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Fast Timing with Microchannel Plate (MCP) PMTs

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Contents

Why fast single photon detection?

MCP PMTs

Timing, limitations

Ageing+mitigation

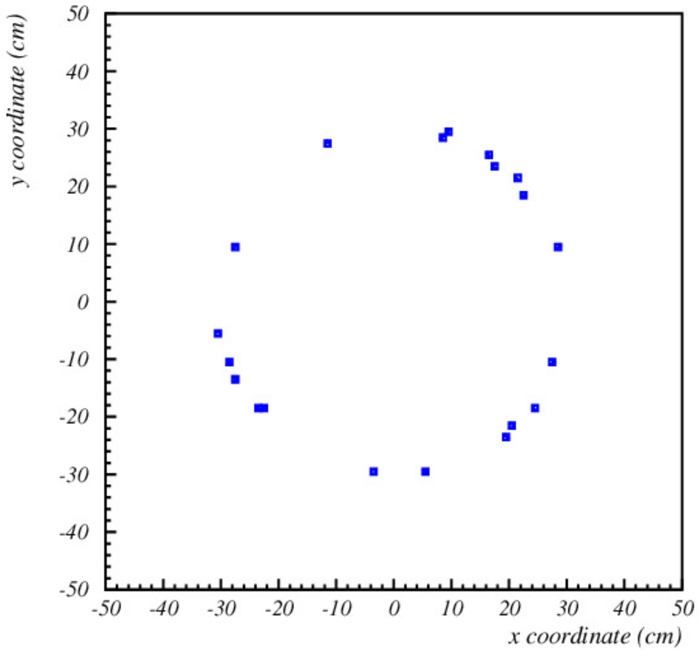
Summary

Photon detection in RICH counters

RICH counter: measure photon impact point on the photon detector surface

→ detection of single photons with

- sufficient spatial resolution
- high efficiency and good signal-to-noise ratio
- over a large area (square meters)



Special requirements:

- Operation in magnetic field
- High rate capability
- Very high spatial resolution
- Excellent timing (time-of-arrival information)

Fast photon detection

New generation of Cherenkov counters: precise time information needed to further improve performance:

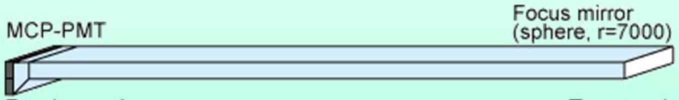
- Reduce chromatic abberation in a RICH detector (measure group velocity): Focusing DIRC
- Combine TOF and RICH techniques: TOP (Time-of-propagation counter), TORCH
- Dedicated TOF

New possibilities in medical imaging: TOFPET with Cherenkov light

→ Need photo sensors with excellent timing

Belle II Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



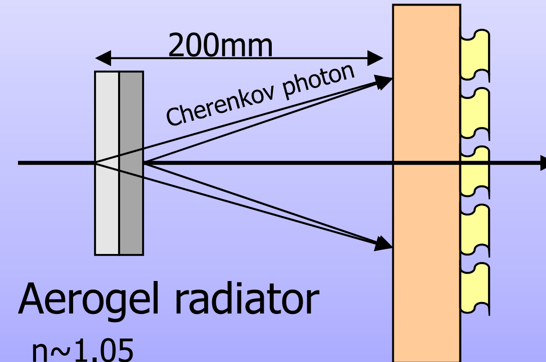
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

Endcap PID: Aerogel RICH (ARICH)

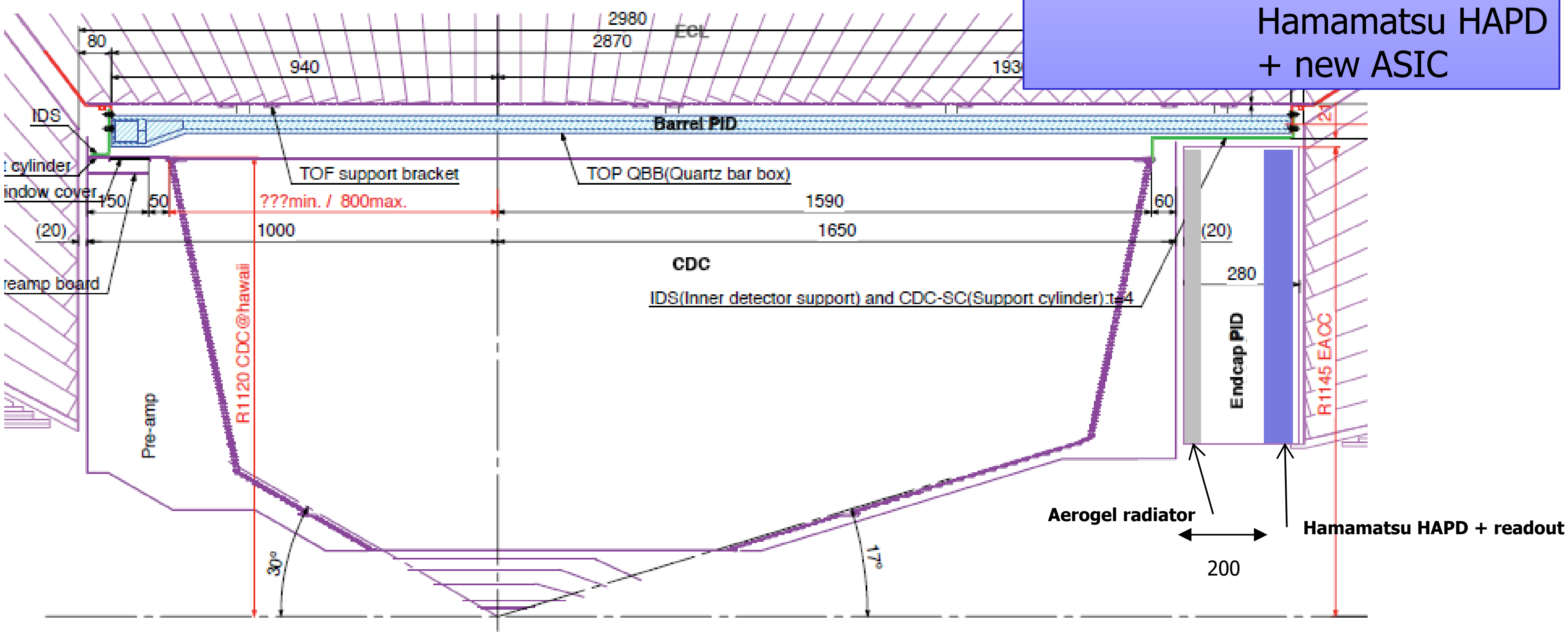


Aerogel radiator

n~1.05

Hamamatsu HAPD

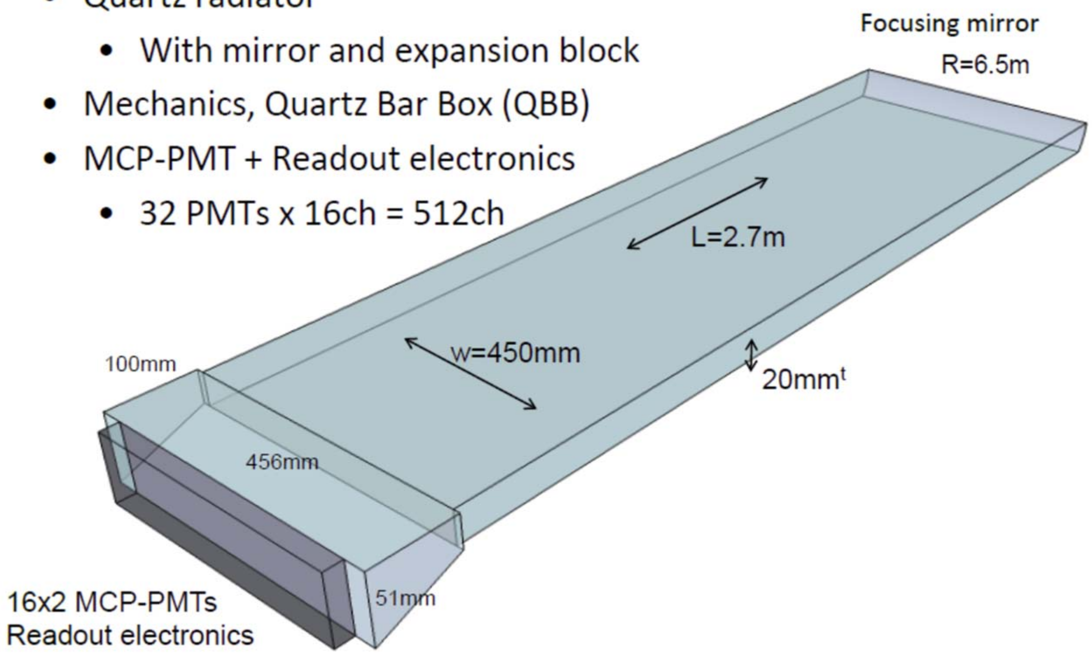
+ new ASIC



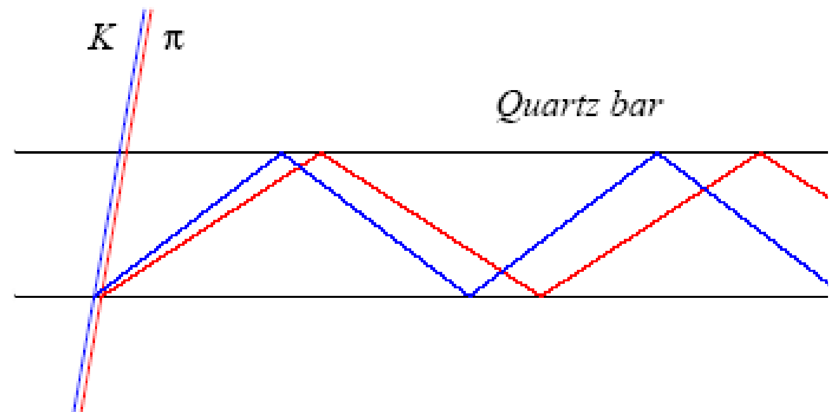
Peter Križan, Ljubljana

Time-Of-Propagation (TOP) counter

- Quartz radiator
  - With mirror and expansion block
- Mechanics, Quartz Bar Box (QBB)
- MCP-PMT + Readout electronics
  - 32 PMTs x 16ch = 512ch



Hamamatsu
SL10 MCP-PMT



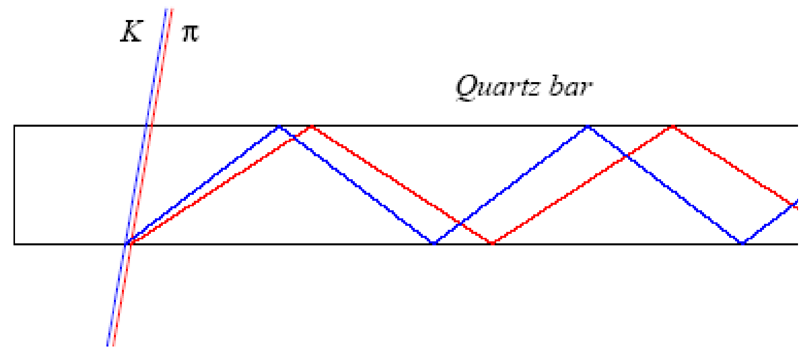
Similar to DIRC, but instead of two coordinates measure:

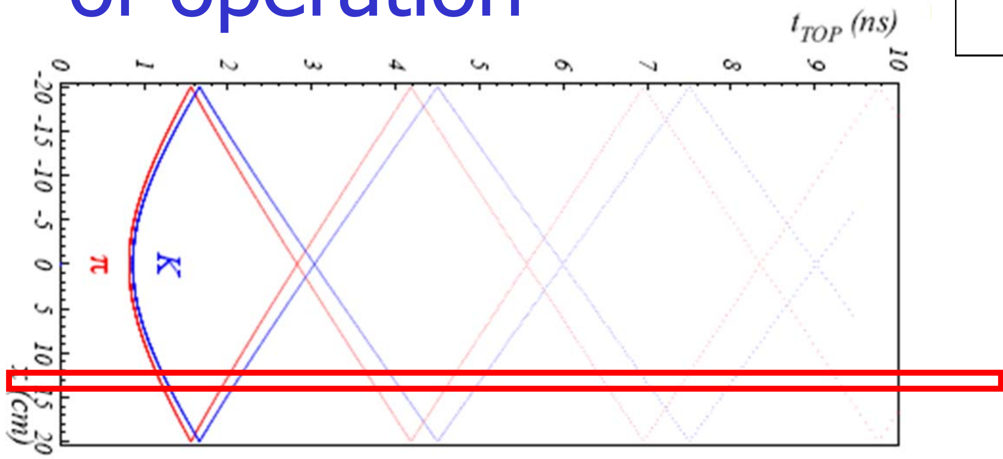
– One (or two coordinates) with a few mm precision

– Time-of-arrival

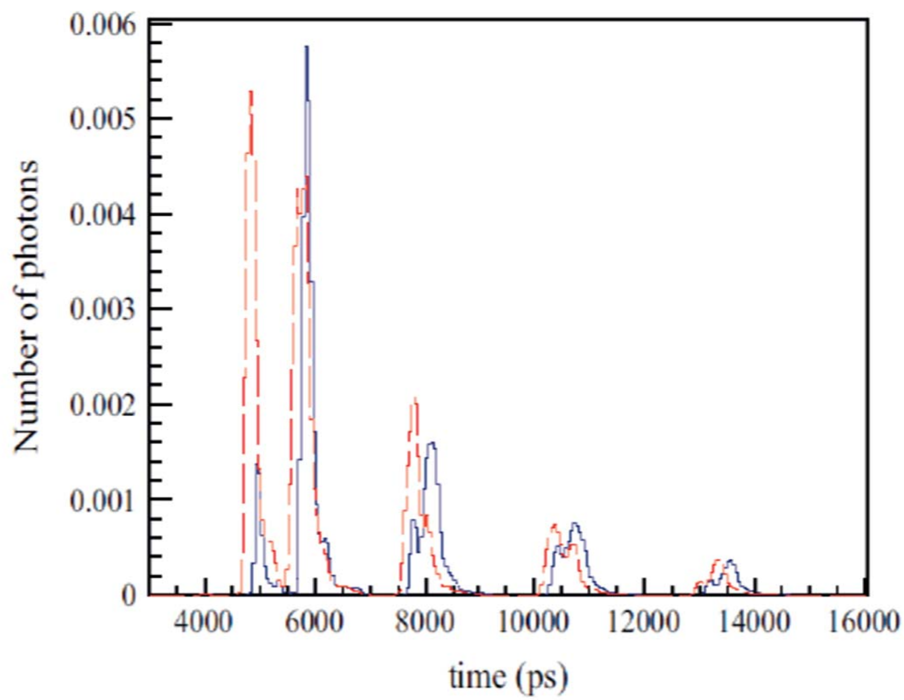
→ Excellent time resolution < 100ps (incl. read-out) required for single photons in 1.5T B field

TOP counter: principle of operation





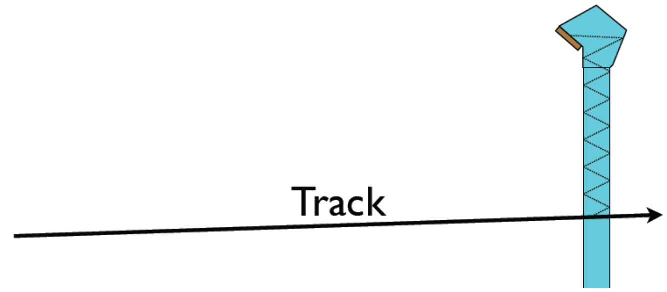
Pattern in the coordinate-time space ('ring') of a pion and a kaon hitting a quartz bar

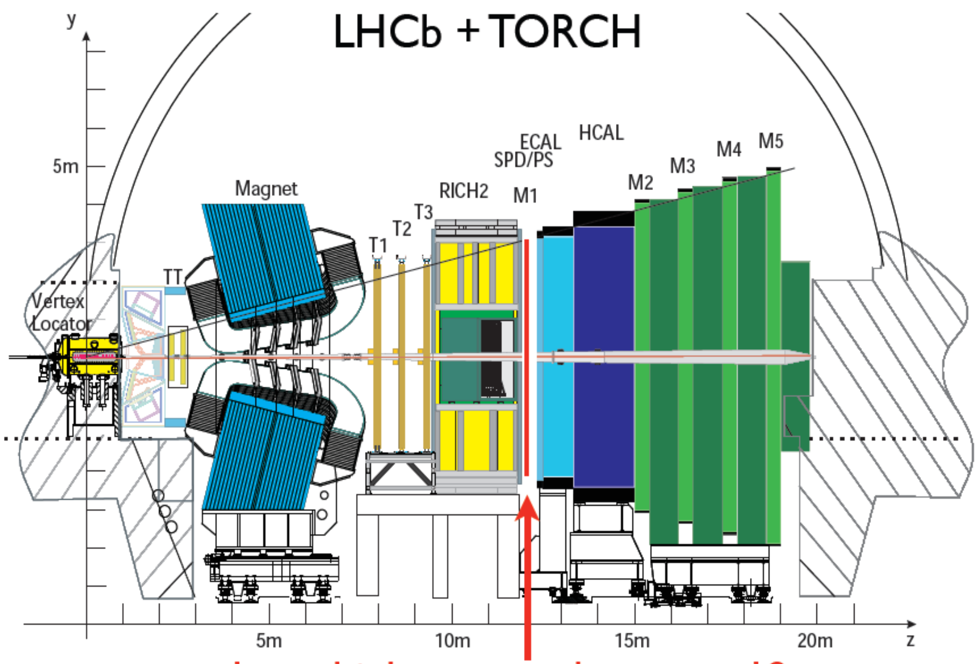


Time distribution of signals recorded by one of the PMT channels: different for π and K (~shifted in time)

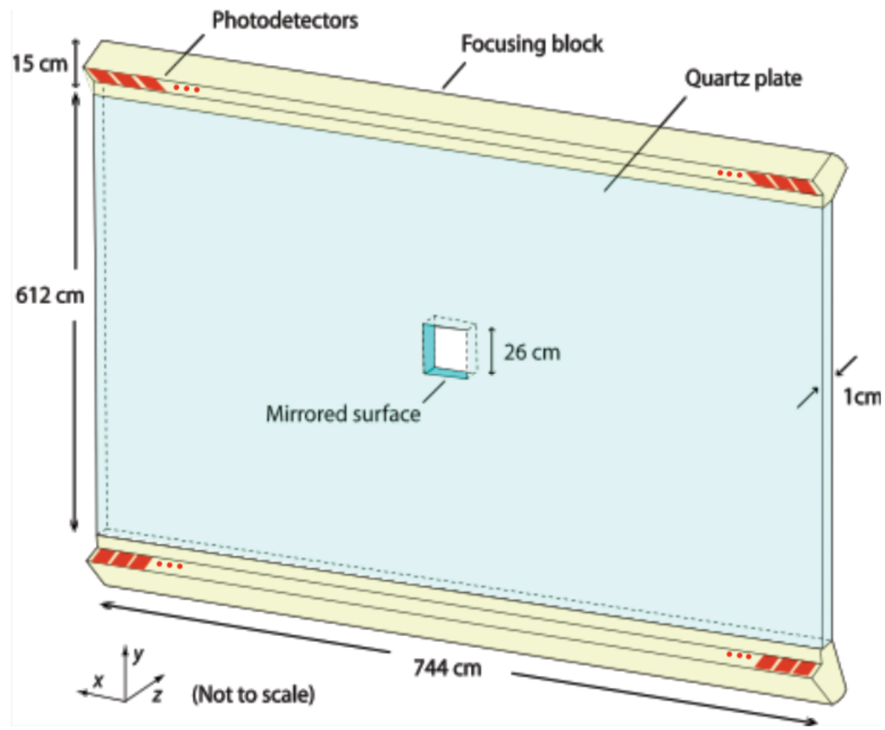
LHCb PID upgrade: TORCH

A special type of Time-of-Propagation counter for the LHCb upgrade





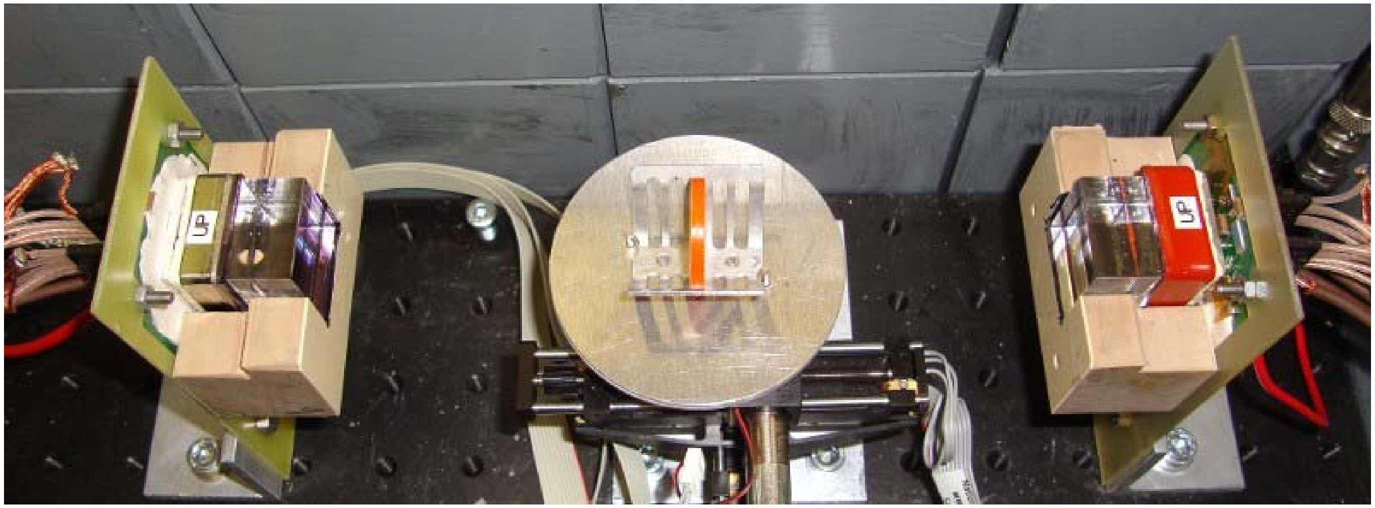
1cm-thick quartz plate at z=12m



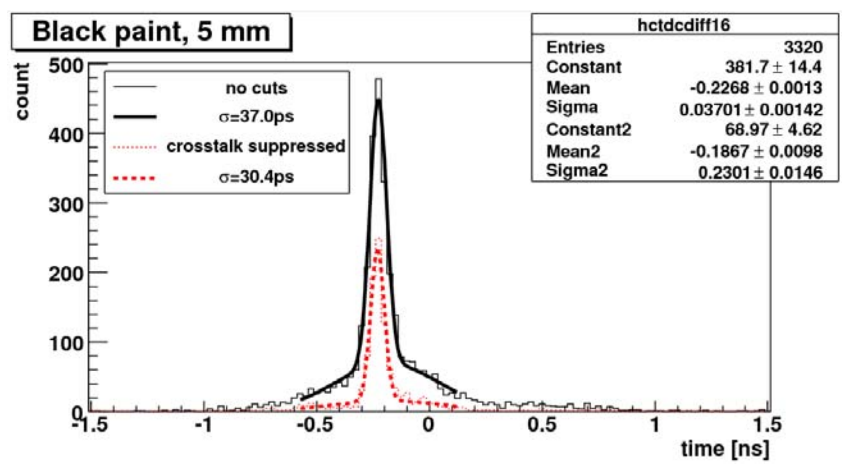
Sides are instrumented too (not shown)

TOF-PET with Cherenkov light

Two detectors in a back-to-back configuration with 25x25x15 mm^3 crystals coupled to MCP-PMT with optical grease.

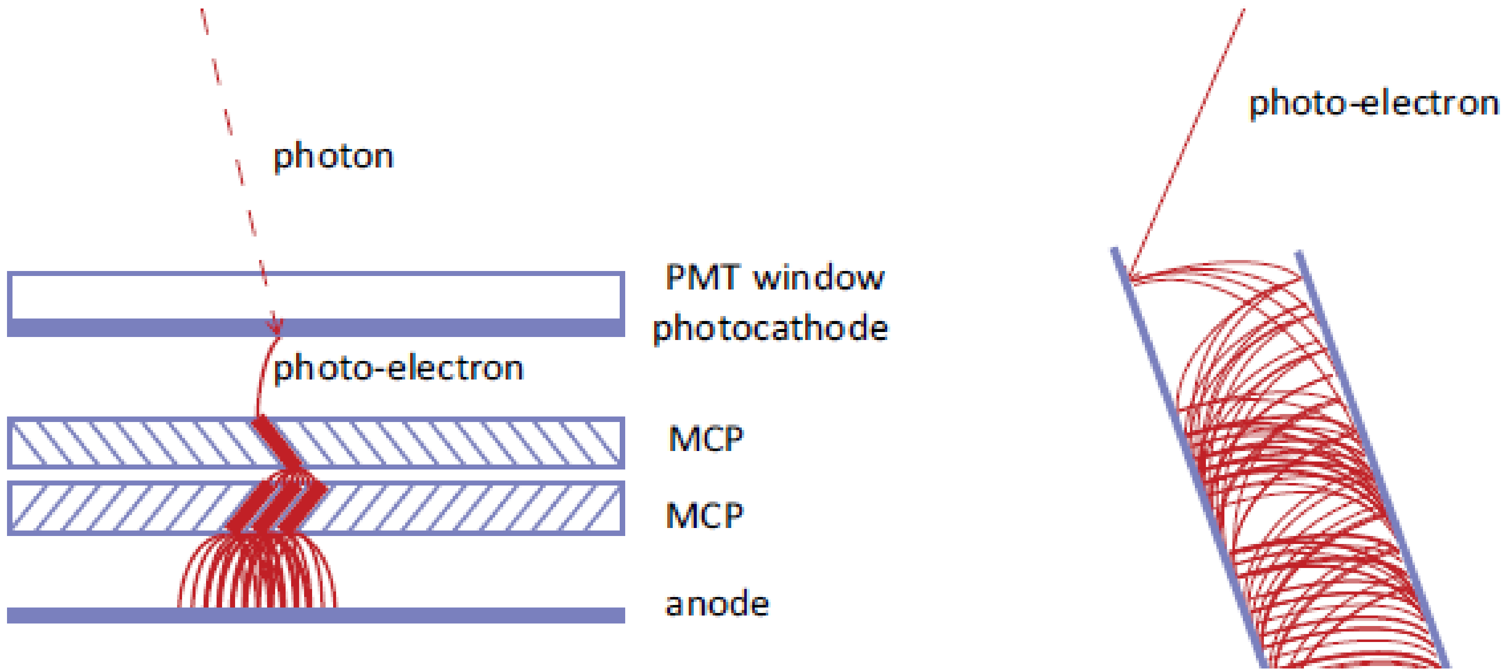


5 mm long crystal:
→ FWHM ~ 70 ps



→ NIM A654(2011)532–538

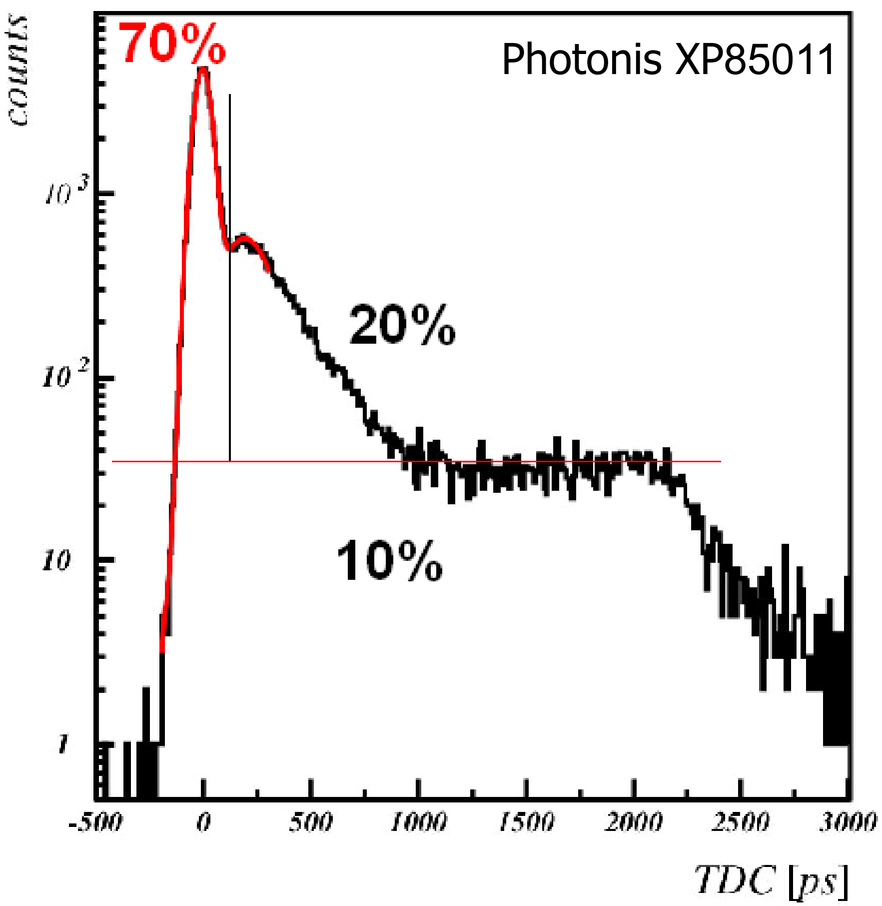
Micro-channel plate PMTs

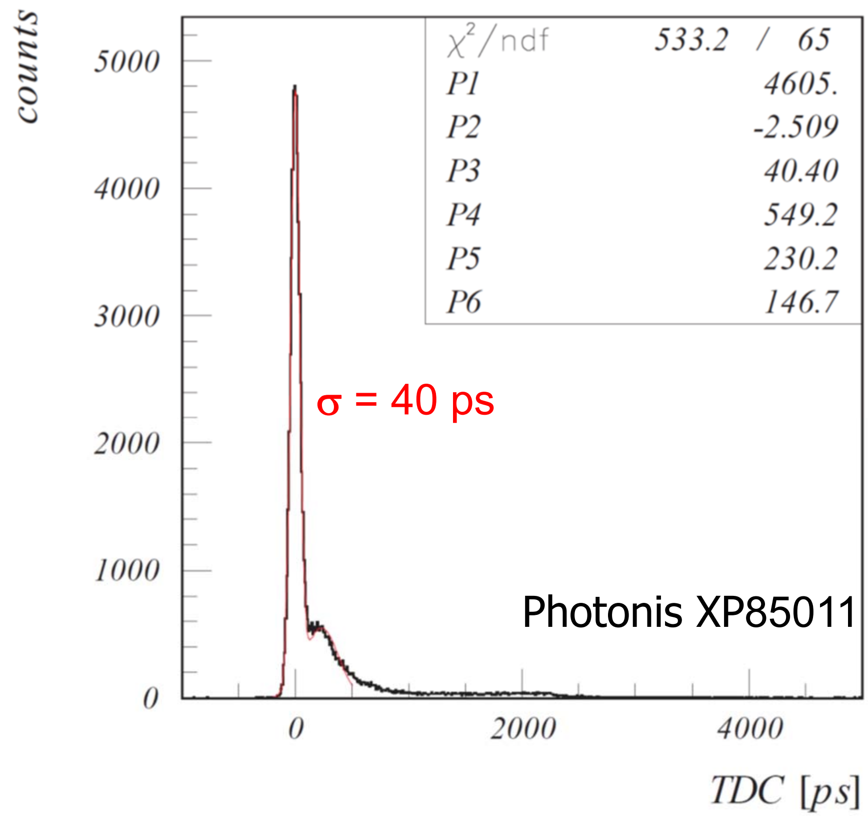


- Fast
- Immune to magnetic field normal to the window

MCP PMT timing

MCP PMTs timing response with a picosecond laser





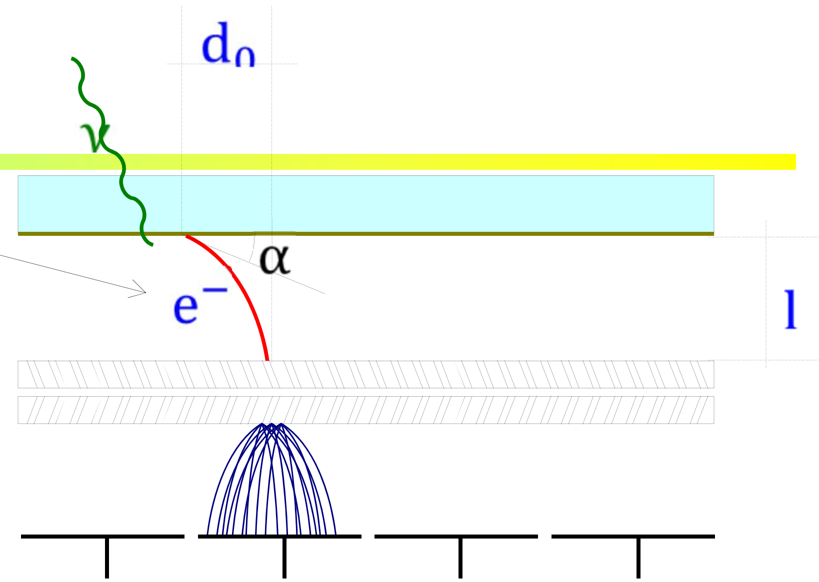
→ Main peak with excellent timing accompanied by a tail

Do we understand these features?

Photon detection

Photo-electron:

- $d_{0,max}$ ~ 0.8 mm
- t_0 ~ 1.4 ns
- Δt_0 ~ 100 ps



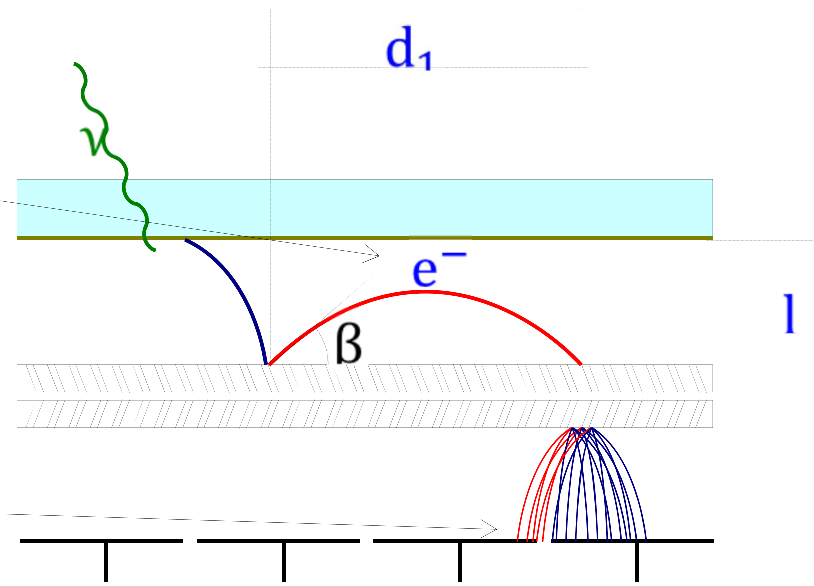
Parameters used:

- U = 200 V
- l = 6 mm
- E_0 = 1 eV
- m_e = 511 keV/c^2
- e_0 = 1.6 10^{-19} As

Backscattering:

- $d_{1,max}$ ~ 12 mm
- $t_{1,max}$ ~ 2.8 ns

Charge sharing



Try with a simple model

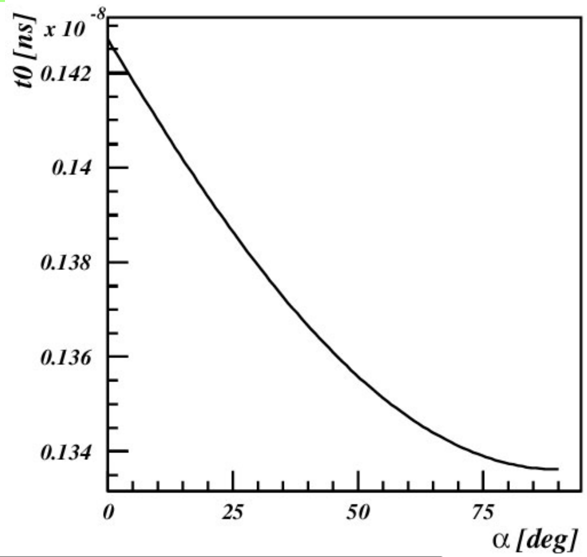
→ S. Korpar et al, NIMA 595 (2008) 169, JINST 4 (2009) P11017

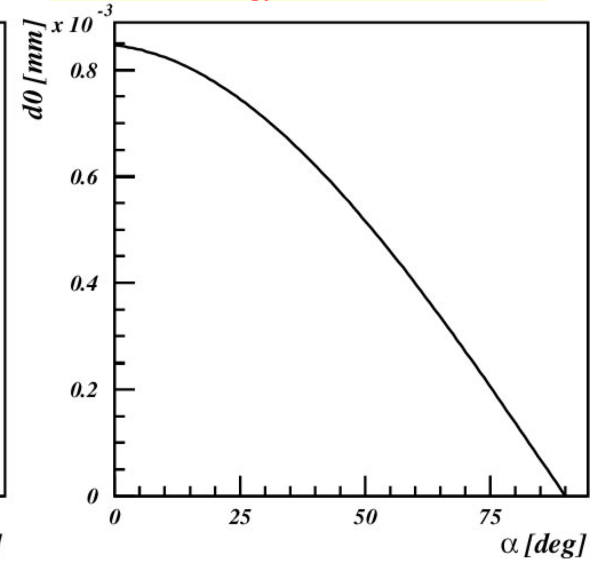
Photo-electron

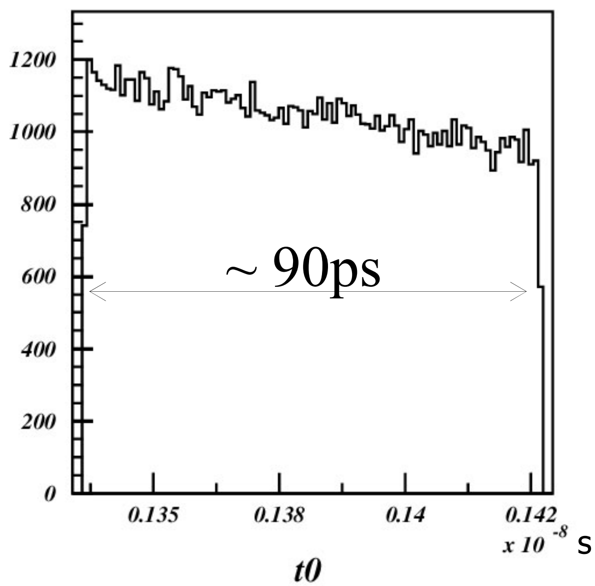
$$t_0 \approx l\sqrt{\frac{2m_e}{Ue_0}}$$

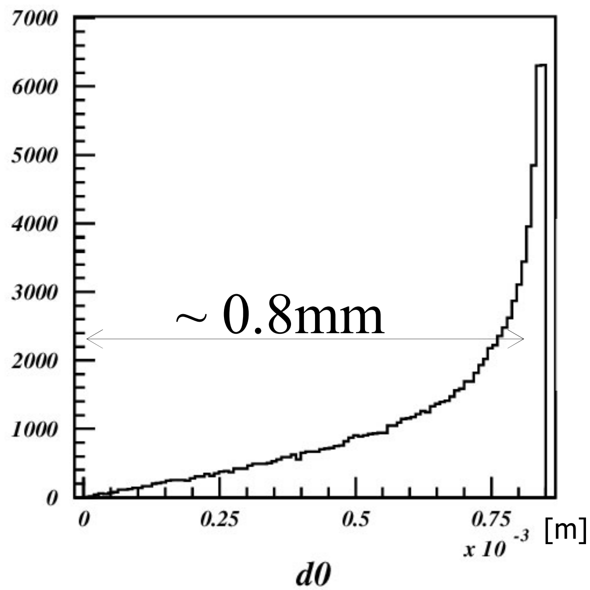
$$d_0 \approx 2l\sqrt{\frac{E_0}{Ue_0}}\cos(\alpha)$$

Generated distributions assuming that photo-electron is emitted uniformly over the solid angle





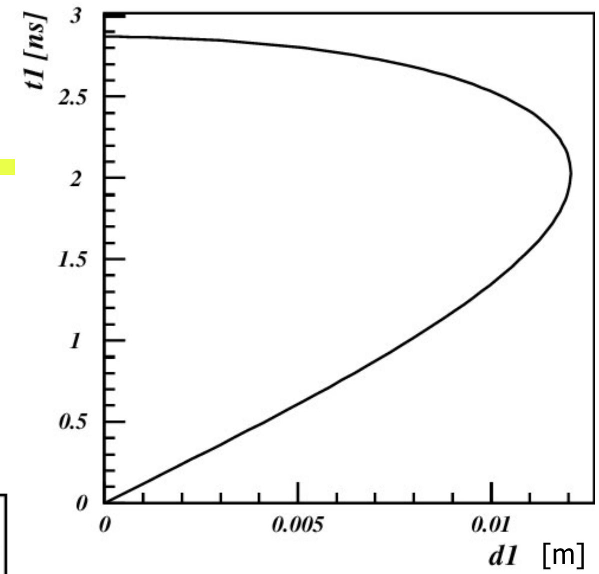




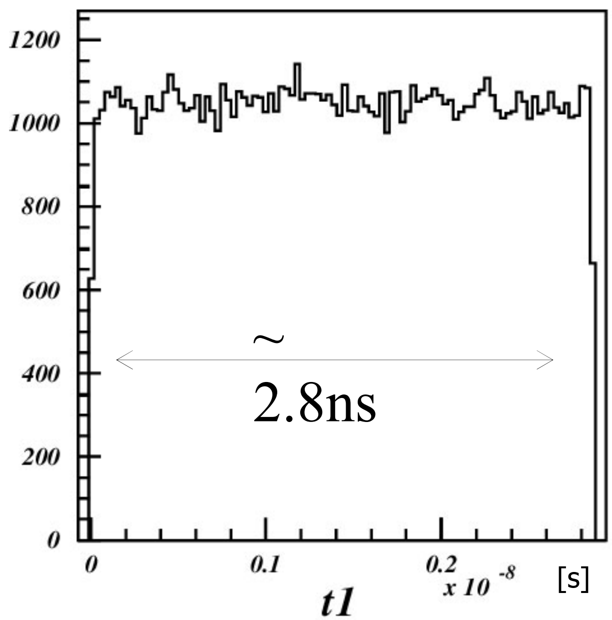
Maximum variation of photo-electron travel time.

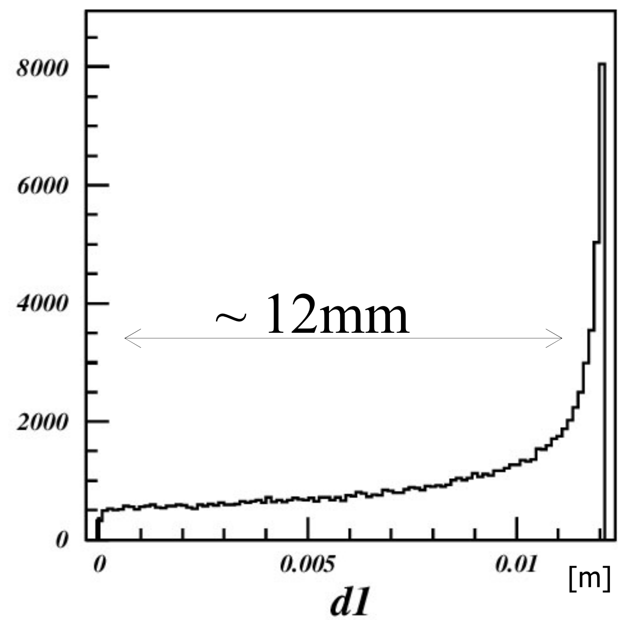
$$\Delta t_0 \approx t_0\sqrt{\frac{E_0}{Ue_0}}$$

Elastic backscattering



Generated distributions assuming that backscattering is uniform over the solid angle





Travel time vs. travel distance

$\mathbf{t_1 = 2t_0 \sin\beta}$

$\mathbf{d_1 = 2l \sin 2\beta}$

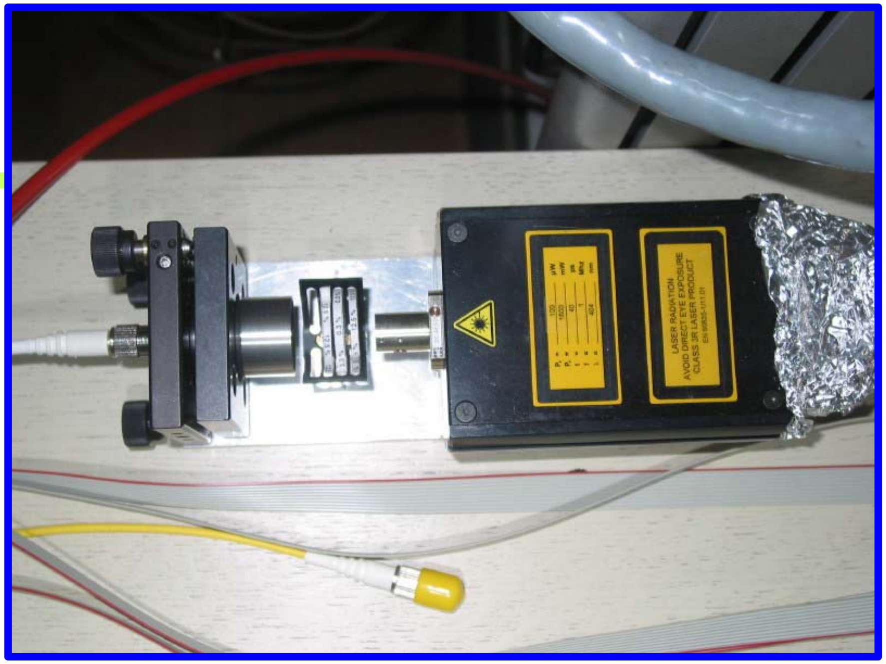
Scanning setup: optical system

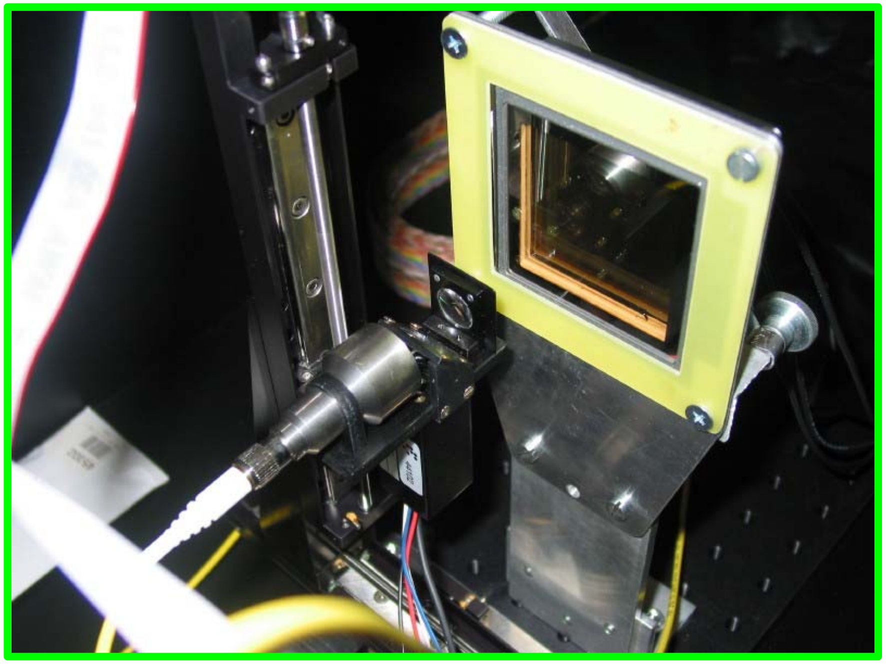
PiLas diode laser system EIG1000D (ALS)

- 404nm laser head (ALS)
- filters (0.3%, 12.5%, 25%)
- optical fiber coupler (focusing)
- optical fiber (single mode,~4μm core)

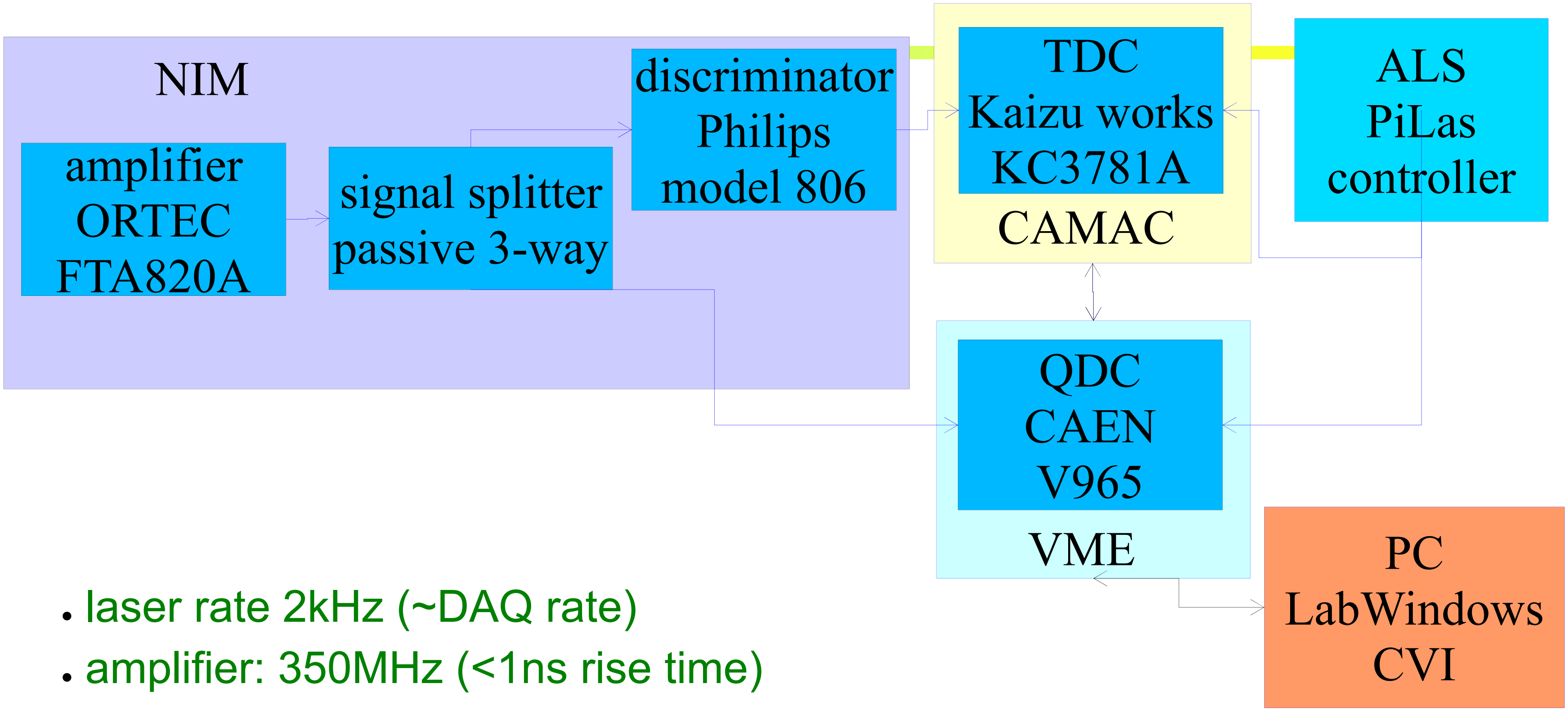
Inside dark box, mounted on 3D stage:

- optical fiber coupler (expanding)
- semitransparent plate
- reference PMT (Hamamatsu H5783P)
- focusing lens (spot size σ ~ 10μm)



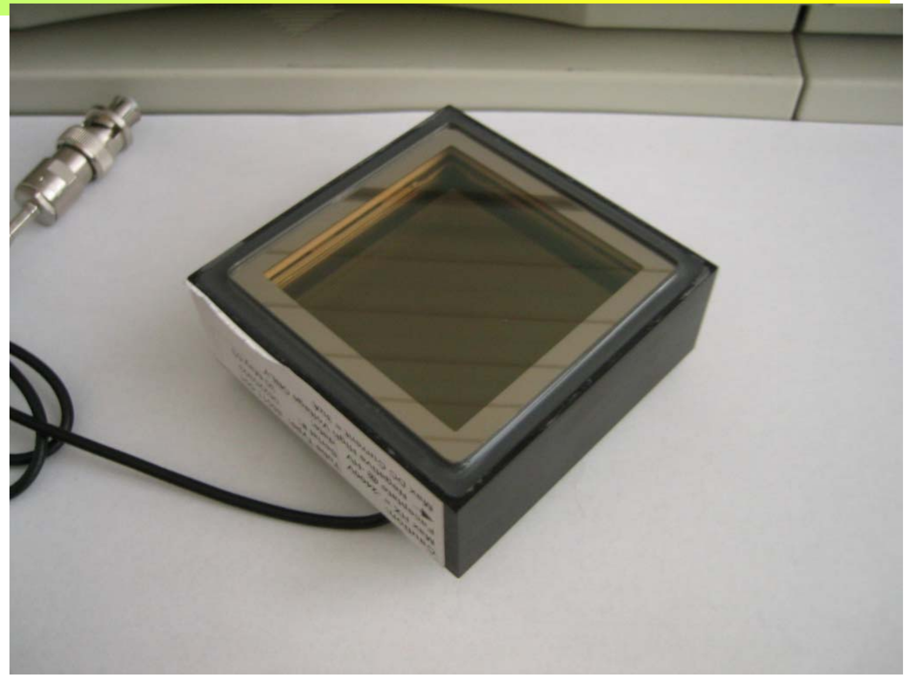


Scanning setup: readout



- laser rate 2kHz (~DAQ rate)
- amplifier: 350MHz (<1ns rise time)
- discriminator: leading edge, 300MHz
- TDC: 25ps LSB(s~11ps)
- QDC: dual range 800pC, 200pC
- HV 2400V

Basic parameters of BURLE MCP-PMTs



- multi-anode PMT with two MCP steps
- bialkali photocathode
- gain ~ 0.6 x 10^6
- collection efficiency ~ 60%
- box dimensions ~ 71mm square
- active area fraction ~ 52%
- 2mm quartz window
- 6mm photocathode-to-MCP distance

BURLE 85011 MCP-PMT

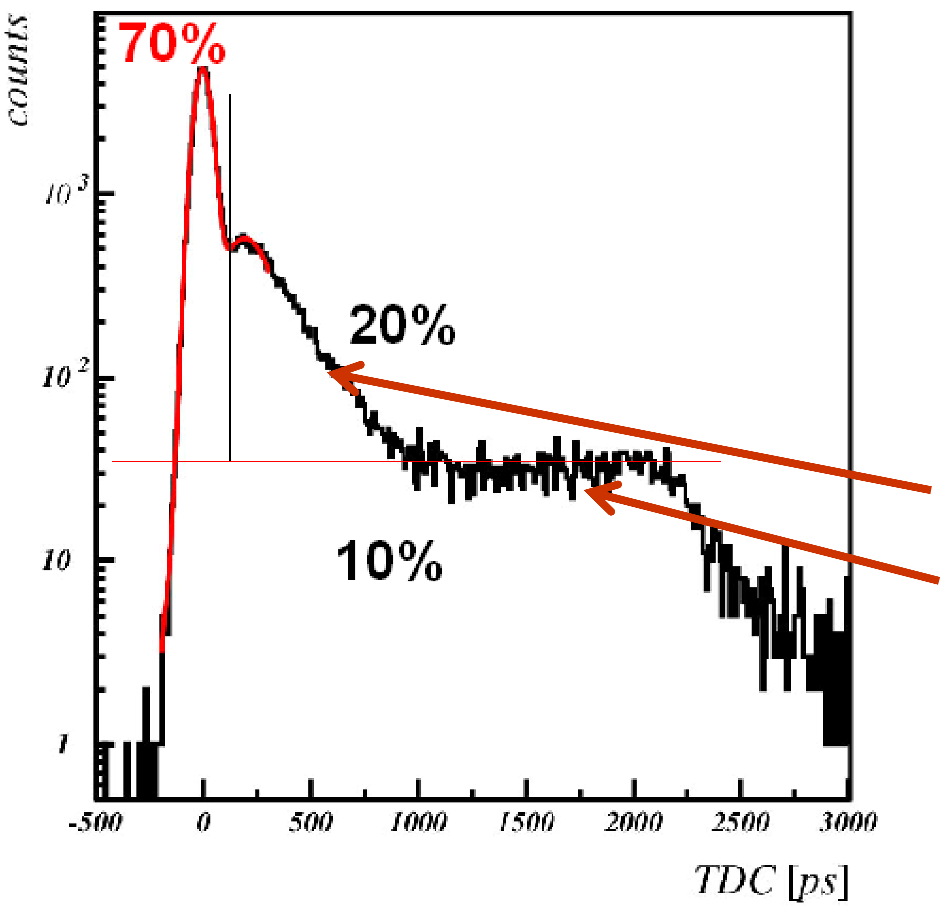
- 64 (8x8) anode pads
- pitch ~ 6.5mm, gap ~ 0.5mm
- 25 μm pores

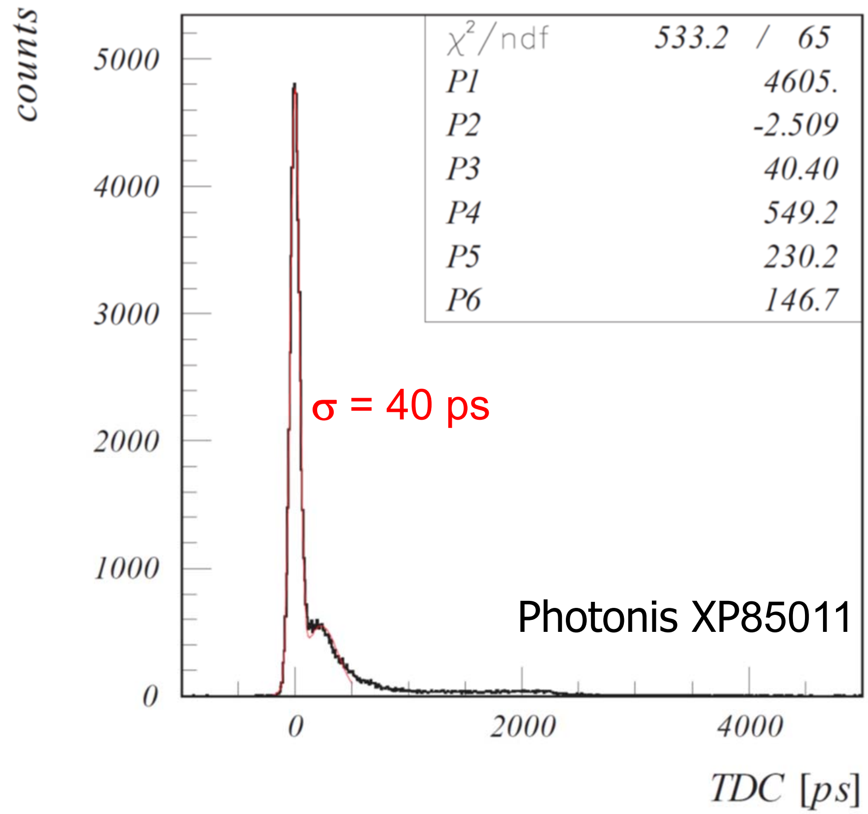
BURLE 85001 MCP-PMT

- 4 (2x2) anode pads
- pitch ~ 25mm, gap ~ 1mm
- 10 μm pores

MCP PMT timing

Time walk corrected photoelectron detection time: main peak with excellent timing accompanied by a tail





- Inelastic back-scattering
- Elastic back-scattering

→good agreement with a simple model

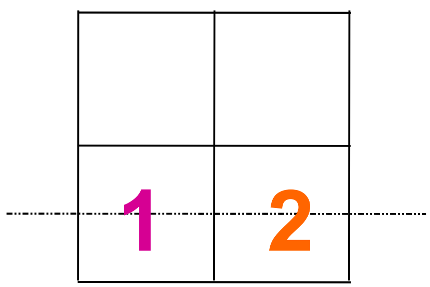
→ NIMA 595 (2008) 169

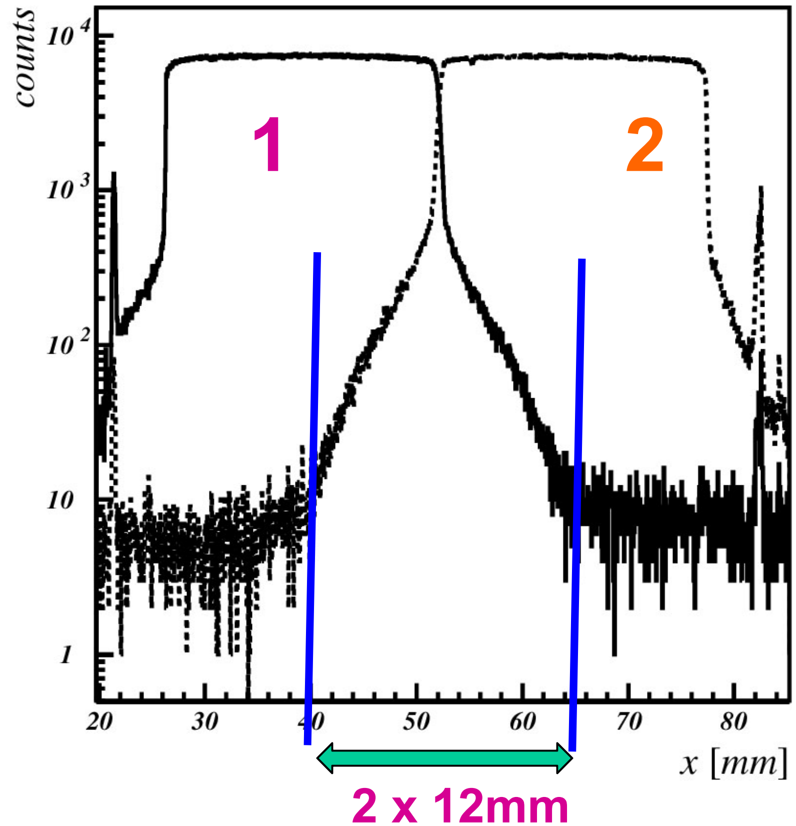
→ JINST 4 (2009) P11017

MCP PMT with 2x2 channels: scan across the tube

- Number of detected signals vs. x
- Small variation over central part
- Long tails from backscattered photo-electrons

Photonis XP85001

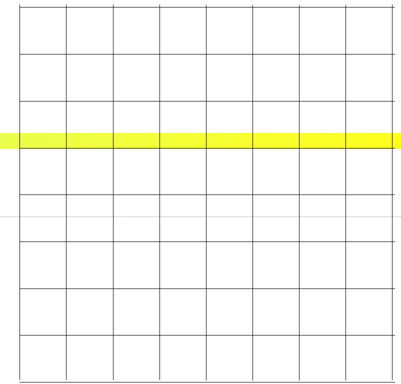




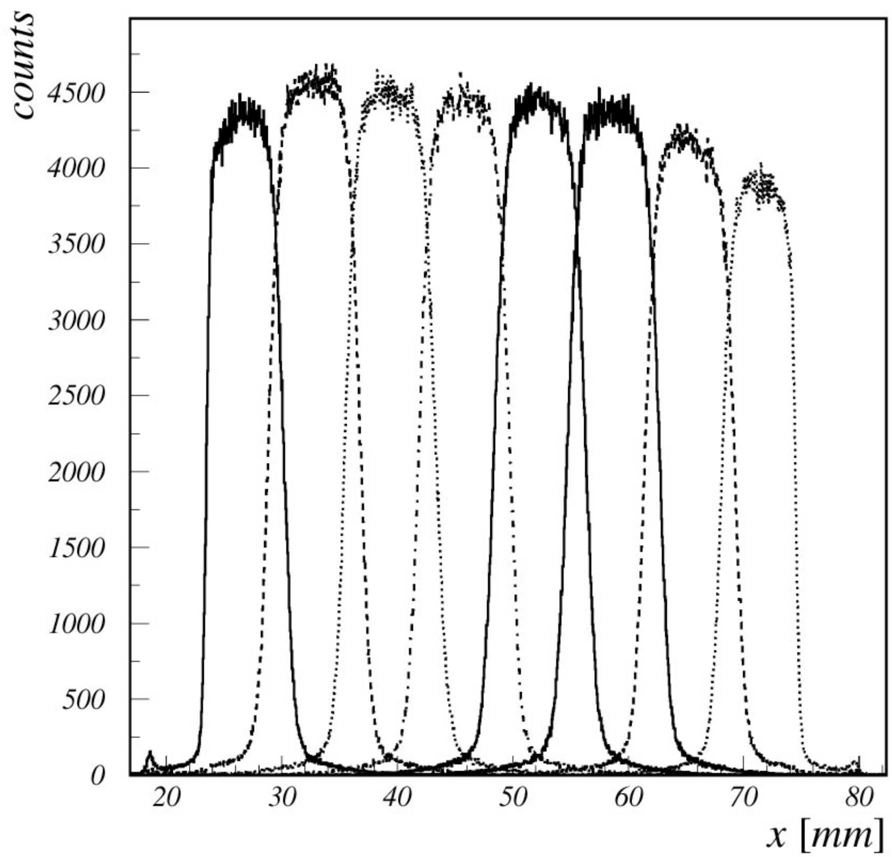
= range of back-scattered photo-electrons

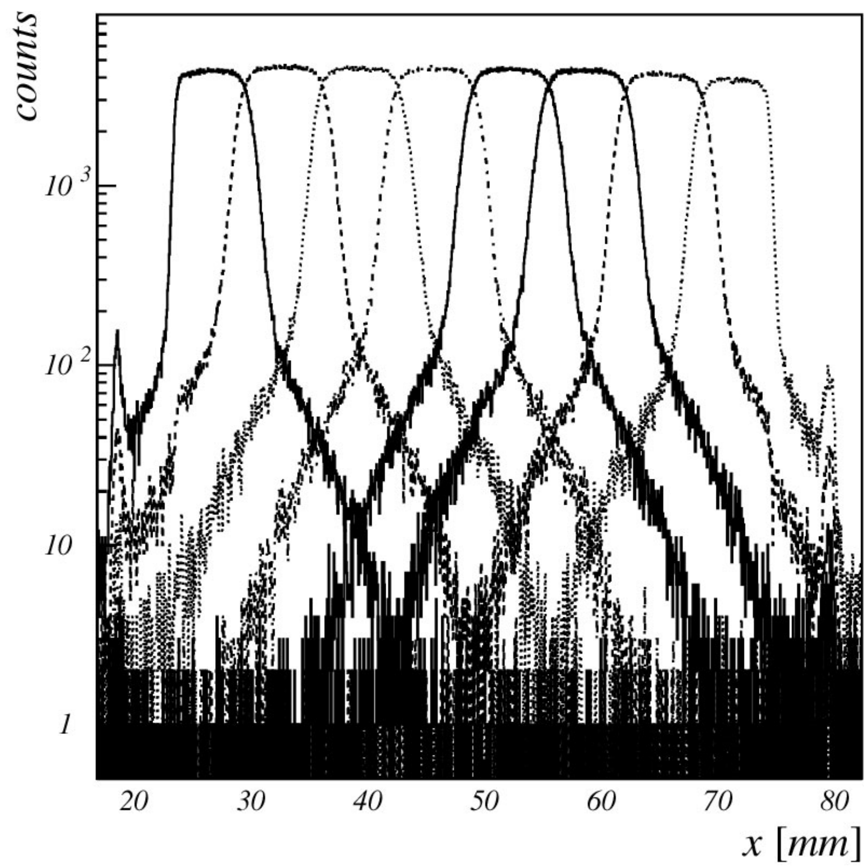
Photonis XP85011

MCP PMT with 8x8 channels: scan across the tube

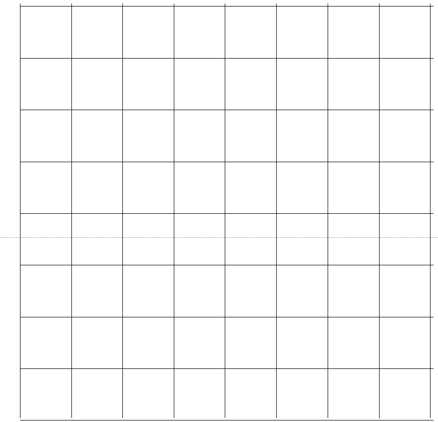


- Number of detected signals vs. x
- Small variation over central part
- Long tails from backscattered photo-electrons



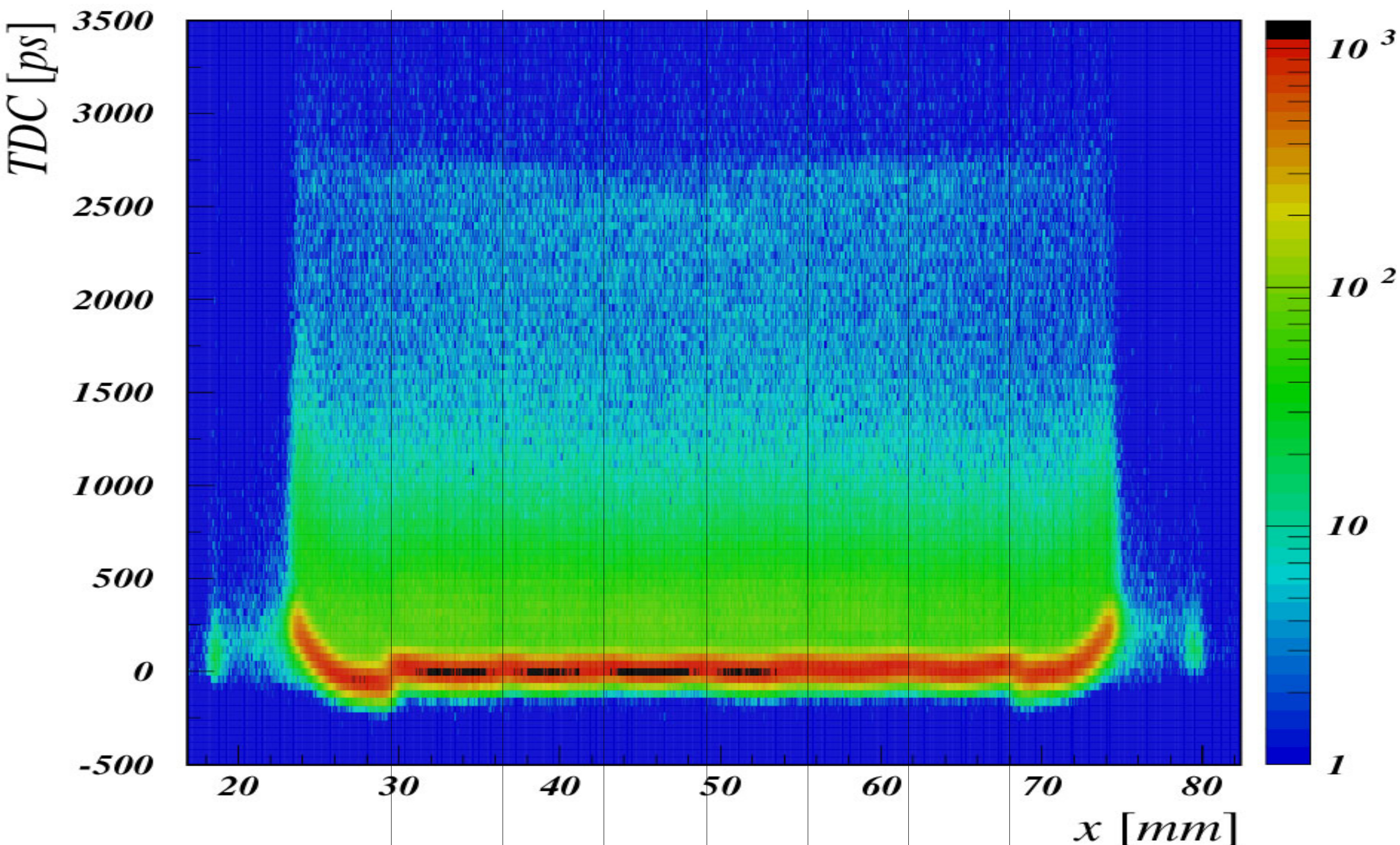


8x8 MCP PMT: Timing uniformity



Scan across the window

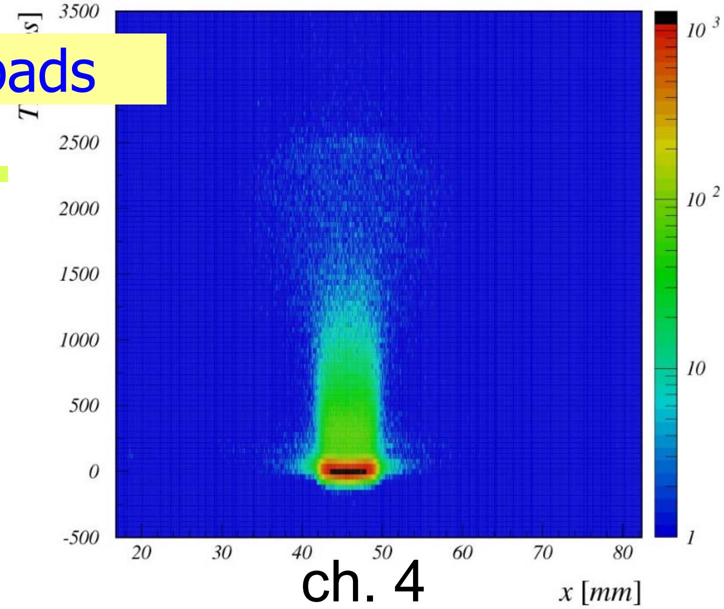
TDC vs. x distribution for all channels

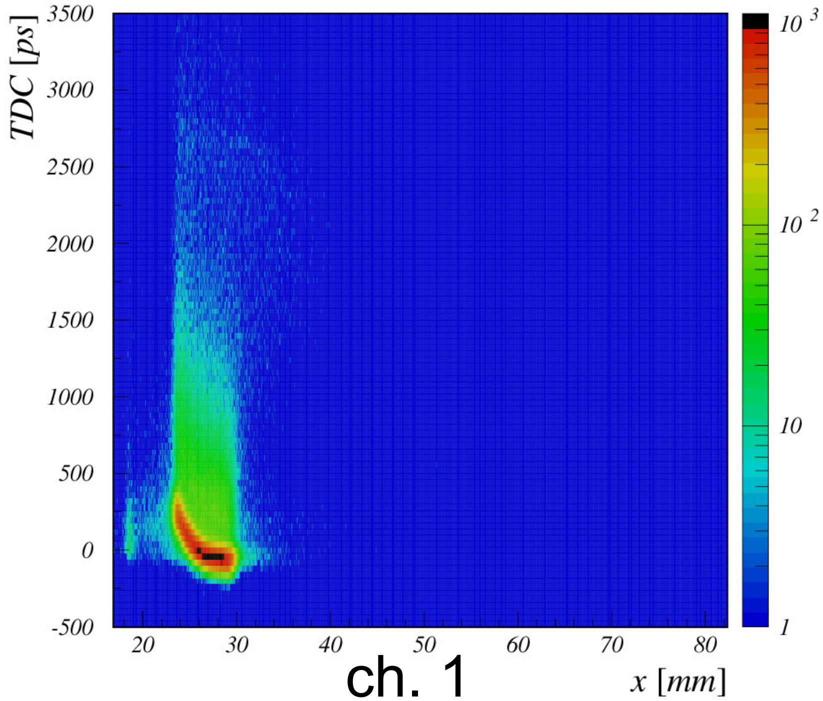


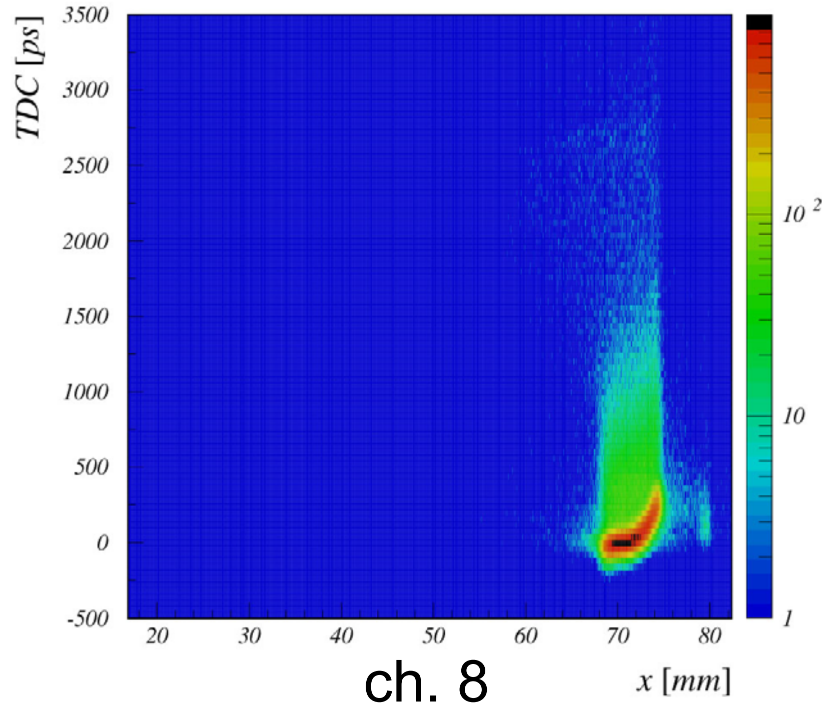
σ = 50.4 | 46.5 | 43.8 | 40.5 | 45.3 | 44.4 | 46.5 | 53.4 ps

8x8 MCP PMT: Timing uniformity for single pads

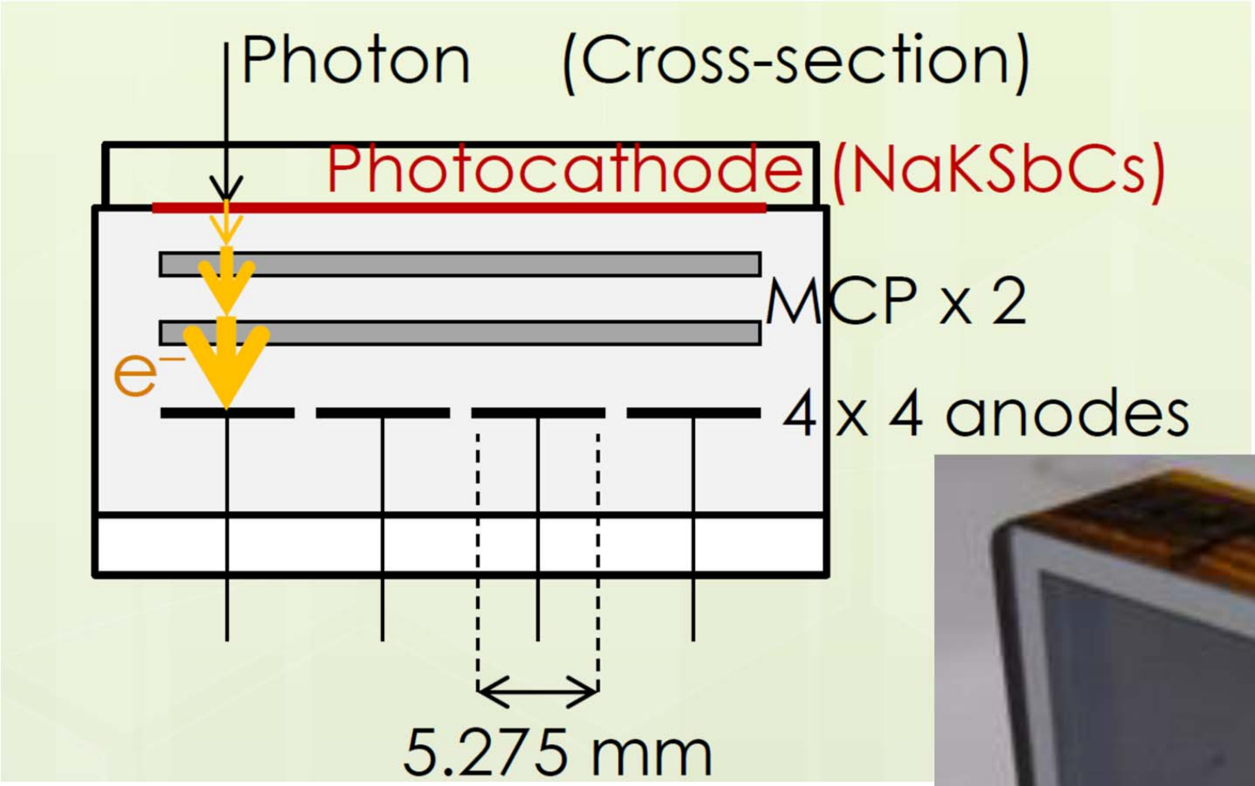
- TDC vs. x correlation of single pads
- uniform for central pads
- large variation for pads at the edge





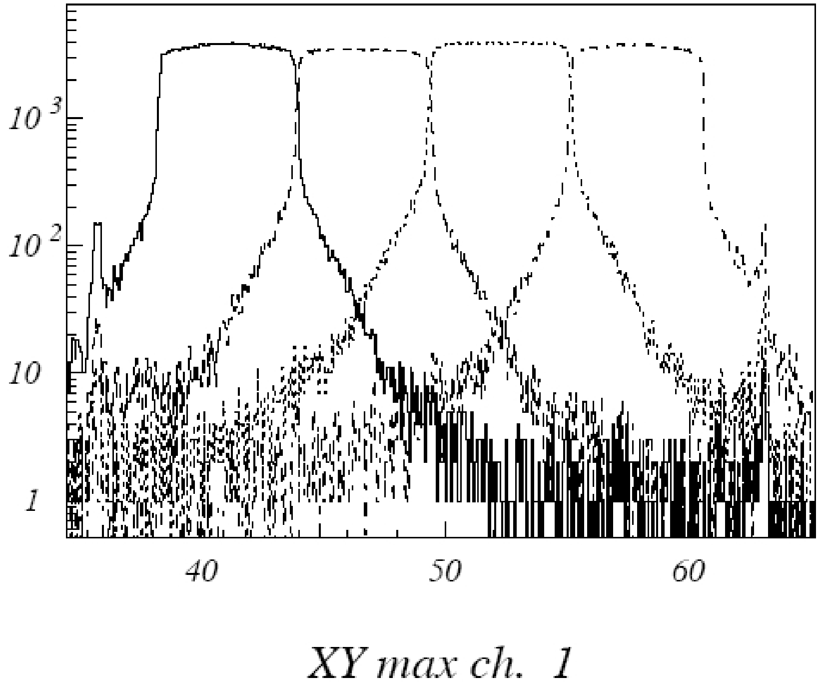


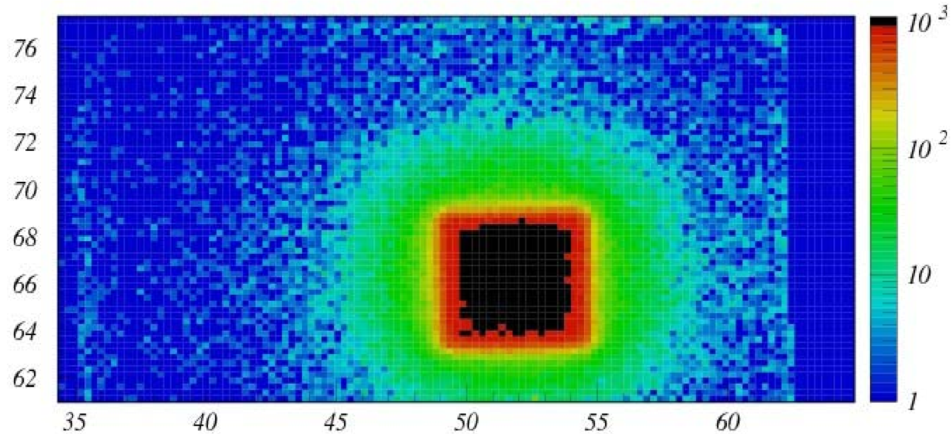
Hamamatsu SL10 MCP PMT

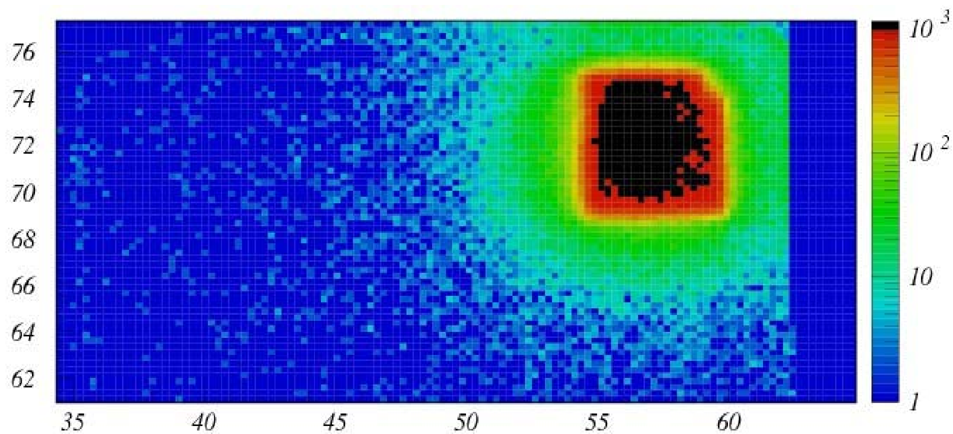


- multi-anode PMT with two MCP steps
- 2mm photocathode-to-MCP distance
- 16 (4x4) anode pads
- 10 μm pores

Hamamatsu SL10 MCP PMT, 4x4: position

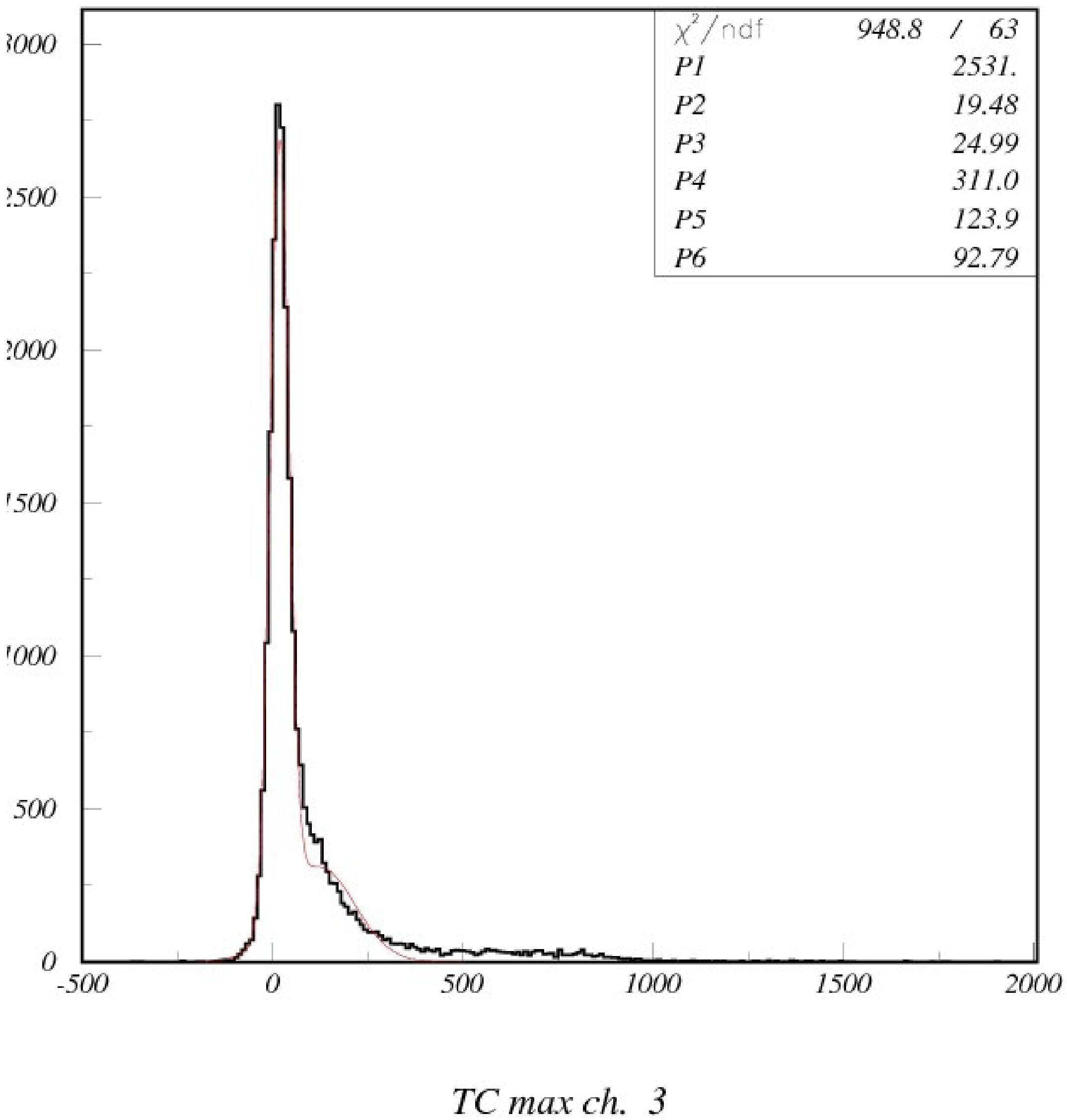


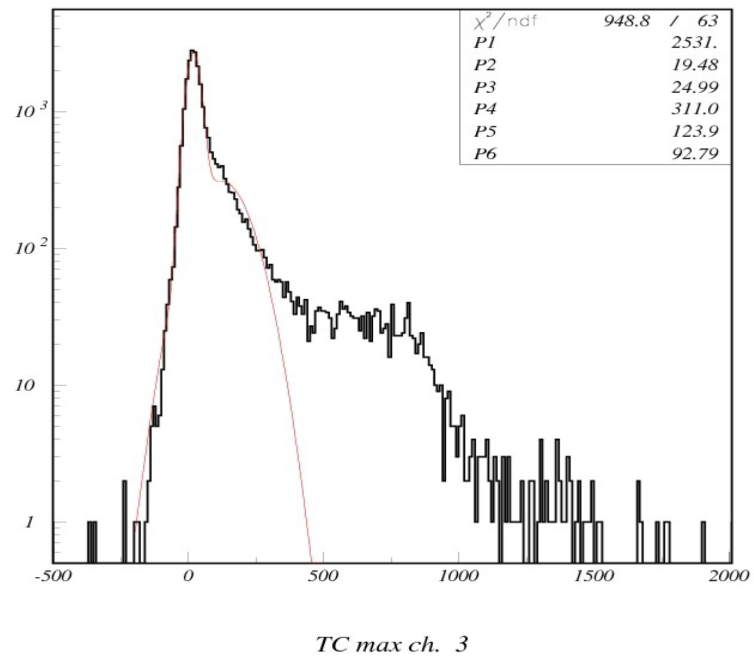




Shorter range of backscattered photoelectrons (up to about 4 mm) due to a smaller (2mm) photocathode-to-MCP distance

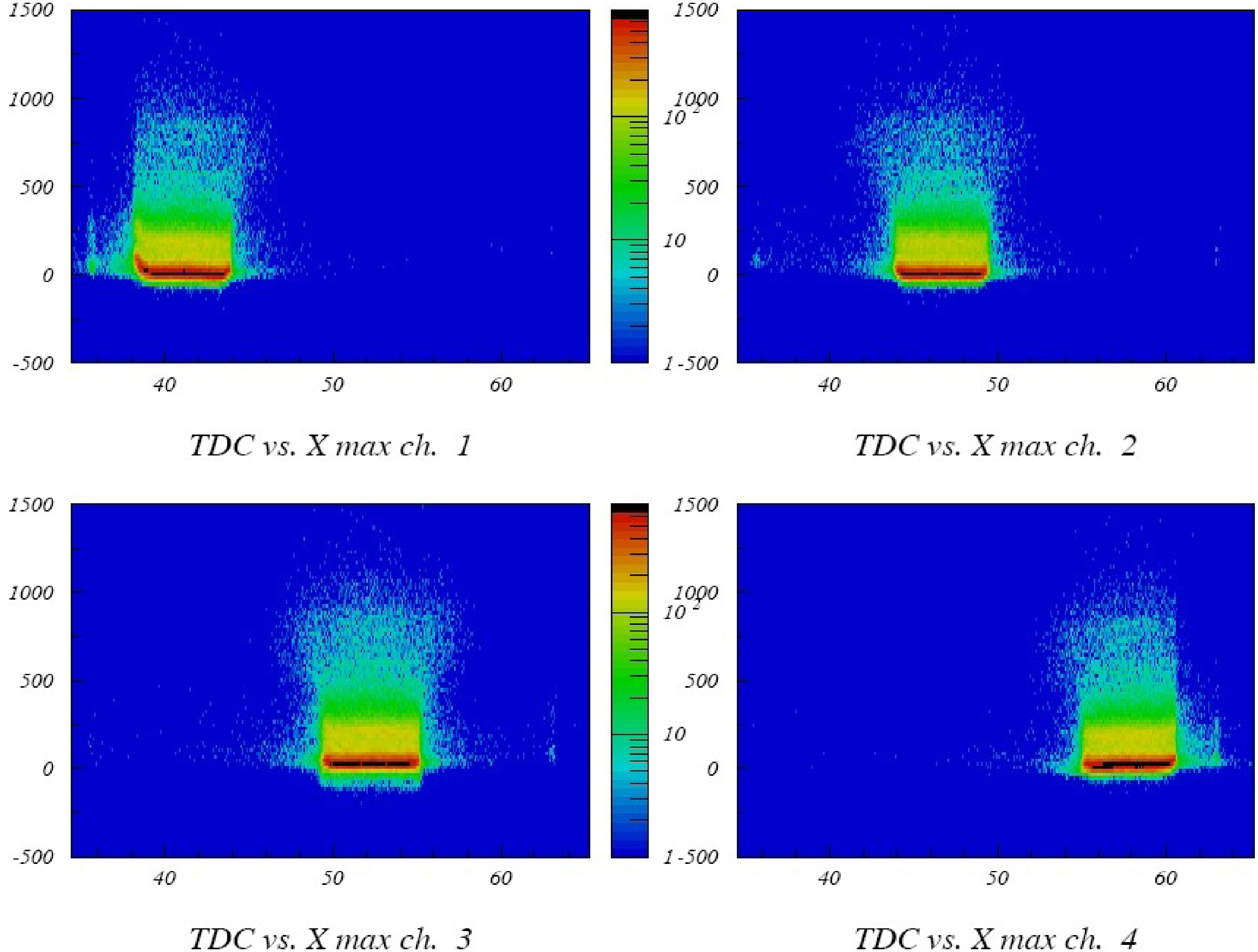
Hamamatsu SL10 MCP PMT 4x4: timing





Shorter constant tail (up to about 0.8 ns) due to a smaller (2mm) photocathode-to-MCP distance

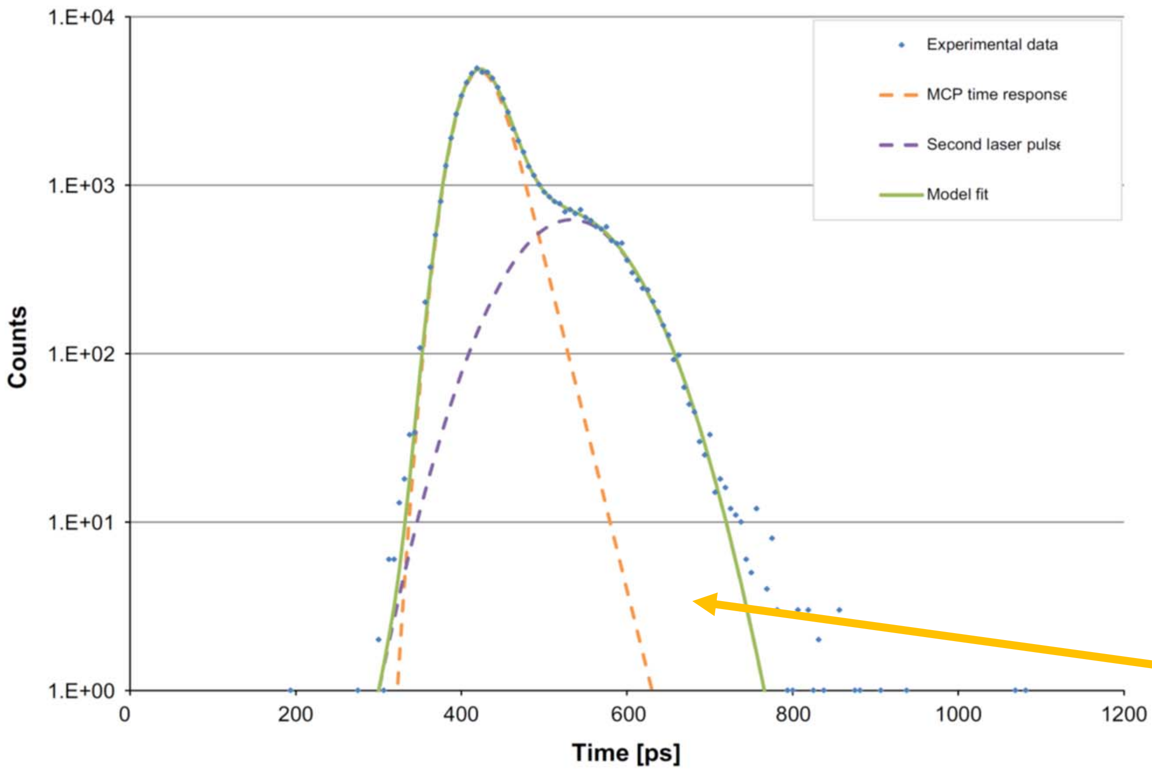
Hamamatsu SL10 4x4: timing, scan across single pads



Smaller gap indeed helps!

Photek PMT225

- 25 mm diameter active area, 10 µm pores, coated using ALD technique
- Photocathode-to-MCP gap: 200 µm

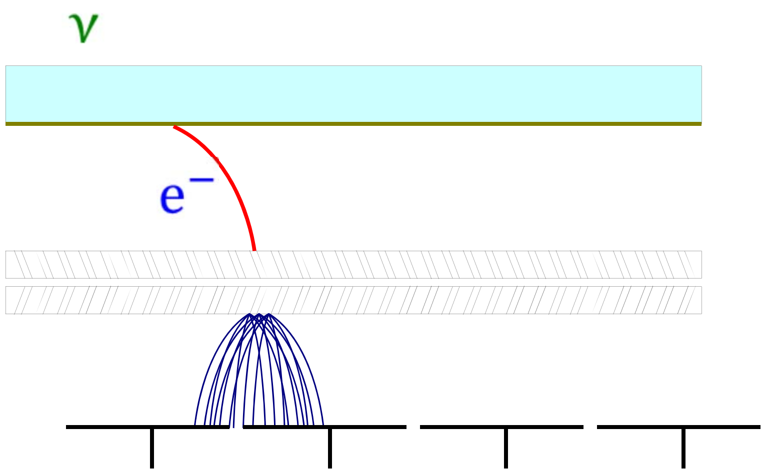


Expected elastic backscattering range: 100ps

Secondary laser peak

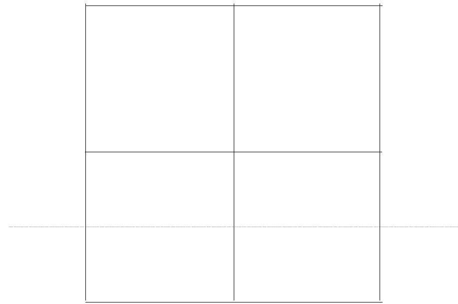
→ L. Castillo Garcia et al NIMA 787 (2015) 197

Charge sharing



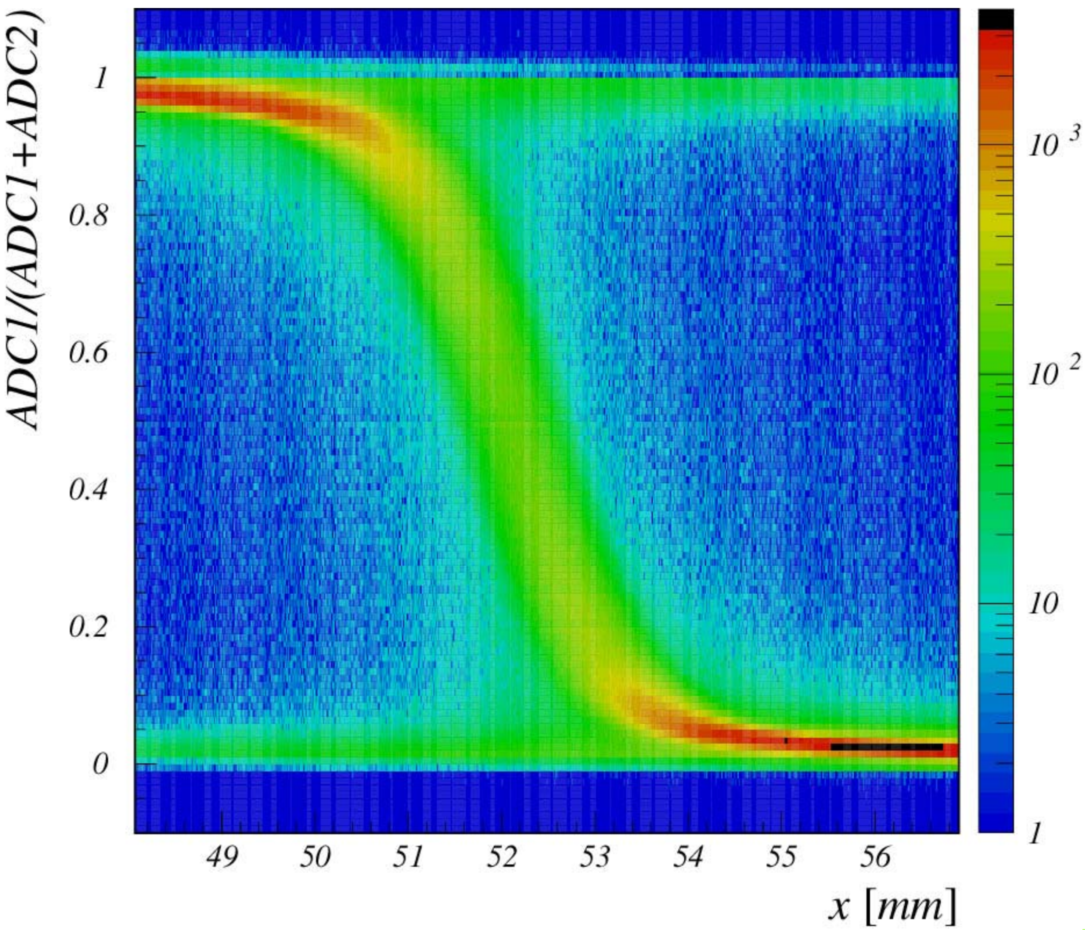
Charge sharing

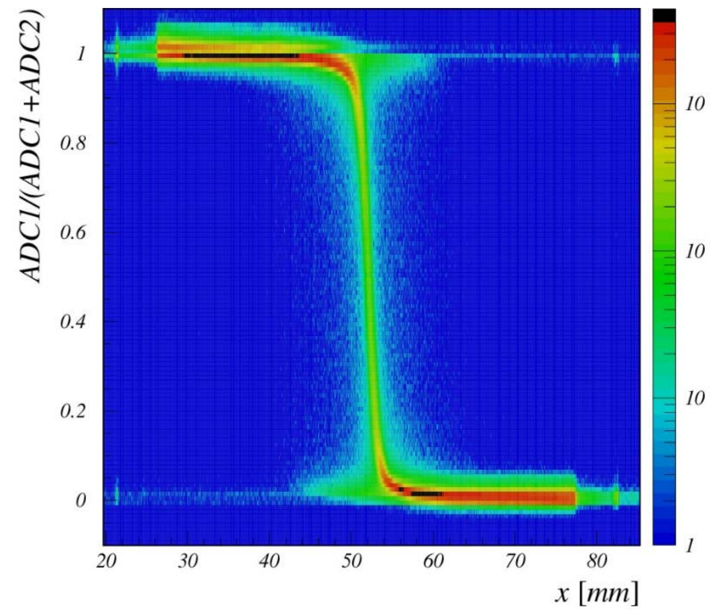
Scan with the laser spot across the entrance window



Fraction of the signal detected on channel 1 vs. x position of light spot

Photonis XP85001



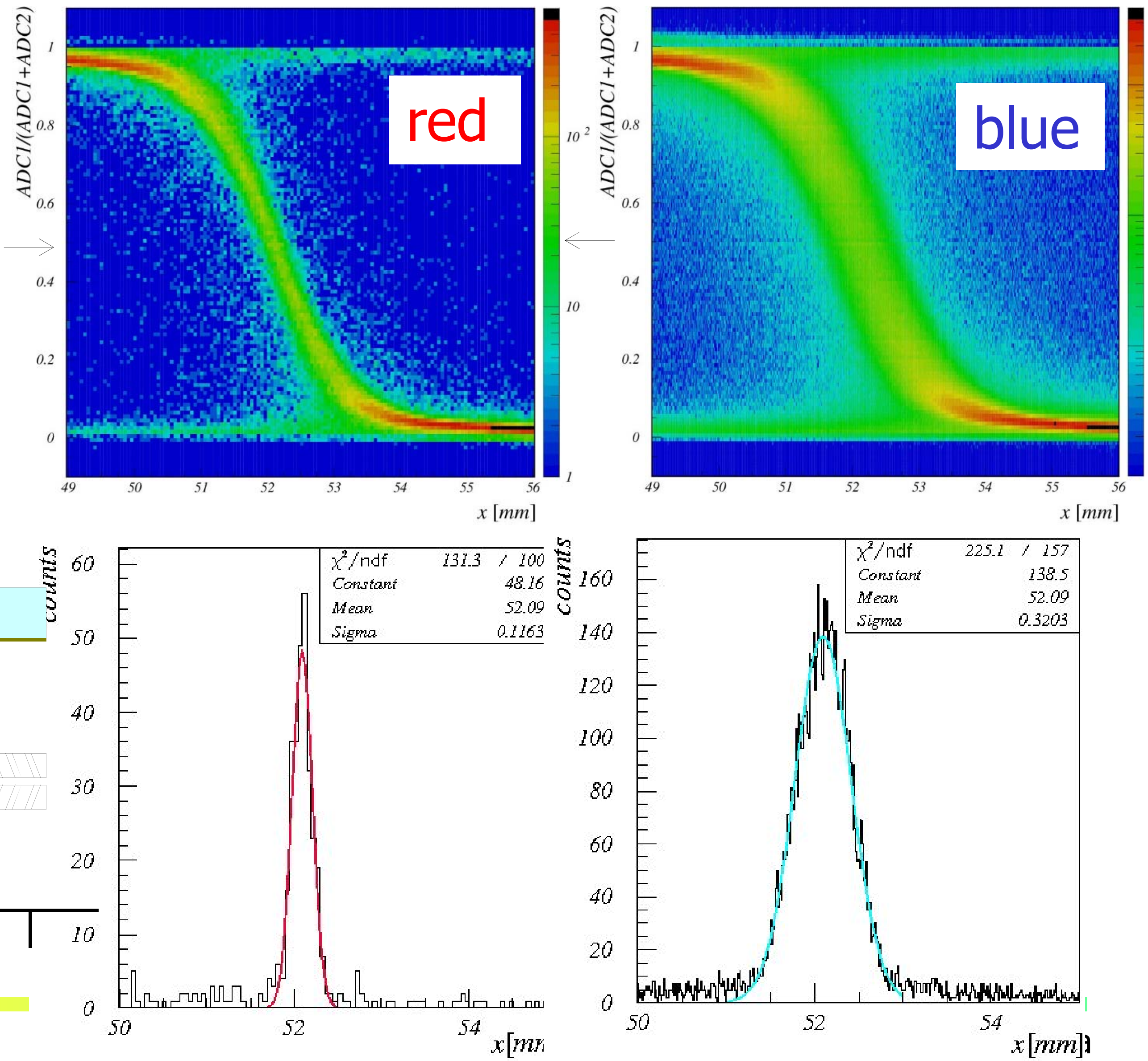


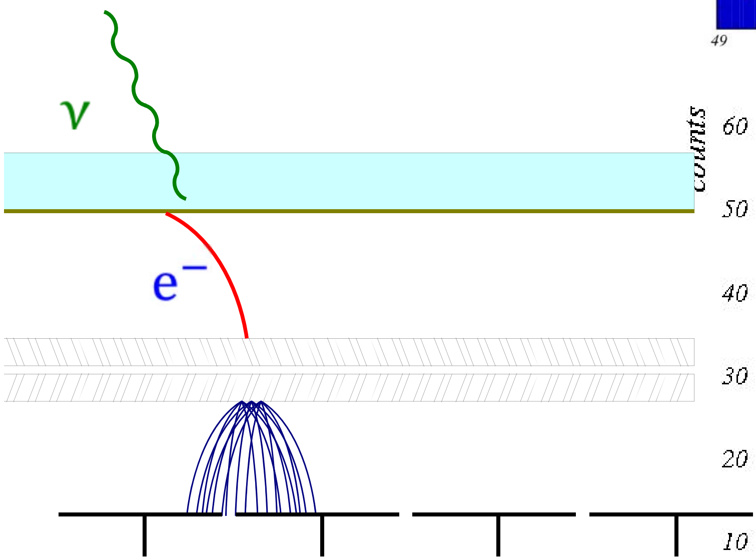
- sizable charge sharing in ~2mm wide boundary area
- can be used to improve position resolution

Charge sharing

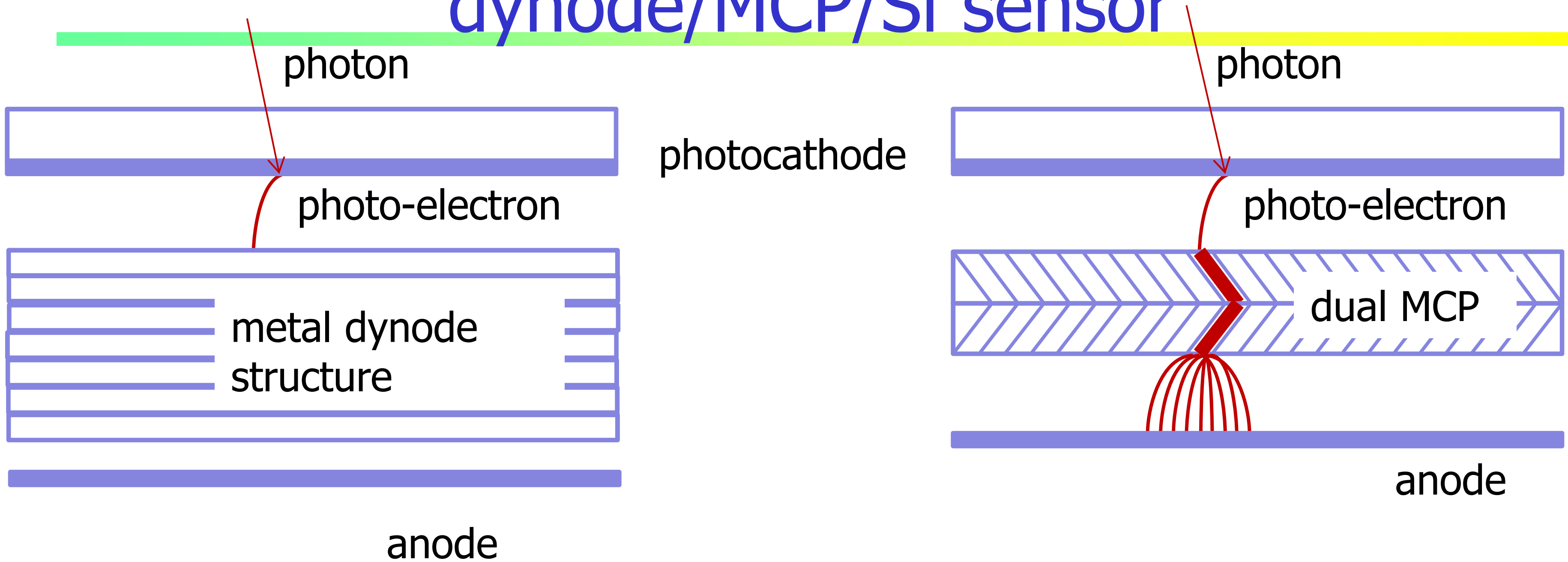
Photonis XP85001

Comparison of the charge sharing effect for red (635 nm, left) and blue (405 nm, right) laser

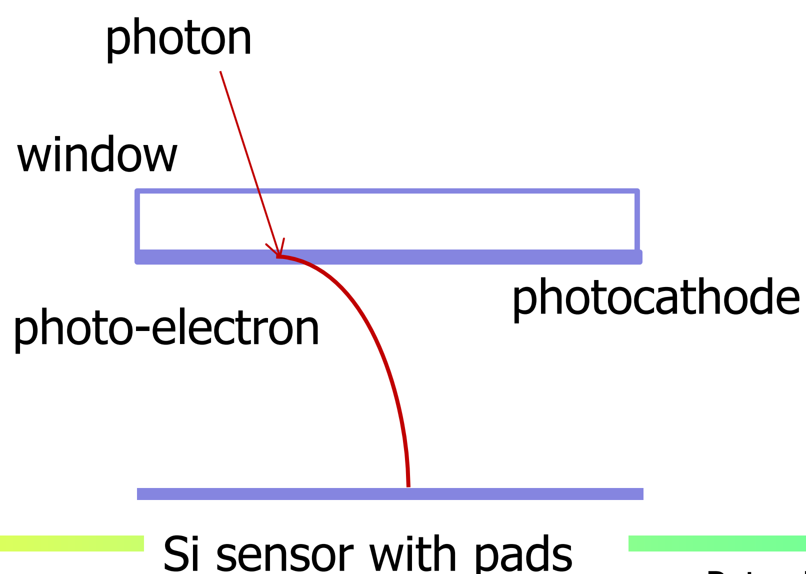




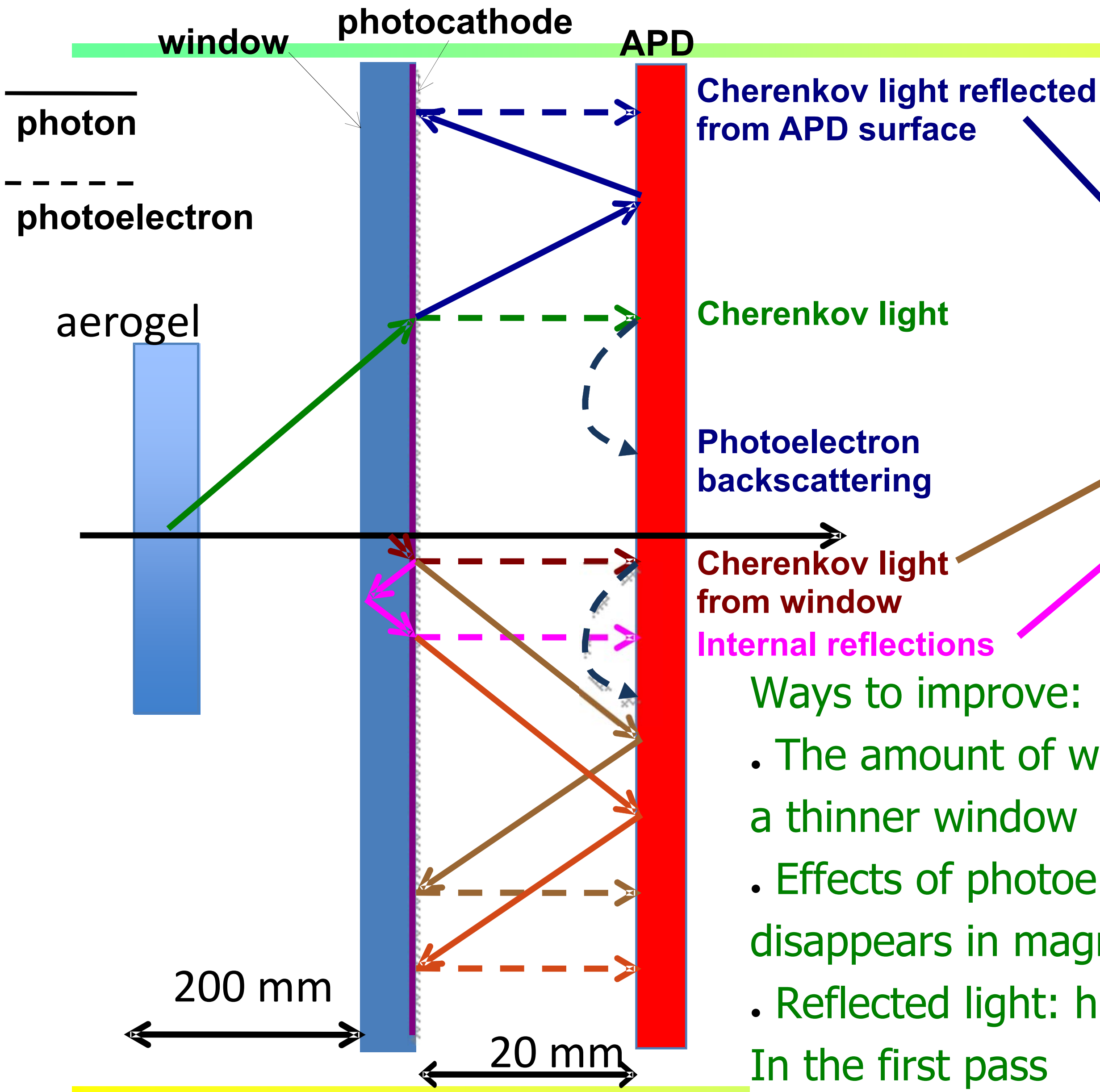
Backscattering, light reflection from the first dynode/MCP/Si sensor

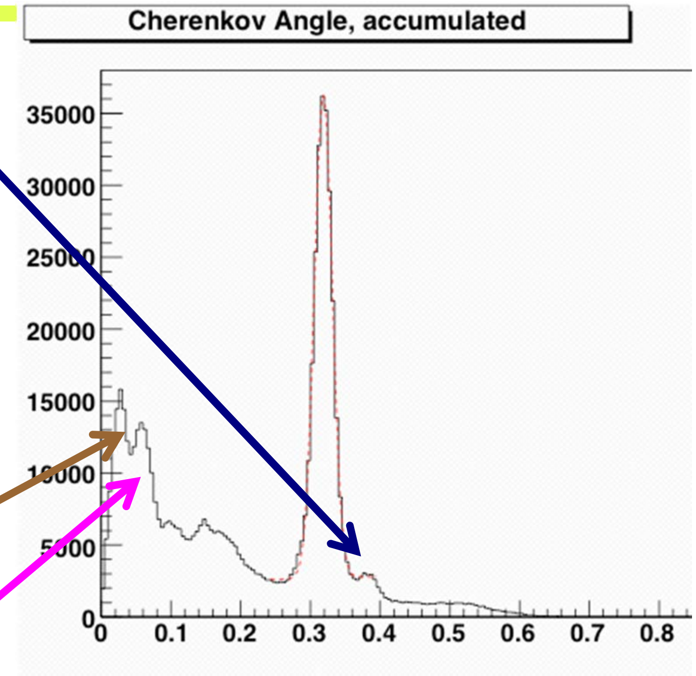


Similar geometries in the photo-electron step
→ A lot of similarities between prox. focusing H(A)PD, MCP PMTs and MA-PMTs



Hybrid (avalanche) photodetector – H(A)PD



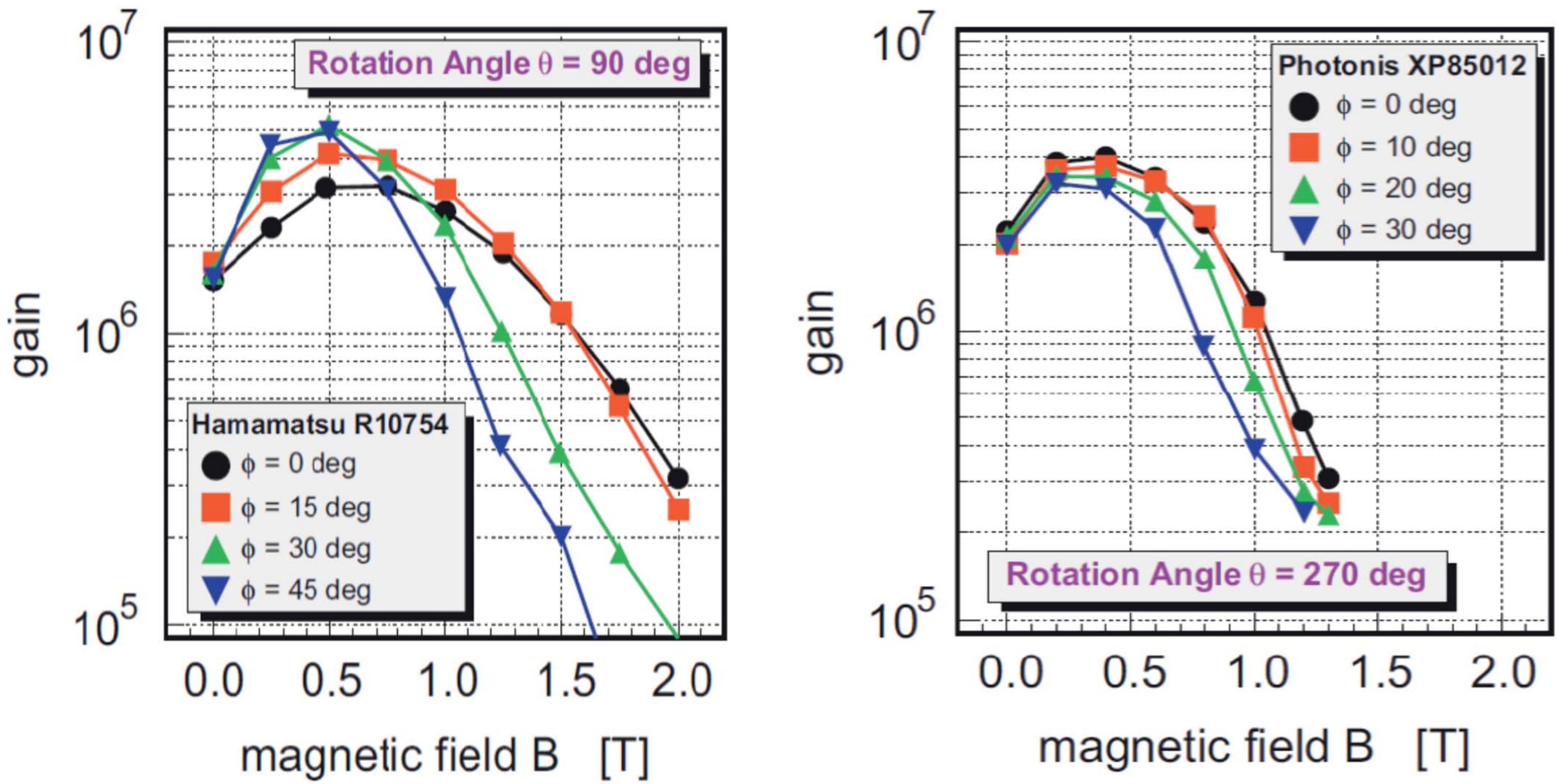


Ways to improve:

- The amount of window light can be reduced by a thinner window
- Effects of photoelectron backscattering disappears in magnetic field
- Reflected light: higher QE, more absorption In the first pass
- Anti-reflective coating?

MCP PMTs in magnetic field

Gain vs B field for different tilt angles



→ A. Lehmann et al NIMA 639 (2011) 144

MCP PMT: Gain in magnetic field

Gain as a function of magnetic field for different operation voltages and as a function of applied voltage for different magnetic fields.

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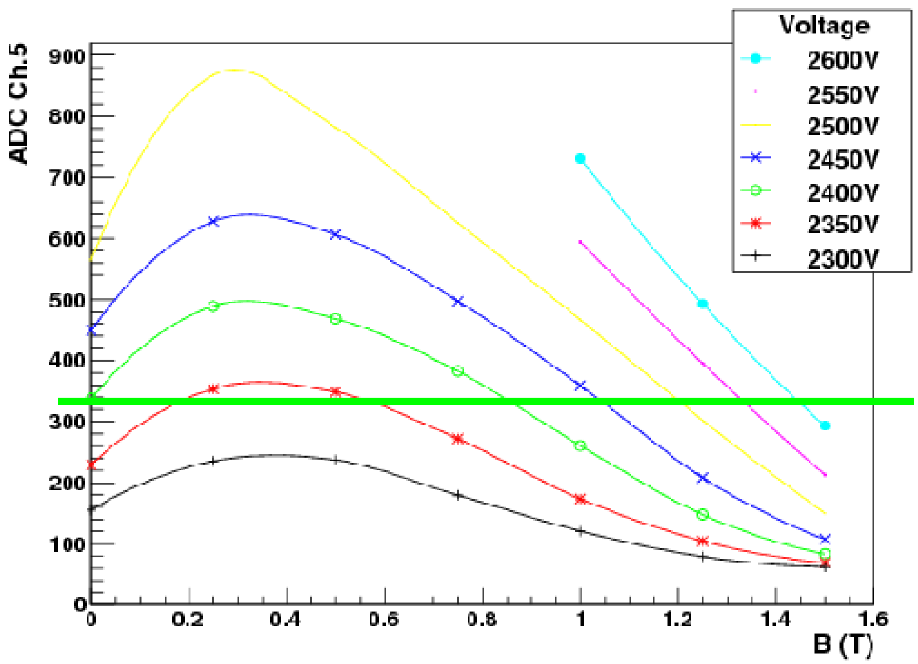
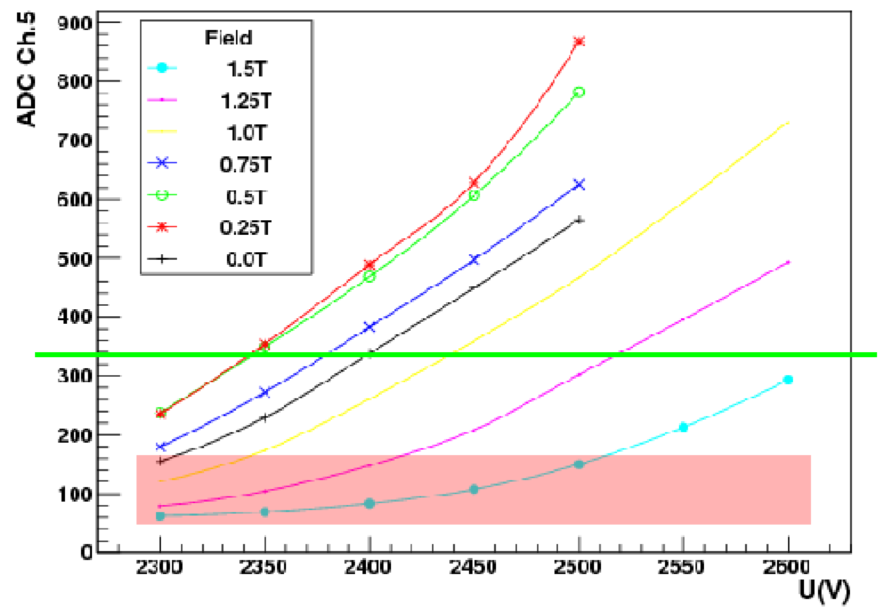
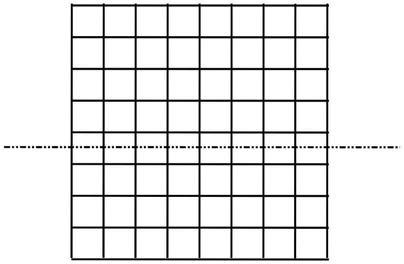




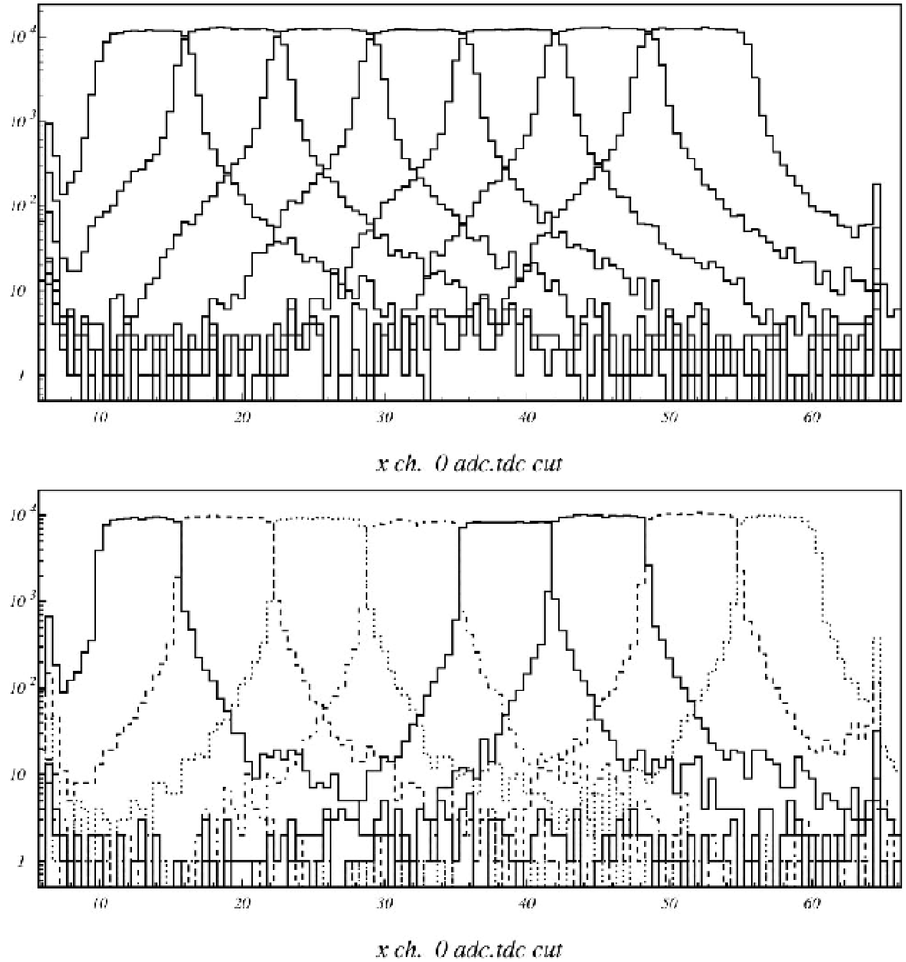
High B field: no problem, to run at the same gain HV → +200V

In the presence of magnetic field, charge sharing and cross talk due to long range photoelectron back-scattering are considerably reduced.



MCP PMT: improved performance in magnetic field

Photonis XP85011



Number of detected hits on individual channels as a function of light spot position.

B = 0 T,
HV = 2400 V

B = 1.5 T,
HV = 2500 V

Backscattered photoelectrons get ″locked″ to the B field lines

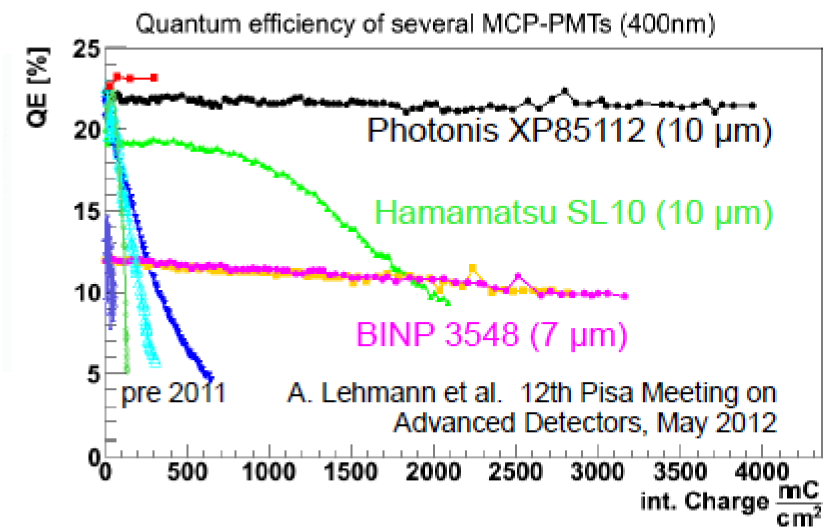
In the presence of magnetic field, charge sharing and cross talk due to long range photoelectron back-scattering are considerably reduced.

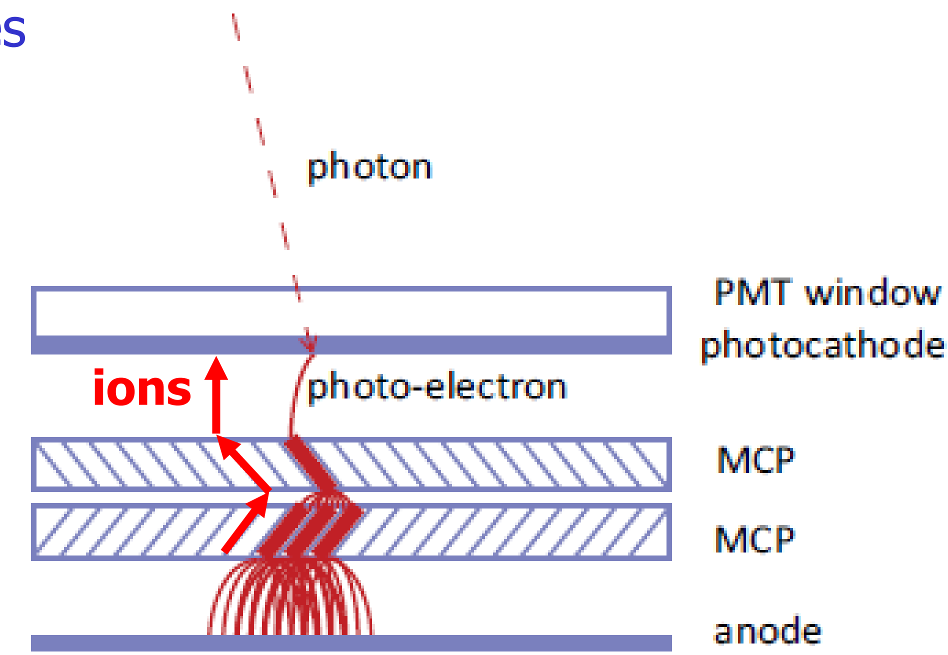
MCP PMTs ageing

MCP PMT ageing: a serious problem in most of the planned aplications.

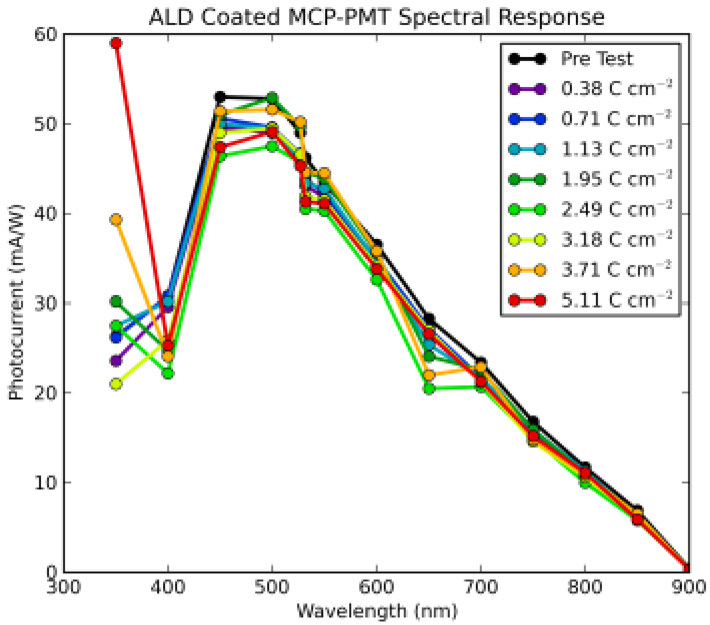
Cures:

- Better cleaning of the MCPs, better vacuum
- Al foil between PC and first MCP
- Al foil between two MPC stages
- Atomic layer deposition (ALD)





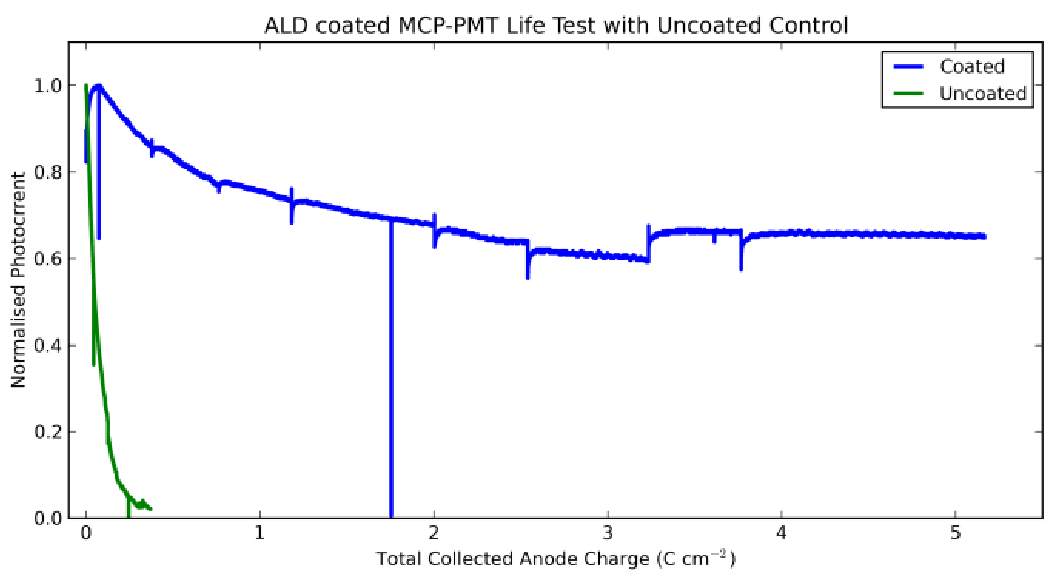
MCP PMTs ageing, cure

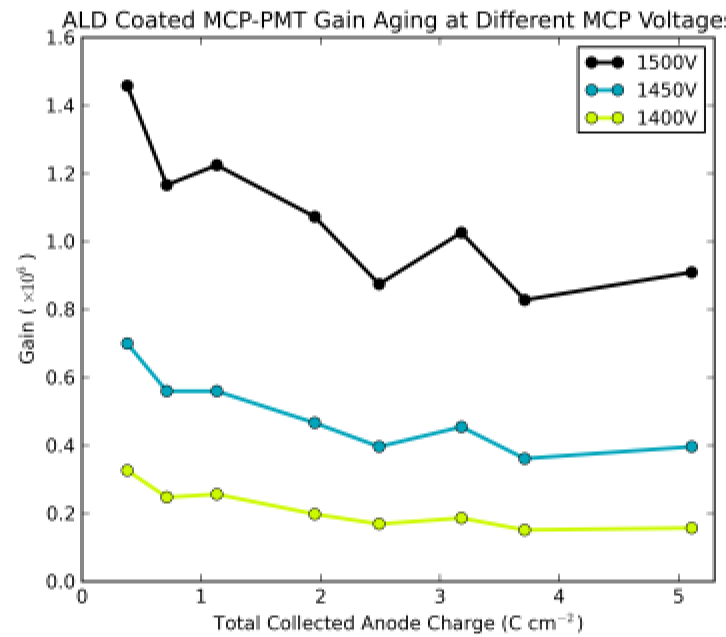


Photek, ALD deposition

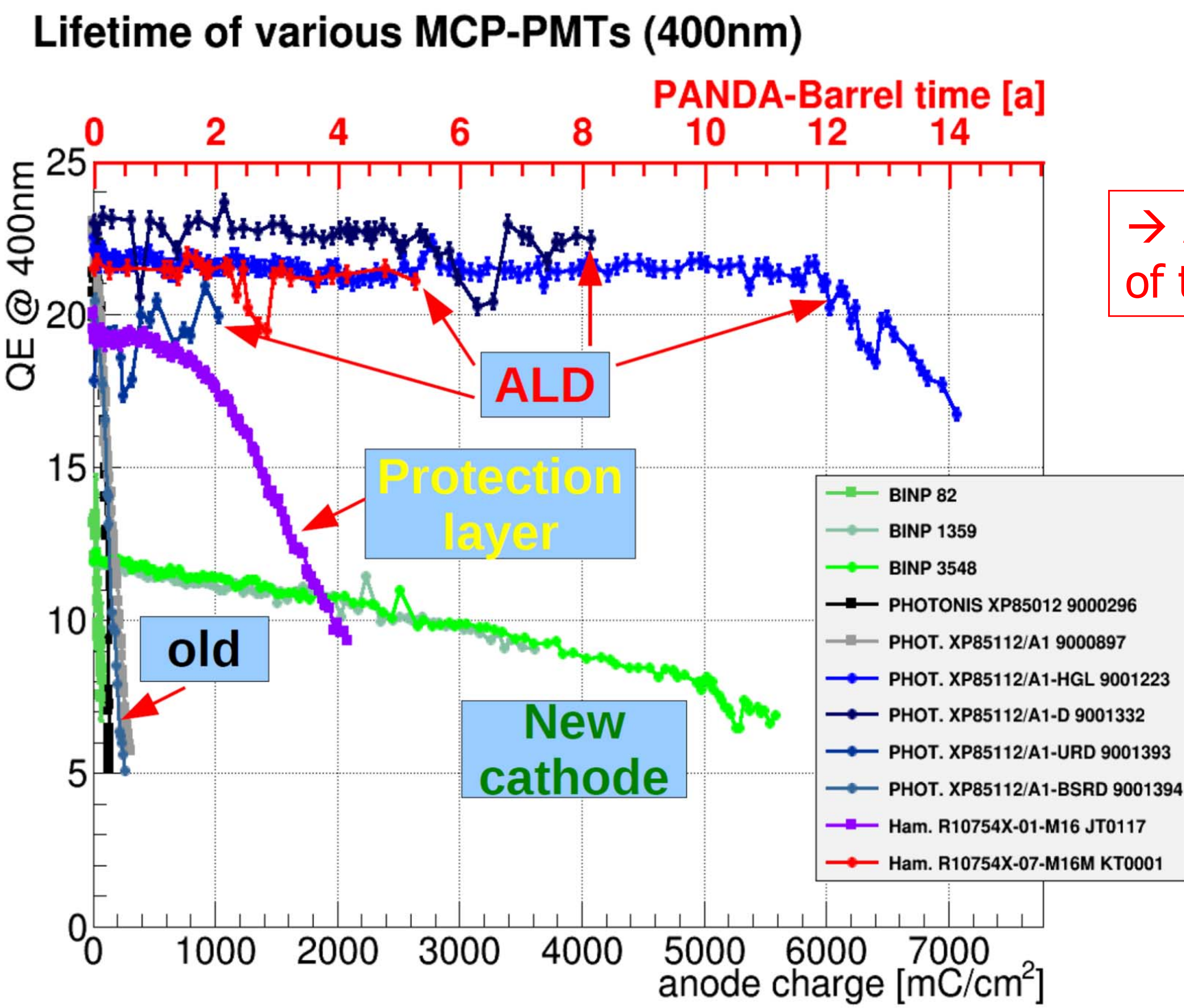
No drop in QE after 5 C/cm^2

Photo current drop due to a reduced gain (microchannel plate ageing)





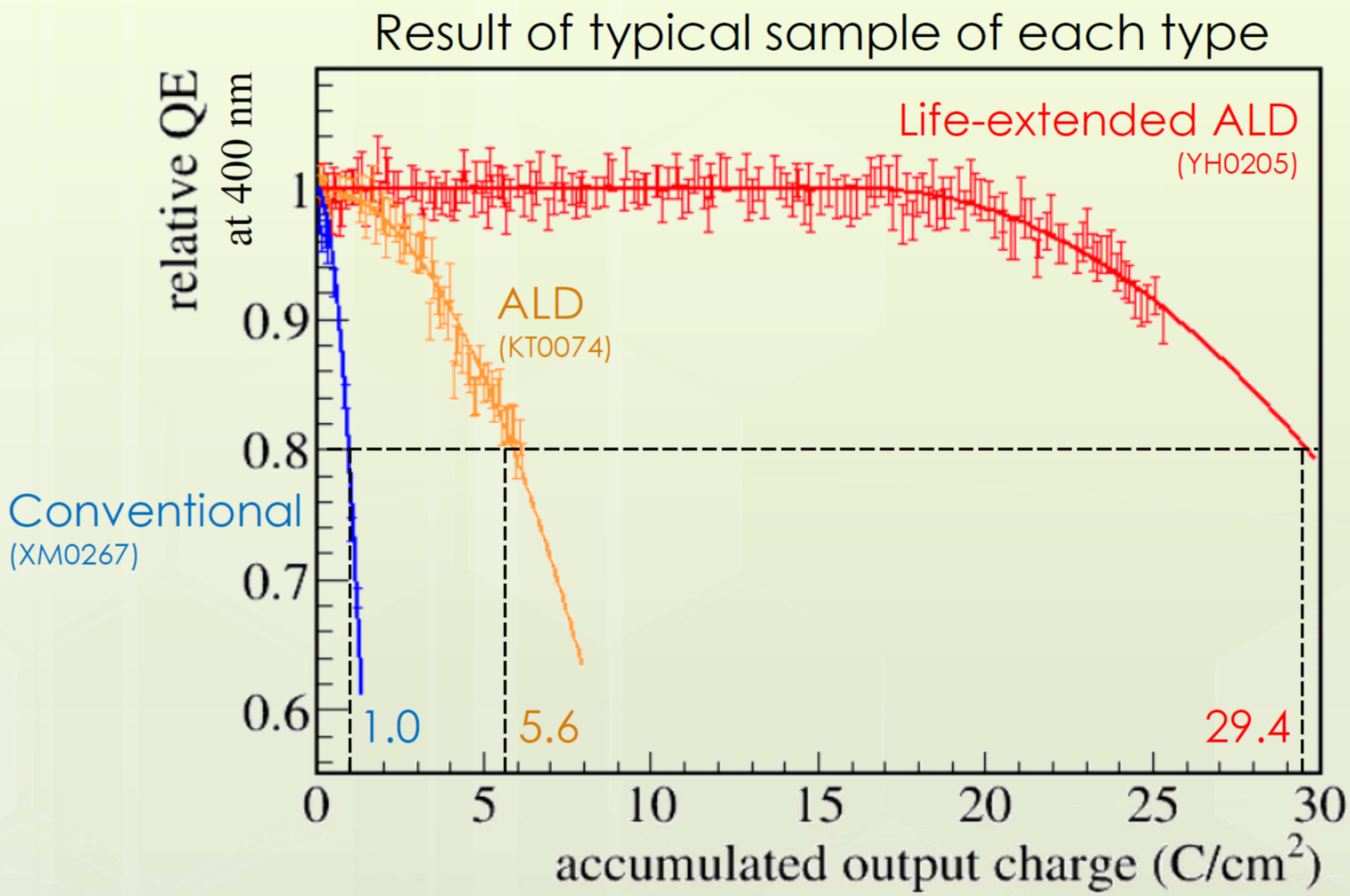
Aging study by A. Lehmann et al (for the Panda DIRC)



→ ALD is the name of the game

Result of the lifetime test

K. Matsuoka, MCP PMTs for TOP, RICH2016

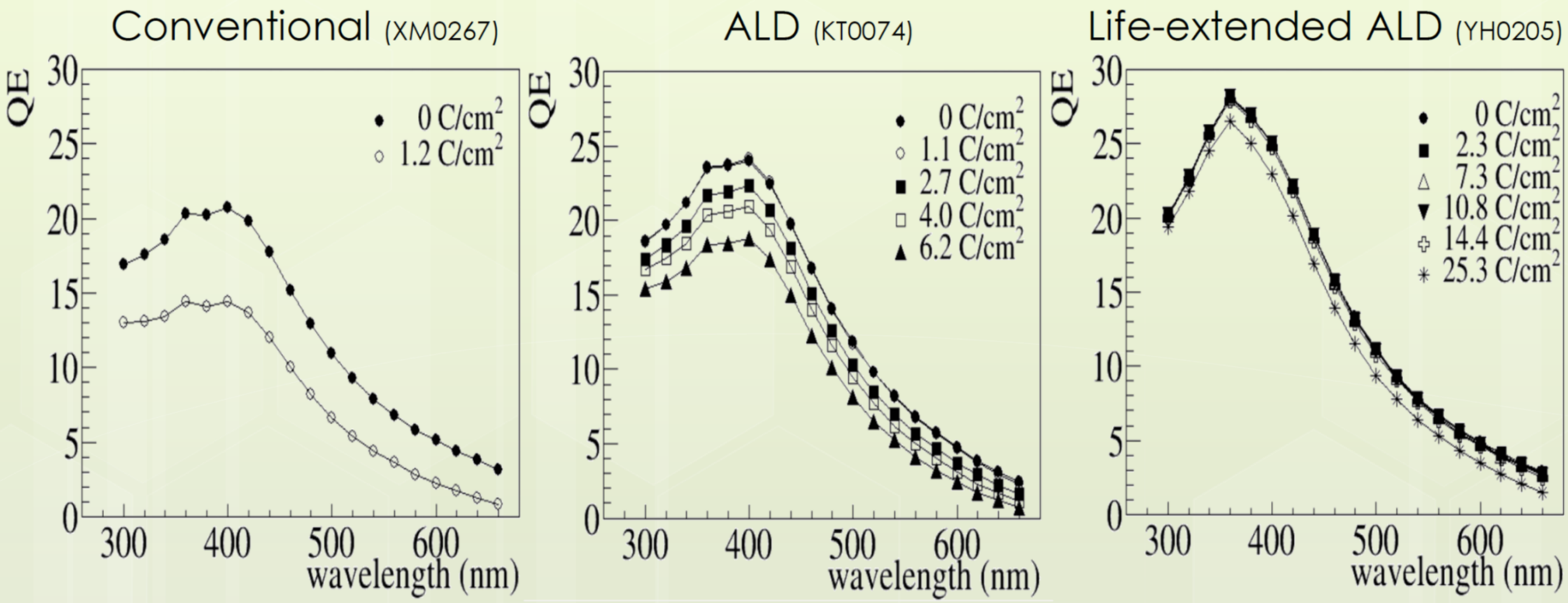


- The QE depression curve is represented by $\frac{\mathrm{QE}(Q)}{\mathrm{QE}_{\mathrm{inital}}} = 1 - 0.2(Q/Q_\tau)^2$
- Longer lifetime with ALD and much longer with life-extended ALD
  =with reduced residual gas

QE spectrum after the lifetime test

K. Matsuoka, MCP PMTs for TOP, RICH2016

- Measured by Xe lamp + monochromator



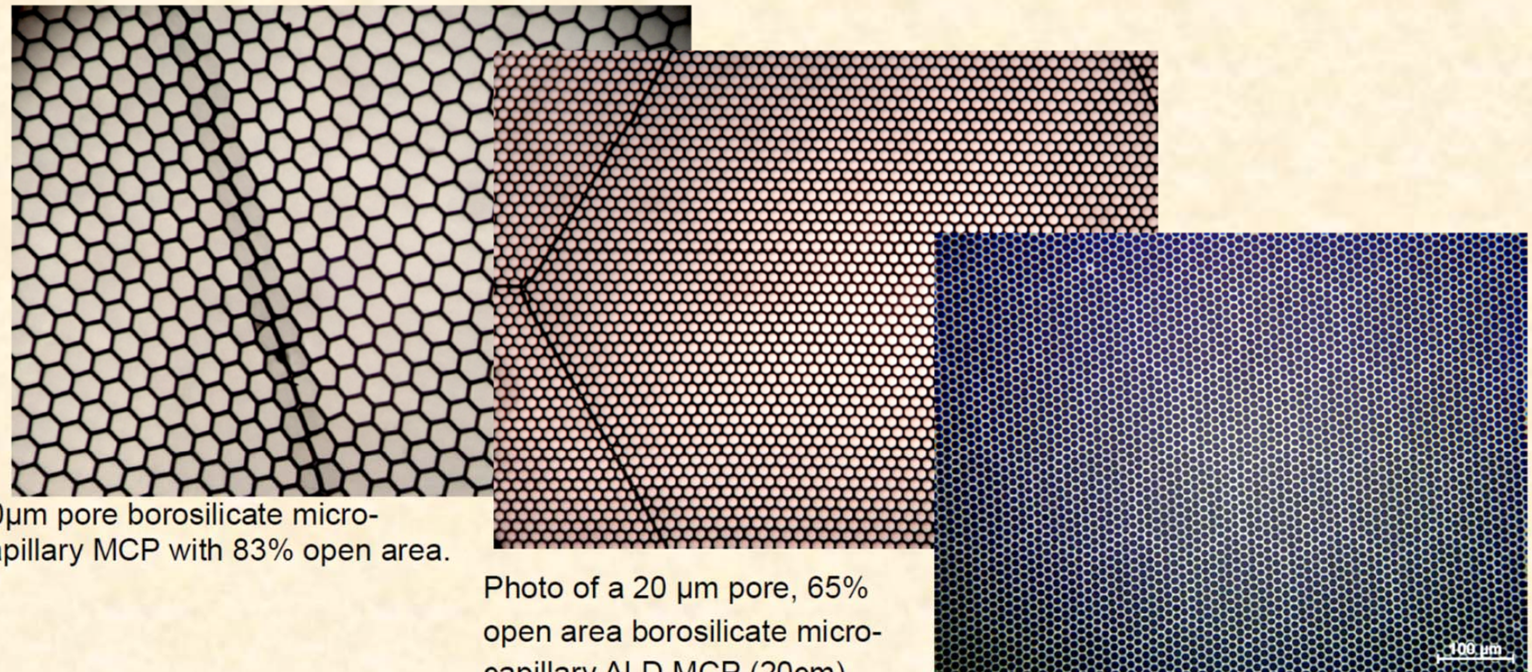
✓ Consistent with the in-situ QE measurement by the laser at 400 nm.

✓ The QE drops more significantly at longer wavelengths as the work function of the photocathode increases.

ALD for MCP PMTs: born at U Chicago.
ALD can turn a borosilicate glass substrate into an MCP

Borosilicate Substrate Atomic Layer Deposited Microchannel Plates

Micro-capillary arrays (Incom) with 10µm, 20 µm or 40µm pores (8° bias) – borosilicate glass. l/d typically 60:1, but can be much larger. Open area ratios from 60% to 83%. Fabricated with using hollow tubes (no etching). Separate resistive and secondary emissive layers are applied (ANL, Arradiance) using atomic layer deposition to allow these to function as MCPs. ALD secondary emissive layers can also be applied to “standard” MCPs to improve yield.



40µm pore borosilicate micro-capillary MCP with 83% open area.

Pore distortions at multifiber boundaries, otherwise very uniform.

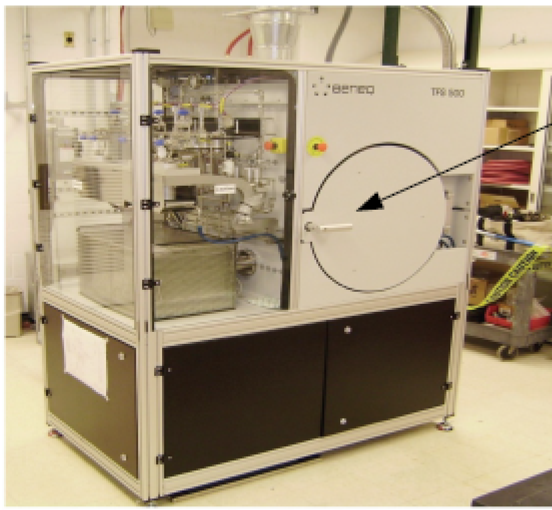
Photo of a 20 µm pore, 65% open area borosilicate micro-capillary ALD MCP (20cm).

Photo of a 10 µm pore, 60% open area borosilicate micro-capillary ALD MCP.

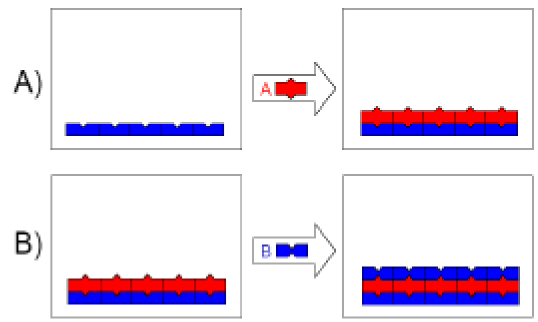
LAPPD – Large Area Picosecond Photon Detector

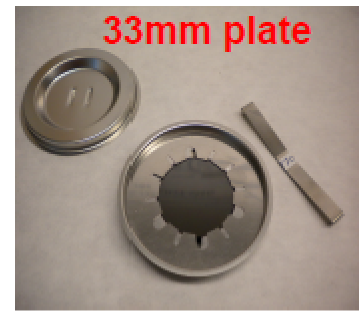
MCP by Atomic Layer Deposition (ALD)

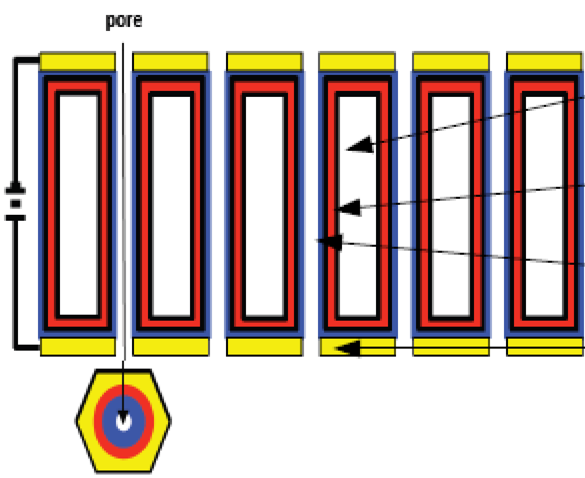
University of Chicago



Beneq reactor for ALD
@Argonne National Laboratory
A.Mane, J.Elam





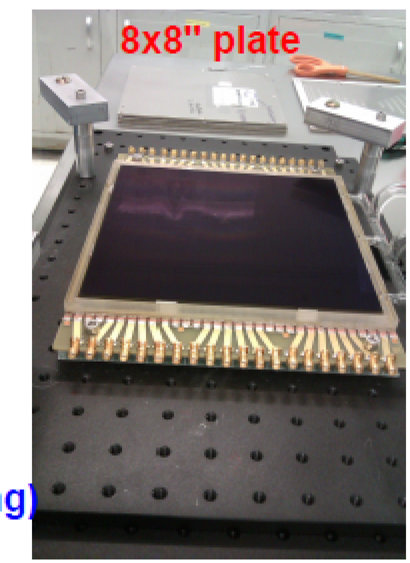


Porous glass

Resistive coating ~100nm (ALD)

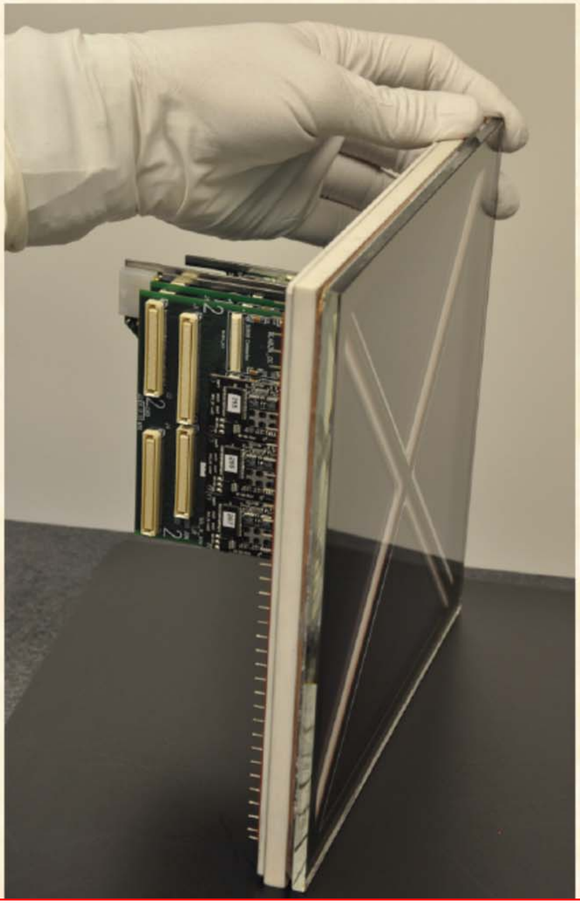
Emissive coating ~ 20nm (ALD)

Conductive coating
(thermal evaporation or sputtering)



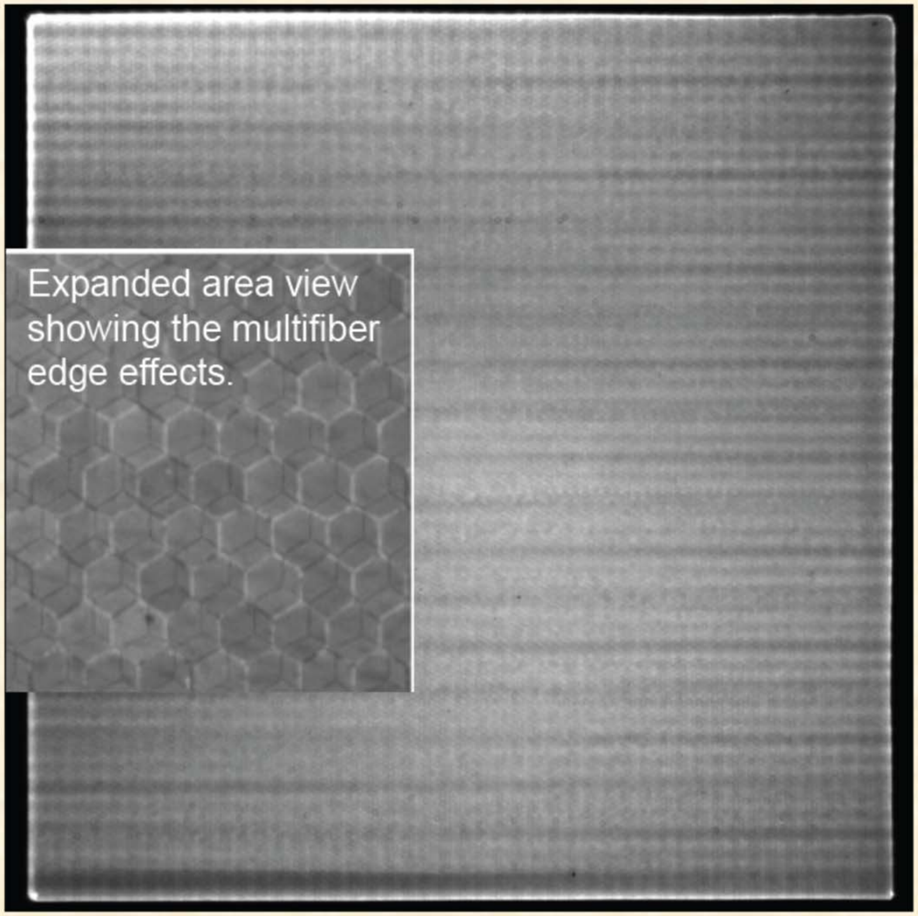
20cm ALD-MCP & Sealed Tube Development

LAPPD collaboration development of 20cm ALD MCPs and sealed tube with bialkali cathode and stripline anode for 2D imaging and <10ps timing.



Also see Incom poster.

First tube did not seal, making new tubes this summer



20cm, 20µm pore, Al_2O_3 SEY, MCP pair image with 185nm non-uniform UV illumination. Cross delay line photon counting anode. Image striping is due to the anode period/charge cloud size modulation.

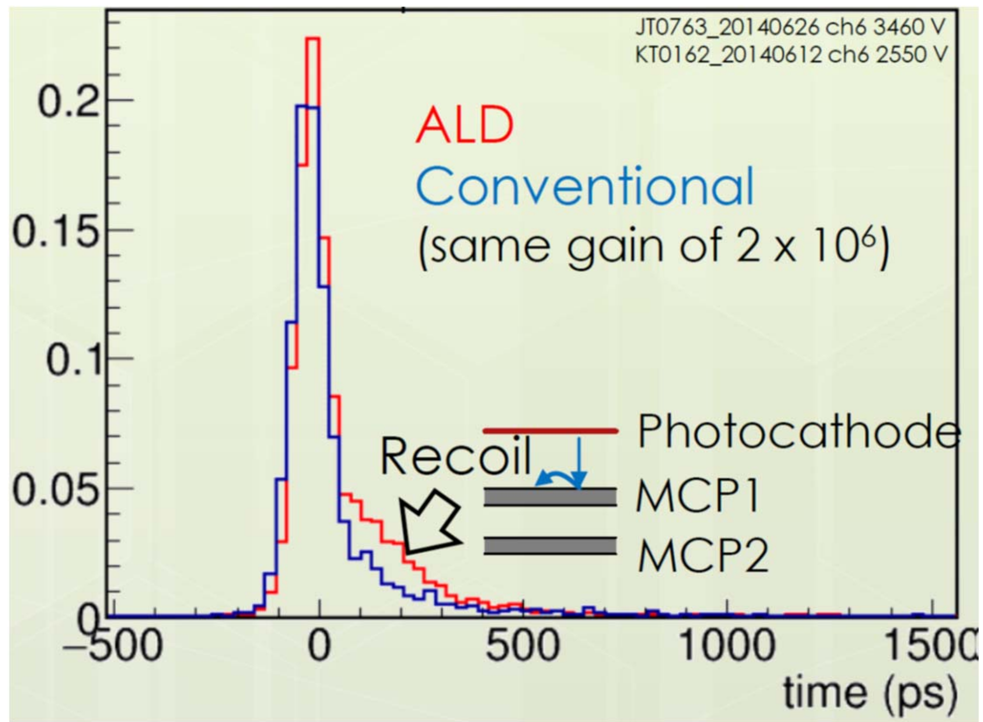
→ Extremely important development, looking forward to their next products

MCP PMTs with ALD MCPs: new properties

ALD has a higher secondary emission yield →

- Same gain at lower high voltage

- More backscattered photoelectrons – very slight degradation of the TTS



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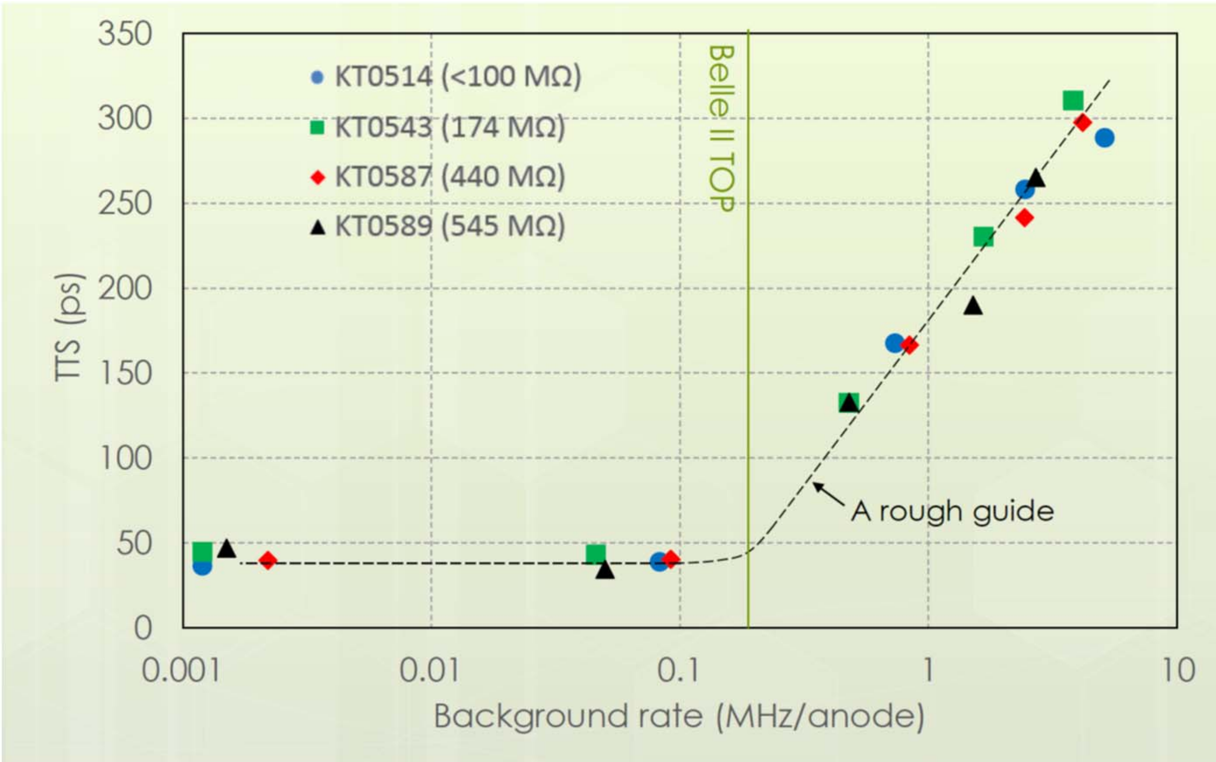
Operation of MCP PMTs in a high background level enviroment

How does additional light from background events that overlap with the signal event affect the timing performance?



→ No influence up to about 200 kHz per channel

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Summary

- MCP PMTs are playing a very important role in ultra-fast (single) photon detection as new methods require very fast timing in radiation harsh environments (and in magnetic fields)
- MCP PMTs were studied to understand their response and behavior
- New MCP based sensors are entering the game
- A very active field!