Status and perspectives of MCP-based photodetectors

Alexander Kiselev (BNL)

RICH 2025, Mainz, Germany, September 15-19, 2025

Outline of the talk

- Introduction to MCP-PMT technology

- Recent developments
  - An incremental update to an excellent talk by A. Lehmann at RICH 2022
  - Overview somewhat biased towards LAPPD / HRPPD research

- New ideas / technologies

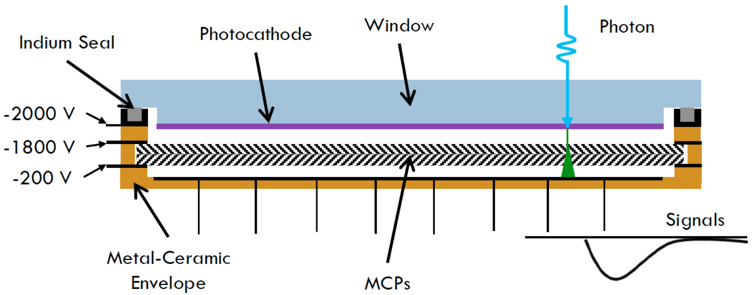
- Summary

RICH application requirements (for MCP-PMTs)

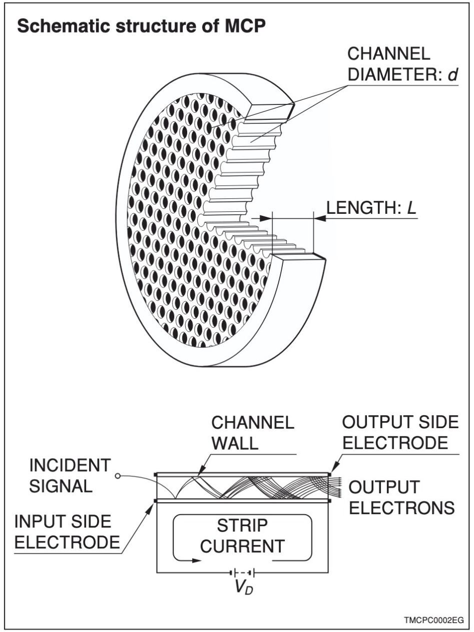
- High Geometric (FF), Quantum (QE) & Collection (CE) Efficiency
  - FF ~ 75-80% for 2” tubes is a standard; peak QE > 30%; CE as close to 100% as possible
- Low Dark Count Rates
  - The lower the better, less than few kHz/cm^2 is considered good enough (compare to SiPMs)
- Sufficiently fine anode pixellation
  - Sub-mm spatial resolution, either using charge sharing or not
- Sufficiently high gain
  - Up to at least 10^6, though it is often beneficial to run at a lower one (aging, rate capability, etc)
- Reasonably good *single photon* timing resolution
  - Well below ~100ps for the Gaussian part; RMS < 100ps for some applications (including tails)
- Longevity, rate capability, …
  - Ballpark numbers are ~10 C/cm^2 integrated anode charge and at least several kHz/cm^2 instantaneous photon flux
- Resilience to a high magnetic field
  - Several applications require placing MCP-PMTs in a >1T field

MCP-PMT technology overview and available options

MCP-PMT concept



Courtesy P. Hink, RICH 2016



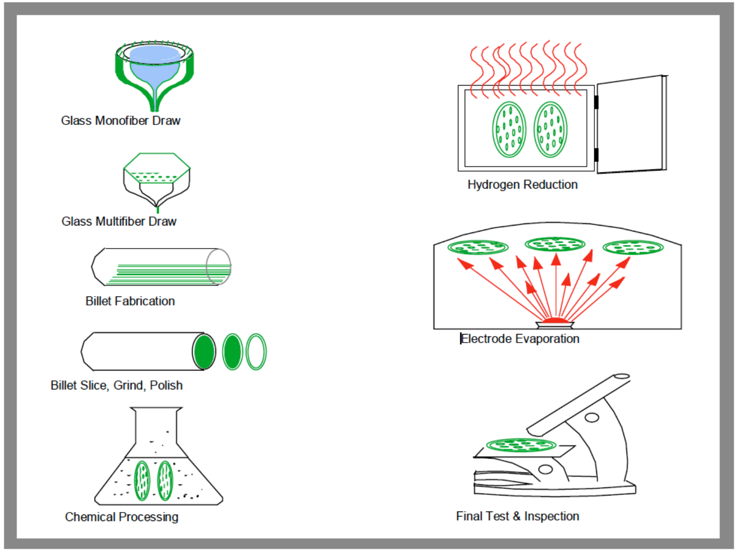
Courtesy Hamamatsu

- Fused silica, sapphire or borofloat glass window
- Proprietary photocathode on the inner (vacuum) side
- Amplification: either a pair (chevron) or a triple (Z-stack) set of MCPs
  - Commercially available with down to 6μm diameter pores
- A glass or ceramic side walls and anode (vacuum assembly)
  - Anode either DC- (as shown in the picture) or capacitively coupled

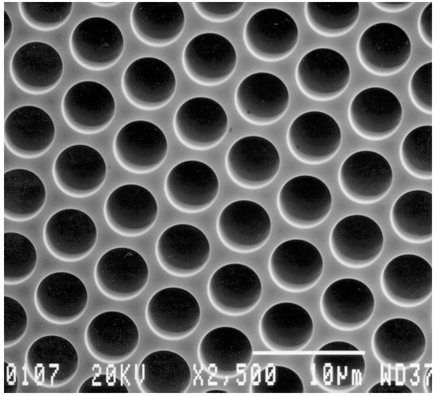
- General behavior of MCP amplification process (gain scaling with the L/D ratio, B-field effects, etc) is well understood

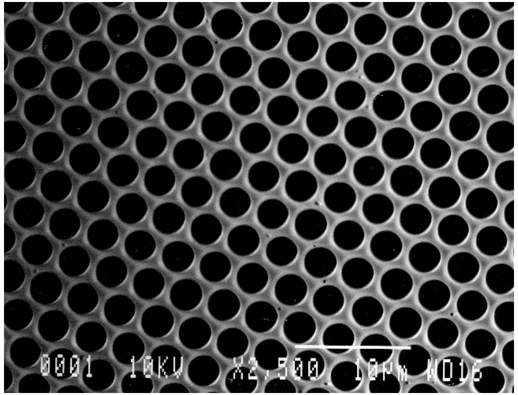
J. Wisa, NIM A162 (1979) 587
G. Fraser, NIM A291 (1990) 595

Conventional MCP production process



SEM images: 5 μm and 2 μm diameter pore MCPs





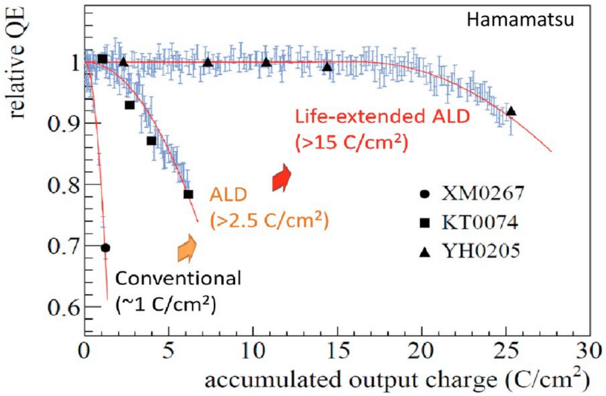
B. Laprade, BURLE technical note (2001)

- Draw individual glass fibers of appropriate diameter
  - Lead silicate glass cladding and etch-able glass core
- Bundle them together (multi-fiber draw step)
- Fuse these bundles into blocks (billets), cut into thin plates, polish
- Chemically etch the cores
- Heat in a hydrogen atmosphere to turn surface into a semiconductor with resistive & emissive properties

ALD coating & borosilicate glass capillary arrays

- These bare lead glass MCPs had a number of problems:
  - One could not tune resistive and emissive properties separately
  - Relatively low secondary emission yield (SEY), ~2-3
  - MCP-PMTs could not survive more than few hundred mC/cm^2 of extracted anode charge (photocathode aging due to ion backflow)

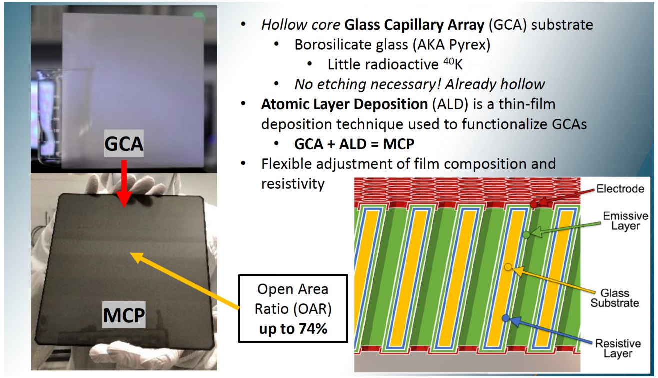
Fixed by applying a thin O(10nm) “sealing” layer with a higher SEY (Al_2O_3, MgO) via Atomic Layer Deposition process (ALD) -> **single ALD layer MCPs**



K. Inami, ECFA 2021 Detector Symposium

- Since ALD process allows one to alternate atomic layers of a different chemical composition, and in particular tune their resistivity, one can build a functional MCP differently:
  - Start off the *hollow core* fibers (regular borosilicate glass)
  - Functionalize a polished MCP by applying a resistive and emissive ALD layers one after the other

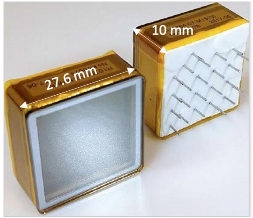
This allows one to decouple the substrate (glass), resistive and emissive properties and tune them separately -> **two ALD layer MCPs**



M. Popecki et al, JGR 10.1002/2016JA022580 (2016)

MCP-PMTs in running and planned RICH detectors

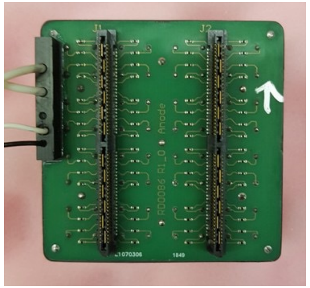
- Hamamatsu R10754-07-M16
  - ~1” size, 10 μm MCP pores, 4x4 pads, DC-coupled, pins embedded in anode
  - Used in Belle II TOP detector *Talk by M. Staric on Monday; poster by R. Komori*



- Photonis Planacons
  - 2” size, 10 μm MCP pores, 8x8 and 3x100 pads, DC-coupled; to be used in PANDA DIRCs

    Next talk by K. Gumbert; talk by A. Lehmann on Thursday
  - Partly off-topic: 2” Planacons (2x2 segmentation) without ALD coating are used in ALICE FIT

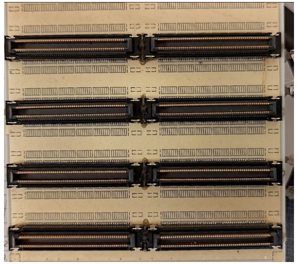
    Talk by Y. Melikyan later in this session

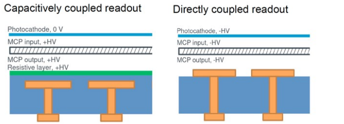


- PHOTEK MAPMT253
  - 2” size, 6 μm and 15 μm MCP pores
  - To be used in LHCb TORCH detector: 16x96 pads, DC-coupled; laser soldered connectors *Talk by M. Lehuraux on Thursday*
  - A 16x16 option is a baseline photosensor for ePIC hpDIRC

    Talk by G. Kalicy on Thursday

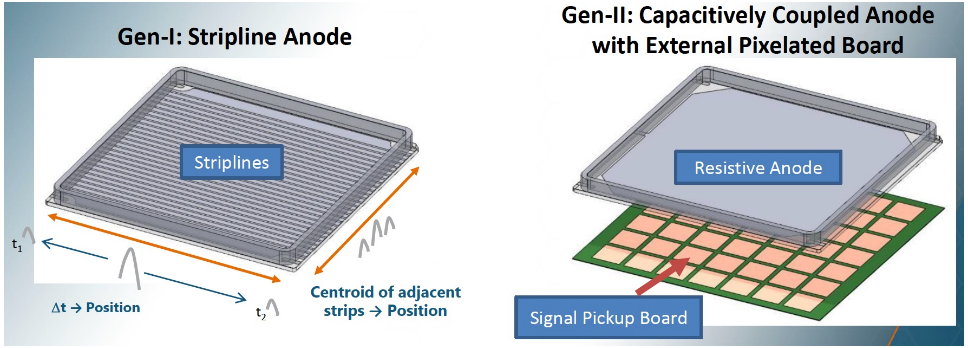
Rear side view

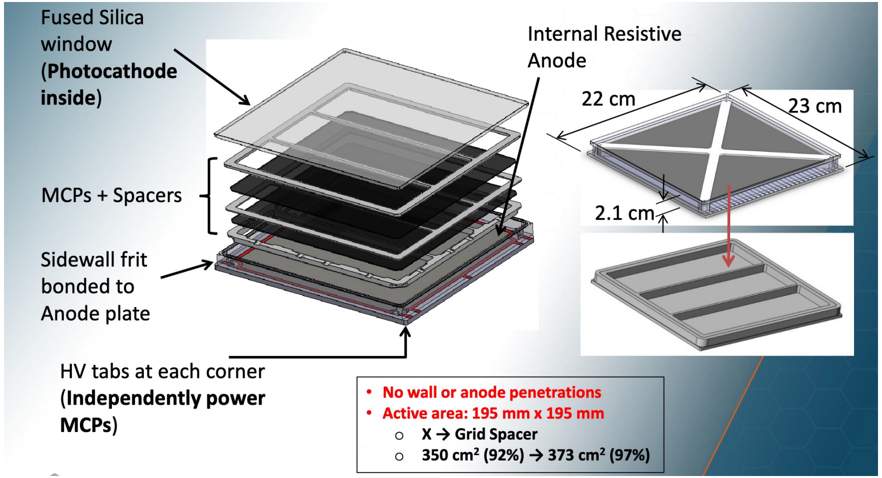




	Capacitively coupled	Directly coupled
number of pixels	8 by 64	16 by 96
number of pixels through centroiding	8 by 128	–
$\frac{1}{\sqrt{12}}$ resolution [mrads]	0.90	1.20

LAPPDs by Incom Inc.



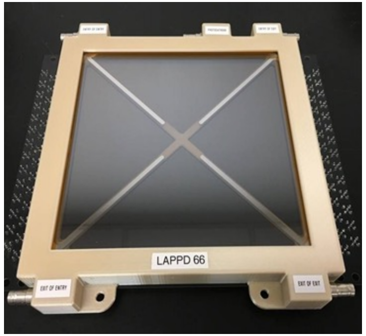


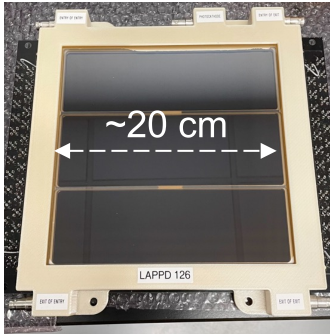
- ~8" x 8" active area, 10 μm and 20 μm MCP pores
- Gen-I: DC-coupled (28 strips)
- Gen-II: capacitively coupled (resistive layer on a vacuum side of a plain glass or alumina anode plate)
- Pixellation is defined by the user
- Used in ANNIE detector

Talk by M. Wetstein later today

- Considered for LHCb RICH upgrade

Poster by D. Foulds-Holt

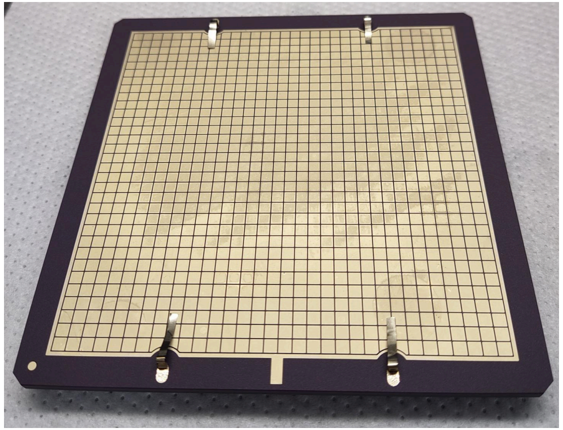




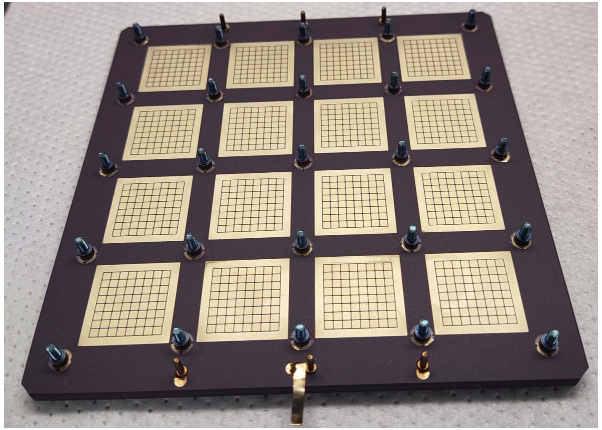
Also, poster by M. Popecki and talks by R. Dolenec and J. Agarwala on Thursday

Incom DC-coupled EIC HRPPDs

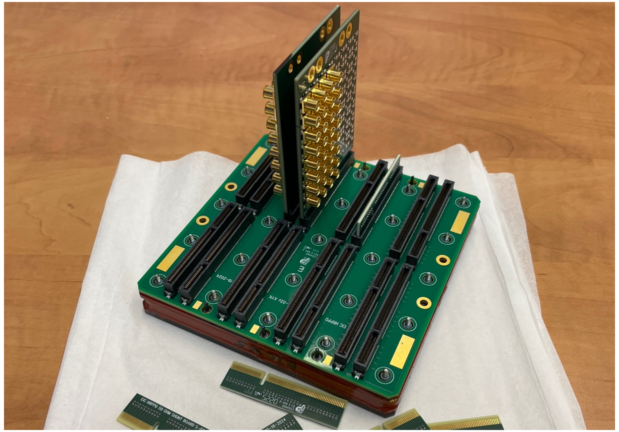
- 120mm x 120mm footprint, 10 μm pore MCPs, 5 mm thick fused silica window
- 104mm x 104mm active area (~75% geometric efficiency), 32x32 pads (pitch 3.25 mm)
- Air side has 4x4 groups of 8x8 pads (2.00 mm pitch), leaving enough space for mounting fixtures



Anode plate vacuum side



Anode plate air side



HRPPD with a passive backplane

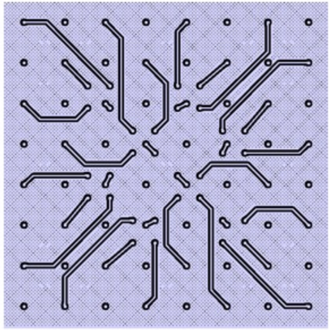
- A baseline photosensor for ePIC pfRICH detector (and a second choice for hpDIRC)

Talks by B. Page and G. Kalicy on Thursday

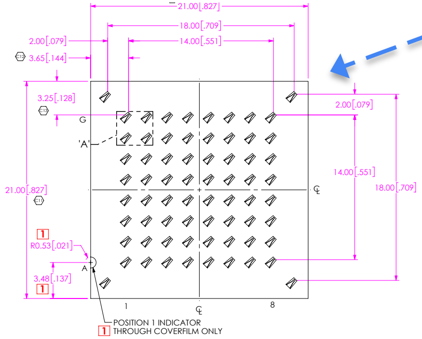
- Evaluation ongoing at BNL, JLab and INFN

Talk by J. Agarwala on Thursday

Incom DC-coupled EIC HRPPDs



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



Fused silica window

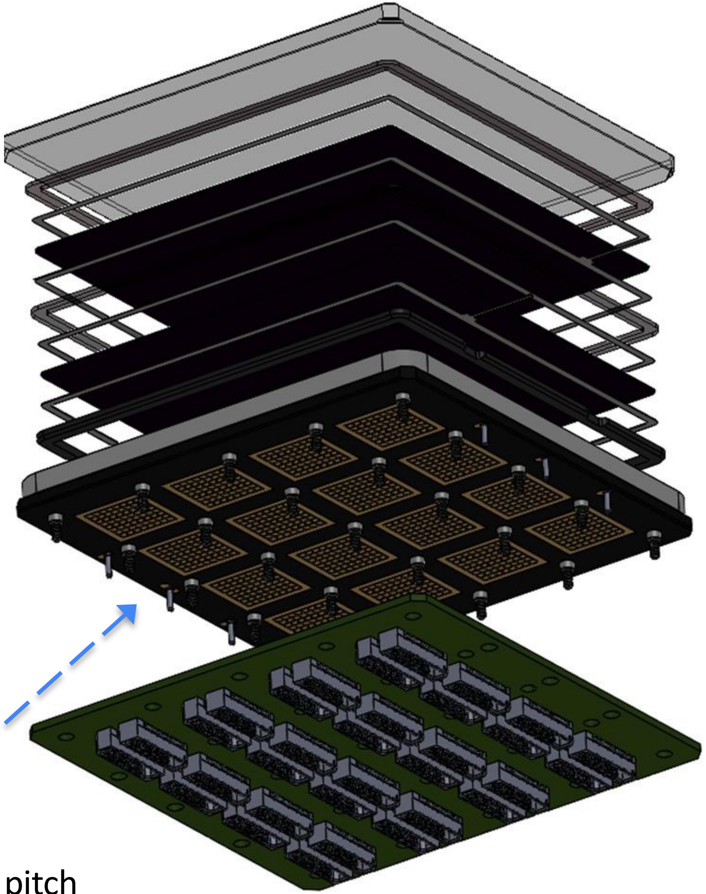
MCPs, spacers, etc

Side wall

Anode plate, a pre-routing ceramic circuit board

Compression interposers (not shown in the blown-up view)

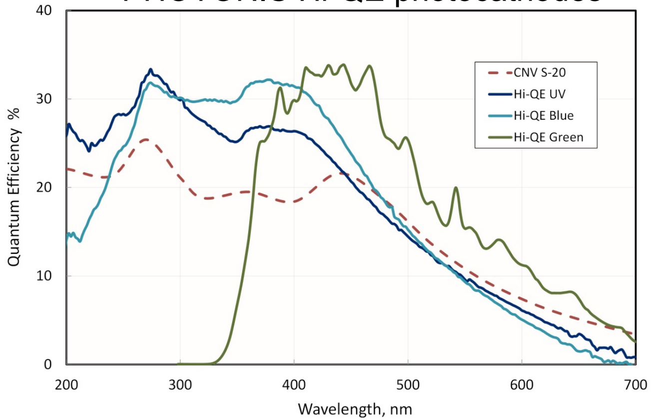
Interface PCB (here: Y05f)

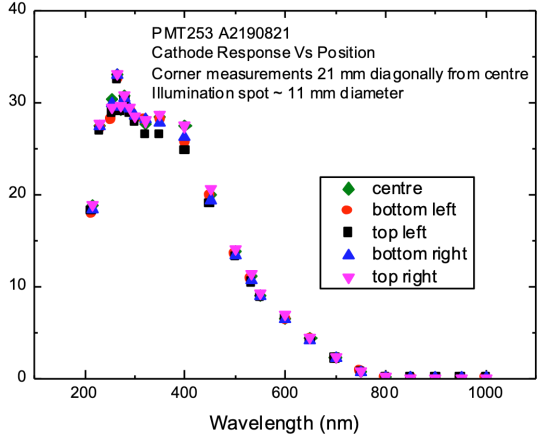


4x4 spots, each with 8x8 square pads; 3.25mm pitch

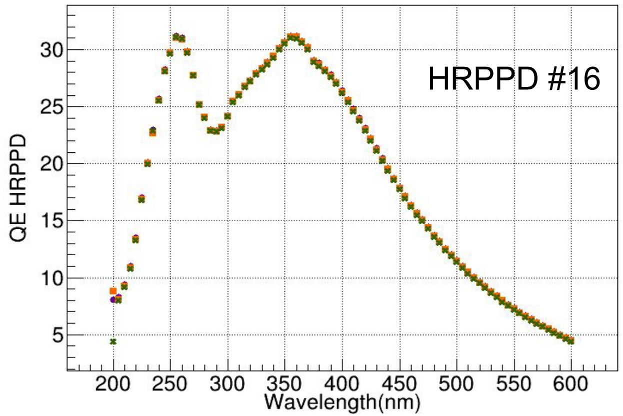
MCP-PMTs: detective efficiency = [FF *] QE * CE

PHOTONIS Hi-QE photocathodes



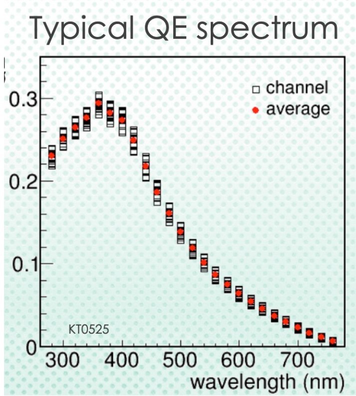


J. Milnes, FAST 2023



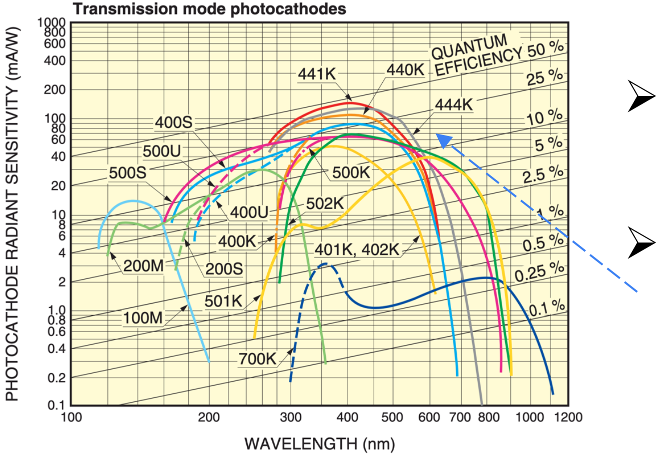
A. Lyashenko et al, NIM A1082 (2026) 170964

Belle II Hamamatsu tubes



K. Matsuoka, DIRC 2019

Hamamatsu PMT handbook 4th edition



- All key manufacturers are able to produce MCP-PMTs with a peak QE exceeding 30%
- Hamamatsu SBA (peak ~35%) and UBA (peak ~45%) 44*K series photocathodes have never been used in MCP-PMTs

Detective efficiency = [FF *] QE * CE [- edges]

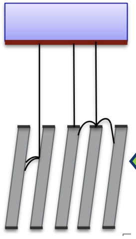
	Photonis XP85112 9001394	Photonis XP85112 9002108	Hamamatu R13266-07 JS0022	Photek MAPMT253 A1171005	Hamamatsu R10754X-07 KT0001
comments	non-ALD, no film	ALD, Hi-CE no film	ALD, film before MCP	no film	ALD, film between MCPs
CE	(63 ± 6)%	(95 ± 9)%	(39 ± 4)%	(83 ± 8)%	(76 ± 8)%

M. Boehm, DIRC 2019

- HRPPD collection efficiency ~70%

Y. Jin et al, arXiv:2506.16490 (2026)

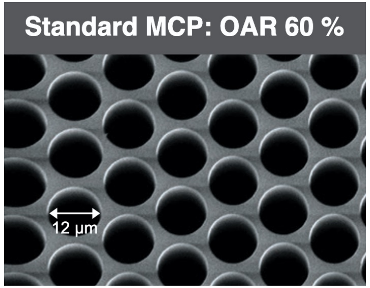
Options to increase the CE	Comment
Thin down capillary walls?	Can gain at most few %
Funnel MCP pores?	Technology exists at Hamamatsu
Cover the top MCP with an emissive layer and collect more efficiently the interstitial space bounced primary electrons?	Implemented in Photek and PHOTONIS tubes

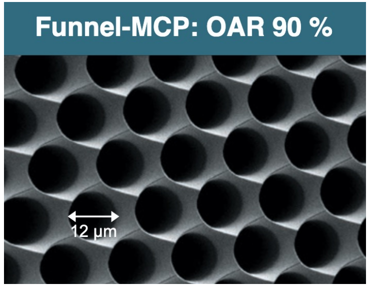


D. Orlov et al., JINST 13 (2018) C01047

	FF (active area fraction)
1” Hamamatsu R10754	~64%
2” Photek MAPMT253	~81%
2” Photonis Planacon	~81%
4” Incom HRPPD	~75%

- Hard to make any better for 1-2” tubes
- FF should scale better for 4” ones?
- Next HRPPD iteration: stick to 75%, but make the active area *fully efficient*



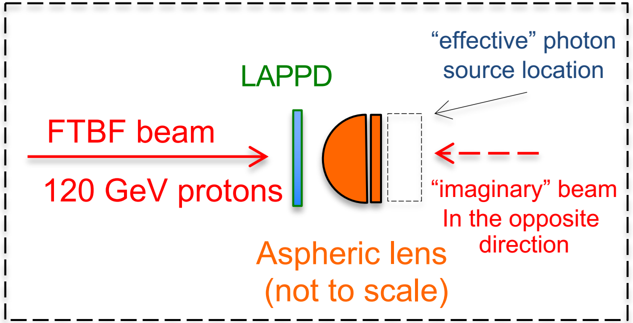


Highlights of recent studies

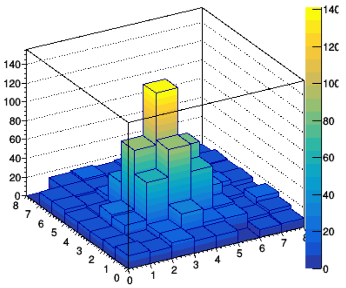
[or a status assessment otherwise]

Incom LAPPDs for Cherenkov ring imaging

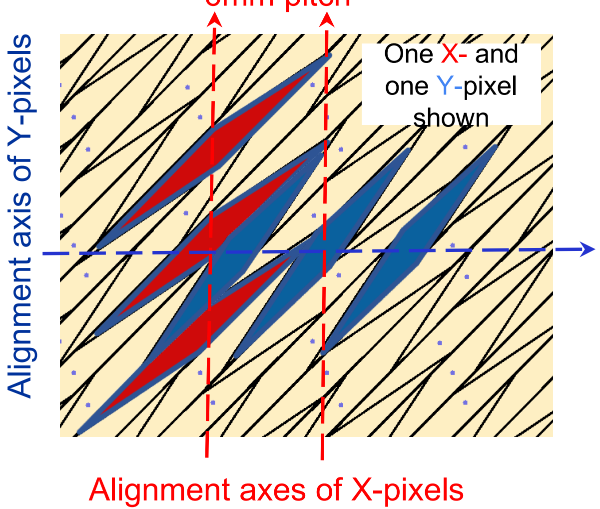
- Beam study at Fermilab *AK, CPAD 2022*
- A thick aspheric lens used as a Cherenkov radiator



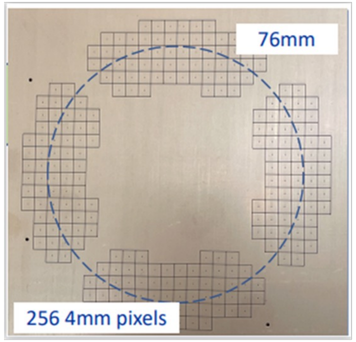
A typical single photon cluster

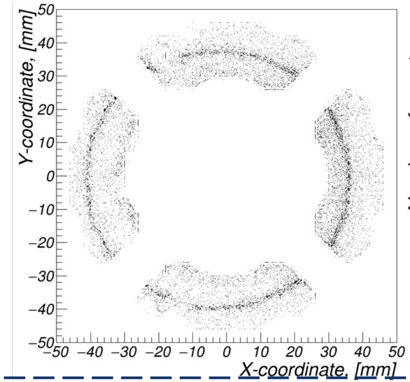


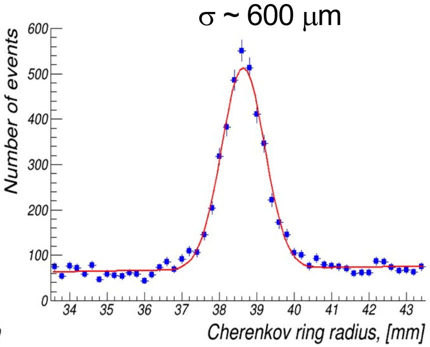
- Lab study with a laser source

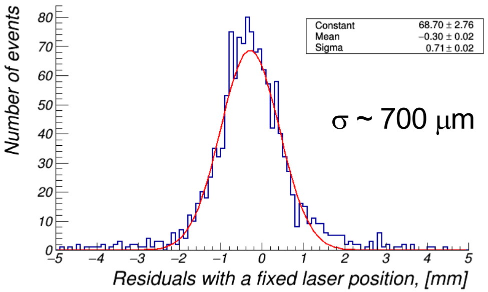


Pixel pattern & accumulated single photon XY-coordinates









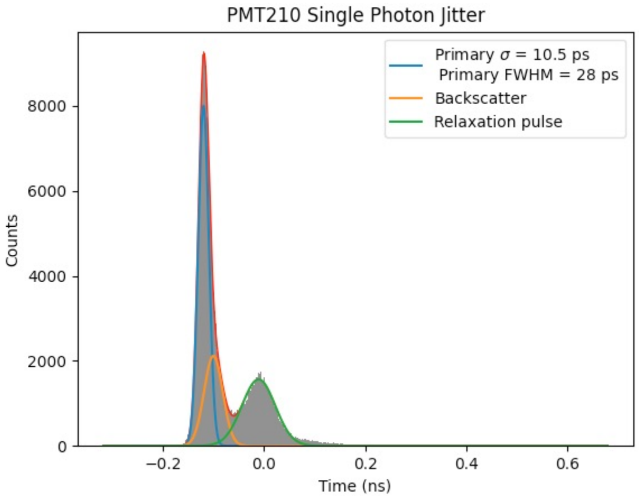
Single photon timing study by Photek

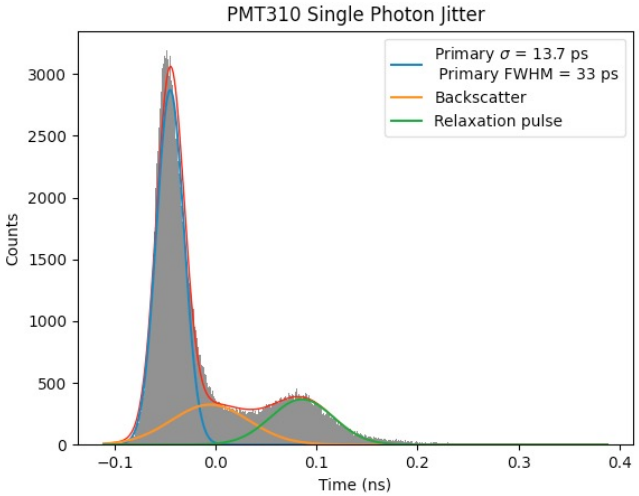
T. Conneely, FAST 2025

- Single anode custom MCP-PMTs
  - 1,2,3 MCPs; 3μm & 10μm diameter pores; 10mm, 25mm & 40mm diameter tubes

Time Response – Pulse Rise Time (ps)

MCPs	10 mm		
	Min	Typ	Max
1	60	65	70
2	75	85	95
3		105	



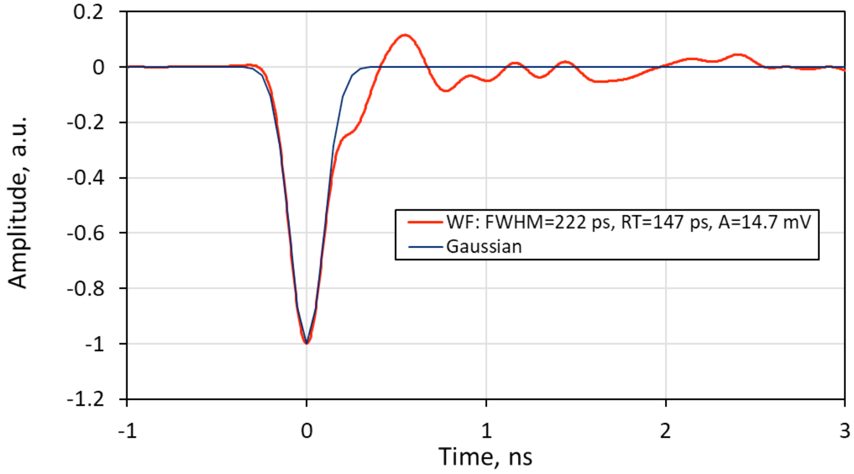


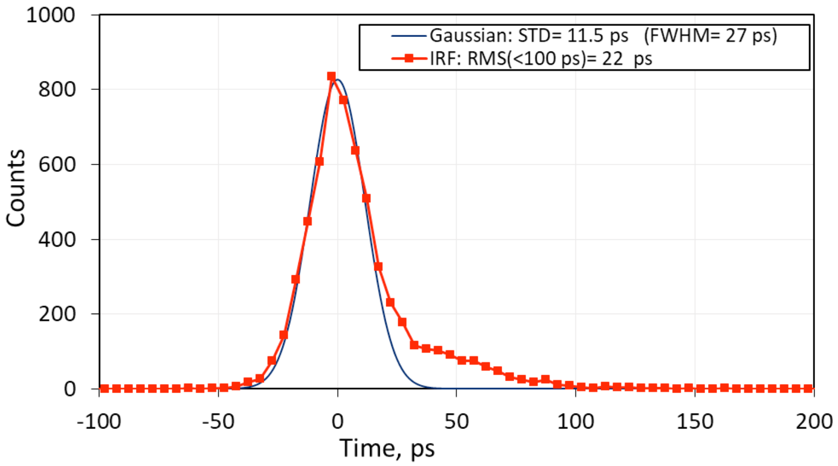
σ ~ 10ps (including laser jitter) in a 2-MCP configuration with 3μm pores

Single photon timing study by PHOTONIS

D. Orlov, FAST 2025

- Single anode off the shelf FT-8 MCP-PMT
  - 6μm diameter pores; 8mm diameter anode



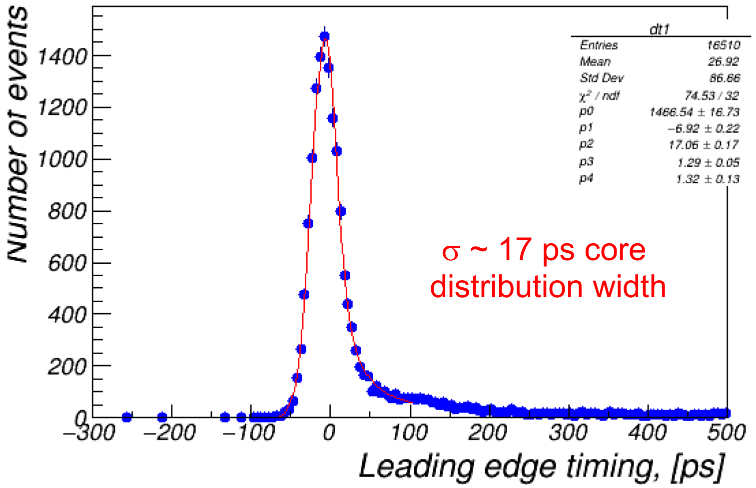


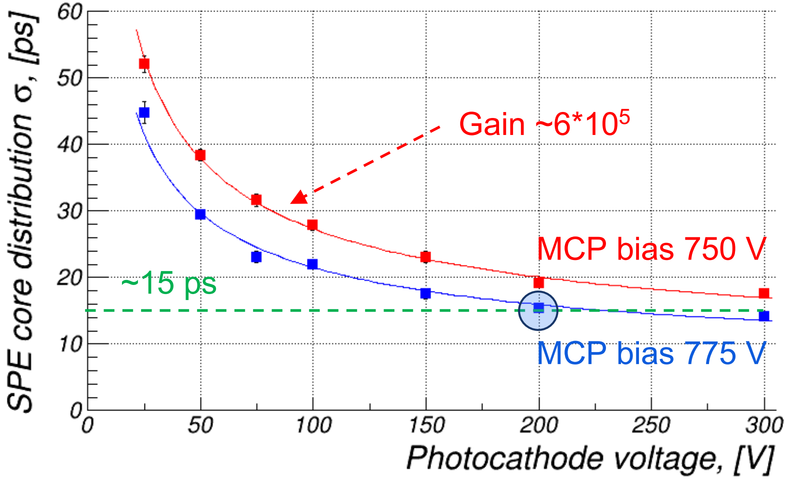
Signal rise time ~150ps, σ ~ 12ps (including instrumental jitter?)

Incom HRPPD single photon timing resolution

- HRPPD 15 @ ROP: bias voltage 775 V, PC and transfer voltages 200 V (gain ~$2.5*10^6$)
- Femtosecond laser used: no additional instrumental jitter

AK, FAST 2025

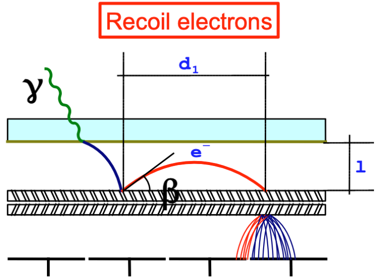


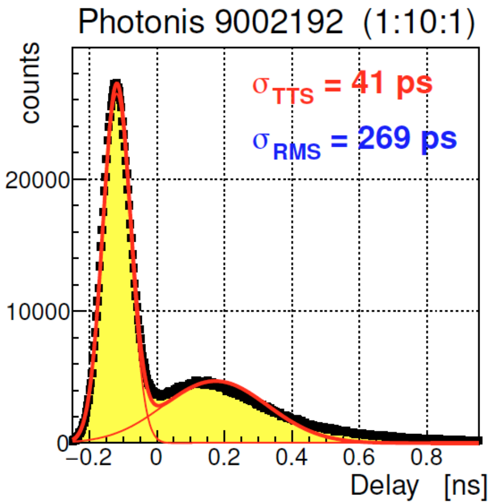


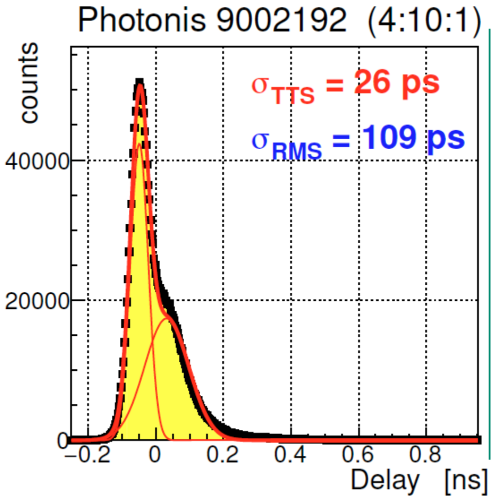
Cannot really compete with small size 3μm & 6μm pore tubes, though seems to achieve σ < 20ps at reasonable HV settings

Backscatter tail in a timing distribution

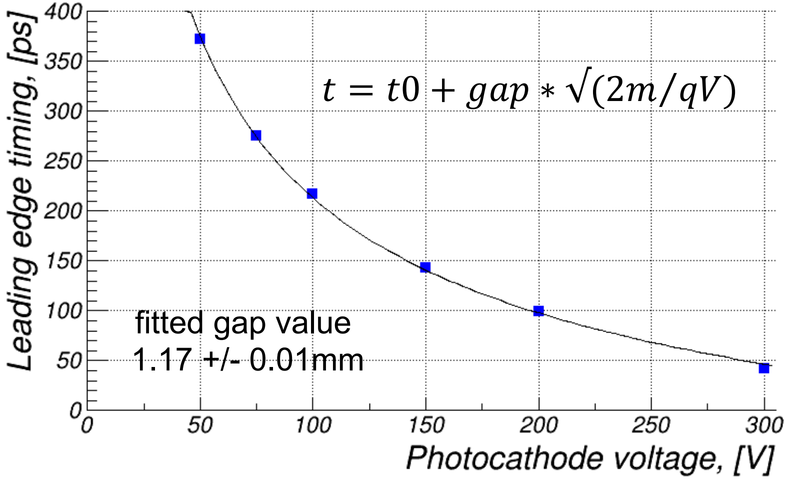
- High CE tubes show a substantial “bump” of backscatter electrons
- For some applications, a small RMS may be more important though than a core distribution width
- Increasing PC->MCP#1 (and / or reducing PC->MCP#1 gap) allows one to “compress” the timing distribution to minimize RMS







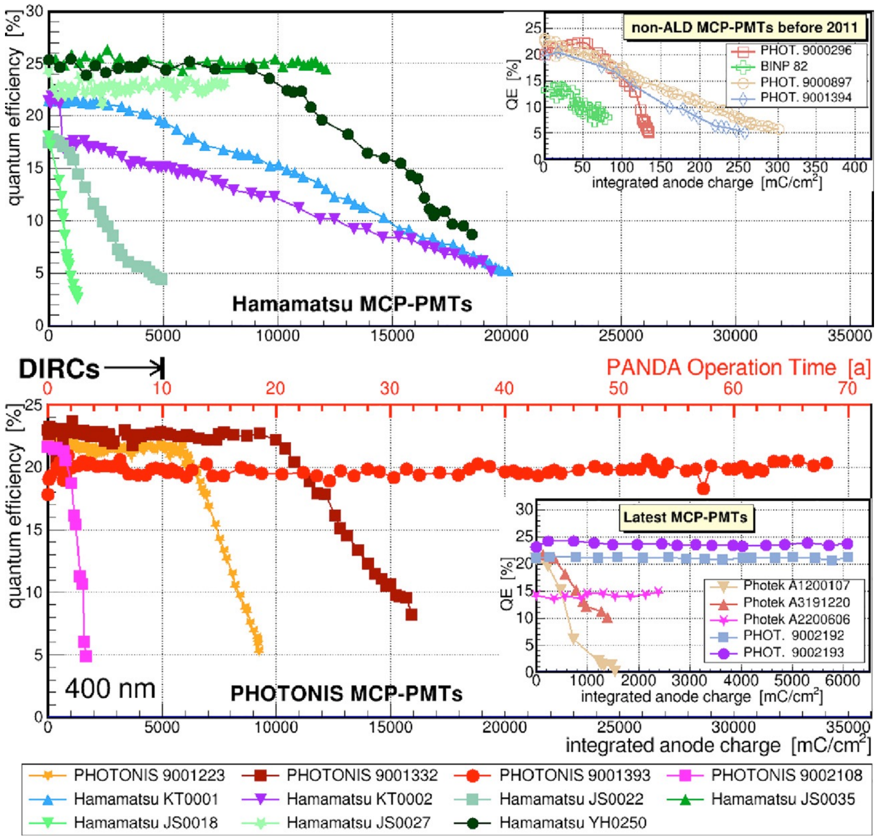
A. Lehmann et al, NIM A1065 (2024) 169536



Measured HRPPD primary electron drift time PC->MCP#1 (gap 1.1mm)

PHOTONIS / Photek / HPK aging studies status

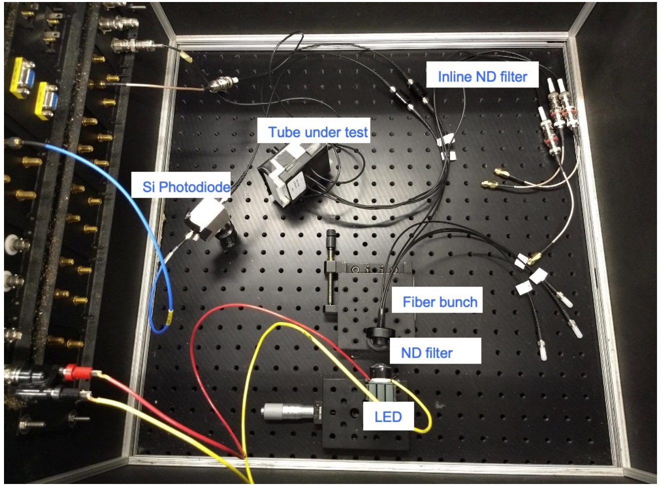
- Essentially no recent changes in the assessment:
  - Before ALD coating was implemented ~15 years ago, MCP-PMTs could not survive more than few hundred mC/cm² AAC
  - ALD coating fixed problems of Belle II Hamamatsu MCP-PMTs, especially after a surface treatment procedure prior to the coating itself was improved (see slide 7)
  - PHOTONIS MCP-PMTs with ALD coating show no QE degradation for several C/cm² AAC (one tile survived more than 30 C/cm²)
  - Photek MCP-PMTs seemingly lag behind

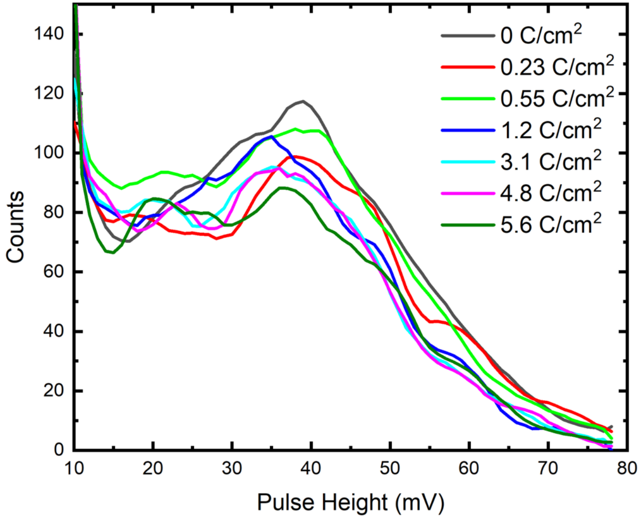


D. Miehling et al, NIM A1049 (2023) 168047

Accelerated pixel-based aging

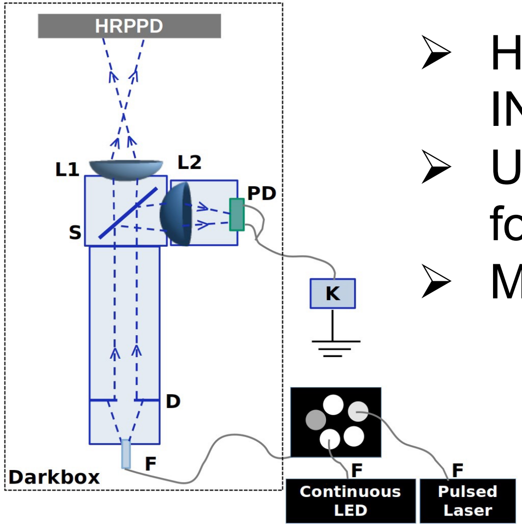
- Procedure:
  - Measure an MCP-PMT pulse height distribution at a single PE level before the test
  - *Irradiate a small region (4.6 mm diameter in case of this study) of MCP-PMT active area, at a close to saturation photon flux*
  - Measure single photon pulse height distribution at regular intervals
- 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



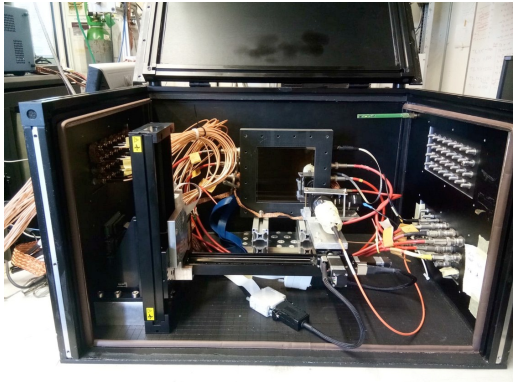


V. Chirayath, LAPPD 2022

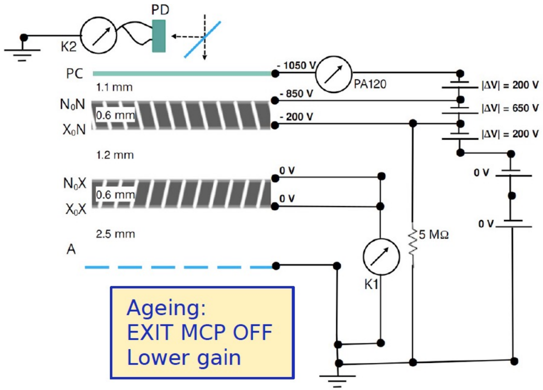
Accelerated pixel-based aging of EIC HRPPDs

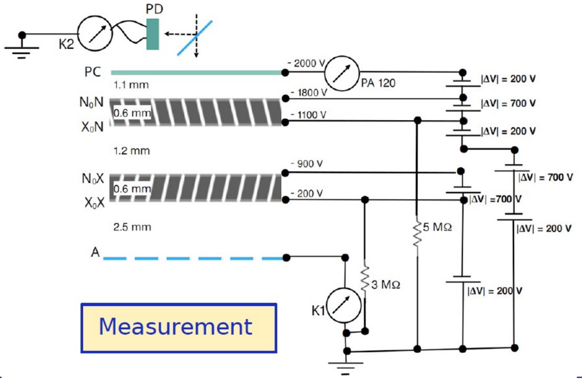


Dark box equipment at INFN Trieste



- Have three similar setups at JLab, BNL (in preparation) and INFN Trieste (first data taken with HRPPD #25 last month)
- Use LED for irradiation and QE measurements, pulsed laser for PDE
- Monitor QE, PDE and pulse height periodically



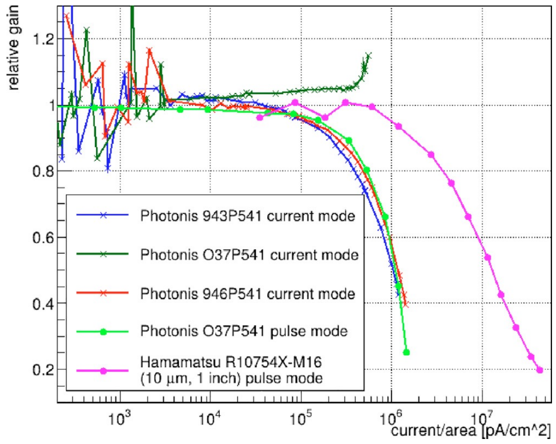


No measurable QE degradation was observed so far, after ~20 C/cm^2 of “extracted charge equivalent” irradiation

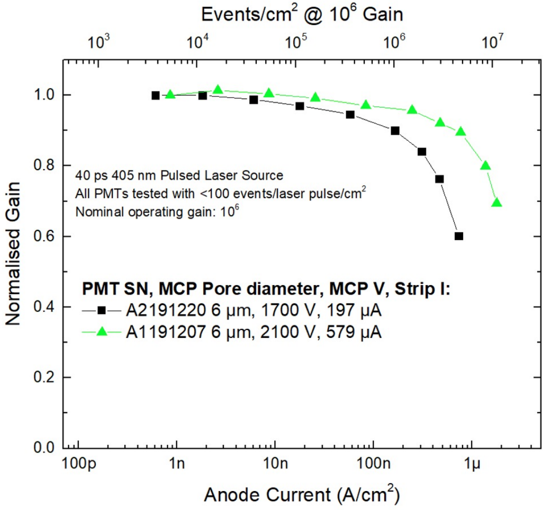
Talk by J. Agarwala on Thursday

Rate capability

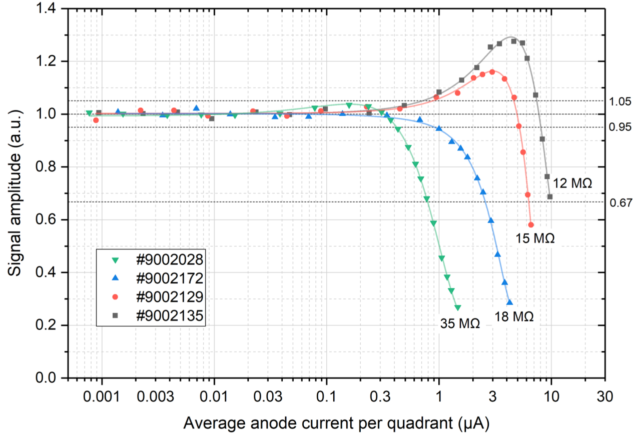
Photonis Planacons (PANDA)



PHOTEK MAPMT253

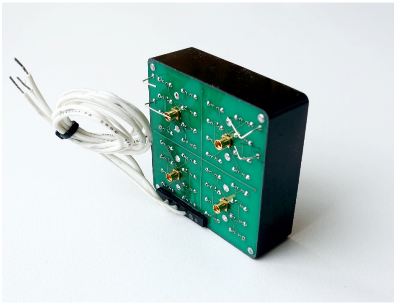


Photonis 2” XP85002/FIT-Q (ALICE)



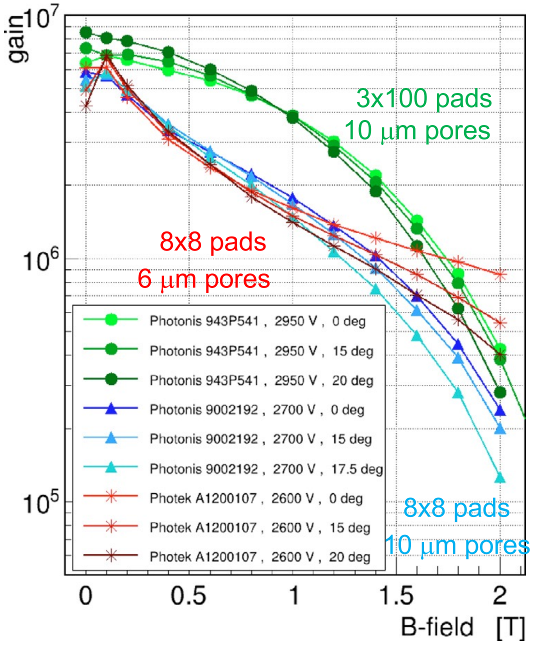
D. Miehling et al, A 1049 (2023) 168047 *J. Milnes, FAST 2023* *Y. Melikyan et al, 2021 JINST 16 P12032*

- Despite several individual “features”, ALD coated PMTs start showing signs of saturation at a gain ~10^6 when anode current approaches ~100nA/cm²
- Options to increase the rate capability (if using ALD-coated MCPs is a must):
  - Lower down MCP resistance (increase nominal strip current for a given gain)
  - Segment the HV electrodes of MCP#2
  - Lower down gain (like in case of ALICE FIT, but for a single photon mode)



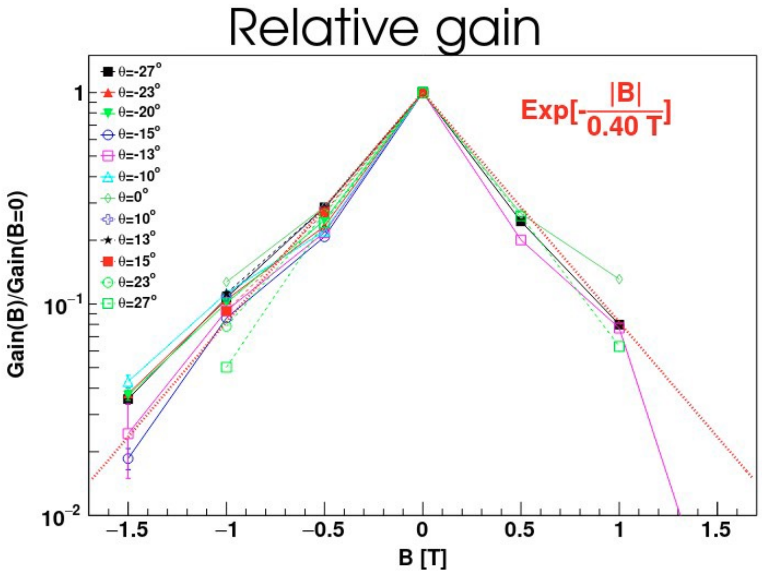
Gain drop in a magnetic field

Recent summary of Photonis & Photek MCP-PMTs



D. Miehling et al, NIM A1049 (2023) 168047

LAPPD #153, 10 μm pores



M. Osipenko, LAPPD 2024

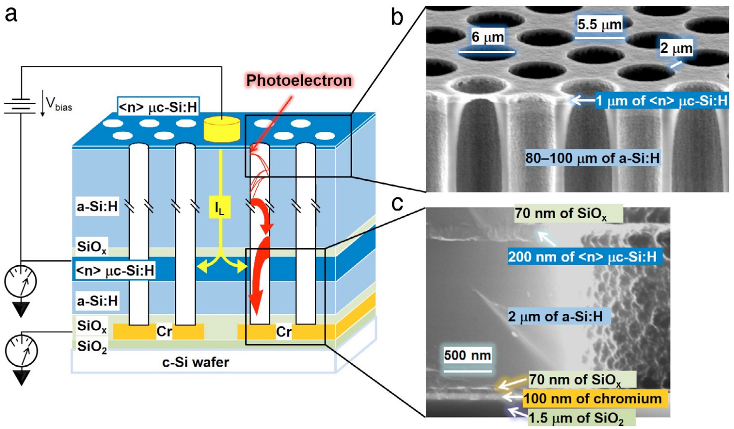
Talk by J. Agarwala on Thursday

- A 6 μm pore Photek is the best at 2T as expected
- Also, gain can be to a large extent recovered by increasing the bias voltage

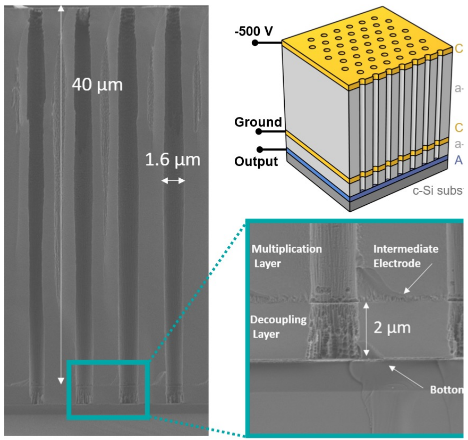
- LAPPD gain drop 0T -> 1T ~10 (more than for other MCP-PMTs with 10 μm pores)
  - Can be an increased stackup gaps feature

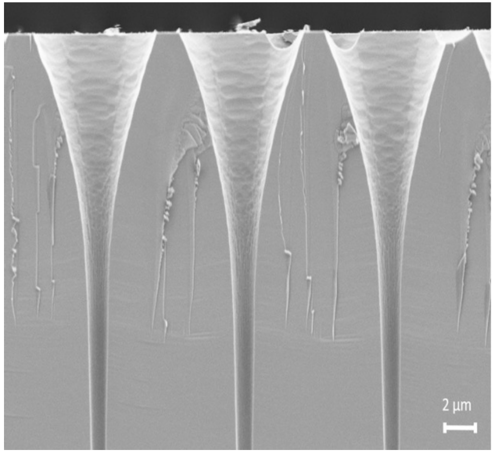
New technologies / ideas

Amorphous silicon MCPs (AMCPs)

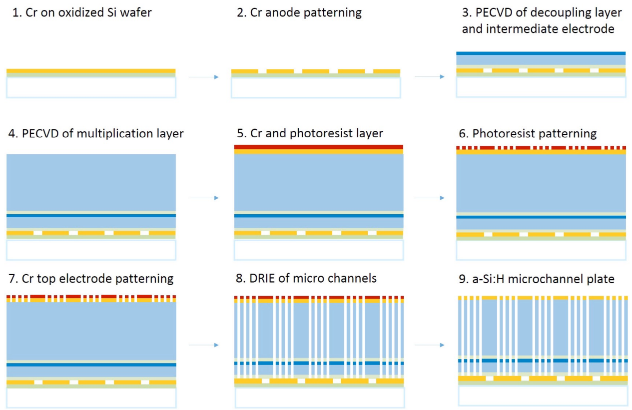


J. Loeffler, NIM A912 (2018) 343





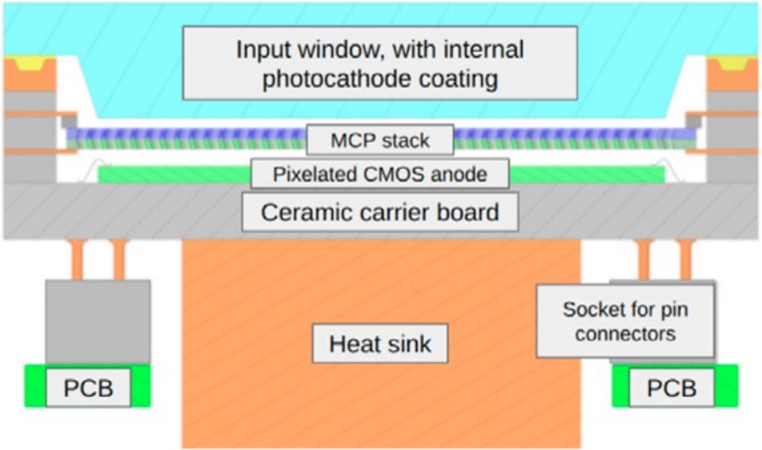
S. Frey et al, IEEE TNS Vol.70 No. 9 (2023) 2226



- Use PE-CVD, photolithography and DRIE to create an MCP-like structure on a substrate (which can be a readout electronics chip surface)
- Achieved a pore diameter of 1.6 µm and an aspect ratio of 25
  - As a consequence, gain increase from ~100 to ~1500
- Demonstrated a capability to etch funnel shape pores

Other new MCP-related technologies

Hybrid MCP-PMT with TimePix4

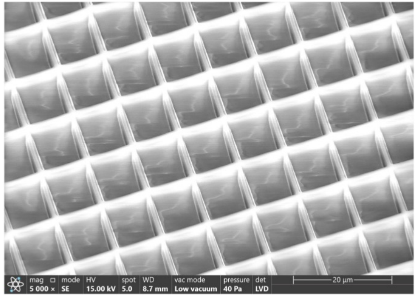


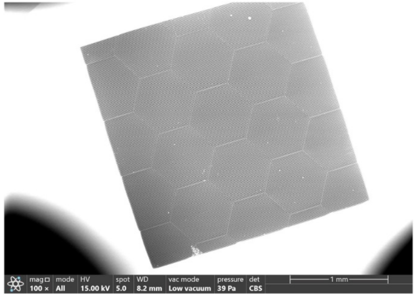
R. Bolzonella et al, NIM A1082 (2026) 170965

- Place TimePix4 chip inside MCP-PMT volume
  - Bump bond pads as micro-anodes with a 55 μm pitch
- Several HPK prototypes tested
- Achieved 65 ps timing resolution

Talk by E. Franzoso later today

3D printed MCPs





C. Ertley et al, Proc. of SPIE Vol.13093, 130935S

- Additive manufacturing
  - Like two-photon polymerization in this case
- Made it compatible with UHV
- Developed low-temperature ALD process
- Picture: 10 μm pores, 20^0 bias angle, 60:1
  - Demonstrated ~10^3 gain

Summary & Outlook

- Despite the fact that a multi-anode MCP-PMT market is rather small, there are still viable options offered by all considered manufacturers
  - Especially if an off the shelf model meets the requirements
- As a matter of fact, R&D activities are presently tailored to the needs of a particular customer (experiment) rather than to a development of general-purpose products
- LAPPDs / HRPPDs a becoming a mature product, but a more thorough evaluation is needed
- MCP-PMTs have a combination of unique features (high timing resolution, low DCR, B field resilience), which - despite high cost - gives them an edge in a competition with other RICH photosensor candidates
- We may see exotic (and potentially more cost efficient) MCP and MCP-MPT implementations, but seemingly no time soon