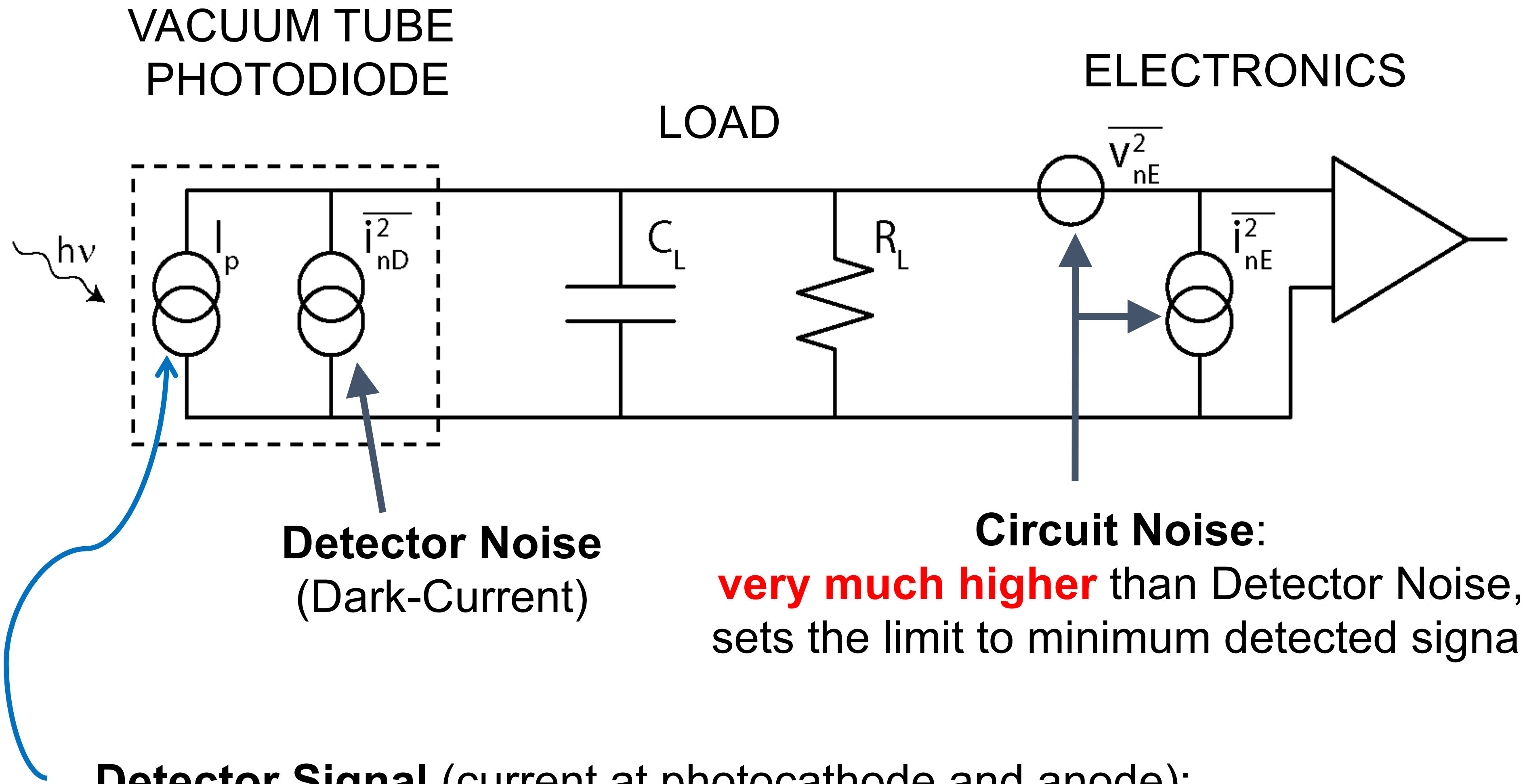
# COURSE OUTLINE

- Introduction
- Signals and Noise
- Filtering
- Sensors: PD4 - PhotoMultiplier Tubes PMT

# Photo Multiplier Tubes (PMT)

- Photodetectors that overcome the circuit noise
- Secondary Electron Emission in Vacuum and Current Amplification by a Dynode Chain
- Photo Multiplier Tubes (PMT): basic device structure and current gain
- Statistical nature of the current multiplier and related effects
- Dynamic response of PMTs
- Signal-to-Noise Ratio and Minimum Measurable Signal
- Advanced PMT device structures

# Circuit Noise limits the sensitivity of photodiodes ...

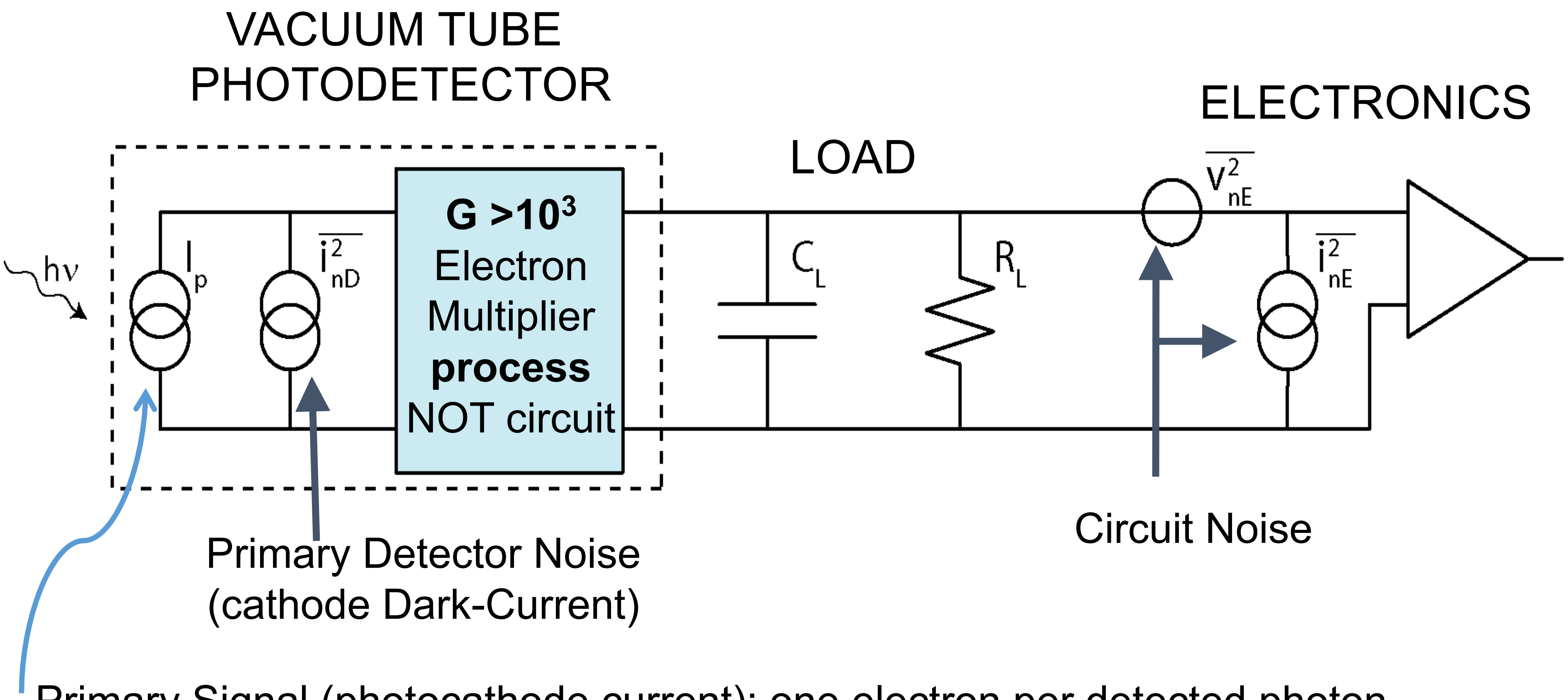


**Detector Noise**
(Dark-Current)

**Circuit Noise**:
**very much higher** than Detector Noise,
sets the limit to minimum detected signal

**Detector Signal** (current at photocathode and anode):
just one electron per detected photon!

# … but an Electron Multiplier Overcomes the Circuit Noise



VACUUM TUBE PHOTODETECTOR

ELECTRONICS

LOAD

**$G > 10^3$** Electron Multiplier **process** NOT circuit

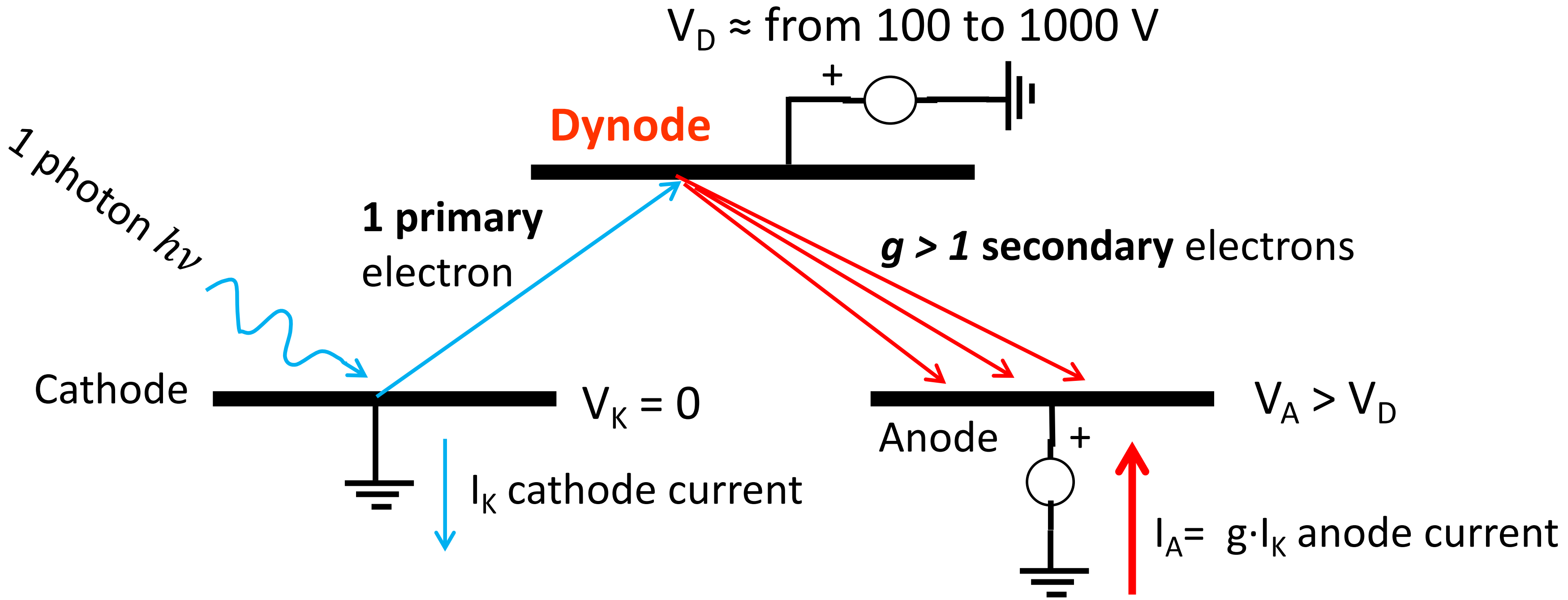
Primary Detector Noise (cathode Dark-Current)

Circuit Noise

- Primary Signal (photocathode current): one electron per detected photon
- Output (anode) current: **$G > 10^3$** electrons per primary electron
- Dark-current noise and/or photocurrent noise at detector output are much higher than circuit noise, which has practically negligible effect

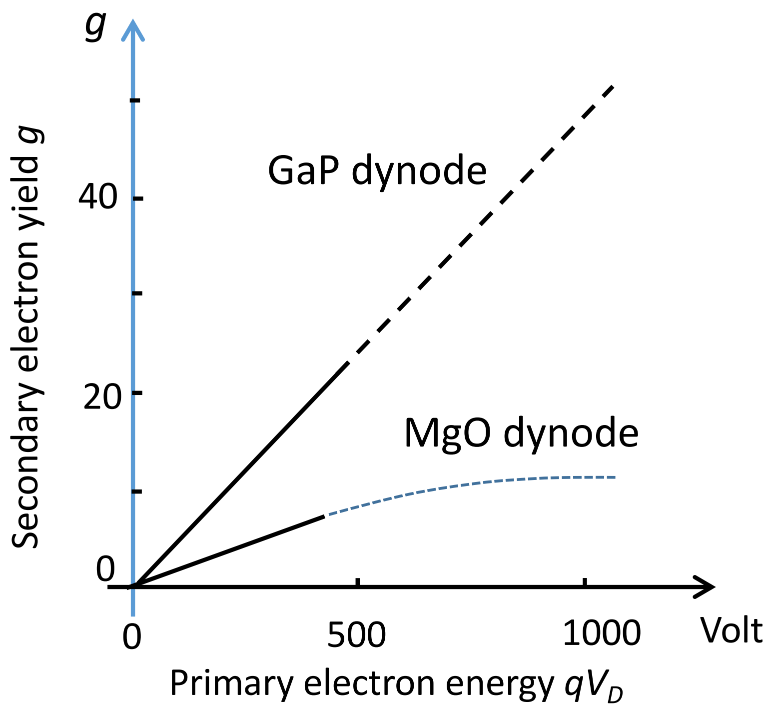
# Secondary Electron Emission in Vacuum
and
Current Amplification by a Dynode Chain

# Secondary Electron Emission in Vacuum



- A primary electron is emitted in vacuum with very little kinetic energy $E_e < 1\text{eV}$
- Driven in vacuum by a high potential difference (some 100V), it impacts with high energy on a **dynode** (electrode coated with suitable material, see later)
- Energy is transferred to electrons in the dynode; some of them gain sufficient energy to be emitted in vacuum; ***g > 1*** is the **yield** of secondary electrons per primary electron

# Dynode materials



Secondary emitter coatings with ordinary yield:

- MgO  Magnesium Oxide
- $Cs_3Sb$  Cesium Antimonide
- BeO  Beryllium Oxide
- Cu-Be  Copper-Beryllium alloys

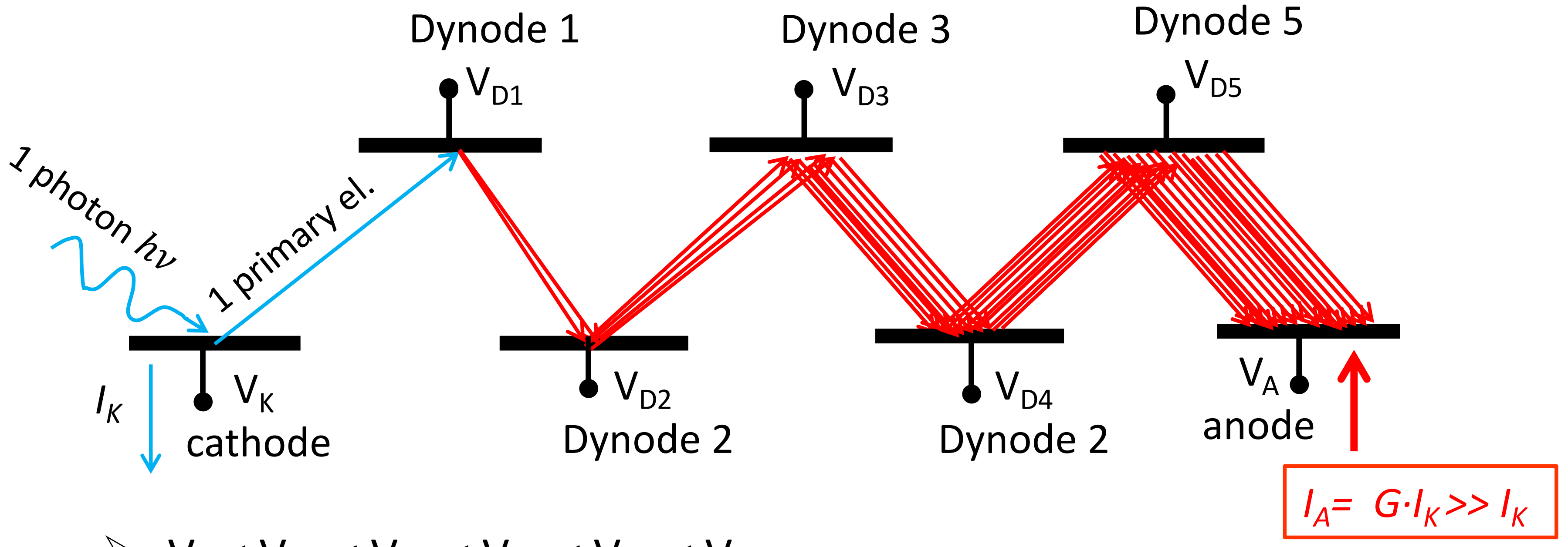
Secondary emitter with high yield (due to NEA negative electron affinity, see slide 26 in PD2) :

- GaP Gallium Phosphide

- In the normal working range up to ≈500V, the emission yield *g* is **proportional** to the accelerating voltage V (i.e. the primary electron energy)   $g = k_s V_D$
- At higher voltage *g* rises slower and tends to saturate (energy is transferred also to electrons in deeper layers, which have lower probability of escape in vacuum)
- In the linear range ordinary emitters work with ***g*** **values from ≈1,5 to ≈7** and GaP dynodes  *g* values from ≈5 to ≈25
- **GaP dynodes are more costly and delicate**, require special care in operation and their yield tends to decrease progressively over long operation times

# Electron Multiplier

## Sketch of the Principle (example with 5 dynodes)



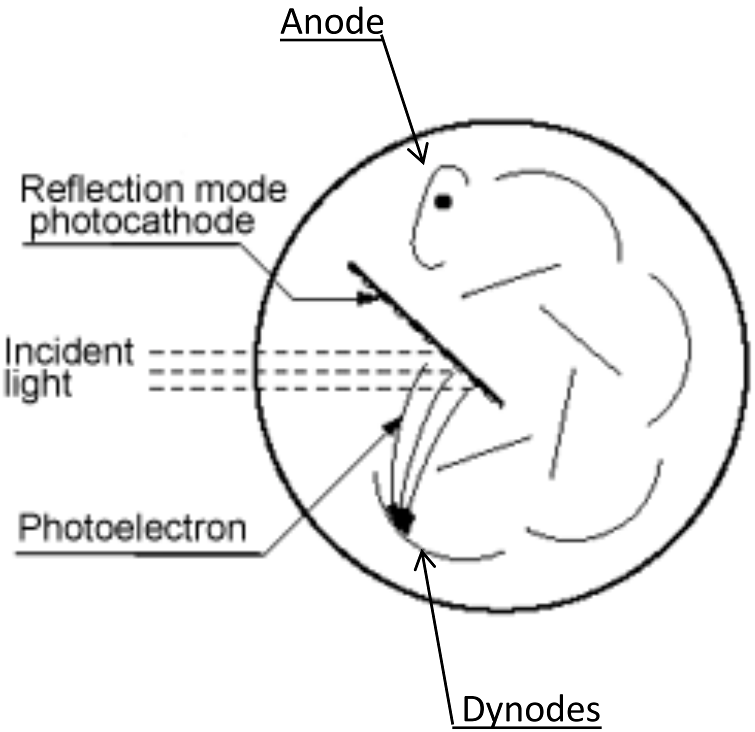
- $V_K < V_{D1} < V_{D2} < V_{D3} < V_{D5} < V_A$
- Electron optics (i.e. potential distribution) **carefully designed to lead the electrons** emitted from each electrode to the next one
- $g_r > 1$ secondary electron yield of dynode $r$
- $G = g_1 \cdot g_2 \cdot g_3 \cdot g_4 \cdot g_5$ **overall multiplier gain**

  that is, $G=g^5$ with equal stages $g_1=g_2=....=g$

# Photo Multiplier Tubes (PMT): device structure and current gain

# Side-on PhotoMultiplier Tubes PMTs

PMTs with side-window and opaque photocathode

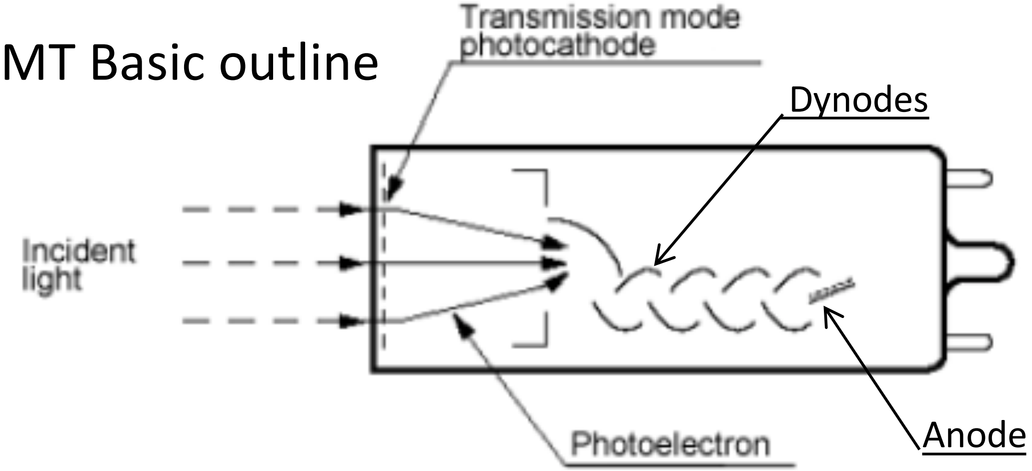


The basic structure of Photomultiplier Tubes with discrete dynodes and electrostatic-focusing was first demonstrated in 1937 by the RCA Laboratories; in the following decades it was progressively improved and developed by various industrial laboratories (RCA, DuMont, EMI, Philips, Hamamatsu... )

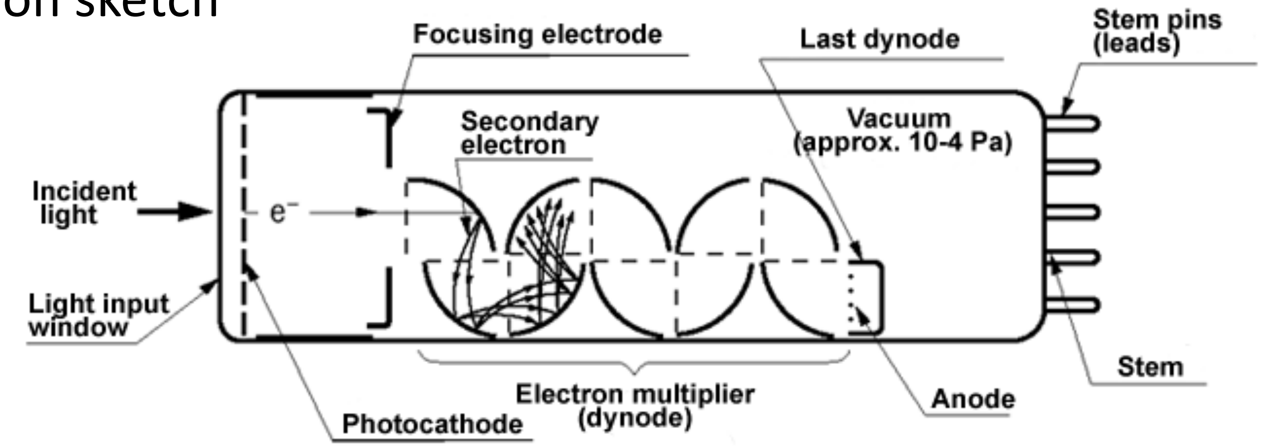
# End-on PhotoMultiplier Tubes PMT

PMTs with end-window and semitransparent photocathode

PMT Basic outline



PMT Operation sketch



# PMTs with semitransparent photocathode

Photocathode

Multiplier
dynode set

For comparison:
APD Avalanche Photodiode
mounted in case

APD Avalanche Photodiode
in silicon chip

# PMT Gain Regulation and Stabilization

- PMTs can have high number *n* of dynodes (from 8 to 12) and attain high gain G.

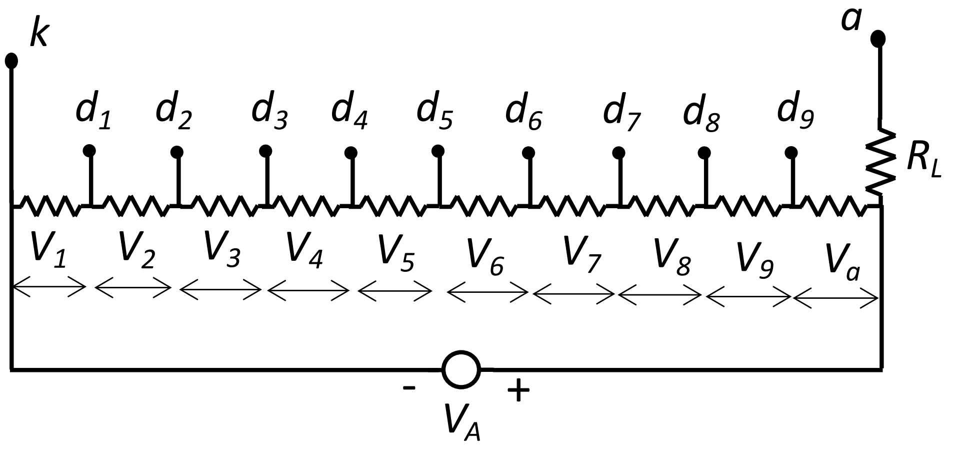
  With n equal dynodes it is $\boldsymbol{G = g^n}$ ; e.g. with 12 dynodes $G=g^{12}$

  $G = 10^4$ with $g = 2,2$

  $G = 10^5$ with $g = 2,6$

  $G = 10^6$ with $g = 3,2$

- G is controlled by the dynode bias voltage, which regulates the dynode yield g
- A single supply is usually employed, with high voltage $V_A$ typically from 1500 to 3000 V. The dynode voltages are obtained with a voltage-divider resistor chain; the potential difference $V_j$ between two dynodes *j* and *(j-1)* is a preset fraction $f_j$ of the supply $V_A$



$$\boxed{V_j = f_j\ V_A}$$

# PMT Gain Regulation and Stabilization

- The supply voltage $V_A$ thus rules the yield $g_j$ of every dynode $g_j = k_S V_j = k_S f_j V_A$

  and the total gain $G = g_1 g_2 \ldots . g_n = k_S V_1 \cdot k_S V_2 \ldots .. k_S V_n = k_S^n f_1 f_2 \ldots f_n \cdot V_A^n$

  which increases with $V_A$ **much more** than linearly

$$\boxed{G = k_S^n f_1 f_2 \ldots f_n \cdot V_A^n = K_G \cdot V_A^n}$$

  *(NB: $K_G = k_S^n \, f_1 f_2 \ldots f_n$ is constant, set by the voltage distribution and dynode characteristics)*

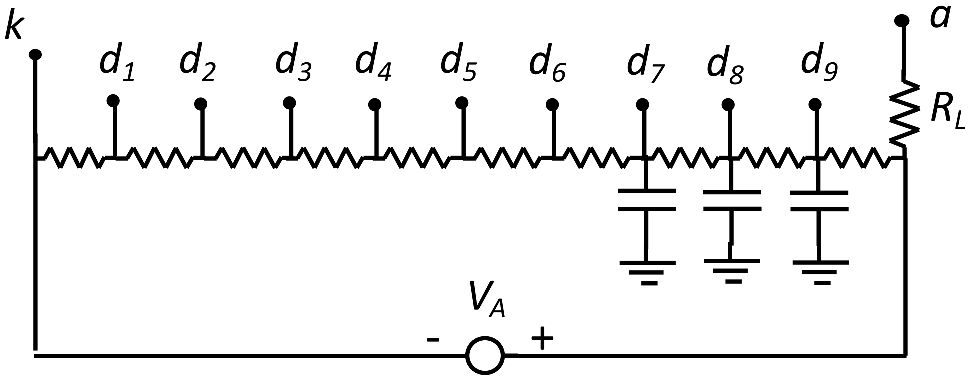
- The gain G is very sensitive to even small variations of the supply $V_A$ : the relative variations of supply voltage are n-fold amplified in the relative variations of gain

$$\boxed{\frac{dG}{G} = n \frac{dV_A}{V_A}}$$

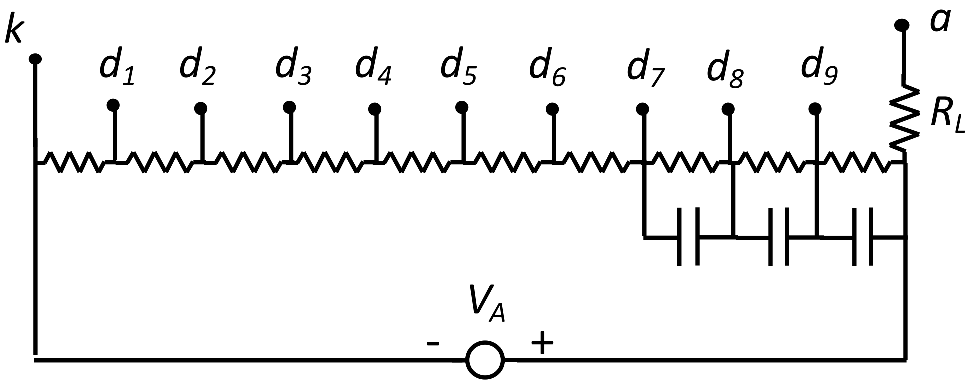
- Consequently, tight requirements must be set to the stability of the high voltage $V_A$ versus ambient temperature and/or power-line voltage variations.
  e.g. getting ***G* stability better than 1%** for a PMT **with n=12 dynodes**
  requires a high voltage supply ***$V_A$* better stable than 0,08 %**

# Cautions and limits in PMT exploitation

- The parameter values in the PMT operation must be carefully selected for exploiting correctly the PMT performance. We will point out some main aspects and call the **user attention on warnings reported in the manufacturer data sheets**.
- For **limiting self-heating of voltage divider** below a few Watt, the divider current must be < 1 mA, hence total divider resistance must be at least a few MΩ.
- In order to avoid nonlinearity in the current amplification, variations of dynode voltages caused by the PMT current should be negligible. The PMT output current must thus be less than 1% of the divider current, i.e. typically a few $\mu A$.
- This limit is acceptable for DC current, but not for pulsed optical signals. However, fast transients of dynode voltages can be limited by introducing in the last stages capacitors in low-pass filtering configurations, as sketched in the examples



# Cautions and limits in PMT exploitation

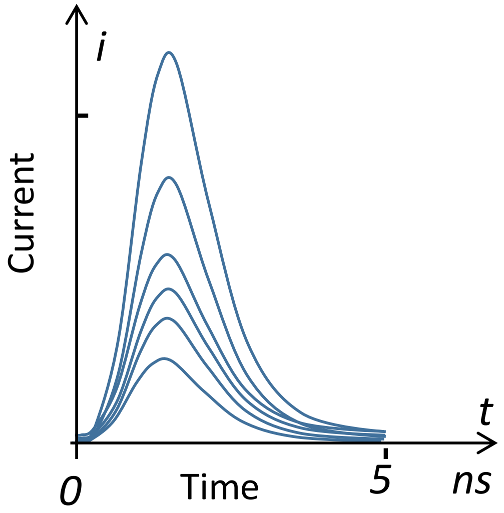


- **Space-charge effects may cause nonlinearities** in the amplification of fast pulsed signals. A high charge of the signal itself can significantly reduce the electric field that drives the electrons: the higher is the pulse, the slower gets the electron collection. The pulse shape is more or less distorted, depending on its size
- Nonlinearity can occur also if the voltage signal developed on the load is high enough to reduce the driving field from last dynode to anode
- **Magnetic fields have very detrimental effect**: the electrons traveling in vacuum are deviated and the operation is inhibited or badly degraded. With moderate field intensity, magnetic screens (Mu-metal shields wrapped around the vacuum tube) can limit the effects; with high intensity fields PMT operation is actually impossible
- **PMTs are fairly delicate** and subject to fatigue effects and their operation is prejudiced by mechanical vibrations

# Statistical nature of the electron multiplier and related effects

# Single Electron Response SER

- The PMT output is superposition of elementary current pulses that correspond to single electrons emitted by the cathode, called **Single Electron Response (SER)** pulses.
- SER current pulses are fast (a few nanosecond width) and fairly high (pulse-charge Gq from $10^5$ to $10^6$ electrons). **They are remarkably higher than the noise** of fast circuits; with PMT weakly illuminated they are well observable on the oscilloscope screen and each of them corresponds to the detection of a single photon.
- The SER current pulses observed have all equal pulse shape, but **randomly varying pulse-amplitude**; i.e. G is not constant, but statistical



- The random fluctuations of G are due to the statistical nature of secondary electron emission
- Since the SER charge is much higher than the minimum measurable detector pulse*, the statistical distribution *p(G)* of the gain *G* (probability density of *G* value) can be directly collected by measuring and classifying the pulse-charge of many SER pulses.

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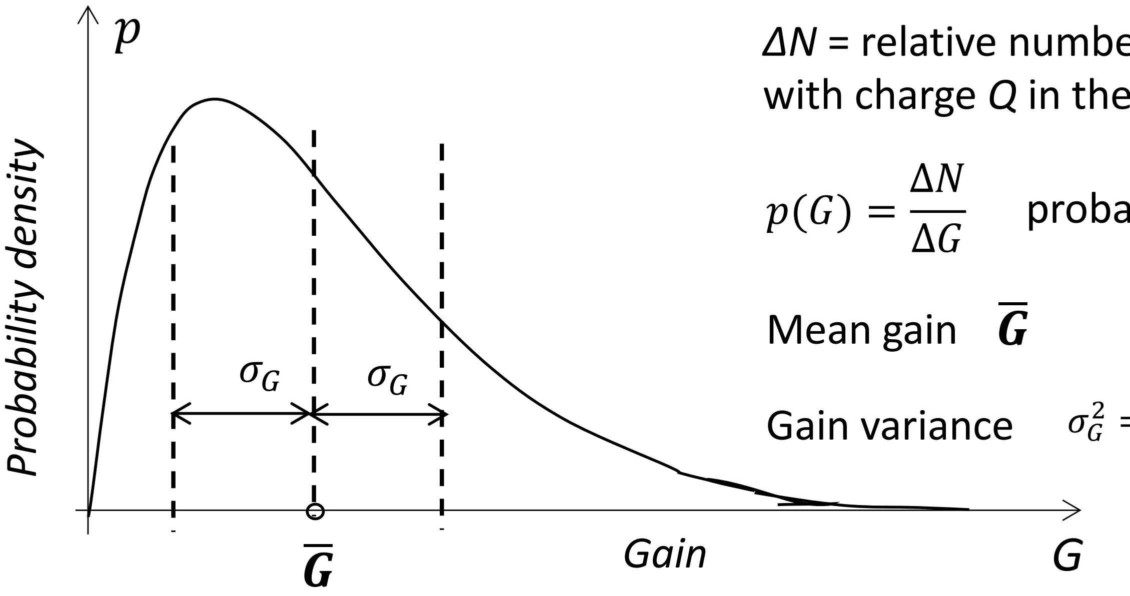
* See the OPF2 slides

# Statistical Distribution of the PMT gain



*ΔN* = relative number of SER pulses observed with charge *Q* in the interval *qG ± qΔG/2*

$p(G) = \dfrac{\Delta N}{\Delta G}$ probability density of *G*

Mean gain $\bar{G}$

Gain variance $\sigma_G^2 = \overline{(G - \bar{G})^2} = \overline{G^2} - (\bar{G})^2$

- The plot above sketches the typical appearance of the statistical distribution *p(G)* of the PMT gain *G.*
- For different PMT models and different operating conditions (bias voltage distribution on dynodes; temperature of operation; etc.) remarkably different *p(G)* are observed. The distributions are roughly akin to gaussian, but skewed toward high *G* values.
- The main parameters to be considered for analyzing the PMT operation are mean gain $\bar{G}$ , gain variance $\sigma_G^2$ and relative variance $v_G^2 = \dfrac{\sigma_G^2}{(\bar{G})^2}$

# Excess Noise due to Gain Fluctuations

- Emission of primary electrons from cathode is a process with Poisson statistics, i.e. mean number $N_p$ , variance $\sigma_p^2 = N_p$ and relative variance $v_p^2 = \frac{\sigma_p^2}{N_p^2} = \frac{1}{N_p}$
- Emission is followed in cascade by statistical multiplication with fluctuating G
- The mean of the cascade output is $N_u = N_p \cdot \bar{G}$ (two independent processes)
- The Laplace theory of probability generating functions shows that the relative variance $v_u^2$ of the output of a cascade is sum of the relative variance of every stage in the cascade divided by the mean value of all the previous stages. In our case:

$$v_u^2 = \frac{\sigma_u^2}{N_u^2} = v_p^2 + \frac{v_G^2}{N_p} = \frac{1}{N_p} + \frac{v_G^2}{N_p} = \frac{1}{N_p}(1 + v_G^2)$$

- The variance $\sigma_u^2$ thus is

$$\sigma_u^2 = N_p^2 \overline{G}^2 v_u^2 = N_p \overline{G}^2 (1 + v_G^2) = \sigma_p^2 \, \overline{G}^2 (1 + v_G^2)$$

In conclusion, the PMT :
1) amplifies the input variance by the square gain $\bar{G}^2$, like an amplifier and
2) further enhances it by the **Excess Noise Factor F** due to the gain fluctuations

$$\boxed{\sigma_u^2 = \sigma_p^2 \cdot \overline{G}^2 \cdot F} \quad \text{with} \quad \boxed{F = 1 + v_G^2 > 1}$$

# PMT Noise versus Amplifier Noise

- A PMT amplifies by $\bar{G}^2$ the input noise like an amplifier and further increases it by the **Excess Noise Factor *F* :** $\sigma_u^2 = \sigma_p^2 \cdot \bar{G}^2 \cdot F$
- We will see that it is ***F* ≤ *2* for most PMT types and *F* is close to unity for high quality PMT types**. The factor of increase of rms noise is always **moderate** $\sqrt{\boldsymbol{F}}$ **≤ 1,4** and often near to unity. Reasonably approximated evaluations can be obtained by neglecting the excess noise, i.e. with *F=1*.
- As modern alternative to a PMT, one could propose a vacuum tube photodiode coupled to a high-gain and low-noise amplifier chip, possibly with amplifier chip inside the vacuum tube. It would offer practical advantages: more simple, rugged and compact structure, lower operating voltage, etc..
- In fact, a PMT outperforms such «photodiode-with-amplifier-inside» by detecting optical signals smaller by orders of magnitude. We can better understand the matter by gaining a better insight about how these devices work.

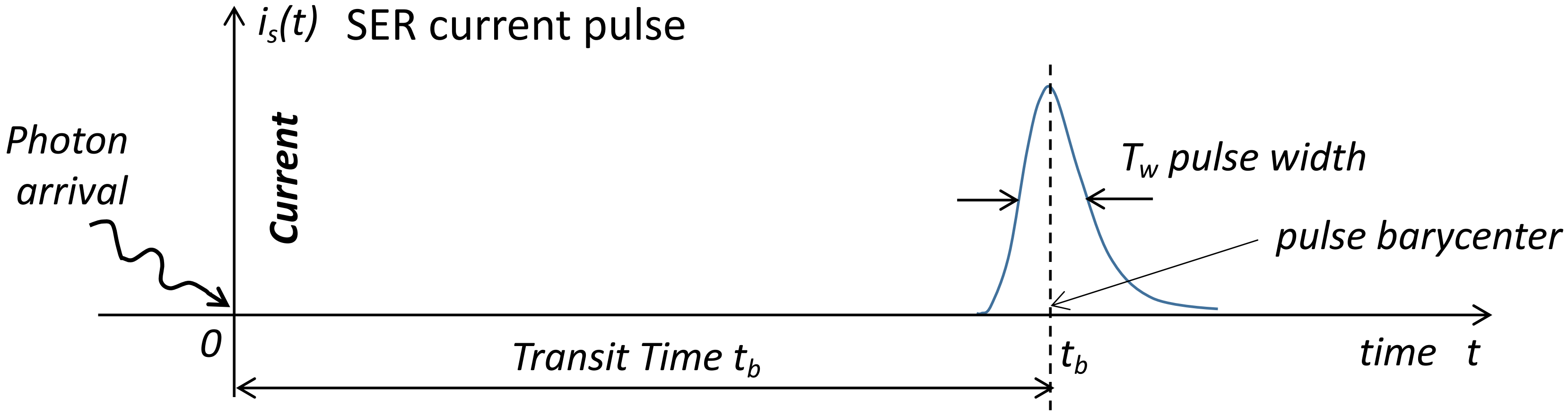
# PMT Noise versus Amplifier Noise

- In the amplifier a **signal gains energy from the power supply by modulating the bias current in transistors**, which must be active all the time. The amplifier **noise sources are always active** (shot noise of transistor bias current; Johnson noise of resistors)
- In a PD-amplifier combination it is the amplifier noise that sets the limit to the minimum measurable signal, since it is much higher than the photocathode dark-current noise
- In a PMT, the **electrons of the signal gain energy directly from the voltage supply**: the bias voltage accelerates them and the kinetic energy gained is exploited in the impact to generate other free electrons. There is **no bias current** in the multiplier chain, the current flows only when electrons are injected from the cathode.
- In a PMT there are **no noise sources in the dynode chain**; the minimum signal is limited by the dark-current noise and/or the photon-current noise at the cathode.
- The cathode noise is indeed slightly increased by the gain fluctuations in the dynode chain, but in practice this is always a minor effect and often it is negligible.

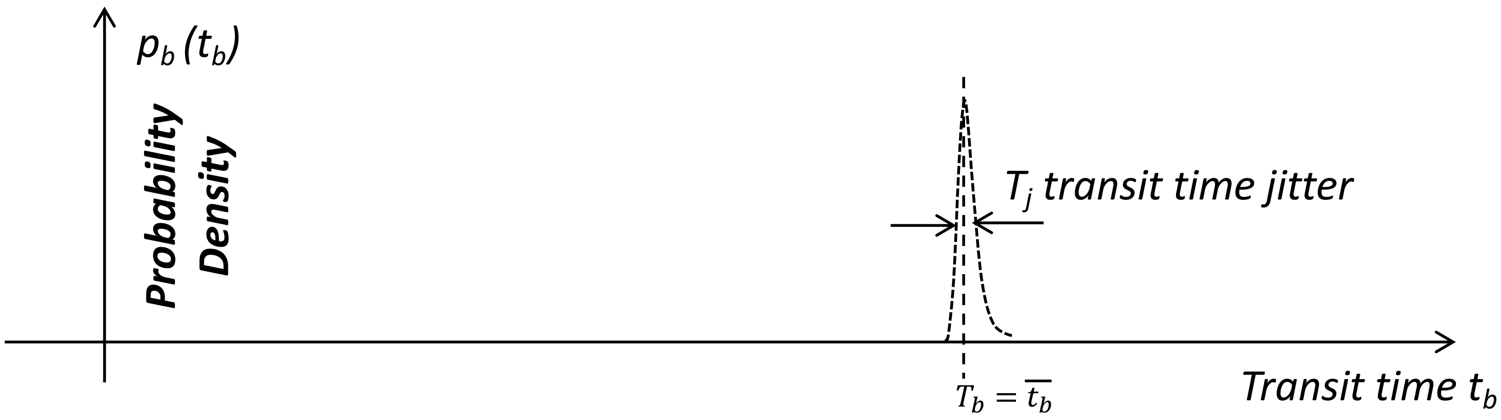
# Dynamic response of PMTs

# PMT Dynamic Response: SER pulse

## PMT response to a single photon



## Transit Time distribution



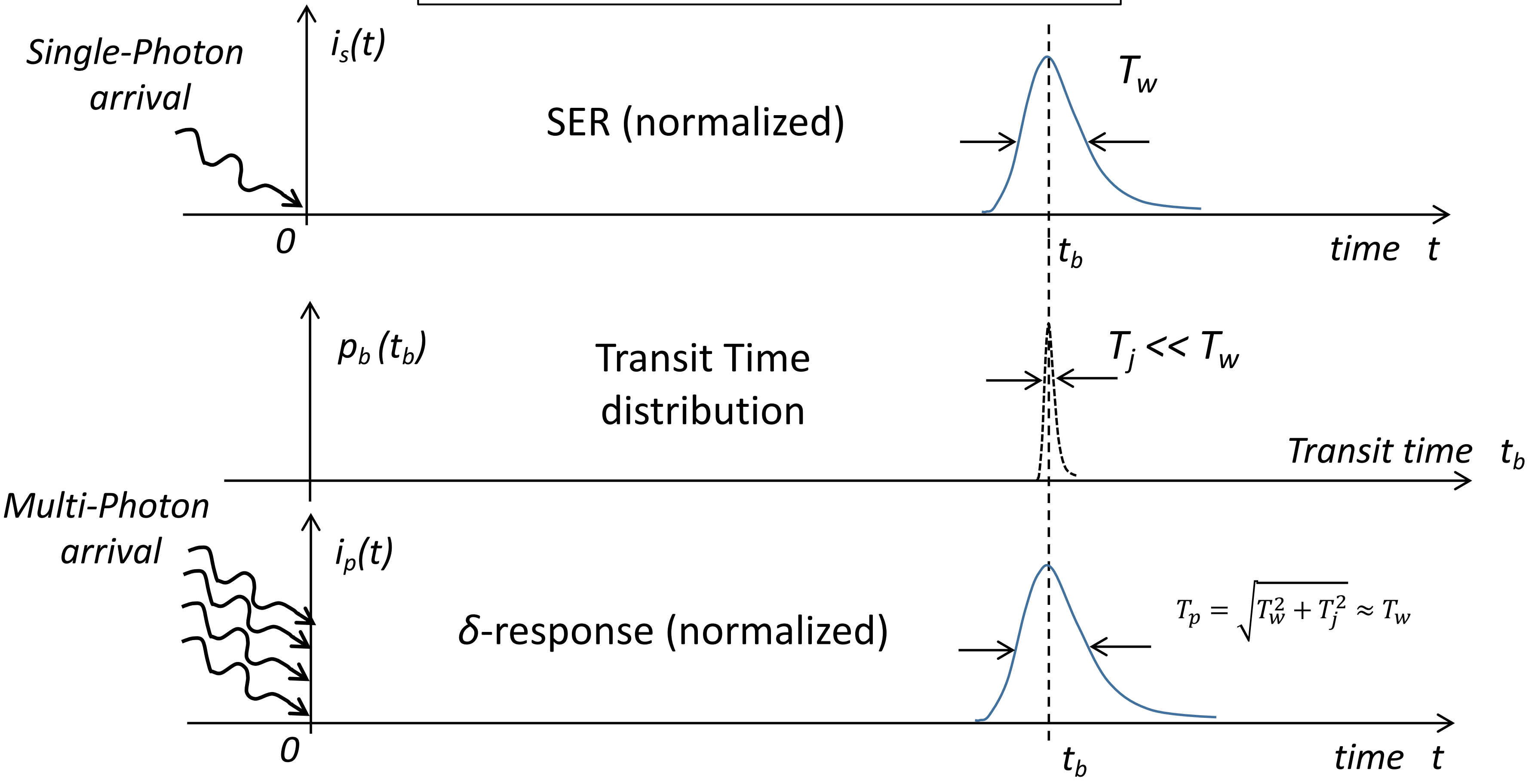
# PMT Dynamic Response: SER pulses

- Differently from vacuum tube photodiodes, in PMT the rise of a SER current pulse is delayed (from ≈10ns to some 10ns dependent on PMT type and bias voltage) with respect to the photon arrival. The dynodes electrostatically screen the anode, so that only electrons traveling from last dynode to anode induce current (Shockley-Ramo theorem).
  The **PMT transit time $t_b$** is defined as the delay of the **pulse barycenter**.
- **The transit time $t_b$ randomly fluctuates from pulse to pulse, with a transit time jitter $T_j$** (full-width at half maximum FWHM of the $t_b$ distribution) from a few 100ps to a few ns depending on PMT type and bias voltage. $T_j$ is due to the statistical dispersion of the electron trajectories in the *first stages of the multiplier*.
- **The SER pulse width $T_w$** (FWHM from a few ns to various ns, depending on PMT type and bias voltage) is always wider than the transit time jitter: $T_w \approx$ 5 to 10 times $T_j$ . It is due to the statistical dispersion of the electron trajectories *in all the multiplier*.
- $T_w$ has very small fluctuations, practically negligible

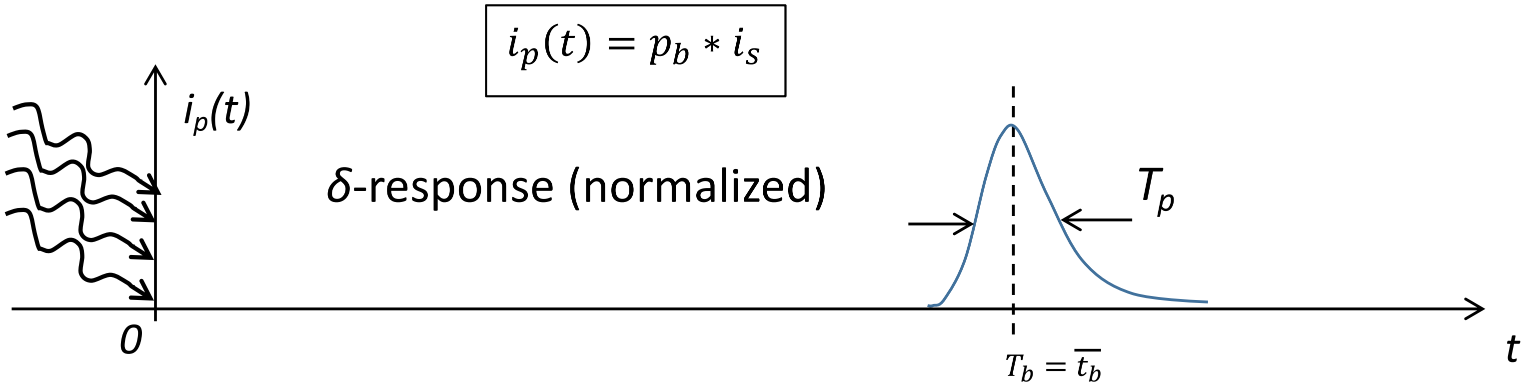
# PMT Dynamic Response: Multi-photon pulses

PMT response $i_p(t)$ to a multi-photon δ-like light pulse:
derived from 1) SER pulse waveform and 2) transit time distribution

$$i_p(t) = \int_0^{\infty} p_b(t_b)\ i_s(t-t_b)dt_b = p_b * i_s$$



# PMT Dynamic Response: Multi-photon pulses



- The δ-response is a convolution $i_p = p_b * i_s$ , hence its FWHM $T_p$ is quadratic sum of FWHMs $T_w$ and $T_j$ of the components

$$T_p = \sqrt{T_w^2 + T_j^2}$$

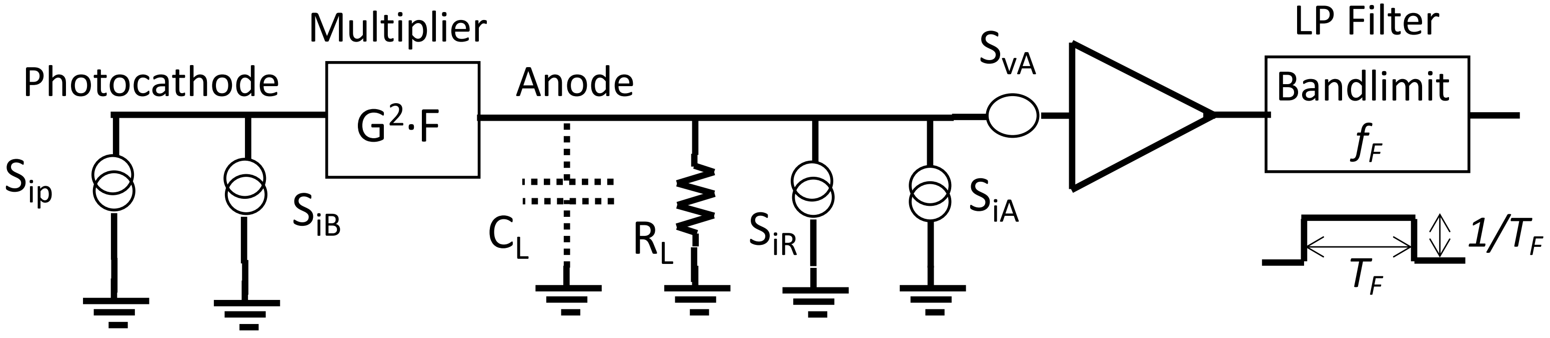
- since $T_j / T_w$ is small (from 0,1 to 0,2) the width of the δ-response is practically equal to the SER current pulse width $T_p \approx T_w \left[1 + \frac{1}{2}\left(\frac{T_j}{T_w}\right)^2\right] \approx T_w$
- The finite SER pulse width establishes a finite bandwidth $f_p$ for the PMT employed as analog current amplifier

$$f_p = \frac{1}{k_a T_w}$$

(the coefficient $k_a$ is from ≈3 to ≈10, depending on the SER pulse waveform)

# Signal-to-Noise Ratio and Minimum Measurable Signal

# Noise sources and filtering with PMTs



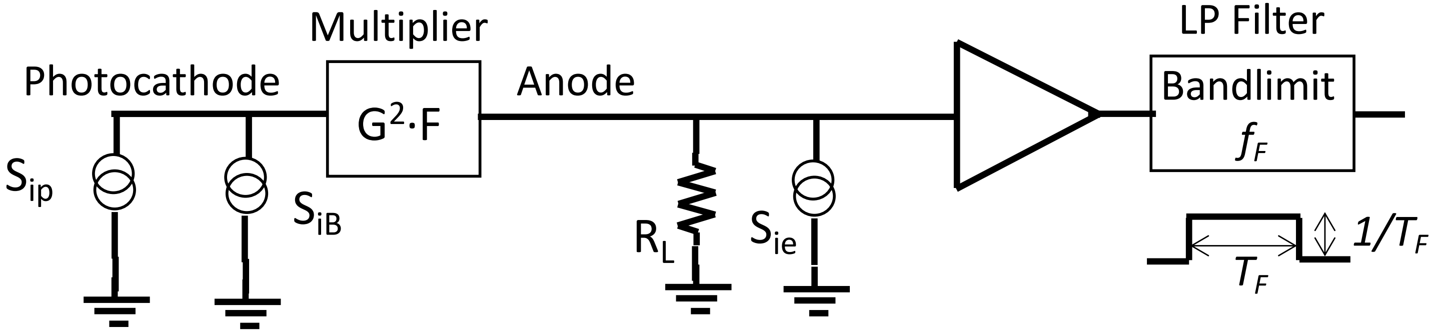
- $n_p$ photoelectron rate → $I_p = n_p q$ photocurrent
- $n_D$ dark electron rate → $I_D = n_D q$ cathode dark current
- $n_b$ electron rate due to photon background → $I_b = n_b q$ photon background current
- $n_B = n_D + n_b$ total background electron rate → $I_B = n_B q$ total background current

Noise sources :

- at cathode: $S_{ip} = 2qI_p = 2q^2 n_p$ photocurrent noise, **increases with the signal**
- at cathode: $S_{iB} = 2qI_B = 2q^2 n_B$ background noise, **independent from the signal**
- at anode: resistor load noise $S_{iR}$ and preamplifier noise $S_{iA}$ and $S_{iR}$

Let's deal with S/N and minimum measurable signal in the basic case:
**constant signal** current $I_p$ and **low-pass filtering** (typically by Gated Integration)

# Noise sources and filtering with PMTs



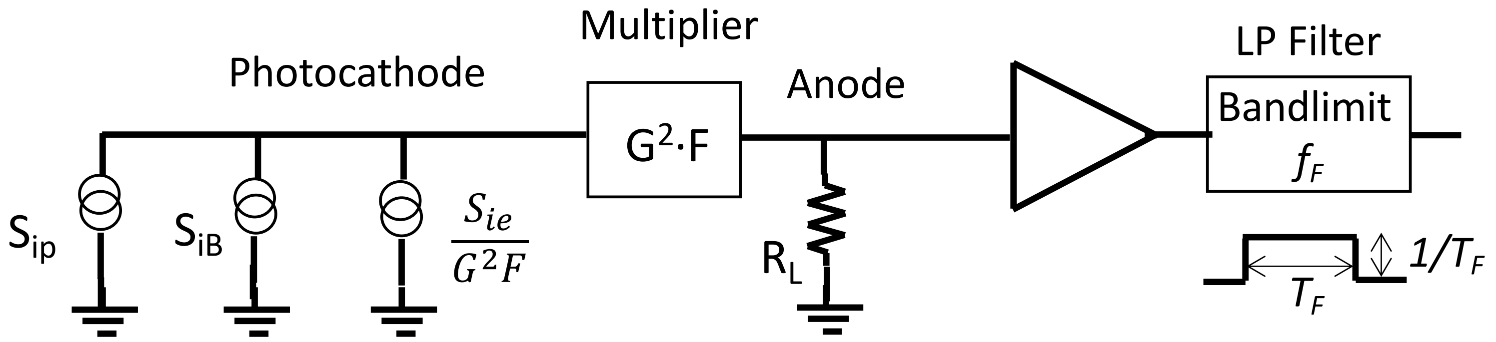
We consider cases with wide-band load, i.e. with $1/4R_LC_L >> f_F$ , such that

a) the filtering effect of $C_L$ is negligible

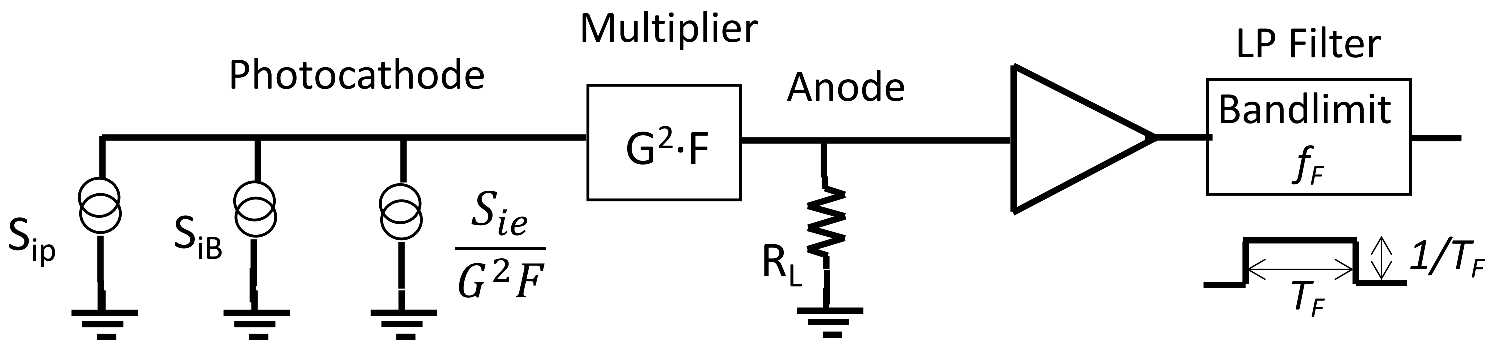
b) the circuit noise can modeled simply by a current generator

$$S_{ie} = S_{iA} + S_{iR} + \frac{S_{vA}}{R_L^2}$$

which can be referred back to the input (at the photocathode) as $S_{ie}/G^2F$



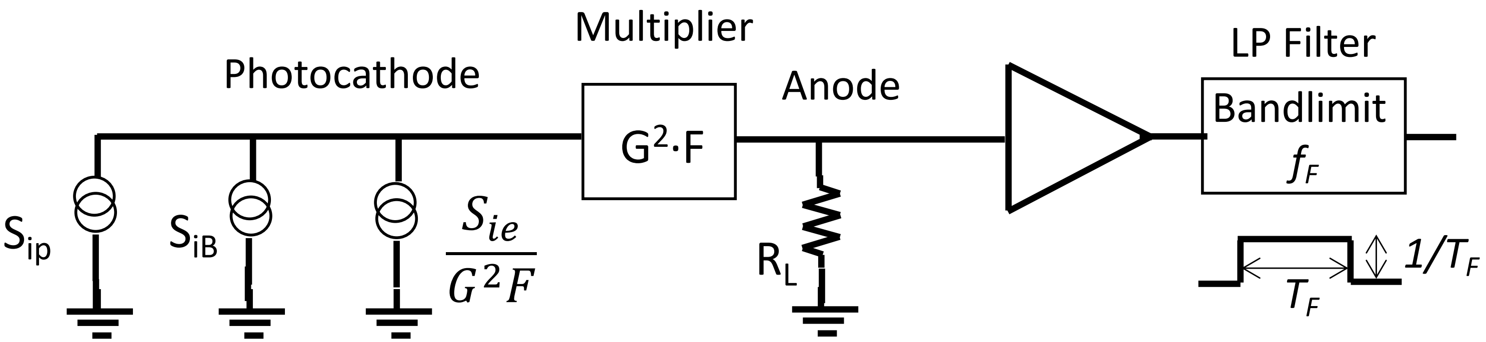
# Role of the Circuit Noise



- The circuit noise $S_{ie}$ can be modeled by a shot current **at the anode:**
  $I_e = S_{ie}/2q$ with electron rate $n_e = I_e/q = S_{ie}/2q^2$
- With wide band preamplifier and low resistance $R_L \approx$ few kΩ the circuit noise typically is $\sqrt{S_{ie}} \approx 2\, pA/\sqrt{Hz}$ or more. The equivalent shot electron rate is $\boldsymbol{n_e \approx 10^{14}}$ ***el/s*** **or more**
- Referred to input (cathode), the circuit noise is modeled by a shot current with **reduced** electron rate $n_e/FG^2$. For instance, with G= $10^6$ it is $\boldsymbol{n_e/FG^2 \approx 100}$ ***el/s***
- The circuit noise referred to the input added to the background noise $S_{iB}=2qI_B=2q^2n_B$ gives the **constant** noise component (i.e. **NOT** dependent on the signal)

$$S_{iB} + \frac{S_{ie}}{G^2F} = 2qI_B + \frac{2qI_e}{G^2F} = 2q^2\left(n_B + \frac{n_e}{G^2F}\right)$$

# Role of the Circuit Noise



$$S_{iB} + \frac{S_{ie}}{G^2F} = 2qI_B + \frac{2qI_e}{G^2F} = 2q^2\left(n_B + \frac{n_e}{G^2F}\right)$$

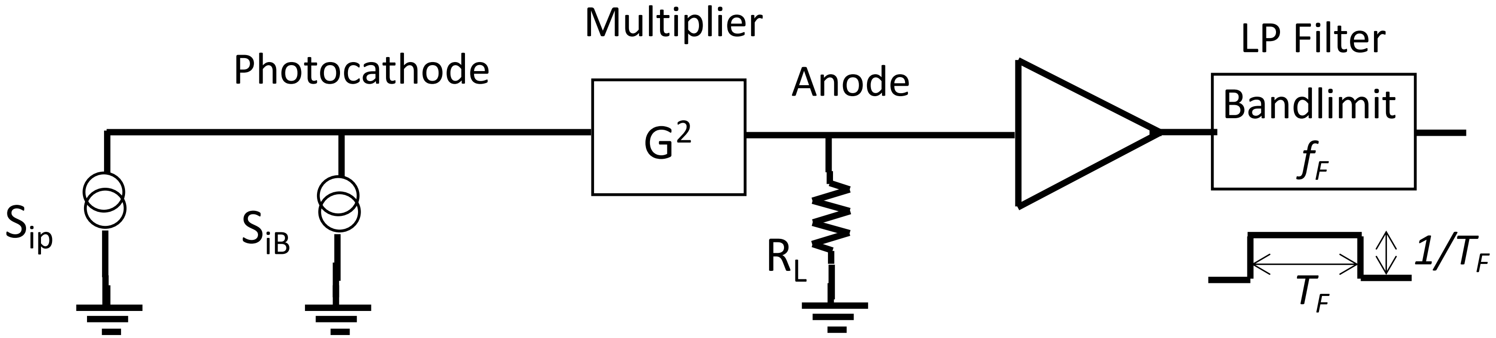
- The role of the circuit noise is assessed by comparing it to the constant noise source of the PMT, the background noise $S_{iB}=2qI_B=2q^2n_B$
- The background electron rate at the cathode $n_B$ may vary ***from a few el/s to a few $10^6$ el/s***, depending on the photocathode type and operating temperature and on the background light level (see Slides PD2)
- In **most cases** of PMT application it is $n_B >> n_e/G^2F$ : the equivalent electron rate $n_e/G^2F$ is **totally negligible** with respect to $n_B$ , the circuit noise plays no role
- In cases with moderate gain G and/or very low dark current the circuit noise contribution may be significant and is very simply taken into account, by employing the resulting density of constant noise component in the evaluation

# Minimum Measurable Signal

For the sake of simplicity in the following computations we consider:

**a)** **negligible circuit noise.** Anyway, we know when it must be taken into account and how to do it, by considering an increased constant component of noise.

b) negligible excess noise, i.e. ***F = 1***. Anyway, cases with non-negligible F > 1 can be taken into account simply by introducing the factor $\sqrt{F}$ to decrease the S/N and increase the noise variance and the minimum signal computed with F=1.



$$\boxed{\frac{S}{N} = \frac{I_p}{\sqrt{S_{ip} f_F + S_{iB} f_F}} = \frac{I_p}{\sqrt{2qI_p f_F + 2qI_B f_F}}}$$

The minimum signal $I_{p,min}$ is reached when S/N = 1 : we will see that the result markedly depends on the **relative size of constant noise vs photocurrent noise**

# Minimum Signal limited by Photocurrent-Noise

- The simplest **extreme case is with negligible background noise:** only photocurrent noise matters. With noise band-limit $f_F = 1/2T_F$ (GI filtering)

$$\frac{S}{N} = \frac{I_p}{\sqrt{2qI_pf_F}} = \frac{I_pT_F}{\sqrt{qI_pT_F}} = \sqrt{\frac{I_pT_F}{q}} = \sqrt{n_pT_F} = \sqrt{N_p}$$

$N_p = n_p T_F$ is the **number of photoelectrons** in the filtering time $T_F$ .

- In fact, the S/N can be obtained directly from the Poisson statistics of photoelectrons: with mean number $N_p$ , the variance is $\sigma_p^2 = N_p$ and

$$\frac{S}{N} = \frac{N_p}{\sigma_p} = \frac{N_p}{\sqrt{N_p}} = \sqrt{N_p}$$

- Remark that in this case the noise is **NOT constant,** independent from the signal: as the signal goes down, **also the noise goes down!!**

# Minimum Signal limited by Photocurrent-Noise

- By making lower and lower $I_p$ , **when S/N = 1 the minimum signal $I_{p,min\text{-}p}$ is reached**

$$\boxed{\left(\frac{S}{N}\right)_{min} = 1 = \sqrt{\frac{I_{p,\min -p} T_F}{q}} = \sqrt{n_{p,\min -p}\ T_F}\sqrt{N_{p,\min -p}}}$$

- The minimum measurable photocurrent signal $I_{p,min\text{-}p}$ corresponds to just **one photoelectron in $T_F$** , the filter weighting time:

$$\boxed{I_{p,\min -p} = \frac{q}{T_F}} \qquad \boxed{n_{p,\min -p} = \frac{1}{T_F}} \qquad \boxed{N_{p,\min -p} = 1}$$

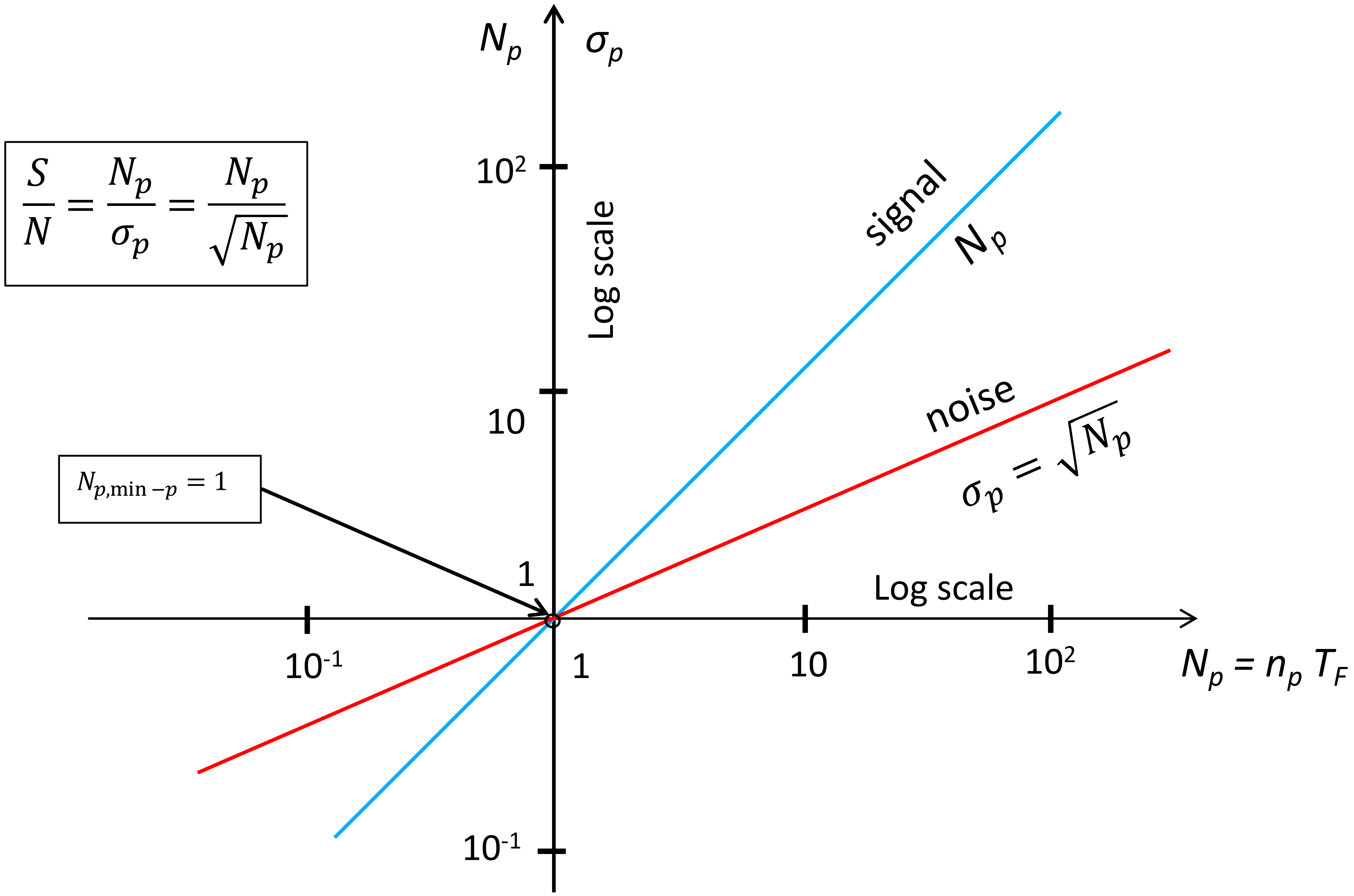
- Observing the complete S/N equation

$$\frac{S}{N} = \frac{I_p}{\sqrt{2qI_p f_F + 2qI_B f_F}} = \frac{I_p T_F}{\sqrt{qI_p T_F + qI_B T_F}} = \frac{n_p T_F}{\sqrt{n_p T_F + n_B T_F}} = \frac{N_p}{\sqrt{N_p + N_B}}$$

we see that the background noise is truly negligible only if $I_B << I_p$ for any $I_p$ **down to the minimum $I_{p,\,min\text{-}p}$** , i.e. only if

$$\boxed{I_B \ll \frac{q}{T_F}} \qquad \boxed{n_B \ll \frac{1}{T_F}} \qquad \boxed{N_B \ll 1}$$

# Minimum Signal limited by Photocurrent-Noise



$$\frac{S}{N} = \frac{N_p}{\sigma_p} = \frac{N_p}{\sqrt{N_p}}$$

$$N_{p,\min - p} = 1$$

Signal measured by **charge**, in terms of **number of photoelectrons $N_p = n_p\, T_F$**

# Minimum Signal limited by Background Noise

- The **opposite extreme case is with negligible photocurrent noise:** only background noise matters. More precisely, it's the case where the limit current $I_p = I_{p,min\text{-}p}$ computed with only the photocurrent noise is much lower than the background current $I_B$

$$\boxed{I_B \gg \frac{q}{T_F}} \qquad \boxed{n_B \gg \frac{1}{T_F}} \qquad \boxed{N_B \gg 1}$$

- There is now a different **minimum signal $I_{p,min\text{-}B}$ limited by the background noise**

$$\boxed{I_{p,\min -B} = \sqrt{\frac{qI_B}{T_F}}} \qquad \boxed{n_{p,\min -B} = \sqrt{\frac{n_B}{T_F}}} \qquad \boxed{N_{p,\min -B} = \sqrt{N_B}}$$

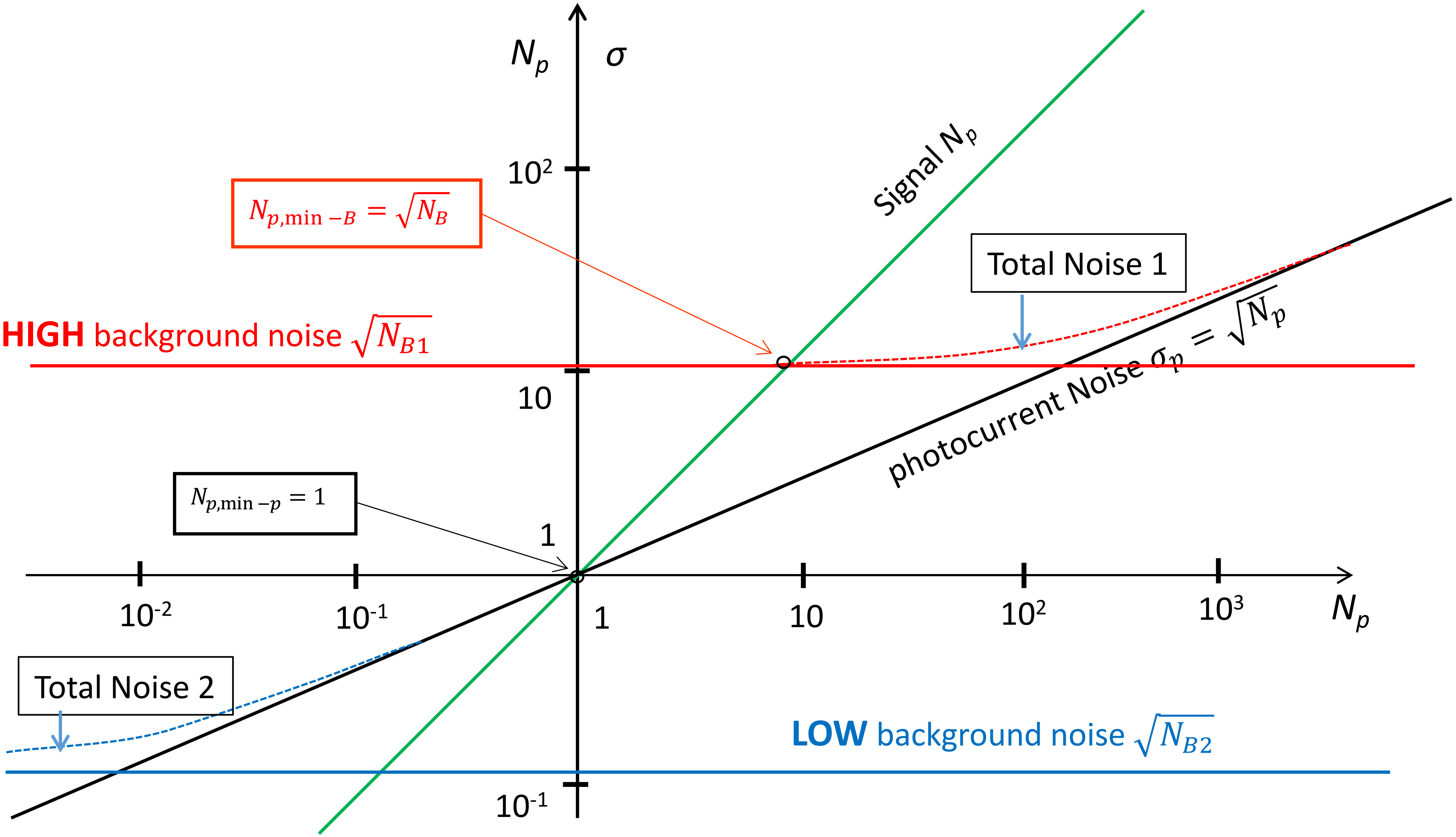
- In **intermediate cases both noise components** contribute to limit the minimum signal, which is computed from

$$\frac{S}{N} = \frac{N_{p,\min}}{\sqrt{NB_{p,\min}}} = 1$$

2nd order equation that leads to $N_{p,\min} = \frac{1}{2}\left(1 + \sqrt{1 + 4N_B}\right)$.

*(NB: the other solution is devoid of physical meaning)*

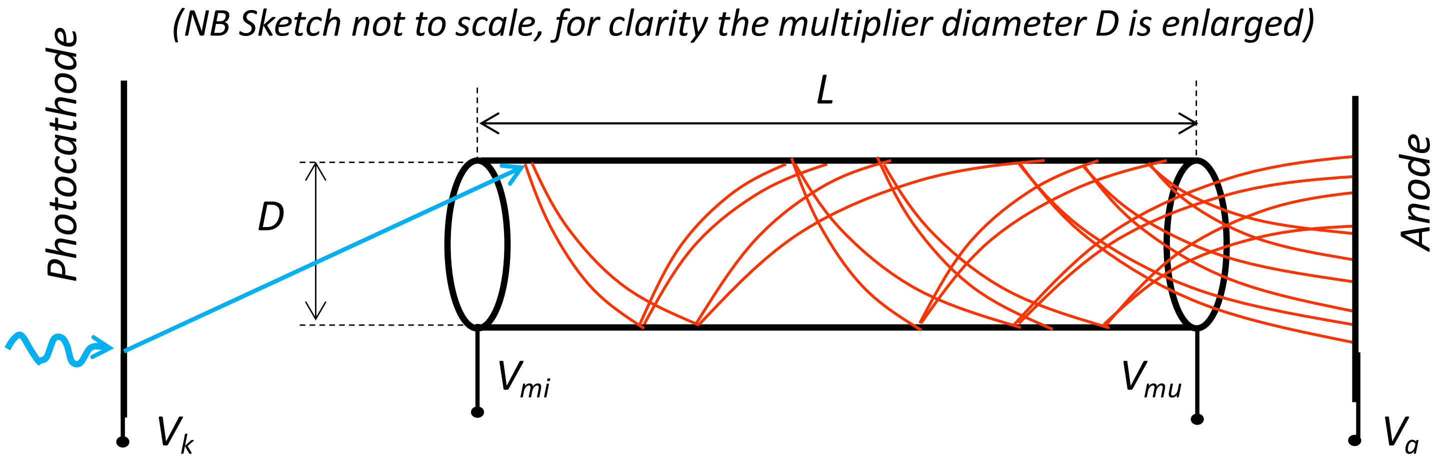
# Minimum Signal limited by Noise



Signal **charge**, in terms of **number of photoelectrons $N_p= n_p T_F$**

# Progress in PMT device structures

# Continuous Channel Multiplier CCM



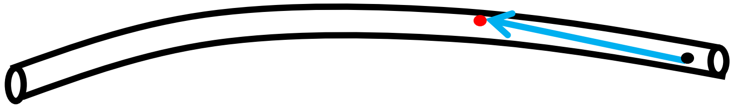
In order to get PMTs more simple, compact, robust and less sensitive to mechanical vibrations, minitubular electron multipliers were introduced (in the late years 60's)

- A special glass **capillary tube with D < 1mm**, called Continuous Channel Multiplier CCM or Channeltron, is at once **voltage divider and electron multiplier**; the inner surface is chemically treated and converted in a semiconductor layer with high resistivity and secondary electron emission yield g ≈ from 1,2 to 3.
- For a given applied voltage the **gain depends on the ratio *L/D***. As *L/D* increases the number of impacts increases, but the yield decreases because the impacting electron energy decreases. Maximum gain is attained with *L/D* ≈ 50
- Gain $G$ from $10^5$ to $10^6$ is attained with applied voltage in the range 2 to 3kV
- **No need to focus electrons** within the multiplier, but the electron optics from cathode to multiplier input must be carefully designed to get good collection efficiency

# Neutralizing the Ion Feedback in Channel

a) Straight channel CCM

b) Curved channel CCM



In order to exploit CCMs it is necessary to neutralize the effect of Ion Feedback.

- In the **last part of the channel the density of energetic electrons is high** and creation of free **heavy ions** (ionized atoms) by collision with residual gas molecules (or with the wall material) becomes probable.
- The free ions drift in the field and by impacting on the wall cause a strong emission of electrons. If the impact occurs near the channel input the emitted electrons undergo all the channel multiplication.
- This is a positive feedback effect, which enhances the current amplification in uncontrolled way and may even cause a self-sustaining breakdown current in the multiplier.
- The effect is avoided by bending the axis of the multiplier tube. Due to the large mass and small charge, a free ion has small acceleration in the electric field and its trajectory is almost straight; the ions thus impact in the last part of the channel, hence the emitted electrons undergo undergo a much lower amplification

# CCM Performance

- Dark current is lower in CCM-PMTs than in dynode-PMTs, which collect also electrons from auxiliary input electrodes contaminated in the photocathode fabrication
- The **excess noise factor F>2 is significantly higher than dynode-PMTs**, because the statistical dispersion in the electron multiplication is clearly greater
- The inner layer resistance is in *GΩ* range, the current in this voltage divider is low *<1μA,* hence for avoiding nonlinearity the **mean output current must not exceed a few nA**. This sets a strict limit to the product of mean photon rate and PMT gain.
- The amplification of a pulse signal leaves a charge on the multiplier surface near to the output. A high charge modifies the electric field, impairing the amplification of the following pulses during a long recovery transient (discharge through the inner layer resistance, with time constant of milliseconds or more). **To avoid this, the product of multiplier gain and input pulse charge and/or repetition rate must be limited**
- Strong nonlinearities due to space charge may occur for high pulses and high gain

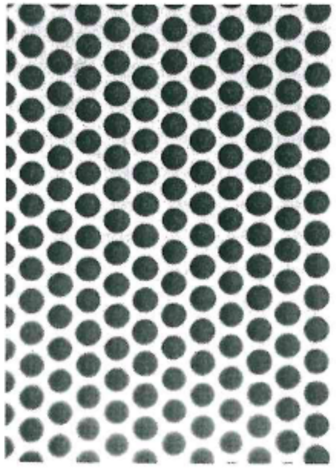
In conclusion, CCM-PMTs are

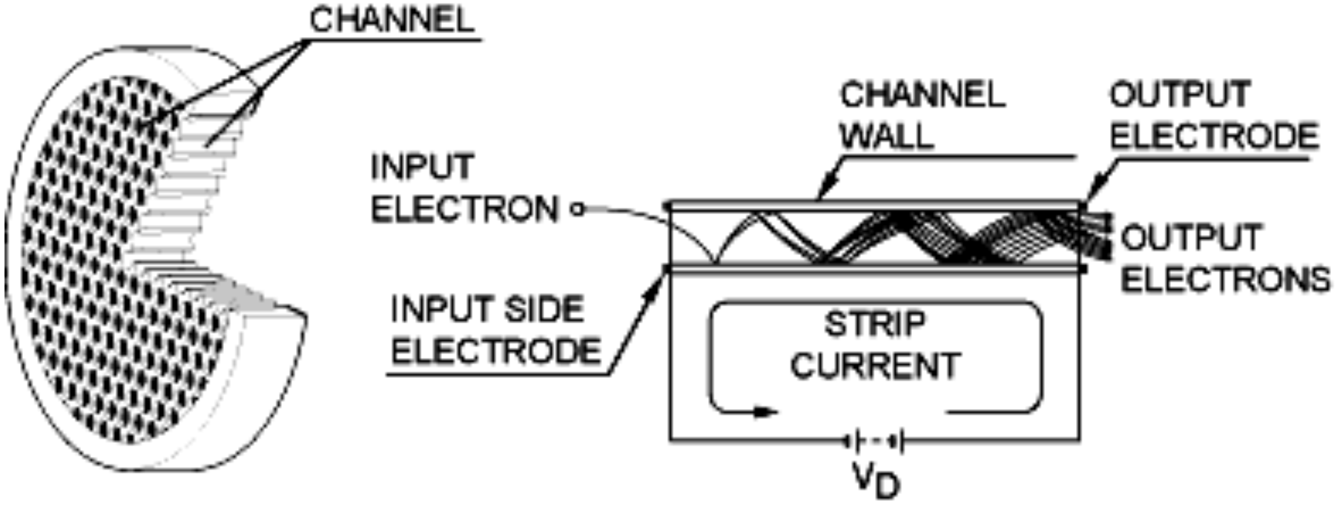
**a)** **well** suitable and provide very good performance for detecting **pulses with moderate repetition rate and small size** (down to single photons).

**b)** **NOT** well suitable for **many-photon-pulses** (e.g. for scintillation detectors of ionizing radiation) and for **stationary light intensity**.

# Micro-Channel Plate Multiplier MCP

MCP front view

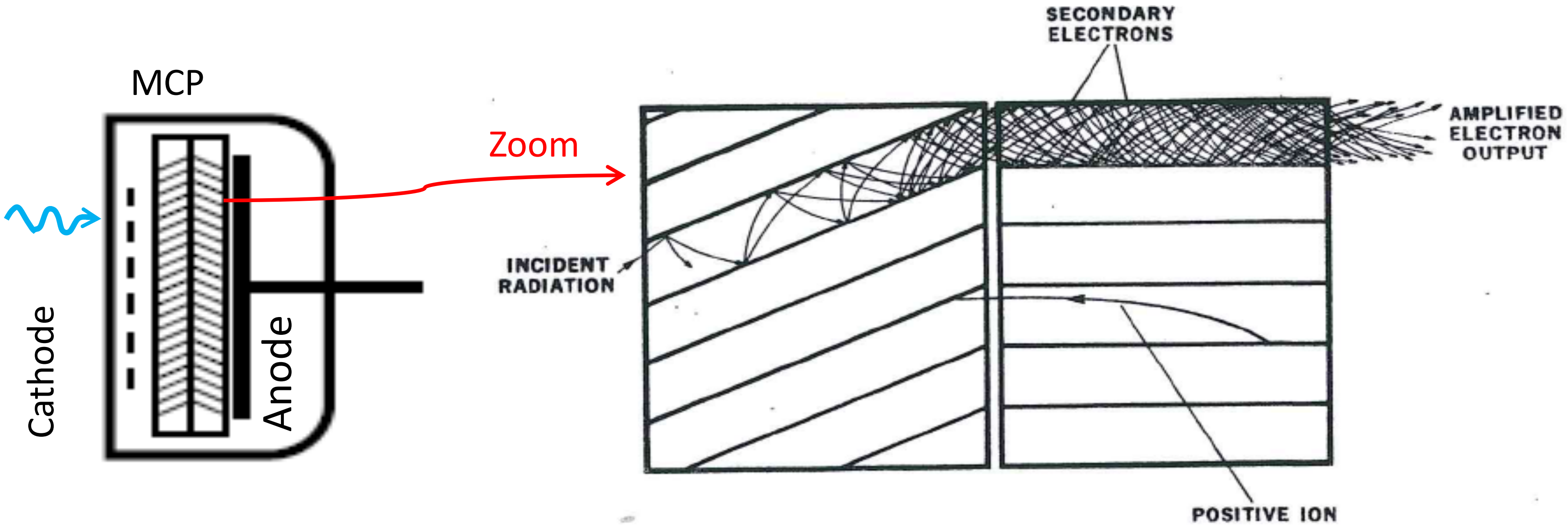




- For overcoming the CCM limitations, the multiplier concept evolved (in early years 70's) to the MicroChannel Plate MCP, implemented with sophisticated glass technology
- An array of many thousands of multiplier microtubes is embedded in beehive structure into a plate. All channels are biased in parallel with the same high voltage $V_D$ , applied via metal electrodes deposited on the two faces of the plate.
- The MCP has a **planar geometry**, well matched to a planar end-window photocathode; focusing of photoelectrons on the multiplier is simply provided by a high voltage from cathode to multiplier input (**proximity-focusing** geometry )

# Micro-Channel Plate Multiplier MCP

- MCPs are implemented with small diameter D from 50µm to 5µm and the useful area (sum of the channel input sections) is ≈50 to 60% of the total plate area
- Each channel operates as an individual miniaturized CCM: the gain is optimized still with L/D ≈ 50
- To avoid ion feedback by bending the channel axis is not convenient for MCPs; the same principle is exploited by two MCPs with inclined channel axis, mounted in series with channel axis of the first and second MCP forming an angle



# MCP Performance

Most of the limitations that plague CCMs are relaxed for MCPs with illumination distributed on the cathode because:

a) Electrons emitted from the same position of the cathode do not enter all in the same microchannel; they are distributed over a group of facing channels in the MCP.

b) The perturbation of the voltage distribution in a channel affects the multiplication and collection of electrons just in that channel and closest neighbors, not farther.

It follows that:

1) the limit to the output mean signal current is much higher; it is a small percentage of the **total** bias current of the MCP, not of a single microchannel

2) also many-photon optical pulses are correctly linearly processed, since the pulse photoelectrons are multiplied in parallel in different microchannels

- The statistical gain distribution of MCPs is similar to CCMs, significantly wider than for dynode-PMTs, with excess noise factor significantly higher F>2
- The dynamic response of MCPs is remarkably superior to that of dynode PMTs.
  The transit time $T_b$ and its jitter $T_j$ are remarkably shorter; in fast MCP types they are reduced down to $T_b \approx 1\text{ns}$ and $T_j \approx$ a few 10ps.
  Also the SER pulse-width $T_w$ is shorter, down to $T_w \approx$ a few 100ps.