# Characterisation of a 16-by-96 multi-anode MCP-PMT

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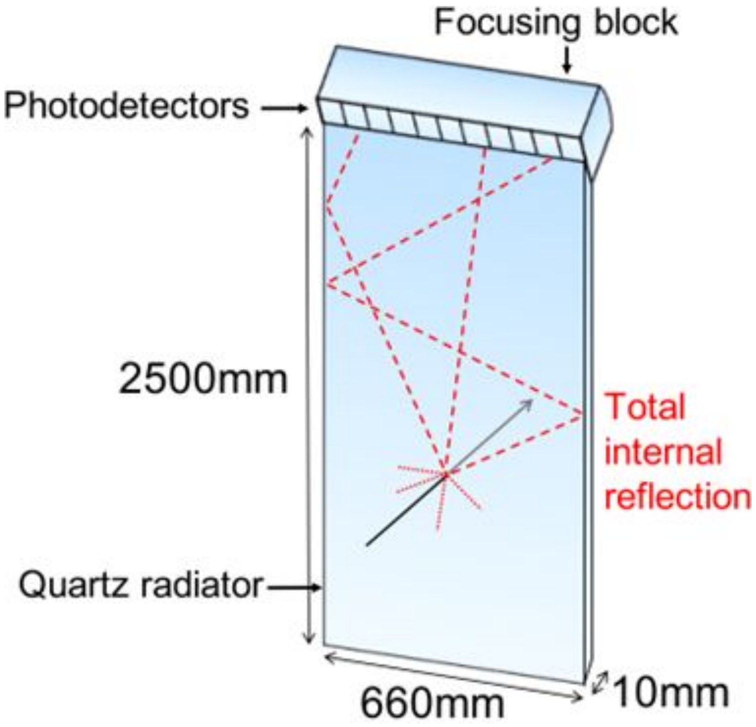
14th FAST workshop  May 18–22 2025

# Quick introduction to TORCH

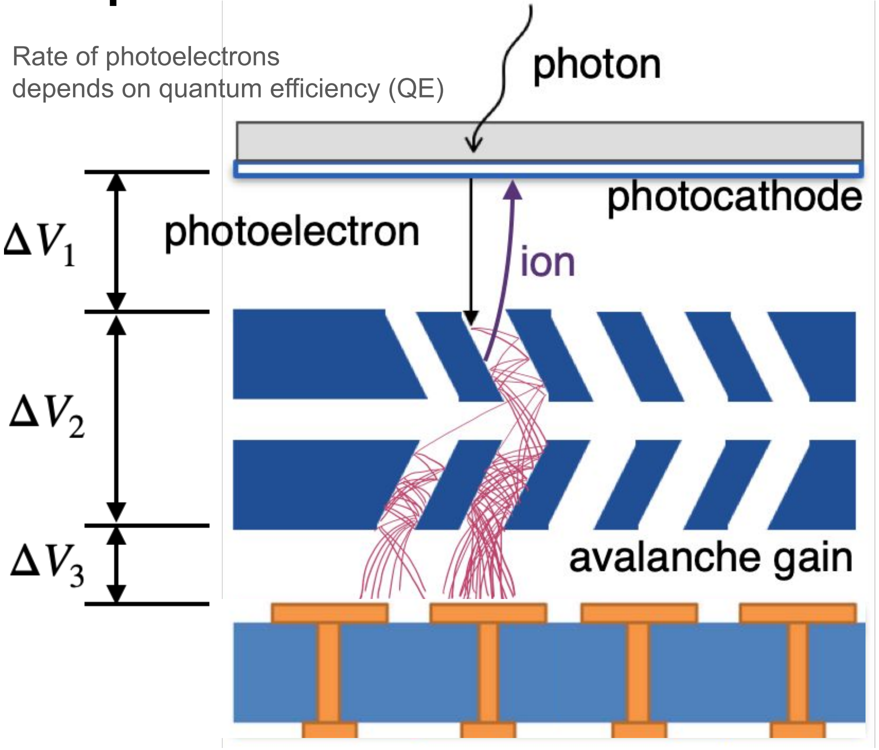
- The Time Of internally Reflected CHerenkov detector (TORCH)* is a proposed detector as part of LHCb experiment's upgrade 2 plan.
- Aim to provide low momentum (2–15 GeV/*c*) particle identification using time-of-flight.
- Charge particles produce Cherenkov photons which propagate to the edge of detector.
- A single photon timing resolution of around 70 ps is needed to reach 15 ps per track, assuming 30 detected photons per particle.
- Microchannel-plate photomultiplier-tubes (MCP-PMTs) are proposed as a fast photon detector.



*[Blake et al., Nucl. Instrum. Meth. A1050 (2023) 168181]

# Micro-channel-plate photomultipliers

- MCP-PMTs have been used in many previous applications within High energy physics such as Belle II TOP and PANDA DIRC*.
- Cherenkov photons get converted to electrons by the cathode.
- Chevron structure leads to multiple impacts with MCP pores, causing avalanche gain.
- There is ongoing work into simulating these effects.

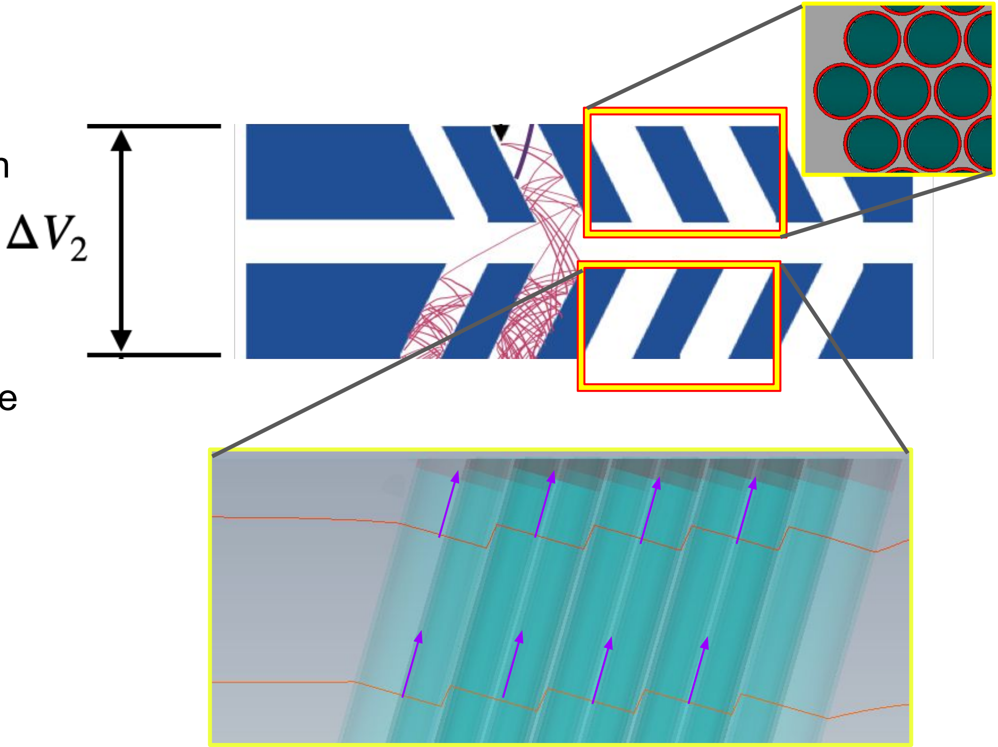


*Cut through of a multi-anode MCP-PMT*

* NIM A 952 (2020) 162208
NIM A 952 (2020) 161790

# Micro-channel-plate

- Made up of a hexagonal array of pores with diameter of O(10 μm).
- High axial fields accelerate the electrons.
- Secondary electrons are produced by a emissive layer coated on the MCP’s surface and pore walls leading to avalanche gain effect.
- Number of secondaries one electron produces is angle and energy dependent.
- MCP-PMTs have an intrinsically fast time response.



*bird's-eye view of a  MCP*

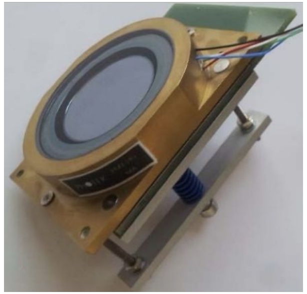
*Equipotential lines inside the pore, with arrows showing the direction of the electric field*

# Initial development of MCP-PMTs for TORCH

- Multi-phase R&D programme to develop MCP-PMTs for use in TORCH*
- Phase I: single-channel circular MCP-PMT, with ALD coated pores to achieve an extended lifetime of (>5 C/cm2).
- Phase 2: multi-channel circular MCP-PMT with charge sharing between pads.
- Phase 3: 53-by-53mm square MCP-PMT with 64-by-64 pads, which are ganged to form 8-by-64 pixels designed to meet the resolution requirements of TORCH.

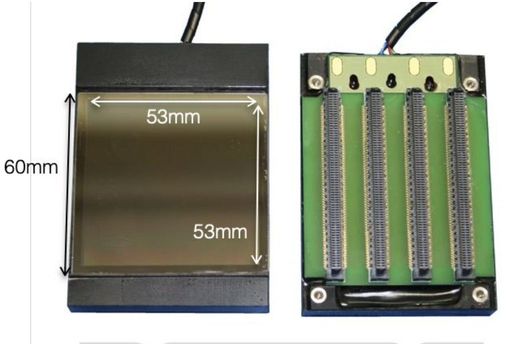
*JINST 10 (2015) C05003

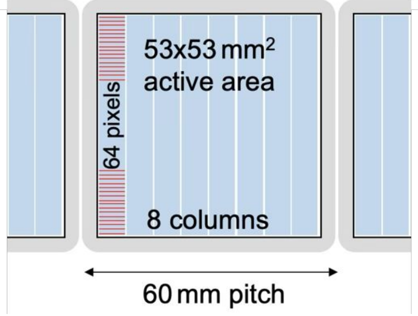
Phase 1



Phase 2

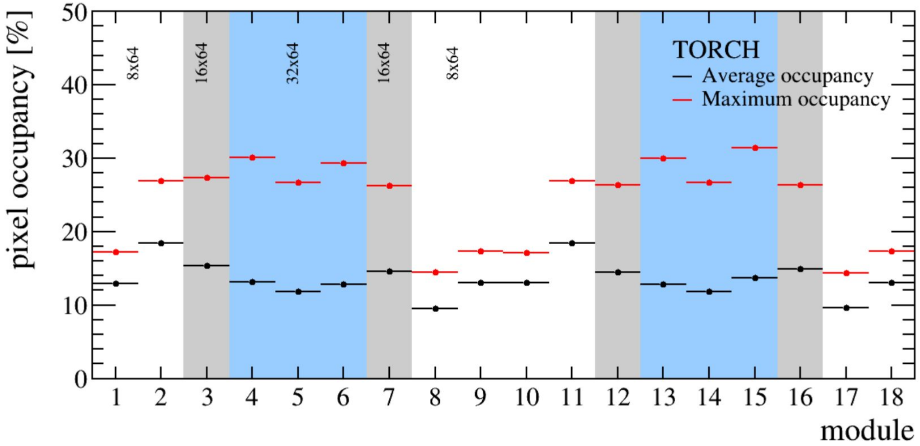
Phase 3





# Motivation for layout for new MCP-PMT

- At LHCb Upgrade 2 luminosities per-pixel occupancy becomes large.
- Aim to reduce occupancy with directly coupled PMT output:
  - Reduces charge-sharing and detector occupancy.
  - Requires increased granularity in fine-pixel direction to compensate for loss of centroiding.

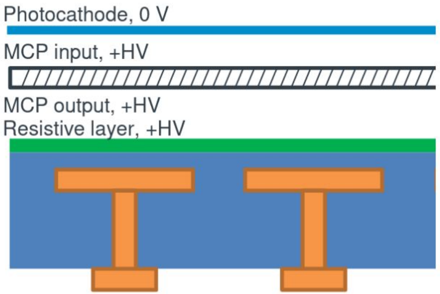


Pixel occupancy from FTDR
(at 1.4x10$^{34}$ cm$^{-2}$s$^{-1}$)

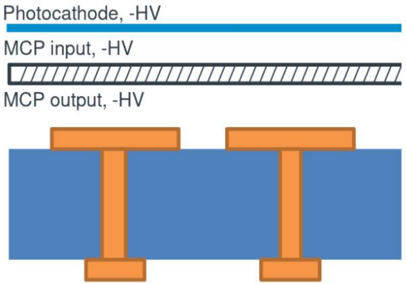
# Motivation for layout for new High granularity MCP-PMT

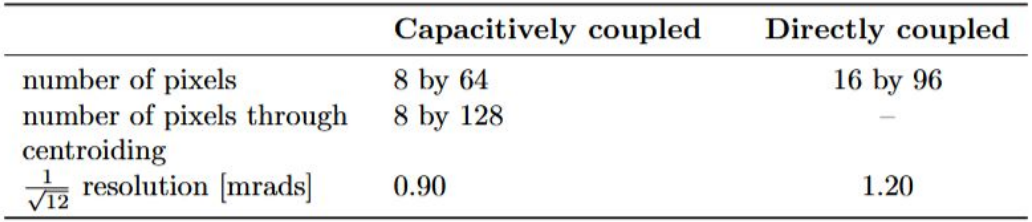
- In the phase 3 MCP-PMTs, a resistive layer spreads charge over multiple pixels.*
- Capacitively coupled through ceramic onto resistive layer.
- Readout made via anisotropic conductive film*.
- New device has a directly coupled anode (via vias) designed to reduce charge sharing.

Capacitively coupled readout



Directly coupled readout





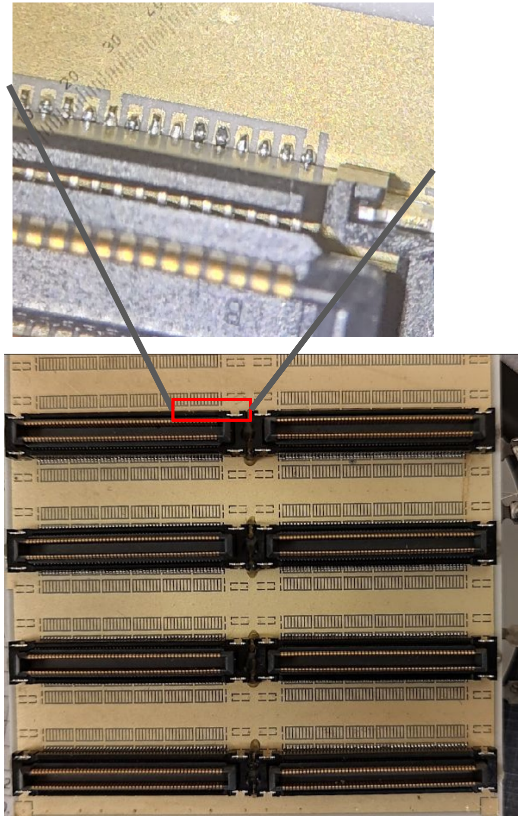
| | Capacitively coupled | Directly coupled |
|---|---|---|
| number of pixels | 8 by 64 | 16 by 96 |
| number of pixels through centroiding | 8 by 128 | – |
| $\frac{1}{\sqrt{12}}$ resolution [mrads] | 0.90 | 1.20 |

Timing performance is linked to reconstruction of the Cherenkov emission angle. The spatial resolution of the PMTs is key for this. Here we are aiming for ≈ 1 mrad.

* JINST 10 (2015) C05003

# New anode layout

- High granularity ceramic anode with 16-by-96 pixels.
- 110 pin Hirose FX25 connectors used for readout with one in eight pins grounded.
- Connectors are laser soldered to the ceramic anode to limit heating of the device after indium sealing.



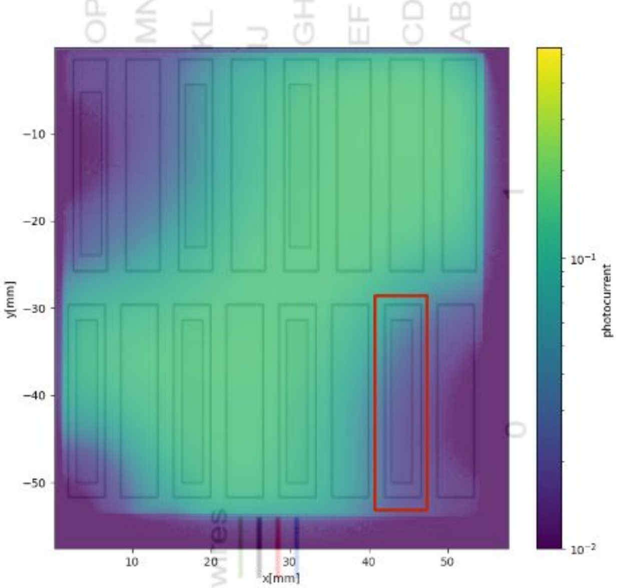
*High density ≈ 0.2mm gap between pins.*

*First test device with half the anode instrumented.*

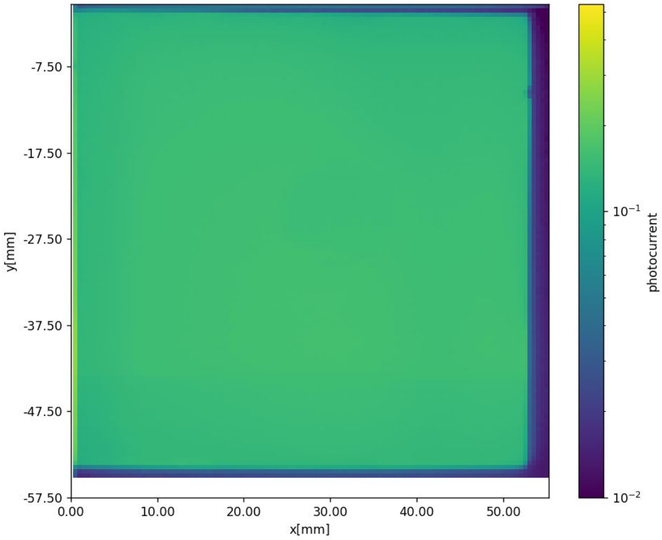
# Quantum efficiency uniformity

- We measure the QE across the full active area of the cathode in 0.25 mm steps.
- First MCP-PMT has non-uniform efficiency.
    - Likely caused by a poor vacuum seal.
    - Dead area has not grown with time.
- Second device has good uniformity.

This is a relative, light source not calibrated



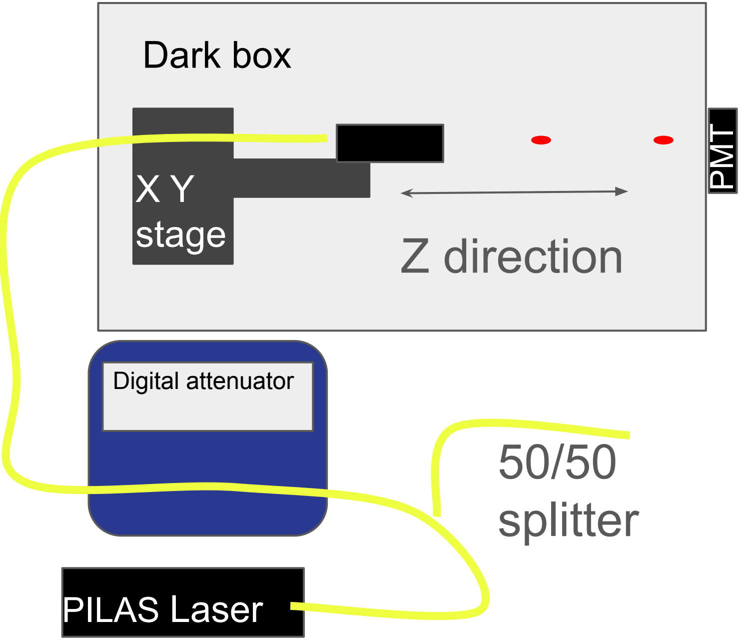
*Similar but separate setup as before but measures the current across the photocathode MCP gap*



*Second MCP-PMT without anode connectors but better QE*

Note: background shows location of anode layout with dark rectangles indicating instrumented connectors

# Lab setup for gain characterisation

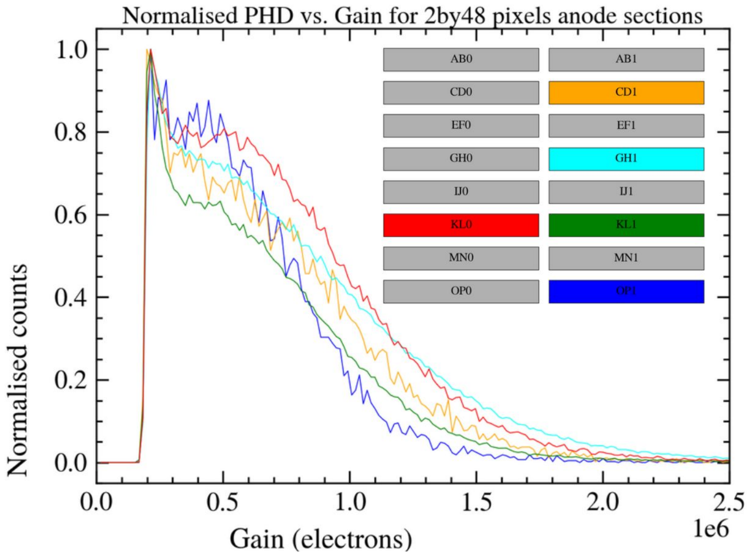


*Monomode fibre optic cable passing light into the box.*

- Optically coupled a 45 ps pulsed Pilas laser with a wavelength of 407 nm and jitter < 3 ps.
- Attenuating laser output with a digital attenuator to get to single photons.
- Laser position in the dark box is controlled by a motorised X/Y translation stage.
- Repetition rate of the laser pulse is controlled by a DG645 delay generator.
- Laser focused to better than a 50 µm diameter.

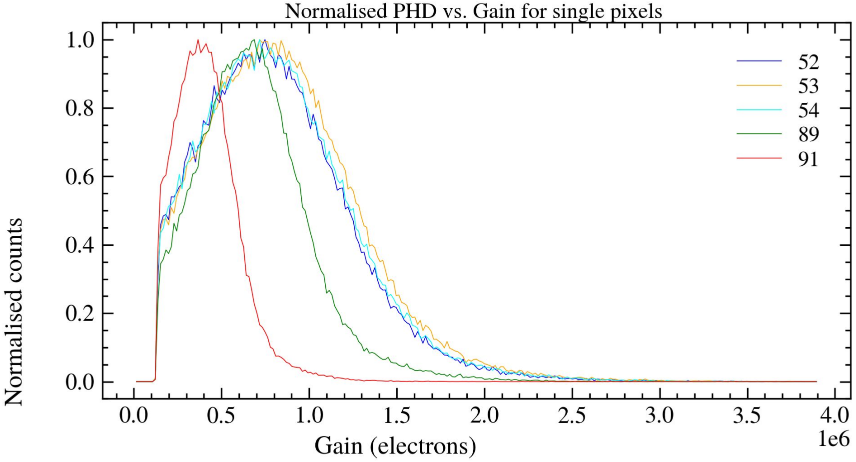
# Gain uniformity

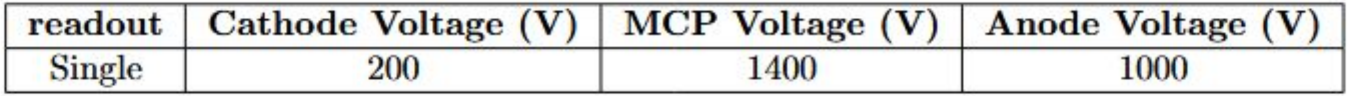
- Gain measured independently of Quantum Efficiency.
- Gain measured for single channels and grouping all channels on a hirose connector (96 pixels).
- Use of dropper chain to apply voltages. V=2.7K
- Expected gain variation to be low in the central regions.
- Gain uniformity appears to be consistent cross the device from measured connectors.



# Gain uniformity

- For single pixels, see some gain variation over the device was seen.
- Largest variation is seen towards the edge of the MCP-PMT (gain variation between pixel 91 and pixels 52–54 is a factor ~2).
- Similar gain variations seen in other MCP-PMT devices.*



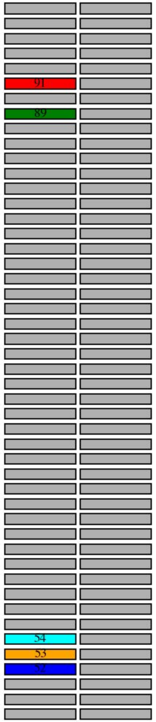


| readout | Cathode Voltage (V) | MCP Voltage (V) | Anode Voltage (V) |
|---|---|---|---|
| Single | 200 | 1400 | 1000 |

*[A. Lehmann et al., Nucl. Instrum. Meth. A1065, 2024, 169536]

Edge

≈92% of active area below pix 91

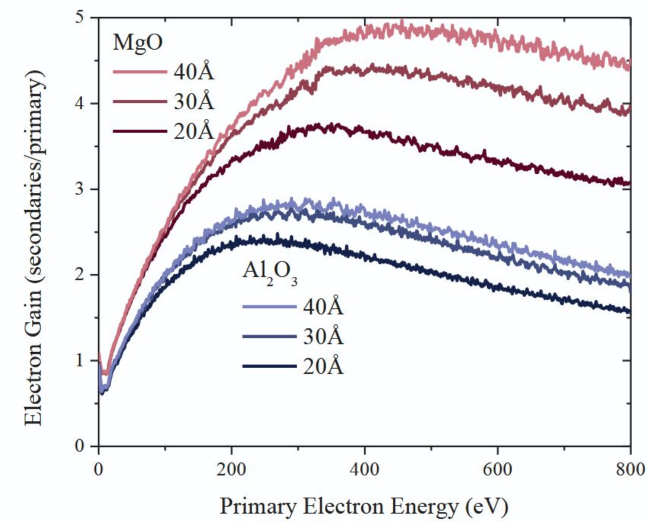


Center

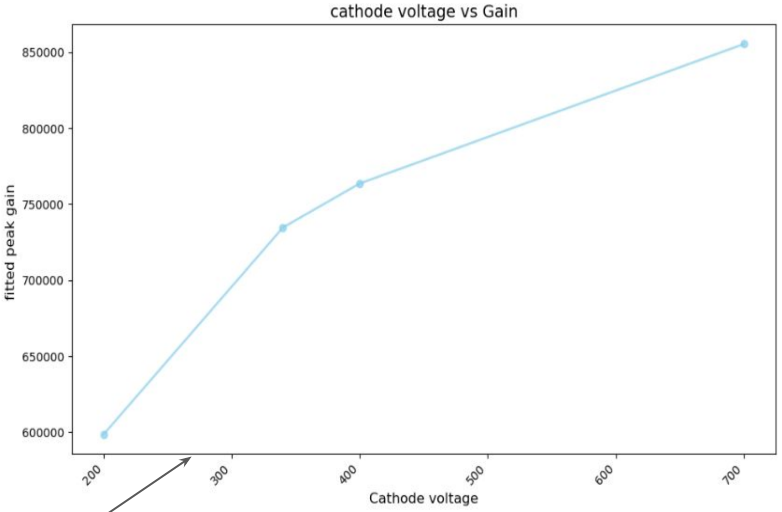
48 more pixels

# Cathode-MCP gap voltage gain dependence

- Gain depends on the voltage difference between photocathode and MCP input.
- This is due to initial photoelectrons impacting with a higher energy produce higher number of secondaries as seen with SEY plot below.
- Expected gain drop not seen, which would suggests this happens at a higher impact energy.



NIM A 929 (2019) 84–89



Taking the gain measured with Polya model as explained on next side

For more info see:

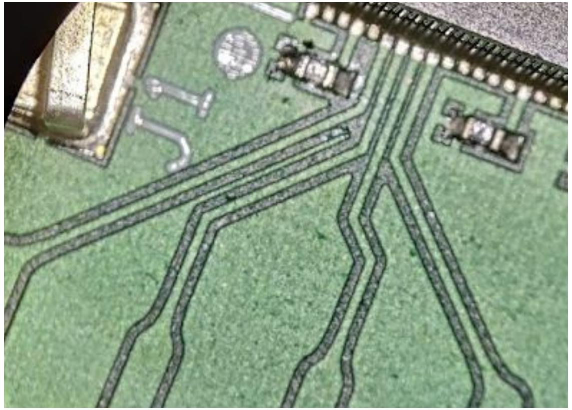
NIM A 357 (1995) 103–109

Phys. Procedia 37 (2012) 740–747

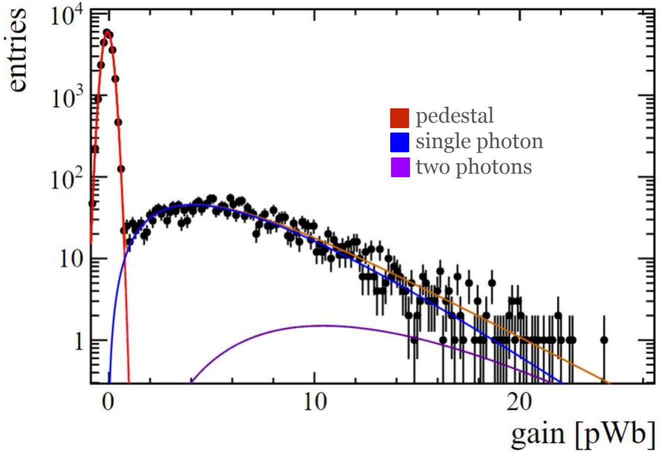
# Charge sharing

- Use an analogue breakout board to analyse the charge-sharing between neighbouring pixels.
- Data was read out to a Lecroy waveMaster 808zi-A (8 GHz, 40 GS/s) oscilloscope where the raw waveform could be processed.
- Oscilloscope was triggered on the DG645 and the area of the pulse (proportional to charge) recorded.
- The gain distribution was then fitted with a model based on the Polya function*.
  - Fit takes into account the contributions of zero photons, single photons, two photons, three photons etc.

*[Prescott, 39 (1966) 173-179]



*Zoom in image of the breakout board for the four individual pixels*



*Example with mean gain around $10^6$*

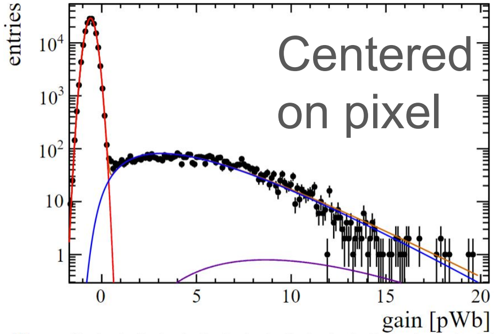
# Image spread in the fine direction

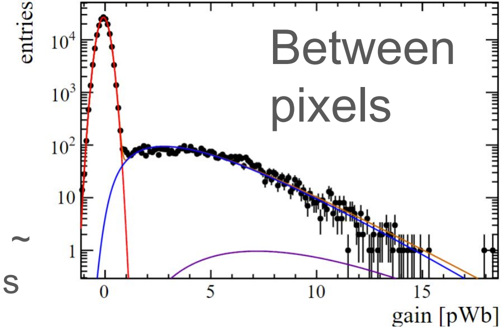
Laser is swept 4 mm in the y direction in 0.1 mm steps.

**Voltage applied**

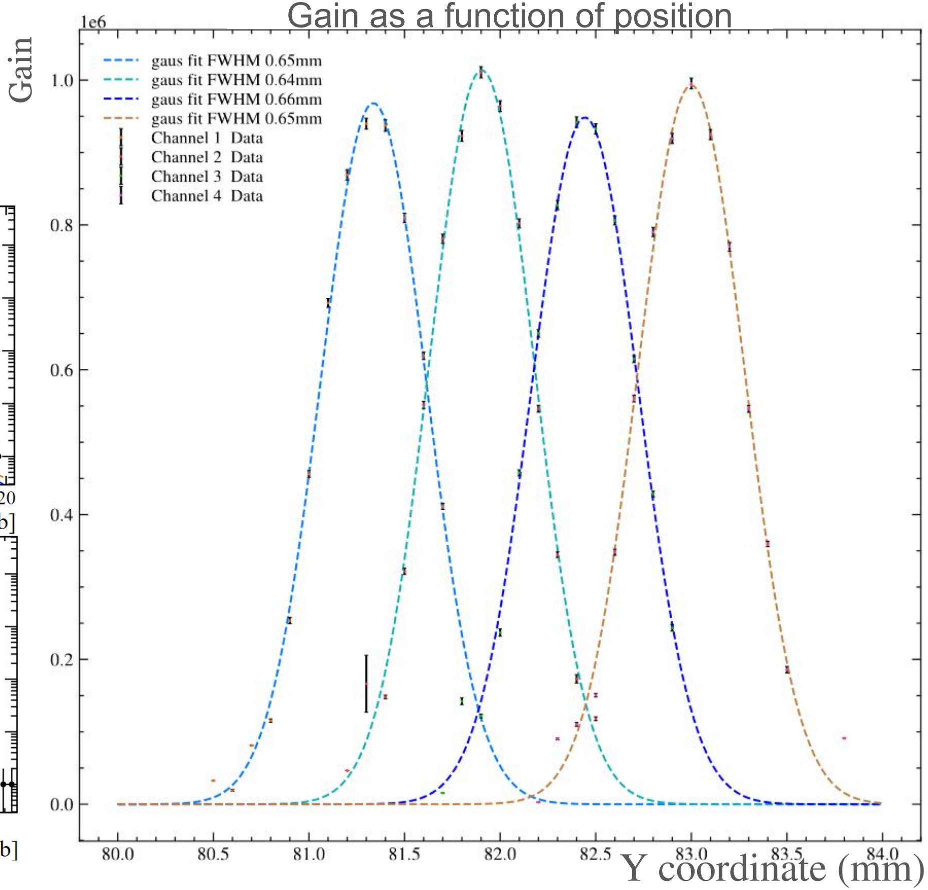
600 V cathode to MCP
1400 V across MCP
1500 V MCP to anode
(with anode at 0 V)

Note 8 pWb ~ $10^6$ electrons



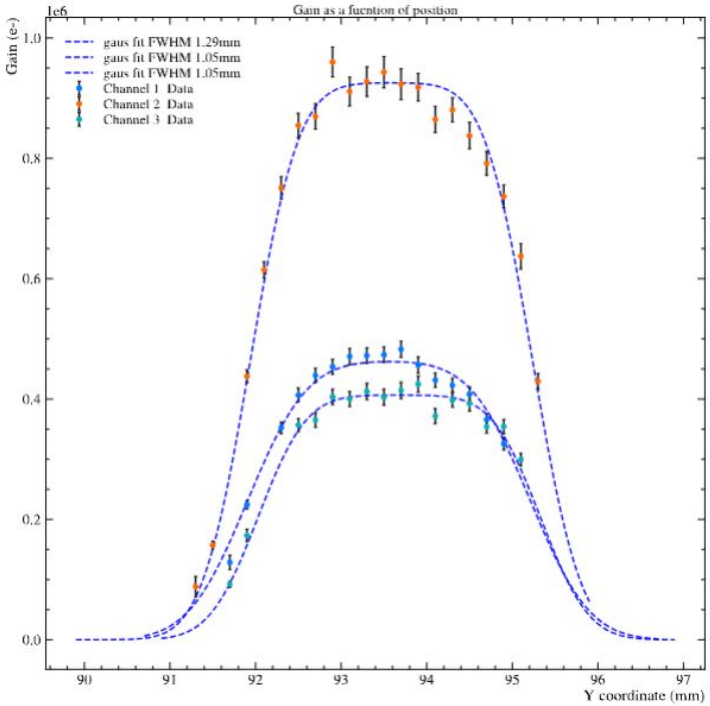


Gain as a function of position

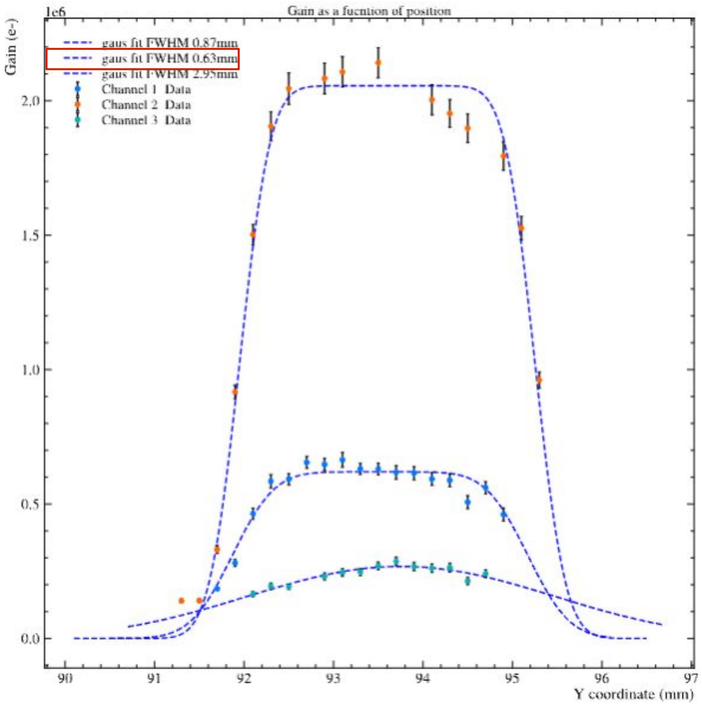


*Fitting a gaussian convolved with a top hat of the pixel size yields a **FWHM of ≈ 0.65 mm***

# Running scans in the coarse pixel direction



Setting the top hat to be the size of the pixel in the coarse direction (3.31mm), FWHM consistent with voltage applied to the back gap.



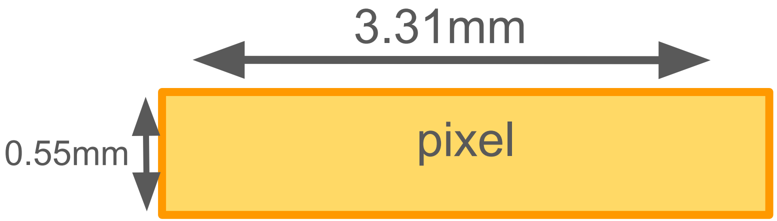
Increase in gain due to electron cloud being more focused.

See shift, in the gain likely due to the laser not be right on the center of the pixel, or could be the pore angle contribution.

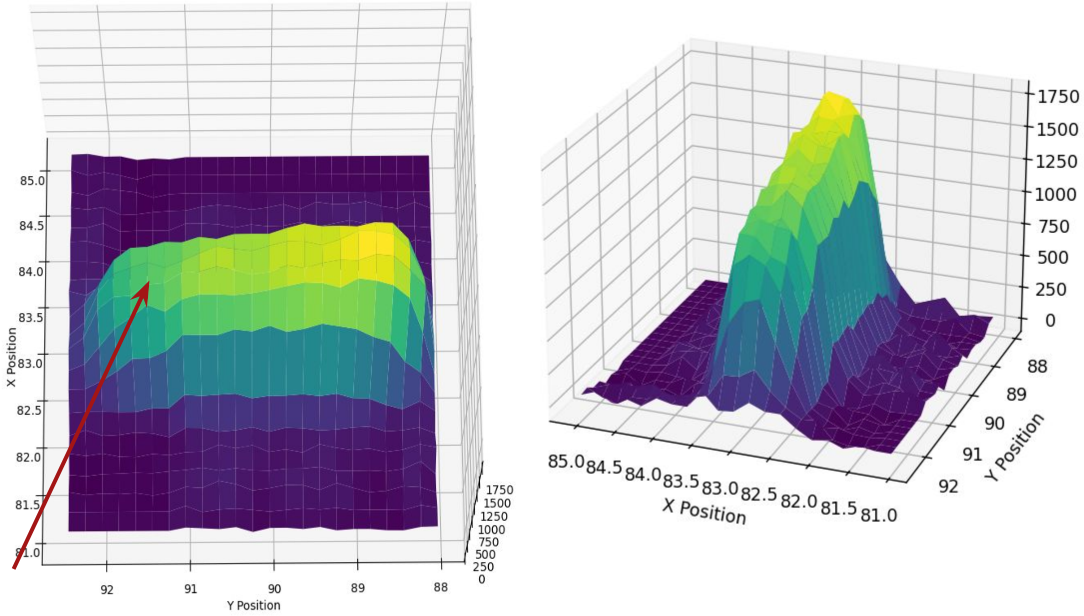
| plot | Cathode Voltage (V) | MCP Voltage (V) | Anode Voltage (V) |
|---|---|---|---|
| 1 | 200 | 1500 | 330 |
| 2 | 200 | 1500 | 1500 |

# 2D scan (coarse/fine direction)

- Sweeping in the X and Y to go over the entirety of a set of four pixels in 0.2 mm steps size.
- Threshold set 5σ above noise pedestal.
- You can see a profile of the full pixel.



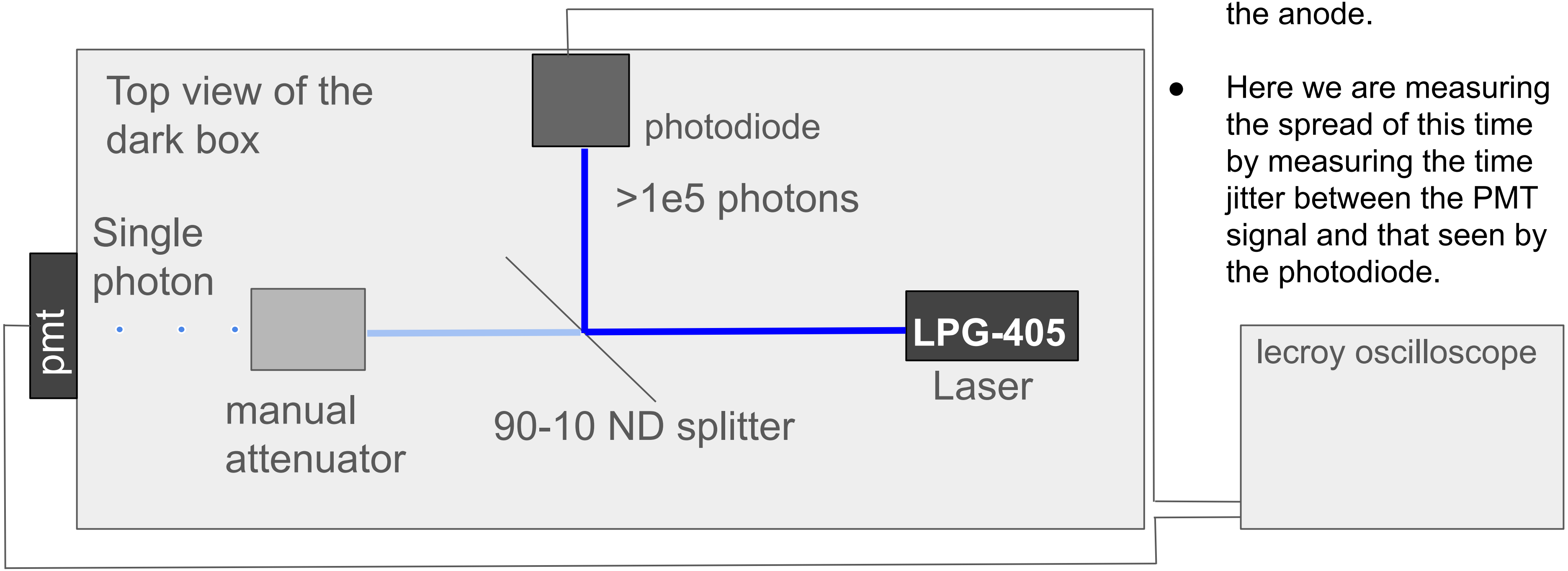
Counts above threshold



Change in number likely due to small QE fluctuations

# Transit Time Spread (TTS) measurement

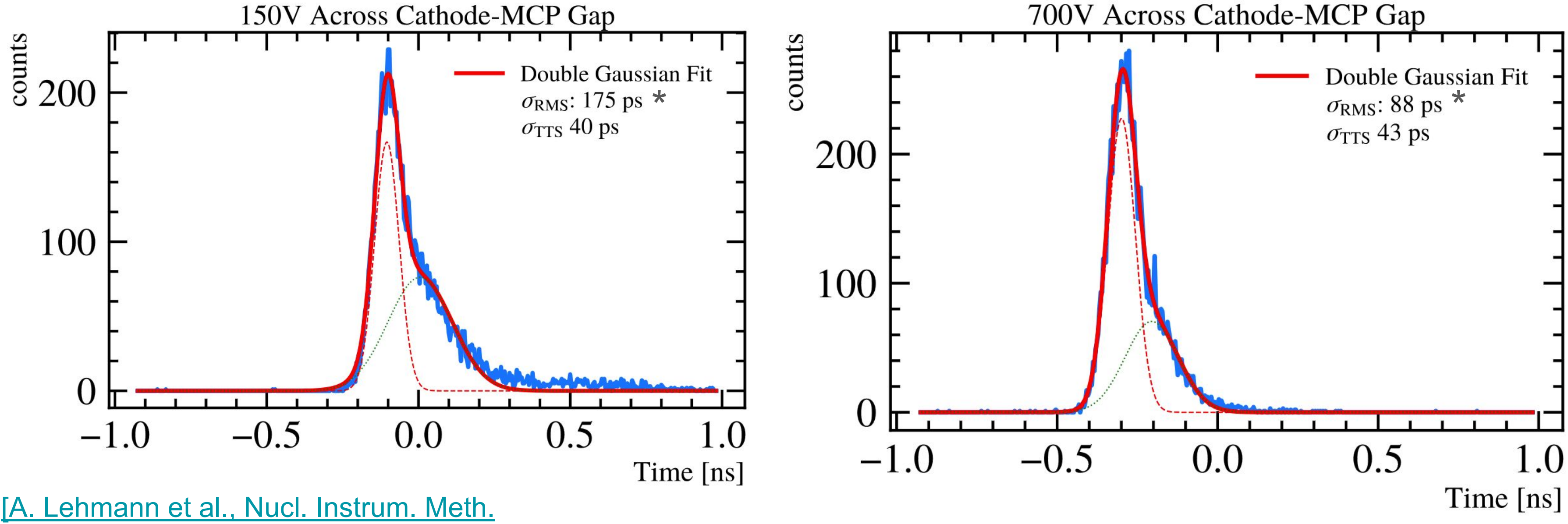
- The transit time is the time taken for electron produced at the cathode to generate a pulse at the anode.
- Here we are measuring the spread of this time by measuring the time jitter between the PMT signal and that seen by the photodiode.



A concerted effort was made to stop reflections getting to the cathode

# TTS results

- Transit time spreads of ~40 ps observed. Which falls within expected values*
- An improvement in the root mean squared from data is seen when the voltage applied between the cathode and MCP is increased. Expected to be due to a reduction in the backscattering contribution.
- Small contribution from lasers relaxation pulse



*[A. Lehmann et al., Nucl. Instrum. Meth. A1065, 2024, 169536]

**RMS taken from data not fit*

# Rate capability

- Pilas laser with a diffuser was used to uniformly illuminate the MCP-PMT in a 0.326 cm$^2$ area. The remainder of the MCP-PMT was masked.
- Expect linearity between laser repetition rate and anode current measured until saturation of strip current.

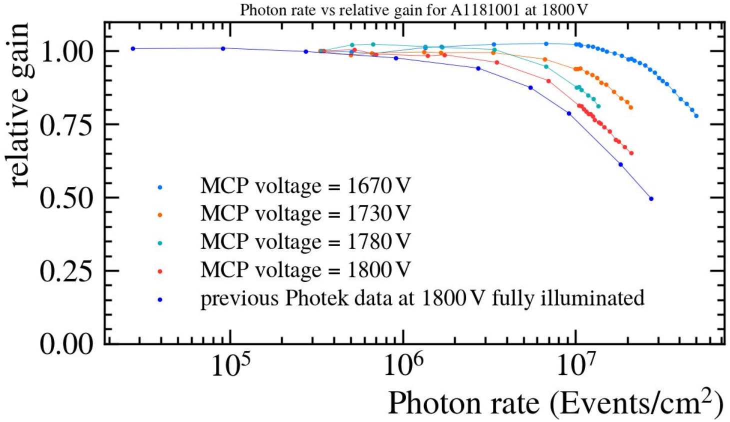
🟨 $T_{np}$ is the total number of photoelectrons per cm$^2$
🟦 Anode current
🟩 Area ( in cm$^2$)
🟥 Gain (Calibrated)

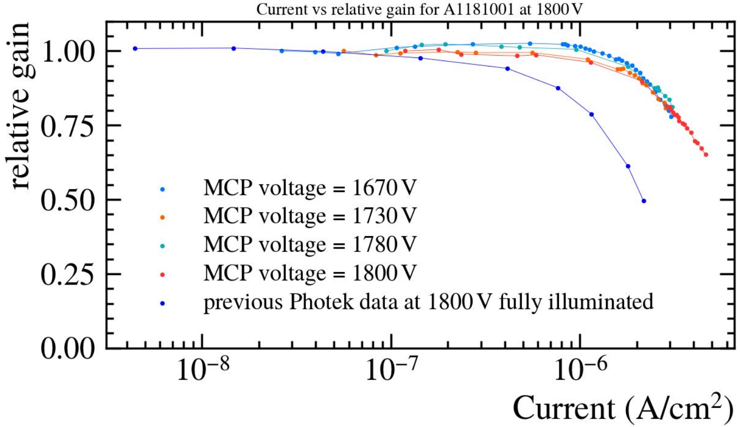
$$\boxed{T_{np}} = \frac{\boxed{I_{anode}}}{\boxed{A}\cdot\boxed{G}\cdot e}$$

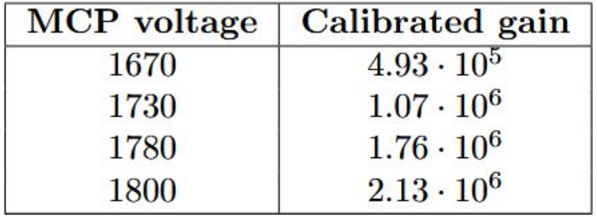
- 16 by 96 MCP PMT was swap out due to a MCP issue, older 8 by 64 PMT but expected similarities as MCPs are like for like. Photek MCP-PMTs previously presented at RICH 2022 [J. Milnes RICH 2022 talk].
- Using the current/gain to calculate the total number of photoelectrons:

# Gain effects on Rate capability

***All data here from A1181008 [8 by 64]***







| MCP voltage | Calibrated gain |
|---|---|
| 1670 | $4.93 \cdot 10^5$ |
| 1730 | $1.07 \cdot 10^6$ |
| 1780 | $1.76 \cdot 10^6$ |
| 1800 | $2.13 \cdot 10^6$ |

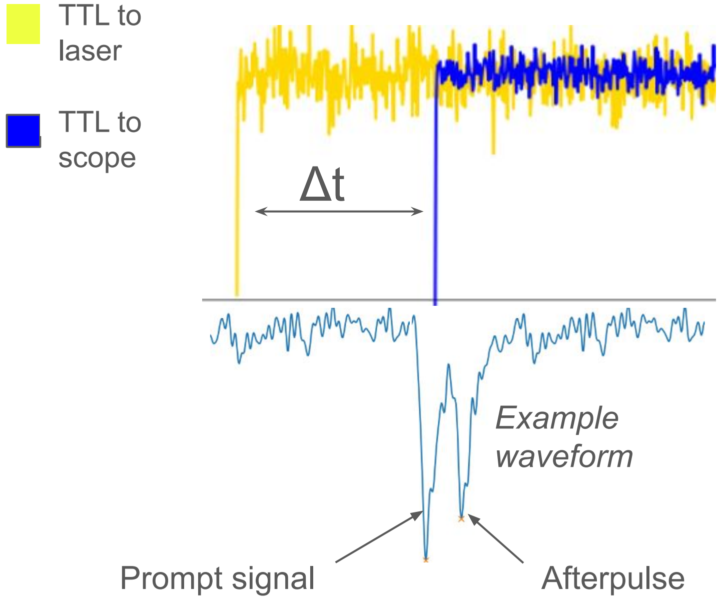
- Gain calibration for this 0.326 cm$^2$ area, compared with previous data which had active area fully illuminated.
- Gain drop off of similar order to literature.*
- As area of illumination is smaller for the new data set a higher current per cm$^2$ is seen (1/86.2 of active area).

*[A. Lehmann et al., Nucl. Instrum. Meth. A1065, 2024, 169536]
*[D. Miehling et al., Nucl. Instrum. Meth. A1049, 2023, 168047]

# Ion feedback (work in progress)

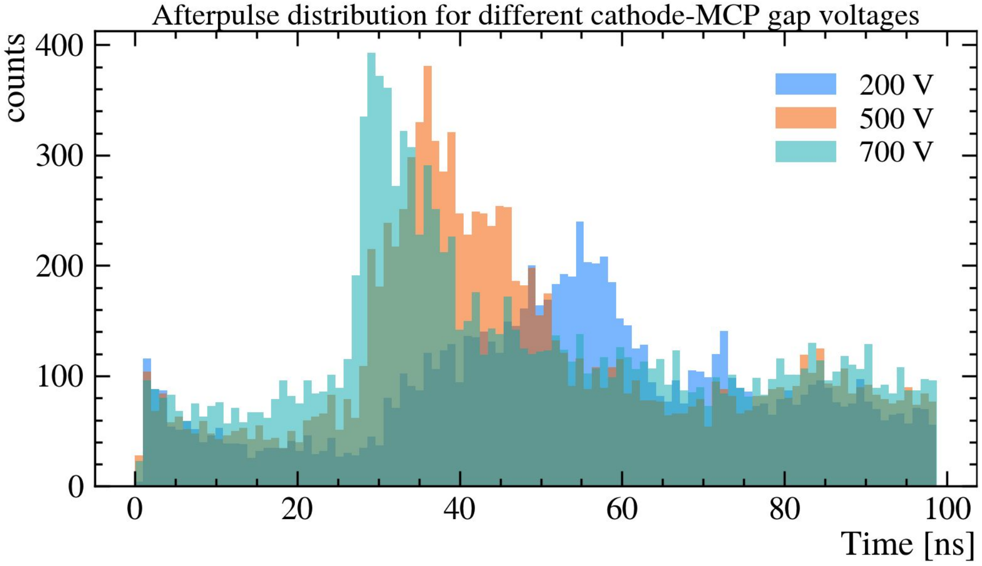
- Main limitation in device lifetime is ion feedback to the photocathode.
- Ions with positive charge travel back to the cathode, can produce electrons leading to afterpulses.
- Same set up as TTS using the photodiode as the time reference but with a trigger window offset by 10 ns to only trigger on afterpulses.

Δt in our case is 10 ns nominal



# Ion feedback data from TORCH MCP-PMT (work in progress)

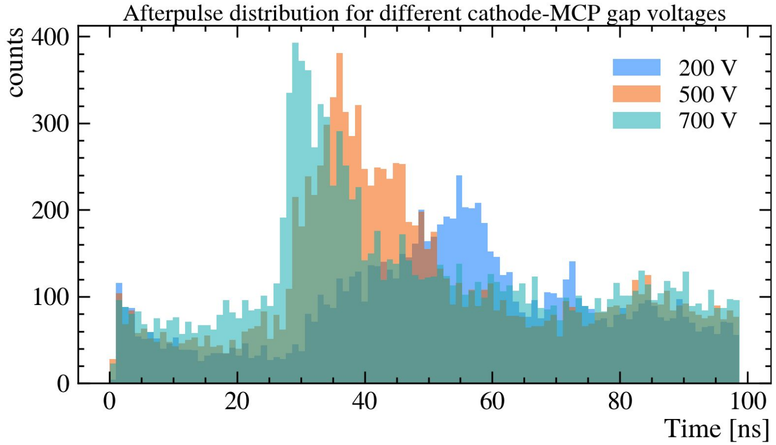
- Use characteristic time-of-flight of afterpulse signals to perform spectroscopy.
  - Peak in the time distribution of afterpulses is characteristic of ion species.
  - Position of peak depends on cathode voltage. As seen before*
- Significant background from dark counts within the acquisition window that are randomly distributed in time.
- Data taken with in a window up to 1800 ns no peaks above background

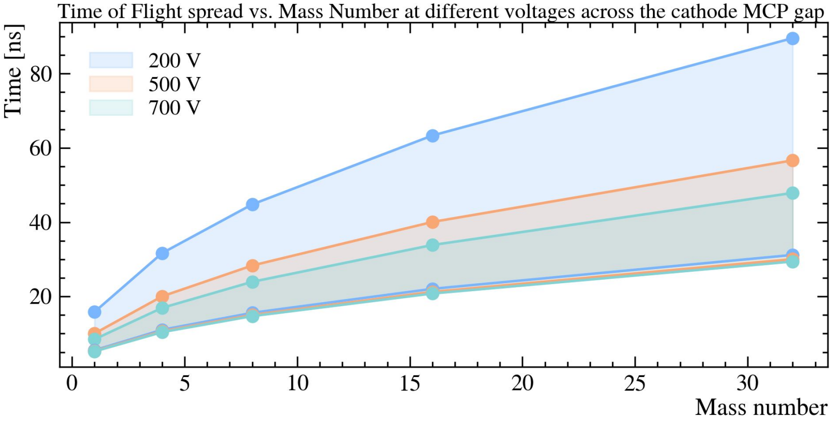


*DRD4 (2025) Gabriele Costi et al.

# Ion feedback data from TORCH MCP-PMT (work in progress)

- Use simulation to connect time of arrival to ion species:
    - Spread in time due to the unknown ion production point in the MCP-PMT.
    - Releasing an ion for rest, from the top and the bottom of the MCP pore, give us a upper and lower bound in expected time to hit the cathode.
- Largest signals are likely due to water vapour released from the pores.
- Larger data sample needed to identify other contaminants.


Afterpulse distribution for different cathode-MCP gap voltages

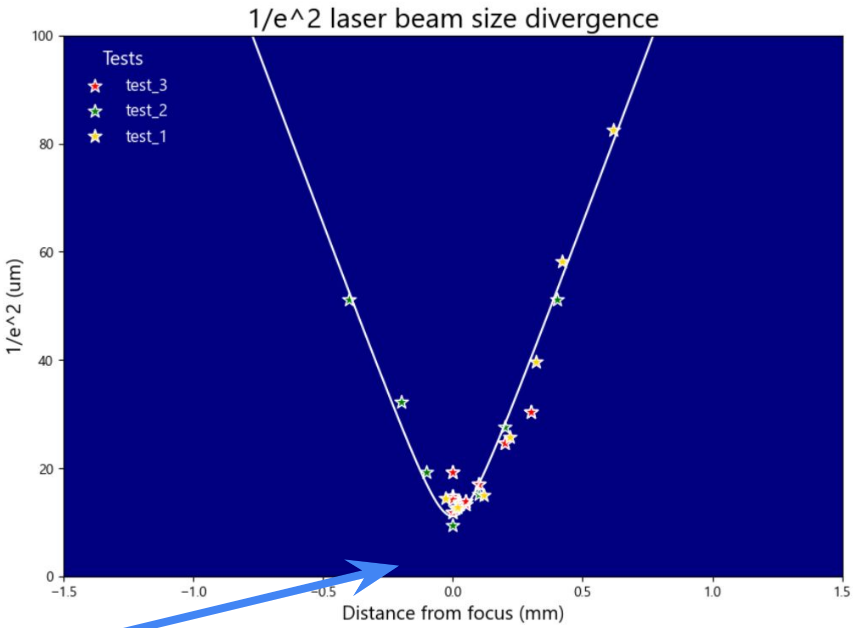

Time of Flight spread vs. Mass Number at different voltages across the cathode MCP gap

# Summary

- Shown characteristic tests and analysis of new 16 x 96 MCP-PMT.
  - Quantum Efficiency / Gain uniformity
  - Image spread/charge sharing
  - MCP Rate capability
  - Photocathode/MCP input voltage dependence
    - Gain
    - TTS
    - Ion feedback
- Results so far in charge sharing and TTS show promise with ongoing  challenges with lifetime and rate capability.
- An Improved understanding of the ion production and the reduction of contaminants within the fabrication process could boost lifetime.
- Programme to compare these characteristic tests to simulation to further understand the internal physics of these devices.

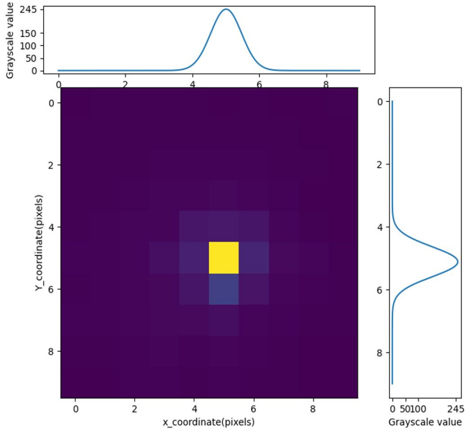
# Back up

# Achieving laser focus



Here we were limited by the size of the CCD pixel.

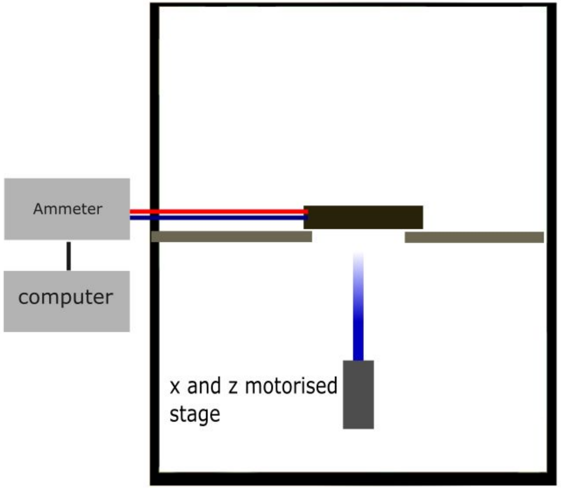
Moving the stage  in the z direction to find focus.



We believe that with our current set up we are below 50 µm  beam diameter (x11 smaller the pixel size on the MCP-PMT).

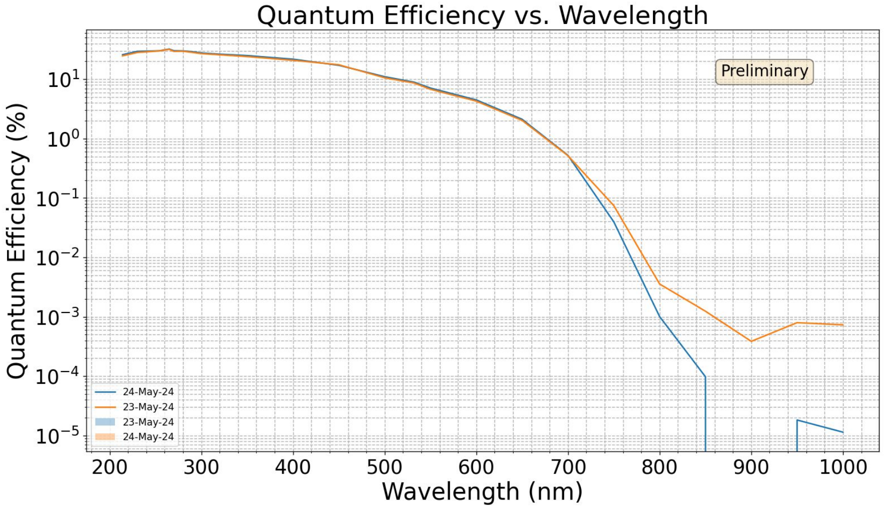
# Measurement of QE

## Scanning 2D QE



## Calibrated QE

- Follows similar set up but has a calibrated light source with a 1cm square cm aperture. A filter wheel is used to get different wavelengths



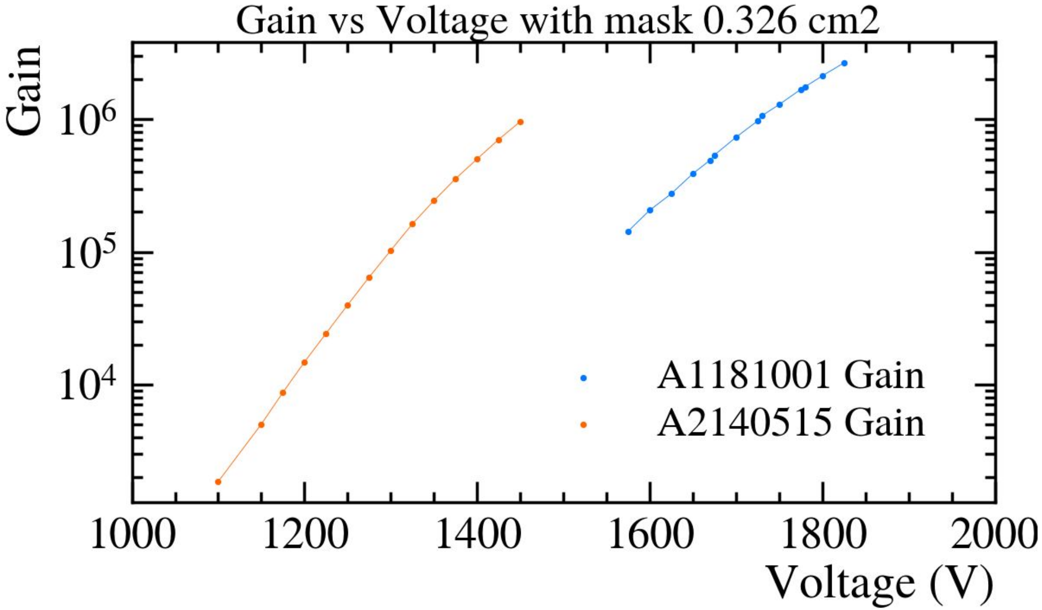
# Gain Calibration

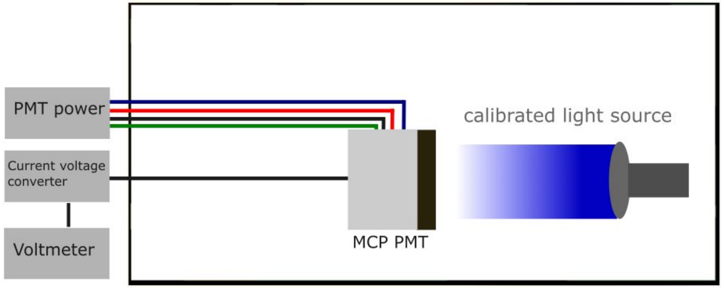
Cathode response R: 3.34 mA/W @ 500 nm ($1\,\mathrm{cm}^2$)

Laser power P = 8 $\mathrm{pW/cm}^2$

Gain use to calculate photon count rate is calculated as follows, using a light source with known power

$$\boxed{G} \propto \frac{I - I_{\mathrm{Dark}}}{\boxed{P} \cdot \boxed{A} \cdot \boxed{R}}$$

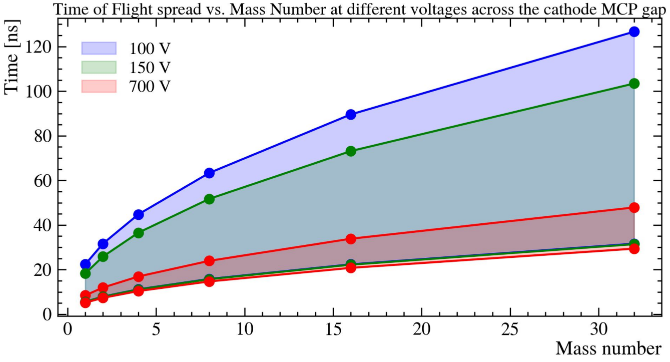


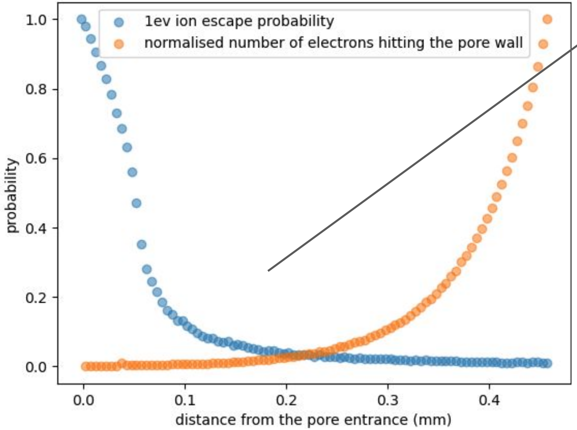


QE is measured in Similar setup but instead current is measured across the cathode

# Ion species selection: transit time and probability of escape

- A Python simulation which uses a the pore geometry and naive electric field is used to determine where electrons are likely to strike the pore walls (orange). A Lambert cosine distribution is then applied to estimate the probability of ion escape (blue).
- The idea is to use the escape probability of a ion, with the number of electrons hitting the wall to get a time distribution between these bounds.





Combining the two..