Radiation Detectors

A collaborative homework for the lecture on measurement methods in nuclear physics.

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Chapter 1

Ionization Chambers

Ionization chambers are constructed as chambers containing a gas in between two electrodes of opposite charge. Incident radiation leaves tracks of charged particles and free electrons by means of ionization. These charged particles and electrons drift to the electrode of opposite charge and arriving donate their charge to a current discharging the electrodes. The most simple type of ionization chamber simply consist of two electrodes and displays the amount of radiation since last recharging of the electrodes by means of an electrometer, an electrostatic device capable of making voltage differences visible. More sophisticated kinds electronically measure the current generated by the charged particles. In order to do this they have to take into account that the total charge in a track of even high energy particles is quite low, so the current to be measured will be quite small. The geometries of ionization chambers show great variance. However to minimize disturbance by charge exchange between the ionization chamber electrodes by other means than ionized particles and their electrons a special geometry of insulation (see figure 1.1) is used.

1.1 Utilization of ion chambers for dosimetry

For direct dose measurement one would require to accumulate all secondary ionization induced by all secondary electrons at the point where the dose were to be measured. As the mean traveling distance of secondary electrons induced by typical gamma energies can be several meters, this would require quite a large ionization chamber. Fortunately, air is usable as a medium for ionization chambers. Provided that gamma rays of the energy to be observed are not noteably blocked by air at the observed energy and length scale of the dosimeter, one can postulate isotropic generation of secondary electrons

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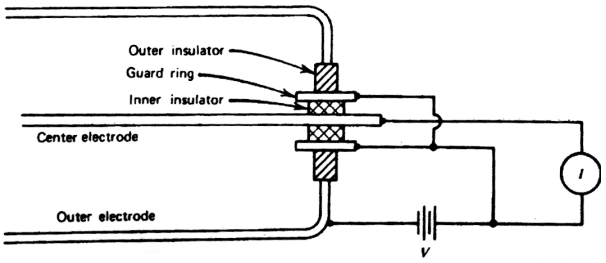

Figure 1.1: *Insulation in ionization chambers: To minimize the current trough the resistance of the insulator, a guard ring carrying the same potential as the measuereing electrode is applied. This way the voltage drop can be restricted to the outer insulator, and no current through the inner insulator will lead to misreadings in the current measurement. [1]*

in- and outside the ionization chamber. Thus the amount of electrons lost flying out of the chamber will cancel out the amount of produced elsewhere and entering the chamber. By measuring the ionization of radiation in air, the amount of ionization taking place in other materials can be calculated and thus dosimetry results are possible.

1.2 Charge Migration an Collection

In an electric field ions an electrons will move from their point of origin. Their drift-velocity can be predicted by formula 1.1.

$$v = \mu \frac{E}{p} \tag{1.1}$$

- v : Driftspeed
- μ : Mobility of the particle
- E : Strength of the electric field
- p : Gas pressure

The mean value of the mobility of ions in gases lies between 1 and $1,5 \cdot 10^{-4}\ \frac{m^2 \cdot atm}{V \cdot s}$. The resulting drift-velocity is of the magnitude of 10 ms which leads to collection-times of 10 ms. For electrons their smaller mass allows a greater acceleration between interactions with gas molecules. Therefor their mobility is bigger by a factor of 1000. Accordingly their collection time is of the magnitude of microseconds instead of milliseconds.

In most cases the drift-velocity increases with higher values of $\frac{E}{p}$, but with some gases a saturation effect comes in to play, which can even lower the drift-velocity after a certain threshold of electric field strength. In an ion chamber the electrons and ions created through irradiation are collected at the anode and cathode and form a electrical current. Losses due to recombination can be reduced through strengthening of the electric field until saturation is achieved an every electron produced is collected. The necessary voltage for saturation is increased by impurity's of heavy charged particles that recombine with electrons on their path. Furthermore strong irradiation increases the density of positive charged ions which increases the chance for recombination. Lastly the drift of positive charged ions to the cathode and negative charged electrons to the anode creates a charge division which electric field opposes the original one.

1.3 Pulse measuerements in ionization chambers

Pulse measurements are possible and explained in 1.2. Chosing the used resistor and capacity one can chose the time of return to equilibrium. Chosing them correctly it is possible to adjust the timescale of the system such that either only the produced electrons are measured or the produced ions are taken into account. Since operated on a timescale of milliseconds the ionization chamber is sensitive to acoustic disturbances, in most cases the chambers are operated in the electron sensitive mode.

1.4 The Frisch grid

The Frisch grid is named after the austrian–british physicist Otto Robert Frisch [3].
Basically it is a grid made of a conductive material that is typically placed between the cathode and anode in ionizationchambers and is commonly on ground potential or weakly charged. In figure 1.3 we see a layout of a ionizationchamber with a frisch grid.

The Frisch grid brings two advantages.
The height of a puls measured in a ionizationchamber depends on the location of the primary ionizsation. So detectors that cover great dihedral angles will have a bad signal quality. By deflecting the anode with the Frisch grid the dependence of the location of the primary ionization is dramaticly reduced [4].

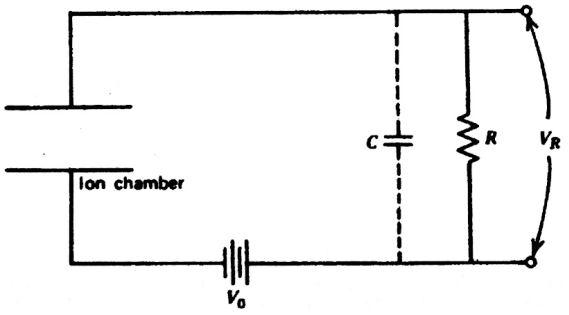

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Figure 1.2: *Pulse measurements in ionization chambers: before Ionization, the system is in equilibrium. After ionization, the produced electrons quickli travel to the negative electrode and virtually produce a current across the chamber. The voltage difference on both ends of the resistor rises as the system tries to reach equilibrium again by producing a current through the resistor. Slowly the equilibrium is reached again. [1]*

As a second advantage of a Frisch grid is the improvement of the resolution of time. The pulse rises after the electrones have passed the Frisch grid so the rise time will be shorter than the rise time without a Frisch grid. In figure 1.4 we see the development of the potential of the anode over time.

As mentioned before the rise time is shorter and the peak is higher, so the Frisch grid improves the quality of the measured signal.

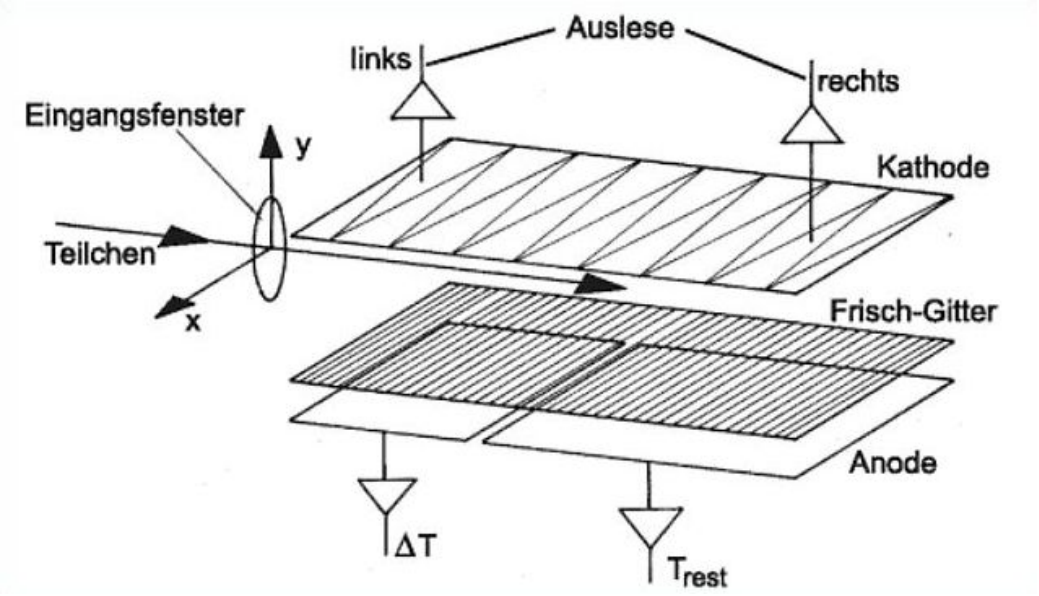

Figure 1.3: *Schematic of a ionizationchamber with a Frisch grid (AS94) [3]*

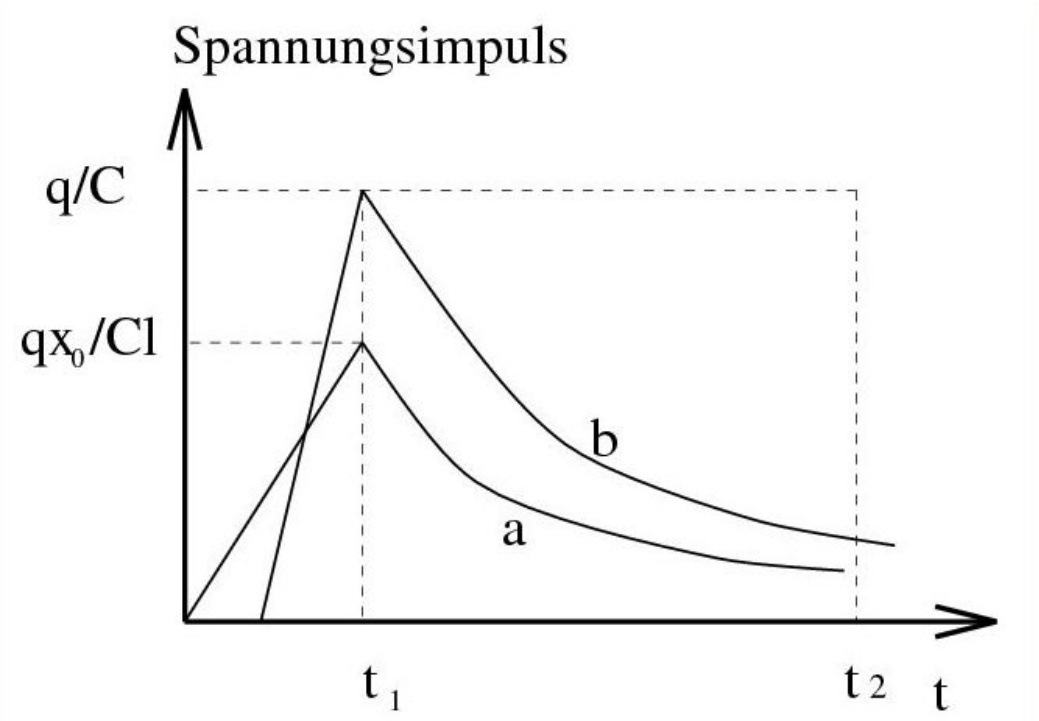

Figure 1.4: *Process of the potential of the anode over time: (a) without (b) with a Frisch grid [4]*

Chapter 2

Proportional counter

The proportational counter is a kind of ionazation chamber for the measurement of the energy of ionizing particles and radiation. Basically the proportional counter consists of a gasfilled, zylindrical condensator. Incoming particles ionize the gas in the detector. Due to the applied electric field the electrons drift to a high voltage wire which serves as anode. Accordingly the gas ions drift toward the outer wall of the detector which serves as cathode. The electrical field perpendicular to the wire in the condensator is given as

$$|E(r)| = \frac{U_0}{r\, ln(\frac{r_2}{r_1})} \tag{2.1}$$

where r_1 is the radius of the wire, r_2 the inner radius of the tube and U_0 the operational voltage. The stronger field near the wire accelerates the free electrons that their kinetic energy is high enough to produce new electron ion pairs. This Townsend avalanche increases the number of free electrons expontionally. If U_0 is choosen correct the amplitude of the generated pulse in the anode is proportinal to the initially deposited energy of the ionizing particle. Proportional counters have good properties in energy resolution especially for low energy particles. Due to the drift time of the electrons in the range of microseconds the time resolution of the proportional counters is not usefull.[6]

2.1 Differences between proportional counters and Geiger-Müller counters

The main difference between the two types of ionization chambers is the operational voltage. Gas filled detectors can be grouped in different operation regions. The first region is the region of ion saturation. After this the gas

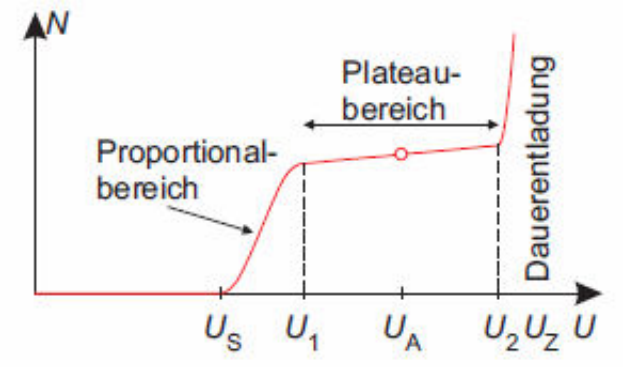

Figure 2.1: *Graph of the pulse amplitude over the operational voltage[5]*

multiplication starts. At the beginnig the multiplication is propotinal to the number of intial ion pairs. This is the operational region of the proportional counter. The Geiger-Müller counter operates with a higher voltage. In this region the avalanche is dominated by nonlinear effects. It countinues till enough positiv ions are created to counter the electric field. So each pulse has the same amplitude. It is no longer possible to determinate the intial energy.[7]

The function of both types of ionizing chambers results from the higher drift velocity of electrons than ions. So it must be prohibited that negativ charged ions are generated. There for the used gas should only ionize in electrons and positive ions. Typical gases are noble gases like argon, neon or xenon. Often these gases are mixed with organic gases like methane. An often used combination is 90% argon and 10% methane.

2.2 Energy resolution in proportional counters

The energy resolution is limited by the statistical processes of the number of electron ion pairs initially created and the number of electrons created in the Townsend avalanche. The overall standard derivation kann be expressed with the following formula

$$\frac{\sigma_Q}{Q} = \sqrt{\frac{W(F+b)}{E}} \tag{2.2}$$

where F is the Fano factor of the gas, b the multiplication variance, W the energy needed for the creation of an ion pair and E the inital deposited

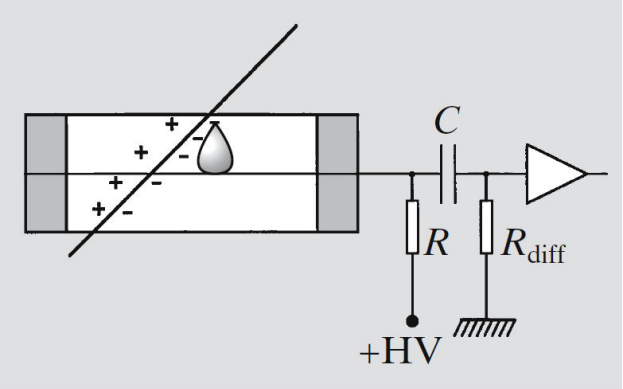

Figure 2.2: *Schematic of a sealed tube proportional counter[6]*

energy. Typical values for the values for the energy resolution are between 10 and 15 %.[7]

2.3 Types of proportional counters

There are different types of proportinal counters which serve different needs. Two types are presented as examples.

2.3.1 Sealed tube

Sealed tubes are normally zylinders. The gas is sealed in the tube. A window either on one end of the tube or in the outer cathode wall. Advantages of this type are its transpotability as it only needs a power source and good energy resolution due to the axial uniform electric field. Disadvantages of this design are that the lifetime is limited due to microleaks in the tube and the need for a casing. The first results in the contamination of the gas through other gases, e.g. air which produces negative ions. The later disadvatange lowers the effectivness of the detector in the measurement of larger particles, e.g. α-particles, because they cannot pass through the casing.[7]

2.3.2 Continues flow counter

A problem of sealed counters is that ionizing particles must pass through an outer casing. Especially for α-particles this can be problematic. This problem is solved by placing the sample in the detector. Also the other problem of a sealed tube can be solved with the current flow counter. The sample is placed inside an hemispherical chamber. The gas is slowly pumped

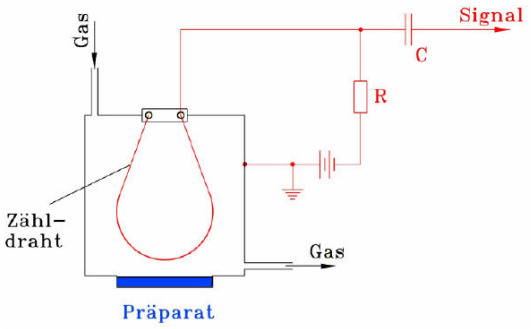

Figure 2.3: *Schematic of a continous flow counter[8]*

through this chamber. The the u-shaped anode wire is placed on the ceiling of the chamber. This detector does not have problems with contaminated gas but needs an external gas distribution system. Another advantage is the extrem high efficiency due to the fact that almost all ionizing particles deposite energy in the detector.[7]

2.4 Fill Gases and the effect of different Gases

A general classification can be made: The gas in the detector can be permanently sealed within the counter or can circulate in a continuous flow. While the lifetime of the first category is limited by microscopic leaks leading to impurities in the fill gas the continuous flow counters require a gas supply system meaking them more difficult to handle. A third kind of propotional counters is a so called "'once through"'-counter where the filling gas is vented to the atmosphere or recycled in another way after passing the detector.
The choice of the fill gas affects the electron drift velocity. This is related to the energy resolution and the dead time of the detector and also important for coincidence measurements.
Besides secondary ionization the electrons can also cause simple excitations of neutral gas molecules. These excited molecules do not contribute to cascade and decay by emitting a visible or UV photon, which causes an undesired loss of proportionality.
Experiments have shown that the addition of a small amount of a polyatomic gas (methane for example) can supress these effects by preferentially absorbing the photons in a mode which does not lead to further ionization. Such an additional gas component is called a *quench gas*.
If a second gas with smaller ionization energy than the first one is used the

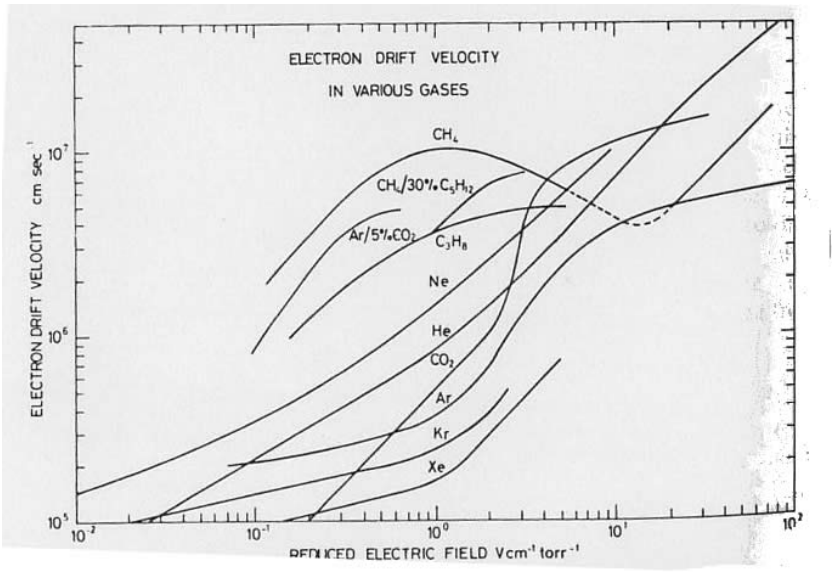

Figure 2.4: *e^- drift velocities in varous gases, as compield by Jeavons et al. [7]*

Penning effect can occur. If long-lived or metastable excited states exist in the principal gas and the excitation energy is larger than that of the additive gas, these excited atoms can ionize neutral atoms of the additive. This results in a greater number of produced ion pairs by the incident radiation, because a greater fraction of its energy is converted into ion pair production. This also reduces the relative fluctuation in the number of ion pairs created, which corresponds to an improvement in energy resolution. So called Penning mixtures of gases are used in proportional counters designed for radiation spectroscopy. In most proportional counters noble gases are used; if the gas multiplication factor is above 100 adding of a quench gas is helpful to reduce instabilities and a loss of proportionality. Argon is the most widely used one because it is the cheapest noble gas. It is often mixed with 10% methane (P-10 gas). If a high efficency for γ-rays is needed it is sometimes substituted by krypton or xenon.
Organic gases such as methane or ethylene are also suitable where no grat stopping powers are needed. If the proportional counter is desigend to detect neutrons BF_3 oder ^{3}He is used (thermal neutrons) oder hydrogen, helium or methane and generally low-Z gases (fast neutrons). For coincidence an fast timing measurements the electron drift velocity in the gas is most important. An overview about suitable gases depending on the electric field strength is shown in fig. 2.4.

2.5 Effects of amplification

The electric field is strong enough to accelerate freed electrons to an energy where they are also capable of ionizing gas molecules in the cylinder. The electrons liberated in these secondary ionizations, of course are also accelerated to produce still more ionization and so on. This results in an ionizaton Townsend avalanche [10].
If the operating voltage is chosen carefully, each avalanche process occurs independently of other avalanches which derive from the same initial ionizing event. Therefore, even though the total number of electrons liberated can increase exponentially with distance, the total amount of charge created remains proportional to the amount of charge liberated in the original event. The geometry of the electrodes and the voltages on them are chosen such that in most of the volume of the counter the electric field strength is not enough to produce a Townsend avalanche. The electrons just drift until they get close to the anode, where a strong field allows avalanche multiplication to occur. In this way each electron is multiplied by approximately the same factor (up to about a million) independent of the distance it has covered in the low-field 'drift region'. If the field strength everywhere is below a critical value, Townsend avalanches do not occur at all, and the detector operates as an ionization chamber. If the voltage (and therefore the field strength) is too high, the degree of charge amplification tends to a maximum value, and all pulses from the chamber have the same amplitude, so the detector operates as a Geiger-Mller counter. [11]
Because of the greater movility of the electrons, the avalanche has the form of a liquid-drop with the electrons grouped near the head and the slower ions trailing behind.
If α is the mean free path of the electron for a secondary ionizing collision, then α is the probability of an ionization per unit path length. This is better known as the first Townsend cofficient. If there are n electrons, then in a path dx, there will be

$$dn = n\alpha dx \tag{2.3}$$

new electrons created. Integrating, this yields the total number of electrons created in a path x,

$$n = n_0 exp(\alpha x) \tag{2.4}$$

where n_0 is the original number of electrons. The multiplication factor is then

$$M = n/n_0 = exp(\alpha x). \tag{2.5}$$

Physically, the multiplication factor is limed to about $M < 10^8$ or $\alpha x < 20$ after which breakdown occurs. This is known as the Raether limit. The multiplication factor or gas gain is of fundamental importance for the development of proportional counters. For this reason, various theorical models have been developed for calculation α for different gases. A very early model by Rose and Korff, for example gives

$$\frac{\alpha}{p} = A \exp\left(\frac{-Bp}{E}\right) \tag{2.6}$$

where A and B are constants depending on the gas.
In figure 2.5 is shown different issues. In the part called FIG.1 shown a cross-sectional view of a proportional counter tube. In FIG.2 illustrates the after-pulsing phenomena with a pure xenon-filled tube as described in connection with FIG.1. In this particular case, the incident radiation was manganese K-alpha with an energy content of 5.9 keV, and potentials of 1850 V, 1900 V and 1950 V were applied to the tube in succesion, producing on the face of an oscilloscope coupled to the output of the porportional counter the three pulse patterns illustred in FIGS. 2a, 2b and 2c, respectively.

2.6 Multiwire Chambers

2.6.1 Multiwire Proportional Chamnbers

In Multiwire Proportional Chambers (MWPC) the principles of the proportional counter are applied to large-scale detectors. MWPCs consist of a surface of anode wires that are placed parallel between two cathode plates. A scheme of such a detector is shown in figure 2.6. The distances between the wires are typically ≈ 2 mm and the distance between the wires and the cathodes is 3- to 4-times that long.

By applying a high voltage between the wires and the cathodes one obtains an electrostatic field that is nearly identical to the one of cylindrical capacitor in the vicinity of the wires and almost homogenous near the cathodes. The electrical field inside a MWPC and its equipotential lines are depicted in figure 2.7.

Electrons released by the incoming particles drift towards the nearest wire. Each wire behaves as a proportional counter and is read out individually. The charge accumulating on the anode wires determines the pulse height, and depends on the gas used, the voltage applied, and geometrical parameters of the chamber. The pulse height is a measure of the energy loss of the particles in the gas and can therefore be used for particle or momentum identification.

The MWPCs can also be used to measure the trajectory of a particle. The coordinate perpendicular to the direction of the wires can be determined by identifying the anode which detected the particle. However, if the path of a particle is not parallel to the detector plane, more than one of the wires will detect it. This is called cluster formation and is shown in figure 2.8. In this case, algorithms have to be used to determine the exact position.

To also obtain the coordinate parallel to the wires there are different techniques:

- Several planes of anode wires with different orientations can be used.
- The signales of the cathodes, which in these cases have to be arranged as pads or as stripes perpendicular to the wires, can be read out as well.
- The signals of the anodes can be read out from both sides. By comparing the pulse heights on both sides the exact position the particle

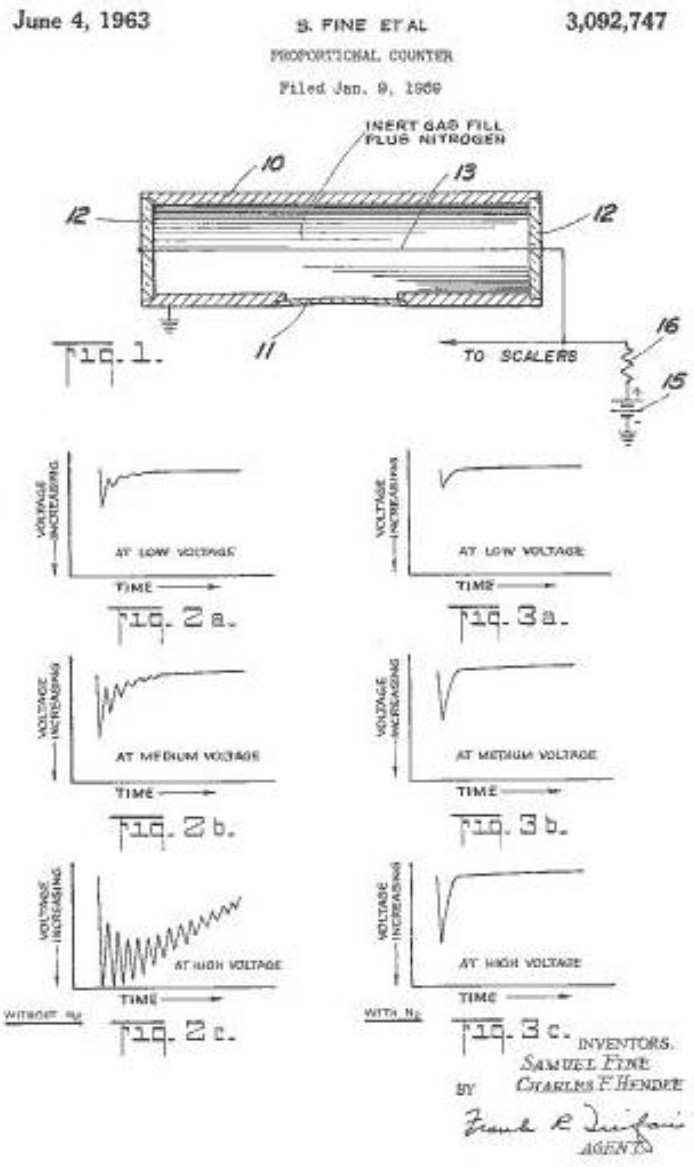

Figure 2.5: *Scheme of a proportional counter and results from experiments. (source: [9])*

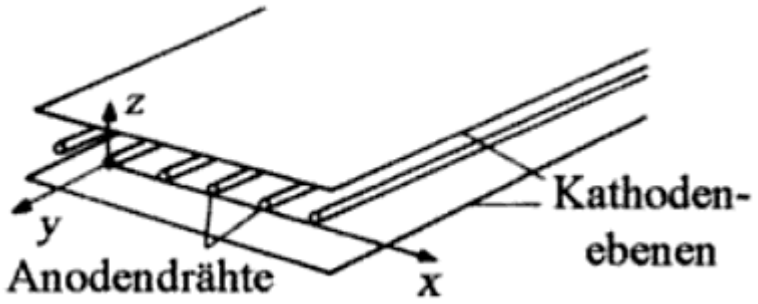

Figure 2.6: *Diagram of a Multiwire Proportional Chamber. [13]*

was detected can be determined.

Multiwire Proportional Chambers have extremely high detection efficiencys of nearly 100 %.

2.6.2 Multiwire Drift Chambers

Multiwire drift chambers are similar to MWPCs, however, the position of a particle is determined by the drift time the electrons take until they reach the anodes. The entire chamber is divided into a drift region, in which the electrical field is homogeneous, and the amplifying region. This done with the help of a grid which is set to a constant potential.

Incoming particles cause the production of free electrons. These move with a velocity of typically $\approx 50\frac{\mu\mathrm{m}}{\mathrm{ns}}$ in direction of the electrical field through the drift region, before they enter the amplifying region where they cause secondary ionisations. To determine the time of the primary ionisation detectors with a fast response time, e.g. scintillators are used.

The advantage of this kind of detectors compared to MWPCs is that the spatial resolution does not depend on the distance between the wires. Also, since there are fewer wires, the mechanical stability is higher. However, since it takes the electrons some time to drift towards the wires, the reaction time of the Drift Chambers is not as good as the one of MWPCs.

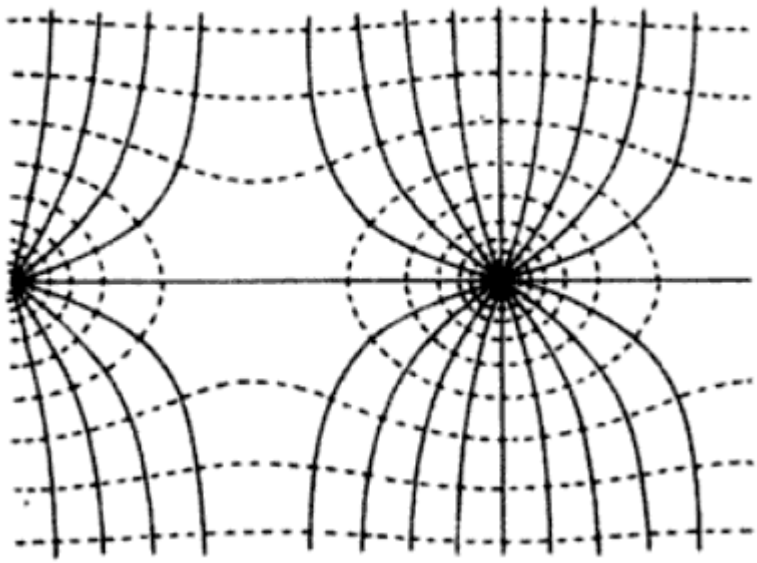

Figure 2.7: *The eletrical field inside a MWPC. The dotted lines are the equipotential lines. [13]*

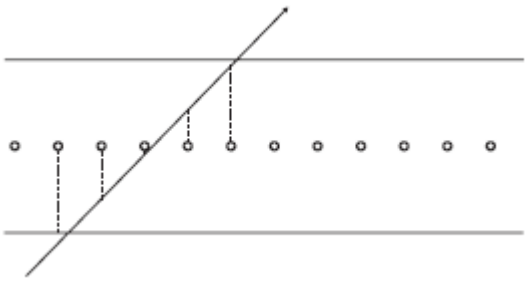

Figure 2.8: *Cluster Formation in a MWPC. [14]*

Chapter 3

Parallel Plate Avalanche Counter

The parallel plate avalanche detector is particularly useful in applications involving heavy charged particles where the associated radiation damage in solid-state detectors may prohibit their use. The parallel plate avalanche counter (PPAC) consists of two parallel plate electrodes separated by a gap that is kept as small as possible for best timing information. An other configuration use fine mesh grids instead of solid plates to reduce their thickness. The electrodes are enclosed in a container in wich a proportional gas is introduced and a homogeneous electric field is produced between the plates which are under conditions of relatively low gas pressure.
If a charged particle cross the gap between the plates, it leaves a trail of ions and electrons which are multiplied through the usual gas multiplication process. The electrons formed nearest the cathode are obviously subjected to more multiplication than those formed near the anode. Maximum gas gains of the order of 10^4 are possible.
Because any typical output pulse contains a mix of gas amplification factors, the energy resolution is seldom better than about 20%. Nonetheless, this performance is often adequate to separate different types of particles with widely different specific energy loss. The parallel plate avalanche detector can also be made to yield two-dimensional position information by using appropriately patterned electrodes.[7]

Chapter 4

Time Projection Chamber

In many experiments around the world it is of great importance to determine several properties of charged particles from collisions in a single detector. For simultaneous particle identification and momentum measurement the time projection chamber is a useful device. The most prominent installations of this kind of detectors can be found at RHIC (STAR TPC)[15] and at CERN (ALICE TPC)[16].

A typical TPC design consists of a large barrel shaped gas container, which holds the drift gas. It is installed around the beam line at the intersection point, where particle collisions take place. In the barrel a high voltage is applied between a center membrane and the barrel end caps, so that a uniform electric field gradient is created. The end caps of the TPC hold the actual particle detectors. An additional magnetic field can be introduced by wrapping the time projection chamber in a solenoidal magnet. In fig. 4.1 a schematic drawing of the STAR TPC at RHIC is shown.

In order to identify particles and determine their momentum, the exact trajectories of the particles from the intersection point through the TPC have to be reconstructed. From the shape of these tracks, which are in first order approximation of helical geometry (cf. fig. 4.2), the particle momentum can be derived. Taking into account second order effects like ionization energy loss per unit length also allows to identify particle types.

For accurate particle tracking several points in space must be recorded for each trajectory, so that a model path can be fitted to these points. The three coordinates for each point are determined by different mechanisms. Lets assume cylindrical coordinated where the z axis is pointing longitudinally along the beam line and the angle θ describes the azimuthal direction. The r coordinate is measured with respect to the distance from the beam pipe. When a charged particle from a collision traverses the barrel, gas atoms are ionized along its path. The applied electric field accelerates the electrons towards the

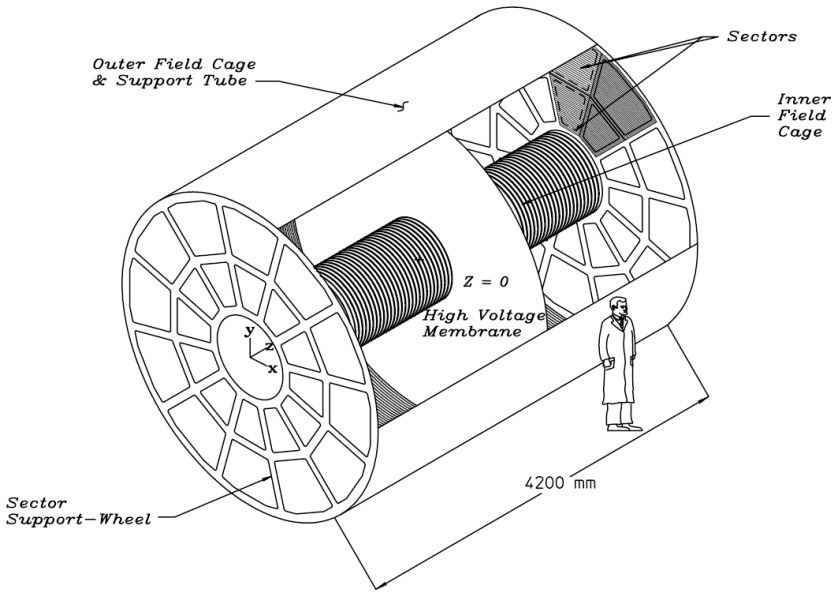

Figure 4.1: *Schematic drawing of the STAR TPC at RHIC. It surrounds the beam-beam interaction region. The collisions take place near the center of the TPC.[15]*

end caps of the barrel. Specialized MWPC (Multi wire proportional counters) detectors with high spatial resolution and accurate timing are used to determine the r and θ coordinates directly. To gain information about the longitudinal distance, the drift time of ionized electrons from their origin to the end cap detectors is measured and then divided by an average drift time for electrons in the setup. In the case of the STAR TPC the employed drift gas is P10 (a mixture of 90% argon and 10% methane) with an average drift velocity of $5.45\,\mathrm{cm}/\mu\mathrm{s}$.

Particle momentum can be determined by fitting circles through the r and θ coordinates of the intersection point and the data points along a particle's trajectory. The radius of the circle and its angle with respect to the beam line then hold information about the particle momentum dependent on the applied magnetic field.

For particle identification the energy that the particles lose to the TPC gas is measured along their trajectory. This results in a characteristic value of $\mathrm{d}E/\mathrm{d}x$ for each type of particle. This identification using TPCs is only possible in the low momentum range, as can be seen in fig. 4.3. Protons and pions can be seperated from each other up to 1 GeV/c.

The tracking resolution is limited by the spacing of the wires and pads in the MWPCs as well as by transverse and longitudinal diffusion of the

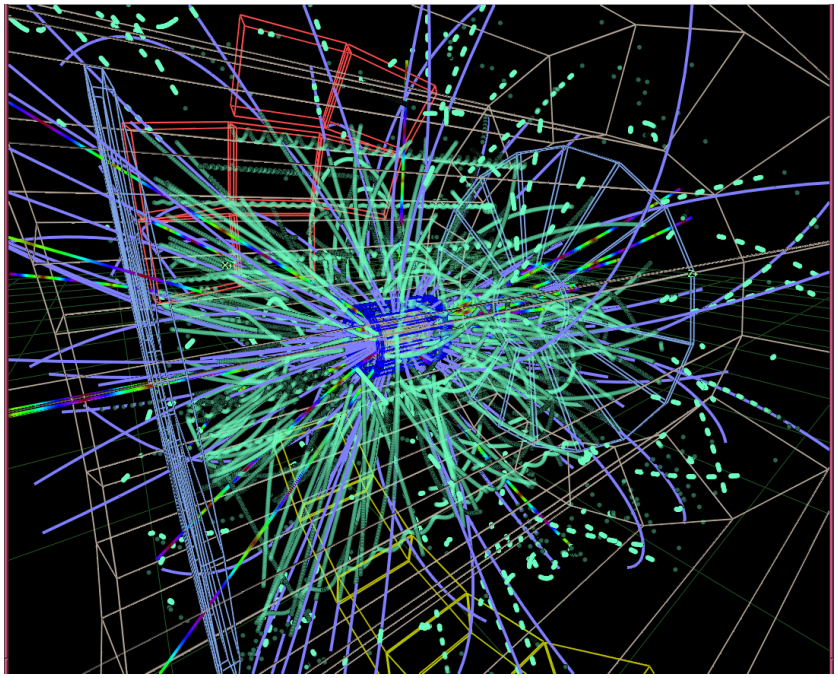

Figure 4.2: *Simulated event in the ALICE TPC. Reconstructed particle tracks with their typical shape are displayed.* Source: http://www.gled.org

secondary electrons in the drift gas. Also the deviations from uniformity of the magnetic field cause tracking errors. Very careful design and calibration of the detector minimize these effects. Several less important effects like space charge or realistic geometrical shapes have to be taken into account as well. For the STAR TPC the overall tracking efficiency is above 70% for particle momenta above 300 MeV/c.

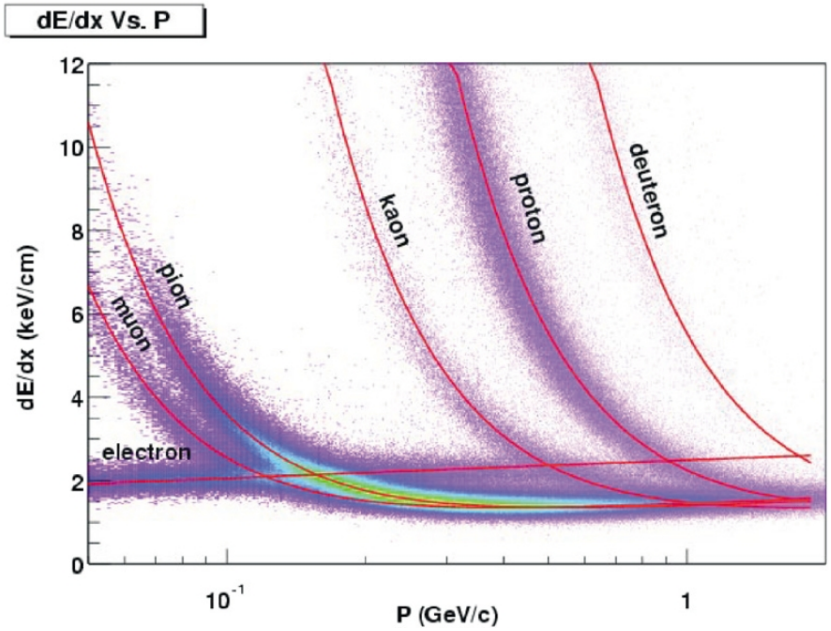

Figure 4.3: *The energy loss distribution for primary and secondary particles in the STAR TPC as a function of the momentum of the primary particle. The magnetic field here was 0.25 T.[15]*

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