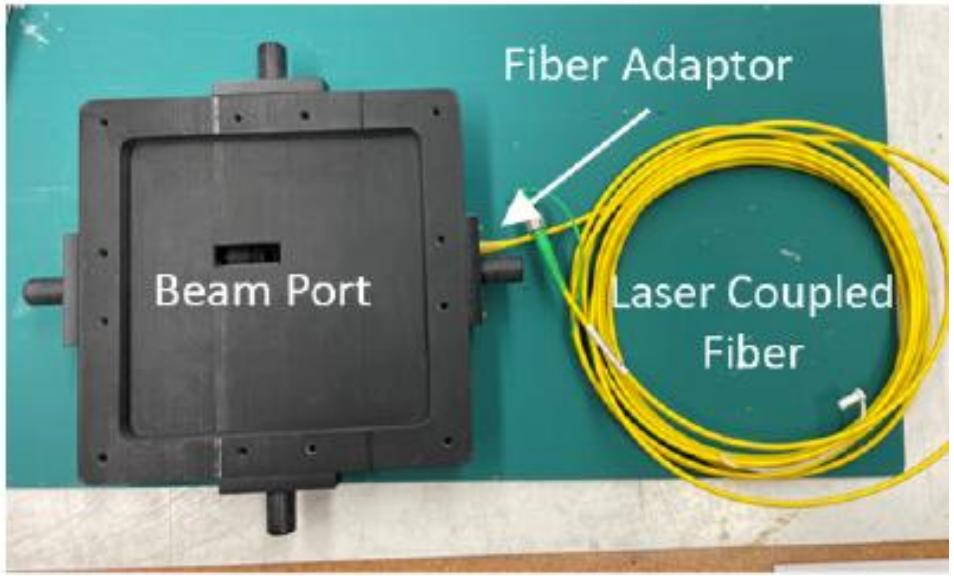


B-field Tests (BNL Superconducting Magnet Div.)

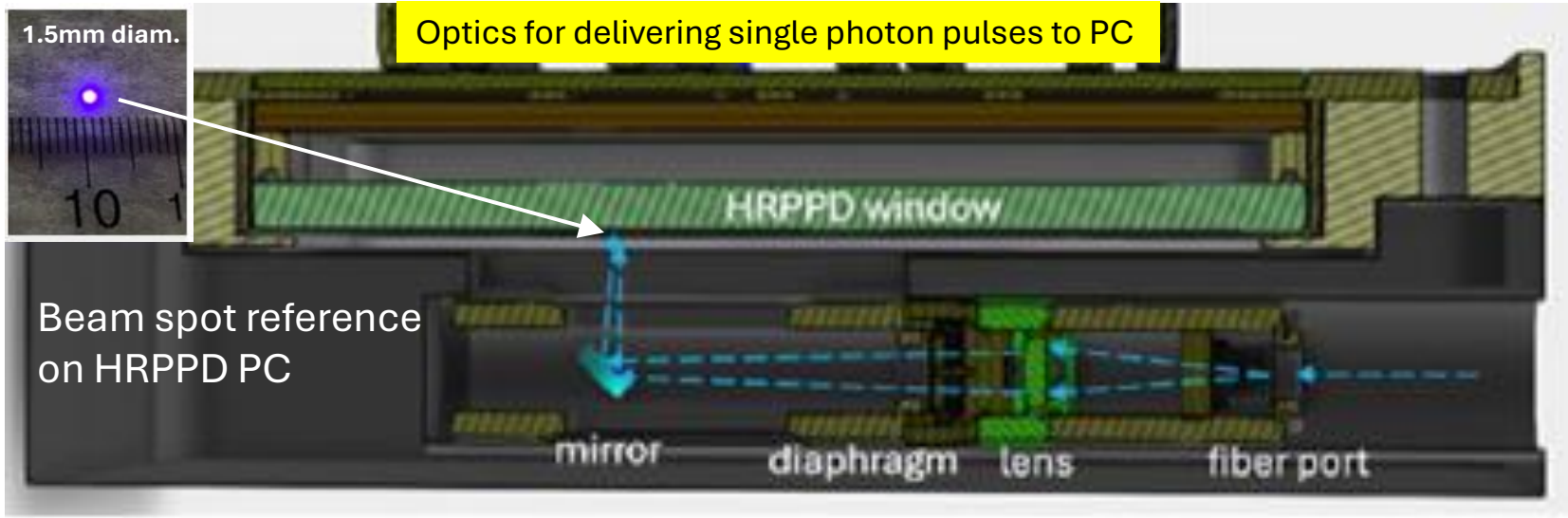
2T Dipole Warm Magnet (6” x 20” x 6’ bore)

HRPPD Enclosure on X, Y pivots



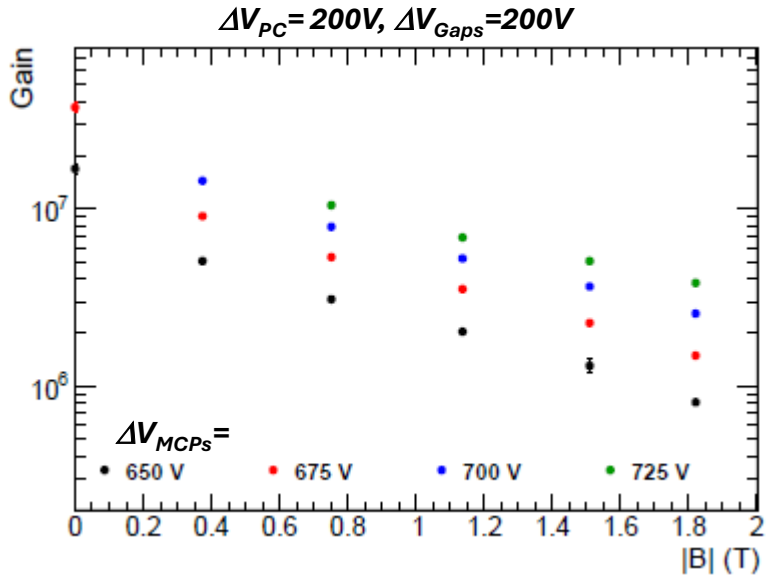


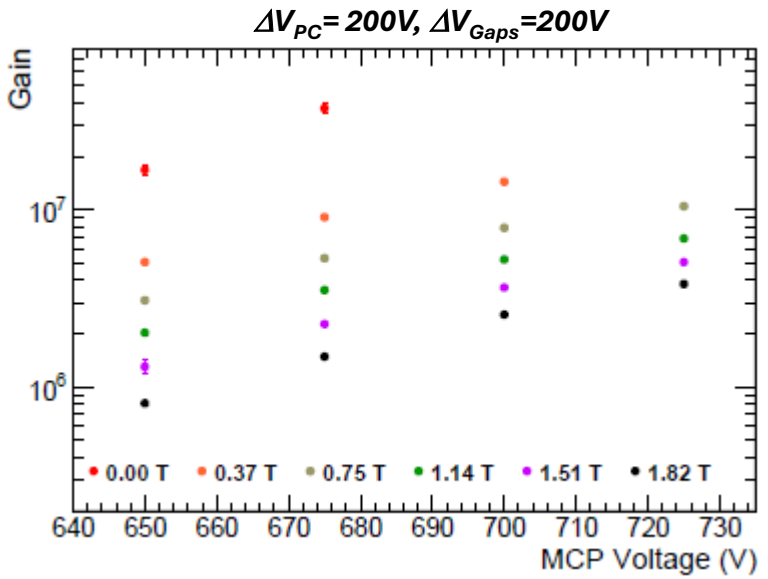
Optics for delivering single photon pulses to PC

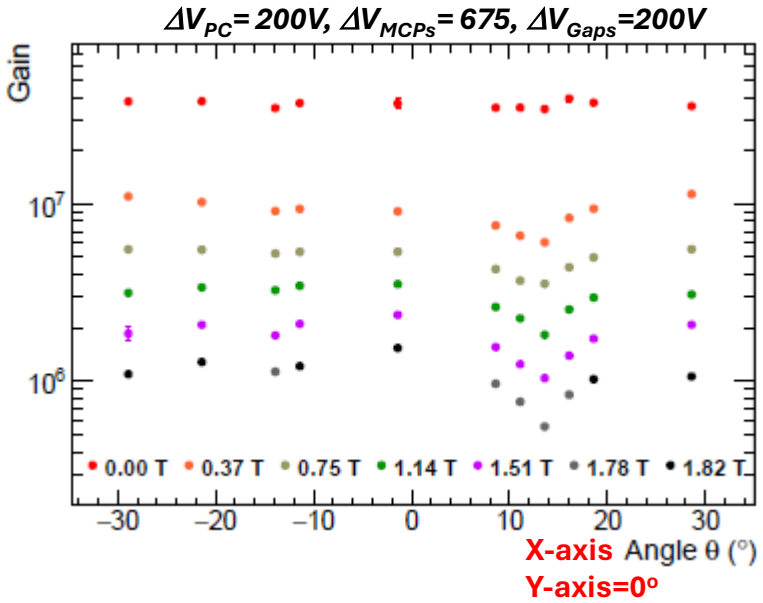


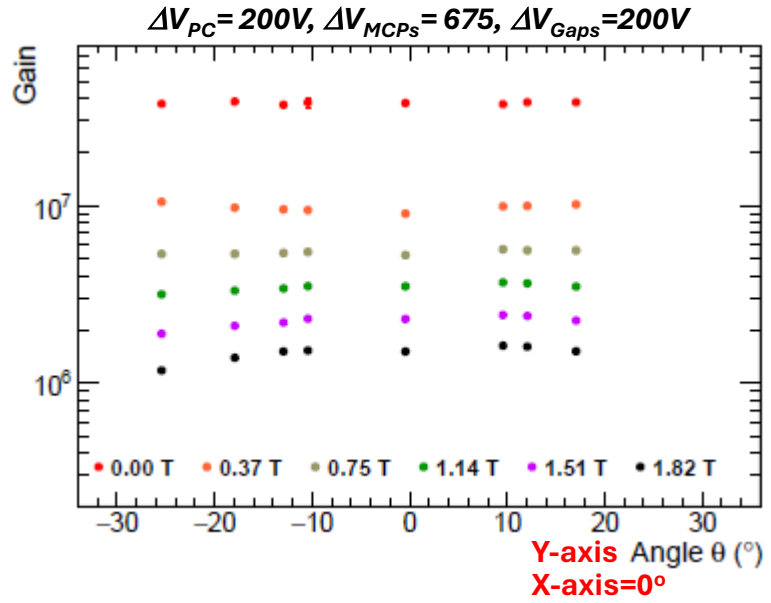
B-field Test Results

- Gain is inversely proportional to B-field strength
- Gain also depends on the angle between the MCP capillary axis and the B-field
- Dip at 13° due to almost full alignment of field with capillary axis of MCP 1 (*X-axis* rotation)
- Dip is not as apparent with *Y-axis* rotation since B-field only partially aligns with capillary axis
- **>10^6 gain can be fully and <u>stably</u> restored** by applying additional 10s of Volts across MCPs



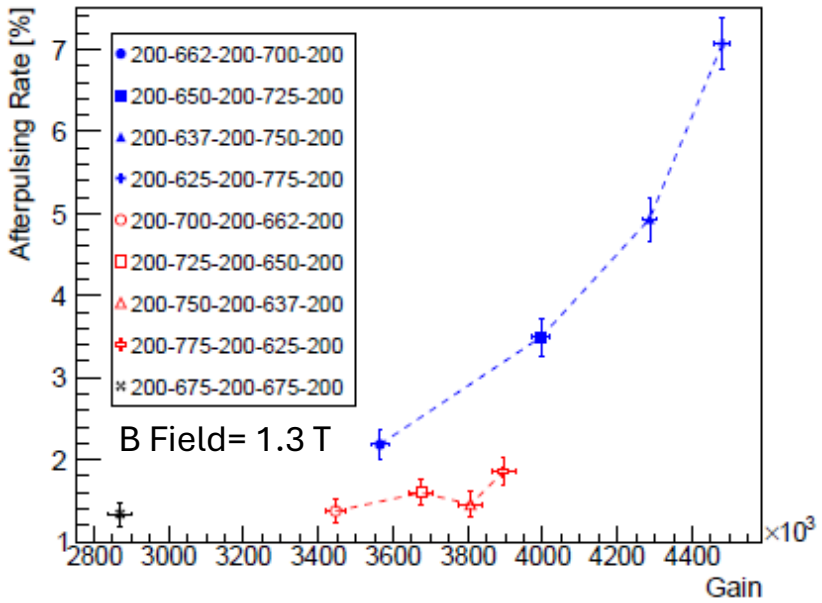






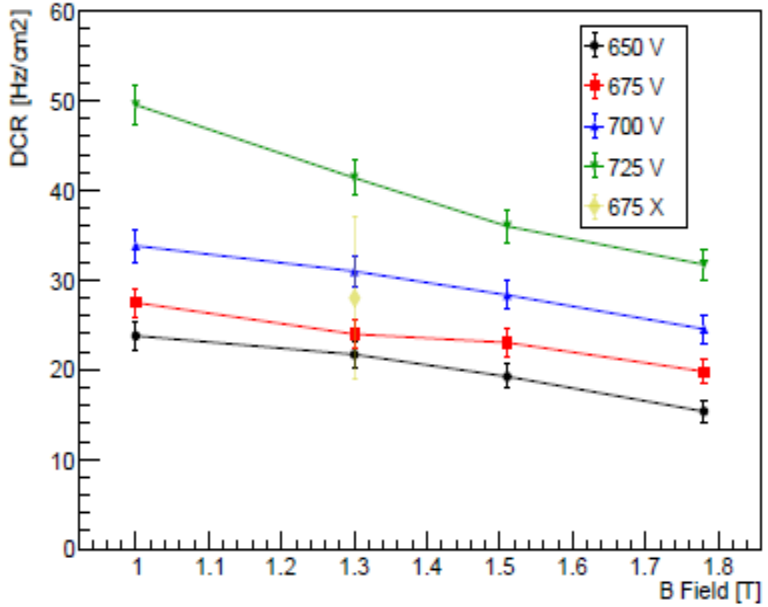
Rate Measurements in Tesla-scale fields

Afterpulsing Rate



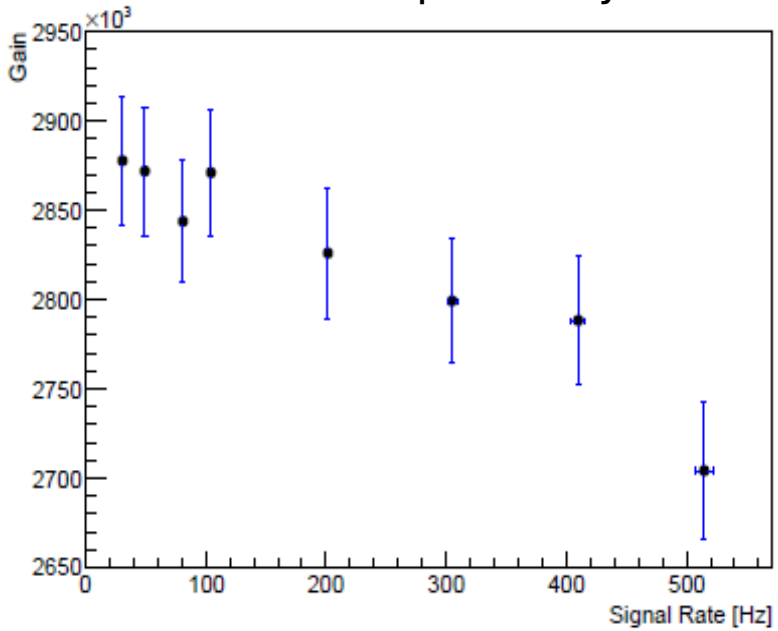
- Afterpulsing rate at nominal gain is at the few % level
- Gain of the MCP closest to the PC is mostly correlated to the after pulsing rate
- Latency is consistent with flight times of H^+ ions trapped in **top** MCP pores

Dark Count Rate (DCR)



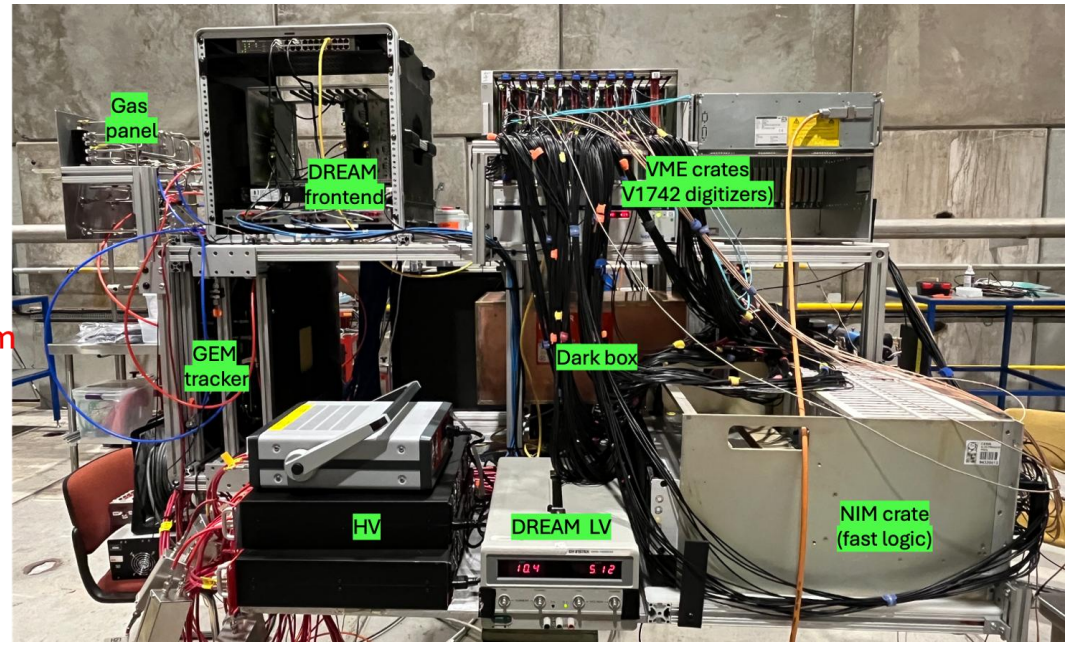
- DCR measured for one 3mm x 3mm pixel
- DCR drops with magnetic field strength/gain, as expected
- DCR at **tens of Hz/cm²** at nominal gains is consistent with Incom

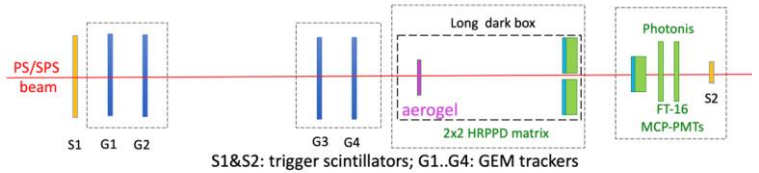
Rate Dependency

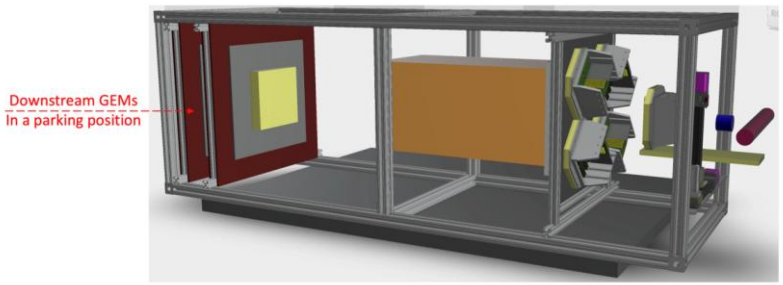


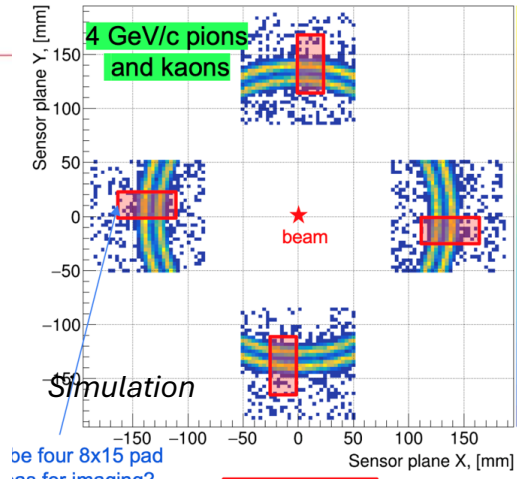
- Signal rate scan performed with 1.5mm beam spot
- Gain decreases monotonically as the rate increases, **indicating a saturation effect**
- The effect is only a few % for over an order magnitude change in rate

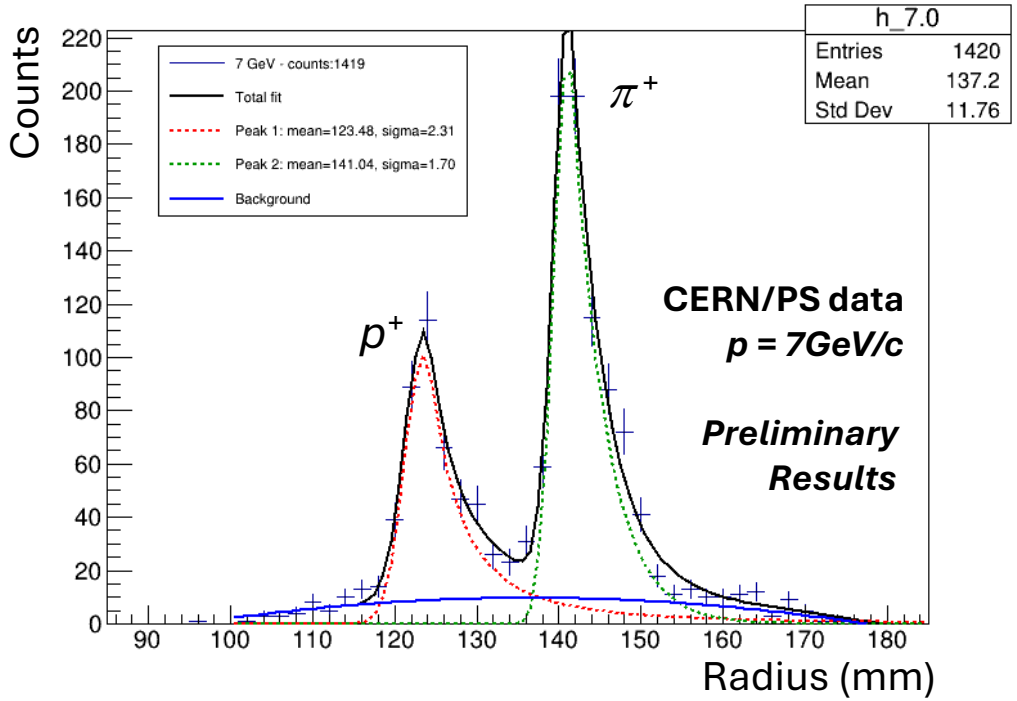
Initial Beam Test Results (CERN SPS)











- RICH det. prototype
  - Aerogel radiator
  - x4 HRPPD sensor array
- **Validation check:**
  - Cherenkov yield roughly matches the simulation (aerogel transparency, wavelength dependency, HRPPD QE convolution)
  - ~5mrad single photon angular resolution also matches the simulation

Summary

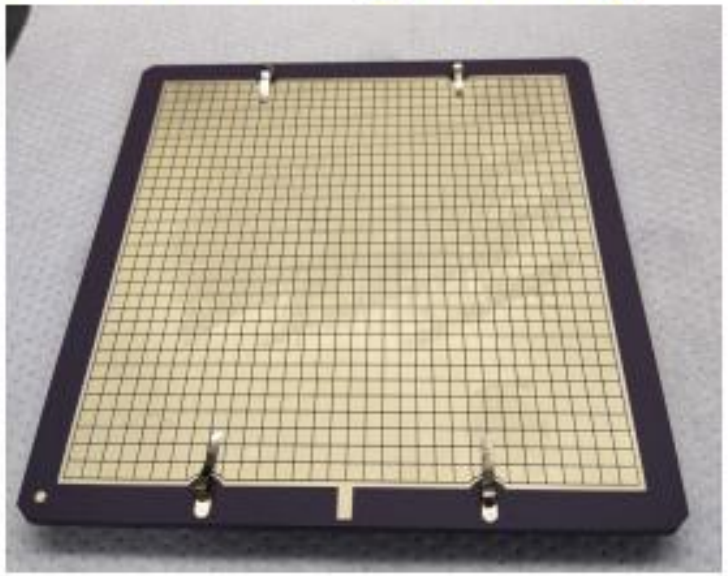
- The HRPPD is the latest MCP photosensor developed by Incom in collaboration with BNL to address the needs of high rate nuclear physics experiments, requiring robust photodetection performance with Tesla scale magnetic field tolerance
- After several design iterations, a first batch of 7 “evaluation tiles” were produced for testing at BNL, JLAB, INFN Trieste, and Yale
- Acquired first tiles in early 2024; multiple in-lab QA tests were carried out and demonstrate that HRPPDs meet required performance criteria
- Dedicated data taking campaigns at BNL SMD and at CERN further demonstrate this performance
- FDR recommends early procurement of 140 tiles use in the EIC ePIC experiment at BNL

Summary of General Performance Specs

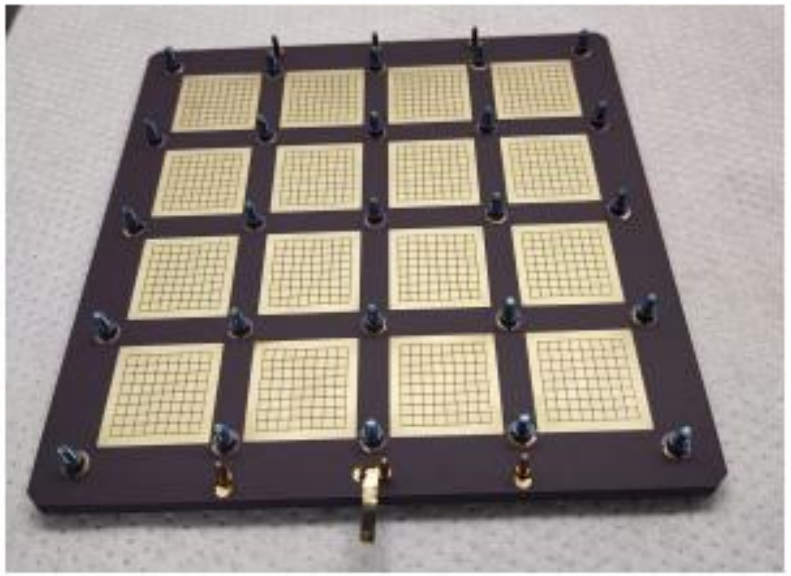
- Rate capability: *O(100Hz)/*pixel @ Gain>10^6 , B=1.3T
- Magnetic field tolerance: 1.5T (tested to 1.8T)
- High gain in 1.8T field >10^6
- High QE ~30% at 365nm
- PDE → CE ~ 70%
- Timing Resolution:15-20ps (optimal)
- Spatial resolution: sub-mm (no charge sharing)
- Dark count rate: 1.8 kHz/cm^2
- After-pulsing rate = few % @ Gain= 10^6

Backup

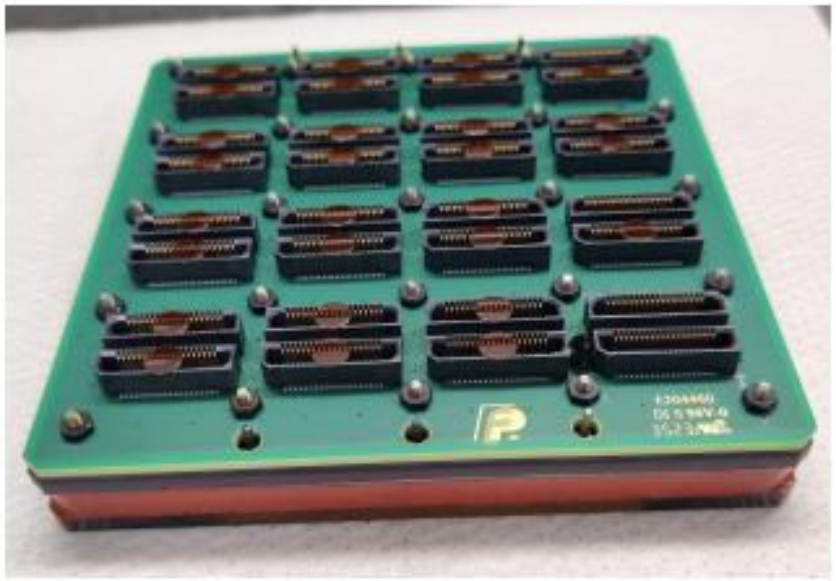
Picture gallery



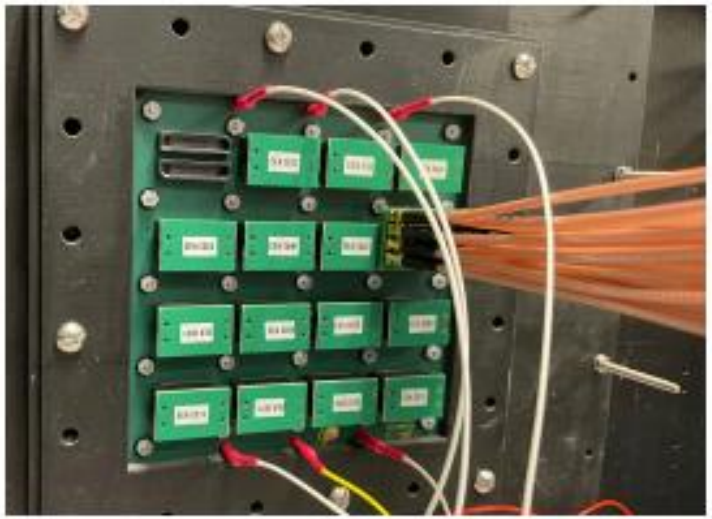
Anode plate vacuum side



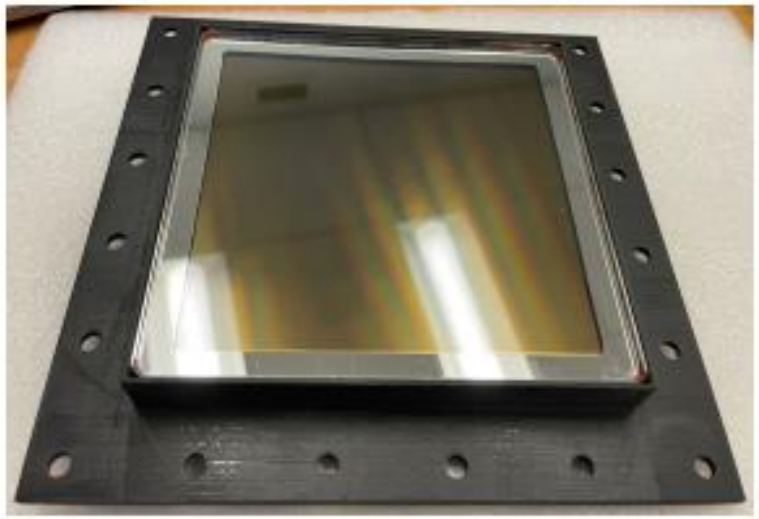
Anode plate air side



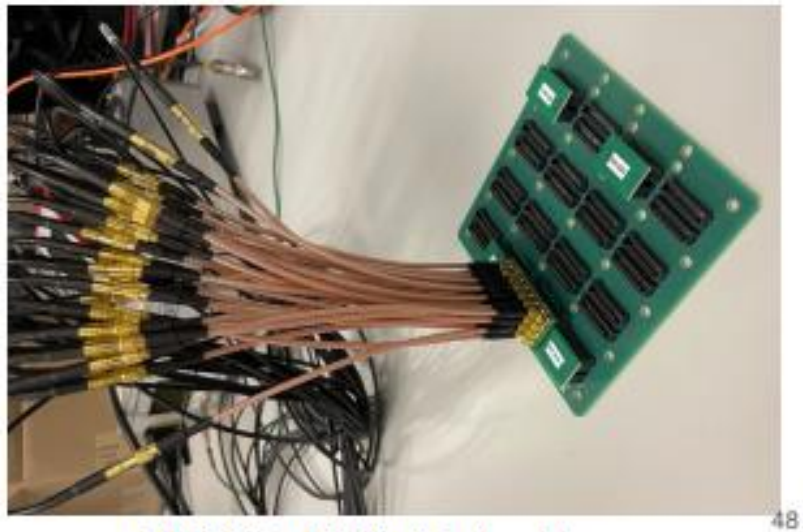
With Y05f board mounted



With MMCX interface



Fused silica window



MMCX -> MCX pigtail cables

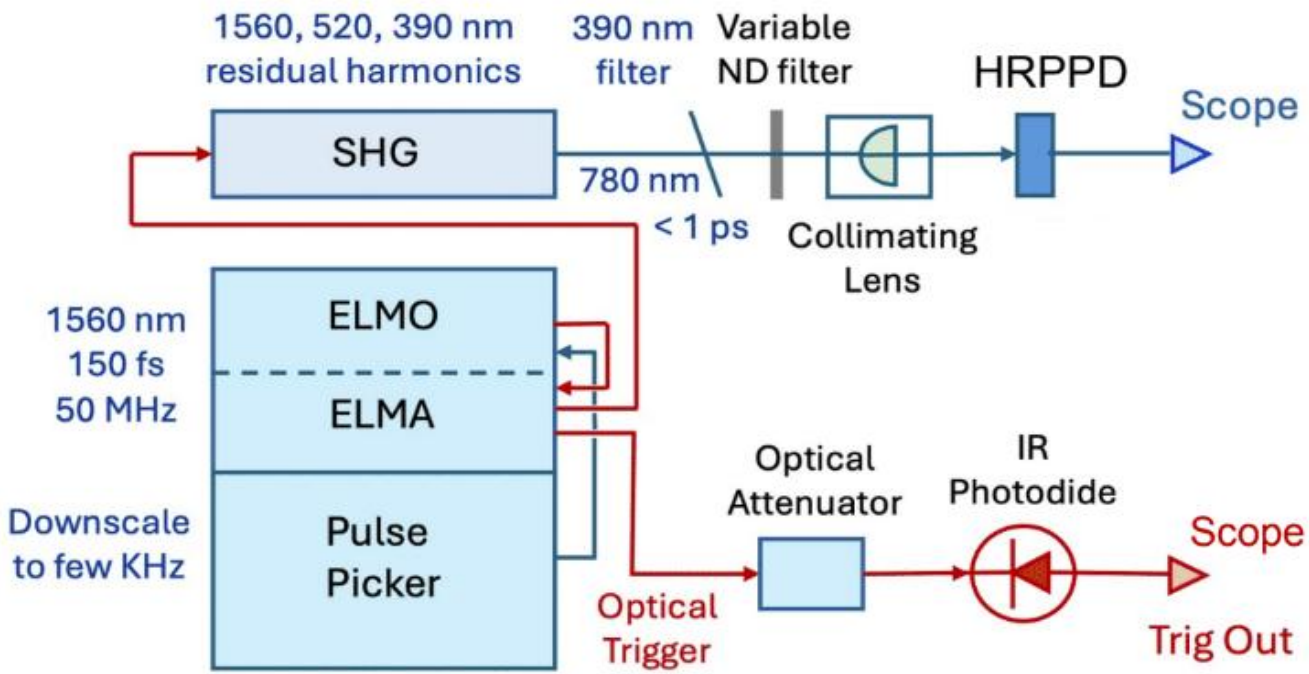
Elmo 780 femtosecond laser system at BNL

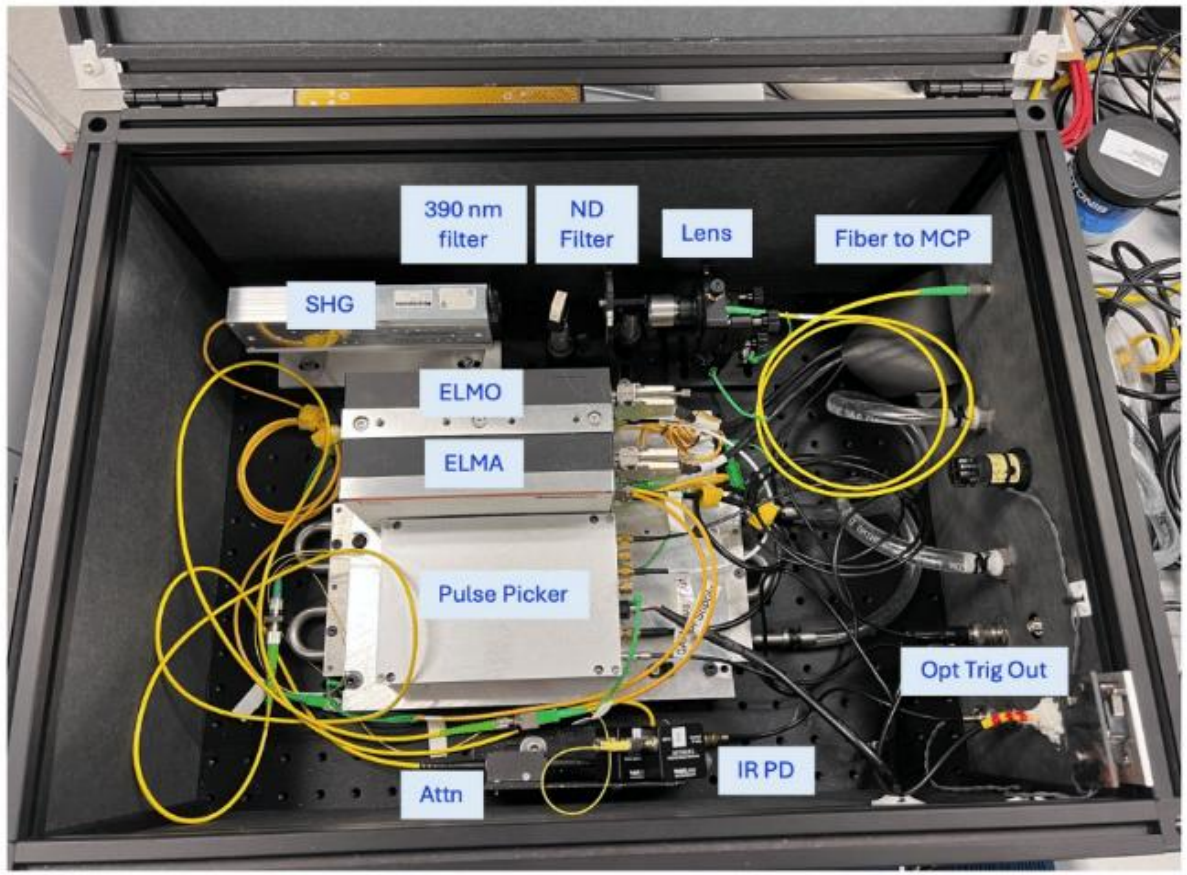
Menlo Systems Elmo 780 Erbium Fiber Femtosecond Laser

ELMO = Primary Laser Oscillator

ELMA = Optical Amplifier

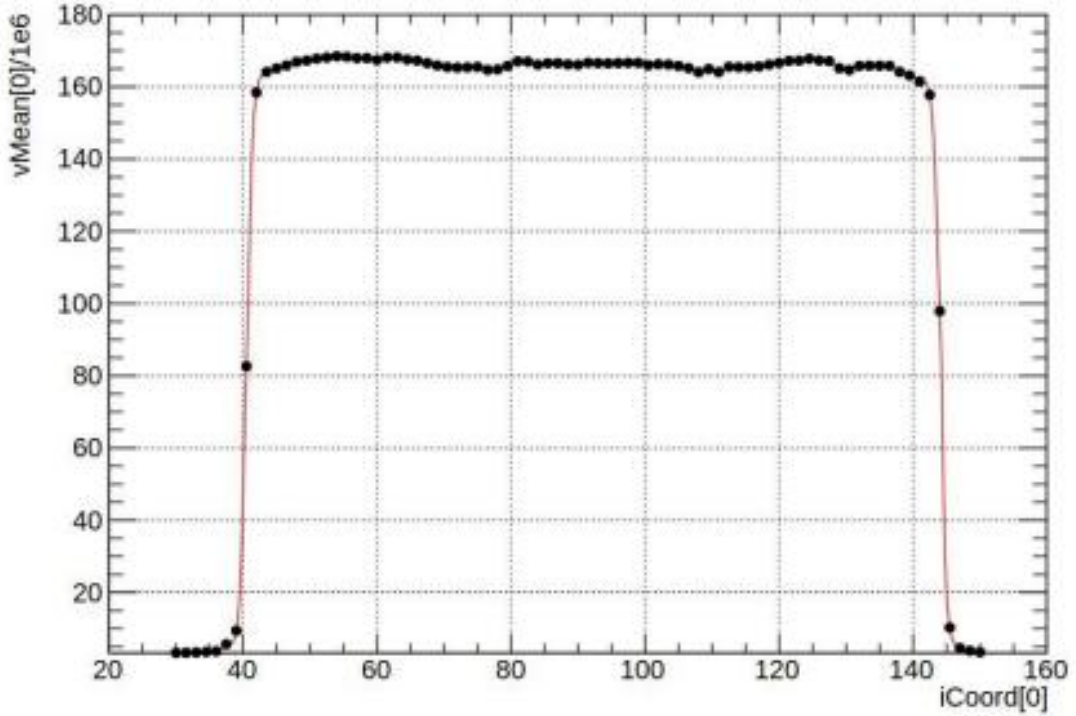
SHG = 2nd Harmonic Generator



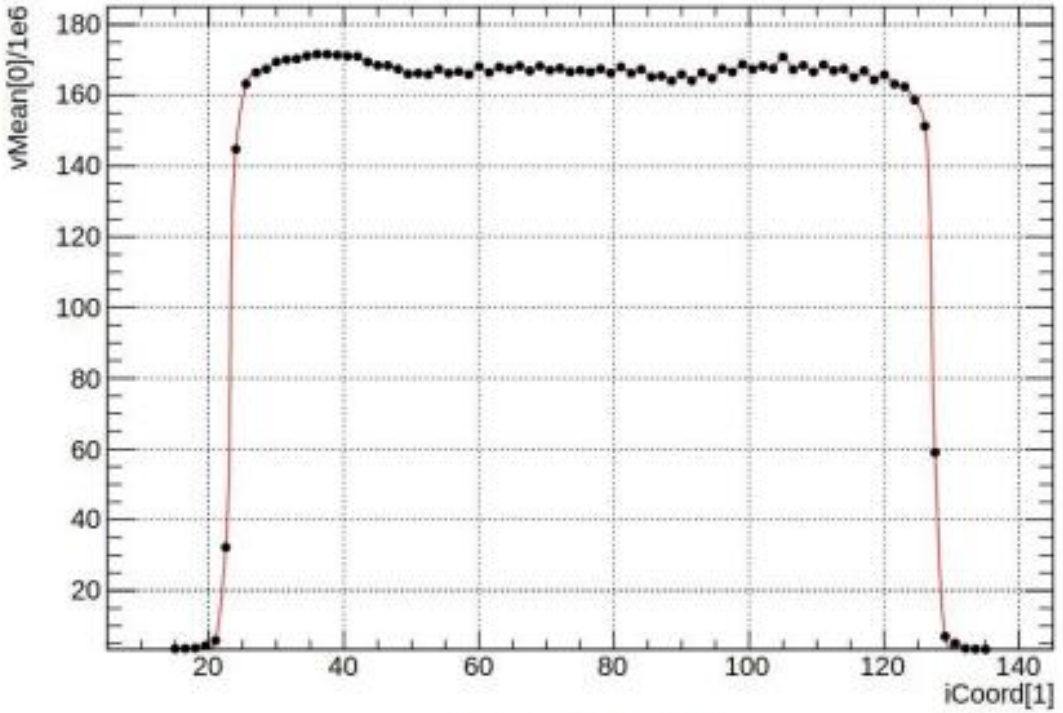


We make use of a very low intensity 3rd harmonic @ 390 nm

QE measurements @ BNL: active area



X-coordinate



Y-coordinate

- ~104mm in both projections, as expected [anode pixellation: 32x 3.25mm]
- Beware: the actual high PED area with a sufficient gain will probably be smaller!

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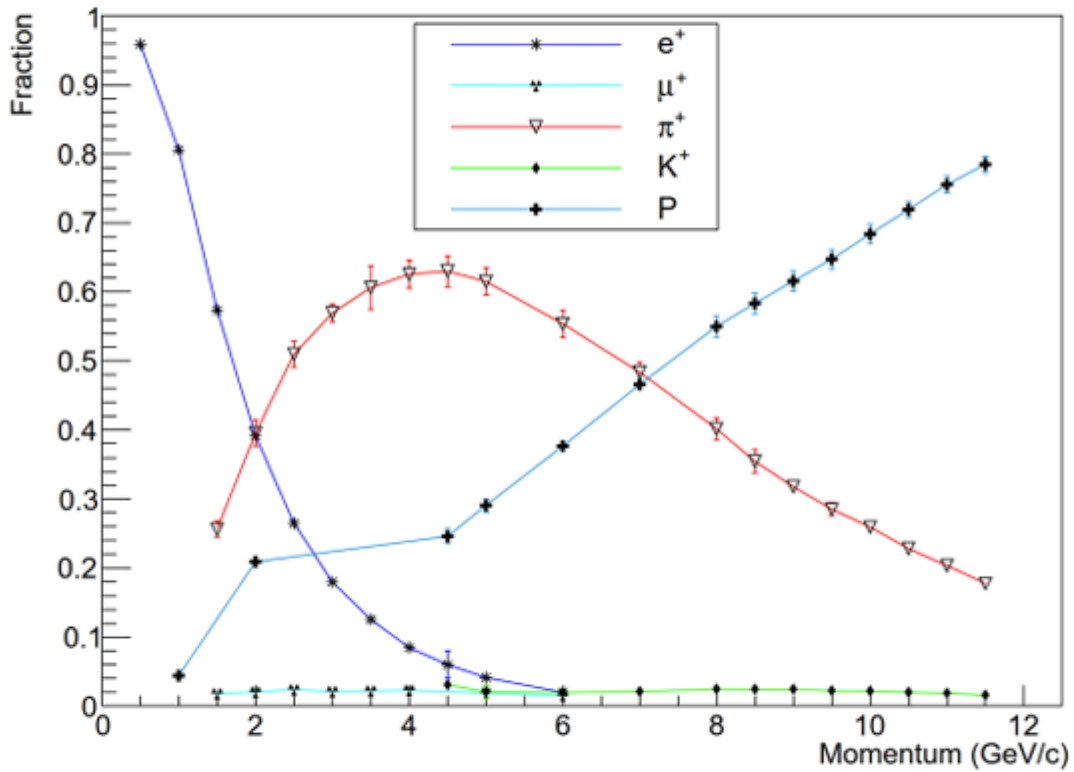
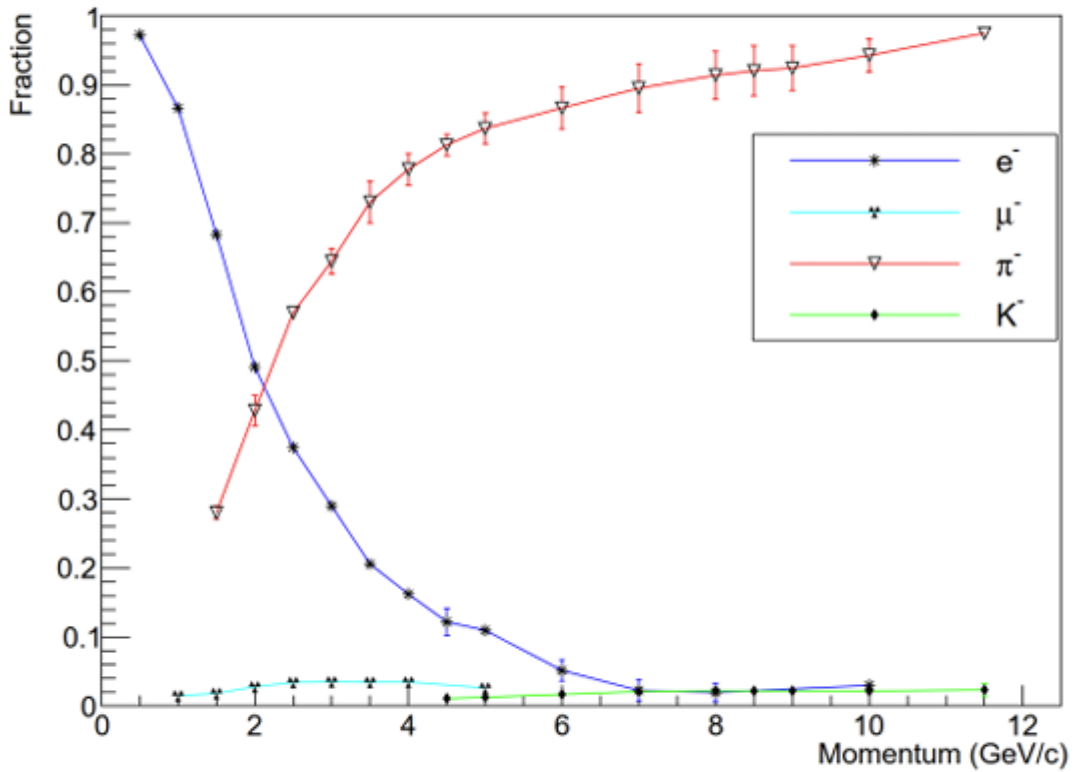
Beam content

- **Paper published last year in NIM B together with BL4S: https://doi.org/10.1016/j.nimb.2025.165907**

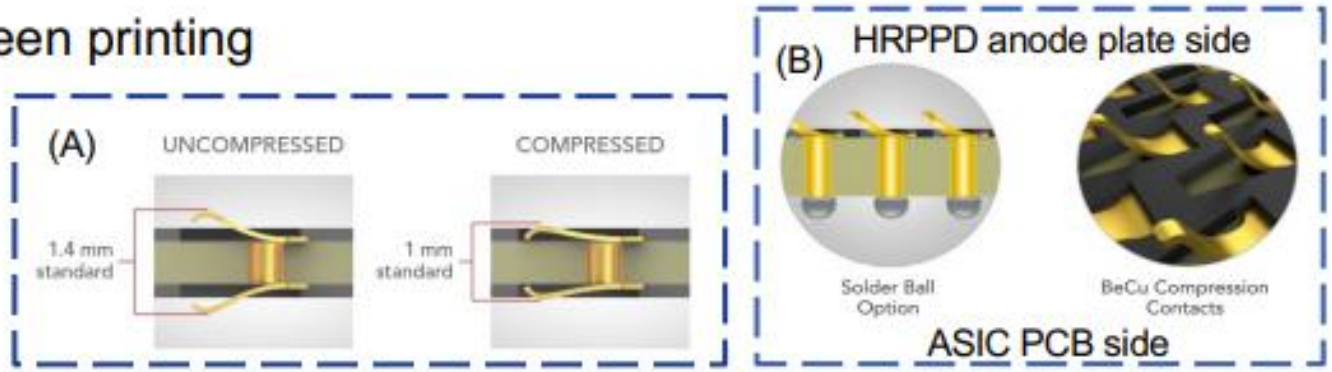


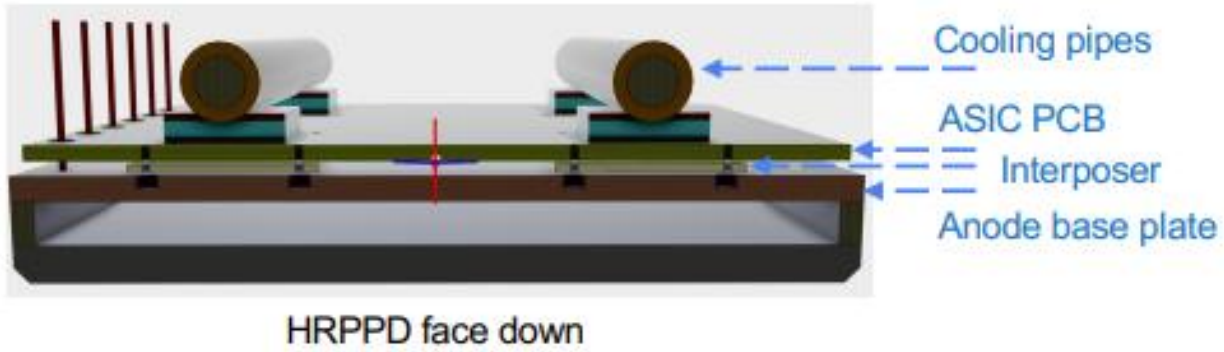


- **Points and particles not yet on these plots still to be measured – input welcome!**

Integration concept: compression interposers

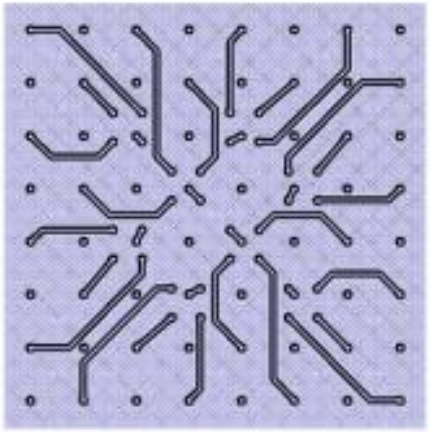
- Design custom LTCC (HTCC) anode base plates for new EIC HRPPDs
  - Samtec compression interposers looked like a reasonable interconnect option
  - Fallback solution: conductive epoxy screen printing



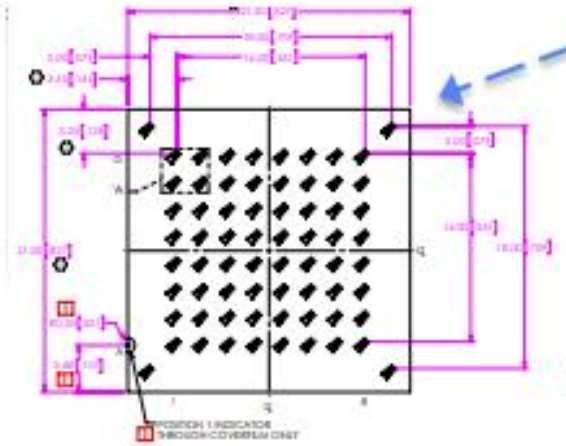


HRPPD face down

EIC HRPPD assembly



8x8 pad pattern compressed from 3.25mm to 2.00mm pitch



Fused silica window

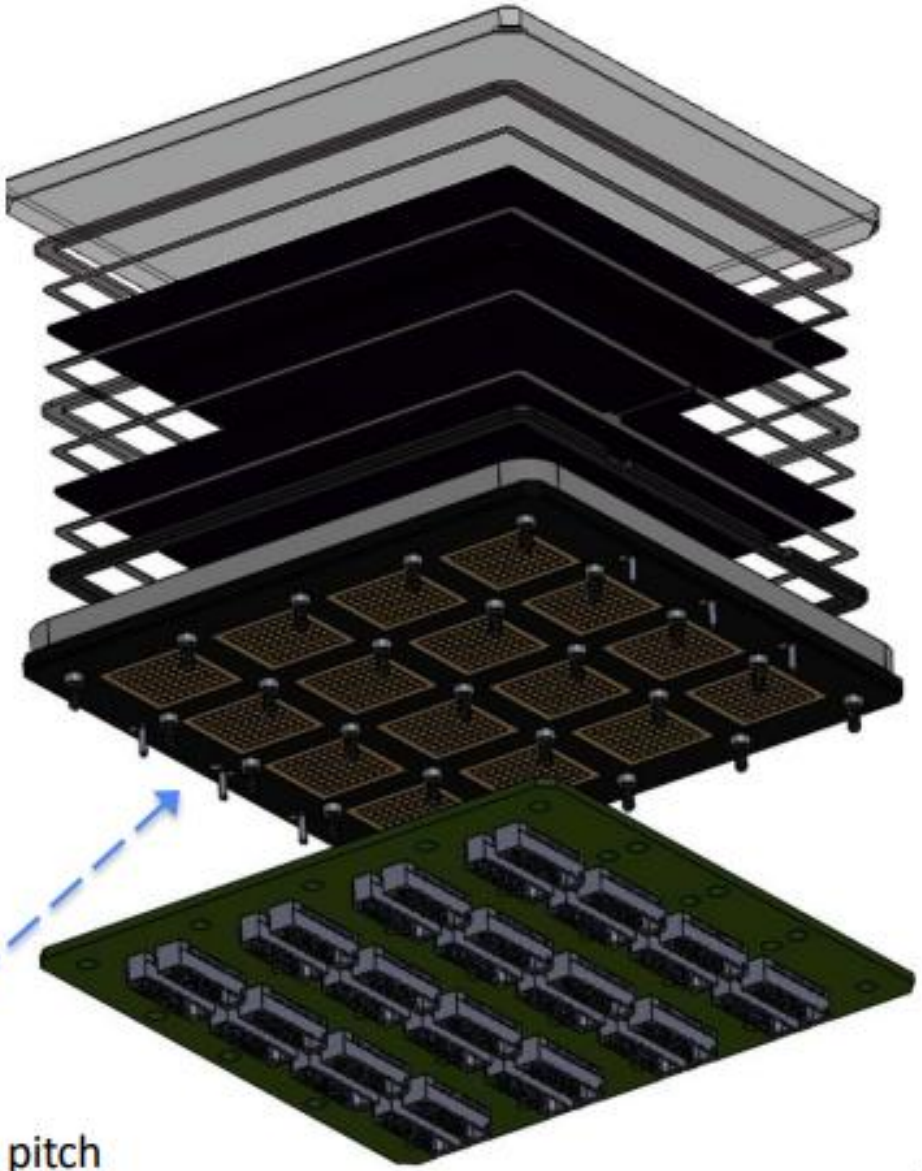
MCPs, spacers, etc

Side wall

Anode plate, a pre-routing ceramic circuit board

Compression interposers (not shown in the blown up view)

Interface PCB (here: Y05f)



4x4 spots, each with 8x8 square pads; 3.25mm pitch

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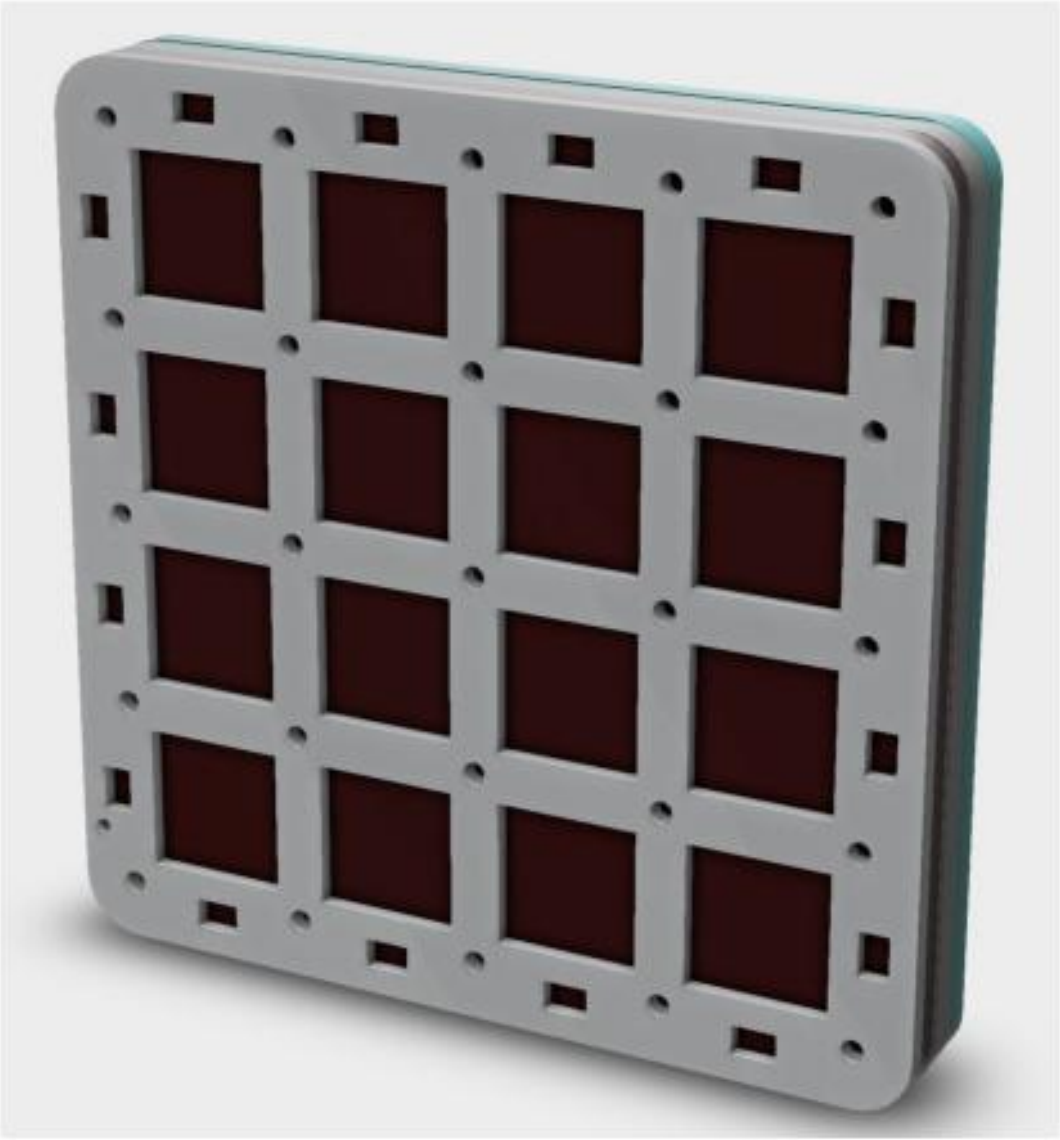
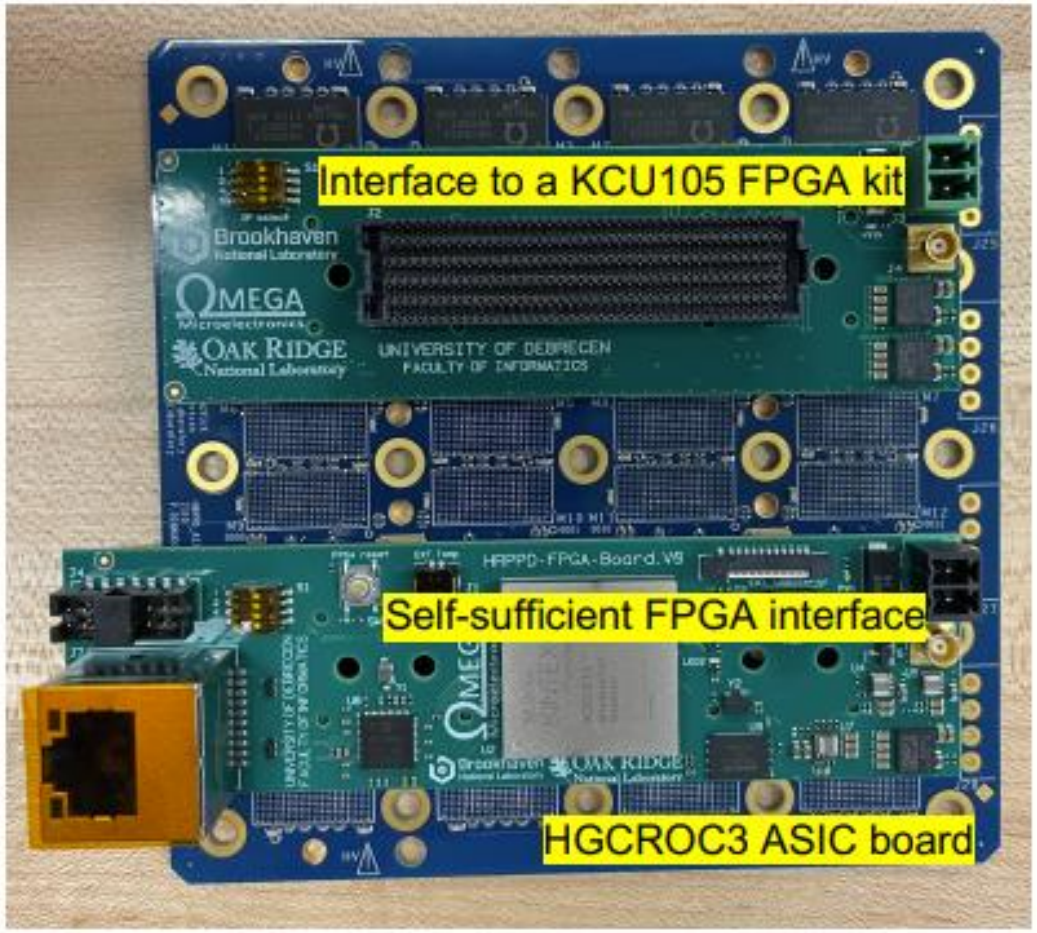
Mechanical interface redesign



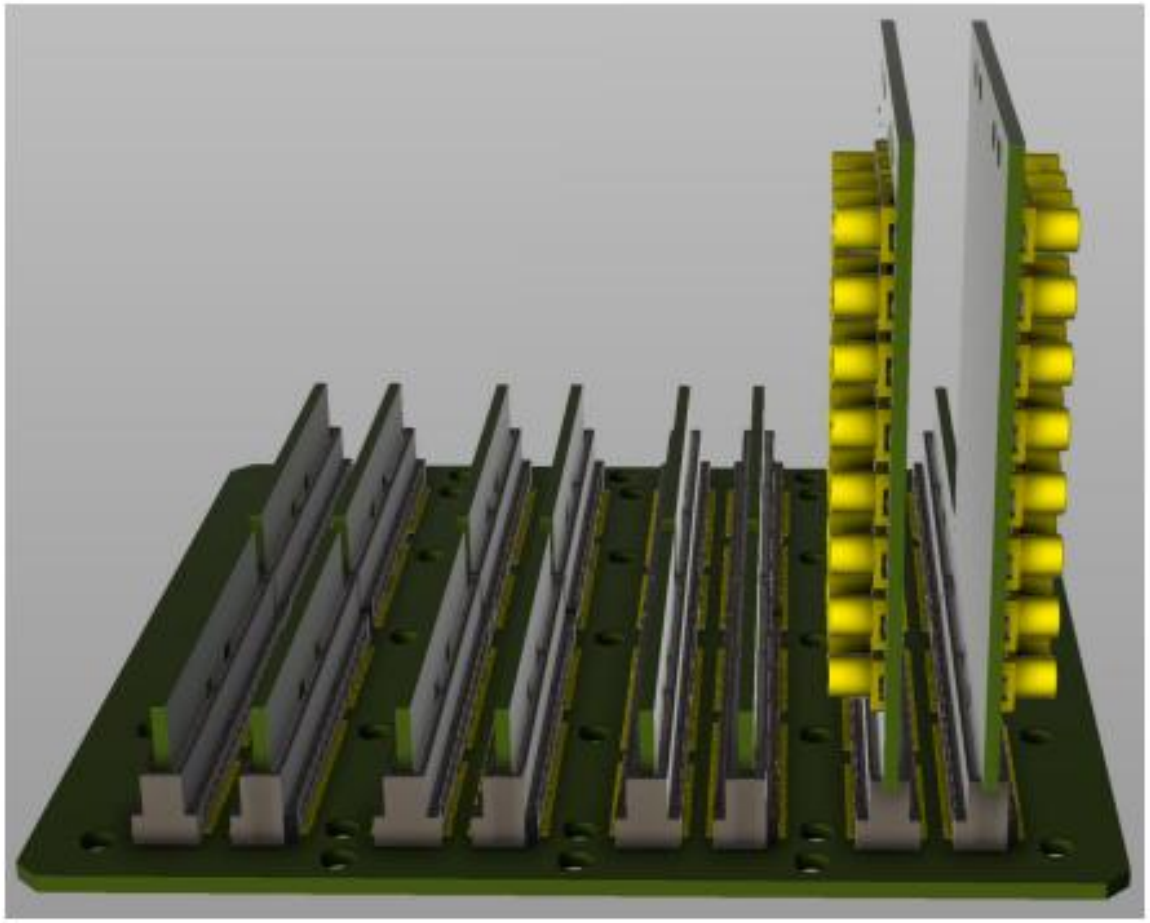
- A permanently glued ~3mm thick plastic (peek?) panel
  - "Floating" signal compression interposers
  - "Floating" HV compression interposers
    - 8x MCP#2 bottom side
    - 4x for other electrodes
    - 4x ground (?)
  - Permanently embedded hex head screws or female threaded mechanical fixtures
- Corners rounded at 8mm radius

Readout interface(s)

Present concept: ASIC backplane



Alternative layout: passive backplane + plugin cards



- Current focus: using HGCROC3, prove that TOA/ADC architecture works for HRPPDs

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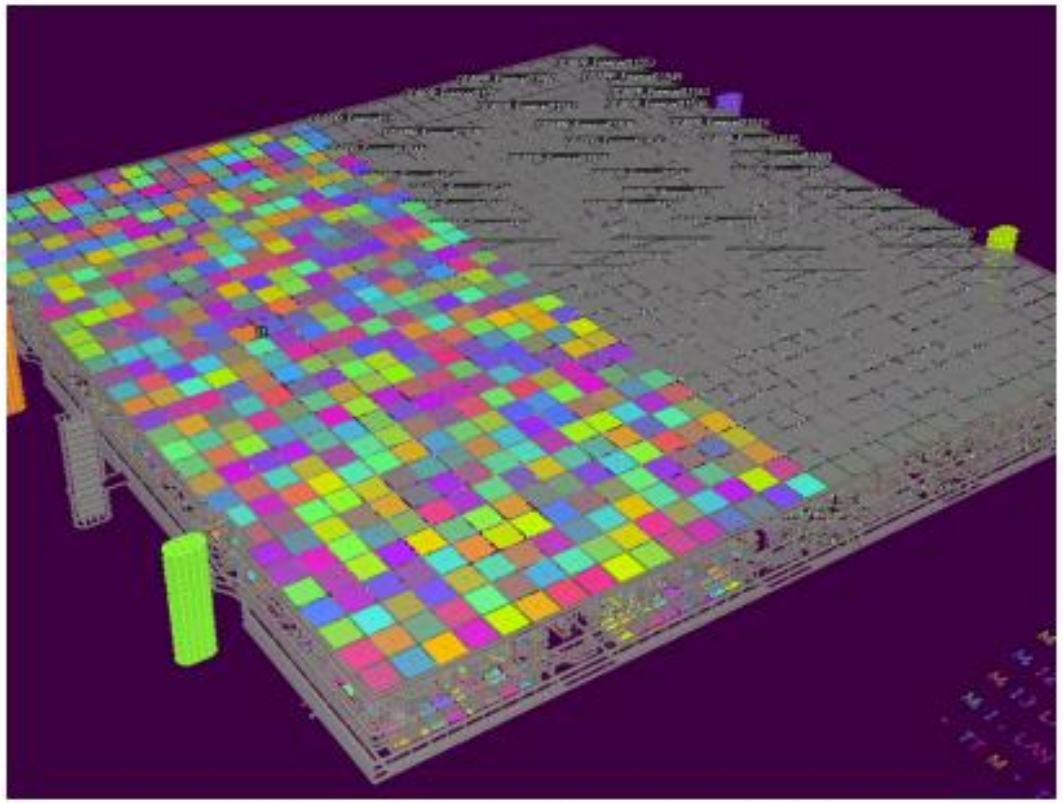
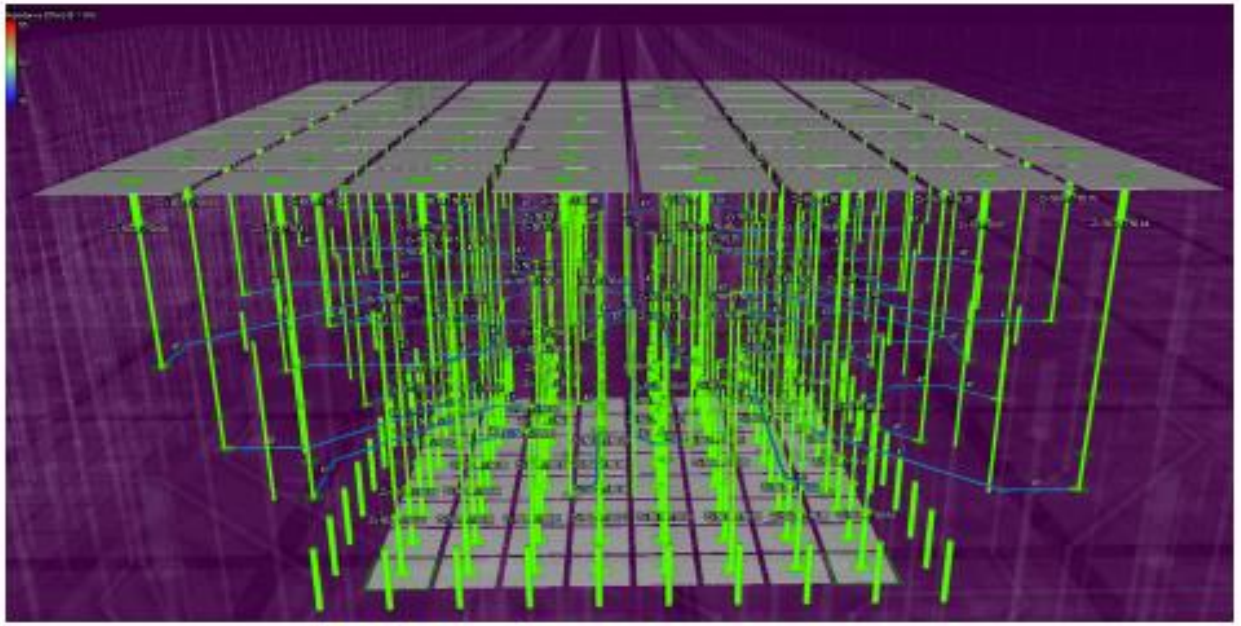
HRPPD anode + backplane signal modeling at JLab



A full HRPPD anode stackup

Use SIMBEOR (3D Electromagnetic Signal Integrity Modeling Software)



A zoomed in 8x8 pad area

- Work in progress; so far confirmed via and trace impedance ~50 Ohm, as well as absence of cross-talk in a 2D configuration (within a single layer)
- Goal: perform a complete 3D modeling and provide recommendations for final HRPPD design modifications, including HV circuitry

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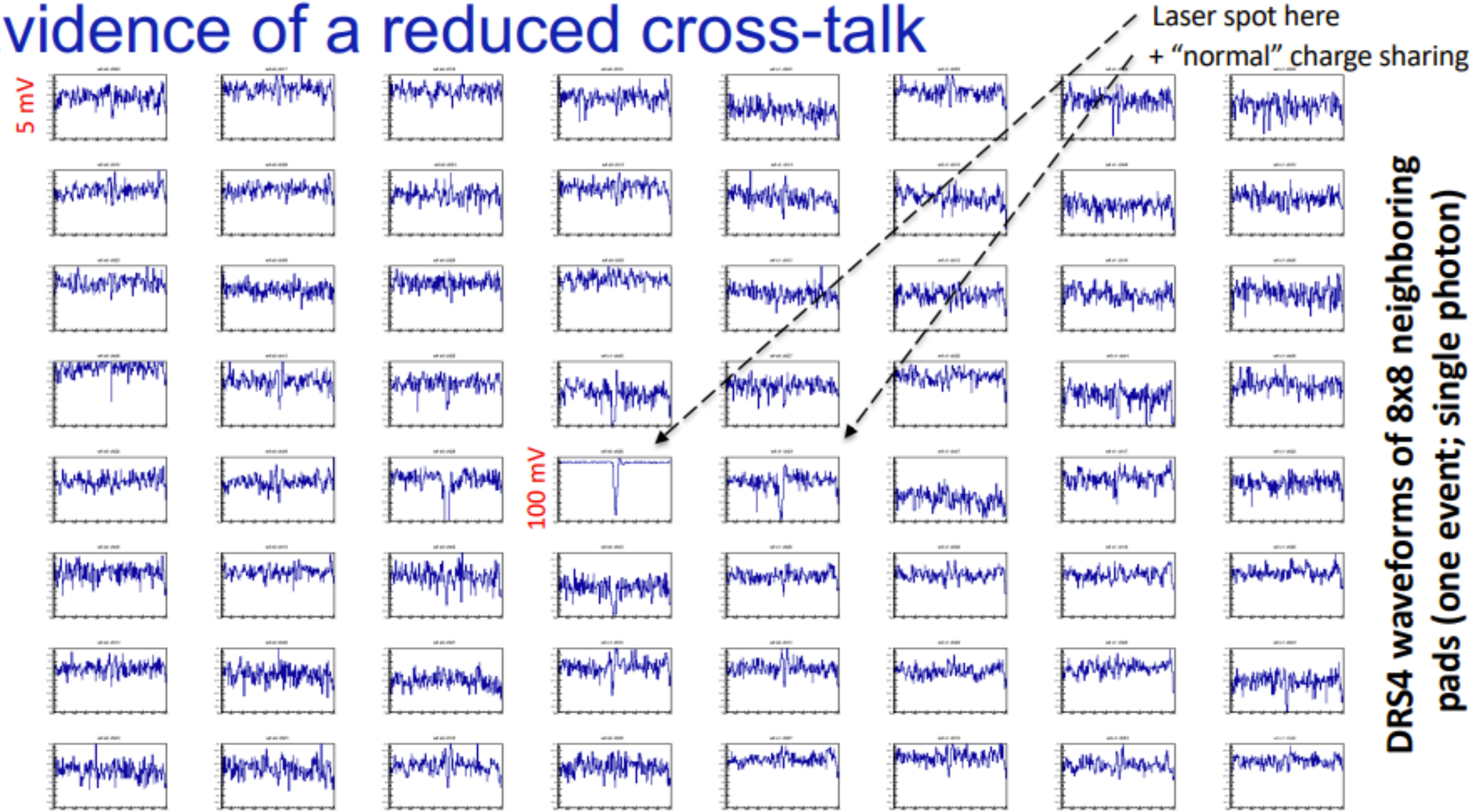
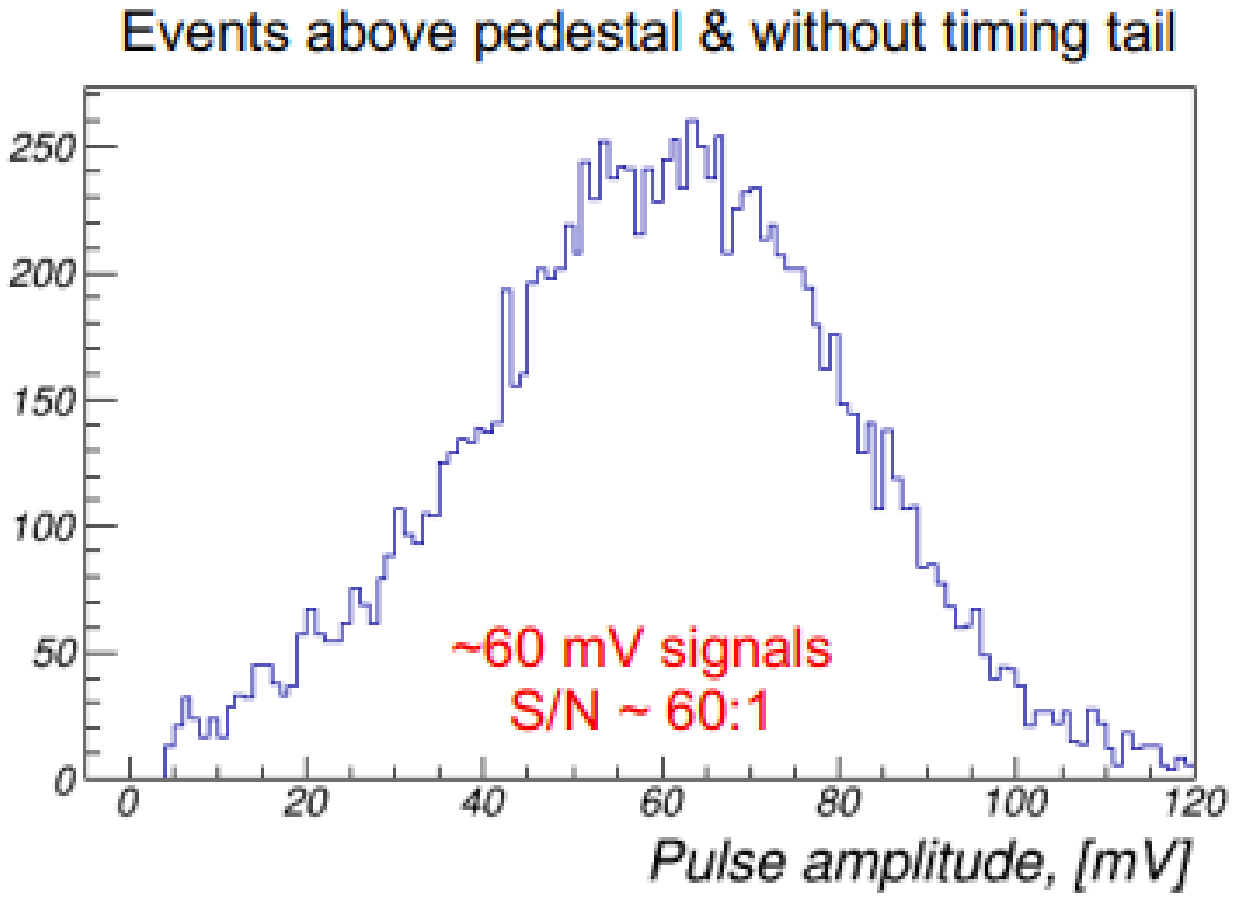
Evidence of a reduced cross-talk



Cross-talk reduced to ~1-2% level?

Pulse Height Distr. for HRPPD timing