Physical and techological principles of particle detecting instruments in satellites

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Contents

1 INTRODUCTION

Measuring different properties of particles in space has applications in space and atmospheric science. It is important to choose the right type of instrument for the mission at hand as different detectors have very different properties. Some things that need to be taken into account in satellites are cost, size, type of particles that need to be measured and what properties should be measured, for example mass or energy or just count of the particles.

To achieve accurate or more complex measurements careful study of physical effects and theory is required in addition to rigorous empirical testing and calibration of the detectors used.

This thesis is going to give brief introduction to some of the methods used for particle detection and some basic physical principles related to them. Commonly used detectors will also be introduced in addition to some example instruments and filtering techniques to support the theory.

2 THEORETICAL BACKGROUND

2.1 BASIC PARTICLE PHYSICS

The detection of particles is based on them being able to interact with detector material through some mechanism. This thesis will mostly deal with charged particles as their interaction with matter is a lot simpler than for neutral ones and often neutral particles are converted to charged ones with some process. The theoretical background presented in chapter 2 is based on great books [1] and [2].

2.1.1 Heavy charged particle interactions

Heavy (compared to electrons) charged particles interact primarily by coulomb force between the particle and orbital electrons of other particles. Interacting with nucleus is also possible but can be disregarded with detectors because it's less prominent [1]. Particle interacts simultaneously with many electrons at the same time causing an impulse that could excite or ionize the atom. Maximum transferable kinetic energy is defined by formula

$E_{kin}^{max} = \frac{2m_e p^2}{m_0^2+m_e^2+2m_e(E_{kin}+m_0c^2)/c^2}$, where m_e is the mass of electron, c is the speed of light, p is momentum, m_0 is the rest mass of interacting particle and E_{kin} is the kinetic energy of the moving particle [2]. For example, for a proton with kinetic energy of 1 GeV, the maximum transferable energy to electron is roughly 1/460 of its kinetic energy.

Typical maximum transferable energy of a particle is around 1/500 of its energy per nucleon, so multiple ionizations or excitations must happen [1]. Heavy charged particle's path through medium tends to be relatively straight, because interaction with electrons only slightly changes its path [1].

2.1.2 Interaction of fast electrons

Electrons lose energy at slower rate than heavy charged particles. The electrons path through the absorbing medium is chaotic because its mass is the same as the electrons it's interacting with [1]. Energy can also be lost by radiation via process called bremsstrahlung or braking radiation, which happens when charged particle is accelerated or decelerated.

Bremsstrahlung also affects heavier ions, but it's only significant for electrons in the context of satellite detectors [1].

Electrons can scatter away from the detector much easier than heavy charged particles so that they are not detected at all or are only partially detected. This is called backscattering and is most prominent in high atomic number absorbers and in case of low energy electrons [1].

2.1.3 Interactions of neutrons

Neutrons don't have charge, so they cannot interact by coulomb force. Neutrons can travel through relatively long distances without any interaction with detector matter and for this reason can be missed entirely by a detector [1]. Neutrons are often converted into secondary charged particle, which can be detected more easily, by some mechanism [1].

2.2 DETECTION

Most detectors either detect electrons or ions directly, electrons generated by other particles through some secondary processes or charge carrier pairs generated in detector medium. Physics behind charge carrier pairs in a medium are examined more closely in this chapter and direct detectors will be introduced in applications in chapter 3.

2.2.1 Ionization counter with gas medium

When a charged particle traverses through matter, it can ionize and excite electrons of the matter. This mechanism can be used to build a detector called an ionization counter.

In the simplest case an ionization counter is a detector with some counting medium with anode and cathode on both ends of the medium and voltage applied between them to collect charge deposited by incoming radiation. We will first look at ionization chamber, which refers to gaseous medium, but most of the same principles can be applied to liquid and solid-state media as well. The medium needs to be resistive so that having a voltage difference over it is possible.

When a charged particle enters the detector, it will ionize the atoms of the detector material if it has enough energy demonstrated in figure 1. If all the energy gets absorbed to the medium, energy of the particle can be measured, otherwise the detector is mostly used for counting the number of particles or more accurately, released pulses of electron charge they create [1]. A small voltage drop between cathode and anode happens when charge carriers reach either end. This voltage changes over time as particles take different time to reach the electrodes resulting in a pulse signal. High energy particles can give electrons enough kinetic energy to cause secondary ionizations or excitations in the medium [1]. Excitation is usually not detected, but it can be ignored if it's not the dominating mechanism for losing energy [2].

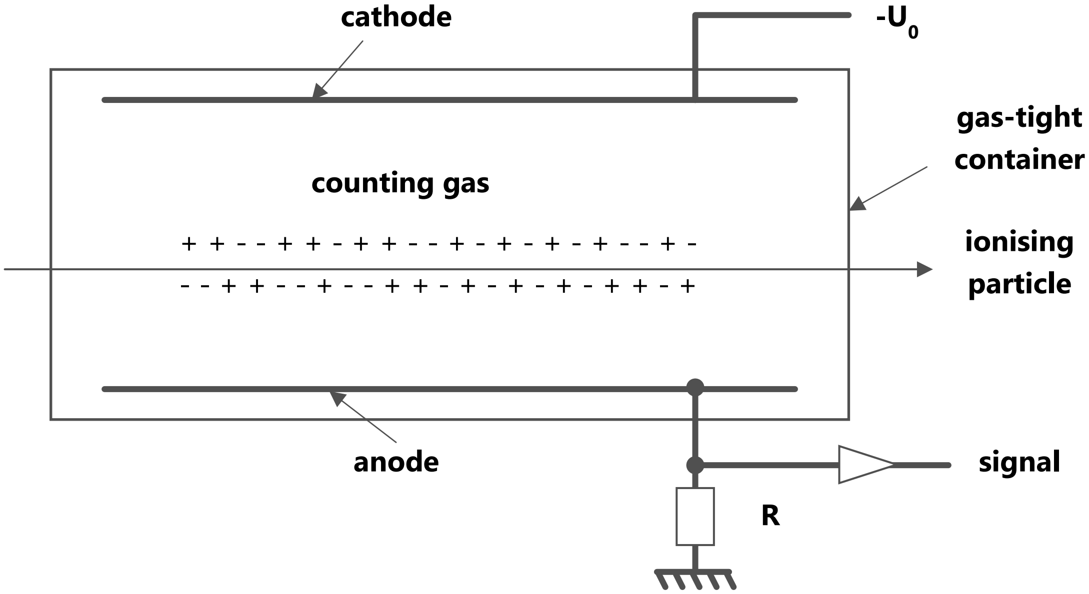

Figure 1 Basic schematic for gas ionization counter. Illustration is based on [2] figure 5.1

It does not matter by which mechanism the charge is created [1], the amount of ion-electron pairs formed is still proportional to the energy of the incoming particle as long as the particle is fully stopped by the detector material. The energy required per ion-electron pair produced or more precisely ionization potential of the detector material determines how much charge an incoming particle with certain energy will release. The smaller the ionization potential, the better the energy resolution [1].

Amount of charge generated by same energy particles fluctuates somewhat randomly. Simple way to describe the spread is by Poisson distribution [1], where standard deviation is equal to square root of the charge amount. It has been observed that the deviation is actually smaller than predicted, so empirical detector specific constant called Fano factor is introduced that gives closer estimate of the deviation [1]. Deviation is smaller in heavy particles and bigger in electrons.

When the electric field between cathode and anode is strong enough, charged particles entering the detector and the secondary particles generated by it may gain enough energy to cause further ionization. This causes amplification of the signal typically around 10^4 or 10^5 in gas detectors [2].

Collection time of charge is an important characteristic of the detector and depends on applied voltage and the type of detector among other things. Quick collection times are required in high intensity environments in order to distinguish entering particles from one another [1]. Collection times also need to be fast enough that ion-electron pairs don't recombine and therefore go undetected [1].

2.2.2 Other media

Using liquid instead of gas as the medium has the advantage that the material density is much larger, so smaller volumes of medium can be used for the same absorption efficiency. Ions in liquids, however, have very slow travel times and noble gases in liquid form require extremely low temperature [2]. Other liquids can be used, but they need to be nearly sphere symmetrical to allow for good drift qualities (for example fast ion and electron velocity in material) and contain very few electronegative impurities [2].

Solid-state detectors mostly follow the same basic principles as gaseous and liquid ionization counters. Instead of ion-electron pairs, electron-hole pairs are produced. Energy required to form an electron hole pair is a lot smaller allowing better energy resolution and detection of lower energy radiation [1]. Solid-state detectors will be examined further in the chapter 2.3.

2.2.3 Modes of operation

Particles entering detectors usually have very short stopping times, sometimes however particles are entering the detector so often that the pulses they generate are indistinguishable from one another [1]. Thus, different modes of operation are required for detectors in different environments.

In pulse mode the full charge deposited by entering particle is recorded and collected. This mode allows calculating energy of an individual particle, however this isn’t feasible in high intensity fluxes because individual pulses may be mixed [1].

In pulse counting mode all spikes above some threshold are registered regardless of their energy [1]. It is useful for determining the intensity of radiation if the specific energy is not needed.

In current mode an average over certain time is taken so that charge produced by multiple events are averaged [1]. This can give an average energy of particles entering the detector over certain timeframe.

A similar technique to current mode is the mean square voltage mode (MSV) where the signal is proportional to event rate and square of charge produced, this simply means that high energy particle will produce higher than normal pulse when compared to lower energy particle, so their pulses are more easily differentiated. This makes MSV mode useful in environments where there are different types of radiation present [1]. MSV could be used to enhance high energy particle signal from background radiation for example [1].

2.3 SEMICONDUCTORS

2.3.1 Semiconductor physics

In solids a continuous energy band is formed from discrete electron energies of the atoms. Similar to discrete situation only a certain number of electrons are allowed on the band. Highest energy electron band that is fully filled is called valence band and lowest energy band that is half full or empty is called conduction band. The zone between the bands is called forbidden band or energy gap.

As the name implies, in the conduction band electrons move relatively freely between atoms and ions, and drift in the lattice when subjected to a net electric field, therefore conducting electricity. Materials with nearly empty conduction bands are very resistive to electron movement, some of the materials are called resistors and some semiconductors depending on the magnitude of their resistance. In resistive materials the electrons moving in conductance band are often ones excited from the valence band leaving behind a hole to the valence band. Hole carries positive charge but is otherwise similar to electron and moves relatively freely in electric field [2]. The main difference between resistors and semiconductors is the width of the forbidden zone, where typically the forbidden zone in semiconductor is significantly narrower, allowing lower energies to excite electrons to conduction band.

It is possible for valence electron to gain enough energy from thermal energy to jump from valence band to conduction band [1]. This happens more frequently in semiconductors due to their narrower forbidden zone leading to higher conductivity. Both holes and electronics contribute to conductivity, but they have different mobilities depending on material and temperature [1].

Semiconductors can be doped with impurities to alter their properties, for example by adding phosphorous with 5 outer electrons to silicon crystal with 4 outer electrons [1]. Silicon naturally forms four covalent bonds between other silicon atoms binding four outer electrons, which causes the fifth outer shell electron of phosphor to become loosely bound [1]. It is easily excited to conduction band without adding a hole to the crystal. In this type of crystal electrons are majority carriers and holes are minority. These are called n-type semiconductors. Similarly, a doped semiconductor with holes as majority carriers are possible to make for example by adding boron impurities to silicon crystal [1]. Heavily doped materials have high conductivity.

2.3.2 Semiconductor detector

Using semiconductor as the detector material is the most common choice in the context of solid-state detectors. Resistors could in theory be used as ionization counters, but low hole mobility makes them undesirable [1]. Plain semiconductors aren't perfect either, as they have relatively high dark currents [2]. Detector material acts as an ionization chamber. Similar to the way gas atoms get ionized in gaseous chambers when hit by particles, electron-hole pairs are formed in semiconductor crystals. It is possible to collect the generated charge with electric field [2].

Ionization energy in the context of semiconductor detector means the energy it takes to create an electron-hole pair. One of the biggest advantages of semiconductor detectors over gaseous ones is their lower ionization energy. Typical ionization energy for a gas detector would be around 30 eV, while for silicon or germanium detectors it is around 3eV [1]. This leads to greatly increased numbers of electron-hole pairs produced per incoming particle which in turn improves statistical accuracy of the energy and energy resolution.

Since there is electric field applied to collect charge deposited by entering particle, there is also leakage current caused by electron-hole pairs that are formed spontaneously, that needs to be filtered from the results. For example, a detector with 5000 Ω resistance and a 500V collection voltage generates large (when compared to typical signal currents) leakage current of 0.1A [1].

2.3.3 PN-junction

When p and n type semiconductors are combined, the excess electrons from n type semiconductor are merged to the excess holes of the p-type semiconductor at the interface of the two materials. Negative ions formed in p-type semiconductor side of the junction have a negative net charge and positive ions in n-type semiconductor side have a positive net charge. An electric field is formed between negative and positive ions that pulls electrons and holes to away from the interface, creating a zone with low amount of charge carriers called the depletion region demonstrated in figure 2 [2].

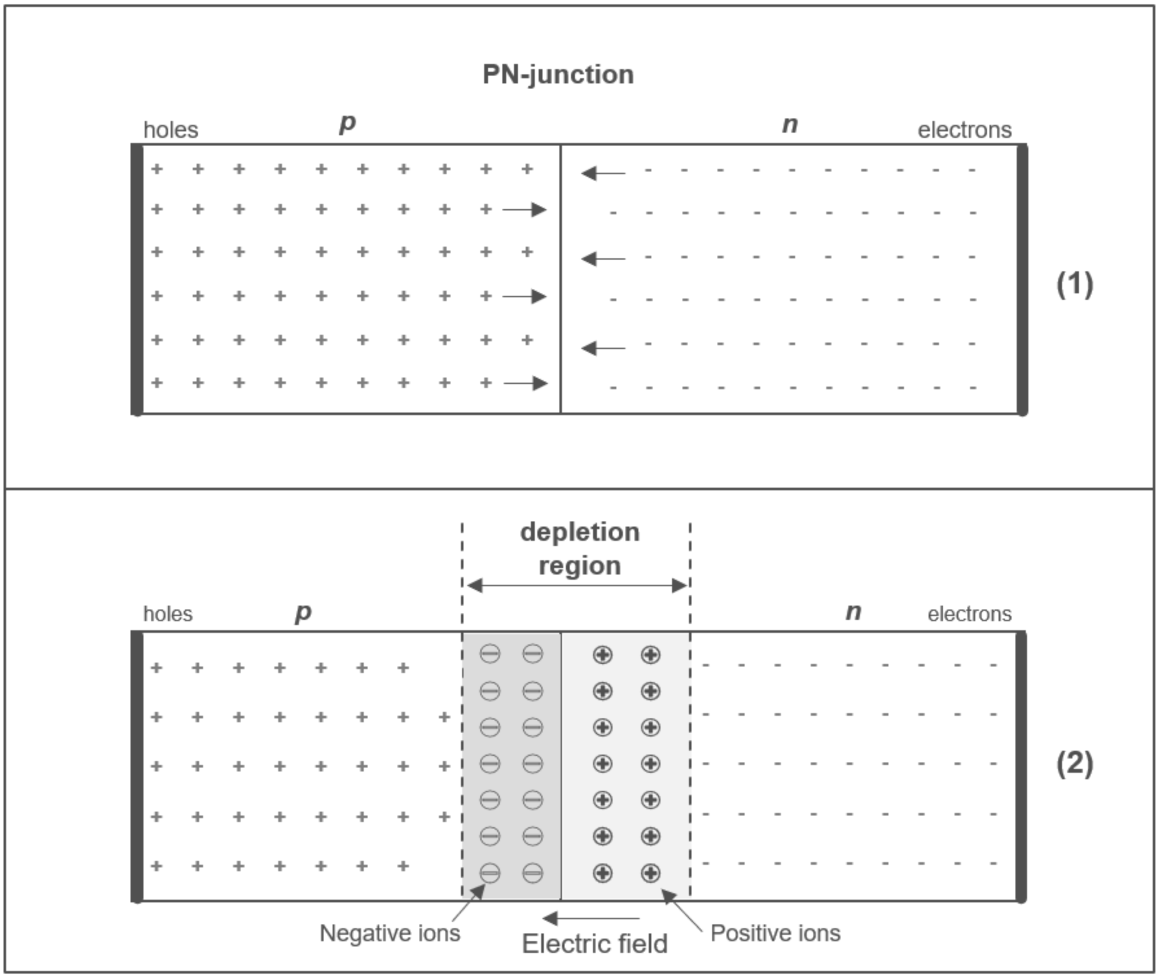

Figure 2 (1) Electrons and holes are merged at the interface of p and n-type semiconductors. (2) Negative and positive ions formed at the interface have positive and negative net charges creating an electric field between them that prevents electrons and holes from moving through it, creating a zone called depletion region.

It is not possible to simply just stack n-type semiconductor on top of p-type due to atom level contact issues, so pn-junction is usually created by first creating p- or n-type crystal and doping one side of crystal with the opposite type impurity [1]. Many different manufacturing methods exist for different configurations of pn-junction detectors including diffused junction detectors, surface barrier detectors, ion implanted layers, fully depleted detectors and passivated planar detectors. Their differences won't be discussed in detail here, but a good explanation can be found in [1].

When an ion or photon interacts with depletion layer a charge proportional to their energy is released that can be collected with an electric field [2].

Depletion region has good properties for a detector as it has very high resistivity due to missing charge carriers [1], so leakage current is smaller. Electrons and holes created in the depletion region will be swept to opposite sides of the pn-junction creating a signal. An external voltage is often applied to pn-junction because depletion region is quite narrow otherwise and naturally occurring contact potential of around 1V is not enough to move electrons and holes fast enough [1].

Voltage can be either in forward or reverse bias. In forward bias the junction conducts more easily and in reverse the junction becomes less conductive and the depletion region becomes wider up to a limit. It is possible to create partially or fully depleted detector this way [1]. Wider depletion region also reduces capacitance of the detector, producing a more accurate signal. There is a dead layer often associated with these types of detectors where detection is inefficient, which radiation or particles must penetrate to reach the active volume of the detector [1].

2.3.4 Trapping

Some impurities have their energy levels near the middle of the forbidden band. These are called deep impurities as opposed to shallow impurities that are closer to conduction band [1]. Holes and electrons can get trapped for a long time in these deep impurities causing the trapped electron or hole not traveling to anode or cathode of the detector fast enough [1]. Some deep impurities can act as recombination centers, trapping both electrons and holes and causing them to recombine leading to loss of charge carriers [1]. These impurities increase the need to collect charge fast enough to get a reliable signal [1].

2.3.5 Components and aging

Especially silicon semiconductor detectors are susceptible to radiation damage [2]. High energy particles or just plain radiation may damage the detector over time by creating interstitial defects, vacancies or adding impurities [2]. The radiation damage can be divided into surface and bulk damage. Interstitial damage in the bulk of the detector increases leakage current in the detector and the defect may also trap charge creating space charge effects, which may require changing the operation voltage [2]. Damage in the surface can lead to charge build-up causing increased surface currents [2]. On the other hand, damage near surface can increase the width of dead layer (the non active area at the detector surface), reducing the detector’s ability to detect low energy radiation [3]. Increased leakage current causes increase in noise in the detector signal and therefore worse energy resolution and it may also reduce voltage across the detector [3]. Low energy protons are especially damaging to the detector [3].

Leakage currents in the bulk can be reduced by keeping the device cool [2]. Some of the defects disappear with time, this process is dependent on temperature as well [2]. The detector may even be fully repaired by heating the device above certain threshold, called annealing temperature [2].

3 SATELLITE IMPLEMENTATIONS

According to [3] There are relatively few detector types used in space physics to detect particles, either charged or neutral. These include Faraday cup devices to measure the current associated with charged particle distributions, windowless electron multipliers such as channel electron multipliers (Channeltrons), microchannel plates and solid-state or scintillation detectors used for higher energy particles [3].

The choice of particle detector and design for a satellite depends on multiple factors, for example what are the accuracy requirements and what needs to be measured. For example, measurement of neutral particles usually requires an ionizer to make them measurable with an electronic device [1]. Measuring electrons often requires that protons are filtered from the detector to avoid neutralizing the electron current.

3.1 FARADAY CUP

3.1.1 Design

Faraday cup is a simple current collector with good accuracy and resistance to degradation. Faraday cups are useful for calibration of more precise instruments, because of their long-term stability in space environments [4]. The most basic design is just a hole drilled into, but not through, a metal plate with electrometer attached [5]. This isn’t practical for most real-world problems, though, as more accurate approach is usually required, but the simple principle design makes them cheap and easy to produce.

3.1.2 Example instrument from Wind satellite

In this thesis we are examining Faraday cups from Wind satellite described in [6] as an example instrument. The Faraday cups from Wind satellite were designed for measuring distribution functions and basic flow parameters of the ion component of the solar wind [6]. In front of two side by side collector plates, there is a dc biased suppressor grid to prevent secondary electrons from escaping and above that a modulator grid with time varying positive potential [6]. A square wave varying between set voltages at 200Hz frequency is applied to the modulator grid [6]. This allows the counting of ions between the set voltage range, for example if the voltage varies between 150V and 159.75V, the current changes, because more particles are filtered by the higher voltage on average. This current difference feeds charge to capacitively coupled preamplifier giving the amount of charge between the voltage range which is directly proportional to energy range as well [6]. The spacecraft is also spinning allowing it to determine velocity distribution in different directions [6]. Current integration from collector plates is done synchronously with the modulator. Collector plate is capacitively coupled to a preamplifier that is then fed to three additional amplifiers in parallel [6]. All amplifier outputs are synchronously read and the ones that aren't saturated are chosen for further calculations [6].

3.1.3 Considerations

When designing a Faraday cup, one must consider its accuracy. First thing to consider is how large the Faraday cup should be in order to prevent high energy particles escaping by penetrating the cup [7]. Losses from backscattering can be reduced by several methods, for example by making the bottom of the cup from low atomic number material or using a magnet or an electric field at the cup entrance to stop low energy particles from escaping [7]. Losses due to leakage currents can be minimized with proper insulation and slide back voltage, keeping the cup close to ground potential [7]. There is a balance however as biasing the cup to certain voltage can prevent secondary electrons from escaping [3]. If you are measuring electron current, losses caused by positive ions entering and neutralizing charge can be reduced by preventing positive ions from entering with proper filtering technique [3].

3.2 CHANNEL ELECTRON MULTIPLIER

3.2.1 Design

Channel electron multiplier (CEM) channel is a tube with a large length compared to its diameter. When a particle hits the end of the tube a cascade of electrons is produced in the tube. A bias voltage of few thousand volts is used to accelerate electrons in the tube to create further cascades [8]. The cascade of electrons is easily measured and as the name suggests CEM works as an amplifier. A single incoming electron can release more than 10^9

secondary electrons [8]. Sometimes particles and electrons ionize residual gas in the tube. The positive ions thus formed are affected by the bias voltage in the tube and may travel back to the entrance of the detector causing another cascade. This can cause noisy and unstable signal, which is usually prevented by making the tube curved so the positive ion will hit the wall before gaining enough momentum to cause a cascade [3].

Channels are usually made from lead glass that has its secondary electron emission characteristics optimized [9]. The walls of the channels are semiconducting for high resistivity and also to allow charge replenishment [9]. Recovery time of the channel depends on voltage, number of charges lost and the resistance of the tube [8]

3.2.2 Considerations

The channel electron multiplier will "detect" any particle or radiation that can excite electrons from the channel wall. Since excited electrons are being detected instead of the incident particle or radiation, it's impossible to determine what caused the cascade event without some kind of filtering or other means of identifying the incoming particle beforehand. Electron multipliers are typically used for counting purposes [3]. Channel surface also deteriorates over time due to material changes and surface contamination [3].

3.3 MICROCHANNEL PLATES

Microchannel plate (MCP) is an array of miniature channel electron multipliers oriented to the same direction. The operating principle is the same as in CEM. The advantage of using MCP instead of CEM is it's 2-dimensional imaging capability [10], typically an array of anodes is used to detect the electron showers. Anodes are then connected to amplifiers and counting circuits.

The top and the bottom of the channels are connected by conducting surfaces that serve as the input and output electrodes. Channels amplify the effect of an incoming particle or energetic photon by causing multiplying cascades of electrons down the channel. Electrical performance of the channel is not dependent on the absolute value of length or diameter, but their ratio, so MCP's can be made arbitrarily small in this regard, but diameter limits the maximum gain from the channel [9]. Microchannel plates function essentially as amplifiers and it's gain depends on bias voltage, geometric factors and initial energy of the secondary electrons [9]. As in CEMs the residual gas left in the channels can get ionized at high gains causing the ionized particle to hit the walls of the channel, sometimes causing a cascade of electrons if the ion gains enough energy [9]. For a straight channel this becomes problematic at high gains. As in a single CEM the problem can be circumvented by curving the channel to prevent ions from gaining critical energy to cause an electron cascade before hitting the wall. Although superior in aspects other than gain and cost of production [10] sometimes alternative solutions need to be used instead of curving. For example, in MCP Chevron device two plates where the channels point in different directions are stacked on top of each other causing positive ions to be trapped between the plates. Three stacks of MCPs is called a Z-configuration. Stacking MCPs allows the cascades to spread from one channel to multiple channels on the lower MCPs.

3.3.1 Considerations

A high gain is helpful in obtaining a better spatial resolution [9]. Highest possible gain can be achieved with chevron or Z-architecture, but at high count rates this can cause the image to be oversaturated due to cascades spreading from one channel to multiple channels in the lower stacks [9].

MCP needs to be operated in vacuum to prevent electrons from ionizing too many gas particles that could cause error to the measurements [9].

After each incoming particle, the channel must be charged before using it again, rendering it unusable for a short period [3]. The channels function individually so particles can still enter the detector without being missed as long as they don’t hit the same channel. At high fluxes MCP can get saturated and the results aren’t as reliable.

3.4 MASS SPECTROMETERS

Mass spectrometers use differences in particle mass to charge ratio to separate them. They can be used for example to determine plasma and gas composition in Earth’s atmosphere, ionosphere and magnetosphere. Two methods are generally used: separation in time and separation in space. A simplified version of each will be examined. There are many variants of each type spectrometer in use better described in [3]. Often an MCP or similar detector is used to do the actual detection and counting of particles.

3.4.1 Magnetic mass spectrometer

Force inflicted by magnetic field to a charged particle moving perpendicular to the magnetic field is proportional to velocity, charge and magnetic field strength and is equal to the centripetal force. We can thus obtain an equation [3]

$$\frac{m}{q}v = Br_M,$$

where m is the mass of particle, v it's speed, q is its charge, B the strength of magnetic field and r_M the radius of the particle path. When particles entering the detector are accelerated to certain energy and filtered to have certain speed (see chapter 4), the particle's mass/charge ratio can be determined based on where it hits a detector [3], for example an MCP. Double focusing magnetic mass spectrometer has been used in Rosetta orbiter [4].

3.4.2 Time-of-flight mass spectrometer

Time-of-flight analyzer measures the time it takes a certain energy particle to travel from one fixed point to another. From known energy and time, mass can be calculated. Often in real scenarios electrostatic analyzer is used to select which energy particles are allowed through to detector (see chapter 4). The start time could be determined by having a foil in front of the detector. When a particle passes through the foil, secondary electrons are emitted, which then trigger the start signal. Ions continue to travel until stop detector is hit. [3]

Time-of-flight type mass spectrometer is used for example in Rosetta orbiter [4].

3.5 SOLID-STATE DETECTORS

Detector thickness must be calculated so that particle's energy loss in the detector matches the desired maximum energy. Solid-state detector can be position sensitive if multiple readout electrodes receive the signal. This can also be achieved by using multiple detectors in an array. Solid-state detector is by far superior to other detectors in terms of accuracy and energy range for protons. For electrons a large percentage [3] will simply be reflected back without leaving all of their energy in the detector. Electrons also travel in chaotic paths inside the detector, making the energy loss patterns complex [1]. This makes it difficult to distinguish low and high energy electrons from one another and requires rigorous calibration and simulations to get accurate results [1].

3.5.1 Limitations

Pure silicon based solid-state detector thickness is limited with current manufacturing methods, so highest energy particles may just pass through the detector [3]. This can be circumvented by stacking multiple detectors on top of each other in a telescope architecture [3]. Sometimes an anti-coincidence detector is placed at the back of the telescope to detect if a particle passed through the telescope without transferring all its energy [3]. Solid-state detectors are also prone to radiation damage, introducing impurities into the crystal [3]. It is generally desired to restrict the access of unwanted particles to reduce radiation damage, this can be done easily for low energy particles by adding a foil to the instrument entrance with a known stopping power to reduce the amount of low energy particles, or using a curved entrance with electric fields allowing only certain energy range of particles to enter the detector while low energy particles hit the wall before detector and high energy particles just pass through. Lithium-doped silicon detectors can be manufactured to a higher thickness, up to 1 cm, this however reduces the energy resolution to ~30 eV in room temperature [3].

4 FILTERING TECHNIQUES AND GENERAL CONSIDERATIONS

It is typically useful to filter out particles that are not essential for the instrument objective, because they may cause measurement errors or cause the instrument to degrade faster. The general way to do this is by either stopping the particle or by altering their direction enough so they won't reach the detector. The number of particles can also be filtered by adjusting field of view of the device.

4.1 GENERAL FILTERING TECHNIQUES

4.1.1 Foil/plate

Using a foil or plate in front of the aperture is a way of filtering that prevents particles below certain energy threshold from entering the detector. The threshold can be calculated with Bethe-Bloch stopping power formula for heavy charged particles [2].

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

From the formula the most important factors to consider are that energy loss is affected by speed, electron density of the material, charge of the incident particle and mean excitation potential. A foil that lets through a particle with some energy and charge 1e may stop a particle with otherwise similar properties, but a higher charge.

Bethe has also created a stopping power formula for electrons similar to the one mentioned above. It should also be considered that because electrons have mass equal to electrons it collides with in the foil, this causes unpredictable scattering of the electrons and even high energy particles may be reflected backwards as mentioned before. This effect causes measurement error and may also subject other devices around the detector to unwanted electrons.

In figure 3 the stopping power of aluminum foil is illustrated for electrons. Stopping power consists of collision and radiation component. When the energies get higher, the collision stopping power becomes negligible while radiation stopping power increases significantly.

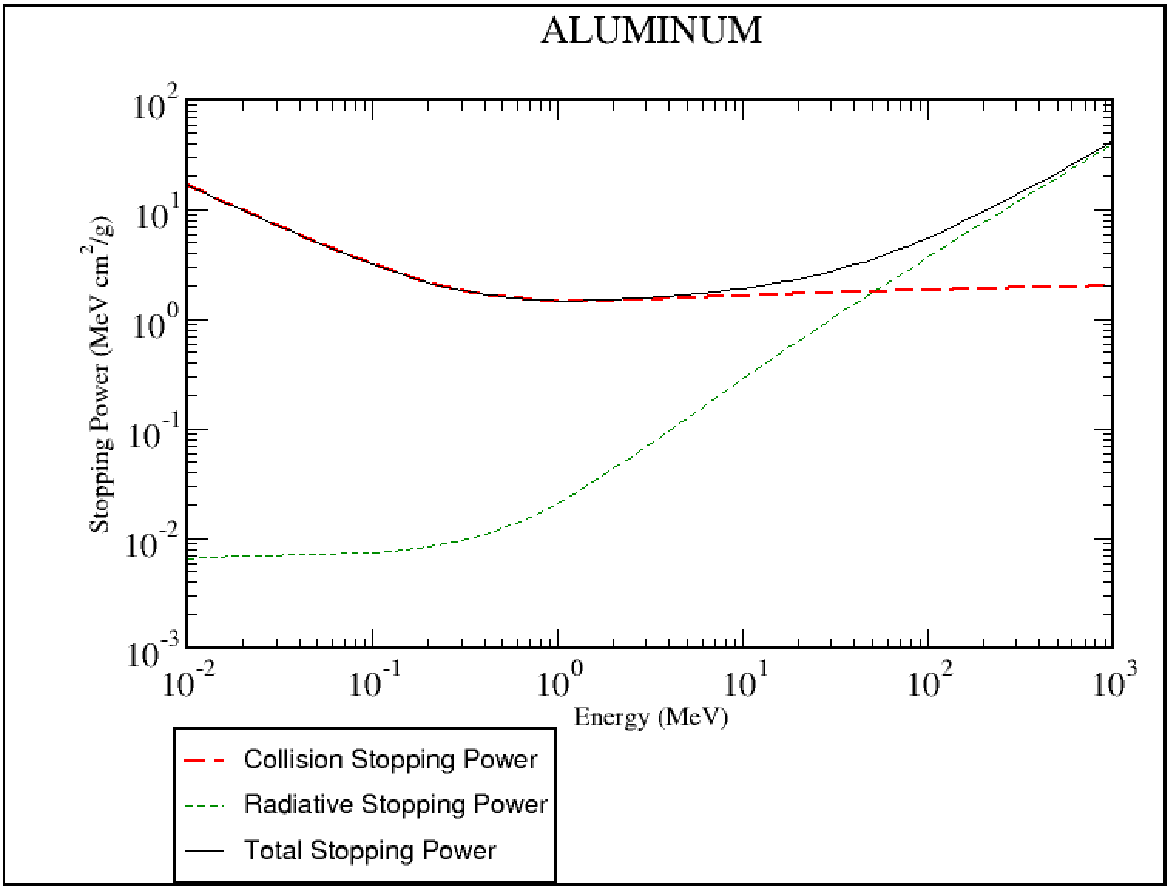

Figure 3 https://physics.nist.gov/cgi-bin/Star/e_table.pl

The advantages of using a foil are that it's possible to use almost arbitrarily thick wall and that they are cheap and easy to build.

4.1.2 Electromagnetic field

A more sophisticated filtering method is to use electric, magnetic or electromagnetic field to prevent certain particles from entering the detector. Using a simple electric field will accelerate a charged particle either to the direction of the electric field if the particle's charge is positive or to the opposite direction if the particle's charge is negative. This interaction follows equation $\vec{F} = q\vec{E}$, where $\vec{E}$ is the electric field strength, q is the charge of the partcile, $\vec{F}$ is force experienced by the particle. This makes it very easy to build a filter with well-defined energy threshold.

A simple magnetic field can also be used. Force inflicted by magnetic field is defined by equation $\vec{F} = q\vec{v} \times \overrightarrow{B}$, where $\vec{F}$ is force, q is charge, $\vec{v}$ is the velocity of the particle and $\overrightarrow{B}$ is the magnetic field. According to the equation, force is perpendicular to the plane containing $\vec{v}$ and $\overrightarrow{B}$ due to cross product and its direction is determined by the sign of the particle's charge. If $\vec{v}$ and $\overrightarrow{B}$ are pointing to same direction, their crossproduct is zero, which in turn means that magnetic field should be designed so that it is mostly perpendicular to the paths of the incoming particles for maximal force production. This will result in curved pathed demonstrated in figure 4, where magnetic field is pointing away from the viewer and particle starts with some speed in y direction. Particles in figure are otherwise similar, but their speeds are different.

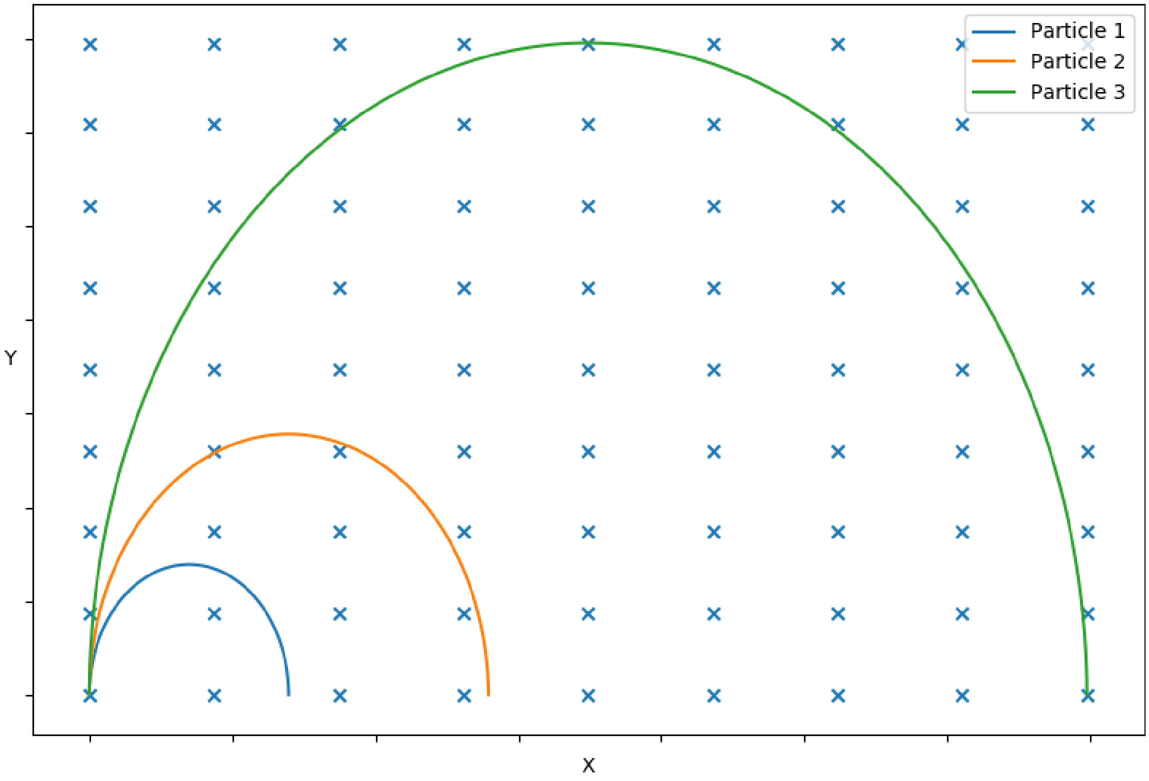

Figure 4 Particle paths become curved in magnetic field, when particle speed has component perpendicular to magnetic field. Particle 1 has the lowest speed, particle 2 second lowest speed and particle 3 has the highest speed.

Electromagnetic fields contain both electric and magnetic fields, but both previously mentioned equations still hold. In electromagnetic fields acceleration experienced by a charged particle is inversely proportional to its mass. This means that electrons are more easily filtered than ions by electromagnetic fields.

Electromagnetic field has the advantage that it can be easily calibrated in flight to filter out different energies. Electrons also won’t scatter from electric field like they would from foil, so the side-effects of filtering are easier to estimate. The disadvantage at least in straight architectures is that it’s difficult to generate an electric magnetic field strong enough to filter higher energy particles.

4.1.3 Curved structure and electromagnetic field

Using a curved structure presented in figure 5 allows filtering high energy particles in addition to low energy particles. Only particles with some energy that experience centripetal force that is roughly equal to force caused by the electric field are able to pass through the curve. This kind of system is sometimes called electrostatic analyzer. Particles with different charge react differently to the electric field. The electric field in curved pipe will only allow either negative or positive charges to enter, because the electric field accelerates the other charges to the wrong direction, causing them to hit the wall. Amount of charge also influences the path of the particle, because force caused by electric field is proportional to particle’s charge. At the end of the curve, there may be an array of detectors, allowing more accurate measurement of energy, due to the way their paths are curved in relation to energy. This type of filtering can be seen in mass spectrometers for example in Wind telescope [4].

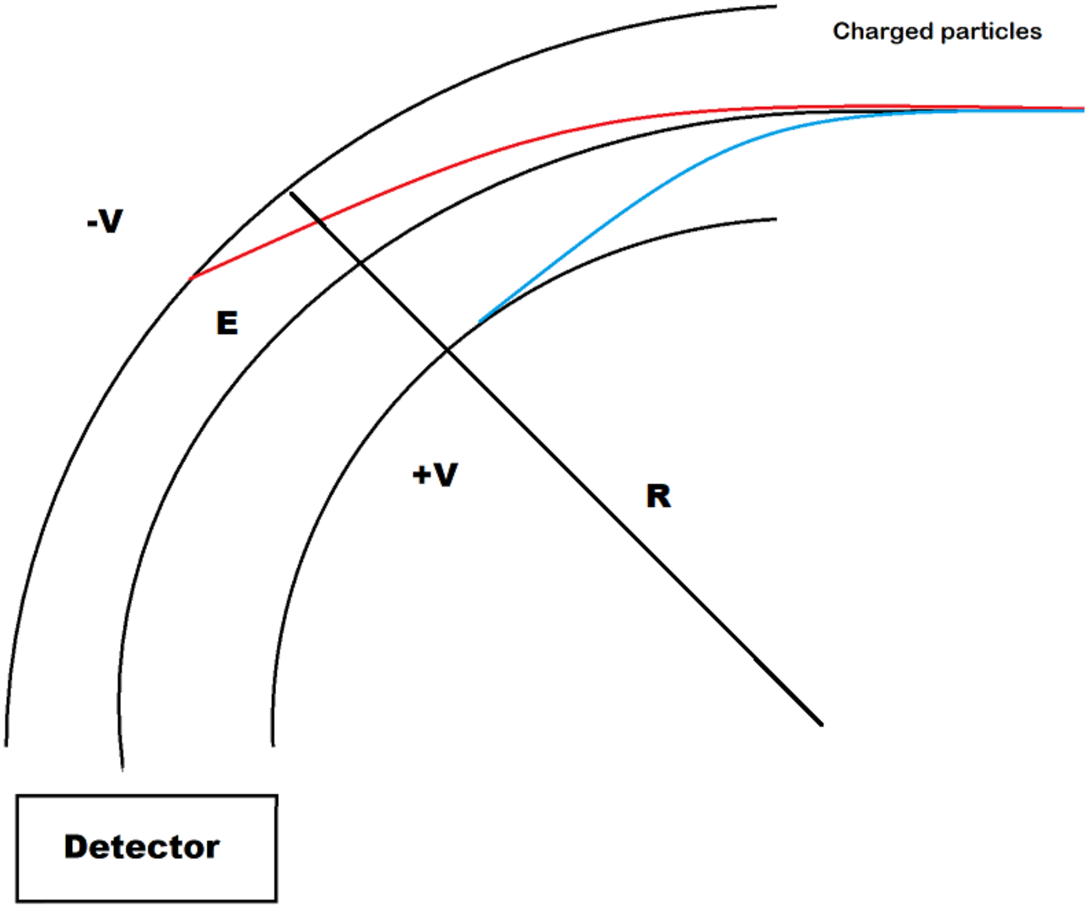

Figure 5 Curved entry path with an electric field between two sides. Blue line particle doesn't have enough energy, red line has too much energy and black line has the right amount of energy and reaches the detector.

4.1.4 Direction filtering

Direction filtering is a technique that is in addition to architecture of the detector dependent on the orientation of the satellite relative electromagnetic fields, fluxes and other aspects that determine the directional particle fluxes in space. Direction filtering is useful for example when doing measurements in Earth's magnetic field. Earth's magnetic field traps particles in certain areas and pointing the telescope along or perpendicular to magnetic field allows either filtering out those particles or measuring them, whichever is the objective.

Controlling detector field of view is another good way of filtering excess particle. In high flux areas, this may help with CEM and microchannel plate gain saturation.

4.2 GEOMETRIC FACTOR

In general, count rate of any detector is somewhat proportional to the physical flux of particle being measured. Geometric factor G is a multiplier that connects true flux of particles to the observed counts of the detector. The meaning of the term geometric factor and what it includes differs from author to author [3], but can generally be understood with equation $N = j\ G$, where N is countrate, j is the flux of particles and G is the geometric factor.

The geometric factor depends on multiple factors, most obvious being field of view of the detector, but despite its name, many other attributes unrelated to geometry must be considered in order to get accurate representation of detector's gathering power. The geometric factor often is different for different types of particles and different energies [3]. For example, electrons can easily backscatter due to their small mass reducing the geometric factor, while protons scatter much less, thus contributing to a larger geometric factor [3]. High energy particles can also sometimes just pass through the detector without properly registering, so their geometric factor could be smaller if not accounted for in the detector design.

4.3 EXAMPLE: FILTERING TECHNIQUES APPLIED IN MEPED DETECTOR

4.3.1 MEPED proton detector

In MEPED (medium energy proton and electron detector) proton detector a magnetic field is applied at the aperture preventing electrons below 1000 keV energy from entering [11]. The detectors are also surrounded by aluminum and tungsten shielding to prevent particles from outside the field of view from entering the detector [11]. The front surfaces of each detectors are covered with an aluminum film to reduce light sensitivity [11].

4.3.2 MEPED electron detector

The aperture of the electron detector is covered with a thin nickel foil to prevent low energy protons from entering and to reduce the detector light sensitivity [11]. The front of the detector is covered by aluminum foil to further reduce light sensitivity [11]. While the proton detector is mostly unaffected by electrons, the electron detector has harder time preventing all protons from entering the detector, meaning the geometric factor for protons is not zero [11].

4.4 EXAMPLE: FILTERING TECHNIQUES APPLIED IN WIND TELESCOPE

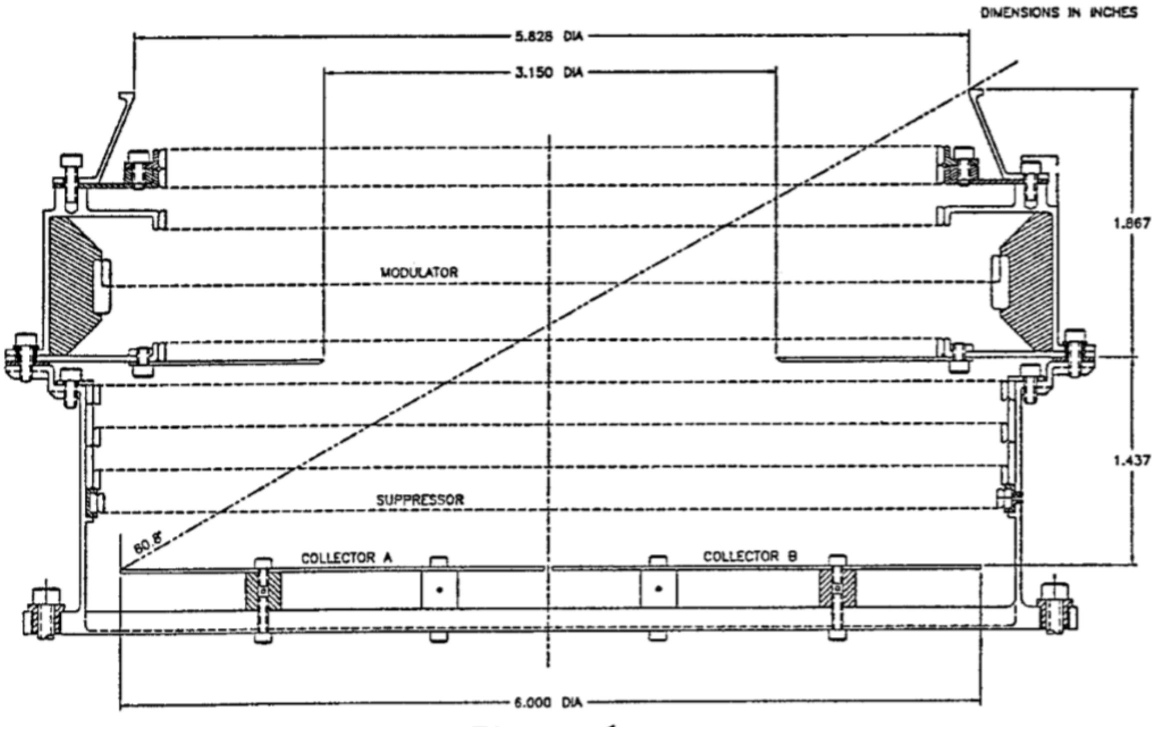

Figure 6 Wind telescope faraday cup with suppressor and modulator grids [6]

Wind telescope's Faraday cup demonstrated in figure 6 facilitates an interesting example of the usage of electric field filtering. The modulator grid in the telescope filters charged particles with an electric field of opposing voltage, allowing only particles above certain energy inside the detector [6]. The voltage is modulated in dc biased square waves [6]. The collector plates are operated in current saturated mode and are capacitively coupled to preamplifiers and the current measuring unit [6]. This capacitive coupling causes only current changes to be registered, which in turn means that only the current caused by particles between the E and ΔE are measured assuming that the flow of particles is otherwise close to constant [6]. This is a great improvement to most basic faraday cups that are only able to measure absolute currents or current caused by particles between E and ∞.

5 SUMMARY

Satellite detectors are often based on charged particle interactions either directly or indirectly by ionizing other particles. Ionization counters or simply direct detection of electrons can be used as is the case in CEM.

Different types of detectors used in satellites are e.g. Faraday cup devices, electron multipliers such as channel electron multipliers, microchannel plates and solid-state or scintillation detectors used for higher energy particles [3]. Mass spectrometers and many other devices for particle identification or counting of specific energies can be built using these detectors and using many different filtering and other techniques to select the right particles to measure.

Many filtering techniques exist, some of which are directional filtering, stopping of particles with foils, stopping or redirecting particles using electromagnetic fields and using curved detector structures with electric fields. Instrument particle gathering efficiency can be described with the geometric factor, which can include not only the geometric properties of the detector but also other lowering or increasing effects on detection efficiency (e.g. different materials and their effects on particle scattering etc.).

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