Photomultipliers and Avalanche Photodiodes

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Beam Diagnostics Using Synchrotron Radiation:
Theory and Practice
US Particle Accelerator School
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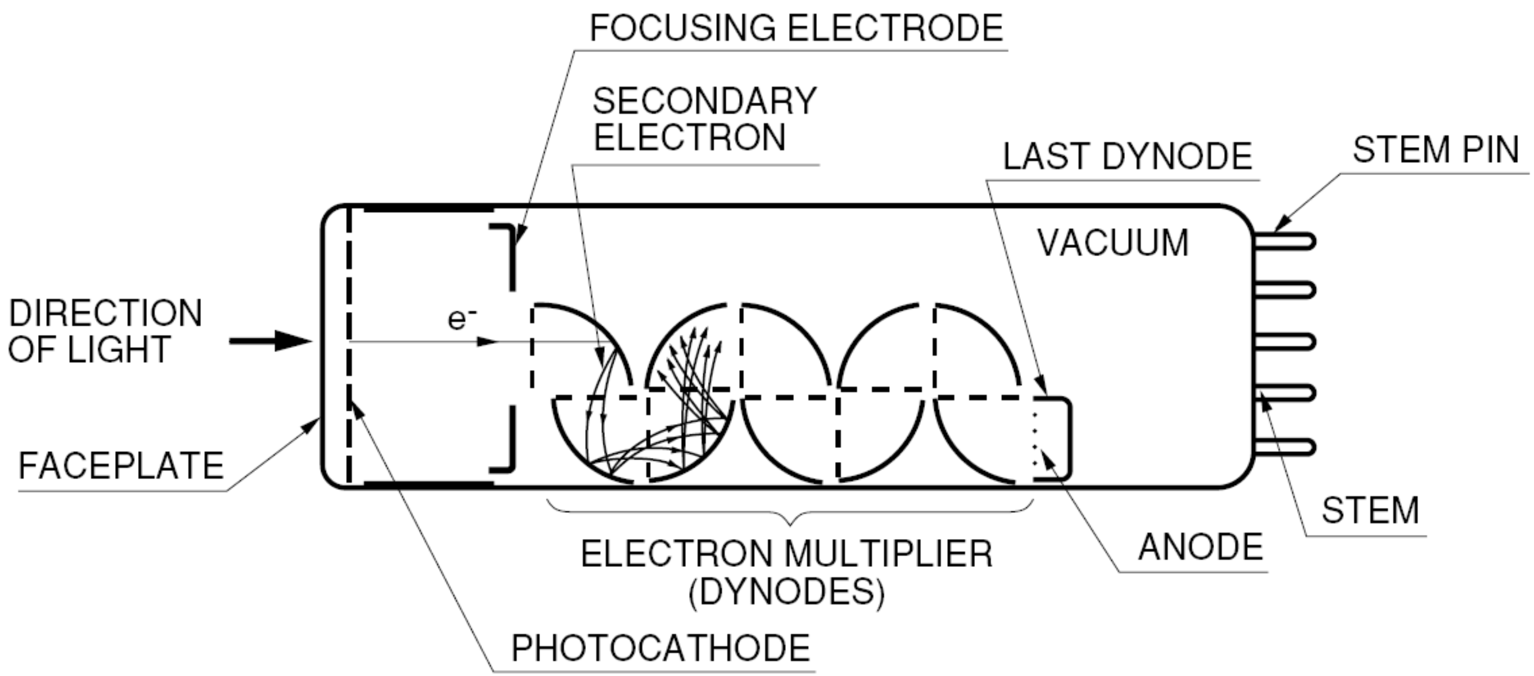
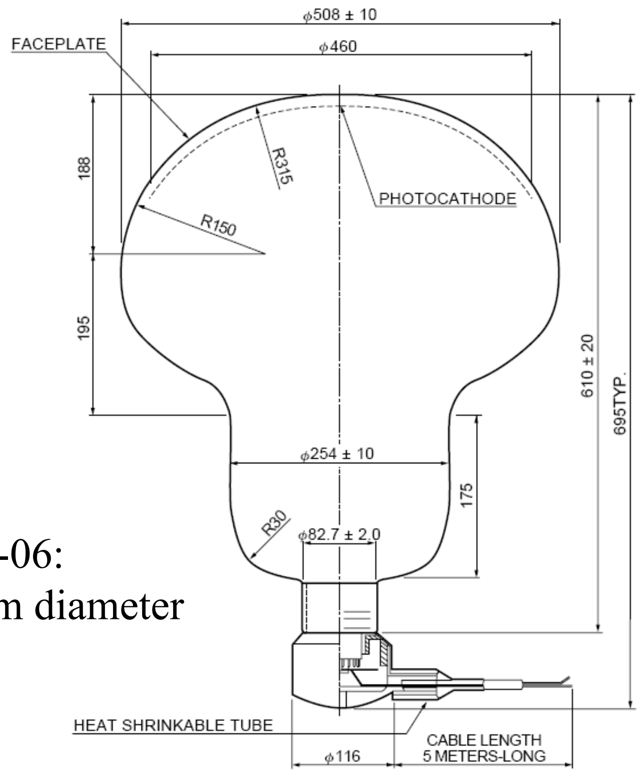
Structure of a PMT

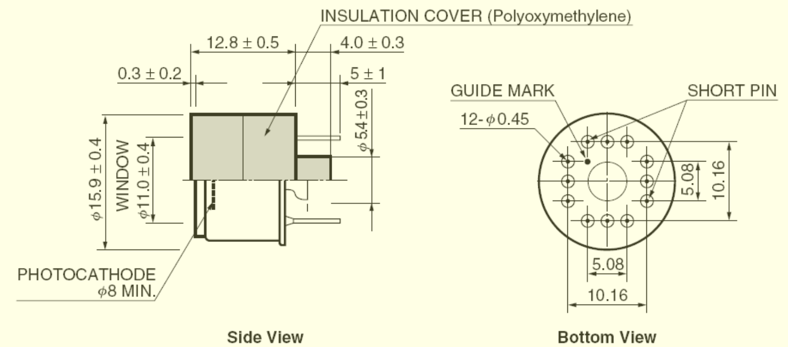


- Photocathode converts light to electrons.
- Dynodes multiply number of electrons by secondary emission.
  - Overall gain can be 10^6, depending on applied voltage.
- Anode collects the resulting current.

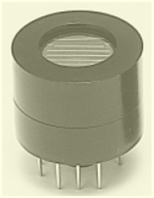
Many Sizes and Shapes



R3400-06:
508 mm diameter



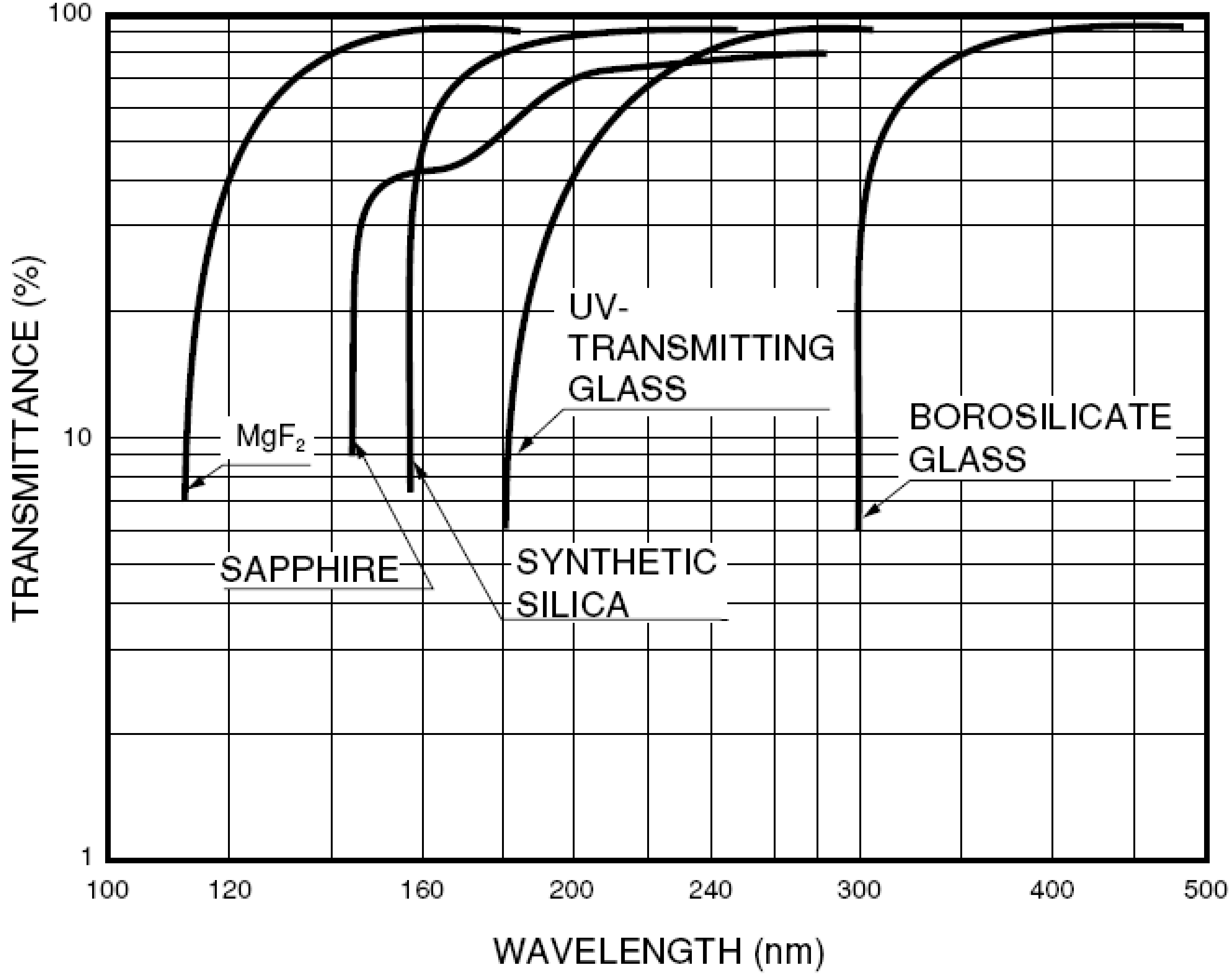
R7400U-06:
16 mm diameter
(our PMT)



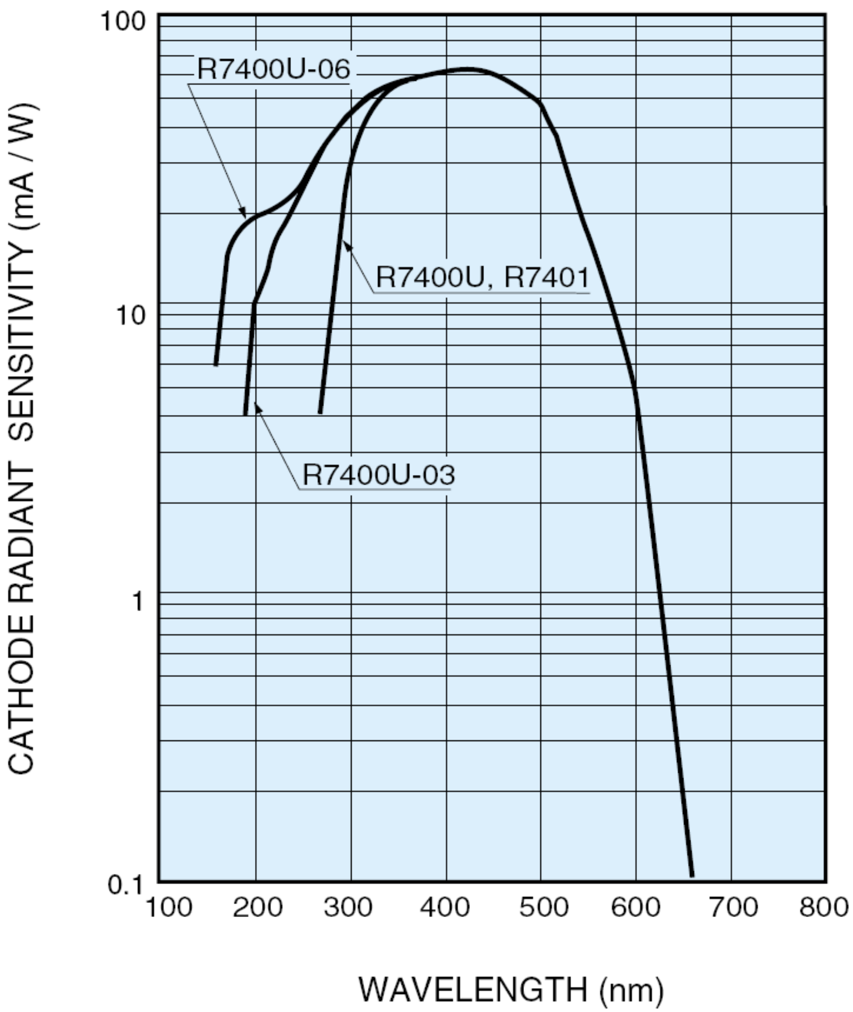
R8520:
30 mm square

R9220:
28 mm diameter
side entry for light

Window Materials



Photocathodes and Quantum Efficiency

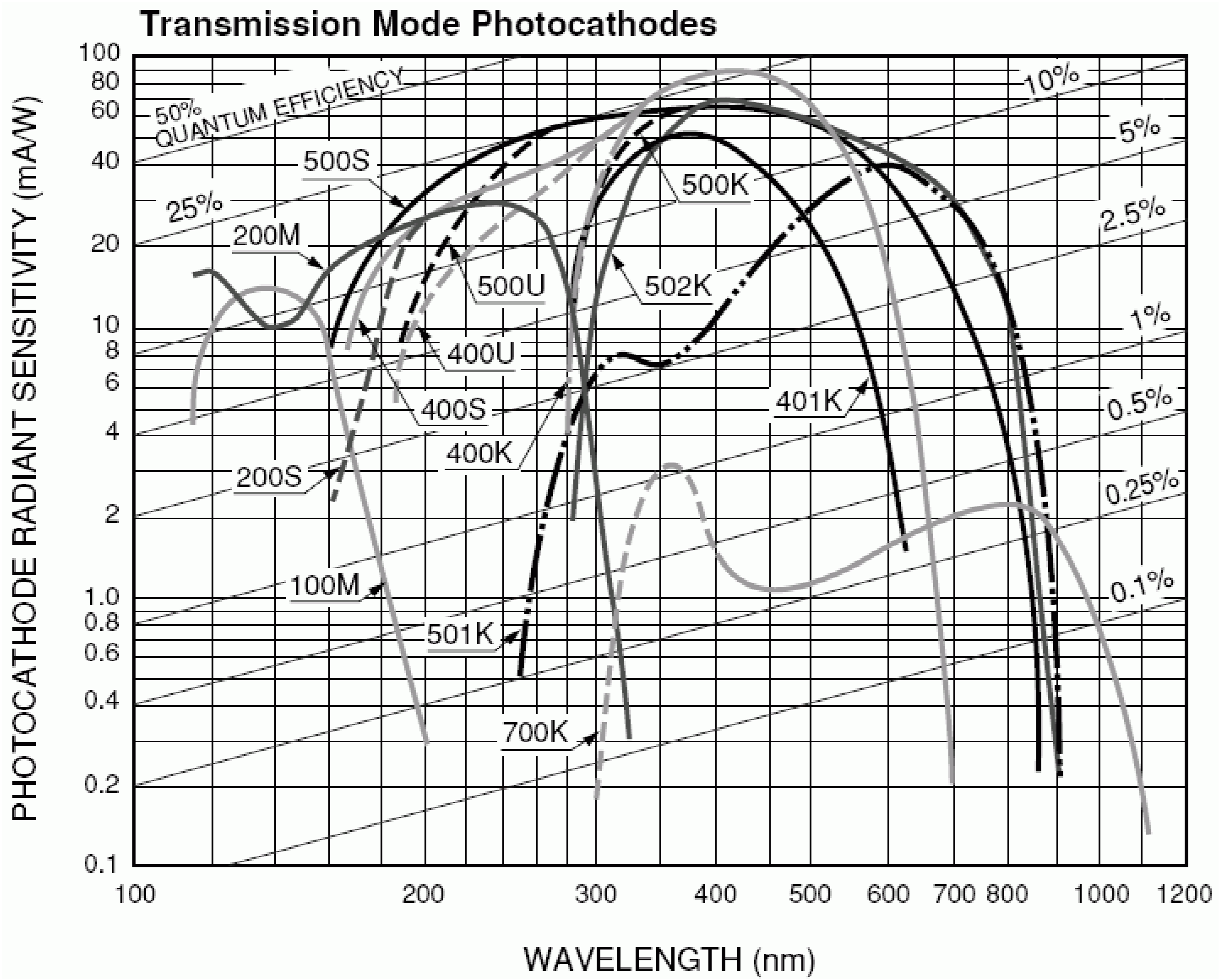


- The quantum efficiency $\varepsilon_{\mathrm{QE}}$ of a photocathode is the number of photoelectrons emitted per arriving photon.
- The QE is related to the radiant sensitivity S (amps/watt, plotted at right) by:

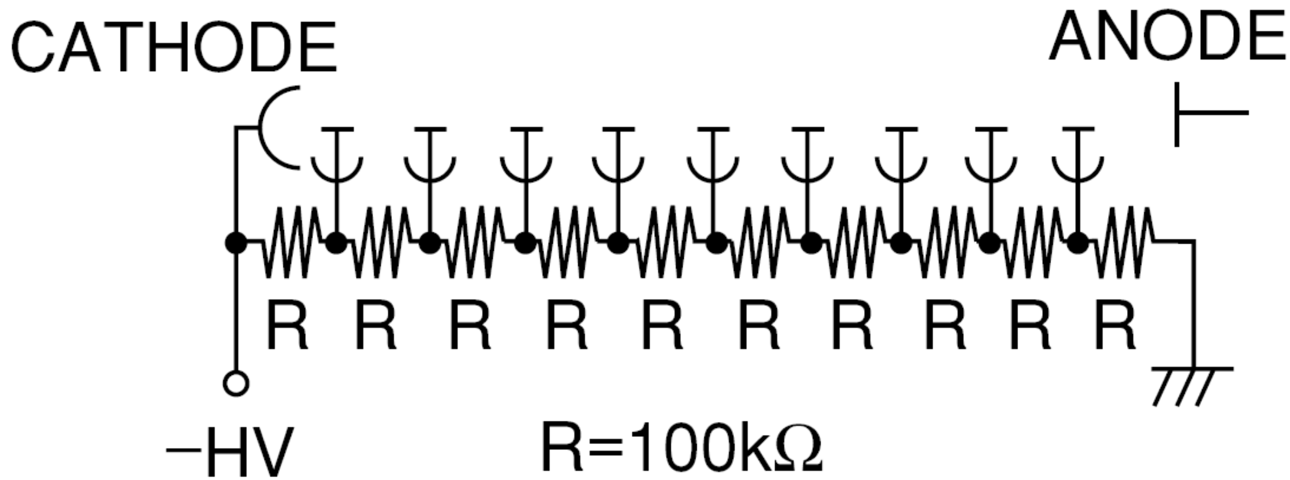
$$\varepsilon_{\mathrm{QE}} = S\frac{hc}{e\lambda}$$

- We will use the Hamamatsu R7400U-06, which has a peak QE of 19%.

Typical Photocathodes and Their QEs

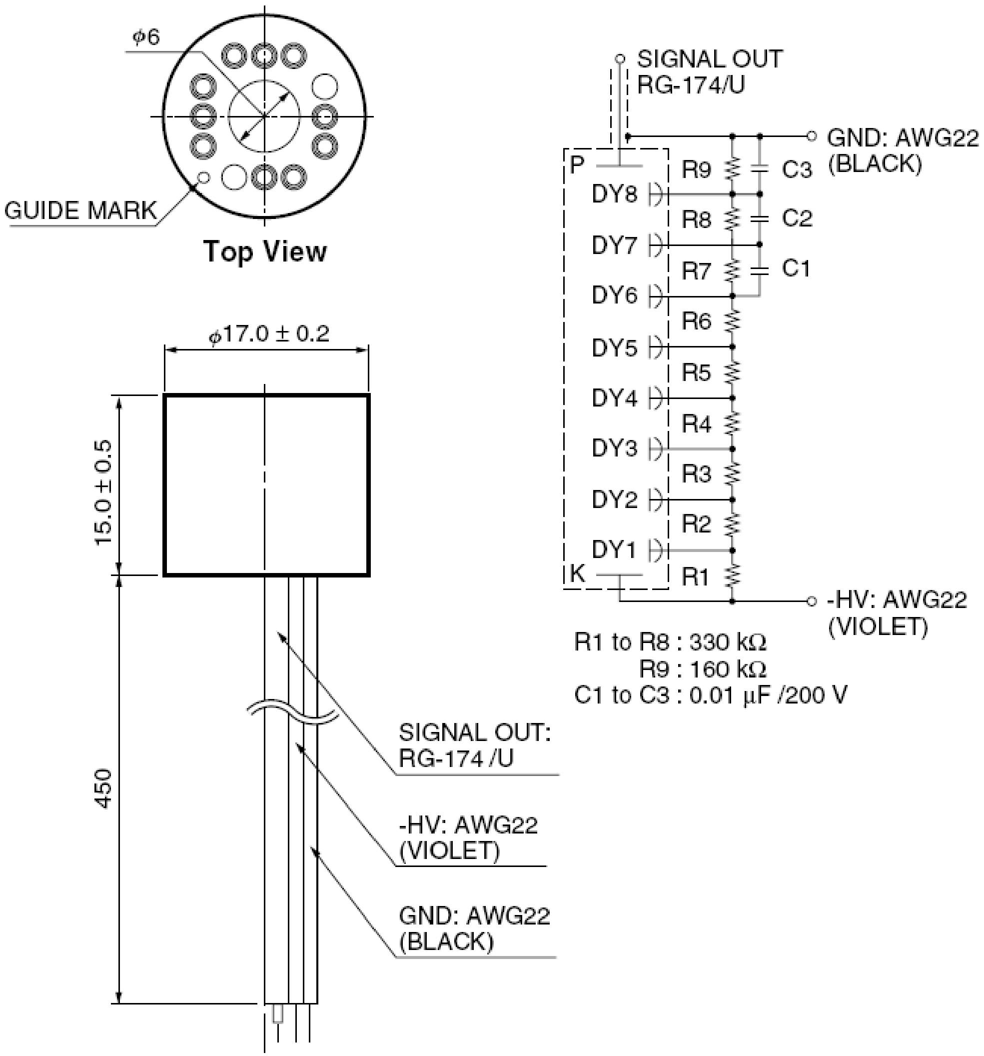


Dynode Bias



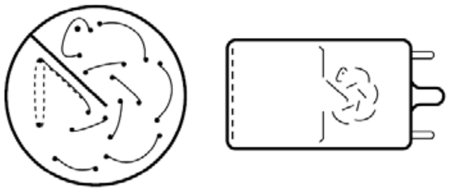
- Usually cathodes are at negative high voltage, from -500 V to -2 kV, and the anode is directly coupled to an oscilloscope or other devices.
  - Sometimes the anode is at +HV, and must then be connected to the scope through a DC-blocking capacitor.
- A resistor chain biases the dynodes at successively more positive voltages.

Bias for our PMT

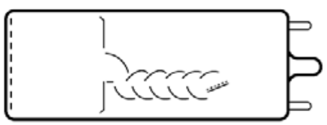


- A resistor chain is built into our PMT socket, a Hamamatsu E5780.
- Capacitors added to final dynodes supply large pulsed currents without reducing biasing current in the resistor chain.

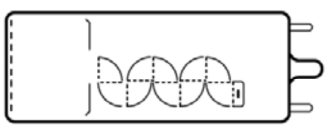
Dynode Structures



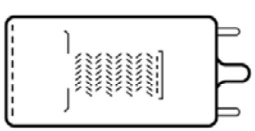
(1) Circular-cage Type



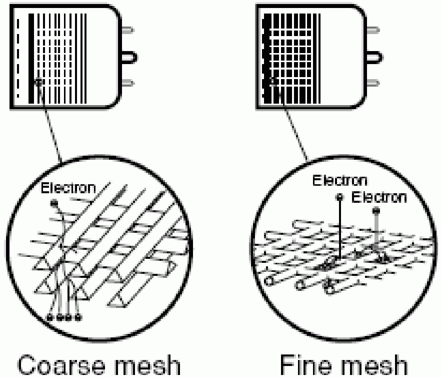
(3) Linear-focused Type



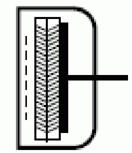
(2) Box-and-grid Type



(4) Venetian Blind Type

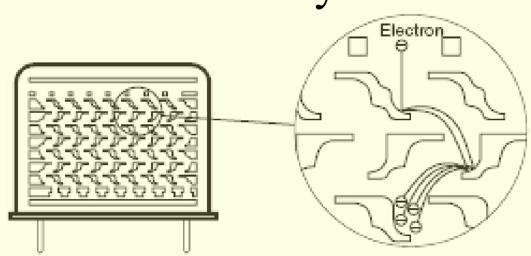


(5) Mesh Type

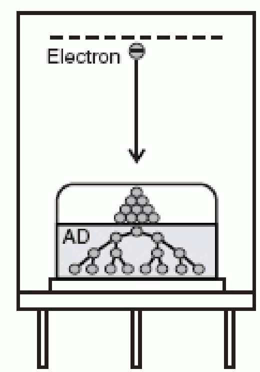


(6) Microchannel Plate Type

Our PMT has eight metal-channel dynodes.

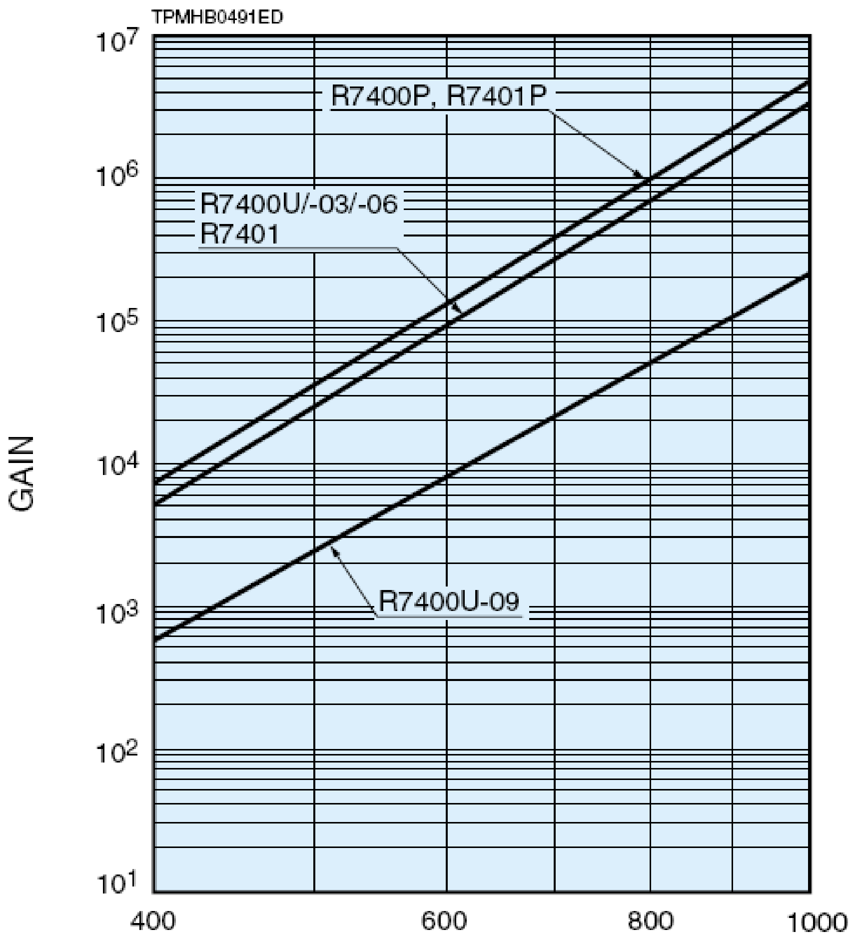


(7) Metal Channel Dynode Type



(8) Eelectron Bombadment Type

Gain in the PMT



- At maximum voltage, $V = 1$ kV, our PMT has a gain
  $$G = 3.2\times10^6$$
  from the 8 dynodes.
- The gain per dynode is
  $$(3.2\times10^6)^{1/8} = 6.5$$
- This gain is a function of the accelerating voltage v_i between adjacent dynodes stages:
  $$g_i = a v_i^k \text{ with } k \approx 0.75.$$

Time Response of a Photomultiplier

- Transit-time delay: Dynode-to-dynode acceleration.
  - Example: 2 kV divided equally in a PMT with 9 dynodes that are 5 mm apart.
    - 10 acceleration stages (to each dynode and to anode) = 200 V/stage
    - Time per stage = 1.2 ns. Transit time for the tube = 12 ns.
- Pulse spread and rise time:
  - Secondaries emitted at random angles.
  - Take different paths to the next dynodes.
- Our small PMT has a faster response:

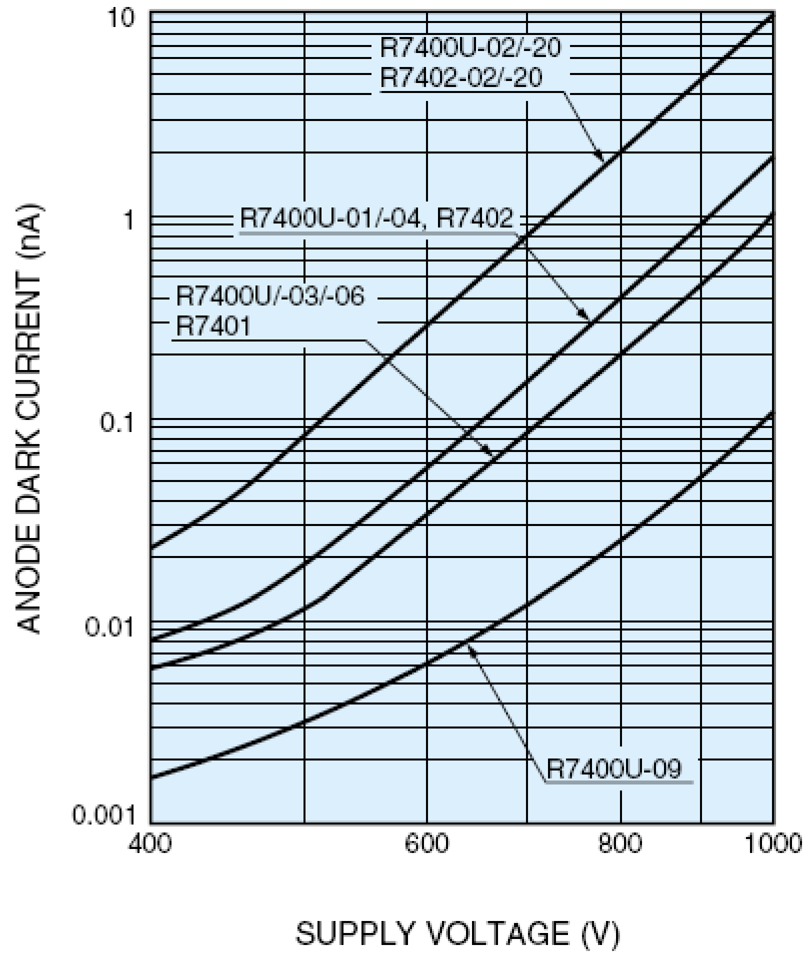
Transit time	5.4 ns
Transit-time spread	0.23 ns
Rise time	0.78 ns

Noise in a Photomultiplier

- Noise in the PMT is due to shot noise at every stage.
  - Model as a Poisson process: Standard deviation = square root of the number of particles.
  - Dominant stage is the photocathode, where N_{ph} incoming photons produces a small number N_{pe} of photoelectrons.

$$\sigma_{\mathrm{pe}} = \sqrt{N_{\mathrm{pe}}} = \sqrt{\varepsilon_{\mathrm{QE}} N_{\mathrm{ph}}}$$

- Dark current
  - Electrons pulled from a surface by the voltage, producing a signal without light.



Avalanche Photodiodes (APD)

- Used in the LBNL fluctuation experiment.
- Solid state with a single stage.
- Cathode diameters from 0.2 to 5 mm.
- Smaller cathode area and faster response than a PMT.
- Higher QE, but lower output than a PMT:
  - This APD: 20 A/W peak
  - Our PMT:
    - 62 mA/W at peak at cathode
    - Peak gain is 3.2×10^6
    - Output of 2.0×10^5 A/W. Useful for:
      - Weak light.
      - Short bursts of high current (with suitable dynode bias, including capacitors).