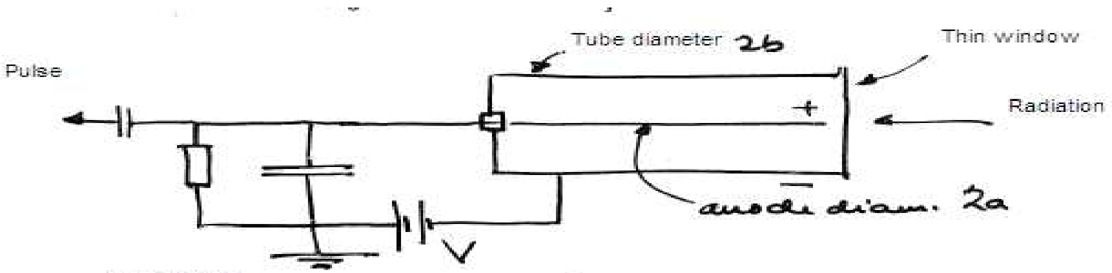
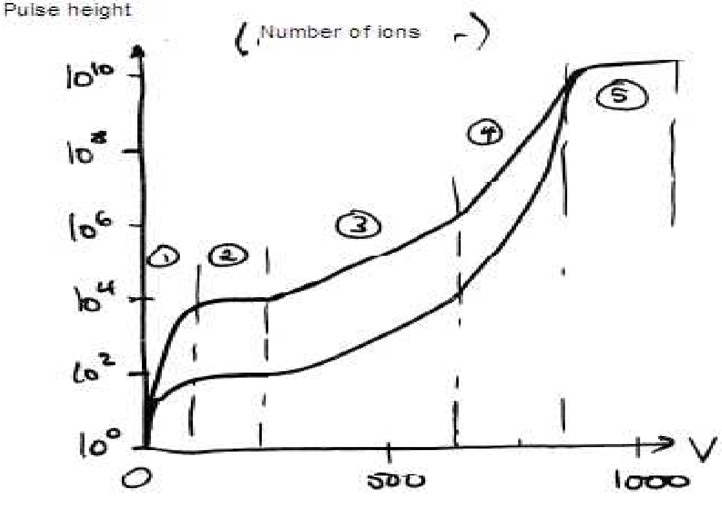
3.)

Particle detectors and accelerators (Lilley Chap. 6)

Detectors

Gas filled ionisation chamber





Gas multiplication factor G

Energy required to create an ion-pair

$W \simeq 20 \to 40$ eV

Electric field $E = \frac{V}{r \ln \frac{b}{a}}$

Gas multiplication factor: G

Required energy per ion-pair produced: $W = 20 - 40 eV$

Figure explanation

1.) Recombination ($G < 1$)

2.) Ionisation chamber. All the ion-pairs produced are collected by the electrodes, and there is no secondary ionisation.

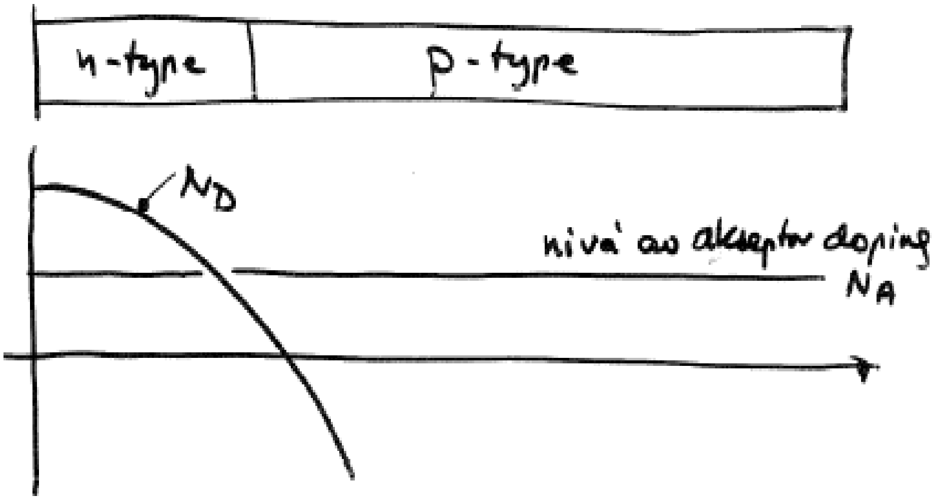
3.) Proportional counter. Puls height $\propto$ energy ($G > 1$)

4.) Area with limited proportionality due to nonlinearity

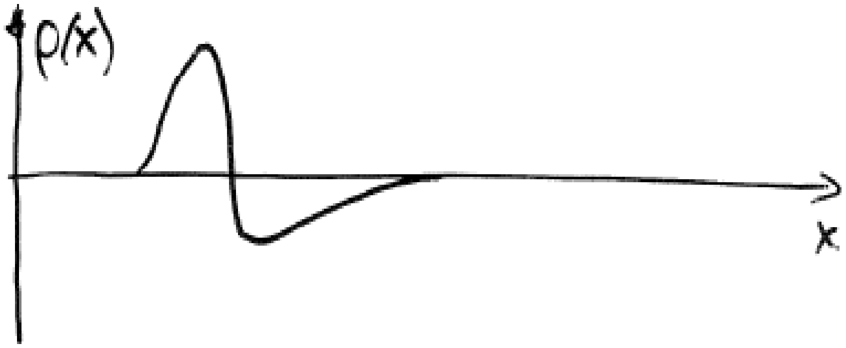
5.) Geiger-Müller range. Full discharge cascade ($G \to \infty$)

Semiconductor detectors

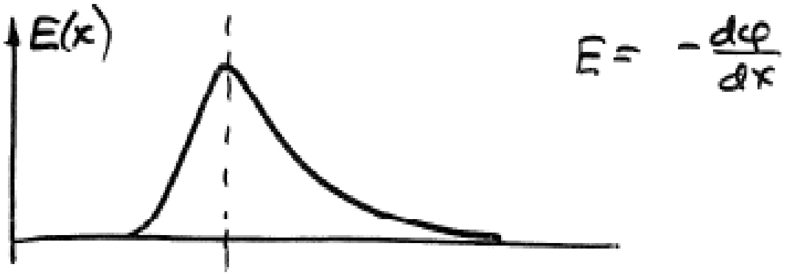
Add donor material to one of the sides.



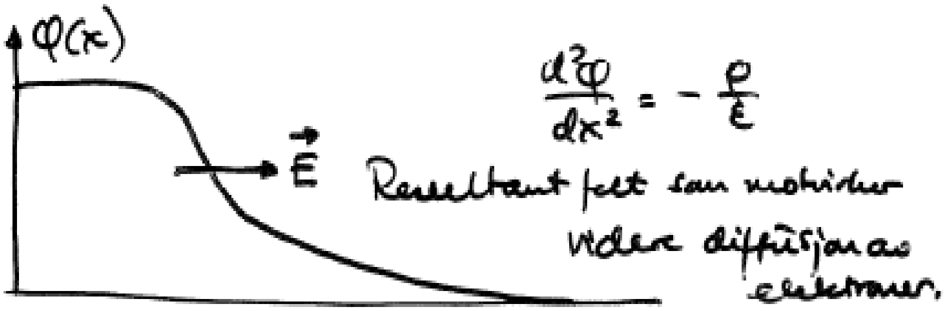
Spatial charge distribution after diffusion of electron from the donor material



Electric field over the diode



Potential difference

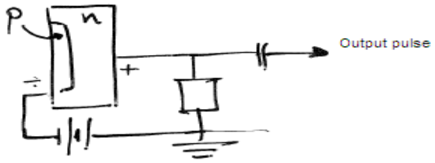


Depletion region:

There is an area containing no free charge-carriers on the border between the n and p material. This is called the active detector volume.

Reversed high voltage:

This results in a greater depletion region, as the active detector volume increases.



Different detectors

Surface barrier detector:

The active detection area is very close to the surface, but it is not particularly thick. This detector is well suitable for $\alpha-$ and $\beta-$ detection.

Ge(Li)-detector($\gamma-$detection):

The active detection volume is large because of neutralization of p-type material by inoculating Li. The disadvantage is that this detector always has to be kept cooled down (Liquid Nitrogen) to prevent leakage of Li.

HPGe-detector:

This is a modern detector for $\gamma-$detection. This detector has a big active detection volume, due to the ultra pure Ge "intrinsic" material inserted between the p- and n-region. The detector is cooled down during the detection sessions to reduce noise, but when not used it can be kept at room temperatures.

General advantages gained by using semi-conductor detectors:

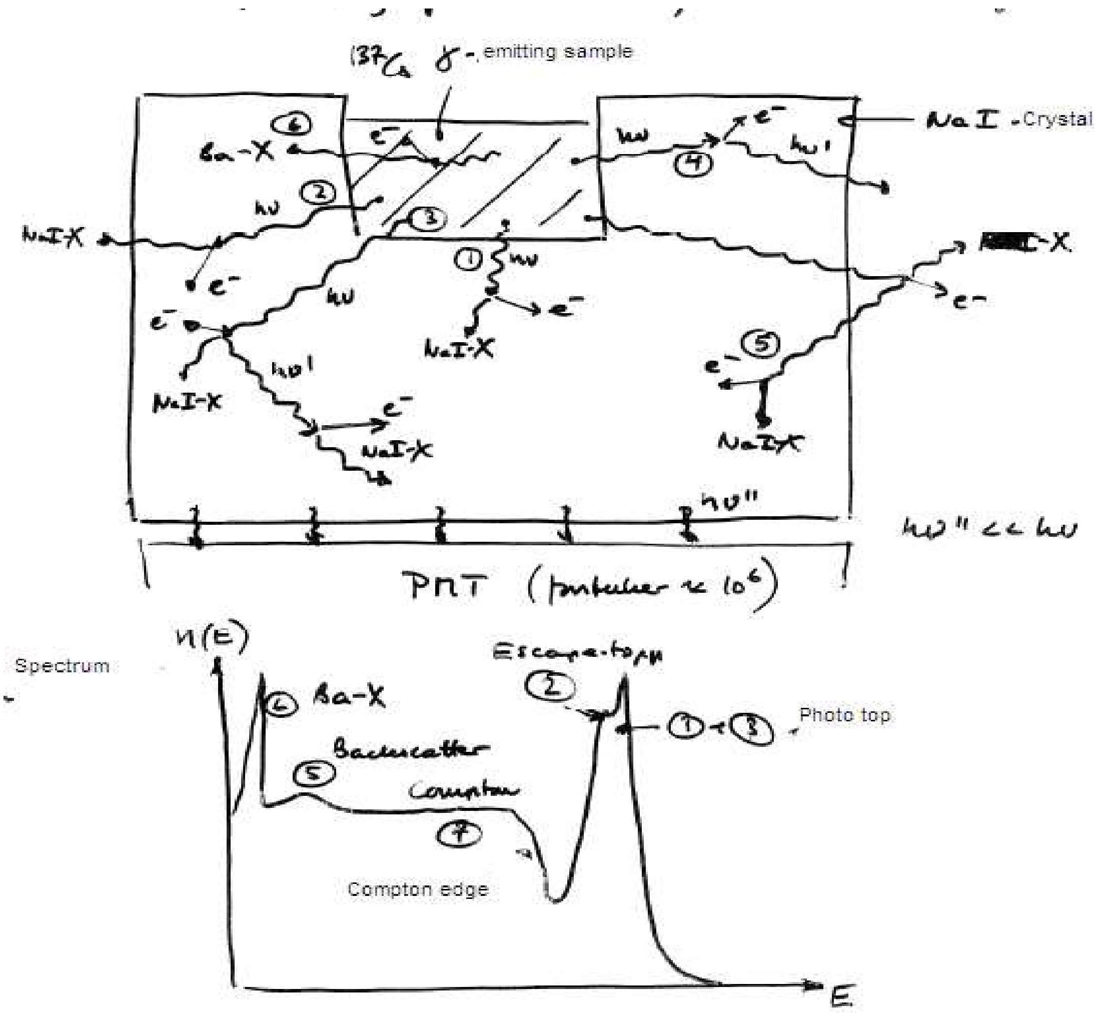
1.) Very good energy resolution, since ion-pair production requires only a small amount of energy.($W \simeq 3eV$)

2.) Well defined linearity and good stability.

Scintillation counter

A scintillator (fluid or crystal) is excited by secondary electrons. This results in emission of visible light which can be detected by a photo-multiplier-tube.(PMT)

NaI(Tl)-crystal detector



The crystal's excitation energy is converted into visible light by Tl-doping.

The Compton edge is given by the maximum energy of the Compton electron:

Maximum energy: $E_{max} = T'_{emax} = h\nu\frac{2\alpha}{1+2\alpha}; \alpha = \frac{h\nu}{m_e c^2}$

Photo-fraction: $f = \frac{\# \text{ Counts in full energy peak}}{\# \text{ Total counts}}$

Counting-efficiency ε, which is used
to find the radioactivity A in a sample
by using the counting rate r in the photo-peak: $r = \varepsilon A$

$$\varepsilon = f \cdot p_{vxv} \Omega \cdot k$$

In the last expression, f is the photo-fraction, p_{vxv} is the probability for interaction within the detector, Ω represents the solid angle seen by the detector and k is the number of photons with energy $h\nu$ emitted per disintegration.

Inside the detector, the photon energy $h\nu$ is deposited as kinetic energy for n charge-carriers (electrons from the photo-cathode of the PMT) which again results in a measurable pulse.

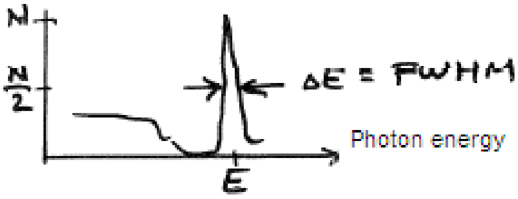
Measured energy E: $E \propto n$

Where n is Poisson distributed, which again means that:

Standard deviation $\sigma = \sqrt{n}$

Energy variance $(\Delta E)^2 \propto \underbrace{n}_{\textit{Poisson variance}} + \overbrace{\sigma_0^2}^{\textit{Rest variance}}$

$$(\Delta E)^2 \simeq a \cdot E + b$$



Neutron detectors

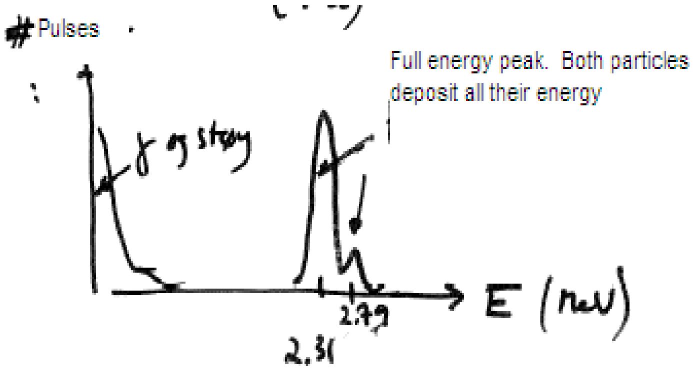
Detection of neutrons is based on detection of secondary ionizing particles.

^{10}B gas detector: BF_3 gas naturally contains 20% ^{10}B

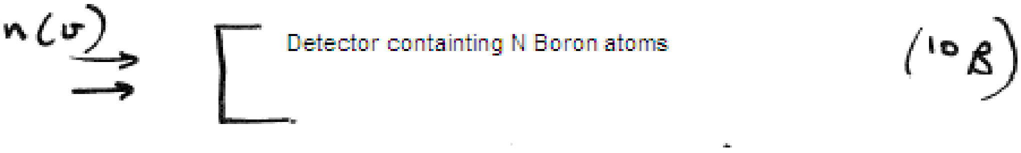
Thermal capture cross-section: $\sigma_{thermalcap} = 3840b$ for $^{10}B \propto \frac{1}{v}$ up to 100keV

$$^{10}_{5}B +^{1}_{0} n \rightarrow \begin{cases} ^{7}_{3}Li^{*} +^{4}_{2} He: & Q_{96\%}{=}2.31\text{MeV} \begin{cases} T_{Li} = & 0.84\text{MeV} \\ T_{He} = & 1.47\text{MeV} \end{cases} \\ ^{7}_{3}Li +^{4}_{2} He: & Q_{4\%}{=}2.79\text{MeV} \begin{cases} T_{Li} = & 1.01\text{MeV} \\ T_{He} = & 1.78\text{MeV} \end{cases} \end{cases}$$

Detection pulse distribution



The advantage of having a $\frac{1}{v}$ dependent cross-section



Flux of neutrons entering the detector with a velocity $v \in (v, v + dv)$: $\dot{\Phi}(v) = n(v)v \cdot dv$

Counting rate: $dR = N\sigma(v)n(v)vdv$

$$R = \int N\sigma(v)n(v)vdv = constant \int n(v)dv = const \cdot n$$

Where n is the neutron density. This means that the detector's counting rate is proportional to the neutron density and hence, independent of the neutrons' velocity.

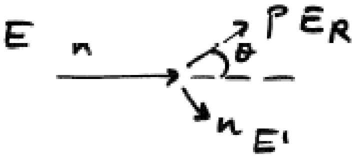
How to find the neutron energy by diffraction

For thermal neutrons, the wavelength $\lambda \simeq 0.1nm$, which is comparable to the distance d between the atoms inside a crystal.

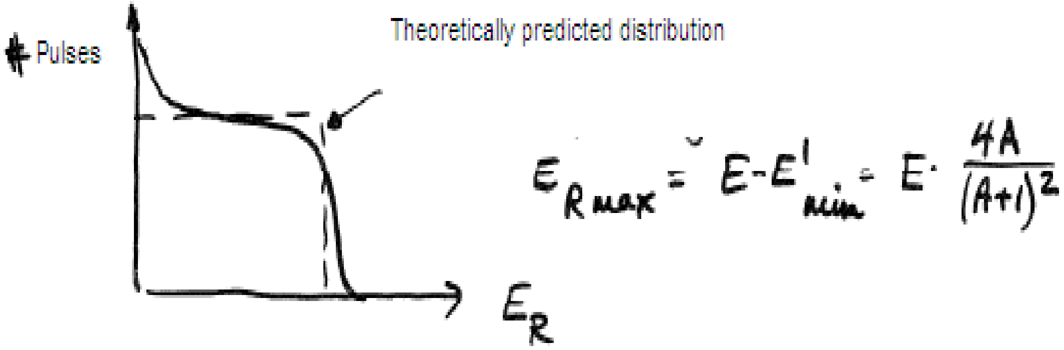
Constructive interference condition: $n\lambda = 2d\sin\theta$, $n = 1, 2, 3...$

Proton recoil spectroscopy:

Conservation of energy: $E_R = E - E' = E \cdot \cos^2\theta$



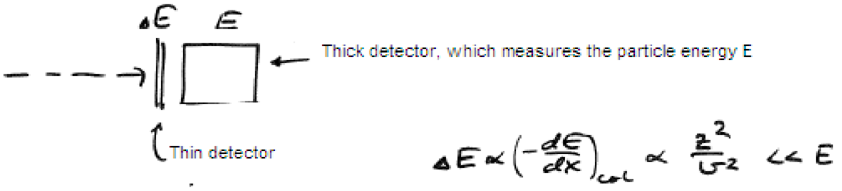
If this interaction is measured using a lioquid scintillator, there is no angular resolution:



$$E_{R\,max} \simeq E - E'_{min} = E \cdot \frac{4A}{(A+1)^2}$$

Particle identification

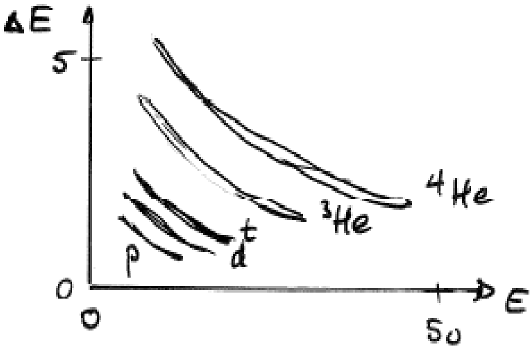
ΔE-E telescope



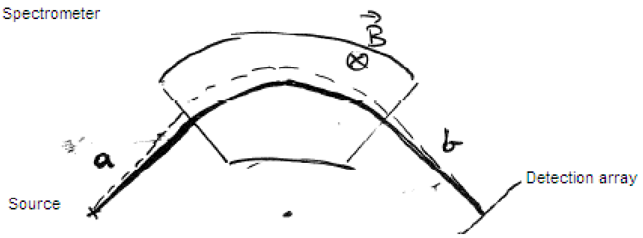
$$\Delta E \propto \left(-\frac{dE}{dx}\right)_{col} \propto \frac{z^2}{v^2} << E$$

Energy loss: $\Delta E = \left[-\frac{dE}{dx}\right]_{col} \propto \frac{z^2}{v^2} \ll E$

$\Delta E - E$ relation: $\Delta E \cdot E \propto \frac{z^2}{v^2}[\frac{1}{2}mv^2] \propto mz^2$; $\Delta E \propto \frac{mz^2}{E}$

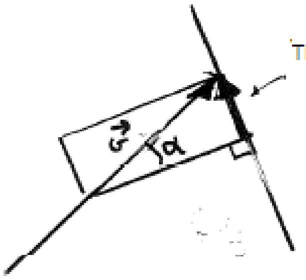


Magnetic spectrometer

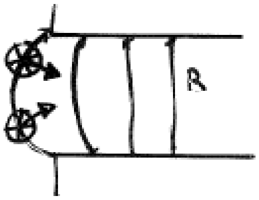


Force acting on particle: $F = qvB = m\frac{v^2}{r} \Rightarrow r = \frac{mv}{qB}$

If $a \cdot b = r^2$, there will be focusing in the horizontal plane. Focusing in the vertical direction takes place when angle of approach $\neq \frac{\pi}{2}$

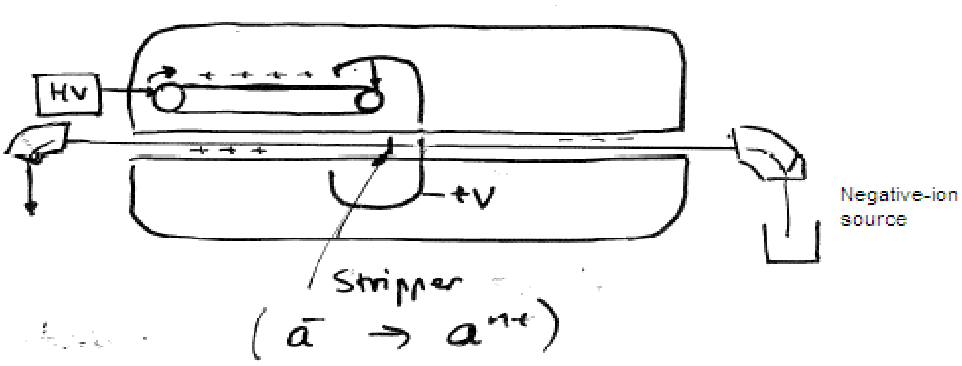


The velocity component along the edge of the magnetic field, causes focusing



Accelerators

Dual Van de Graaf accelerator

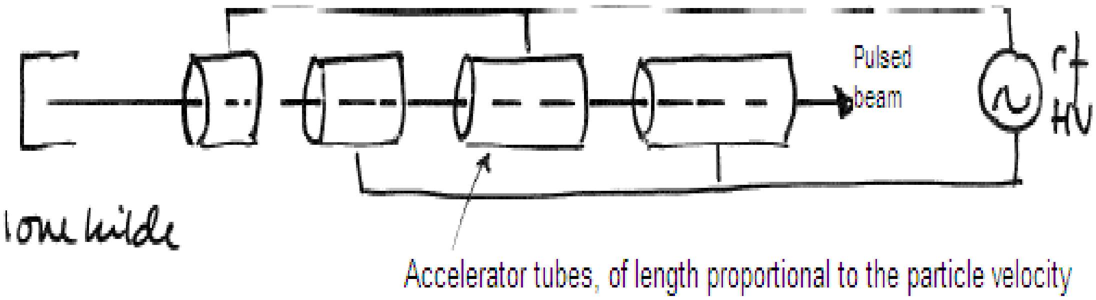


Terminal potential: $HV = 20$ MV

Particle energy: $E = (1+n)eHV$

The advantage is that you get a DC beam with very high intensity.

Linear accelerator

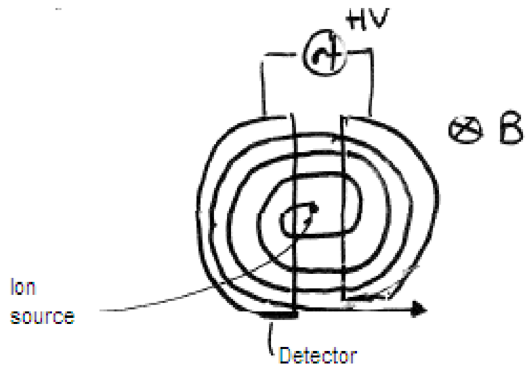


A phase stabilization is possible to achieve, if the particles are crossing the accelerator gap between two tubes when the field is increasing. Delayed particles will then feel a stronger acceleration. The phase stabilization gives a certain lateral defocusing, because the field is strongest at the end of the particle track between the tubes. The lateral defocusing described above, must be compensated for by adding several focusing rings inside the accelerator tubes.

SLAC: (Stanford Linear Accelerator) 20GeV electrons. It is about 3km long.

Linear accelerators are being used as radiation-therapy machines.

Cyclotron



Force acting on particle $F = qvB = m\frac{v^2}{r} \rightarrow v = \frac{qBr}{m}$

Period: $T = \frac{2\pi r}{v} = \frac{2\pi m}{qB} \equiv \frac{1}{f}$

Max energy for r=R: $E_{max} = \frac{q^2B^2R^2}{2m}$

To keep the period constant as E approaches E_{max}, the magnetic field B has to increase with r when $r \rightarrow R$. This results in a defocusing of the particle beam in the vertical plane. This has to be compensated for by splitting up the cyclotron in different sectors with higher and lower magnetic-field magnitudes, and using the focusing effect which is achieved at incoming angles $\neq \frac{\pi}{2}$