IV. Instruments for Cosmic Rays

The instruments that we have discussed in connection with the solar wind, electrostatic analyzers and time-of-flight mass spectrometers, are ideal for low energy ions. This means solar wind energies (1 – a few keV/Nucleon), pick up ions (a few 10 - a few 100 keV/Nucleon) and ions accelerated moderately out of these distributions. If we want to extend the application regime, we face limitations.

We use

$$\frac{M}{Q} = \frac{E}{Q} \Big/ \frac{E}{M} \qquad \text{(IV.0\_1)}$$

to determine the species. The M/Q determination hinges on good E/Q and E/M measurements.

a) Time-of-flight measurement:

The uncertainty from this measurement is:

$$\frac{\Delta M/Q}{M/Q} \approx 2\frac{\Delta\tau}{\tau} \qquad \text{if } E/Q \text{ is accurate}$$

$\Delta\tau$ cannot be measured more accurately than 0.1-0.5 nsec

For a time-of-flight spectrometer ULEIS on ACE it presented a real challenge to approach the lower end of this uncertainty range. Already delay time variations in the electronic circuits play a major role here.

Let us compare a few numbers for a typical time-of-flight distance s = 10 cm:

1 keV/Nuc $\rightarrow$ τ = 220 nsec

100 keV/Nuc $\rightarrow$ τ = 22 nsec

10 MeV/Nuc $\rightarrow$ τ = 2.2 nsec

We reach a limit for good TOF resolution soon.

We can make s longer. However, this option is limited by the S/C size and weight limitations.

b) Electrostatic Analyzer

The energy/charge of the incoming ion determines the size of the analyzer and the voltage that needs to be applied:

$$\frac{E}{Q} = \frac{R}{\Delta R} U \qquad \text{(IV.0\_2)}$$

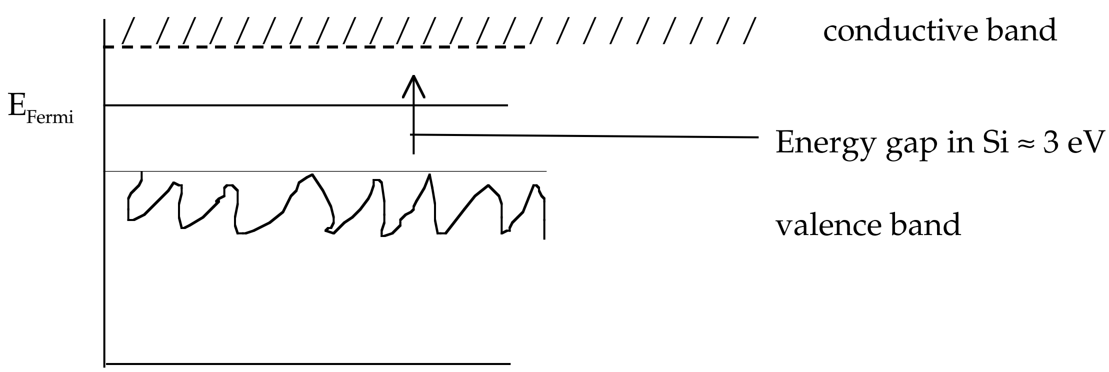
In order to accommodate higher energies either a higher voltage (and thus a stronger electric field) between the analyzer plates and/or a larger radius R is needed. Higher electric fields face the limitations of breakdown (beyond a few kV/mm). HV supplies which are small are extremely difficult to build for voltages > 30 kV. Finally, a larger radius R means a larger instrument, which does not fit on a S/C.

Generally the size of the electrostatic analyzer reaches the limit first. we need to look for alternative options.

VI.I Solid State Detectors

If we just want to know the energy of a particle (e or ions) or the energy, we can use a solid state detector (SSD), which stops the particle and returns a signal whose amplitude is proportional to the total energy (E). We can determine the mass of an ion by combining an SSD with a TOF spectrometer. From the TOF spectrometer we get E/M. Together with E this leads to M.

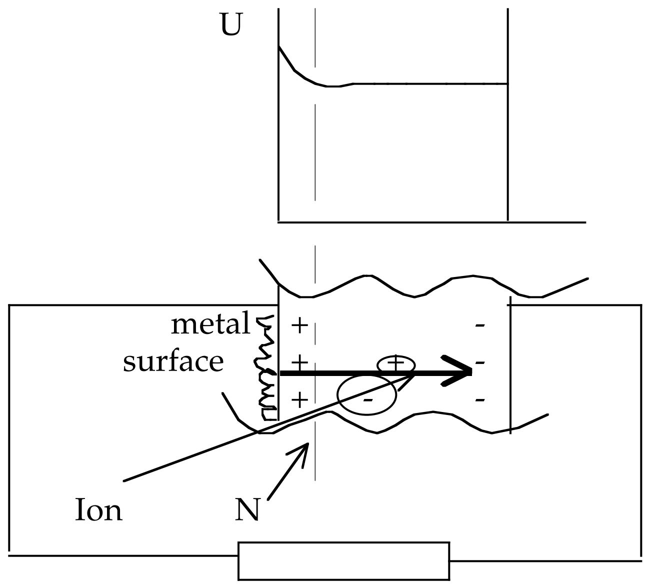
A SSD makes use of the inner photo effect in a semiconductor. A photon or similarly an energetic particle can lift electrons from the valence band (where they are fixed) into the conduction (energy) band, where they can move freely. The separation of positive (holes) and negative (electrons) particles in the semiconductor creates a charge pulse. With the appropriate circuit this is converted into a voltage pulse that can be analyzed.



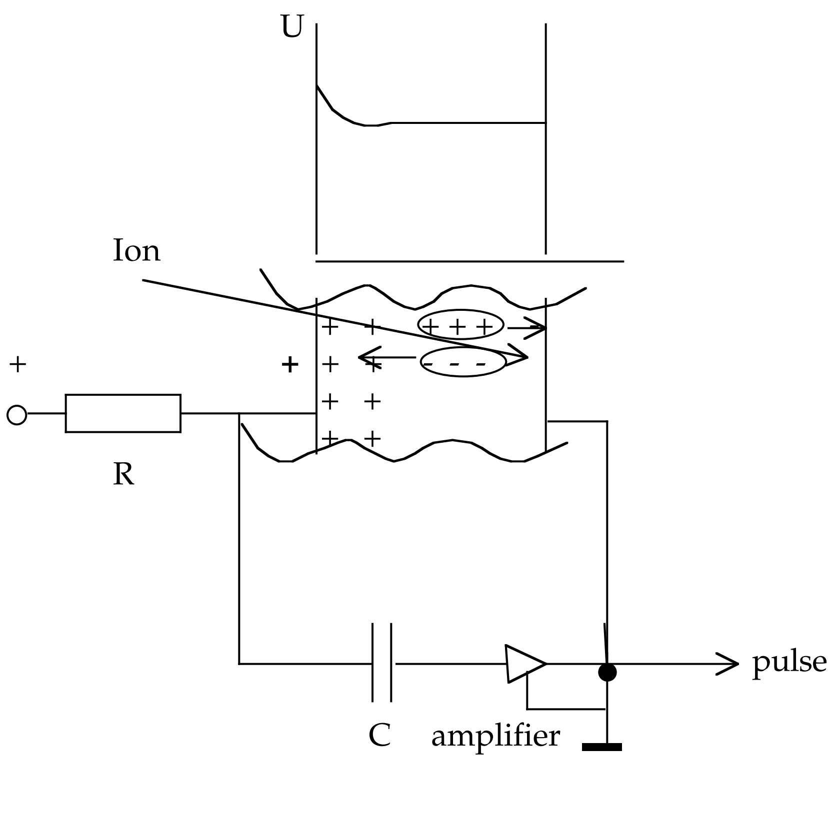
Si is a widely used semiconductor. Doped with artificial defects it can be tailored for many uses.
For example:

Si has 4 outer electrons
+N has 5 outer electrons → It is a donor

of an additional electron, which can easily move to the surface.



With a metal contact on both sides and connected via a resistor, a thin layer with N (donors) leads to a depletion of electrons (a positive depletion layer). When an energetic particle penetrates the Si many electron-ion pains are produced (electron-defect pairs). Typically 3 eV is needed for the creation of each pair. The electrons move to the positive depletion layer, the defect-electrons (by exchanging electrons) to the other sides. This creates a charge pulse. In this simple set up the charge is not collected well. The electric field is only concentrated in the depletion layer. To make the SSD equally useful throughout the crystal an external bias voltage is applied.



Now there is an electric field throughout the SSD, and all the charge can be collected.

We can calculate the charge that is produced by a penetrating particle according to

$$q = e\frac{E}{\Delta w} \qquad \text{(IV.1\_1)}$$

where $\Delta w \approx 3$ eV for Si.

For example:

1 MeV = $3 \bullet 10^5$ electrons = $5 \bullet 10^{-14}$ Cb

Such a signal is easy to measure.

However, a SSD also produces noise:

- For example e-i pairs are created thermally (more at higher temperatures).

- Together with the capacitance of the SSD all amplifiers create noise (more for higher C). Larger and thinner detectors have a higher C!

Typical values of the noise generated by SSDs are
3 – 30 keV (equivalent to a signal of a particle with that energy)
i.e. 1000 – 10,000 electrons

Therefore, SSDs are better for higher energies. The relative importance of the noise contribution decreases:

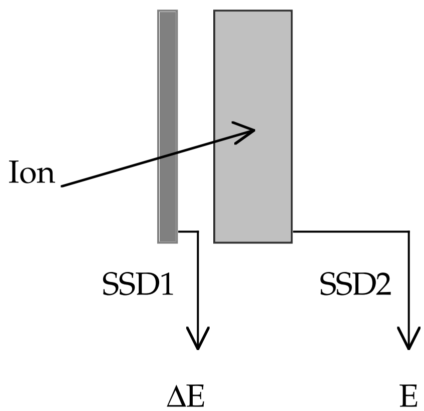
$$\frac{\Delta E}{E} \longleftarrow \text{noise equivalent } \Delta E$$

and the resolution is improved.

Thus the SSD should be better and better with higher energies. But, what happens for ions with higher and higher energies?
Beyond a certain energy the ion will pass through the detector. It will only deposit a fraction of its energy in the detector. To measure the total energy, we need thicker SSDs. This is a limitation for energy measurements, but it will also open another opportunity.

IV.2 Energy Loss in Matter

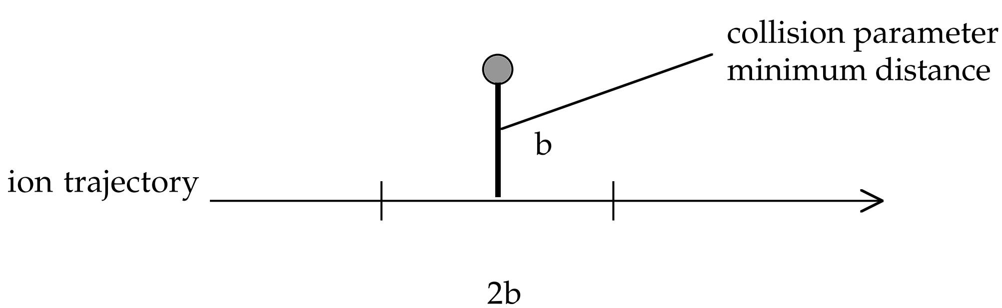
The energy loss which is used to produce the signal in the SSD is a problem for TOF spectrometers for low energies. Therefore, the foil has to be thin here. However, the energy loss can be put to use in a different way for higher energies, where TOF measurements fail to provide us with an accurate mass determination. The energy loss itself depends on the nuclear charge Z, i.e. depends on the element. If we can measure the energy loss in a known layer of material, for example in a thin SSD, and the remaining energy in a thick SSD, we get both Z and E.



The energy loss is mainly collision with electrons in the larger material, i.e. Coulomb interaction.

$$F = \frac{Ze \bullet e}{4\pi \varepsilon_o r^2} \qquad \text{(IV.2\_1)}$$

Where Z is the nuclear charge of the projectile (we assume a fully stripped ion to begin with).



The momentum exchange is: $\Delta p = \int_{-\infty}^{\infty} F\,dt$

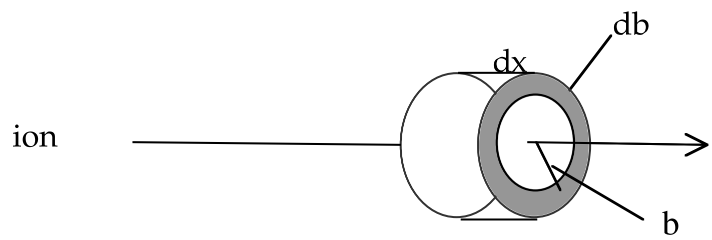
$$\Delta p \approx \overline{F} \bullet \overline{\Delta t} = \frac{Ze^2}{4\pi\varepsilon_o b^2} \bullet \frac{2b}{v} = \frac{2 \bullet Ze^2}{4\pi\varepsilon_o b v} \qquad \text{(IV.2\_2)}$$

The corresponding energy loss is:

$$\Delta E = \frac{\Delta p^2}{2m_e} = \frac{2\,Z^2 e^4}{(4\pi\varepsilon_o^2 b^2 v^2 m_e)} \qquad \text{(IV.2\_3)}$$

$\rightarrow$ and therefore proportional to Z^2 and $1/v^2$ of the penetrating ion.

The total energy loss also depends on the density of electrons in the target material



We compute the number of electrons in the volume dV:

$$dV = 2\pi b\ db\ dx \qquad \text{(IV.2\_4)}$$

The specific energy loss in the material is then (IV.2_3 and IV.2_4).

$$-\frac{dE}{dx} = \int_{b_{\min}}^{b_{mas}} \frac{2\,Z^2\,e^4\,n_e}{(4\pi\varepsilon_o)^2\,b\,v^2\,m_e} 2\pi\,db$$

$$= n_e \frac{Z^2\,e^4}{4\pi\varepsilon} \ln\frac{b_{\max}}{b_{\min}} \qquad \text{(IV.2\_5)}$$

At $b_{\min}$ the maximum momentum loss occurs, i.e. $2\ m_e v$

$$b_{\min} = \frac{Ze^2}{m_e v^2} \ln\frac{b_{\max}}{b_{\min}} \qquad \text{(IV.2\_6)}$$

At $b_{\max}$ a minimum energy of $\Delta E \geq I$, the average excitation energy of the atoms in the material, has to be transferred. Thus

$$b \leq b_{\max} = \frac{Ze^2}{v\sqrt{2m_e I}} \qquad \text{(IV.2\_7)}$$

Combine IV.2_5, 6 and 7:

$$-\frac{dE}{dx} = n_e \frac{Z^2 e^4}{8\pi\varepsilon_o^2 m_e v^2} \ln\left(\frac{2m_e v^2}{I}\right) \qquad \text{(IV.2\_8)}$$

A full Q.M. treatment leads to 4π instead of 2π. The dE/dx curves go as $\sim 1/v^2$ for high energies, but become constant at relativistic energies. At low energies they turn over, with a maximum at ≈1 MeV/Nucleon.

Viewgraph

At low energies there is a modification, since the particles are not fully ionized anymore. However, the curves are well known for all elements from measurements and can thus be used to determine the species for a penetrating particle from measurements of ΔE and E.

For energies of ≈1 MeV/Nucleon to several MeV/Nucleon SSDs are too thick to be used as te component to measure ΔE. The range of the ion

$$R=\int_o^R dx=-\int_E^0 \frac{dE}{f(E)} \qquad \text{(IV.2\_9)}$$

where $f(E) = -\dfrac{dE}{dx}$ is too short in the solid state material.

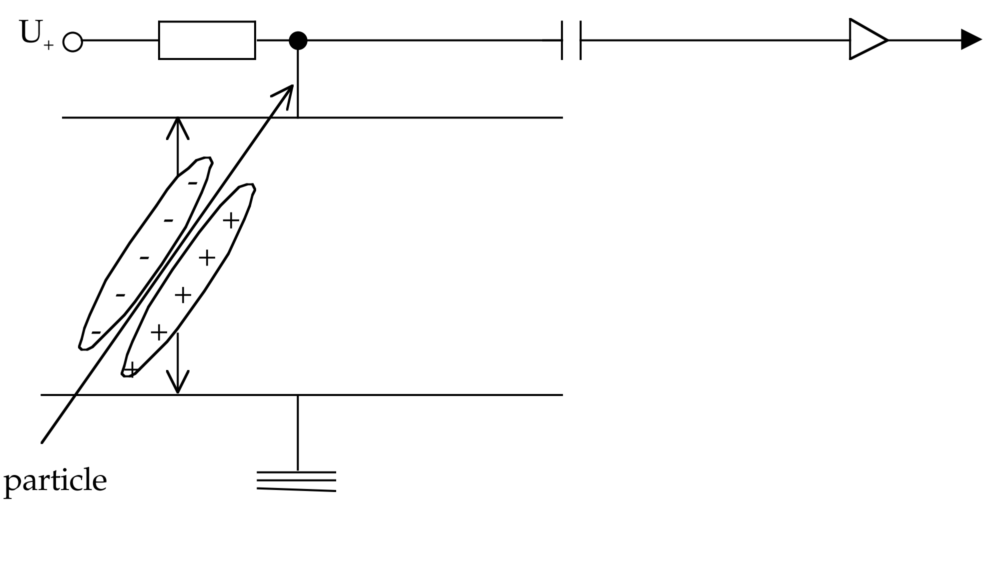
Here gas counters are used. The material layer of gas can be made much thinner than a SSD.

IV.3 Proportional Counters

In a gas counter the incoming energetic particle ionizes gas atoms on its way through the counter such that

$$\Delta E = N_o \bullet I \qquad \text{(IV.3\_1)}$$

where I the average ionization energy and N_o the number of electron-ion pairs created.



The charge q = C • e is collected at the electrodes when a voltage u is applied. The pulse is detected through an amplifier chain. Typical ionization energies for counter gases (Ar or Isobutane [C_4H_{10}]) are $W_i \approx 30$ eV.

Example: 2 cm counter with 40 Torr gas
1 MeV/Nucleon α-particle
$\Delta E \approx 200$ keV $q = 10^{-15}$ Cb

This is at the limit of detection for this operation of a gas counter, which is called an ionization chamber.

If the electric field E, i.e. the voltage U is increased, such that the electrons reach the ionization energy W_i of the gas, more electron-ion pairs are generated. We get gas amplification.

The average energy of an electron in an electric field and with collisions in a gas can be written as

$$\varepsilon = e \bullet E \bullet \lambda \qquad \text{(IV.3\_2)}$$

where λ is the mean free path between 2 collisions with neutral atoms.

Since $\lambda \sim 1/P$ P = gas pressure

$$\varepsilon \sim E/p \qquad \text{(IV.3\_3)}$$

For $\varepsilon \gtrsim W_i$ we get plenty of ionizing collisions and

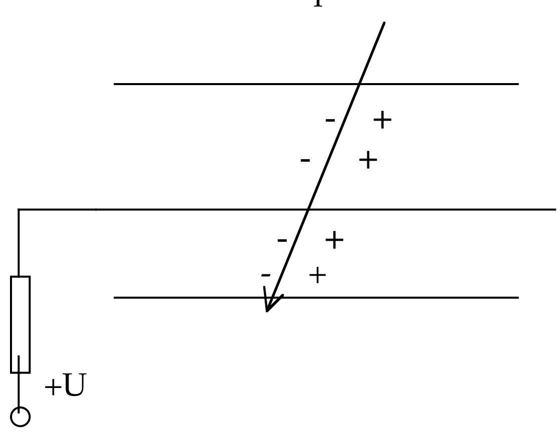
$$\frac{d\,n_e(x)}{dx} = n_e(x) \bullet n_o \bullet \sigma_i$$

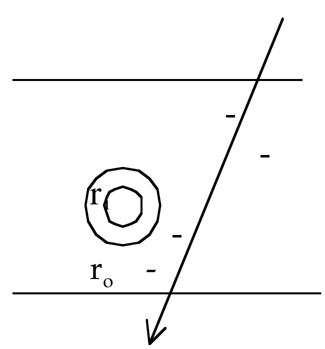
$$\textit{with integration:} \qquad \text{(IV.3\_4)}$$

$$n_e = n_{eo} \bullet e^{\int n_o \bullet \sigma_i \bullet dx}$$

where the exponential is the amplification factor.

The plate geometry is not favorable for a counter, because it is hard to achieve fields high enough to get good amplification without risking a permanent discharge. Secondly, the amplification varies for each location in the counter. Therefore, counters with thin anode wires are preferred.





Around the counter wire a cylindrical potential is formed with

$$E = \frac{U}{r}\frac{1}{\ln(r_o / r_i)} \qquad \text{(IV.3\_5)}$$

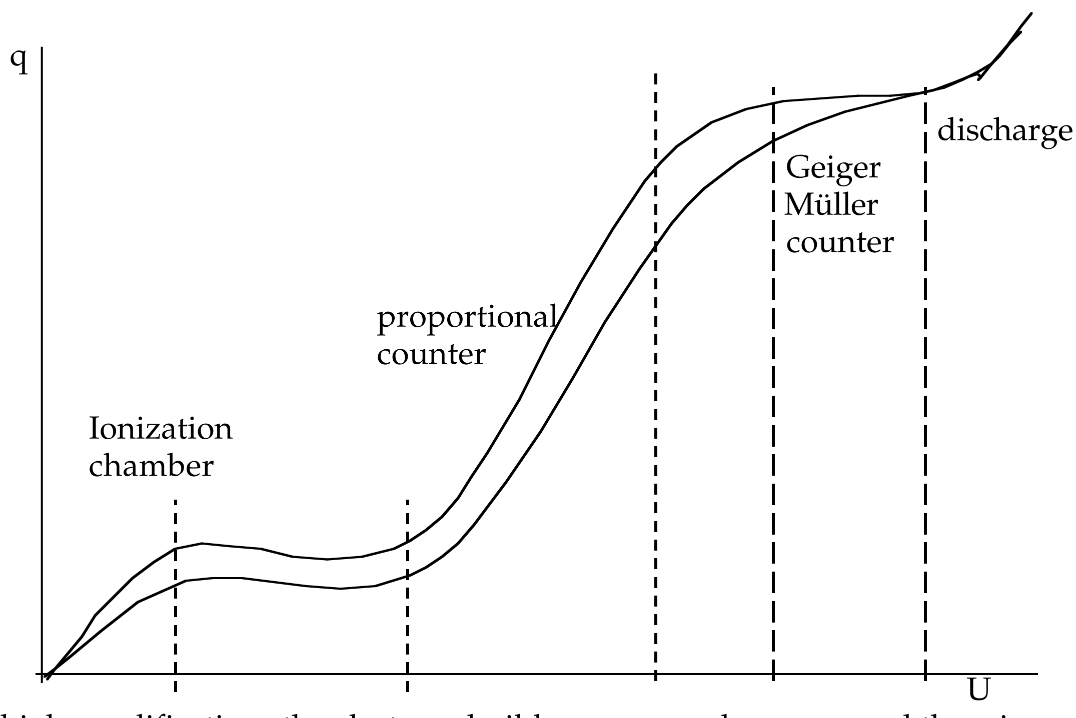
i.e. the field and therefore the average energy of the electrons scales as 1/r. Inside a threshold radius r_T $\varepsilon > W_i$. Thus (IV.3_4) can be turned into

$$n_e = n_{eo} e^{n_o \sigma_i (r_T - r_i)} \qquad \text{(IV.3\_6)}$$

$r_T = \rho_T \bullet \frac{U}{P}$ *because* $\varepsilon \sim \frac{U}{P}$ and $n_o = P/kT$. ρ_T is a constant that only depends on the type of gas used.

$$n_e = n_{eo} \bullet e^{\frac{P}{kT}\sigma_i}\left(\rho_T \frac{U}{P} - r_i\right) \qquad \text{(IV.3\_7)}$$

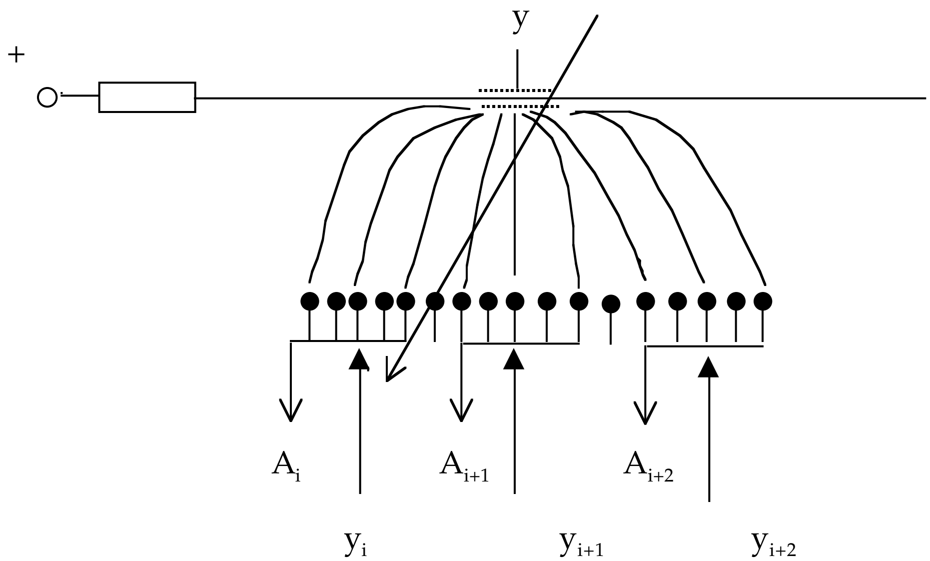
The gas amplification is on weakly dependent on the gas pressure, but varies almost exponentially with the counter voltage U. However, the total number of electron-ion pairs n_e is still proportional to the original number n_{eo}. This regime is called a proportional counter. As a function of u we get the differential operational regimes of gas counters.



For high amplifications the electrons build up a space charge around the wire and limit the signal. The saturation the gas counter is operated as a Geiger-Mhller counter.

Demo

The scheme of a proportional counter can be extended to an imaging counter by going to many wires instead of one.



The charge collected at the anode at y creates capacitively image charges at the multiwire strips of the cathode, with the signals proportional to the individual capacitances. We find the position y as the center of gravity of the measured pulses A_i.

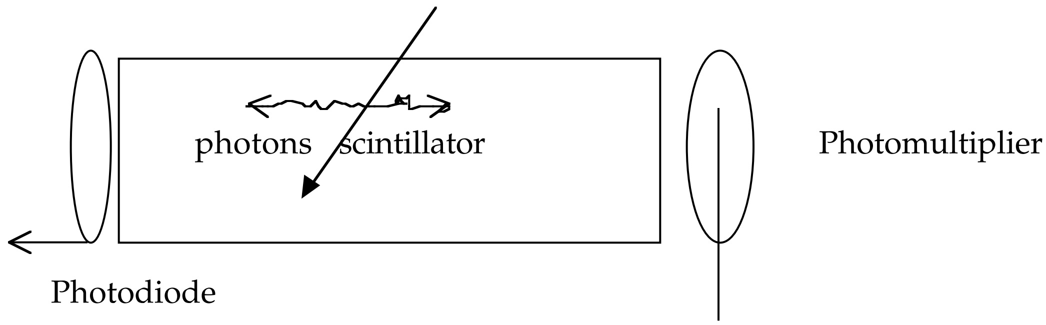
$$y = \frac{\sum_i A_i y_i}{\sum_i A_i} \qquad \text{(IV.3\_8)}$$

Wire chambers have been in use as detectors at accelerators and as x-ray cameras on satellites. We will use it as ΔE and position detector for a new instrument in combination with electrostatic deflection.

Demo

IV.5 High Energy Detectors

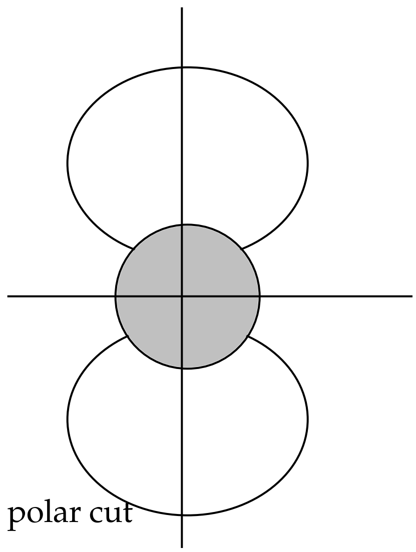
In order to stop high energy particles thicker and thicker materials are necessary. Very thick SSDs are impractical because they would need a very high bias voltage. For thicknesses beyond a few mm the use of scintillators is very common.

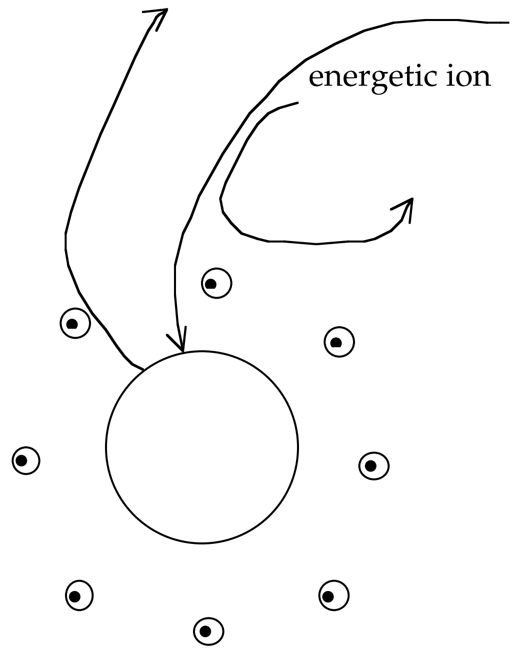


In a scintillator crystal the conversion of ion energy into photons through excitation of bound electrons is put to use. The photons are detected
by - a photodiode or
by - a photomultiplier.
The total measured photon energy is proportional to the deposited energy. In combination with SSDs scintillators can be employed as a $\Delta E - E$ detector to determine Z and E.

Can we also determine the charge state Q at energies > 10 MeV/charge? All electrostatic deflection methods in an instrument become impractical. However, we can use the Earth's magnetic field as spectrometer.

Earth's magnetic field





equatorial cut

Only particles with a "rigidity"

$$R > R_{cutoff} = \frac{P}{Q_e}$$

have a large enough gyro radius to reach the ground at the equator. This cutoff rigidity can be estimated by asking the question, whether the ion can escape from Earth. Penetration and escape are equivalent. An approximation of the value can be obtained by computing the rigidity necessary for a spherical orbit.

The cut-off rigidity contains the momentum (and thus the energy) and the ionic charge. Therefore, we get the charge Q by determination of R cutoff and E. To get R_{cutoff} more accurately, the arrival direction of particles is measured and then the trajectory is calculated backwards for different latitudes on Earth. The cutoff depends on latitude and gives a fairly accurate value for the charge of the particles, which just make it through.