Queen Mary University of London
Science and Engineering

Radiation Detectors (SPA 6309)

Lecture 14

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What is this lecture about?

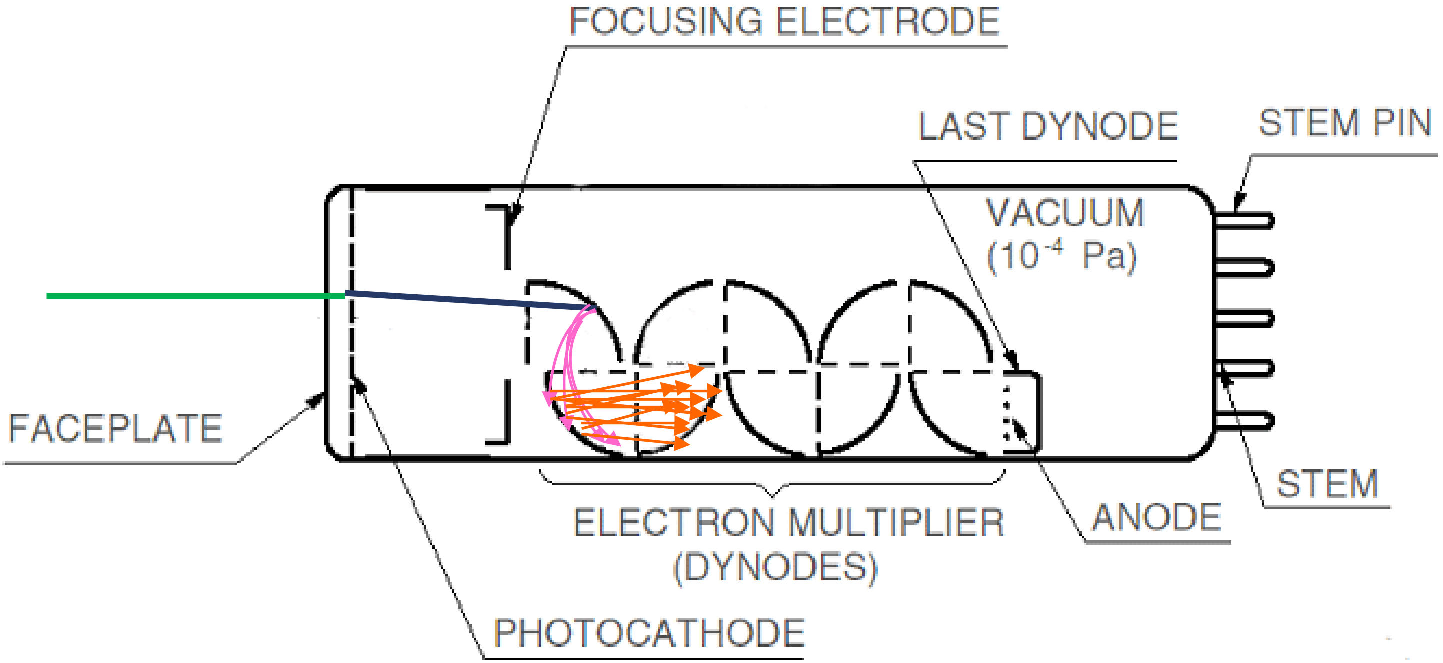
- Scintillators
  - Basic principles
  - Important materials in current use
  - Light detection
  - Low energy applications (spectroscopy, medicine)
  - High energy applications (calorimeters, Time-of-flight)

Key points from previous lecture

- Diode structures (PIN and APD in particular) are important visible/near-UV light sensors used to readout scintillators.
- APD devices have gain.
- Large area diodes are limited to about ~ 100 mm^2 (also capacitance effects)
- The Geiger-mode multi-cell “silicon photomultiplier” is becoming increasingly important in many applications, note however it has some limitations. In photon counting applications (i.e. 1 or 2 or 3 or 4 photons) it is now almost unrivalled.
- Design of diodes for radiation sensor applications need to take into account that the diode is also a good direct detector of radiation.

Photodetectors – the photomultiplier tube (PMT)

- A *free* electron is liberated from a *photocathode* (photoelectric effect) into a vacuum under an electric field
  - The free electron is accelerated to a few hundred volts and hits a *dynode*
  - Low energy *secondary electrons* are liberated from the dynode (4 to 10 dependent on voltage and material of dynode)
  - Each secondary electron is accelerated and hits the next dynode
  - And so on …
- A typical tube used in HEP has 10 to 14 dynodes
- Thus a high gain is achieved (10^6 to 10^7)
- Large areas (hundreds of cm^2) are possible, but low QE compared to silicon devices
- Most PMT are *very sensitive* to magnetic fields



Typical dynode gain is about 5 and a typical PMT has 12 dynodes. Gain is therefore of order $12^5 \sim 250000$.

Electron multiplier

A very special amplifier, with a simultaneous high gain (O 10^6) and high bandwidth (O 1 GHz).

It comprises a set of metal surfaces (dynodes) which have the property of providing electron multiplication for incoming electrons of energies in the range 100 to 300 eV. Cascading a sequence of dynodes (8 to 14) gives stable gains exceeding a million coupled with fast rise time current output.

Exceptionally sensitive to magnetic fields!

Photocathode can be much larger in area than the electron multiplier acceptance (electrostatic focussing).

Dynode geometries

Different types of electron multiplier have different characteristics regarding linearity, minimising pulse distortion, sensitivity to external magnetic field etc.

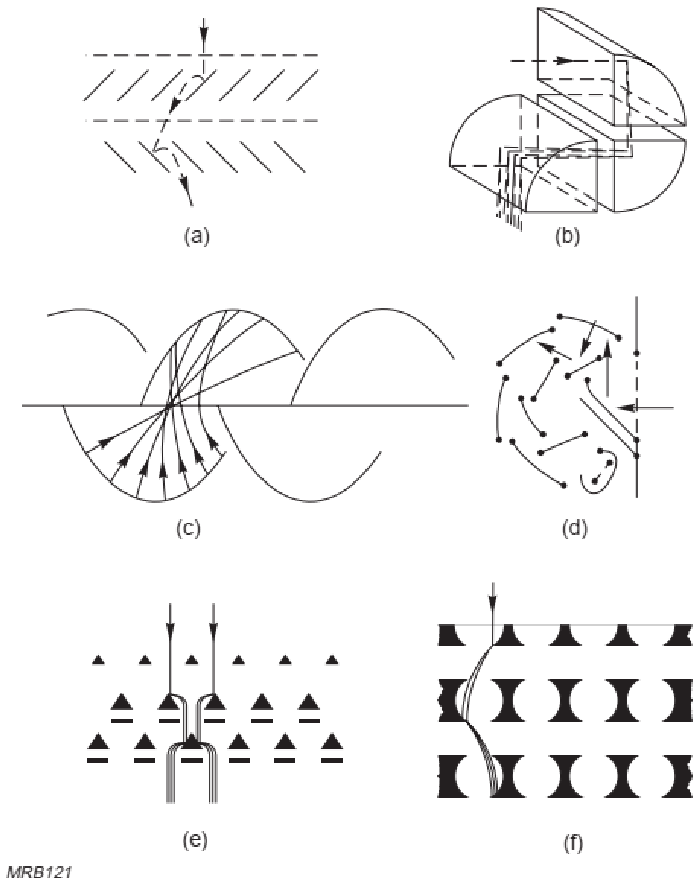
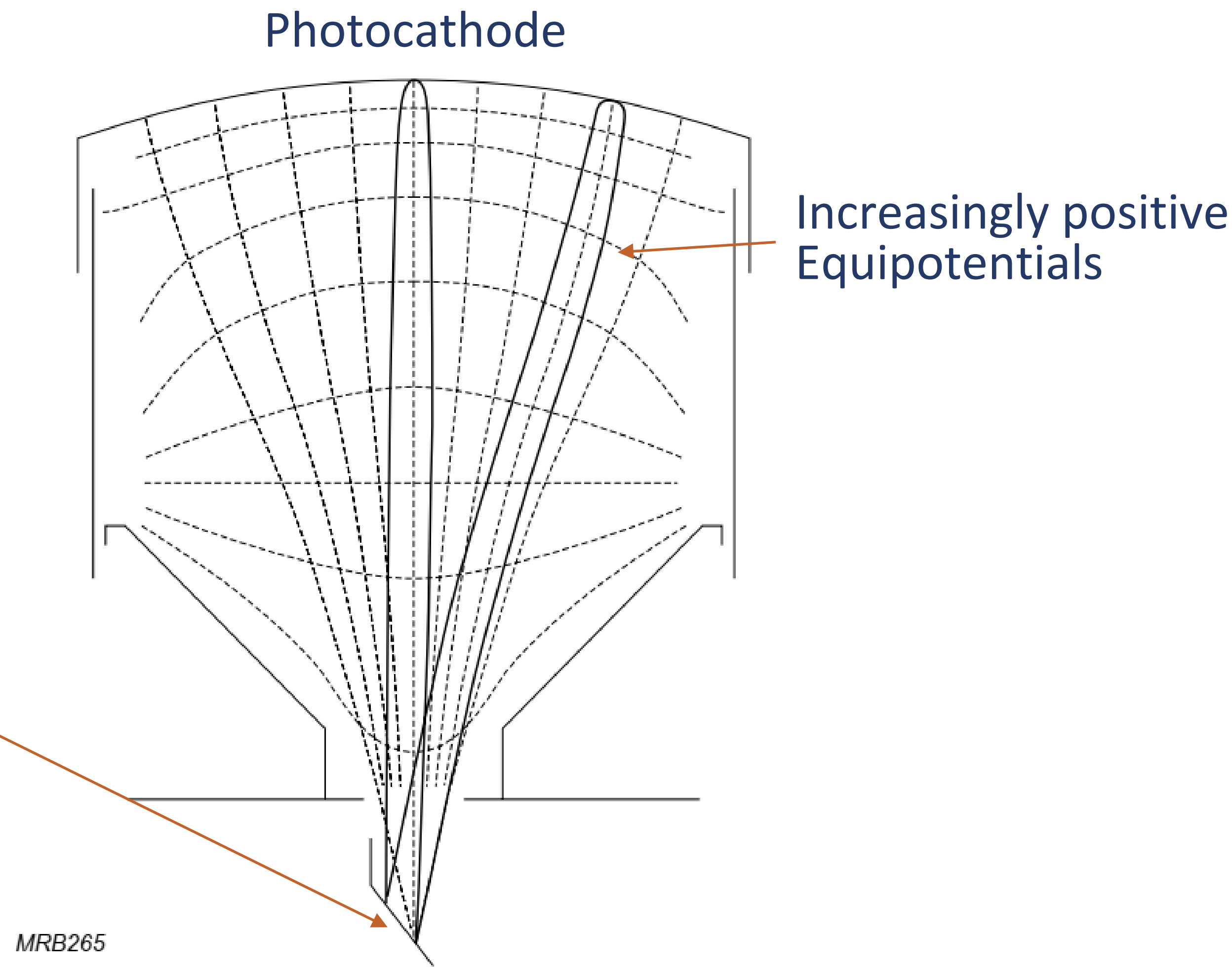


Fig.1.11 Dynode configurations: (a) venetian blind, (b) box, (c) linear focusing, (d) circular cage, (e) mesh and (f) foil

Fast large area PMT

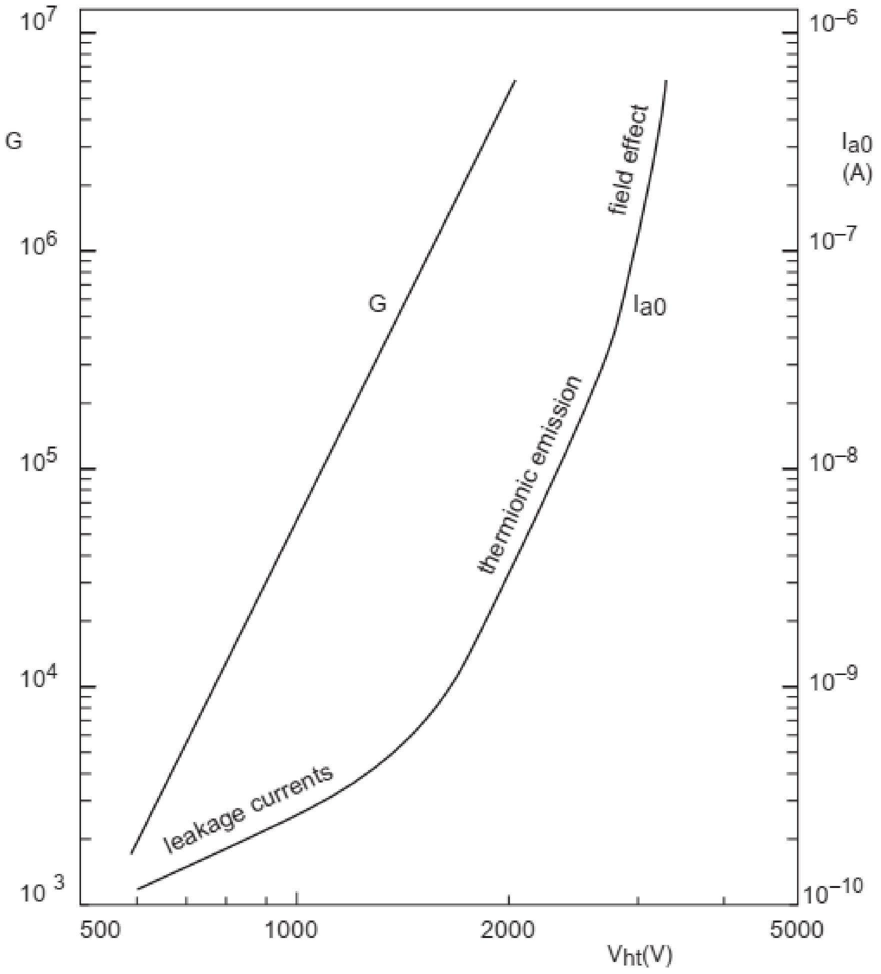
Use electrostatic focussing to minimise the time differences from a large photocathode focussing onto a small area electron multiplier. Note use of a variety of electrodes. This type of PMT is very sensitive to external magnetic fields.



Gain and noise

G = gain

I_{a0} = dark current



Spectral response, dynode gain, noise

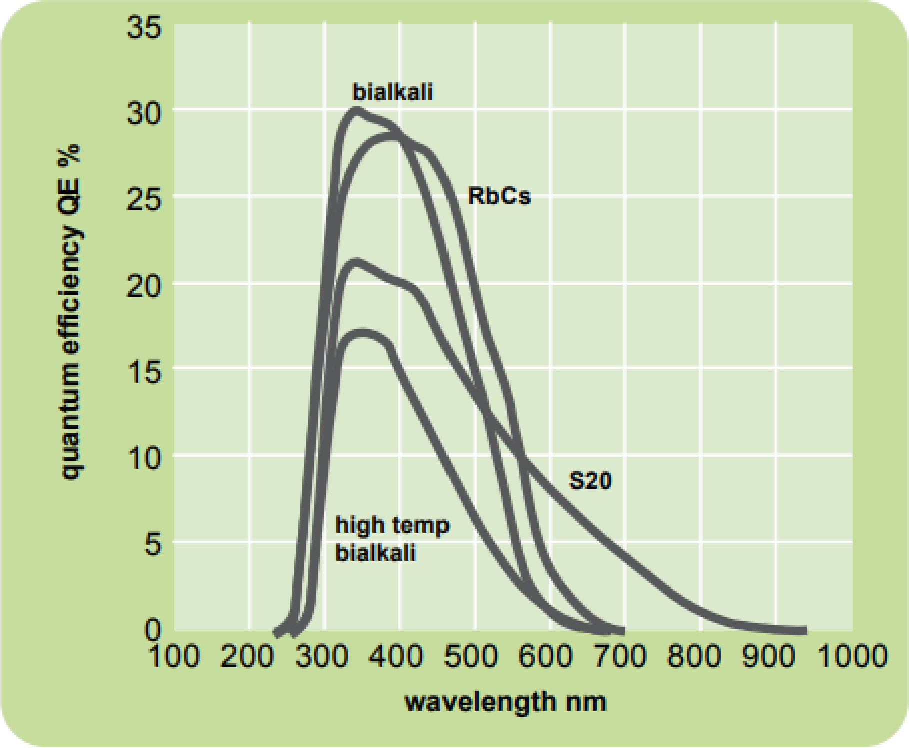


figure 4a Spectral response curves for various photocathodes deposited on borosilicate glass. The naming of photocathode types is historical. Measured values of QE against wavelength can be provided, at extra cost.

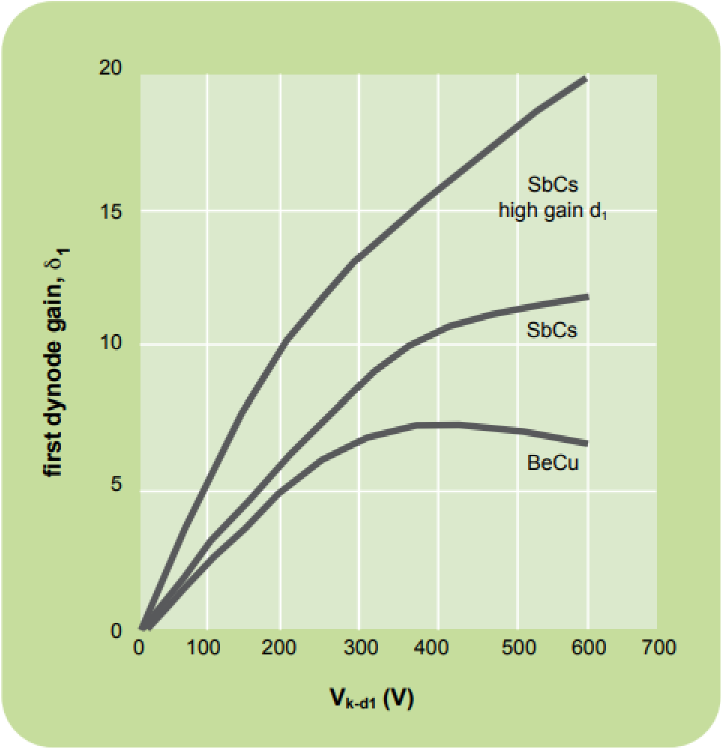
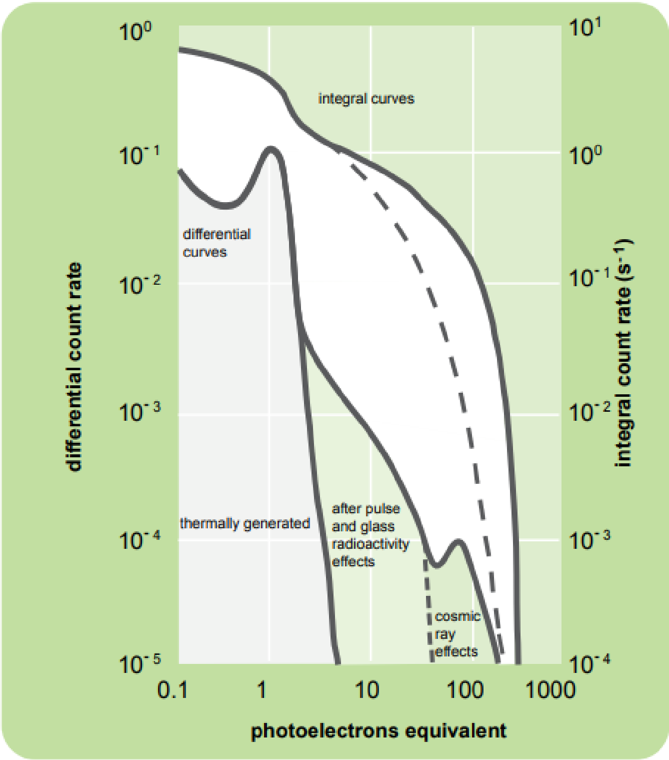


figure 9 Variation of first dynode gain, δ_1, with k-d $_1$voltage.



Plots from ET Enterprises Limited, Uxbridge, UK

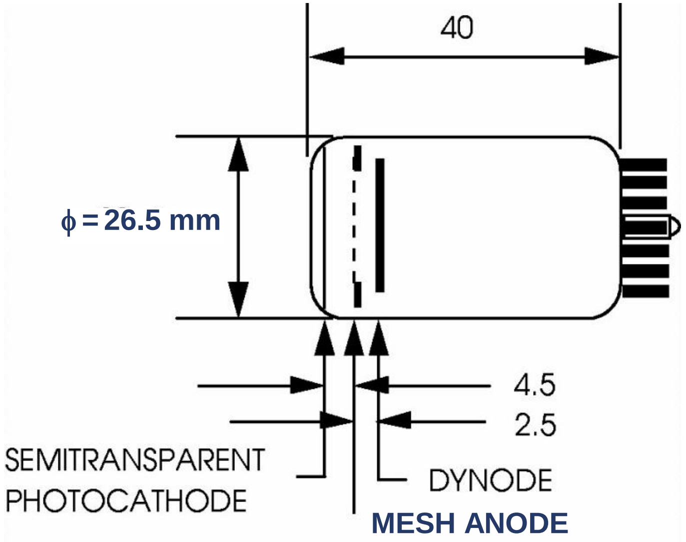
Photomultipliers for High magnetic fields

Fine mesh dynode approach – gains in thousands, fields up to ~ 1T
Fine mesh anode – gain ~ 10 but operating at fields up to at least 4T

Vacuum Phototriodes (VPT)

B-field orientation in end caps favourable for VPTs
(Tube axes $8.5^o < |\theta| < 25.5^o$ with respect to field)
Vacuum devices offer greater radiation hardness than Si diodes

- Gain 8 - 10 at B = 4 T
- Q.E. ~ 20% at 420 nm
- Insensitive to ionising particles
- UV glass window - less expensive than ‘quartz’
  - more radiation resistant than borosilicate glass



Photomultipliers for many channels

Using proximity focus, and semi-transparent dynodes you can transfer, with gain, the localised photon signal on the photocathode to an array of anodes.

Hamamatsu have also developed a very compact “metal channel dynode” design that enables multi-anode capability. This is very useful for reading out small area scintillating crystals used in PET scanners for medicine.

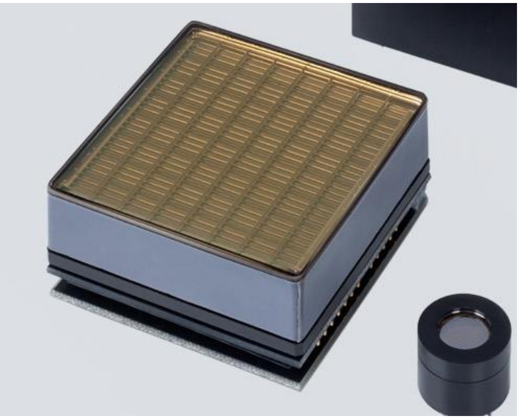
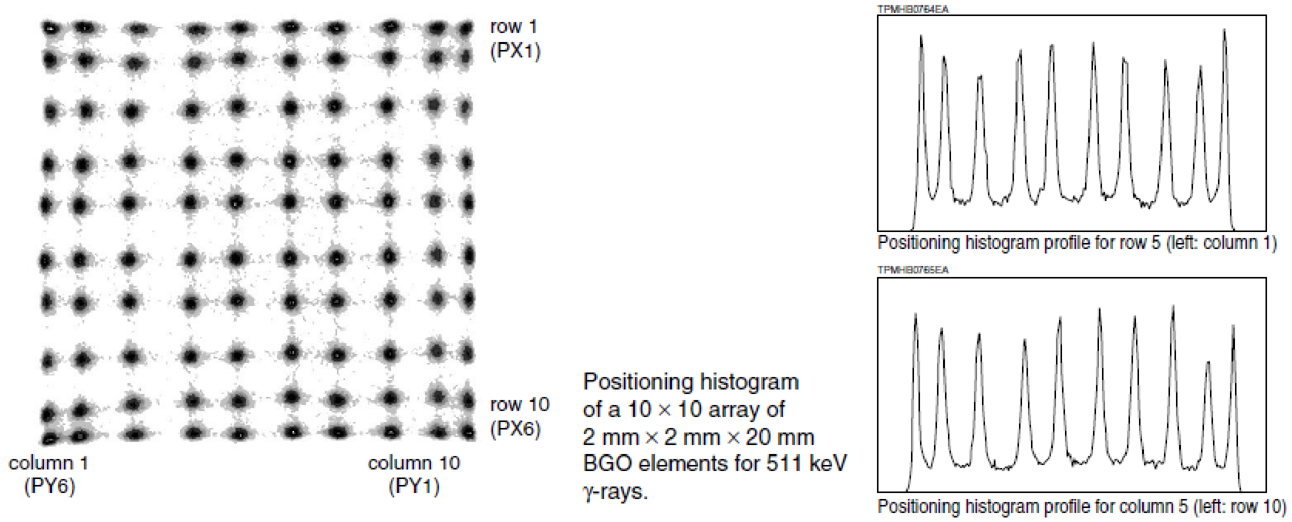


Figure 5: Positioning Histogram Example



Hamamatsu R8900 6×6 anode PMT. Gain ~ 700000 @ 1kV

Producers

Hamamatsu

https://www.hamamatsu.com/eu/en/product/optical-sensors/pmt/index.html

ET Technologies Ltd

http://et-enterprises.com/products/photomultipliers

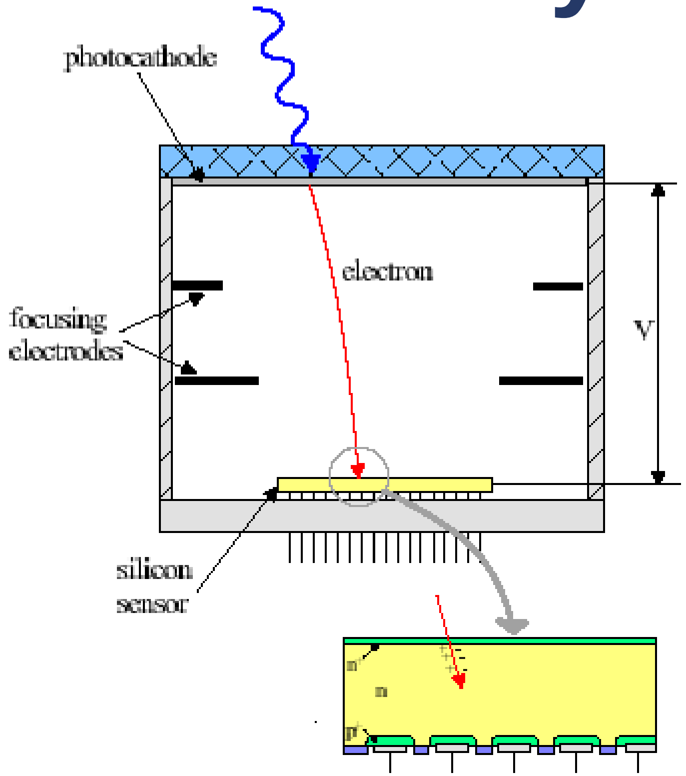
RIE

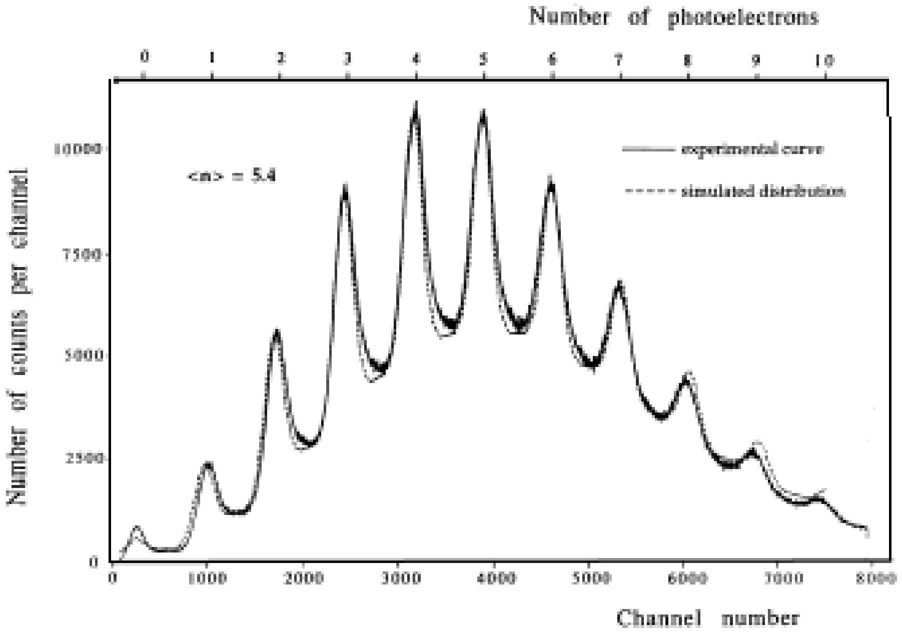
http://www.niielectron.ru/

Hybrid photodetector

- Generate free photoelectrons in a vacuum (like a photomultiplier tube)
- Accelerate photoelectrons to a high (10 to 20 kV) energy
- Use a silicon diode as a *particle (electron) detector*. Get approximately 2500 eh-pairs for each photoelectron at 10 kV
- *Large* photocathode plus *small* area diode (low capacitance, thus speed)
- Use a pixel detector (CMOS) to provide a position sensitive photon counter.

Hybrid photodetector





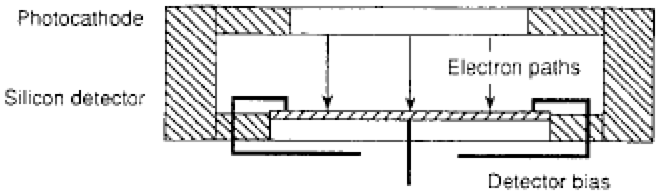
Note the resolution of 1,2,3,… photons <n> = 5.4

C. Joram, CERN, *Large Area Hybrid Photodiodes*
6th International conference on advanced technology and particle physics, Como, Italy, October 5-9, 1998
See lhcb-doc.web.cern.ch/lhcb-doc/presentations/conferencetalks/postscript/1998presentations/como.pdf

Hybrid photodetector

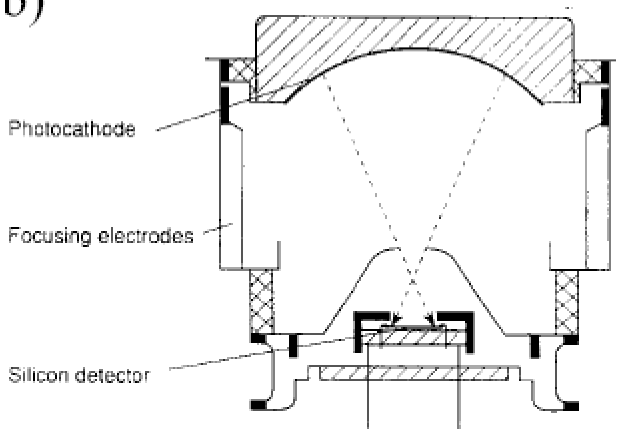
Proximity focussed

a)



Cross focussed

b)



type	ε_Q[%]	gain	photon counting	spatial resolution	speed
HPD	≈ 25	$\approx 10^3$	yes	high	high
PMT	≈ 25	$\approx 10^6$	limited	no	high
MAPMT	≈ 25	$\approx 10^6$	no	medium	high
PIN diode	≈ 80	1	no	high	high
APD	≈ 80	≈ 100	limited	no	high
CCD	≈ 80	1	no	high	low
VLPC	≈ 70	$\approx 10^6$	yes	no	high

Comparison of HPD's with various other photodetectors (MAPMT = Multi Anode PMT, APD = Avalanche Phododiode, CCD = Charge Coupled Device, VLPC = Visible Light Photon Counter).

C. Joram, CERN, *Large Area Hybrid Photodiodes*
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Advantages and disadvantages of PMT

High gain and large electrical bandwidth.
Large photocathode areas are possible.
Insensitive to ionising radiation generating a signal.
Very low dark count obtainable.
Very well understood technology.
Surprisingly robust.
Low noise at high(ish) temperatures

Few manufacturers available.
Low peak QE (~ 25%) compared to silicon devices.
Poor photocathode response in the red/near-IR
Does not complete with Geiger mode diodes for multi-photon counting.
Susceptible to gamma radiation induced darkening of faceplate (except quartz)
Sensitive to helium ingress – afterpulsing issues.
Handcrafted aspect for some tubes = £££
Uses high voltage (1 to 2 kV).

Hamamatsu R12860, 508 mm diameter PMT