Status and Perspectives of Vacuum-based Photon Detectors

Albert Lehmann (Universität Erlangen-Nürnberg)

- Introduction
- Status and innovations of basic photo detector elements
- Status, applications and perspectives of
    - Single and multi-anode dynode PMTs
    - Hybrid (avalanche) photo diodes
    - Microchannel-plate PMTs
- Comparison of selected performance parameters
- Summary and outlook

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Sensor Requirements for Cherenkov Devices

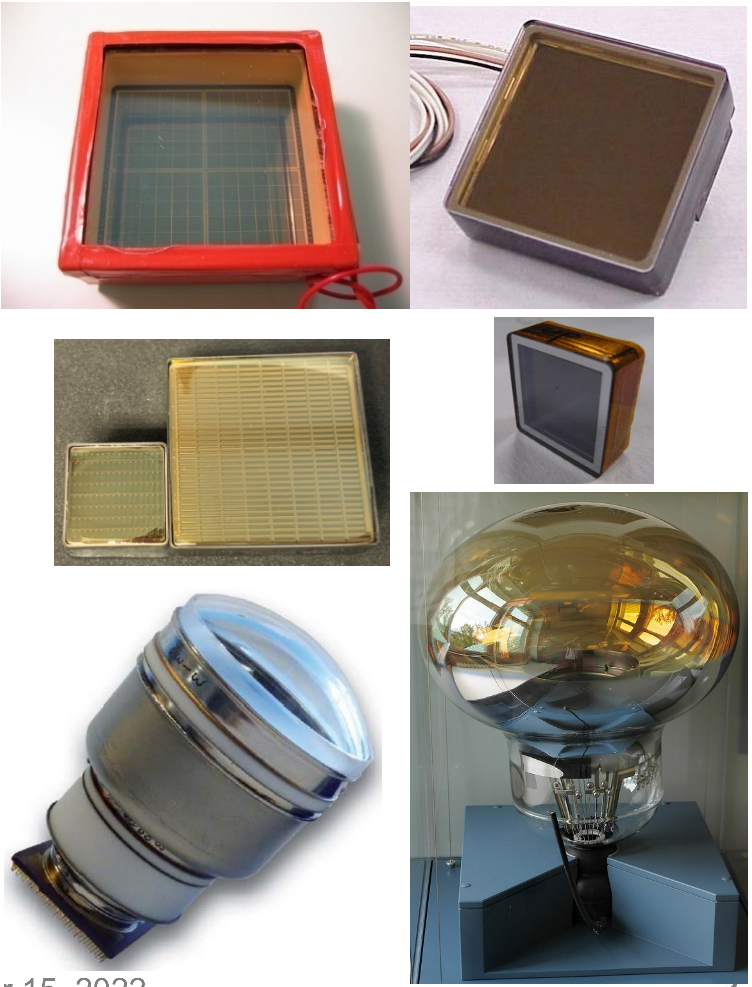
- Detection of (few) single photons
  - Broad wavelength range (~200 nm to ~1000 nm)
  - Large signals → **gain ≥10^6**
  - High detection efficiency (**PDE = QE * CE * FF**)
  - Very low dark count rate (few Hz to <1 kHz/cm²)
- Timing issues
  - Fast time response
    - Low transit time spread (σ_{TTS} < 50 ps to few ns)
    - **Good** (RMS) **time resolution** (down to **σ_t < 100 ps**)
  - Low probability of delayed secondary signals (afterpulses, recoil electrons, ...)
  - **Rate capability** few Hz **to ~100 MHz/cm²**
- Others
  - **Lifetime up to >>10 C/cm²** integrated anode charge
  - Readout rate from few Hz to >>1 MHz
- Geometrical constraints
  - **Compact sensors** because of lack of space
  - Large (active) area coverage
    - Total surface coverage **up to many m²** (even km²)
    - **Active area ratio (FF) up to >90%**
  - Spatial resolution
    - Down to **few mm²** in xy and <1 mm in one dimension (x or y)
    - Down to O(~10 µm) for some applications
- Environmental constraints
  - **Magnetic field immunity** from 0 to 4 Tesla
    - Axial and/or transverse
  - **Radiation dose**
    - Charged particles: >>1 kRad/year (= 10 Gy/year)
    - Neutrons: up to >1 x 10^{11} cm^{-2}

Photon Detectors (for Cherenkov Counters)

- Principle: **Conversion of photon to electron** by external or internal photo-electric effect with **subsequent electron multiplication** stage

- Non-vacuum photon detectors (among others)
  - Semiconductor devices **Review Talk of A. Gola on Thursday**
    - CCDs, (avalanche) photo diodes, silicon photomultipliers (SiPM), ...
  - Gaseous devices **Review Talk of F. Brunbauer on Friday**
    - Photosensitive (**TMAE/TEA** in gas) multi-stage and drift chambers
    - MWPC / MPGD / (TH)GEM / … + **CsI**

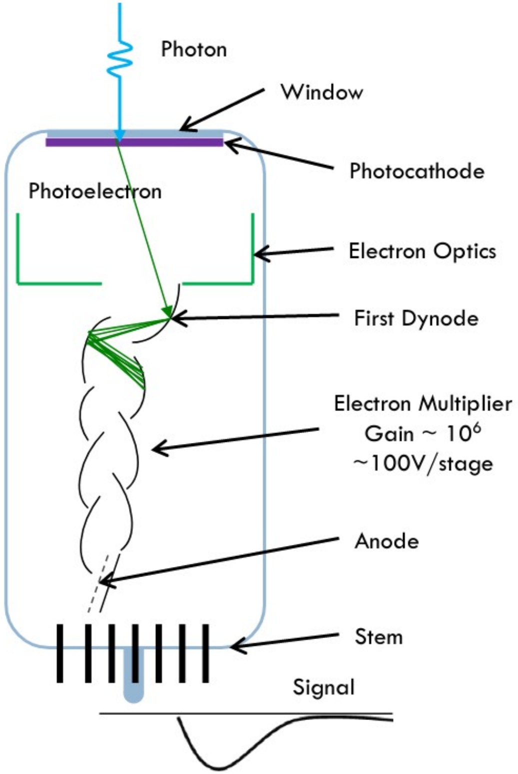
- Vacuum-based photon detectors
  - **Covered in this talk:**
    - **Standard dynode photo-multiplier tube (PMT, MaPMT)**
    - **Hybrid photo detector (HPD, HAPD)**
    - **Microchannel-plate photomultiplier (MCP-PMT, LAPPD)**
  - Not covered here (because not relevant for Cherenkov counters):
    - Photo triode, streak tube, etc.



Structure of Vacuum-Based Photo Detectors

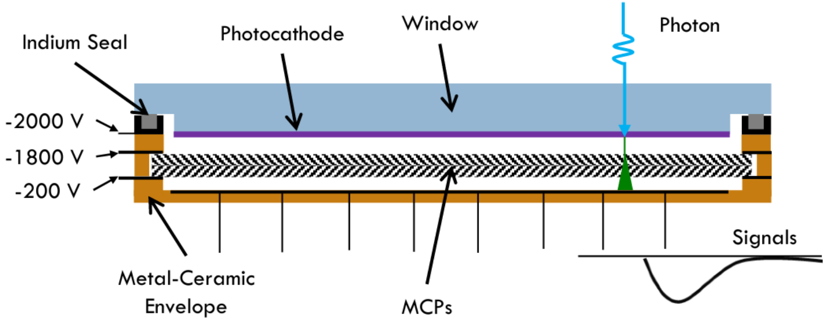
Dynode Photomultiplier

- **Discrete** electron multiplication stages (→ 7 – 14 dynodes)
- Often bulky glass/ceramic housings



Microchannel-Plate PMT

- **Continuous** electron multiplication in thin (Ø 3-25 μm) glass capillaries of a few hundred μm thickness → typically **2 microchannel-plates** (MCPs) in Chevron configuration
- Very compact designs possible



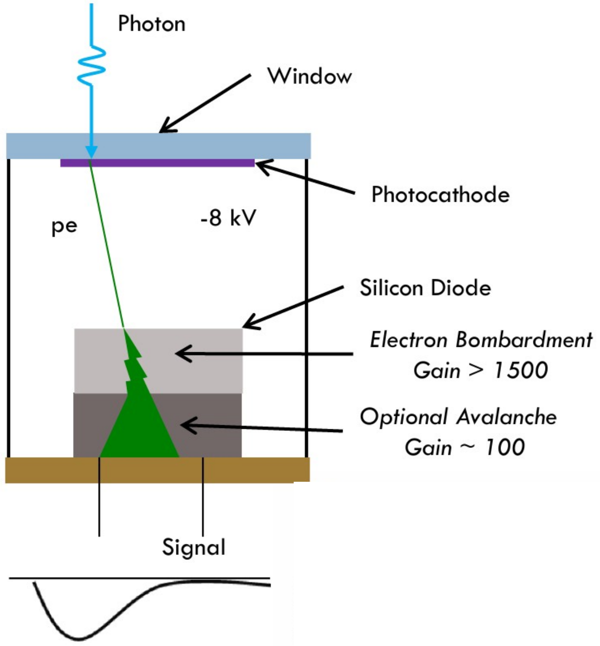
Common to all these photon detectors:

- **Photo cathode**
- **Electron multiplication stage**
- **Single or segmented anode**

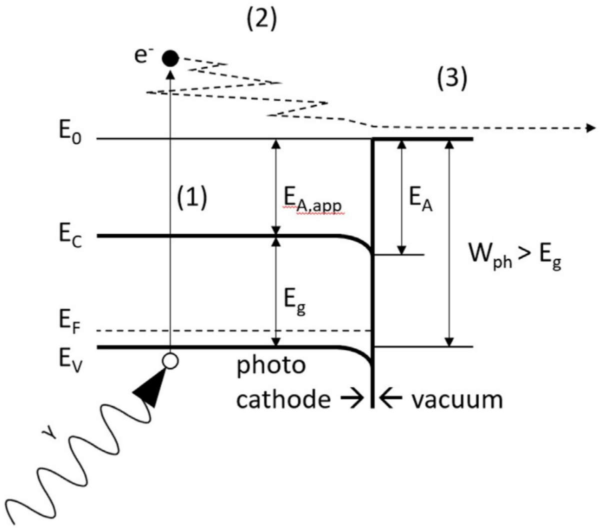
All schematics from P. Hink, Talk at RICH2016

Hybrid Photo Detector

- **Direct** electron acceleration in static electric field (8 to 25 kV) and electron detection with
  - Segmented PIN diode (HPD)
  - Avalanche photo diode (HAPD)
  - Silicon photomultiplier (VSiPMT)



Photon-Electron Conversion



$$QE(\%) = \frac{N_{pe}}{N_{\gamma}} = \boxed{(1-R)\cdot\frac{P_{pe}}{k}} \cdot \boxed{\left[\frac{1}{1+\frac{1}{kL}}\right]} \cdot \boxed{P_E}$$

N_{pe} = number of released photo electrons
N_{γ} = number of photons hitting the photocathode (PC)
R = PC surface reflectivity
P_{pe} = probability of a photon exciting an electron above vacuum level
k = photon absorption coefficient
L = mean electron excape length
P_E = probability of an electron reaching the PC surface being released into the vacuum

- Photon-electron conversion (3-step model)
  - (1) **Photon absorption**
  - (2) **Electron diffusion to surface**
  - (3) **Electron escape to vacuum**
- Often used photo-sensitive materials
  - **Alkali antimonides** (bialkali, multialkali [S20, S25])
  - **III-V PCs** (GaAsP, GaAs, GaN, InP, InGaAs, …)
  - Solar blind PCs (CsTe, CsI, ...)

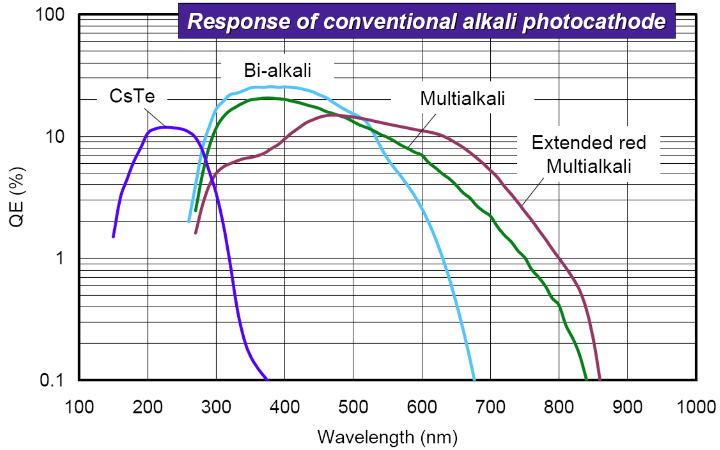
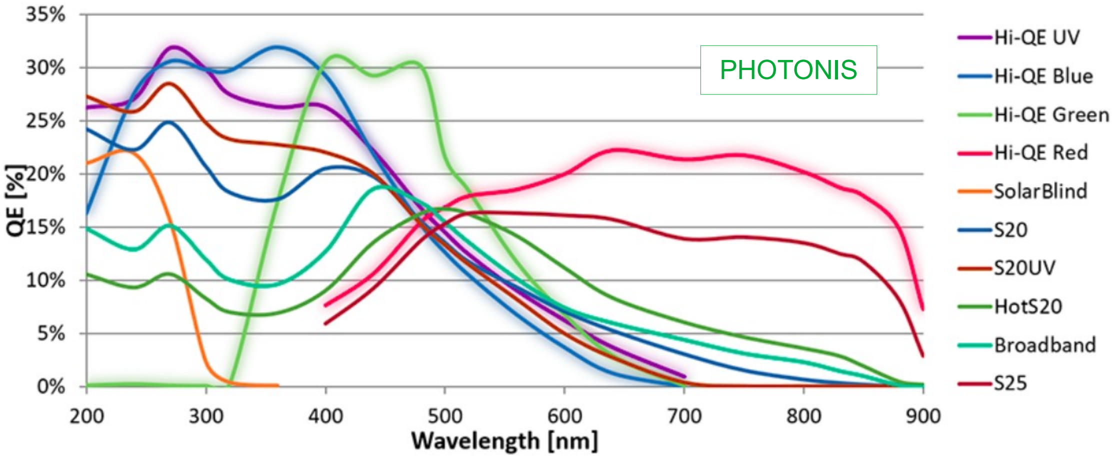


Photo Cathode (PC) and QE

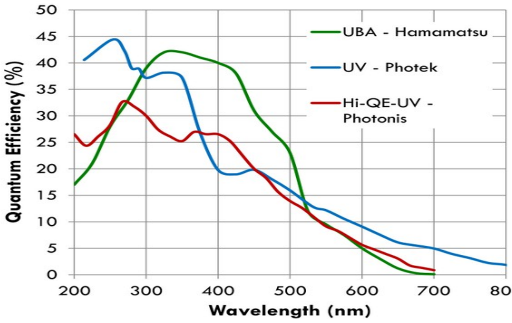
- QE of latest PCs
  - Photonis
    - **HiQE** (>30%) **in different wavelength bands**
    - Originally developed for image intensifiers, now also available for MCP-PMTs
  - Hamamatsu
    - Bialkali: **SBA/UBA (35%/45%)** for MaPMTs and HAPD, reached by better PC quality (not yet in MCP-PMTs)
    - III-V: GaAs (30%) and **GaAsP (>60% in visible range)**
      → reached by better crystallinity
      → improved absorption, diffusion, and emission
  - Photek
    - **>40% in UV** region with bialkali PC



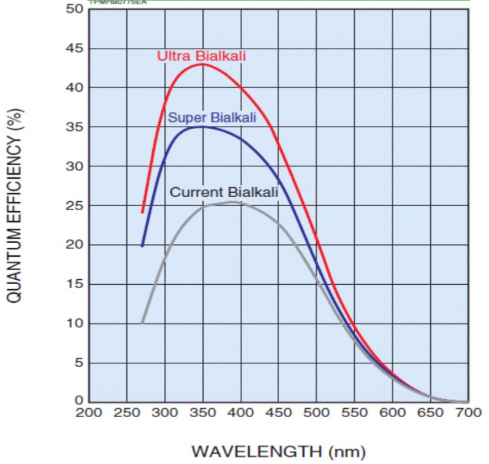
PHOTONIS

comparison of **recent UV/blue** alkali-antimonide photo cathodes

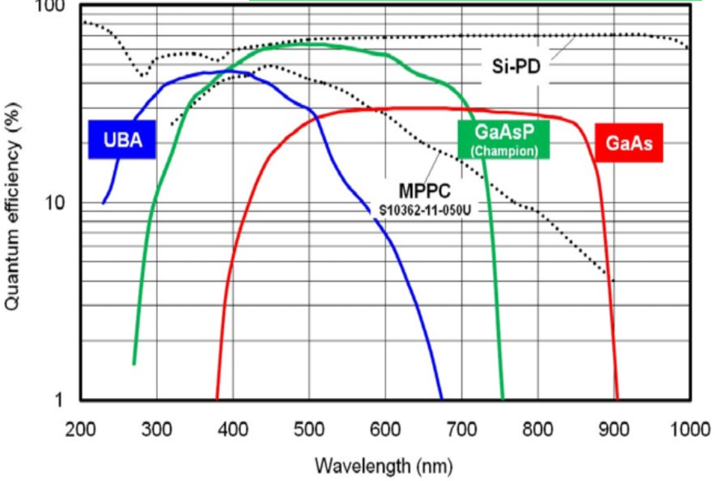
P. Hink, RICH2016



S. Nishida, Talk at NDIP 2014



M. Suyama, K. Nakamura, PoS (PD09) 013



Conventional Electron Multiplication

Standard dynode configurations

- Up to 14 dynode stages, usually single anode
- Venetian blind, box, linear focused, circular cage, etc. types and configurations
- **Very poor B-field tolerance**

Mesh dynodes

- Up to 15 mesh stages, cross wire readout
- **Good B-field tolerance** (up to ~1 Tesla)
- Very good spatial resolution (cross wire anodes)

Metal channel dynodes (MaPMTs)

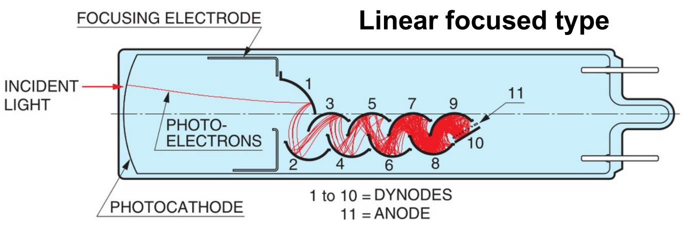
- Multi-anodes PMT with good position resolution
- **Limited B-field tolerance** (<50 mT)

Hybrid photo detectors (HPD)

- One stage electrostatic electron acceleration
- e-detection (and amplification) in Si-detector
- Very **good** spatial resolution and **B-tolerance**

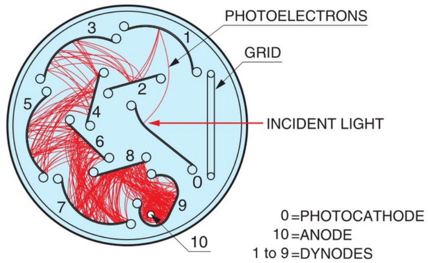
Standard dynode configurations

Linear focused type



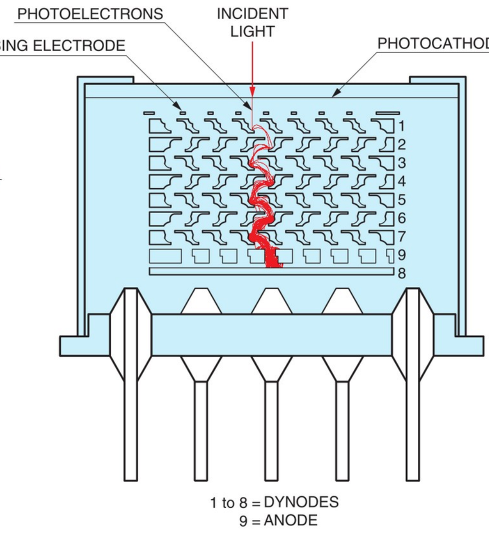
1 to 10 = DYNODES
11 = ANODE

Circular cage type



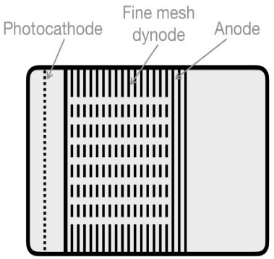
0 = PHOTOCATHODE
10 = ANODE
1 to 9 = DYNODES

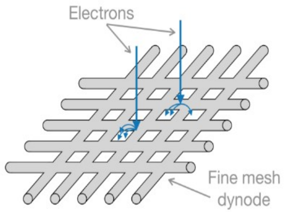
Metal channel dynodes



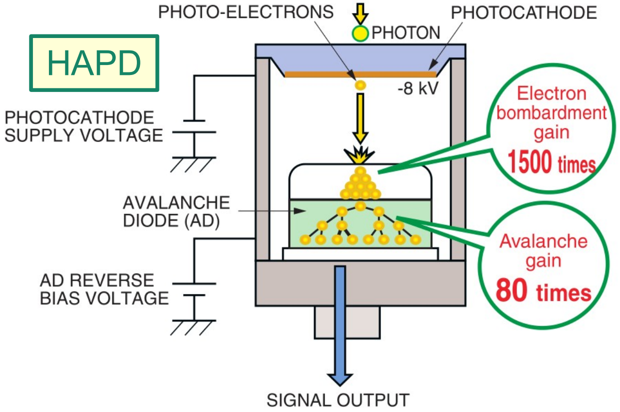
1 to 8 = DYNODES
9 = ANODE

Mesh-type dynode configuration





HAPD



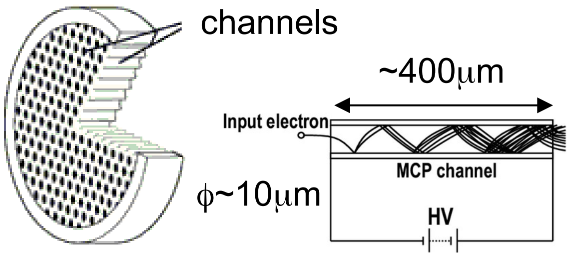
Electron bombardment gain
1500 times

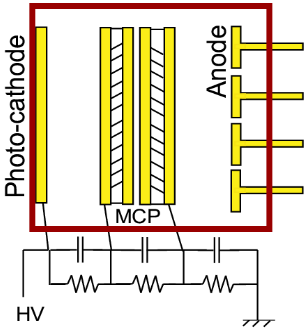
Avalanche gain
80 times

Continuous Electron Multiplication

- Electron multiplication in thin glass capillaries
  - Standard microchannel-plates (→ **MCP-PMTs**)
    - Array of many such capillaries (MCP) with 3 – 25 mm diameter each
    - Hydrogen-fired lead glass capillaries to produce resistive surface
    - Exponential dep. of gain on aspect ratio L/D (pore length / diameter)
  - **High gain** (>10^6) **even in strong magnetic fields** (>1 T)
  - **Very fast** (<50 ps TTS ; <100 ps RMS)
  - Limits: **PC aging** (feedback ions) and **rate capability** (τ = RC)

MCP operation

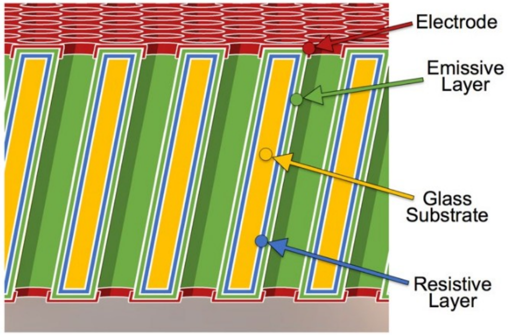




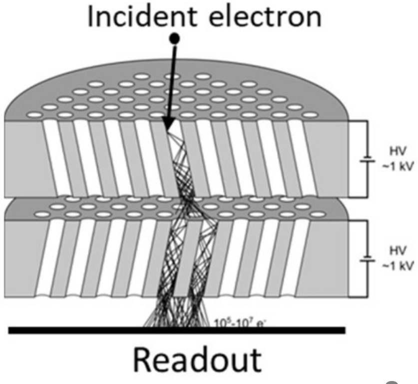
- Atomic Layer Deposition (ALD) coated MCPs
  - **Ultra-thin films of resistive and emissive layers** (MgO, Al_2O_3) applied to (borosilicate) glass capillary arrays (MCPs)
    - Technique originally developed by **Arradiance Inc.**
    - **No PC aging up to >10 C/cm² IAC** (integrated anode charge)
    - Higher gain due to higher secondary electron yield → **lower HV**
    - Rate capability still marginal (1 - 10 MHz/cm² dep. on PMT size)
  - PMT sizes range from **1x1/2x2 inch²** (Hamamatsu, Photonis, Photek) **to 20x20 cm²** (LAPPD, ANL, Incom)
  - ALD-coated MCP-PMTs are considered for several future Cherenkov and non-Cherenkov applications

Cremer et al., DOI: 10.1109/NSS/MIC42677.2020.9507831

Different layers of ALD coated pores



Electron trajectories with 2 MCP stages

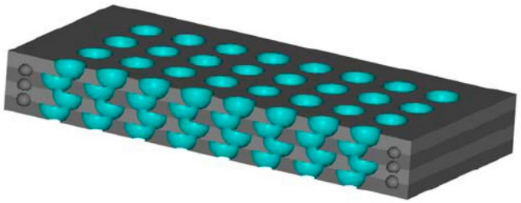


Possible Future of Electron Multiplication

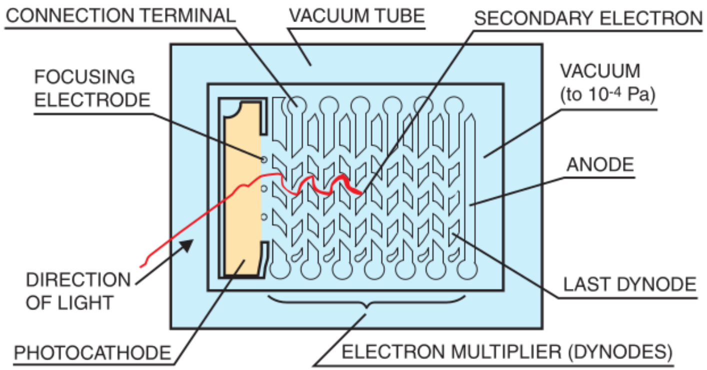
- Micromachined PMTs (→ μPMTs)
  - First developed by Hamamatsu ~2010
    - Pro: easy mass production and customization
    - Con: poor active area ratio and B-field tolerance
  - Improved MEMS/NEMS PMTs (R&D)
    - MEMS: micro-electro-mechanical systems
    - Compact: dynode stage thickness 100 – 500 µm → **PMT thickness of <3 mm** with 8 – 10 dynodes
    - High time/spatial resolution and minor crosstalk
    - High rate capability and B-field tolerance

MEMS/NEMS PMT

D. Winn, Talk at CPAD 2021

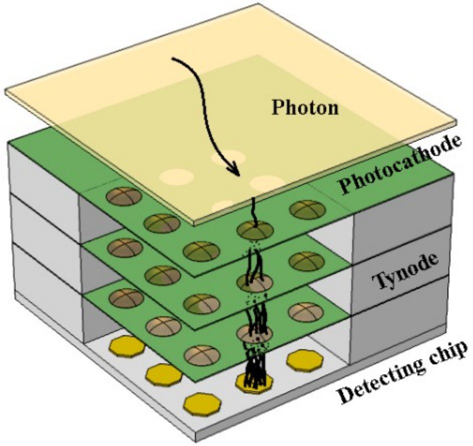


μPMT

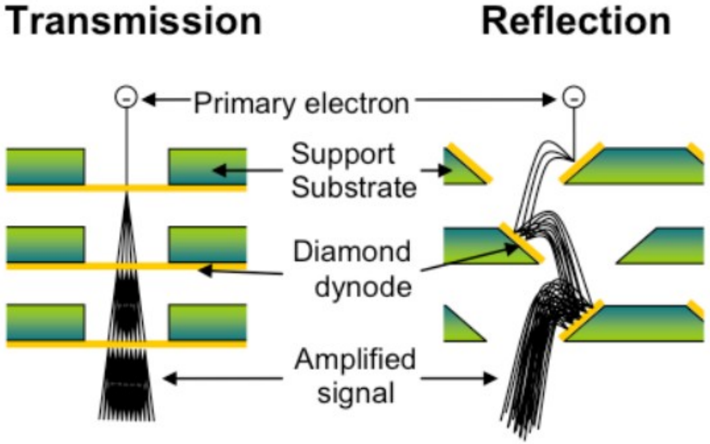


- Tynodes (→ Time Photon Counter)
  - Transmission mode dynode → tynode
  - Fabrication of tynodes (MgO ALD, diamond) using MEMS technology
  - “Anode” is a CMOS chip (e.g., TimePix)
  - Very promising properties
    - Very compact; high B-field tolerance; very fast
    - Very low DCR; very good 2D spatial resolution

H. van der Graaf et al., NIM A847 (2017) 148



TiPC operation

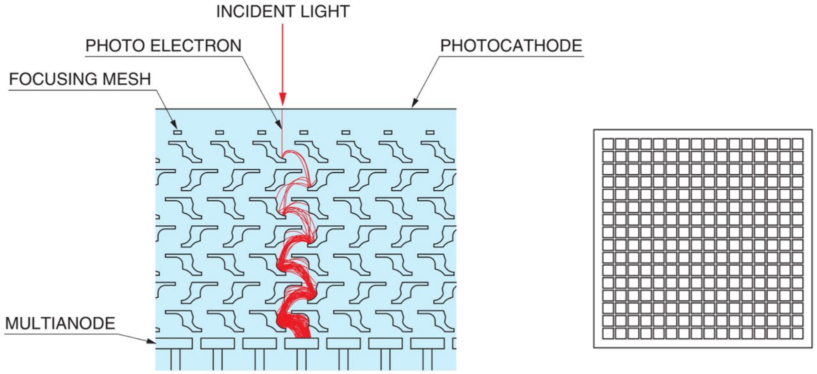


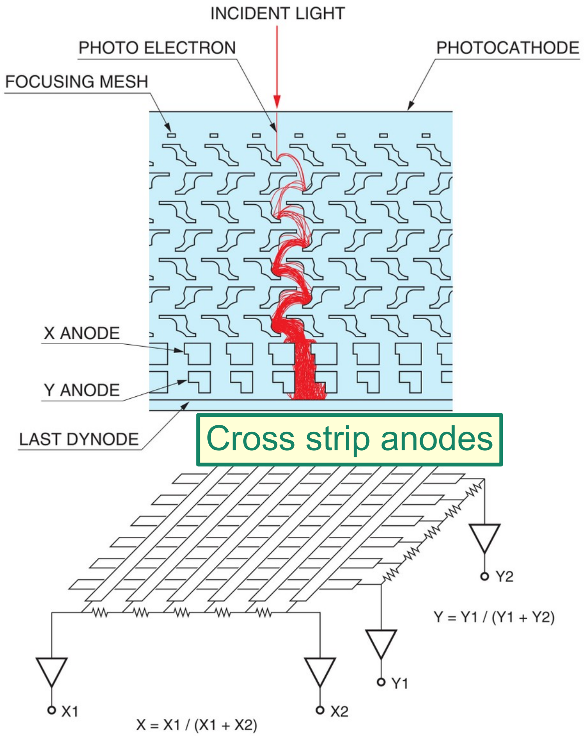
Anode Designs and Readout

All drawings from Hamamatsu PMT Handbook

- Dynode and Mesh PMTs
  - Direct charge readout of discrete anode pads
    - Single and multi-anode
    - Pixel arrays in 1D and 2D (up to 32x32 pads)
  - Cross strip anode readout in MaPMTs
  - Cross wire anode readout in Mesh PMTs
  - Position resolution
    - Good for MaPMTs (few mm)
    - Excellent for mesh PMTs for many photons (<< mm)

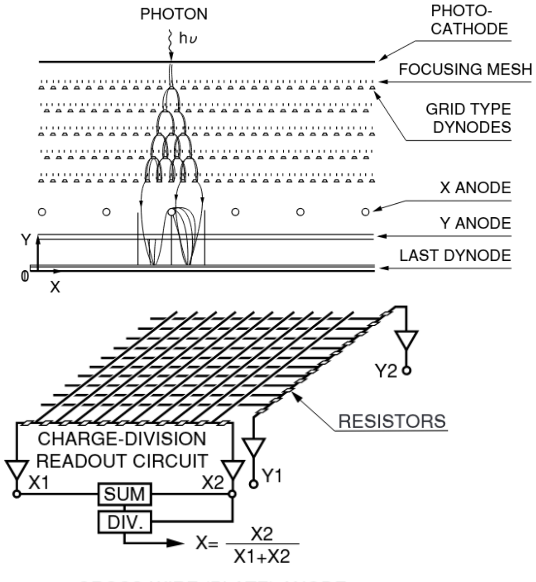
Discrete pixel array anodes





Cross strip anodes

Cross wire anodes in mesh PMTs



CROSS-WIRE (PLATE) ANODE

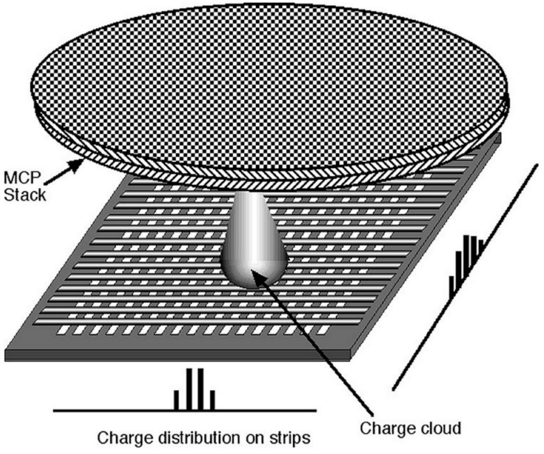
- HPDs
  - Anode replaced by (segmented) Si-detector
  - Readout very similar to conventional Si-strip or pixel detectors

Anode Designs and Readout

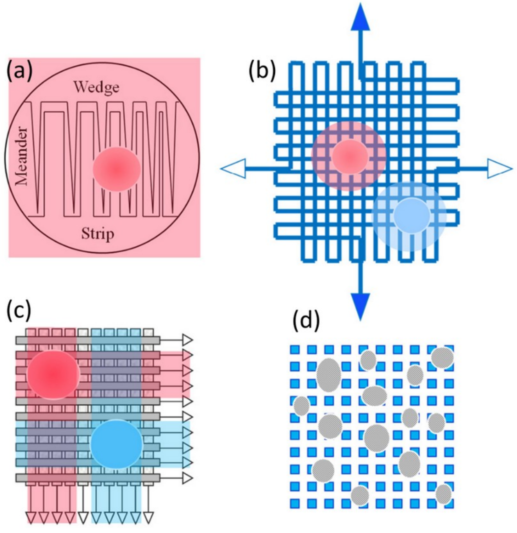
- MCP-PMTs (position resolution)
  - Resistive Anode Strips (few to many channels)
    - Wedge Strip Zig (WSZ) charge division readout (a)
    - Cross Strip (XS) readout (c)
  - Delay line readout (few to many channels)
    - Transmission line readout → t, x, Q
    - (XDL) charge propagation readout (b)
  - **Pixelated readout** (up to >1000 channels)
    - **Direct readout** of discrete anode pixel arrays (d)
    - Specially shaped readout elements → allows accurate charge centroiding despite larger pixel dimensions
  - **Capacitively coupled readout**

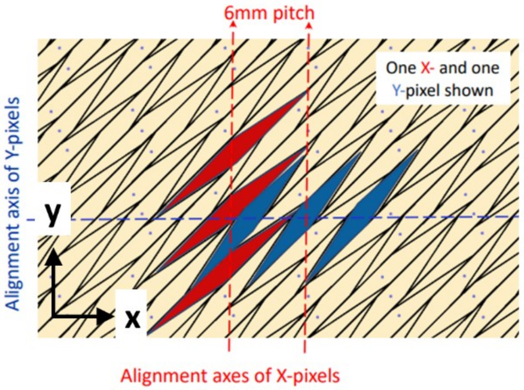
    Talk of A. Kiselev on Thursday
    - **Charge collected inside PMT** and capacitively coupled to segmented conductors at **PCB outside of PMT**
    - More flexibility in backplane design
- MCP-PMTs (timing)
  - Backplane has to be well designed to keep the excellent timing properties of the PMT
    - Avoid reflections and interferences (Tremsin, Va'vra, ...)

Siegmund et al. (2004) doi:10.1117/12.562696



Tremsin et al., NIMA 949 (2020) 162768

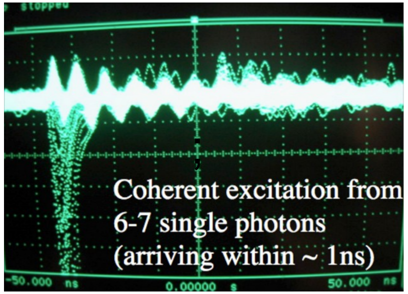




Kiselev, BNL-222830-2022-COPA

Poor backplane design in former Photonis Planacon MCP-PMT

J. Va'vra, NIM A876 (2017) 185



Readout and Signal Processing

- Readout requirements
  - High count rate per channel
  - High speed
  - High signal-noise-ratio

- Digitizing electronics in HEP Cherenkov Counters
  - Refined ASIC or TDC FE boards followed by FPGA logic cards
    - Waveform sampling, time stamping, Time-over-Threshold (ToT), etc.
  - Table below shows used photo detectors and readout designs
    - Red color: applications not running yet

Application	#PMTs	Photo detector	Pixel size (mm^2)	Readout
COMPASS RICH	576	4x4 ch. R7600-03-M16 MaPMT	4.5 x 4.5	CMAD FE + DREISAM F1 TDCs
CLAS12 RICH	2344	8x8 ch. H8500/H12700 MaPMTs	6 x 6	MAROC3 FE + digital FPGA board
GLUEX DIRC	180	8x8 ch. H12700 MaPMT	6 x 6	MAROC3 FE + digital FPGA board
LHCb RICH Upgrade	3072	8x8 ch. R13742/R13743 MaPMTs	2.8x2.8 / 5.6x5.6	CLARO ASIC chip + further FE boards
CBM RICH	1100	8x8 ch. H12700 MaPMT	6 x 6	DiRICH: FPGA-TDC board
Belle2 iTOP	512	4x4 ch. Hamamatsu MCP-PMT	5.3 x 5.3	IRSX waveform sampling ASIC
Belle2 ARICH	420	12x12 ch. Hamamatsu HAPD	4.9 x 4.9	4 ASICs + Spartan6 FPGA
Proto-TORCH	11	8x128 or 64x64 ch. MCP-PMT	6x0.4 or 0.8x0.8	Customised: NINO + HPTDC + FPGA
PANDA Barrel DIRC	128	8x8 ch. Photonis MCP-PMT	~ 6 x 6	DiRICH: FPGA-TDC board
PANDA Endcap DIRC	96	3x100 or 6x128 ch. MCP-PMT	0.4-0.5 x 16	TOFPET ASIC
EIC mRICH	open	LAPPD or SiPM	open	Still open, with waveform sampling ASICs being considered
EIC hpDIRC		Commercial MCP-PMTs / HRPPD		
EIC dRICH		LAPPD of SiPM		

Very Large PMTs and Optical Modules

- Latest 20-inch PMTs

  Talk of J. Kisiel on Tuesday

  - Box&Line PMT Hamam. R12860 for Hyper-Kamiokande
    - **Twice the PDE** and faster than R3600 used in SuperK
  - 20-inch MCP-PMTs (>12500)

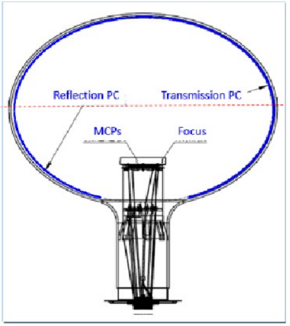
    Talk of S. Qian on Thursday

    - **New type of photomultiplier** developed for JUNO
    - ~4π PC effective area and amplification in small MCP unit
- Trend: set of 3'' PMTs replaces large diameter PMT
  - single glass sphere contains PMTs / HV / electronics
  - KM3NeT multi-PMT (starting 2024/26)
    - 31 3'' PMTs with HV, calib. dev., and electronics in same housing
    - **Larger PC area**, **sensitivity to incident photon direction**, broad angular coverage, accurate timing, etc.
    - **Added value first time demonstrated in 2013**
  - IceCube-Gen2 Upgrade mDOM (from 2026)
    - 24 3'' PMTs with integrated HV and readout system
    - Deployment of first 700 modules (phase 1) in 2022/23
  - Hyper-Kamiokande (starting 2027)
    - mPMTs (19 3'' PMTs) as option for Far Detector (HK-FD) and Intermediate Water Cherenkov Detector (IWCD)

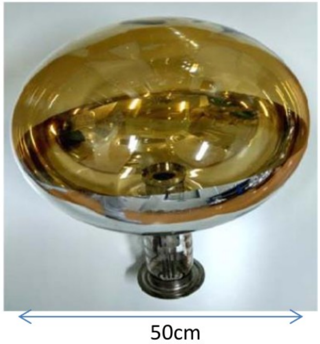
JUNO

Pictures from Z, Qin Talk at ICHEP2018

Hyper-Kamiokande

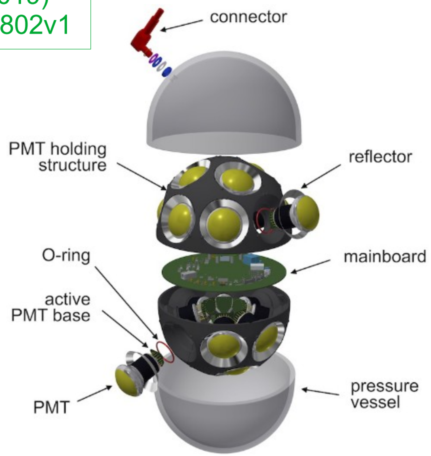


MCP PMT



20-inch PMT R12860

Dorn et al., (2019) arXiv:1908.10802v1



IceCube

KM3Net

Aiello et al., (2022) arXiv:2203.10048v1

De Rosa, NIMA (2019) 163033

Hyper-Kamiokande

PMTs in Neutrino and Astroparticle Physics

Most data taken from S. Lubsandorzhiev, PoS(ICRC2021)1104; **this list is by far not complete!!**

PMT	size	Experiments	Photocathode	QE	Dynode
Various PMTs	≤1.5-inch	HESS, MAGIC, MAGIC-II, VERITAS, etc.	(super-)bialkali,	20% – 35%	
R12992, R11920	1.5-inch	CTA	super-bialkali	>35%	Linear-focused (LF)
R14374, R12199-02	3-inch	KM3NeT multi-PMT Optical Module (OM)	bialkali		Circular & LF
R15458-02	3-inch	IceCube Upgrade mDOM	bialkali		
XP72B22, XP82B20	3-inch	JUNO, Hyper-Kamiokande		~25%	
R1408	8-inch	IMB, IMB-3, MACRO, SNO, SNO+	bialkai		
R5912	8-inch	MILAGRO, Daya Bay, HAWC,	bialkali K_2CsSb	28 – 30%	Box & Line
R5912-100		Super-Kamiokande, TAIGA, LHAASO	super-bialkali	35 – 40%	
ETL9350	8-inch	MACRO, SNO, Borexino, GERDA, Tunka-133, Neutrino-4, etc.	bialkali K_2CsSb or Rb_2CsSb (green)	<25 – 28%	
R14688-100	8-inch	New development	super-bialkali	~35%	Box & Line
R7081	10-inch	Ice-TOP, TAIGA-HiSCORE, etc.	bialkali	25 – 30%	Box & Line
R7081-100		Double-Chooz, RENO, STEREO, etc. IceCube, ANTARES, GVD, etc. + LBNT	super-bialkali	35 – 40%	
R7250	17-inch	KamLAND, KamLAND-Zen	bialkali		Box & Line
R1449, R3600	20-inch	Kamiokande, Super-Kamiokande	bialkali		Venetian blind
R12860	20-inch	Hyper-Kamiokande, JUNO	bialkali	25 – 30%	Box & Line
MCP-PMT	20-inch	JUNO	bialkali	33 – 35%	MCP

Dynode PMTs in RICH and DIRC Applications

- Detectors with single-anode PMTs
  - DELPHI RICH
  - Hermes RICH
  - SELEX (E781) RICH
  - BaBar DIRC
  - **NA62 RICH** (still online)

- Applications using multi-anode PMTs
  - **Various high-performance MaPMTs available in different designs** (see experiment table below)
    - Only producer: Hamamatsu; and **hardly new developments**
  - Tracking Ring Imaging Cherenkov Detector (TRICK)
    - Prototype: **5D readout** (position, time, and particle ID)
    - Attempt to combine **RICH+TPC** → 3D spatial resolution ~100 µm

Poster of G. Mezzadri

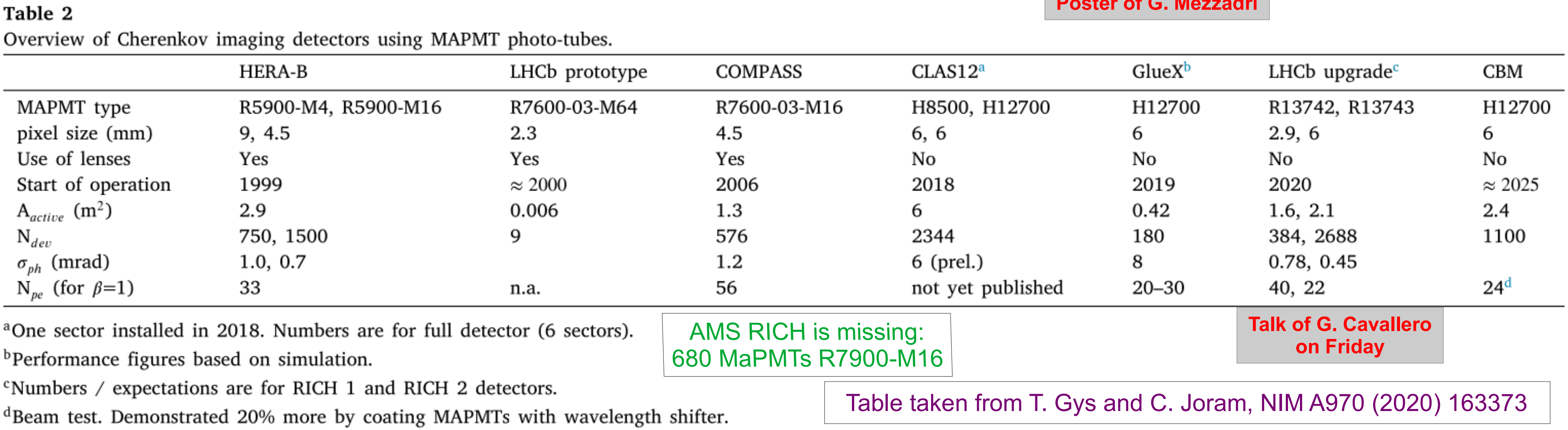


Table 2

Overview of Cherenkov imaging detectors using MAPMT photo-tubes.

	HERA-B	LHCb prototype	COMPASS	CLAS12[a]	GlueX[b]	LHCb upgrade[c]	CBM
MAPMT type	R5900-M4, R5900-M16	R7600-03-M64	R7600-03-M16	H8500, H12700	H12700	R13742, R13743	H12700
pixel size (mm)	9, 4.5	2.3	4.5	6, 6	6	2.9, 6	6
Use of lenses	Yes	Yes	Yes	No	No	No	No
Start of operation	1999	≈ 2000	2006	2018	2019	2020	≈ 2025
A_{active} (m^2)	2.9	0.006	1.3	6	0.42	1.6, 2.1	2.4
N_{dev}	750, 1500	9	576	2344	180	384, 2688	1100
σ_{ph} (mrad)	1.0, 0.7		1.2	6 (prel.)	8	0.78, 0.45	
N_{pe} (for β=1)	33	n.a.	56	not yet published	20–30	40, 22	24[d]

[a] One sector installed in 2018. Numbers are for full detector (6 sectors).

[b] Performance figures based on simulation.

[c] Numbers / expectations are for RICH 1 and RICH 2 detectors.

[d] Beam test. Demonstrated 20% more by coating MAPMTs with wavelength shifter.

AMS RICH is missing:
680 MaPMTs R7900-M16

Talk of G. Cavallero on Friday

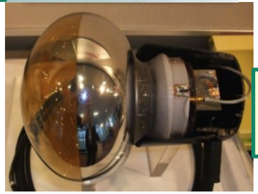
Table taken from T. Gys and C. Joram, NIM A970 (2020) 163373

Currently Available Hybrid PDs

- Standard HPDs
  - HEP experiments (e.g., LHCb RICH)
    - **Various sizes and (focusing) designs possible**
    - Highly segmented "anodes" (spatial resolution down to <1 mm)
    - **Moderate time resolution** (>1 ns)
  - Neutrino and astroparticle experiments
    - **Latest developments:** Hamamatsu 8'' R12112 and 20'' R12850
- Hamamatsu 144ch HAPD
  - Developed for Belle-II Aerogel RICH (ARICH)
    - >4σ K/π separation @ 0.5 to 4 GeV/c in 1.5 T B-field
    - **High radiation tolerance (n,γ) needed**
    - The only running Cherenkov imaging application using HAPDs
  - Sensor characteristics and performance
    - **Proximity focused design** (~2 cm between PC and APD)
    - **4 APDs** with 36 channels each (420 HAPDs for whole ARICH) read out by 4 ASICs and Spartan6 and Virtex5 FPGA
    - **Peak QE up to >30%**; sensitive area ~65%; **gain ~70k**
    - Excellent photo electron separation even in B-field of 1.5 T
    - **Radiation tolerance tested up to 5x10^{11} n/cm²**
    - Problems with large pulses in B-field and APD leakage current

Talk of K. Uno on Monday

LHCb RICH HPD

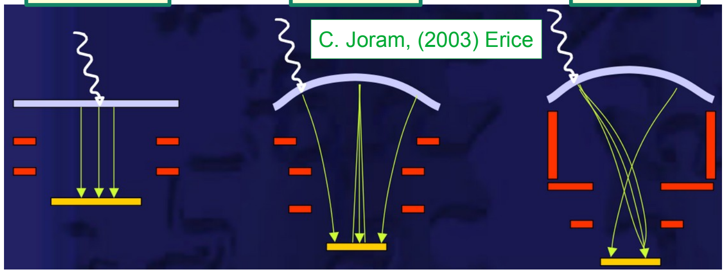


8-inch HiQE HPD

proximity focused

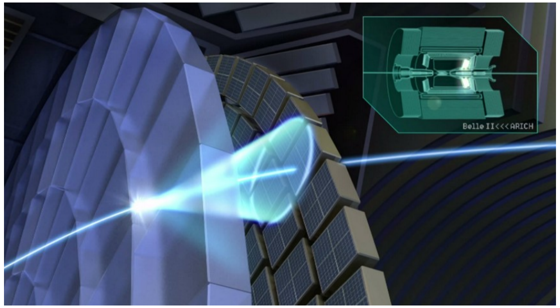
fountain focused

cross focused

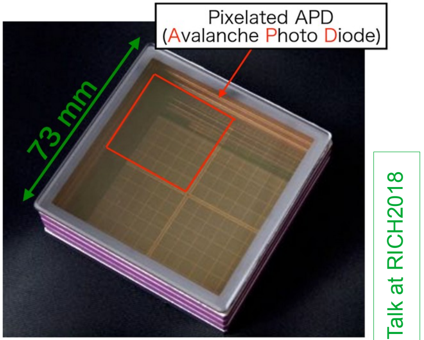


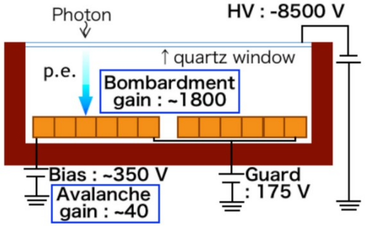
C. Joram, (2003) Erice

ARICH concept



Hamamatsu 144ch HAPD



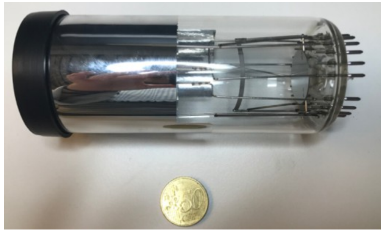


M.Yonenaga, Talk at RICH2018

New HPDs with SiPMs

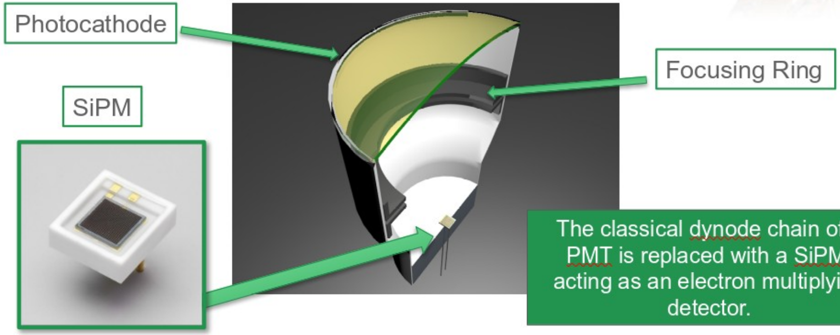
- Vacuum Silicon PhotoMultiplier Tube (VSiPMT)
  - Hybrid PD with SiPM as electron multiplier
    - Goal: increase SiPM surface
    - R&D was started in 2007 for future astroparticle experiments
    - **One amplification stage:** photo electron is accelerated to **~2 keV** to trigger a Geiger avalanche in the **SiPM** (for **electron multiplication**)
  - Performance
    - **Higher gain** (>10^6) **than other HPDs** and faster than dynode PMTs
    - Compact and simple
    - Weak point: **high DCR** → single photon sensitivity questionable
- ABALONE photo detector
  - Hybrid PD read out by scintillating window and outside SiPM
    - **Goal:** build **photon detector with few components** → radio purity
    - **Two amplification stages:** electron accelerated to scintillator layer → creates N(ph) proportional to ~25 keV electron energy → SiPM
  - Performance
    - Very high **gain of up to 10^8** [10^6 from SiPM and 10^2 from N(ph)]
    - **Excellent single photon sensitivity**
    - **Very low afterpulse rate** (~5x10^{-3}) and **low DCR** (~1 Hz/cm^2)

VSiPMT 2-inch prototype



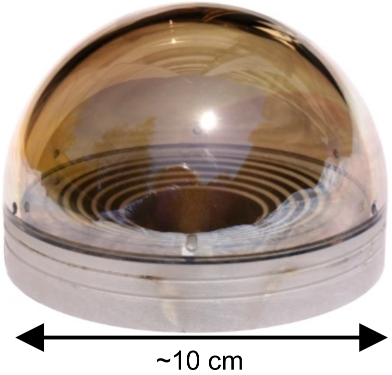
VSiPMT concept

F.C.T. Barbato et al., NIMA 958 (2020) 162144

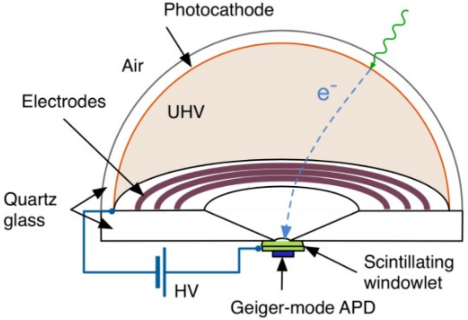


The classical dynode chain of a PMT is replaced with a SiPM, acting as an electron multiplying detector.

ABALONE photo detector for astroparticle experiments



V. D'Andrea et al., JINST 17 (2022) C01038



Currently Available MCP-PMTs

Talk of J. Milnes on Thursday

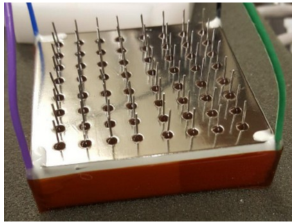
- Photonis, Hamamatsu, Photek
  - **1- and 2-inch PMT types in various configurations**
  - Segmented anode (4x4, 8x8, 16x16, 3x100, 8x128, etc.)
- Fast MCP-PMTs (China)

  Talk of S. Qian on Thursday

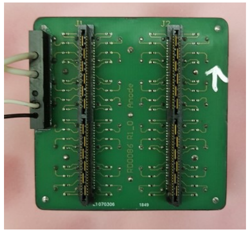
  - R&D for 8x8 pixel 2-inch PMT (prototypes produced)
- **LAPPD**, ANL and Incom
  - MCP-PMTs designed for **large area coverage**
    - LAPPD Collaboration formed in 2009
    - Commercialization process transferred to Incom Inc. in 2013
    - ongoing R&D in collaboration with ANL and Univ. of Chicago
    - Now available: sizes of 6x6 (ANL), 10x10 or **20x20 cm²**
  - Anode and readout options
    - Gen-I: strip line (delay line) anode with ~1.5 mm resolution
    - Gen-II: **anode capacitively coupled to highly segmented external readout board** provides <<1 mm² 2D-resolution
    - Gen-III: **pixel anode design** studied for EIC applications
  - Working on Gen-III HRPPD (10x10 cm²)
    - Design **optimized for high rates** and B-field tolerance

Backplane design of some commercial 2-inch MCP-PMTs

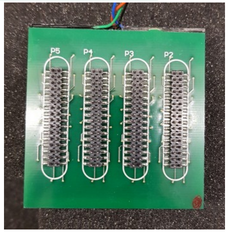
Hamamatsu



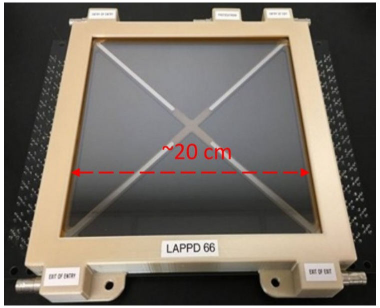
Photonis



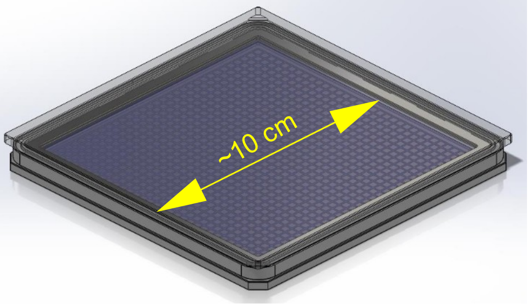
Photek Ltd



LAPPD



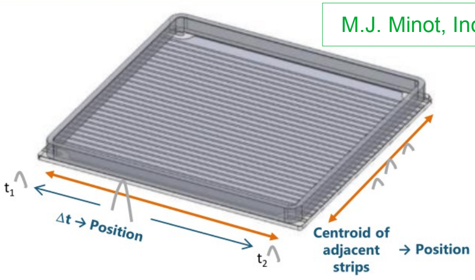
Pixelated HRPPD

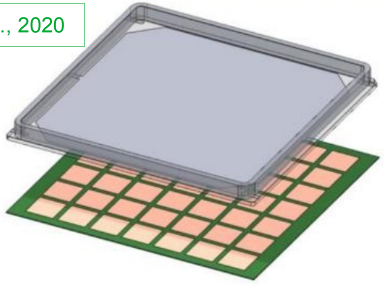


Gen-I Direct Read-out Strip Line Anode

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

M.J. Minot, Incom Inc., 2020





Some LAPPD Performance Parameters

S. Shin, LAPPD Workshop March 2022

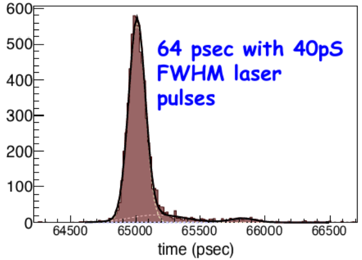
Parameters for recent 8-inch devices

- Bialkali (e.g., K_2NaSb) photocathode
- Peak QE ~ 30% @ 365 nm
- Glass and ceramic bodies with **10 µm** and **20 µm borosilicate 2-layer ALD MCPs**
- **97% active area** with new internal support
- Low (<1 kHz/cm²) dark count rate (DCR)
- ~30 ps single photon TTS resolution
- ~1x10^7 gain
- O(mm) position resolution
- Direct (Gen-I) and capacitively coupled (Gen-II) readout available

Personal Remarks

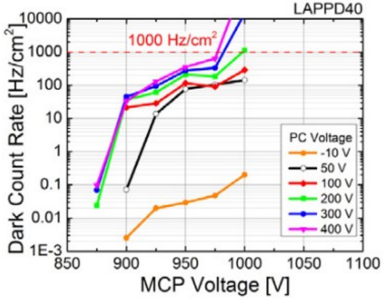
- B-tolerance seems still marginal
- Gain uniformity?
- Rate/cm² or current/cm² info would help to compare to other data
- Seems unlikely that 8x8" devices can stand MHz/cm² rates as required in high rate experiments

TTS of LAPPD #25

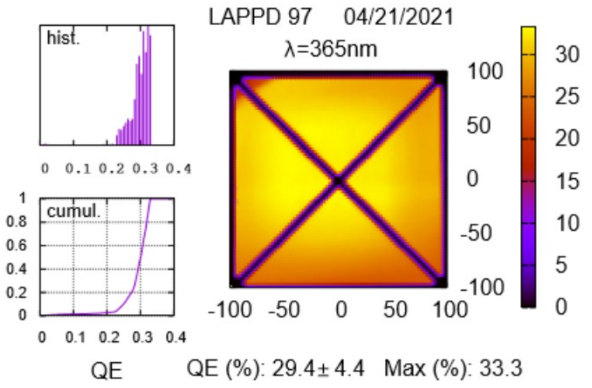


Poster J. Xie and Talk F. Oliva

DCR



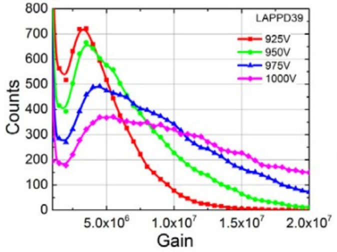
QE of Na_2KSb PC with fused silica window

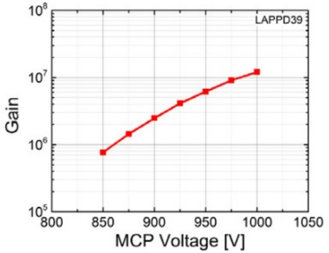


QE (%): 29.4± 4.4 Max (%): 33.3

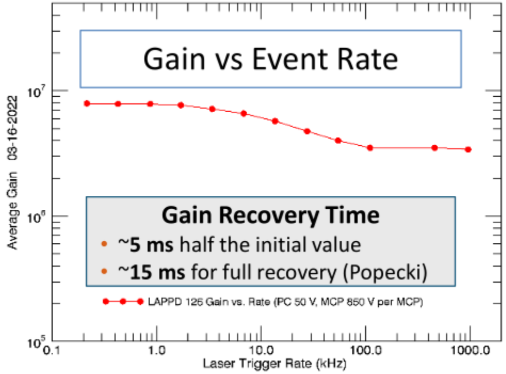
S. Shin, LAPPD Workshop March 2022
A. Lyashenko, NIM A958 (2020) 162834
A. Lyashenko, Talk at VCI 2019

Gain and pulse height





Rate capability
(not clear about rate/cm²)



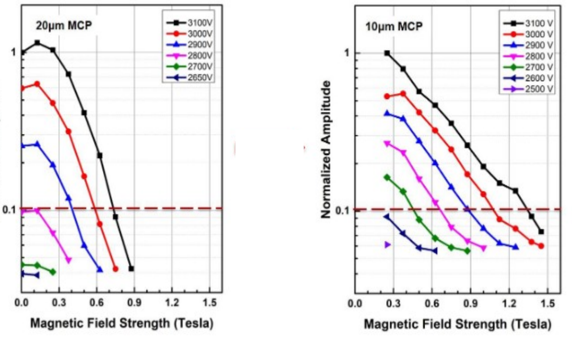
Gain Recovery Time

- **~5 ms** half the initial value
- **~15 ms** for full recovery (Popecki)

Gain of 6x6 cm² ANL device inside B-field

version 2: IBD design 20 µm

version 3: IBD design 10 µm



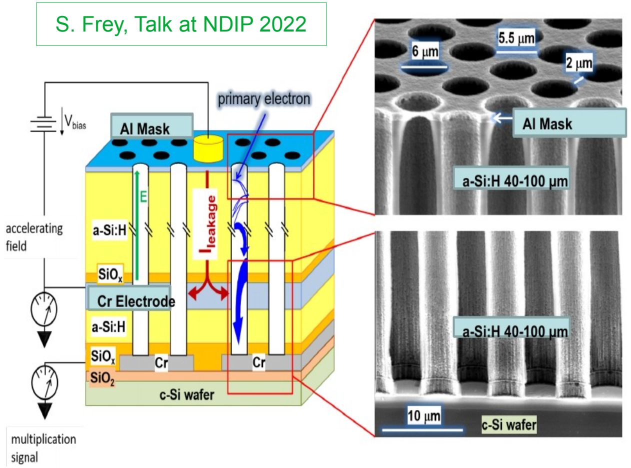
Possible Future MCP-PMTs

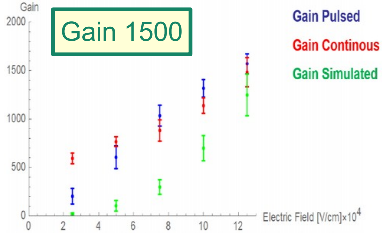
Monolithic MCP from amorphous Si (a-Si:H)

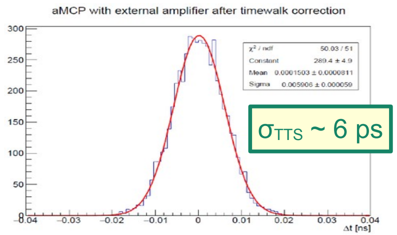
- Goal: overcome complicated fabrication process and long channel dead time of conventional glass MCPs
  - Possibility of much **higher rate capability** and spatial resolution
- Fabricated by chemical vapor deposition of a-Si:H layer (80 µm) on any substrate and deep reactive-ion etching
  - Reactive-ion etching process → pores with aspect ratio (L/D) >20
  - **Aspect ratio ~25 led to gain of 1500** (~8000 with ALD coating)
  - Readout electronics can be embedded into Si-wafer
  - Funnel-shaped AMCPs with ~95% open area being tested

MCPs based on hydrogenated amorphous Si

S. Frey, Talk at NDIP 2022







MCP-PMT with CMOS anode

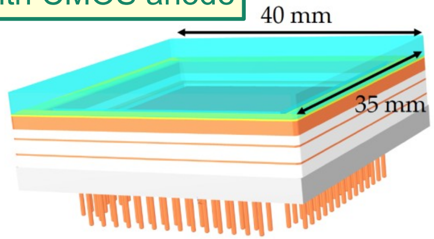
- Conceptual design for 4D detection of single photons
  - Hybrid concept: **MCP-PMT** where the **pixelated anode** is an **ASIC** (CMOS) embedded **inside the vacuum**
  - **Prototype** with Timepix4 ASIC as anode (array of 23k pixels)
- Envisaged performance

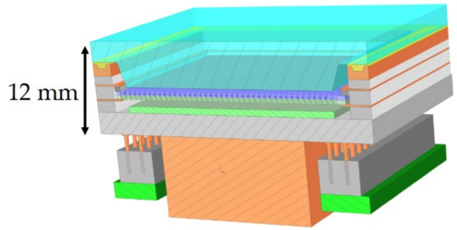
Talk of M. Fiorini on Friday

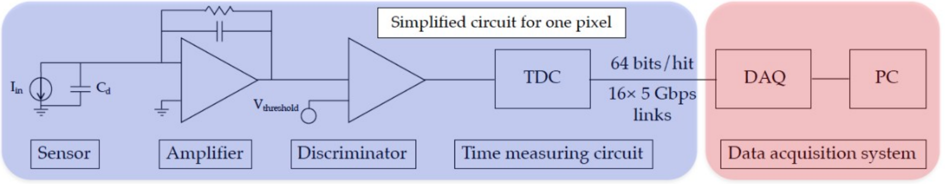
  - <100 ps time resolution and 5-10 µm spatial resolution
  - **Rate capability** of **>100 MHz/cm²** (<2.5 Ghits/s @ 7 cm² area)
  - Low gain (~10⁴) operation possible → x100 **lifetime increase**

MCP-PMT with CMOS anode

Bolzonella, Talk at NDIP 2022







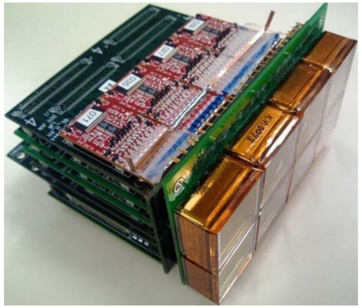
First DIRCs Applying MCP-PMTs (from ~2005)

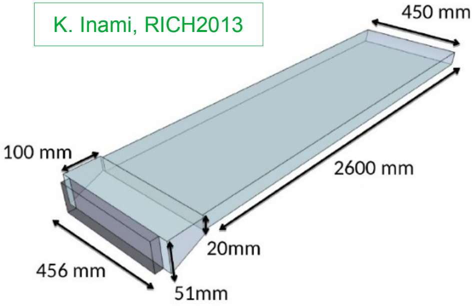
- Belle-II TOP detector

  Talk of R. Okubo on Friday

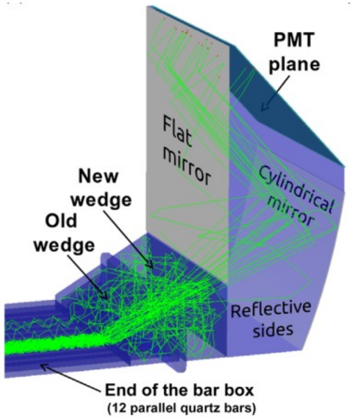
  - Imaging Time-of-Propagation (iTOP) DIRC
    - 16 radiator bars read out by linear array of MCP-PMTs to measure x and TOP (~50 ps resolution required)
    - Ring image from 3D information (x, y, TOP)
  - Photon sensors and readout
    - For each bar: **2x16 MCP-PMTs** (1x1 inch² 4x4 chan. **Hamamatsu R10754X** MCP-PMTs)
    - **>1 C/cm² integrated anode charge (IAC)**
    - ASIC waveform sampling readout of “IRS” series
- Focusing DIRC (FDIRC) for SuperB
  - Tested **MaPMTs** (H8500, H9500) and **MCP-PMT** (Burle Planacon) sensors with different anodes
  - 3D readout (x, y, t) used for chromatic corrections (needs excellent timing) in the Cherenkov angle
    - Only a prototype was built and tested, but FDIRC studies paved the road for other focusing DIRCs.
    - J. Va’vra: **“Combining precise angular and time measurements are likely to provide the ultimate performance in the future DIRC detectors.”**

Schematic and readout of TOP detector



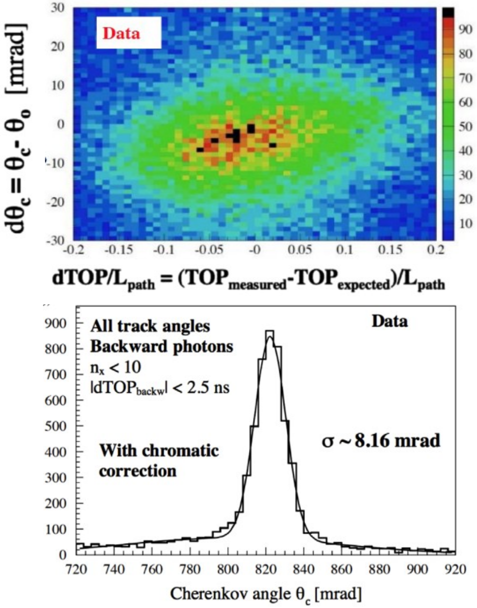

K. Inami, RICH2013

FDIRC prototype optics design



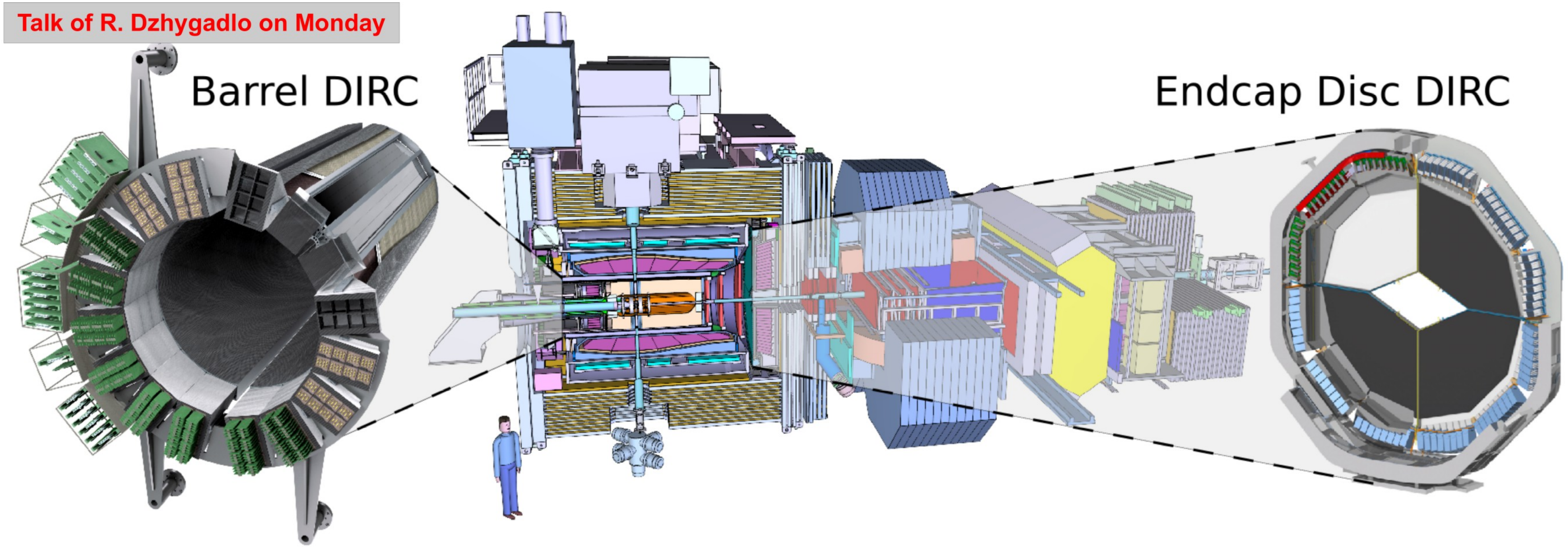
FDIRC prototype results

B. Dey et al., NIM A775 (2015) 112



MCP-PMTs for PANDA DIRCs

Talk of R. Dzhygadlo on Monday



- Barrel DIRC
  - 16 sectors with three 5.3 cm wide radiator bars
  - Readout
    - Lenses and prism
    - 128 8x8 pixel 2-inch Photonis **MCP-PMTs** in ~1 T B-field
    - ~200 kHz/cm² photon rate and 5 C/cm² IAC lifetime
    - GSI-designed DiRICH/TRB FPGA readout electronis

Talk of S. Krauss on Thursday

- Endcap Disc DIRC
  - Dodecagon-shaped radiator disc split in 4 quadrants
  - Readout
    - 24 (or 27) special focusing light guides
    - ~100 ≥3x100 pixel 2-inch **MCP-PMTs** in ~1 T B-field
    - Up to 1 MHz/cm² photon rate and >5 C/cm² IAC lifetime
    - TOFPET ASIC frontend electronics

Sensors at EIC Cherenkov Imaging Detectors

High performance DIRC (hpDIRC)

- Efficient and fast single photon detection in high B-fields
- π/K separation from 1 GeV/c to 6 GeV/c
- ~1 mm spatial and 100 ps time resolution
  → **MCP-PMTs (commercial or LAPPD)** or SiPMs
- Waveform-sampling ASIC and/or FPGA-based readout

Dual radiator RICH (dRICH)

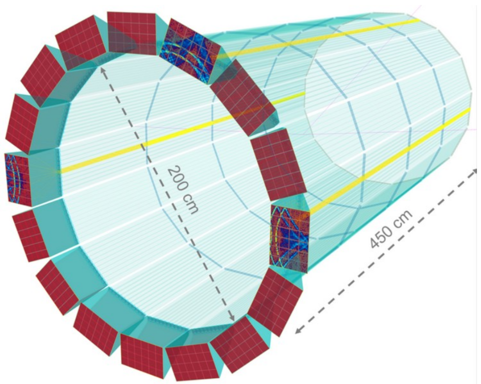
- Aerogel and gas radiators
- Cherenkov photons reflected by spherical mirror to dedicated sensor areas (in ~1 T B-field)
- Forward π/K/p separation from 3 GeV/c to 50 GeV/c
- Moderate radiation dose expected: $<10^{11}$ 1 MeV n_{eq}/cm^2
- ~3 mm pixel sensors: SiPMs or **MCP-PMTs (LAPPD?)**
- Readout not decided yet

Modular aerogel+lens RICH (mRICH)

- Consists of several identical compact aerogel RICH modules with Fresnel lens and sensor plane
- Backward π/K (e/π) separation from 3–10 (< 2) GeV/c
- ~3 mm pixel sensors: **MCP-PMTs (LAPPD?)** or SiPMs
- Readout not decided yet

Talk of G. Kalicy on Wednesday

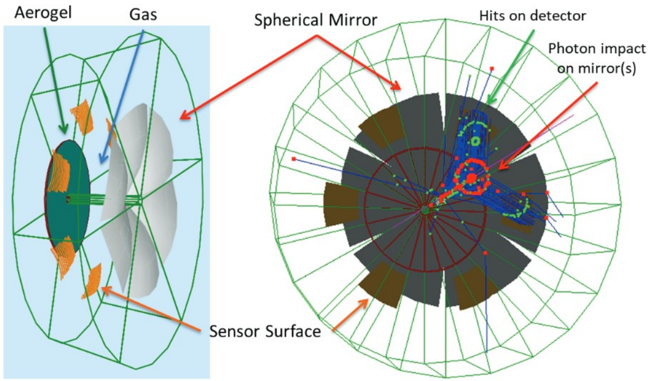
hpDIRC



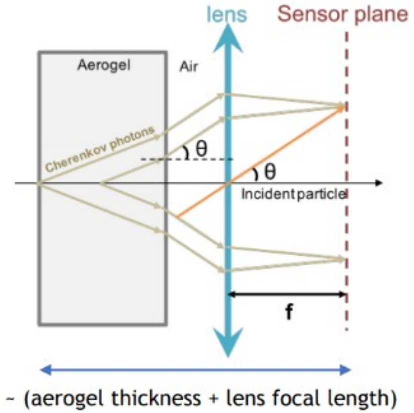
Talk of R. Preghenella on Thursday

dRICH

L. Barion et al., JINST 15 (2020) C02040

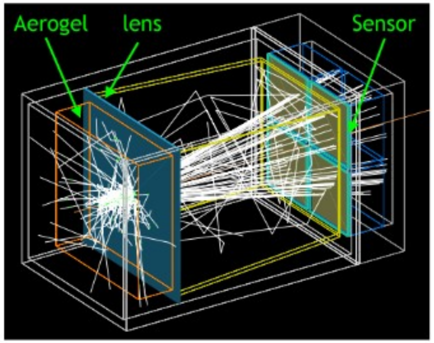


Talk of X. He on Thursday



mRICH

L. Barion et al., JINST 15 (2020) P10031



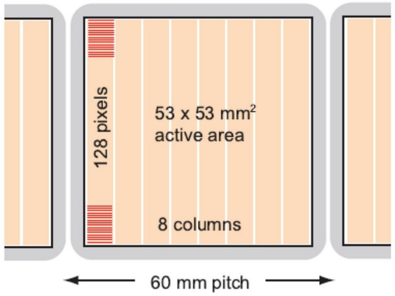
Geant4 Simulation

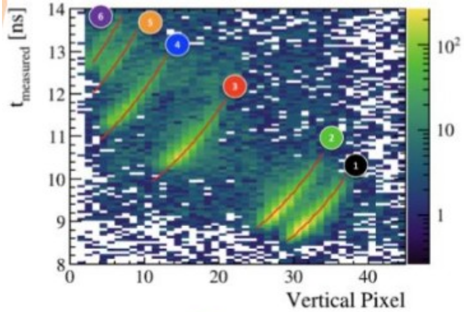
MCP-PMTs in Cherenkov TOF Counters

- TORCH for LHCb Upgrade-II **Talk of M. van Dijk on Wednesday**
  - **Time-of-flight Cherenkov detector** providing π/K PID for low momenta (2 – 10 GeV/c) over 10 m flight path
    - **σ(TOF) ~ 15 ps** (30 det. photons) → **70 ps / single photon**
    - First **prototype built and tested** → σ_{TOF}(s.ph.) ~ 70 – 120 ps
  - MCP-PMTs
    - **128x8 channels** (~0.4 x 6.4 mm² for 2” tube) from **Photek**
    - Expected photon rate: 1-10 MHz/cm²
    - Integrated anode charge per year: 1 – 10 C/cm²

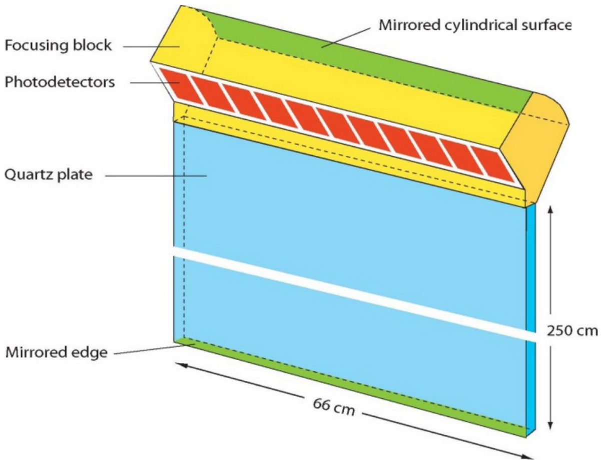
Schematic, readout and prototype results of TORCH detector

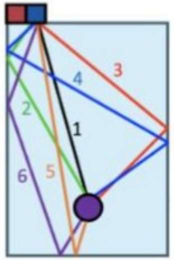
M.J. Charles et al., NIM A639 (2011) 173
N. Harnew, Pisa Meeting 2022





- Tau-Charm Factories **Talk of A. Barniakov on Wednesday**
  - Super Charm-Tau (SCT) Factory in Novosibirsk
    - Super Charm Tau Factory, Conceptual Design Report, 2018 https://ctd.inp.nsk.su/wiki/images/4/47/CDR2_ScTau_en_vol1.pdf
  - Super Tau Charm Factory (STCF) in China
    - https://doi.org/10.7693/WL20200803 (in Chinese)
  - **MCP-PMTs**, **HAPDs**, and SiPMs are considered as options for RICH and DIRC-like TOF PID detectors
    - Studies to define performance requirements are in progress





Particle Detection Efficiency (PDE = QE*CE*FF)

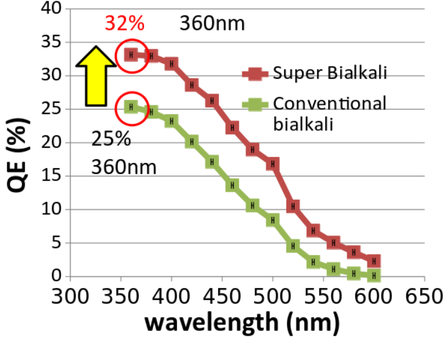
- Quantum efficiency (QE)
  - PMT: ~35% for SBA (R13743, H12700)
  - HPD: >50% for GaAsP (R9792U [MAGIC])
  - HAPD: ~32% @ 360 nm for SBA
  - MCP-PMT and LAPPD
    - **Varying from 20% to >30%** @ ~400 nm
- Collection efficiency (CE)
  - (Ma)PMTs and HPDs: up to >95%
  - MCP-PMTs: typically 60 – 70 %, but **90 – 95 % for most recent devices**
- Active area coverage (FF)
  - MaPMTs: up to 90%
  - 144ch HAPD: ~65%
  - MCP-PMTs
    - 1-inch: 69% (R10754-M16)
    - 2-inch: 70% (Photek) – 80% (Photonis)
    - **LAPPD: ~97% for most recent 8'' design**

Collection Efficiency of recent MCP-PMTs

Manufacturer	S/N	comments	CE
Hamamatsu	JS0022	ALD, film in front of MCP	(39 ± 4) %
Hamamatsu	YH0250	ALD, no film, most recent	(65 ± 7) %
Photek	**A1200116**	**ALD, most recent**	**(90 ± 9) %**
Photonis	9001393	2 ALDs, standard layout	(65 ± 7) %
Photonis	**9002192**	**ALD, most recent**	**(92 ± 9) %**

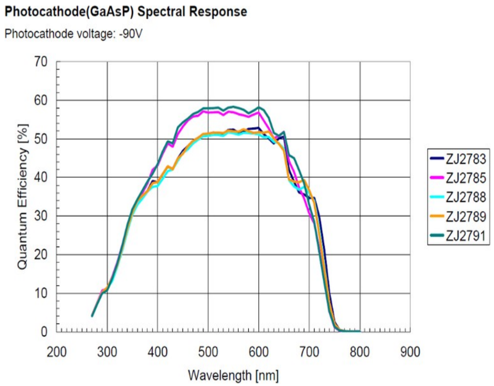
S. Shiizuka, Talk at VCI 2010

QE(λ) of 144ch HAPD

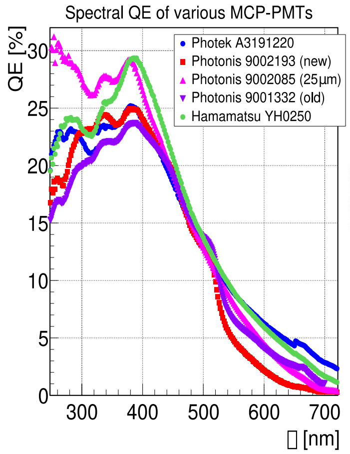


R. Mirzoyan, Talk at PD 2015

QE of R9792U-40 HPD

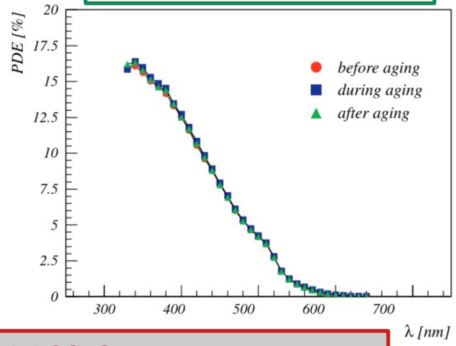


PANDA MCP-PMT Tests



Belle-II TDR 2010

PDE(λ) of 144ch HAPD



Recent years: significant PDE increase to ~30% for many PMTs

Gain inside Magnetic Field

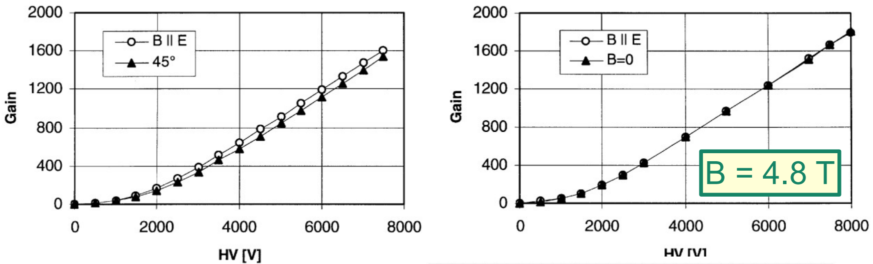
- H(A)PD
  - Basically no gain loss in axial B-fields (up to 5 T)
  - Image translation and distortions for transverse B-fields
- MaPMT
  - More tolerance in transverse than in axial B-fields
    - Axial/longitudinal: ~50% gain loss at <10 mT / better with shielding
    - Transverse: minor gain loss up to ~20 mT, but dependent on dynode structure
  - **B-field tolerance** depends on type of MaPMT (but **usually <<50 mT**)
- MCP-PMTs
  - ALD PMTs more sensitive to B-field than non-ALD
  - Very good Peak/Valley ratio up to >1 T
  - **Gain ratio ~3 between 0 and 1 T** (for 6 and 10 µm pores)
  - Gain ratio between 1 T and 2 T more dependent on pores
    - **2 – 5 for 6 µm pores** dependent on tilt angle
    - 10 – 20 for 10 µm pores dependent on tilt angle
  - First simulations of magnetic field effects available
    - L. Li et al., JINST 15 (2020) C03048
    - L. Li Jr. et al., IEEE Trans. Nucl. Sci., VOL. 69, NO. 4, APRIL 2022

Poster of E. Baldwin

10 µm MCPs: up to 1 T
6 µm MCPs: up to 2 T

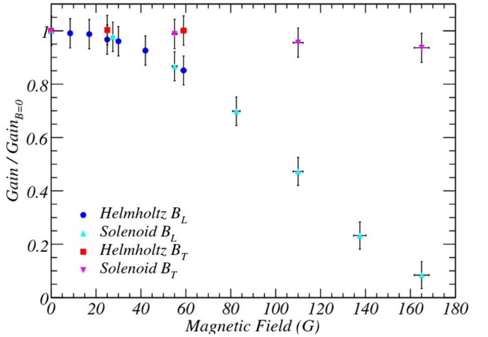
P. Cushman et al., NIM A418 (1998) 300

HPD test for CMS



M. Calvi et al., JINST 8 (2013) P02012

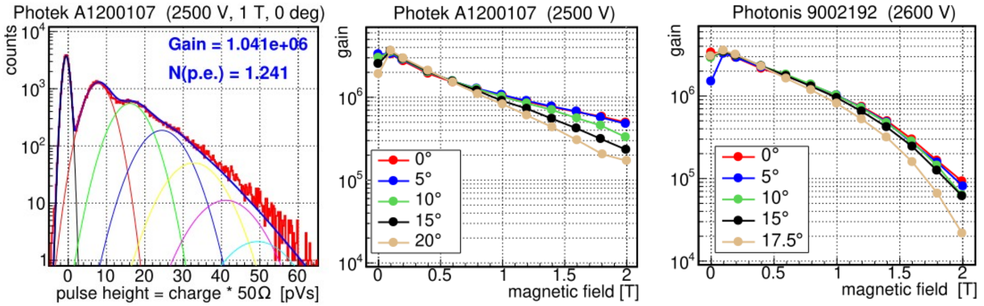
R7600 MaPMT



6 µm pore MCPs

Tests for PANDA

10 µm pore MCPs

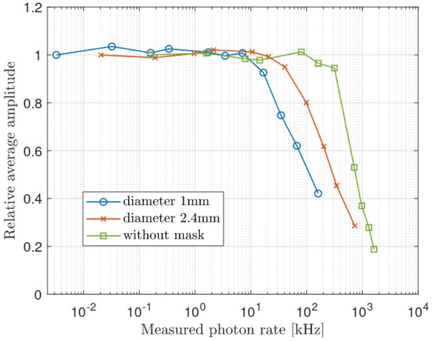


Rate Capability

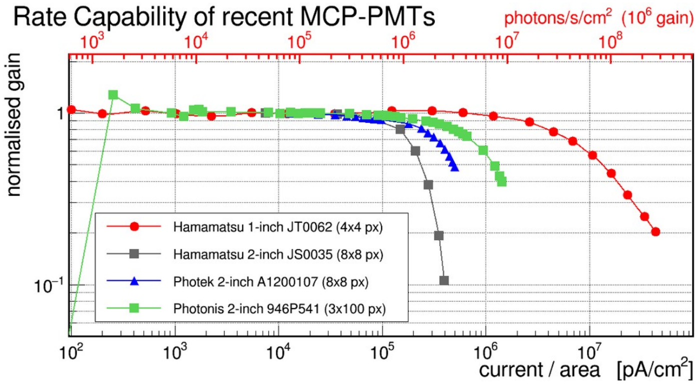
- MaPMT
  - MaPMT R13742: no gain loss to 10 MHz/mm^2
- MCP-PMTs
  - Gain decreases at high photon rates (τ = RC)
    - 8-inch LAPPD-64: ~100 kHz at 4.6 mm Ø laser spot
    - **2-inch** MCP-PMTs: **~1 MHz/cm^2 (with 10^6 gain)**
    - **1-inch** Hamamatsu R10754 PMTs: **≥10 MHz/cm^2**
  - LHCb: miniPlanacon XPM85112–S–R2D2 MCP–PMT
    - Rate capability depends on MCP resistance
    - **Up to 20 MHz** (for ~25 p.e.) **in low gain operation** mode
- Increasing rate capability in MCP-PMTs
  - Lower MCP resistance (ranging at tens of MΩ)
  - Lower capacitance
    - E.g., subdivision of MCP layers into smaller partial areas
    - Second MCP layer was divided in previous Hamamatsu tubes
  - Low gain operation (for single photon detection)
    - May be possible with amplifiers included directly in the anode (e.g., monolithic or CMOS designs)

R10754 MCP-PMT

M. Calvi et al., JINST 15 (2020) P10031

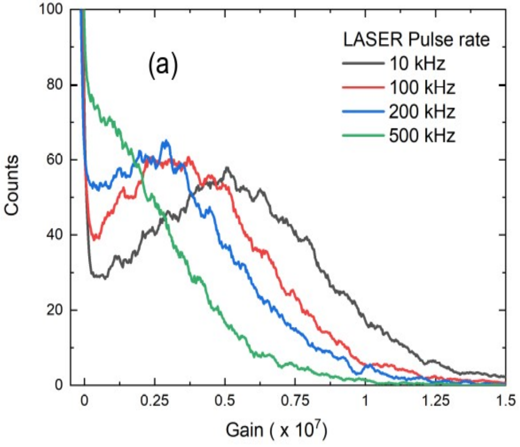


PANDA Tests

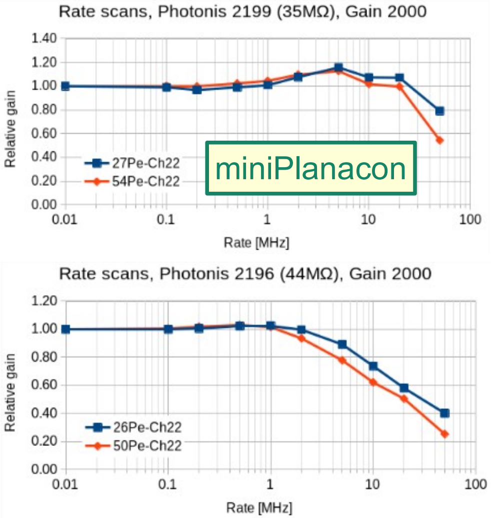


LAPPD-64

V.A. Chirayath et al., Talk at CPAD 2021



T. Komarek et al., NIM A (2022) 167330

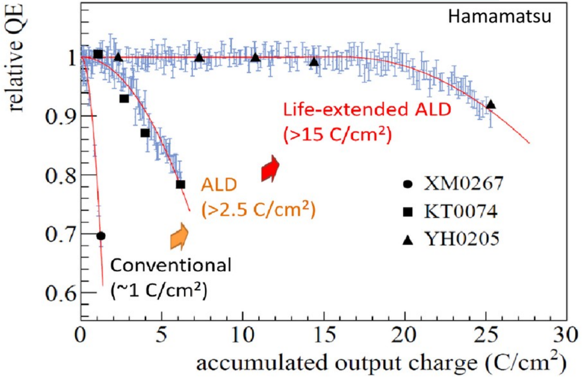


PC and MCP Aging and Lifetime

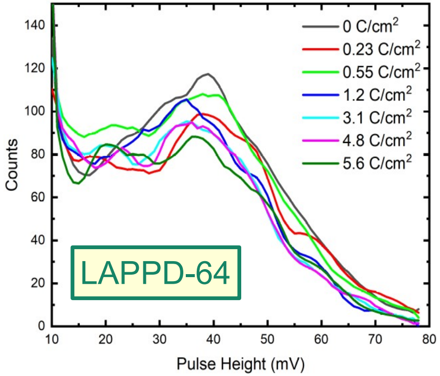
- Photo cathode aging due to ion feedback (IFB) is one of the main concerns in high intensity experiments
- Dynode PMTs and H(A)PDs
  - PMT and MaPMT: **main aging effect is a gain drop** over time
  - HPD (LHCb): “glow light” from IFB damages PC → lower QE
  - HAPD (ARICH): no QE loss seen; IFB rate decreases over time
- Aging of MCP-PMTs
  - **Aging of PC** → much shorter lifetime than dynode PMTs
    - **Main issue** for high intensity experiments is **QE degradation**
    - Lifetime was poor (<200 mC/cm² IAC) until ~12 years ago
  - **ALD** coating of MCP pores → **~100x PC lifetime increase**
    - Little QE degradation in LAPPD 8-inch up to 5.6 C/cm² [V. A. Chirayath, CPAD2021]
    - Hamamatsu 1-inch YH0205 (>20 C/cm²) [K. Inami, 2021]
    - **No QE degradation** for Photonis MCP-PMT (R2D2) to **>34 C/cm²**
  - **Aging of MCPs** → private comm. V. Vagnoni (LHCb)
    - MgO ALD MCPs: **gain as function of integrated charge** → **Gain drop of factor 5 – 6 at 300 C/cm²**
    - Baspik lead glass MCPs: factor ~2 gain drop at 120 C/cm²

K. Inami, 2021, Talk at ECFA Detector Symposium

Hamamatsu MCP-PMTs

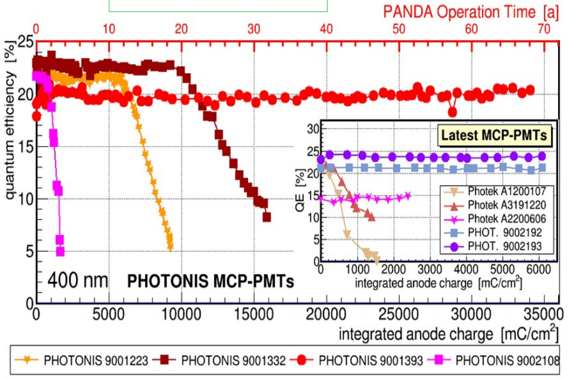


V.A. Chirayath et al., Talk at CPAD 2021



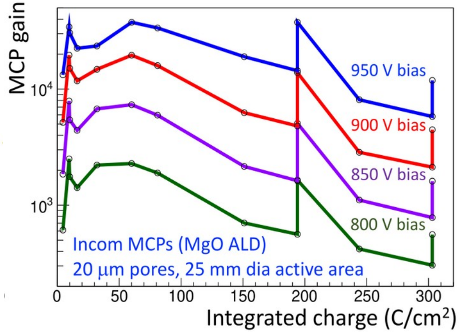
Photonis and Photek ALD MCP-PMTs

PANDA DIRC R&D



Gain of ALD-coated MCP

V. Vagnoni, 2022, paper in preparation

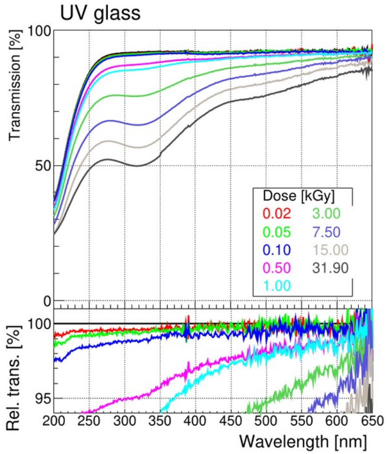


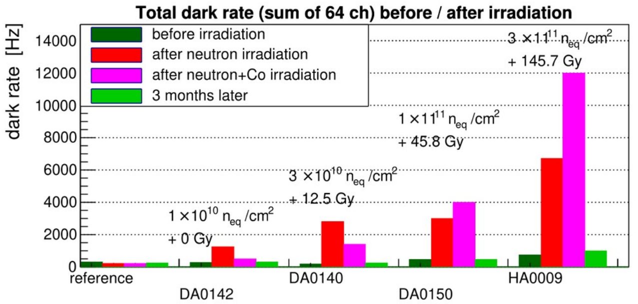
Radiation Tolerance

- MaPMT
  - Recently tested for CBM (H12700 and H8500)
    - Irradiation dose up to **$3x10^{11}$ n/cm²** and **150 Gy gammas**
    - Few kHz increase of DCR but recovers after few months
    - UV glass: 1-2% transmission loss @ 400 nm up to 1 kGy
    - **No negative effects on gain and pulse height spectrum**
    - **Neutron activation of Kovar metal alloy is a minor effect**
- H(A)PD
  - Radiation tolerance dominated by silicon detector
  - Intensively studied for 144ch HAPD for ARICH
    - Basically **no QE loss at $5x10^{11}$ n/cm²**
    - **Increase of APD leakage current** leads to significantly worse S/N ratio: ~17 before, ~3 after irradiation
    - S/N ratio partly regained by adjusted readout parameters
- MCP-PMT
  - Entrance window: should be similar to other PMTs
  - **MCPs**: currently no data existent
    → **irradiation tests are highly desirable**

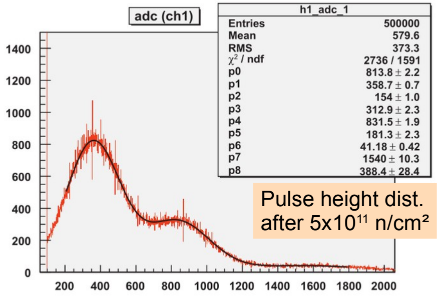
H8500/H12700 MaPMT

C. Pauly et al., NIM A1040 (2022) 167177





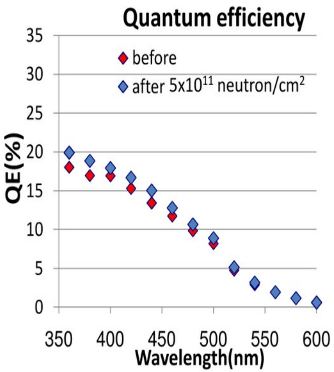
144ch HAPD

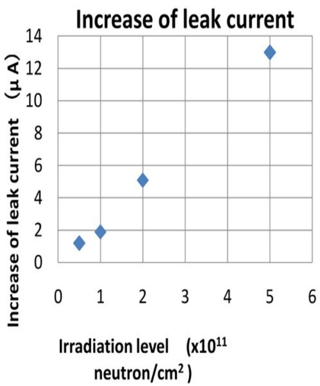


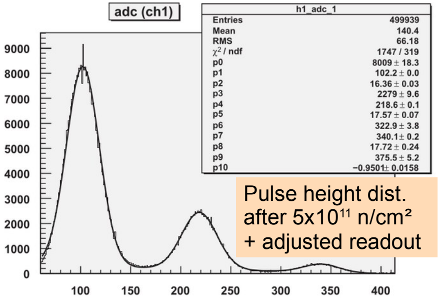
Pulse height dist. after $5x10^{11}$ n/cm²

144ch HAPD

S. Shiizuka, Talk at VCI 2010







Pulse height dist. after $5x10^{11}$ n/cm² + adjusted readout

I. Adachi, NIM A639 (2011) 103

Summary and Outlook

- Summary
  - Vacuum-based PMTs are still very important photon detection devices even 90 years after their “invention”
    - Recent developments led to significant improvements in QE, CE and FF
    - Latest PMTs produced with QE > 30% and CE ≈ 95% leading to PDE ≈ 30%
  - In neutrino and astroparticle physics experiments single-anode dynode PMTs are still widely used
  - The usage of MaPMTs and H(A)PDs seems to decline in new experiments
  - **Since ~2010 there is a clear trend towards multi-anode MCP-PMTs for HEP Cherenkov imaging devices**
    - MCP-PMTs with <10 μm pores can be operated up to ~2 T magnetic fields
    - ALD-coating of MCP pores increased lifetime to ~35 C/cm² integrated anode charge
    - Rate capability is not yet enough for very high rate experiments
    - No irradiation tests for MCP-PMTs available
- Outlook with respect to MCP-PMTs
  - Currently there are several types of 1- and 2-inch high-quality MCP-PMTs commercially available (Hamamatsu, Photek, Photonis), also in highly segmented anode designs
  - LAPPDs (up to 8-inch) are promising candidates for low-cost photon sensors in HEP (and other) experiments
  - **Despite the success of SiPMs, vacuum PMTs will probably remain important devices** for many neutrino and astroparticle experiments and for detecting single photons (RICH, DIRC, etc.) in high radiation environments