14th Workshop on Picosecond Timing Detectors, Electronics and Applications

Transmission Dynodes: Enhancing Vacuum Photodetectors

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Outline

- MCP-PMT Performance
- Dynode electron gain process
- How to Improve on the MCP-PMT
- Transmission Dynodes
- Diamond as a dynode material
- Proposed Hybrid Solution
- Long Term Ambition
- Conclusions

MCP-PMT Performance

- Time Resolution, down to σ 20-30 ps (single photon)
  - Better as MCP pore size is reduced → NanoChannel Plate
- QE, up to ~35% (visible wavelengths)
  - Dependent on wavelength and photocathode (PC) technology
  - MCP p.e. detection efficiency → funnelled pores, ALD coatings, E-field
- Low noise – limited by PC thermal dark noise
  - Typically 1e2-1e3 Count/cm^2/s – PC and T dependent
- Radiation – radiation hard cf. silicon sensors, electronics
- Magnetic field – electron trajectory distortion $\geq 1T$
  - Efficiency and gain loss, dependent on field strength and orientation
- Count rate, 100’s Mcount/s
  - Ultimate limit – MCP strip current and gain
- Lifetime – limited by PC damage (ion feedback)
  - Dependent on extracted charge - typically $\leq$10’s of C/cm^2
- Single photon counting, large MCP gain variance
  - Simultaneous photon # unresolvable cf. SiPM

MCP-PMT Performance
– **major limitations**

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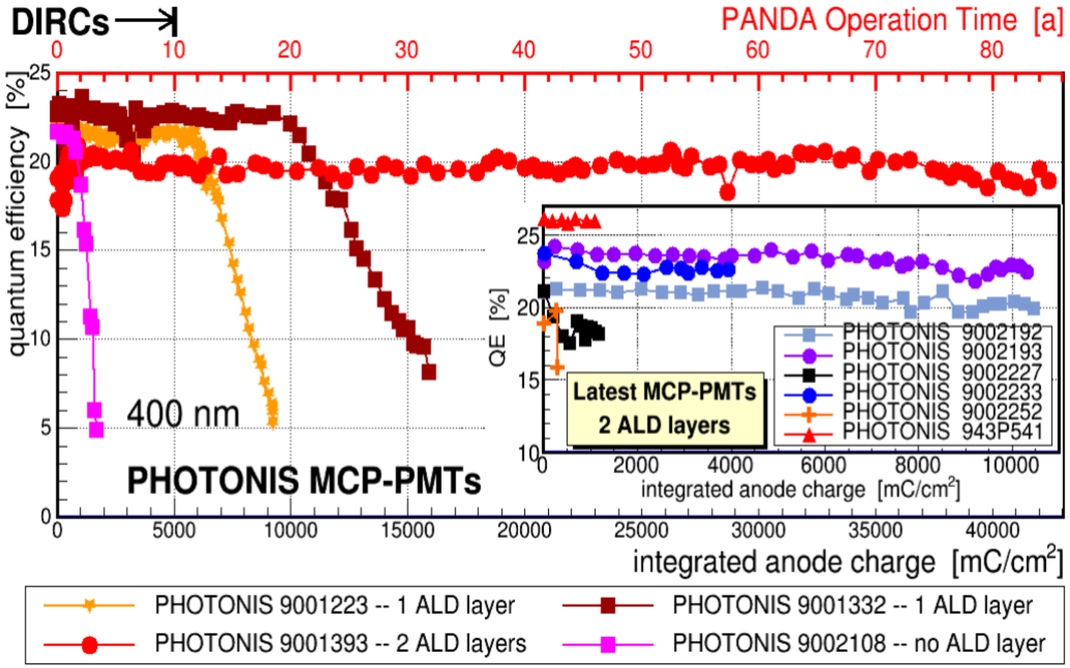
MCP-PMT Lifetime

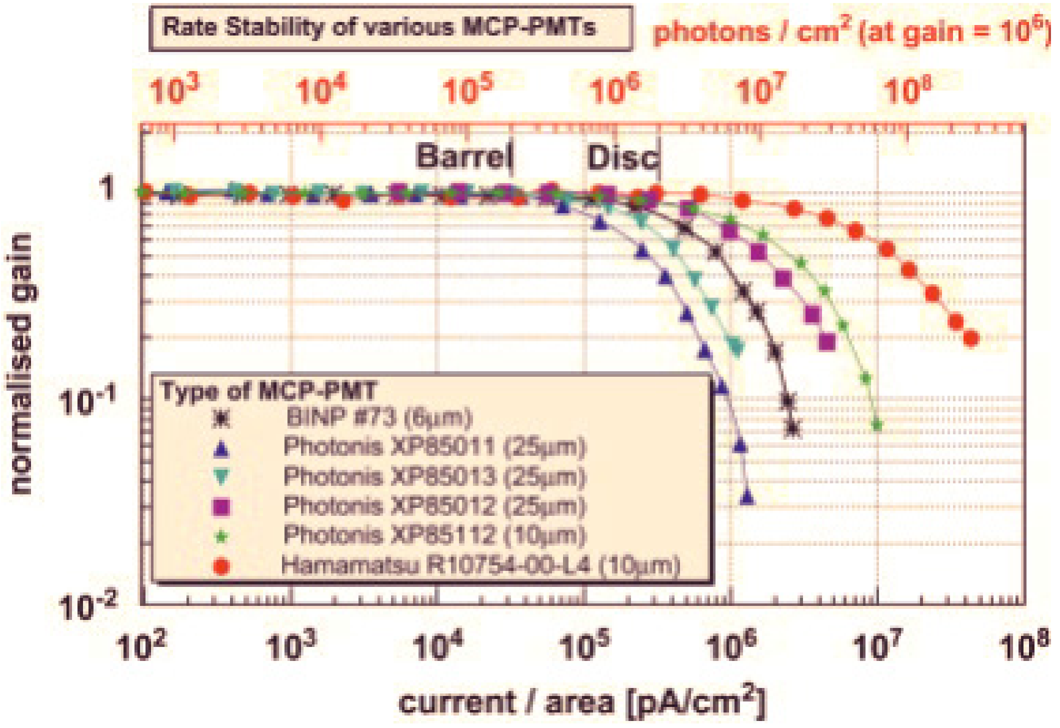
Effect of ALD coatings on lifetime



A. Lehmann, WG1 DRD4, April 2025

- Lifetime dominated by photocathode degradation – highly sensitive chemistry, low Φ for visible light.
- MCP geometry – large surface area (~m^2) → large amount of adsorbed contaminants (H_2, H_2O, He etc.)
- Electron gain desorbs and ionises contaminants → ions
- MCP-PMT E-fields drift and accelerate ions back to PC
- Energetic ions (100's eV) damage photocathode chemistry → reduced QE
- MCP scrub, ALD coating ion barrier films → reduced ion feedback
- Lower gain → lower ion feedback → QE reduces slower → longer lifetime
- Lower gain → wider PHD

MCP-PMT Count Rate



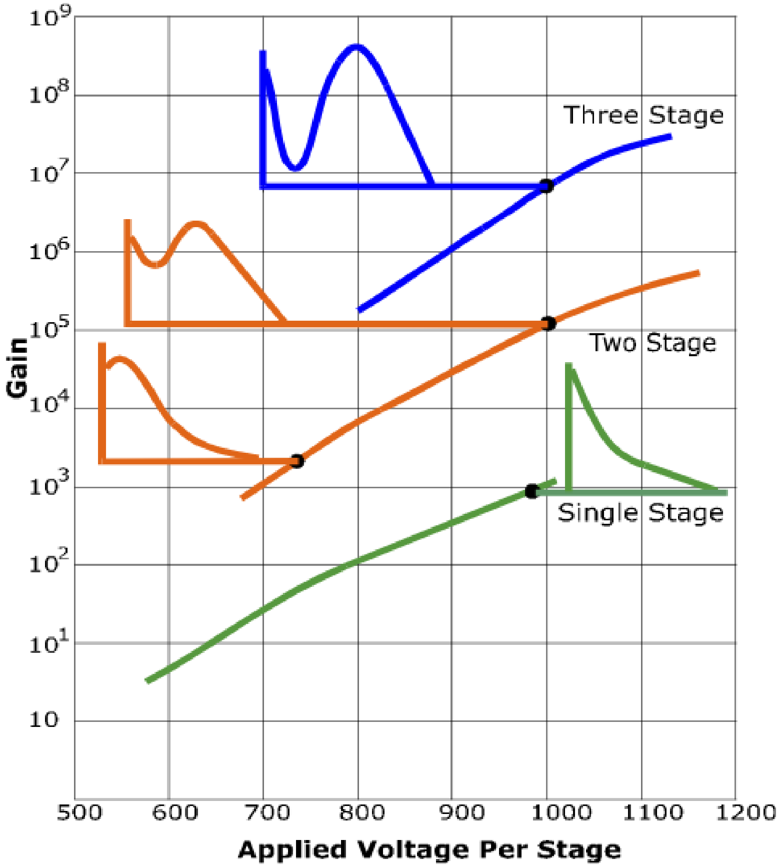
T. Gys, CERN Detector Seminar, Feb. 2014

- Maximum signal current limited to 10-20% of MCP strip current (standing current in pore wall)
- Strip current can be increased by lowering MCP (input/output) resistance
- Minimum MCP resistance fundamental limit → -ve coefficient of resistance → thermal runaway
- Maximum count rate proportional to reciprocal of gain
- Lower gain → lower signal current → allows higher maximum count rate
- Lower gain → wider PHD

MCP-PMT Photon Counting

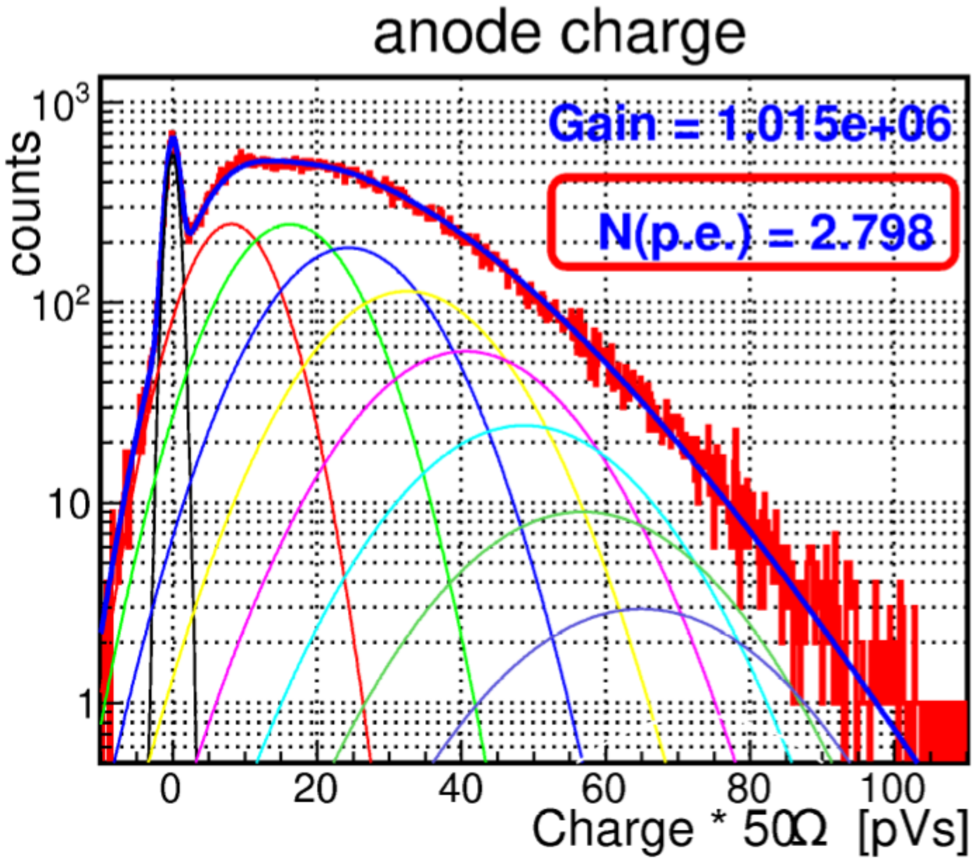
- MCP pore wall comprises a continuous dynode
    - cf. discrete dynodes of conventional PMT
- Effective dynode length and thus electron energy gain between dynode collisions, and # # of effective dynodes, is variable
- Gain per collision also relatively low (~3-4
    - → produces a large gain variance
    - → PHD is ~negative exponential with 1 MCP
- As operating voltage per MCP increases, and using a stack of 2 or more MCP's:
    - → Gain saturation begins to occur
    - → Increasingly narrow PHD with improved peak-valley ratio
- Caused by dynamic positive charge up of the lower pore wall, reducing the field in the lower pore and causing gain to saturate

MCP-PMT pulse height variation with applied voltage for different numbers of MCP stages



MCP-PMT Photon Counting

- High gain variance of MCPs from event to event
- Prevents measurement of number of simultaneously detected photons
- Not ideal for electronics – needs wider dynamic range and lower noise for single photon counting
- Cf. SiPMs:
  - Geiger mode operation injects ~constant charge per photon
  - Number of detected photons can be easily resolved at low #



A. Lehmann, WG1 DRD4, April 2025

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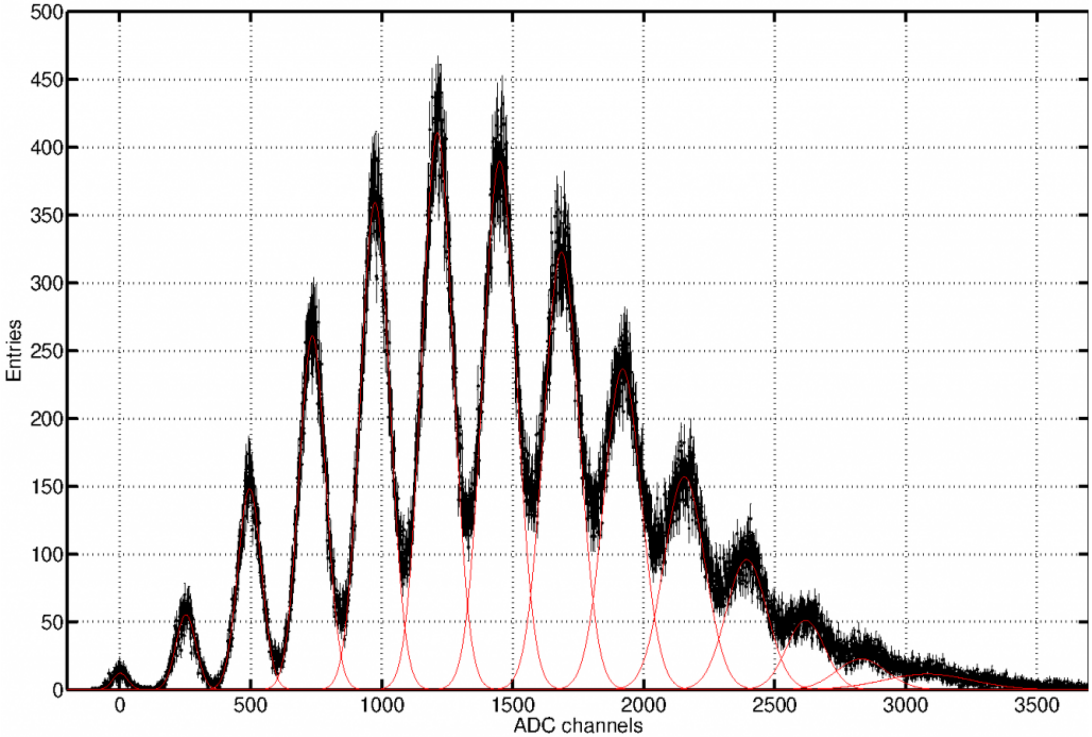
SiPM resolves single photons well



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Performance Trade-offs

- Lifetime – PC damage countermeasures:
  - ion barrier film(s) – traditional approach

  → reduced efficiency
  - ALD MCP coating – reasonable success

  → significant lifetime extension
  - Advantage by reducing MCP gain – trades-off with peak-valley ratio

  → degrades efficiency, counting statistics

Performance Trade-offs

- Maximum count rate
  - MCP signal current limited to 10-20% of strip current
  - Lower the MCP resistance /□

  → Limited by –ve coefficient of resistance

  → Thermal runaway

  - Advantage by reducing MCP gain – trades-off with peak-valley ratio

  → degrades efficiency, counting statistics

Performance Trade-offs

- Single photon counting
  - Benefits from narrow pulse height distribution (PHD)

  → better efficiency, counting statistics, lower electronics dynamic range
  - MCP gain saturation (MCP stack of 2+ MCPs and higher V_{op})

  → Narrow PHD at higher gain
  - Higher gain

  → Higher ion feedback (shorter lifetime)

  → Lower maximum count rate

Need a gain process that overcomes these MCP trade-off limitations

Secondary Electron Emission from Dynodes

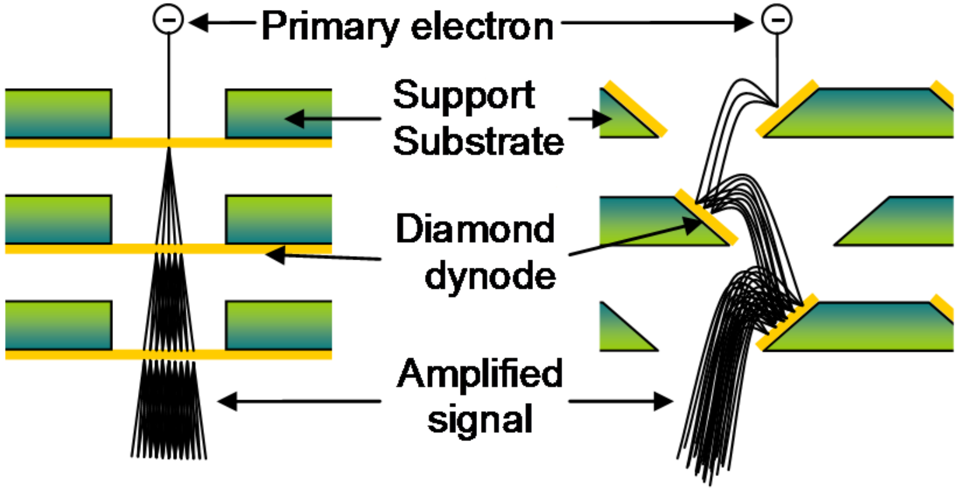
- Four processes:
  - Excitation – of energetic photoelectron
    - Generation of secondary electrons by interaction of primary electron
    - Absorption depth and number of secondaries related to primary electron energy and band gap
  - Thermalisation – to maximise # of secondary electrons
    - Thermalisation of initial energetic secondaries to ~CBM energies
  - Transport – to dynode output
    - Transport efficiency dependent on scattering, trapping, and escape depth
    - Scattering: band gap influences number of conduction band electrons causing scatter
    - Trapping: dependent on crystallinity – defects cause traps, degrade efficient transport
    - Escape depth depends on primary energy and device geometry
  - Emission – to vacuum
    - Majority of secondary electrons thermalised – energies close to CBD
    - Dynode surface modification → Negative Electron affinity (NEA)
    - NEA allows electrons near CBD to be ejected into vacuum

Reflection and Transmission Dynodes

- Conventional PMTs - discrete dynodes in reflection mode
- MCPs – continuous dynode in reflection mode

  → variable dynode length, number, and large range of trajectories
- Transmission dynode requires a thin membrane

  →Linear geometry – confined range of trajectories



How to improve the MCP-PMT?

Primary Design Goals

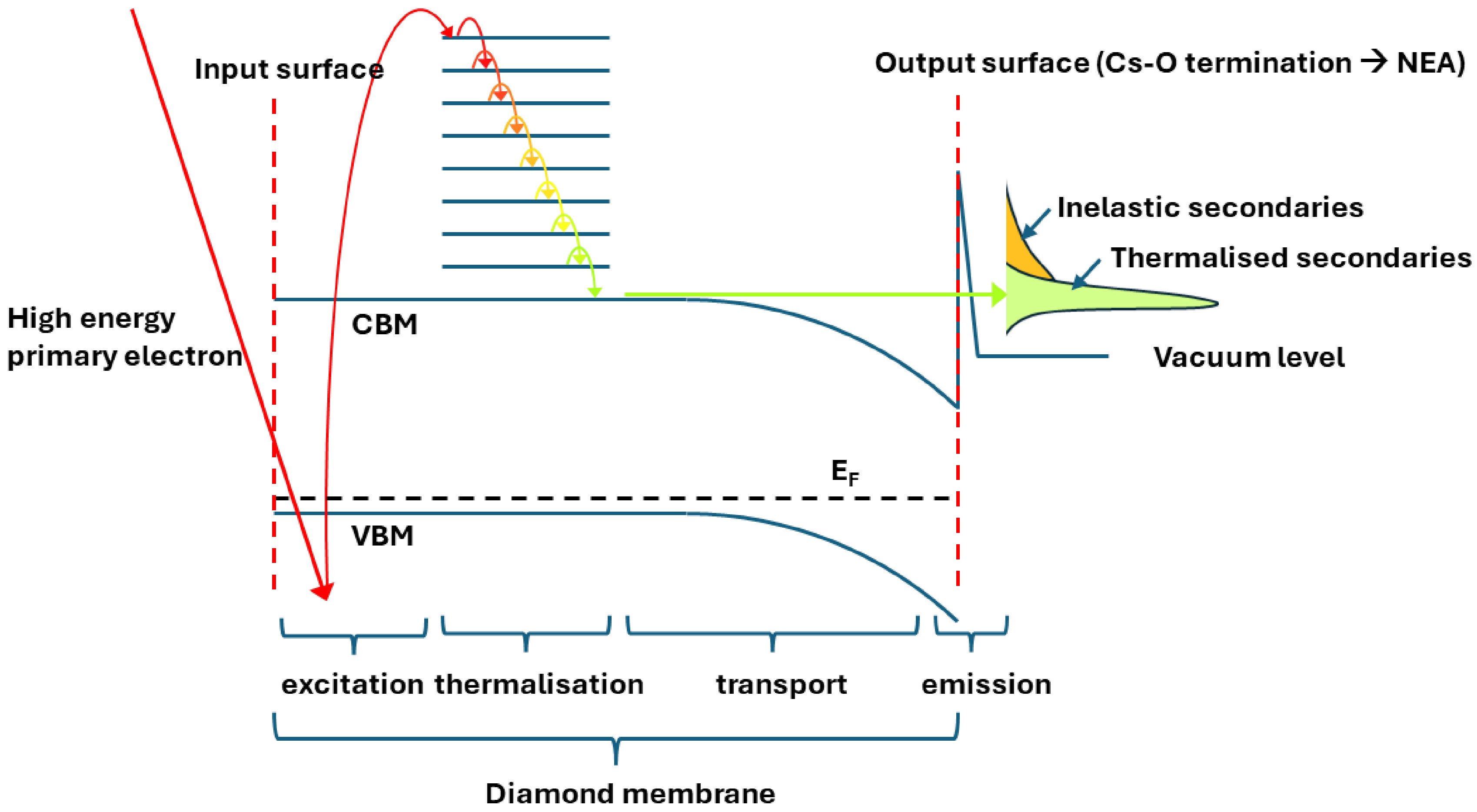
- Prevent ion feedback reaching PC → overcome PC lifetime limitation
- Reduce gain → maximise maximum count rate (MCP-limited)
- Achieve tighter PHD → Better efficiency, counting statistics, electronics

How to achieve these simultaneously?

- First gain stage impermeable to ion feedback
- First gain stage achieves tight PHD with high gain
- Utilise discrete dynode in transmission mode (impermeable)
- High gain by using high secondary electron yield material (diamond)

Implement a high gain transmission dynode as first gain element

Band Structure of a Transmission Dynode



Diamond – a Suitable Dynode Material

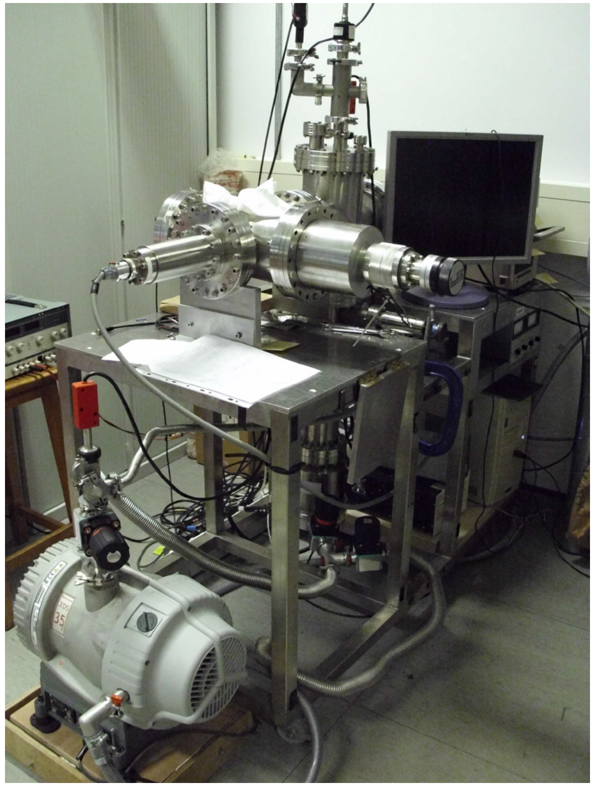
- High Band Gap (5.47 eV) and Mobility (4500 cm^2/Vs)
  - Low # of charge carriers in conduction band at RT – low scattering → good electron transport characteristics (SCD)
  - Good transport increases mean free path of thermalised secondaries allowing use of thicker membrane – easier practically
  - However, number of thermalised secondary electrons ∝ band gap – offset by transport characteristics
- Surface Termination to produce NEA surface
  - Range of surface terminations provide NEA in diamond e.g. Cs-O, X-O dipole
  - Important feature is to achieve stability in presence of long term signal current
- Diamond can be doped
  - Helps for good electrical contact – signal recharge
  - Possible to introduce static E-field – aid to secondary electron transport and emission

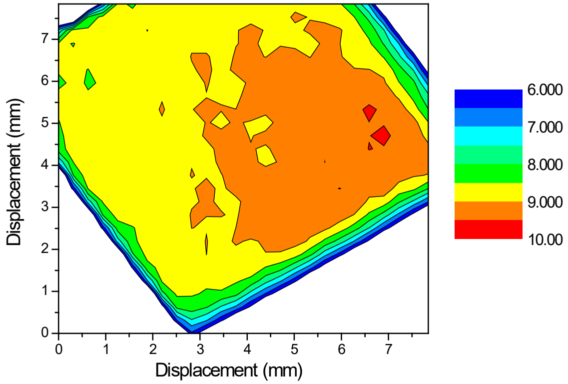
Previous work with diamond

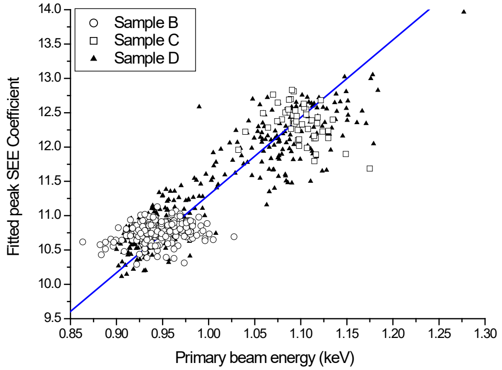
- Measured a high secondary electron yield – reflection mode only
- Manufactured thin diamond membranes – but transmission mode not such good results as reflection
- First tests using available polycrystalline diamond (PCD) material
- PCD has graphitic grain boundaries – compromises electron transport
  - Especially a problem for continuous thin membranes
- Transmission diamond dynodes not realistic without single crystal diamond
  - No grain boundaries, defects, traps – large improvement in electron transport

SCD not readily available at the time

Diamond SEE measurement







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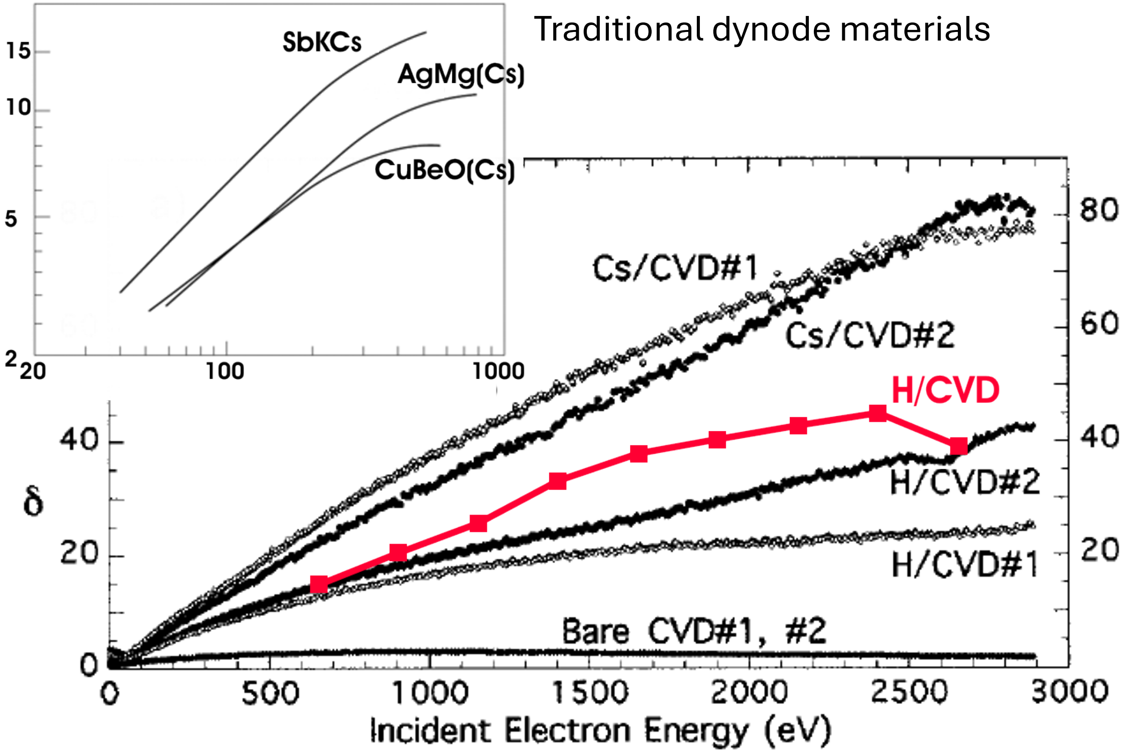
- Gain Advantage of Diamond

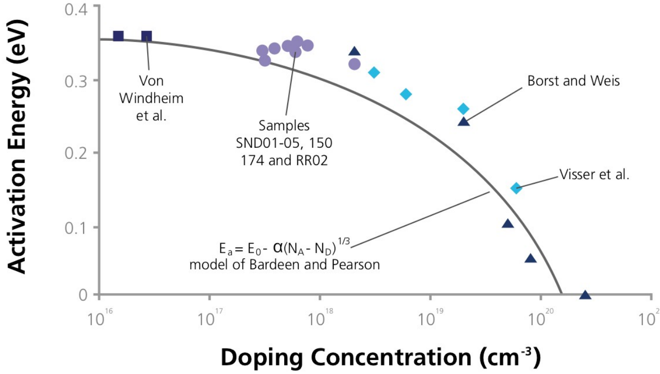


Traditional dynode materials

Measured diamond secondary electron yield (reflection)

Recent Developments in Diamond

- New growth techniques developed for large scale single crystal diamond (SCD)
- Commercially available SCD material – several sources, cost-effective
- New doping methods produce improvements in n- and p-type materials
- New termination processes/ materials producing stable NEA surfaces have been developed



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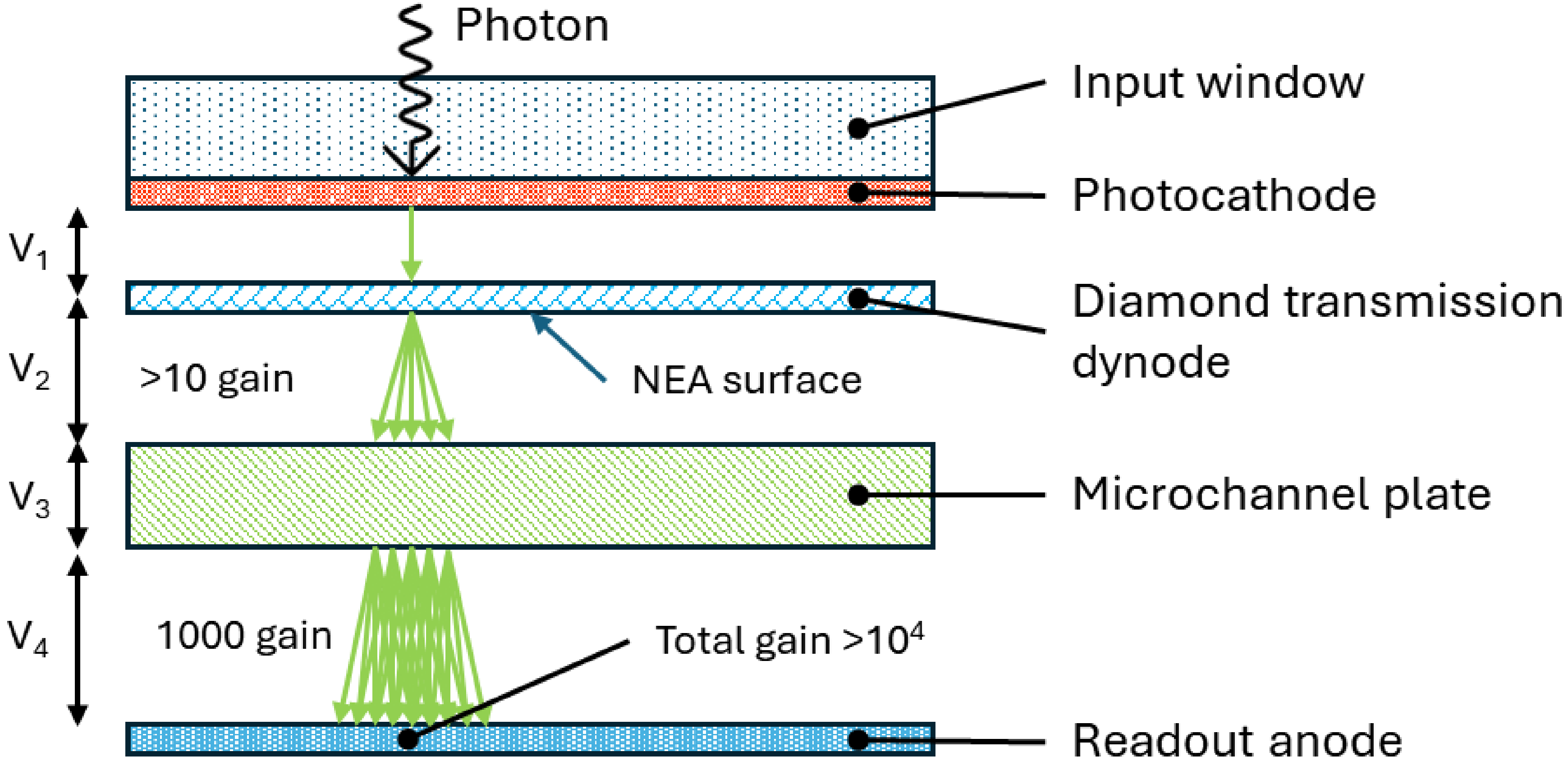
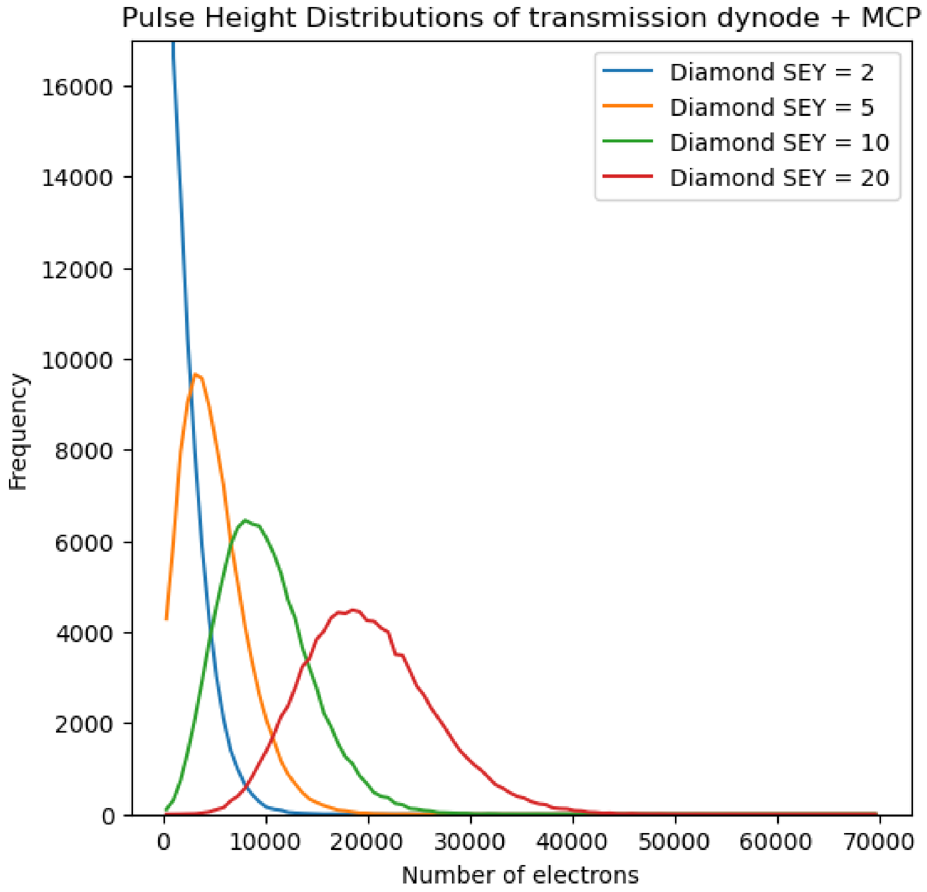
Proof-of-Concept Hybrid Detector



Proof-of-Concept Hybrid Detector

- Transmission diamond dynode
  →between photocathode and MCP
- Provides a barrier for ion backflow
  → longer photocathode lifetime
- Provides electron gain
  → Tighter pulse height distribution at lower overall gain
  → Higher maximum count rate
- Thin diamond membrane
  - 100's - 1000 nm thick
  - High OAR support structure
- Diamond has NEA surface
  - for good charge extraction



Pulse height distribution for simulated diamond-MCP-PMT for varying diamond gains

Longer Term Ambition

- Complete replacement of the MCP component
  - → Stack of diamond transmission dynodes
- Diamond transmission dynode stack
  - → high stage gain and fixed number of gain stages
  - → necessary tight pulse height distribution even at low overall gain
- Linear electron trajectories through the stack
  - → Result in much improved time resolution (anticipate $\ll$ 10 ps)
- In comparison with MCP-MPT
  - relatively low electron gain per collision
  - continuous dynode geometry
  - large range of possible electron trajectories
  - → high gain variance per event – broad PHD
  - → larger time transit spread

Vision

- Direct replacement of MCPs
- Monolithic stack of diamond transmission dynodes (3-5 dynodes)
- Gain of 10^3–10^5 with narrow PHD for single photon counting accuracy
- Linear dynode geometry → time resolution $\ll$10 ps
- Diamond transmission dynode stack integrated with an active pixel sensor e.g. Medipix, Timepix, TDCpix etc.
- Choice of readout ASIC allows customisation of performance
- Variable focus: high spatial resolution, picosecond time resolution, maximum throughput

Project Team

- **University of Leicester** – long heritage in space science inc. MCP-PMTs, development of alternative detector technologies inc. diamond dynodes
- **University of Bristol** - expertise in diamond manufacture and use in energy applications, and detector development for high energy physics
- **University of Warwick** - expertise in detector development for high energy physics with focus on photo-detector characterisation
- **University of Birmingham** - expertise in detector development, characterisation, technology survey, and comparison with state-of-the-art MCP-PMTs
- **Photek** - one of the leading worldwide manufacturers of vacuum tube devices with more than 25 years of custom detector design and fabrication expertise

This project is part of the Vacuum-based Photodetectors programme within DRD4 WP4.2

Conclusions

- Major MCP limitations – lifetime, count rate, single photon counting – difficult to overcome for future high-rate applications
- Diamond has much promise as a high gain dynode material
- Transmission dynode geometry offers significant advantages
- Advances in diamond production and processing make this a realistic prospect
- Integration with the latest readout ASICs:

→ 10+ GHz photon counter; ≥1 Mpixel resolution; ≪10 ps time resolution, combined with photon counting cf. the SiPM?