R&D on position sensitive photon detectors

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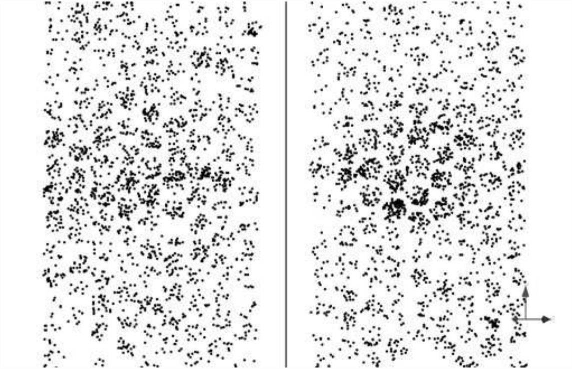
STFC PPTAP meeting

Position sensitive photon detectors

- vacuum photon detectors
  preferred option in the past 10-20 years to cover large focal planes in Cherenkov detectors
- solid state photon sensors
  about to replace vacuum photon detectors in scintillating fibre tracking and calorimetry applications
- gaseous photon detectors
  not covered in this talk, see Ioannis Katsioulas's talk from yesterday



[Eur. Phys. J. C (2013) 73:2431]
Distribution of the number of pixel hits per event in the RICH 2 of LHCb

R&D on position sensitive photon detectors

The challenges for the Future Facilities
$\Rightarrow$ the wish list for the next generation of photon detectors:

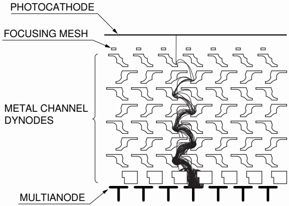
- detection of single photons (PID detectors)
- high active area ($> 80\%$)
- high detection efficiency in visible range (QE$> 30\%$)
- high granularity (pixel size $\sim 1\text{mm}^2$)
- High timing resolution (≤ 100 ps)
- High rate (LHC 40 MHz)
- Large areas to cover (1-10 m^2)
- High magnetic field (up to 1.5 T)
- low material budget (4π detectors)
- radiation resistance (LHC)

Multi-anode Photomultiplier Tubes

development of position sensitive photon detectors based on conventional PMTs over many years, first demonstration of feasibility in 1985
[IEEE Trans. Nucl. Sci., 32 (1) (1985), pp. 355-359]

Main challenges across the years:

- close packing of dynode chains (metal channel dynode allowed to pixel size reduction)
- cross-talk (dynodes arrangement allowed significant reduction)
- active area (limited to ≈43%, requirement of lenses)
- Quantum Efficiency
- magnetic field tolerance (Kovar body)

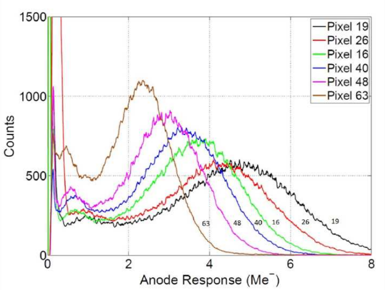


Main developer: Hamamatsu ⇒ R5900 series installed in HERA-B RICH employing lenses to compensate for limited active area

MaPMTs: state of the art

Hamamatasu R11265 ($2.54 \times 2.54 \text{cm}^2$) and R12699 ($5.2 \times 5.2 \text{cm}^2$) installed in LHCb RICH upgrade (~3000 units)

- pixels size $2.88 \times 2.88 \text{mm}^2$
- low DCR
- gain $> 10^6$
- gain uniformity $1 \div 4$
- active area 83%
- QE $\approx$ 40%



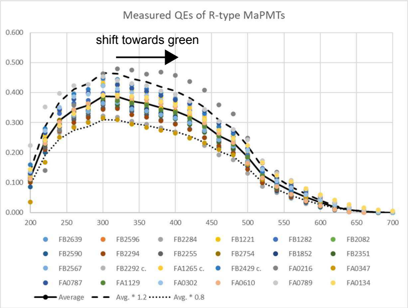
[Nucl.Instrum.Meth.A 766 (2014) 156-159]
[JINST 10 (2015) 09, P09021]

programme led by Edinburgh

MaPMTs: future developments and limitations

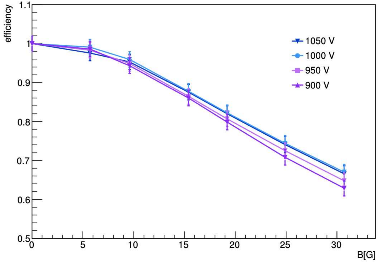
New developments:

- new developments in Super Bialkali photocathodes for QE peaking in the green $\Rightarrow$ reduction of chromatic error in RICH detectors based on fluorocarbon radiators (LHCb RICH future upgrades)
- micro-PMT: $13 \times 10 \times 2\text{mm}^3$, with photo-cathode covering $3 \times 1\text{mm}^2$ area, miniaturised approach quasi-planar dynode structure produced from a silicon wafer, sandwiched between two glass plates [IEEE Trans. Nucl. Sci. 61 (5) (2014) 2687-2693]



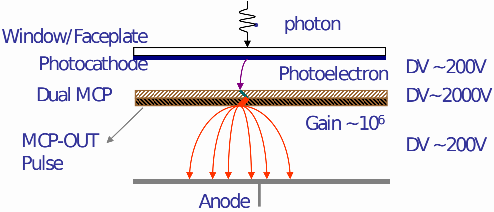
Limitations:

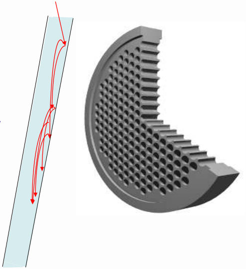
- very robust technology, market dominated by Hamamatsu: developments follow custom features for applications or new directions from HPK
- limitations due to magnetic field tolerance
- limitation due to cost
- limitations in applications requiring timing: TTS $\approx$ 300ps



Micro Channel Plate PMT

dynode structure replaced with MCP: compact and close-packed set of miniature channel electron multipliers each acting as a continuous dynode. the plate is manufactured from lead-glass billets





Typical parameters:

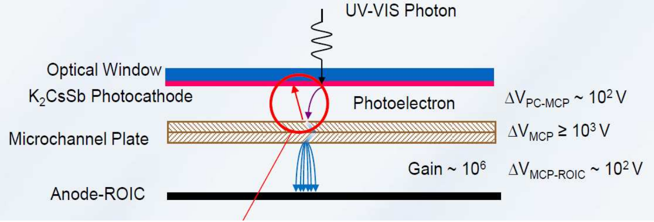
- channel pore diameter d: 6-25 μm
- channel length L: 400-1000 μm
- diameter-to-length ratio α=L/d: 40-100 (parameter defining gain)
- Open-area-ratio OAR: 55%-65%
- two MCP layers Chevron configuration

General features:

- gain: $10^6 - 10^7$
- compact size $\Rightarrow$ essentially immune to high magnetic field
- intrinsically high spatial resolution
- intrinsically high time resolution
- low DCR

MCP-PMT: ageing

MCP lifetime and ageing effects are critical parameters: many studies carried out, causes partially isolated and mitigated, work functions cannot fully explain measured ageing [Nucl. Instrum. Methods A 952 (2020) 161821]

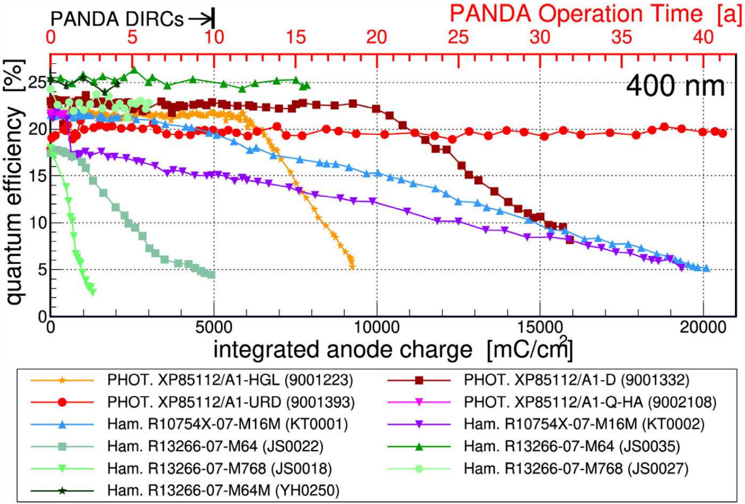


- neutral molecules from residual gas react with photocathode
- ion feedback:
  - desorption of atoms from MCP material
  - damage to MCP surfaces (gain affected)
  - ionisation of residual gas atoms
  - ions accelerated towards photocathode
  - photocahode damaged (loss of QE)
- electron back-scattering from MCP

mitigation: Atomic Layer Deposition (ALD) → Deposition of ultra-thin atomic layer (MgO, Al_2O_3) on MCP substrate

MCPs coated in three steps: resistive layer, secondary electron emission (SEE) layer, electrode layer [NIM A639 (2011) 148]

MCP-PMT: lifetime



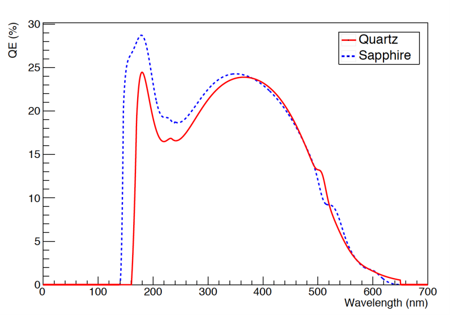
[Nucl. Instrum. Methods A 952 (2020) 161821]

improvement of production techniques ⇒ more models available tailored for various applications

MCP-PMTs: recent developments

Device being considered as future KTAG photon detector

- both Photonis and Hamamatsu devices provide excellent single photon time resolution (< 50ps)
- 2 ALD layers from Photonis is compatible with expected Integrated Anode Charge (IAC) ($\sim 16/C/cm^2/year$)
- 75% active area
- peak QE lower than current photon detector but broader spectrum
- DCR & gain similar to current photon detector

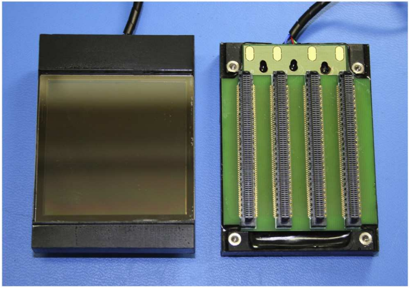


studies ongoing in Birmingham

MCP-PMTs: Recent developments

basic requirements for the TORCH photon detectors:

- compactness, low noise and radiation hardness
- operation in a 10 mT magnetic field
- anode segmentation: $\sim 128 \times 8$ pixels for a 2 inch square MCP-PMT
- overall per-photon time precision: 70 ps
- single photon rate: $\sim 1 - 10\text{MHz}/\text{cm}^2$
- IAC: 10-20 C/cm^2



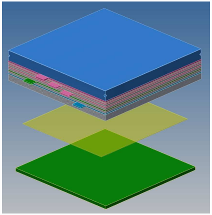
EU-funded R&D programme with Photek as industrial partner

for the development of photon detectors [JINST 10 (2015) C05003]

CERN-UK joint effort

R&D for TORCH

R&D carried out in three phases

- phase I: circular single-channel MCP-PMTs processed with ALD for lifetime studies
- phase II: circular MCP-PMTs with a quarter-size anode having the required granularity [Nucl. Instrum. Methods A 908 (2018) 256-268] [Nucl. Instrum. Methods A 952 (2020) 161692])
- phase III: combined the required lifetime and anode segmentation

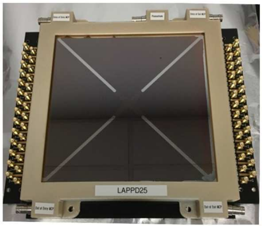
Phase III tubes are $53 \times 53\text{mm}^2$ in active area, with 60 mm pitch
MCP-PMTs are processed with ALD and have a segmentation of 64×8 pixels
$\Rightarrow$ required spatial resolution recovered via charge-sharing effects across pixels and the estimate of charge centroids

The Large Area Picosecond PhotoDetector

First studies: R&D at US universities and national labs ⇒ commercialisation was transferred to a US-based company (Incom) and the design was refined

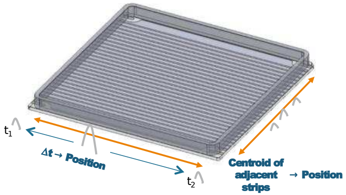
A Brief Technical History of the Large-Area Picosecond Photodetector Collaboration

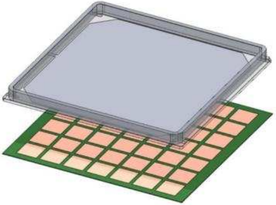
- $20 \times 20\text{cm}^2$ sensor based on MCP technology
- single photon time resolution < 60ps
- gain $> 10^7$
- capable of imaging single photons
- first deployment of LAPPDs in ANNIE coming up this year
- first Gen-I units arriving in the UK this year (Sheffield and Edinburgh)



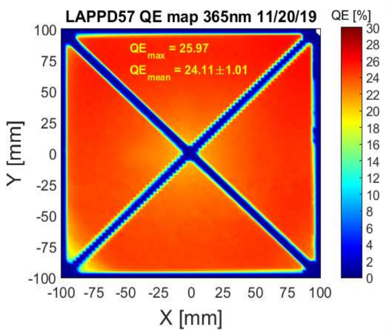
Gen-I Direct Read-out Strip Line Anode

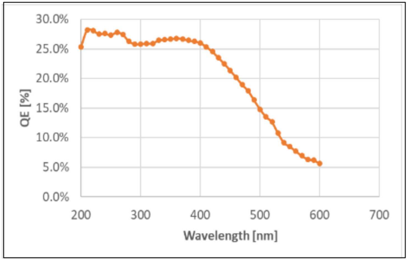
Gen-II Resistive Interior Anode with Capacitive Coupled Patterned Signal Board





LAPPDs





Fused Silica 3.8mm Window (LAPPD #63)

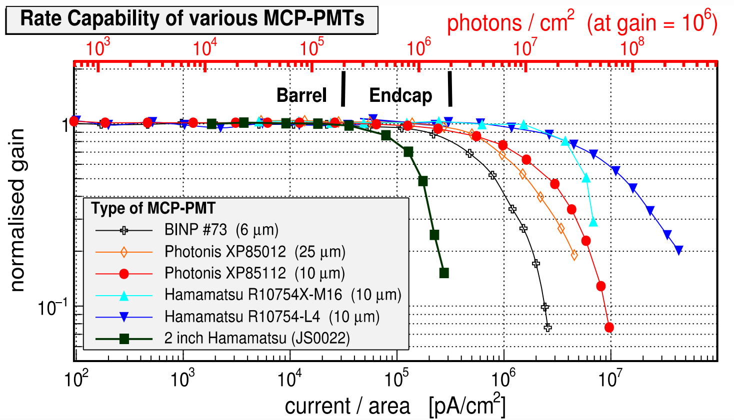
- QE: 25 ± 2, ∼ 90% uniformity (both borosilicate and fused silica windows employed)
- 2.4 & 0.76 mm spatial resolution for GEN I or GEN II
- dead area across spacers
- rate capability under test

⇒ extremely promising technology to equip large areas! (discussed for neutrino experiments, LHCb RICH upgrade II, FCC)

price per tile still high (≈ 54k) but significant improvement expected when moving from R&D to production phase

MCP-PMTs: limitations

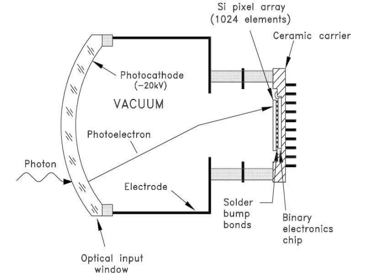
Rate capability (measured by the Panda collaboration)

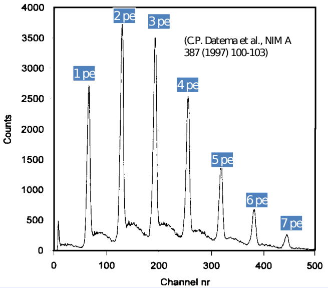


- ageing concerns depending on IAC
- rate capability: limited for high occupancy applications
- cost....

Hybrid Photon Detectors

Hybrid photon detector tubes combine vacuum photo-cathode technology with solid-state technology. First devices available with progress both in semiconductor and in vacuum technology [Nucl. Instrum. Methods A 315 (1992) 375-384]





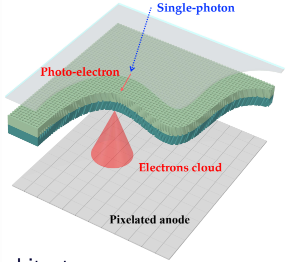
- excellent gain uniformity
- excellent linearity
- high spatial resolution
- low noise: optimal configuration when front-end electronics is encapsulated in vacuum tube
- complicate manufacturing procedure

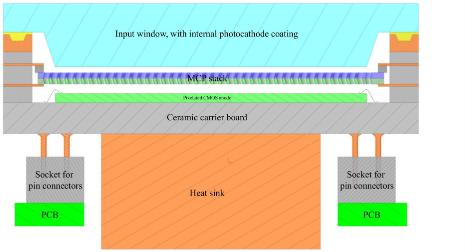
HPDs operated in LHCb RICH (2010-2018), [Eur. Phys. J. C (2013) 73: 2431]

R&D on HPDs: ideas for the future

new developments in HPD area motivated by the R&D for finely-segmented devices coupled to ultra high-speed electronics

devices encapsulating stack of two MCPs in Chevron configuration and high-performance pixel readout ASICs at the anode





architecture:

- vacuum based detector
- photocathode with high QE in spectral region of interest
- proximity focusing geometry
- MCP amplification
- silicon ASIC embedded in vacuum

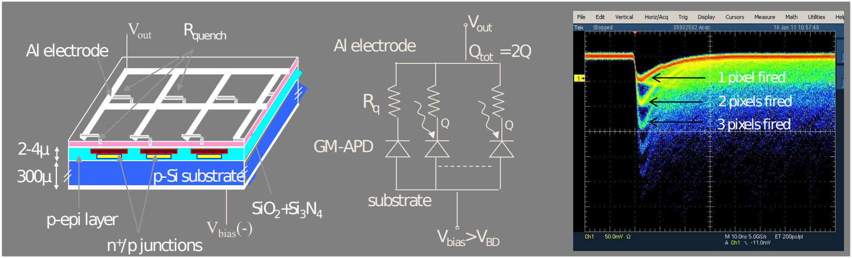
main advantages:

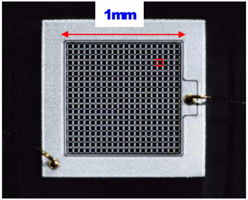
- possibility to operate the MCPs at lower gain → increased lifetime
- high pixel count rate
- local data processing
- preserves all good qualities of MCP-PMTs (timing, DCR, magnetic field tolerance)

[J. Instrum. 9 (2014) C05055], [Nucl. Instrum. Methods A 787 (2015) 20-25], [JINST, Vol. 13, December 2018]

Silicon Photomultipliers

Matrix of n pixels connected in parallel on a common Si substrate: each pixel is a GM-APD in series with a quenching resistor R_{quench}

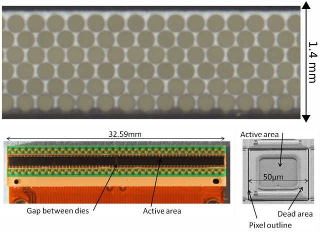


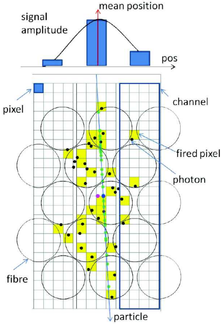


see more details in Andrzej Szelc's talk

- each pixel is a binary (on/off) device
- counts incident photon by summing the pixels: output from SiPM proportional to the number of hitting photons
- large detectable output for each incident photon
- excellent granularity
- good time resolution (∼100 ps)
- magnetic field tolerant
- high photon detection efficiency
- high DCR at room temperature

SiPM in tracking



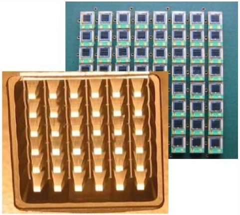


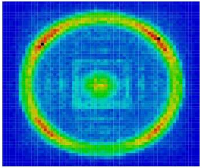
- SiPM ideal photon detectors for applications requiring high granularity and multiple photons
- LHCb Scintillating Fibre tracker being currently installed:
  - fibre mats composed by 6 layers of fibres with diameter of 250 Î$\frac{1}{4}$m
  - SiPM with 128 channels per array coupled to mats
  - operating temperature: -50°C to limit DCR
  - clustering algorithms to reconstruct tracks

SiPMs in PID detectors

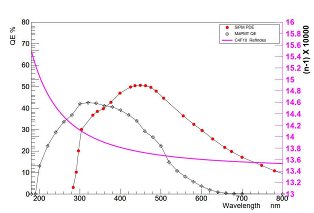
Hi-Lumi conditions will be challenging for PID detectors of LHCb future upgrades

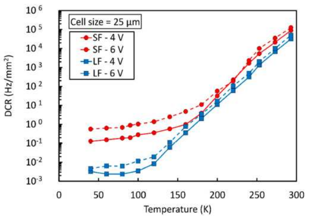
- SiPM particularly attractive because of the small granularity and good timing
- possibility to reduce peak occupancy
- QE shifted towards the green combined with fluorocarbon gases can significantly reduce chromatic uncertainty
- DCR extremely challenging for single photon photon detection in high radiation environment ⇒ need for cryogenic cooling





$1 \times 1\text{mm}^2$ SiPM equipped with light guide





R&D in collaboration with FBK started: focus on radiation hardening

LHCb RICH UK groups well involved in R&D programme

Conclusions

- future facilities are challenging current technology for photon detection
- development of new devices ongoing
- time resolution one of the key points of future developments
- UK groups actively involved in R&D on photon detectors
- many opportunities for the future!