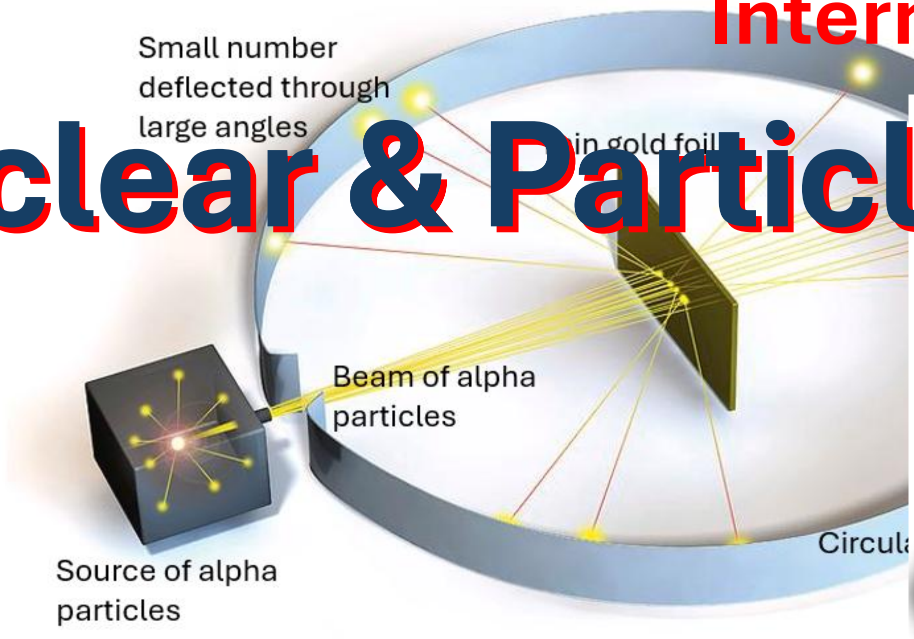
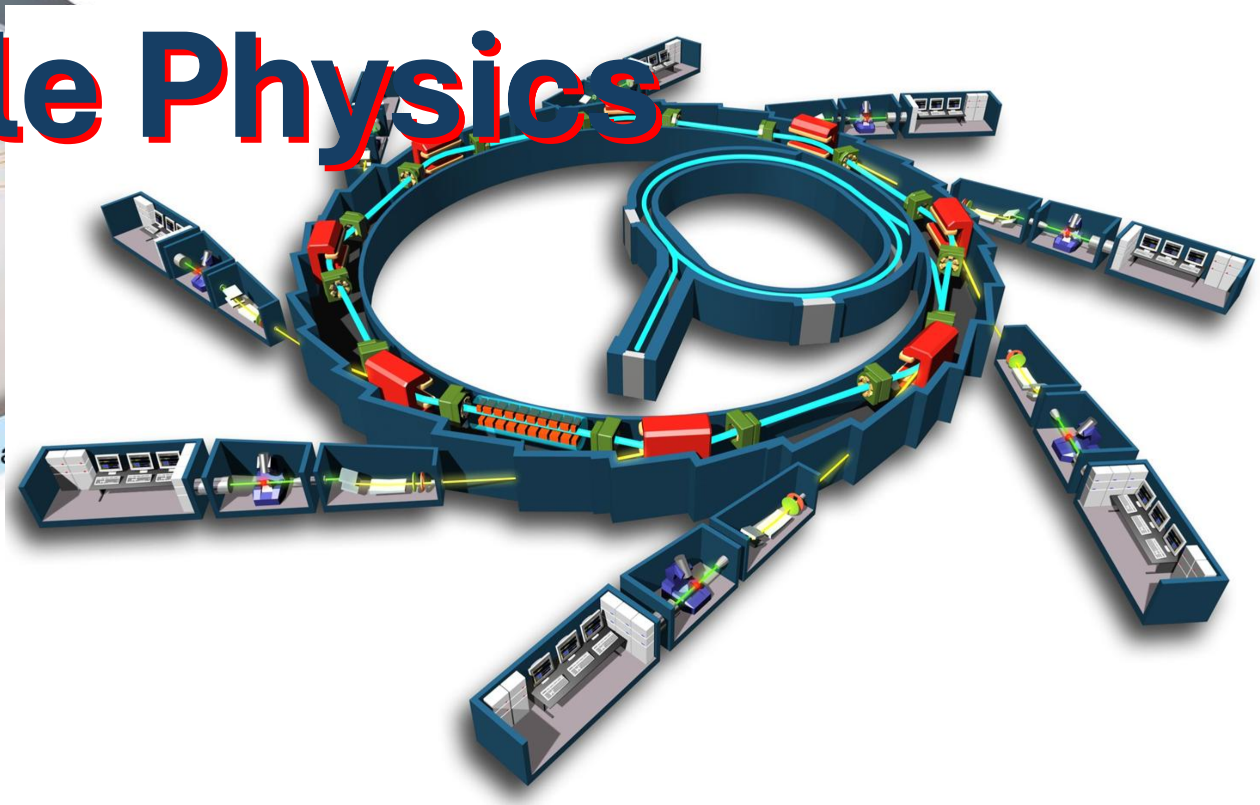
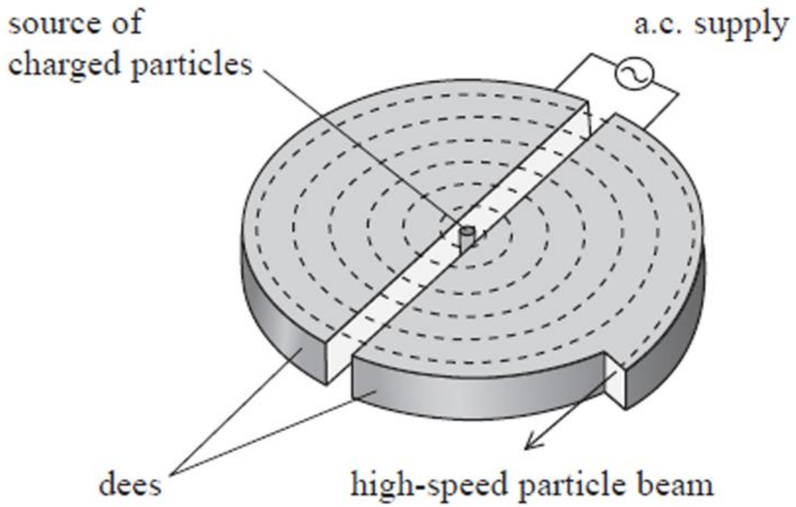
International Advanced Level A2-Physics

Nuclear & Particle Physics







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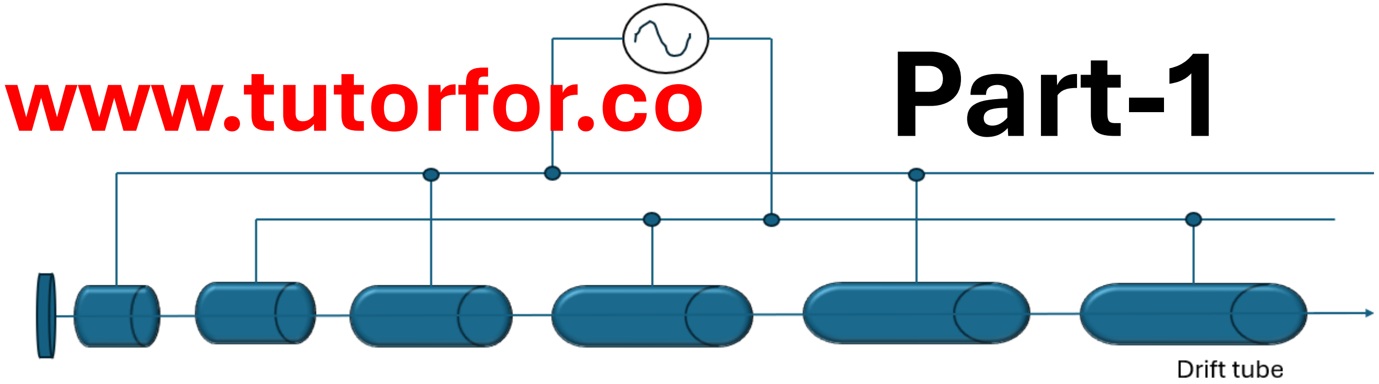
Part-1



Youtube: TutorFor ExamPhysics

Lesson Objectives:

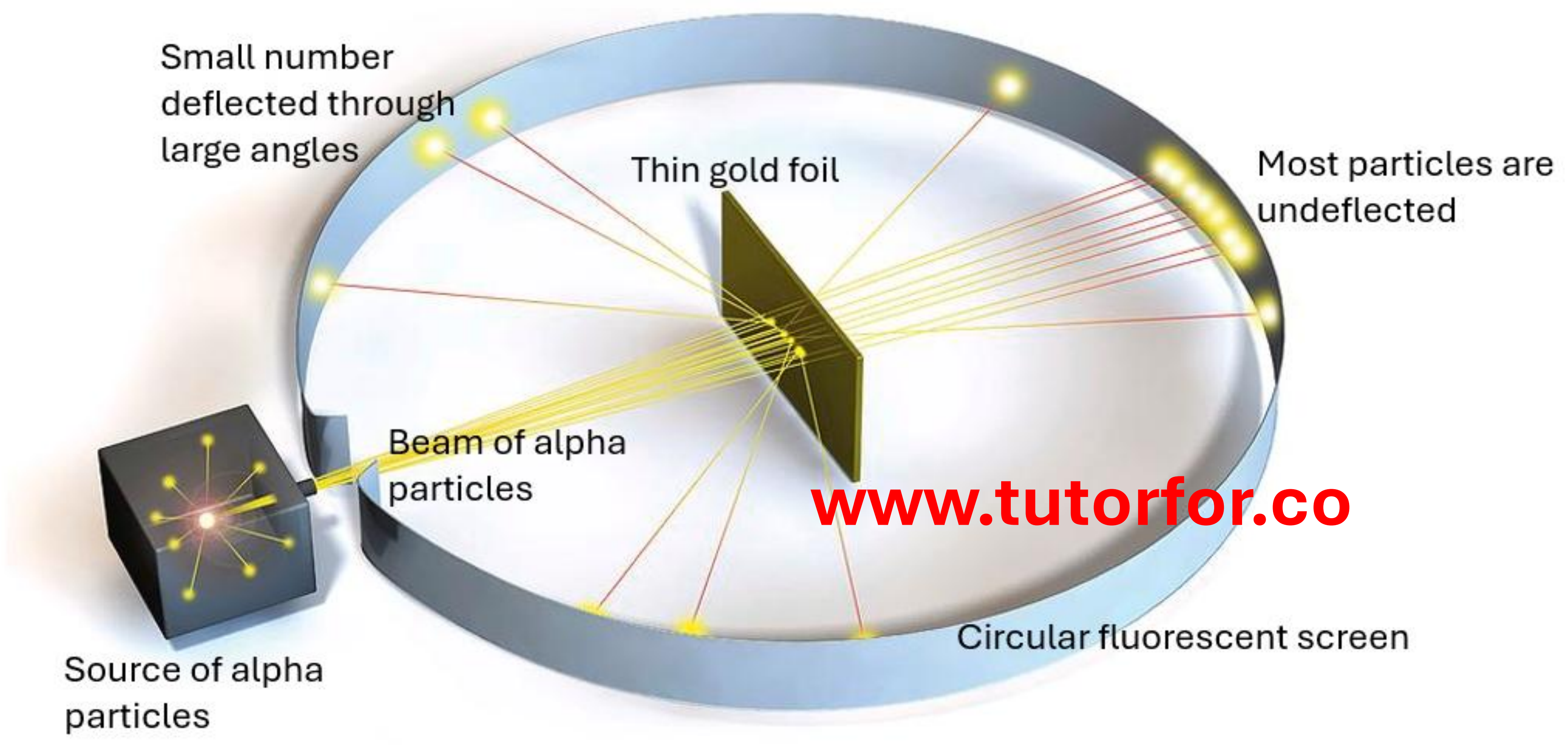
111	understand what is meant by *nucleon number (mass number)* and *proton number (atomic number)*
112	understand how large-angle alpha particle scattering gives evidence for a nuclear model of the atom and how our understanding of atomic structure has changed over time
113	understand that electrons are released in the process of thermionic emission and how they can be accelerated by electric and magnetic fields
114	understand the role of electric and magnetic fields in particle accelerators (linac and cyclotron) and detectors (general principles of ionisation and deflection only)
115	be able to derive and use the equation $r = \frac{p}{BQ}$ for a charged particle in a magnetic field
116	be able to apply conservation of charge, energy and momentum to interactions between particles and interpret particle tracks
117	understand why high energies are required to investigate the structure of nucleons
118	be able to use the equation $\Delta E = c^2 \Delta m$ in situations involving the creation and annihilation of matter and antimatter particles
119	be able to use MeV and GeV (energy) and MeV/c^2, GeV/c^2 (mass) and convert between these and SI units

120	understand situations in which the relativistic increase in particle lifetime is significant (use of relativistic equations not required)
121	know that in the standard quark-lepton model particles can be classified as: • baryons (e.g. neutrons and protons), which are made from three quarks • mesons (e.g. pions), which are made from a quark and an antiquark • leptons (e.g. electrons and neutrinos), which are fundamental particles • photons and that the symmetry of the model predicted the top quark
122	know that every particle has a corresponding antiparticle and be able to use the properties of a particle to deduce the properties of its antiparticle and vice versa
123	understand how to use laws of conservation of charge, baryon number and lepton number to determine whether a particle interaction is possible
124	be able to write and interpret particle equations given the relevant particle symbols.

🧪 Evolution of the Atomic Model – Summary Table

Scientist	Time Period	Key Contribution	Clarification
Democritus	~400 BCE	First proposed the concept of indivisible "atomos"	Philosophical, no experimental basis.
John Dalton	1803	Proposed the first modern atomic theory	Based on chemical evidence (e.g. law of multiple proportions).
J.J. Thomson	1897	Discovered the electron; proposed the plum pudding model	Based on cathode ray tube experiments.
Ernest Rutherford	1911	Discovered the nucleus via gold foil experiment	Replaced Thomson's model with the nuclear model.
Niels Bohr	1913	Introduced quantized orbits (Bohr model)	Successfully explained hydrogen emission spectra.
Erwin Schrödinger	1926	Developed the wave equation and the quantum model	Electrons are treated as wavefunctions; orbitals, not orbits.
James Chadwick	1932	Discovered the neutron	Essential to complete the understanding of the nucleus.
Murray Gell-Mann	1964	Proposed the quark model	Introduced the idea that protons/neutrons are made of quarks.

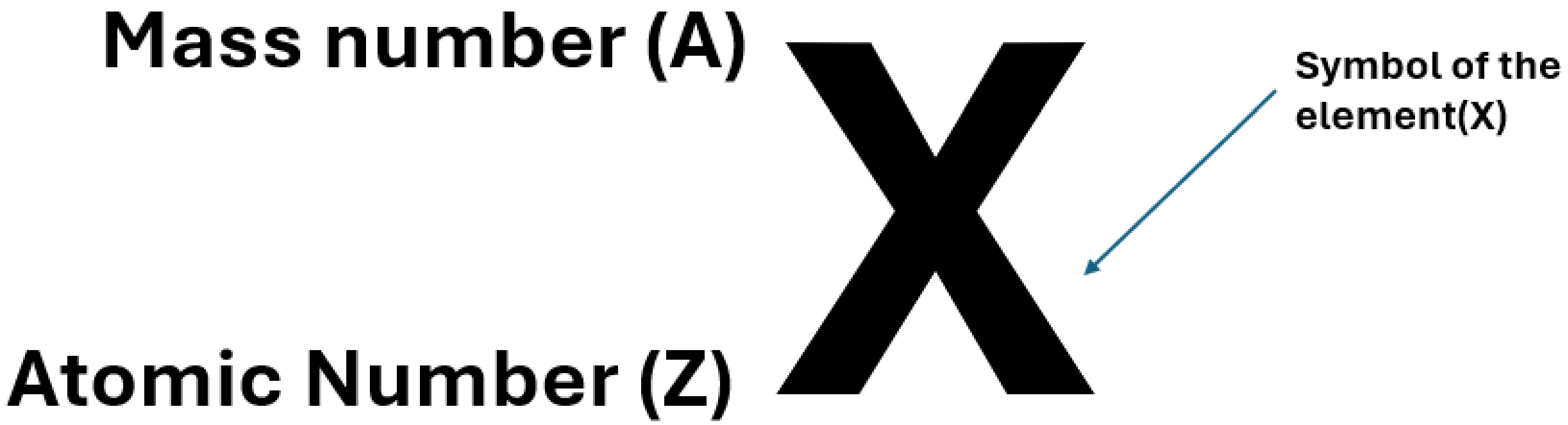
Rutherford's Alpha Scattering Experiment



Observations and the corresponding conclusions made from the alpha particle scattering experiment.

Observation	Conclusion
Most alpha particles were undeflected Or pass through with little or no deflection	Most of the atom is empty space
Few alpha particles were deflected by small angles	There is a concentration of charge in the atom
Very few alpha particles were deflected by more than 90°	Most of the mass is concentrated in a small region of the atom Or concentrated in nucleus

Nuclear Structure



- Atomic number = Number of protons
- Mass number(nucleon number) = Total number of protons and neutrons

The neutrons help to bind the nucleus together as they exert a strong nuclear force on other nucleons, and they act as a space between the positive charges of the protons which all repel each other.

Example

$^{226}_{88}Ra$

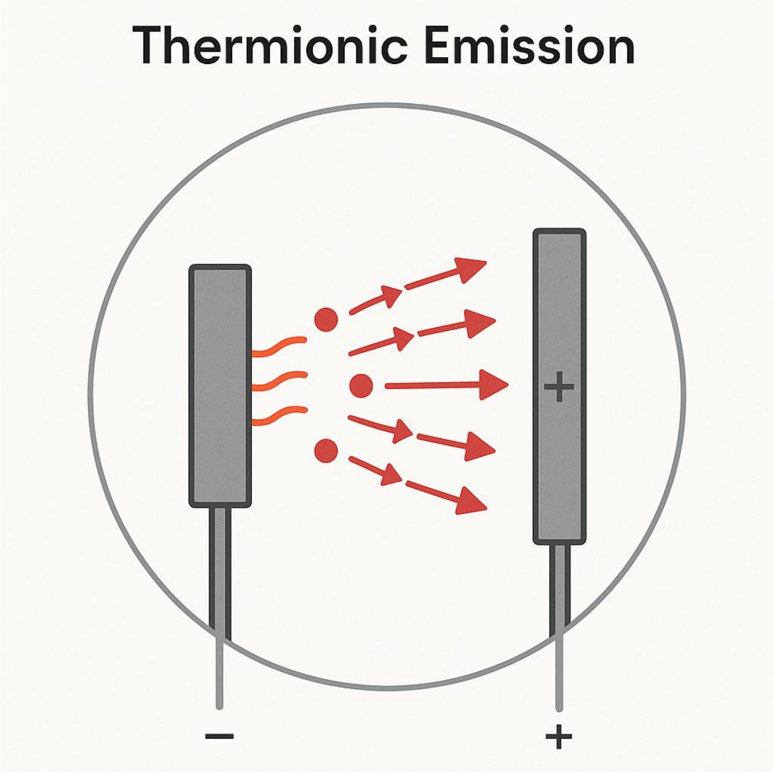
Mass number = 226

Atomic number =88

Number of Protons = 88

Number of Neutrons = 226 – 88 = 138

Number of Nucleons = 226



The release of electrons from the surface of a metal as it is heated is known as **thermionic emission.**

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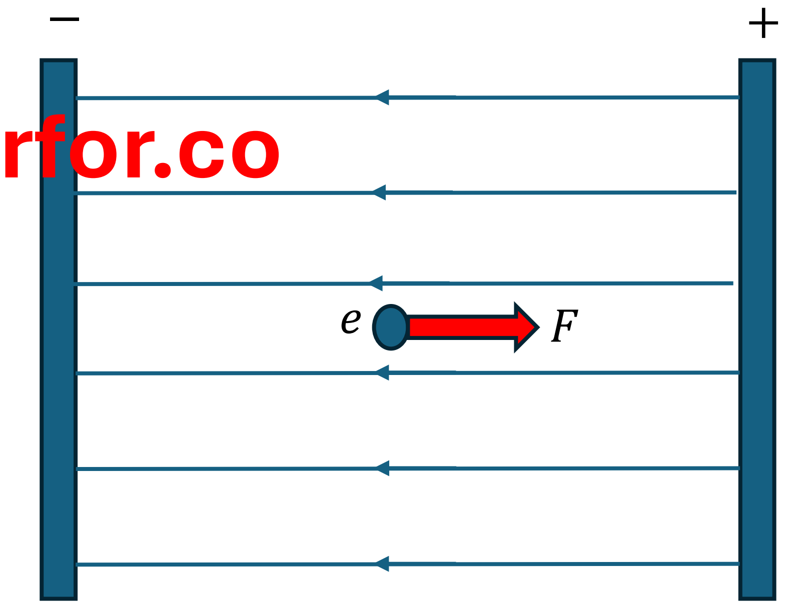
By heating a metal to release electrons through thermionic emission and then accelerating them using an electric field, we can produce high-speed electrons known as a **cathode ray.**

Concept Learning Question



$F = EQ$

$F = ma$

$a = \frac{Eq}{m}$

V – Potential Difference

E-Electric Field Strength

E_k -Kinetic Energy

$E_k = qV$

$E_k = \frac{1}{2}mv^2$

Charge of an electron $= -1.6 \times 10^{-19}\ C$

Mass of an electron $= 9.11 \times 10^{-31}\ kg$

1) How fast would an electron be moving if it was accelerated from rest through a p.d. of 4000 V ?

2) Electrons are accelerated from rest to a kinetic energy of 2.5 keV. Calculate the potential difference that the electrons were accelerated through.

Concept Learning Questions.

In 1927, Davisson and Germer demonstrated that electrons fired at a crystal create a diffraction pattern, revealing the crystal's structure. Their experiment confirmed Louis de Broglie's earlier theory that electrons, like light, can exhibit both wave and particle behavior.

The de Broglie equation is:

$$\lambda = \frac{h}{p}$$

Since momentum $p = mv$ (mass × velocity), the equation can also be written as:

$$\lambda = \frac{h}{mv}$$

Plank constant(h) = 6.63 × $10^{-34}\ Js$

3) What is the wavelength of an electron in a beam which has been accelerated through 2500 V ?

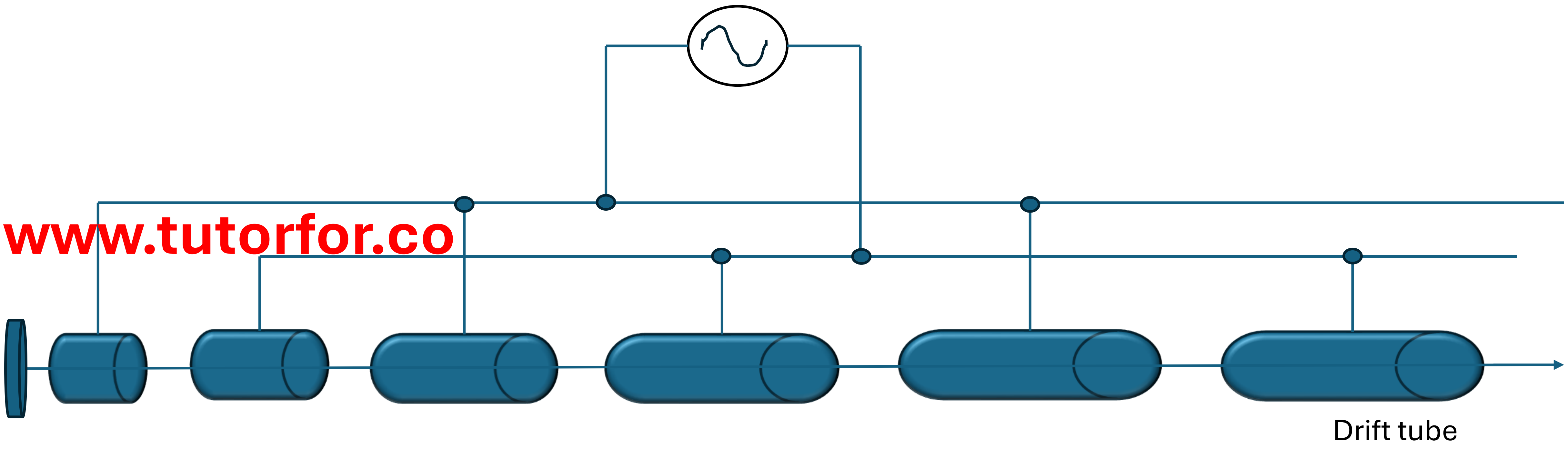
Particle accelerators.

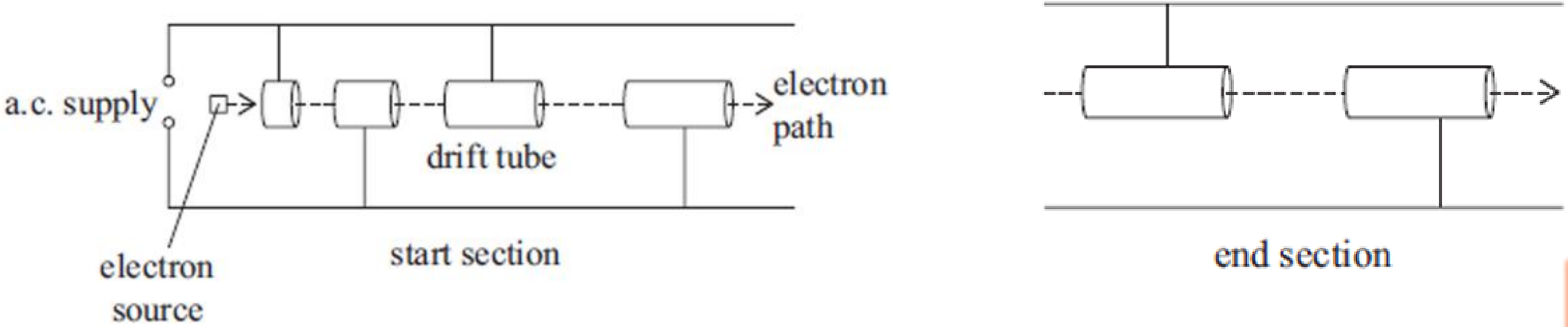
To probe the internal structure of nucleons such as protons and neutrons, scientists use high-energy particle collisions. At low energies, particles simply scatter without revealing their internal components. However, at sufficiently high energies, collisions can break particles apart, exposing their substructure and often producing new particles from the collision energy, in accordance with energy-mass equivalence

To achieve high particle speeds, the following types of accelerators are commonly used.

- Linear accelerator(LINAC)
- The Cyclotron
- The Synchrotron

Linear Accelerator(LINAC)





Important!

- Electrons are accelerated by an electric field between the drift tubes.

- The alternating current (a.c.) polarity changes while the electrons are inside the tubes, so the electric field is always in the correct direction when the electrons are in the gaps.
  (The a.c. polarity continuously changes in such a way that the particles are always being accelerated)

- The a.c. frequency remains constant.

- The length of the drift tubes increases along the linac to ensure electrons spend equal time in each tube and gap.
  (The length of the gaps increases along the linac for the same reason — to keep the time spent in each region constant)

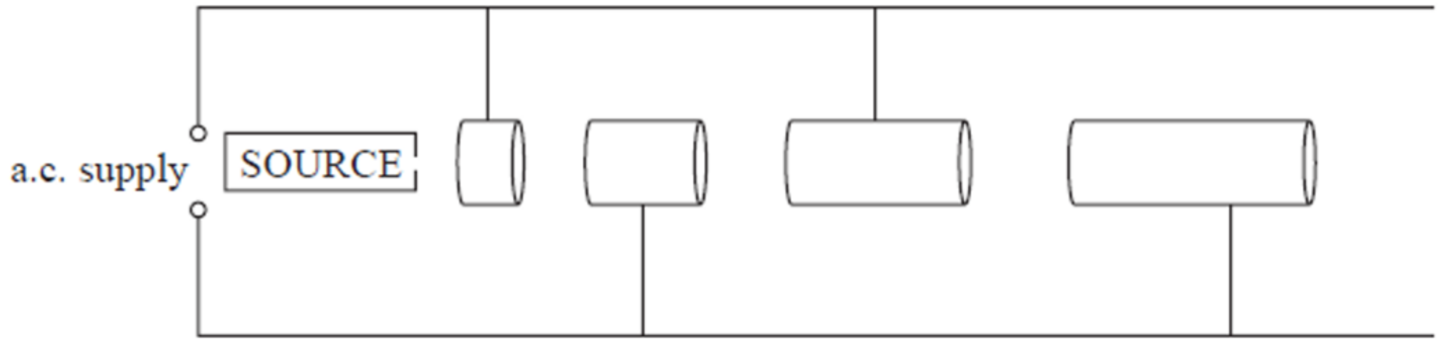
- At the end of the linac, the drift tubes have constant length.

- As electrons approach (but never reach) the speed of light, their speed stops increasing.

Concept Learning Questions

A particle collider can include a LINAC.

(a) The diagram represents a LINAC.



Explain why this arrangement works with a constant frequency a.c. supply.

Einstein's Theory of Special Relativity (1905)

Special relativity is a theory that describes how space and time behave for observers moving at constant velocities, especially when those velocities approach the speed of light. It fundamentally changed our understanding of time, space, mass, and energy.

1. **The laws of physics are the same everywhere**

    - Whether you're standing still or moving at a steady speed, the rules of physics don't change.

2. **The speed of light is always the same**

    - No matter how fast you're moving, if you measure the speed of light, you'll always get the same answer:

      $c = 300,000,000\,\mathrm{m/s}$

Major Implications

1. Time Dilation

Time runs slower for a moving observer compared to a stationary one.

$$t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Where:

- t is the time measured by the stationary observer,
- t_0 is the proper time (time measured in the moving frame),
- v is the relative velocity between observers,
- c is the speed of light.

2. Length Contraction

Objects moving at high speed appear shorter in the direction of motion.

$$L = L_0\sqrt{1 - \frac{v^2}{c^2}}$$

Where:

- L is the contracted length,
- L_0 is the proper length (measured in the object's own rest frame).

3. Relativistic Mass and Energy

As an object's speed increases, its mass appears to increase, and it requires more energy to accelerate further.

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$E = mc^2$$

Relativistic Kinetic Energy:

$$\mathrm{E_k} = \frac{\mathrm{m_0 c^2}}{\sqrt{1 - (\mathrm{v/c})^2)}} - \mathrm{m_0 c^2}$$

where m_0 is rest mass, v is velocity, c is speed of light.

🚫 Why Nothing Can Go Faster Than Light

According to special relativity:

- As an object with mass accelerates and approaches the **speed of light** (c), its **relativistic mass increases**.
- This means it takes **more and more energy** to keep accelerating the object.
- At exactly $v = c$, the equations show that the mass becomes **infinite**, and the energy required becomes **infinite** as well.

⚡ Equation:

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

- When v gets close to c, the denominator gets very small, and m becomes very large.
- At $v = c$, the denominator becomes zero — and division by zero is undefined — meaning **infinite mass**, which is physically impossible.

Classical Mechanics fails at high speeds Reference!

In 1964 William Bertozzi demonstrated at very high speeds, particles deviate from the equation

$$\frac{1}{2}mv^2 = qV$$

and never accelerated beyond the speed of light.

Bertozzi was able to show that the energy added by the accelerating p.d. started to become more than the amount expected from

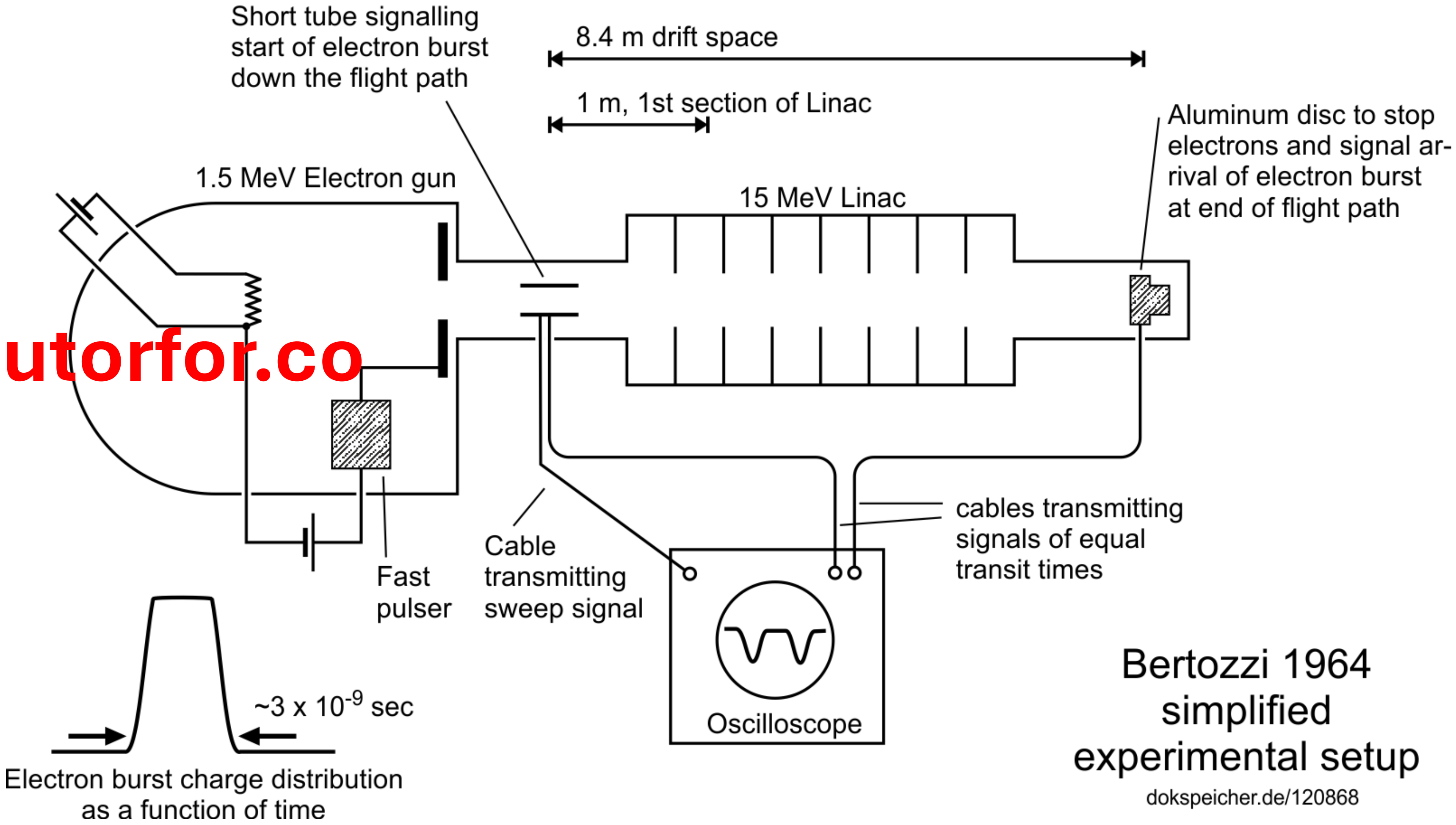
$$\frac{1}{2}mv^2$$

William Bertozzi's Experiment – Measuring Electron Speed

Reference!

Purpose:

To demonstrate that as particles (electrons) gain more energy, their speed **approaches** the speed of light **but never exceeds it,** as predicted by **Einstein's theory of special relativity**.



Bertozzi 1964
simplified
experimental setup

dokspeicher.de/120868

Bertozzi's Experiment

Reference!

1) Electron Acceleration:

•Electrons were accelerated to different **kinetic energies** (from around 0.5 MeV up to ~15 MeV) using a **linear accelerator**.

2) Time-of-Flight Measurement:

•After acceleration, the electrons were sent down a long tube (~8 meters).

•A **scintillator detector** at the end of the tube measured how long the electrons took to travel the known distance (time-of-flight).

3) Speed Calculation:

•Using the time and known distance, the speed of the electrons was calculated.

4) Kinetic Energy Measurement:

•When electrons hit an aluminum target, they deposited energy as heat.

•A **calorimeter** measured this heat to determine the **kinetic energy** of the electrons.

Bertozzi's Experiment

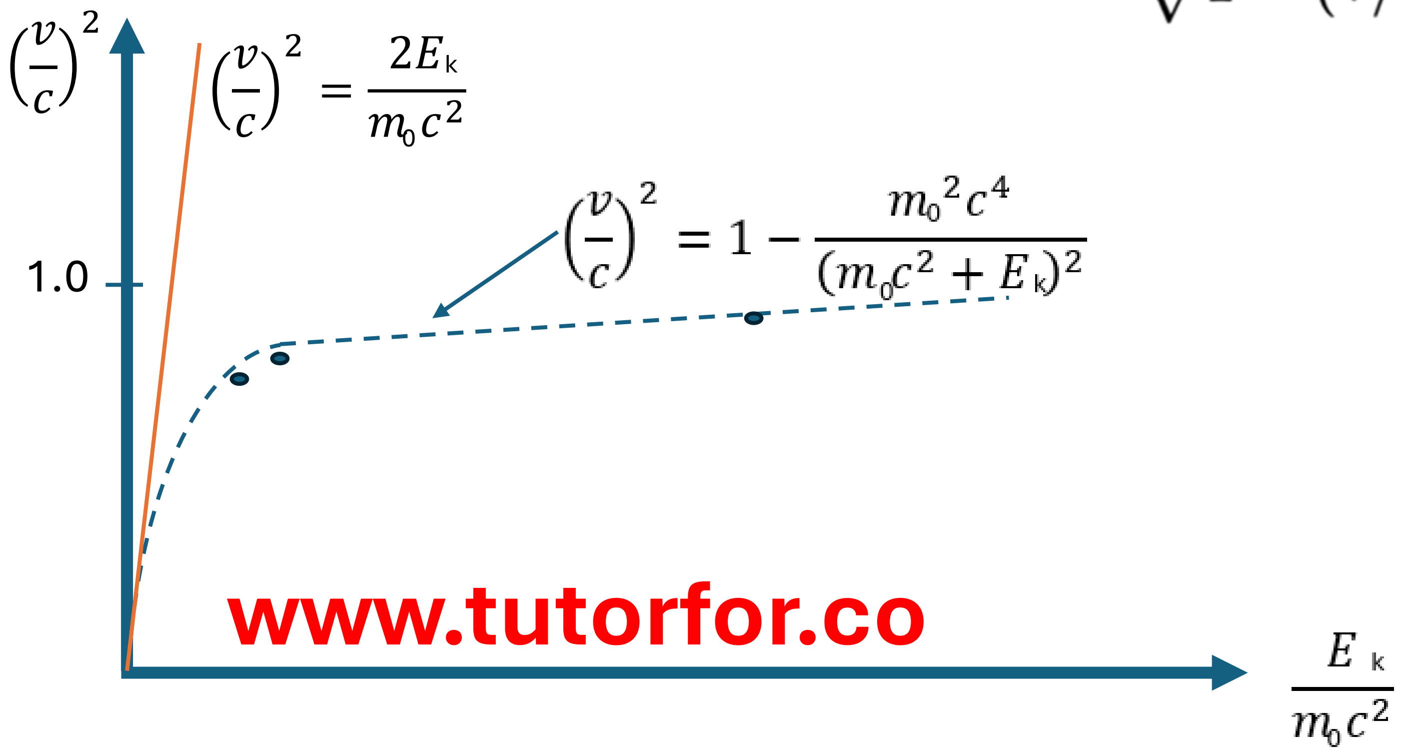
Reference!

$$E_k = \frac{m_0 c^2}{\sqrt{1-(v/c)^2)}} - m_0 c^2$$

Key Observation:

As the kinetic energy increased, the speed increased, but not linearly.

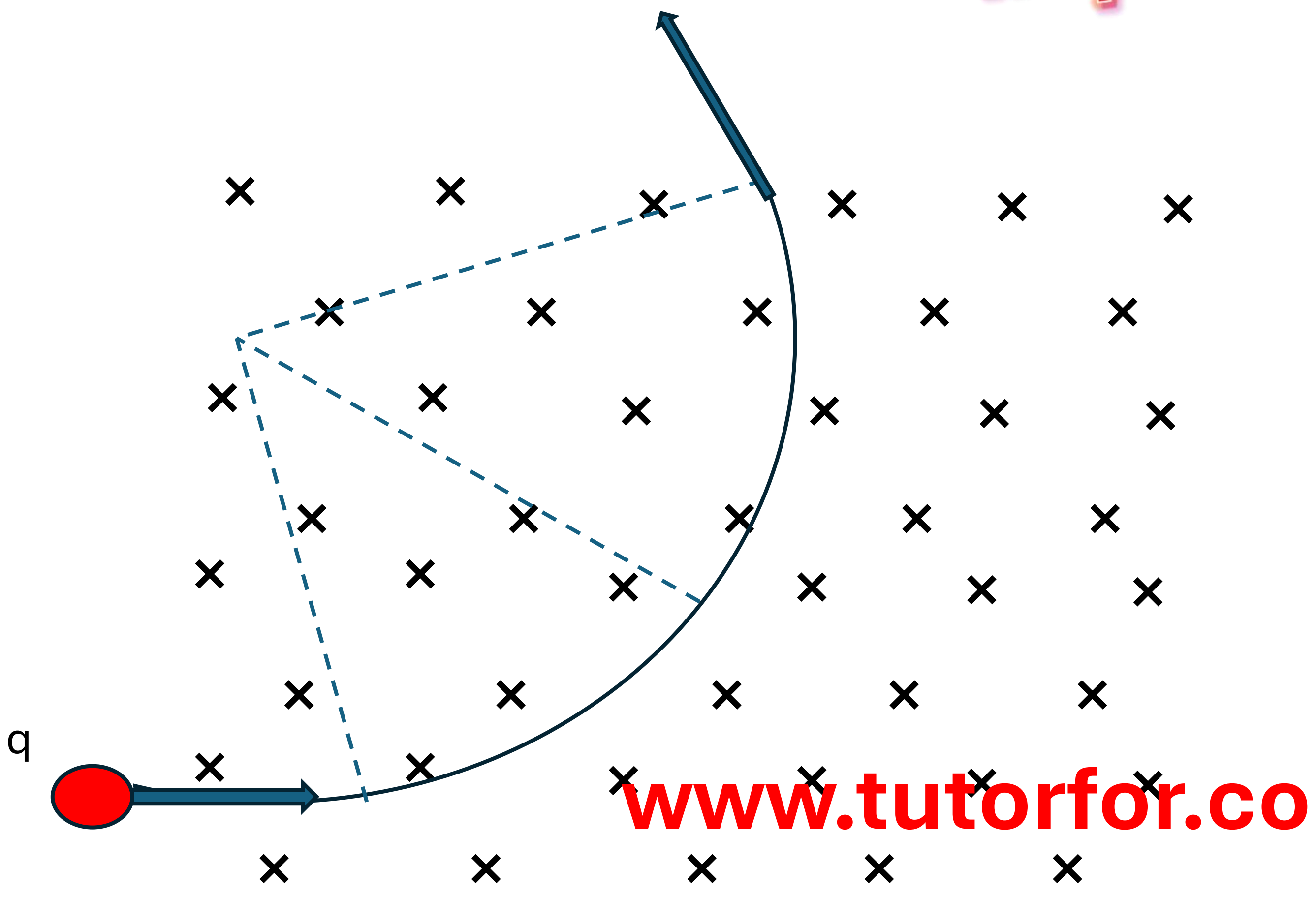
At higher energies, the speed asymptotically approached the speed of light, but never reached or exceeded it, matching Einstein's prediction.



Bertozzi's experiment was a direct and elegant test of special relativity, showing that:
Newtonian mechanics fails at high speeds.
Relativistic predictions are accurate: energy continues increasing, but speed plateaus.

Moving in a circular path

Important!



Magnetic field into the page

$$F = \frac{mv^2}{r}$$

$$F = Bqv$$

$$Bqv = \frac{mv^2}{r}$$

$$\boldsymbol{r = \frac{mv}{Bq}}$$

$$\boldsymbol{r = \frac{p}{Bq}}$$

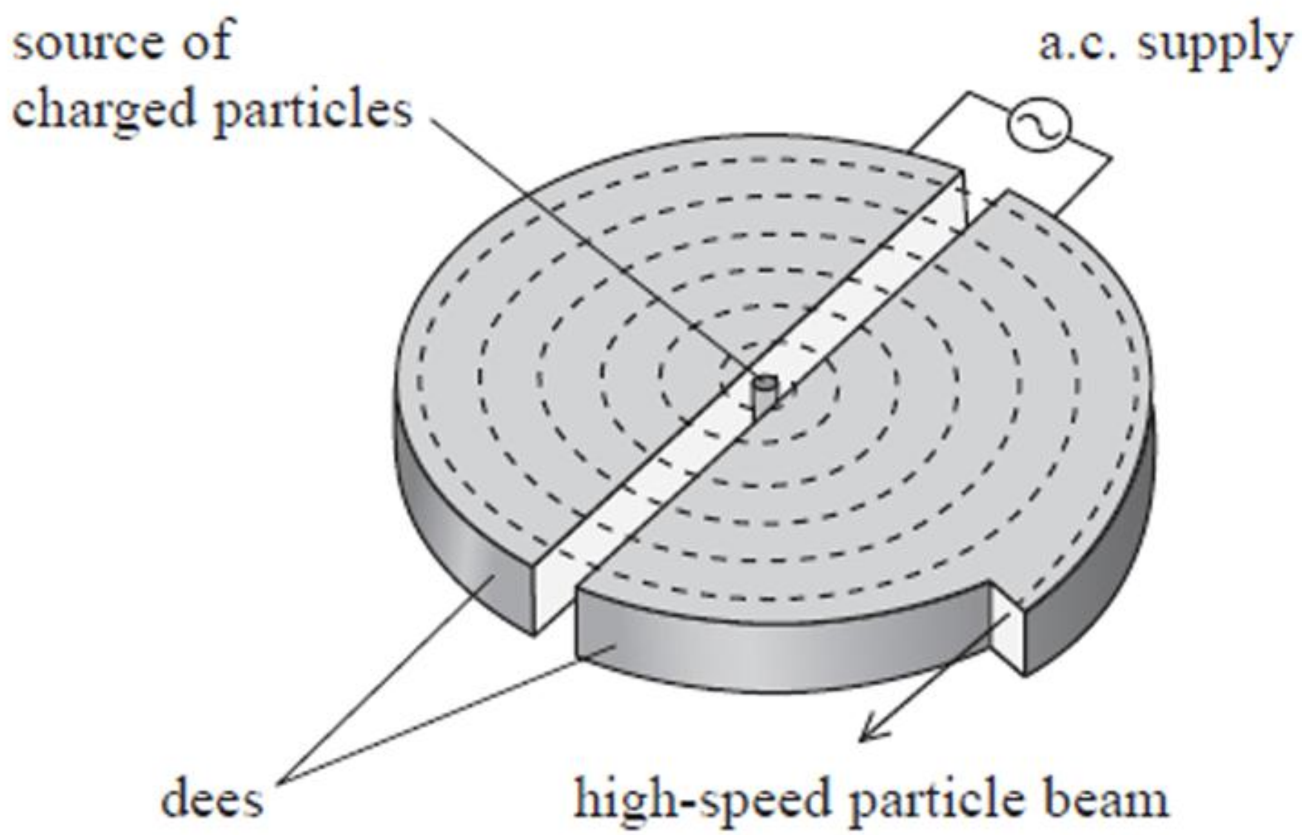
$$\boldsymbol{r \ \alpha \ v}$$

$$\boldsymbol{r \ \alpha \ p}$$

$$\boldsymbol{r \ \alpha \ \sqrt{(KE)}}$$

The Cyclotron

Important!



$$f = \frac{1}{T}$$

$$T = \frac{2\pi r}{v}$$

$$r = \frac{mv}{Bq}$$

$$T = \frac{2\pi m}{Bq}$$

$$f = \frac{Bq}{2\pi m}$$

f is independent of radius.

f with the relativistic effects of mass increase :

$$f = \frac{qB}{2\pi m_0 \sqrt{1 - \frac{v^2}{c^2}}}$$

How cyclotron works? Important!

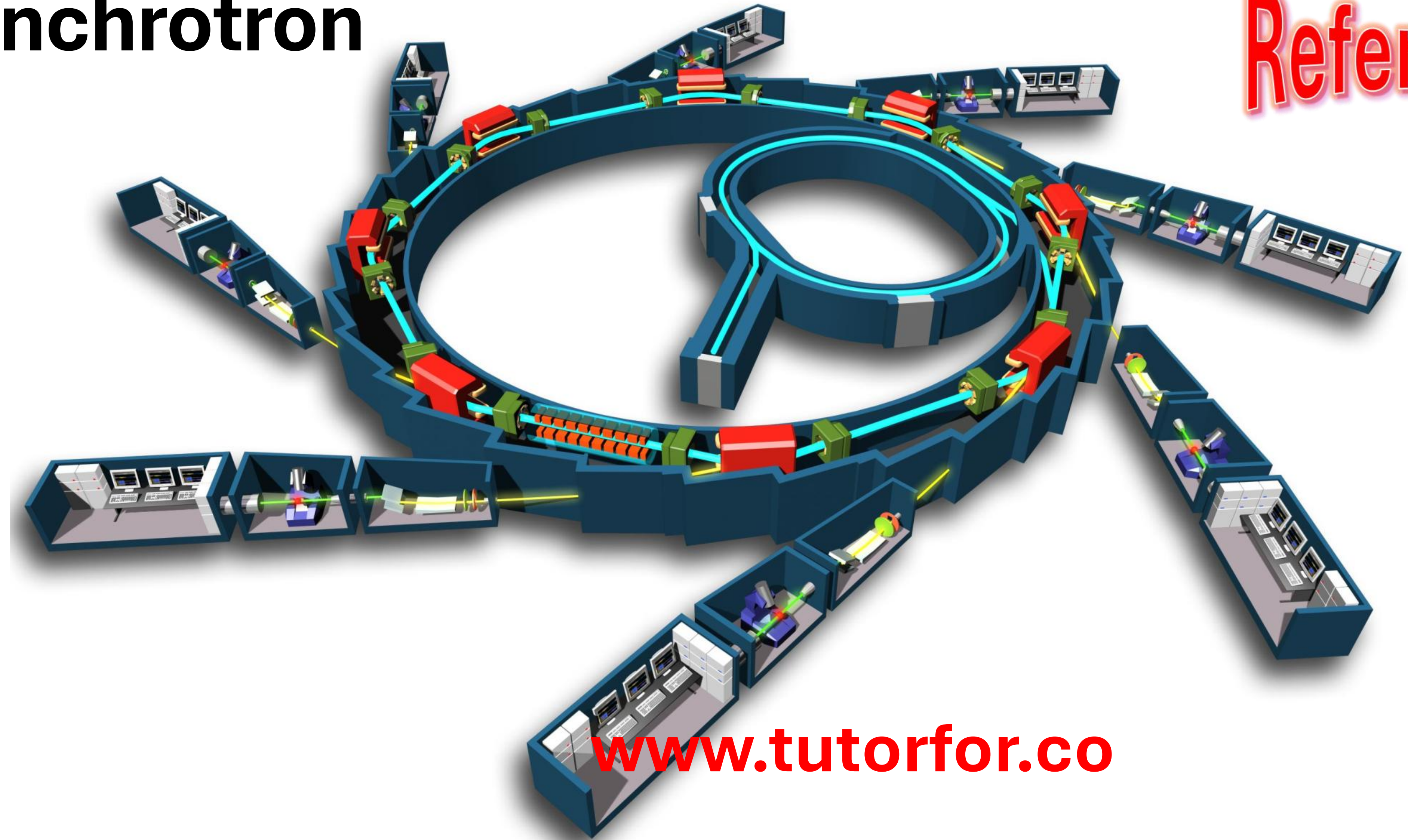
Flemings left hand rule can be used to find the direction of the particles path. (clockwise / anticlockwise)

- Magnetic field acting perpendicular to the velocity of particles.
- Magnetic force on particles perpendicular to velocity.
- Particles experience centripetal force/acceleration, so they undergo circular motion.
- Alternating potential difference between dees changes direction while particle in dees.

- Particle accelerated by electric field between dees.
- Electric field in correct direction so that force on particle further increases speed.
- Particles radius increases with the speed , so the particles travel along outwardly spiraling path. $r \propto v$

The Synchrotron

Reference!



In a synchrotron, a type of single-ring accelerator, the radius of the particle beam's path is kept constant by increasing the strength of the magnetic field using an electromagnet as the momentum of the particles increases.