Chap. 9 – Photomultiplier Devices

The scintillation process produces photons in proportion to the primary ionization (or in some cases, the range) … we need to count the number of photons to obtain the energy deposited by the primary radiation in the detector.

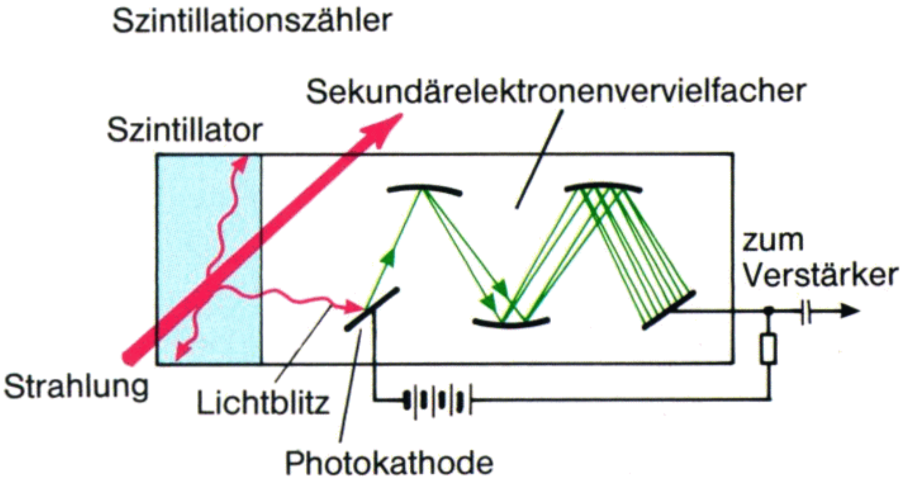
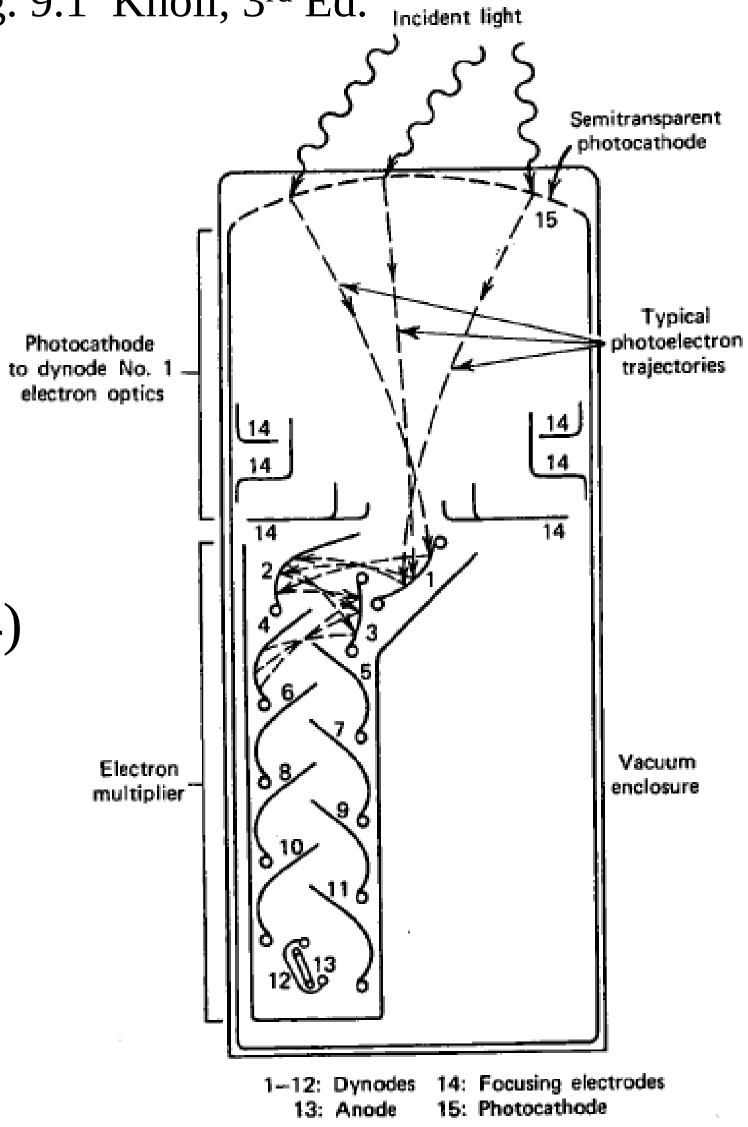


Fig. 9.1 Knoll, 3rd Ed.



- Photocathode / photoelectric effect
- Various coatings, low w & high quantum efficiency
- Electrons avalanche down a string of “dynodes” (8-14)
- Dynodes are also coated to enhance cascades
- HV can be positive or negative (schematics later)
- Vacuum tube – internal getter to maintain vacuum
- Low potassium glass (^{40}K)
- KE of electrons start out very low – some electron optics and external magnetic shields

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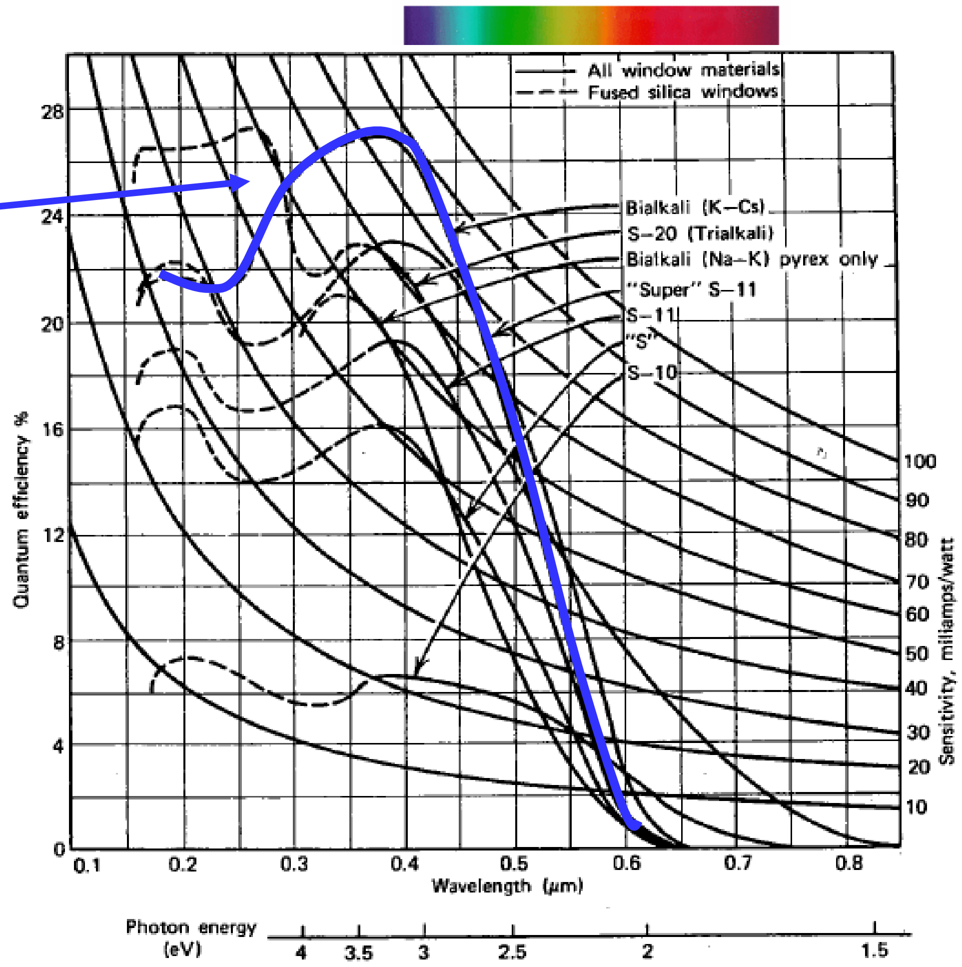
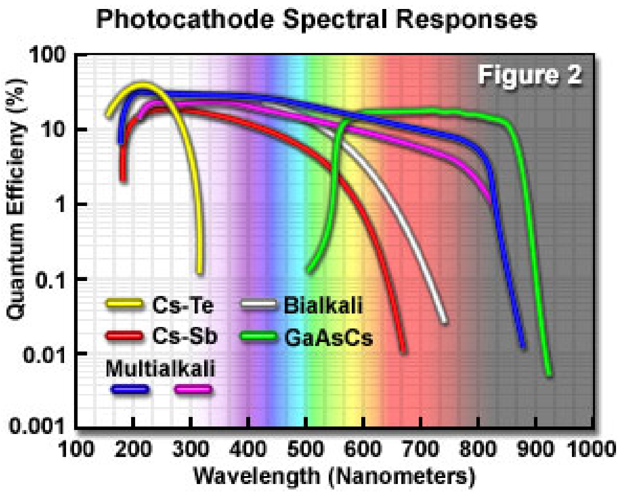
PMTs – Photocathode

Photocathode material should be matched to the output spectrum of the scintillator and is characterized by a quantum efficiency $\eta = N_e / N_{h\nu}$ or radiant sensitivity in mA/W or by luminous sensitivity in μA/lm .

Insulators/semiconductors are better than metals, all electrons are bound.
Free electrons in a conduction band tend to rescatter the Photoelectron and thermalize it before it can leave the metal.
"Bialkali" K_2CsSb $\eta \sim 25\%$
The layer is very thin (~30 nm) to allow the P.E to escape the layer – lowers absorption

Fig. 9.2 Knoll, 3rd Ed.





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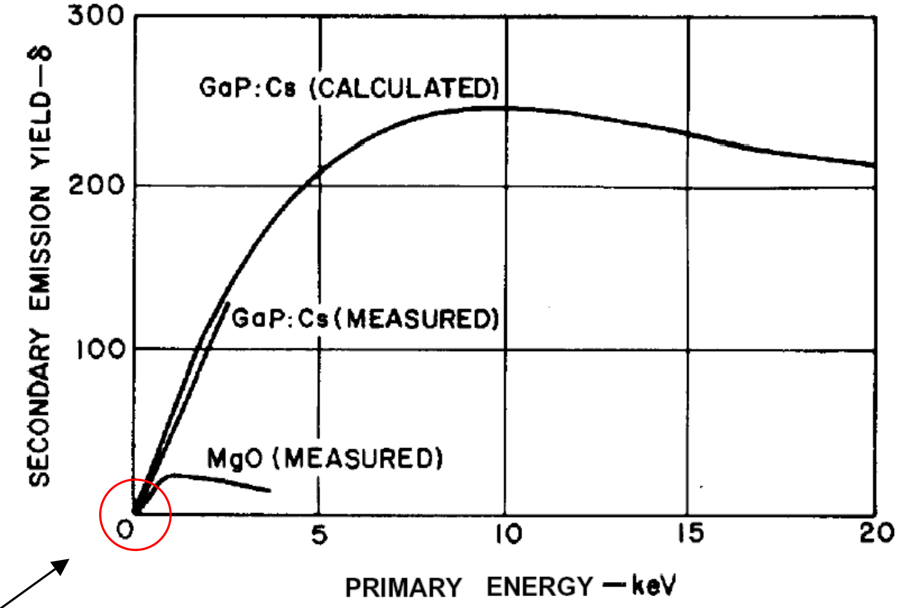
PMTs – Secondary Emission

The electrons are accelerated between dynodes $\Delta V \sim 100$ V, penetrate into the material (recall dE/dx …) and release secondary electrons.
Secondary emission from the dynodes is characterized by a coefficient: $\delta = N_s / N_p$.

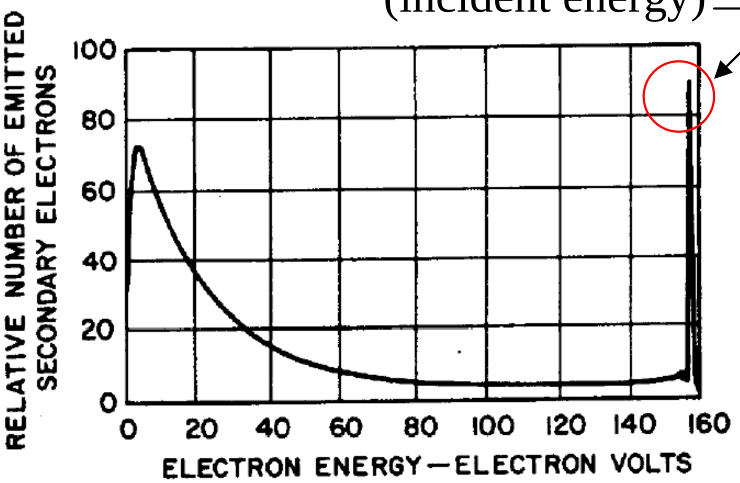
Typical dynode material is MgO, BeO, Cs_3Sb, recent materials are “negative electron affinity” GaP:Cs (see Fig. 9.4)



From Burle’s Photomultiplier Handbook

Secondary energy spectrum

(incident energy)



Typical value $\delta \sim 5$, range 3 – 10
Total gain in tube: $M = \delta^N$
Example: $\delta = 5$, N=10 gives $M = 5^{10} = 9.8 \times 10^6$
1% change, $\delta = 5.05$, $(5.05 / 5)^{10} \sim 10$ %

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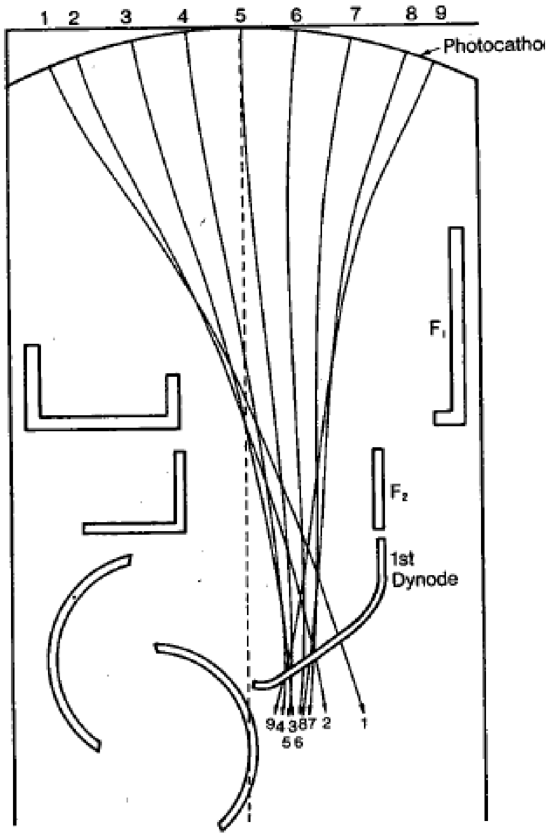
PMTs – Time Distribution



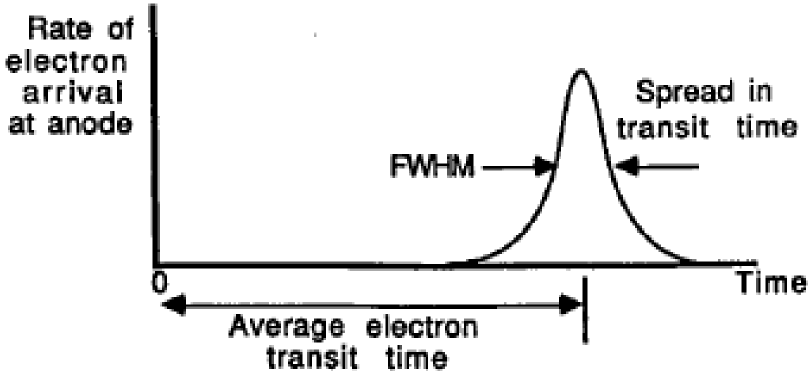
Electron optics between cathode and first dynode “focus” adjustment …

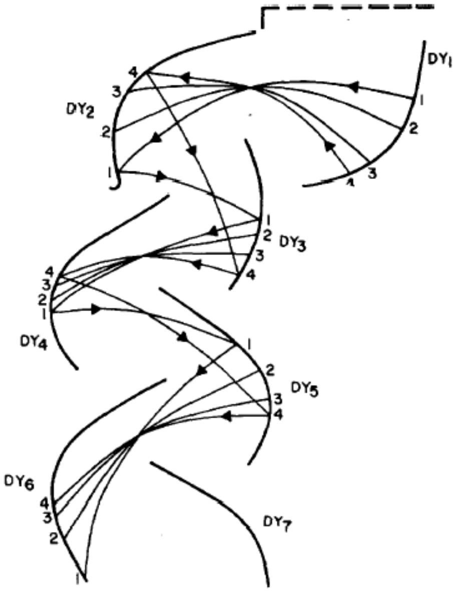
Nonrelativistic velocities: $qV = \frac{1}{2} mv^2$

Transit time: $t \sim N\,\Delta x / v \sim (N / \sqrt{V})$

Time Variance: $\sigma^2_{total} = \sigma^2_{Cath} + \sigma^2_{Dyn}\,\delta/(\delta-1)^2$

Figs. 9.10, 11 Knoll, 3rd Ed.





Beware of cartoon, $t \sim 50$ ns, $\sigma \sim 1\text{-}2$ ns

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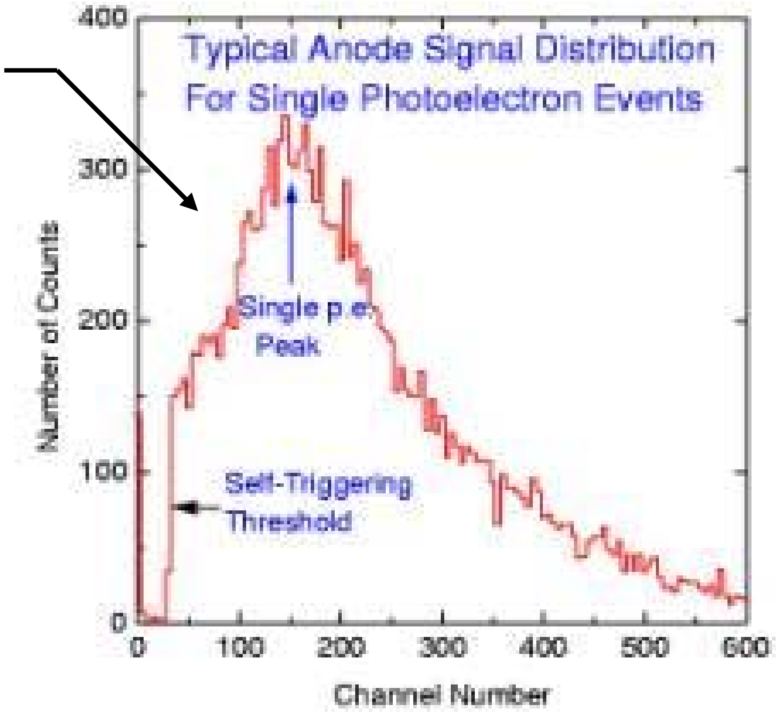
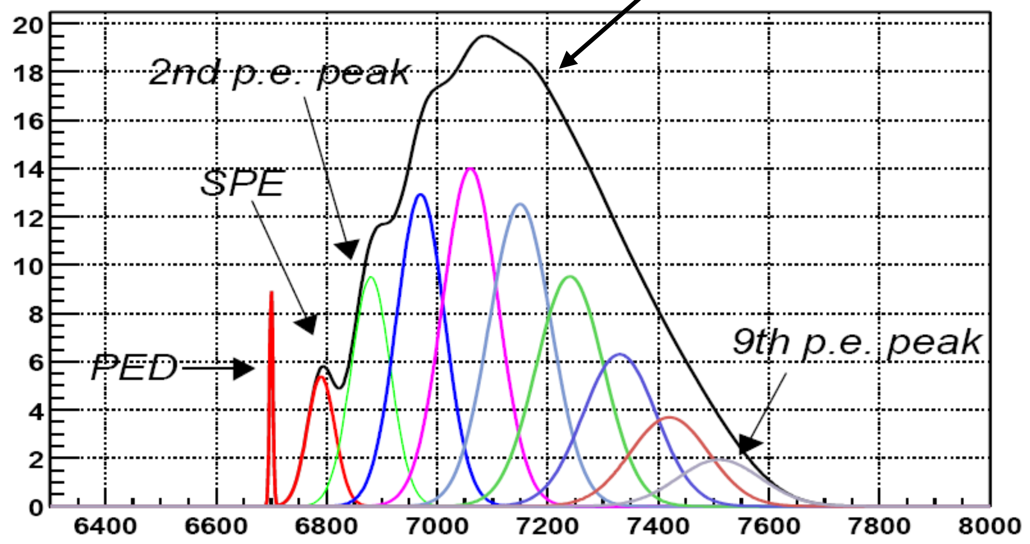
PMTs – Single Photoelectron Spectrum

PMTs can be run in high-gain modes that are sensitive to single photoelectrons. In such cases the anode current must follow a Poisson distribution characterized by a mean and width of 'one.' Multiple photoelectrons can be easily distinguished.

Only single photoelectron events



Curve from many events made up from individual events with discrete numbers of photoelectrons.



From *C.Andreopoulos, et al. NuMI-ANA-994 US/PHYS/HEP/18-10-2001*

(Related Fig. 9.6 in text shows separate peaks for n=1 – 4)

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PMTs – Resolution

$$Q = \alpha\, M = \alpha\, \delta^{N} \qquad \textit{where} \qquad \alpha = N_{PhotoElectrons} = N_{Photons}\,\eta\varepsilon_{collection} = \left(N_{IP}S\right)\eta\varepsilon_{collection}$$

$$\left(\frac{\sigma_Q}{Q}\right)^2 = \left(\frac{\sigma_\alpha}{\alpha}\right)^2 + \left(\frac{\sigma_\delta}{\delta^N}\right)^2$$

η < 1 so the number of photoelectrons essentially determines the resolution

The cascade across one dynode:

$$\bar{x} = \delta = \sigma_\delta^2$$

$$\left(\frac{\sigma_\delta}{\delta}\right)^2 = \left(\frac{\sqrt{\delta}}{\delta}\right)^2 = \frac{1}{\delta}$$

i-th sequential, identical dynode:

$$\left(\frac{\sigma_{\delta\, i}}{\delta_{\ i}}\right)^2 = \frac{1}{\delta_{\ 1}} + \left(\frac{1}{\delta_{\ 1}}\right)\left(\frac{1}{\delta_{\ 2}}\right) + \cdots + \left(\frac{1}{\delta_{\ 1}}\right)\left(\frac{1}{\delta_{\ 2}}\right)\cdots\left(\frac{1}{\delta_{\ i}}\right)$$

$$\left(\frac{\sigma_{\delta\, i}}{\delta_{\ i}}\right)^2 = \frac{1}{\delta} + \left(\frac{1}{\delta}\right)^2 + \cdots \left(\frac{1}{\delta}\right)^i$$

$$\textit{if}\ \ \delta > 1\ \&\ i\ \textit{large then} \left(\frac{\sigma_{\delta\, i}}{\delta_{\ i}}\right)^2 = \frac{1}{\delta - 1}$$

If number of photoelectrons is Poisson :

$$\left(\frac{\sigma_Q}{Q}\right)^2 = \left(\frac{1}{\alpha}\right) + \left(\frac{1}{\delta - 1}\right)$$

Potential problems:

- Are photons monochromatic? η
- Are photoelectrons monoenergetic? ε
- Is *S* a constant?

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PMTs – other resolution issues

Stray B-fields – use so-called mu-metal or iron shields

Differential sensitivity of photocathode surface – diffuse light over surface

Dark current – thermal photoelectrons, electronic noise, cosmic rays

High voltage stability … Q ~ V^n where n ~ (number stages minus a few)

Gassy tubes … electrons ionize residual gas and give afterglow.

Photocathode glass … transparent to uv or not?

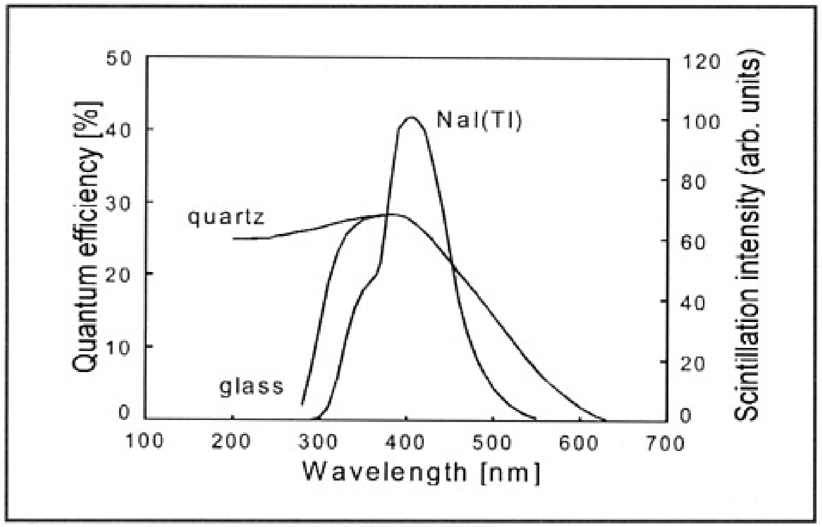

Fig. 4.2 ***Quantum efficiency curve of a standard bialkali photocathode together with the scintillation emission spectrum of NaI(Tl).***

http://www.scionixusa.com/

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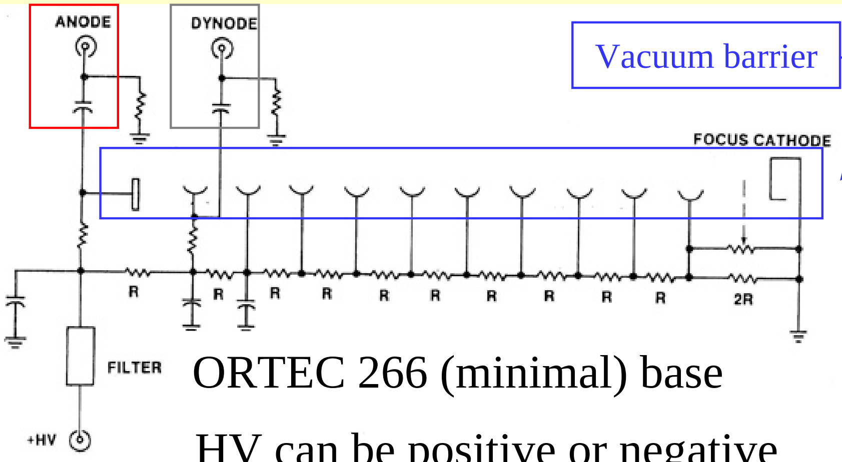
PMT Bases – Voltage Distribution

Vacuum barrier



ORTEC 266 (minimal) base

HV can be positive or negative
If (+) then anode is +HV, “AC-coupled”

If (–) then anode is Gnd, “DC-coupled”
cathode is –HV … glass becomes charged

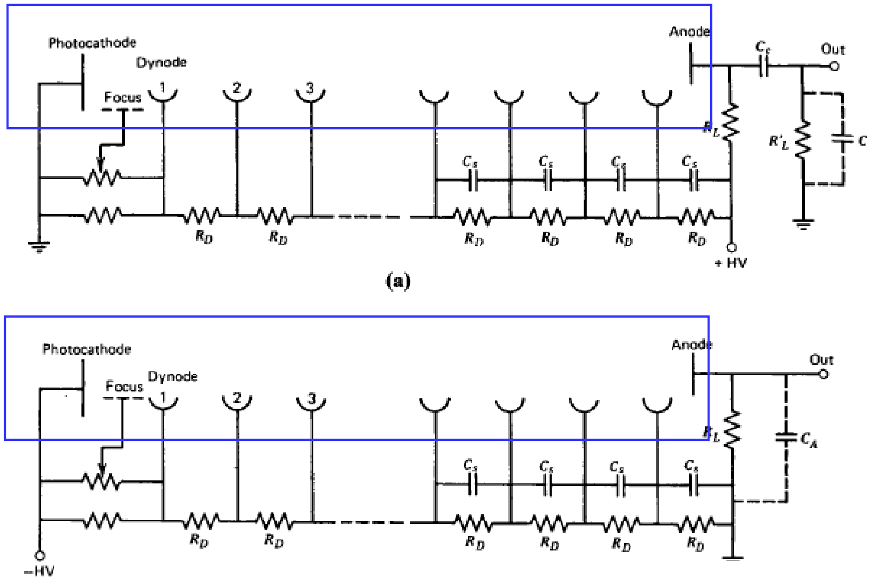


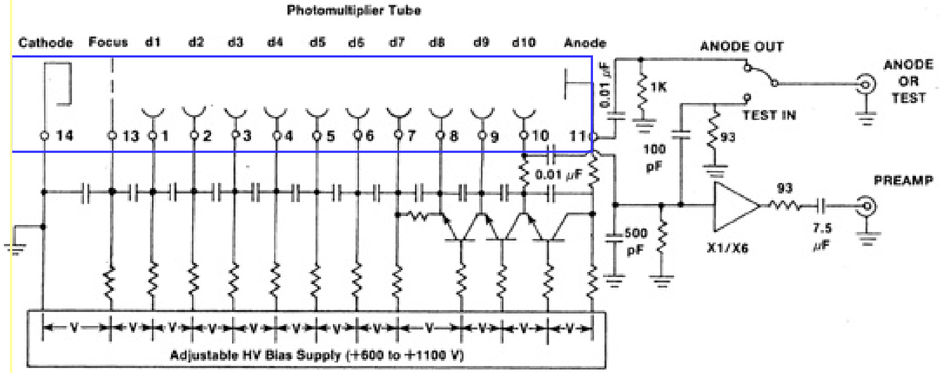
Fig. 9.13 Knoll, 3rd Ed.

Example: Estimate the anode current in a typical PMT for a NaI(Tl) scintillator.

NaI(Tl) ~40k photons/MeV, τ =230ns,
PMT: $\eta = 0.25$, $M=10^6$
rough Photoelectron Rate ~ N(e$^-$)/τ ~ 43 /ns
I = dQ/dt ~ (43 e$^-$/1x10^{-9} s) 10^6 (1.602x10^{-19} coul/e$^-$)

I ~ 7x10^{-3} A = 7 mA !! for one pulse
Crude approach: set current in Resistor chain “10x I”
but this leads to high power dissipation P = V I ~ 100W

Bypass capacitors:
C ~100 Q /V so that the voltage drop is no more than 1% of V



ORTEC 296 “active” base

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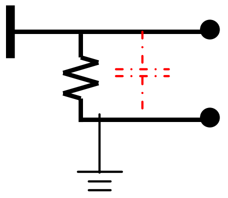
PMTs – DC Pulse shape

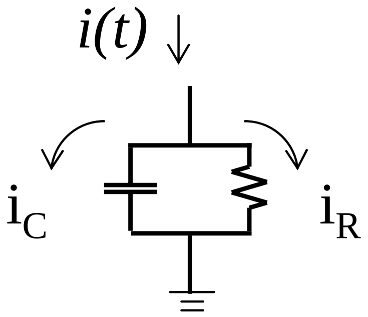


Model of the connection to the anode of a DC-coupled PMT

$i(t) = i_0\, e^{-\lambda t}$ with λ from scintillator,

with boundary condition: $Q = \int_0^\infty i_0 e^{-\lambda t} dt = i_0 / \lambda$

$i(t) = \lambda Q\, e^{-\lambda t}$



$$i(t) = \lambda Q e^{-\lambda t} = i_C + i_R \quad \leftrightarrow \quad i(t) = \frac{dq}{dt} + \frac{V(t)}{R}$$

$$i(t) = \lambda Q e^{-\lambda t} = C\frac{dV}{dt} + \frac{V}{R}$$

$$\frac{dV}{dt} = \frac{\lambda Q}{C} e^{-\lambda t} - \frac{V}{RC}$$

$$V(t) = \frac{1}{\lambda - \Theta}\left(\frac{\lambda Q}{C}\right)\left[e^{-\Theta t} - e^{-\lambda t}\right] \quad \Theta = \frac{1}{RC}$$

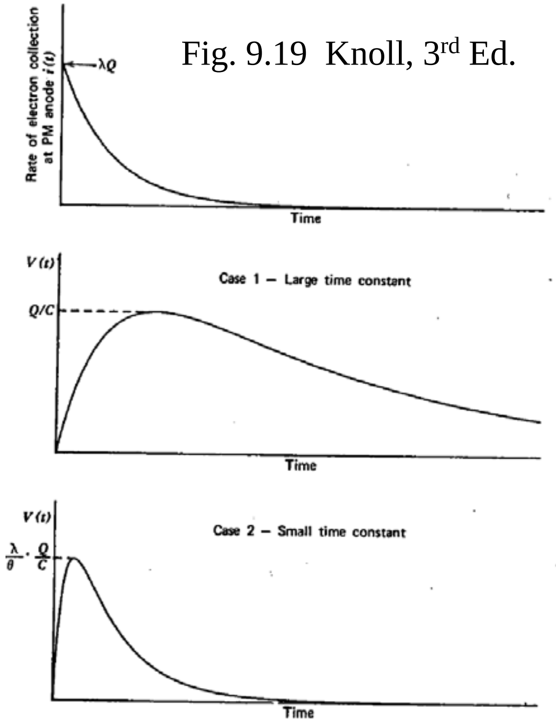


Fig. 9.19 Knoll, 3rd Ed.

Pulse maximum, set dV(t)/dt = 0

$$t_{\max} = \frac{1}{\Theta - \lambda}\ln\left(\frac{\Theta}{\lambda}\right) = \ln\left(\frac{\Theta}{\lambda}\right)^{\frac{1}{\Theta-\lambda}} \qquad V(t_{\max}) = \left(\frac{\lambda Q}{C[\lambda - \Theta]}\right)\left[\left(\frac{\Theta}{\lambda}\right)^{\frac{-\Theta}{\Theta-\lambda}} - \left(\frac{\Theta}{\lambda}\right)^{\frac{-\lambda}{\Theta-\lambda}}\right]$$

If “slow” electronics: RC >> τ then $\Theta \ll \lambda$ and $V(t_{\max}) = Q/C$

If “fast” electronics: RC << τ then $\Theta \gg \lambda$ and $V(t_{\max}) = Q\lambda/\Theta C \ll Q/C$

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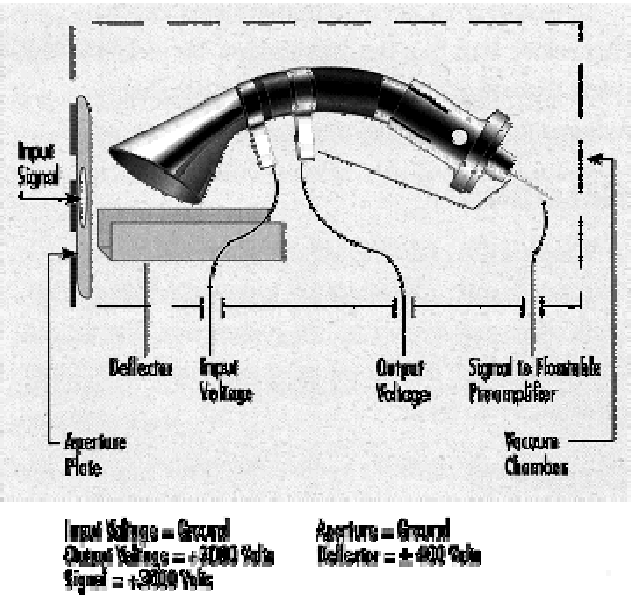
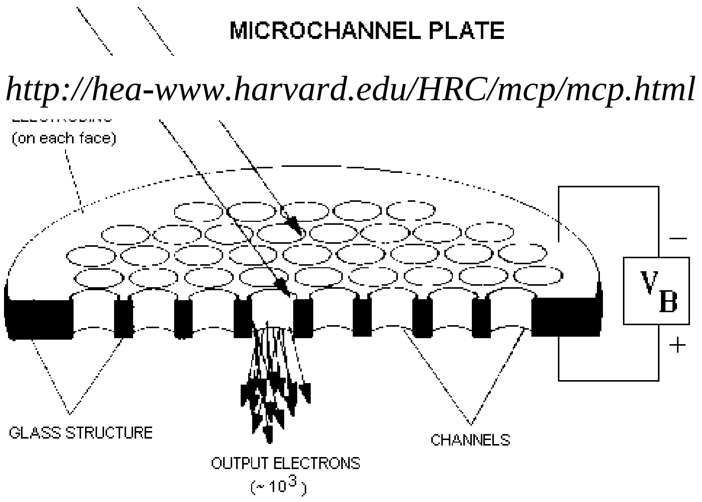
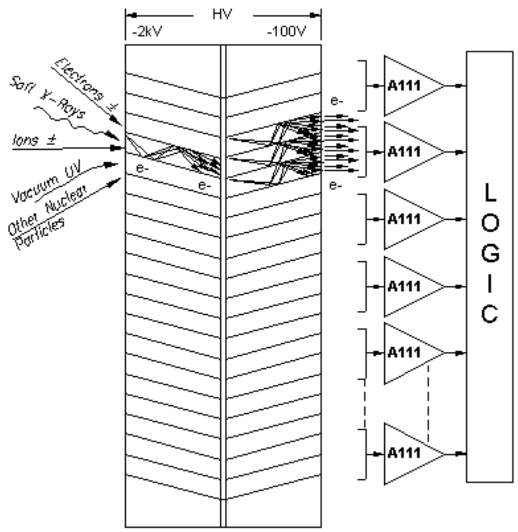
Electron multipliers – other devices

Channeltron: essentially a continuous dynode in a curved tube.





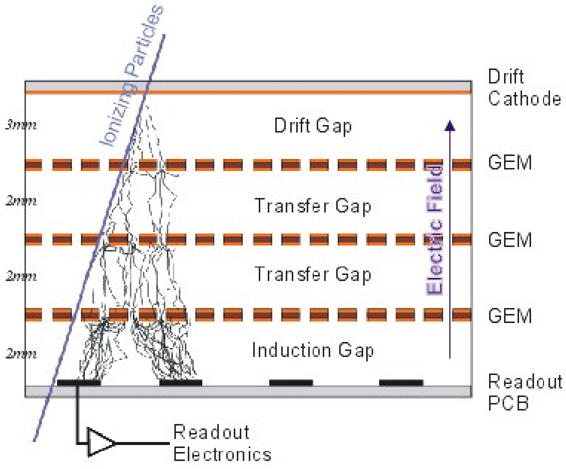
http://hea-www.harvard.edu/HRC/mcp/mcp.html

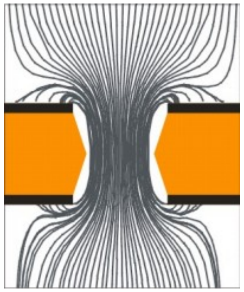


Chevron configuation is “opaque”

Typical Phillips device 12.5 μm ϕ 15 μm apart $\rightarrow \varepsilon_{geo} \sim 0.55$

GEM gaseous electron multiplier: derivative of gas-filled proportional counter





Copper
Kapton
Copper

Typical device 70 μm ϕ 140 μm apart, M ~ 10^3

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