Gas Detectors

By: Ulfat Hussain
V. **Lecturer**
University Of Sargodha
(Sub Campus Bhakkar)

25/03/2020

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Introduction

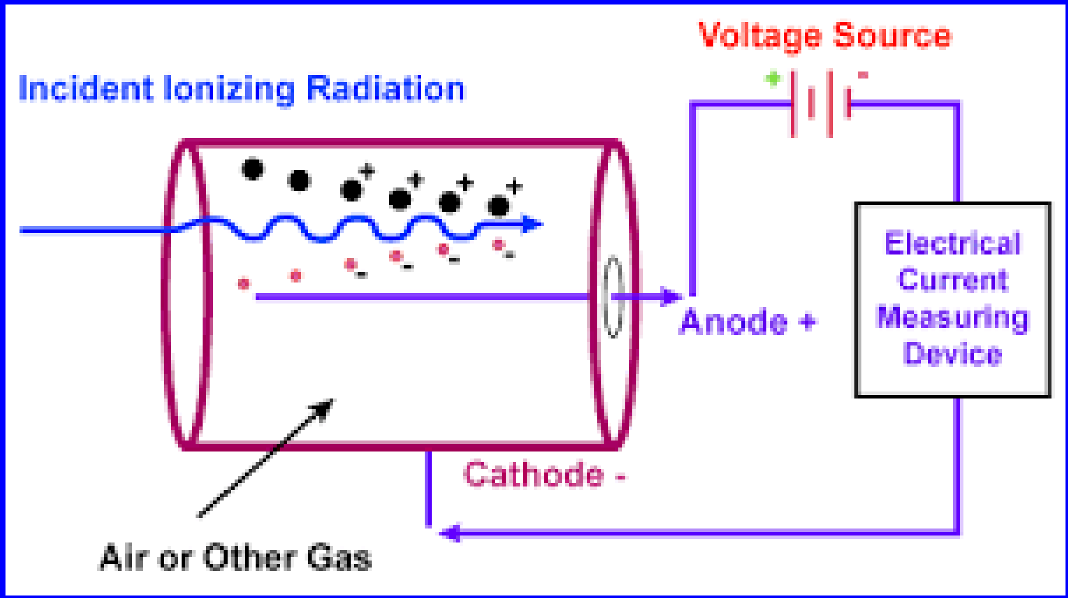
Types of Gas Detectors

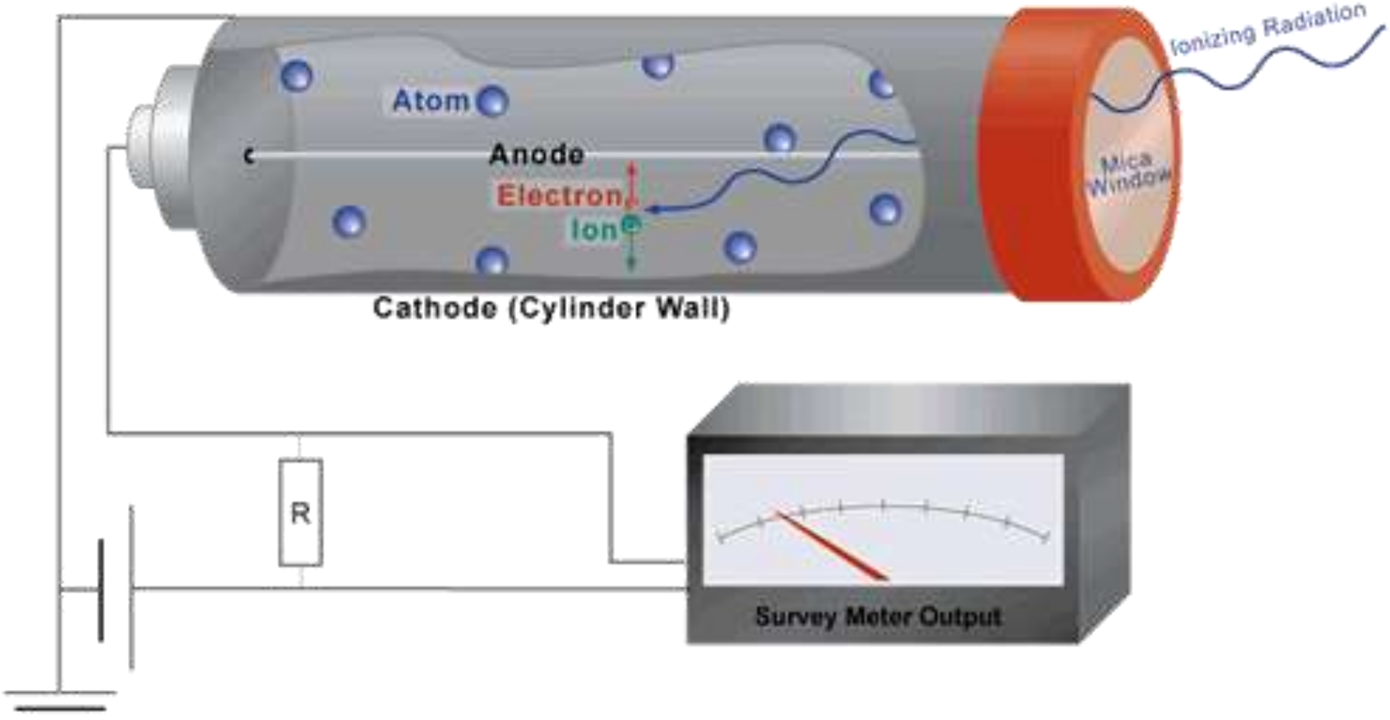
There are three types of gas detectors:

1. Ionization chamber
2. Proportional counter
3. Geiger Mueller counter

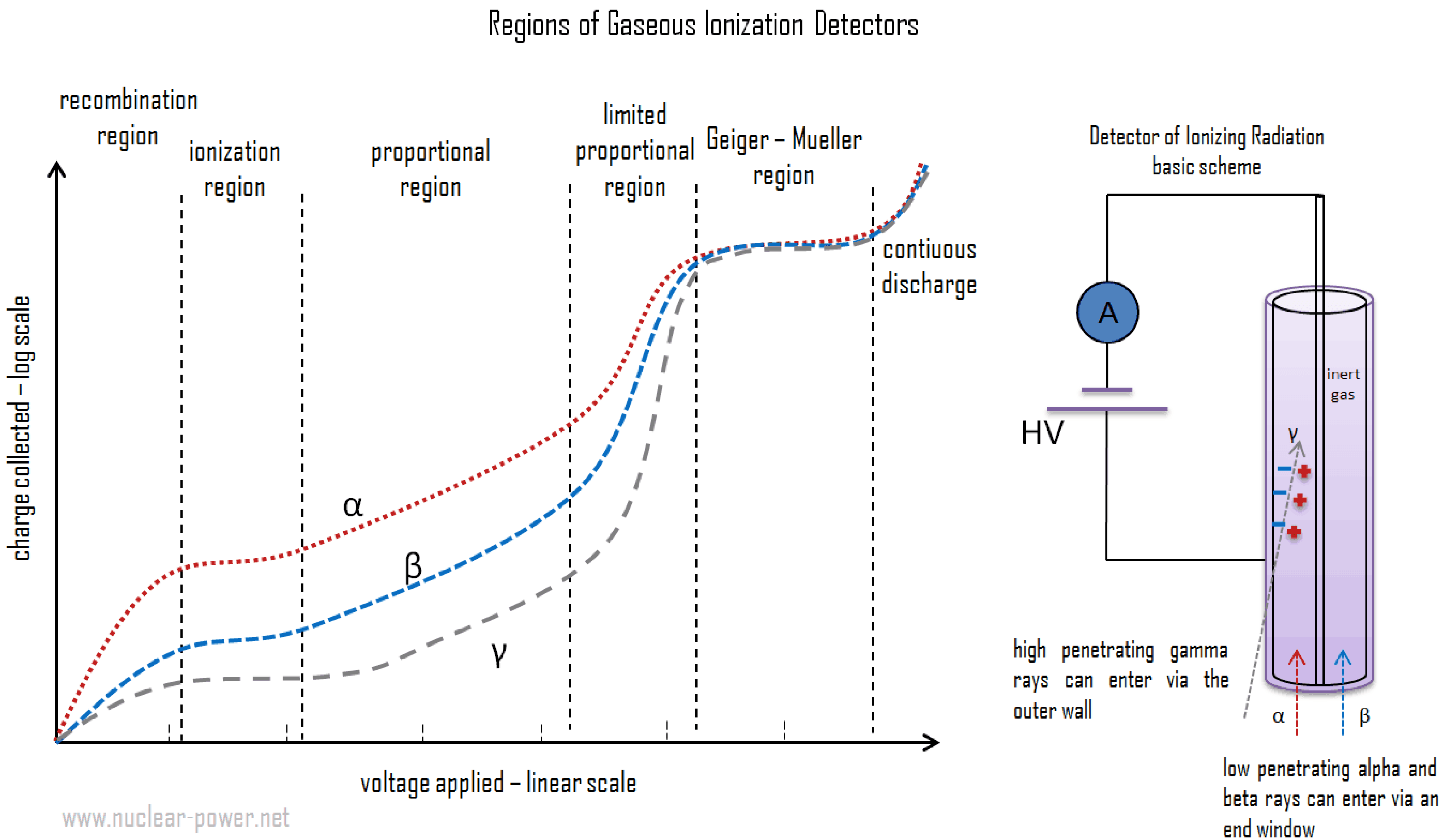
Introduction

Schematic Diagram





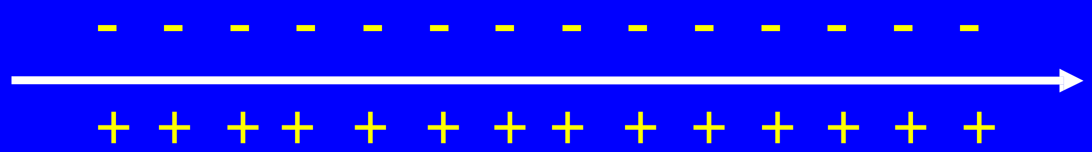
Six Region Curve



Introduction

Ionization of the Detector Gas

They are referred to as gas detectors because the signal is produced when charged particles ionize the gas in the detection chamber.



If the gas is neon (the most common gas in a GM detector), the positive member of each ion pair is a neon ion (Ne^+) while the negative member of the pair is a freed electron (e^-).

If the detector gas is air, the positive member of the ion pair is usually a positively charged nitrogen molecule (N_2^+) and the negative member of the ion pair is the freed electron (e^-).

Introduction

Ionization of the Detector Gas

The term “ion” usually refers to the positive member of the pair. Sometimes the electron is also referred to as an ion.

In the absence of an electric field, the ion pairs created in the gas of the detector simply recombine.

However, if the ionization occurs between two oppositely charged electrodes, and if the electric field is sufficiently strong, the positive and negative members of the ion pairs will separate and be collected at the electrodes.

Introduction

Electrodes

An electric field is established by creating an potential difference between two electrodes. The potential difference is the voltage applied across the electrodes.

Anode: the positively charged electrode

Cathode: the negatively charged electrode

In most systems, the cathode is grounded. That way an individual touching the cathode won't receive a shock. The cathode is still negative with respect to the anode however.

Introduction

Basic Electrode Configurations

There are two general electrode configurations:

1. Parallel plate electrodes
2. Coaxial electrodes

Variations on these configurations are common and the situation in a given instrument might only approximate one of them.

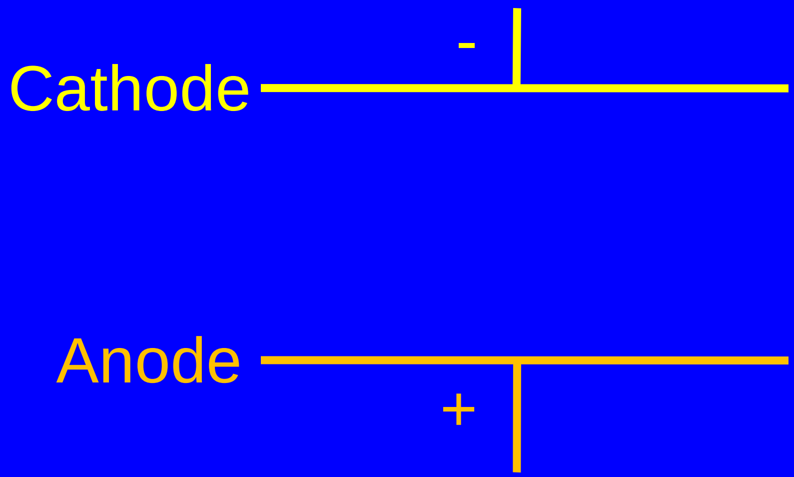
Calculating the strength of the electric field is straightforward for the parallel plate and coaxial configurations, but it can be far more complicated in a real instrument.

Introduction

Parallel Plate Electrodes

Parallel plate electrodes are only used in ionization chambers. Nevertheless, many ion chambers employ a coaxial configuration. Parallel plate configurations are most common for the ion chambers used in radiology.

As the name implies, the two electrodes are parallel plates arranged as shown in the following diagram.



Introduction

Parallel Plate Electrodes

The strength of the electric field is:

$$Electric\ Field\ Strength\ (\xi) = \frac{V}{d}$$

ξ is the strength of the electric field (e.g., volts /meter)

V is the potential difference (e.g., volts)

d is the distance between the two plates (e.g., meters)

The strength of this field is uniform – it is the same throughout the space between the electrodes.

Introduction

Coaxial Electrodes

The coaxial electrode configuration, or a variant thereof, is far more common than the parallel plate configuration.

In the most typical coaxial configuration, the cathode is a cylinder that serves as the detector chamber wall. In some cases, the cathode is a conductive coating on the inside of the chamber wall.

The anode consists of a central wire running that runs along the chamber’s axis.

Introduction

Coaxial Electrodes

$$\textit{Electric Field Strength}\ (\xi) = \frac{V}{r \ln\left(\frac{b}{a}\right)}$$

ξ is the strength of the electric field (e.g., volts /meter)

V is the potential difference (e.g., volts)

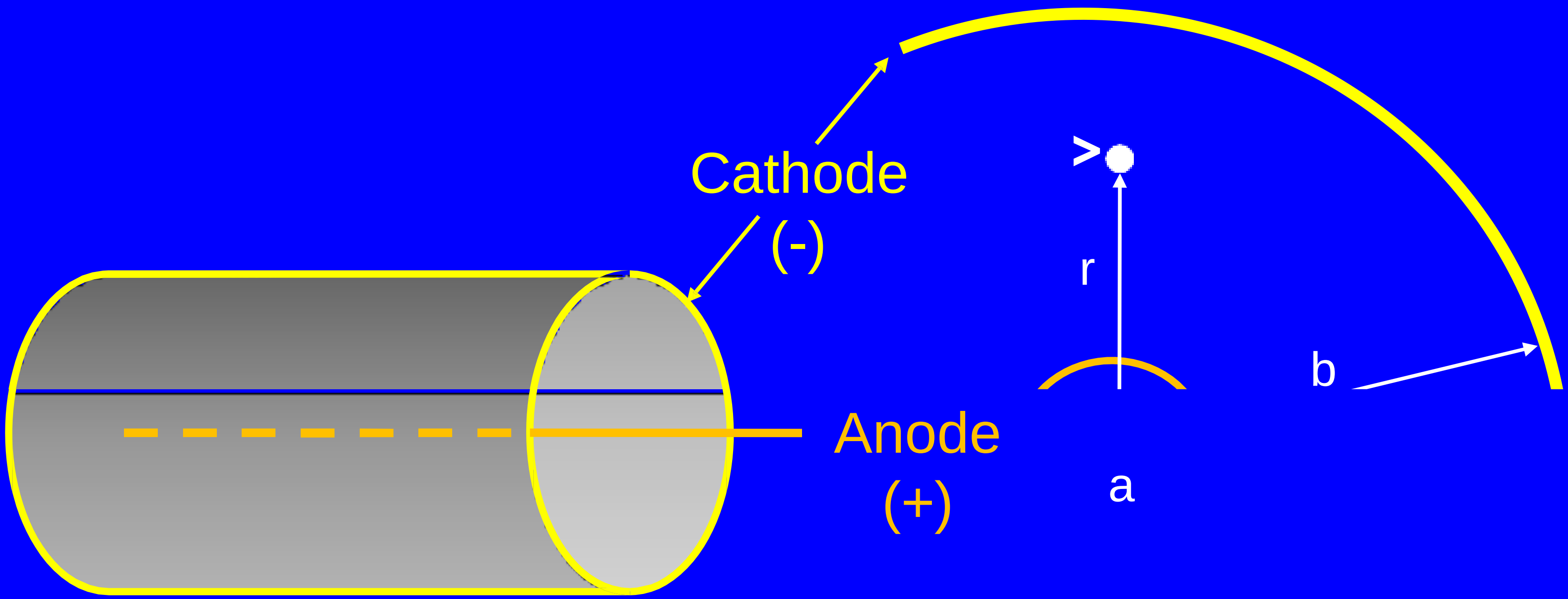
r is the radial distance from the anode center to the point at which the electric field strength is calculated (e.g., meters)

a is the anode radius (e.g., meters)

b is the cathode radius (e.g., meters)

Introduction

Coaxial Electrodes



The strength of the electric field varies throughout the chamber volume. It increases rapidly as we move towards the central electrode and decreases as we move towards the outer electrode.

Introduction

Movement of Ion Pairs to Electrodes

If the electric field strength is sufficiently large, the ion pairs won't recombine. The electrons move to the anode and the positively charged gas ions move towards the cathode.

The drift velocity is the velocity at which the ions move towards the electrodes. It is given by the following formula:

$$DriftVelocity\,(v) = \mu \frac{\xi}{\rho}$$

ξ is the electric field strength (e.g., V/m)
v is the drift velocity (e.g., m/s)
u is the mobility factor of the ion (e.g., m^2 atm/V s)
p is the gas pressure (e.g., atmospheres)

Introduction

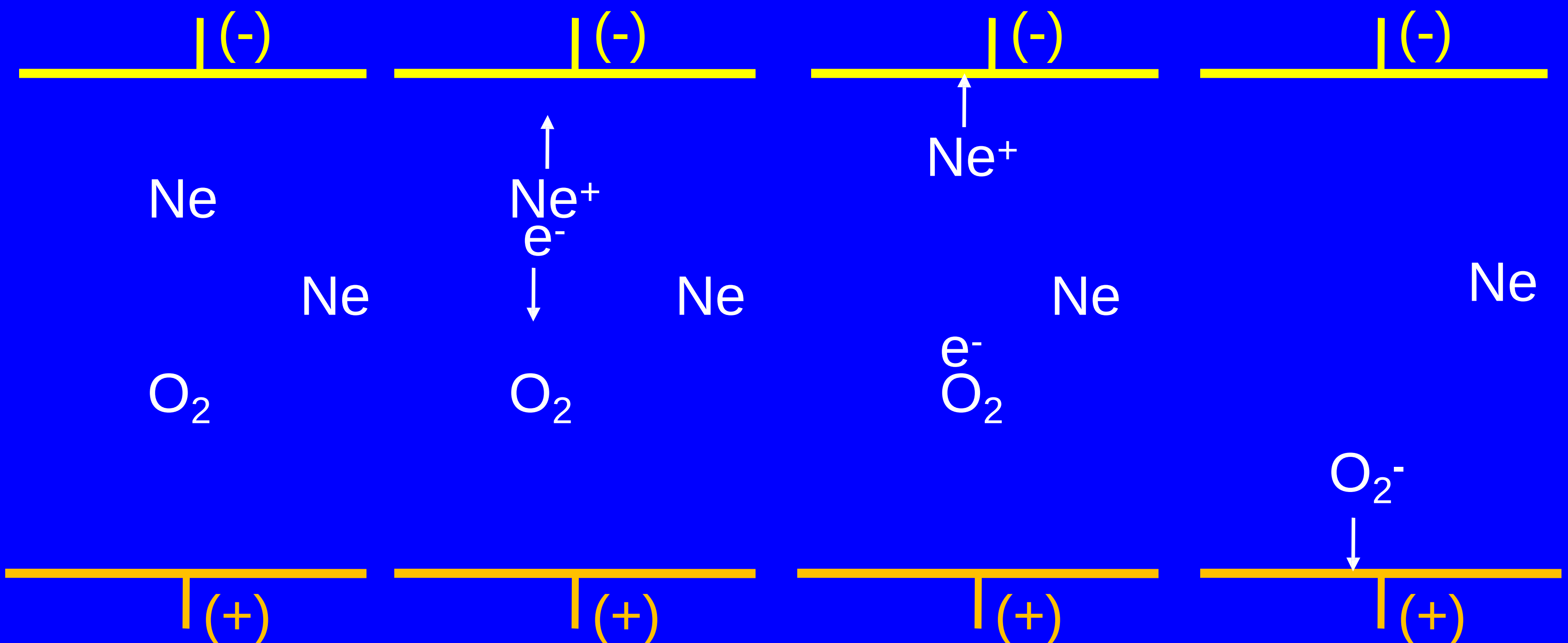
Movement of Ion Pairs to Electrodes

Positively charged gas ions take approximately 10 milliseconds to reach the cathode in a typical detector - their mobility constant is about 1.3×10^{-4} m^2 atm/V s. Since the mobility constant for electrons is roughly 1000 times larger, electrons reach the anode in microseconds.

As the positive ions and electrons move to the electrodes, they collide with various gas molecules and sometimes transfer their charge to those molecules (depending on the latter's electro-negativity). If an electron collides with a highly electronegative molecule (e.g., O_2), the electron will be captured and the now negatively charged gas molecule rather than the electron proceeds to the anode..

Introduction

Movement of Ion Pairs to Electrodes over Time

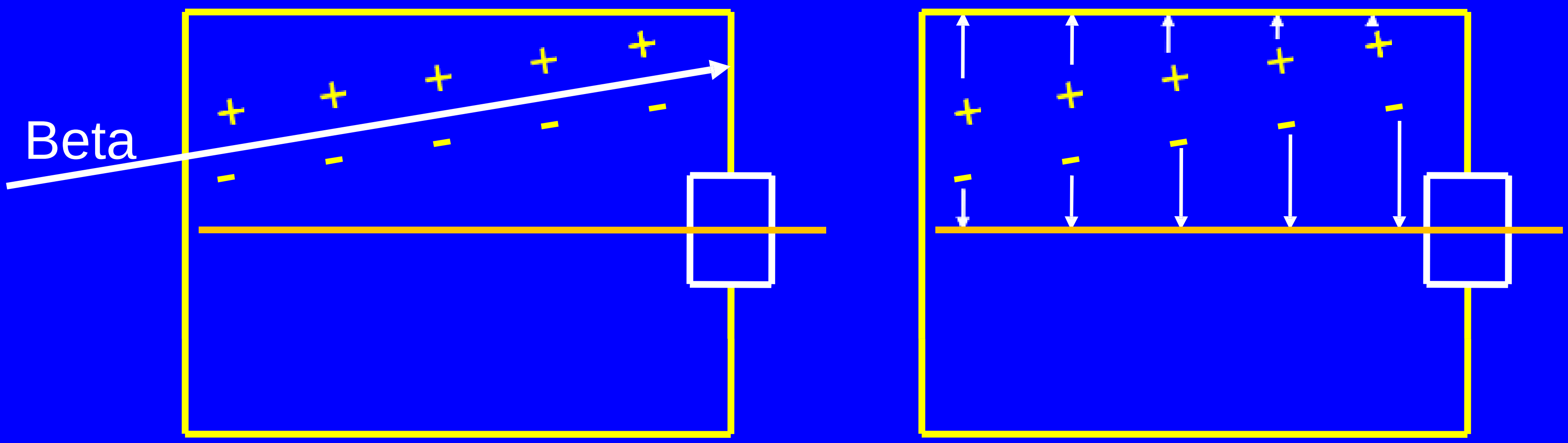


A neon atom is ionized. The neon ion goes to the cathode and the electron heads towards the anode

The electron collides with an O_2 molecule and is captured. The negative O_2 ion goes to the anode.

Introduction

Beta Particle Interaction with the Detector

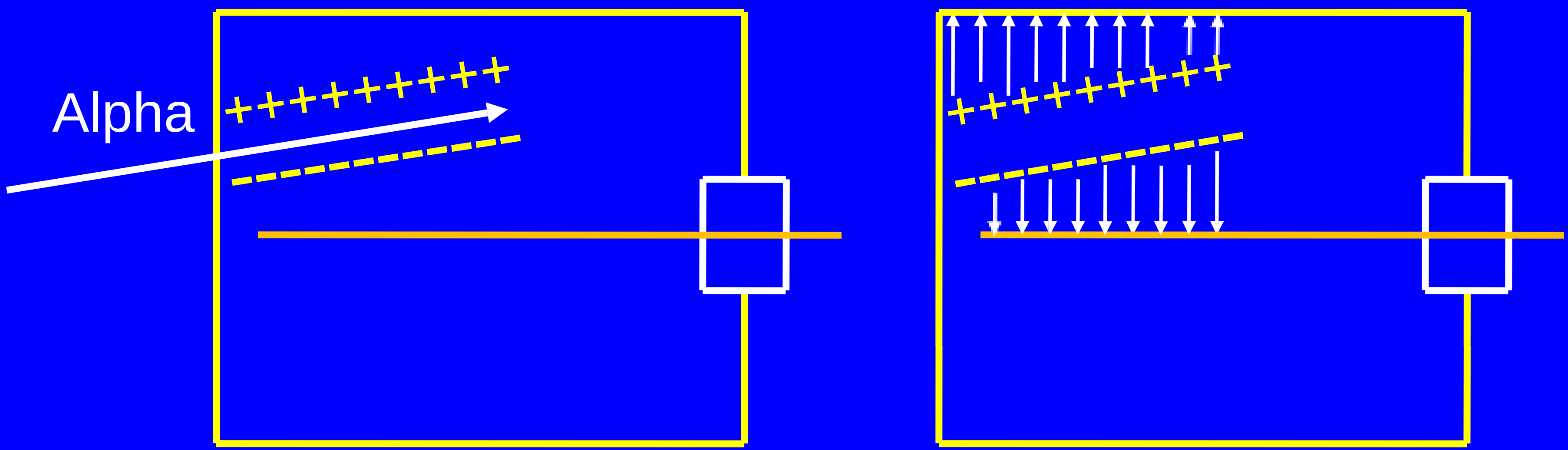


The average energy lost by a charged particle per ion pair produced is approximately 34 eV. Since a typical electron/beta particle produces 100 ion pairs per cm of travel, a 1 Mev electron might have a range of 300 cm.

Given the size of a typical gas detector, beta particles usually transfer a small portion of their energy to the detector gas.

Introduction

Alpha Particle Interaction with the Detector

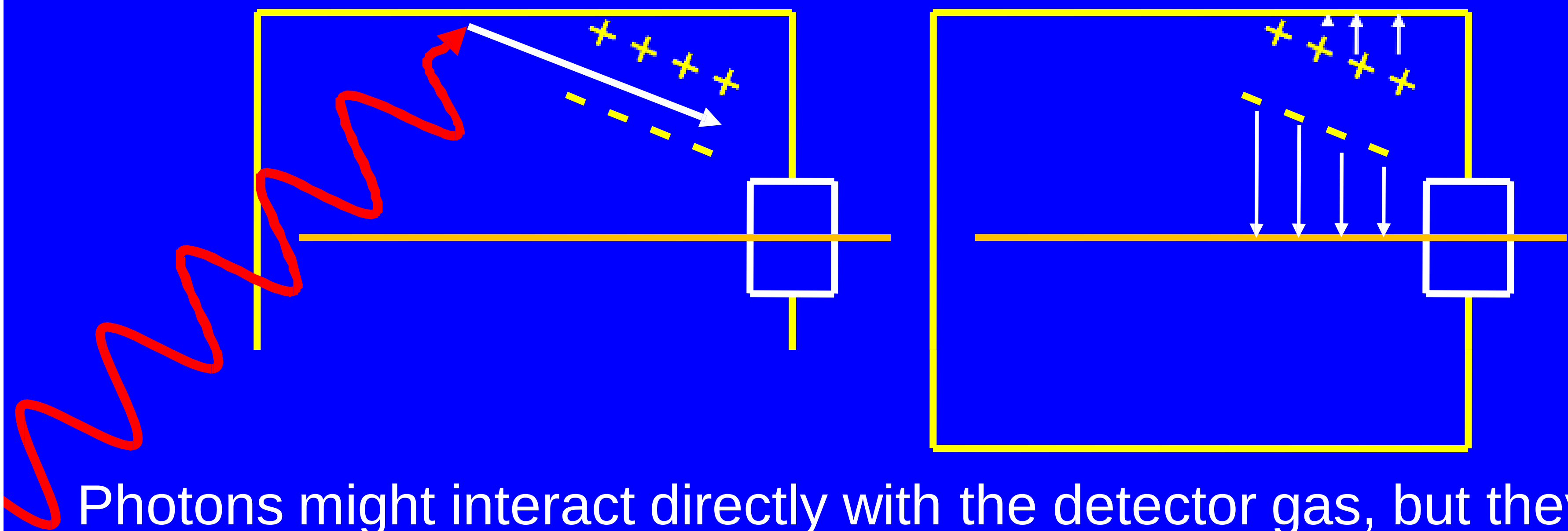


The average energy lost by a charged particle per ion pair produced is approximately 34 eV. A typical alpha particle produces 40,000 ion pairs per cm. As such, a 6 Mev alpha particle will have a range of about 4.5 cm.

Given the size of a typical gas detector, it is possible for some alpha particles to expend all their energy in the detector gas.

Introduction

Photon Interaction with the Detector



Photons might interact directly with the detector gas, but they are more likely to interact with the detector wall (the cathode).

In some of these interactions, an electron is “knocked off” the detector wall This electron then traverses the gas inside the detector chamber. This electron might, or might not, have sufficient energy to cause further ionizations.

Introduction

Radiation Type and the Size of the Detector Signal

With ion chambers and proportional counters, the magnitude of the detector signal depends on the number of ion pairs produced in the gas by the incident charged particle.

In general, but not always, the largest to smallest signal would be produced by:

Alpha particles (largest signal)

Beta particles

Photons (smallest signal)

Introduction

Modes of Operation

A gas detector can operate in one of two modes:

1. Current Mode

2. Pulse mode

Ion chambers usually operate in the current mode because their pulses are too small to be easily distinguished from electronic noise.

Proportional counters and Geiger Mueller detectors usually operate in the pulse mode.

The Six (or five) Region Curve

Six Region Curve

General

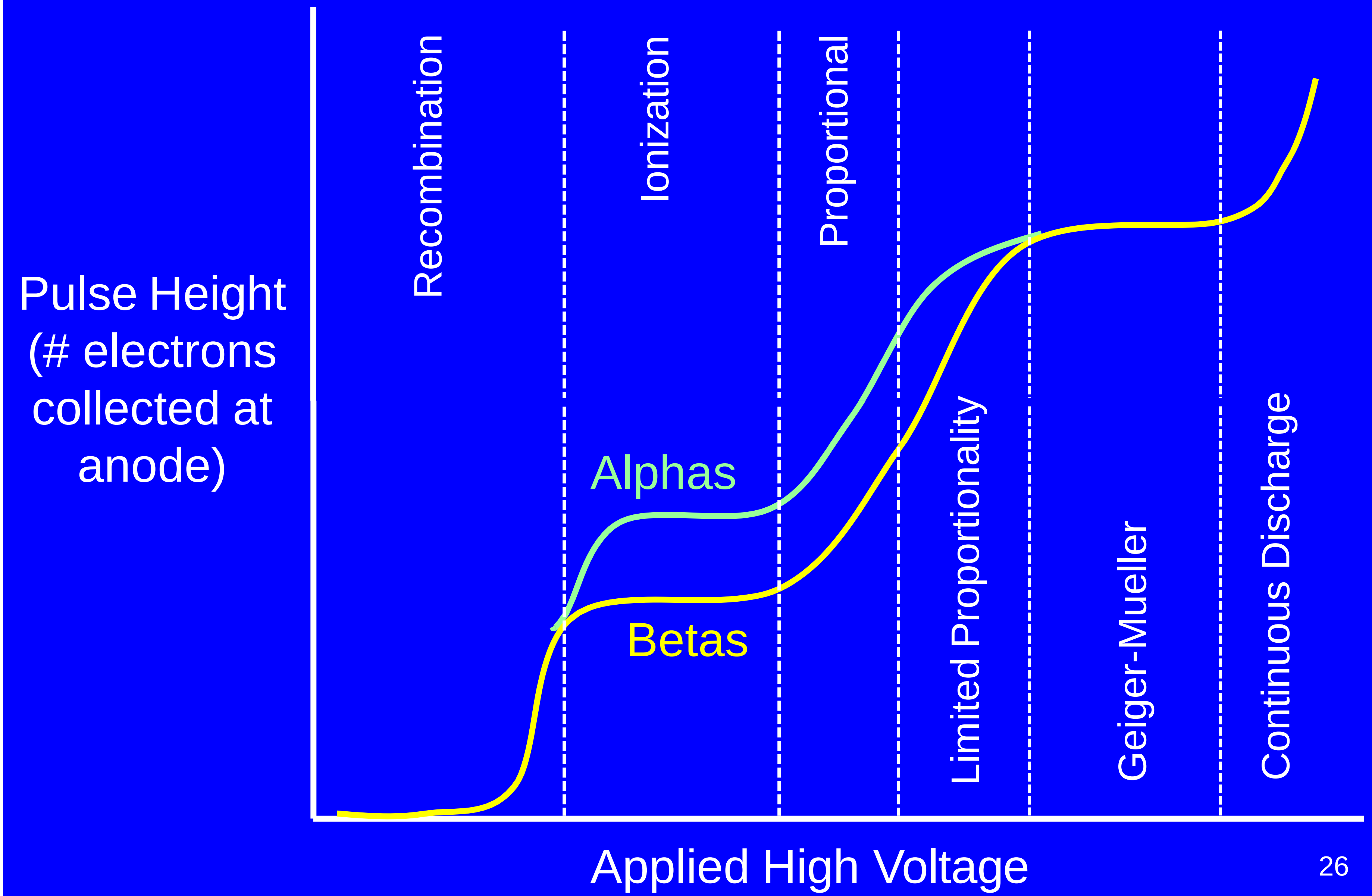
The six region curve is a plot of pulse height as a function of the high voltage applied to a gas detector.

It is sometimes depicted as a five region curve with the proportional region and the region of limited proportionality merged together.

It indicates that theoretically a single detector can function as an ionization chamber, proportional counter or Geiger-Mueller detector depending on the applied high voltage.

When interpreting it, it can be helpful to consider the pulse height as the number of electrons collected at the anode.

The Six Region Curve



Six Region Curve

General

This curve, which applies to a single detector, shows the Geiger-Mueller region at a higher voltage than the proportional region.

In practice, there are design differences between Geiger-Mueller tubes and proportional counters that cause most Geiger-Mueller detectors to operate at lower voltages than most proportional counters.

Six Region Curve

1. Recombination Region

At the lowest voltages, the strength of the electric field is sufficiently low that many of the primary ion pairs created in the gas by the incident charged particle (e.g., alpha, beta) simply recombine.

If no electrons reach the anode - there is no pulse.

Six Region Curve

2. Ionization Region

In the ionization region, the electric field is just strong enough to prevent recombination of the ion pairs produced in the gas.

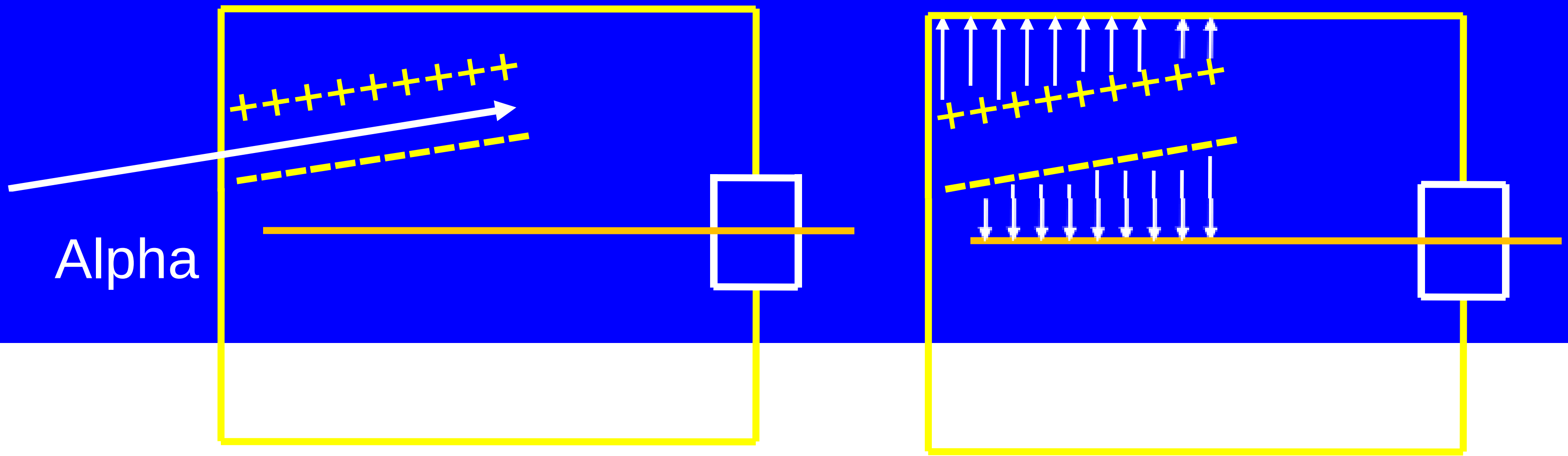
One electron reaches the anode for each primary ion pair created by the incident radiation. The curve (plateau) is flat because increasing the voltage doesn't increase the number of electrons reaching the anode.

The resulting current is referred to as a saturation current.

Since an alpha particle produces considerably more ion pairs than a beta particle, the alpha pulses are correspondingly larger.

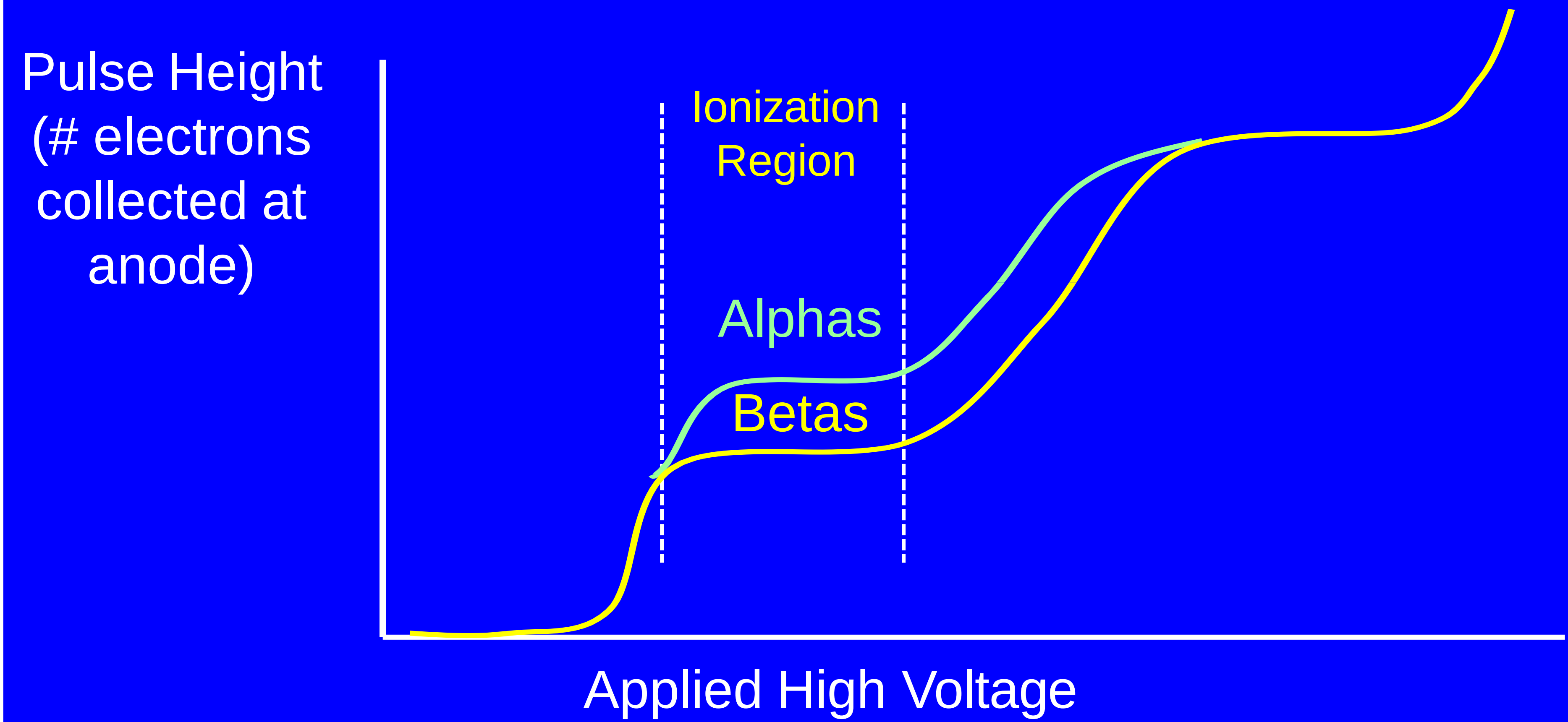
Six Region Curve

2. Ionization Region



Six Region Curve

2. Ionization Region



Six Region Curve

3. Proportional Region

The applied high voltage is greater and the electric field is substantially stronger than in the ionization region.

As the electrons of the primary ion pairs move towards the anode, they gain kinetic energy. When they get close enough to the anode, the electric field is sufficiently strong (ca.10^6 V/m), that these electrons gain enough kinetic energy to create secondary ion pairs.

The electrons produced in these secondary ion pairs, along with the primary electrons, continue to gain energy as they move towards the anode, and as they do, they produce more and more ionizations.

Six Region Curve

3. Proportional Region

The result is that each electron from the primary ion pairs produces a cascade, or avalanche of ion pairs (Townsend avalanche).

For every primary ion pair created in the chamber by the ionizing radiation, 10^2 to 10^4 electrons reach the anode. The increase in the number of electrons is referred to as the multiplication factor.

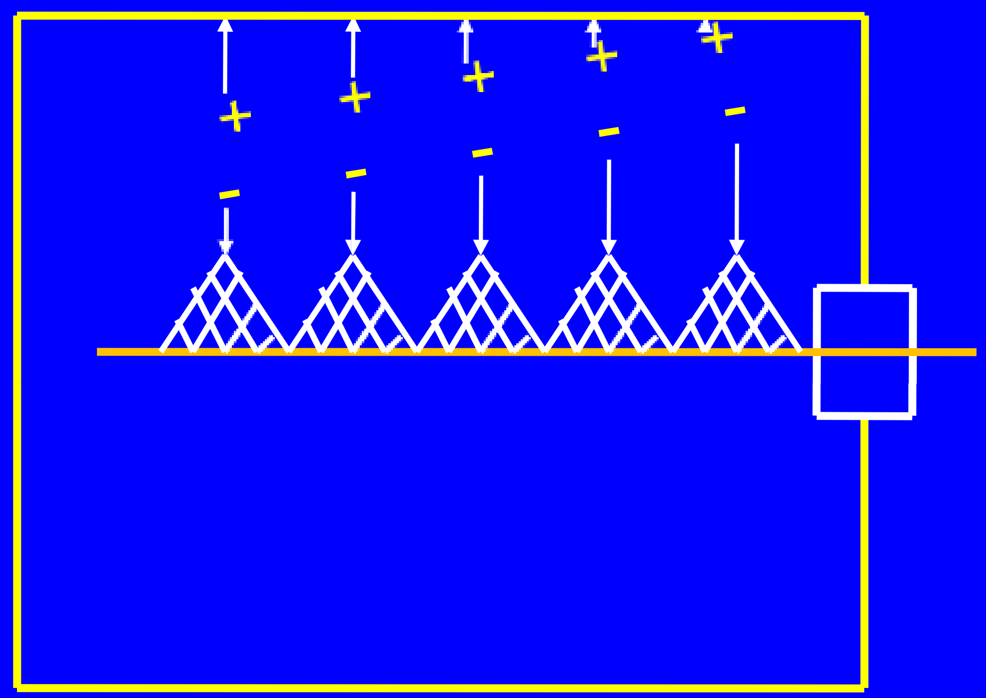
As the high voltage increases, the distance from the anode at which the field strength exceeds 10^6 V/m increases. As the avalanches are initiated further away from the anode, the multiplication factor (and pulse size) increases.

Six Region Curve

3. Proportional Region

The greater the number of primary ion pairs the larger the pulse.

The higher the voltage, the larger the avalanches and the larger the pulse.



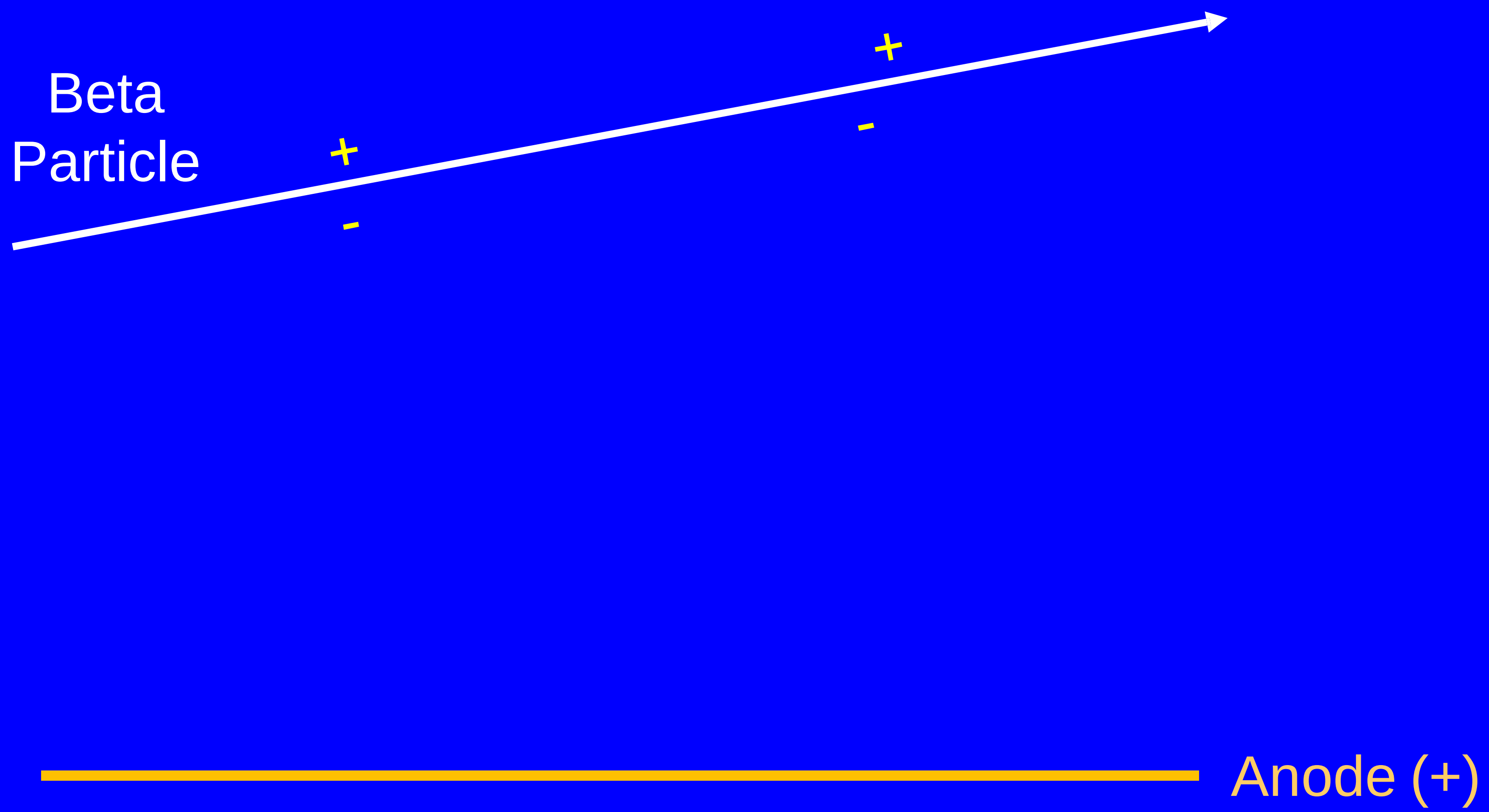
The figure illustrates a single pulse consisting of simultaneous five avalanches.

Six Region Curve

3. Proportional Region

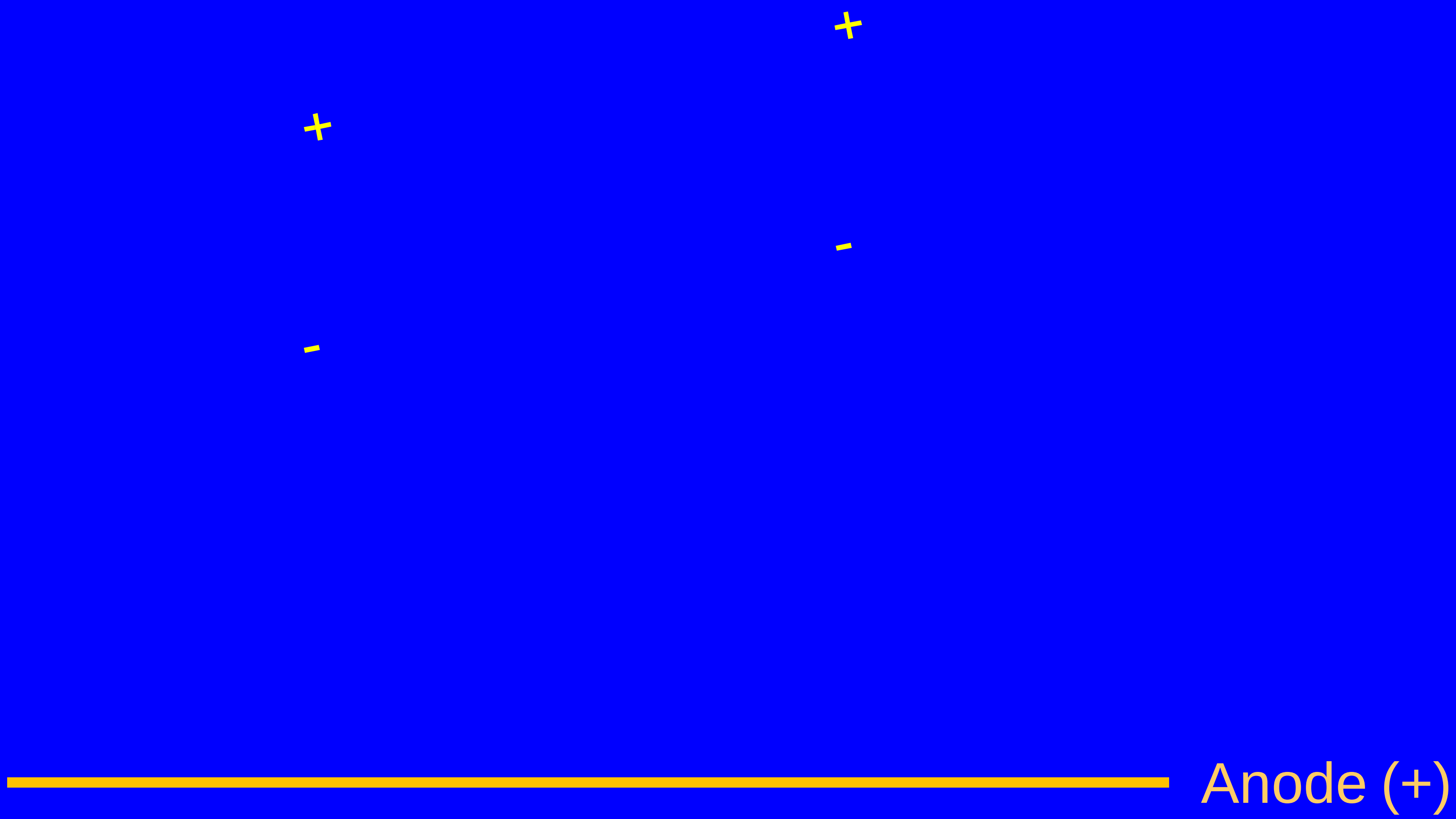
Six Region Curve

3. Proportional Region



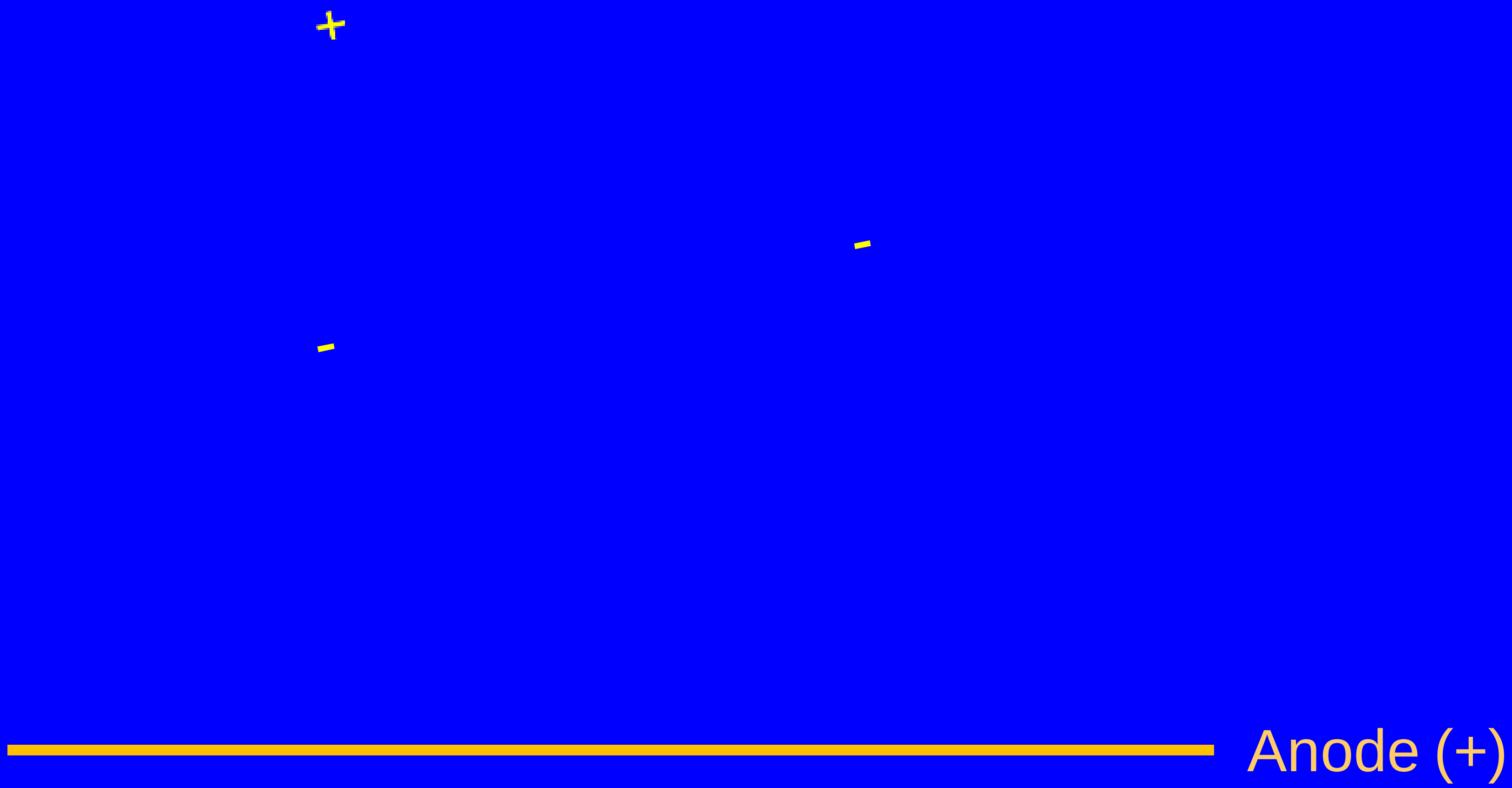
Six Region Curve

3. Proportional Region



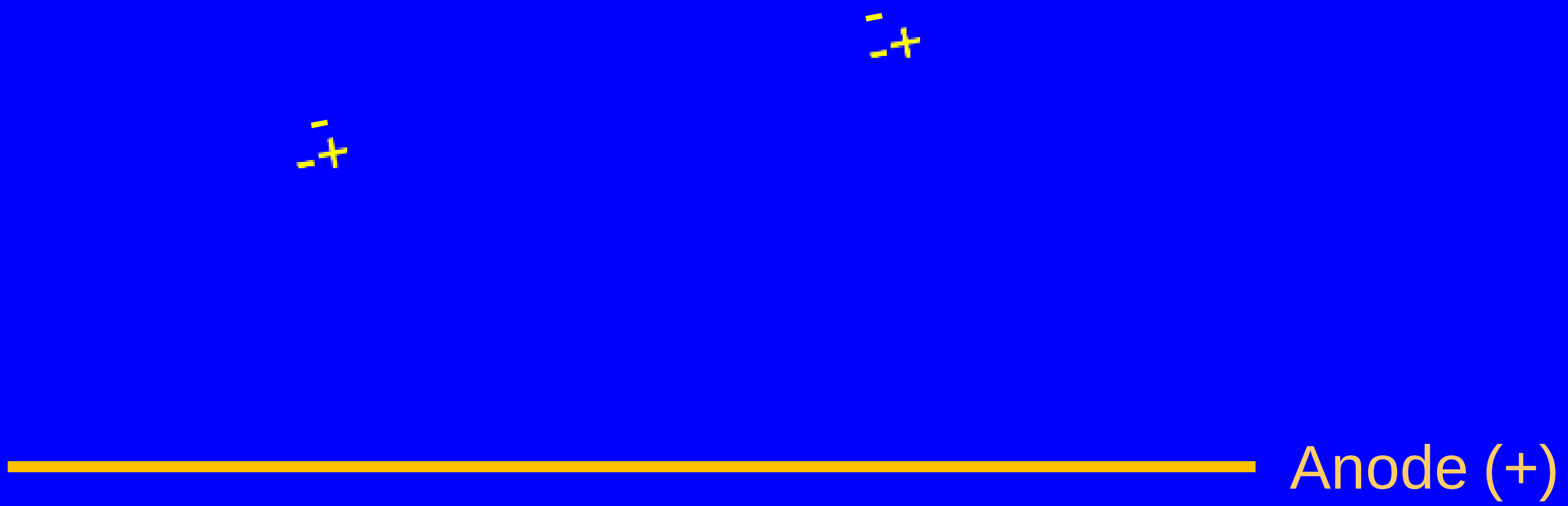
Six Region Curve

3. Proportional Region



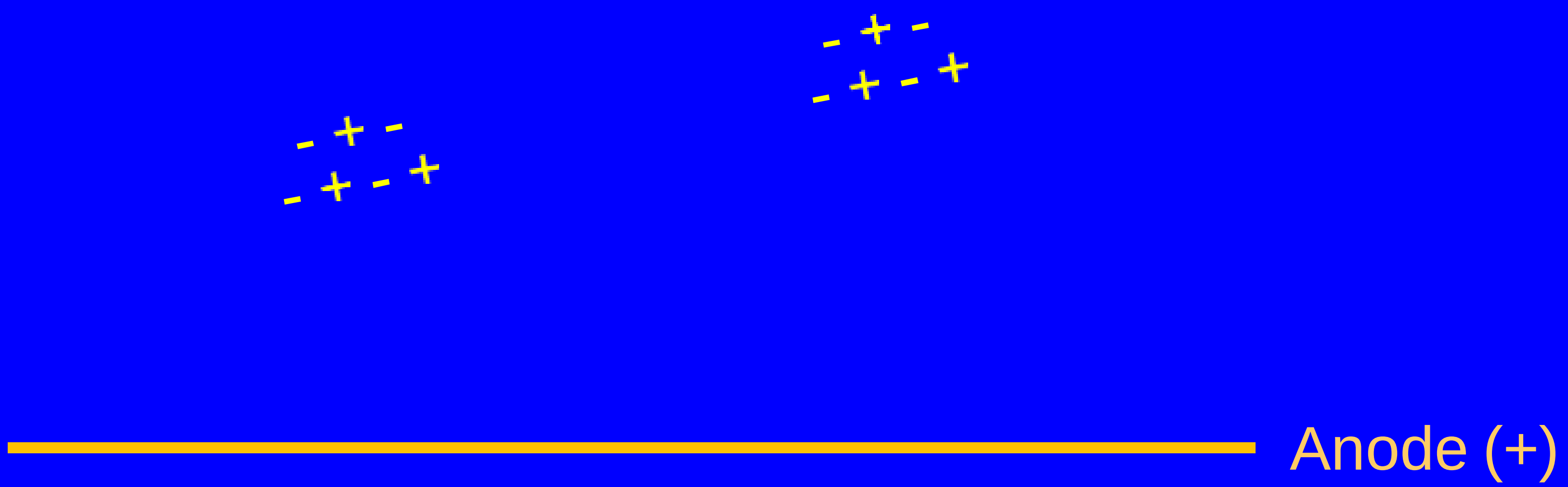
Six Region Curve

3. Proportional Region



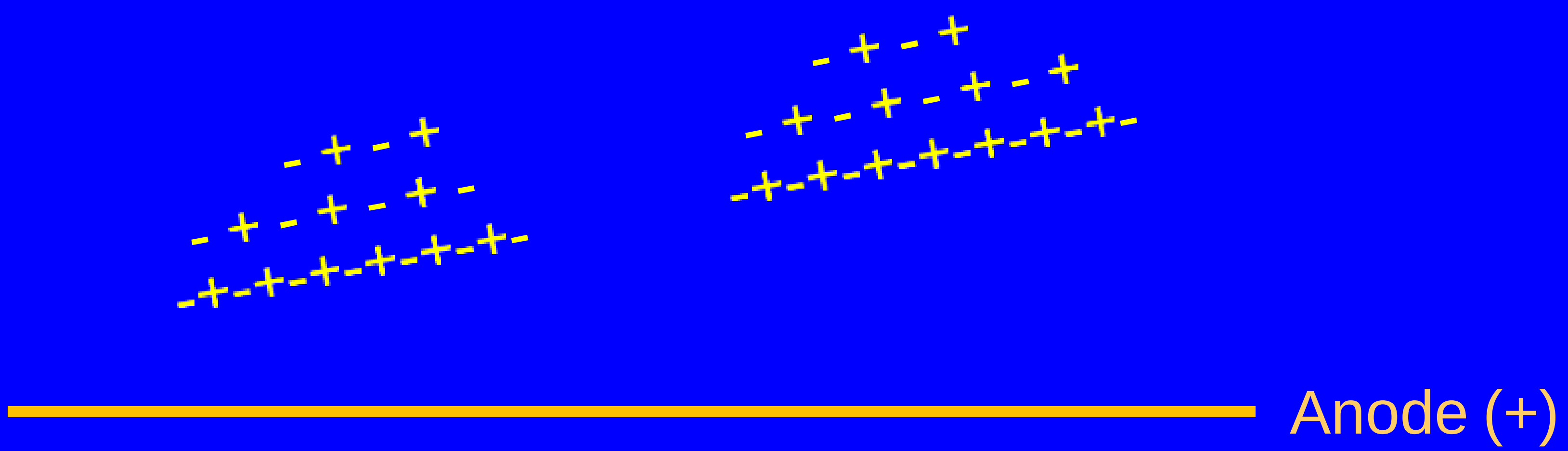
Six Region Curve

3. Proportional Region



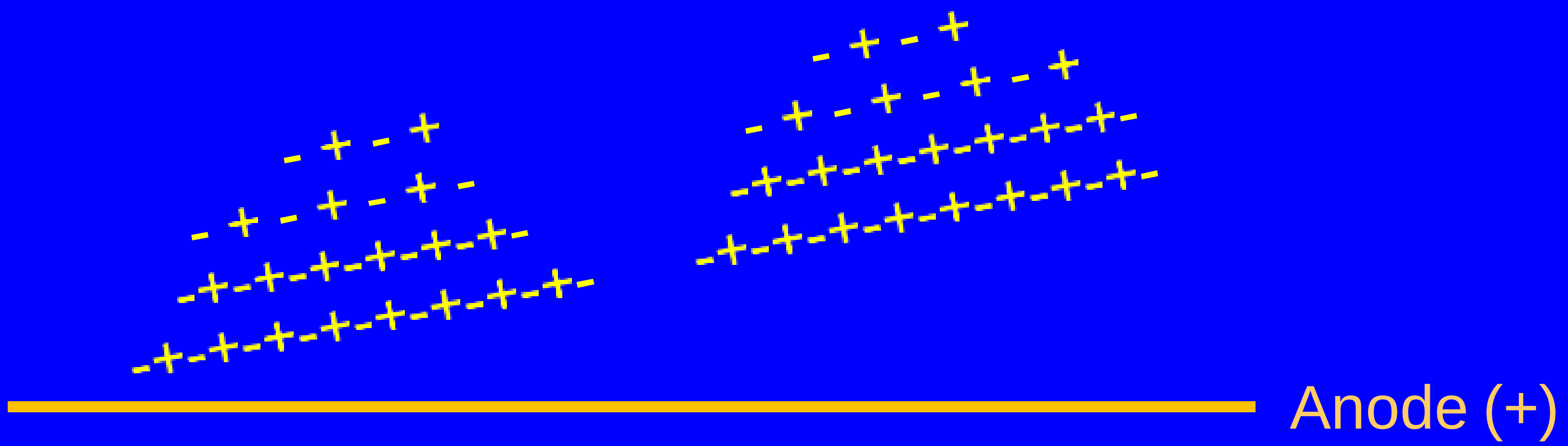
Six Region Curve

3. Proportional Region



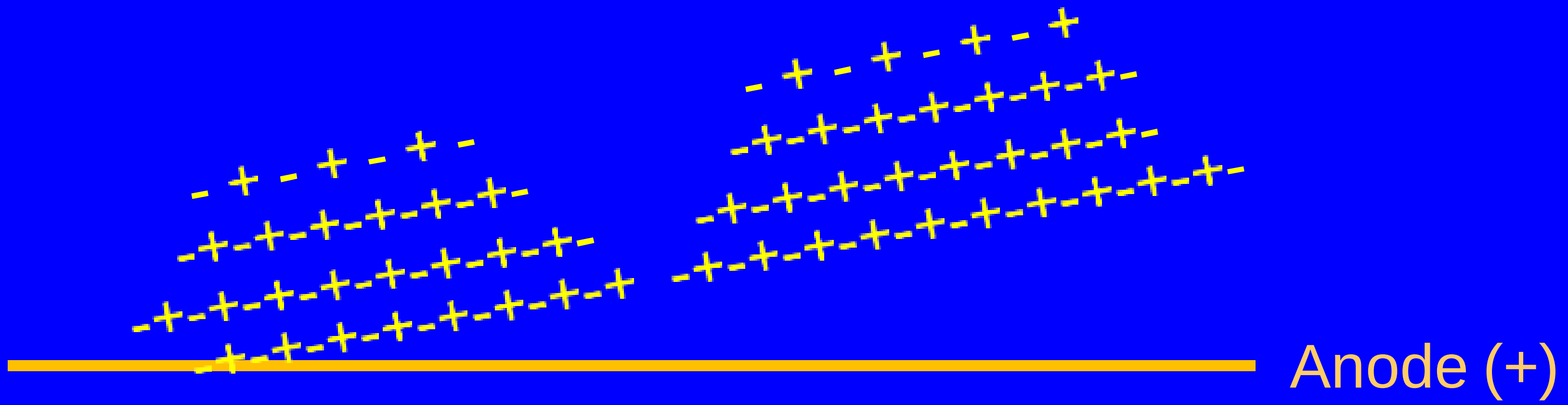
Six Region Curve

3. Proportional Region



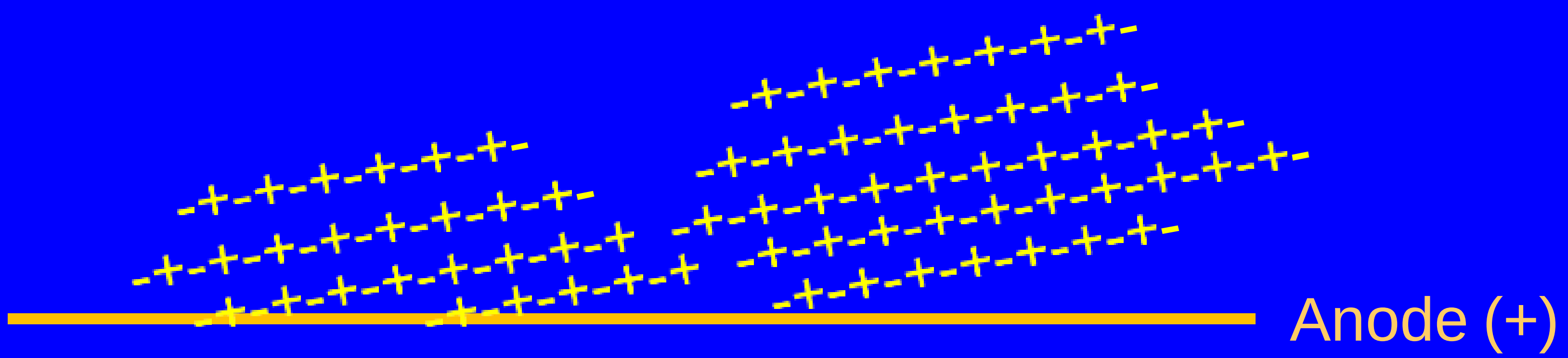
Six Region Curve

3. Proportional Region



Six Region Curve

3. Proportional Region



Six Region Curve

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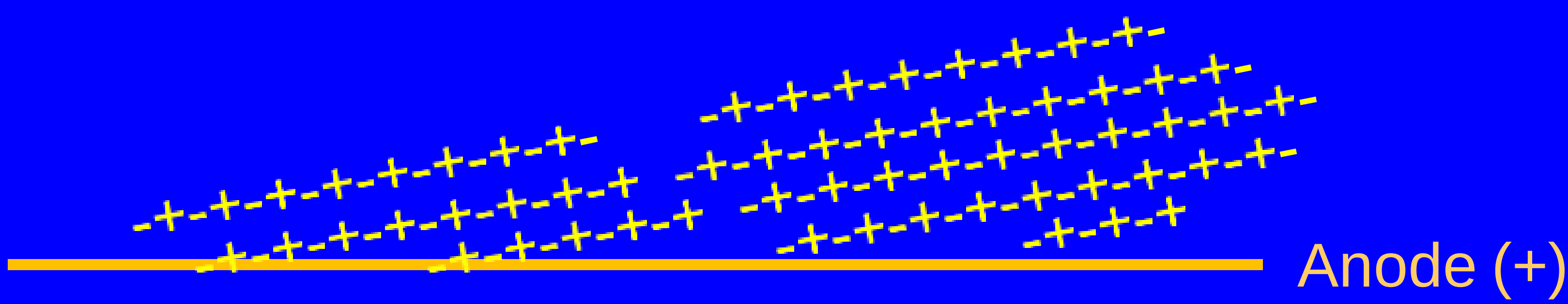
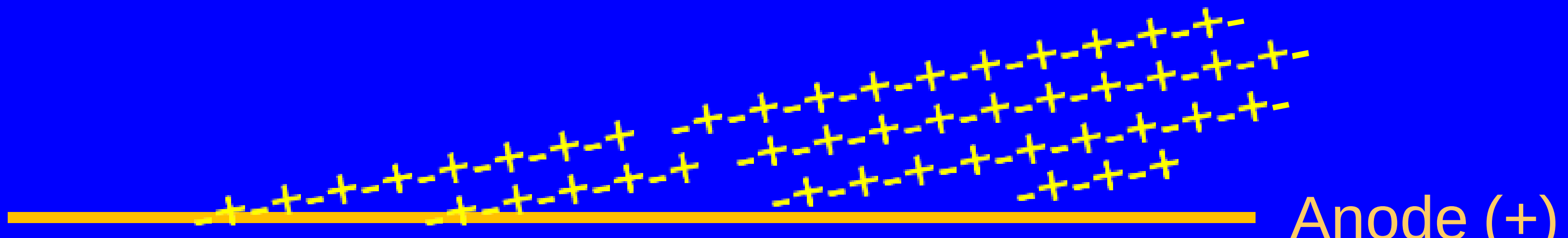


Six Region Curve

3. Proportional Region



Six Region Curve

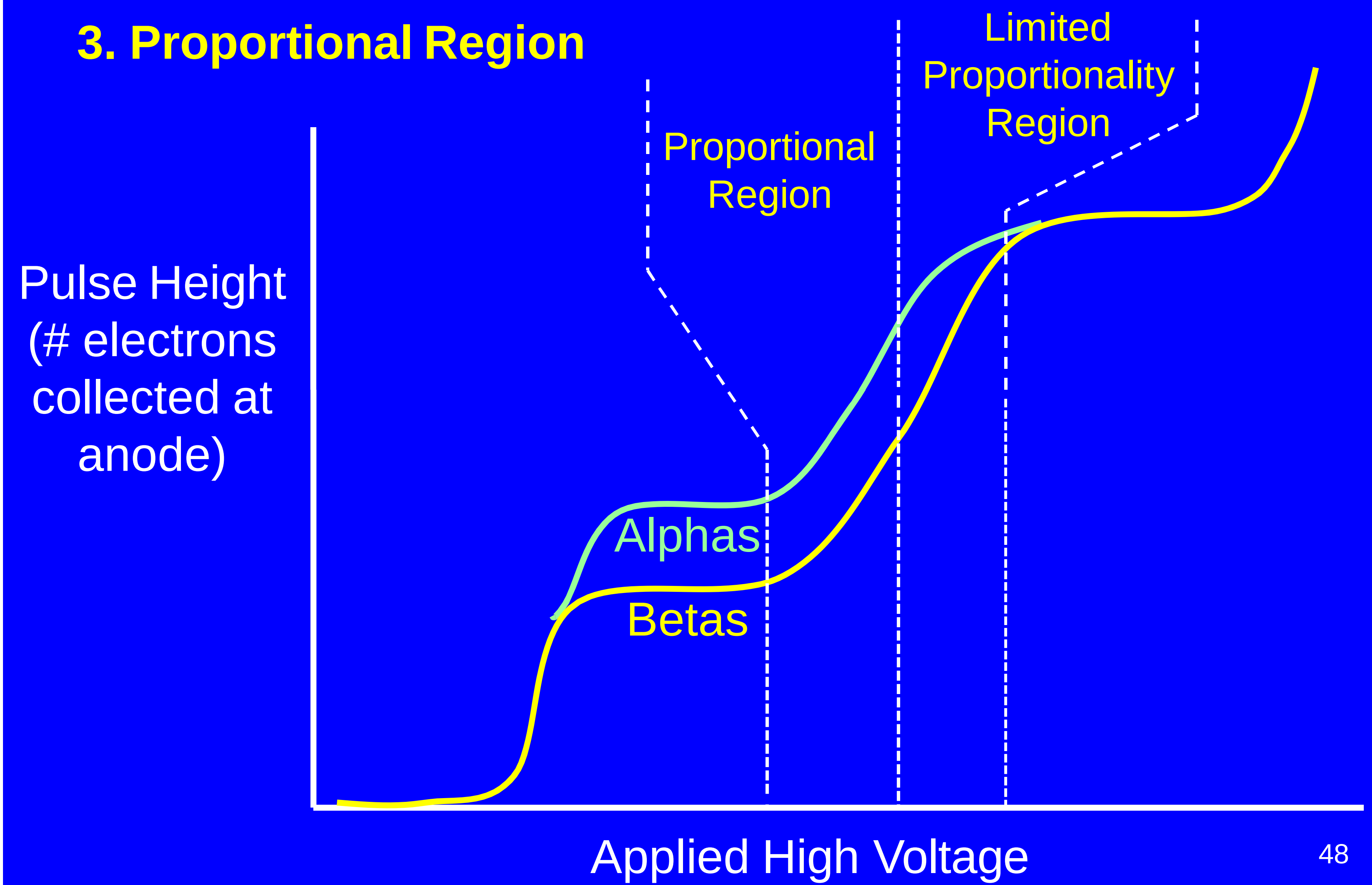
3. Proportional Region

The voltage at which the electric field strength becomes large enough for avalanches to be produced marks the end of the ionization region and the beginning of the region of proportionality.

The proportional region is sometimes referred to as the region of true proportionality because there is a linear relationship between the number of primary ion pairs and the number of electrons reaching the anode.

Six Region Curve

3. Proportional Region



Six Region Curve

4. Region of Limited Proportionality

The high voltage and the multiplication factor are larger than in the proportional region.

What is now different is that pulse size is no longer linearly related to the number of primary ion pairs produced by the incident radiation. In other words, doubling the number of primary ion pairs, doesn't double the pulse size.

This increases the uncertainty of using pulse size to distinguish different types of radiation (e.g., beta vs. alpha).

Six Region Curve

5. Geiger-Mueller Region

In this region, the size of the pulse is totally independent of the number of primary ion pairs produced by the incident radiation.

In other words, alpha particles, beta particles and photons produce pulses of exactly the same size.

There is a complete loss of proportionality between the radiation energy deposited in the detector gas and the pulse size.

Six Region Curve

5. Geiger-Mueller Region

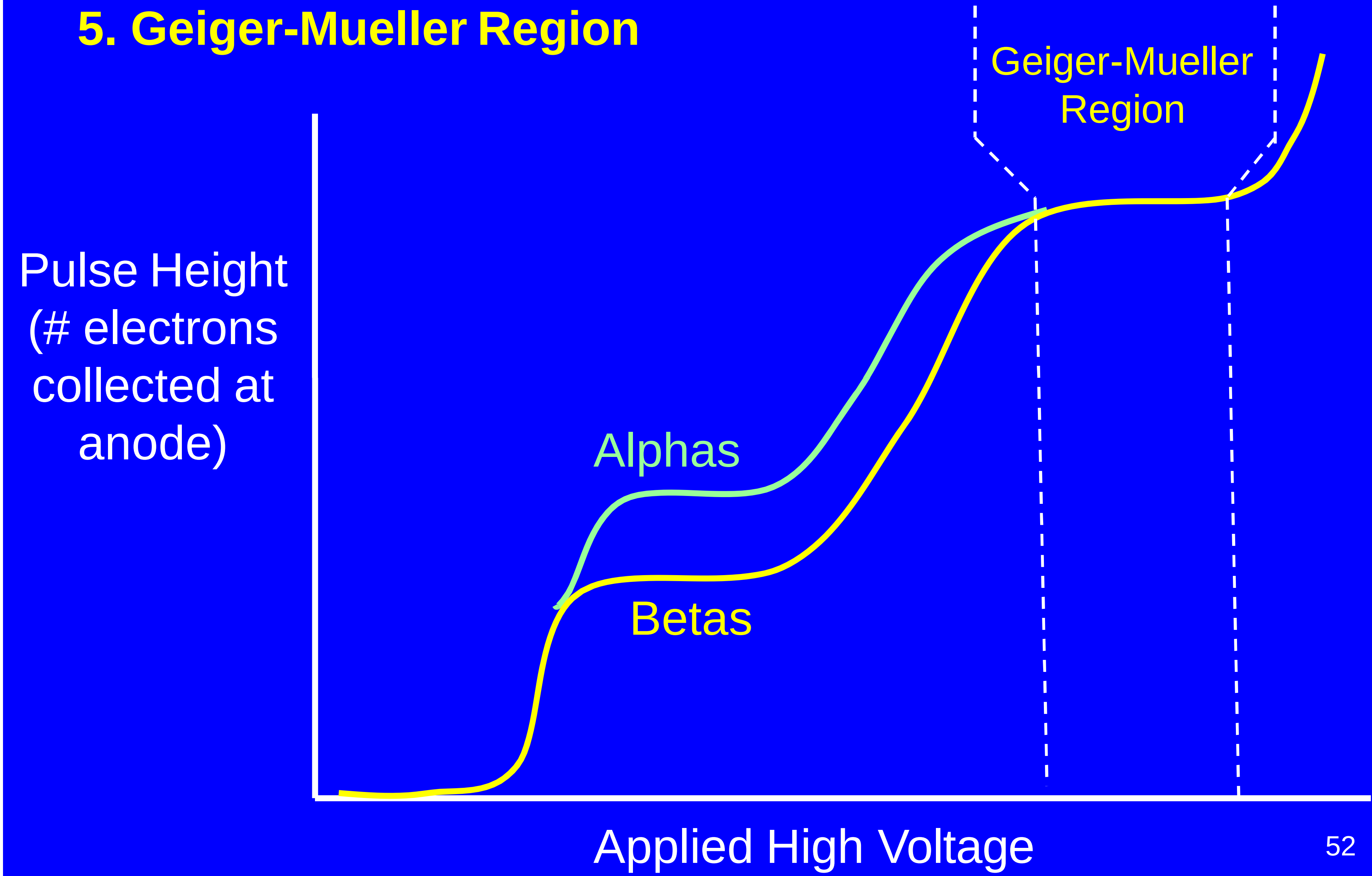
At the high voltages associated with the Geiger-Mueller Region, the avalanche spreads along the complete length of the anode.

The pulse shuts itself down when the accumulation of positive ions around the anode reduces the strength of the electric field below that required for continued propagation.

At a given voltage in the Geiger region, the size of the pulse is the same no matter how many primary ion pairs were produced by the incident radiation.

Six Region Curve

5. Geiger-Mueller Region



Six Region Curve

5. Geiger-Mueller Region

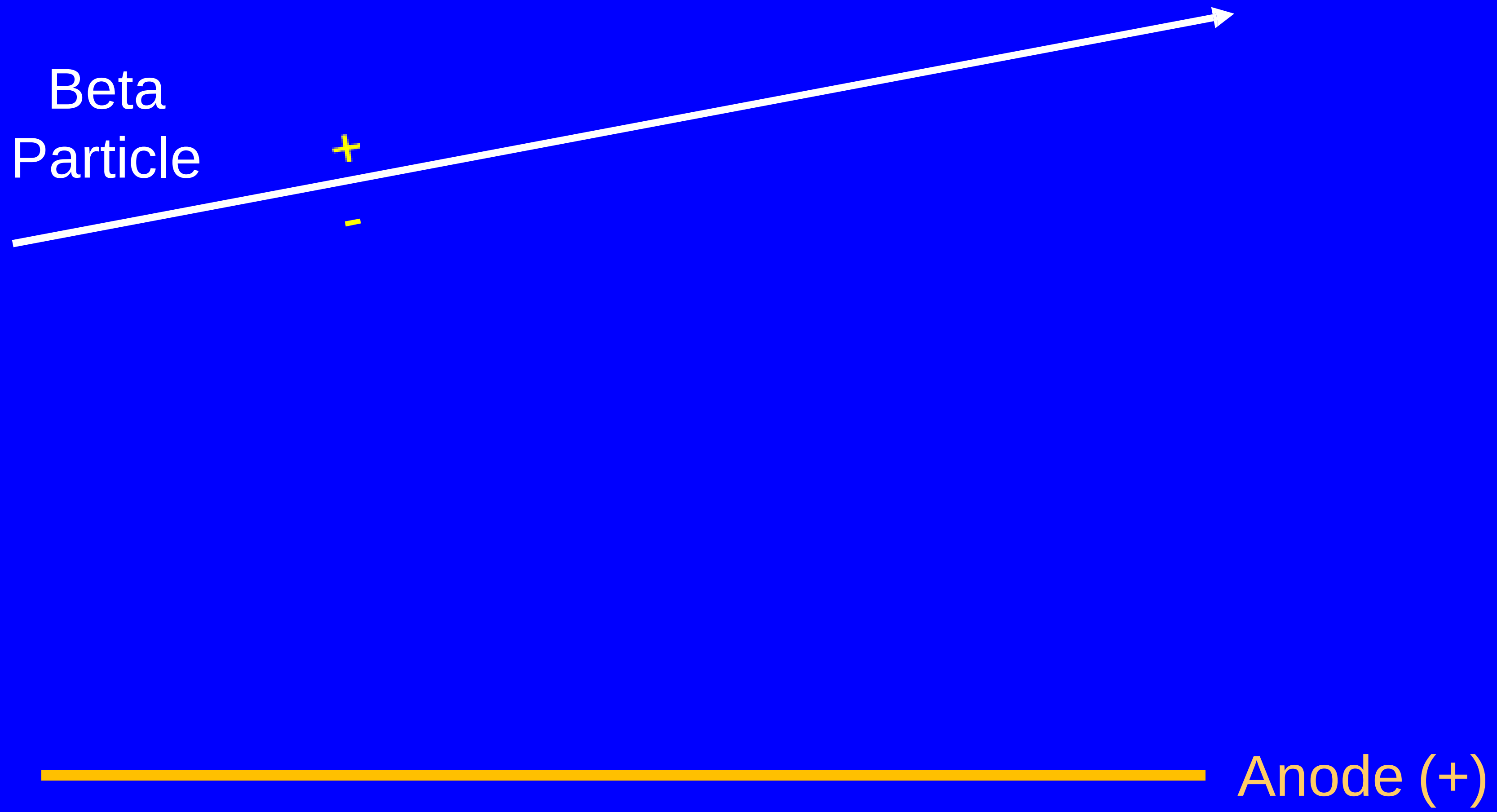
Why does the avalanche spread along the anode? Because avalanches not only involve ionization, they also involve the excitation of gas molecules. And when excited molecules in an avalanche de-excite, they can emit UV photons.

In the Geiger-Mueller region enough UV photons are produced for some to be absorbed by the gas molecules via the photoelectric effect. This leads to further ionization of the gas and the creation of additional avalanches. By this means, a single avalanche becomes thousands of avalanches.

The gases used in GM tubes are selected to promote this generation and absorption of UV photons.

Six Region Curve

5. Geiger-Mueller Region



Six Region Curve

5. Geiger-Mueller Region

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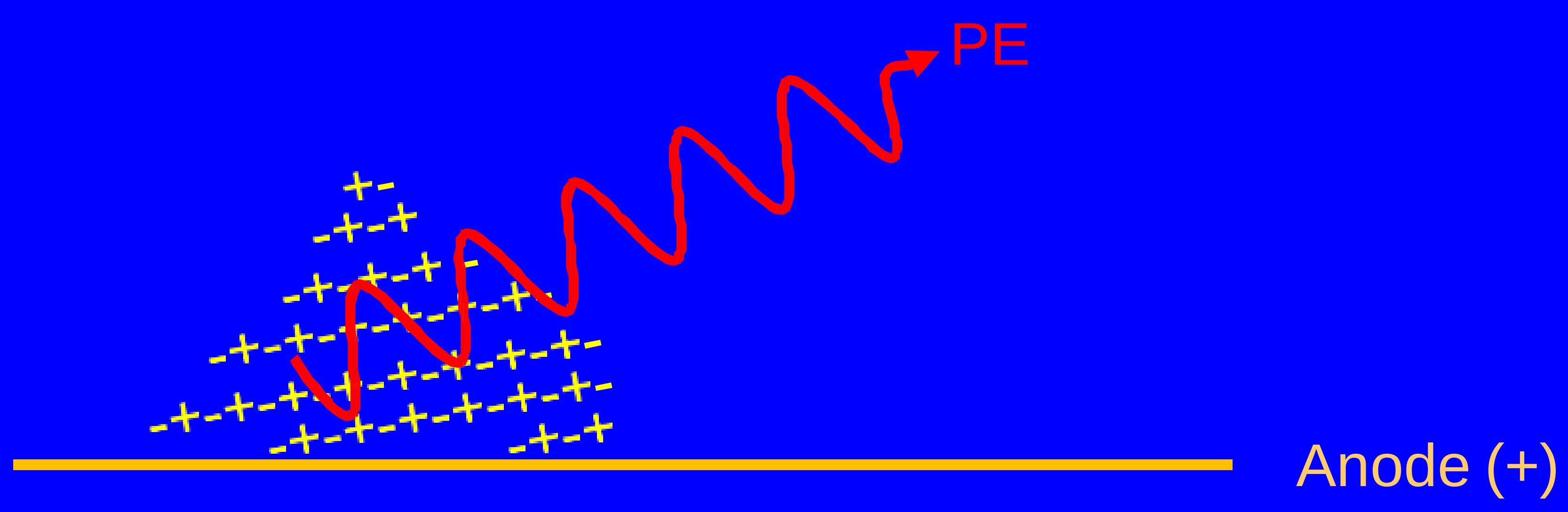
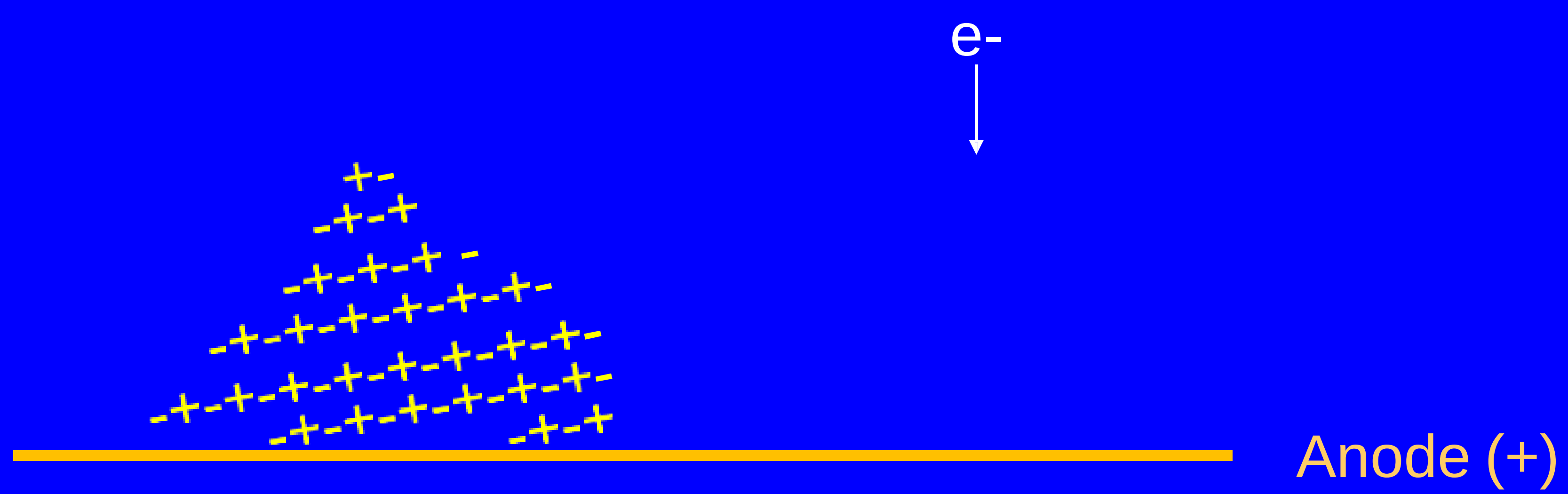


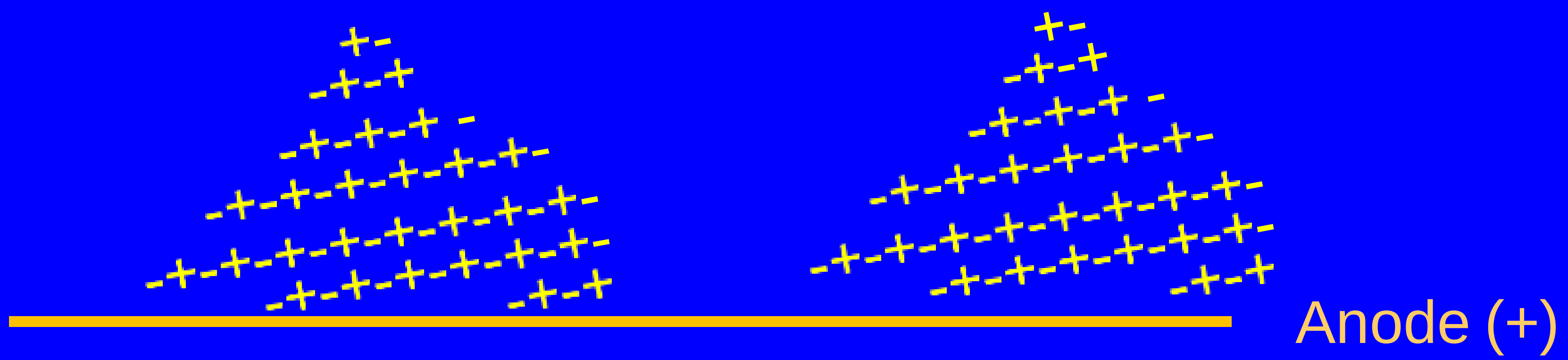
Six Region Curve

5. Geiger-Mueller Region



Six Region Curve

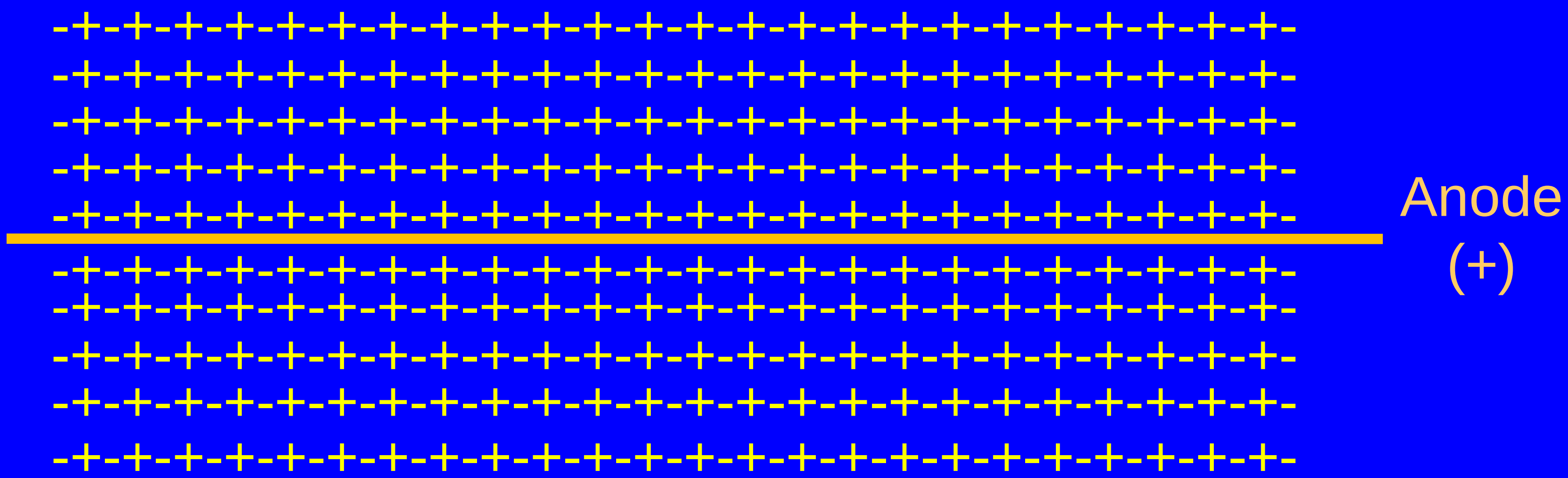
5. Geiger-Mueller Region



Six Region Curve

5. Geiger-Mueller Region

The result:



The avalanche completely envelops the anode.

Six Region Curve

5. Geiger-Mueller Region

The electrons in the avalanche are collected quickly, but not the positive ions.

This creates a positive “space” charge in the vicinity of the anode.

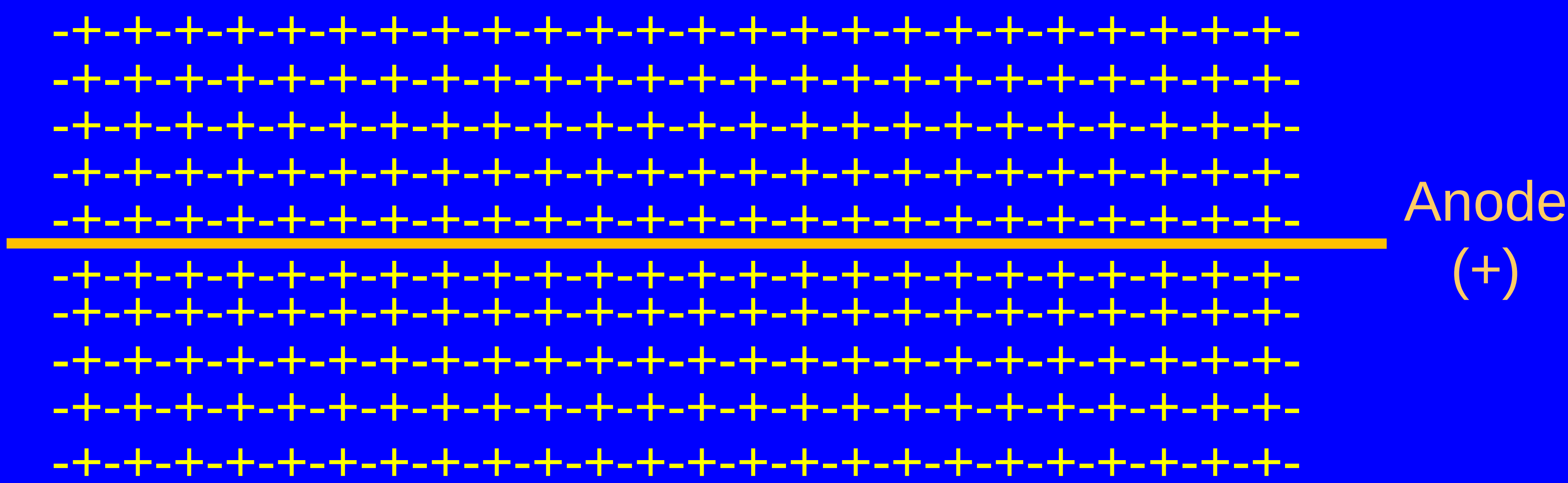
This positive charge reduces the strength of the electric field near the anode.

The reduced electric field strength shuts down the pulse since further ionization is impossible.

Six Region Curve

5. Geiger-Mueller Region

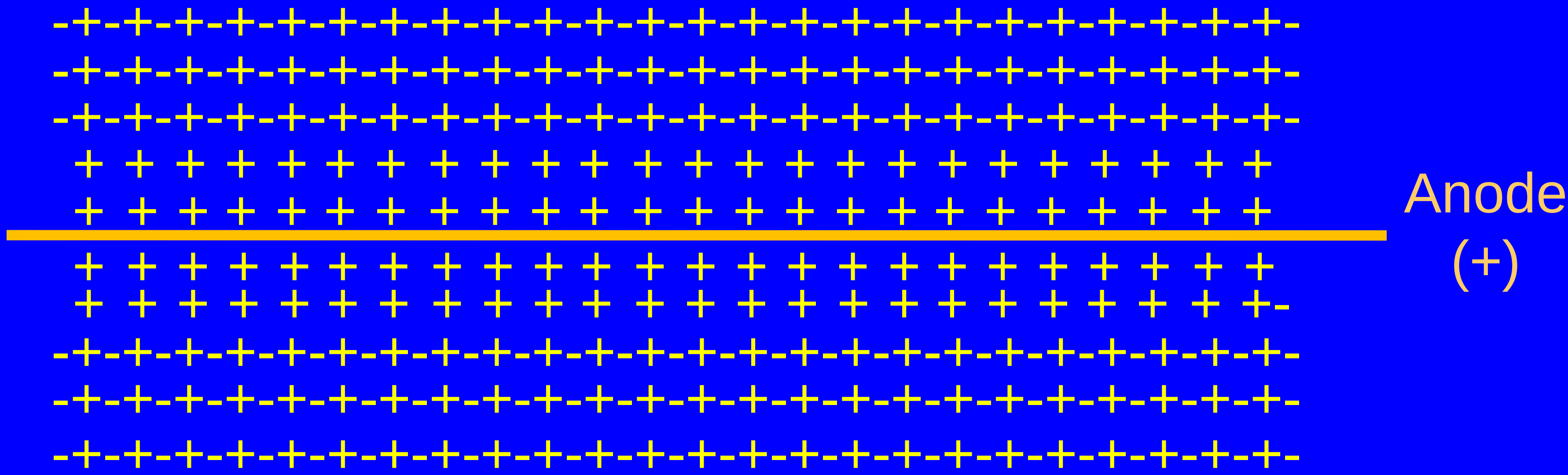
The result:



The avalanche completely envelops the anode.

Six Region Curve

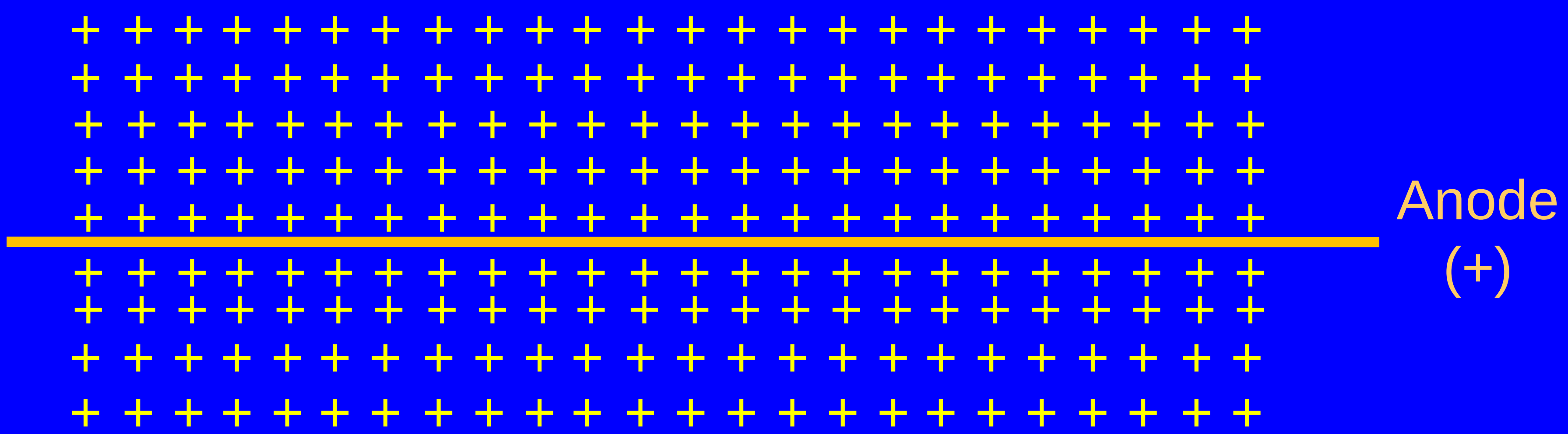
5. Geiger-Mueller Region



The electrons are collected quickly, but not the positive ions.

Six Region Curve

5. Geiger-Mueller Region



This positive charge reduces the strength of the electric field near the anode which shuts down the pulse. Further ionization is impossible.

Six Region Curve

5. Geiger-Mueller Region

In the Geiger-Mueller region, the plateau still slopes upwards.

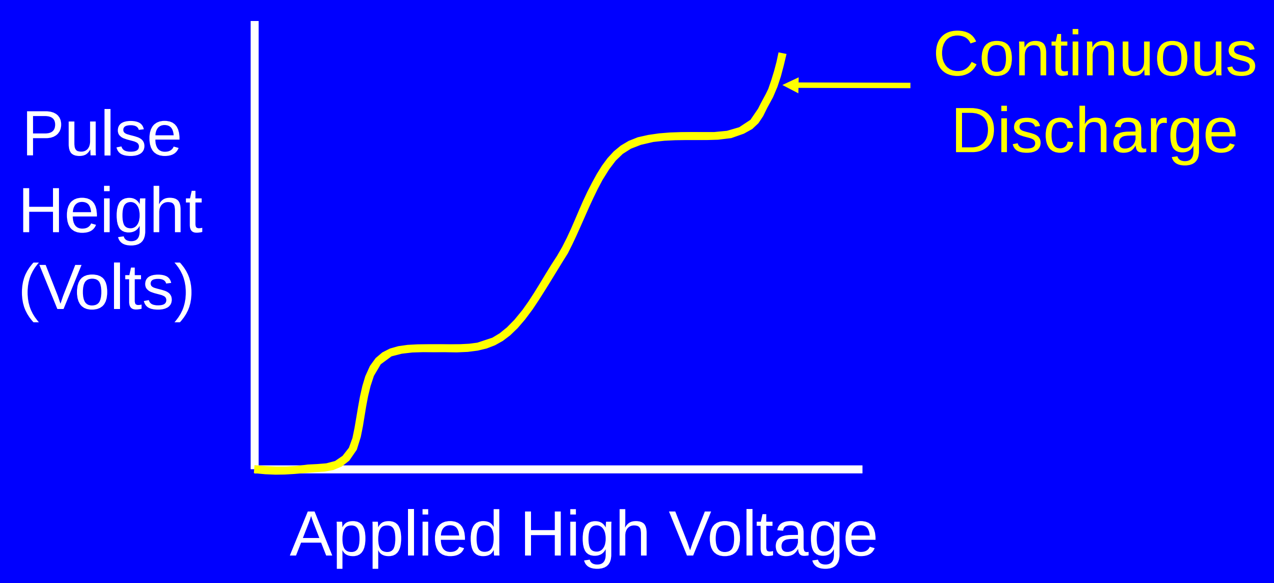
As the high voltage increases on the plateau, it takes more positive ions to produce a large enough space charge to overcome the increased field strength.

Six Region Curve

6. Continuous Discharge

In this region, arcing will occur that can result in a complete breakdown of the gas.

Any extended operation in this region will destroy the tube.



Six Region Curve

Where the Avalanche Occurs

We want all the avalanches to be produced within a small volume around the anode, i.e., within a fraction of a millimeter.

This way, the primary ion pairs produced by the radiation will be created outside the region in which the avalanche is produced. This is necessary if the pulse size is to reflect the energy deposited in the gas.

If primary ion pairs were produced inside the avalanche region, their avalanches would be smaller than those produced by primary ion pairs formed outside this region. This is because the avalanches would begin closer to the anode.

Basic Characteristics of Gas Detectors

Basic Characteristics of Gas Detectors

Ion Chambers

- operate in the ionization region
- can use both parallel plate and coaxial electrodes
- usually operate in the current mode
- primarily used to measure exposure rates due to gamma rays and x-rays
- usually poor response at low exposure rates (< 1 mR/hr)
- capable of measuring high exposure rates (1–1000 R/hr)
- energy independent (flat relative response curve)
- air often used as the fill gas
- might be sealed or open to the atmosphere
- if open to atmosphere: they use a desiccant (silica gel) to dry the air; their response is affected by ambient pressure and temperature

Basic Characteristics of Gas Detectors

Proportional Counters

- operate in the proportional/limited proportionality region
- use coaxial electrodes or variant
- almost always operate in the pulse mode
- primarily used to count alpha and beta sources and surface contamination
- can distinguish small beta pulses from larger alpha pulses
- much shorter dead time than GMs, therefore better at high count rates
- might be sealed or operate in gas flow mode
- gas flow mode allows operation at one atmosphere and the use of larger an thinner window which improves efficiency
- P-10 is common fill gas: 90% argon and 10% methane

Basic Characteristics of Gas Detectors

Geiger-Mueller Detectors

- operate in the Geiger Mueller region
- use coaxial electrodes
- usually operate in the pulse mode
- used to measure exposure rates or count beta sources and surface contamination
- exposure rate measurements ca. 0.1 mR/hr to 1 R/hr
- energy dependent: when measuring exposure rate they over respond at low photon energies (ca. < 200 keV)
- all pulses are the same size, hence no discrimination between alpha and beta and gamma pulses.
- usually sealed with gas at a fraction of an atmosphere
- neon fill gas with halogen (Cl_2) quench gas is common
- sometimes helium fill gas with organic quench gas
- large dead times (e.g., 100 us)