Ionising Radiation Physics
Detectors I
Detector Fundamentals and Gas Detectors

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Overview

- 6 hours on Detectors over the next 2 weeks

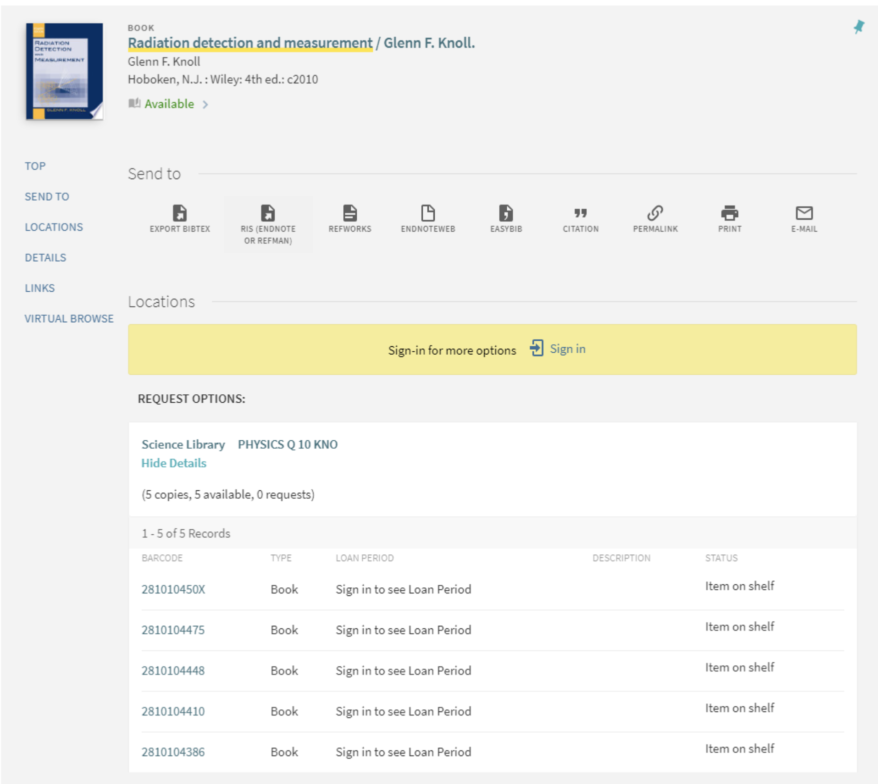
DETECTORS I

– Detector Fundamentals
– Group Exercise
– Gas Detectors

DETECTORS II

– Semiconductor Detectors
– Group Exercise/Demonstration
– Scintillation Detectors

Recommended Text



READ IT!

- *Radiation detection and measurement - Glen F. Knoll*

- Online (3rd Edition)
  - http://users.lngs.infn.it/~dimarco/Radiation%20Detection%20and%20Measurement,%203rd%20ed%20-%20Glenn%20F.pdf
  - https://phyusdb.files.wordpress.com/2013/03/radiationdetectionandmeasurementbyknoll.pdf

Detector Fundamentals

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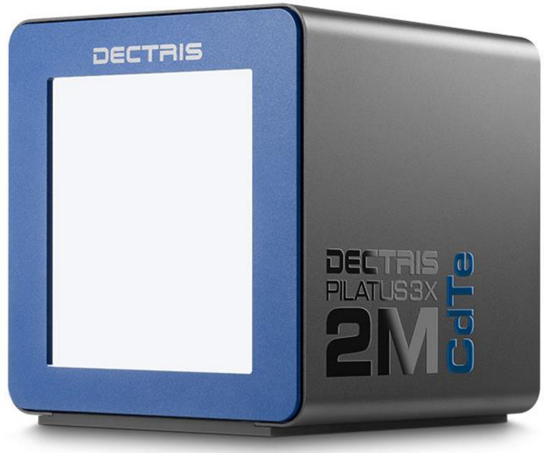
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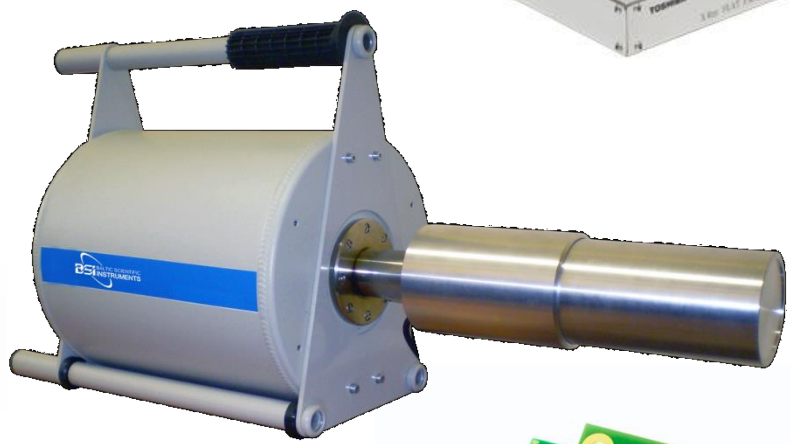

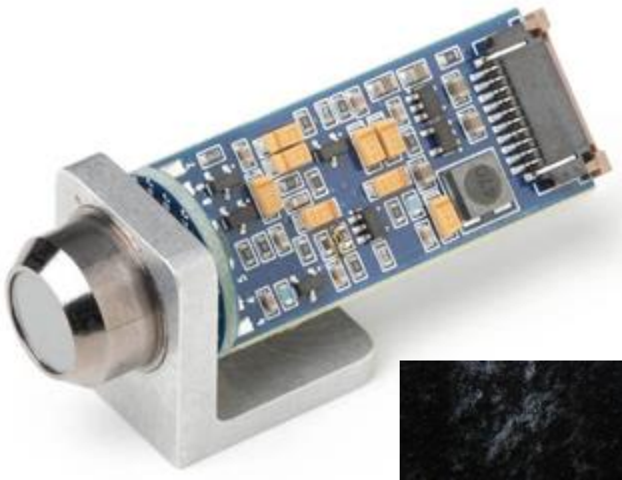

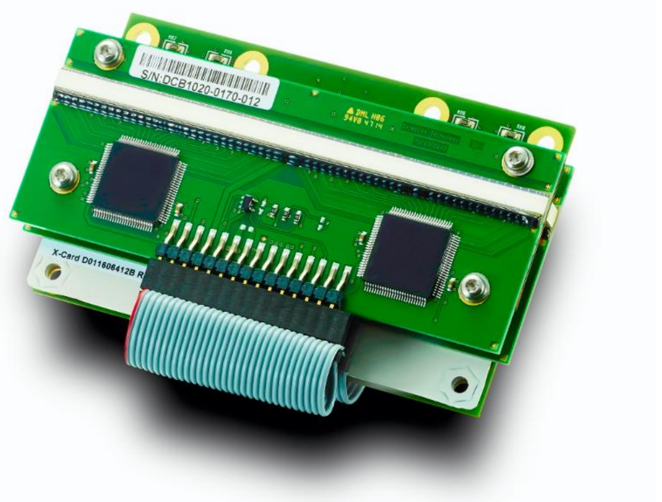
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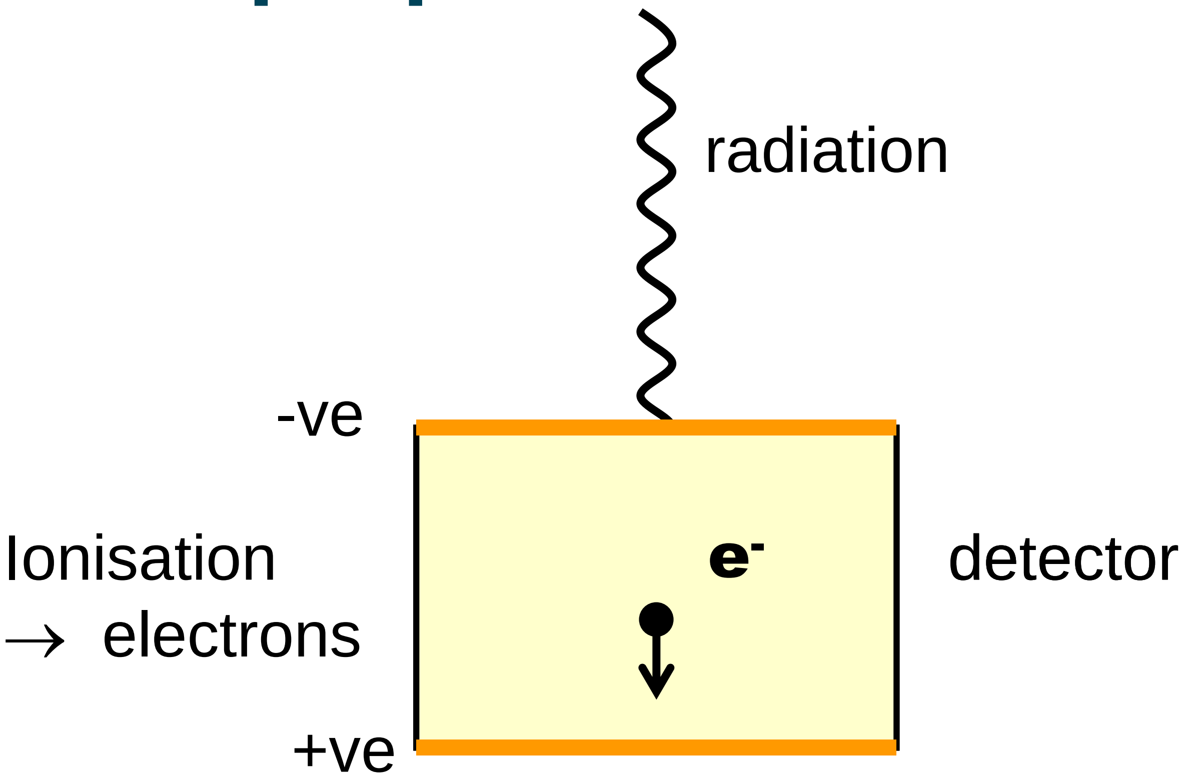
General properties of a detector

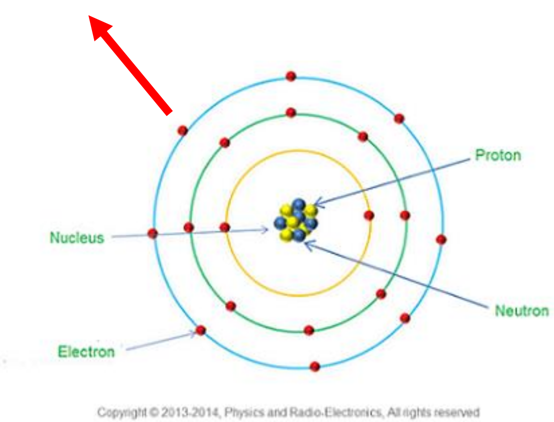


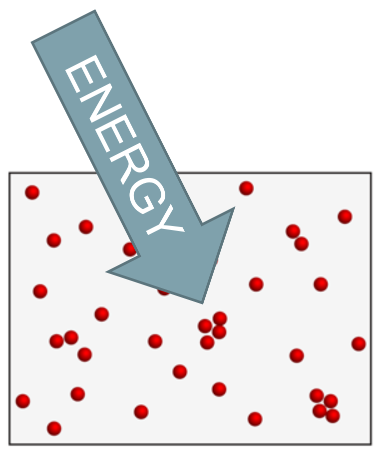
Electrons take time to reach electrode
- depends upon distance and charge mobility

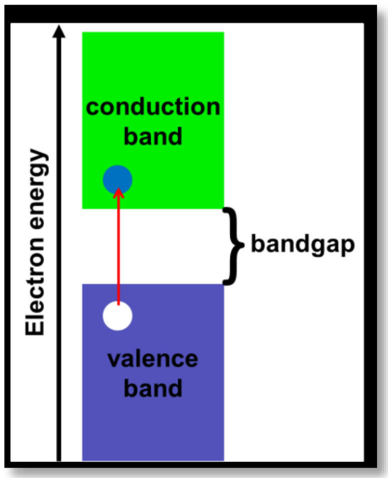
How many electrons are produced?

Average energy to create an electron – ion pair generally a few electron volts in a semiconductor to 10’s of eV in a gas.

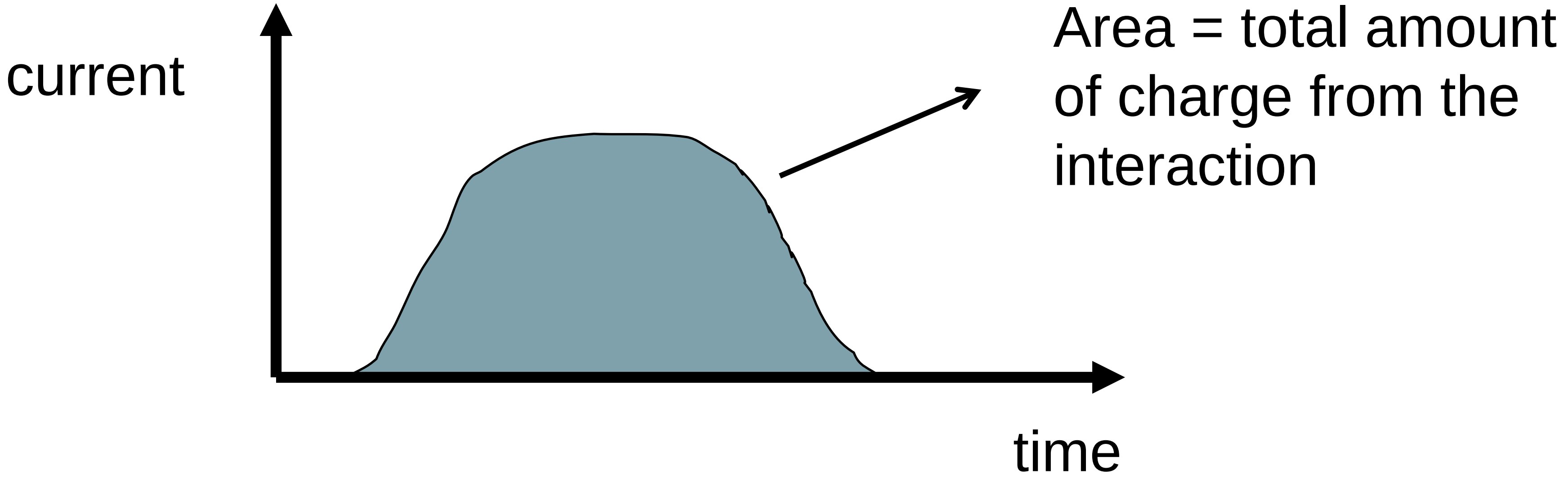
Described by *ionisation potential, W-value, band gap*, etc.



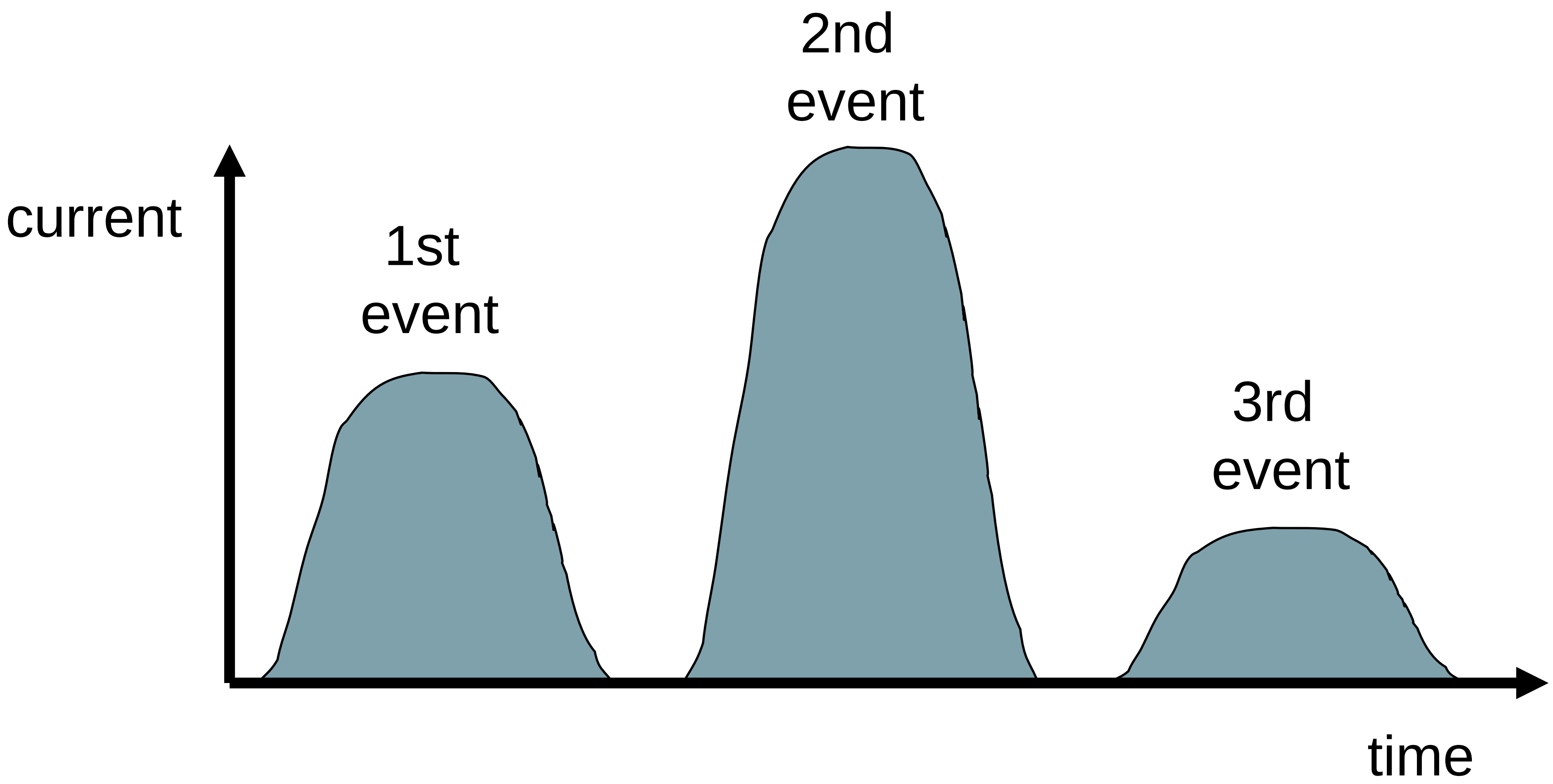




- 1 interaction produces given amount of charge
- electrons arrive at electrode over a short time period



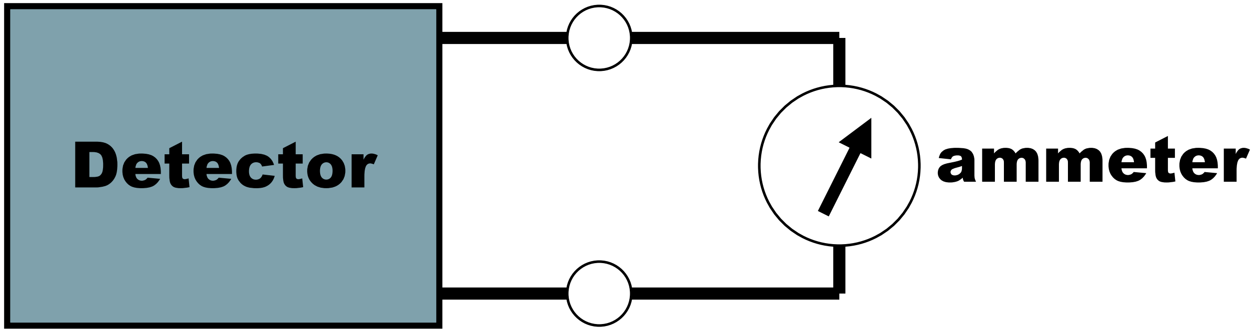
- Different energies deposited in the interaction
  → different amounts of charge to be generated



Readout methods

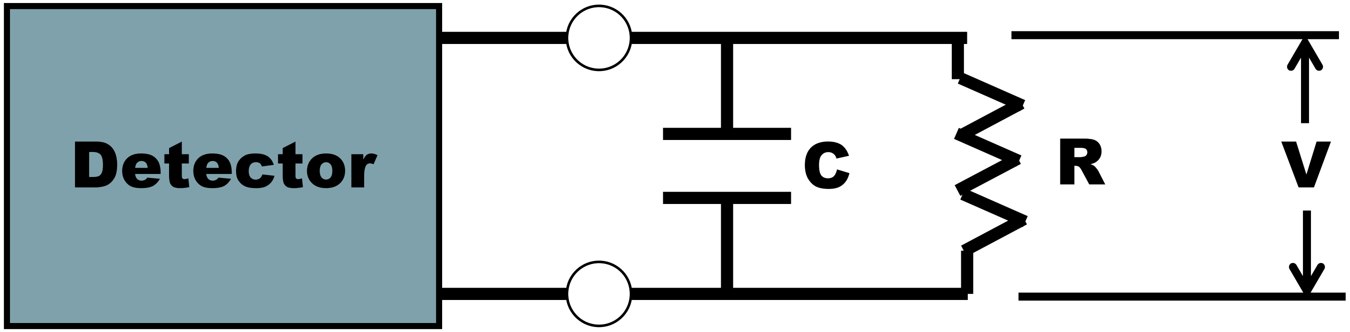
Current mode

- Measure time averaged current



Pulse mode

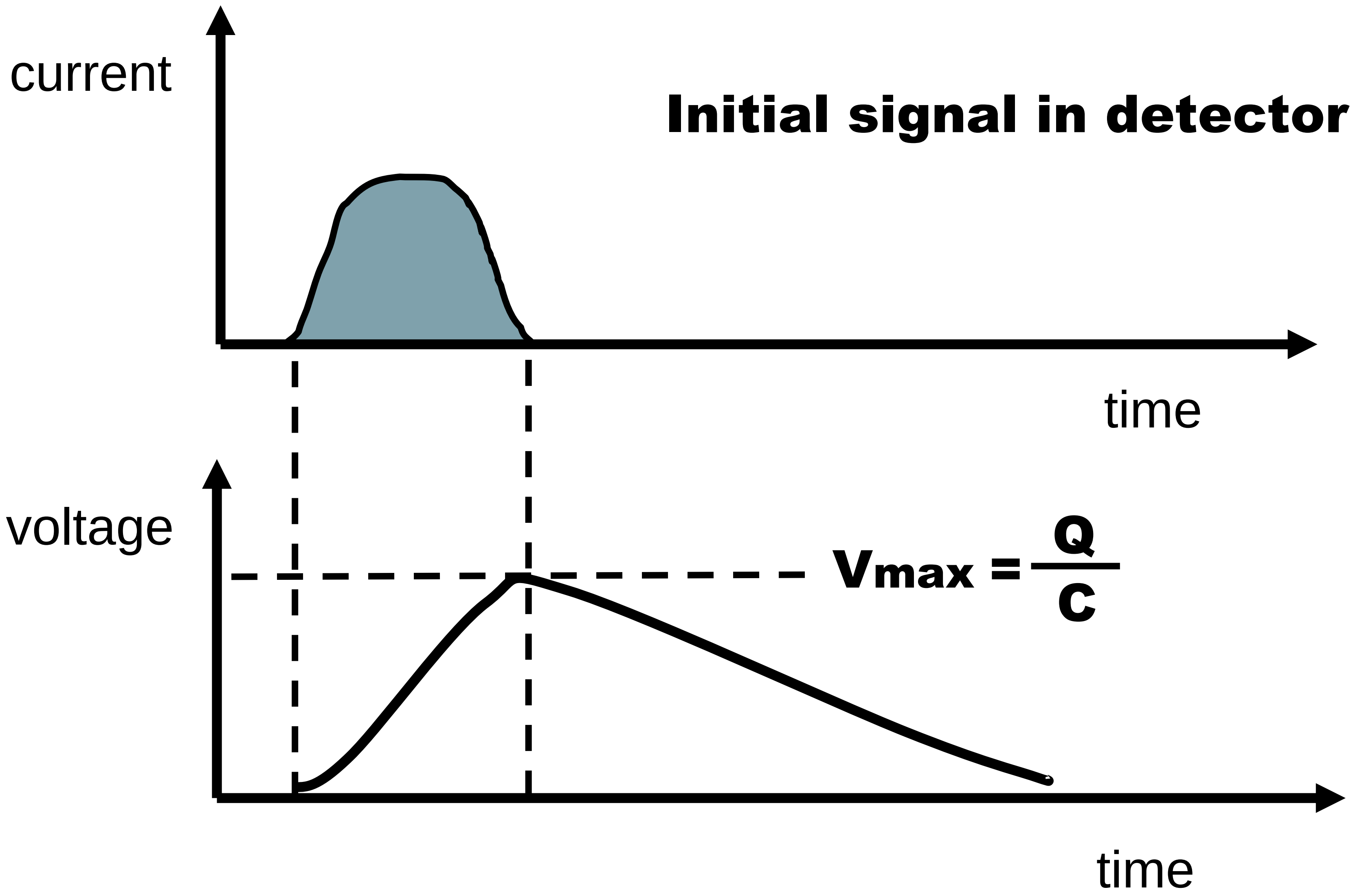
- Records each individual event



Time constant τ = RC

Typically make τ >> detector charge collection time

- current slowly builds up on capacitor & then discharges through resistance


current
Initial signal in detector
time
voltage
Vmax = Q / C
time

The Perfect Detector

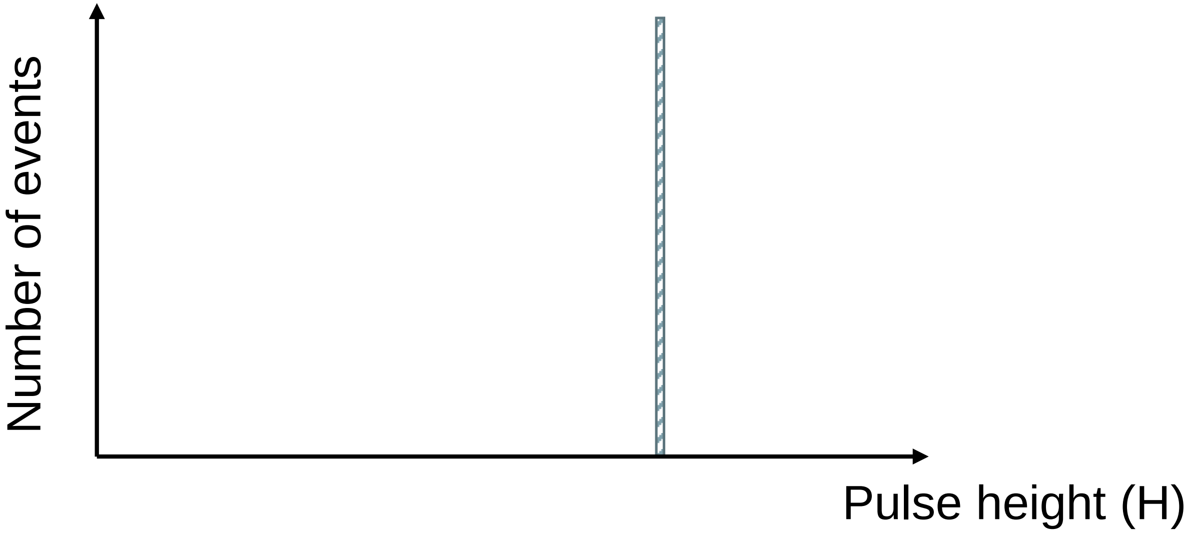
- Use a source of monochromatic radiation (assume photons for simplicity)

- Every photon creates the **same** quantity of charge (Q) in the detector

- The electronics always measure and record the **same** V_{max}

Perfect Pulse Height Spectrum

- V_{max} converted to a digital number → pulse height (H)
- H ∝ Energy of incident radiation
- Histogram each H value in to pulse height spectrum



The Practical Detector

- Every photon creates an **average** quantity of charge (Q) in the detector

- Described by Poisson statistics

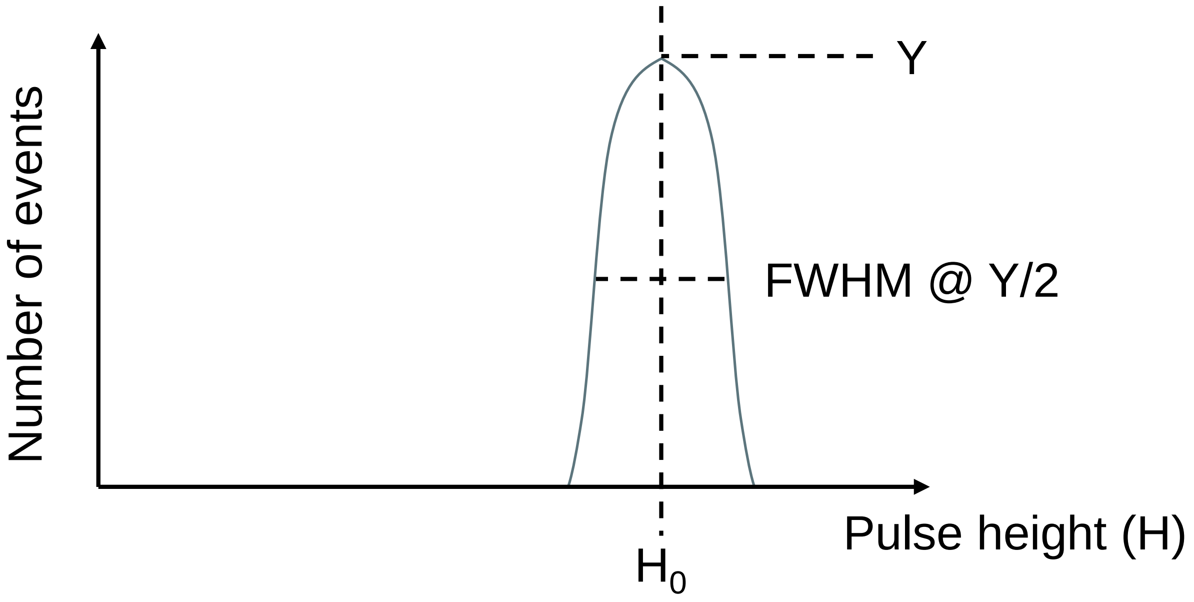
Mean number of electrons produced = N

Standard deviation = $\sqrt{N}$

- The electronics measure and record **different** V_{max} even for photons with same energy

Practical Pulse Height Spectrum

- H depends on number of electron produced
- H is distributed about some mean values (H_0)
- Gives rise to **Energy Resolution** (R)



$$R = \frac{FWHM}{H_0}$$

Energy Resolution

- Poisson stats → Gaussian response

$$G(H) = \frac{A}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(H-H_0)^2}{2\sigma^2}\right)$$

- Define R in terms of N (∝ H)
  - Average H value (H_0)
  - Standard deviation in H (σ)
  - Full Width at Half Maximum

$$H_0 = kN$$

$$\sigma = k\sqrt{N}$$

$$FWHM = 2.35\sigma$$

- Poisson limit to Resolution

$$R_{Poisson} = \frac{FWHM}{H_0} = \frac{2.35k\sqrt{N}}{kN} = \frac{2.35}{\sqrt{N}}$$

Energy Resolution

- Poisson limit on resolution depends on N only
- Observed resolution is not adequately described by Poisson alone
- Indicates event independence assumption is not valid
- Introduce Fano Factor (F) to account for variance

$$R_{Statistical} = \frac{2.35k\sqrt{N}\sqrt{F}}{kN} = 2.35\sqrt{\frac{F}{N}}$$

- F ≈ 1 for scintillators, F << 1 for semiconductors

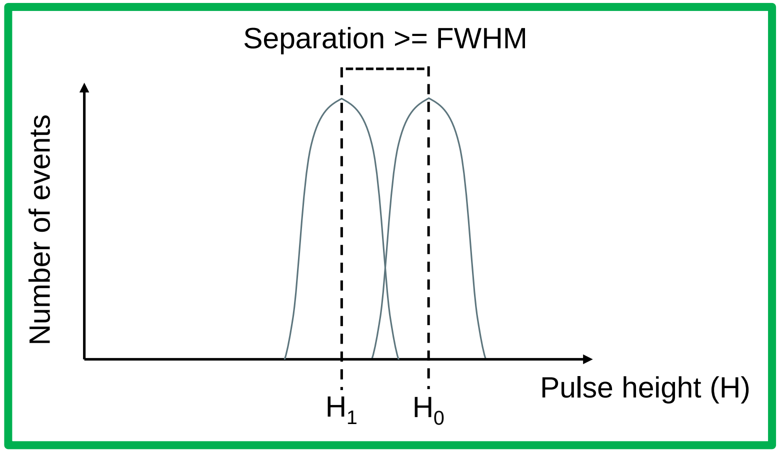
Energy Resolution

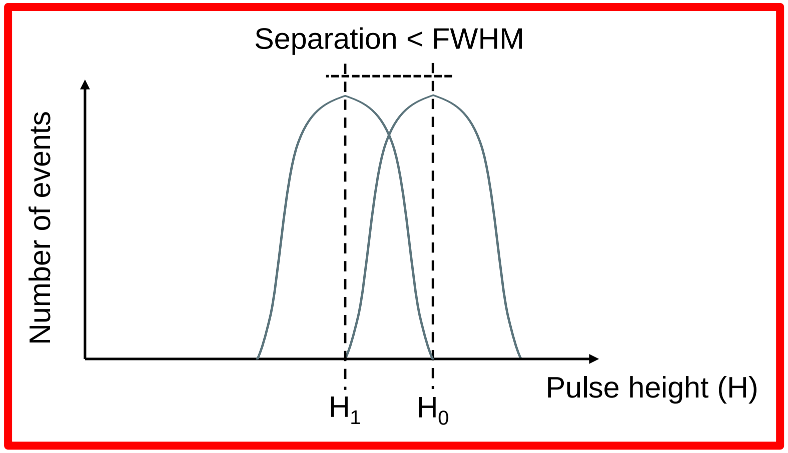
- Real measurement of R include other factors
  - Statistical fluctuations
  - Electronic noise
  - Temporal drift

$$FWHM_{total}^2 = FWHM_{statistical}^2 + FWHM_{noise}^2 + FWHM_{drift}^2 + \cdots$$

Energy Resolution

- Measured FWHM defines ability to distinguish between two nearby energies





Detection efficiency

2 terms describe efficiency: absolute & intrinsic

absolute efficiency

Includes geometry of the source and detector

$$\varepsilon_{abs} = \frac{\text{no. of pulses recorded}}{\text{no. of radiation quanta emitted by source}}$$

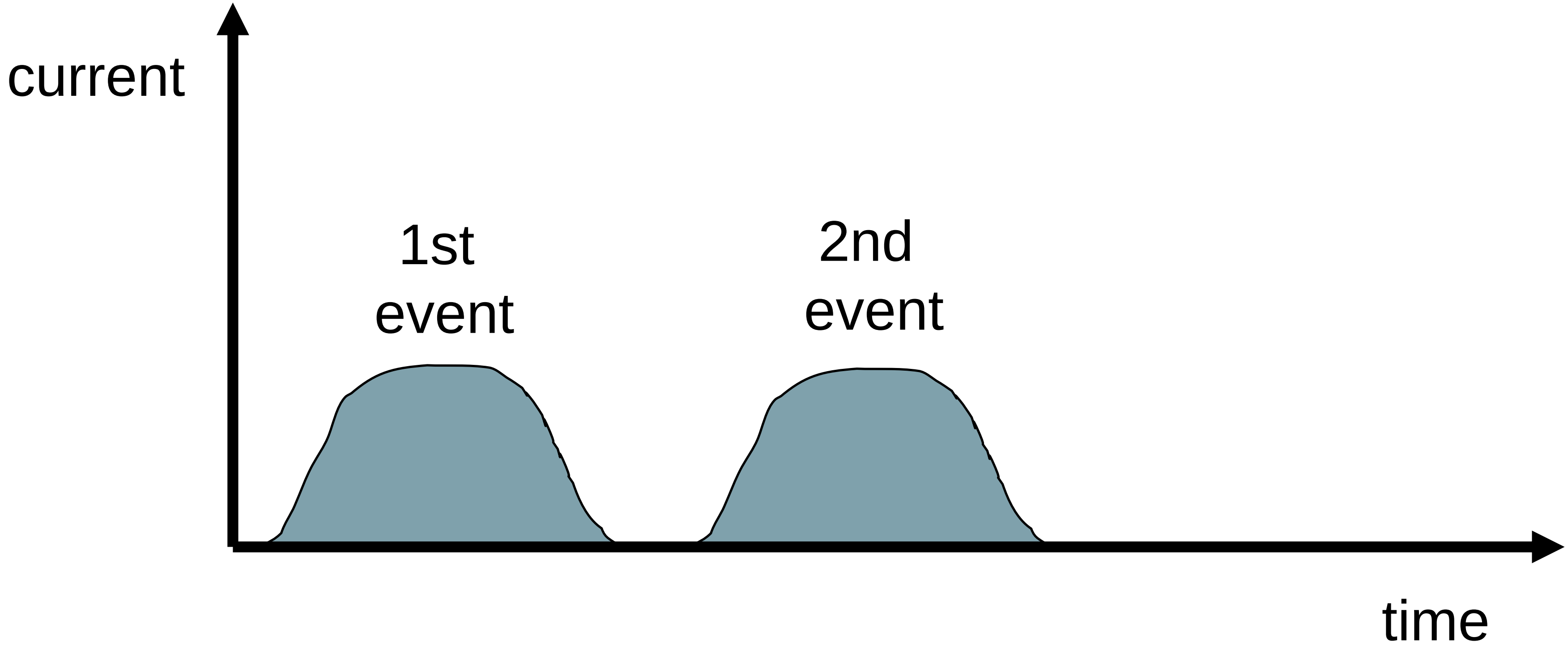
intrinsic efficiency

Related to how good detector is at absorbing radiation

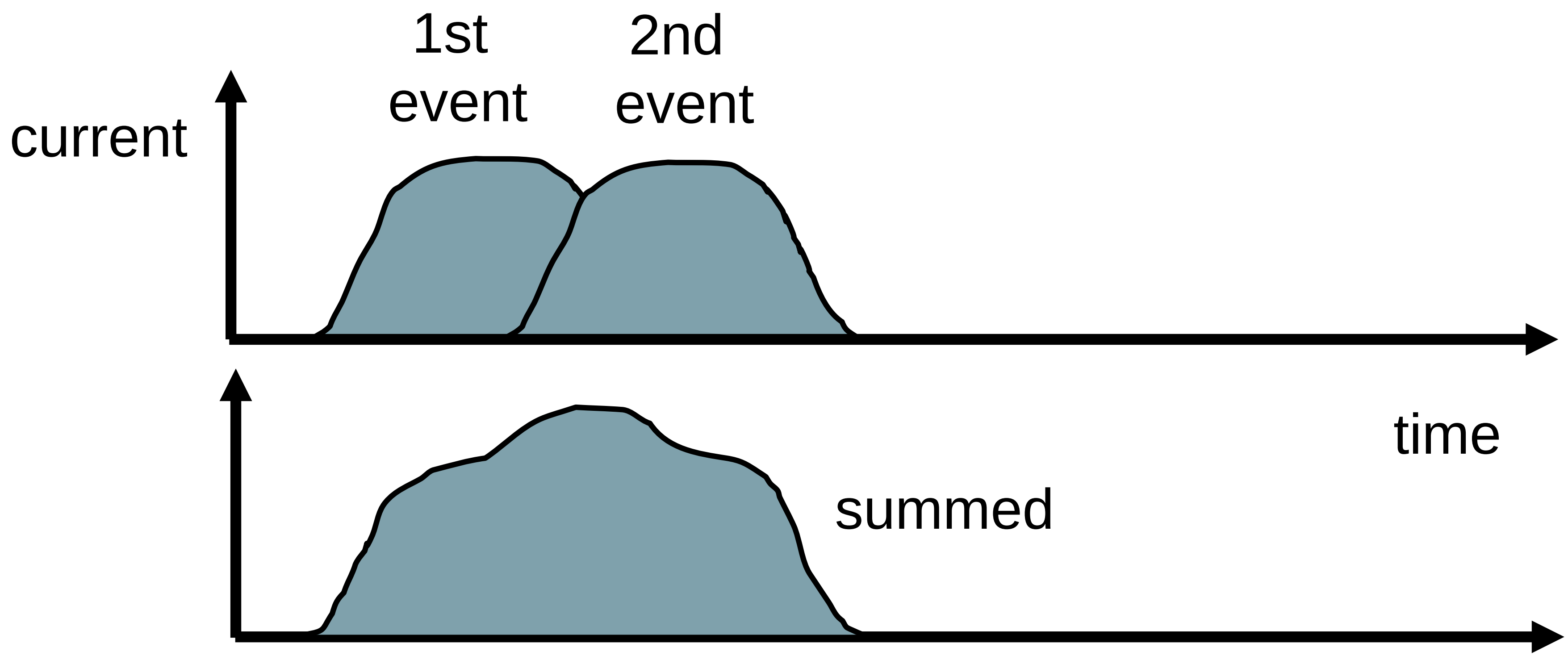
$$\varepsilon_{int} = \frac{\text{no. of pulses recorded}}{\text{no. of radiation quanta incident on detector}}$$

Dead time

- A detector requires a minimum amount of time between 2 events to record 2 separate pulses

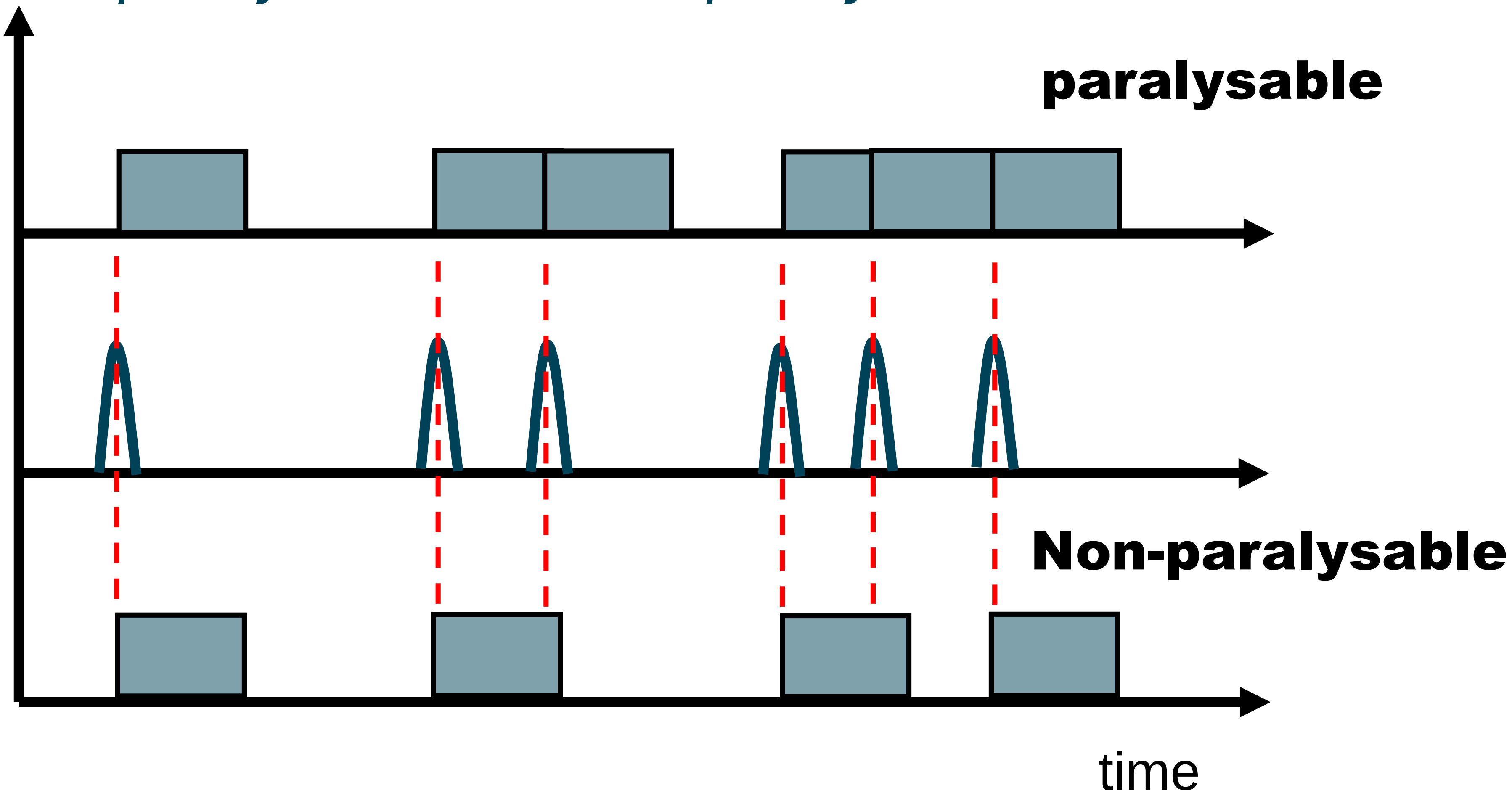


Can be identified as 2 separate pulses

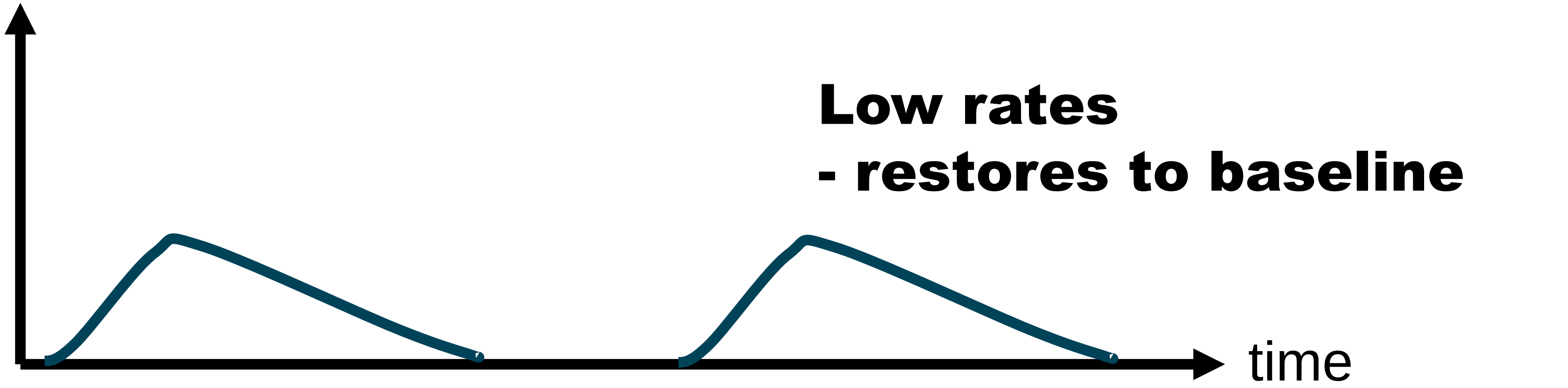


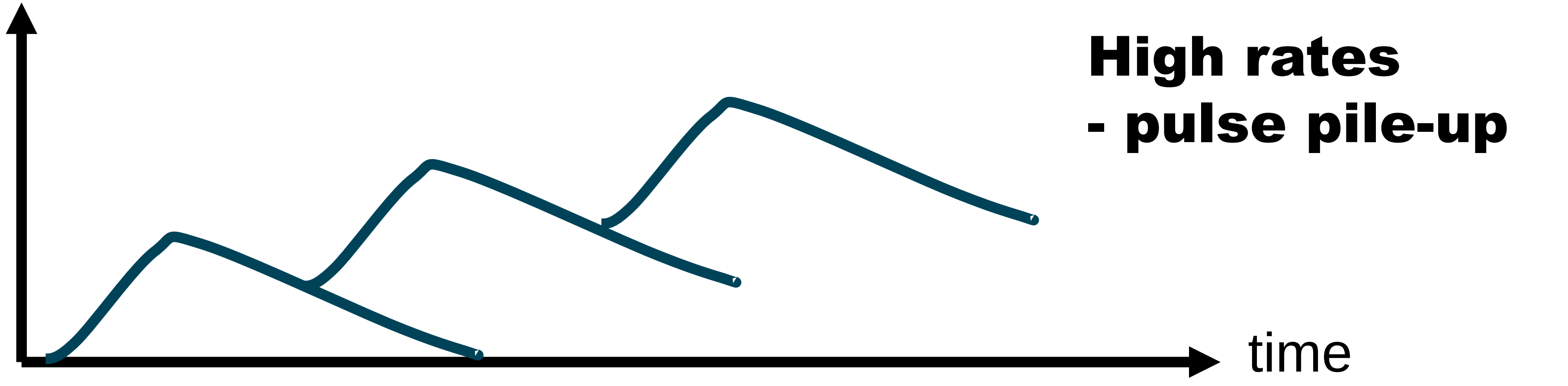
- Events cannot be distinguished
- limiting time could be detector properties (as above) or electronics limit
- at high count rates dead time losses can be high

- 2 models of dead time behavior can be used to describe detector systems
  - *paralysable* and *non-paralysable*



- *Paralysable system* - distorted spectrum or shut down at high rates

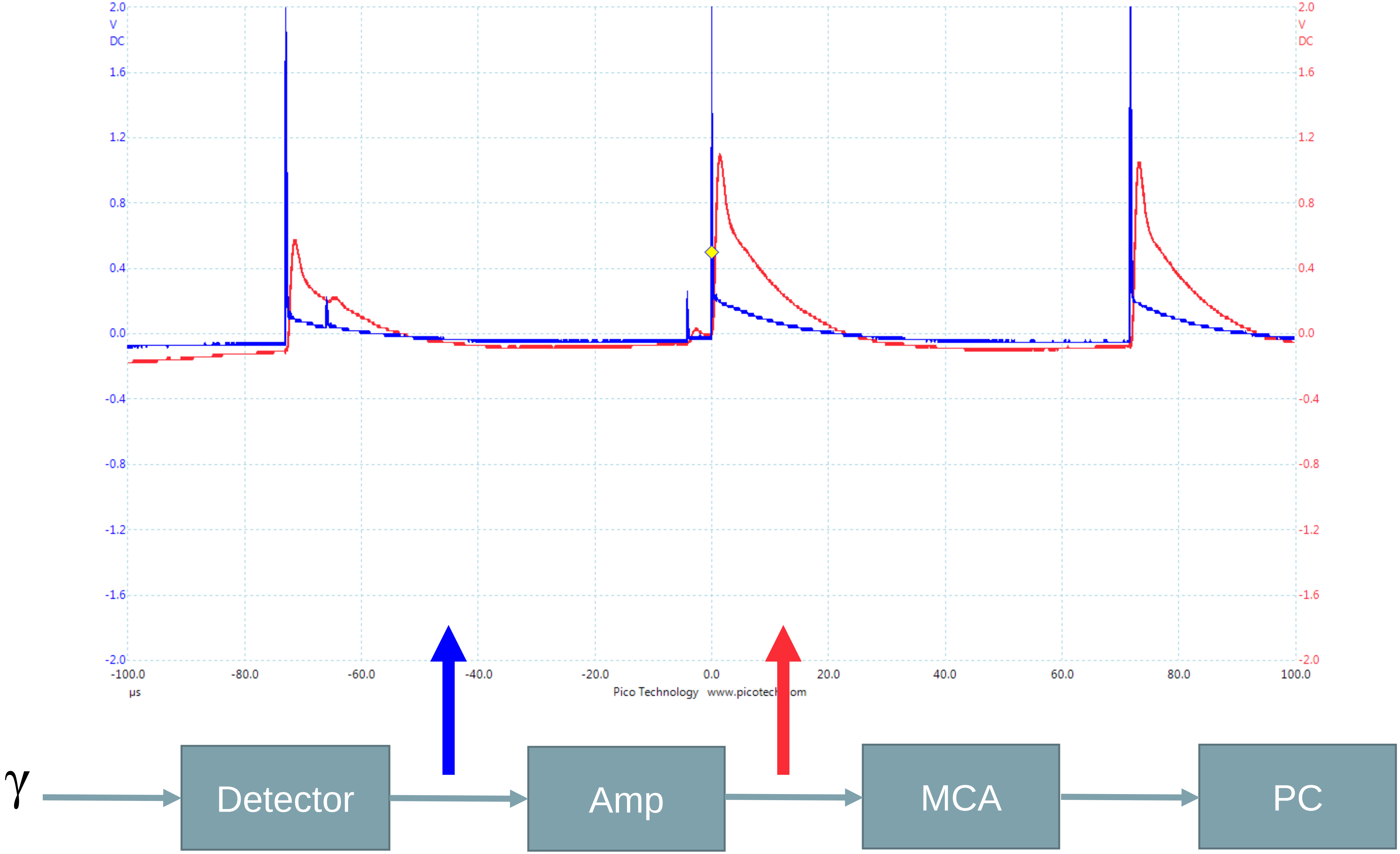




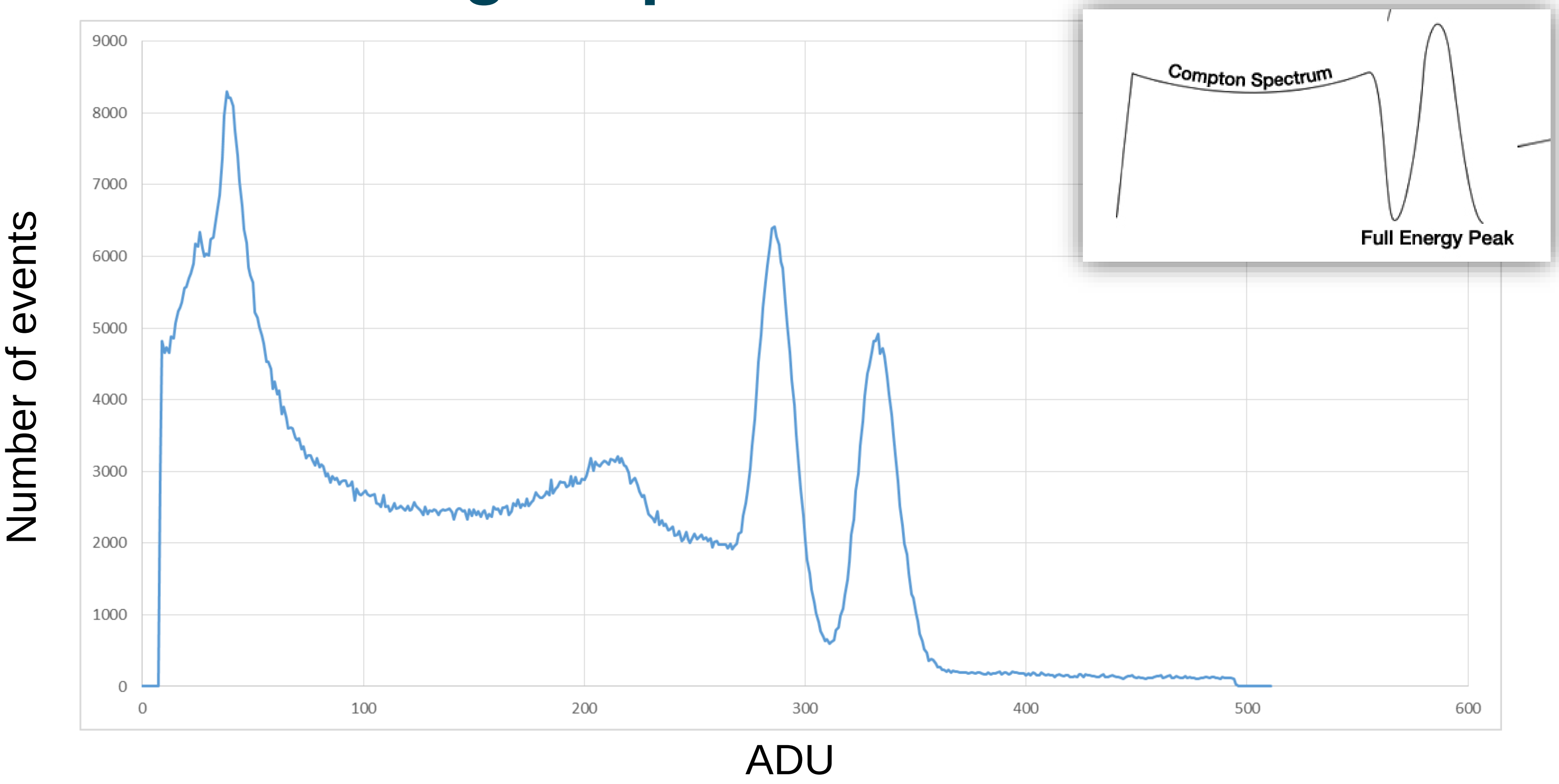
Detection Chain

Component	Purpose
Detector	Absorbs particles (including photons) and outputs a quantity of charge which is proportional to the energy of the absorbed particle. Output can be current or voltage depending on detector design.
Amplifier	Shapes the pulse to make it more suitable for further electronic processing and filters noise.
Multi Channel Analyser	Sorts pulses into bins (channels) according to their amplitude – ‘energy’ histogram. User defined thresholds. Number of channels depends on MCA design but few 1,000 is typical.
PC	Store the output of the MCA in memory and allow onward processing of the data.

Real Signals

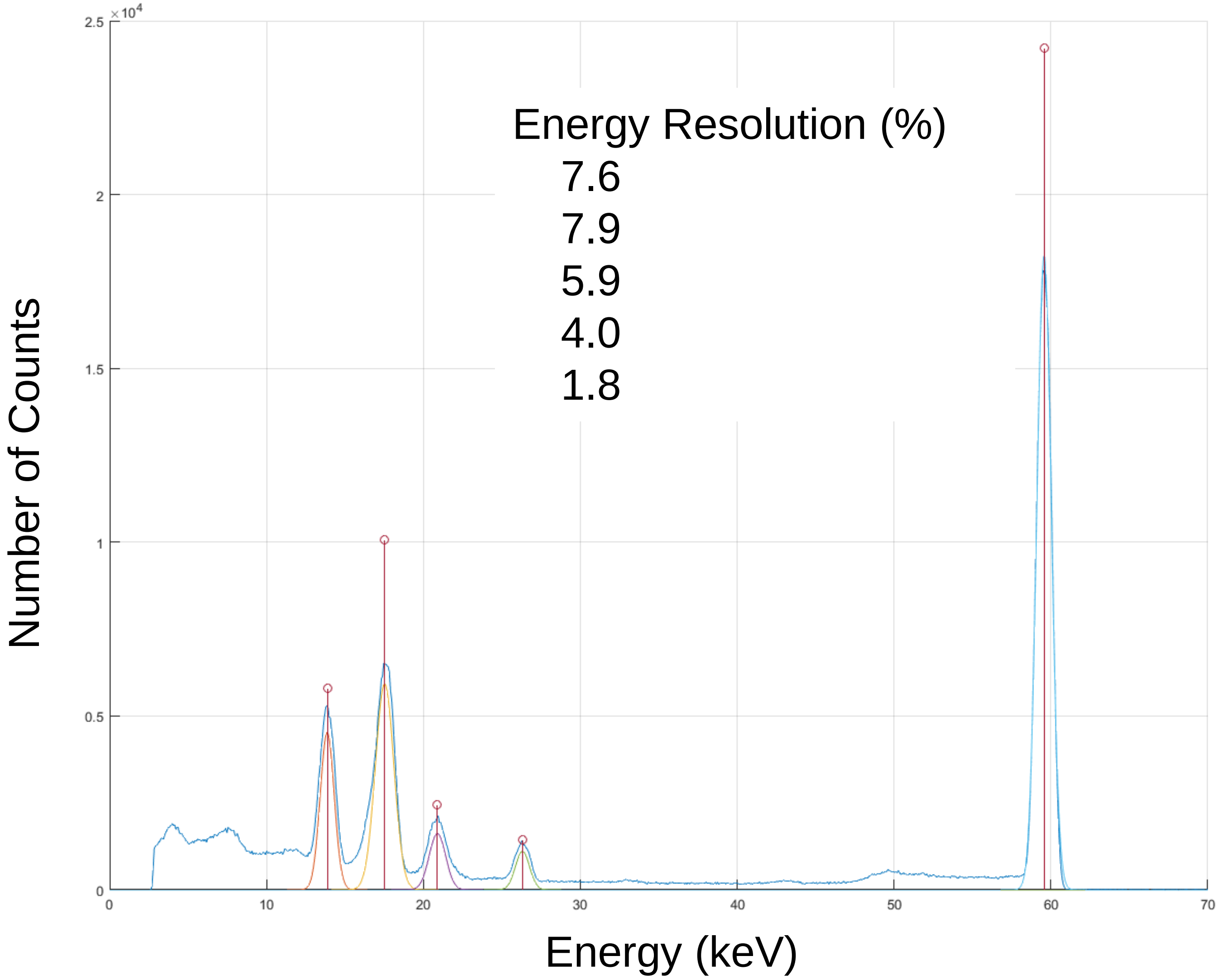


Real Pulse Height Spectrum



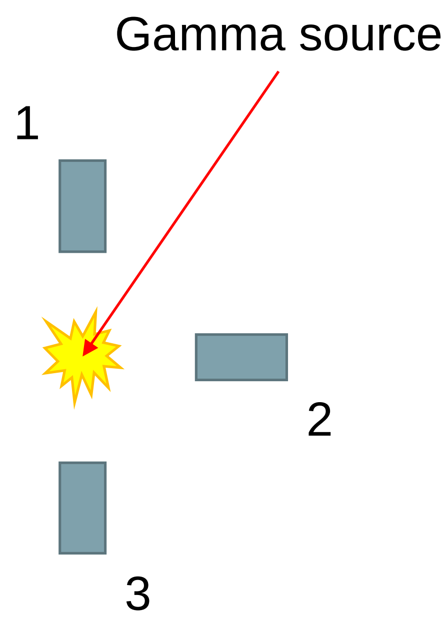
- ADU is unit provided by the MCA
- Calibration required from ADU to Energy

Real Energy Resolution



Group Task

- Split into even groups
- Laptop with Excel
- Characterise the detector:
  - energy calibration
  - energy resolution



- Data from 3 different detectors

- Isotopes: Am241, Ba133, Ba133+Cs137, Co60, Na22

Group Task

Group	Isotope
1	Am241_2
2	Ba133_1
3	Ba133Cs137_2
4	Na22_1
5	Co60_1
6	Am241_1
7	Ba133Cs137_3
8	Ba133Cs137_1

Gas Detectors

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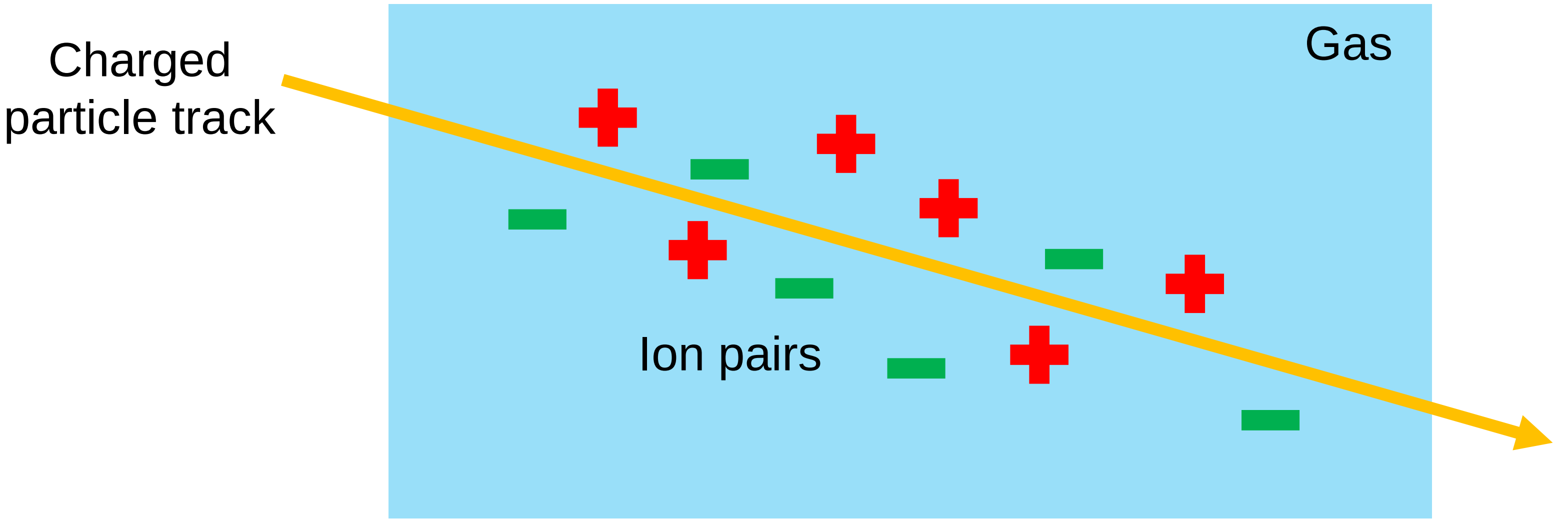
Ionisation Processes in a Gas

- Charged particles interact with gas molecules
- Create ***ion pairs*** (electron & positive ion)
- Basis of electrical signal = output of detector

- Important quantity = number of ion pairs created



Energy Transfer

- Ionisation energy/potential (IE)
  - Energy required to create ion pair
  - Particle transfers energy >= IE
  - IE typically 10-20 eV

- W-value
  - **Average energy** to create ion pair
  - Non-ionisation energy loss (e.g. molecular excitation)
  - W-value typically 30-35 eV (>> IE)
  - Number of pairs $\propto$ energy deposited

How many ion pairs are created if 1 MeV particle is completely stopped in a gas?

Gas Comparison

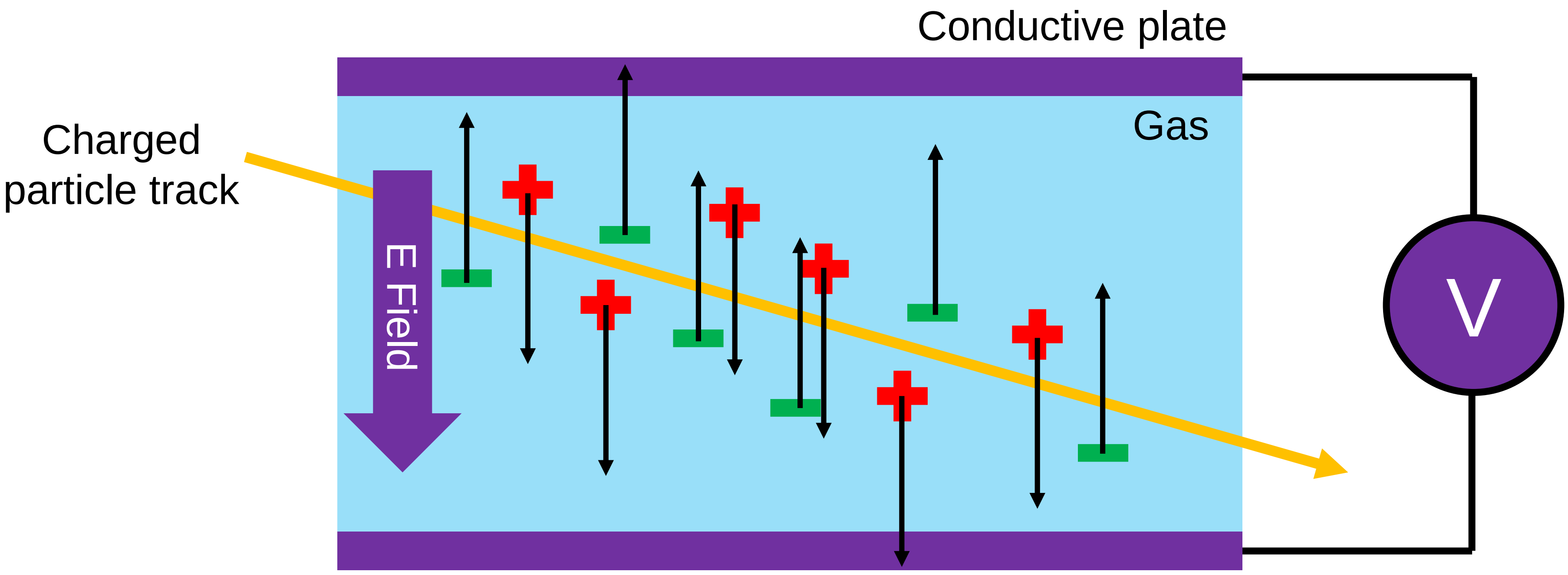
Gas	Atomic Number (per atom)	Ionisation Energy (eV)	W-value (eV)
Hydrogen (H_2)	1	15.4	36.5
Helium (He)	2	24.6	41.3
Nitrogen (N_2)	7	15.6	34.8
Argon (Ar)	18	15.8	26.4

Diffusion, Charge Transfer & Recombination

- Random thermal motion
  - Neutral atoms/molecules, electrons and positive ions
  - Range → 10^{-6}-10^{-8} m, mean free path
- Possible interactions
  - Positive ion encounters neutral → charge transfer
  - Electron encounters neutral → electron attachment (negative ion formed)
  - Electron/negative ion encounters positive ion → recombination

Basic Gas Detector

- Two electrodes
- Gas filled volume
- Applied voltage → E field
- Charge collection

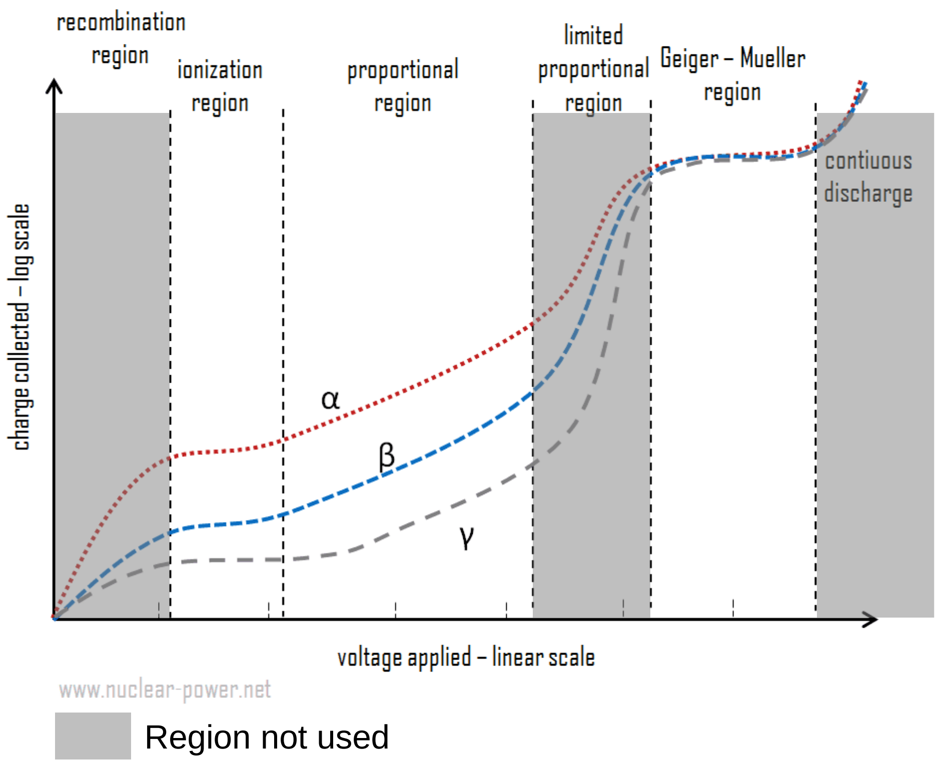


Types of Gas Detectors

- Three types:
  - Ionisation chambers
  - Proportional counters
  - Geiger-Mueller tubes
- All derive some kind of ‘output’ due to ion pairs in the gas
- Achieve this in different ways
- Detectors differ in:
  - Magnitude of applied voltage
  - Construction and geometry

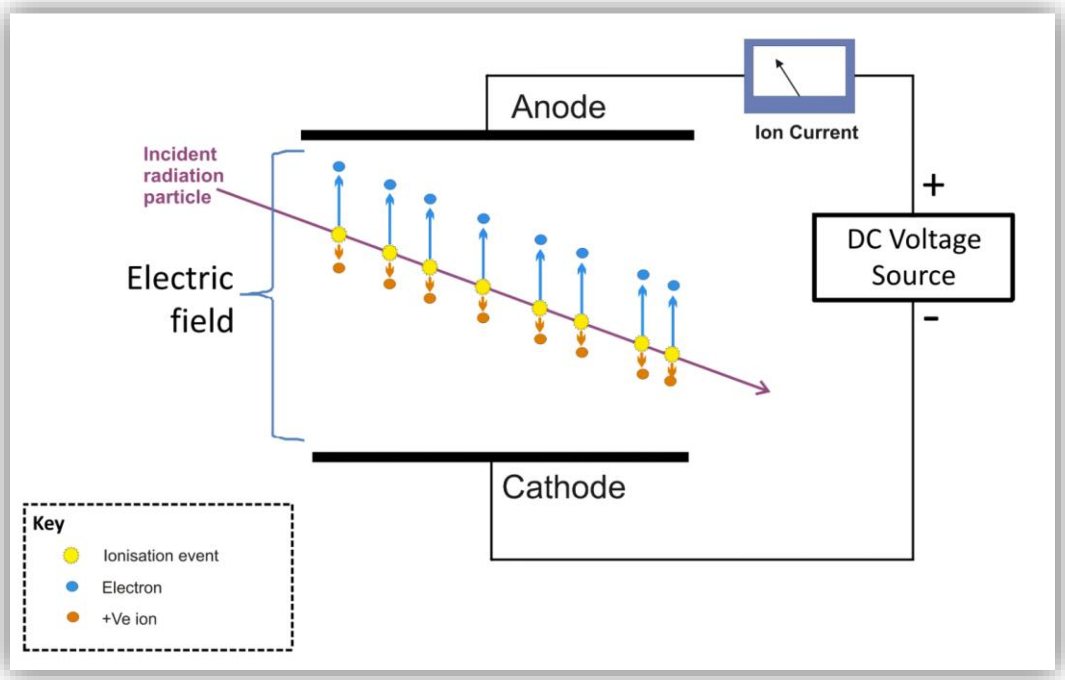
Regions of operation

- Ionisation/saturation region
  - Charge created by ionisation collected
- Proportional region
  - Charge is multiplied by factor proportional to detector bias
- G-M region
  - Uncontrolled multiplication creates avalanche of charge



Ionisation Chamber

- Operate in ‘ionisation region’ or ‘saturation region’
- Low E field strength
- Recombination negligible → all charge collected
- Current independent of applied voltage (within region)



Charge Mobility

- E-field superimposes a drift velocity on thermal velocity/diffusion

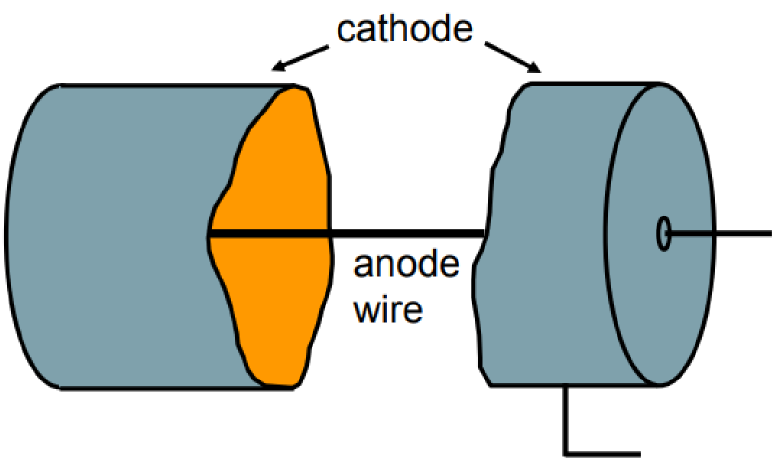
- Typical values
  - $E = 10^4$ V/m
  - p = 1 atm
  - v ~ 1 m/s for ions
  - v ~ 1000 m/s for electrons

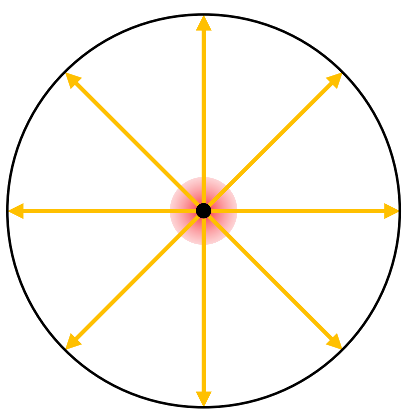
$$v = \mu E / p$$

v = drift velocity
μ = mobility
E = electric field strength
p = gas pressure

Proportional Counters

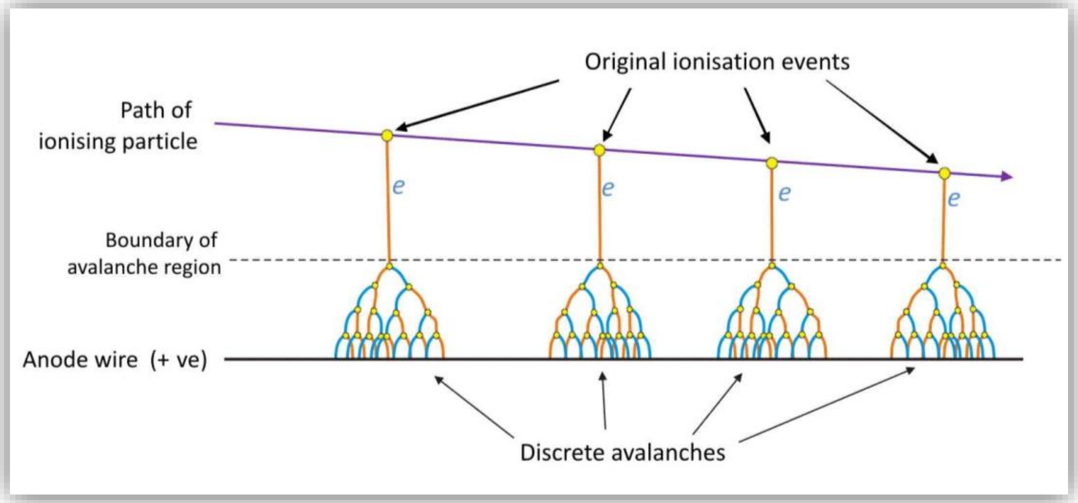
- Operated in pulse mode
- High E field induces multiplication → avalanche
- Uniform field would be problematic
  - Spatial dependence on multiplication
- Cylindrical geometry used to create high field





Proportional Counters

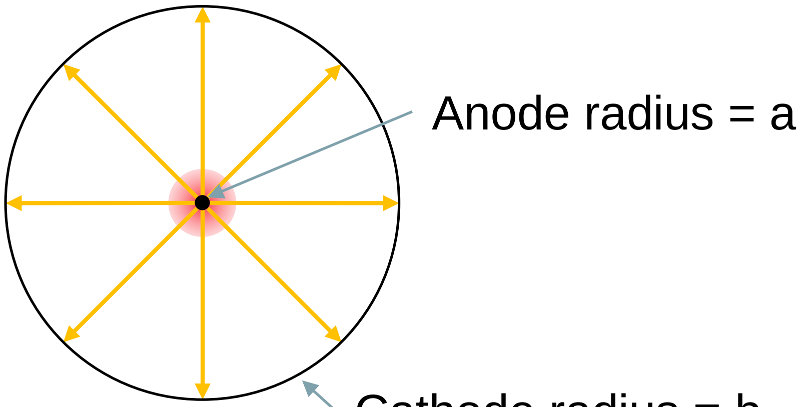
- Electric field strength increases towards anode wire
- E field > 10^6 V/m
- Avalanche region only very small (0.2% of volume)
- All electrons multiplied equally



Example

- Calculate E field at anode surface
  - a = 0.008 cm
  - b = 1.0 cm
  - Applied voltage = 2000 V

$$E(r) = \frac{V}{r \ln\left(\frac{b}{a}\right)}$$



Gas Multiplication Factor

- Quantity of change produced event

$$Q = n_0 e M$$

- Analytical approximation

$$\ln M = \frac{V}{\ln(b/a)} \cdot \frac{\ln 2}{\Delta V}\left(\ln \frac{V}{pa\ln(b/a)} - \ln K\right)$$

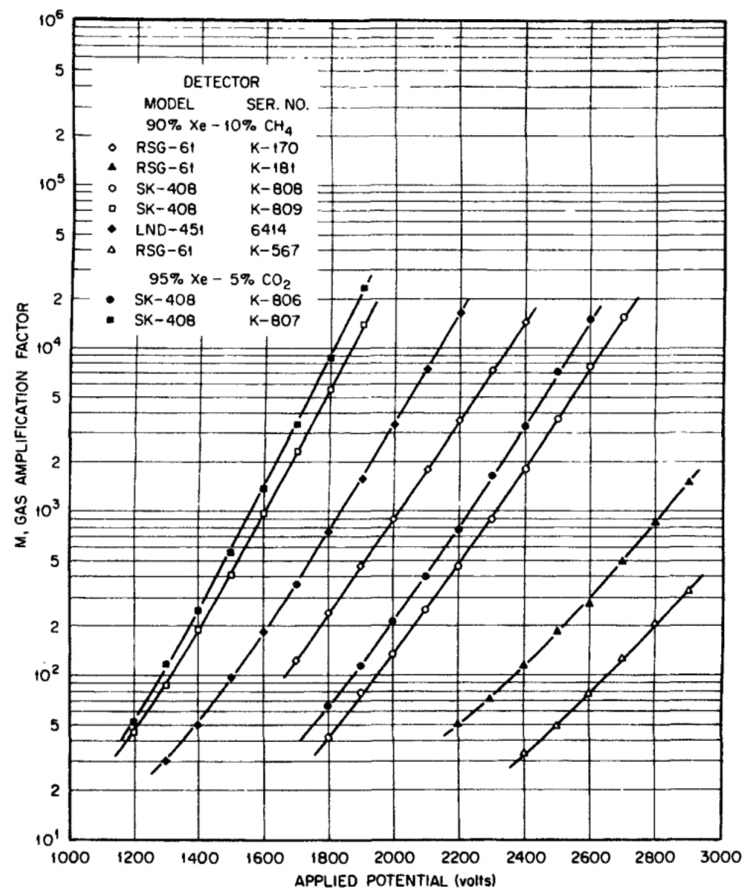
Gas Mixture	K (10^4 V/cm · atm)	ΔV (V)	Reference
90% Ar, 10% CH_4 (P-10)	4.8	23.6	50
95% Ar, 5% CH_4 (P-5)	4.5	21.8	50
100% CH_4 (methane)	6.9	36.5	50
100% C_3H_8 (propane)	10.0	29.5	50
96% He, 4% isobutane	1.48	27.6	50
75% Ar, 15% Xe, 10% CO_2	5.1	20.2	50
69.4% Ar, 19.9% Xe, 10.7% CH_4	5.45	20.3	50
64.6% Ar, 24.7% Xe, 10.7% CO_2	6.0	18.3	50
90% Xe, 10% CH_4	3.62	33.9	49
95% Xe, 5% CO_2	3.66	31.4	49

Q = total charge generated
n_0 = number of original ion pairs
e = electron charge
M = multiplication factor

V = applied voltage
a = anode radius
b = cathode radius
p = gas pressure
K and ΔV are empirical terms (tabulated)

Gas Multiplication Factor

- M increases rapidly with V
- Requires very stable voltage supply
- Gas mixture
  - ‘P-10’ is popular
- Gas pressure
  - Typically operated at 1 atm.
  - Can be adjusted for applications



Quench Gas

- For proportionality require 1 electron = 1 avalanche
- Gas dexcitation may result in UV photon emission
- Absorption of UV by primary gas could result in additional avalanche – not desirable
- Add complex molecular gas to absorb UV
- Dissipate energy through processes that do not release electron

P-10: 90% Ar and 10% methane (CH_4)

Proportional Counters Summary

- Each electron gives rise to one avalanche
- quench gas stops additional UV induced discharges
- Each avalanche is independent
- Multiplication factor is constant
- Recorded current is proportional to number of original ion pairs created

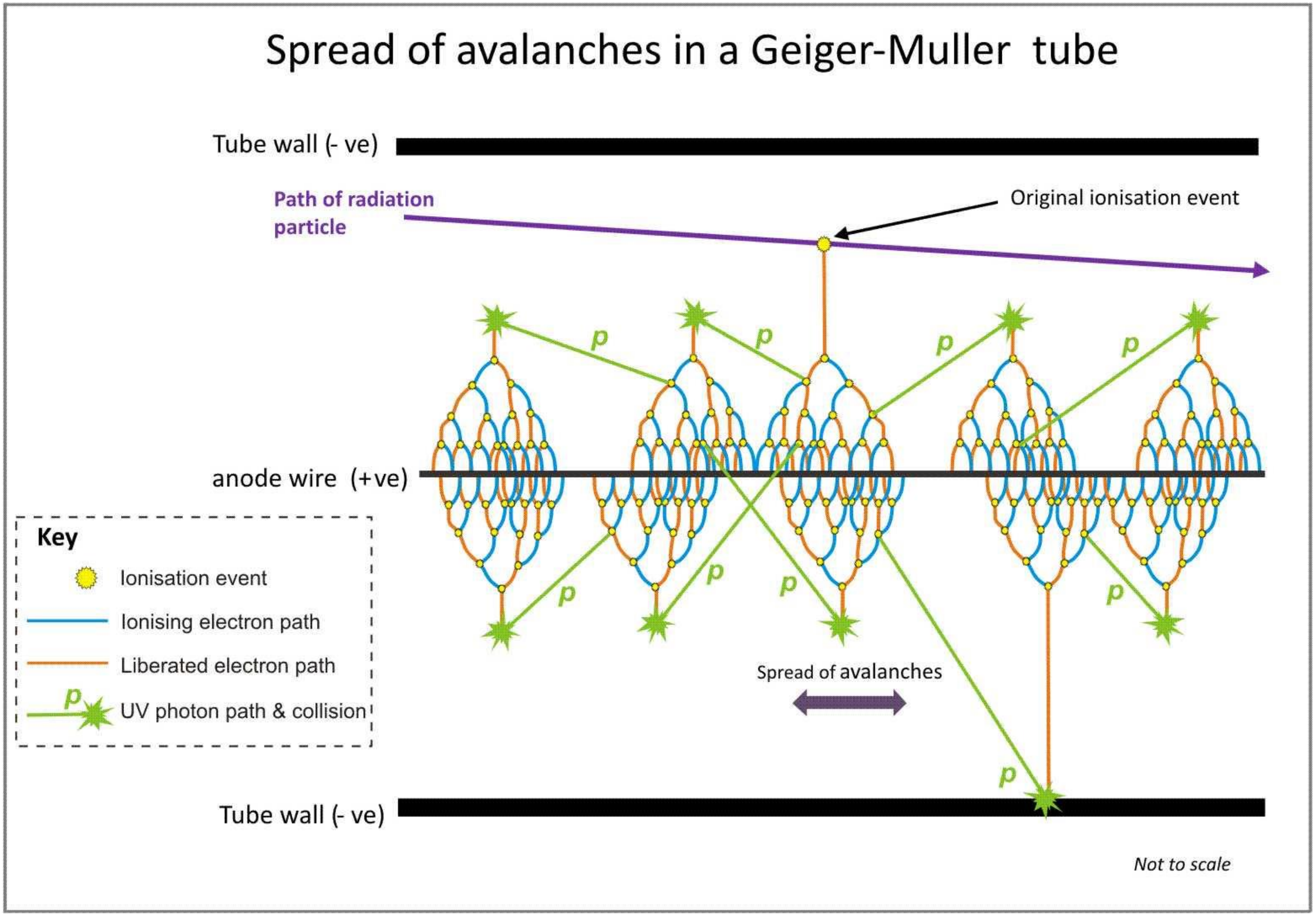
Geiger-Mueller Tubes

- Construction same as proportional counters
- Operated in pulse mode
- Very high E field → increase intensity of avalanches
- Each avalanche can create another avalanche → chain reaction

Geiger Discharge

- During avalanche
  - Secondary ions
  - Excited molecules
- Dexcitation via UV photon emission
- UV photon interacts with gas or tube body
- Liberates another electron
- Creates new avalanche

Geiger Discharge



Geiger Discharge Termination

- Multiplication relies on high E field
- Ionisation creates positive ion ‘cloud’ near the anode wire
- Ion mobility is low $\rightarrow$ remain ‘motionless’ during discharge process (~1 μs)
- Field strength is reduced below critical point
- Discharge stops

- Same signal amplitude regardless of number of ion pairs created originally

Quench Gas

- After termination
  - Positive ions drift away from anode
  - Replenish neutrality with electron from cathode
  - An amount of energy can be released (IE minus φ)
  - If energy greater than φ, additional electron could be released
  - Discharges starts again – never ending cycle
- Quench gas has lower IE that primary
  - 5-10% of gas fill
  - Neutralisation via staged charge transfer collisions
  - Excess energy lower that φ at cathode

G-M Tube Summary

- Each electron gives rise to many avalanches
- Run-away process
- Energy/type information of interacting radiation is lost
- Quench gas prevents new discharge due to ion neutralisation at cathode