气体探测器

Gas-filled Detector

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Outline

- Motion of electrons and ions in gas
- Ionization chamber
- Proportional counter
- G-M counter

MOTION OF ELECTRONS AND IONS IN GAS

Ionization of gas

- Primary ionization
  - Number of ion pairs that produced directly by injecting charged particles
- Secondary ionization
  - Number of ion pairs that produced by fast electrons which produced in primary ionization
- Total ionization
  - Sum of primary ionization and secondary
- Specific ionization
  - Number of ion pair produced in unit path of charged particles

ionization energy and ionization potential

- Ionization energy w
  - Average energy charged particle loss per ion pair produced
- Ionization potential I_0
  - Least energy needed to produce one ion pair
- Obviously, $w>I_0$
- Total ionization $N = E_0/w$

Data Sheet of Ionization Energy

Unit: eV

气体	$w(\alpha)$	$w(X, \gamma)$	$w(\beta)$	I_0
He	46.0±0.5	41.5±0.4	29.9+0.5	24.5
Ne	35.7±2.6	36.2±0.4	28.6±8	21.6
Ar	26.3±0.1	26.2±0.2		15.8
O_2	32.3±0.1	31.8±0.3	31.5±2	12.5
CH_4	29.1±0.1	27.3±0.3		12.8
C_2H_4	28.03±0.05	26.3±0.3		12.2
空气	34.98±0.05	33.73±0.15	36.0±0.4	

Distribution of ion pairs Number

$$\sigma^2(N) = F \cdot \frac{E_0}{w}$$

Fano factor,For gas: 0.2~0.5
For Semiconductor: 0.1~0.15

Motion of Ions and Electrons

- Drift
  - Ions or electrons drift along electric field line because of Coulomb force
- Diffusion
  - Ions or electrons move from high density region to low density region because of density difference

Drift of Ions

$$W^{\pm} = \mu^{\pm}\frac{E}{P}, \text{for } \frac{E}{P} \le 0.03\text{V}\cdot\text{cm}^{-1}\cdot\text{Pa}^{-1}$$

drift velocity

drift rate

reduced field strength

In gas-filled detector, drift velocity is usually ~10^3 cm/s for Ions, which is much less than its velocity u of random motion.

Drift rate for Different Gas

表 3.2　离子的迁移率和扩散系数

气　体	$\mu^{+}\mathrm{cm}\cdot\mathrm{s}^{-1}\cdot V^{-1}$	$\mu^{-}\mathrm{cm}\cdot\mathrm{s}^{-1}\cdot V^{-1}$	$D^{+}\times10^{2}\mathrm{cm}^{2}\cdot\mathrm{s}^{-1}$	$D^{-}\times10^{2}\mathrm{cm}^{2}\cdot\mathrm{s}^{-1}$
H_2	5.7	8.6		
D_2				
He	5.1	6.3		
N_2	1.29	1.82	2.9	4.1
O_2	1.33	1.80	3.0	4.1
CO_2	0.79	0.95	2.5	2.6
Ar	1.37	1.7		
空气	1.37	1.8	3.2	4.2
水蒸气	0.83	0.72		

Drift of Electrons

- not proportional to E/P
- 10^3 times greater than that of ions, about 106 cm/s
- Very sensitive to components of gas. Mixing monatomic gas (such as Ar, Xe, Kr) with a little polyatomic gas could increase drift velocity by one order of magnitude.

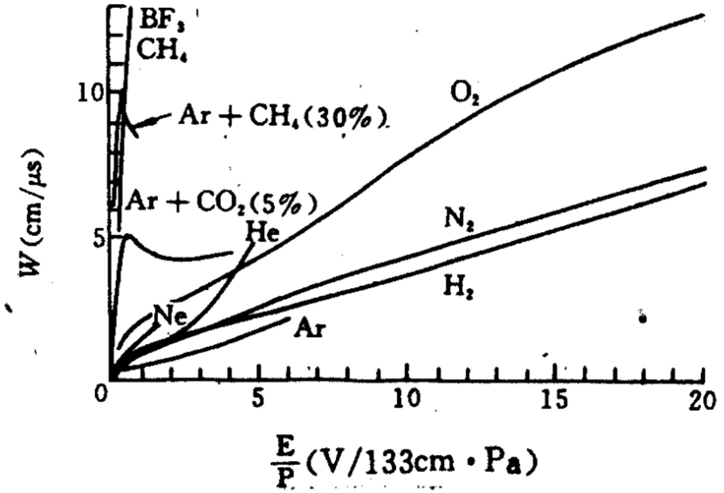


图 3.1 电子在气体中的漂移速度

Diffusion of Ions and Electrons

$$\frac{dn}{dt} = -D\nabla n$$

n: density of ions or electrons
D: diffusion constant

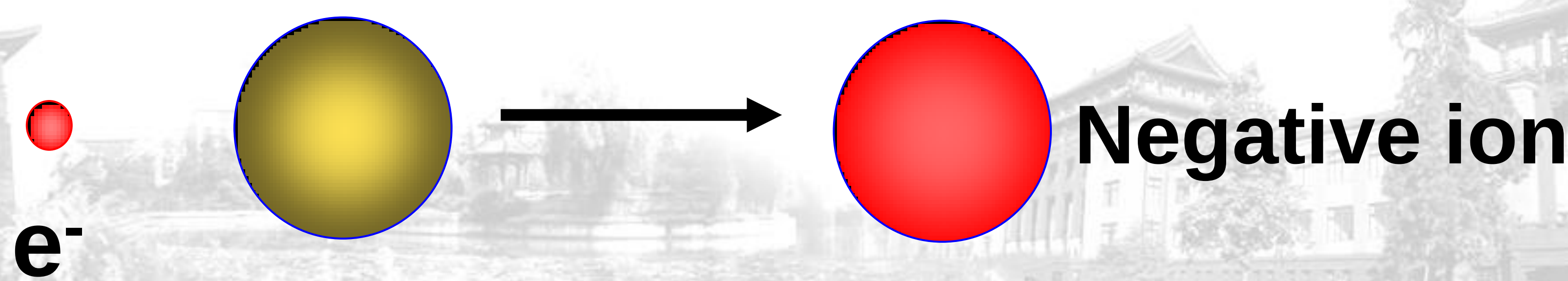
$$D = \frac{1}{3}\lambda u$$

λ: mean free path
u: velocity of random motion

Diffusion constant of electrons is greater than that of ions, for electrons have greater λu.
Diffusion constant has connection with property, temperature and pressure of gas.

Electron Attachment

- Electrons could be captured by gas molecules when they are colliding with each other.
- Capture probability p has connection with characteristics of gas.
- For O_2, water steam, halogen gas, which are called electronegative gas, $p \approx 10^{-3} \sim 10^{-4}$
- For inert gas, N_2, CH_4, H_2, $p \leq 10^{-6}$



Avoid Influence of Electronegative Gas

- Using pure gas to avoid electronegative impurity
- mix monatomic gas with a little diatomic gas

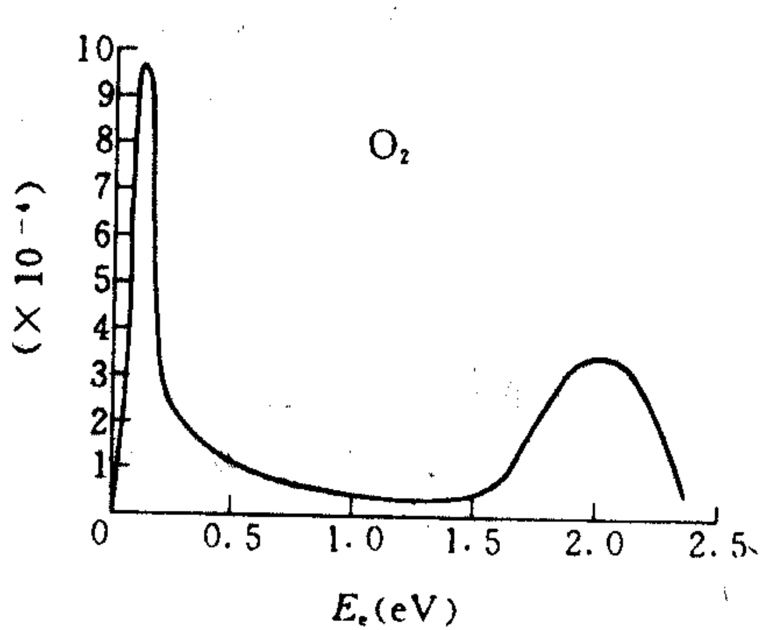


图 3.2 氧分子的捕获概率与电子能量的关系

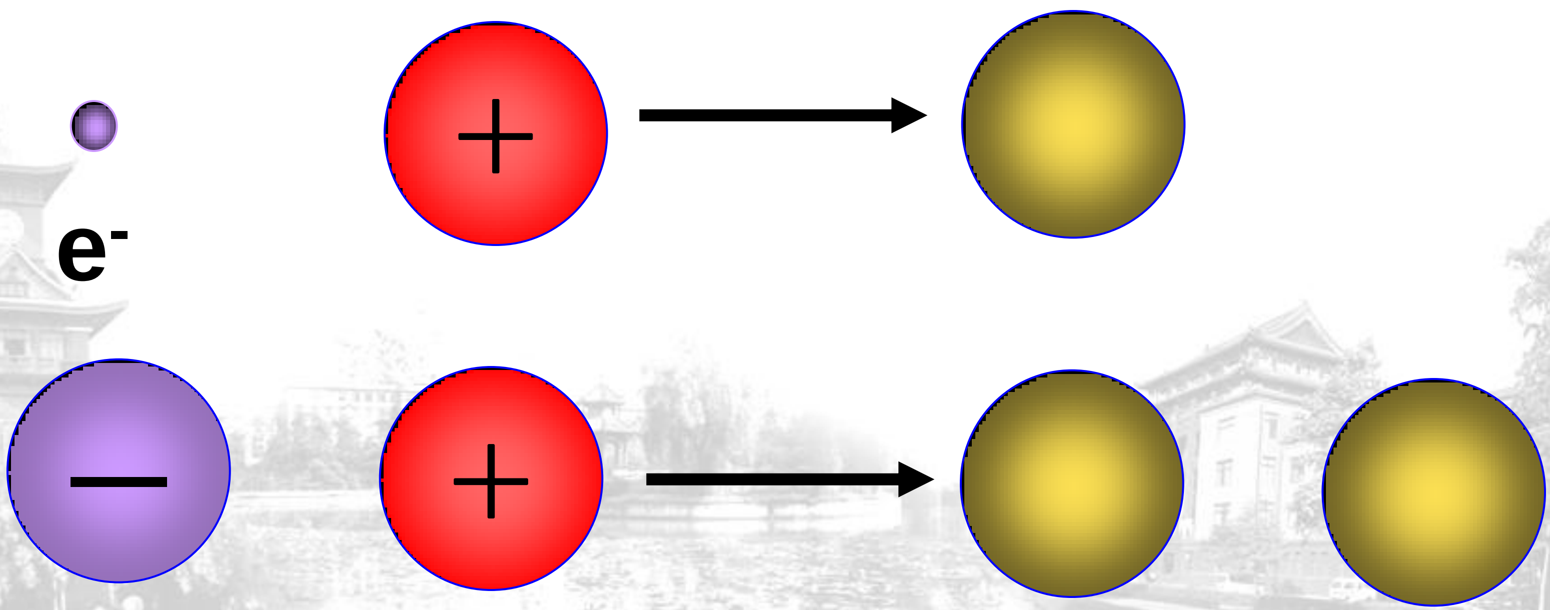
Exercise: Let u=10^7cm/s, λ=10^{-4}cm, estimate how many times that a electron collides with gas molecules.

Recombination

$$\frac{dn^+}{dt} = \frac{dn^-}{dt} = -\alpha n^+ n^-$$

$$\alpha_{\mathrm{i}} \approx 10^{-6}\,\mathrm{cm}^3/\mathrm{s}$$

$$\alpha_{\mathrm{e}} \approx 10^{-7} \sim 10^{-10}\,\mathrm{cm}^3/\mathrm{s}$$



Collection of Ions

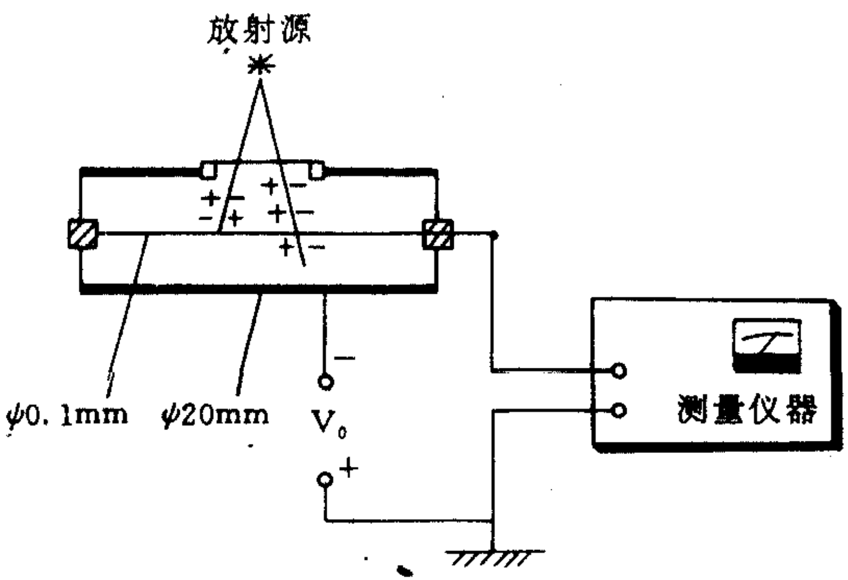


图 3.3　离子收集装置的示意图

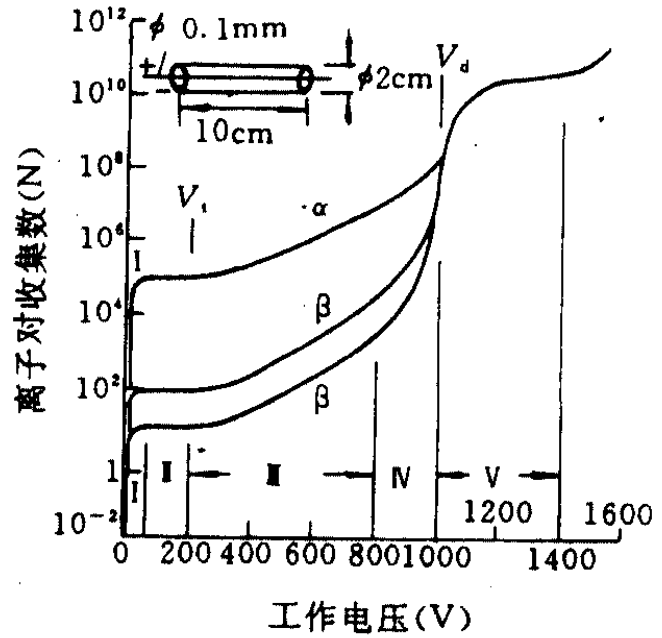


图 3.4　离子收集的电压电流曲线

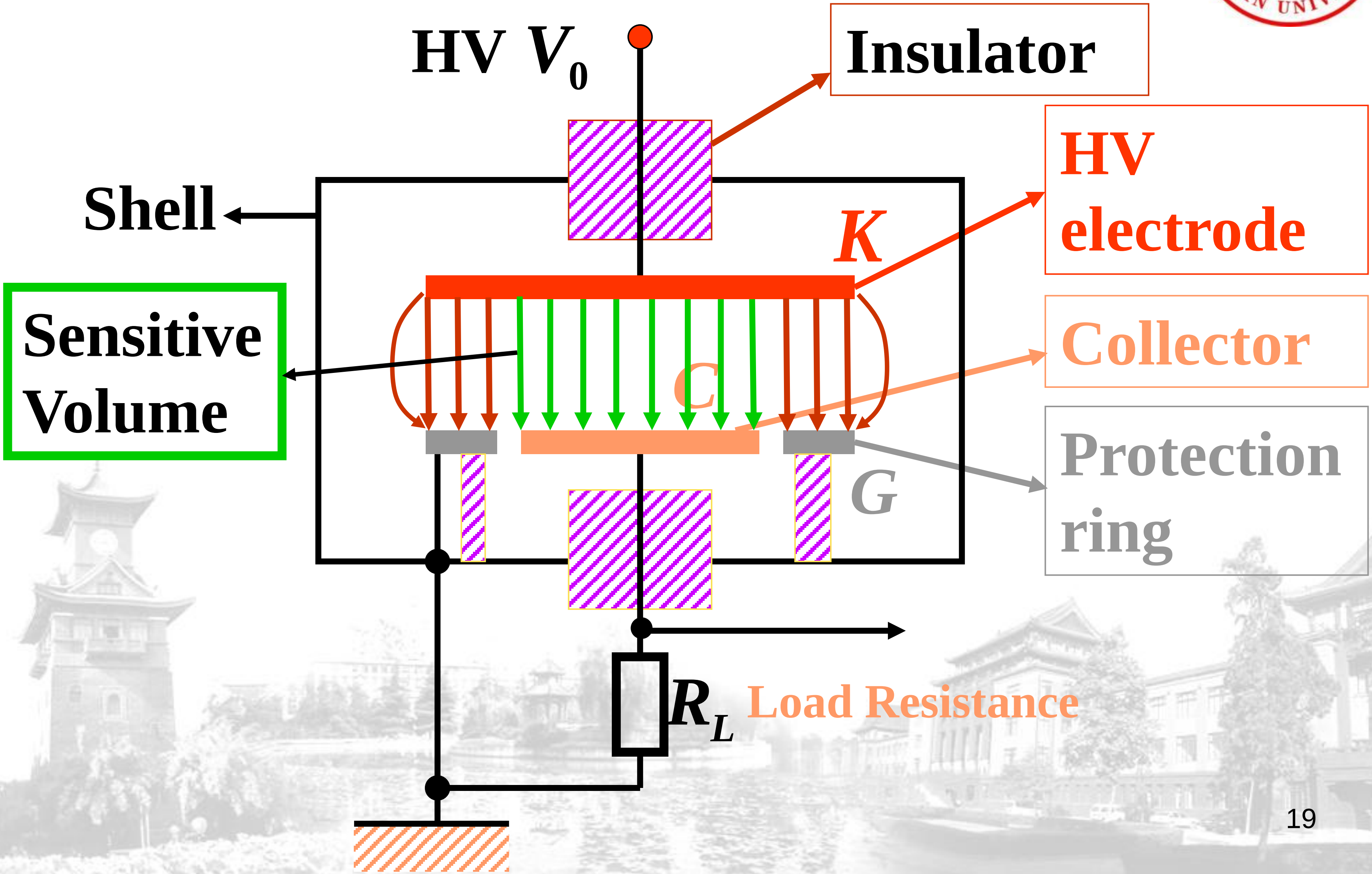
I: Recombination region
II: Saturation region
III: Proportionality region
IV: Limited proportionality region
V: G-M region

IONIZATION CHAMBER

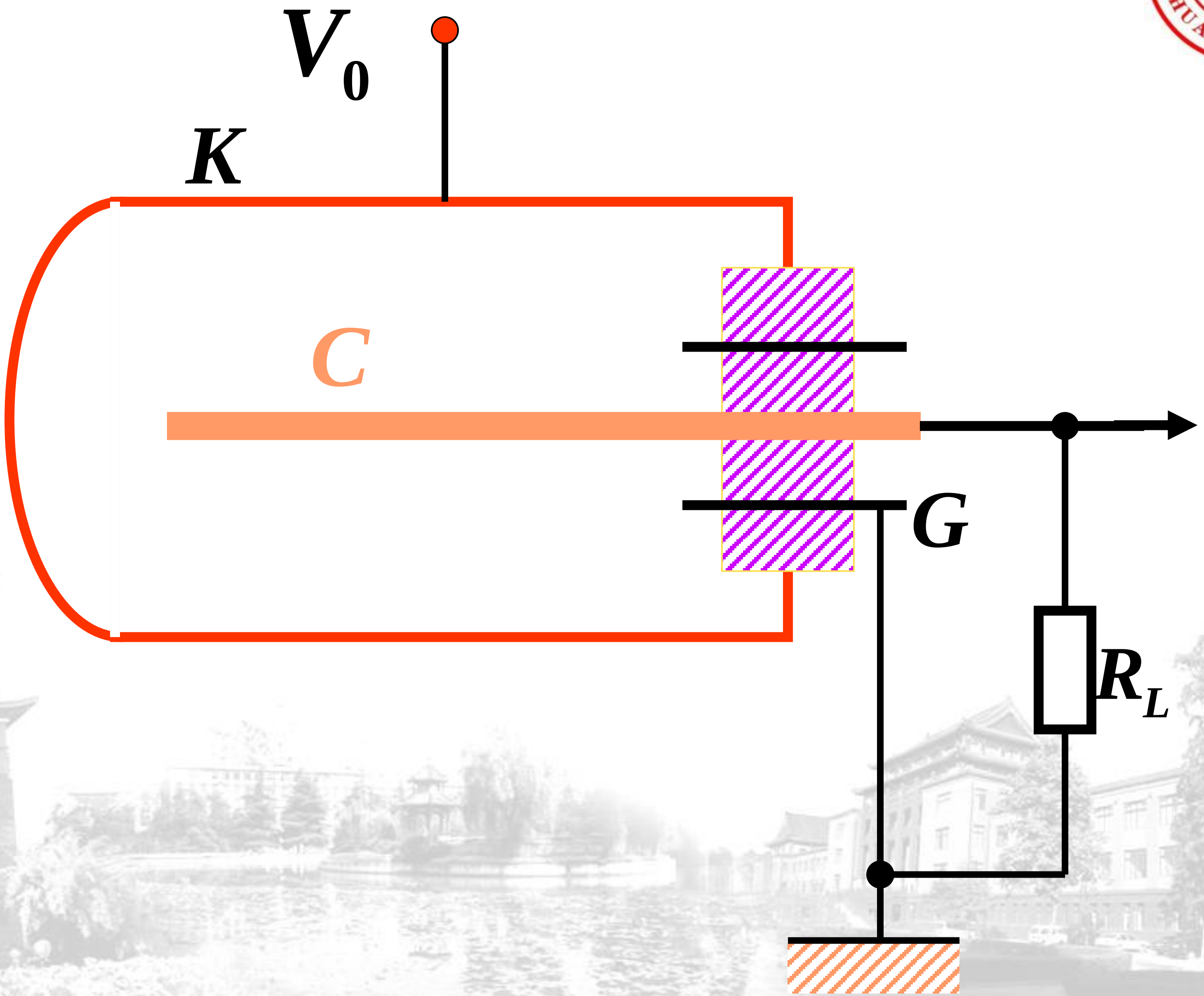
Two Sorts of Chamber

- Pulse Chamber
  - Recording ions one by one,
  - Mainly be used to measure energy and intensity of heavy charged ions
- Current Chamber
  - Recording mean effect of large amount of ions
  - Mainly be used to measure intensity or flux, dose, dose rate of X, γ, β and neutrons.

Flat Chamber



Cylinder Chamber



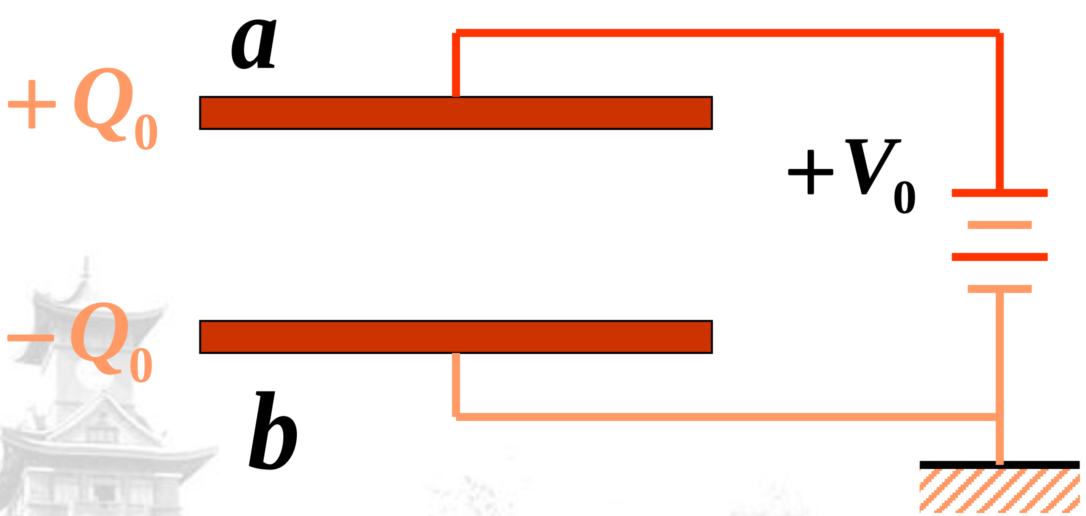
Operating Gas

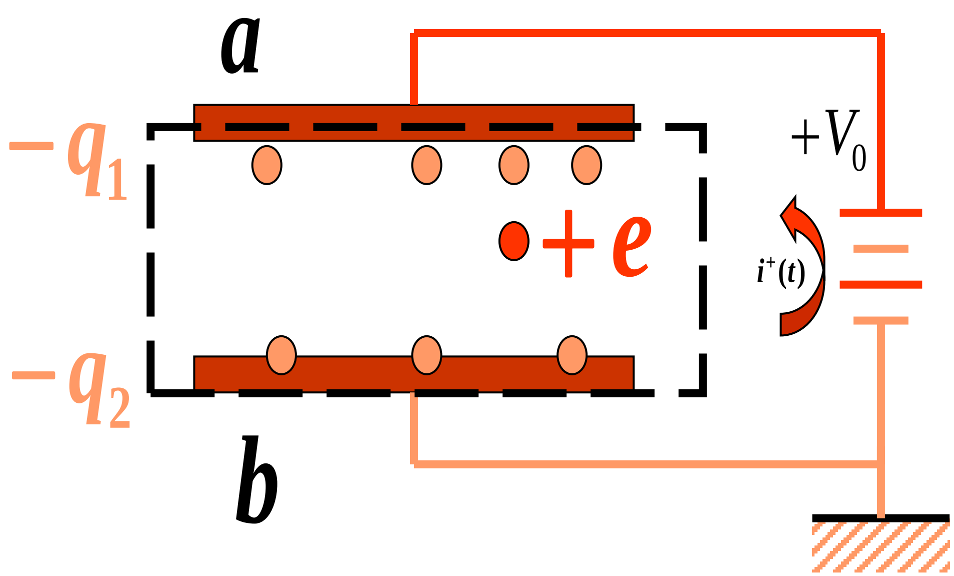
- Inert gas, N_2, air
- For pulse chamber, inert gas + a small quantity of polyatomic gas
  - for example, 90%Ar + 10%CO_2(or CH_4),
- BF_3, CH_4, H_2, ^3He for neutron detection
- With pressure of 10^5~10^6 Pa
  - When use high pressure gas, purity of gas must be ensured to avoid serious recombination

Signal Generation of Chamber

$$+Q_0 = -Q_0 = C_1 V_0$$

C_1: capacitance of plates





Total charge transferred from positive plate to negative plate through circuit is q_1(negative) while the positive charge move to negative plate.

Similarly, if a -e charge produced in the same place and drift to positive plate finally, q_2(positive) charge transferred from negative plate to positive plate.

$$\oint \vec{E} d\vec{s} = 4\pi q = 0$$

$$q = (+Q_0) + (-Q_0) + e + (-q_1) + (-q_2) = 0 \Longrightarrow \boldsymbol{q_1 + q_2 = e}$$

Obviously, q_1 and q_2 have connection with the distance from the positive charge to the corresponding plate.

Conclusion:

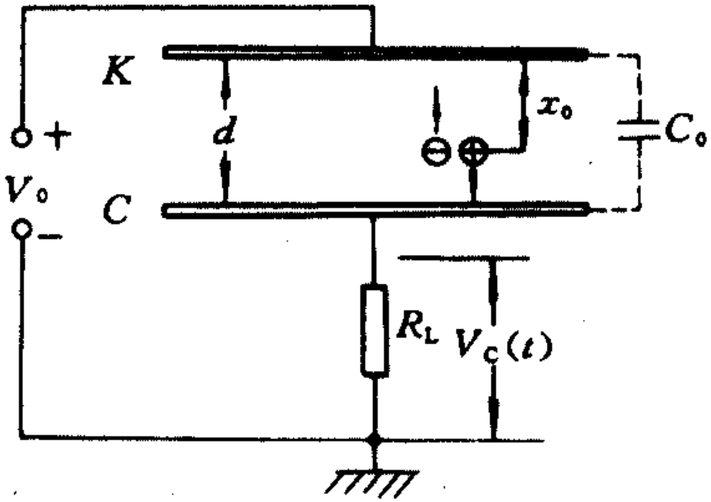
if a ion pair produced and than the positive ion drift to negative plate and the negative one drift to the other, the total charge transferred through circuit is e, which has no connection with the ion's initial place.

Discussion

- There is current in circuit only when charged ions are moving between the plates.
- When N ion-pairs produced because of injecting particles, the total charge transferred through circuit is Ne.

Voltage Pulse and Current Pulse

$$\varepsilon = \frac{1}{2} C_0 V^2 \qquad \frac{d\varepsilon}{dt} = C_0 V \frac{dV}{dt} = -C_0 V \frac{dV_C}{dt}$$



$$-\frac{d\varepsilon}{dt} = e(E^+W^+ + E^-W^-)$$

$$\frac{dV_C}{dt} = \frac{e}{C_0 V}(E^+W^+ + E^-W^-)$$

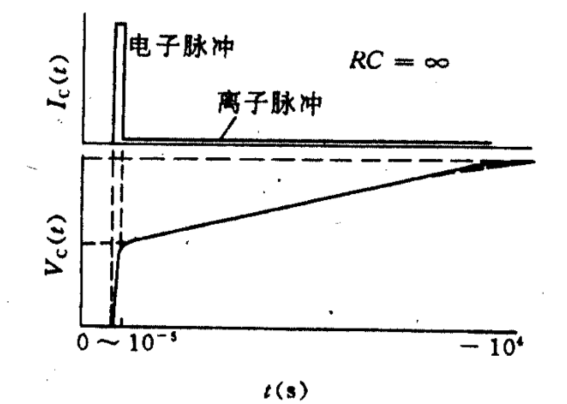
For Flat Chamber

$$E = \frac{V}{d}, T^- = \frac{x_0}{W^-}, T^+ = \frac{x_0}{W^+}$$

$$V_C(t) = \frac{e}{C_0 d}(W^+ + W^-)t \quad \text{for } t < \frac{x_0}{W^-} \qquad I_C(t) = \frac{e}{d}(W^+ + W^-)$$

$$= \frac{e}{C_0 d}(W^+ t + x_0) \quad \text{for } \frac{x_0}{W^-} \le t < \frac{d - x_0}{W^+} \qquad = \frac{e}{d} W^+$$

$$= \frac{e}{C_0} \quad \text{for } \frac{d - x_0}{W^+} \le t \qquad = 0$$



Excierse

- Prove that if N ion pairs produced by one injecting particle, the voltage pulse amplitude is $V_\infty = eN/C_0$.
- Prove the current

$$I(t) = \frac{e}{V}\sum_i (E_i^+ W_i^+ + E_i^- W_i^-)$$

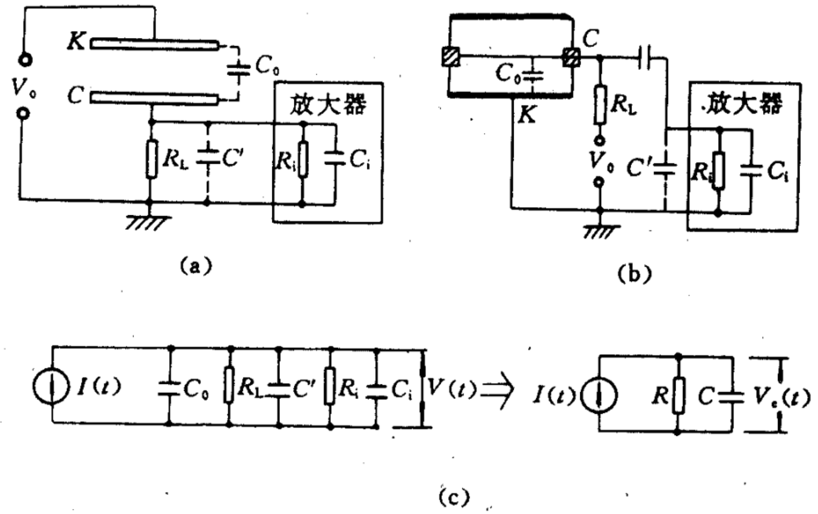
Discussion

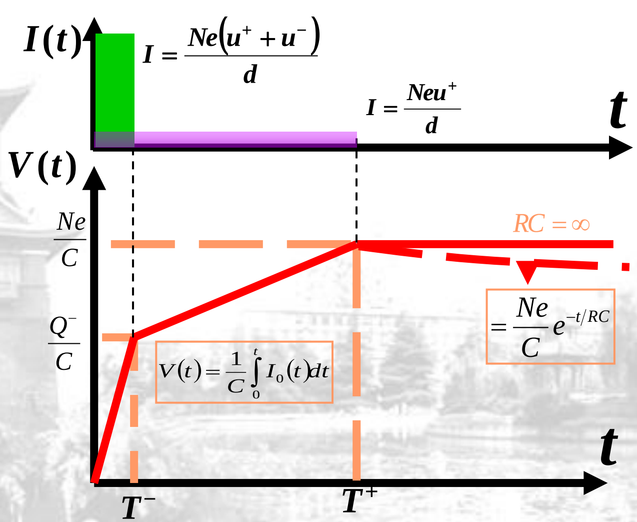
- Voltage and current pulse produced not by charge collection but by change of induced charge, which is cause by drift of electrons and positive ions.
- Rate of pulse change depends on drift velocity. The fast leading edge is contributed by electrons, for its drift velocity is 10^3 times as that of positive ions.
- Electron attachment would decrease the fast component of the pulse.

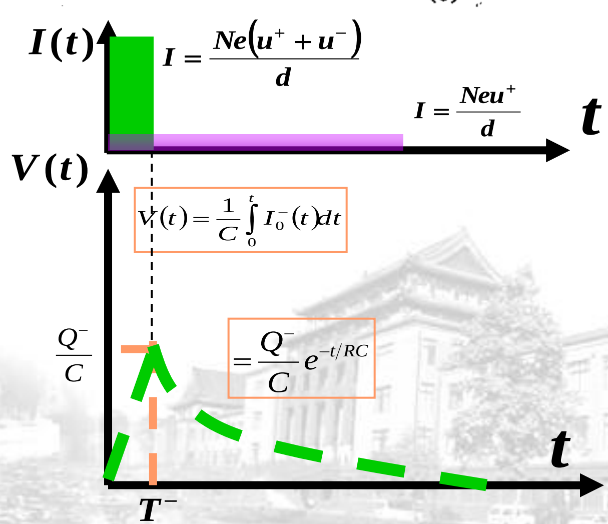
Output circuit

$$I_C(t) = \frac{V_C(t)}{R} + C\frac{dV_C(t)}{dt}$$

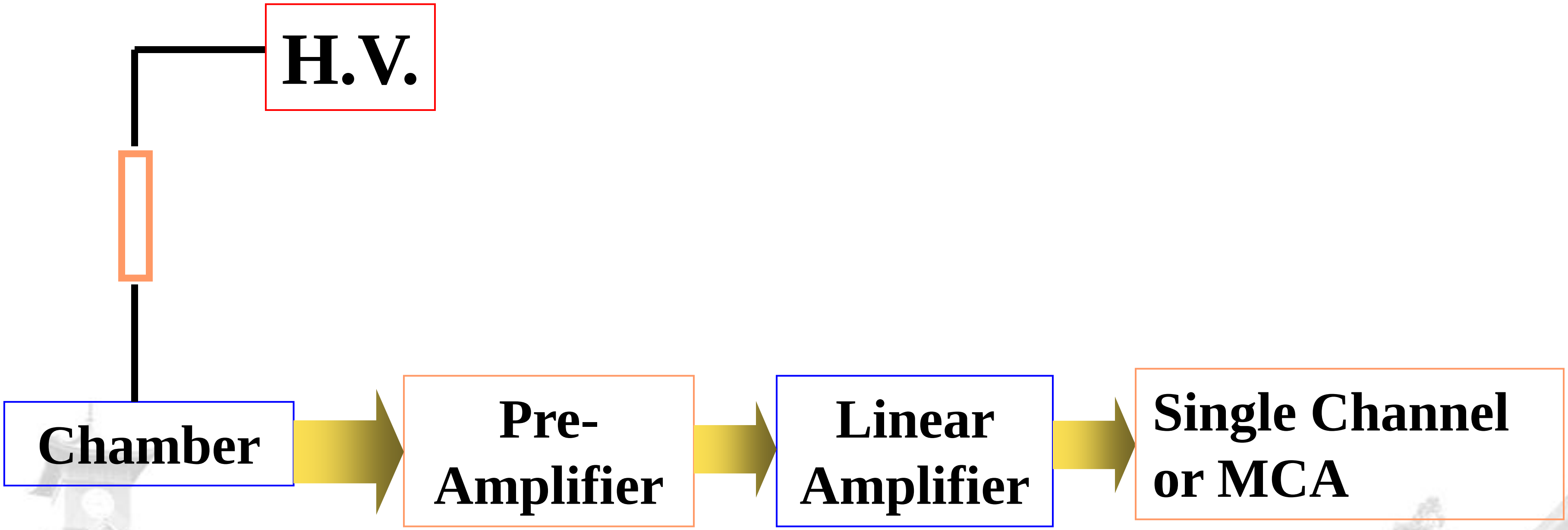
$$V_C(t) = \frac{e^{-\frac{t}{RC}}}{C}\int_0^t I_C(t)e^{\frac{t}{RC}}dt$$



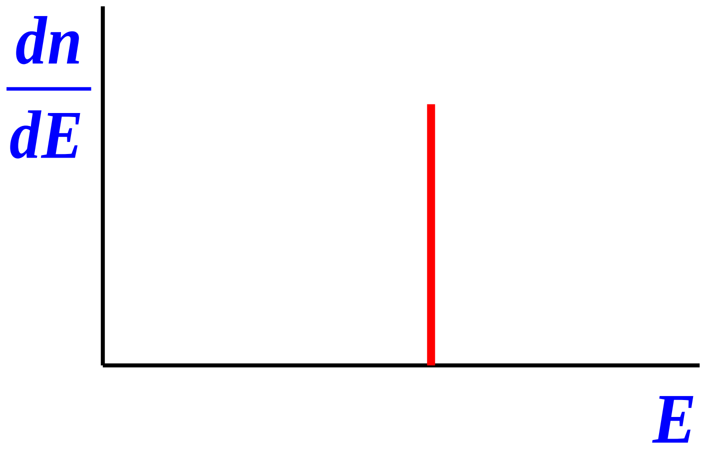


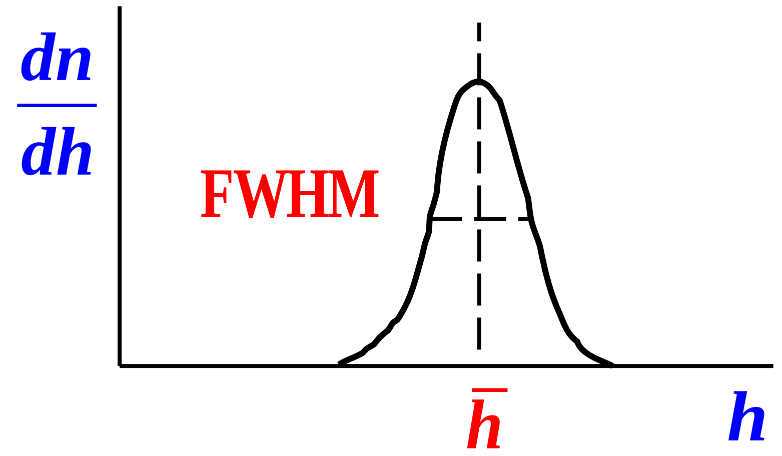


Energy Spectrometer

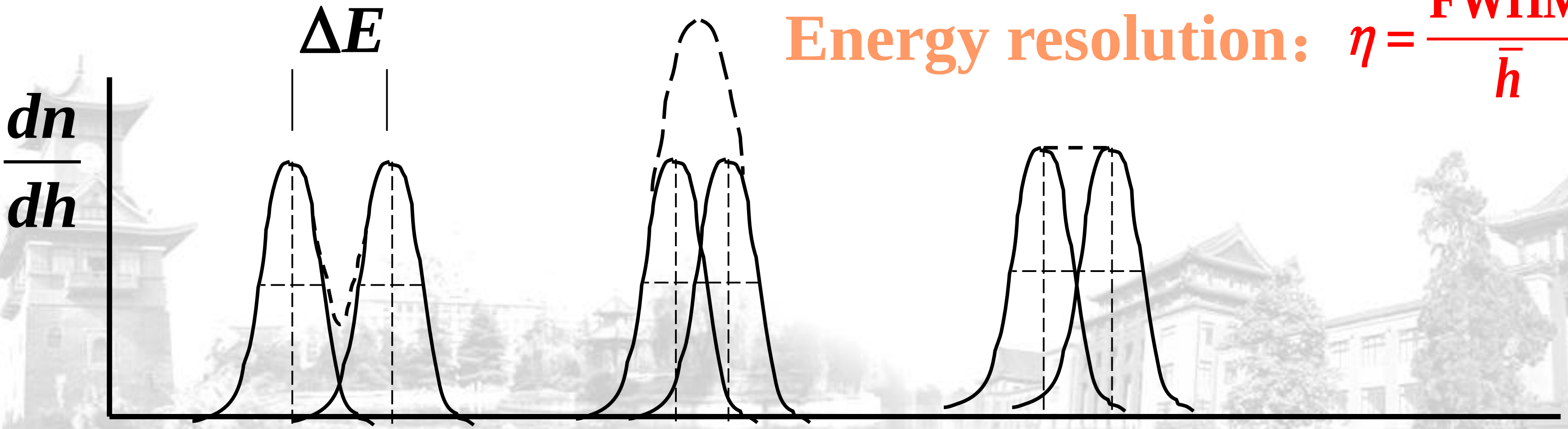


Pulse Amplitude and SpectrumEnergy Spectrum





Energy resolution: $\eta = \dfrac{FWHM}{\bar{h}}$



$\Delta E > \eta E$ $\Delta E < \eta E$ $\Delta E = \eta E$

Energy Calibration

$$E = ah + b$$

For N kinds of particles, energy of which is E_1, E_2, ...,E_N, the spectrometer give their central channel are h_1, h_2, ..., h_N.

Found a, b to make $$\sum_{i=1}^{N} \left[E_i - ah_i + b \right]^2 = \min$$

Energy Resolution

$$\bar{h} = \frac{\bar{N}e}{C} = \frac{e}{C}\bar{N}$$

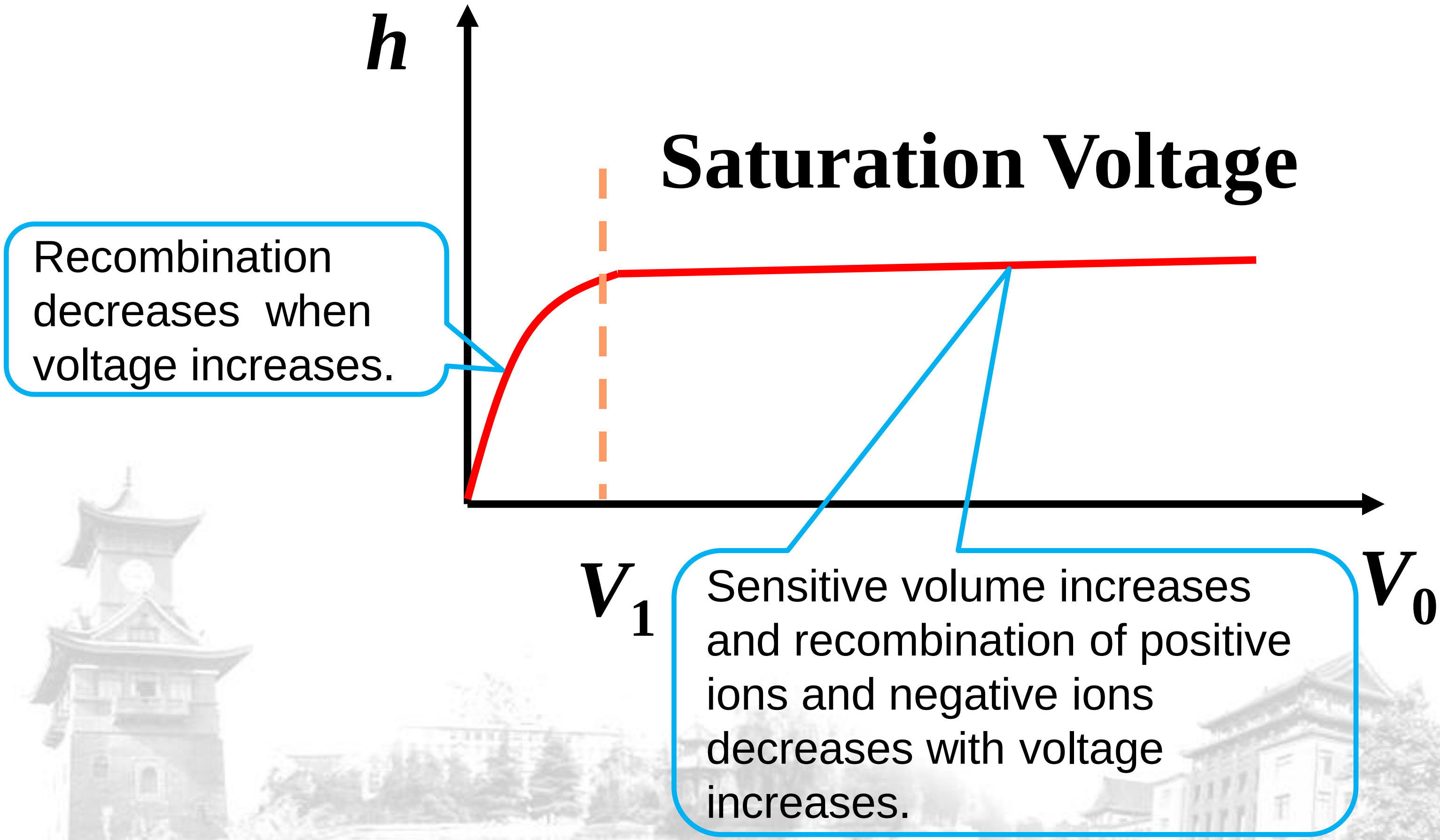
$$P[h] = \frac{1}{\sqrt{2\pi}\sigma_h} e^{(h-\bar{h})^2 / 2\sigma_h^2}$$

$$\sigma_h = \frac{e}{C}\sigma_N = \frac{e}{C}\sqrt{F\bar{N}}$$

$$\nu_h = \frac{\sigma_h}{\bar{h}} = \sqrt{\frac{F}{\bar{N}}}$$

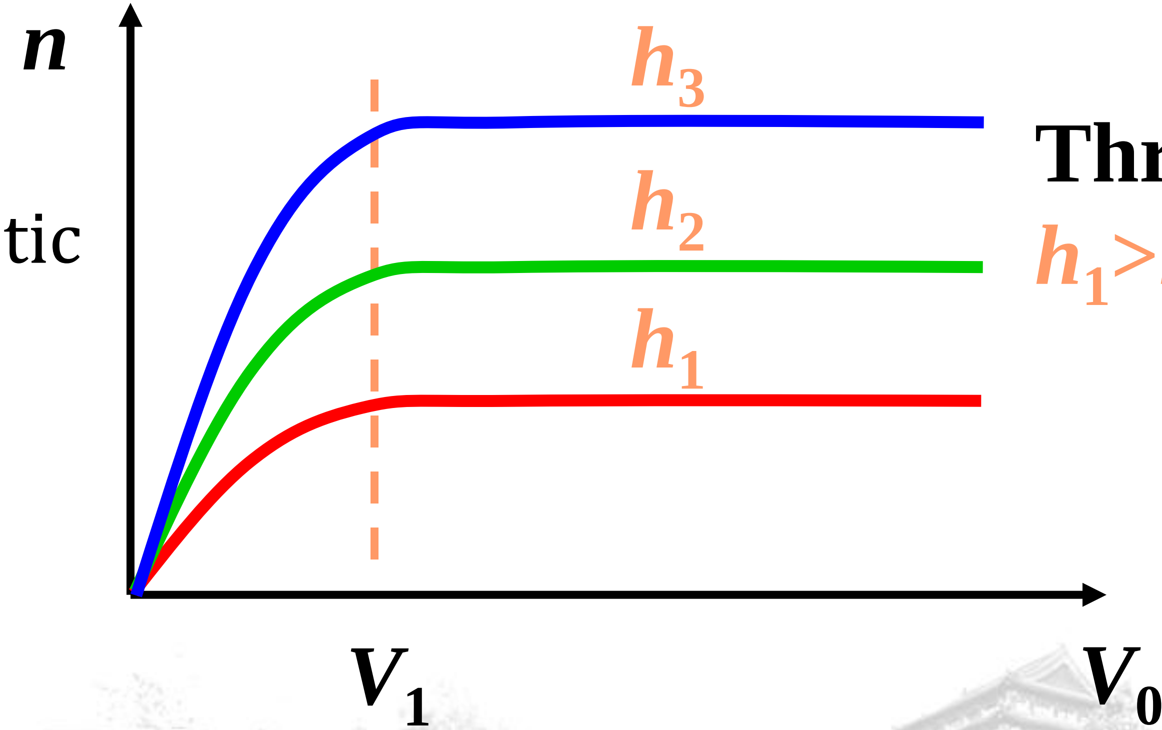
$$\eta \equiv \frac{\Delta h}{\bar{h}} = \frac{2.355\sigma_h}{\bar{h}} = 2.355\nu_h = 2.355\sqrt{\frac{F}{\bar{N}}} = 2.355\sqrt{\frac{FW_0}{E_0}}$$

Saturation Curve



Plateau Characteristic

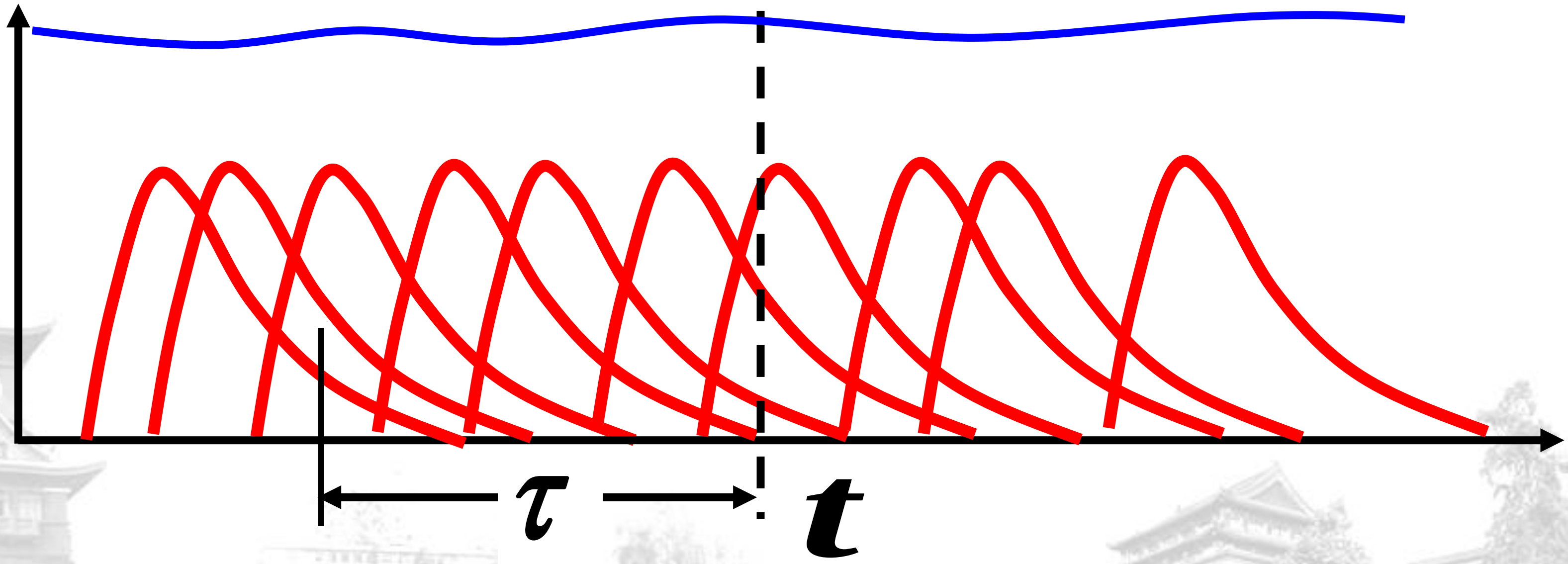
Monenergitic particles injection



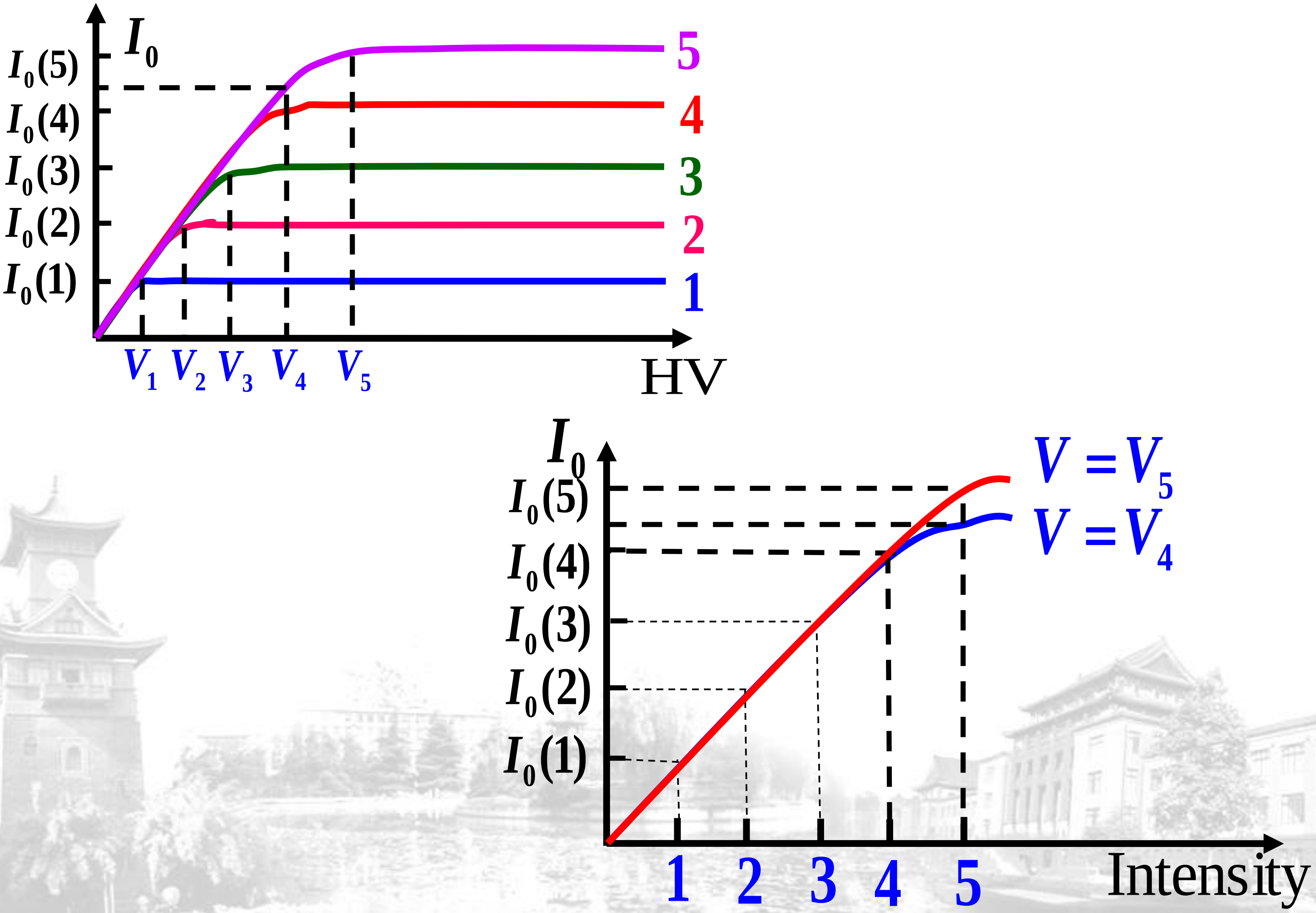
Threshold

$h_1 > h_2 > h_3$

Current Chamber



Saturation Characteristic and Linear Region



Sensitivity

- Sensitivity is the output caused by injecting particles of unit intensity.

$$\eta = \frac{\text{Output Current}}{\text{Injecting Particles Intensity}} [\text{A} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}]$$

$$\eta = \frac{\text{Output Voltage}}{\text{Injecting Particles Intensity}} [\text{V} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}]$$

Response Time

- Response time is used to describe that how fast the output changes when the injecting particles intensity changes.
  - For output current, response time is the maximum collecting time of ions.
  - For output current, response time depends on the output circuit parameters, which is about 5RC~7RC.

Energy Response

- Energy response describes the relationship between sensitivity and injecting particles' energy.

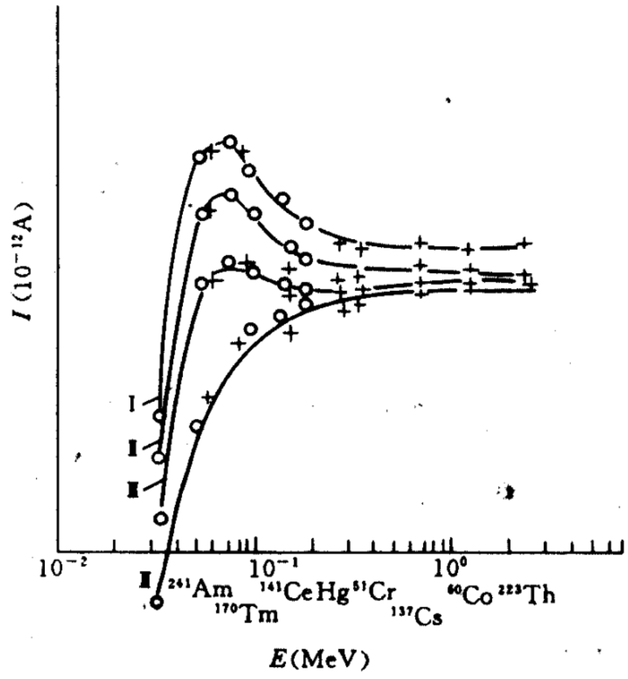


图 3.13 γ射线电离室的能量响应

Ⅰ—工作气体为 Ar；Ⅱ—工作气体为 50%Ar＋50%N_2；Ⅲ—工作气体为 20%Ar＋80%N_2；Ⅳ—工作气体为 N_2。

PROPORTIONAL COUNTER

Condition of Gas Amplification

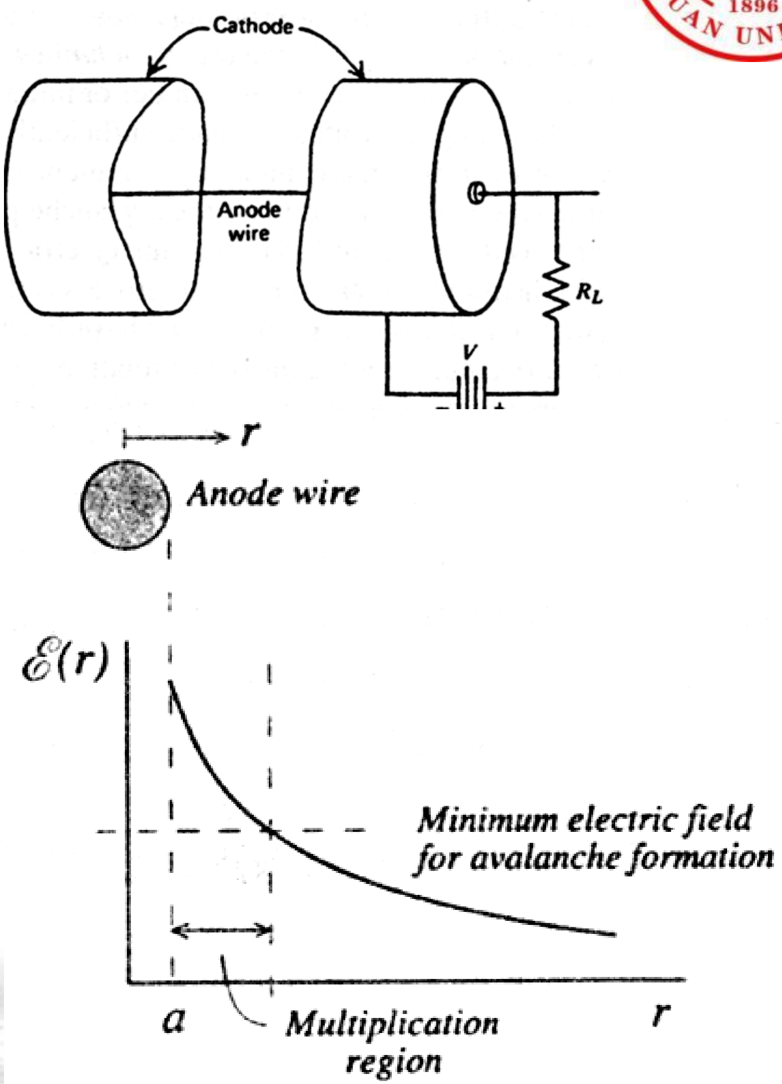
- The free path of electrons at one atmosphere pressure is 10^{-3}~10^{-4}cm
- While the ionization potential is about 20eV
- So, the electric field should be at least 10^{4} V/cm to accelerate the electron to enough energy in one free path which can cause next ionization.

Cylinder Structure

$$E(r) = \frac{V_0}{r \ln b/a}$$

Example: V_0=1000V, a=10μm, b=1cm, r=0.15mm, E≈10^4V/cm

Question: How to determine the minimum voltage of a proportional counter?



Threshold Voltage and Amplification Factor

Threshold Voltage

$$E_T = \frac{V_T}{a \ln \frac{b}{a}} \sim 10^4 V/cm$$

Electron number at r_0, or electron number produced by primary ionization

Amplification Factor $A = n(a)/n(r_0)$

Electron number collected by anode surface

$$\ln A \propto V_0^{1/2} \cdot \left[\sqrt{\frac{V_0}{V_T}} - 1 \right]$$

While $V_0 >> V_T$

$$\ln A \propto V_0$$

Photon Feedback

Gas molecules are excited because of collision with electrons.

↓

Ultraviolet is emitted by de-excitation of gas molecules.

↓

Secondary electrons are emitted in photoelectric effect when Ultraviolet is injecting into cathode.

↓

Ionization and gas amplification occured by secondare electrons.

Let γ be the probability that one electron achieving anode produce one secondary electron through photon feedback, then:

$$A_{\text{total}} = A + \gamma A^2 + \gamma^2 A^3 + \cdots$$

$$\text{if } \gamma A < 1$$

$$A_{\text{total}} = \frac{A}{1-\gamma A}$$

Photon Feedback

- It takes only 10^{-9}s for photon feedback, which is much shorter than drift time(10^{-6}s) of electrons
- Polyatomic gas could absorb ultraviolet. So, introduce some polyatomic gas could suppress photon feedback.

Ion feedback

- It is probable that secondary electrons are emitted when positive ions are collecting by cathode, which could introduce another gas amplification process.
- Introducing some polyatomic gas in operating gas could also suppress ion feedback.

Output Current

- $A >> 1$, the primary ionization is ignored;
- $r_0 \approx a$, the signal caused by electrons is ignored.

$$I_0 = \frac{ANe}{V_0} \vec{E}(r(t)) \cdot u^+(\vec{r}(t))$$

$$E(r) = \frac{V_0}{r \ln b/a}$$

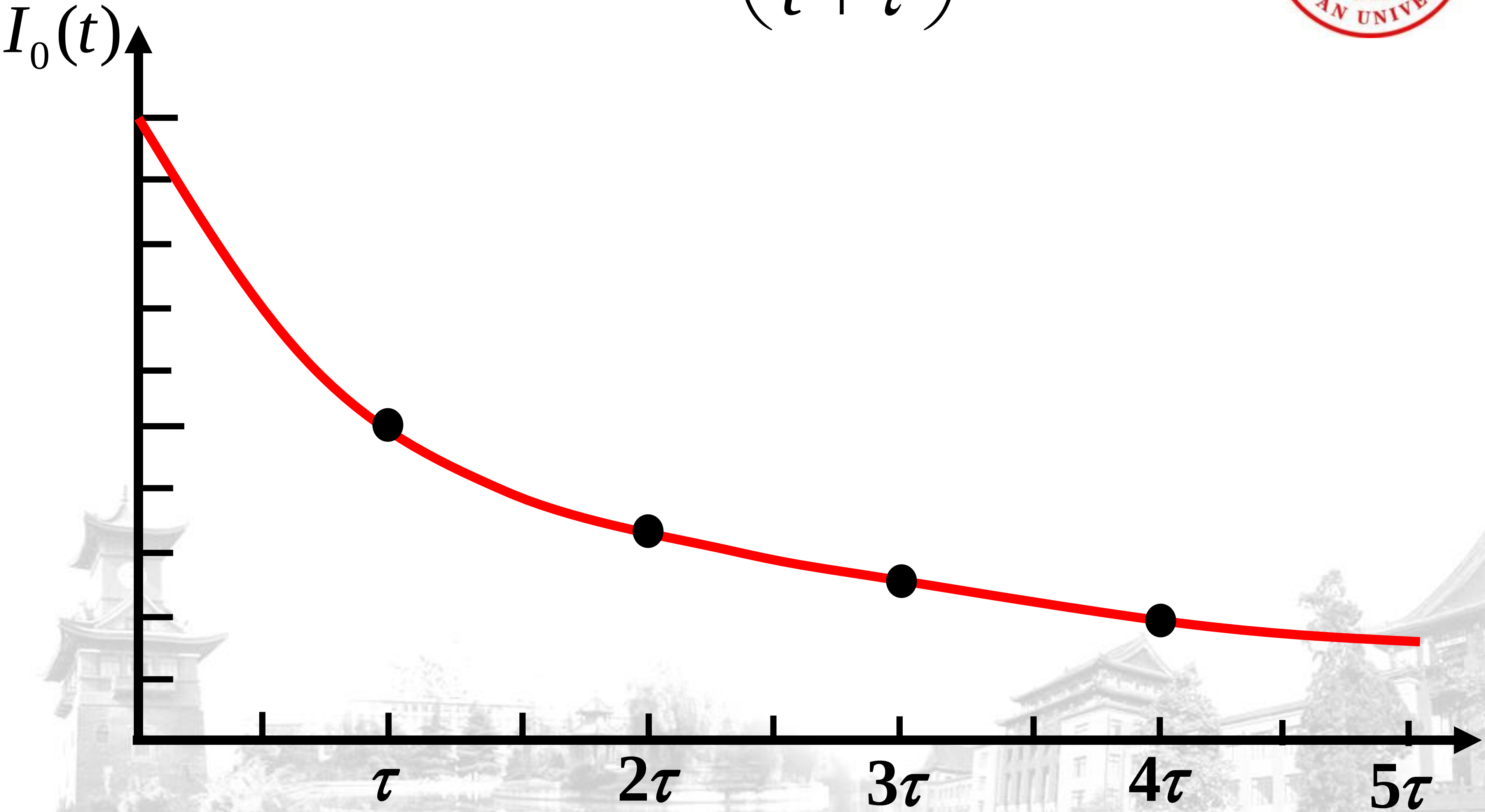
$$u^+(r) = \mu^+ \frac{E}{P}$$

$$u^+(r) = \frac{dr(t)}{dt}$$

$$I_0(t) = \frac{ANe}{2\ln b/a}\left(\frac{1}{t+\tau}\right)$$

$$\tau = a^2 \frac{\left(\ln b/a\right) \cdot P}{2V_0 \mu^+} \approx 10^{-8} s$$

$$I_0(t) \propto \left(\frac{1}{t+\tau}\right)$$



Output Voltage

$$V(t)=\frac{ANe}{2C\ln b/a}e^{-t/RC}\int_0^t e^{t/RC}\left(\frac{1}{t+\tau}\right)dt$$

$$V(t)=\frac{ANe}{2C\ln b/a}f(t)$$

$V(t)$ has no connection with the injection place.

Discussion

- I(t) has constant shape, which has no connection with injection place.
  - Accordingly, the output voltage has constant leading edge.
- Because of $\tau \sim 10^{-8}$s, it only takes about 1μs that output current decrease to 1%.
  - Fast time response could be obtained.
- No matter what value RC is, the amplitude of voltage pulse is proportional to ANe.
  - So, we could decrease RC to obtain short dead time.

Energy resolution

$$h \sim ANe / C_0$$

h is a cascade random vale.

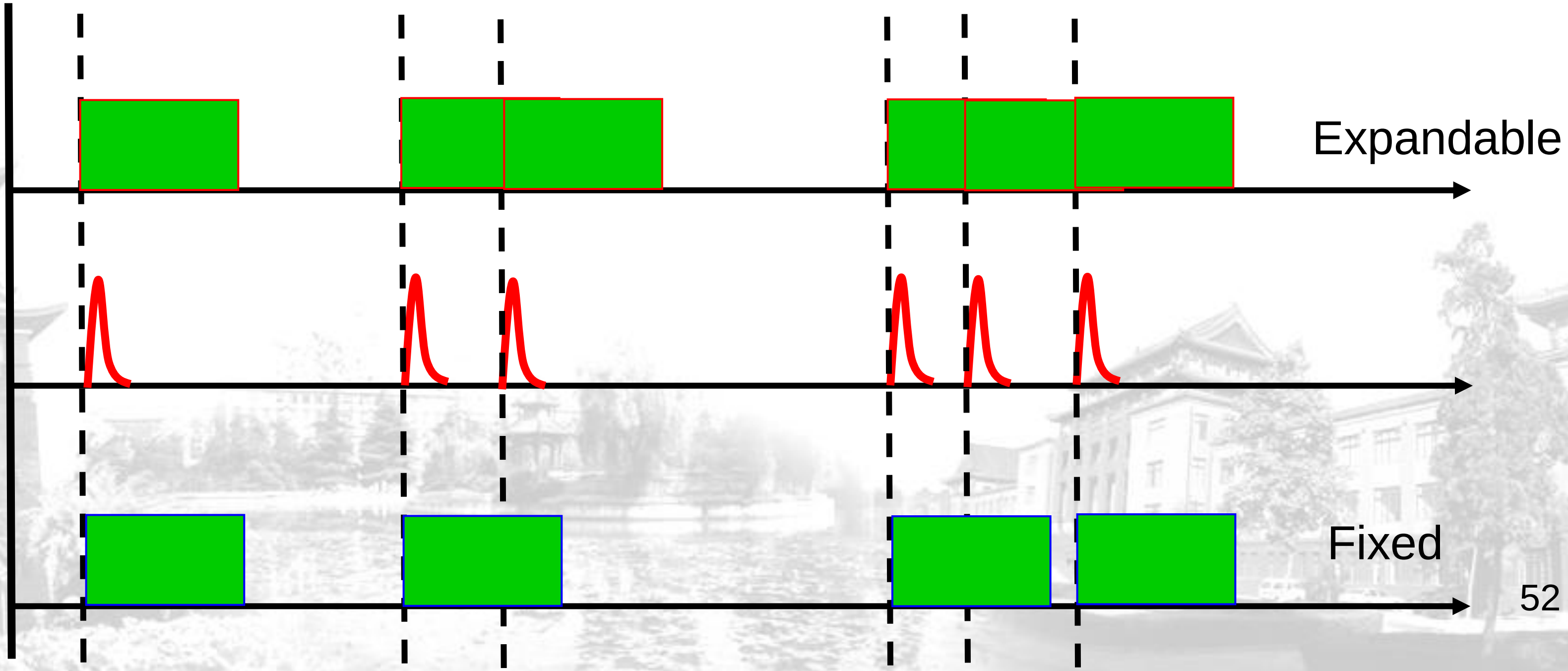
$$\nu_h^2 = \nu_N^2 + \frac{1}{\bar{N}} \nu_A^2 = \frac{F}{\bar{N}} + \frac{1}{\bar{N}} \nu_A^2$$

$\nu_A^2 \approx 0.68$ (From experiment result)

$$\eta = 2.355 \nu_h = 2.355 \sqrt{\frac{F + 0.68}{\bar{N}}}$$

Dead Time

- The dead time of proportional counter is expandable.
  - Because another gas amplification caused by next injecting particles could begin when the former pulse has not finished.



Counts Calibration

- A detector has expandable dead time τ. if the detector recorded n counts per second, estimate the counting loss.
  - ➢Let m be the true count rate, than

$$P_T(T<t)=1-e^{-mt}$$

$$n=m-m(1-e^{-m\tau})=me^{-m\tau}$$

  - ➢if mτ<<1, then

$$n=me^{-m\tau}\approx m(1-m\tau) \Rightarrow m=\frac{n}{1-n\tau}$$

GM COUNTER

Characteristics

- Invented by Geiger and Muller
  - That's why it is called G-M tube or Geiger tube
- Simple, cheap, convenient
- High sensitivity, large amount of charge output
- Long dead time
  - ~0.1ms
- Only record counts
  - Con NOT record type and energy of particles

Various G-M detector

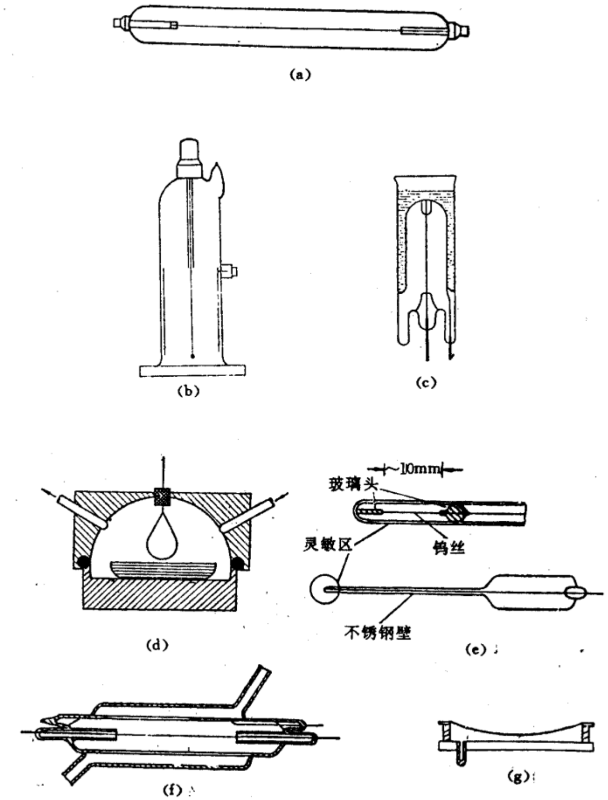


图 3.25　不同类型的 G-M 计数管
(a)圆柱型；(b)钟罩型；(c)液样管；(d)流气式；
(e)针型；(f)套式；(g)平行板型。

Electron Avalanche and Self-maintaining Discharge

Considering photon feedback process, when $\gamma A \geq 1$, than

$$A_{\text{total}} = A + \gamma A^2 + \gamma^2 A^3 + \cdots \to \infty$$

Continuous electron avalanche occurred! Gas discharge seems to be self-maintaining and would never finished.

However, positive ions around anode would weaken electric field near anode, which make avalanche stop.

New Avalanche

Positive ions would drift to cathode, while the electric field become strong again, because of which, new avalanche occurred!

electrons emitted by positive ions injection to cathode would contribute to new avalanche.

One injecting particles would produce output pulse again and again!

Quenching of Avalanche

- Introduce photo-ionization
- Block photo feedback
- Suppress ion feedback

Ar + (10%~20%)C_2H_5OH:

Organic G-M Tube

Ne (or Ar) + (0.1%~1%)Br_2 (or Cl_2):

Halogen G-M Tube

Organic G-M Tube

$$I_{\mathrm{Ar}} = 15.7\mathrm{eV}$$

$$E^{*}_{\mathrm{Ar}} = 11.5\mathrm{eV}$$

$$I_{\mathrm{C_2H_5OH}} = 11.3\mathrm{eV}$$

- High operating voltage
  - Organic gas has multiple energy which would prevent energy accumulate of electrons
- Short life
  - Organic gas would decompose after absorbing ultraviolet
  - Maximum counts: $10^7 \sim 10^8$

Halogen G-M Tube

$$I_{\mathrm{Ne}} = 21.6\mathrm{eV}$$

$$E^{*}_{\mathrm{Ne}} = 15.6\mathrm{eV}$$

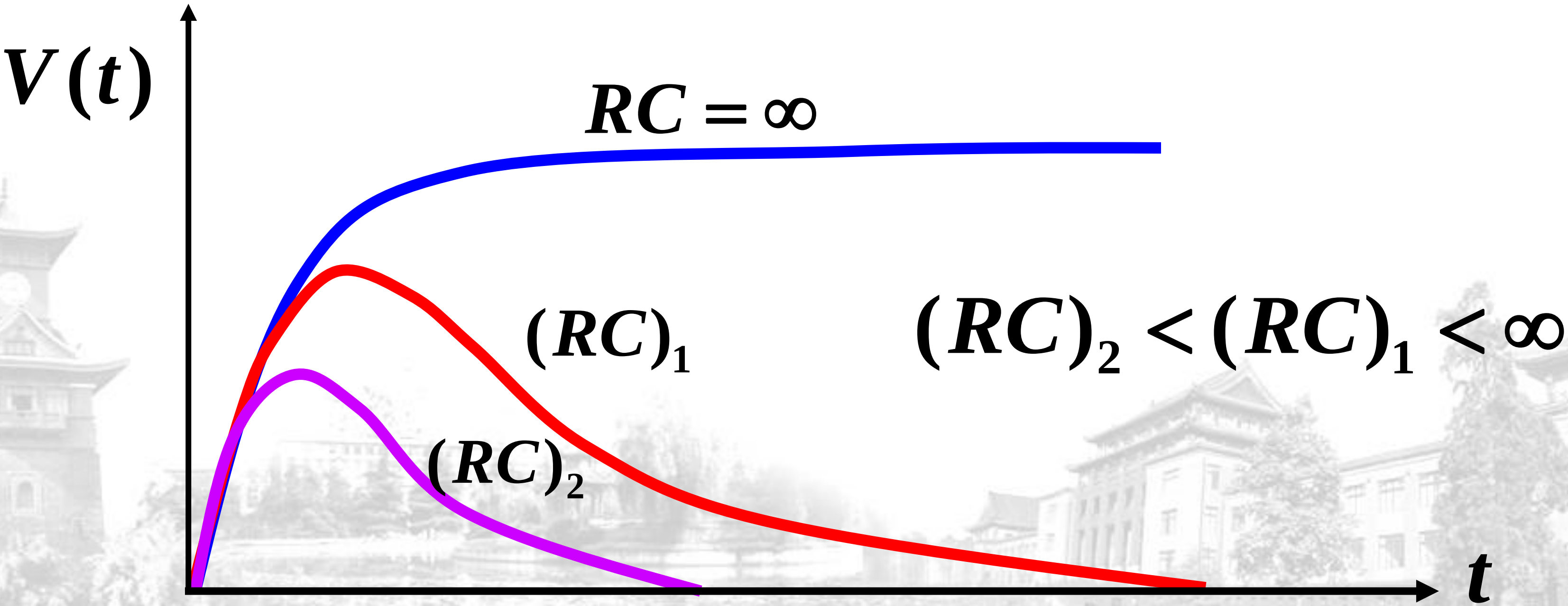
$$I_{\mathrm{Br_2}} = 12.8\mathrm{eV}$$

- Lower operating voltage
- Longer life

$$\mathrm{Br} + \mathrm{Br} = \mathrm{Br_2}$$

Signal Output

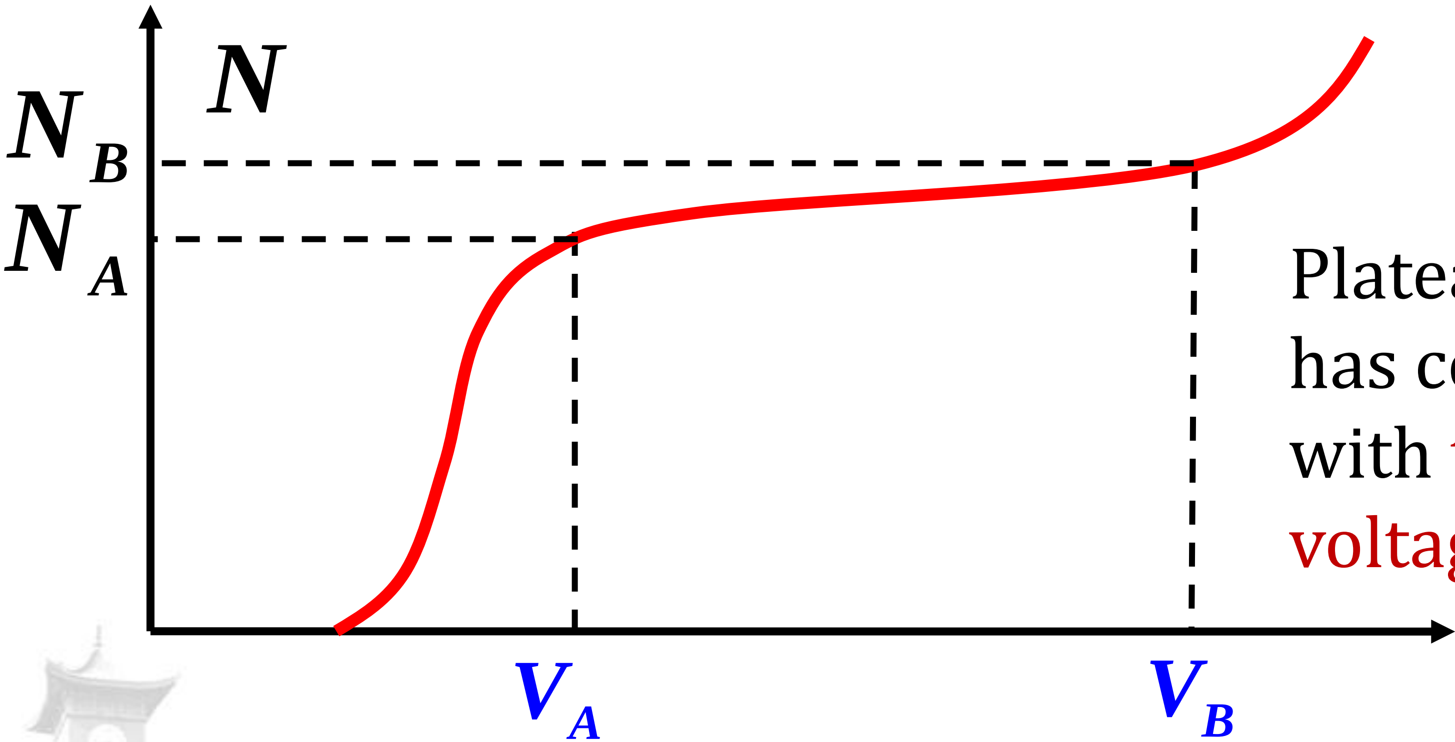
- Voltage pulse amplitude is determined by RC and total charge Q.
  - ➢has NO collection with primary ionization.



Time lag

- Time between the moment particle injecting and that signal output
  - has connection with primary ionization place
  - depends on the drift time of electrons from the first ionization place to anode.

Plateau Curve



Plateau curve has connection with threshold voltage.

plateau initial voltage——V_A

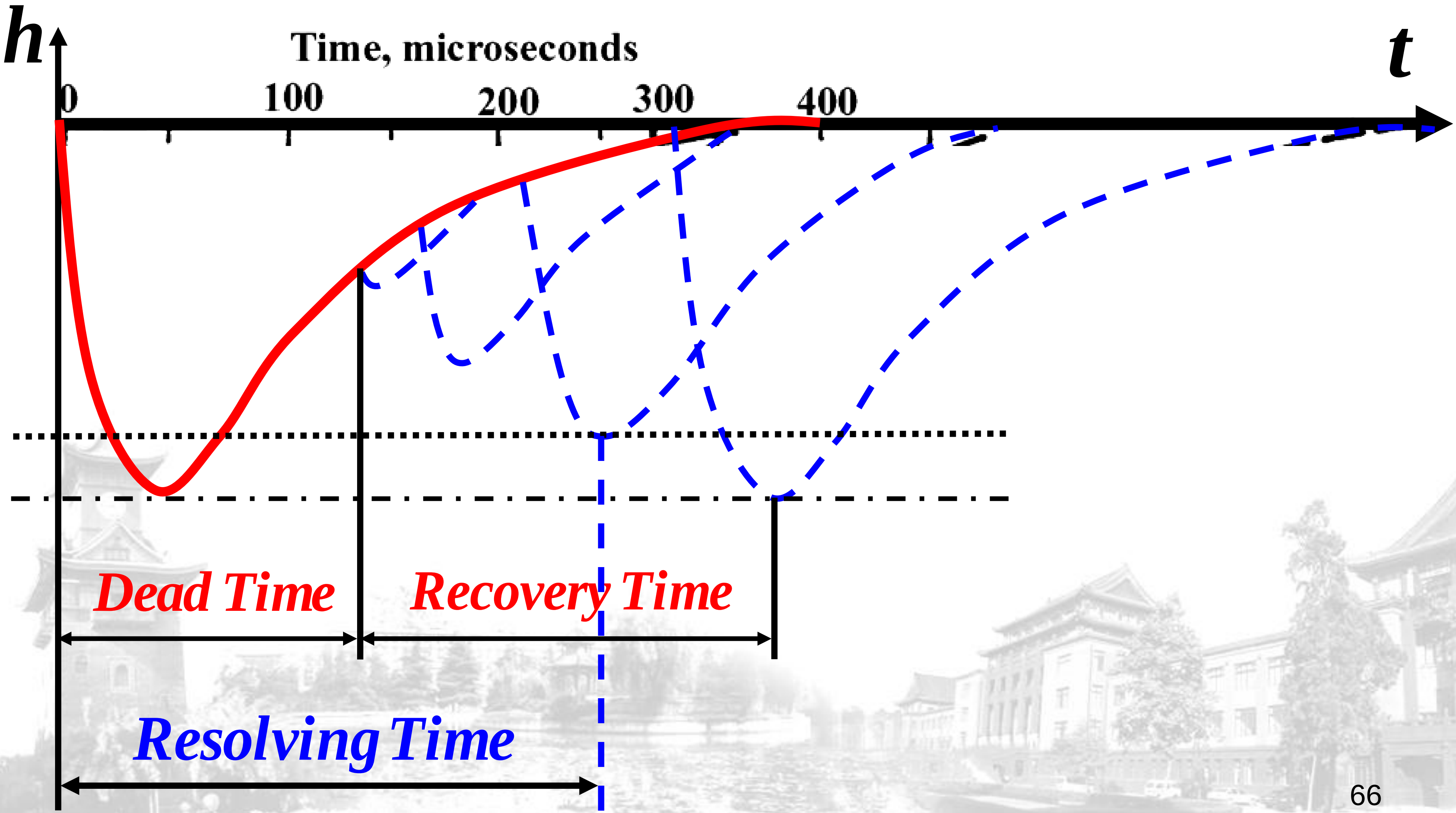
plateau length——$V_B - V_A$

plateau slope —— $\frac{N_B - N_A}{N_A} \Big/ (V_B - V_A) \times 100\% \quad [\%/100V]$

Sensitivity

- For charged particles, ~100%
- For γ photons, they are only record when
  - 1: interaction occurs between γ photons and tube shell and secondary electrons are emitted.
  - 2: secondary electrons injects into sensitivity volume of G-M tube.
  - ~1%

Dead Time



h
Time, microseconds
t
0
100
200
300
400
Dead Time
Recovery Time
Resolving Time

Counts Calibration

- Dead time of G-M Tube is Fixed.
  - ➢Positive ions shell around anode prevent new primary electrons from drifting to avalanche region to cause new avalanche.
- A detector has fixed dead time τ. if the detector recorded n counts per second, estimate the counting loss.
  - ➢Let m be the true count rate, than

$$m - n = nm\tau$$

$$m = \frac{n}{1 - n\tau}$$

Homework

- 1,2,3,6,7.