Medical University of Białystok
Department of Biophysics

PRE-COURSE (PHYSICS)

RADIOACTIVITY (3)

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THE METHODS OF DETECTION OF IONISING RADIATION

The ionizing radiation detectors:

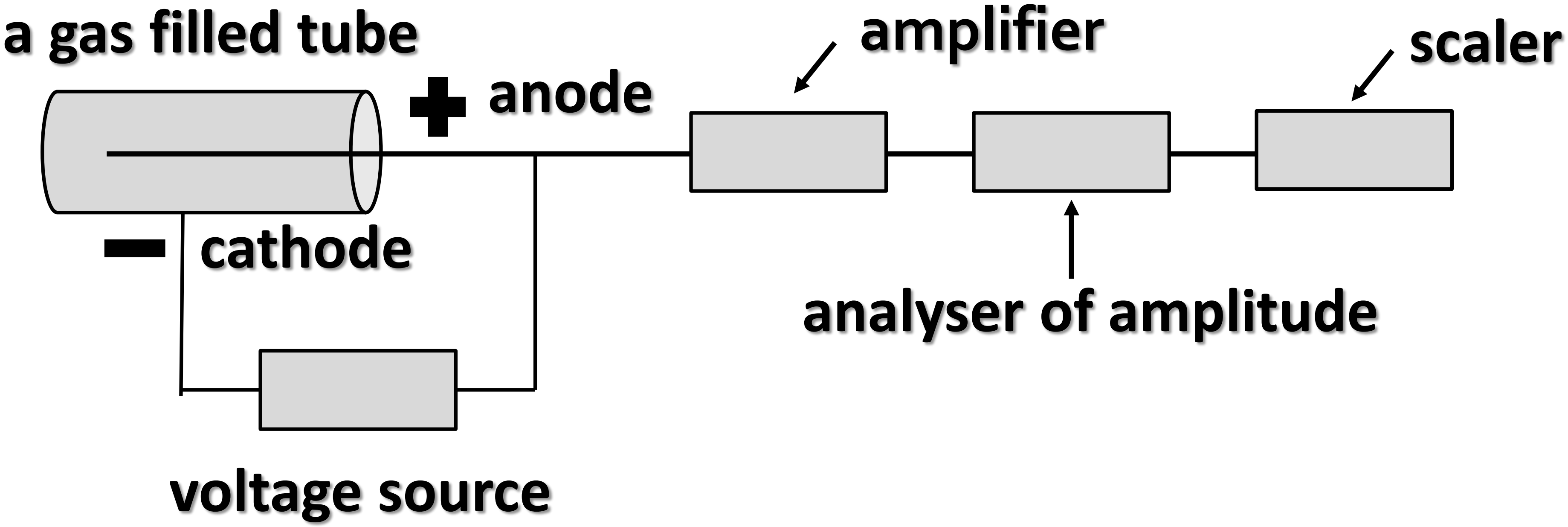
- **Gas filled detectors e.g Geiger-Müller counter**
- **Scintillation detectors**
- **Semiconductor detectors**

Gas filled detectors

The ability of atomic radiation to ionise a gas and provide a measurable electronic signal is used in gas counters.

Gas counters were most popular in measuring radioactivity in the twentieth century because of their simplicity and flexibility of technology.

Gas filled detectors



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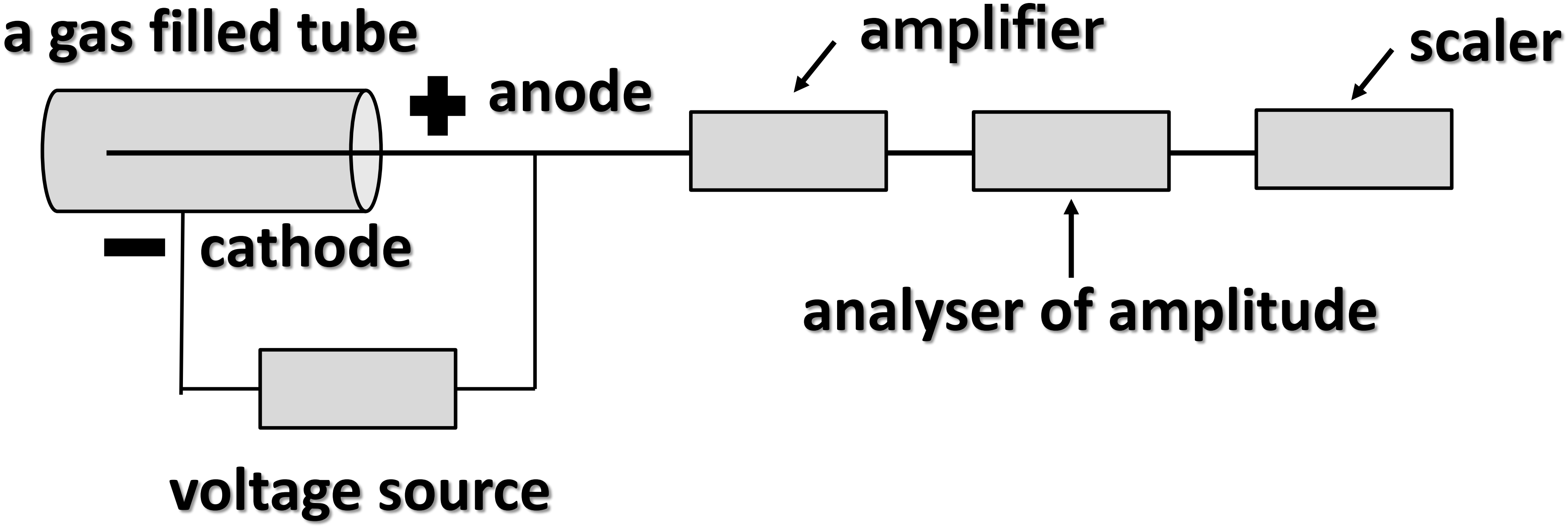
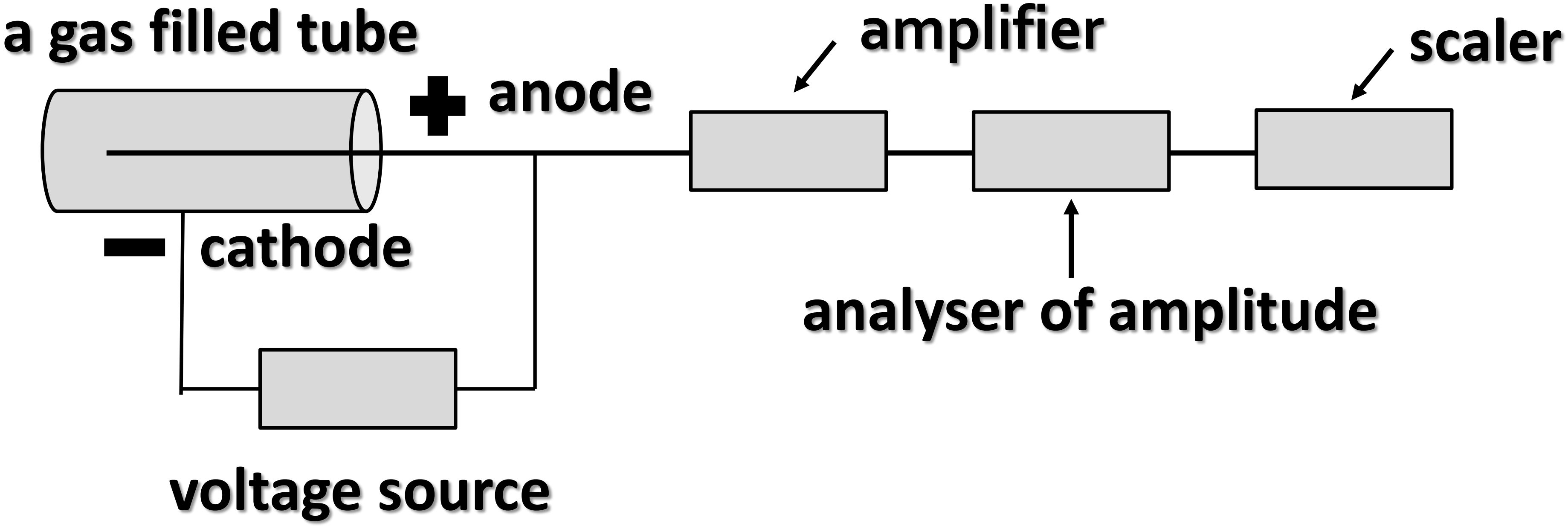
Gas filled detectors



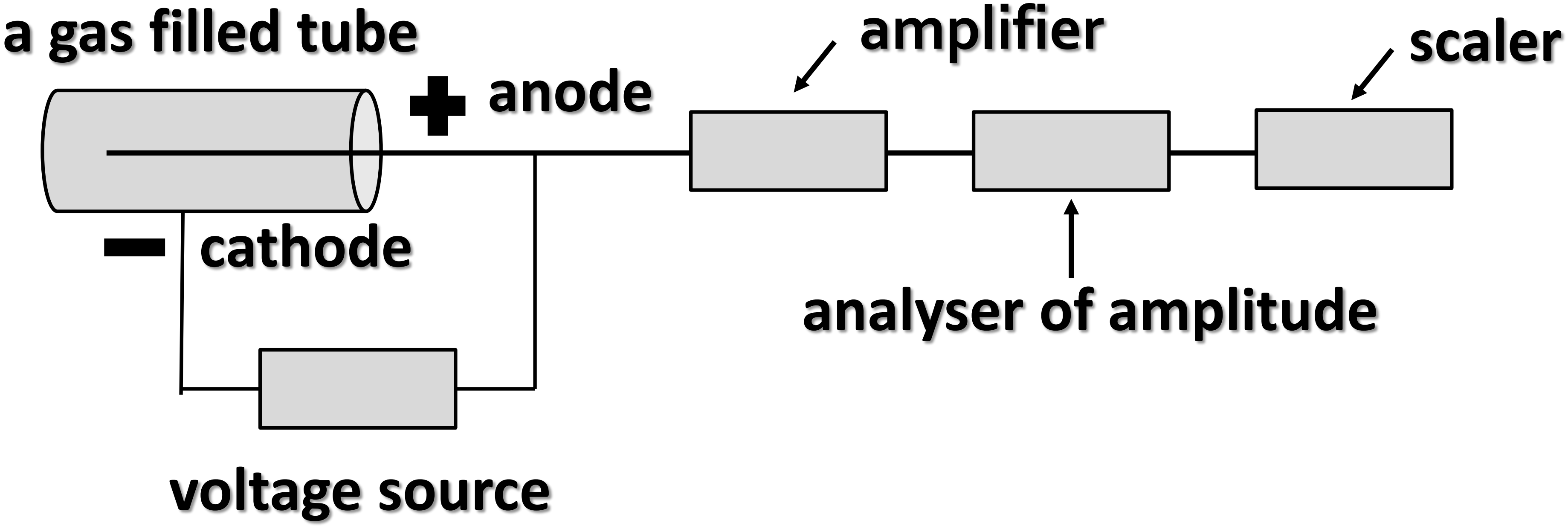
A gas filled detector consists of a gas filled tube, a positive (+) anode wire and negative (-) cathode tube, ionising radiation entering the tube, atoms of gas are ionised, producing positive and negative ions and electrons.

Gas filled detectors



If a potential is applied across the tube, the positive ions will migrate towards the cathode and electrons and the negative ions towards the anode (Coulomb attraction).

Gas filled detectors



The migration of electrons and ions to the electrodes result in a current flow or electrical charge, which can be amplified in an amplifier, analysed in the analyser of amplitude and displayed in the scaler.

Gas filled detectors

Only a fast charged particle (alpha, beta) can ionise gas inside the tube.

Any neutral particles such as gamma ray or X-ray quanta and neutrons must first be converted into charged particles before detection can take place.

Gas filled detectors

This is done in the case of X-rays and gamma rays in three processes:

- photoelectric effect,
- Compton effect
- pair production

Gas filled detectors

Neutrons are converted by means of nuclear reactions in a component of the counter gas.

A typical process is:

- $n_0^1 + He_2^3 \longrightarrow p_1^1 + H_1^3 + hv$

Gas filled detectors

The number of ionising events inside the tube of gas detector depends on the electric field (and applied voltage).

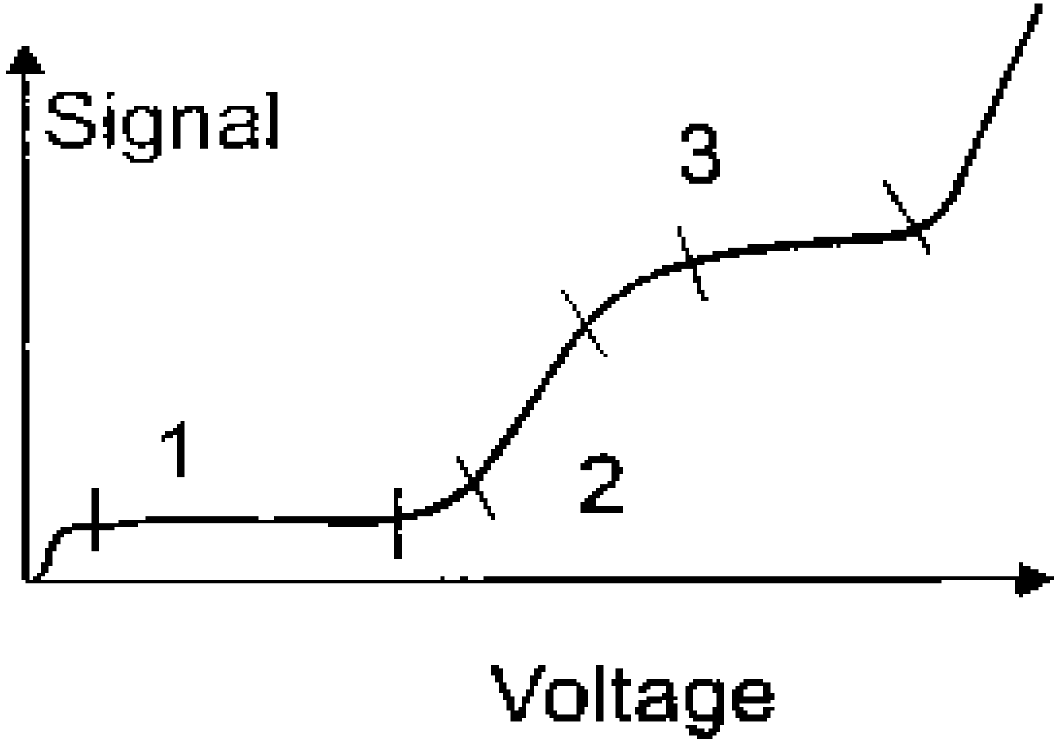
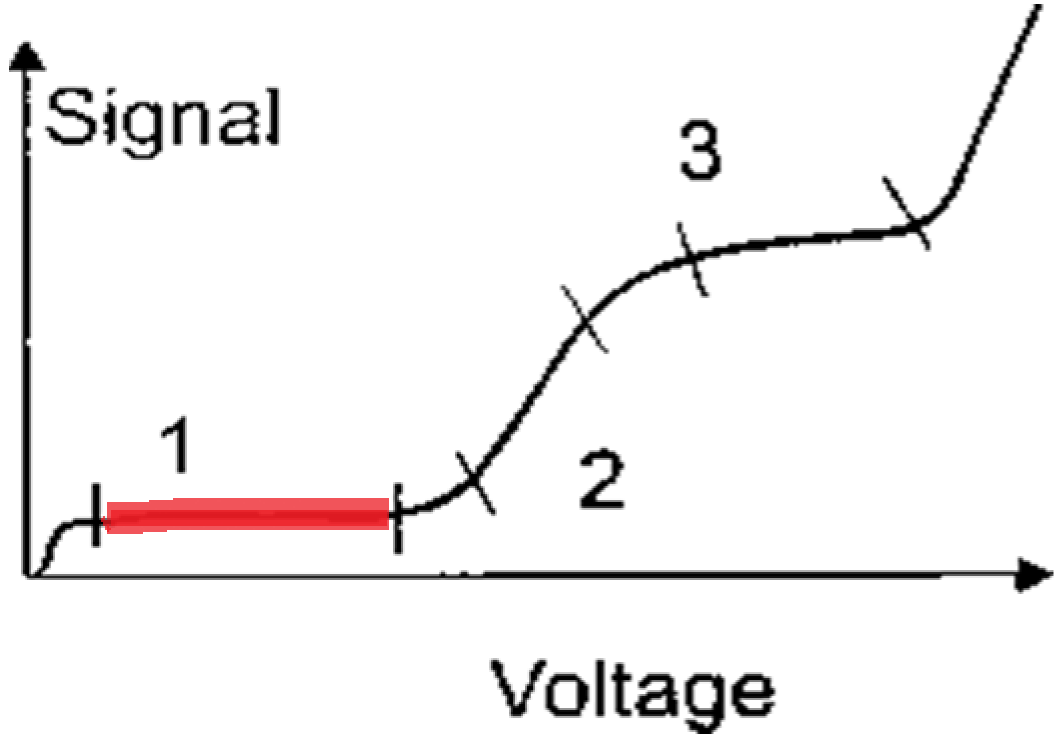


Fig. 2. The regions of the gas filled detectors.

Gas filled detectors

<u>Ionisation (ion) chamber region 1.</u>

The electric field causes the electrons and ions created by the incident radiation to migrate to the collecting electrodes.

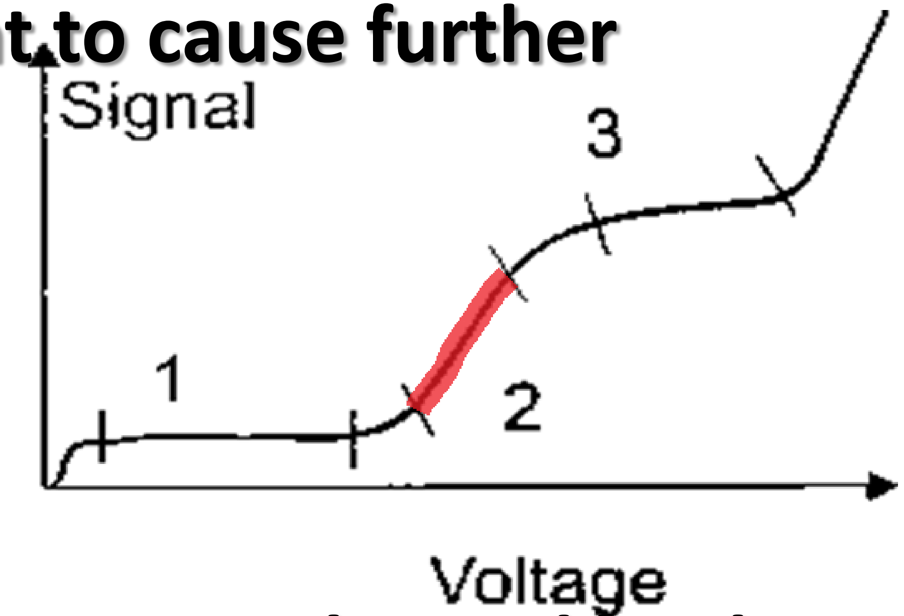


The changes in output signal amplitude depending on the applied voltage.

Gas filled detectors

proportional counter region 2.

As the electric field is increased, the free electrons are accelerated and can achieve kinetic energy sufficient to cause further ionisations within the detector gas.



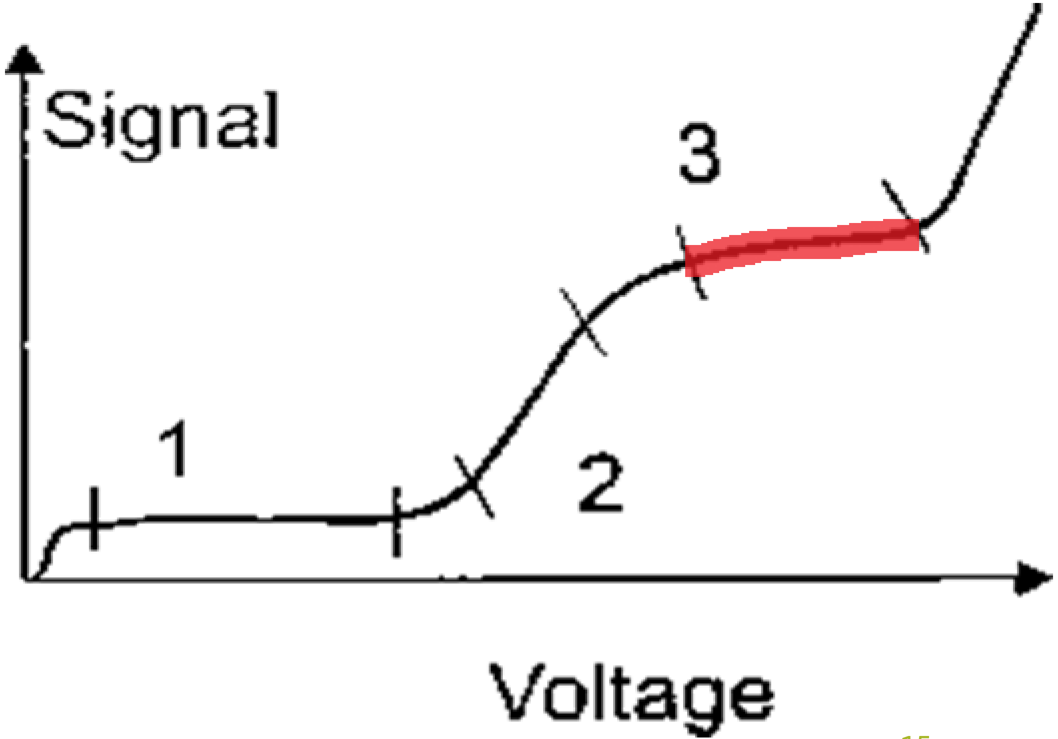
The electrons freed by these ionisations are accelerated by the field and cause additional ionisations (gas amplification). First the number of secondary ionisation events is proportional to the number of primary ions.

Gas filled detectors

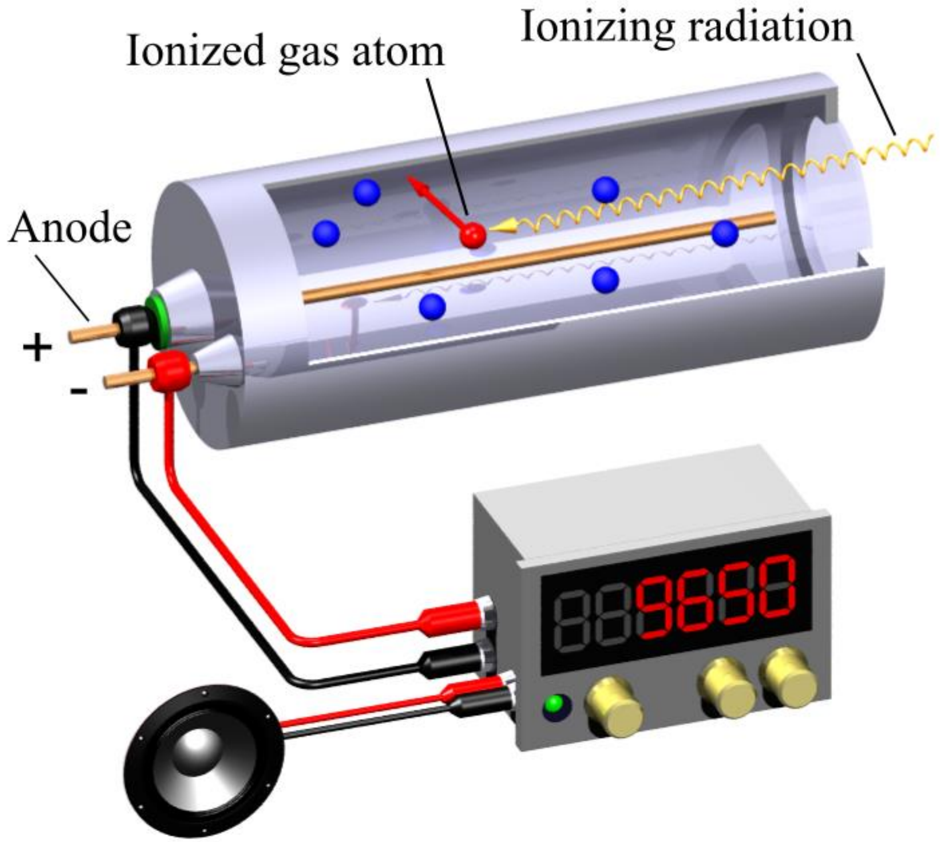
Geiger-Müller counter region 3.

If the voltage is sufficiently high, each output pulse from the detector is the same for all energies of ionising radiation

Gas amplification can provide a charge gain up to 10^6, which can give pulses of several volts. If the applied voltage is increased above the Geiger-Müller region, the gas goes into continuous discharge.



Geiger-Müller counter



The Geiger-Müller counter needs suppressing of the secondary pulse caused when the large cloud of positive ions (excited noble gas) hits the cathode and releases electrons.

Geiger-Müller counter

This can be done by:

- **making the load resistor on the anode supply decrease the voltage**
- **using a few percent of a quench gas with lower ionisation potential whose charge exchanges with the noble gas ions and does not cause electron emission at the cathode.**
- **Chlorine is a commonly used quencher. Argon and helium are favourite filling gases.**

Geiger-Müller counter

The time after each pulse until the quenching is complete (dead time) can be hundreds of microseconds, which limits the counter to low count rate applications.

Geiger-Müller counters for measuring particle's radiation are available with a thin mica window, permeable to the particles.

The applications of gas counters in bio-medicine:

- monitoring (dosimetry) and calibration of radioactive sources (ion chambers)
- detection of weak activities and contamination (Geiger-Müller counters)
- diagnostic imaging and autoradiography - still in research phase (with the use of the multi wire proportional counters MWPC):

  a/ digital radiographic scanner

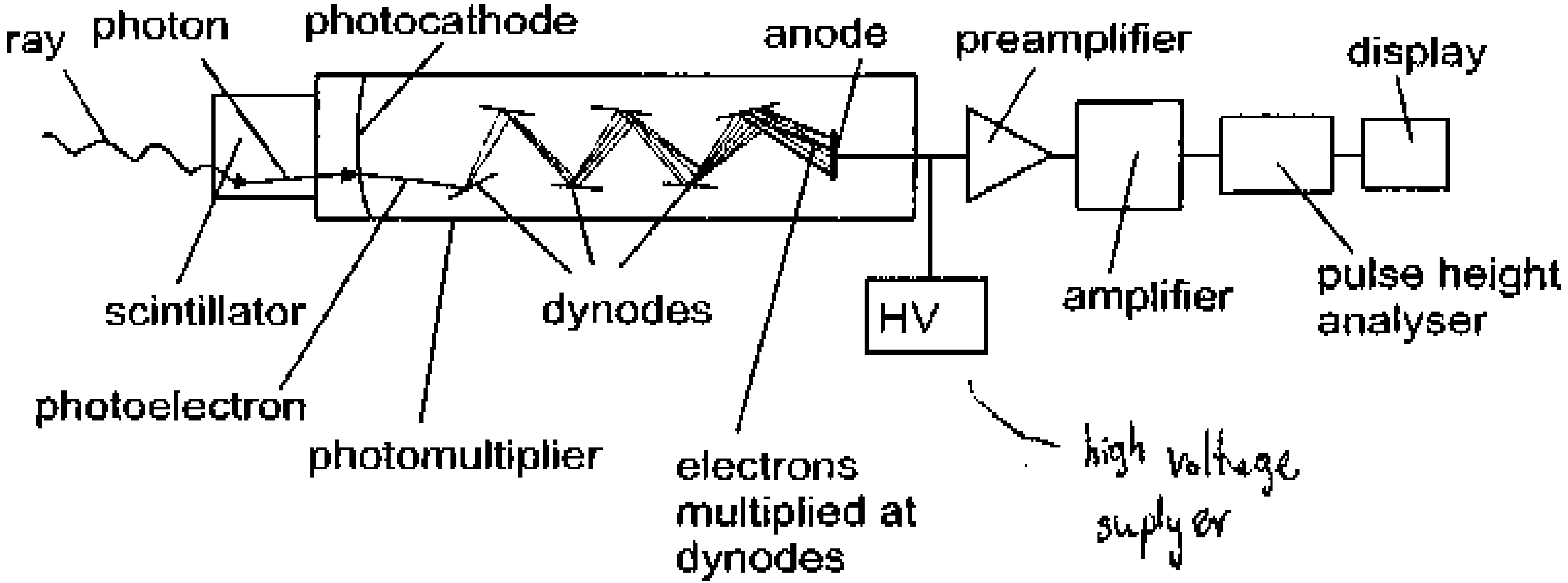
  b/ angiography using an MWPC gamma camera

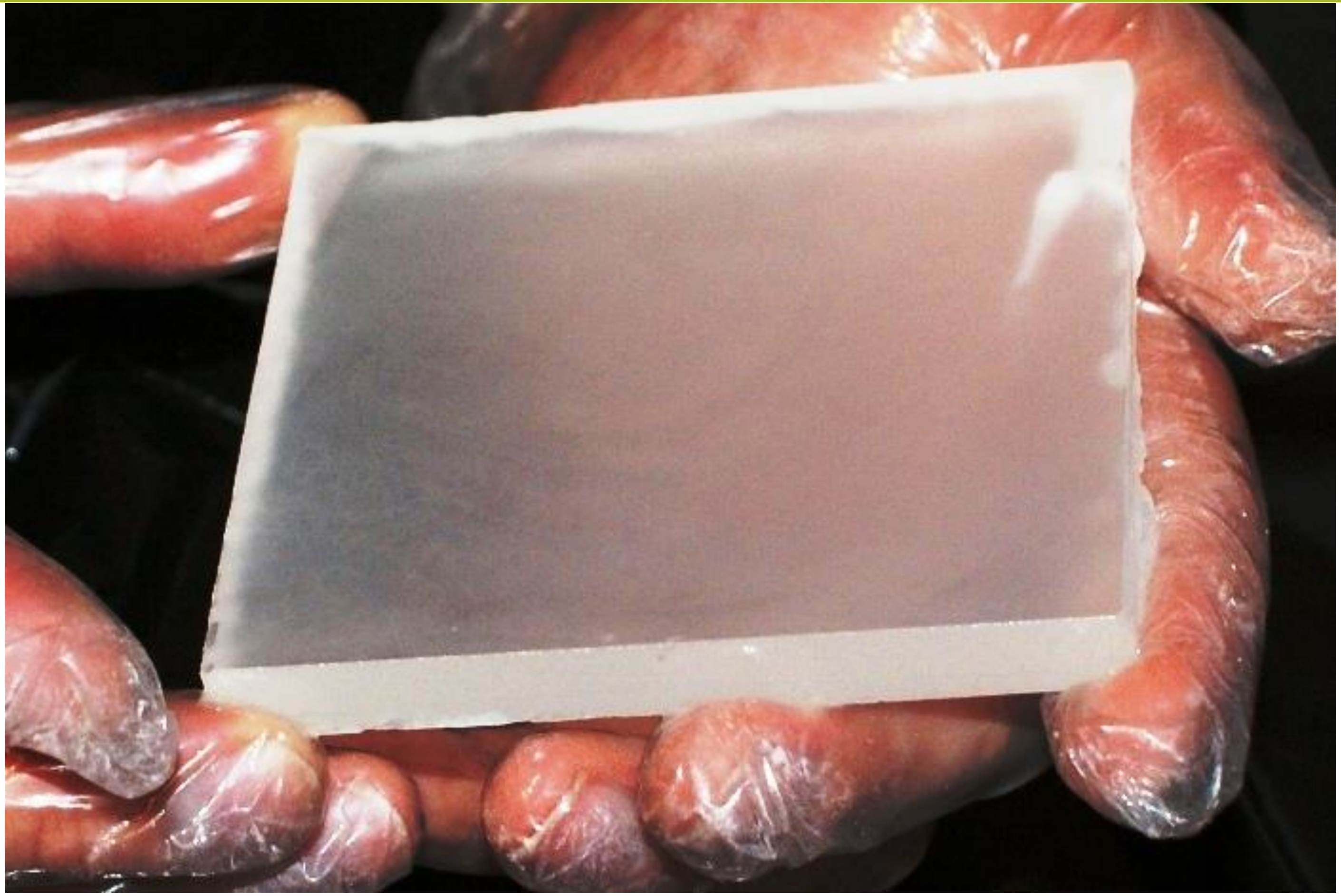
  c/ Positron Emission Tomography PET

Scintillation detectors

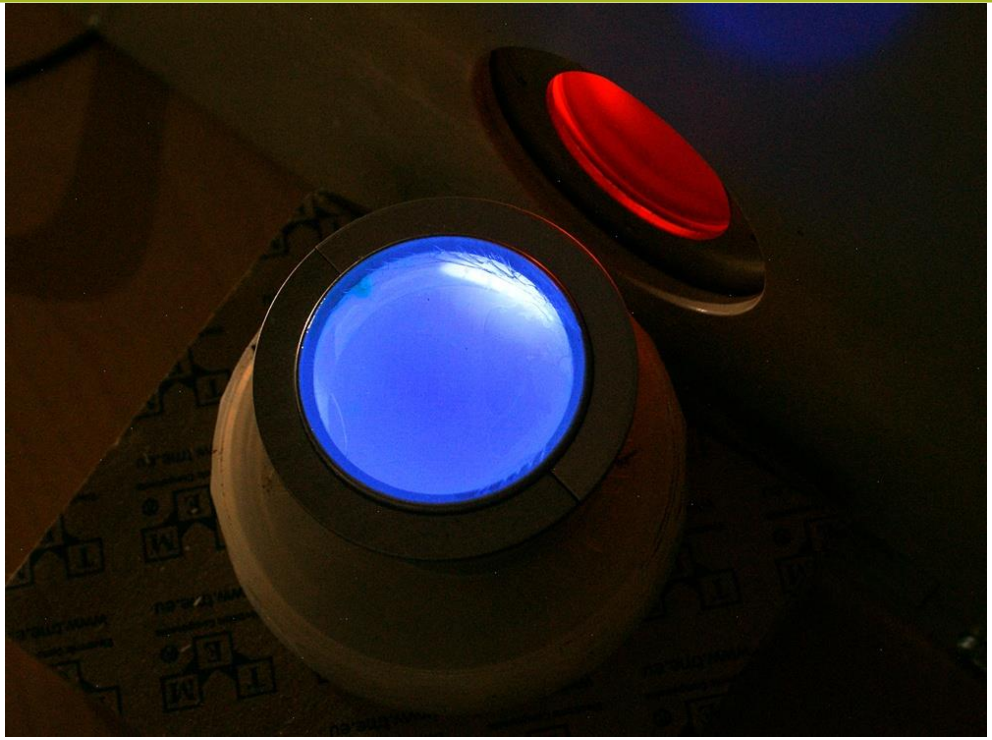
In some crystals in the processes of energy loss radiation excites some atoms above the ground state, these atoms then decay back to the ground state. When this process emits photons we have scintillation.

Scintillation detectors





Scyntylator - Sodium iodide activated with thallium.



NaI (Tl) scintillator in x-ray beam

Scintillation detectors

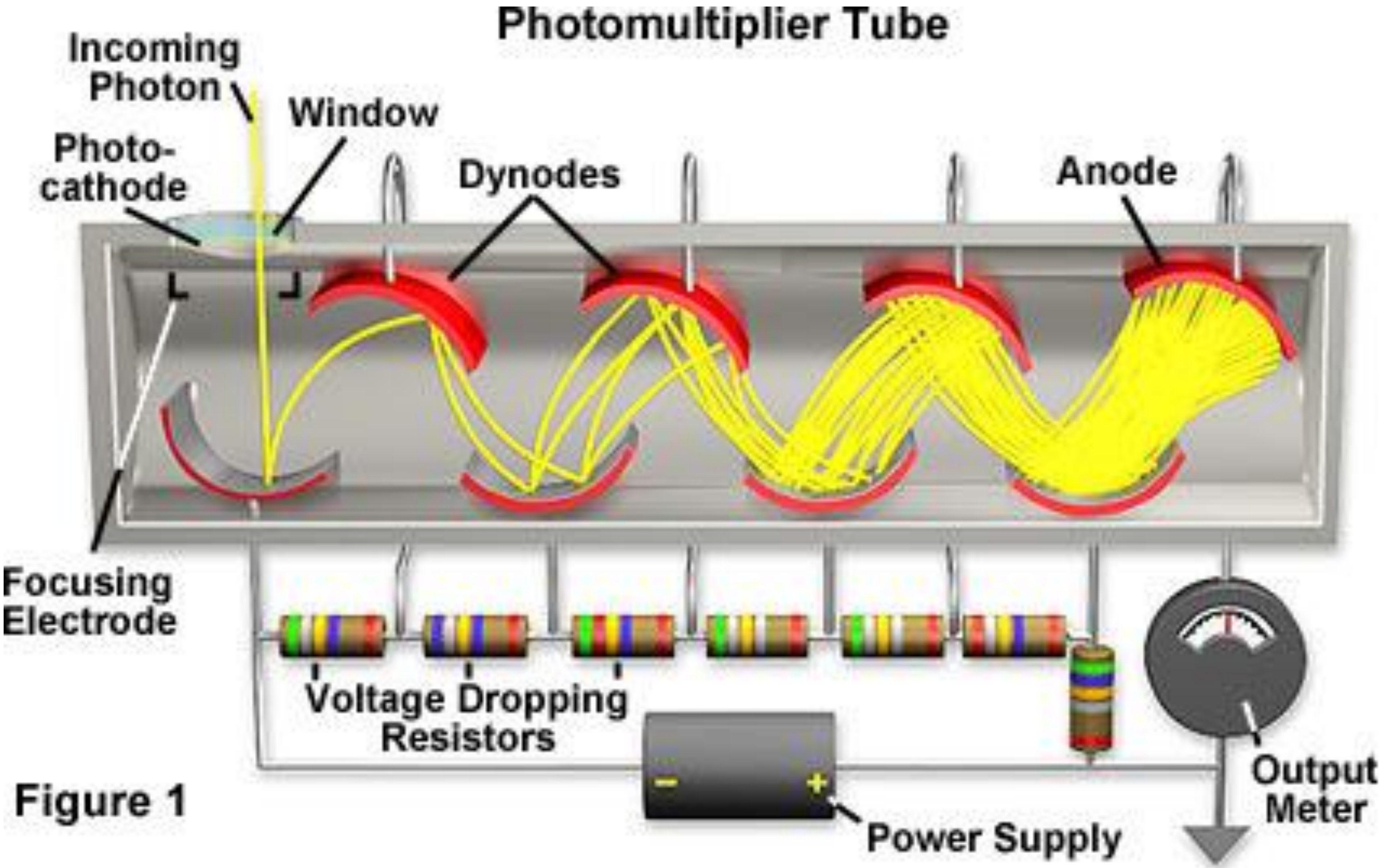
In the scintillation detector the radiation interacting with a scintillator produces a pulse of light (proportional to the energy deposited within the crystal) which is converted to an electric pulse by a photomultiplier tube (PMI).

Scintillation detectors

The photomultiplier consists of:

- **a <u>photocathode</u> which converts light photons into low energy electrons,**
- **10 or more <u>dynodes</u> that multiply the number of electrons striking them several times each**
- **<u>anode</u>**

The anode and dynodes are biased by a resistor dynode chain located in a plug-on tube base assembly. Total gain of the 12 stages of multiplier is 10^8.


Photomultiplier Tube
Incoming Photon
Window
Photo-cathode
Dynodes
Anode
Focusing Electrode
Voltage Dropping Resistors
Output Meter
Power Supply
-
+
Figure 1

photomultiplier tube (PMI).

Scintillation detectors

Next the pulse is amplified by preamplifier and amplifier and analysed by pulse height analyser.

An amplitude of the final pulse is proportional to the number of photons and the energy of the measured radiation.

Scintillation detectors

The properties of scintillation material required for good detectors are:

1) **transparency**
2) **availability in large size**
3) **large light output proportional to rays energy.**

Major types of scintillators

Organic (plastic) scintillators

- Organic scintillators consist of a transparent host material (a plastic) doped with a scintillating organic molecule and are mostly used for the detection of beta and other particles. The others are: naphtalene, stilbene.

inorganic scintillators

The most frequently used inorganic scintillation crystal is sodium iodide doped with thalium - NaI(Tl). The different types are: ZnS, CsI(Tl). These crystals combine a good detection efficiency with a large light output for the detection of gamma rays.

Liquid scintillators

Many samples include tritium and C^{14} - very important beta-emitting isotopes used in medical and biological researches and tests. They are sources of very low energy beta rays (19keV and 155keV) which are too low to detect with solid scintillators.

Liquid scintillators

The liquid scintillation detection involves mixing a liquid scintillator with the sample (processed in liquid form and transparent) and then observing the light pulses with photomultiplier tubes.

Semiconductor detectors (scintillation)

The <u>silicon photodiode</u> consists of a thin layer of silicon in which the light is absorbed and the free charge carriers (electron and holes) are created.

When the photodiodes are optically coupled to a crystal a scintillation light pulse will generate a small charge pulse in the diode which can be observed after amplification.

Semiconductor detectors (scintillation)

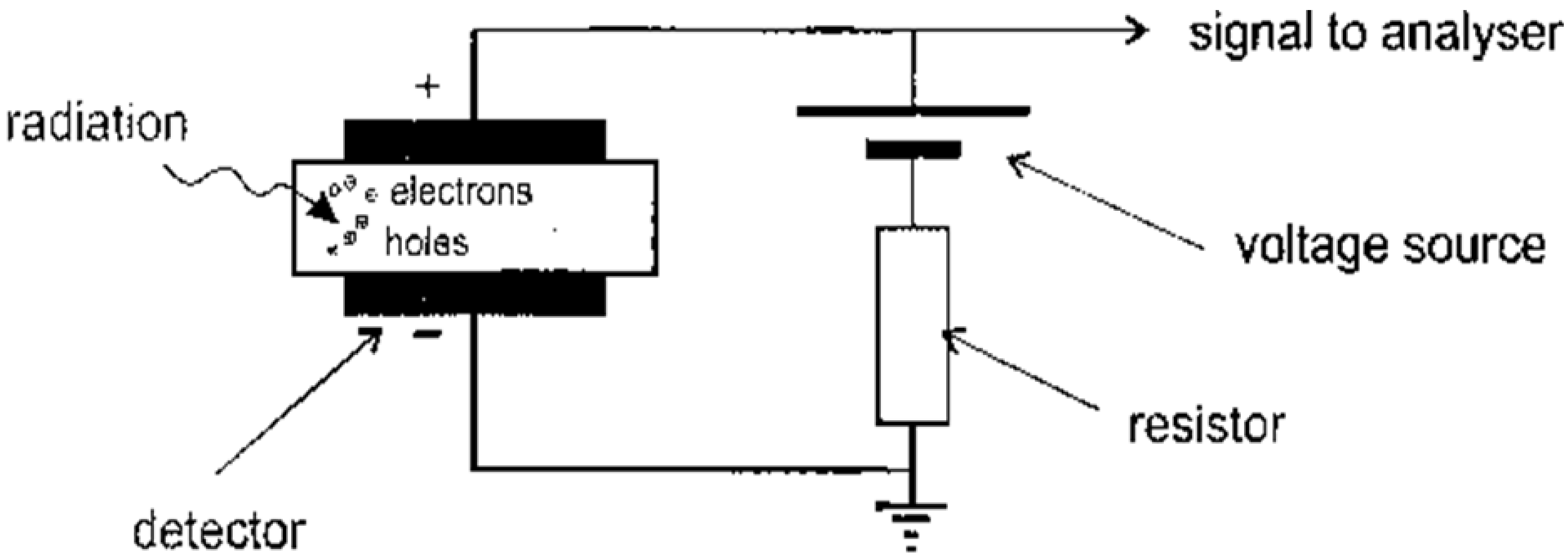
In contrast to photomultiplier tubes photodiodes do not require a high voltage but only a bias voltage of about 30 volts.

Photodiodes are thin, rugged and insensitive to magnetic field. Due to the electronic noise which increases with an increasing surface area, the dimension of PIN photodiode is limited to a few square cm.

Applications of scintillation detectors in medicine:

- Gamma Cameras
- SPECT (Single Photon Emission Computed Tomography)
- PET (Positron Emission Tomography)
- CT (Computed Tomography)

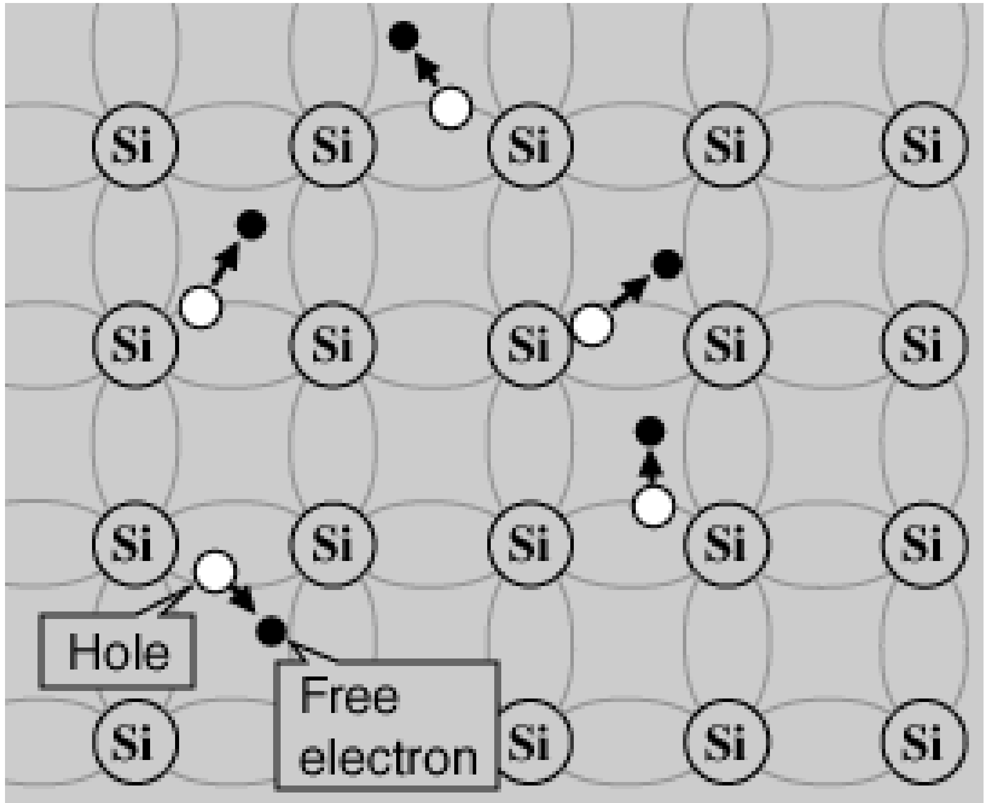
Semiconductor detectors



Semiconductor detector

Semiconductor detectors

Semiconductor detectors are the solid detectors that operate like ionisation chambers.



The charge carriers are <u>not electrons</u> and <u>ions</u> as in the gas filled detectors,
but <u>electrons</u> and <u>holes</u> (absences of the electrons).

Semiconductor detectors

Major types of semiconductor materials used in construction of detectors are as follows:

- **pure silicon (Si),**
- **high-purity germanium (Ge),**
- **germanium lithium-drifted (GeLi),**
- **silicon lithium-drifted (SiLi).**

Semiconductor detectors

Semiconductor detectors have a PIN (positive-intrinsic-negative) diode structure in which the intrinsic region is created by depletion of charge carriers when a reverse bias is applied across the diode.

Semiconductor detectors

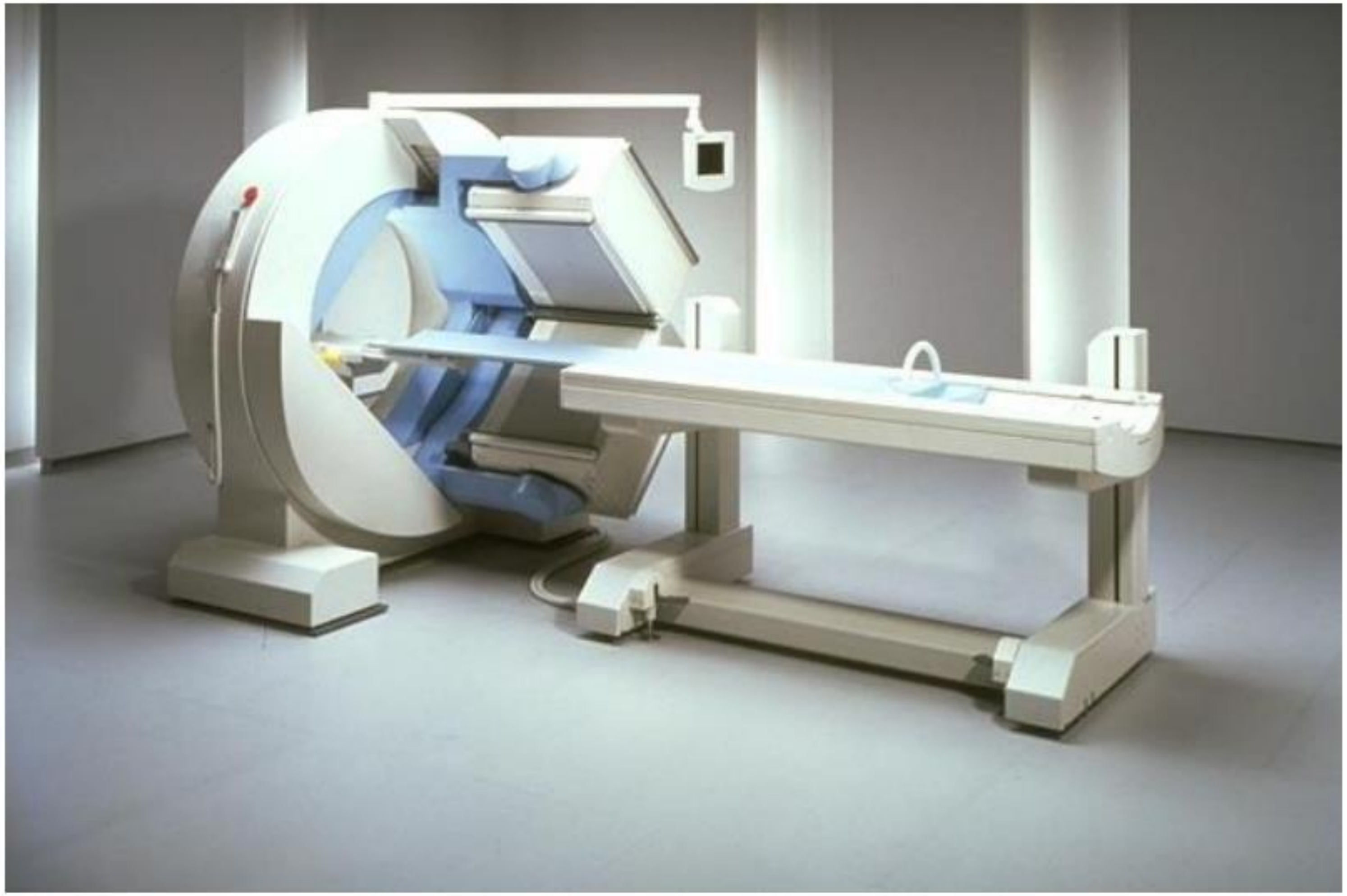
When photons interact within the depletion region, charge carriers (holes and electrons) are freed and are swept to their respective collecting electrode by the electric field.

Semiconductor detectors

The resultant charge is integrated by a charge sensitive preamplifier and converted to a voltage pulse with an amplitude proportional to the energy of radiation.

Medical radiation detectors

Planar imaging in nuclear medicine - **the Anger gamma camera**



the Anger gamma camera

The Anger camera is most commonly used to image the distribution of radioactive tracer within human body.

The device yields information regarding the energy and position of incident gamma photons.

The data acquired can be used to form a single image of the distribution or a series of images which can be used to assess the time course of the tracer (static study and dynamic study).

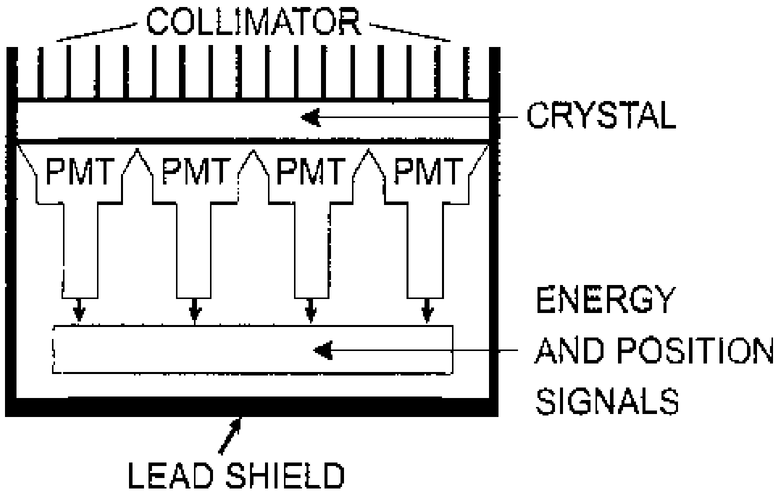
the Anger gamma camera

The tracer consists of the pharmaceutical to which a radioactive material is chemically bonded (radiopharmaceutical).

Many different radionuclides are used for this - but more then 90% of nuclear medicine procedures employ Technetium-99m, which is a gamma emitter (energy = 140keV, half-life = 6 hours).

the Anger gamma camera

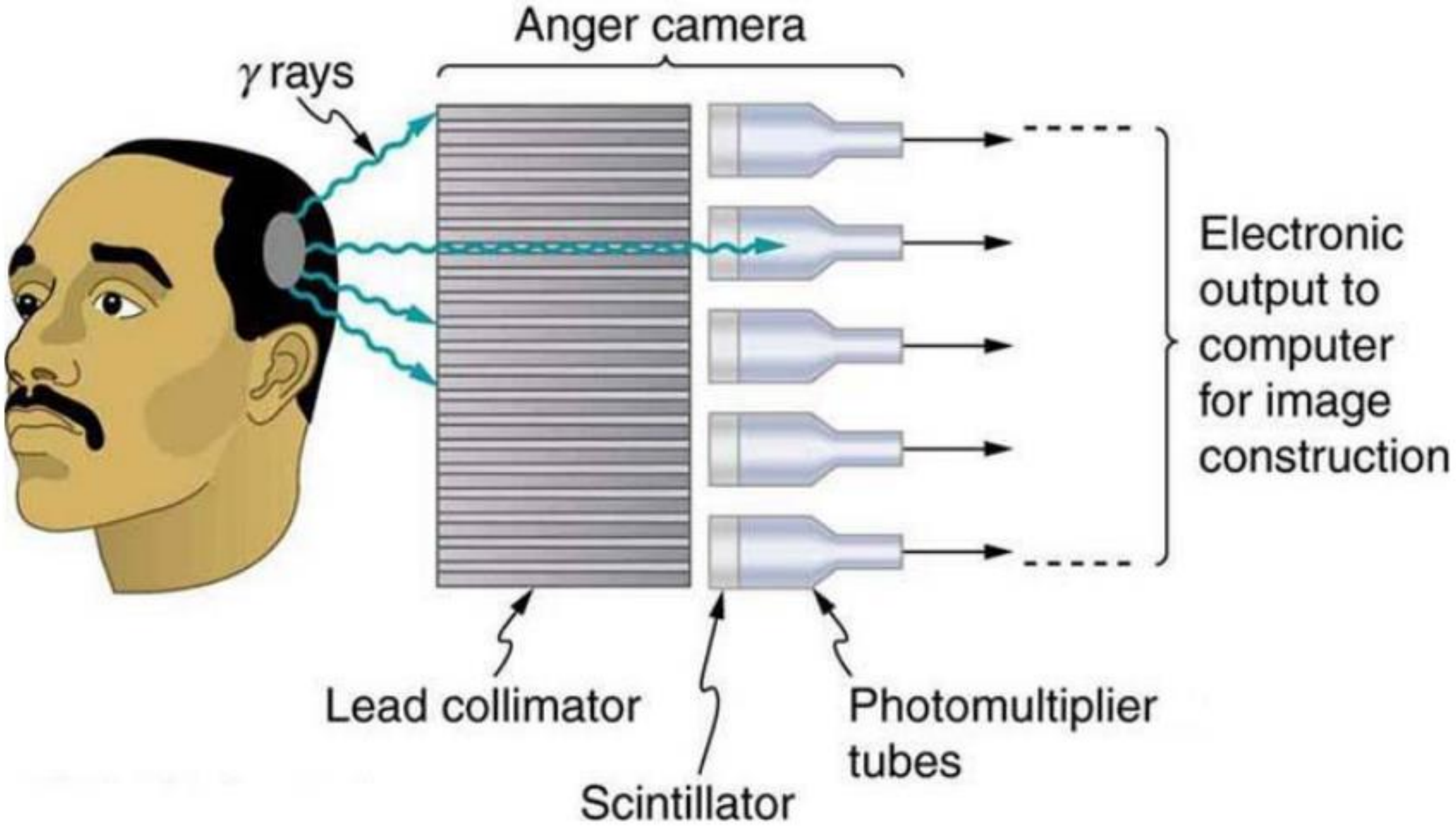
The construction of an Anger gamma camera.



The Anger camera consists of a single crystal of NaI(Tl) (20-60 cm in size) and an array of photomultiplier tubes (30-150) coupled directly to the optical window of the crystal which are contained within a light-tight lead shield.

The collimator which is positioned between the source and the crystal produces a geometrical relationship between the position of source and the position at which photons emitted from it strike the detector.

the Anger gamma camera



Medical radiation detectors

All medical imaging systems represent the compromise between:

- **spatial resolution,**
- **low contrast detectability**
- **radiation dose**

Medical radiation detectors

During the diagnostic examination the detectability of a given tissue embedded within another depends on:

- **the energy of photons,**
- **the patient thickness,**
- **the thickness of structure of interest,**
- **the linear attenuation coefficient of the tissues**
- **the detector characteristics.**

Medical radiation detectors

- X-ray imaging (**Computed Tomography (CT)**)

Medical radiation detectors

- X-ray imaging (Computed Tomography (CT))

The first clinically used CT system was installed in 1971.

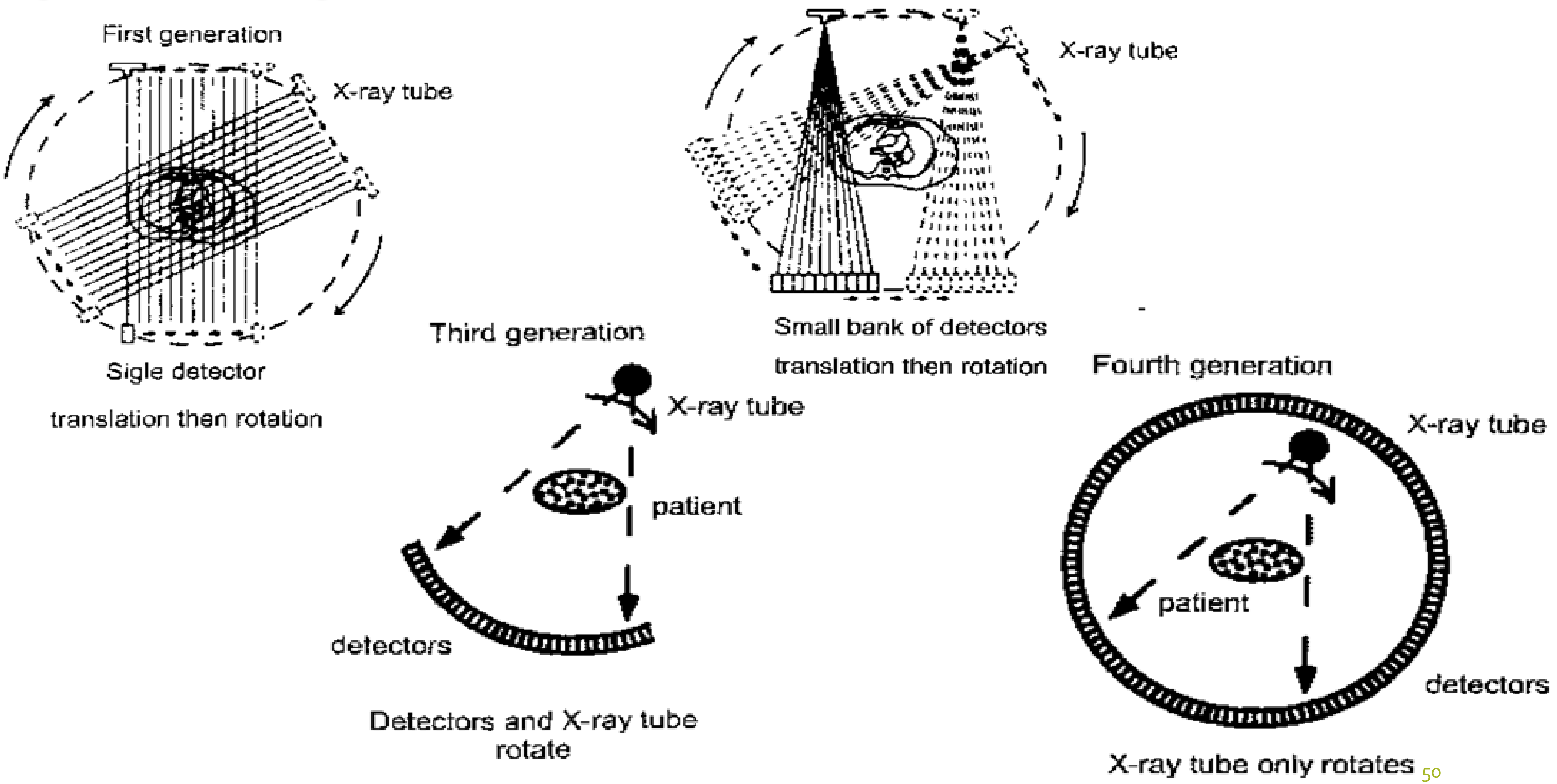
Since that year several developments have taken place in the system design.

These changes have been brought about by the need for faster scan times (lower doses) coupled with a need for improved spatial resolution (viewing images of high spatial resolution lends confidence to the diagnosis).

https://www.youtube.com/watch?v=nJRv8hfuuyg

https://www.youtube.com/watch?v=l9swbAtRRbg

Fig. 8. The four generations of CT



The features of the different CT systems

Feature	Kirsl Generatio n	Second Generation	Third Generation	Fourth Generation
X-ray source	Single	Single	Single	Single
Detectors type	Single NaI(Tl)	NaI(Tl)	gas proportional chambers or scintillation with photodiode	scintillation with photodiode
Number of detectors	1	20-32	400-800	2000
Scan time	4.5-6 minutes	10-70 seconds	1-5 seconds	1-5 seconds

Medical radiation detectors

- 3. Radiographic films

In diagnostic radiology photographic film is used for the direct imaging of X-rays and for recording the images produced by fluorescent screens and image intensifiers.

In autoradiography a standard method of visualising particular molecular species in gel is to label it with beta emitter which then reveals its presence by exposing a photographic emulsion laid on top of it.

Counting statistics

Successive counts of a long-lived radioisotope will yield different counts, even though the sample geometry, equipment settings, etc. remain unchanged.

The differences are, of course, due to the random nature of the decay process.

If we were to take a very large number of counts, the distribution of the recorded data would be quite accurately described by the normal distribution, or Gaussian curve.

Counting statistics

This is expressed as:

$$N(n) = \frac{k}{\sqrt{2\pi}} e^{\frac{-(n-\bar{n})^2}{2\sigma^2}}$$

where: **k – number of measurements**

n – any count

$\bar{n}$ **- true mean count**

$N(n)$ **- probability of obtaining a count of n**

σ **– standard deviation**

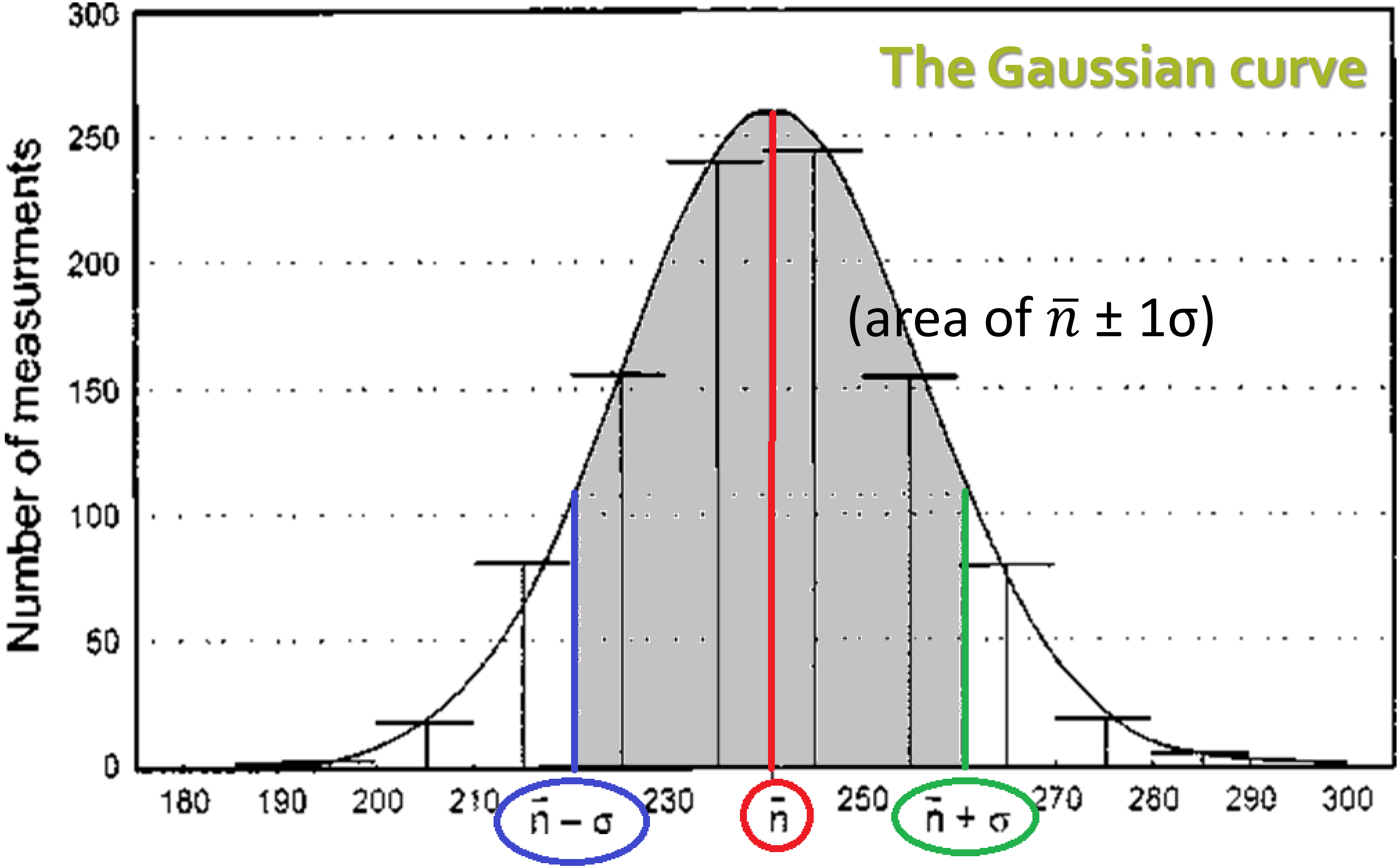
Standard deviation

σ – standard deviation is defined as:

$$\boldsymbol{\sigma} = \sqrt{\bar{\boldsymbol{n}}}$$

$\bar{n}$ **- true mean count**

The Gaussian curve



The area under the curve, bounded by two coordinate values n_1 and n_2, is the probability of attaining a value of n between n_1 and n_2. The value under the entire curve is 1.

- 68.3% of the counts will be within ±1 standard deviation of the true mean, $\bar{n}$
- 95.5% will be within ±2 standard deviations of $\bar{n}$
- 99.7% will be within ±3 standard deviations of $\bar{n}$

In practice we often have the opportunity to take only one measurement of a sample (n). In this case, the single count becomes the only estimate of the mean, and the standard deviation is given by the following expression, from before:

$$\boldsymbol{\sigma} = \sqrt{\overline{\boldsymbol{n}}} = \sqrt{\boldsymbol{n}}$$

Relative error

It is common practice to describe the precision of the measurements of the number of counts (n) by expressing Standard Deviation (σ) as a part and percent of n (relative error ε):

$$\boldsymbol{\varepsilon} = \frac{\sigma}{n}$$

$$\boldsymbol{\varepsilon_{\%}} = \frac{\sigma}{n} \cdot \mathbf{100\%}$$

Thank you for your attention