Detectors for Ion Beam Analysis

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Outline

- Interaction of Heavy Particles with Matter
- Interaction of gamma –rays with Matter
- Detectors – General Aspects
- Semiconductors
- Scintillators
- Gaseous Detectors
- Timing Detectors

General Information

A **Detector** is any device that when radiation (particles, gamma rays, x-rays) interacts with it produces a measurable effect (e.x. ionization, light,..)

The characteristics of each detector (efficiency, resolution, e.tc.) depend on the type of ionization and associated electronics

Because of the differences of interaction of radiation with matter different detectors are needed for a complete IBA setup

Most commonly used detectors for IBA:

RBS – NRA : Charged particles – Surface Barrier Detectors
PIXE : X – rays – Si(Li) and SSD detectors
PIGE: Gamma – rays – Ge(Li), High Purity Germanium, NaI(Tl)
TOF – ERDA: Timing detectors + Ionization Chambers or Surface Barrier Detectors

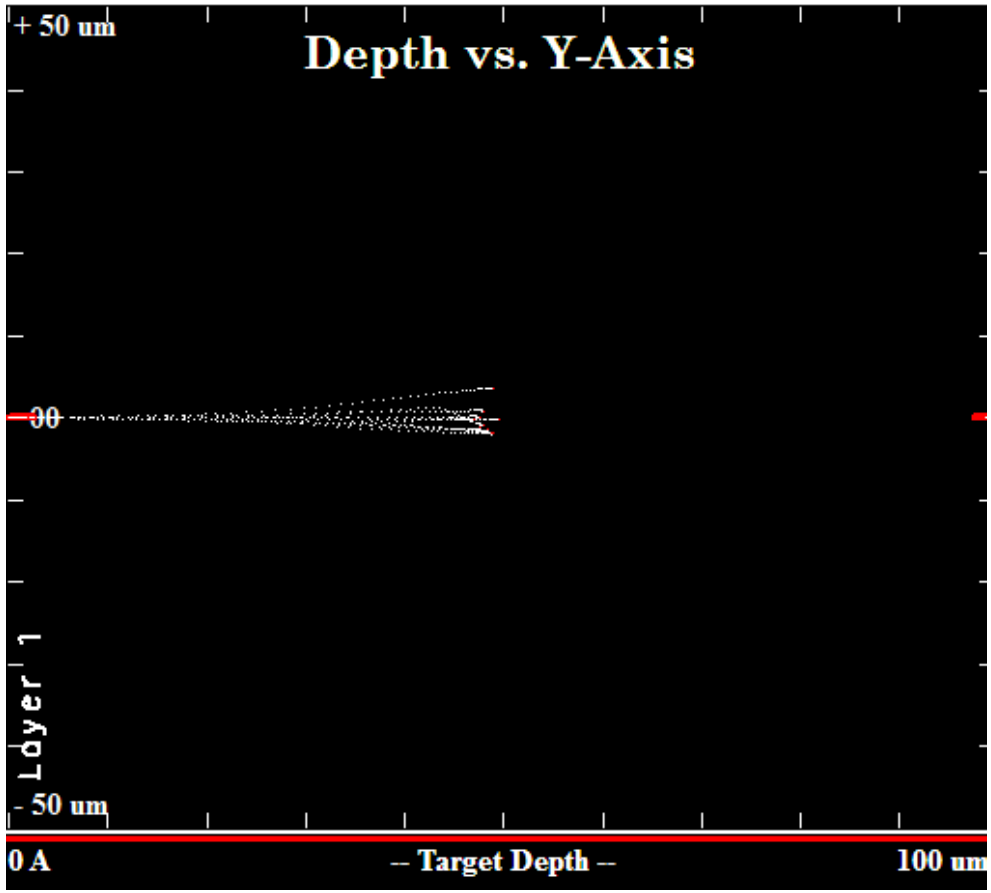
Interaction with Matter – Charged Particles

Charged particles → Loss of energy (stopping power)

Charged particles → Deflection from their initial trajectory

Processes of Energy Loss

- Inelastic collisions with atoms
- Elastic scattering from nuclei
- Cherenkov radiation
- Nuclear reactions with nuclei
- Bremsstrahlung



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Inelastic Collisions

Charged particle interacts with electrons of matter through the Coulomb interaction
Depending on the proximity the absorber atom may get excited or ionized.
The particle loses energy through this procedure.

The maximum energy transferred from 1 collision of a particle m with kinetic energy E is 4Em0/m or about 1/500 energy per nucleon
Multiple interactions are needed for a particle to loose all its energy

The inelastic collision are purely statistical BUT because of their number we can define an average energy loss per unit path length.
This is what we call Stopping Power dE/dx

Analytical description of inelastic collisions:

- Classical approach: Bohr's calculation
- Quantum approach: Bethe – Bloch formula

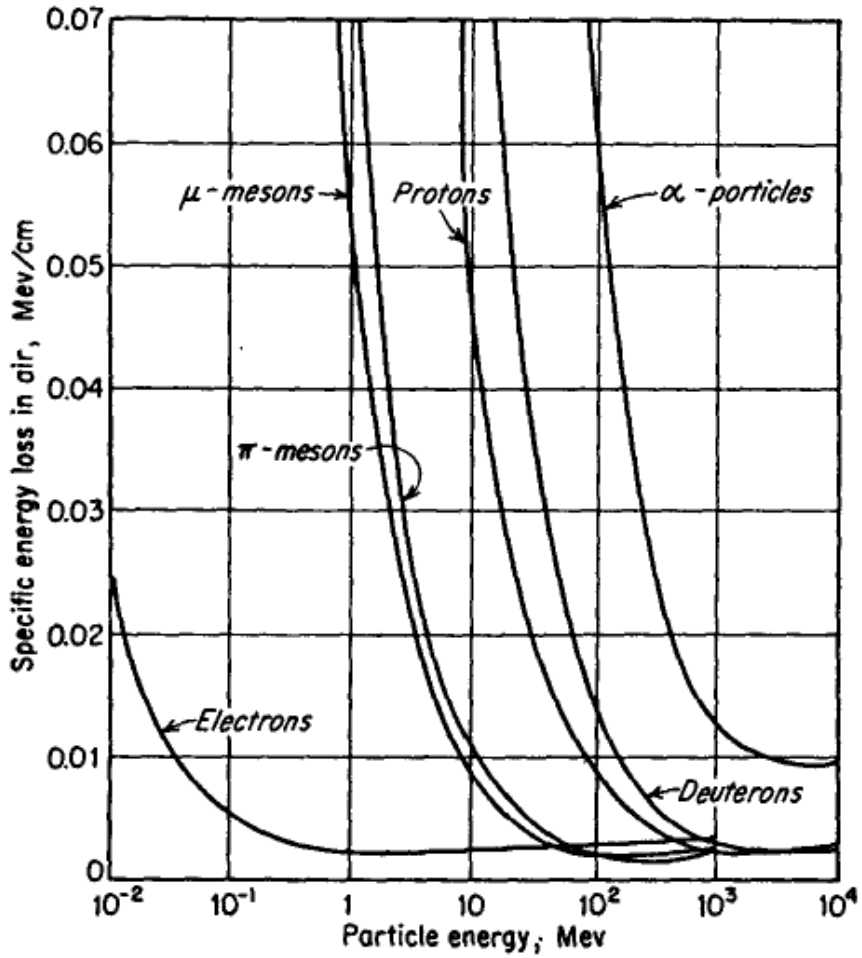
Inelastic Collisions

- Classical approach : Bohr's calculation

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2} N_c ln \frac{\gamma^2 m_e v^3}{z e^2 \bar{\nu}}$$

- Quantum approach: Bethe - Bloch

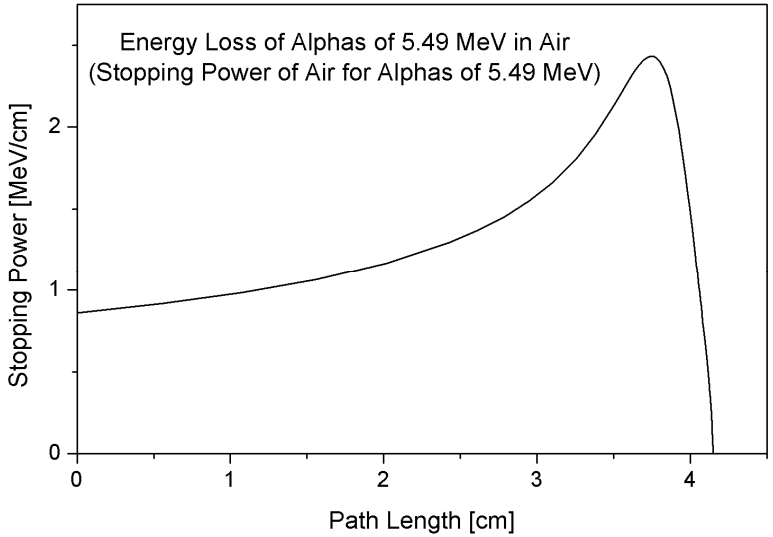
$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[ln\left(\frac{2m_e\gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right]$$

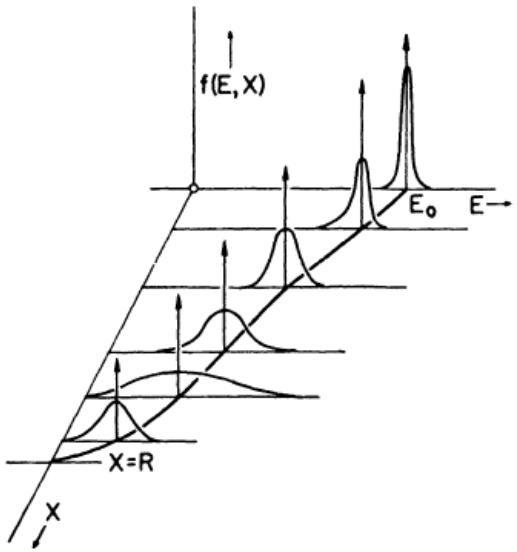


Additional Quantities

Bragg Curve:

The stopping power increases as the particle penetrates matter (energy of the particle decreases) giving a maximum peak and then goes to zero





Energy straggling:

As the particles penetrate matter the distribution of energies (assume Gaussian) is getting wider
The energy is no more well defined

Additional Quantities

Range:

The range is defined as the thickness of material necessary to decrease the intensity of the particles (beam) at one half

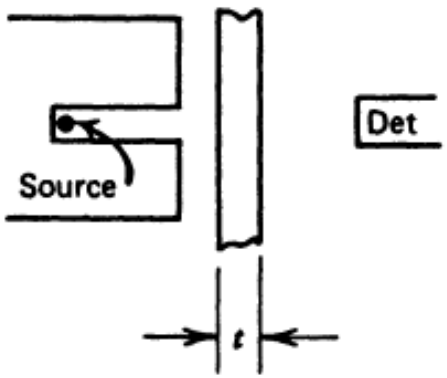
Extrapolated Range:

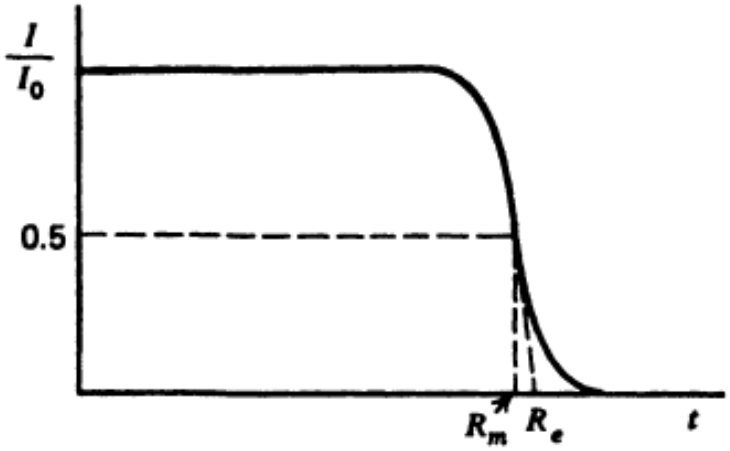
The range is defined as the thickness of material necessary to stop particles (beam)

– In other words how far the particles travel

Range straggling and Angular straggling:

The same manner as the energy straggling works Range and Angle (assuming a well defined direction of the particles) have a statistical distribution





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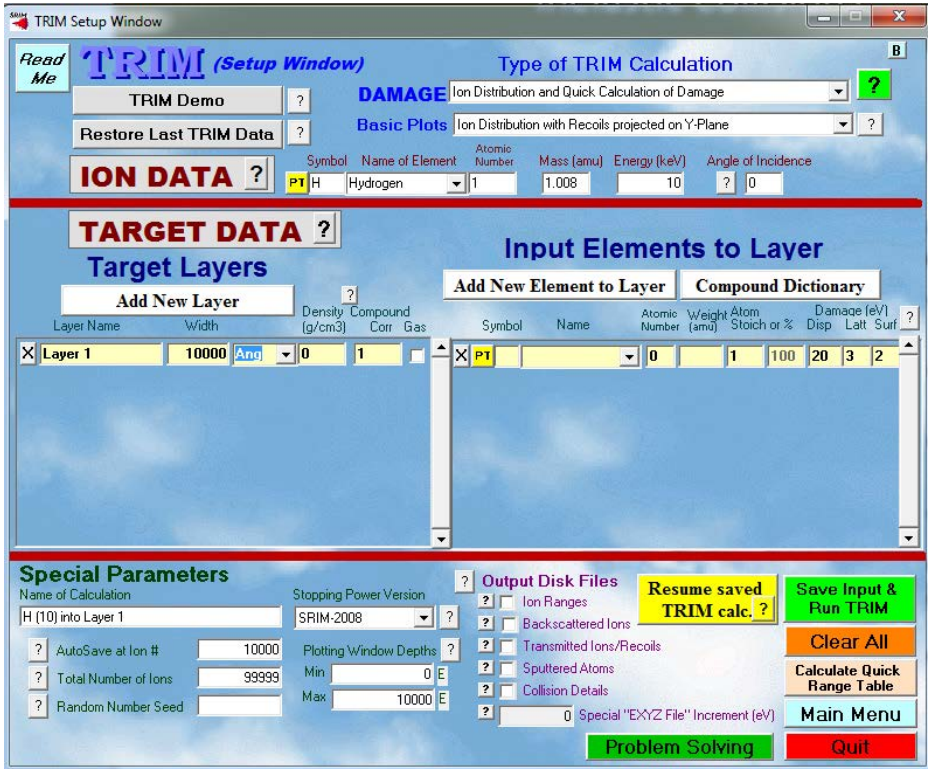
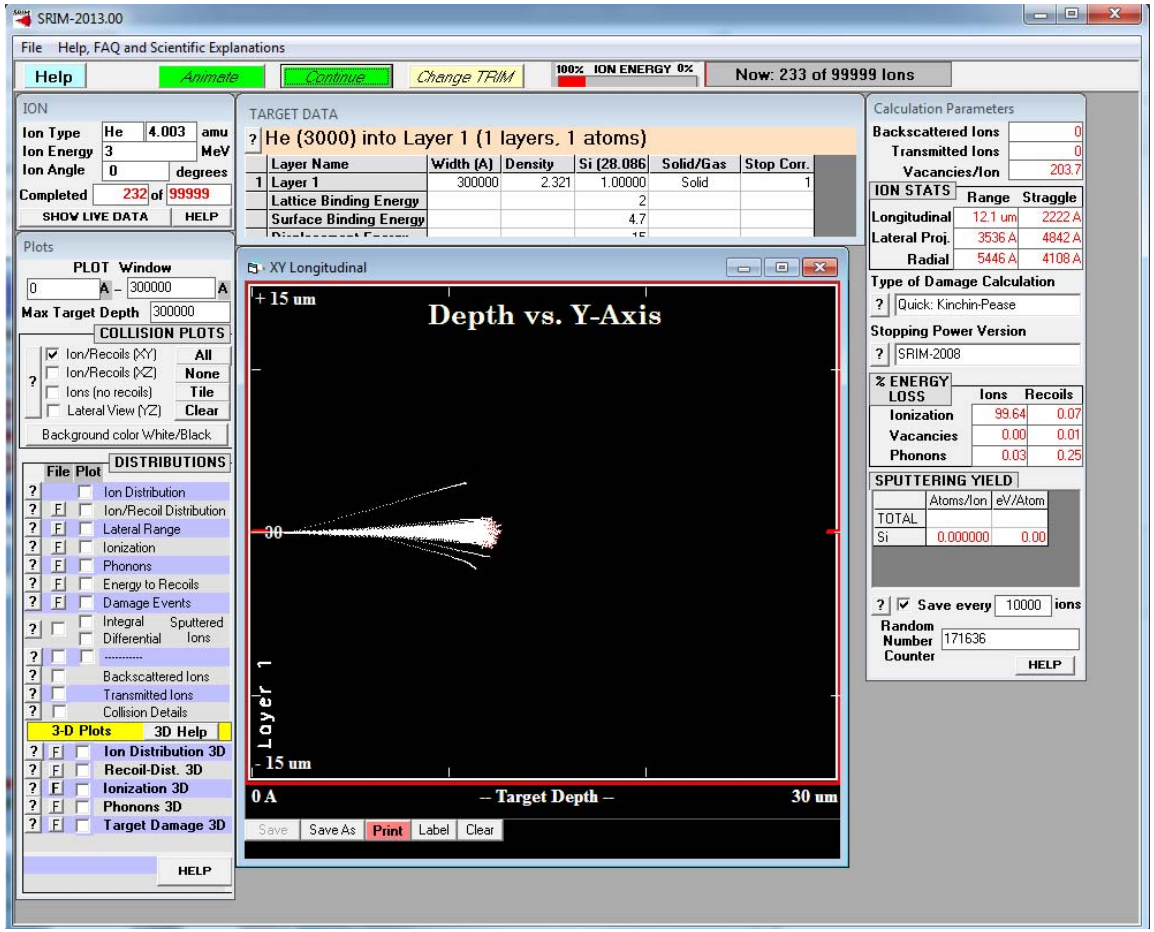
Energy loss tools

Nowadays SRIM is the most common tool to perform energy loss calculations





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Interaction with Matter – Photons

Processes of interaction between photons (gamma – rays) and matter

- Photoelectric Absorption

Energy of the photoelectron

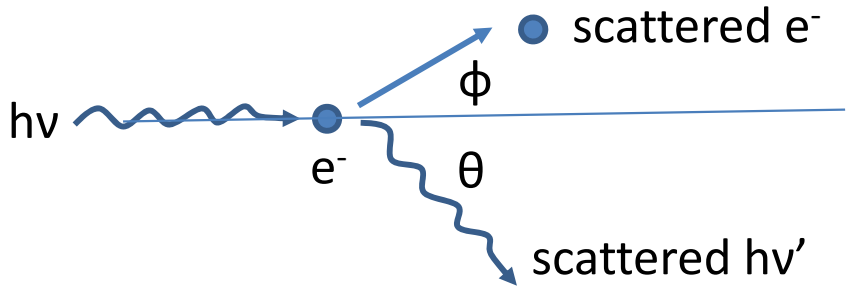
$$E_{e^-} = h\nu - E_b$$

where Eb is its binding energy

Probability: $$\tau \cong \frac{Z^n}{E_\gamma^{3.5}}$$

n varies between 4 and 5 depending on the energy

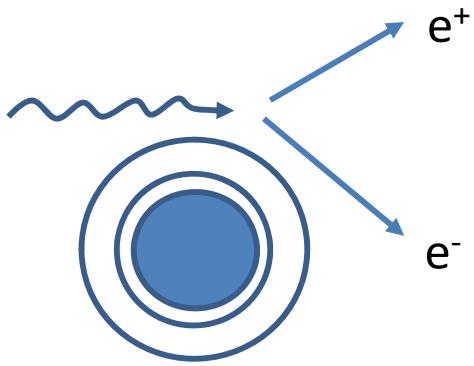
- Compton Scattering



$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0 c^2}(1 - cos\theta)}$$

- Pair Production

When Eγ > 1022 MeV



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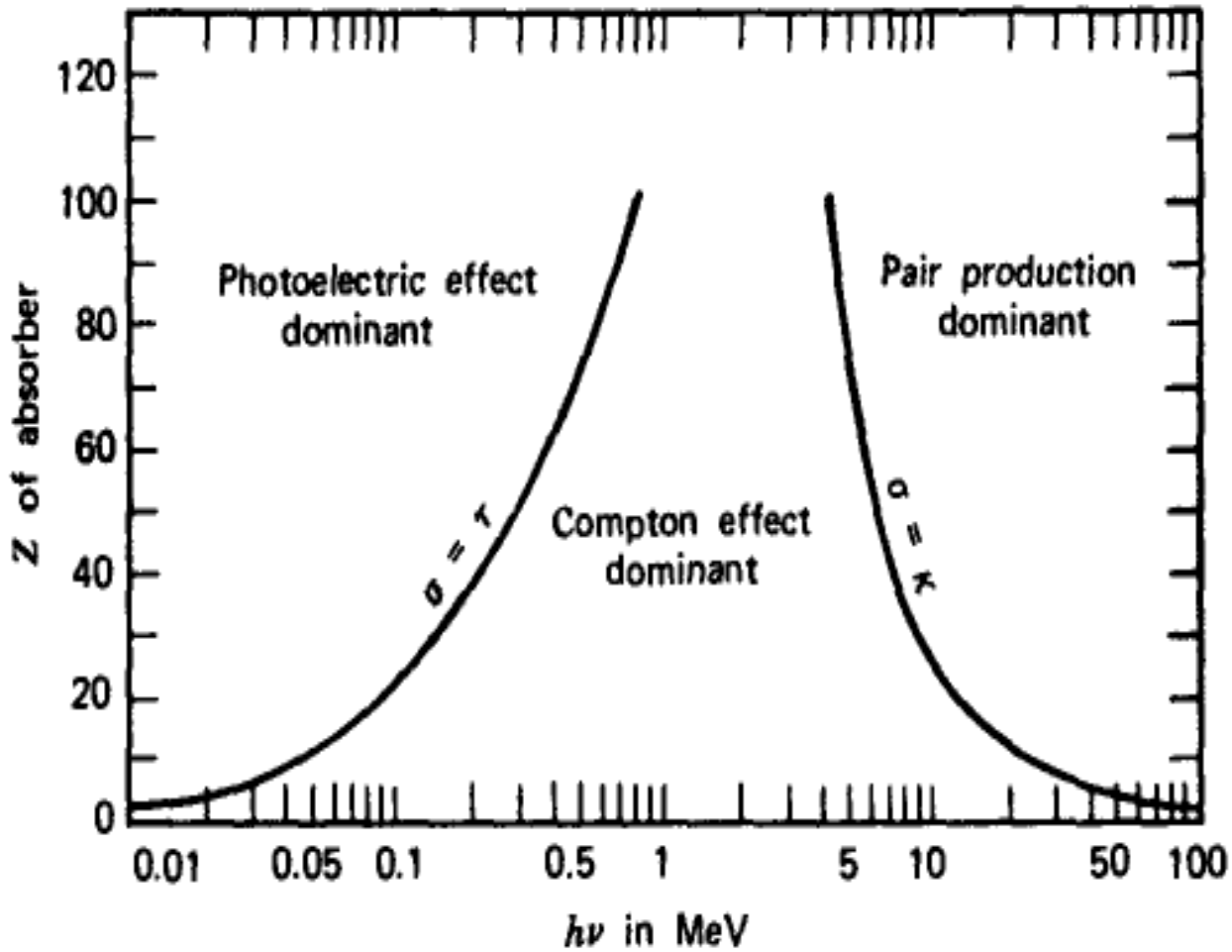
Probabilities



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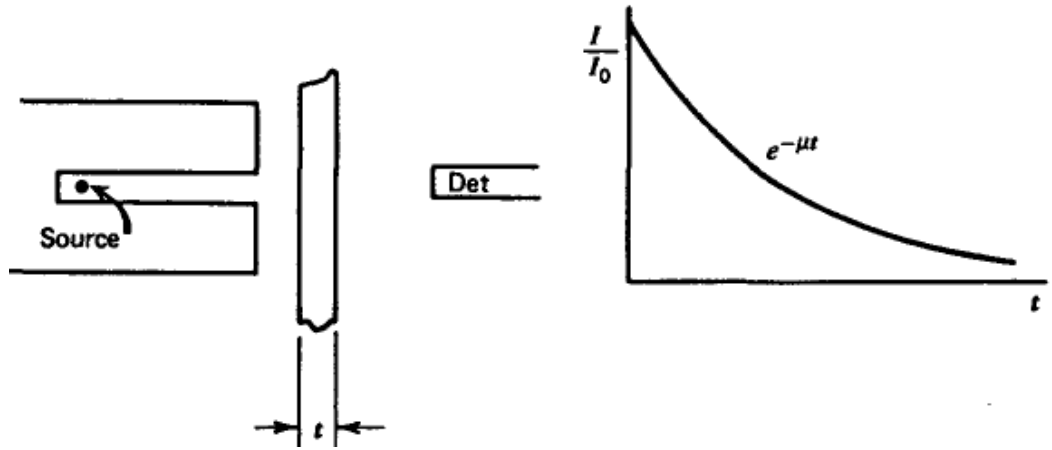
Additional Quantities

Linear attenuation coefficient

$$\mu = \tau(photoelectric) + \sigma\ (Compton) + \kappa\ (pair\ production)$$

$$\frac{I}{I_0} = e^{-\mu x}$$



Mean free path

Average distance before an interaction takes place

$$\lambda = \frac{\int_0^\infty x e^{-\mu x} dx}{\int_0^\infty e^{-\mu x} dx} = \frac{1}{\mu}$$

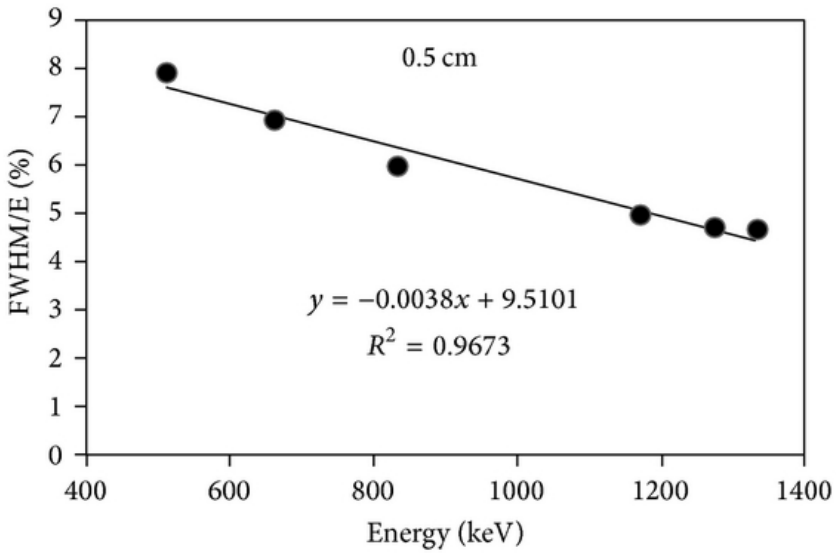
General Characteristics

Energy Resolution

Ability to distinguish between two events with different energy

Particle detectors : Energy resolution depends from the particle detected
common values 13-15 keV for α – particles of 5.4 MeV

Gamma detectors : Energy resolution depends on the energy of the gamma
Can be given as a value at a certain energy or as percentage
typical values 2.6 keV @ 1332 keV for Germanium detectors
7% @ 661 keV for NaI detectors



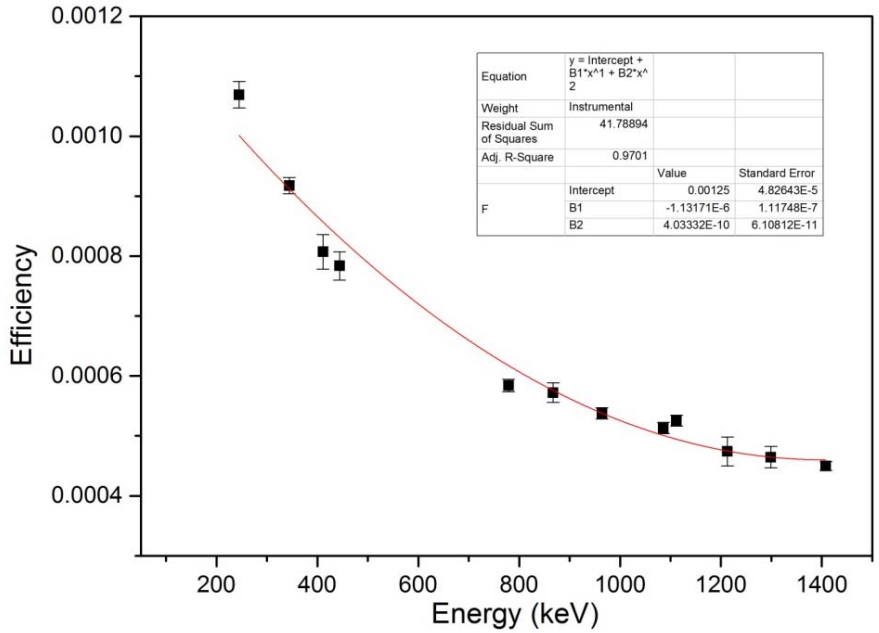
General Characteristics

Detection Efficiency

Ability to detect radiation

Particle detectors : 100 % in most of the cases independent of particle type

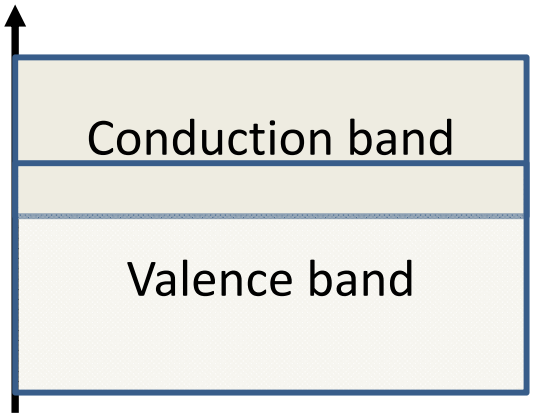
Gamma detectors : Efficiency depends on the energy of the gamma
(in most applications solid angle is incorporated)
Relative efficiency (%) with respect to NaI detectors



Semiconductors

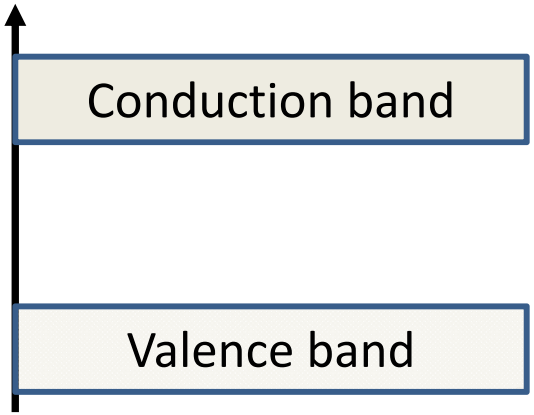
Radiation ionizes matter. The question is
Can we distinguish (collect) pairs of electron – holes in matter ?

Conductors



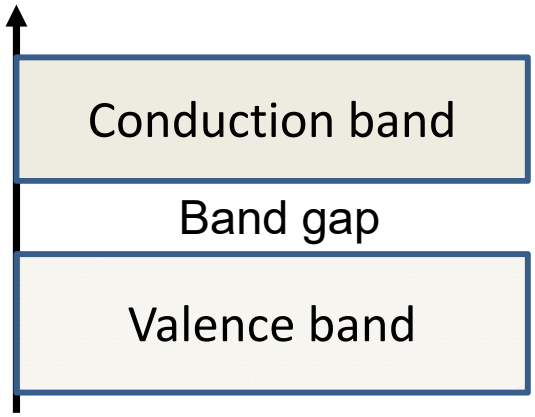
Free electrons
in room temperature
With external voltage

Insulators



No electrons
in room temperature
Or with external voltage

Semiconductors

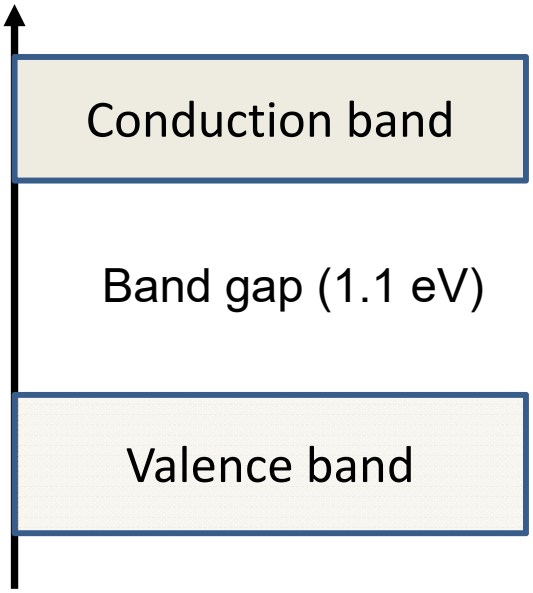


Some free electrons
in room temperature or
with external voltage

	E_{gap}
Si	1.12 eV
Ge	0.66 eV

Types of Semiconductors

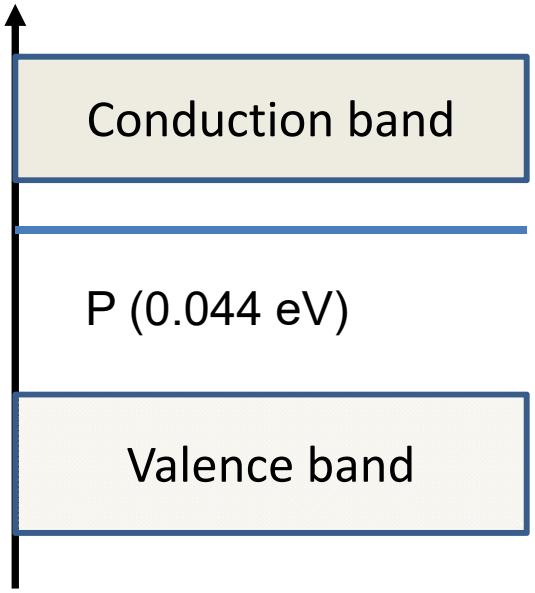
Intrinsic (Pure)



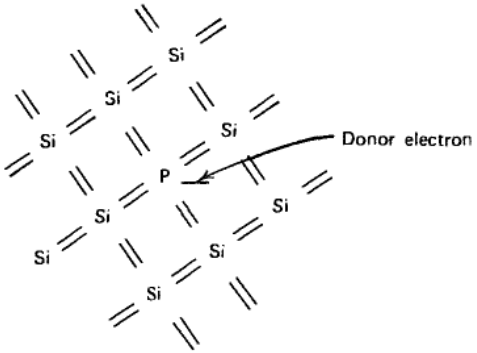
$N_{elec} = N_{holes}$

Question:
Is there a way to increase number of holes or electrons ?

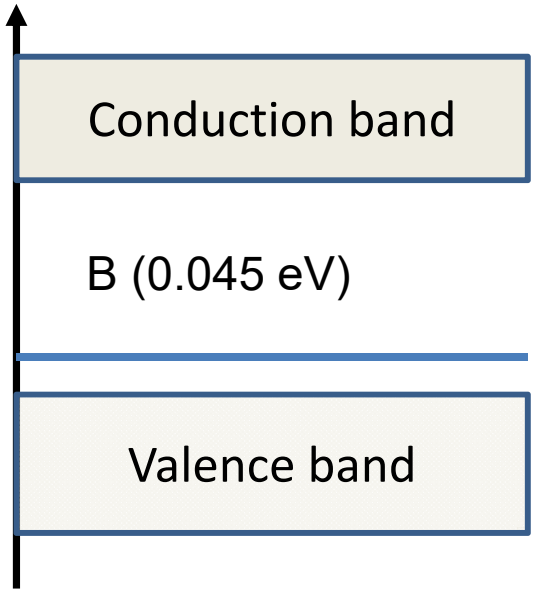
n - type



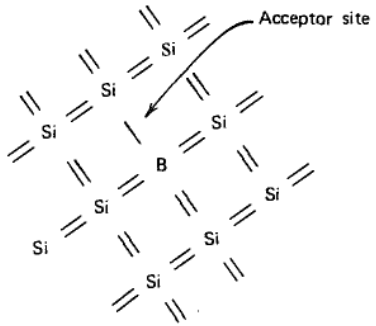
Add Donors



p - type



Add Acceptors

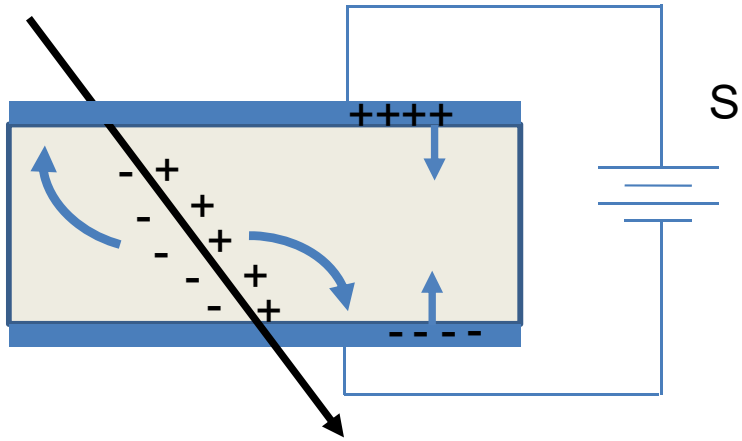


Semiconductors as Detectors

Ohmic Plate

Semiconductor

Ohmic Plate



Silicon typical resistivity 50.000 Ω cm

Consider 1 cm2 slab
Resistivity 5000 Ω

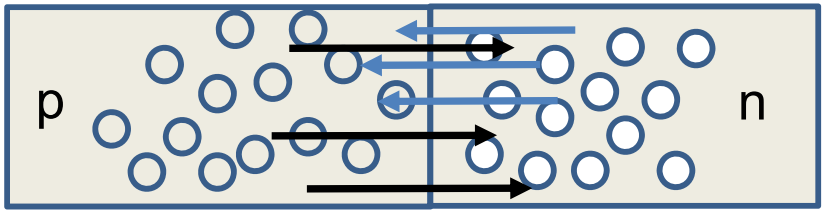
Problem: If we apply 500 V leakage current 0.1 A
Radiation will produce 105 carriers i.e. 1 μA. Impossible to be detected

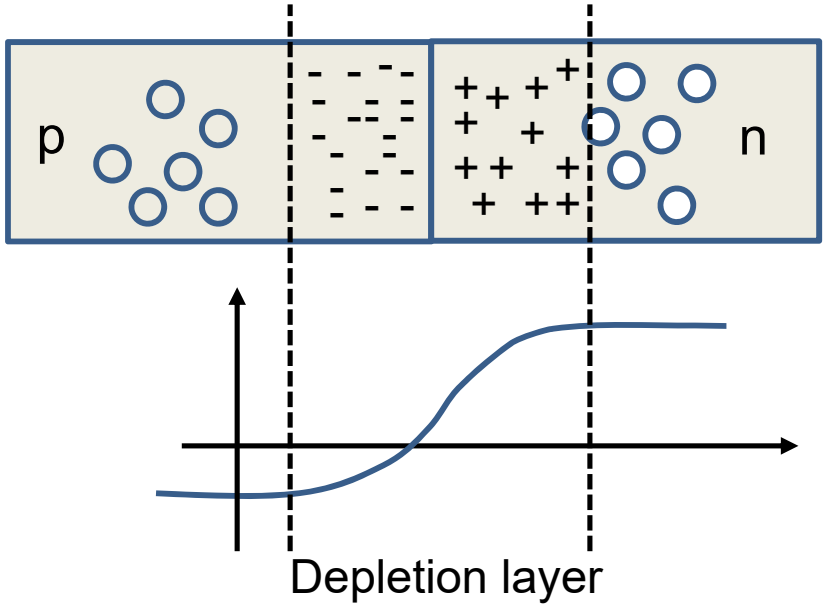
Solution: non - injecting or blocking electrodes p – n semiconductor detectors
The doped surfaces will act as blocking electrodes

Types of realization

- Diffused junction detectors
- Surface Barrier detectors
- p – i – n detectors
- High purity detectors

p – n Junction

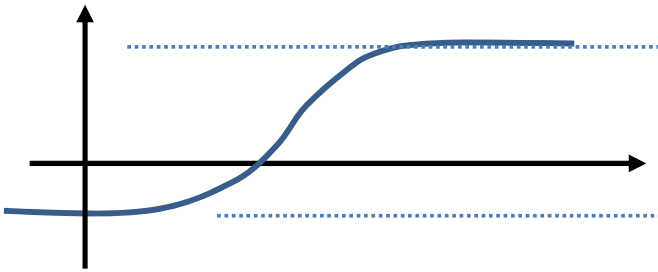




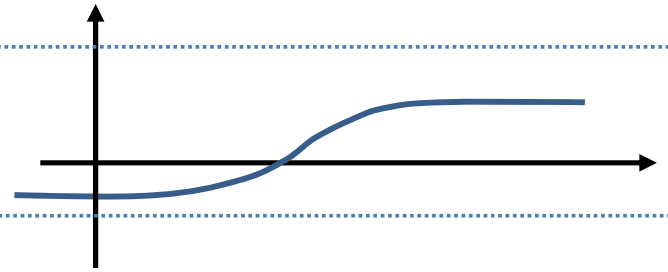
Electrons diffuse towards the p side
Holes diffuse towards the n side

As charge is accumulated an electric field is created that embeds the further diffusion of carriers

Unbiased

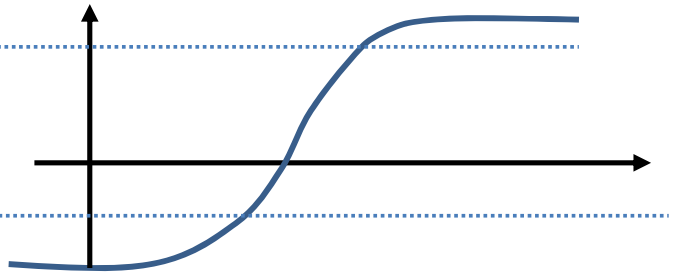


Forward biasing



Narrow Depletion layer

Inverse biasing



Wider Depletion layer

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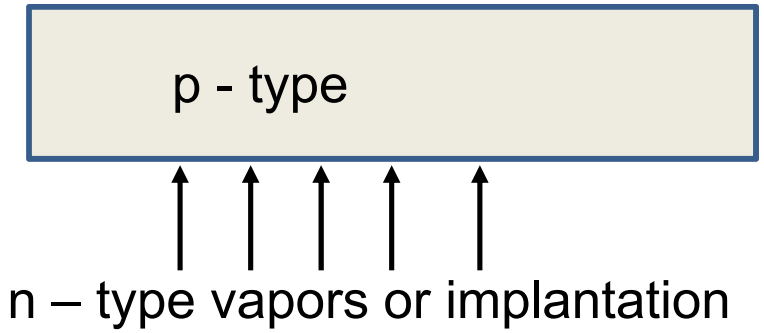
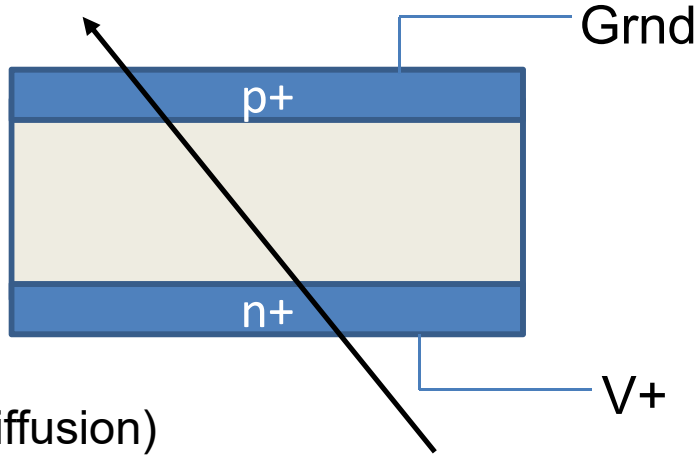
Diffusion junction and SSB detectors

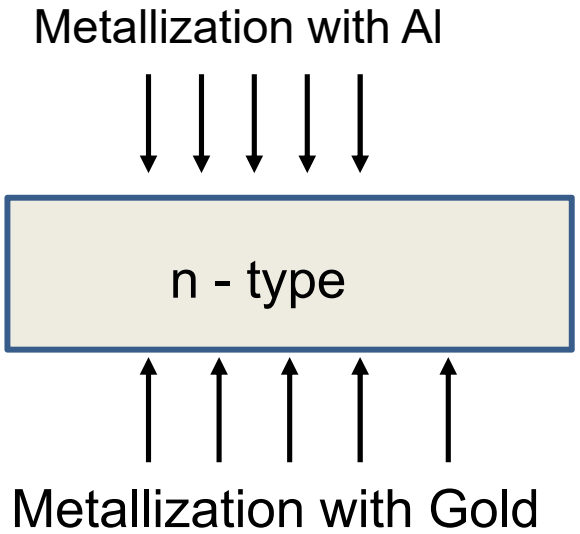




Depletion layers between 50 nm (implantation)up to 2 μm (diffusion)

n+ side acts as a dead layer Energy is lost and low energy particles not detected

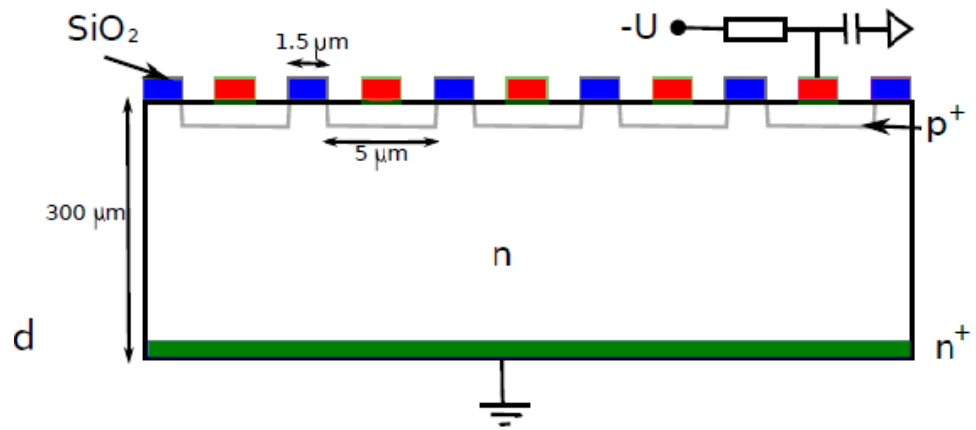
Surface Barrier Detectors

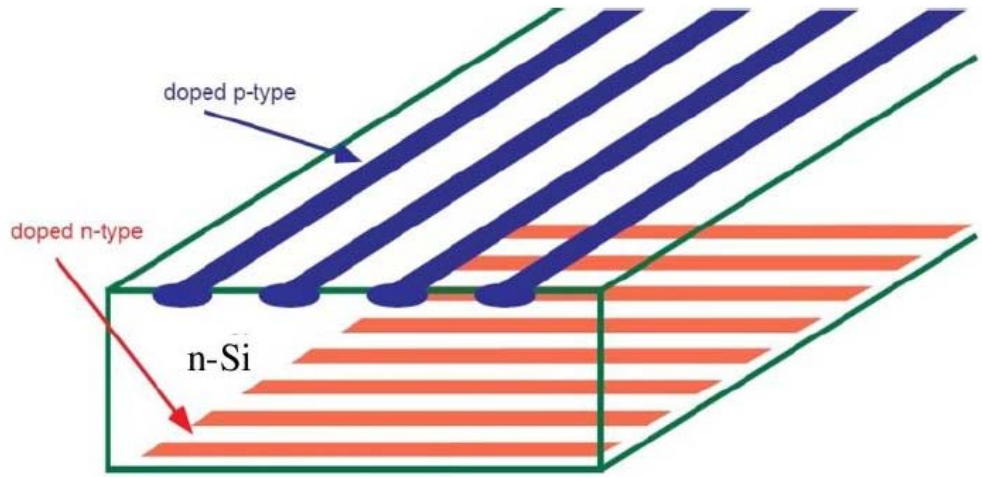


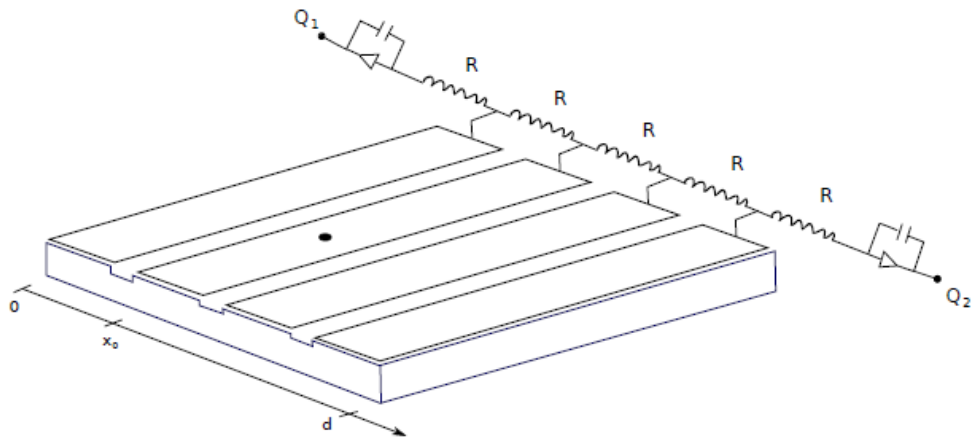
Electrons diffuse into metals.
A junction must alike the p-n junction is formed

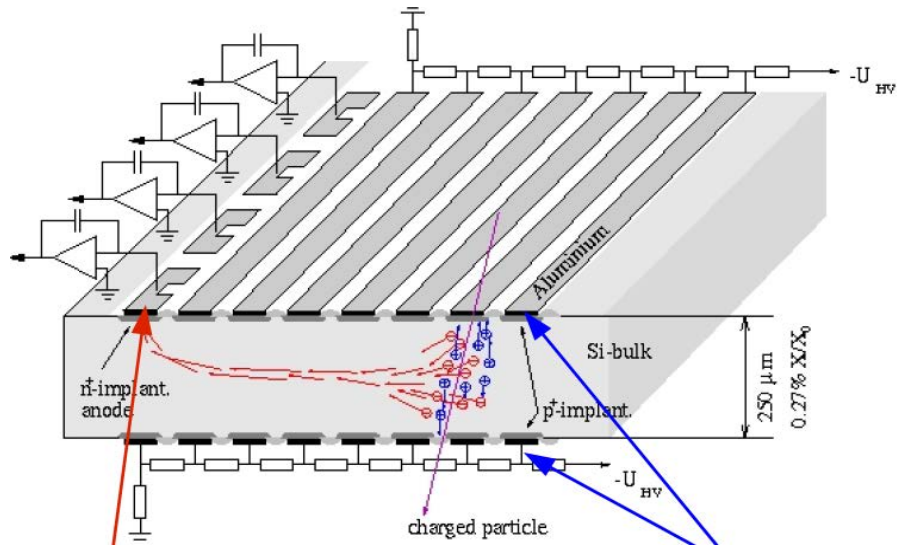
Depletion layers up to several mm
Thin entrance window
Sensitive to light

Position Sensitive Detectors









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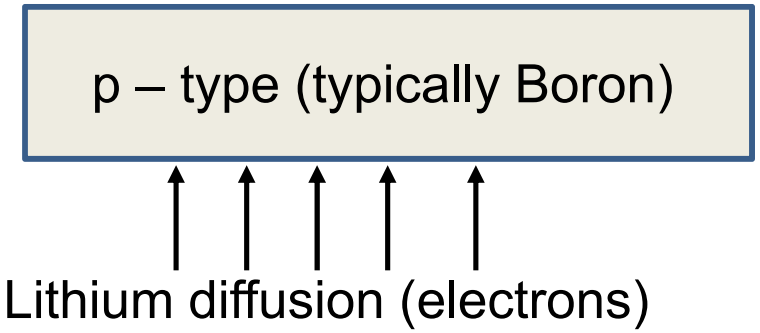
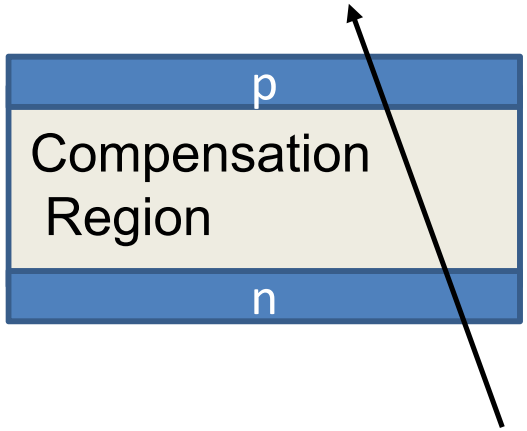
p – i – n Detectors





Typical detectors Ge(Li) and Si (Li)

Ideal for gamma and x-ray detection

Depletion layer up to mm

Germanium due to the photo-electric effect better for gamma – rays
Silicon used for x – ray detection

Low efficiency with respect to Scintillators
Better resolution

Should be always kept in liquid Nitrogen temperature (even when they are not used) to avoid drifting of Lithium. Can be easily destroyed

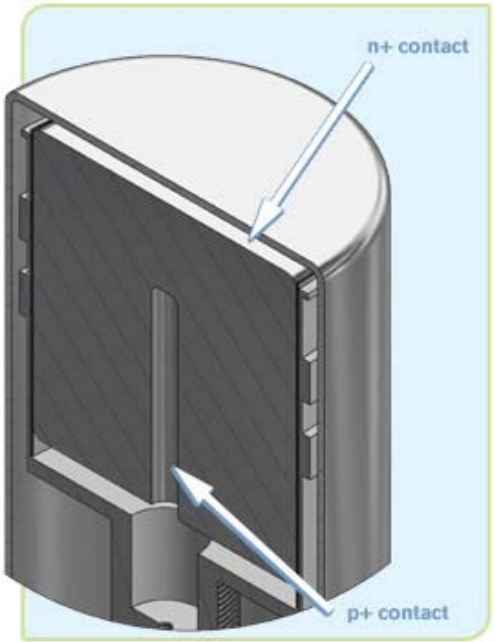
HPGe - Geometries

The idea is the same as compensated detectors.
The compensation region is achieved through Multiple purification processes.

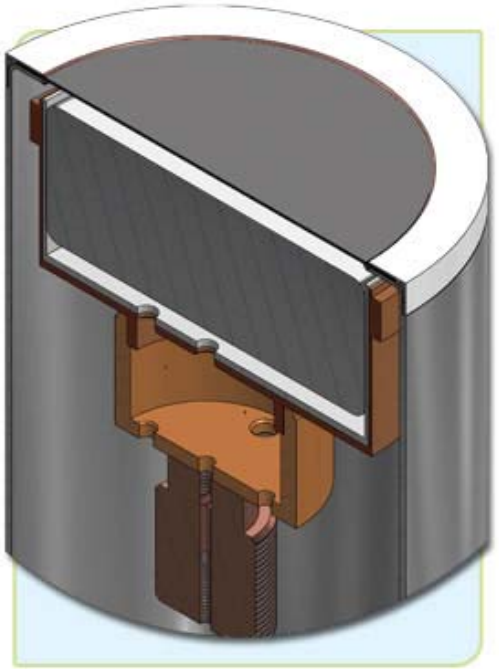
Same characteristics as Ge(Li) but need Liquid Nitrogen only when in use
(noise because of thermal excitation is greater than in silicon – smaller gap)

Coaxial

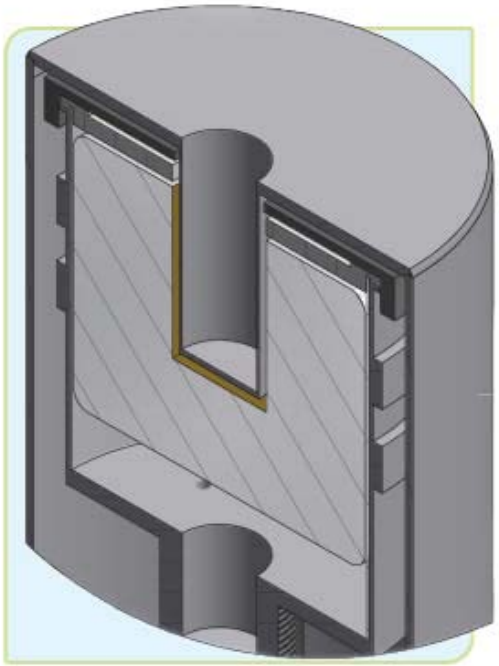
Images from Canberra brochures



Planar

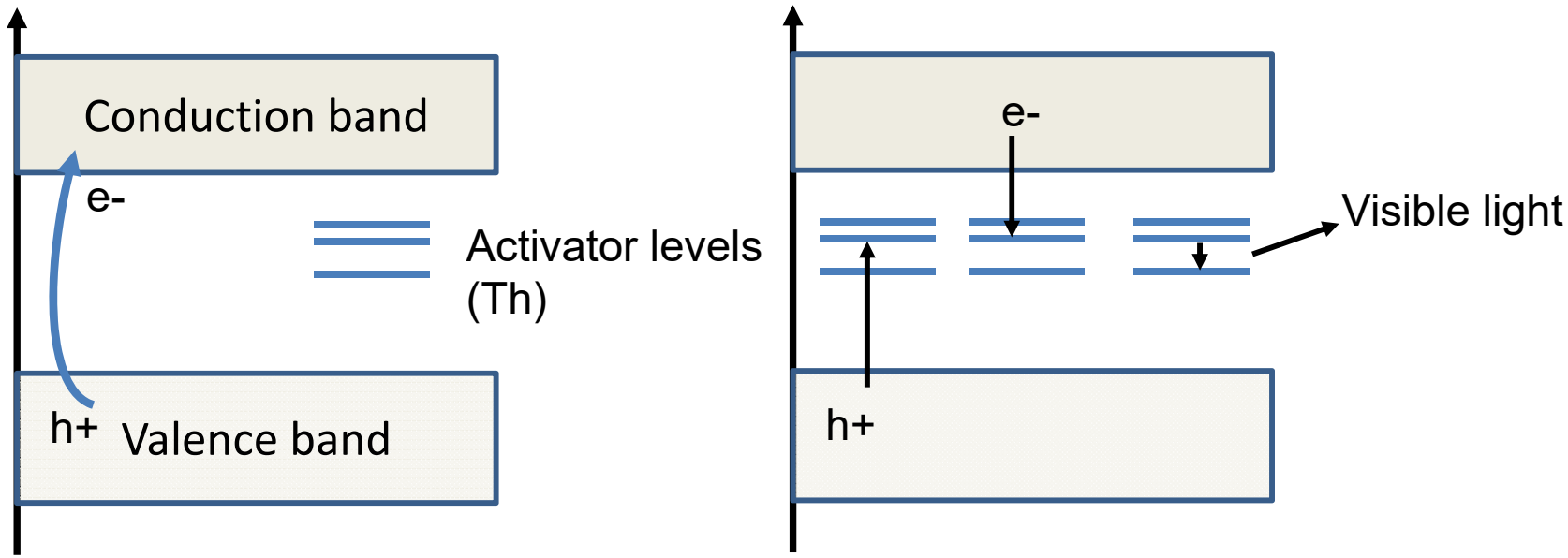


Well



Scintillators

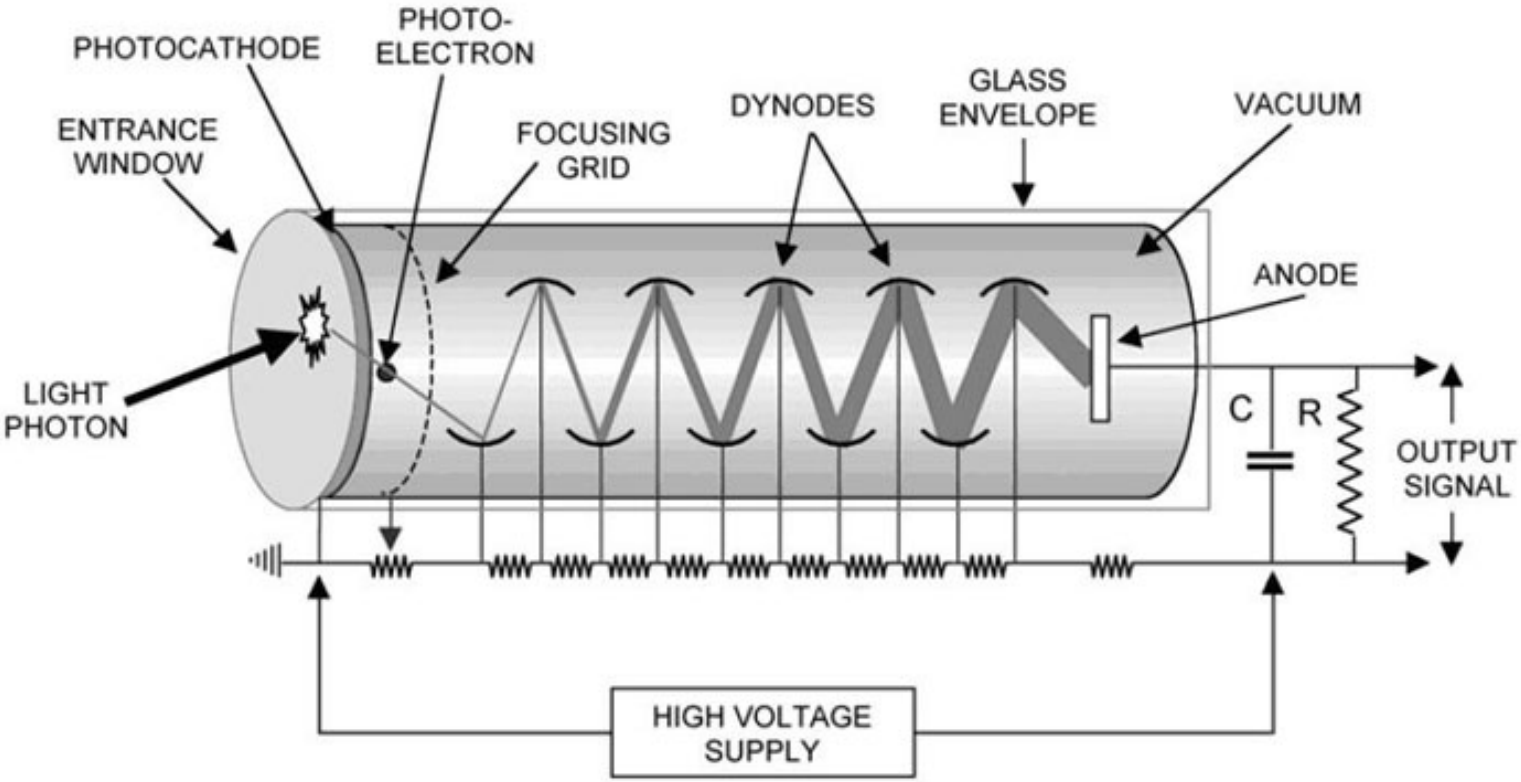
Scintillators can be Organic (also liquid) or Inorganic
In Ion Beam Analysis Inorganic are mostly used (NaI, LaBr, CrBr,…)



The e and h propagate either separately or as an exciton.
The h ionizes the activator and the e fills the gap
De-excitation produces visible light

Photomultipliers

Visible light must be translated into current



Scintillators

Scintillators are highly efficient
Robust with no external cooling
Hydroscopic (enclosed in aluminum cases)
Bad resolution

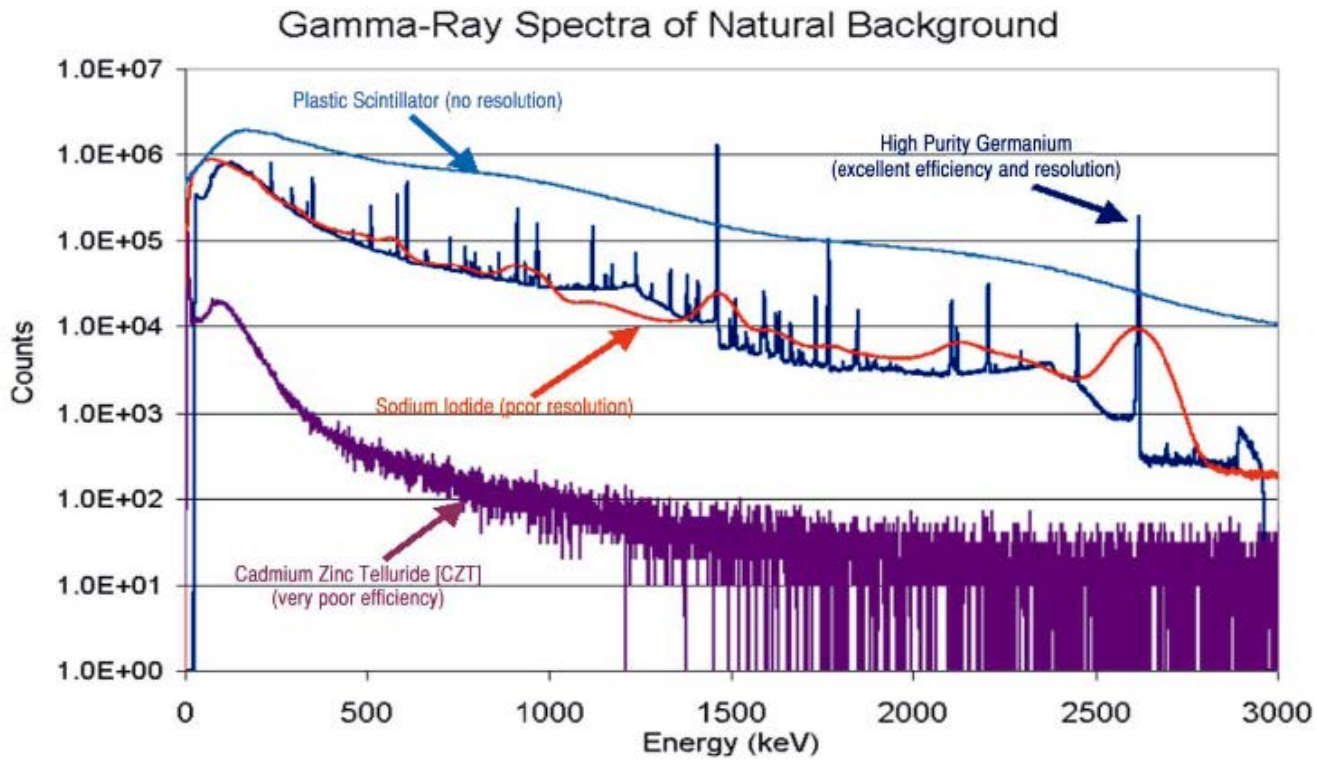
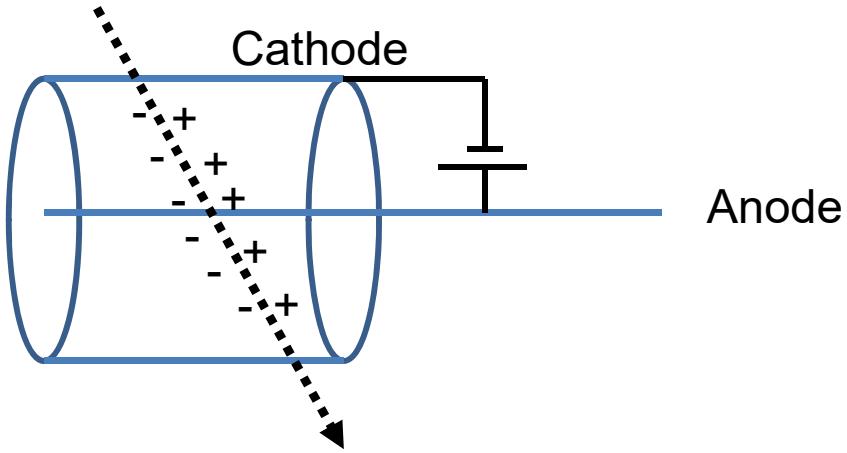


Image taken from Ortec White Paper: Why High-Purity Germanium (HPGe) Radiation Detection Technology is Superior to Other Detector Technologies for Isotope Identification

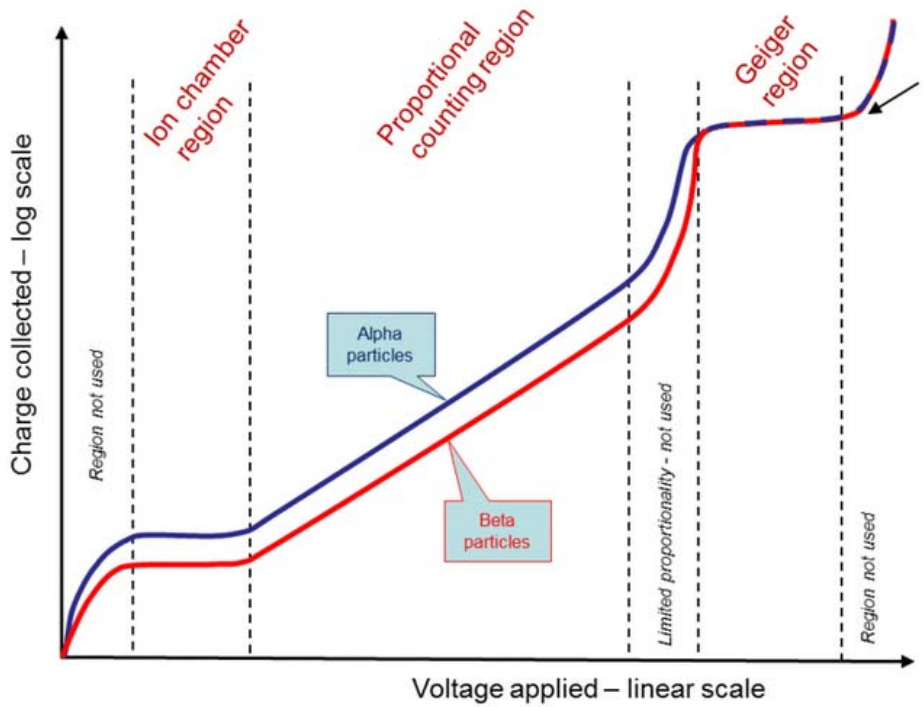
Gas Detectors

Oldest and Simplest detectors



Electrons are drifted towards the anode where they are collected

Voltage selection (and shape) depends on:
Type of detector

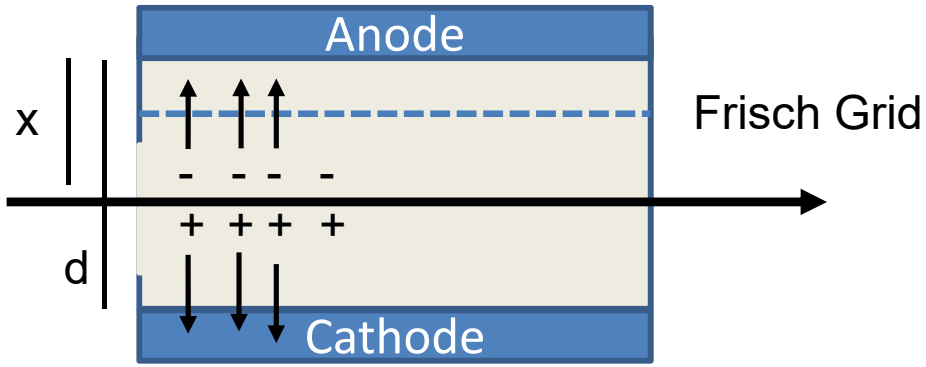


Gas selection depends on:
Radiation to be detected
Number of pairs to be created
Stopping powers (also pressure)

Minimum-ionizing particles (Sauli. IEEE+NSS 2002)

GAS (STP)	Helium	Argon	Xenon	CH_4	DME
dE/dx (keV/cm)	0.32	2.4	6.7	1.5	3.9
n (ion pairs/cm)	6	25	44	16	55

Ion Chamber Detectors



Electrons are drifted towards the anode where they are collected

They also induce current at the anode

Ions (much slower) are drifted towards the cathode but induce current at the anode (too)

Signal induced

$$V = \frac{n_0 e}{C}\frac{x}{d}$$

Where C is the Capacitance of the chamber

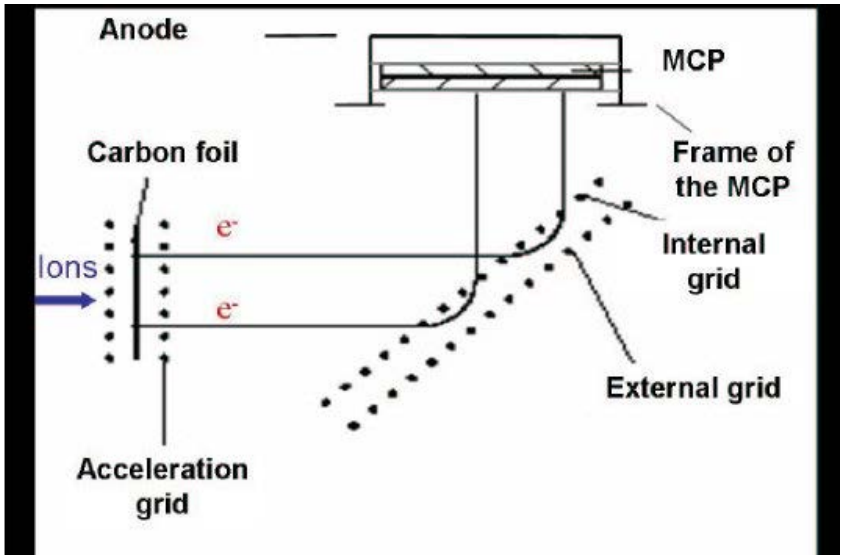
Problem:
The signal is position dependent

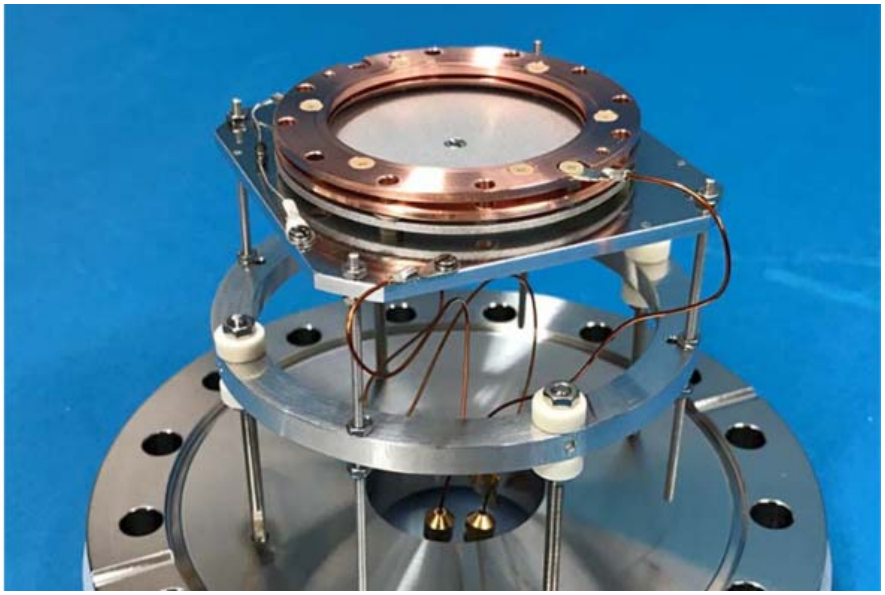
Solution: Frisch Grid

The anode "sees" the electrons after they pass the grid
It is "blind" to the movement of ions

BUT the Frisch Grid must be transparent (depends on construction)

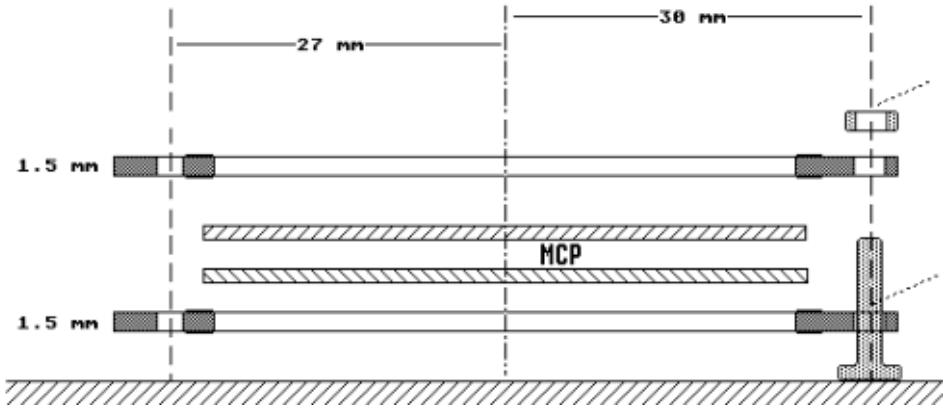
Timing Detectors





Electrons are produced as the ions pass the carbon foil.
They are accelerated towards an electrostatic mirror where they bend and are detected by an MCP detector
Multi Channel Plates act as multiplication and electron detection devices. Very fast signal acting as Timing detectors

Commonly a Chevron configuration is used



Images from Roentdek brochures

Questions ?

Thank you !