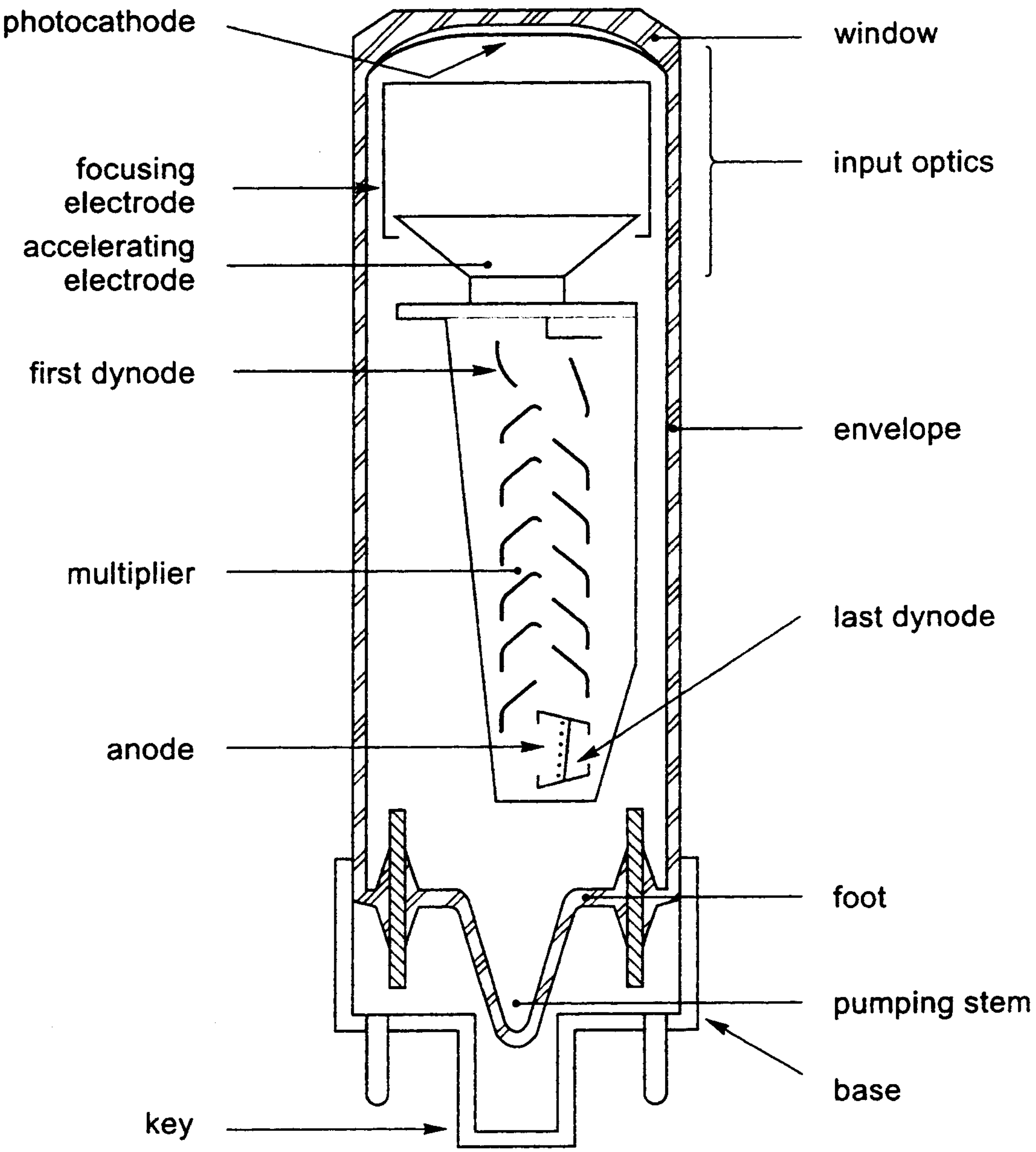
Conversion of Scintillation Light to Electrical Signal

Most Common Device:

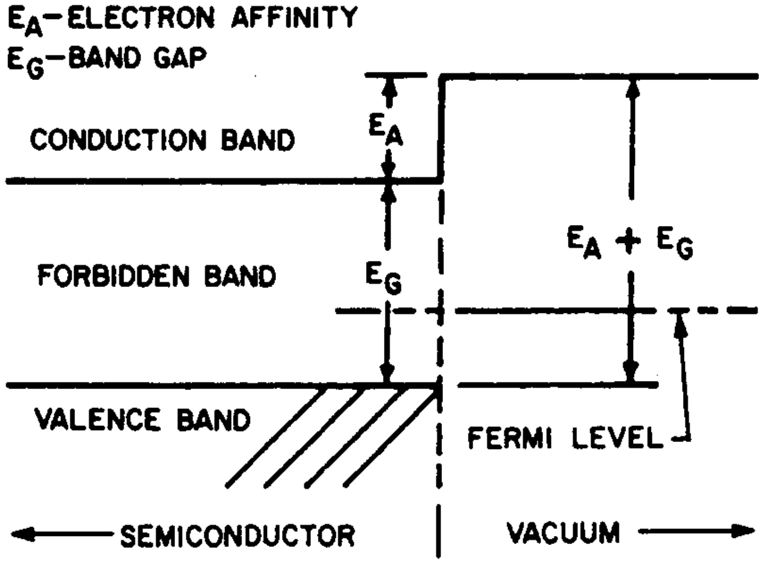
Photomultiplier Tube



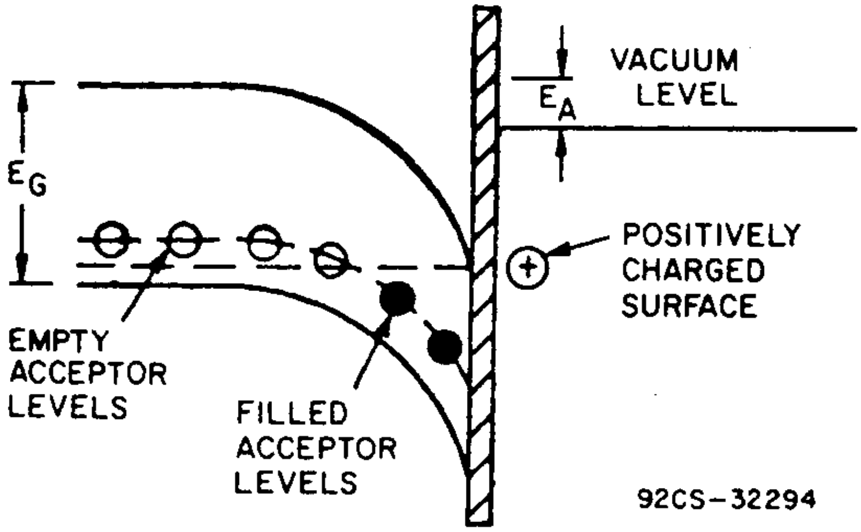
(from *Photomultiplier Tubes*, Philips Photonics)

Photocathodes

Band structure in “standard” photocathode



Band structure in “negative electron affinity” photocathode



(from *Photomultiplier Handbook*, Burle Industries)

Summary of Photocathode Materials

(from Derenzo)

Cathode type	Composition	Peak Q.E.	Peak λ
S1	AgOCs	0.4%	800 nm
S10	BiAgOCs	7%	420 nm
S11	CS_3SbO	21%	390 nm
S20 (multi-alkali)	Na_2KSbCs	22%	380 nm
Bialkali	K_2CsSb	27%	380 nm
Bialkali (high temp)	Na_2KSb	21%	360nm
	KCsRbSb	24%	440 nm
Bialkali	RbCsSb	25%	450 nm
Solar blind*	CeTe	18%	200 nm
Solar blind**	CsI	15%	135 nm

S1, S10, S11, S20: vendor designations

* Q.E. < 0.1% above 320 nm
** Q.E. < 0.1% above 210 nm

Maximum quantum efficiency in above table is 27%.

Is this reasonable?

- no electric field within photocathode to direct electrons to emitting surface
- photoelectrons initially emitted isotropically
    - Þ ½ directed toward faceplate
    - Þ ½ directed toward dynode structure
- transmission losses (bialkali photocathodes 40% transmissive

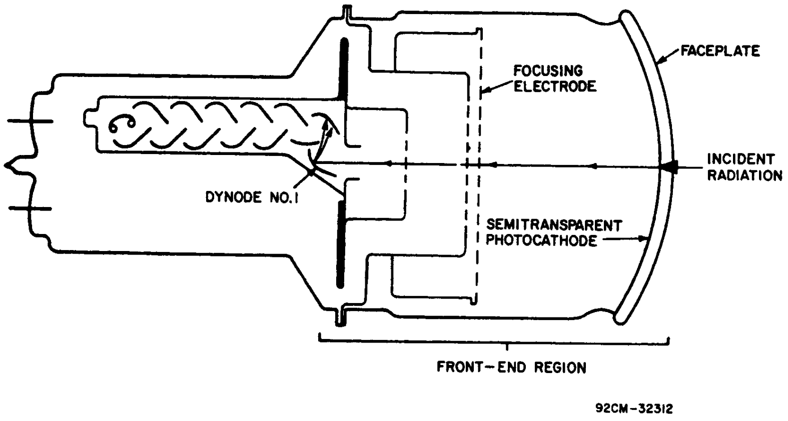


Fig. 26 - Photomultiplier design with curved faceplate and in-line dynode structure to provide a minimum transit time and transit-time spread.

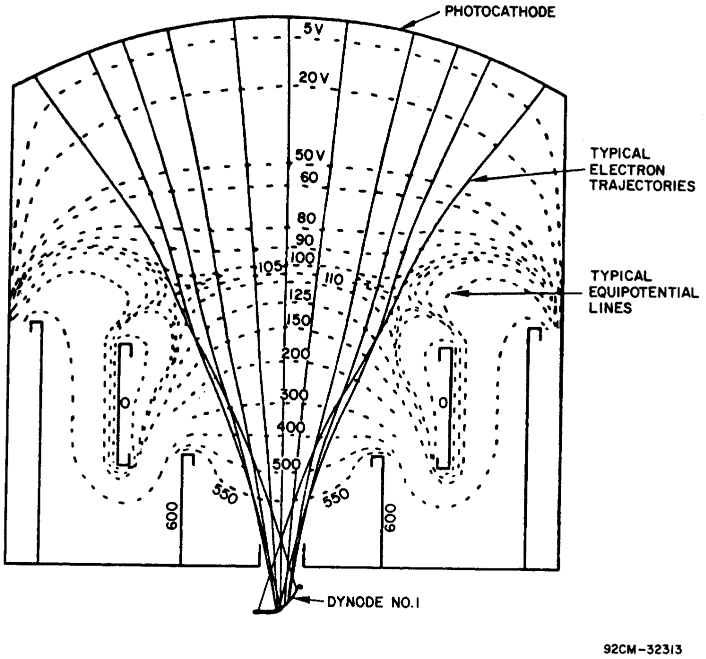
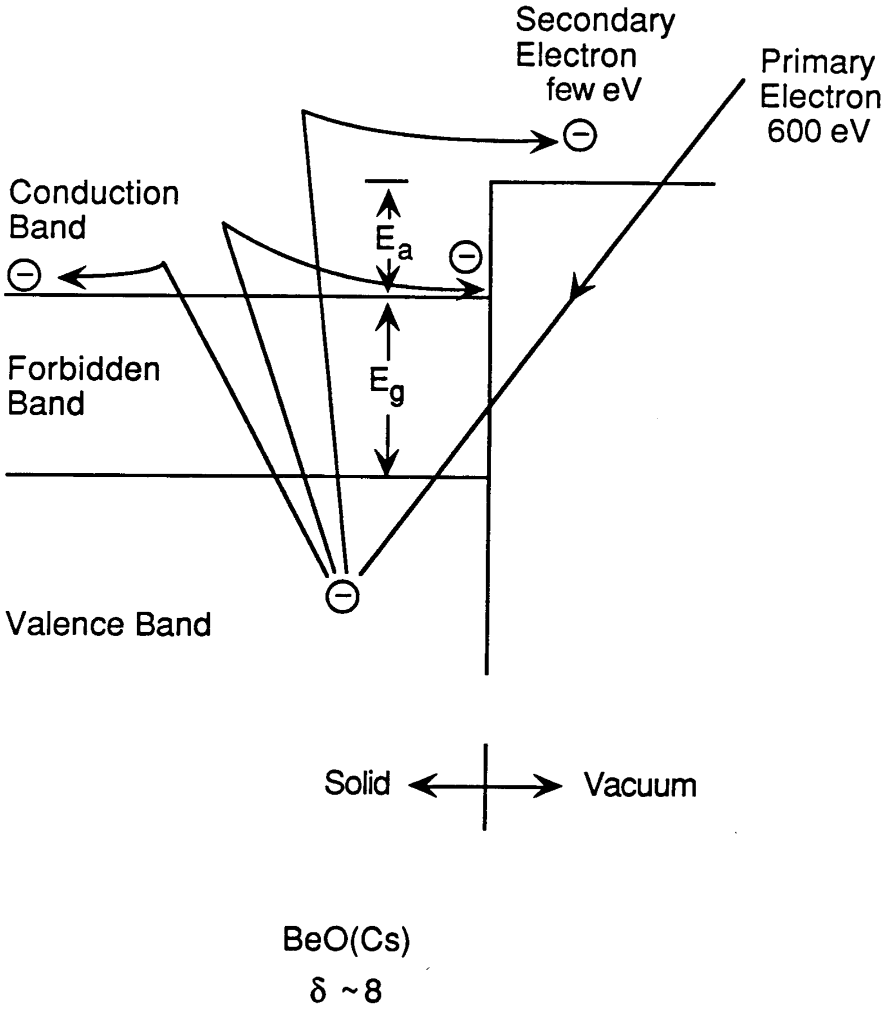


Fig. 27 - Cross section of a photomultiplier showing equipotential lines and electron trajectories that were plotted by computer.

(from *Photomultiplier Handbook*, Burle Industries)

Secondary Emission in Dynodes



(D. Persyk)

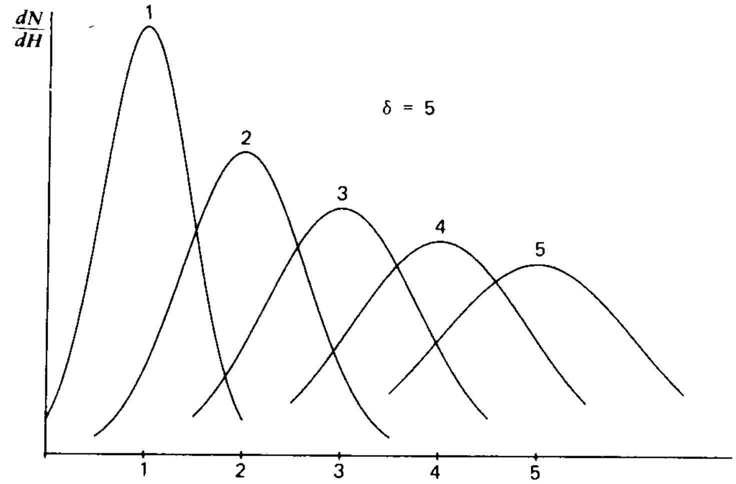
Process similar to photocathodes, but here the incident quantum is an electron.

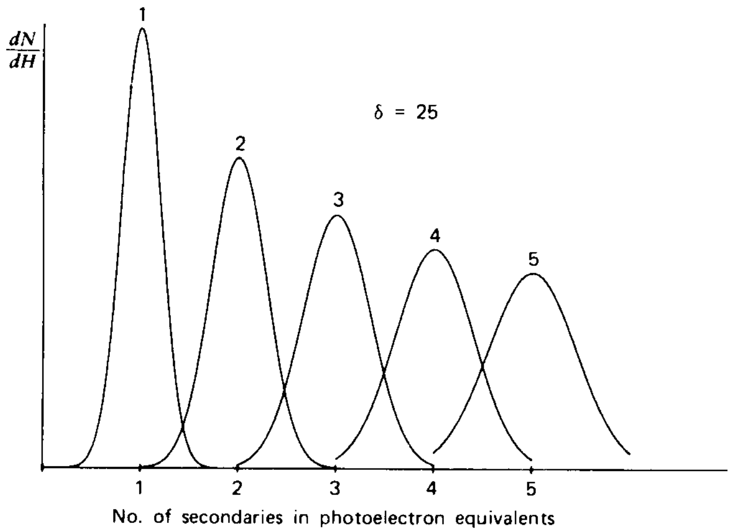
Desirable to obtain high secondary emission yields to reduce fluctuations (spectral broadening).

Typical dynode materials: Be0(Cs), Cs_3Sb, MgO

Negative electron affinity materials can also be used in dynodes, e.g. GaP(Cs) – higher emission yield, but more difficult to fabricate.

Spectra at output of PMT for 1, 2, 3 primary photoelectrons using conventional (δ = 5) and high gain (δ = 25) dynodes.

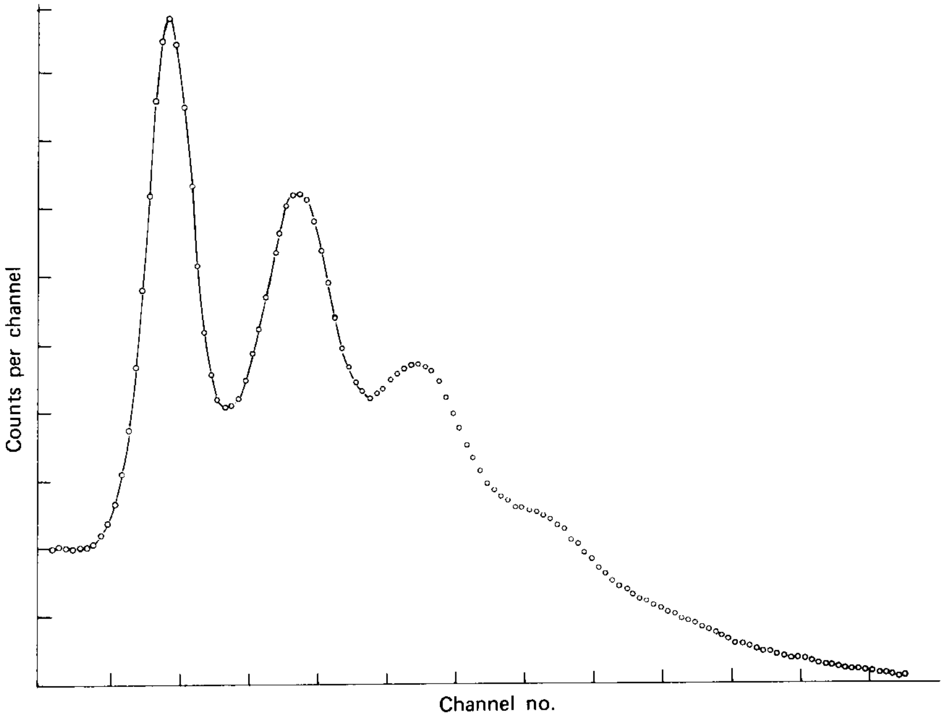




(from Knoll)

High emission dynodes allow resolution of single photoelectrons.

Output spectrum of a phototube using a high gain secondary electron emitter in the first dynode.



(from Knoll)

If the secondary electron yield in the first dynode is sufficiently high, the statistical fluctuations in the first gain stage will dominate.

Many different dynode configurations have been developed to reduce size, or improve gain, uniformity over large photocathode diameters, transit time and transit time spread.

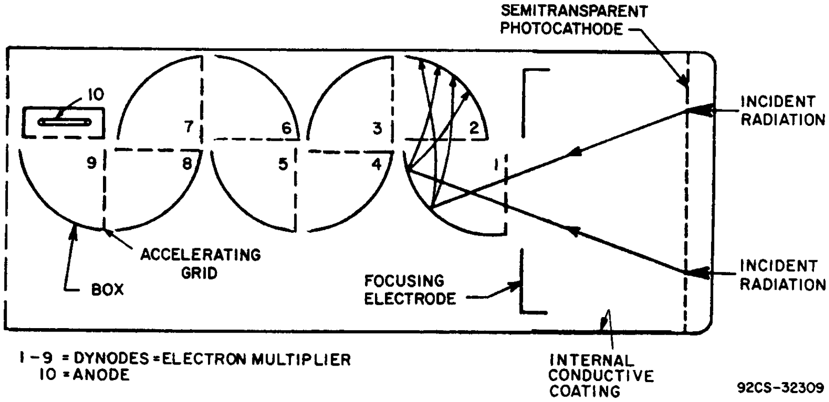


Fig. 23 - The box-and-grid multiplier structure.

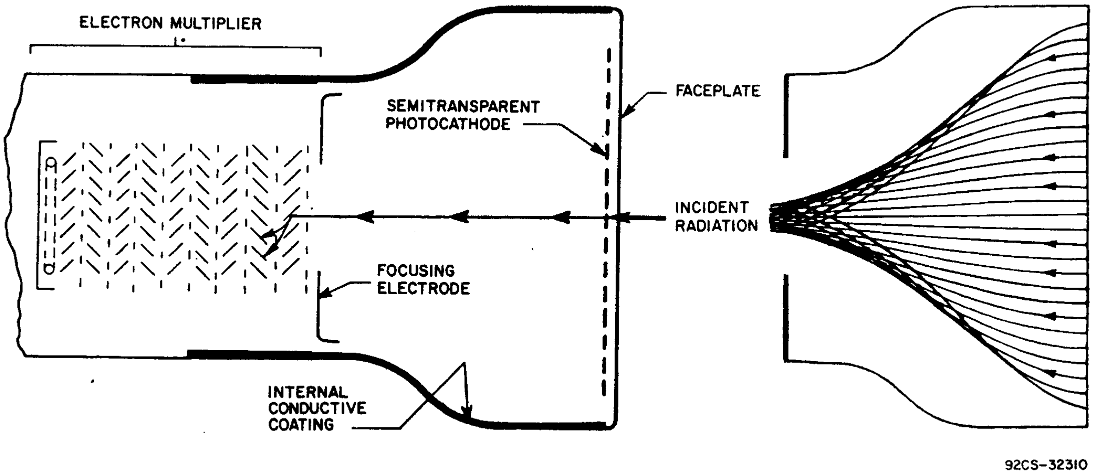
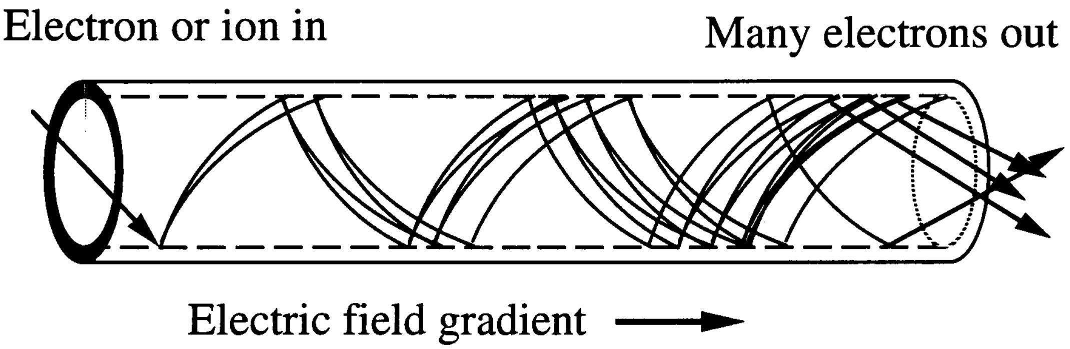


Fig. 24 - The venetian-blind multiplier structure.

(from *Photomultiplier Handbook*, Burle Industries)

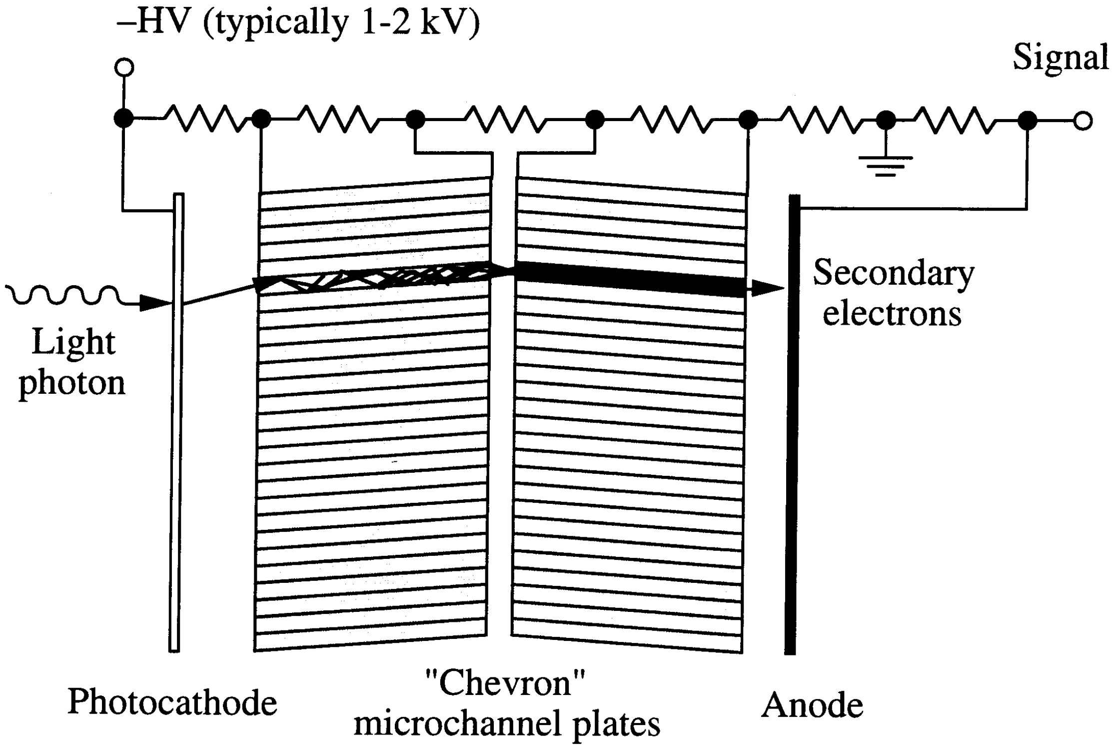
Continuous multiplier structures

Channel electron multiplier



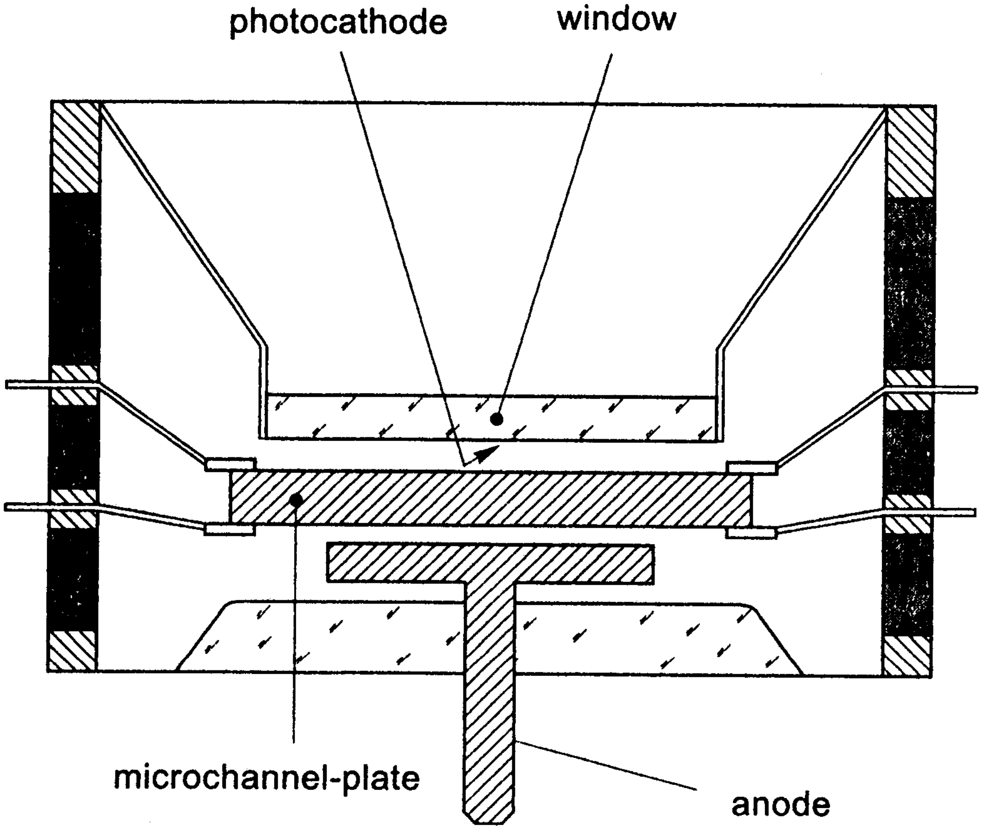
(from Derenzo)

Can be combined in “microchannel plates”



(from Derenzo)

Microchannel plates can be utilized in photomultipliers for ultra-fast timing with low time-dispersion.



(from *Photomultiplier Tubes*, Philips Photonics)

Signal Evolution

1. energy is absorbed in scintillator
2. population of states that emit photons

   number of radiative states

   $N_0 = E_{abs}/e_i$

E_{abs}	energy absorbed in scintillator
e_i	energy required to produce 1 photon

3. population of radiative states decays

   Þ rate of photon emission

   $$\frac{dN_{ph}}{dt} \equiv n_{ph}(t) = \frac{N_0}{t} e^{-t/t}$$

   Total number of photons emitted after time T

   $$N_{ph}(T) = \int_0^T n_{ph}(t)dt = N_0(1 - e^{-T/t})$$

4. photons absorbed in photocathode,
   producing photoelectrons

   $$n_{pe}(t) = QE \cdot n_{ph}(t) = QE \cdot N_0 e^{-t/t}$$

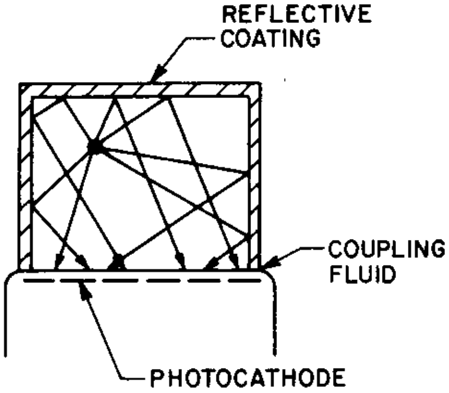
5. photoelectrons transported through gain structure (dynodes in PMT) multiplied by G

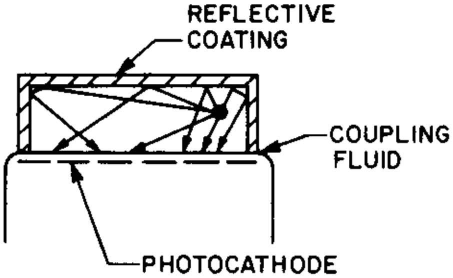
   Þ electric current at anode

   $$I_{anode}(t) = G \cdot QE \cdot N_0 e^{-t/t}$$

How much of this signal is actually obtained?

1. Scintillator is coupled to PMT at one surface





(from *Photomultiplier Handbook*, Burle Industries)

Scintillation light is emitted isotropically.

Depending on the geometry, at least half of emitted photons must be reflected one or more times to reach the faceplate of the photodetector.

Light losses due to

a) absorption in crystal

b) reflection losses

Invariably, scintillation crystals are optically denser than air.

examples:
NaI(Tl) $n = 1.85$
CsI(Tl) $n = 1.795$
$CdWO_4$ $n = 2.2 – 2.3$
BGO $n = 2.152$

NE102 $n = 1.581$ (plastic)
NE213 $n = 1.508$ (org. liquid)

air $n = 1$

⇒ Requirement for total reflection

$$\sin a \geq \frac{1}{n_{xtal}}$$

Light incident within an angle α from normal incidence will leave the crystal.

example $n_{xtal} = 1.5$ ⇒ $\alpha = 42°$

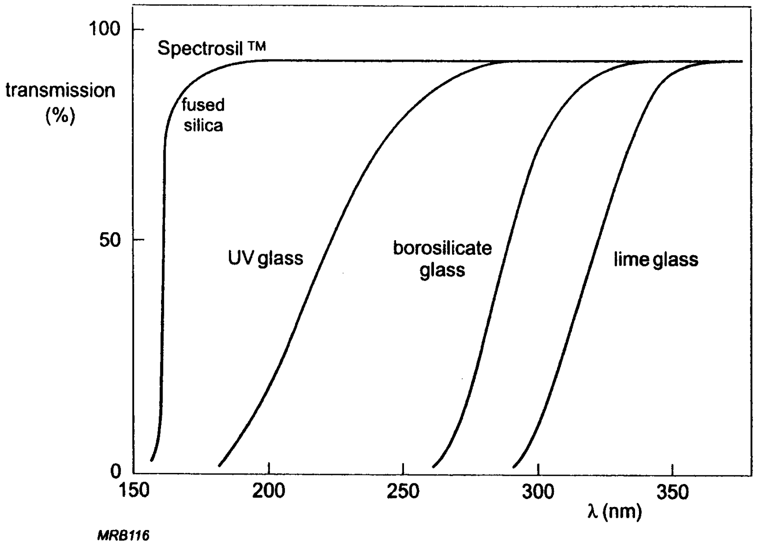
External reflective layers can improve this situation (see following discussion of light-guides).

2. Upon reaching the faceplate, light can be either transmitted or reflected

refractive index of faceplate
(borosilicate glass or fused silica) $n_{fp} \approx 1.5$

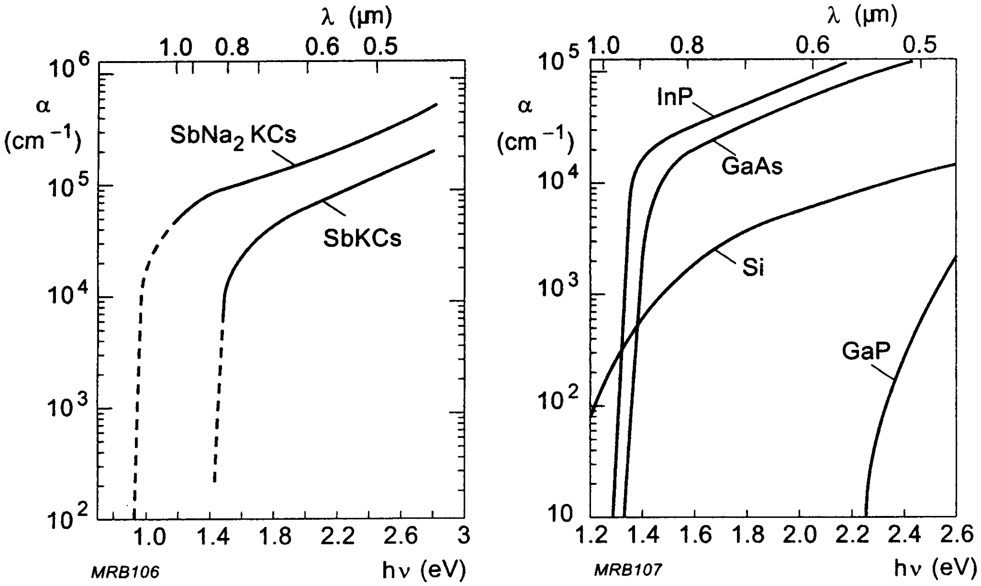
Important to avoid air-gap
(use optical grease to provide index match)

3. photons must be transmitted through the faceplate



(from *Photomultiplier Tubes*, Philips Photonics)

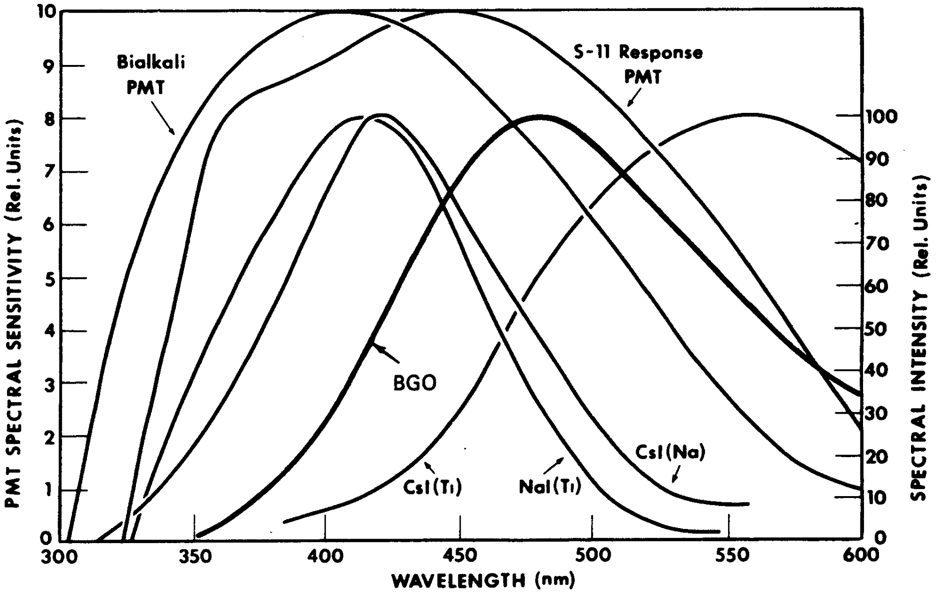
4. Photons must be absorbed in the photocathode



(from *Photomultiplier Tubes*, Philips Photonics)

5. Photoelectrons must traverse the photocathode and reach the first dynode to be multiplied.

It is important that the emission spectrum of the scintillator, the transmission through the faceplate and the absorption in the photocathode are matched.



(from Knoll)

Note that for short wavelength scintillators (for example the fast component of BaF_2 at 220 nm) conventional borosilicate faceplates are very inefficient – use fused silica for extended UV response.

Typical NaI(Tl) system (from Derenzo)

511 keV gamma ray

ß

25000 photons in scintillator

ß

15000 photons at photocathode

ß

3000 photoelectrons at first dynode

ß

$3\cdot10^9$ electrons at anode

2 mA peak current

Resolution of energy measurement determined by statistical variance of produced signal quanta.

$$\frac{\Delta E}{E}=\frac{\Delta N}{N}=\frac{\sqrt{N}}{N}=\frac{1}{\sqrt{N}}$$

Resolution determined by smallest number of quanta in chain, i.e. number of photoelectrons arriving at first dynode.

In this example

$$\frac{\Delta E}{E}=\frac{1}{\sqrt{3000}}=\text{ 2\% r.m.s. } = \text{ 5\% FWHM}$$

Typically 7 – 8% obtained, due to non-uniformity of light collection and gain.