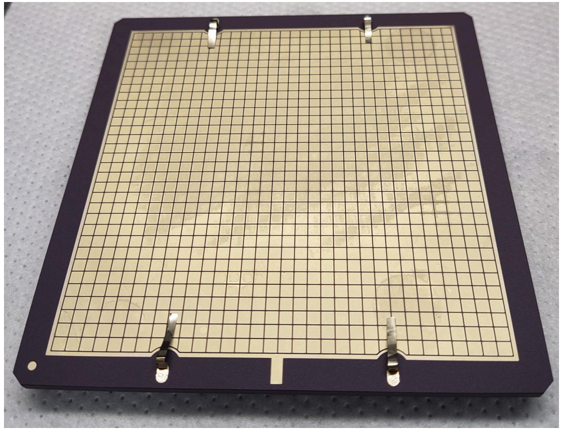
# HRPPD characterization: Status and next steps

**Alexander Kiselev (BNL)**

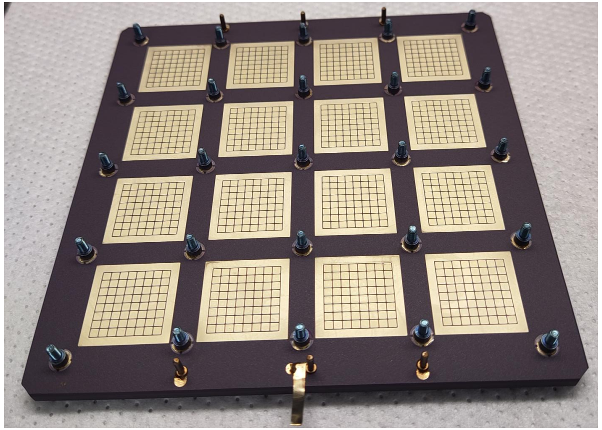
**ePIC TIC meeting, October 20, 2025**

# Incom's DC-coupled EIC HRPPDs

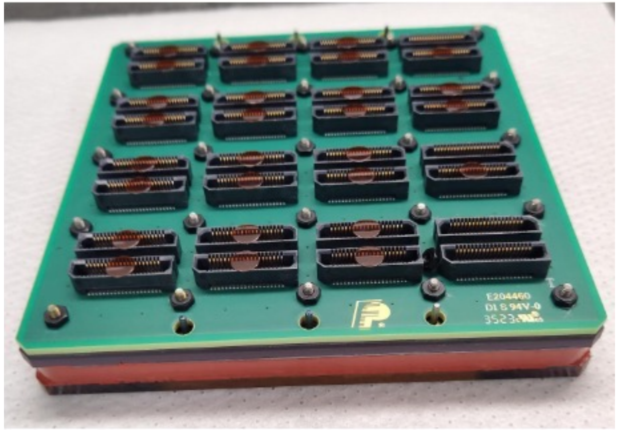
- 120mm x 120mm footprint, 10 μm pore MCPs, 5 mm thick fused silica window
- 104mm x 104mm active area (~75% geometric efficiency), 32x32 pads (pitch 3.25 mm)
- Air side has 4x4 groups of 8x8 pads (2.00 mm pitch), leaving enough space for mounting fixtures



Anode plate vacuum side



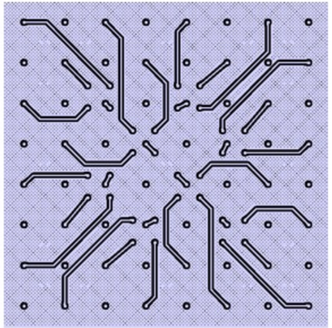
Anode plate air side



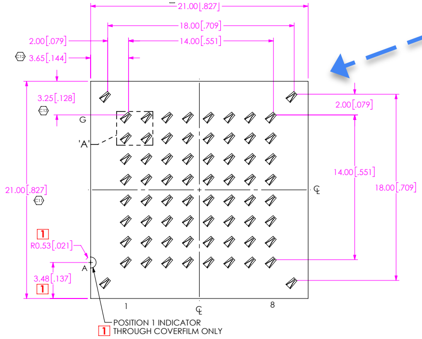
HRPPD with a passive backplane

- A baseline photosensor for ePIC pfRICH detector (and a second choice for hpDIRC)

# Incom’s DC-coupled EIC HRPPDs



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




Fused silica window

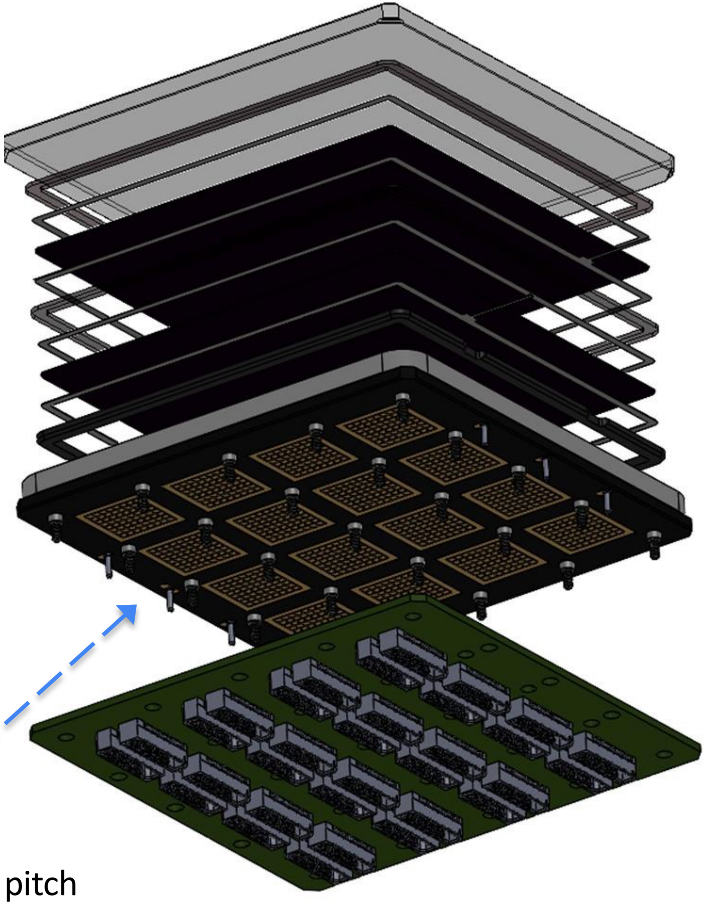
MCPs, spacers, etc

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

# Incom's internal testing summary of our seven tiles

| HRPPD # | Operating Voltage Range (V/MCP) | Dark Rates @ 1X10^6 Gain (Hz/cm^2) | EIC Standard – Dark Rates |
|---|---|---|---|
| 15 | 750-850 | 160 | ≤ 2E3Hz/cm^2 at ≥ 10^6 Gain |
| 16 | 625-725 | 0.18 | |
| 17 | 600-700 | 19 | |
| 23 | 600-700 | 0.37 | |
| 24 | 575-700 | 69 | |
| 25 | 650-750 | <100 | |
| 26 | 650-700 | | |

| HRPPD # | Operating Voltage Range (V/MCP) | Gain Range at ≥ 100V Bias on Photocathode (PC) |
|---|---|---|
| 15 | 750-850 | 6.5E5 – 1.4E7 |
| 16 | 625-725 | 9.2E5 – 1.3E7 |
| 17 | 600-700 | 1.0E6 – 1.8E7 |
| 23 | 600-700 | 2.9E6 – 3.7E7 |
| 24 | 575-700 | 6.8E5 – 2.2E7 |
| 25 | 650-750 | 1.4E6 – 3.2E7 |
| 26 | 650-700 | 8.0E5 – 8.7E6 |

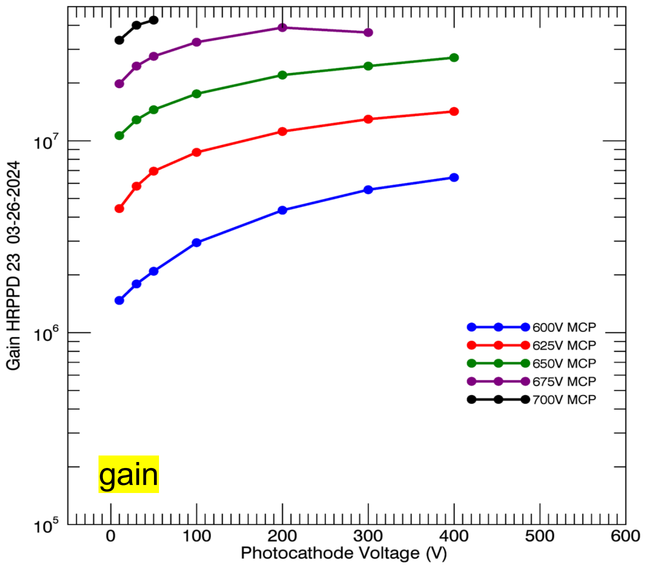
| HRPPD # | Transit Time Spread (lowest recorded, in ps) | EIC Standard – TTS |
|---|---|---|
| 15 | 59 | ≤60 ps, limited by testing apparatus |
| 16 | 59 | |
| 17 | 58 | |
| 23 | 58 | |
| 24 | 70 | |
| 25 | 72 | |
| 26 | | |

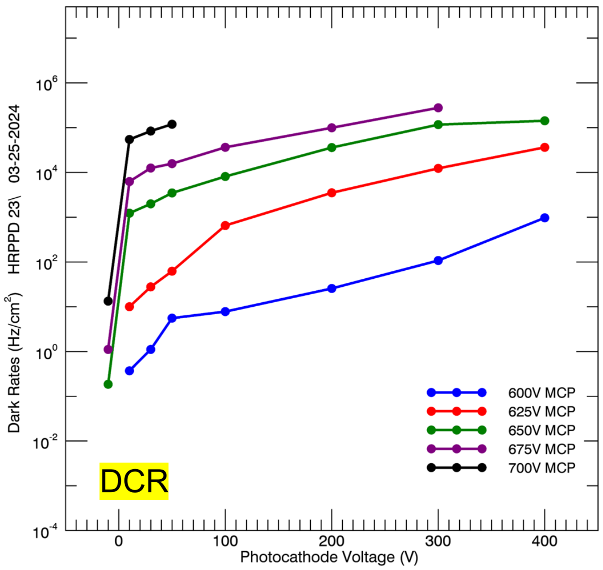
| HRPPD # | QE @ 365nm (Avg./Max.) | Std. Dev. |
|---|---|---|
| 15 | 32.9% / 34.0% | 1.1% |
| 16 | 34.0% / 35.3% | 0.6% |
| 17 | 35.2% / 36.2% | 0.9% |
| 23 | 26.8% / 28.8% | 1.7% |
| 24 | 36.5% / 37.3% | 0.5% |
| 25 | 26.3% / 28.8% | 1.2% |
| 26 | 32.8% / 34.0% | 0.9% |

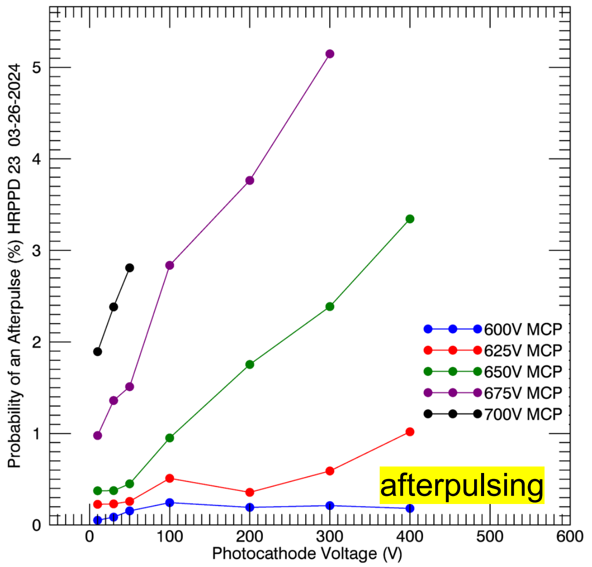
*by Mark Popecki (Incom)*

Link to a May 8th 2024 LAPPD / HRPPD Workshop talk

# Incom’s internal testing: DCR, gain, afterpulsing

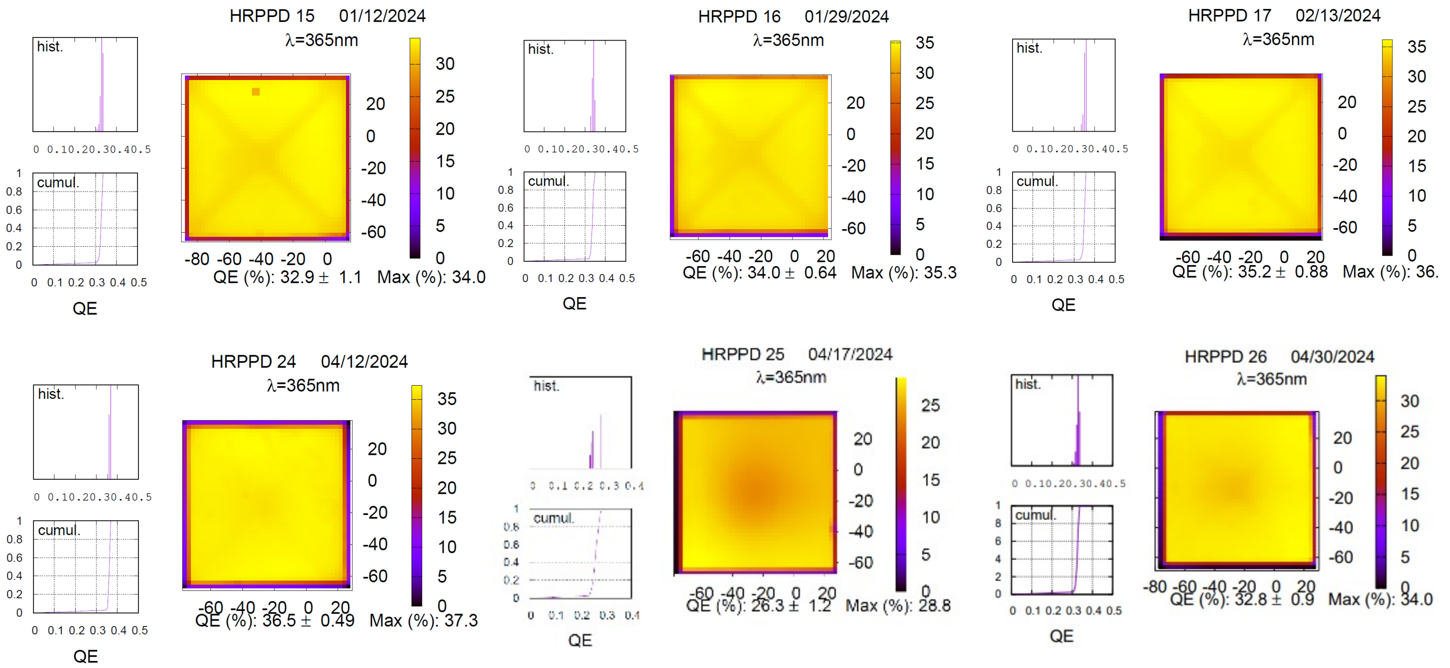


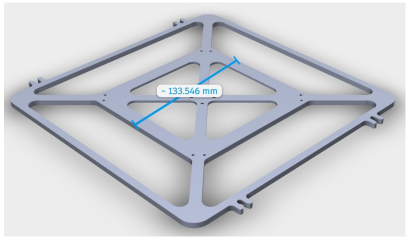




- Newly developed ALD process allows for a high gain at a remarkably low bias voltage
  - HRPPD #23: dark rates at mid-$10^6$ gain are below 1 kHz/cm$^2$ with afterpulsing on a ~1% level

# QE scans from Incom's internal testing

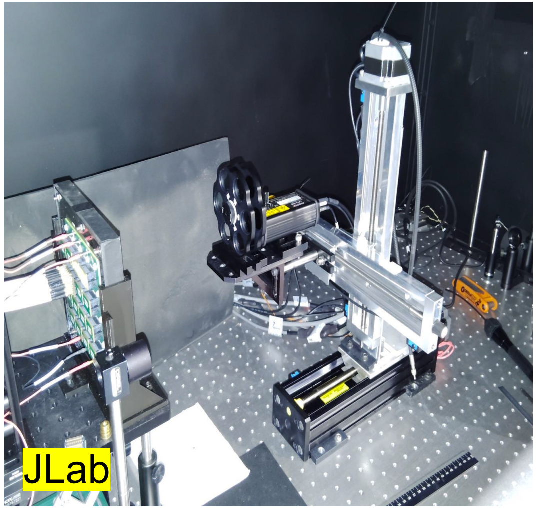


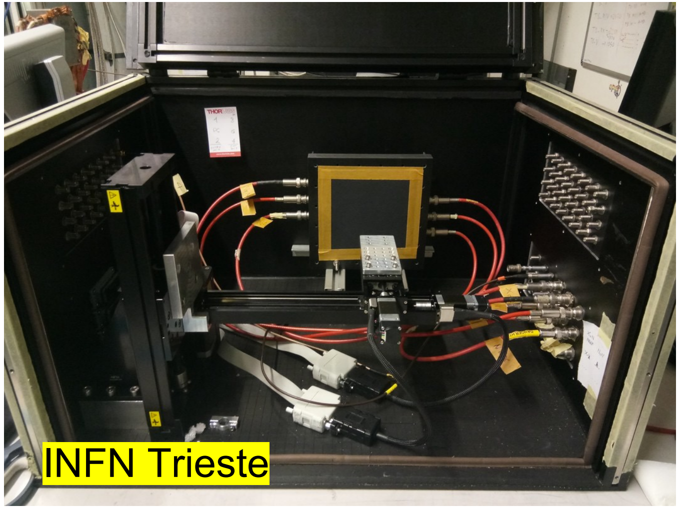



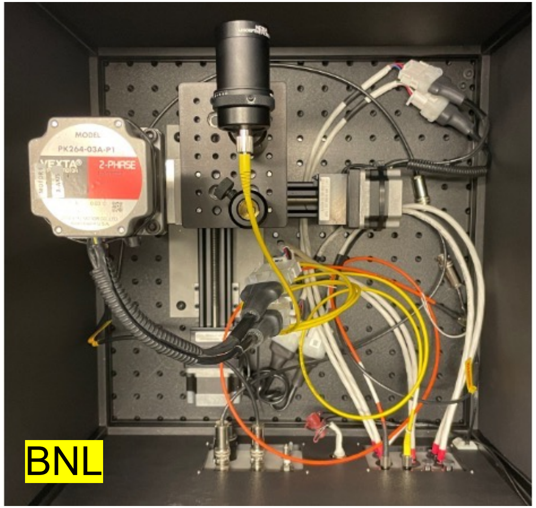

Window support structure

- ➢ Tiles sealed in vacuum tank #2 (with an X-cross pattern) are well above 30%
- ➢ Uniformity better than expected
- ➢ Issues with a fraction of tiles produced in tank #1 are by now understood

# EIC HRPPD / MCP-PMT test setups



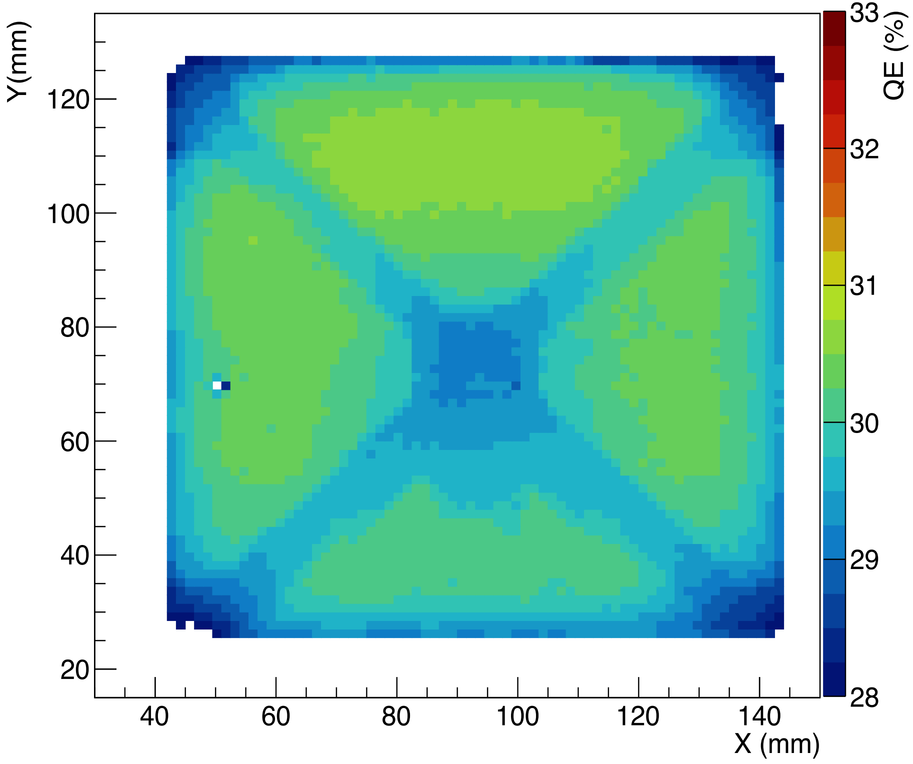



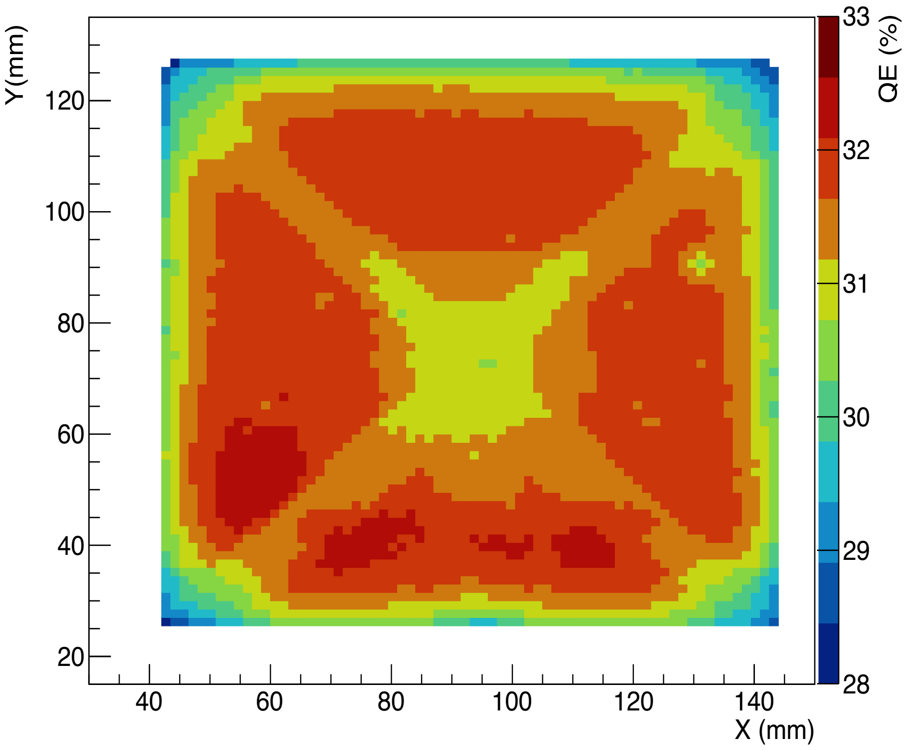

- Three fully functional QA / test stations available at JLab / BNL & INFN Trieste
- There is also an MCP-PMT / HRPPD test stand at Glasgow …
- … a new HRPPD aging test station at BNL …
- ... and another emerging HRPPD setup at Yale

# QE surface scans at BNL

Both plots are @ 365 nm




HRPPD 15 (sealing tank #2)

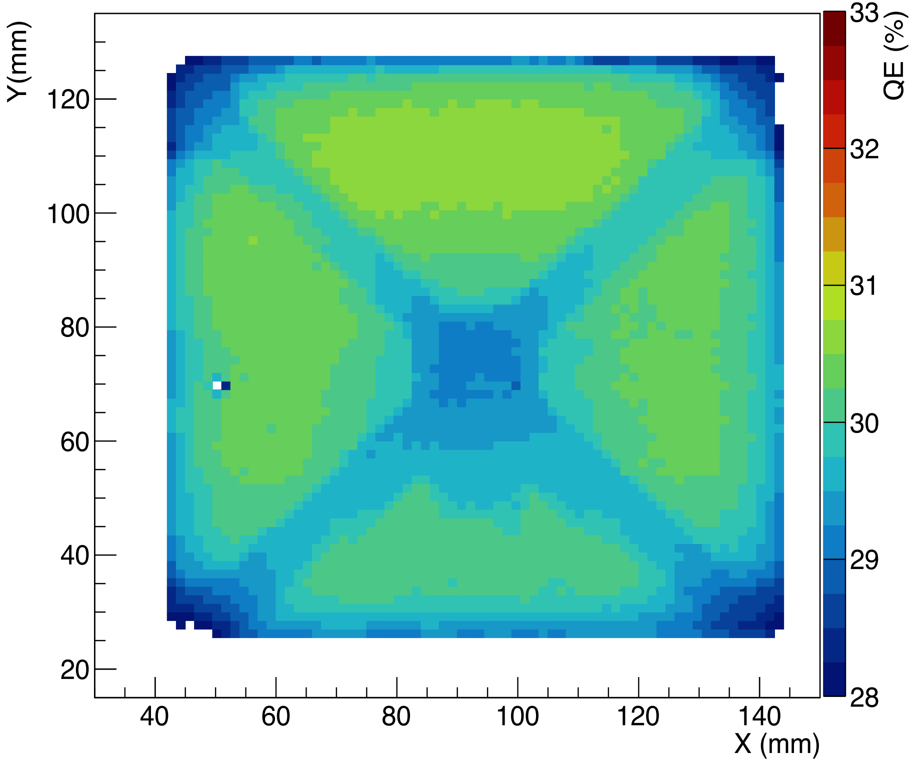



HRPPD 16 (sealing tank #2)

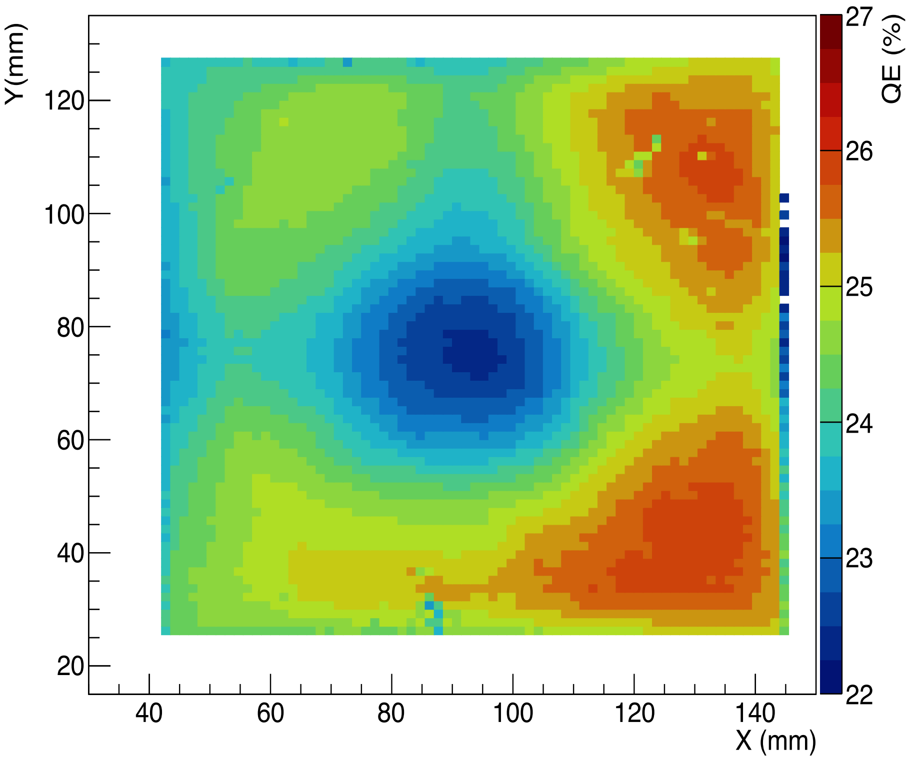
Apart from the X-profile, HRPPDs sealed in tank #2 exhibit high QE uniformity

# QE surface scans at BNL

Both plots are @ 365 nm




HRPPD 15 (sealing tank #2)

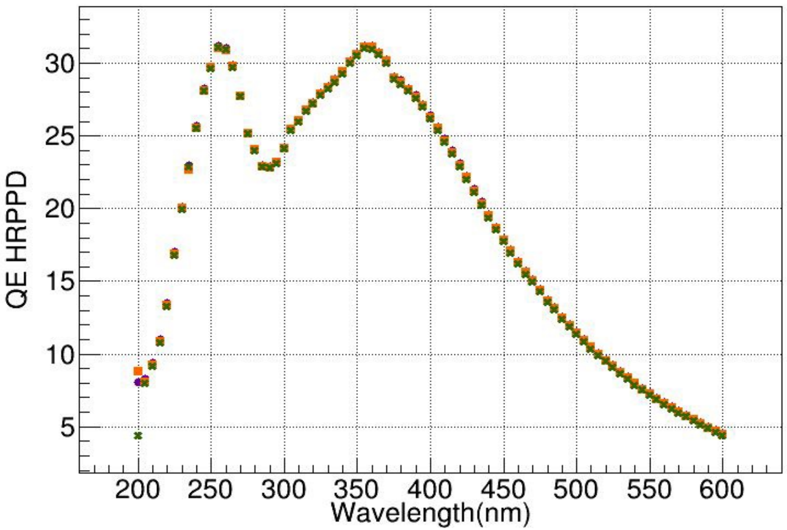



HRPPD 23 (sealing tank #1)

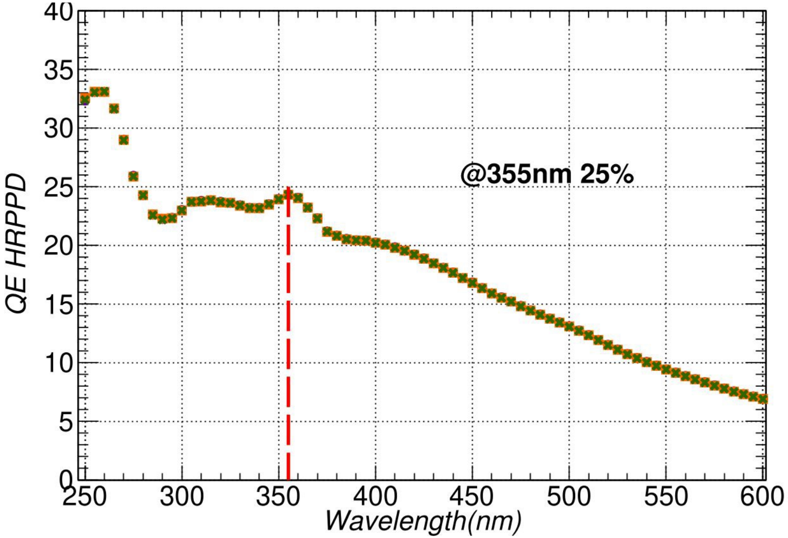
HRPPDs sealed in tank #1 had on average smaller QE and a different pattern

# QE(λ) measurements at BNL

Interestingly enough, also a QE(λ) dependency was different for HRPPDs sealed in two different tanks



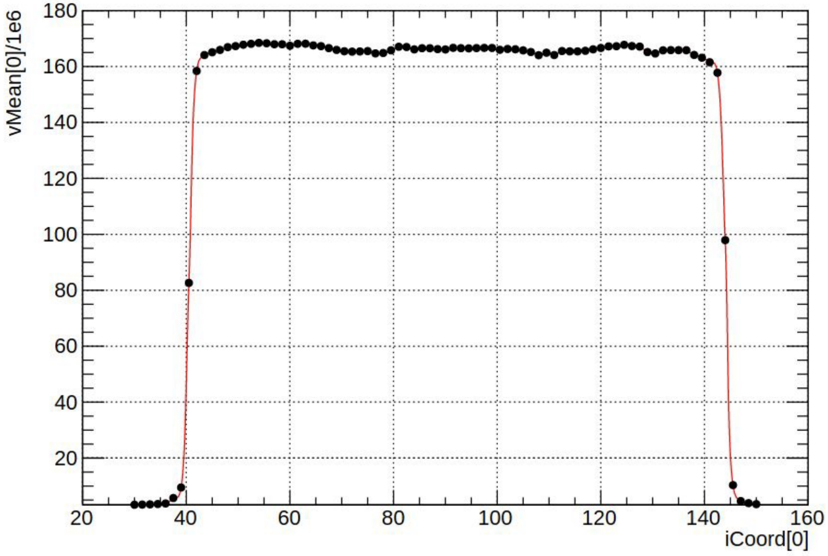

HRPPD 16 (sealing tank #2)



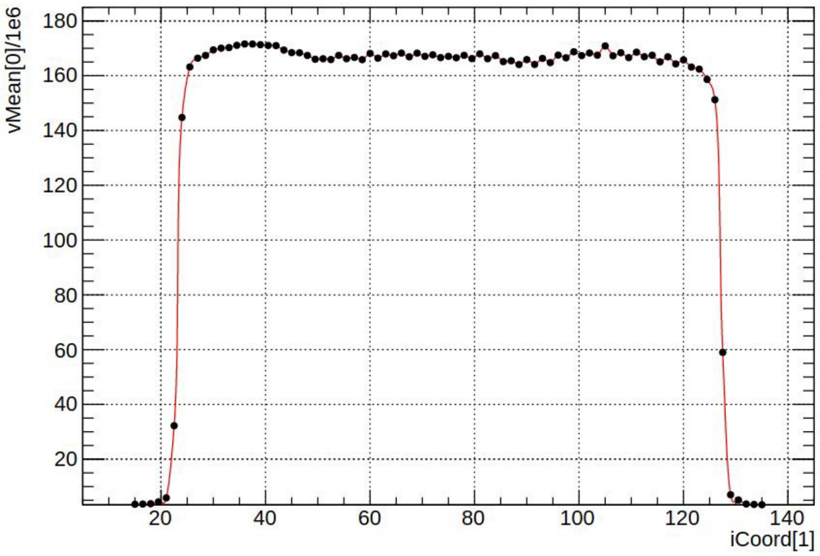

HRPPD 23 (sealing tank #1)

Production capacity: using a single sealing talk allows Incom to produce one tile per week (which is fine, assuming EIC needs up to ~150 pieces in three years)

# QE measurements @ BNL: active area




X-coordinate

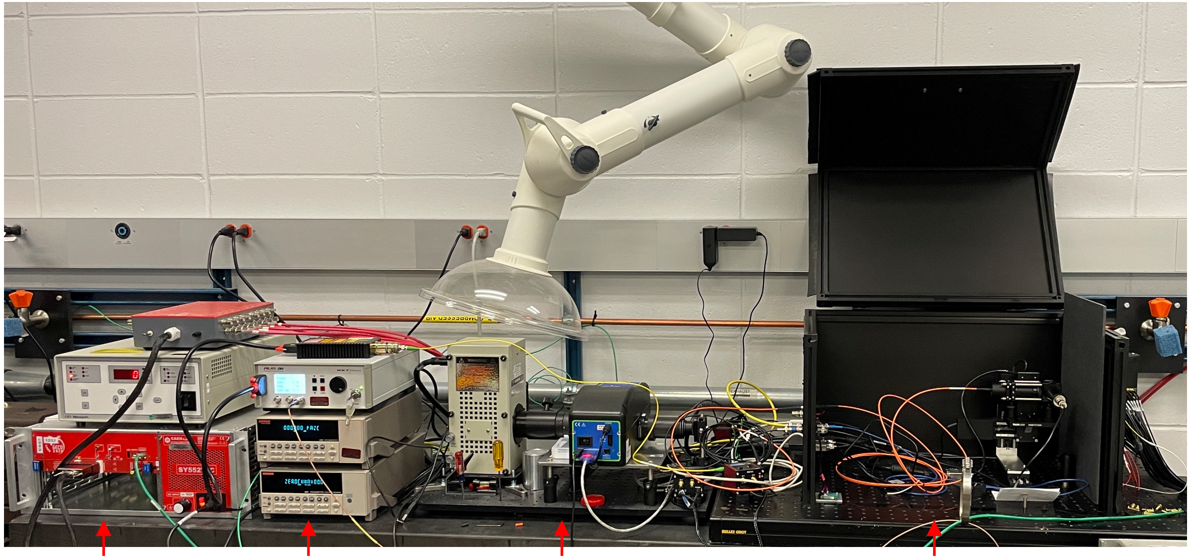



Y-coordinate

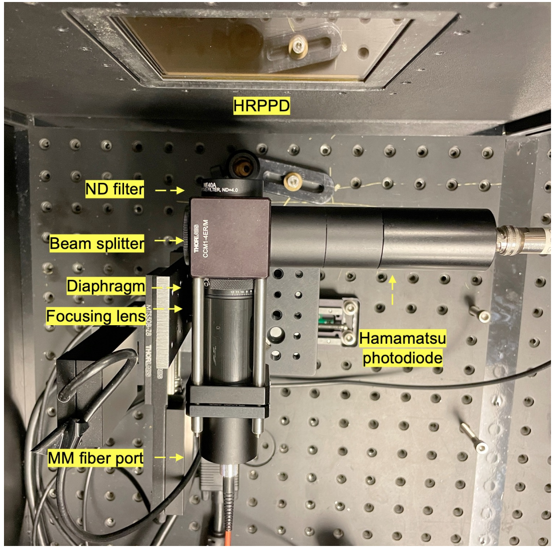
- ~104mm in both projections, as expected [anode pixellation: 32x 3.25mm] -> 75% G.E.
- Beware: the actual high PED area with a sufficient gain will probably be smaller!

- One of the objectives of a final PED run is to make this nominal active area fully efficient

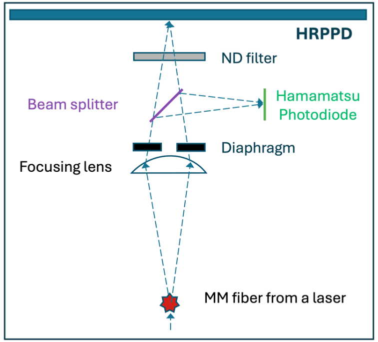
# Photon detection efficiency & collection efficiency



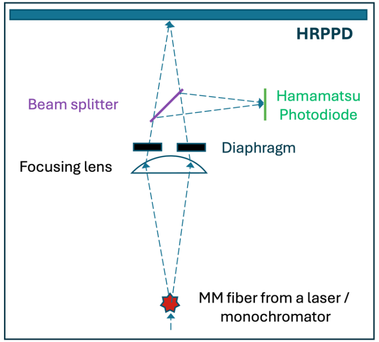
HV
Picoammeters
PiLas laser
Monochromator
Dark box




- Use a newly built HRPPD aging test station at BNL
- Usable to measure PDE (in a pulse counting mode)
  - Where from **CE = PDE / QE ~ 70.3 +/- 1.6%**

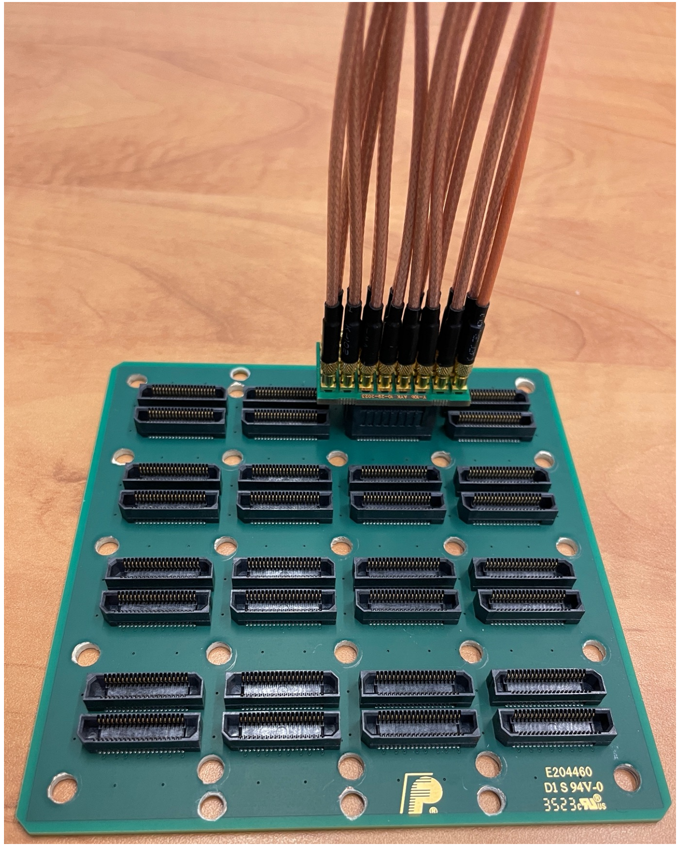



PDE (counting mode)

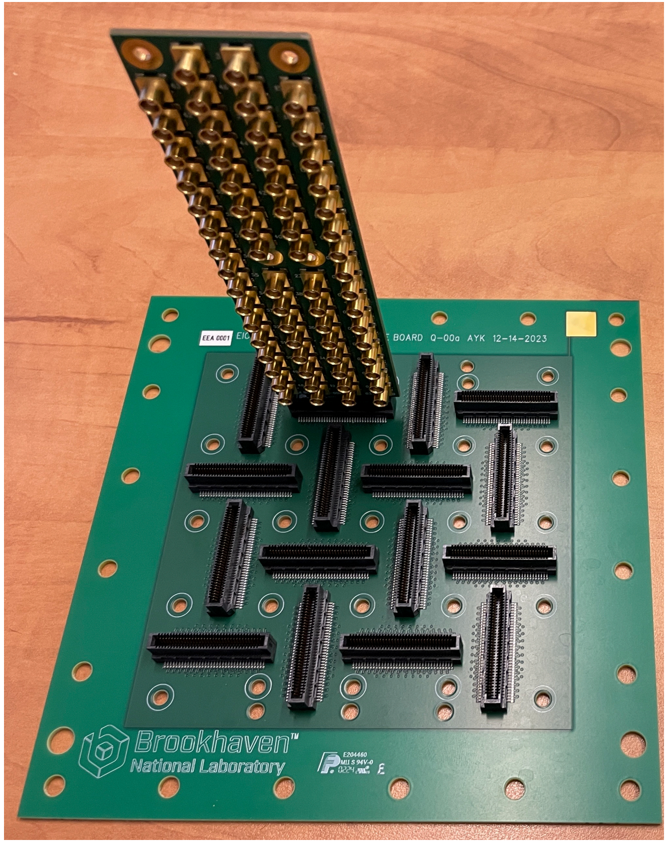



QE (PC current mode)

# First EIC HRPPD passive interfaces #1 and #2



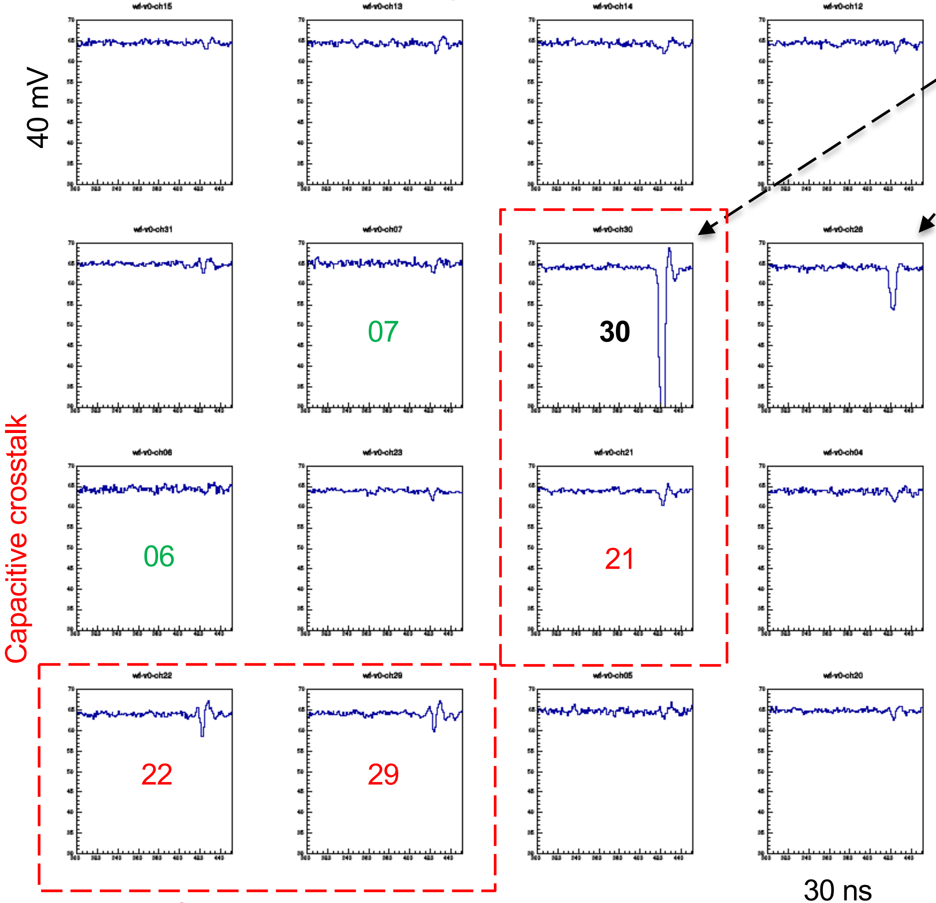

For setups with a low electronics channel count




For systematic ¼ active area scans

- ➢ Samtec -> MMCX adapter; MMCX -> MCX pigtail cables, grounding caps
- ➢ Samtec interface to the existing 64-channel edge-to-MCX adapter cards

# Crosstalk signature




These four pads are neighbors
on a Samtec ERF8 connector

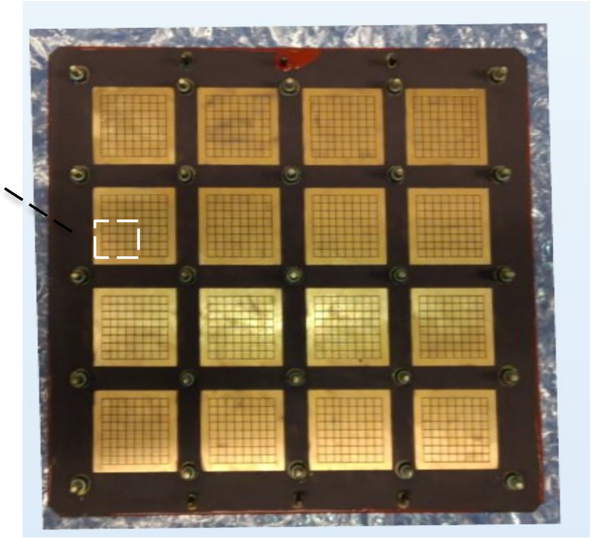
Laser spot here

“Normal” charge sharing

V1742 channel numbering 00 .. 31

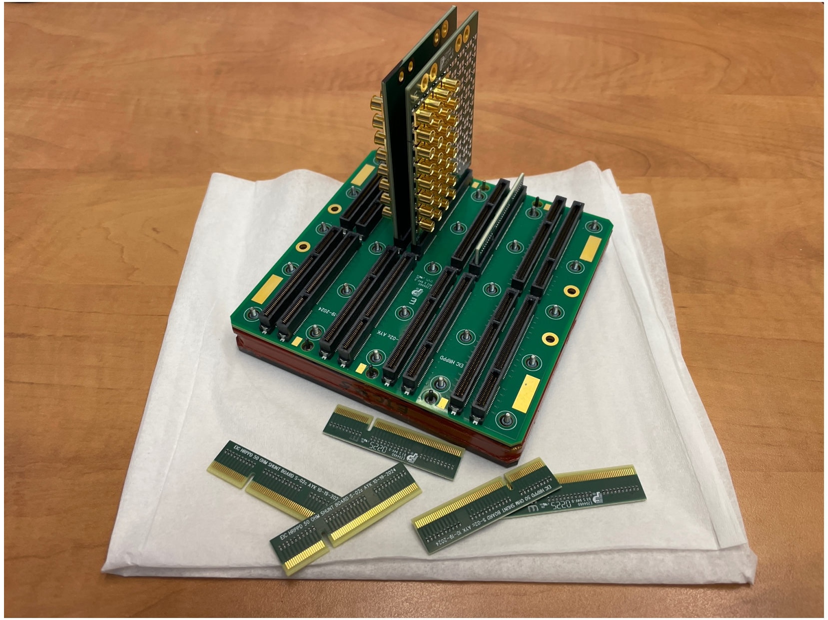
| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15 | 07 | G | 14 | 06 | 13 | 05 | G | 12 | 04 | 11 | 03 | G |
| 31 | 23 | G | **30** | 22 | 29 | 21 | G | 28 | 20 | 27 | 19 | G |

Samtec ERF8 / ERM8 connector pinout

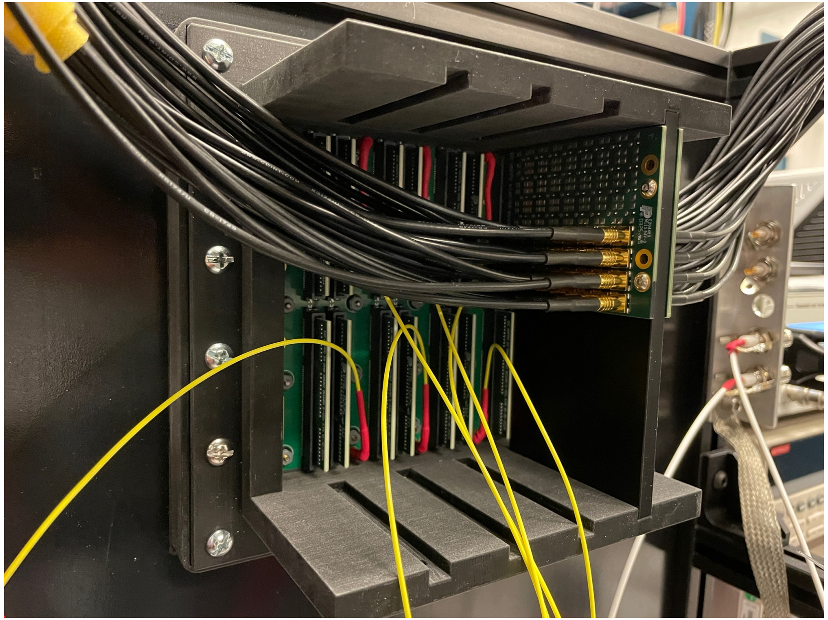


**DRS4 waveforms in a 4x4 pad area (single event)**

# Backplane #3 with a better trace isolation



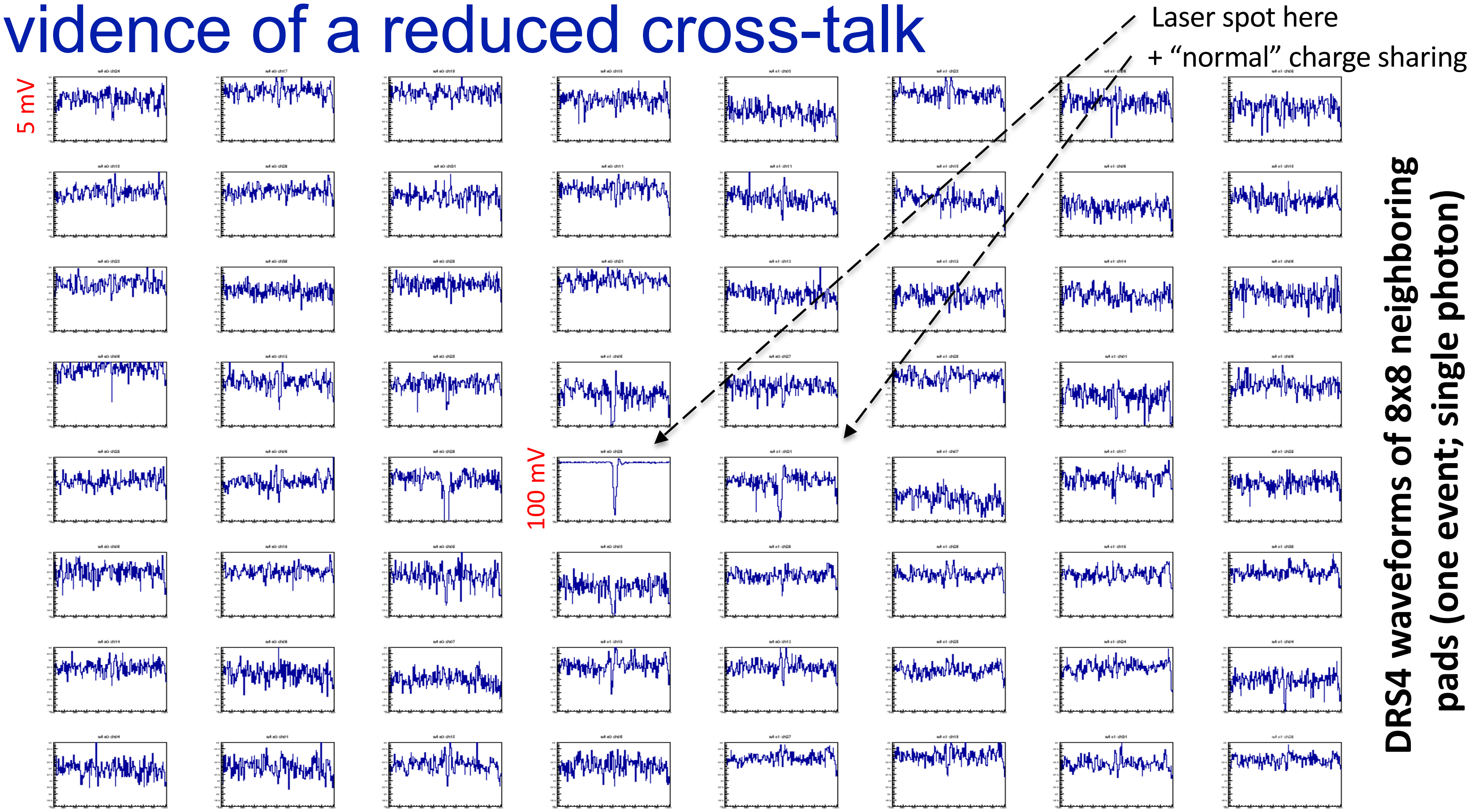
Q02c backplane, MCX adapters,
50 Ohm termination cards



HRPPD with this backplane mounted
in a QA station at BNL

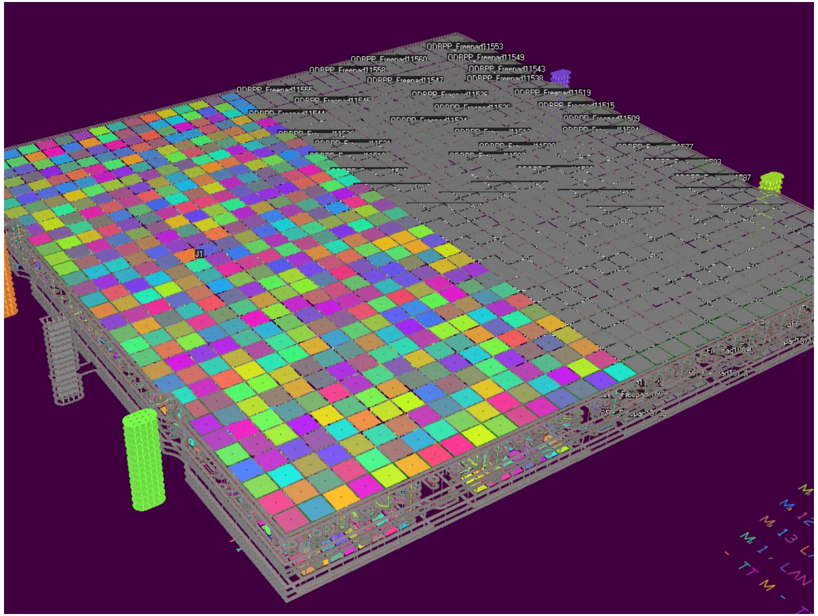
- Substantially improved grounding / individual trace isolation
- 50 Ohm termination of un-instrumented pads
- Will be used in a first FCFD ASIC implementation (JLab design; November?)

# Evidence of a reduced cross-talk



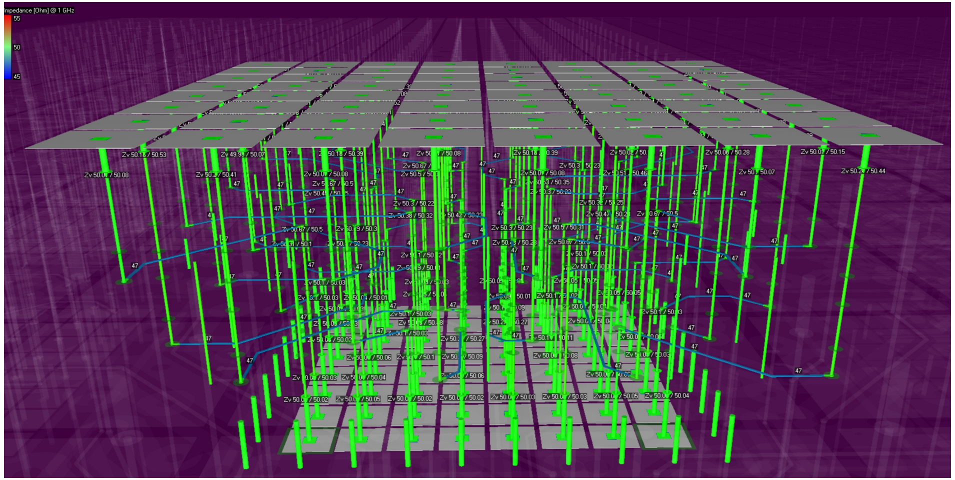

**Cross-talk reduced to ~1-2% level?**

# HRPPD + backplane signal modeling at JLab



A full HRPPD anode stackup

Use SIMBEOR (3D Electromagnetic Signal Integrity Modeling Software)



A zoomed in 8x8 pad area

- Confirmed via and trace impedance ~50 Ohm, as well as a cross-talk on a few % level
- Present focus: cross-talk minimization by optimizing grounding pad configuration

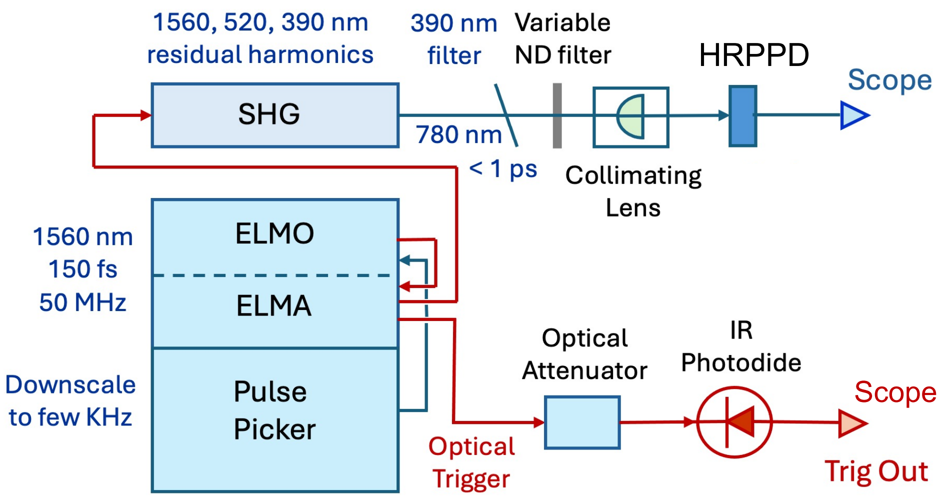
# Elmo 780 femtosecond laser system at BNL

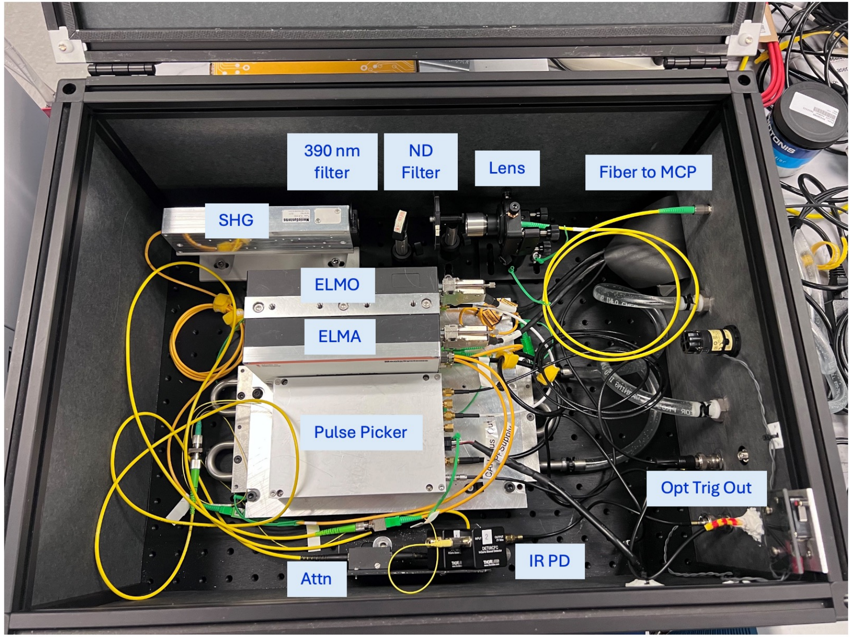
Menlo Systems Elmo 780 Erbium Fiber Femtosecond Laser

ELMO = Primary Laser Oscillator

ELMA = Optical Amplifier

SHG = 2nd Harmonic Generator

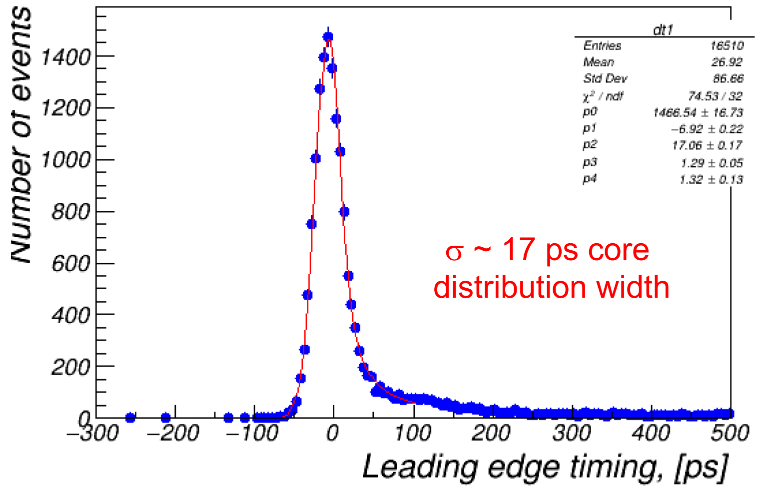


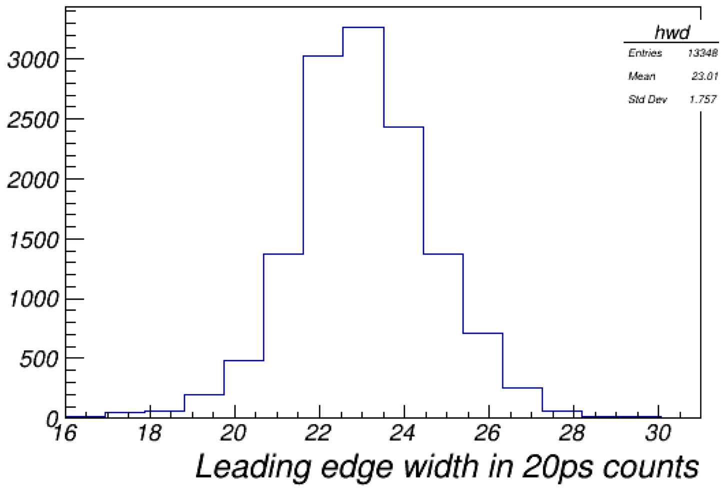




We make use of a very low intensity 3rd harmonic @ 390 nm

# HRPPD single photon timing resolution

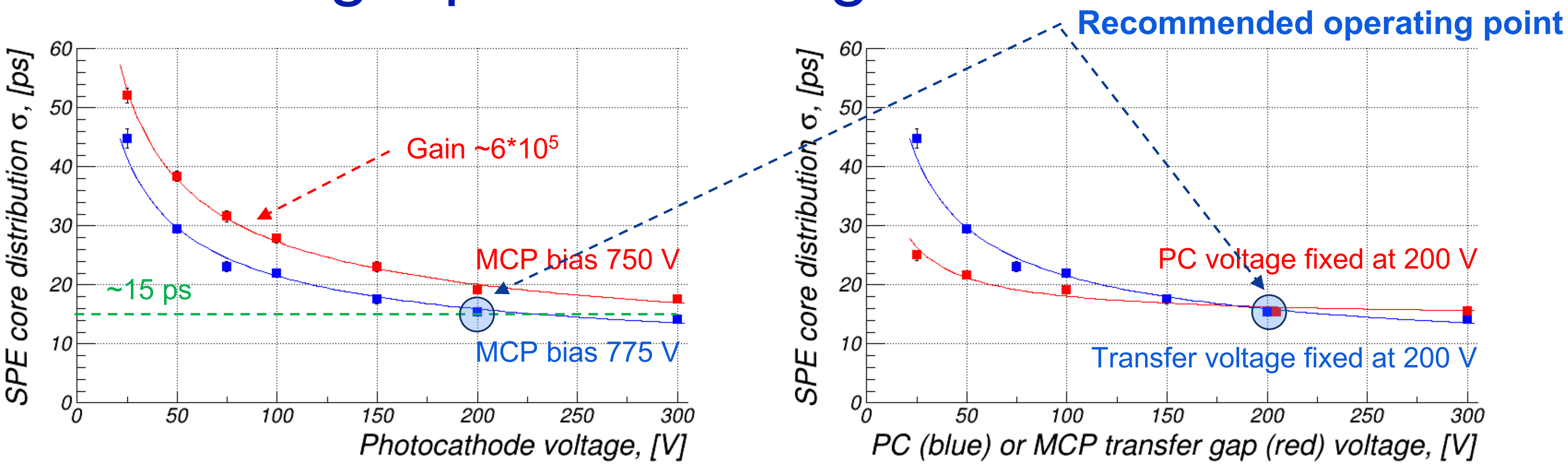
- Laser beam focused on a single HRPPD pad center; *intensity tuned down to >90% empty events*
- Fast IR photodiode signal used for triggering
- Signal waveform data taken with a Tektronix MSO66B scope (50 GS/s, 8 GHz ABW)
  - Leading edge fits [10% .. 90%] performed offline; $\Delta t = t_{HRPPD} - t_{FastPD}$ is a plotted quantity
  - Crystal Ball fit of a Gaussian+tail $\Delta t$ spectrum in a [-3$\sigma$ .. +4$\sigma$] range for all HV settings (see next slide)




HRPPD 15 @ ROP: bias voltage 775 V, photocathode and transfer voltages 200 V (gain ~$2.5 \times 10^6$)

# HRPPD single photon timing resolution




| | 25 | 50 | 75 | 100 | 150 | 200 | 300 |
|---|---|---|---|---|---|---|---|
| **750 mV** | 11 | 13 | 15 | 17 | 21 | 25 | 30 |
| **775 mV** | 27 | 34 | 38 | 42 | 49 | 55 | 61 |

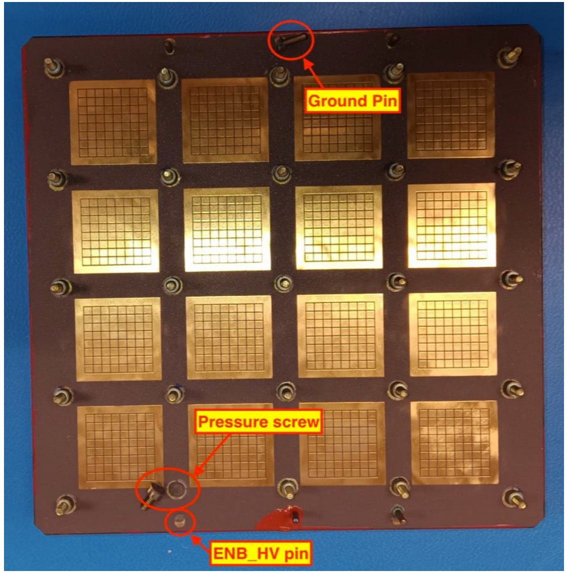
Average signal amplitude in [mV]

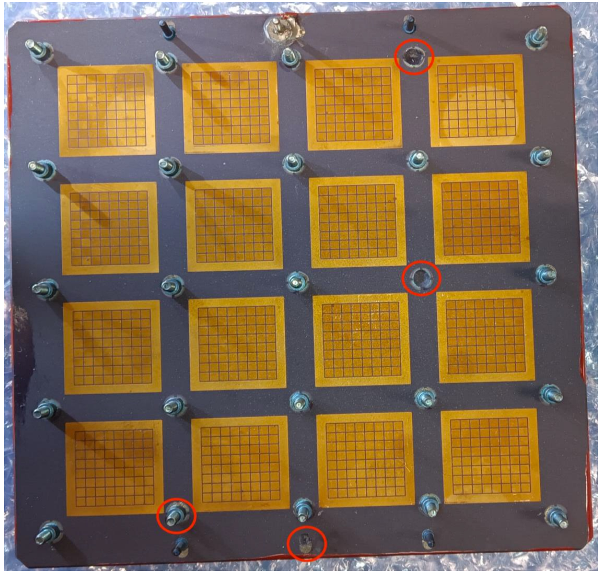
| | 25 | 50 | 75 | 100 | 150 | 200 | 300 |
|---|---|---|---|---|---|---|---|
| | 22 | 30 | | 42 | | 55 | 59 |
| | 27 | 34 | 38 | 42 | 49 | 55 | 61 |

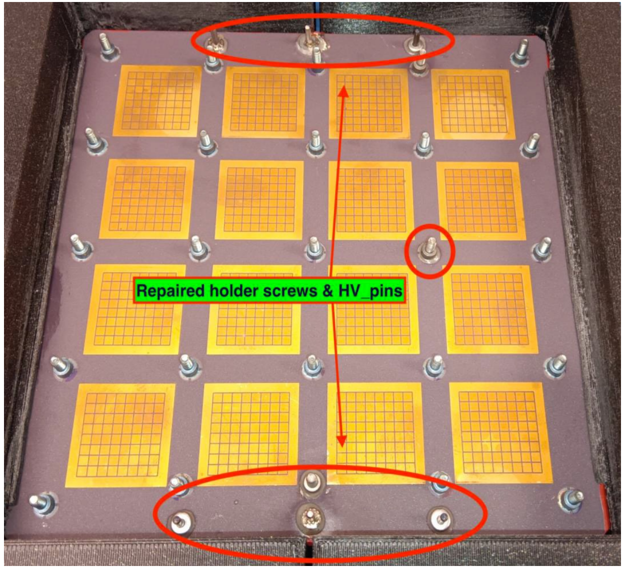
Average signal amplitude in [mV]

- SPE timing resolution is <20 ps for nominal HRPPD 15 HV settings (bias 775 V, PC & transfer 200 V)
- Photocathode voltage dependency present, beyond just a varying S/N ratio
- Much less pronounced dependency on MCP1->MCP2 transfer voltage

# External mechanical and electrical interfaces



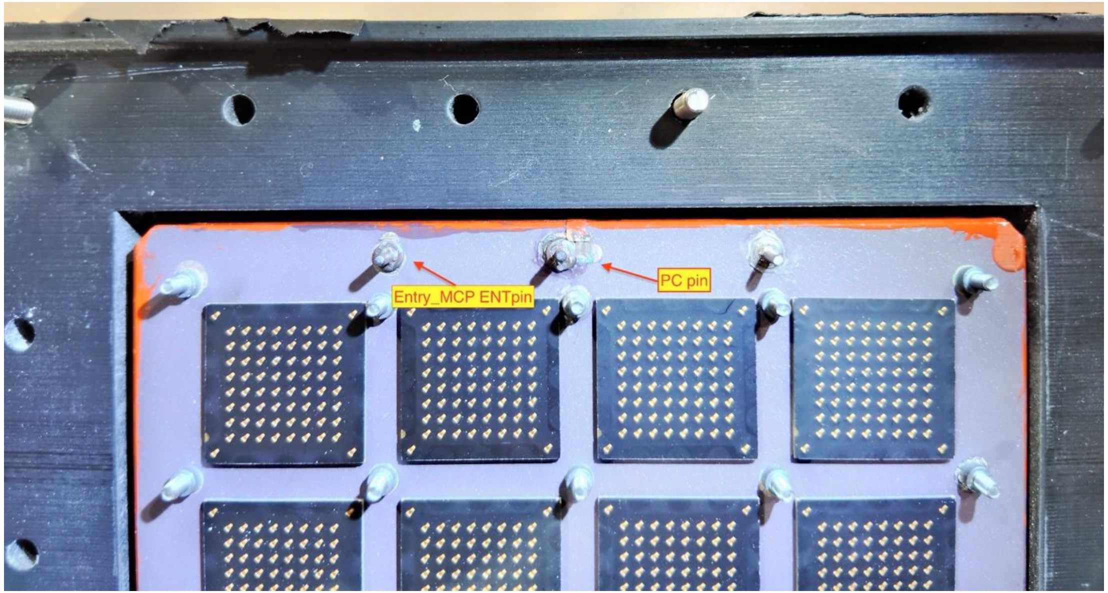


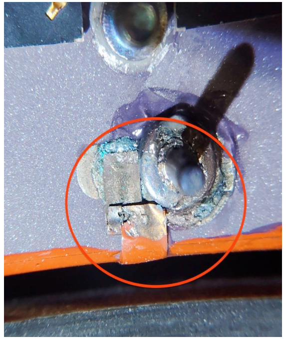

Examples of failed HV pins and screws

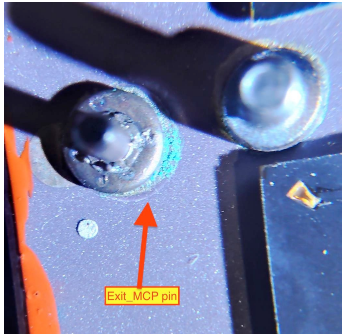
A present fix by Incom

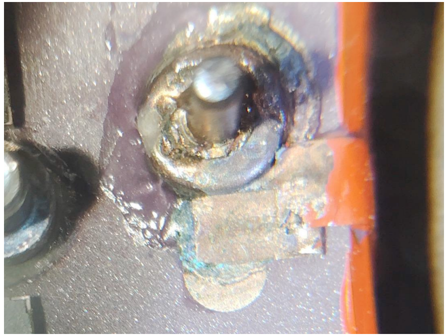
- *Several HRPPDs showed issues with falling off HV pins and mechanical screws*
  - Those were promptly fixed by Incom
- Solutions for a “final EIC HRPPD design” are being developed
  - Get rid of HV pins; embed screws into either the ceramic anode body or a permanent sturdy spacer

# Signs of corrosion in a high humidity environment



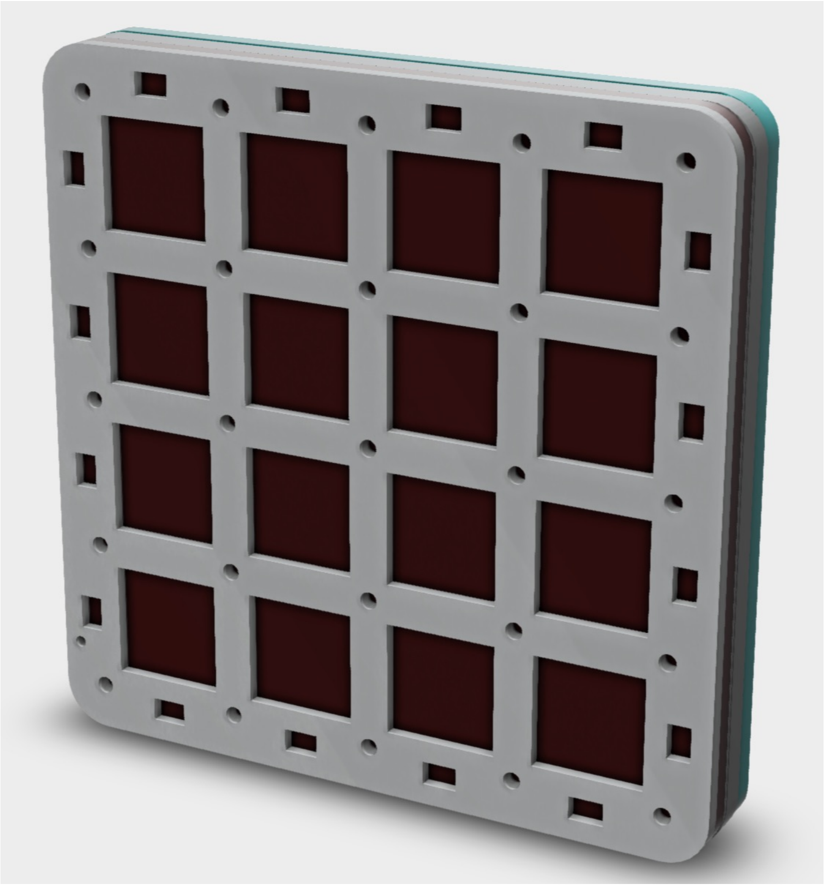


- Observed at JLab
  - Caused HV instabilities
- Kind of fixed by Incom

- Prospects:
  - Brasing will not be used for either screws or HV pins
    - What about photocathode?
  - Cannot be eliminated completely because HV leads on the vacuum side are brased as well
    - Use spot welding?

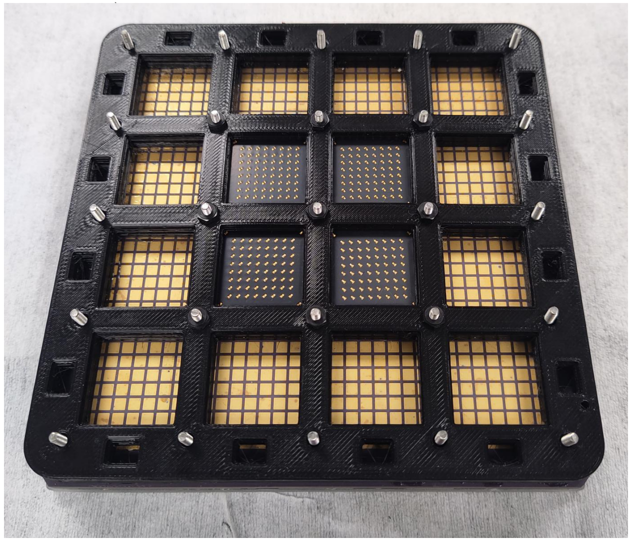
# Mechanical interface redesign

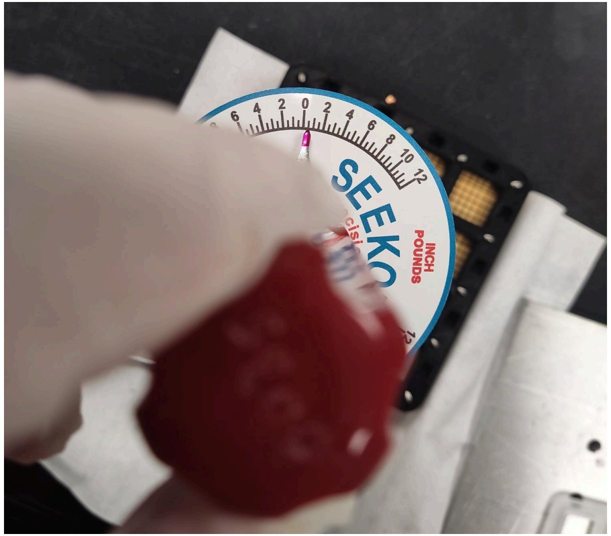


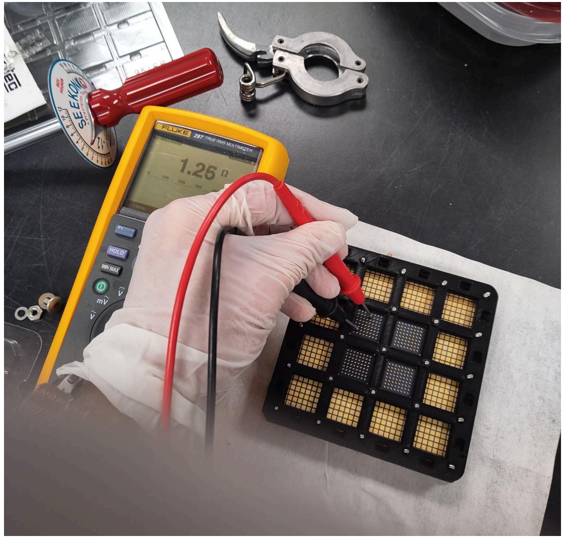
- A permanently glued ~3mm thick plastic (peek?) panel
  - "Floating" signal compression interposers (1mm pitch; extra ground pads)
  - "Floating" HV compression interposers
    - 8x MCP#2 bottom side
    - 4x for other electrodes
    - 4x ground (?)
    - Yet using pogo pins is a viable option
  - Permanently embedded hex head screws or female threaded mechanical fixtures
- Corners rounded at 8mm radius
  - Nope: should be cut at $45^0$ (Kyocera)

# Mechanical interface redesign

- A first trial at Incom performed a couple of weeks ago using an old HRPPD
  - Step #1: align and glue screws to this thick 3D printed spacer
  - Step #2: glue the spacer with screws onto the anode



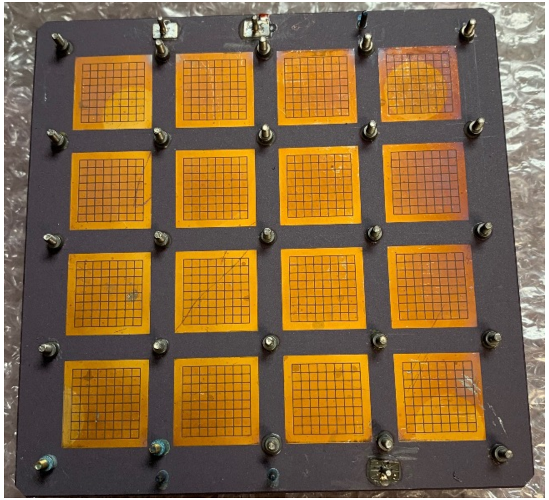


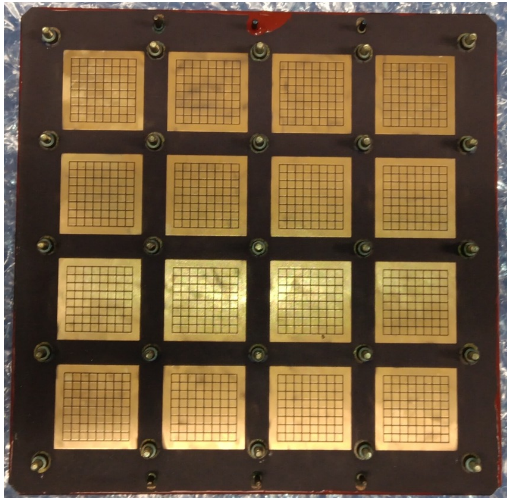

Looks encouraging (screws can sustain a substantial torque, etc)

# Gold plating tarnish issue

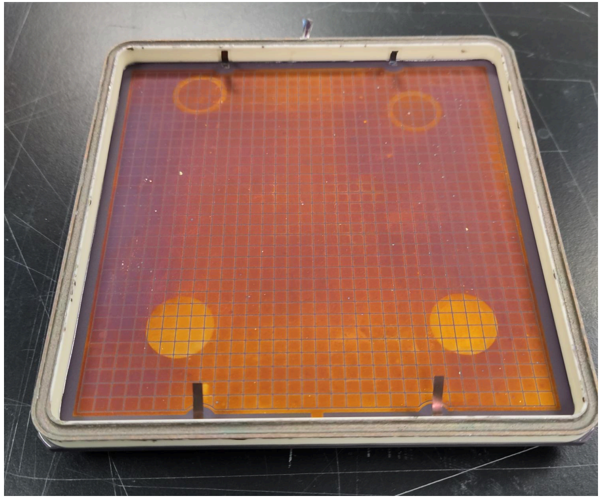
tarnish was sanded off this one



HRPPD #15 (air side)



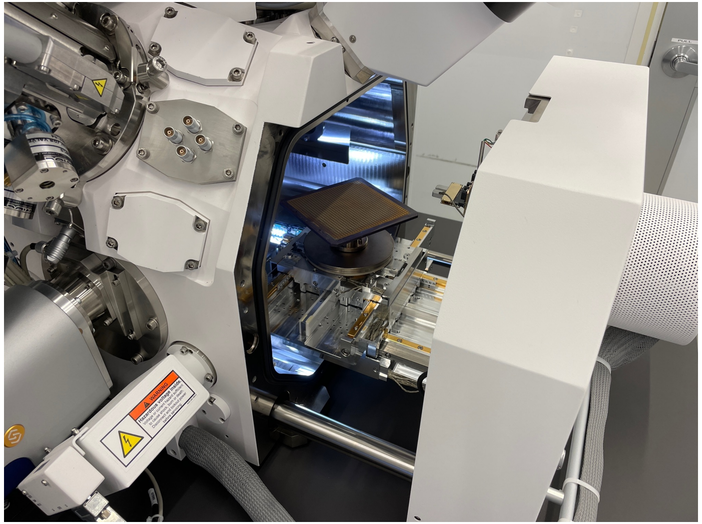
HRPPD #17 (air side)



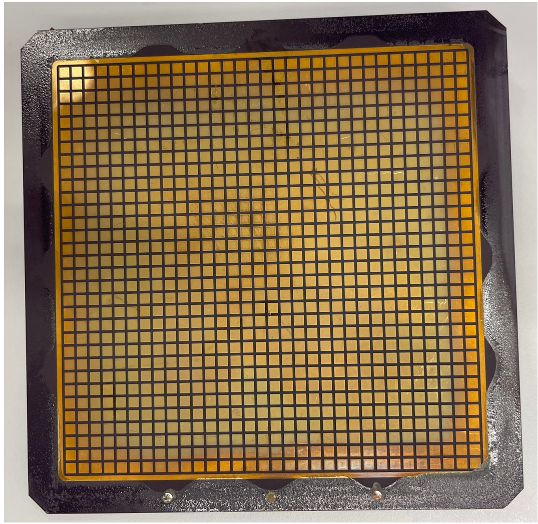
HRPPD #18 (vacuum side)

- An apparent tarnish of unknown nature is seen on all Kyocera HRPPD anodes
  - It is not visible after a ~750 C brazing cycle in vacuum needed to attach HV springs, …
  - … but a pattern of support structure used in this iteration is clearly seen after fritting in air
  - It becomes apparent only after fritting of side walls in air at about 550 C

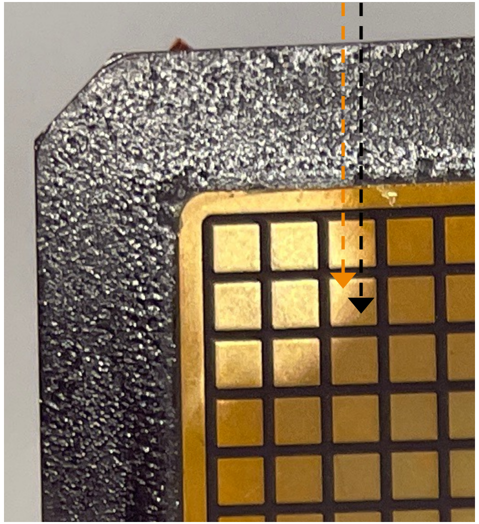
# Gold plating tarnish study at BNL



Thermo Fisher Scientific Helios G5 microscope



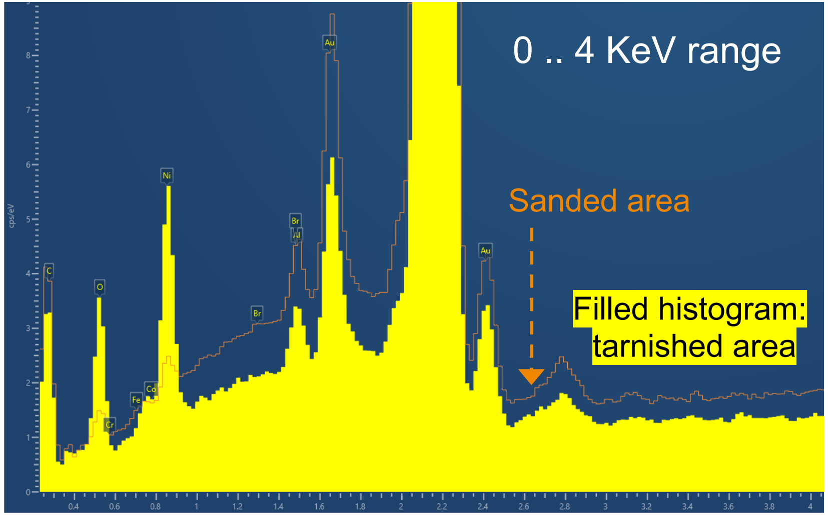
Old HRPPD anode

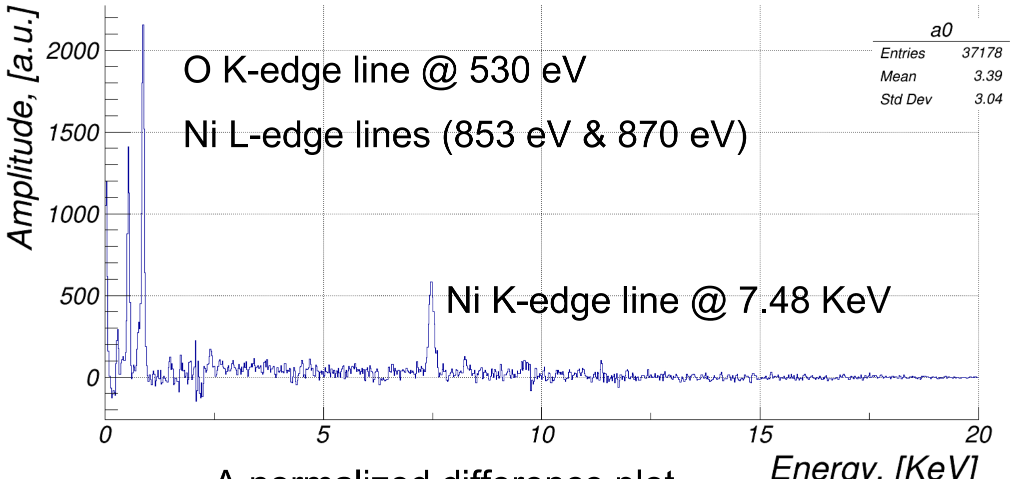



Spot under study

- Looks like a Nickel oxide present on the surface (see next slide)
  - Sure, Ni is present in the system (right beneath a thin gold plating layer)

# Gold plating tarnish study at BNL



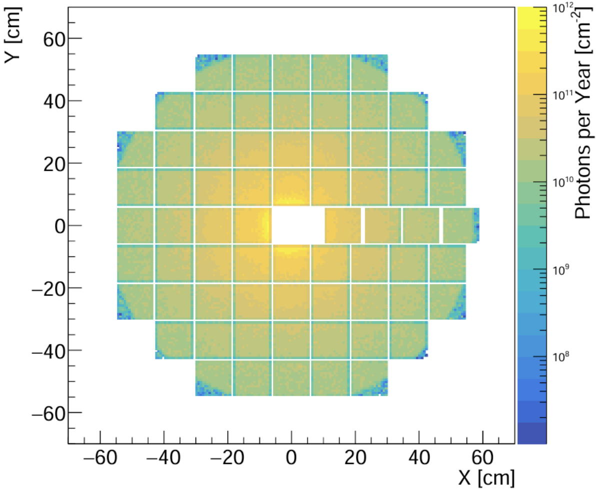

A normalized difference plot

- Whether Ni diffuses through gold plating during brazing cycle or “evaporates” off the exposed areas (and then pollutes the anode surface) is still a question
  - Ni diffusion through gold grains is a well-known effect, though …
  - … we know that obscuring / covering a fraction of pad area suppresses tarnish
  - There is a strong Ni signature at the very edge of gold-plated pads in the data

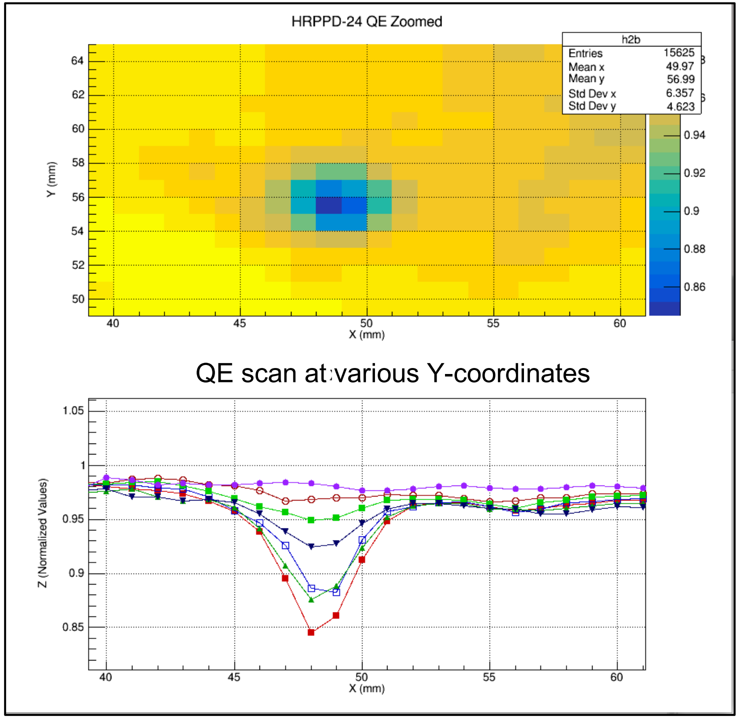
# Accelerated pixel-based aging studies

- Setups at JLab / BNL / INFN Trieste
- Experts in LAPPD aging (UT Arlington) participating
- Microscopic photon fluence modeling at ePIC pfRICH location by BNL and Yale

https://indico.bnl.gov/category/605/

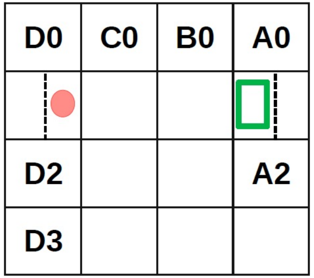


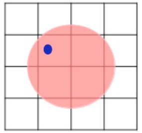

$<10^{12}$ $\gamma$/cm$^2$/year from all sources [preliminary]



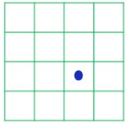

First HRPPD aging data from JLab
[after ~$2*10^{19}$ $\gamma$/cm$^2$ irradiation at a nominal HV]

# Accelerated pixel-based aging studies at INFN



AGEING D1B



REFERENCE A1T

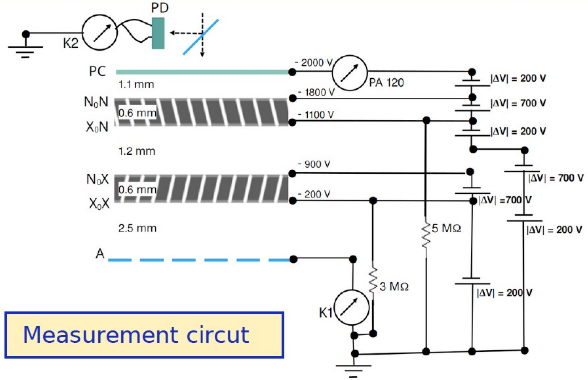
$r_{AGEING}$: 5.32 mm

$r_{FOCUSED}$: <0.5 mm

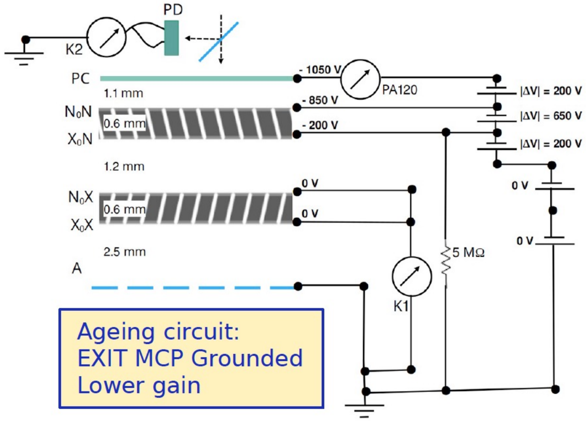
**$10^{14}$ photons/cm² in 10 years** at ePIC (simulation)

10 years → 10 days in lab ***(Accelerated ageing)***

| Measurement | HV bias | Light source | Light spot |
|---|---|---|---|
| **PDE SCAN** | ROP | pulsed Laser, λ=0.20 (OD1) | focused |
| **QE SCAN** | -50 V at PC<br>EntryMCP at G | Cont. LED<br>$I_{LEDSET}$=300 mA | focused |
| **Average QE** | -50 V at PC<br>EntryMCP at G | Cont. LED<br>$I_{LEDSET}$=300 mA | defocused |
| **Gain** | ROP | pulsed Laser, λ=0.01 (OD2) | focused |
| **DCR** | ROP | X | X |
| **APR** | ROP | pulsed Laser, λ=3 | focused |

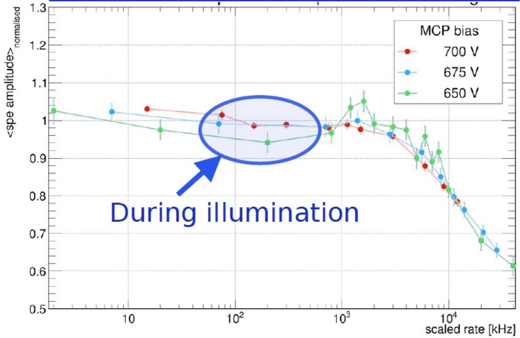



Measurement circut



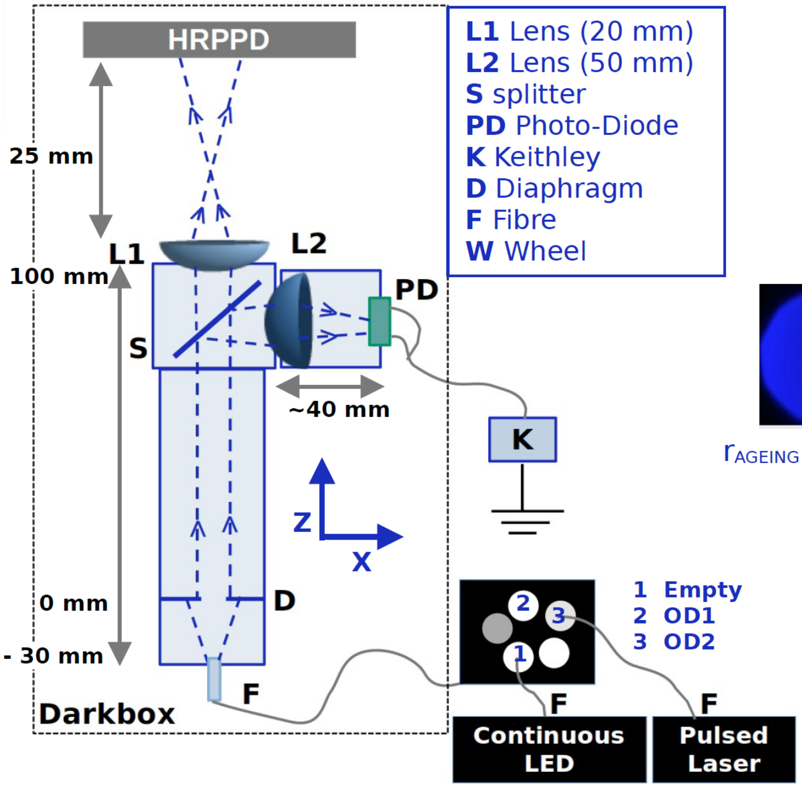

Ageing circuit:
EXIT MCP Grounded
Lower gain

Universal amplitude vs. rate curve
($10^6$ gain)

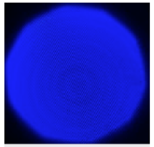



Rate capability is a big concern

# Accelerated pixel-based aging studies at INFN




- Optics installed on movable (XYZ) system
- Same optics at two different Z positions – focused/ defocused spots
- Same optics at two different X positions – Ageing/Reference region



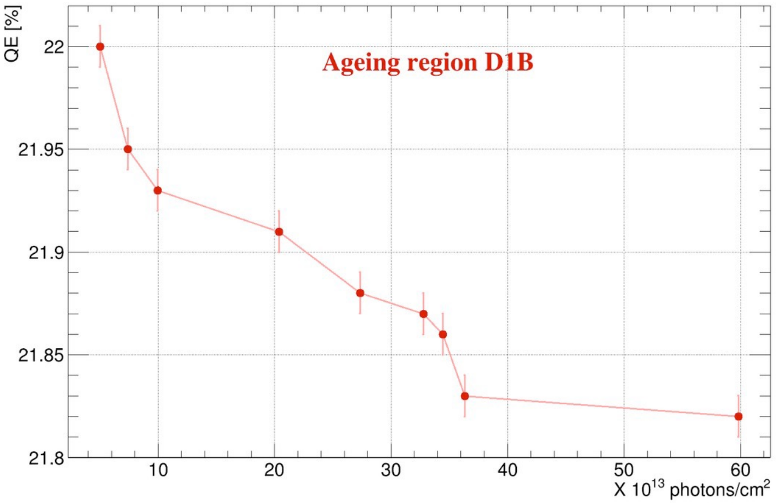
$r_{AGEING}$: 5.32 mm

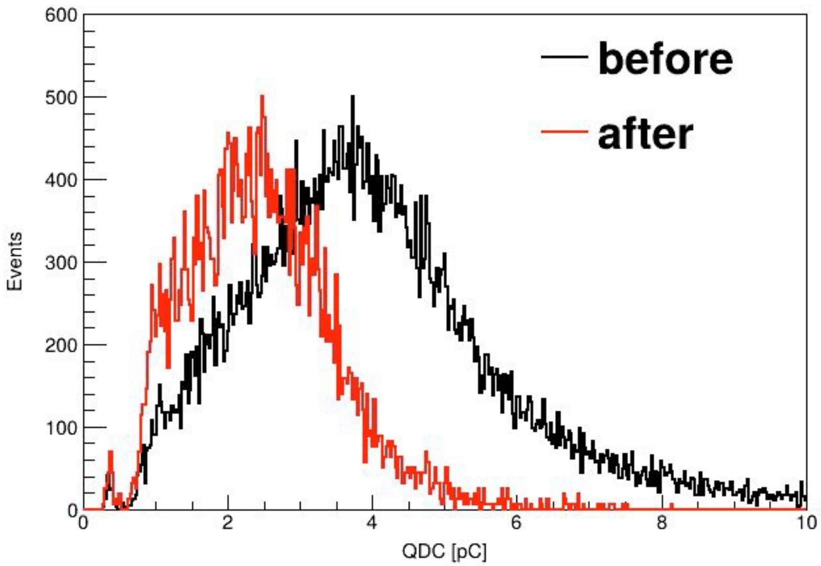
| Five optics configurations (405 nm) | |
|---|---|
| Picoquant Pulsed Laser | Continuous LED (M405F3) |
| ~1% SPE (λ=0.01), OD2 **measurements** | Fibre direct **QE** LED $I_{SET}$ = 300 mA |
| ~20% SPE (λ=0.2), OD1 **measurements** | Fibre via 1 **AGEING** LED $I_{SET}$ = 85 mA |
| ~3 PE (λ=3) **measurements** | |

Same optics for ageing and intermediate measurements

# Accelerated pixel-based aging studies at INFN

- Preliminary results after illumination equivalent to ~60 years of ePIC pfRICH running



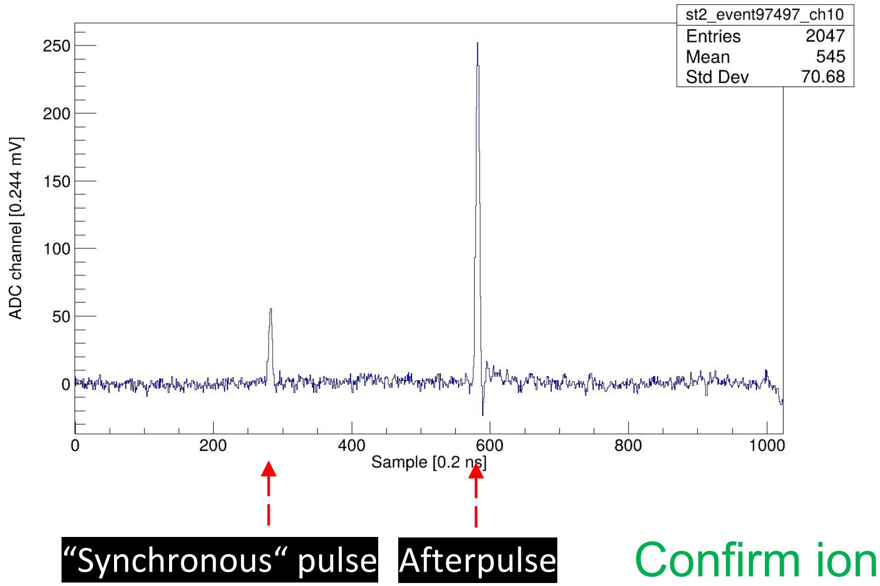

No measurable QE degradation

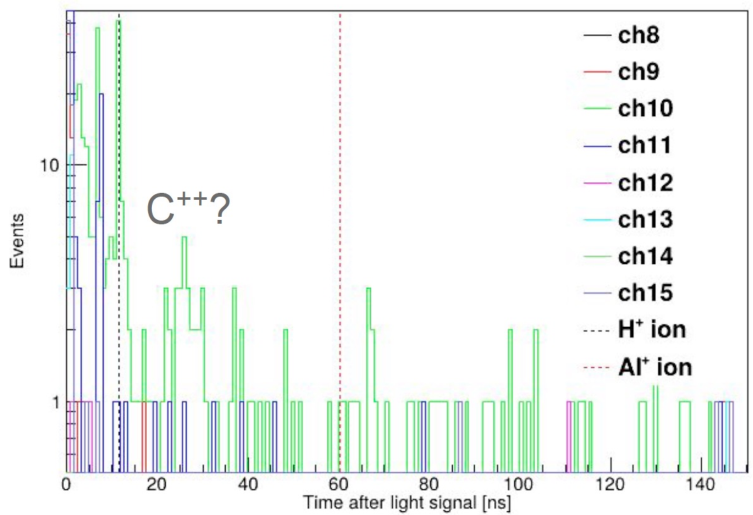
Gain drop of ~40%

# Study of afterpulses at INFN

- using high threshold =5*40 samples (=5*10 mV) >=SPE (51 mV) observe few afterpulses, but without clear structure;
- most afterpulses are seen in the laser spot ch10;
- Seems to observe $H^+$ peak, and peaks at 6.7 ns and 26 ns.

$10^5$ pulses, λ=0.22

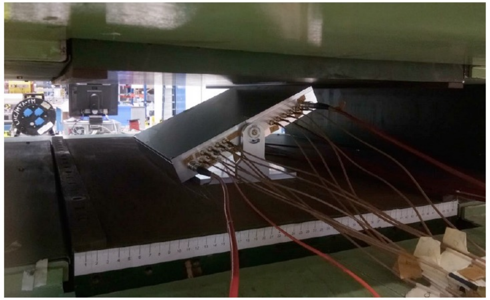


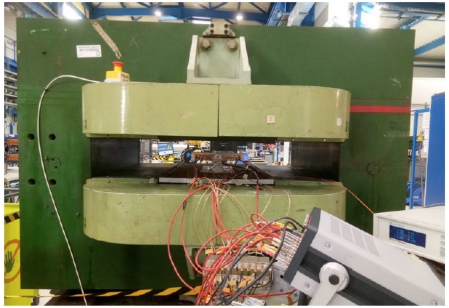

Confirm ion feedback related afterpulsing on a <1% level (at a used HV); work in progress

# LAPPD performance in a magnetic field by INFN

➢ 2023 / 2024 campaigns at CERN



- Vertical dipole magnets, Current to **B**-field converter
- Water cooling system, room temperature operation



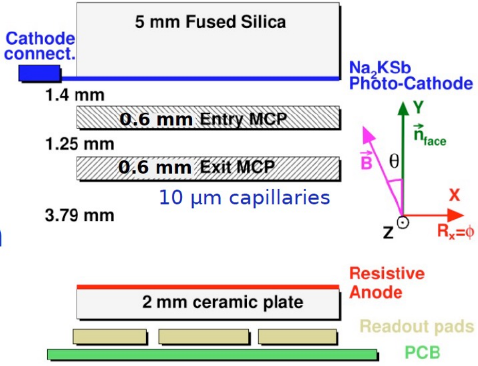
- Inclined Darkbox
- Picoquant pulsed laser (λ=405 nm),
- Laser Sync. out fast trigger for DAQ
- CAEN V1742 digitizer module

**MNP-17**

- 0.5 T
- field direction UP
- 30 cm aperture ~ ±40⁰

**M113**

- 1.5 T
- field direction Up & Down
- 17 cm aperture ~ ±27⁰



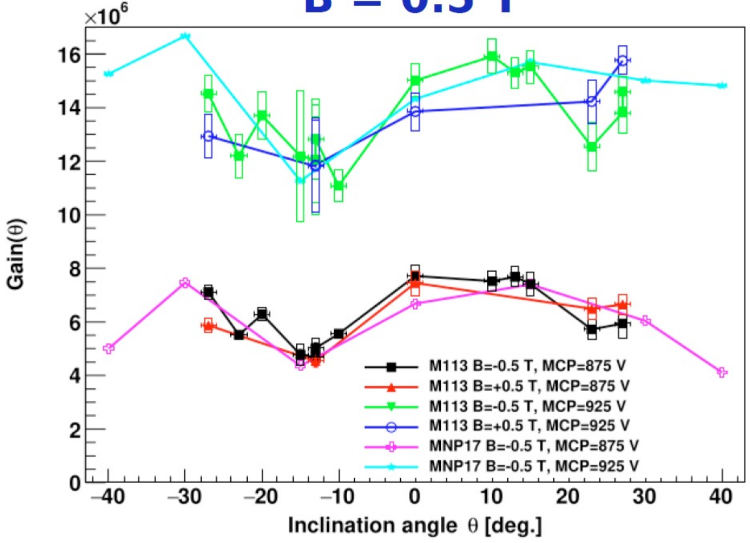

NOT TO SCALE

θ in Chevron plain

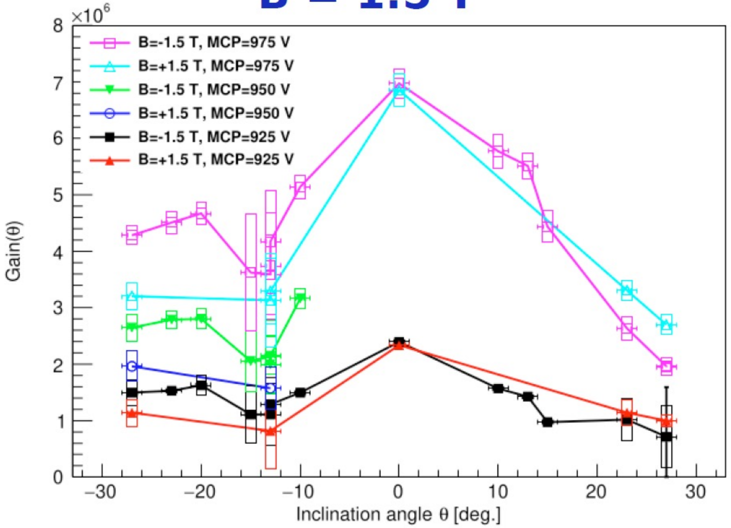
θ +ve when **B**-field along capillaries of Entry MCP

# LAPPD performance in a magnetic field by INFN

B = 0.5 T




B = 1.5 T



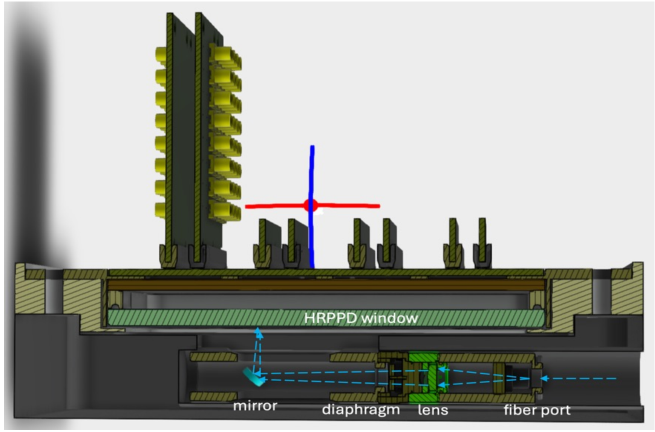

- Very small angular dependence at **B** = 0.5 T
- Some dependence at $\theta > 20^0$ and **B** $\geq$ 1.0 T
- Dips at -13$^0$ are observed

Gain drop can be largely recovered by ramping up a bias voltage

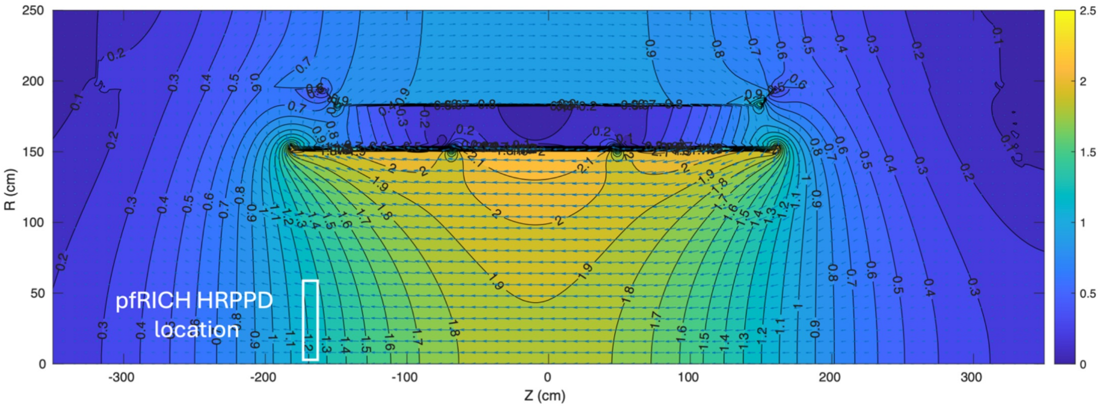
Measurements with an HRPPD are being planned

# B-field resilience studies at BNL


A type 18D72 2.2 Tesla dipole with a 6” gap




Dark “box” setup



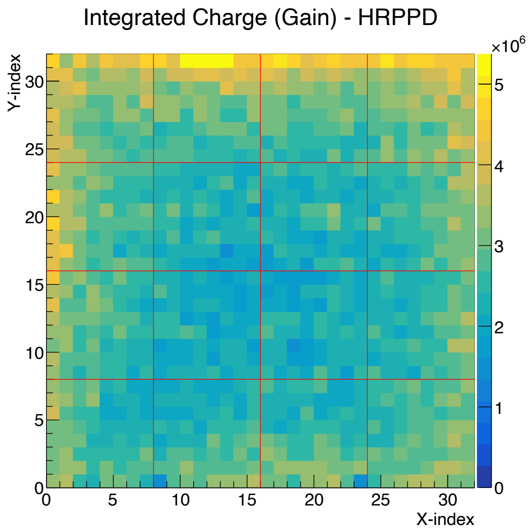

ePIC solenoid field map

- All optical components as shown in the above picture have been received
- Mechanical setup is finalized

Measurements: week of Nov,17

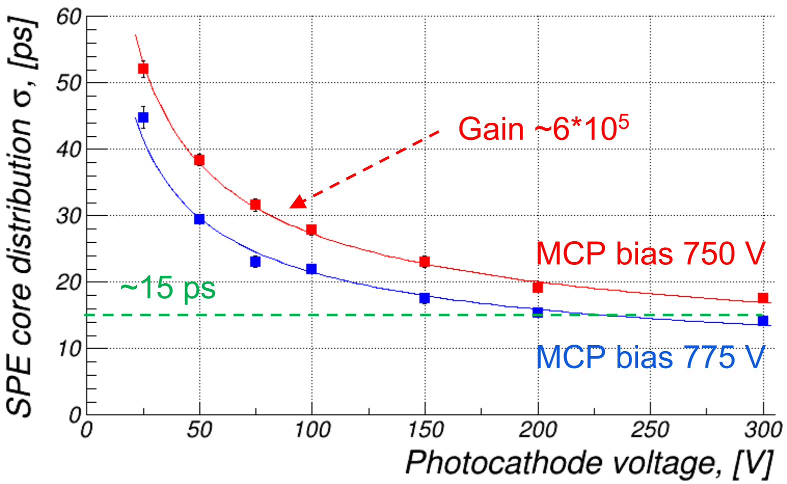
# Our present EIC HRPPD performance assessment

- Yields: **all ten** Kyocera anodes were functionalized into working HRPPDs at the end
  - s/n 15 .. 17 (success)
  - s/n 18 .. 22 (failure, after an attempt to use a second sealing tank)
  - s/n 23 .. 29 (success, after establishing a way to recycle the lower tile assemblies)
- QE: higher than expected and remarkably uniform across the active area
- Gain: stable operation at ~$10^7$ and beyond
  - We will hopefully not need more than $10^6$ in the experiment
  - Uniformity is relatively poor, with gain going up by a factor of ~2 towards the active area edge
- Timing: looks better than expected
  - As a consequence, ePIC pfRICH should be able to use single photons as a complementary $t_0$ measurement
- Dark rates: very small, even at mid-$10^6$ gain
- High-rate capability seems to be questionable
- B-field resilience & aging yet to be quantified

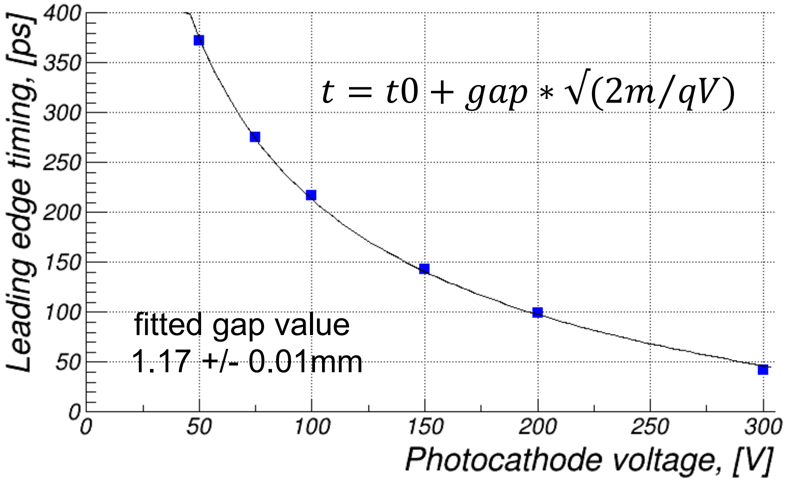


# *Backup*

# HRPPD single photon timing resolution



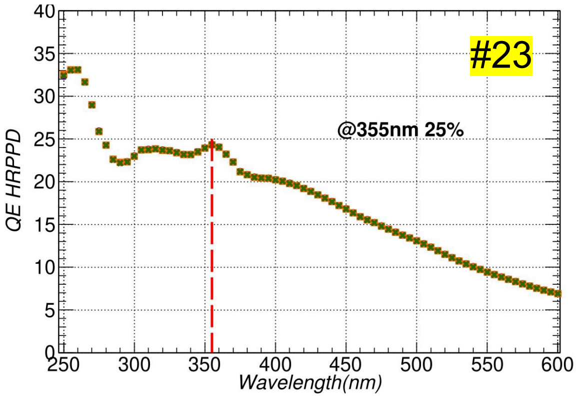

Single photon timing resolution

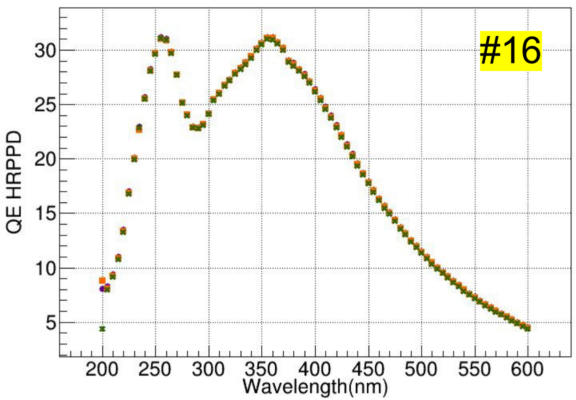


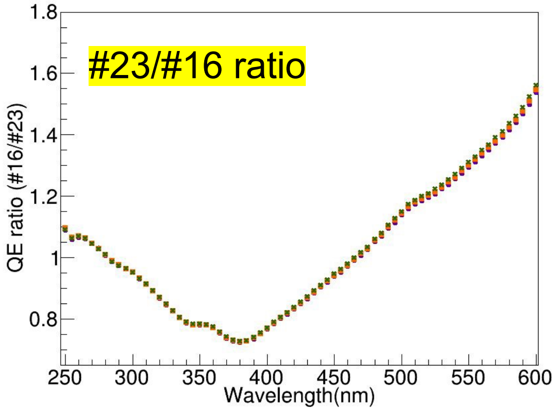

Primary electron drift time PC->MCP#1

- SPE timing resolution is <20 ps for nominal HRPPD 15 HV settings (bias 775 V, PC 200 V)
- A common sense cross-check: primary electron drift time decreases with PC voltage as expected
  - Nominal PC->MCP#1 gap is 1.1 mm per design [compare to a fit value of ~1.2 mm]

# QE measurements @ BNL & Incom [differential scans]

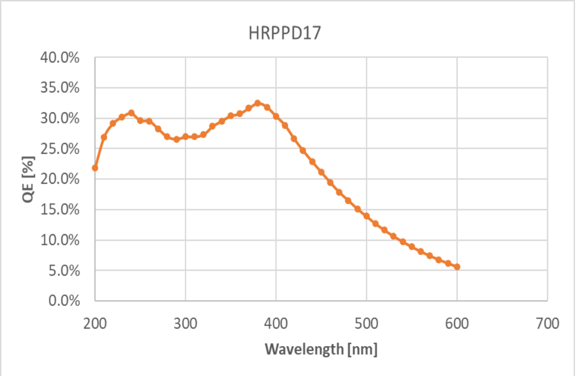


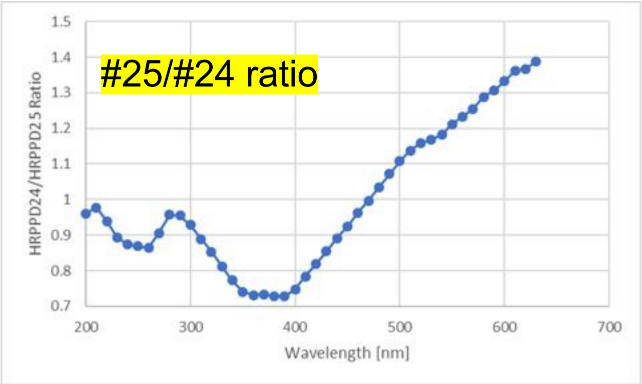




*by Chandradoy Chatterjee (INFN Trieste)*


High QE area



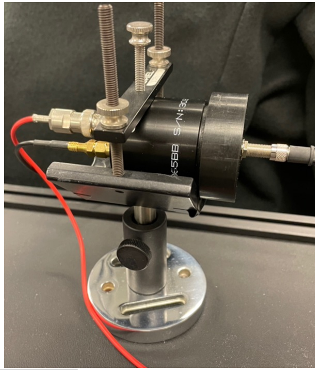

Center spot (X-profile)

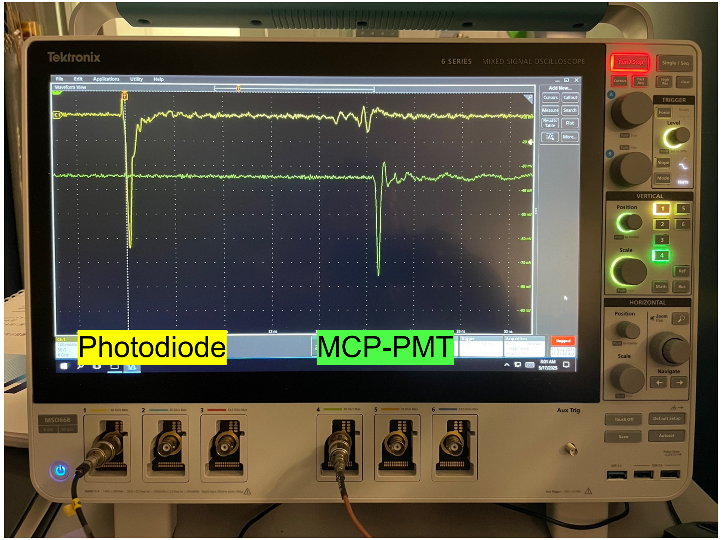



*by Alexey Lyashenko (Incom)*

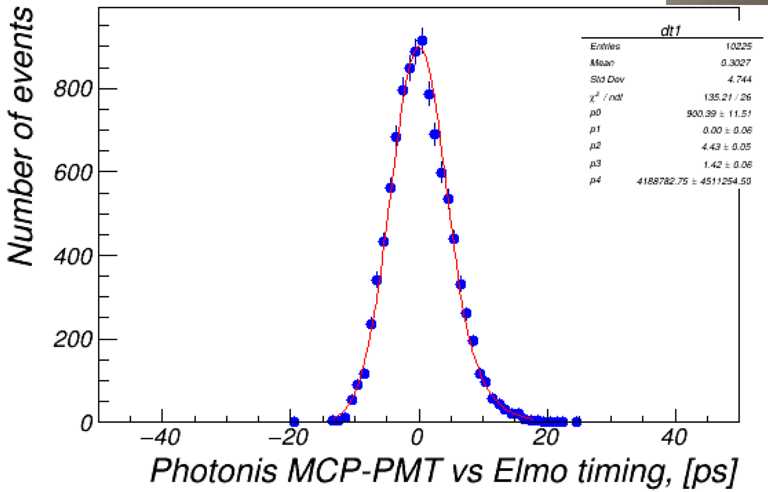
# Test measurement with a fast Photonis MCP-PMT

- ➢ Laser beam pointing to a Photonis FT-16 MCP-PMT window (multi-photon mode)
- ➢ Fast IR photodiode signal (see last slide) used for triggering
- ➢ Signal waveform data taken with a Tektronix MSO66B scope (50 GS/s, 8 GHz ABW)
  - ➢ Leading edge fits [10% .. 90%] performed offline; $\Delta t = t_{FT\text{-}16} - t_{FastPD}$ is a plotted quantity



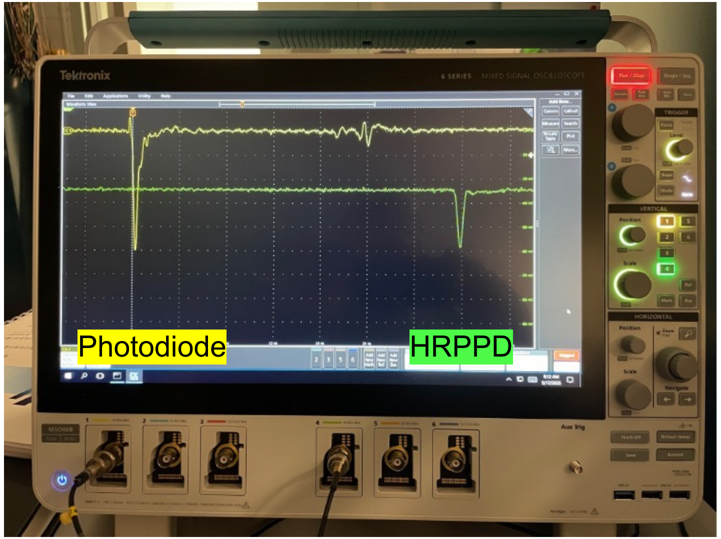

FT-16: a very fast >100mV signal

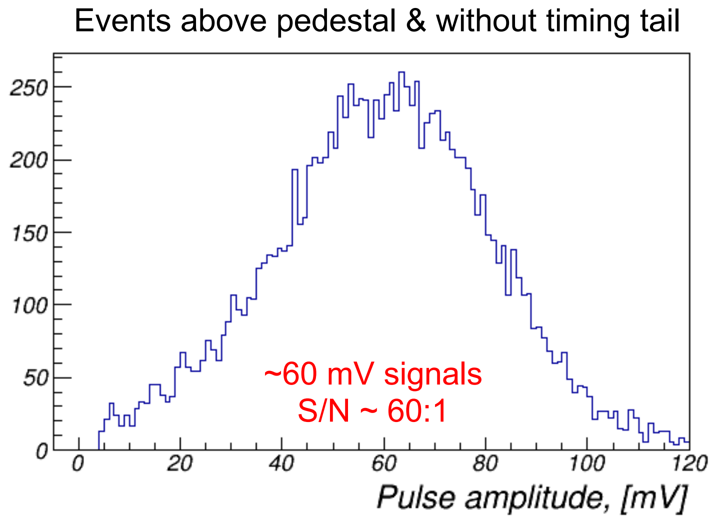



<5 ps timing resolution observed

# HRPPD single photon timing resolution

- Laser beam focused on a single HRPPD pad center; *intensity tuned down to >90% empty events*
- Fast IR photodiode signal used for triggering
- Signal waveform data taken with a Tektronix MSO66B scope (50 GS/s, 8 GHz ABW)
  - Leading edge fits [10% .. 90%] performed offline; $\Delta t = t_{HRPPD} - t_{FastPD}$ is a plotted quantity

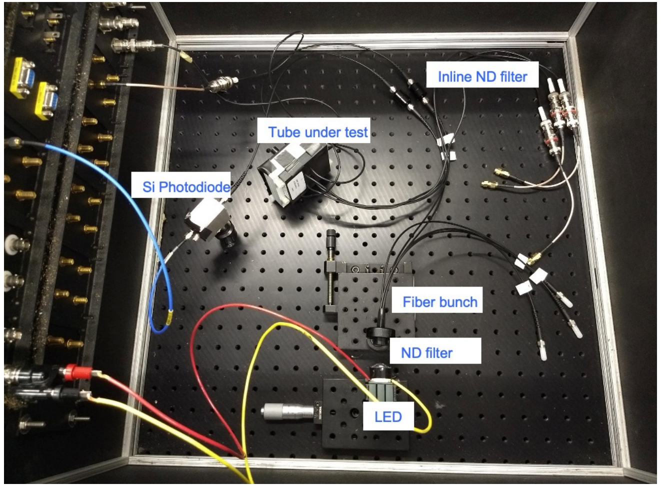


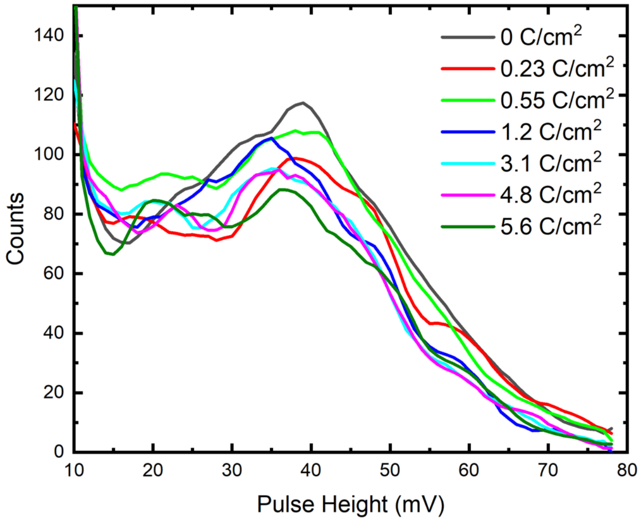




HRPPD 15 @ ROP: bias voltage 775 V, photocathode and transfer voltages 200 V (gain ~$2.5*10^6$)

# Accelerated pixel-based aging

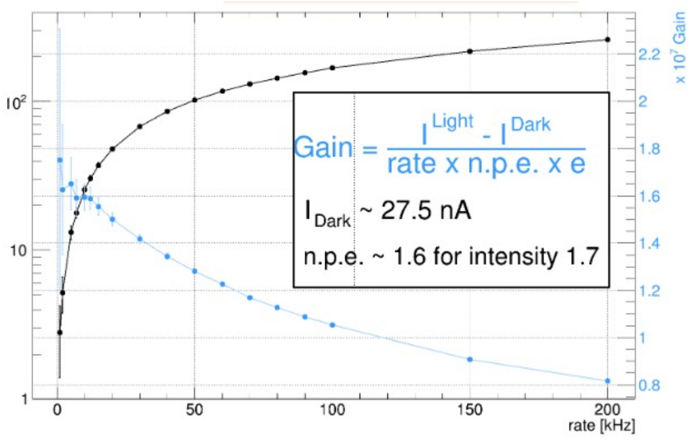
- Procedure:
  - Measure an MCP-PMT pulse height distribution at a single PE level before the test
  - *Irradiate a small region (4.6 mm diameter in case of this study) of MCP-PMT active area, at a close to saturation photon flux*
  - Measure single photon pulse height distribution at regular intervals
- LAPPD #64 was used in this study
- A QE scan was performed at Incom afterwards and did not reveal any damage after a 5.6 $C/cm^2$ of extracted charge




*V. Chirayath, LAPPD 2022*

# Gain saturation measurements at INFN




*Gain saturation as effect of increasing light intensity*