STATUS AND PERSPECTIVES OF VACUUM-BASED PHOTON DETECTORS

PAUL HINK
plhink@hinkconsulting.com

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Outline

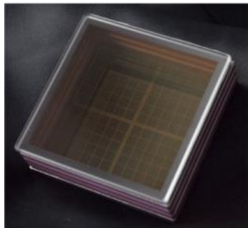
- Vacuum Photon Detectors Overview
- Photocathodes
- Discrete Electron Multipliers
- Continuous Electron Multipliers
- Hybrid Photodetectors
- Summary

Types of Vacuum Photon Detectors

Vacuum Photon Detectors come in many varieties

- ☐ Image intensifier
- ☐ Photo Multiplier Tubes
- ☐ MCP-PMT
- ☐ Streak Tube
- ☐ Image Tube
- ☐ Hybrid Tubes
- ☐ …..



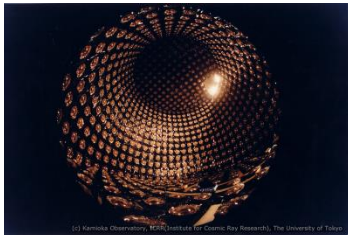




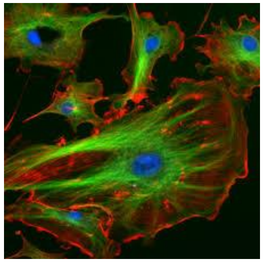

Applications

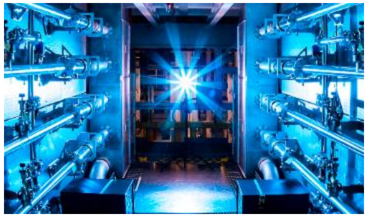
Diverse Applications

- ☐ Physics
- ☐ Astrophysics
- ☐ Astronomy
- ☐ Fusion
- ☐ Medical Imaging
- ☐ Life Science
- ☐ Analytical Instrumentation
- ☐ Defense
- ☐ Process Control
- ☐ Oil exploration

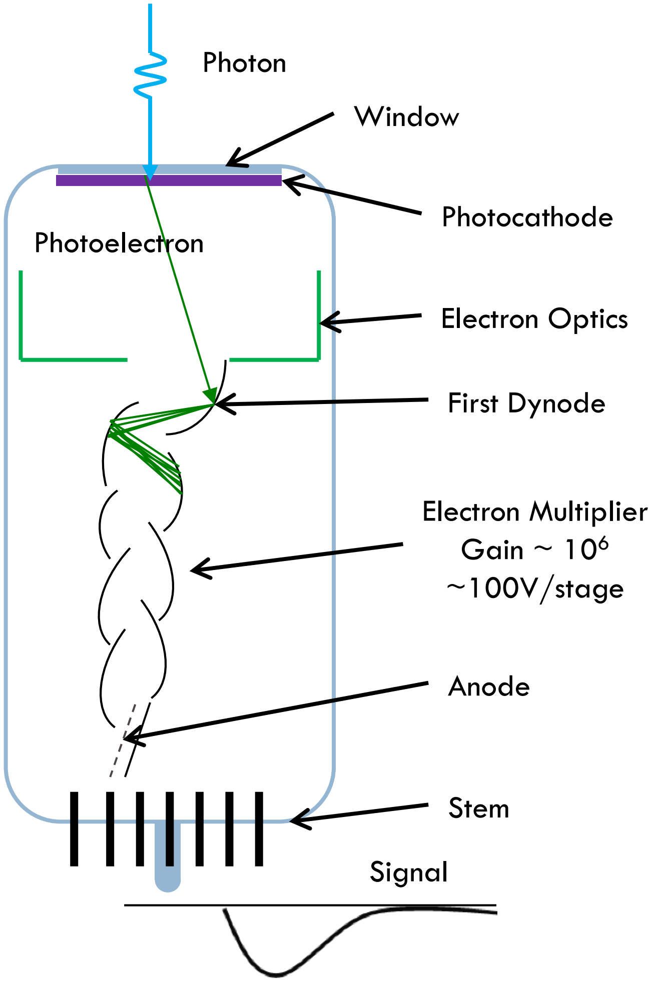


(c) Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo



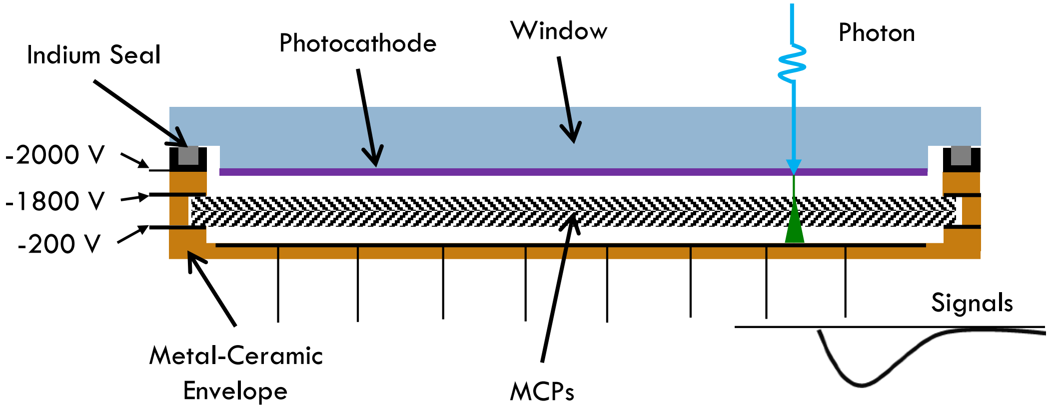


Anatomy of a Photomultiplier Tube



- ☐ Traditionally glass vacuum envelope, alternatively metal or metal/ceramic
- ☐ Typically the photocathode is processed in-situ
- ☐ Vacuum sealed using a glass or copper tubulation after processing
- ☐ Wide variety of electron optics and discrete dynode structures, often optimized for specific applications
- ☐ Relatively low cost of production

Anatomy of an MCP-PMT

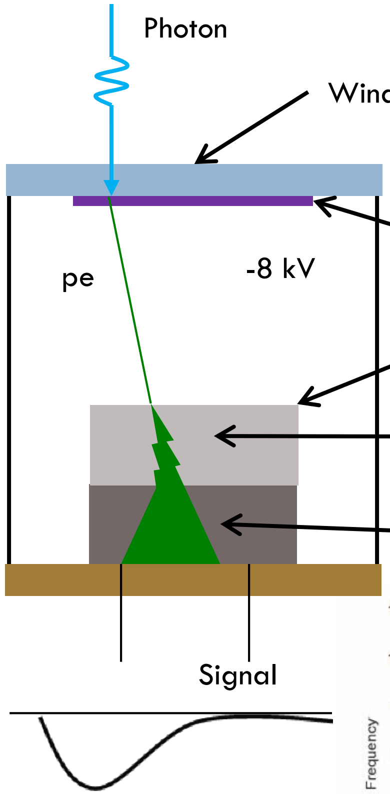


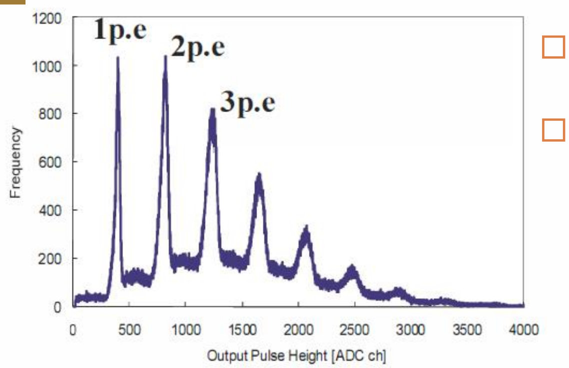
- ☐ Based on Image Intensifier design and construction – proximity focused, compact
- ☐ Gain via Microchannel Plate (MCP)
- ☐ Photocathode typically produced via transfer technique – remote from the body

Compared to PMTs

- 👍 Improved temporal resolution
- 👍 Improved spatial resolution
- 👍 Magnetic field performance
- 👎 Higher cost of production
- 👎 Reduced Dynamic Range
- 👎 Reduced lifetime
- 👎 Reduced Collection Efficiency

Anatomy of a Hybrid Photodetector





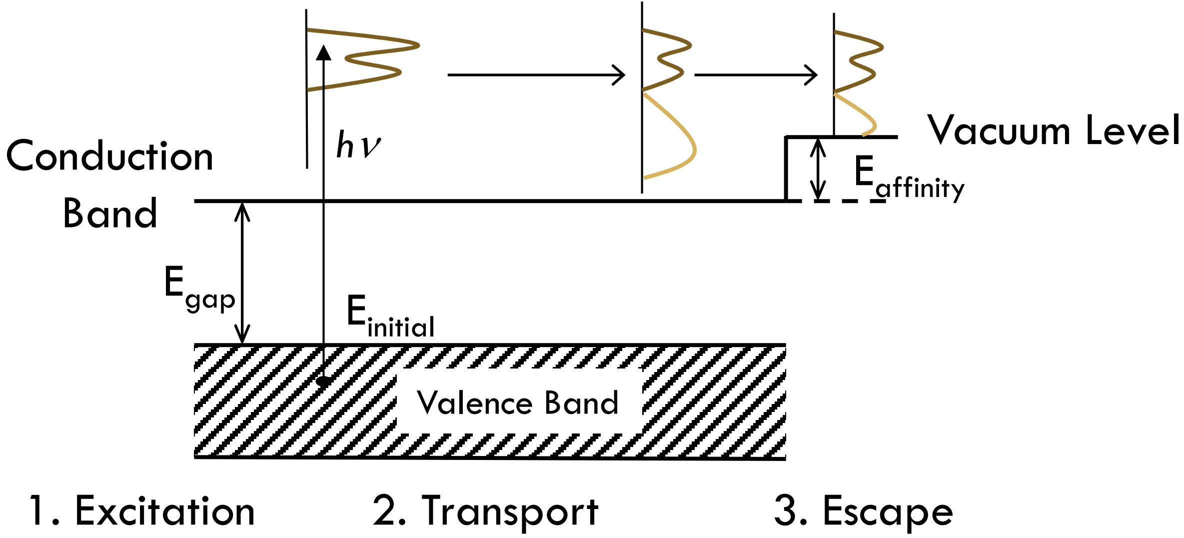
Belle 144-channel HPD

Iwata et al, NSS/MIC 2012, N17-6

- ☐ Hybrid PhotoDetectors (HPD) can use either a Photodiode or an Avalanche Photodiode for direct detection of the photoelectron
- ☐ Excellent Pulse Height Distribution, resolving multiple pe peaks
- ☐ Gain is typically lower than PMTs, $10^4 – 10^5$
- ☐ Good immunity to magnetic fields
- ☐ Timing good, but long signal recovery can limit count rate, depending on diode design

PHOTOCATHODES

Photocathode Operation



Spicer 3-step model

1. Photoexcitation
2. Transport to surface
3. Escape to vacuum

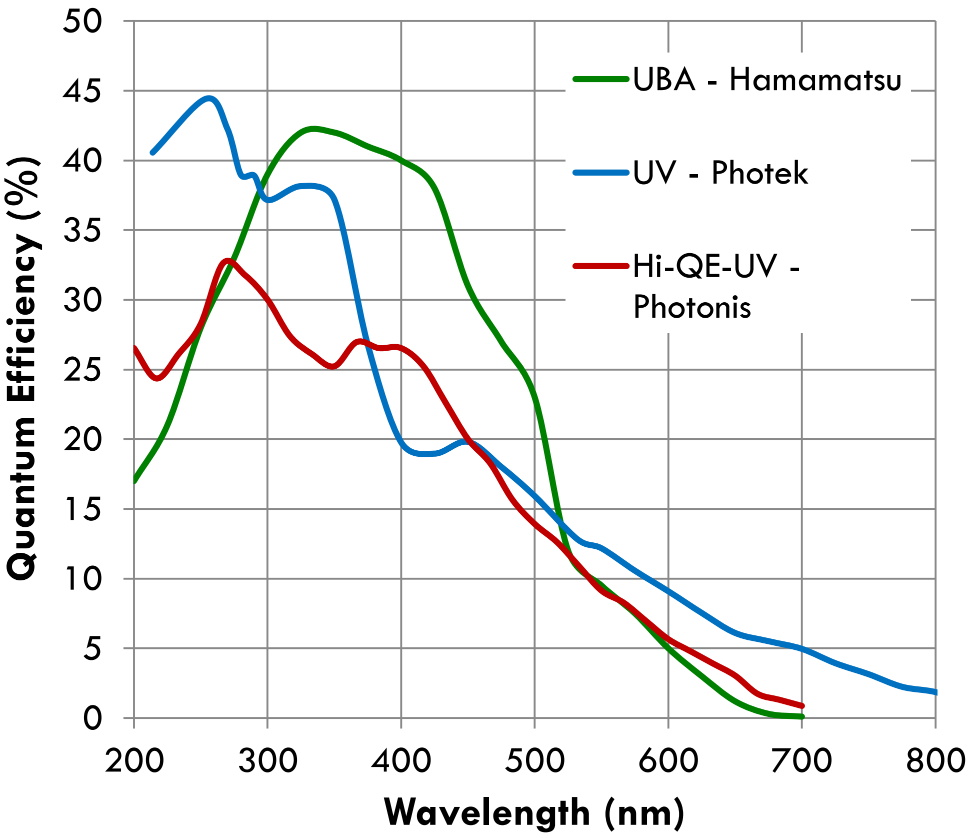
$$QE = (1-R)\frac{\alpha_{PE}}{\alpha}\frac{1}{\left(1+\frac{l_a}{L}\right)}P_E$$

R = reflectivity (*minimize*)
α_{PE} = fraction of photo-excited electrons above vacuum level (*maximize*)
α= absorption coefficient (*maximize*)
l_a = optical absorption length (*minimize*)
L = electron escape length (*maximize*)
P_E = Probability of escape at vacuum surface (*maximize*)

Photocathodes Today

UV/Blue Alkali-Antimonide Transmission Photocathodes

Current Commercial State-of-the-Art

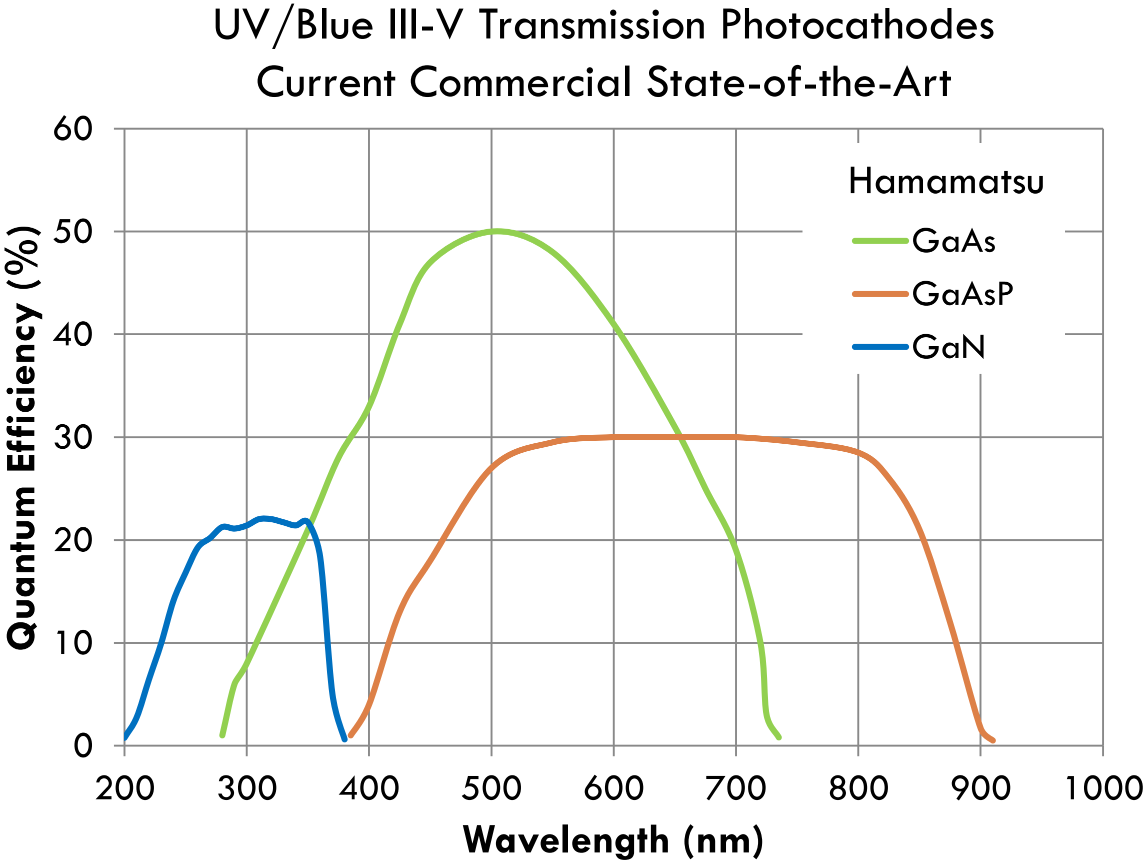


Alkali Antimonides:

- Cs_3Sb
- K_2CsSb
- Na_2KSb
- Rb_2CsSb
- $Na_2KSb{:}Cs$ ...

Medical Imaging (PET and SPECT) initially drove many advances in UV/Blue Photocathodes. Now HEP and Scintillation Detectors are driving further advances

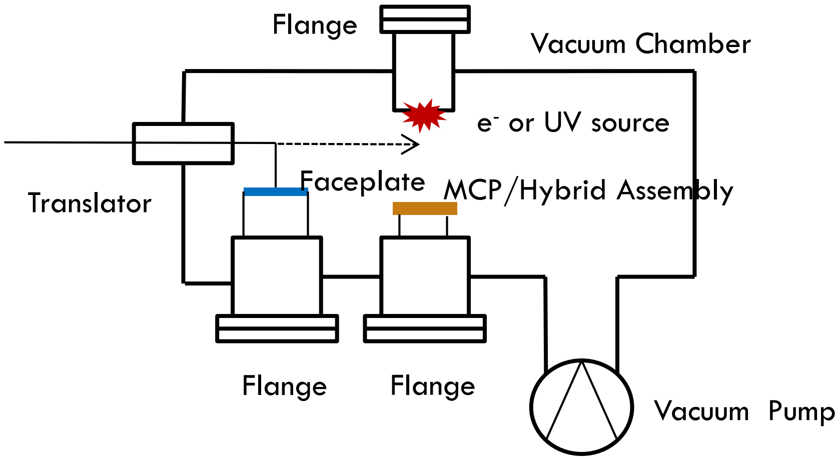
Photocathodes Today



III-V Semiconductor Photocathodes originally developed for night vision – adapted to life science and industry

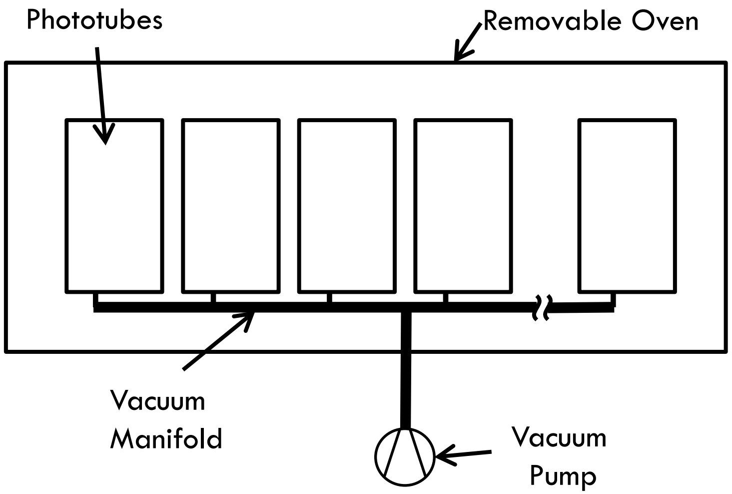
- GaAs – VIS/NIR
- InP/InGaAs – NIR/SWIR
- GaAsP – VIS
- GaN – UV

Photocathodes - Processing



Transfer Process

- Photocathode processed remote from the body/MCP
- Photocathode "**transferred**" in the vacuum chamber to body and sealed
- Expensive process and equipment
- Typical method for **MCP-PMT and HPD**



In-Situ Process

- Photocathode processed inside the tube envelope
- Vacuum manifold enables multiple tubes to be processed in parallel
- **Low cost** process and equipment
- Typical method for **PMTs**

Photocathodes – Future Prospects

Continued improvements with alkali antimonides

Molecular Beam Epitaxy/Deposition

- **Increased mean free** path in photocathode – higher QE
- S20 demonstrated by Photonis in 2008 (Massegu et. al., Electronics Letters 44(4):315 - 316 · Feb 2008)

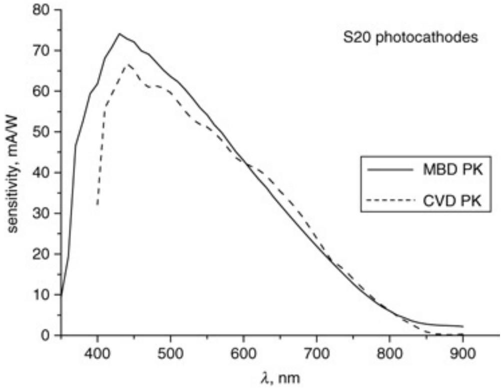


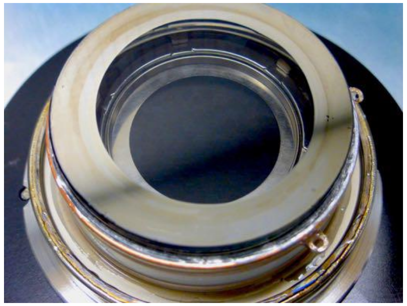
Photo-injector R&D

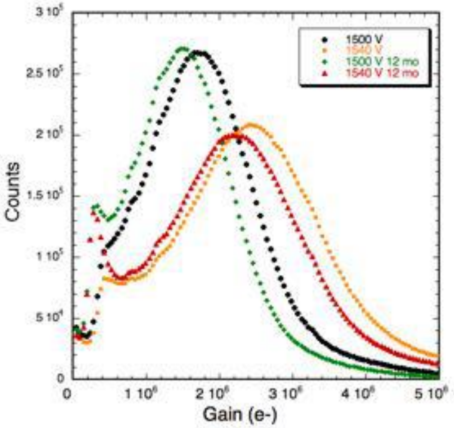
- Significant R&D on Photocathodes for next generation **Photo-injectors**
- **In-situ characterization** of growth process
- Desire very low emittance, high current, high QE
- **Sputter growth** is being developed by Radiation Monitoring Devices, BNL, ANL, LBNL, Berlin, Stony Brook, U Chicago
- In addition to Alkali-Antimonides work is being performed on III-V and metals with **plasmonic enhancement**

Photocathodes – Future Prospects

Growth on MCPs

- ☐ Alternative MCP materials open up potential for direct growth of photocathode on MCP substrate
- ☐ Reflection mode GaN grown on ALD MCPs has already been demonstrated, albeit with low QE.



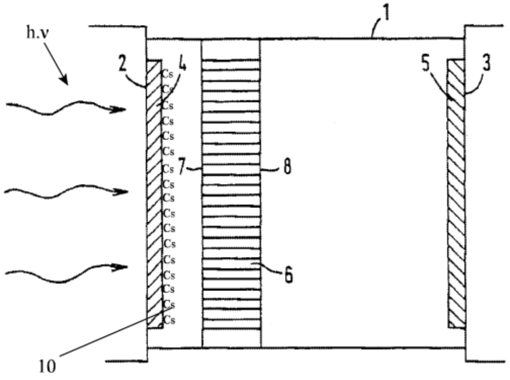


Siegmund, O., et al., Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, held in Wailea, Maui, Hawaii, September 15-18, 2014, Ed.: S. Ryan, The Maui Economic Development Board, id. 94. Vol. 1. 2015.

Protective films

Two patent applications disclosing a Carbon layer between the photocathode and NEA surface – Photonis and Los Alamos

- ☐ Increases QE
- ☐ Improved robustness



US 8816582 B2 - Photonis

DISCRETE DYNODES

Discrete Dynodes

"Traditional"Photomultiplier Tube

- ☐ The metal dynodes are processed to have high secondary electron yield (SEY)
  - Alkali antimonide, BeO, GaP, Diamond
  - First dynode often processed to have higher SEY to provide better detection efficiency and SNR
- ☐ Many designs for different applications
- ☐ Mostly single anode devices
- ☐ Low cost per area

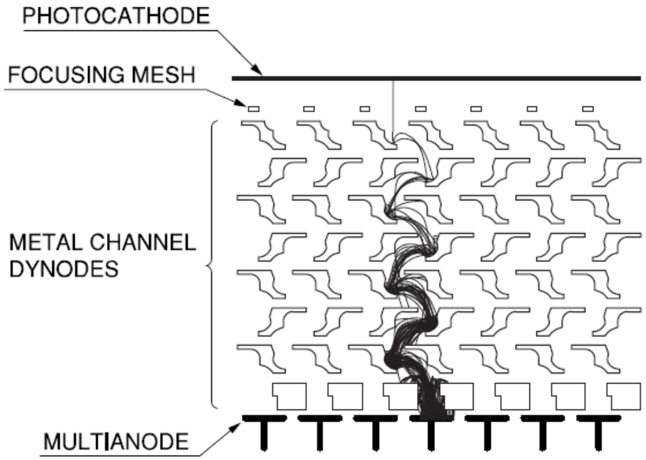
ET Enterprises Ltd.

Active Area (diameter)	**10 – 500 mm**
Transit Time Spread	0.35 – 10 ns
Pulse FWHM	1 – 20 ns
Max avg anode current	**1 – 120 mA**
Typical Gain	10^6 - 10^7
Pulse Height Distribution	50 – 150%
Spatial Resolution	N/A
Maximum Magnetic Field	0.1 mT

Discrete Dynodes

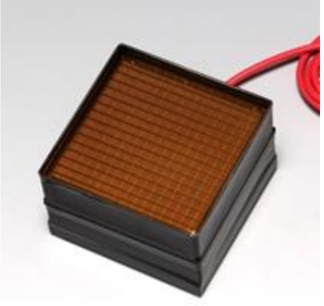
Metal Channel

- ☐ Compact form factors
- ☐ Multi-anode options with few mm scale square/linear anodes
- ☐ Good timing characteristics
- ☐ Square format enables close packing
- ☐ Has been used by many instruments with **multiple papers at RICH2016**
- ☐ The Go-TO multi-anode PMT given the modest cost and good performance



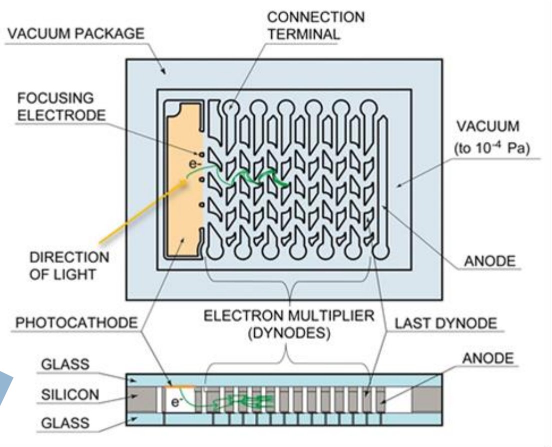
Hamamastsu Metal Channel PMT

Active Area	Up to 50mm sq
Transit Time Spread	*0.4 ns*
Pulse FWHM	*2 ns*
Max avg anode current	*0.1 mA*
Typical Gain	10^6
Pulse Height Distribution	150% FWHM
Spatial Resolution	~ **2 mm**
Max Magnetic Field	*5 mT*



Discrete Dynodes – Future Prospects

- Continued **incremental improvements** in collection efficiency, linearity, timing etc.
- Look for more use of **MEMS** (see µPMT adjacent) and **nano-technology** in the fabrication of parts for dynodes
- **Atomic Layer Deposition** for improved SEY materials on dynodes and electron optics



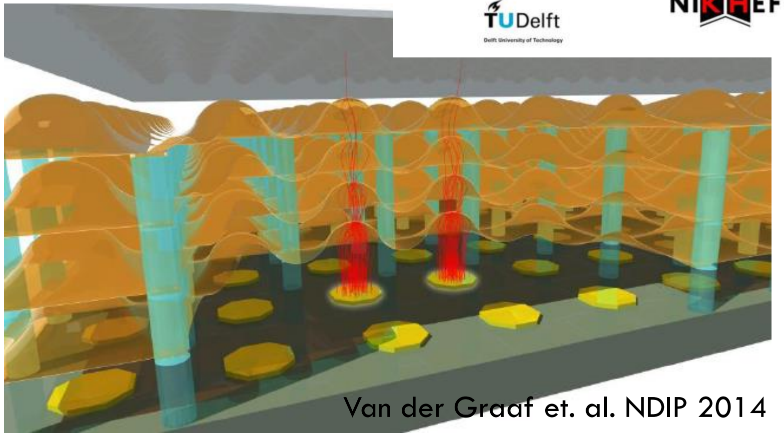
http://www.hamamatsu.com/us/en/community/optical_sensors/articles/intro_to_uPMT/index.html

Active Area	1x3 mm
Transit Time Spread	1.3 ns
Pulse FWHM	2.5 ns
Max avg anode current	0.005 mA
Typical Gain	10^6
Pulse Height Distribution	150% FWHM
Spatial Resolution	n.a
Max Magnetic Field	5 mT

Discrete Dynodes – Future Prospects

TIPSY

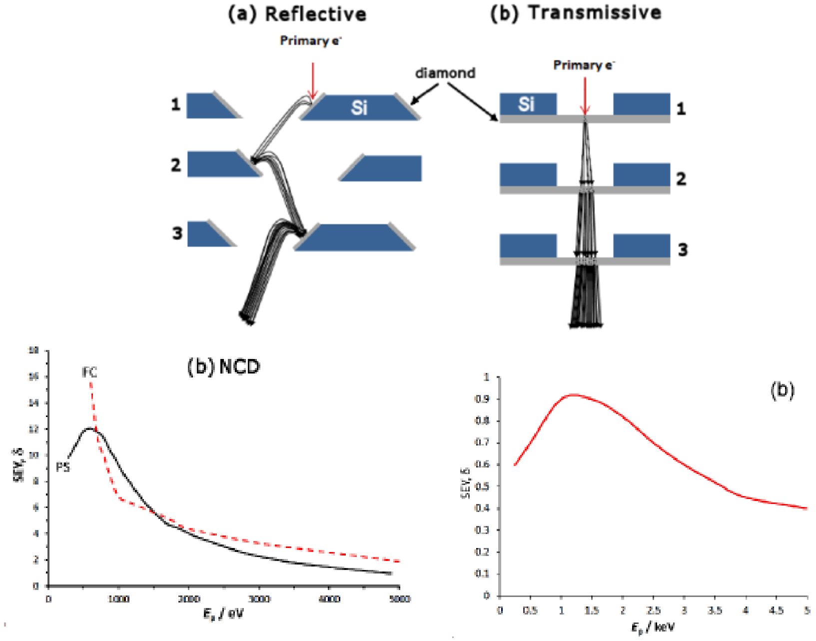
- Transmission mode dynode
- ~10nm thick diamond/Si_3N_4/…
- 20µm separation
- Roughly 5ps / dynode transit time
- Potential for few ps single electron timing
- CMOS readout



Van der Graaf et. al. NDIP 2014

FAST PMT Development

- Lapington (Leicester) and May (Bristol) developing PMTs with both reflective and transmissive CVD diamond films



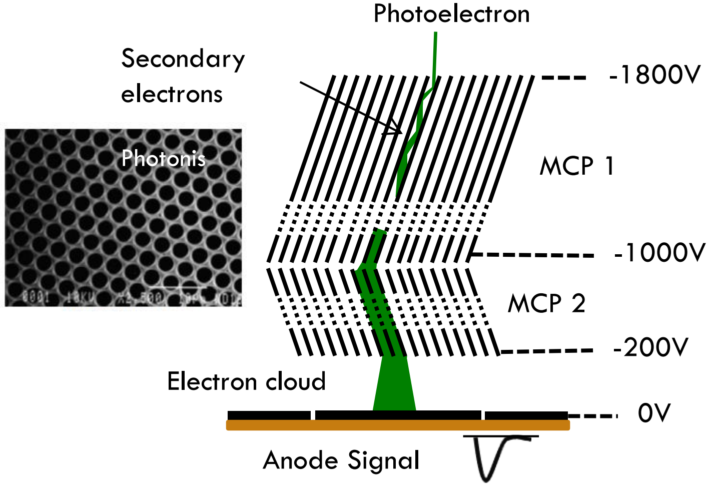
Vaz et. al. JINST 2015 10 P03004

CONTINUOUS ELECTRON MULTIPLIERS

Continuous Electron Multiplier

Conventional Microchannel Plate

- Lead-glass preform is successively drawn into fibers resulting in a fused block which is sliced
- The core glass is **chemically etched** leaving a glass capillary array (GCA)
- The CGA is **hydrogen fired** to produce a PbO resistive surface layer
- Further processing provides **alkali** rich silica emissive layer with **SEY of 2 – 3**
- Diameter/pitch of pores ranges from 2/3 – 25/32µm, typically **10/12µm** for MCP-PMTs
- Length to Diameter ratio (L:D) of pores ranges from 40 – 120, typically **60:1 for 10 µm pores**
- Transit time decreases with decreasing pore size – **smaller pores have better timing**
- Typical resistance is 20MΩ @ 1000V, or a strip current of 50 µA. Maximum **signal current is limited** to ~10% of strip current - **5 µA**
- MCP glass has a negative temperature coefficient of resistance – **self-heating limits practical strip current**
- **Lifetime limitations** due to ion feedback and poisoning of photocathode

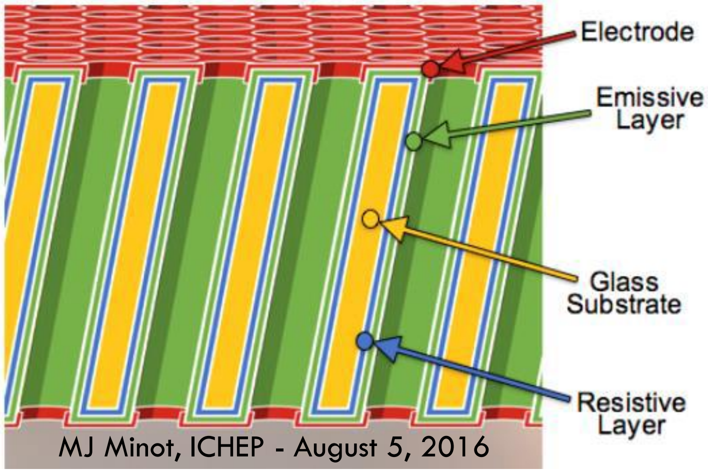


Active Area	Up to 150mm
Transit Time Spread	**0.03 ns**
Pulse FWHM	**0.15 – 1.5 ns**
Max avg anode current	~0.005 mA
Typical Gain	10^6 - 10^7
Pulse Height Distribution	<100% FWHM
Spatial Resolution	**10µm**
Max Magnetic Field	**1.5 T**

Continuous Electron Multiplier

Atomic Layer Deposition (ALD) functionalized MCP

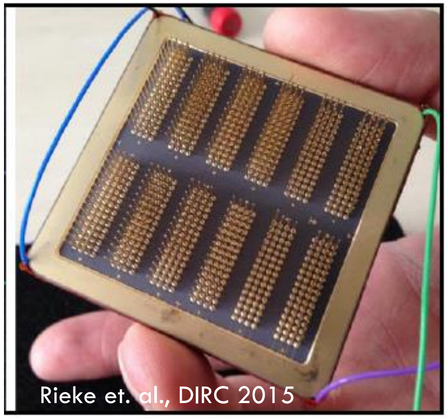
- Arradiance Inc. developed an Atomic Layer Deposition (ALD) technique for applying films of resistive and emissive layers on GCA – licensed to Photek, Hamamatsu and Incom
- Argonne National Laboratory has further developed the ALD process
- Advantages, including future prospects:
  - No hydrogen fire is required on lead-glass GCA, enabling continued use of standard MCPs
  - Use of **non-lead glass** substrates including Borosilicate, silicon, ceramic, plastic, …
  - **Larger substrates** can be used
  - **Dramatically increased lifetime**
  - Controlled resistivity
    - Better reproducibility
    - Variable resistivity along the pore
    - Reduce TCR to **enable higher count rates**
  - Improved SEY enabling
    - lower voltage operation
      - reduced noise, increased count rate
    - OR smaller L:D (improved timing)
    - **improved pulse height distribution**



MJ Minot, ICHEP - August 5, 2016

Continuous Electron Multiplier

Photonis, 45x45mm,
3x100 Anodes, 0.5mm pitch



Hamamatsu 53 x 53mm,
6x128 Anodes, 0.4mm pitch

Photek Torch Phase 2
prototype

Hamamtsu R10754-07-M16
23mm square16 anodes

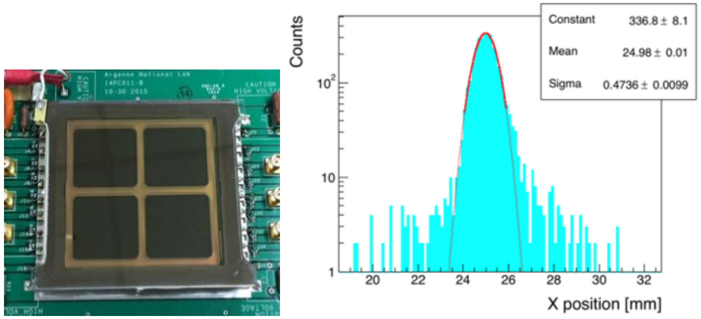
Photonis XP85012, 53x53mm, 64 anodes

- MCP-PMTs are now a standard photon detector for large scale photon detection for Physics experiments
- Multiple papers at RICH2016, **including the next!**
- New formats being developed including higher density anodes for improved spatial resolution

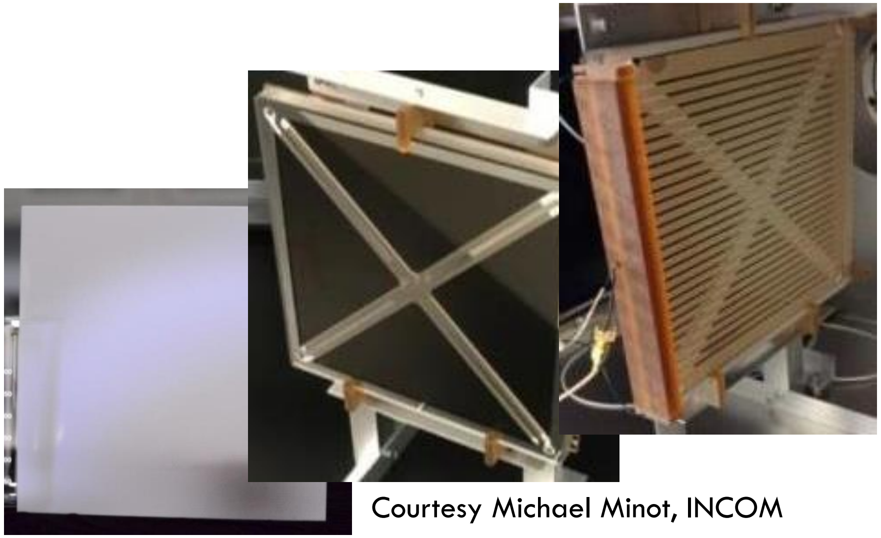
CEM - Future Prospects

LAPPD™

- Large area – **20cm x 20cm** – transfer from Argonne Natl Lab to Incom
- **All glass body** to reduce cost/area
- **1-D Strip readout** to preserve timing and provide moderate spatial resolution (working on capacitive coupling)
- New **Alkali-free MCP** glass by Incom to reduce noise and improve stability
- Incom **pilot production** of 20 cm x 20 cm in-process
- Argonne **6 cm x 6 cm** prototypes have been delivered to users
- Argonne spatial resolution based on timing along the 6cm strip is **~1mm** (see paper **today**)



Courtesy Robert Wagner, Argonne

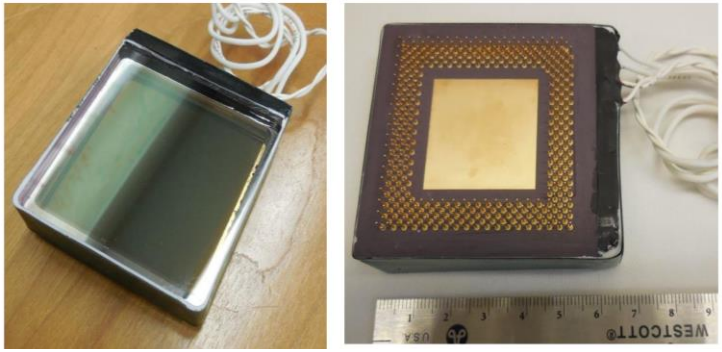


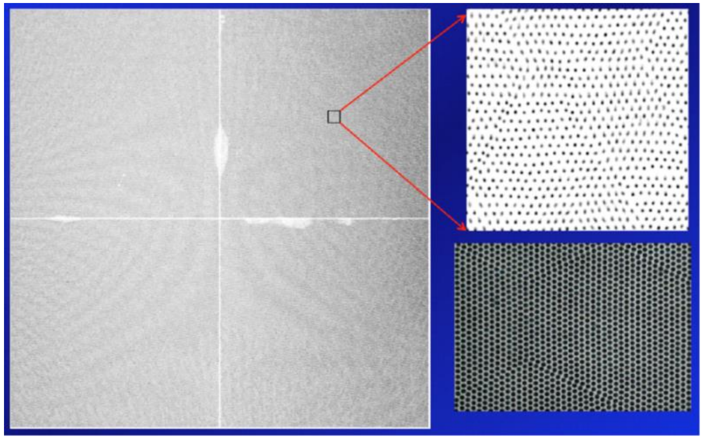
Courtesy Michael Minot, INCOM

CEM – Future Prospects

MCP-TIMEPIX

- Quad Timepix mounted in Photonis Planacon body
- Using centroiding can resolve individual pores in the MCP
- Operates at lower gain than typical MCP-PMT, as low as 10^4.
  - Higher count rates > 100MHz
  - Longer lifetime at lower count rates
- Proof-of-concept for future MCP-CMOS detectors, enabling customized CMOS readout for specific applications.



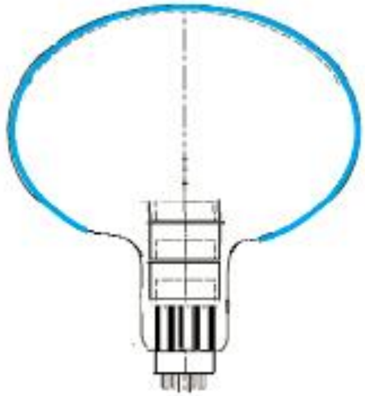


J Vallerga *et al* 2014 *JINST* **9** C05055

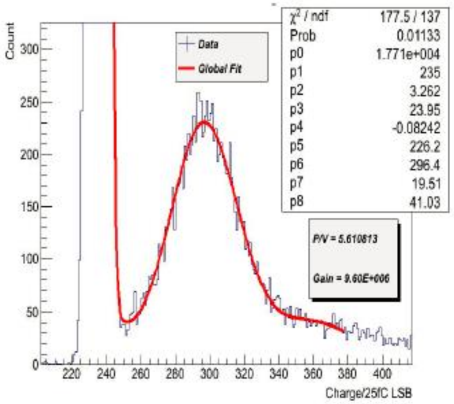
CEM – Future Prospects

4π MCP-PMT

- Prototypes of an MCP multiplier in a 20” PMT for JUNO
- Extend photocathode closer to the PMT base to improve effective QE
- MCP multiplier provides excellent Peak-to-Valley and good pulse risetime and width as compared to R12860 Box+Lin dynode 20” PMT
- TTS is not as expected, 12ns FWHM, probably driven by electron focusing



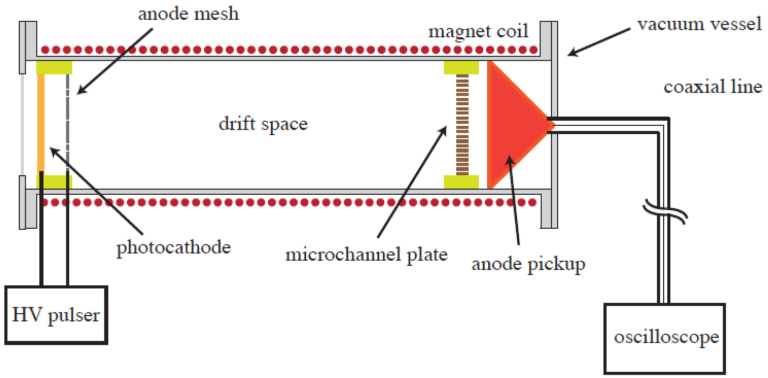
Qian & Liu, ICHEP 2016



Pulse-Dilation PMT

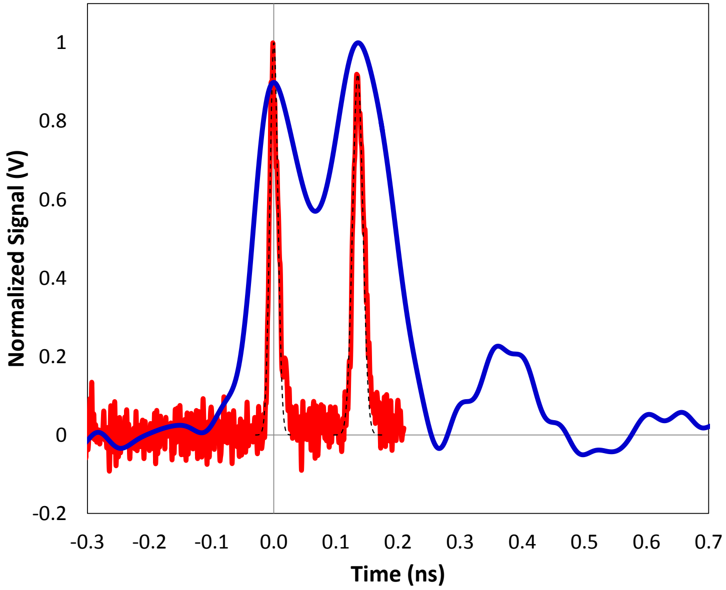
Pulse-Dilation PMT

- Photocathode voltage is ramped to spread out the velocity of generated photoelectrons
- PEs travel through a long drift section where the velocity dispersion encodes the arrival time at the photocathode



Journal of Physics: Conference Series **717** (2016) 012093

Pulse FWHM ~20ps
Capable of resolving 10ps



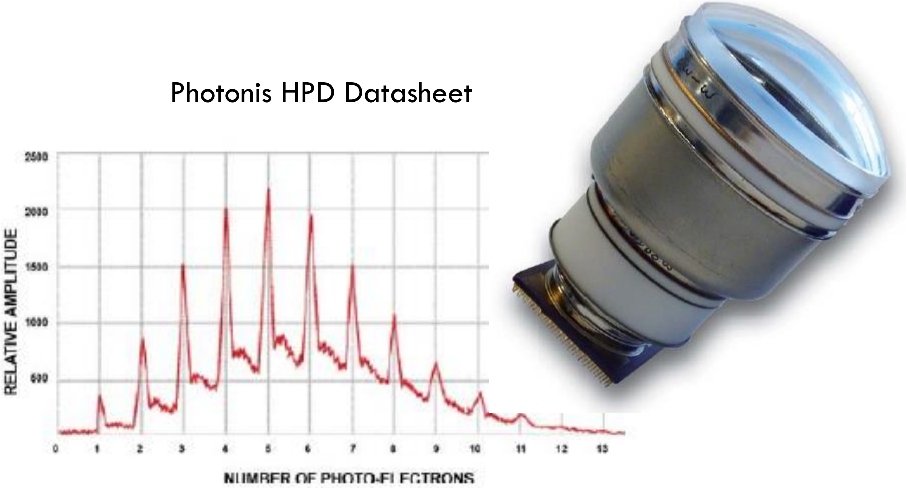
Pulse Dilation -PMT developed by **Kentech/Photek** (w/ Sydor as US Distributor); funded by **LANL** and tested at **AWE**

HYBRID PHOTODETECTORS

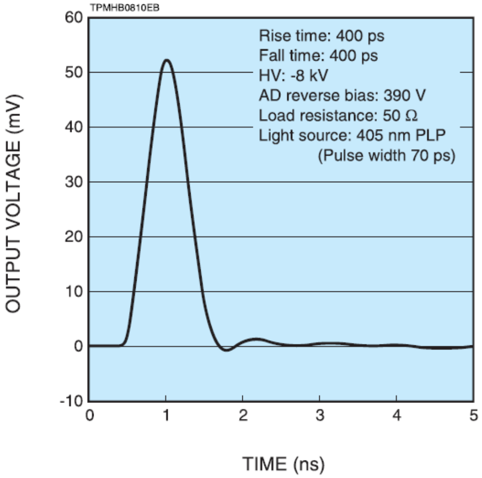
Hybrid Photodetector

- Electron Bombardment (EB) of device to achieve gain via ionization loss
- LHCb RICH detectors used a non-avalanche diode structure
- With Avalanche Diode can get further gain and improve timing performance
- Can further amplify using avalanche gain
- The EB gain enables superior detection efficiency of the photoelectrons with resolution of many photoelectrons

Photonis HPD Datasheet



Hamamatsu R10467U Datasheet

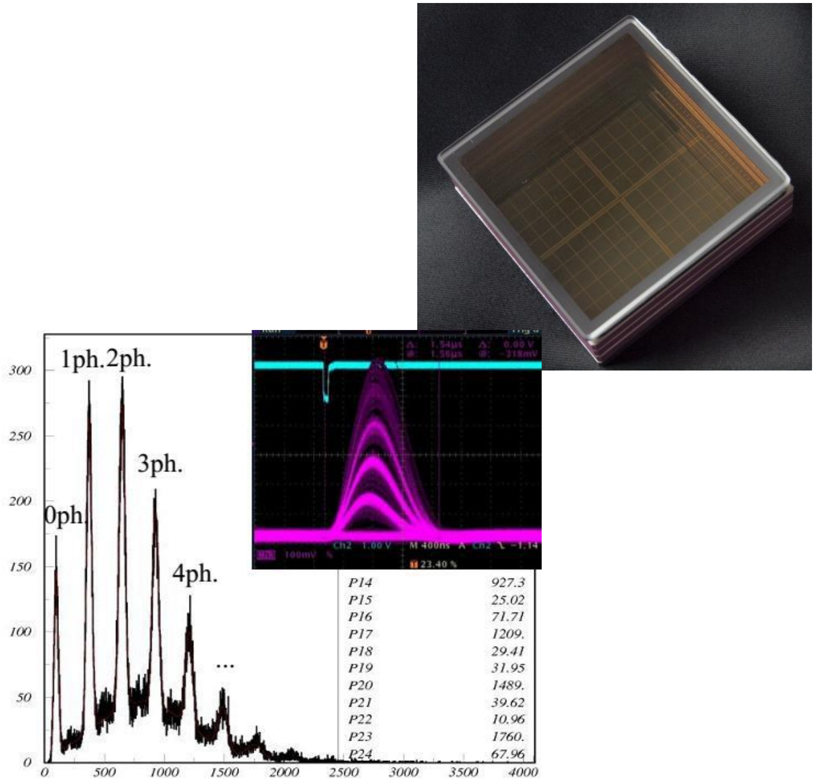


Hybrid Photodetector

Multi-anode HPD for Belle-II ARICH

- 144 pixel HPD
- 63mm x 63mm active area with 4.8mm square pixels
- EB plus Avalanche diode provides gain of ~7x10^4
- Operates in 1.5T magnetic field
- Excellent PHD, with Signal to Noise of 10
- Radiation Tolerant
- Multiple Papers at RICH2016

Nishida et al NDIP 2014

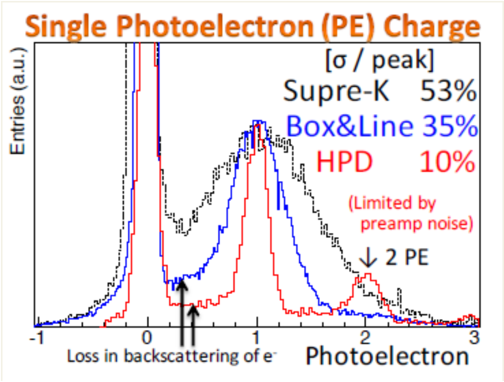


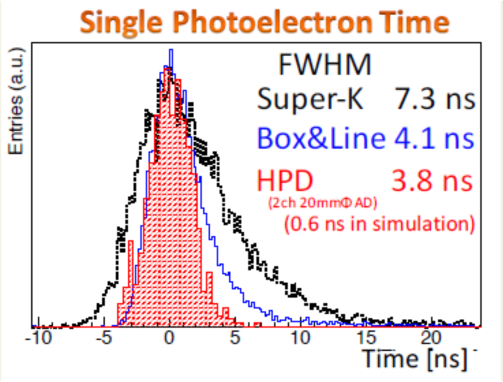
HPD – Future Prospects

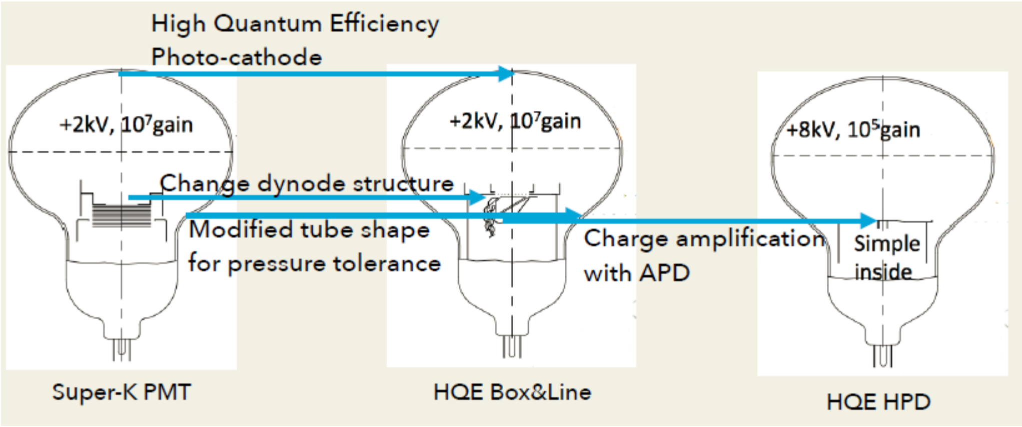
Hyper-K Photodetector development

- Developed 20” PMT and HPD
- Significant improvement over Super-K PMT
- HPD requires preamplifier which limits the achievable noise level
- Also investigating multi-PMT similar to KM3NeT (see paper on Thursday)
- Paper on Thursday

Hartz for Hyper-K 2016 NUFACT, Vietnam


Single Photoelectron (PE) Charge


Single Photoelectron Time



HPD – Future Prospects

VSiPM

- Goal to develop a large are Photodetector using a SiPM as the multiplier
- Prototype by Hamamtsu:
  - Gain ~10^6
  - 3mm GaAsP photocathode
  - 1mm MPPC SiPM
  - TTS < 0.5ns
  - DQE of 23%
  - Linear to 20 pe – probably too tight of focus on MPPC
  - Dark Counts 100 – 1000 kHz
  - Could reduce Si thickness for electrons – reducing noise
- See paper today

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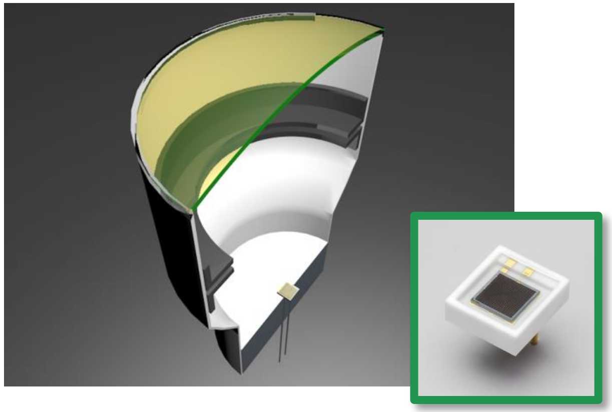

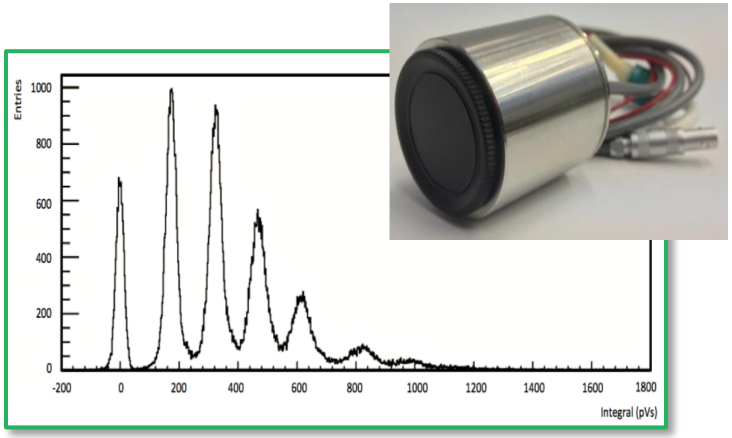

Summary

- Materials Science studies of Photocathodes are leading to new understanding of their growth and structure
- Affordable, moderate area QE of > 50% is possible in 10 – 20 years
- The application of Micro/Nano Engineering is opening up new possibilities
  - Improved Performance
  - Miniaturization
  - New production capabilities leading to reduced cost
- 3ps single photon timing may become possible in the next 10 – 20 years
- Vacuum PhotoDetectors remain the most cost effective solution for large area, low light applications
- Many opportunities for Academia and Industry to work together
- The future of Vacuum Photodetectors is very Bright

Thank-You for your attention