chap.3 General Characteristics of Detectors

Many different types of detectors

- Scintillation counters
- Cherenkov counters
- Proportional chambers
- Neutral particle detectors
- Semiconductor detectors

.....

All based on the same fundamental principle

The transfer of part or all of its radiation energy to the detector mass where it is converted into some other form

More accessible to human perception

Charged particle

Transfer their energy to matter through direct collisions with atomic electrons

Neutral radiation

First -> produce charge particle in the detector

Then -> ionize and excite the detector atoms

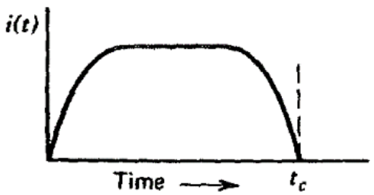
The form of the converted energy depends on detector and its design:

Gaseous Detectors:

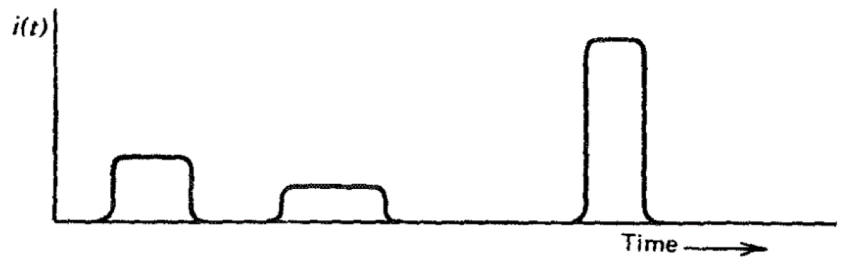
•collect the ionization electrons to form an electric current signal

Scintillators:

•both the excitation and ionization contribute to inducing molecular transition which result in the emission of light



$$\int_0^{t_c} i(t)\, dt = Q$$



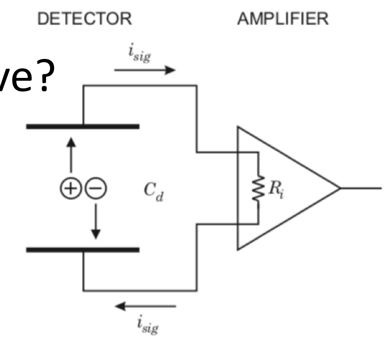
Modern Detectors

the info from detector is transformed into electrical impulses which can be treated by electronic means, taking advantage of great progress made in electronics and computers to provide faster and more accurate treatment of the information

Signal formation – current pulse

charge moving in the sensitive volume of the sensor gives rise to a signal current

When does the signal current begin?
When the charge reaches the electrode or when the charge begins to move?

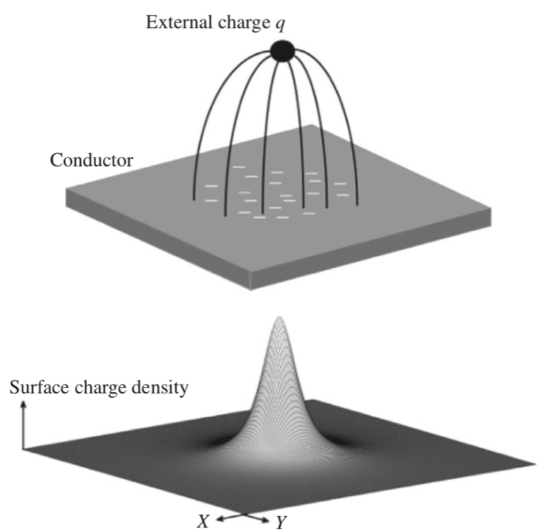


Although the first answer is quite popular (encouraged by the phrase "charge collection"), the second is correct; current flow begins instantaneously.

Metal Surface: Electric Field perpendicular to surface.

→ Charges are only on the surface, no electric field in the conductor.

→ Surface Charge Density σ and electric E field on the surface are related by $\sigma = \varepsilon_0 E$



$$\sigma(x,y) = -\frac{q z_0}{2\pi(x^2+y^2+z_0^2)^{\frac{3}{2}}}$$

$$Q = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\sigma(x,y)\,dx\,dy = -q$$

Moving the point charge closer to the metal plate, the surface charge distribution becomes more peaked, the total induced charge is however always equal to –q， no current.

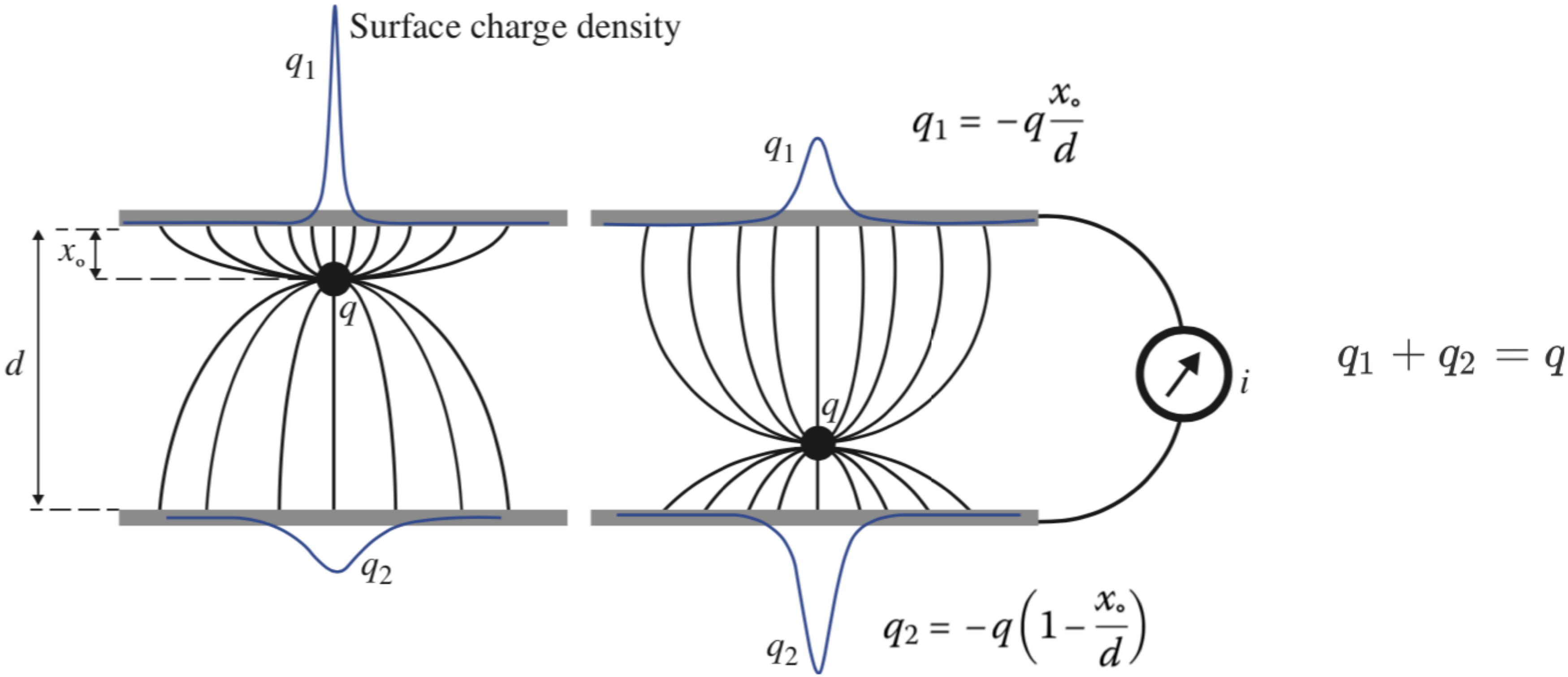


Figure 1.2 The induction of current by a moving charge between two electrodes. When charge q is close to the upper electrode, the electrode receives larger induced charge, but as the charge moves toward to the bottom electrode, more charge is induced on that electrode. If the two electrodes are connected to form a closed circuit, the variations in the induced charges can be measured as a current.

As a charge traverses the space between the two plates the induced charge changes continuously, so current flows in the external circuit as soon as the charges begin to move.

感应信号

• To calculate the induced signal one has to solve the Poisson equation at each step on the drift of the electron-ion pair ➔ very complicated

• Solution (by Ramo and Shockley):

$$i(t) = q \cdot \vec{E}_w \cdot \vec{v}$$

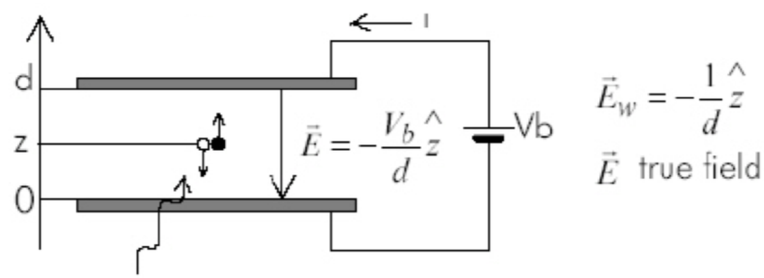
with q: charge; E_w: weighting field; v: velocity

$$Q(t) = \int_0^t i(\tau)d\tau = q\int_{x1}^{x2} \vec{E}_w d\vec{x}$$

- How to get the weighting field?

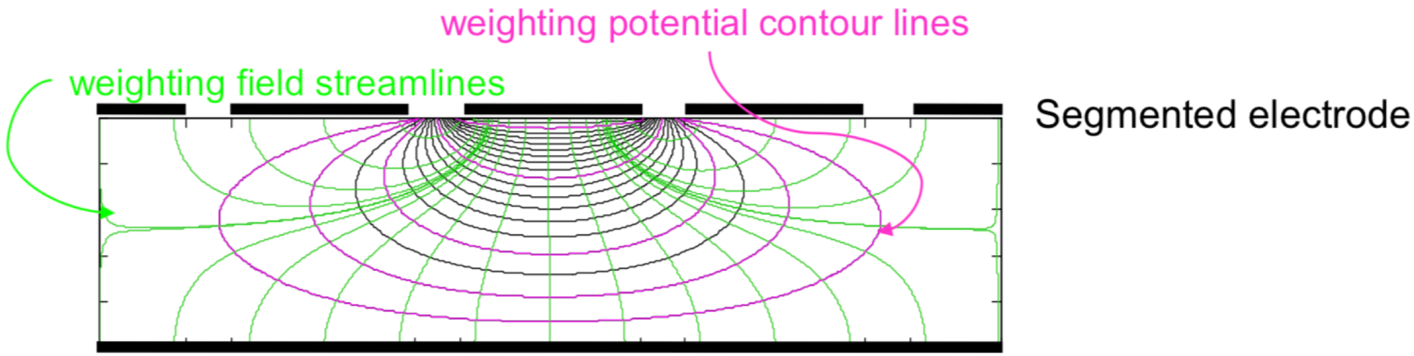
– Calculate the electrostatic field for each electrode by:
  - removing the signal charge
  - setting the electrode to U = 1V and all others to 0 V

- Simple example:



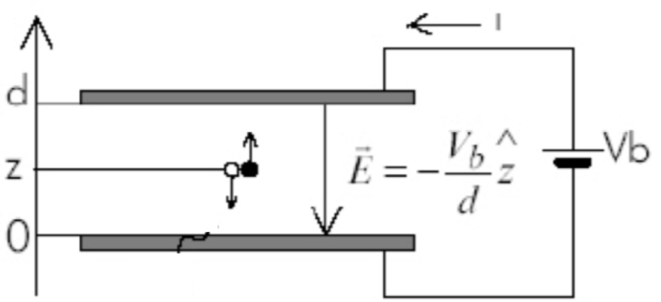
- Only for setups with two electrodes the weighting field and the true field look alike. In general they are different!

- The actual electric field determines the path and the drift velocity of the carrier. The weighting field depends only on geometry and determines how the motion of the carrier couples to the electrode.



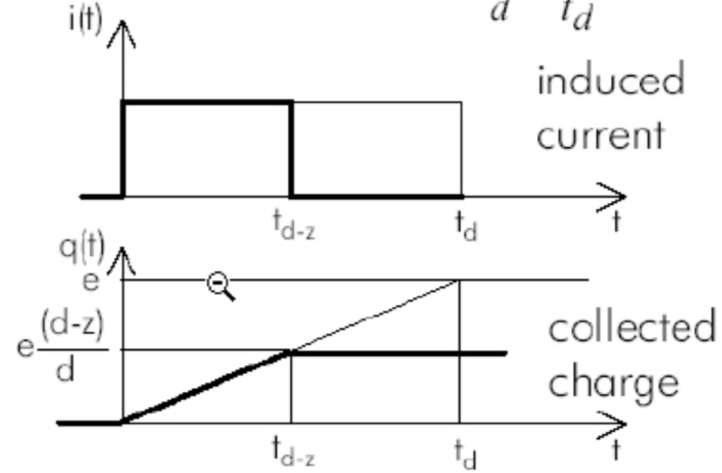
- Induced signal in parallel plate detector

$$i(t) = q\,\vec{E}_w \cdot \vec{v} = -e(-E_w v) = e\frac{v}{d} = \frac{e}{t_d} \qquad 0 \le t \le t_d$$



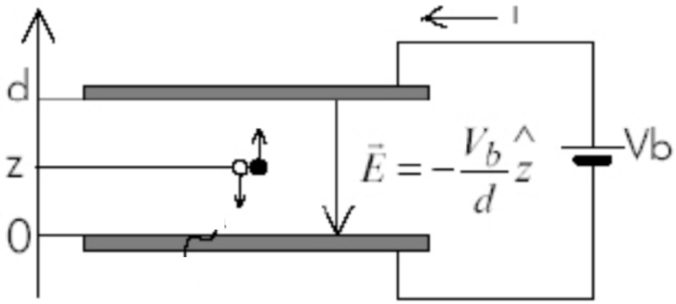
$\vec{E}_w = -\frac{1}{d}\hat{z}$

$\vec{E}$ true field



Both positive and negative charged particles contribute to the output signal with the same polarity.

Delta pulse



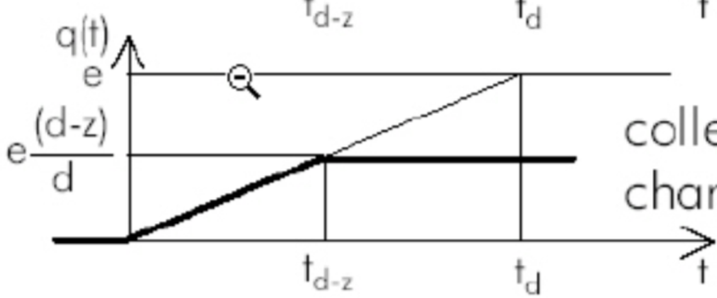
$$\vec{E} = -\frac{V_b}{d}\hat{z}$$

$$\vec{E}_w = -\frac{1}{d}\hat{z}$$

$\vec{E}$ true field

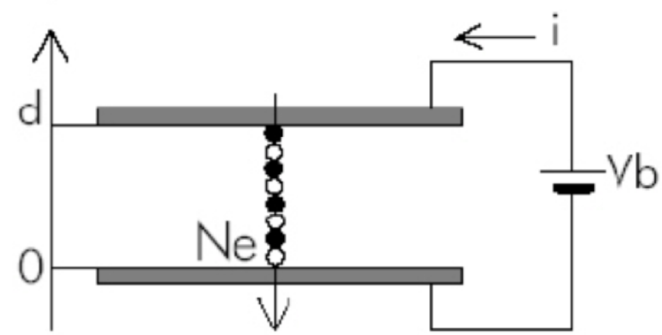
$$i(t) = q\,\vec{E}_w \cdot \vec{v} = -e(-E_w v) = e\frac{v}{d} = \frac{e}{t_d} \qquad 0 \le t \le t_d$$

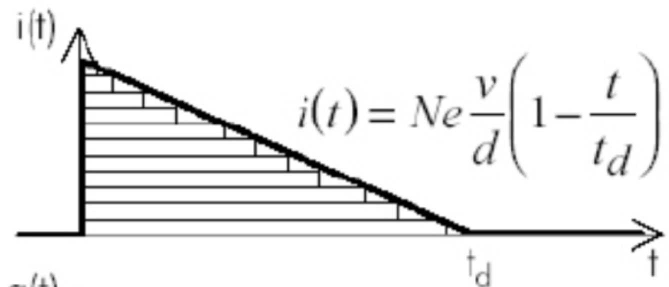
induced current



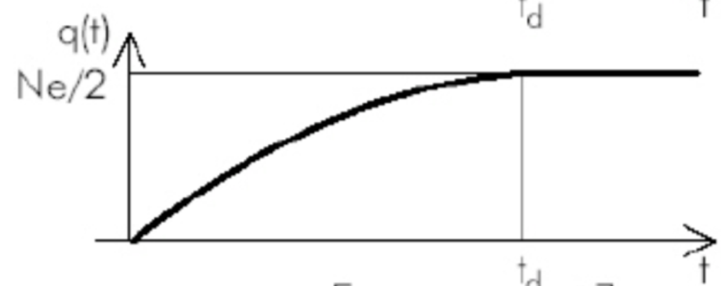
collected charge

Continuous pulse (charged track)





$$i(t) = Ne\frac{v}{d}\left(1 - \frac{t}{t_d}\right)$$



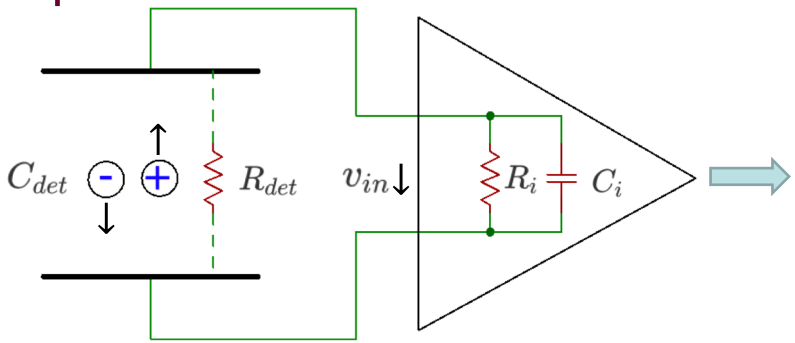
$$Q_s(t) = \int_0^t i(\tau)\,d\tau = Ne\left[\frac{t}{t_d} - \frac{1}{2}\left(\frac{t}{t_d}\right)^2\right]$$

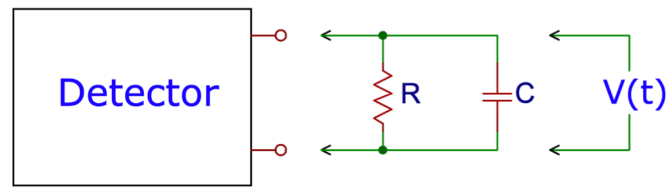
Modes of detector operation

Pulse mode

Most applications are better served by perserving information on the amplitude and timing of individual events that only pulse mode can provide.

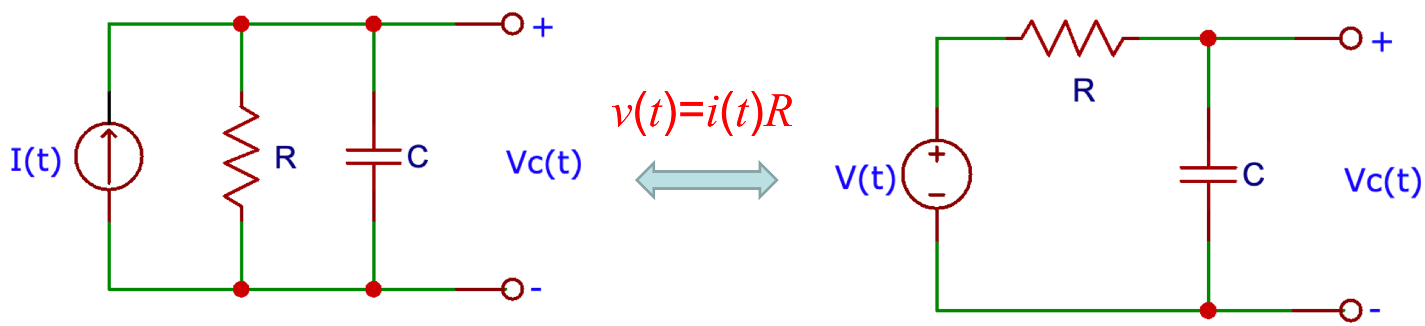
Equivalent circuit for a detector connected to the read-out electronics.





$R = R_i \,||\, R_{det} \sim R_i$ $(R_{det} >> R_i)$ $C = C_{det} + C_i$

detector equivalent circuit in current variant or voltage variant

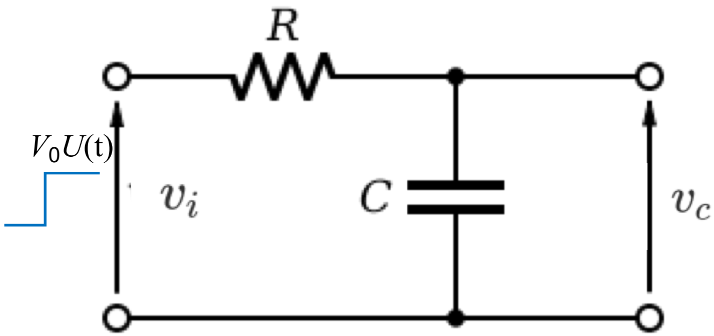


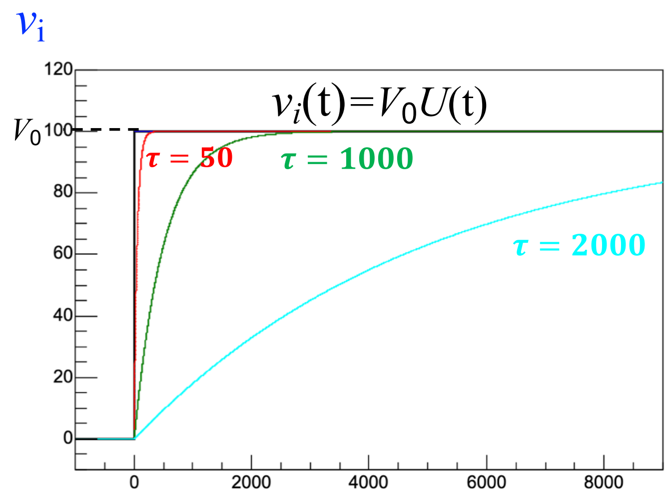
$$RC\frac{dv_c(t)}{dt} + v_c(t) = i(t)R$$

$$RC\frac{dv_c(t)}{dt} + v_c(t) = v(t)$$

$$Q = \int i(t)dt \qquad v_{cmax} = Q/C$$

- **The step response of a RC circuit**



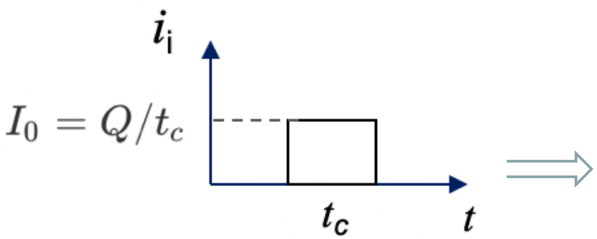


$$v_c(t) = V_0(1 - e^{-t/\tau})$$

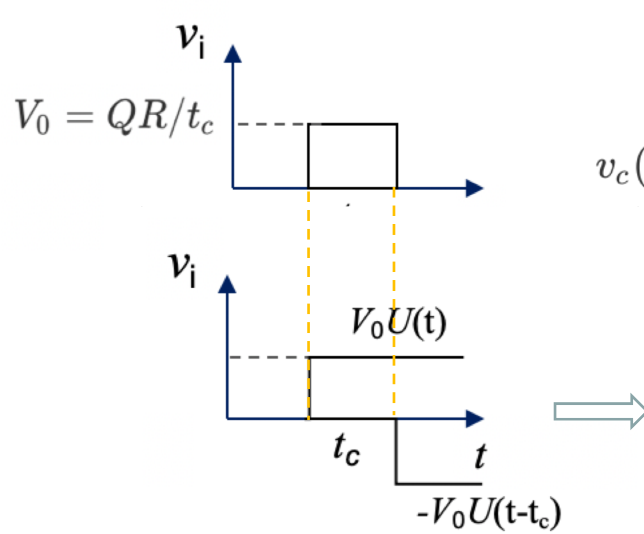
$$\tau = RC \quad [ns]\ [\mu s]$$

time constant

- **$v_c(t)/v_{cmax}$ for a square wave input**

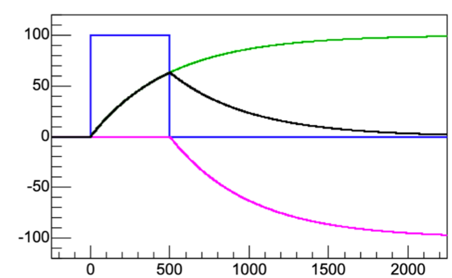


t_c: collection time of detector

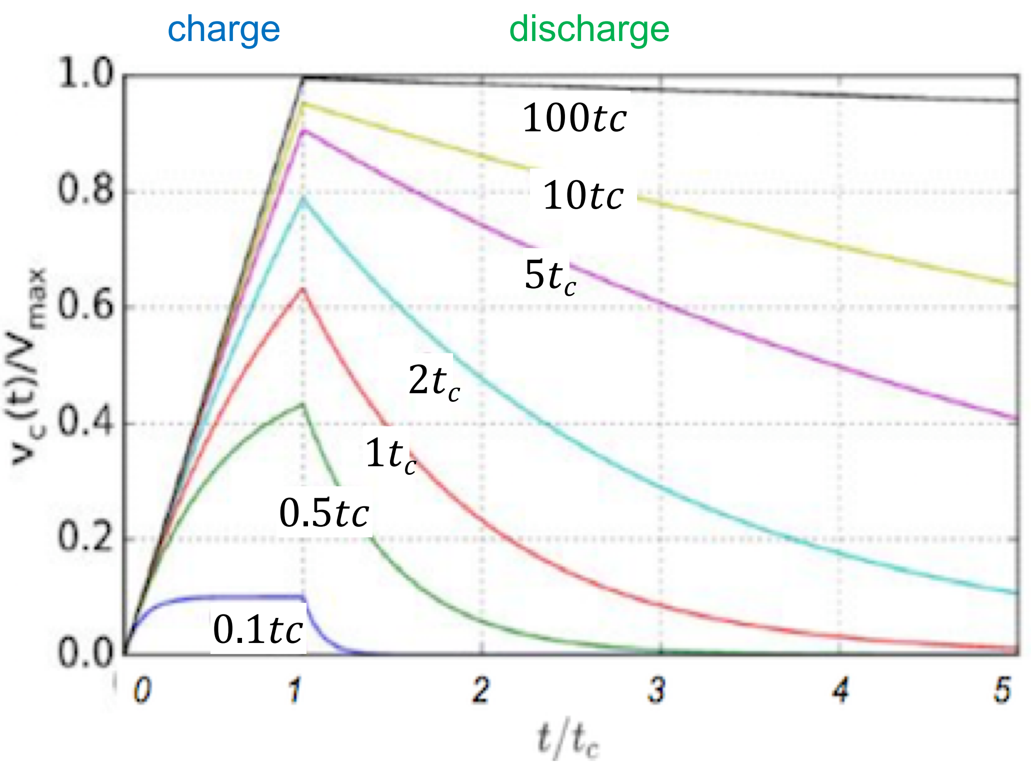


$$v_{cmax} = Q/C$$

$$v_c(t)/v_{cmax} = \tau/t_c[e^{-(t-t_c)/\tau} - e^{-t/\tau}]$$

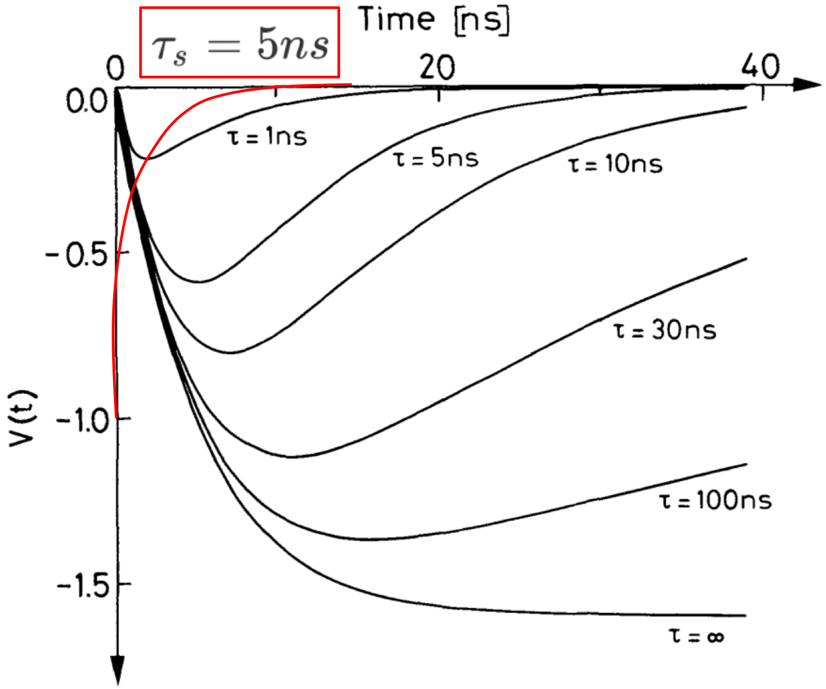


pulse shape vs. τ=RC and t_c.



- The rise time is deternided mainly by the charge collection time whithin the detector itself.
- The decay time is deternided only by the time constant of load circut.
- The capacitance is normally fixed, the amplitude of the signal pulse is directly proportional to the corresponding charge generated within the detector and is given by the simple expression: $V_{max} = Q/C$

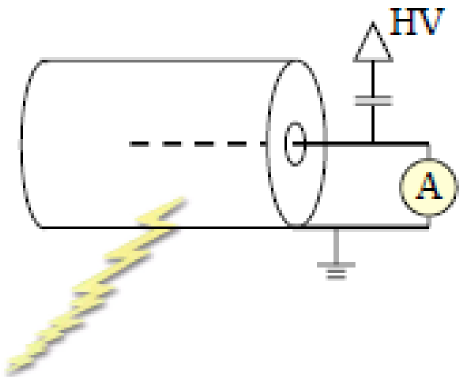
Scintillator signal $i(t) = \frac{GeN_0}{\tau_s} e^{-t/\tau_s}$ Rapid rise, slow decay

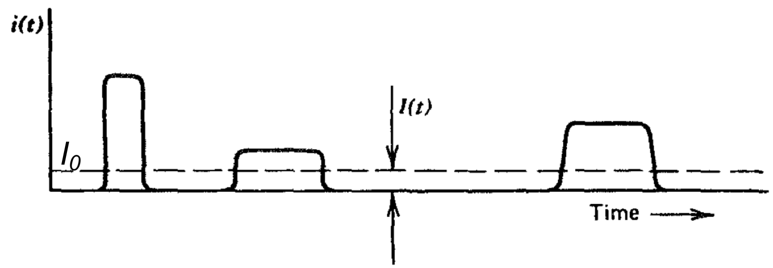


$$V(t) = \begin{cases} -\frac{GNeR}{\tau - \tau_s}\left[\exp\left(-\frac{t}{\tau_s}\right) - \exp\left(-\frac{t}{\tau}\right)\right] & \tau \neq \tau_s \\ \left(\frac{GNeR}{\tau_s^2}\right) t \exp\left(-\frac{t}{\tau_s}\right) & \tau = \tau_s \end{cases},$$

- RC<<t_c :Circuit is fast enough to follow the collection of the ionization and one has a current pulse.
  Time signal : Fast rise time, small amplitude.
  - ex: Scintillator+PMT : τ<10ns
- RC>>t_c Circuit is slower than the collection time and one gets a voltage pulse.
  Energy signal : Slow rise time, large amplitude.
  - ex: Silicon detector+PreAmp: $\tau \sim 200 \mu s$

Current mode





If we assume that the measuring device has a fixed response time T, then the recorded signal from a sequence of events will be a time dependent current given by $$I(t) = \frac{1}{T}\int_{t-T}^{t} i(t')dt'$$

High rates

Ion Chamber：the individual pulses are summed in a system that has a long time-constant

$$I = r(E/w)q_e = rQ$$

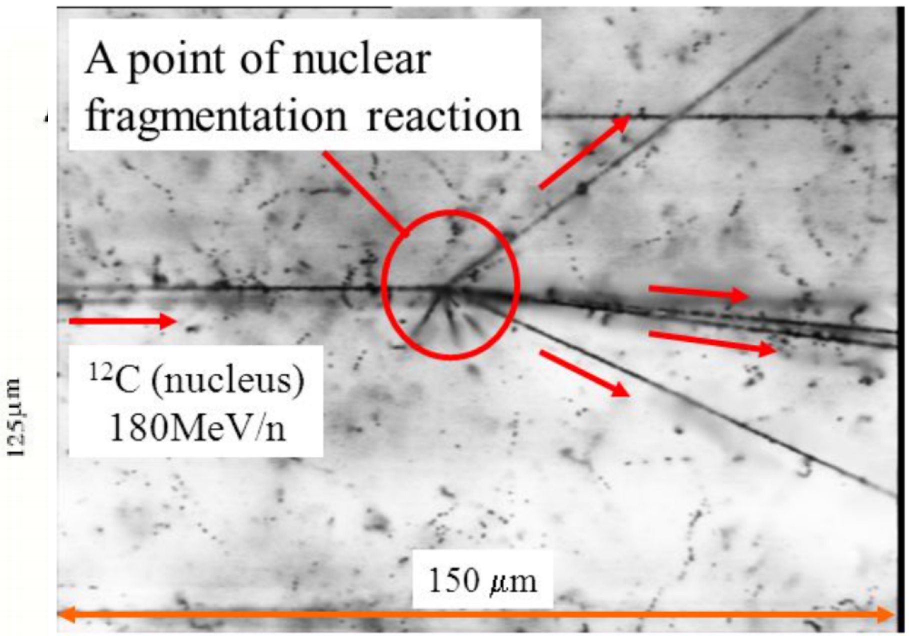
r : the rate of the incident radiation.
E : the energy deposited in the sensitive volume
w: the average energy required to produce an ionization

“Old” ionization detectors

- Photo emulsion
- Cloud chamber
- Bubble chamber
- Spark chamber

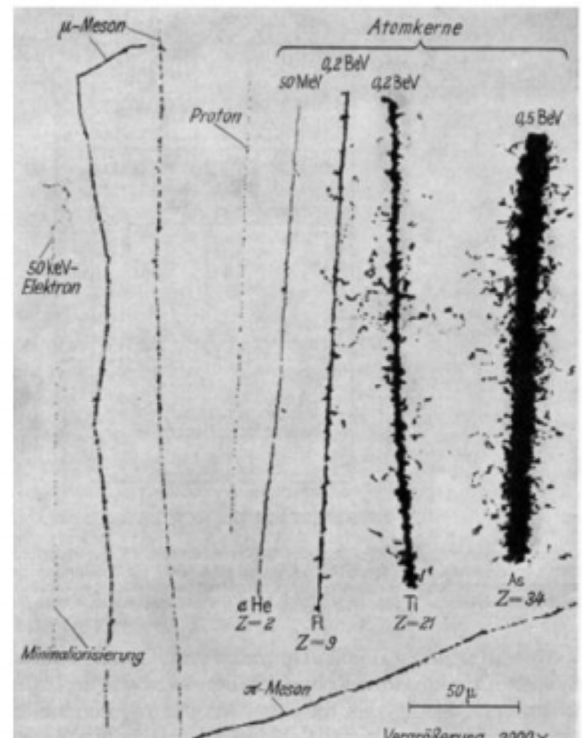
Photo emulsion

Ionization tracks can be measured in photo emulsions.
With a microscope the darkening of the film is measured.



Micrograph of a fragmentation reaction recorded on a nuclear emulsion

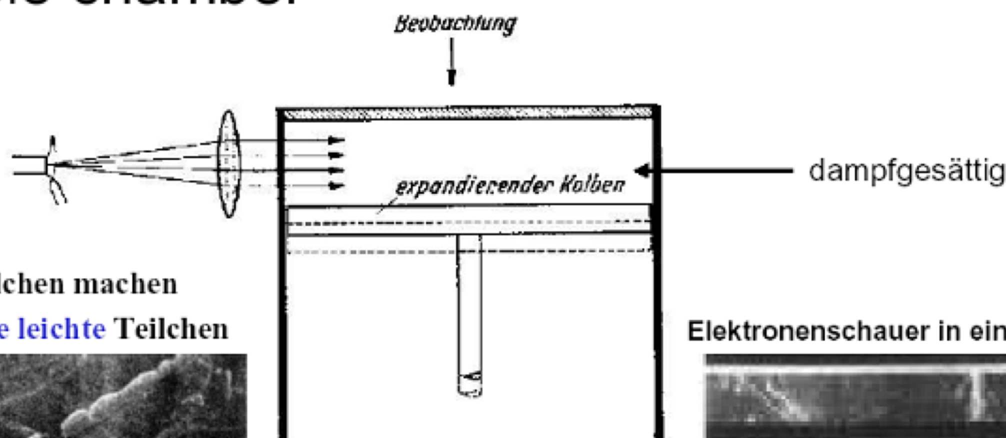
Space resolution ≈ 1µm
Unbeaten record



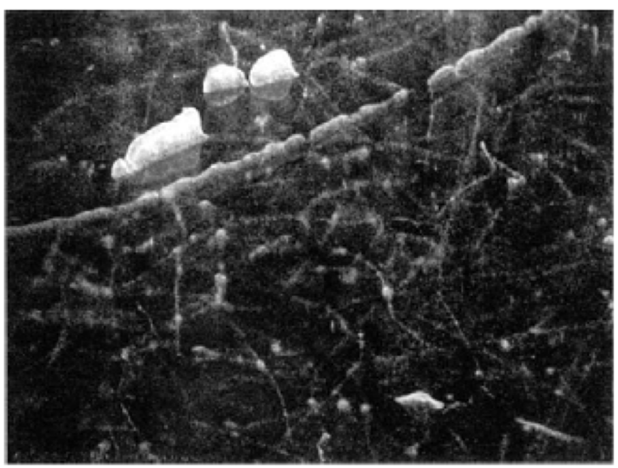
Slow heavy particles make more ionization as fast light particles

Cloud chamber

Ionization as condensation or evaporation nucleus:
cloud or bubble chamber

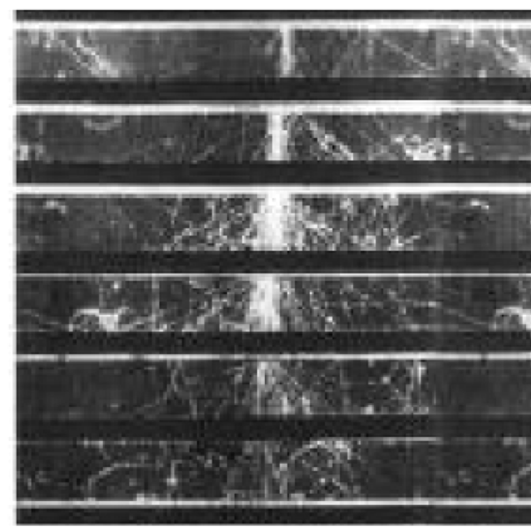


Langsame schwere Teilchen machen
mehr Ionisation als schnelle leichte Teilchen

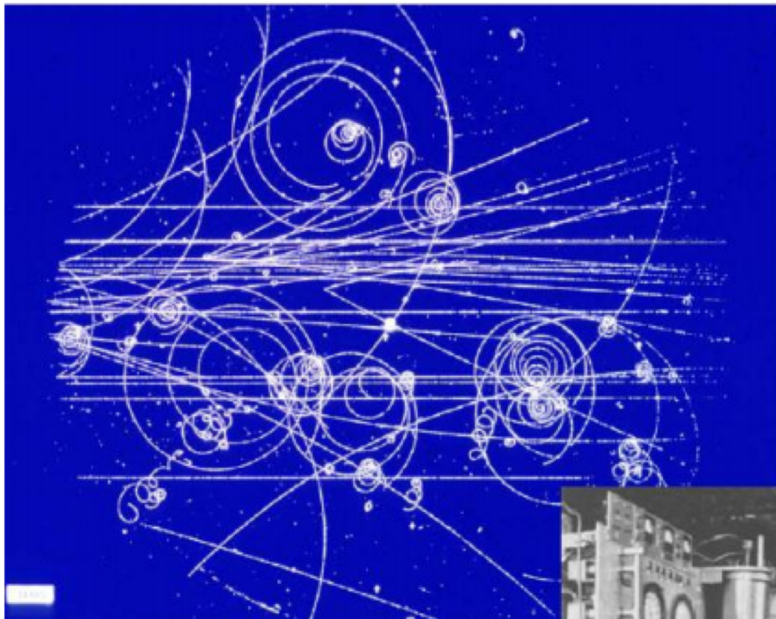


Zeuthener Nebelkammer

Elektronenschauer in einer Nebelkammer



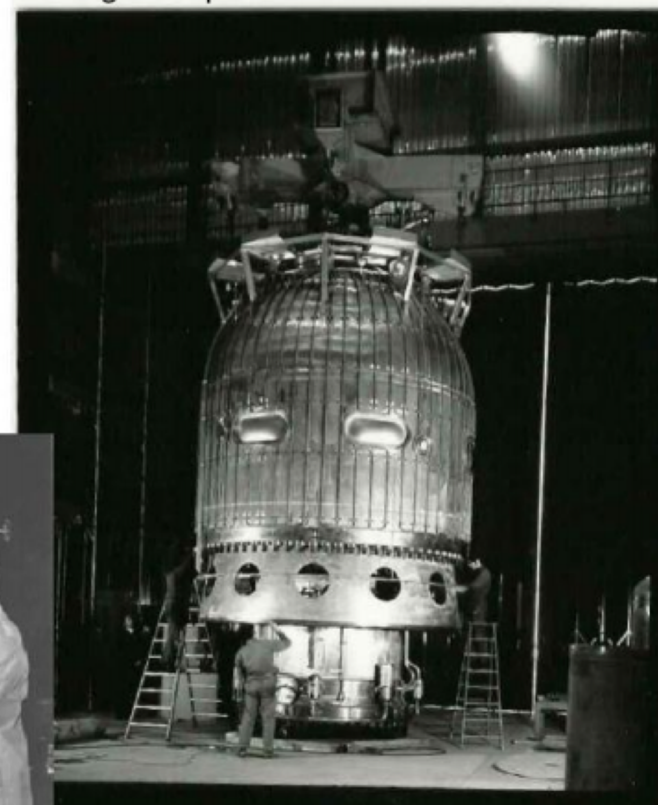
Bubble chamber



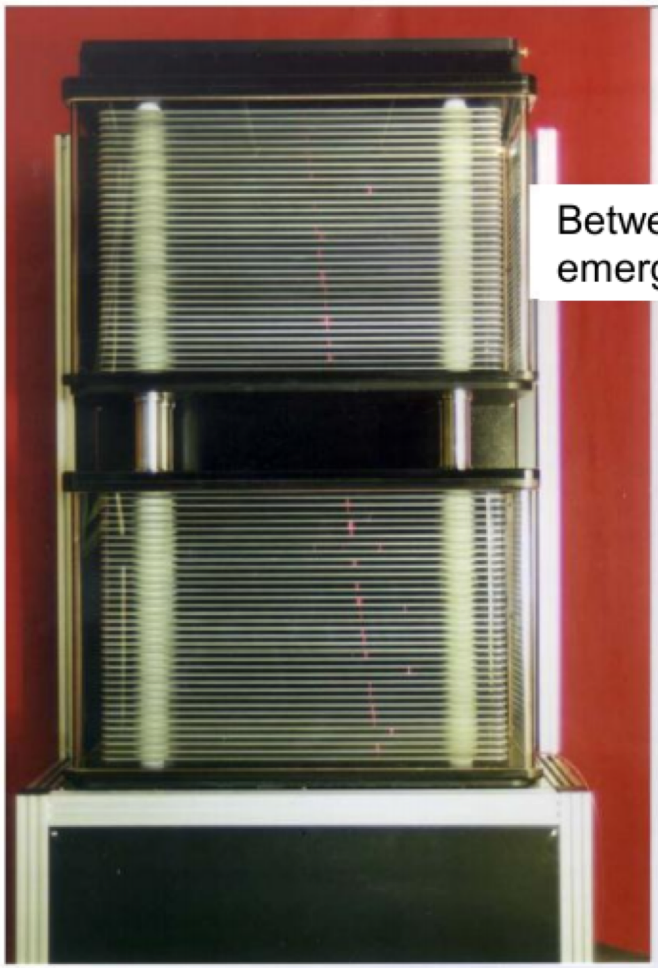
Spuren durch
Magnetfeld gekrümmt

D.A.Glaser, Nobelpreis 1960

Big European Bubble Chamber



Spark chamber



Between 2 plates with high voltage a spark emerges along the ionization track

- Too slow
- Needs trigger for high voltage at plates
- Spark makes electromagnetic debris
- Difficult to read out electronically

Is also true for emulsion, cloud and bubble chamber

Sensitivity

Detectors are designed to be sensitive to certain types of radiation in a given energy range. Going outside this region usually result in unusable signal or greatly decreased efficiency.

No detector can be sensitive to all types of radiation at all energies

FACTORS EFFECTİNG DETECTOR SESİTİVİTY

1. The cross section for ionizing reactions in the detector

   Neutral particles: less ionizing , Much smaller interaction cross section

   -> need higher mass density and volume

2. The detector mass

   For neutrino -> the order of tons

3. The inherent detector noise

   Ionization signal->Average noise level

4. The protective material surrounding the sensitive volume of the detector

   Only radiation with sufficient energy to penerate covering can be detected.

Energy Resolution

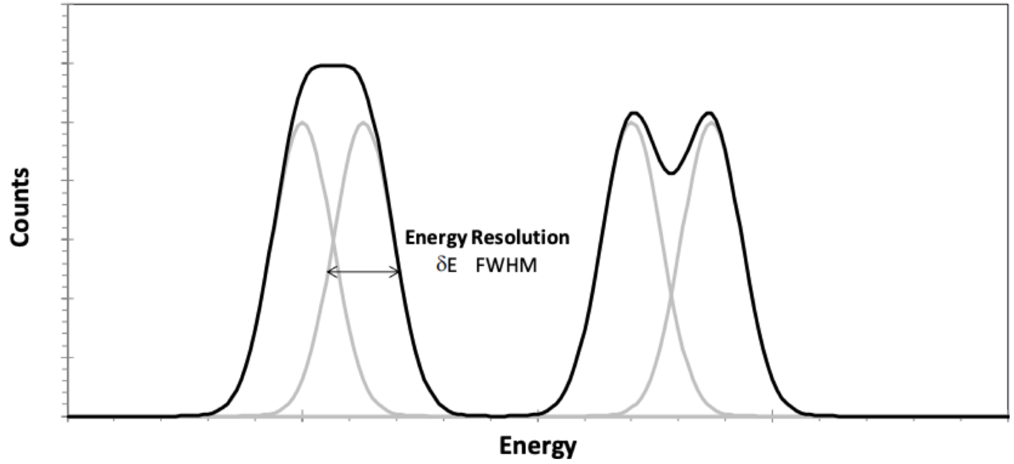
The minimum detectable signal and the precision of the amplitude measurement are limited by fluctuations. The signal formed in the detector fluctuates, even for a fixed energy absorption.

This width arises because of fluctuations in the number of ionizations and excitations produced.

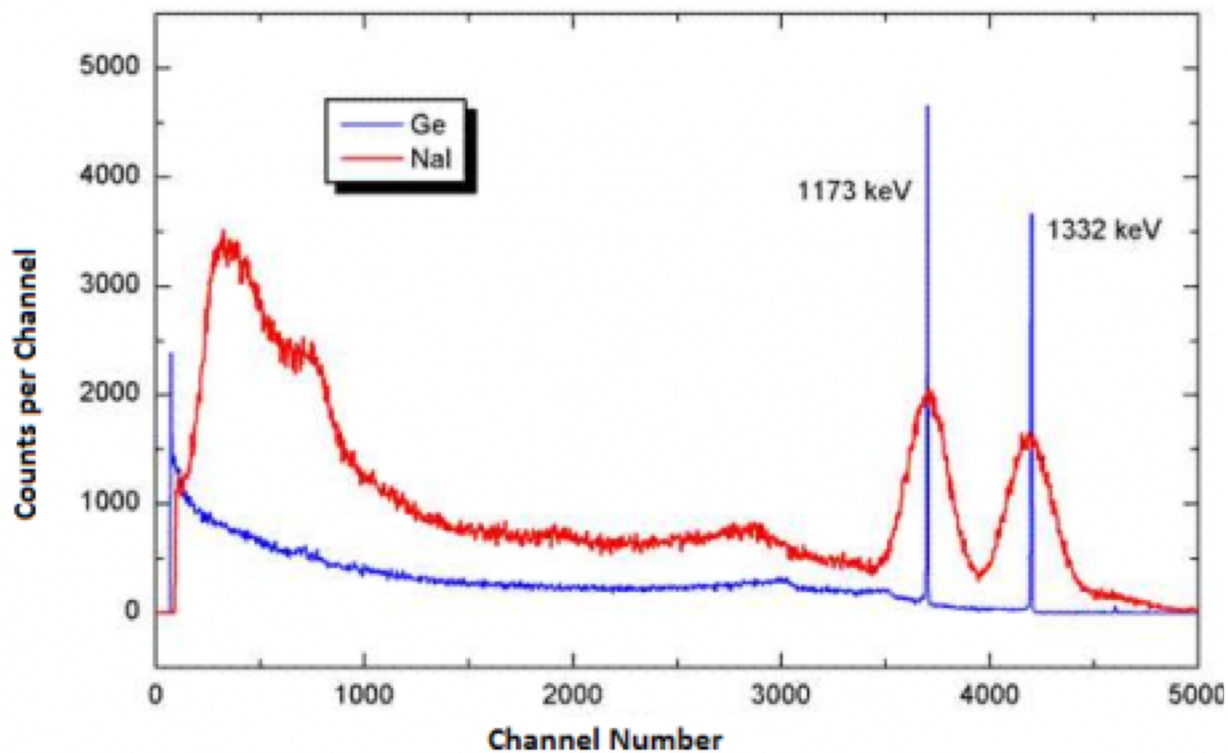
Resolution ΔE Full width at half maximum of the peak (FWHM)

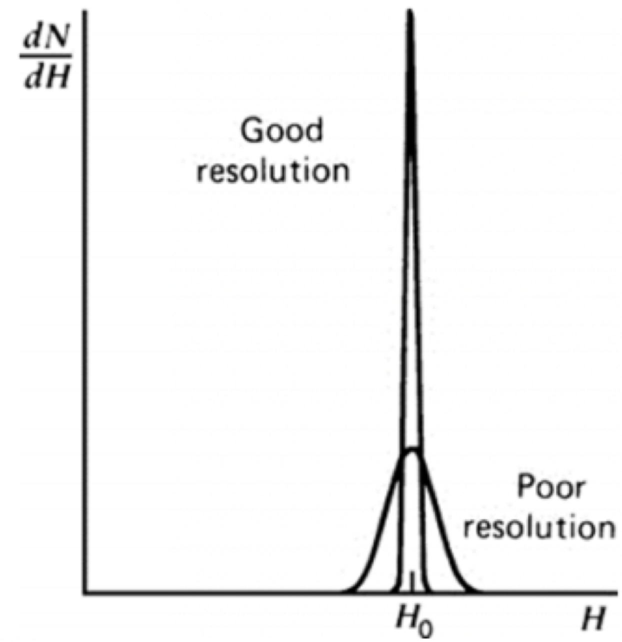
Energies closer than this integral considered unresolvable

Relative resolution R(E)= $\frac{\Delta E}{E}$ relative resolution at E



•NaI: 8% or 9% resolution for gamma rays @1MeV
•Germanium detectors: order of 0.1% @ 1MeV





- scintillation detector: energy -> No. scintillation photons.
- ionization chamber: energy -> No. charge pairs.

Average energy required to produce an ionization w $E = w\bar{N}$

- Fixed number depends only on material

Silicon detectors: w ≈ 3.6 eV

Gas detectors: w ≈ 30 eV

scintillator: w ≈ 200-500 eV

•Average number of ionizations: $\bar{N} = E/w$, E: deposited Energy

Poisson Statistics: $\sigma_{\bar{N}} = \sqrt{\bar{N}} = \sqrt{E/w}$

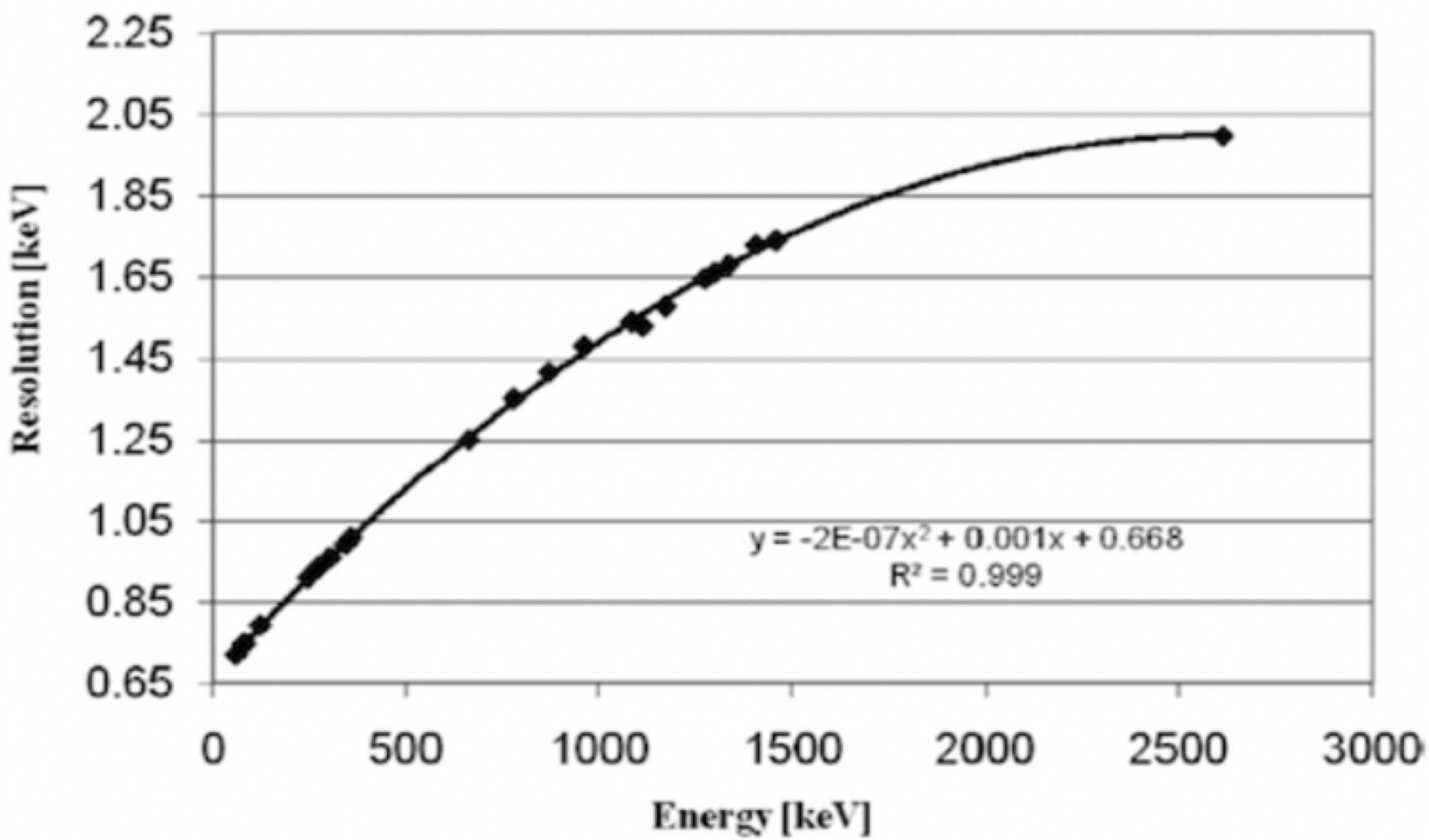
$$\sigma_E = w\sigma_{\bar{N}} = \sqrt{wE}$$

$w \downarrow \ \rightarrow \ \sigma_E \downarrow$

Relative Energy resolution $R = 2.35\frac{\sigma_E}{E} = 2.35\sqrt{w/E} \propto 1\sqrt{E}$

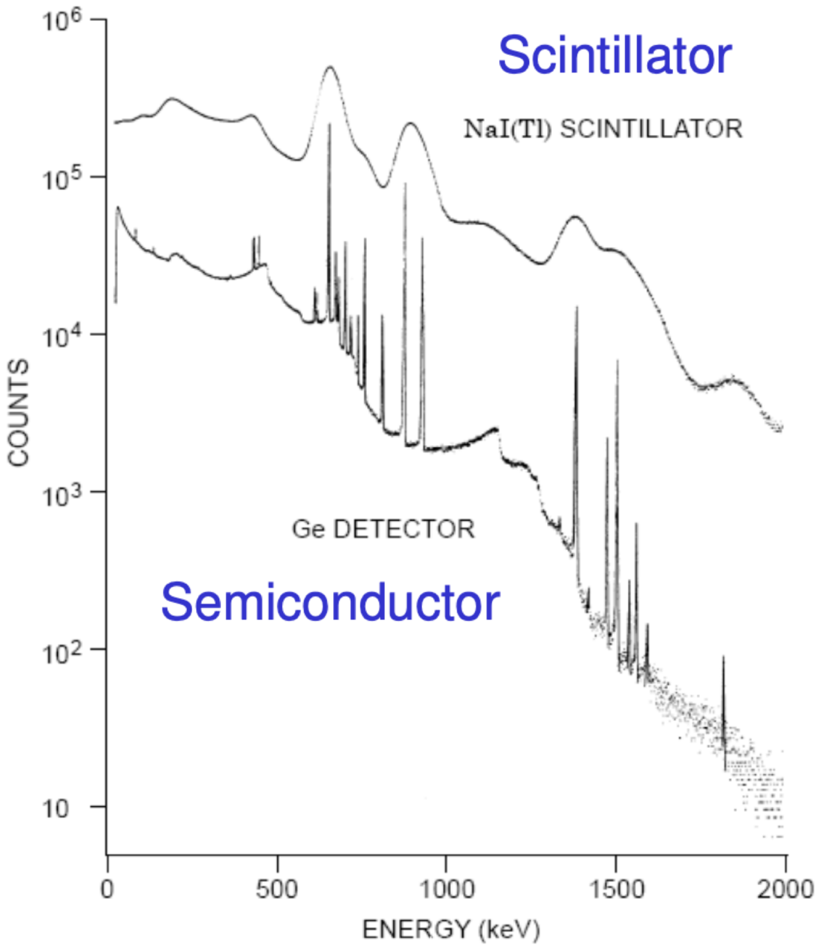
Resolution curve of HPGe detector

$$\sigma = \sqrt{N} = \sqrt{E/w}$$

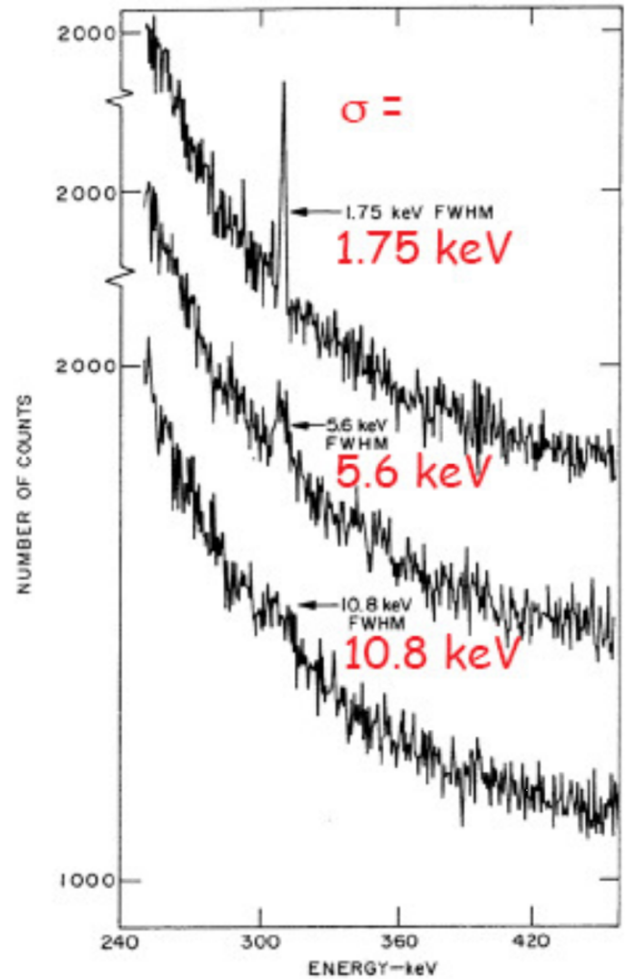


Resolution increases sensitivity

- Signals to background ratio improves with better resolution.



(J.Cl. Philippot, IEEE Trans. Nucl. Sci. **NS-17/3** (1970) 446)



Fano factor

Experience has shown that the fluctuations are smaller than what the equation above gives. The observed statistical fluctuations are expressed in terms of the Fano factor F: $\sigma = \sqrt{FE/w}$ $R = 2.35\sqrt{Fw/E}$

Silicon, CdTe	F ~ 0.1 to 0.15
Pure gas	F ~ 0.2 to 0.4
Scintillator	F ~ 1

The two extreme values of F are 0 and 1.

- F = 0 means that there are no statistical fluctuations in the number of pairs produced. That would be the case if all the energy was used for production of charge carriers.

- F = 1 means that the number of pairs produced is governed by Poisson statistics. small p, only very small fraction of incident radiation is converted to ion pairs

Fano factor - for semiconductor

In the case of Silicon, two mechanisms contribute to the mean ionization energy.

- Pair generation: $E_i \sim 1.2$eV
- Excitation of the crystal(phonons): $E_x \sim 0.04$ eV

The average number of charge carriers cannot be simply discribed by N=E/w

$$E_0 = E_{ion} N_{ion} + E_x N_x$$

Since the available energy is fixed

$E_i \sigma_i = E_x \sigma_x$ (by propagation of errors)

$$\Rightarrow \sigma_i = \frac{E_x}{E_i} \sqrt{\bar{N}_x}$$

Width of the energy loss distribution

$$E_i \bar{N}_i + E_x \bar{N}_x = E_0 \Rightarrow \bar{N}_x = \frac{E_0 - E_i \bar{N}_i}{E_x}$$

$$\sigma_i = \frac{E_x}{E_i} \sqrt{\frac{E_0 - E_i \bar{N}_i}{E_x}}$$ make use of $\bar{N}_i = \frac{E_0}{\varepsilon}$

$$\Rightarrow \sigma_i = \sqrt{\bar{N}_i} \sqrt{\frac{E_x}{E_i} \left(\frac{\varepsilon_i}{E_i} - 1\right)} = \sqrt{F \bar{N}_i}$$

F Fano factor – improvement in resolution

For silicon:

$E_x = 0.037eV, \quad E_{ion} = E_g = 1.1eV,$

$E_i = 3.6eV \rightarrow F = 0.08$

$(measured : \approx 0.1)$

External factors affecting the overall resolution:

Effects from associated electronics such as noice, drifts, etc

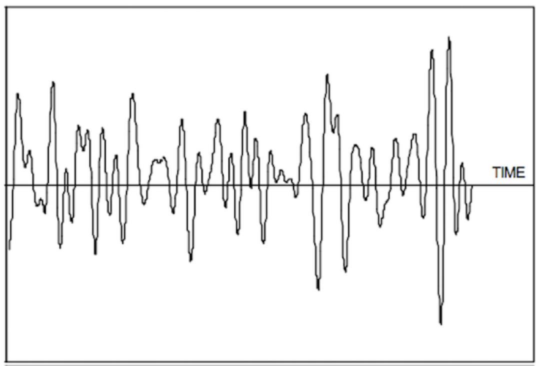
$$(FWHM)^2_{all} = (FWHM)^2_{stat.} + (FWHM)^2_{noise} + (FWHM)^2_{drift} + \ldots$$

Choose a time when no signal is present.

Amplifier's quiescent output level (baseline):

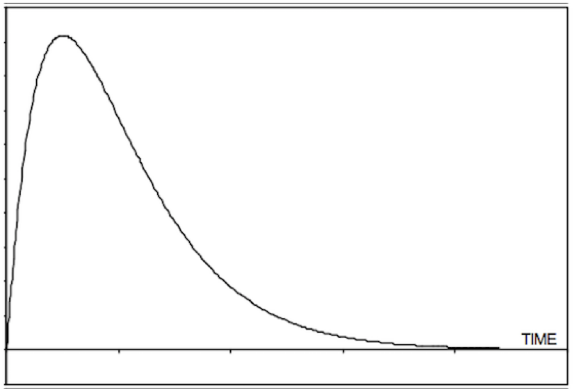
sensitivity x10

These fluctuations are added to any input signal

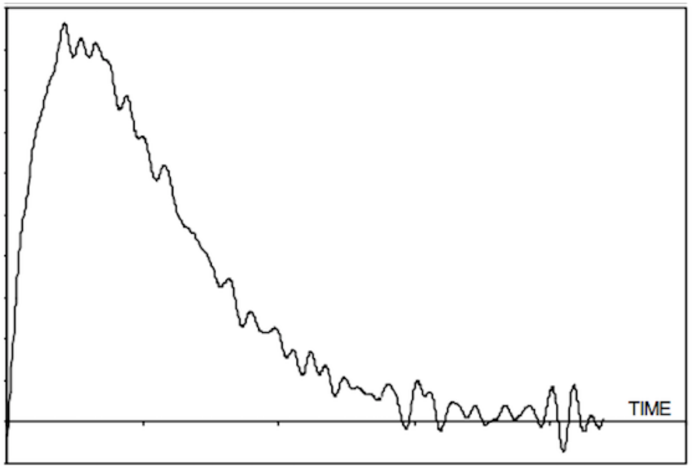


Pulse output of the ideal system

(sensitivity x1)



Signal + Noise



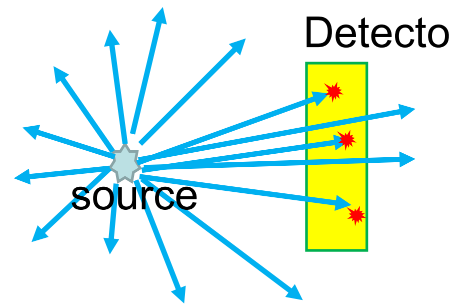
Measurement of peak amplitude yields
signal amplitude + noise fluctuation

Detector efficiency

Two definitions:

Absolute efficiency: $$\epsilon_{abs} = \frac{\#\text{ of recorded}}{\#\text{ of emitted}}$$

Intrinsic efficiency: $$\epsilon_{int} = \frac{\#\text{ of recorded}}{\#\text{ of incident}}$$



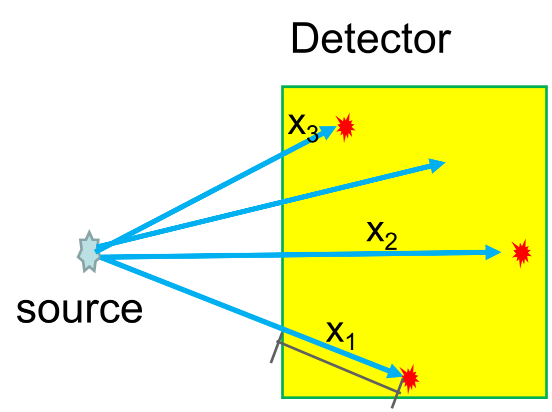
- Absolute efficiency depends on the detector geometry
- Intrinsic efficiency depends on the detector material and construction and interaction properties

$\epsilon_{int}(E)$ may also depend on geometry

$$\epsilon_{int}(E, x) = \epsilon_{int}(E)[1 - \exp(-x/\lambda)]$$

Complex setup requires simulation

Software:
MCNP, Geant4…



If x does not vary too much:

$$\epsilon_{abs} = \epsilon_{geo} \cdot \epsilon_{int}$$

ϵ_{geo}: geometric acceptance

$$\varepsilon_{geo} = \frac{\Omega}{4\pi} \leftrightarrow \Omega = 4\pi\, \varepsilon_{geo}$$

- Peak efficiency: accepted only interactions with full energy deposition

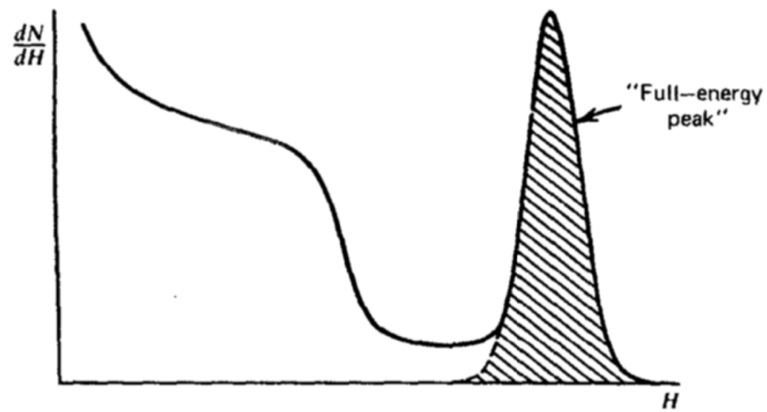
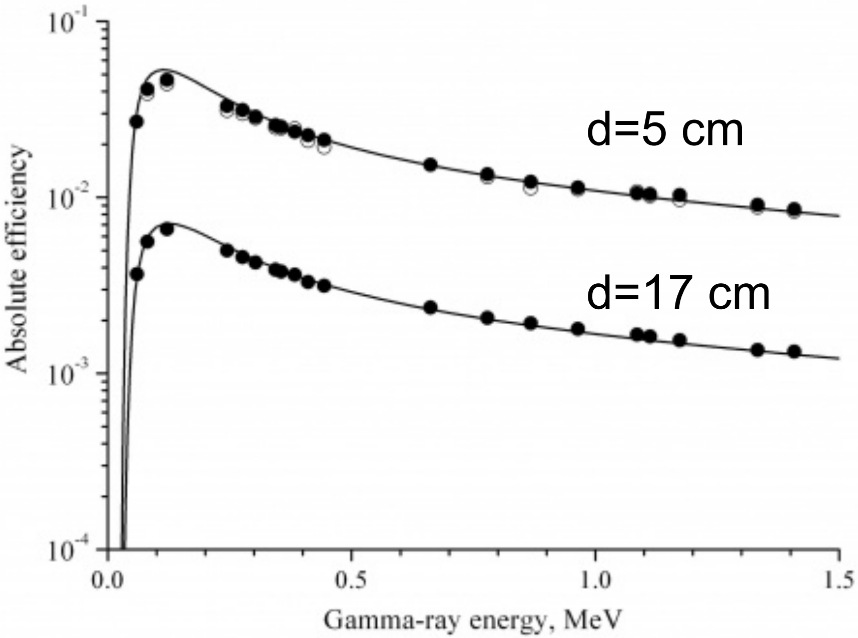


Figure : Full-energy peak in differential spectrum



gamma efficiencies for 5 cm and 17 cm distances between source and HpGe detector end cap

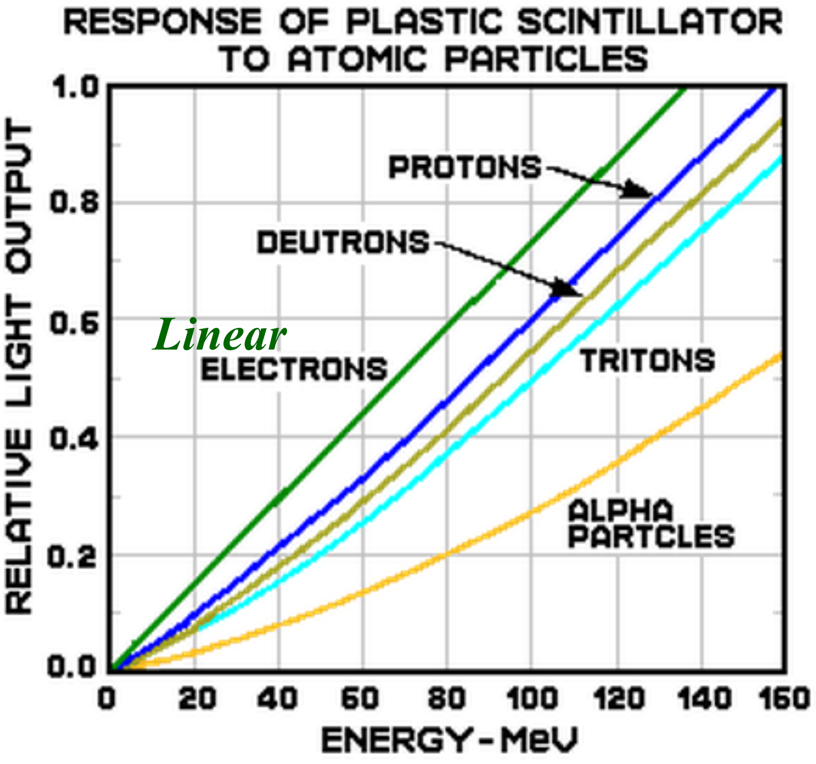
Detector Response

Detector response: the relation between the radiation energy and total charge or pulse height of the output signal.

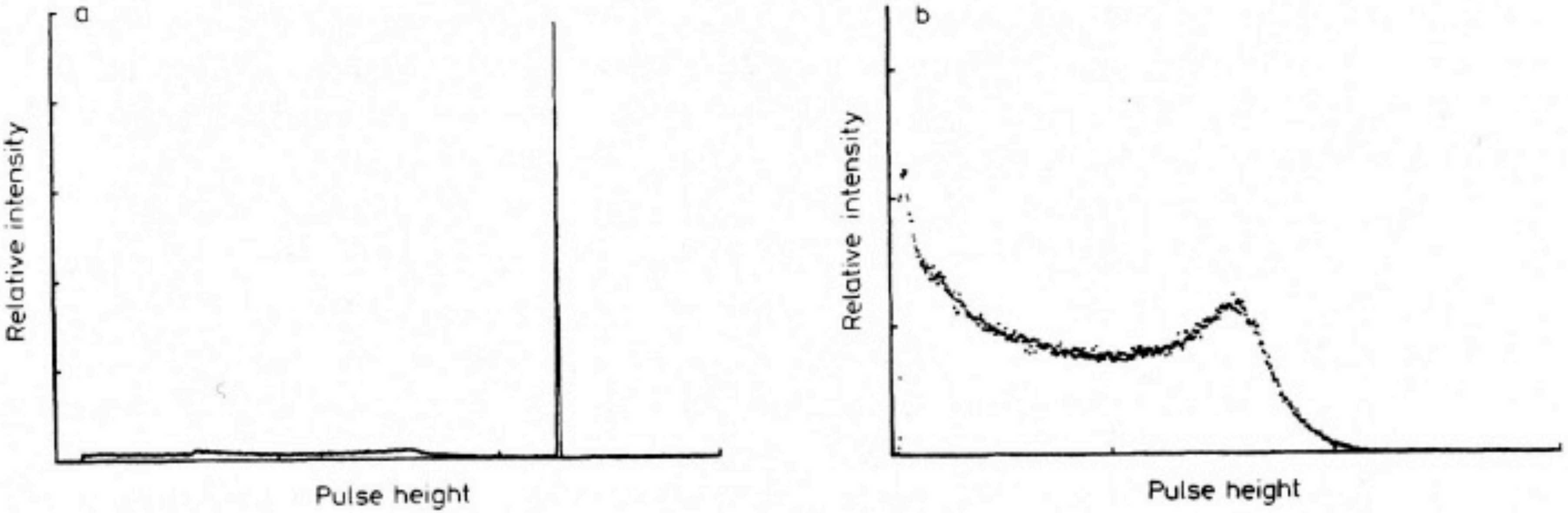
For many detectors, the response is approximately linear over a certain range of energies.

The resopnse is linear for one type of particle but not for others due to the different reaction machanisms which are triggerd in the medium by the different particles.

Function of the particle type and energy



Response function for a germanium detector and an organic scintillator detector for 661 keV gamma rays



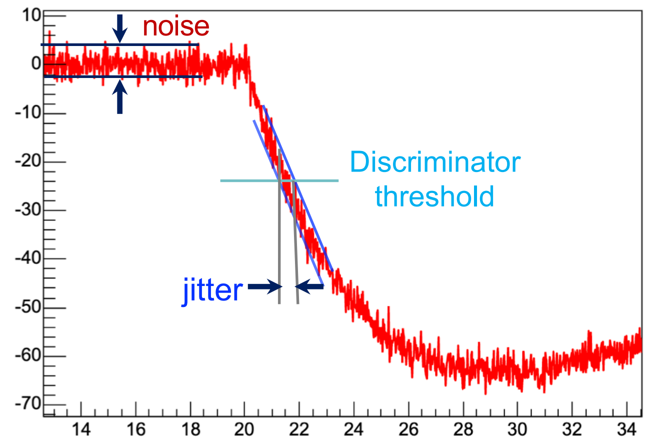
Response Time

The time which the detector takes to form the signal after the arrival of the radiation.

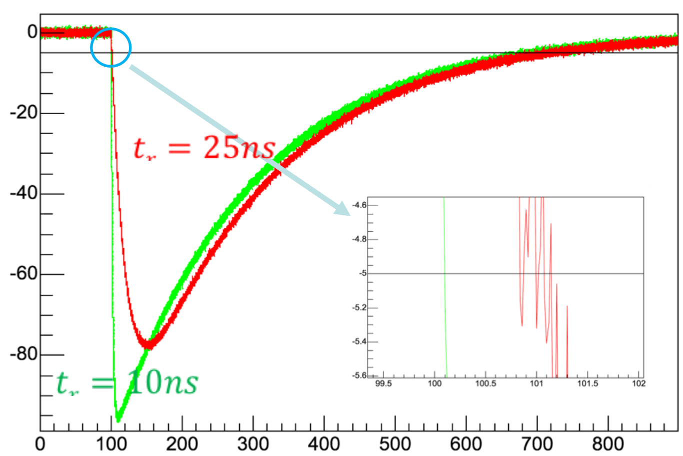
- Crutial to timing properties of the detector
- Signal quickly formed into a sharp pulse with a rising flank as close to vertical as possible. - More precise moment in time is marked by signal.

For timing, the figure of merit is not signal-to-noise, but slope-to-noise ratio

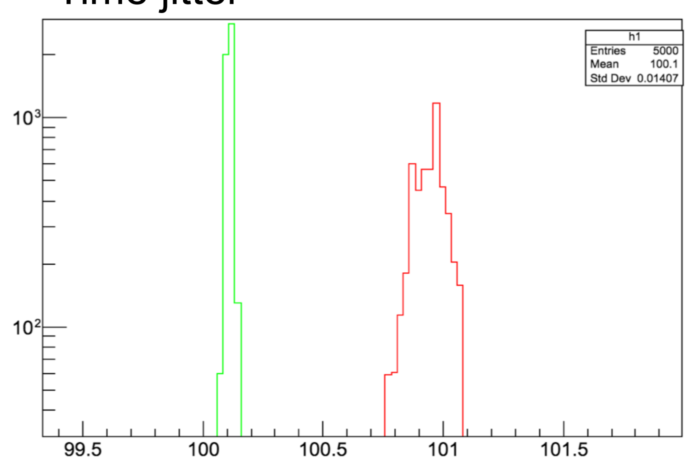
$$\sigma_t = \frac{\sigma_n}{\frac{dV}{dt}\Big|_{V_T}}$$



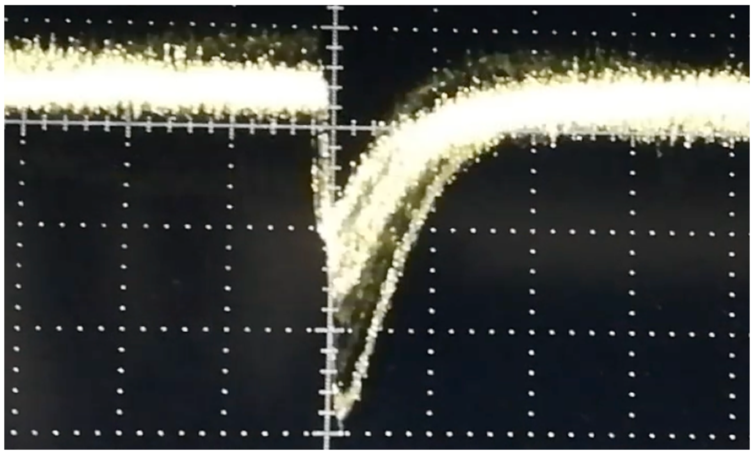
Pulses with different rise time



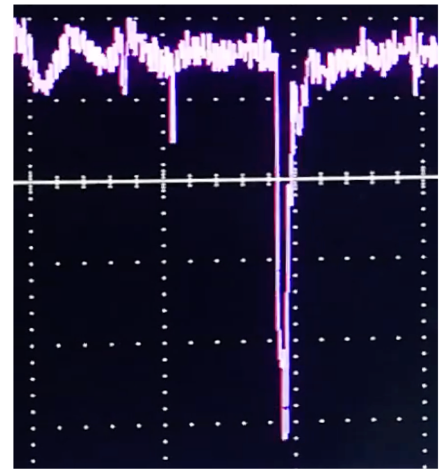
Time jitter



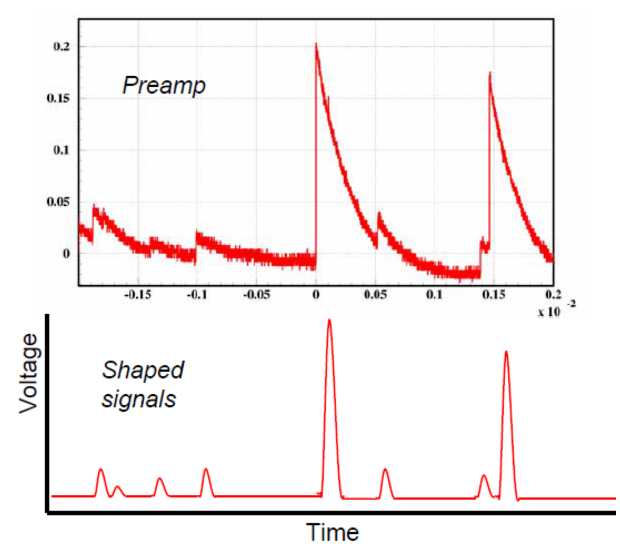
CsI $t_r = 200ns$



Plastic scintillator $t_r = 3ns$



- Duration of signal is also important
  - Second signal pile up on the first, second event can not be accepted.
  - Contributes to the DEAD TIME
    - -Limits the count rate



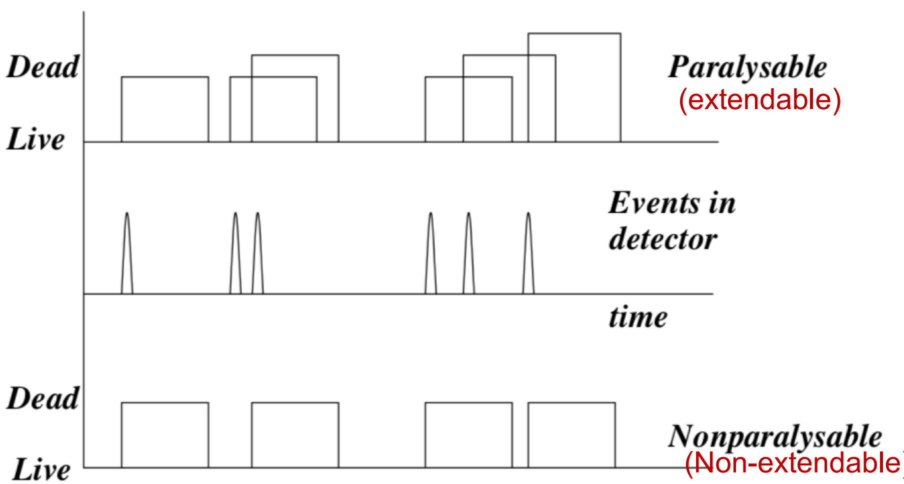
Dead time

The finite time required by a detector to process an event, during which no additional signal can be registered.

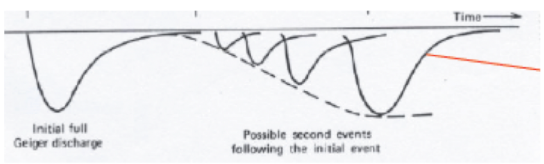
Dead Time Models:

a) Extendable – The same dead period τ is assumed to follow each true event that occurs during the live period. True events that occur during the dead period, although still not recorded as counts do further extend the dead period by τ following the lost event.

b) Non-extendable – A fixed dead period τ is assumed to follow each event that occurs during the `live period' of the detector. Real events that occur during the dead period are lost and have no effect whatsoever on the system behavior.



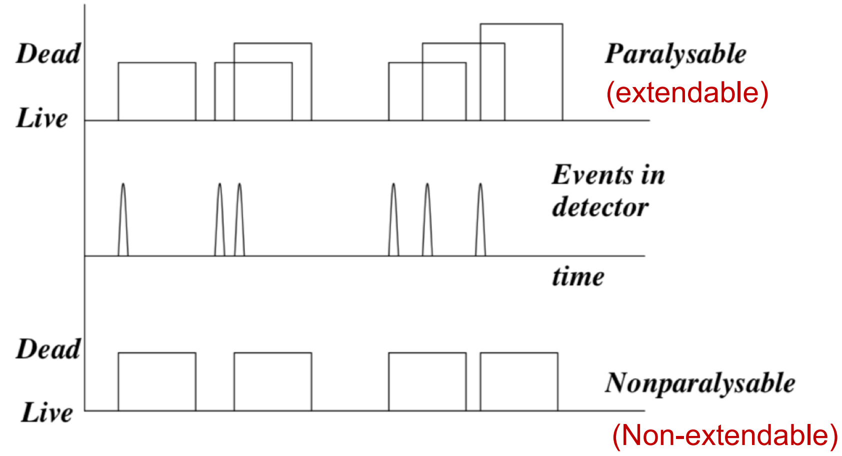
G.M counter



n=true interaction rate

m=recorded count rate

τ =system dead time



For the non-extendable case:

The fraction of all time that the detector is dead is simply the product $m\tau$.

Therefore, the rate at which true events are lost is $nm\tau$.

Therefore, the rate of loss is $n - m = nm\tau$

Solving for n gives $\mathbf{n = m/(1 - m\tau)}$

For the extendable case:

The distribution function for intervals between adjacent random events with rate n:

$$p(t) = n\ exp(-nt)$$

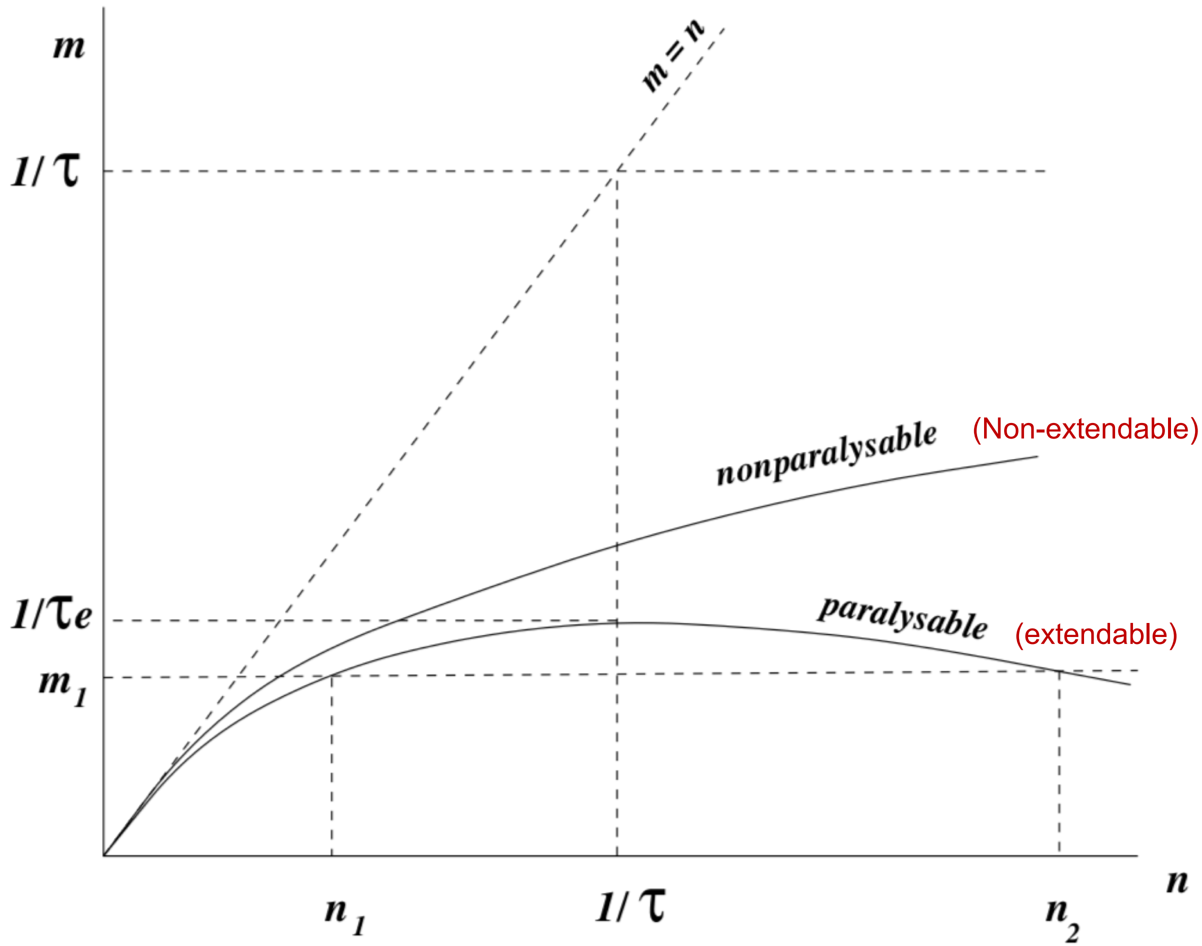
Only events arriving later than τ is recorded.

$$p(t > \tau) = \int_{\tau}^{\infty} p(t)dt = exp(-nt)$$

The rate of occurrence of such intervals is obtained by multiplying by the true rate n,

$$m = n\ e^{-n\tau}$$

Variation in the observed rate *m* versus true rate *n* for the two models of dead-time losses



For **extendable** systems the observed rate goes through a maximum!
Very high true interaction rates result in an extension of the dead period following an initial event, hence very few events are recorded!