TYBSc [Semester-6] Physics

US06CPHY23 Nuclear Physics

UNIT- 4 Part 1 Lecture 1

Detectors and Accelerators

Ch 6 Accelerators: Topics

6.1 Introduction
6.2 Cockcroft and Walton Generator
6.3 Van de Graff Accelerator
6.4 Tandem accelerator
6.5 Linear Accelerator or Drift Tube accelerator,
6.7 Magnetic resonance accelerators or cyclotron
6.8 Betatron
6.9 Synchrocyclotron or frequency modulated cyclotrons

Ch 6 Accelerators: Topics

Recommended Books:

Nuclear and Particle Physics (2nd edition)
V K Mittal, R C Verma and S C Gupta
PHI Learning Pvt. Ltd.

Chapter 6

Accelerators

Introduction:

- *A particle accelerator is an instrument* ***used to increase the kinetic energy of charged particles.***

- The accelerator can increase kinetic energy of electrons, protons, alpha-particles and other heavy ions etc..

Introduction:

- Relationship

- Microscope :: Biologist
- Telescope :: Astronomer.
- Particle accelerator :: Nuclear scientist

- Examples of small-scale or mini particle accelerators:

  - Picture tube in Television
  - CRT in Cathode Ray Oscilloscope

Introduction:

- Television and Cathode Ray Oscilloscope have many common features.
- Both require
- a **source of charged particles**
- an **electric field to accelerate particles** (10^4 V in a picture tube and 10^7 V in accelerator)
- **Focusing electrodes** to focus the beam
- **Deflectors**

Introduction:

- Television and Cathode Ray Oscilloscope have many common features.
- In both accelerator and picture tube all the components are **housed in a chamber with high vacuum**. This avoids the beam from scattering with air molecules.

Introduction:

- **Rutherford** demonstrated that nitrogen nucleus can be modified by bombarding it with α-particles.

Introduction:

- **Rutherford** demonstrated that nitrogen nucleus can be modified by bombarding it with α-particles.
- During that period, it was felt that **more energetic projectiles** produce changes in atomic nuclei.
- The kinetic energy of these particles should be higher so as to overcome the repulsive Coulomb force between positively charged nucleus and positively charged projectile.

Introduction:

- It was in 1932 that J. D. Cockcroft and E. T. S. Walton built **first particle accelerator**.

- It was capable of accelerating protons to **400 keV** and these protons induced an artificial nuclear reaction in ^{7}Li.

6.2 COCKCROFT AND WALTON ACCELERATOR

6.2 COCKCROFT AND WALTON ACCELERATOR

- The first accelerator was built in 1932 by J.D. Cockcroft and E. T. S. Walton in Cavendish laboratory at the University of Cambridge.
- This accelerator was capable of producing potential difference of **400 kV** and thereby accelerating protons to **400 keV**.

6.2 COCKCROFT AND WALTON ACCELERATOR

6.2.1 Principle

- When a positively charged particle having a charge ***q*** unit, is left near a point, where the potential is positive (***V_0*** volts), the particle repelled towards the point at (say) ground potential, its kinetic energy will be ***q V_0*** eV.
- For example, if V_0 = 400 kV, and the particle is proton, its kinetic energy will be 400 keV and
- If the particle is **He atom** with both the electrons removed, its kinetic energy will be 2 x 400 keV = 800 keV.

6.2 COCKCROFT AND WALTON ACCELERATOR

6.2.2 Construction

- It consists of voltage multiplier circuit.
- It consists of capacitors C_1, C_2, C_3 and C_4 of equal capacity and four diodes, D_1, D_2, D_3 and D_4.

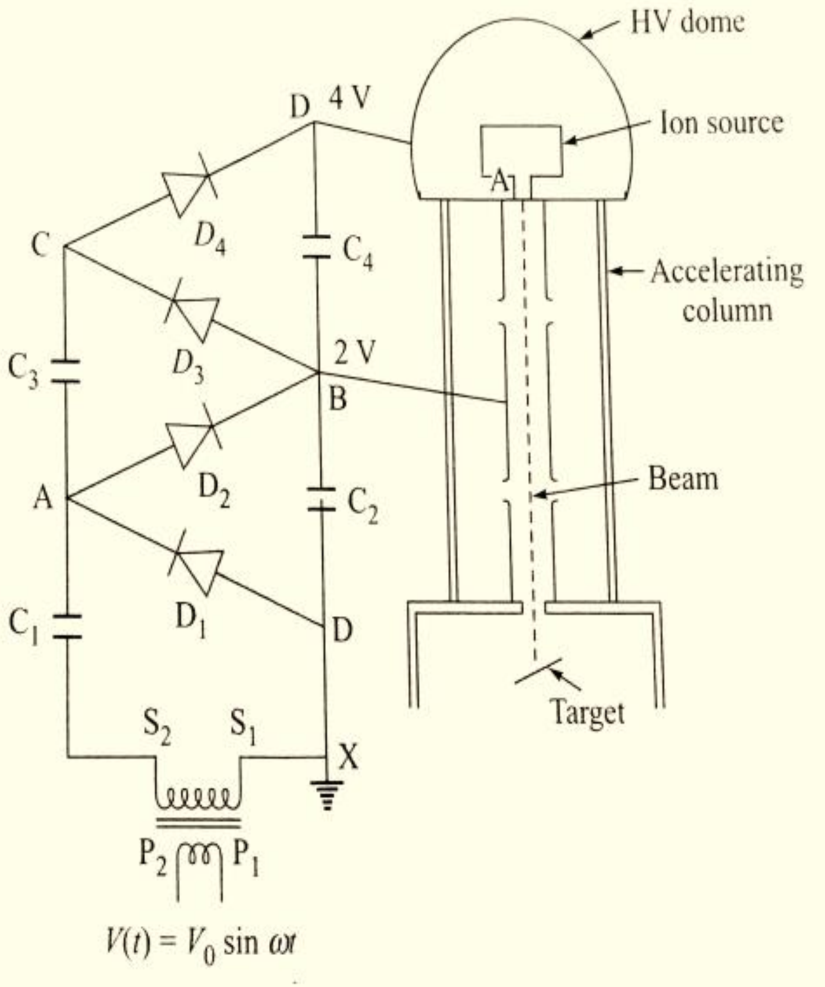


Figure 6.1 Cockcroft and Walton accelerator.

6.2 COCKCROFT AND WALTON ACCELERATOR

6.2.2 Construction

- This arrangement is connected to the **secondary** of a high-voltage step up transformer.
- The voltage in the secondary coil of the transformer
  $$V(t) = V_o \sin \omega t.$$
- Here V_0 is of the order of **100 kV**.

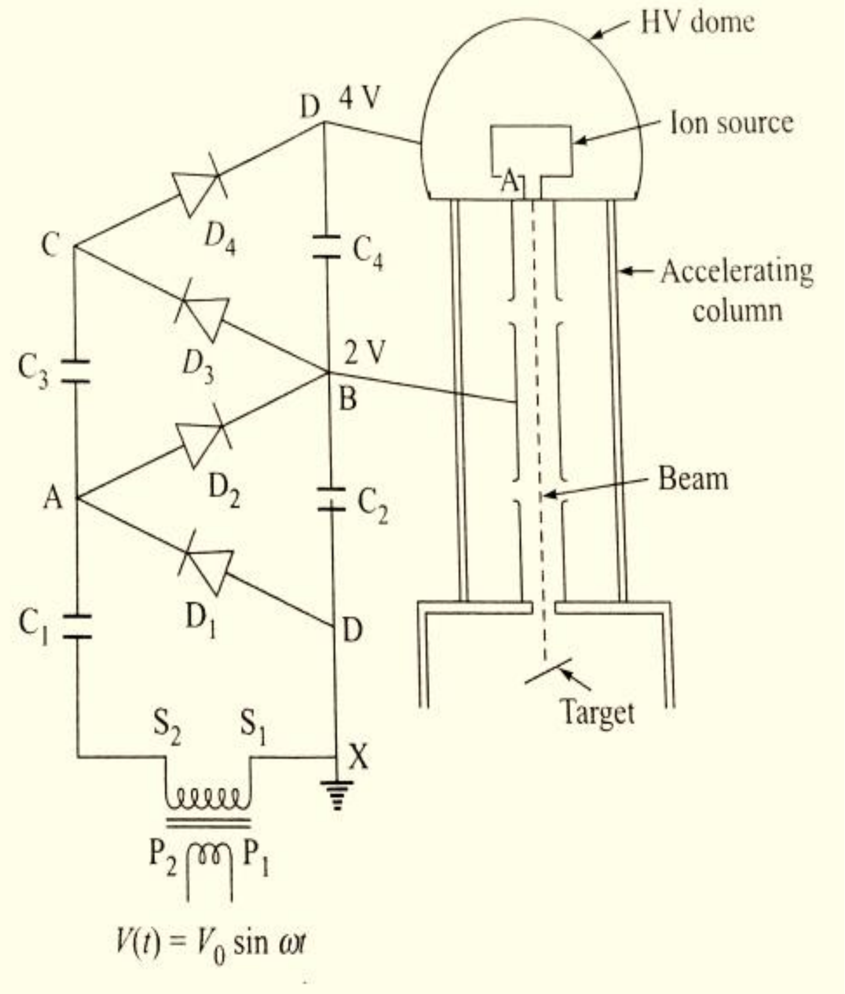


Figure 6.1 Cockcroft and Walton accelerator.

6.2 COCKCROFT AND WALTON ACCELERATOR

6.2.2 Construction

- In the circuit
- the **point X** is always at **ground potential** and
- the upper **point D** is at highest potential which is connected to the **high-voltage dome**. which is spherical hollow conductor.

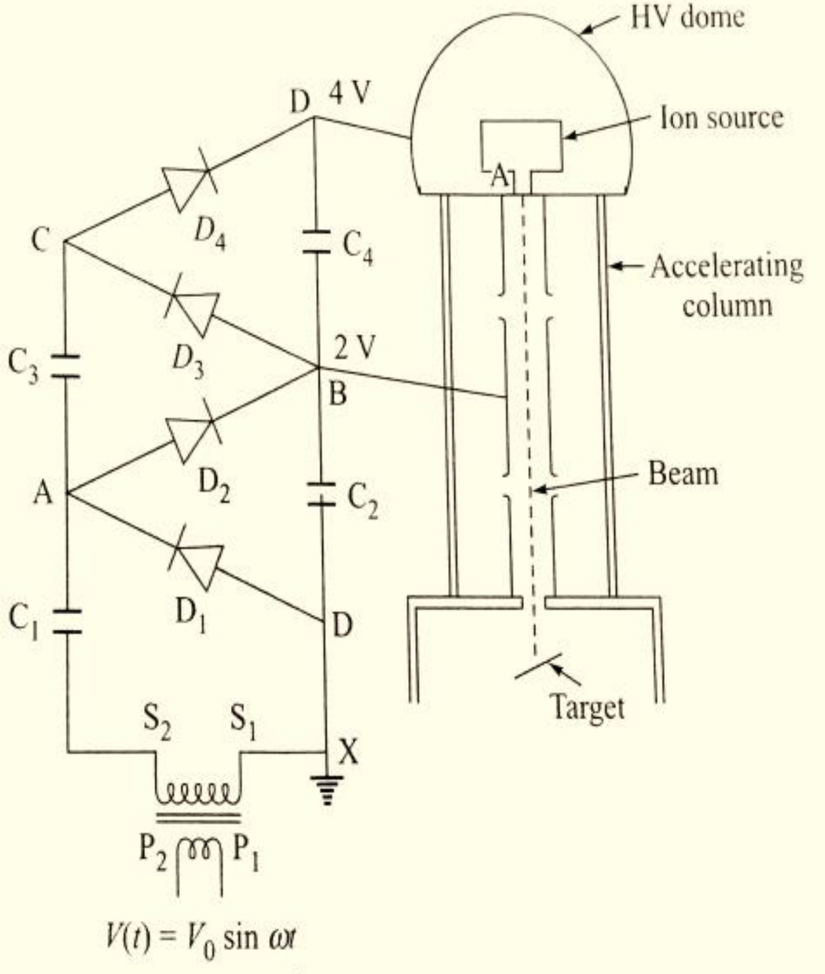


Figure 6.1 Cockcroft and Walton accelerator.

6.2.2 Construction

- In this high-voltage dome there is an **ion source**, which by ionization produces, **ions** to be accelerated.

- Suppose we wish to accelerate **protons**, then ion source ionizes **hydrogen gas** and

- for α **-particles**, the gas to be ionized is ^{4}**He.**

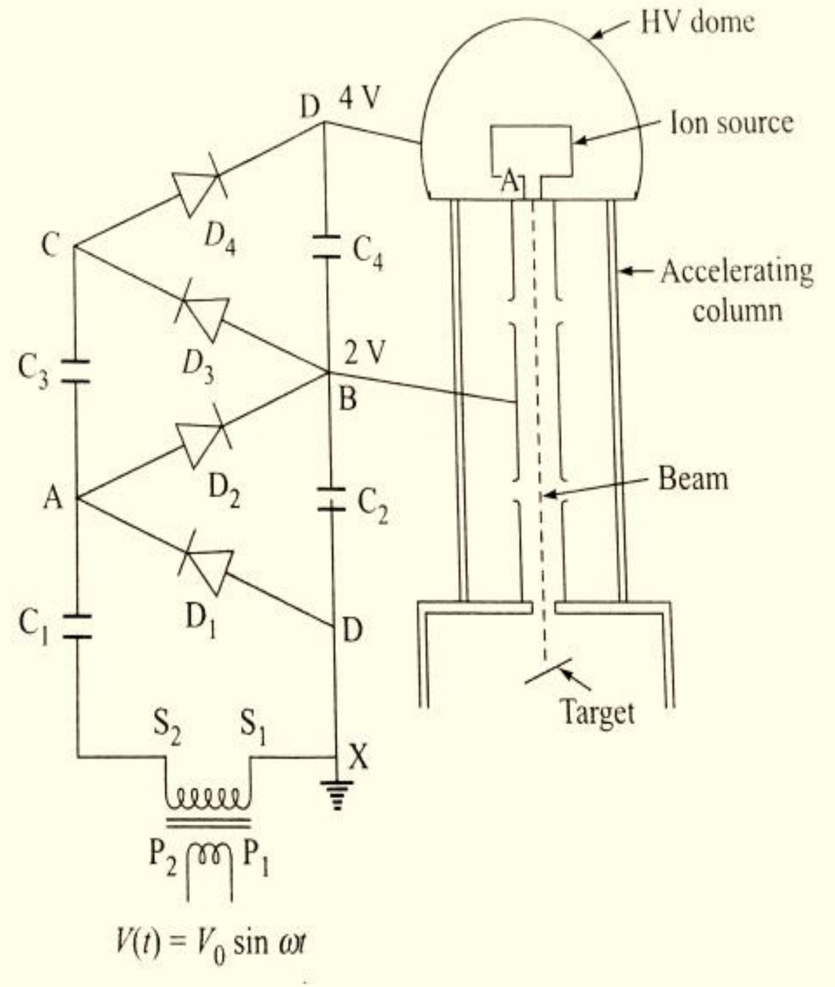
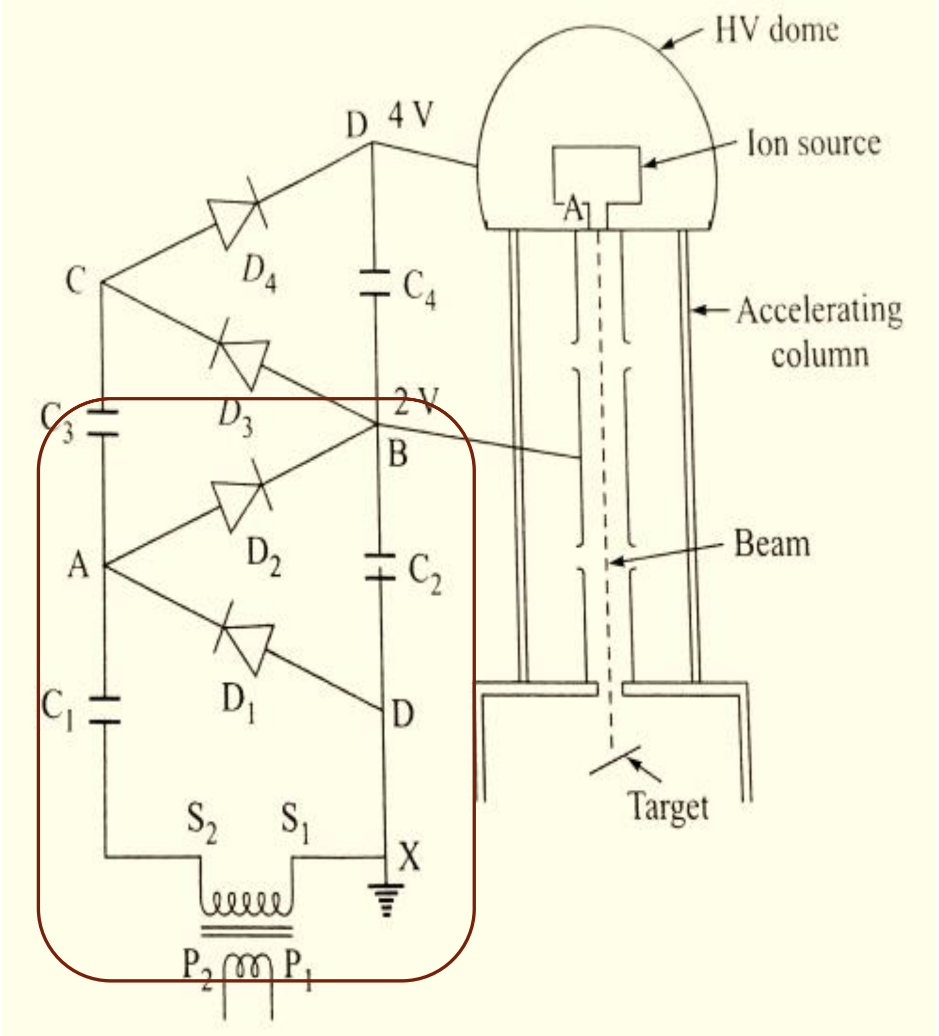


Figure 6.1 Cockcroft and Walton accelerator.

6.2 COCKCROFT AND WALTON ACCELERATOR

6.2.3 Working

- First let us consider capacitors C_1 and C_2; and diodes D_1 and D_2.
- Suppose during the first-half cycle, lower end S_1 of the transformer is positive and upper end S_2 of transformer is negative.



6.2.3 Working

- **First-half cycle**, S_1 is positive and S_2 is negative.
- This makes diode **D_1** forward biased and diode **D_2** reverse biased.
- Due to this capacitor C_1 is charged to peak voltage V_0.

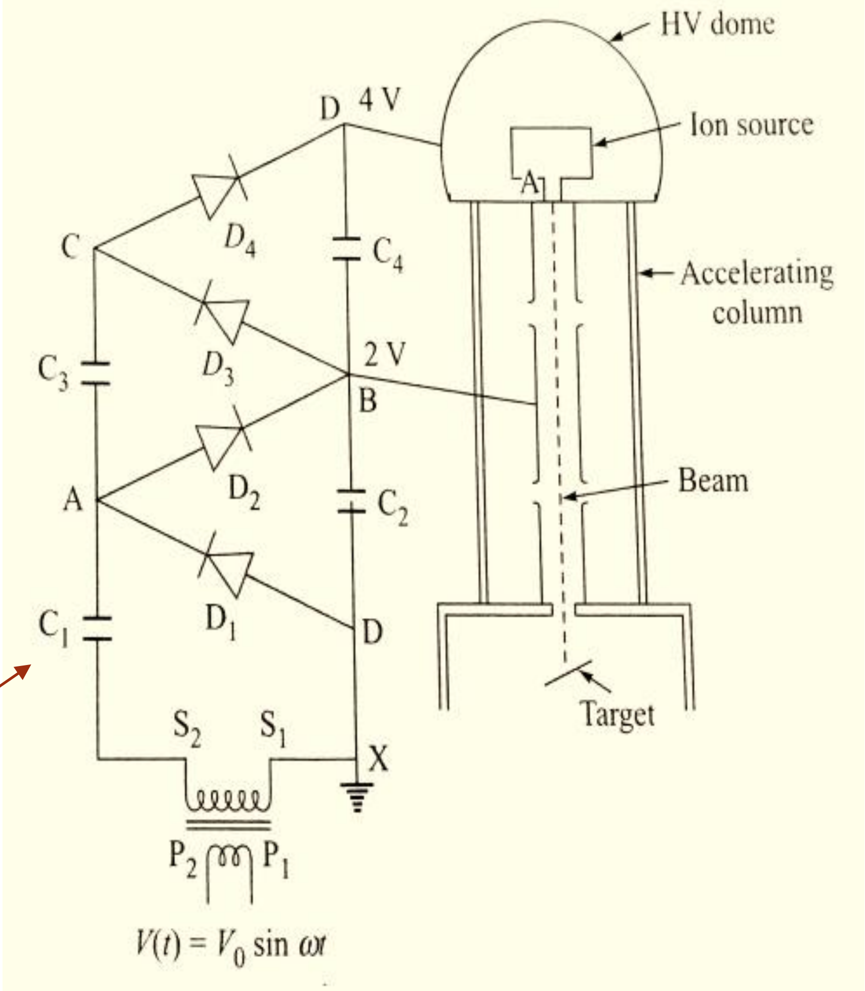


Figure 6.1 Cockcroft and Walton accelerator.

6.2 COCKCROFT AND WALTON ACCELERATOR

6.2.3 Working

- Since the voltage at the secondary of the transformer is varying between **maximum** value $+V_0$ to **minimum** value $-V_0$, therefore, the **net voltage at point A** varies between 0 and $2V_0$
- $[+V_0 + (-V_0)]$ to $[+V_0 - (-V_0)]$.

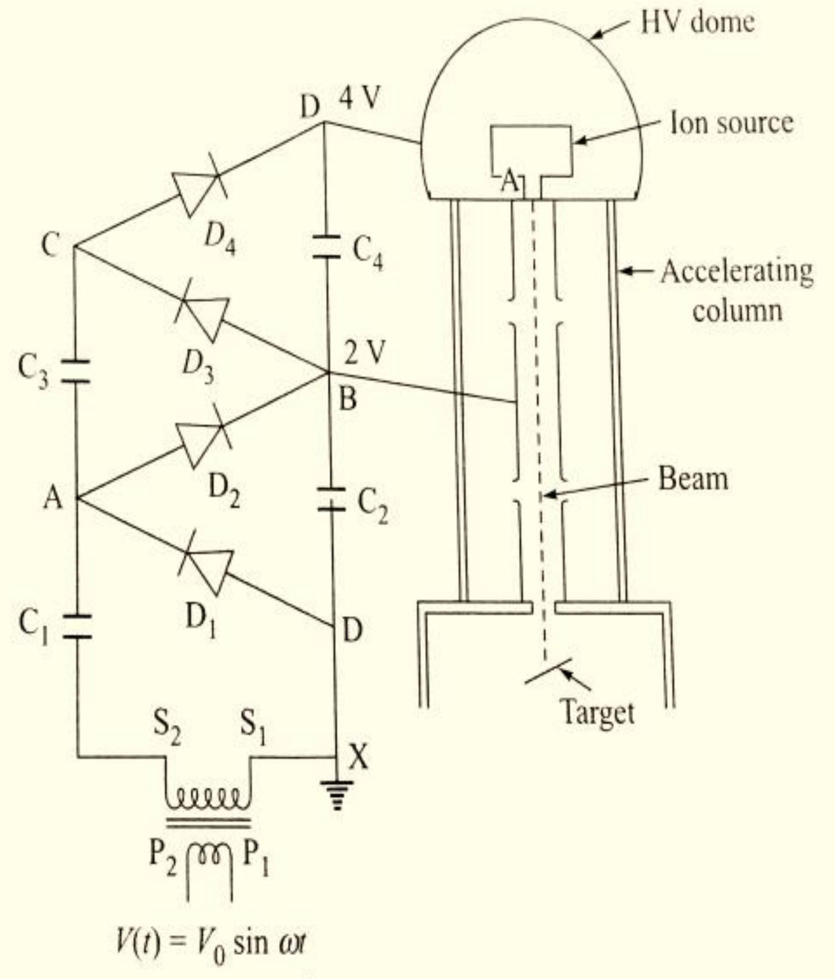


Figure 6.1 Cockcroft and Walton accelerator.

6.2 COCKCROFT AND WALTON ACCELERATOR

6.2.3 Working

- During the **second-half** of ac cycle, diode D_2 becomes **forward biased** and conducts, while diode D_1 is **reverse biased.**

- Therefore, point B reaches $2V_0$ and the potential difference between B and X is $4V_0$.

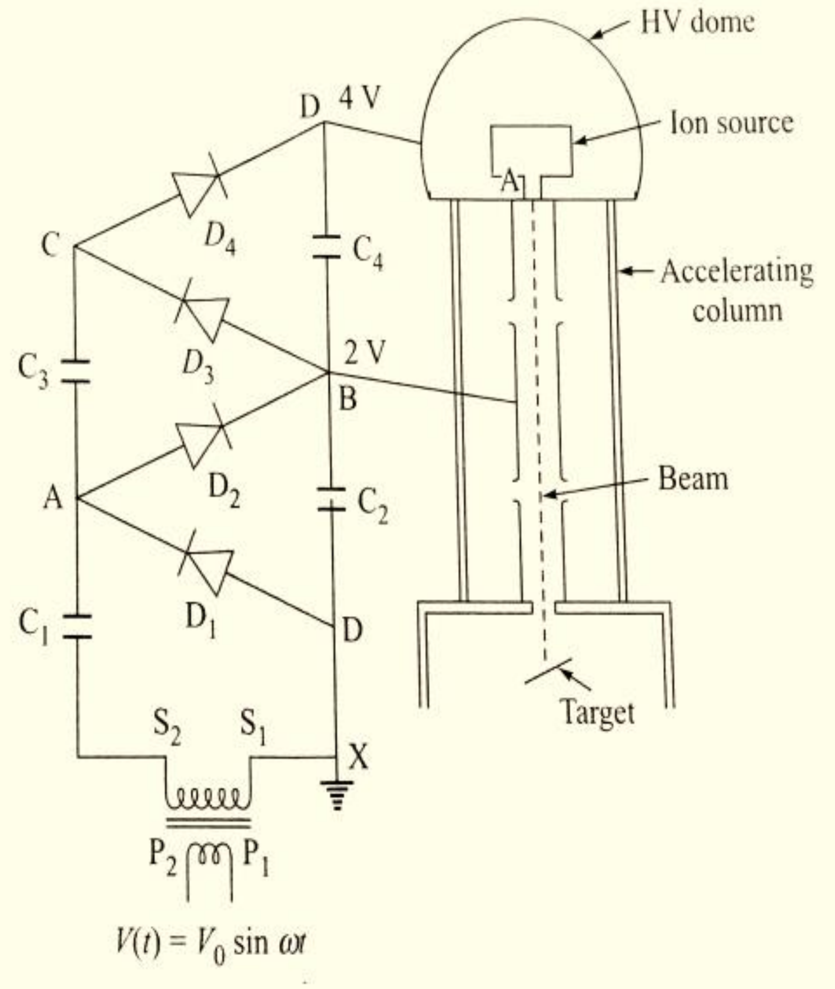


Figure 6.1 Cockcroft and Walton accelerator.

6.2 COCKCROFT AND WALTON ACCELERATOR

6.2.3 Working

- Continuing the same argument capacitor $2V_0$ and the **potential difference between point D and X** is $4V_0$.
- If $V_0 = 100$ kV, then this potential difference will be 400 kV.
- This circuit is known as **volage multiplier** or **cascade rectifier**.

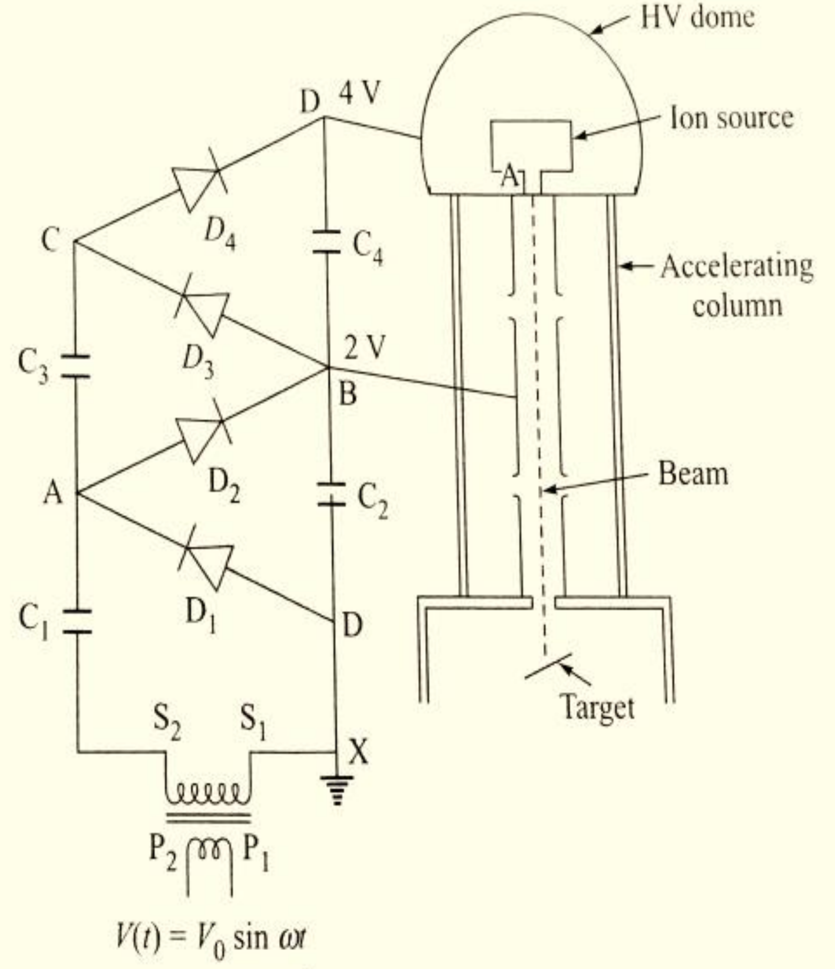


Figure 6.1 Cockcroft and Walton accelerator.

6.2.3 Working

- This high-voltage is applied to a hemispherical dome, known as **high-voltage terminal** or **simply terminal.**

- The particles to be accelerated are produced here by ionizing suitable gas with the help of an ion source.

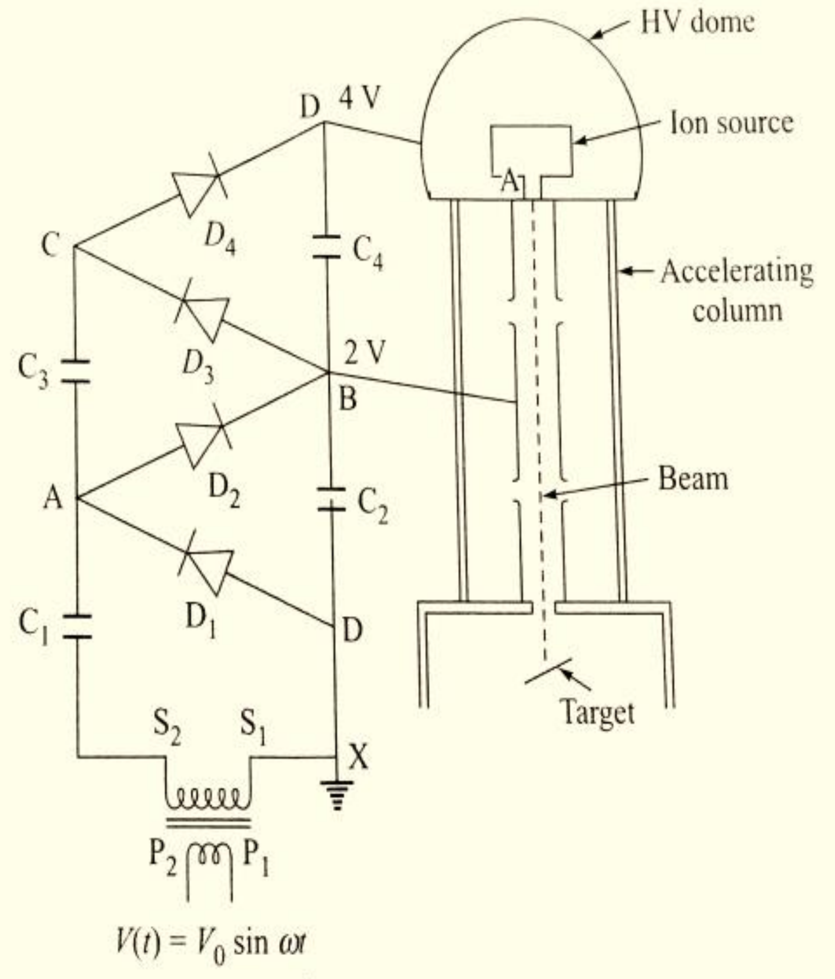


Figure 6.1 Cockcroft and Walton accelerator.

6.2.3 Working

- **The resultant positive charged particles or ions are accelerated towards the target kept at ground potential.**
- The particles are accelerated in an **evacuated tube** to avoid collisions and scattering from air molecules.

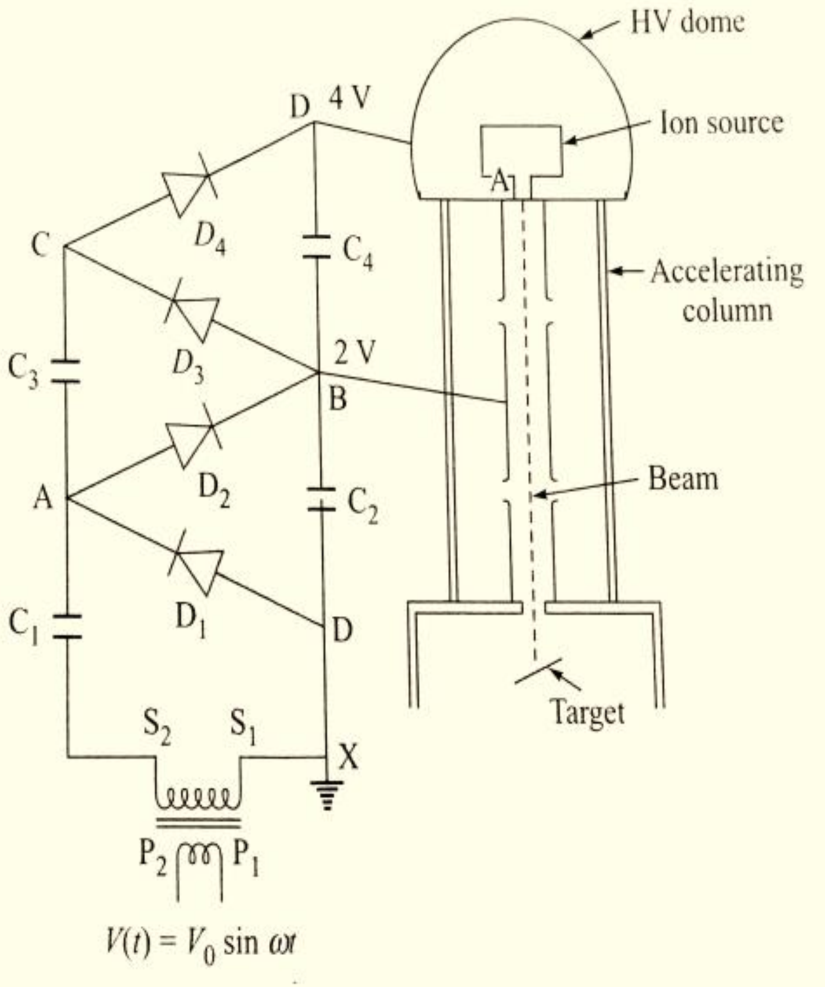


Figure 6.1 Cockcroft and Walton accelerator.

6.2.3 Working

- *There is a limit of holding potential to dome without sparking with the surroundings.*
- *Therefore higher voltages on the high-voltage terminal* are **limited.**
- Though the **first accelerator** was able to stand about **400 kV** only, but with **modern technology** it is possible to build Cockcroft and Walton accelerators, which can stand a potential of the order of **4 MV**.

6.2.3 Working

- The earliest Cockcroft and Walton accelerator was used to perform the **first nuclear disintegration** of ^{7}Li using artificially accelerated protons.

$$p + {}^{7}Li \rightarrow {}^{4}He + {}^{4}He$$

6.2.4 Advantages

1. This accelerator is **extremely simple in design** and **can easily be fabricated**.

2. It provides a **relatively large beam current** or ion flux at the target.

3. It can be used to accelerate **electrons** also.

6.2.5 Limitations (1)

The **maximum energy obtained** on Cockcroft and Walton accelerators is **low** in comparison to other accelerators.

6.2.5 Limitations (2)

As the voltage applied to the high-voltage terminal is **not filtered**, generally there is large ripple or ac component in the terminal voltage, which results in **large energy spread** in the final energy of the accelerated particles.

6.2.5 Limitations (3)

The **ion source is placed in the high-voltage area.**

If we wish to **make some adjustments in the ions source** like replacing the burnt-out filament, etc., we have to reduce the high-voltage to zero, make adjustments and then increase the voltages.

The entire operation takes many hours.

6.2 COCKCROFT AND WALTON ACCELERATOR

Some of these limitations have been taken care of in another accelerator known as ***Van de Graaff accelerator***.

6.3 Van de Graff Accelerator

6.3 Van de Graff Accelerator

- This accelerator was developed by **Robert J. Van de Graff** in 1931 at Massachusetts Institute of Technology, USA.
- It was initially capable to stand a potential difference of **5 million volts** but later on it was upgraded to withstand a potential difference of **7 million volts**.

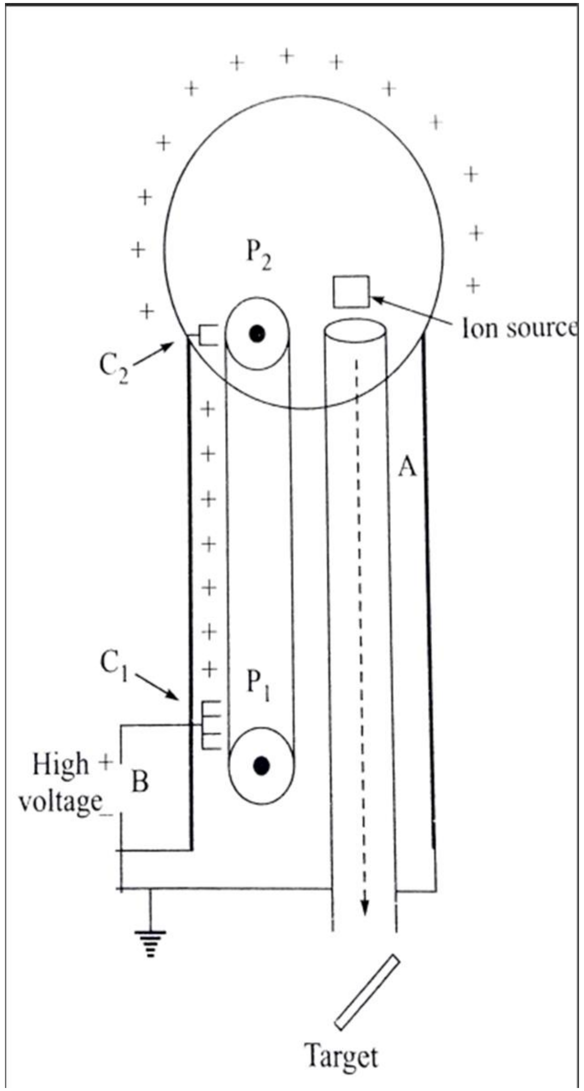
6.3 Van de Graff Accelerator

6.3.1 Principle

- If a charged conductor is brought in internal contact with another conductor, which is hollow, all of its charge gets transferred to the hollow conductor, no matter how high the potential is on the later.
- Therefore, by successfully adding charge, the potential of the hollow conductor can be raised to any desired value.

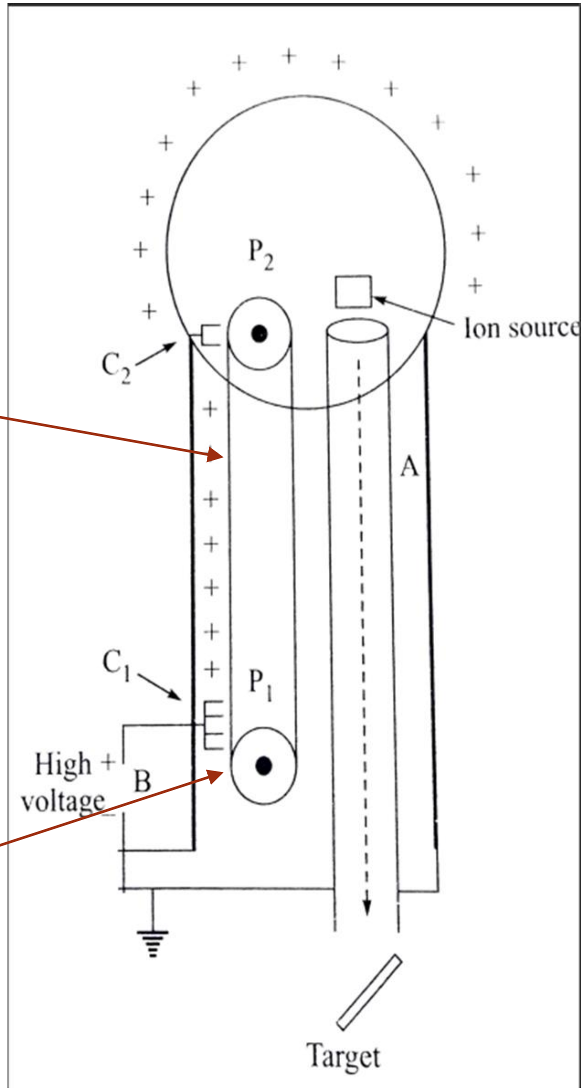
6.3.2 Construction

- It consists of a **hollow spherical-shaped conductor**, which is mounted on a long insulating support. The hollow conductor is also known as **high-voltage terminal** or **terminal** or **dome**.



6.3.2 Construction

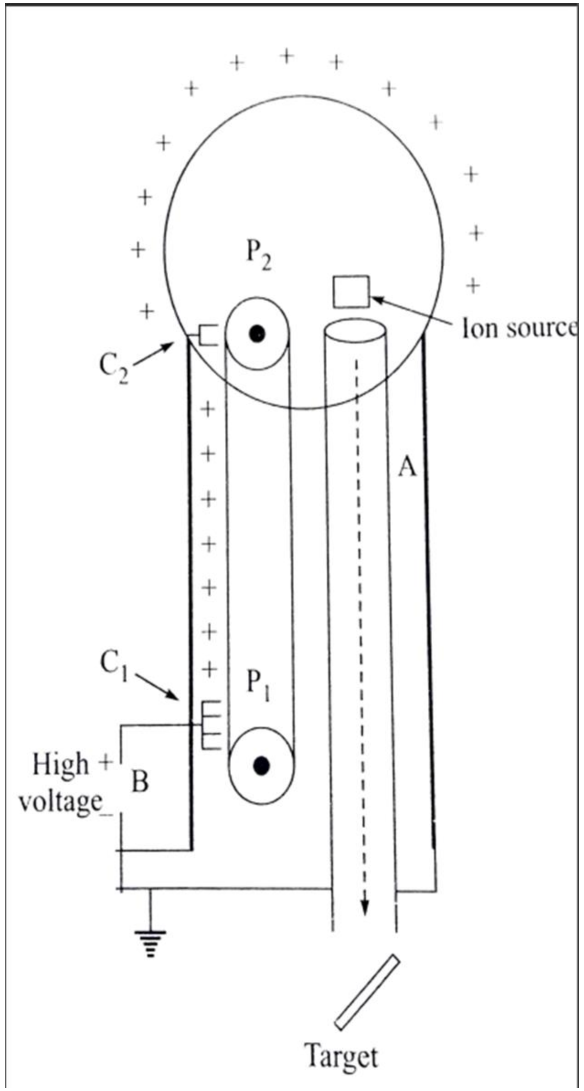
- An **insulating belt** made up of silk, rubber or plastics, etc., passes over two frictionless **pulleys**, P_1 and P_2.



6.3 Van de Graff Accelerator

6.3.2 Construction

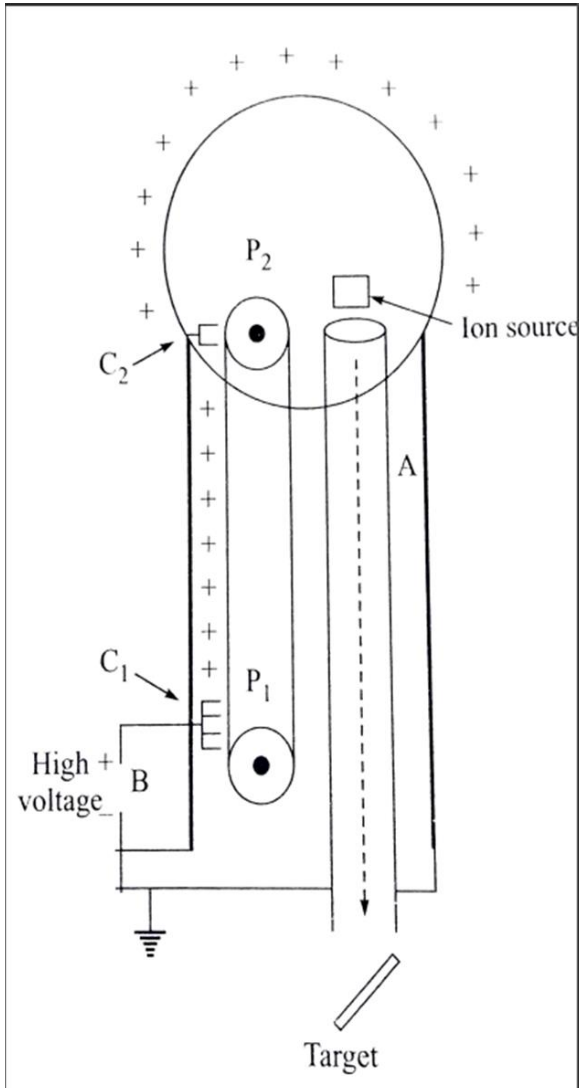
- Pulley **P_1** is mounted on the **grounded end** of the structure.
- Pulley **P_2** is enclosed within spherical-shaped high-voltage terminal as shown in Figure.



6.3 Van de Graff Accelerator

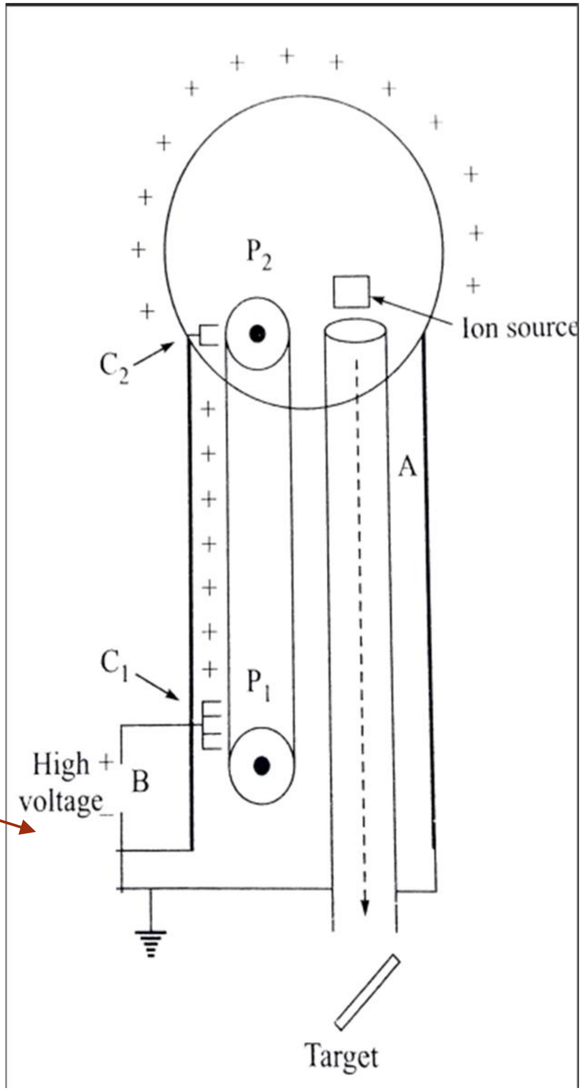
6.3.2 Construction

- C_1 and C_2 are two sharp pointed combs.
- Comb C_1 called **spray comb**, charges the belt with charge sprayed by its sharp needles, close to the belt at the ground pulley.



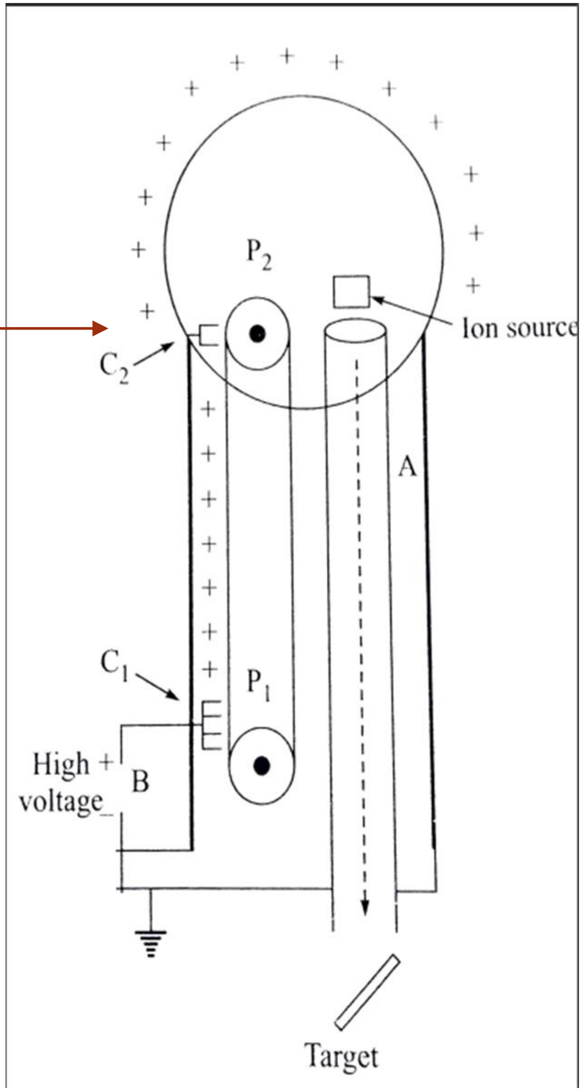
6.3.2 Construction

- This comb is connected to a **power supply** that raises its potential to a few tens of kilovolts.



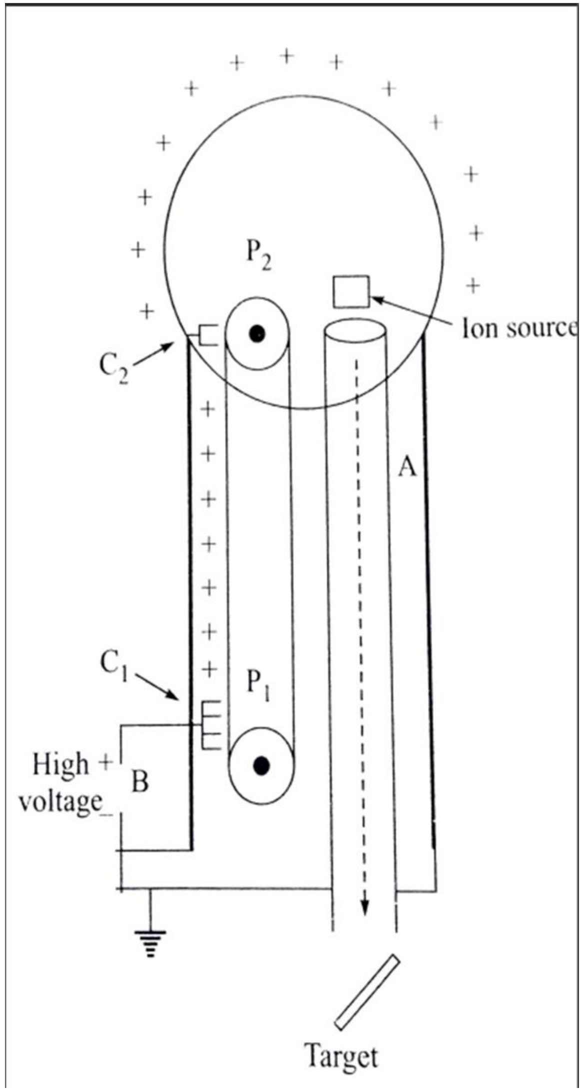
6.3.2 Construction

- The comb C_2 is called **charge collection comb.**
- It is placed near the belt inside the high-voltage terminal or dome and is connected to the inner side of the dome.



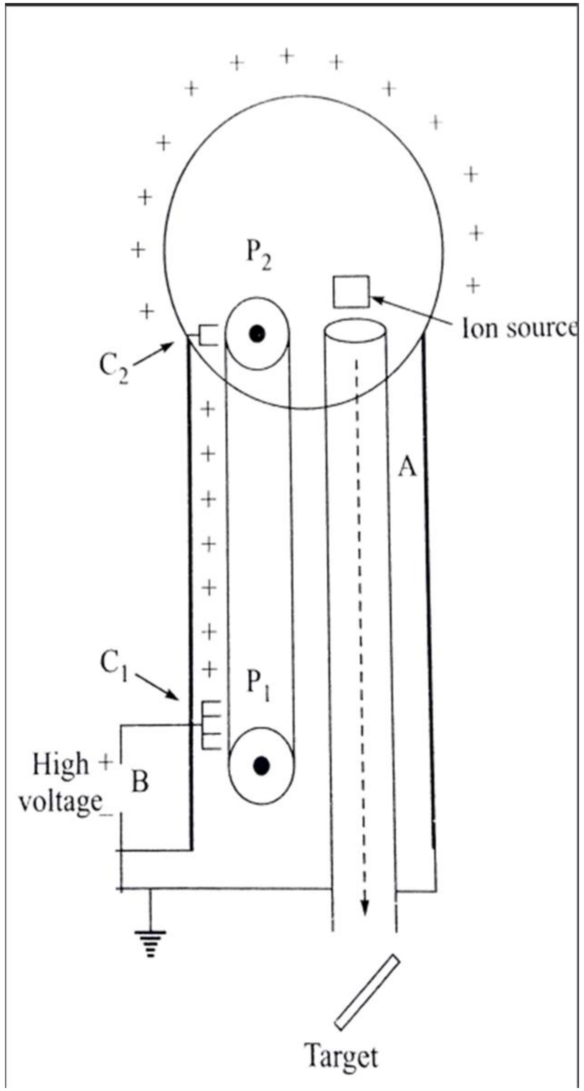
6.3.2 Construction

- An **ion source** is placed inside the dome and is connected to the accelerating tube A.
- On the other side of the accelerating tube, the target is placed in the **vacuum**.



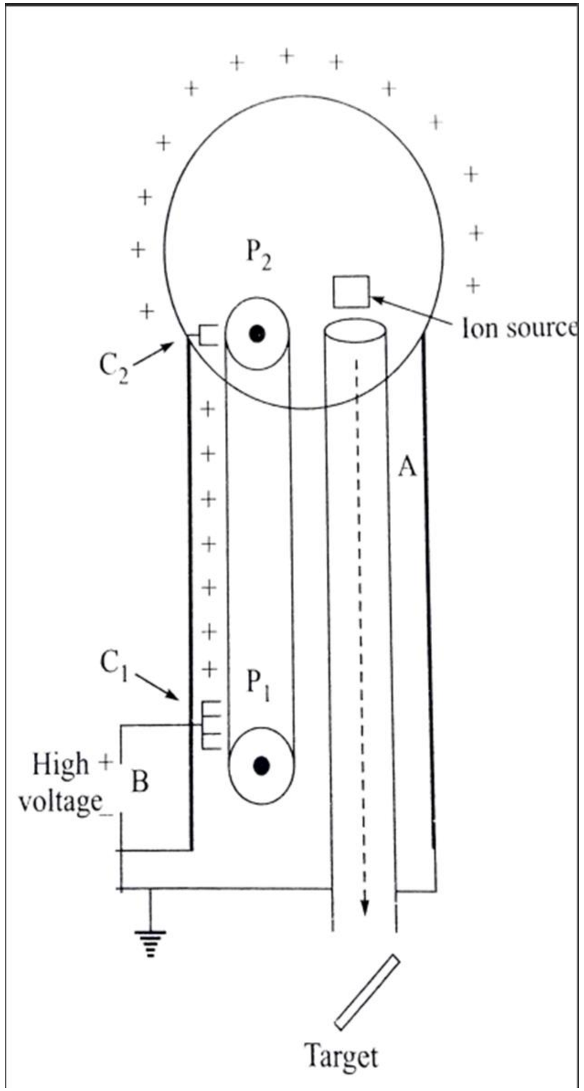
6.3.2 Construction

- The entire accelerating tube is **highly evacuated**.
- This is to make sure that accelerated particles do not collide with air molecules and get scattered.



6.3.2 Construction

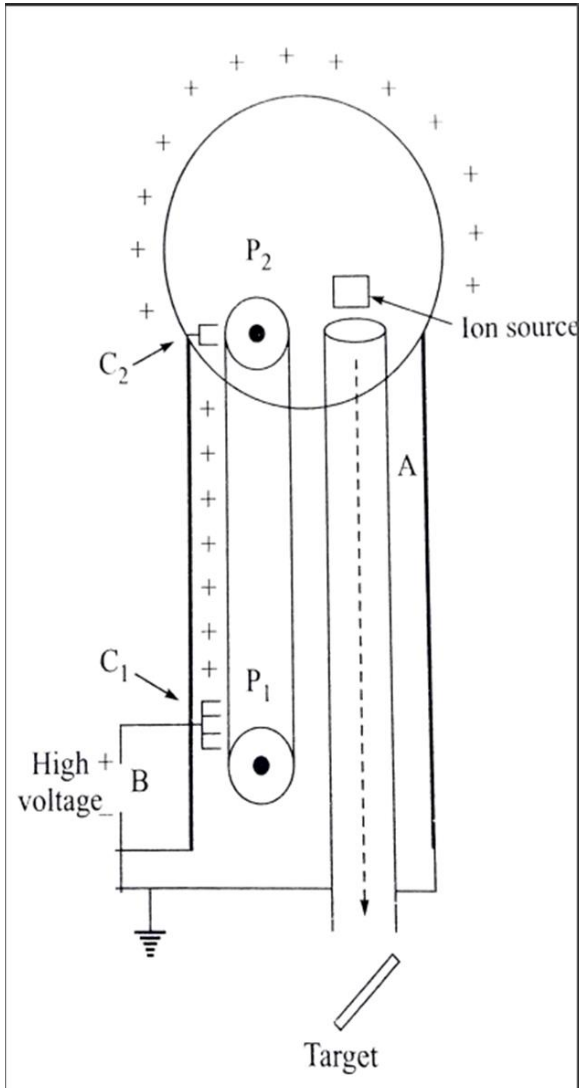
- This entire structure including high-voltage terminal, pulleys, belt, etc. is **enclosed in a steel pressure tank** (not shown in Fig. 6.2).



6.3 Van de Graff Accelerator

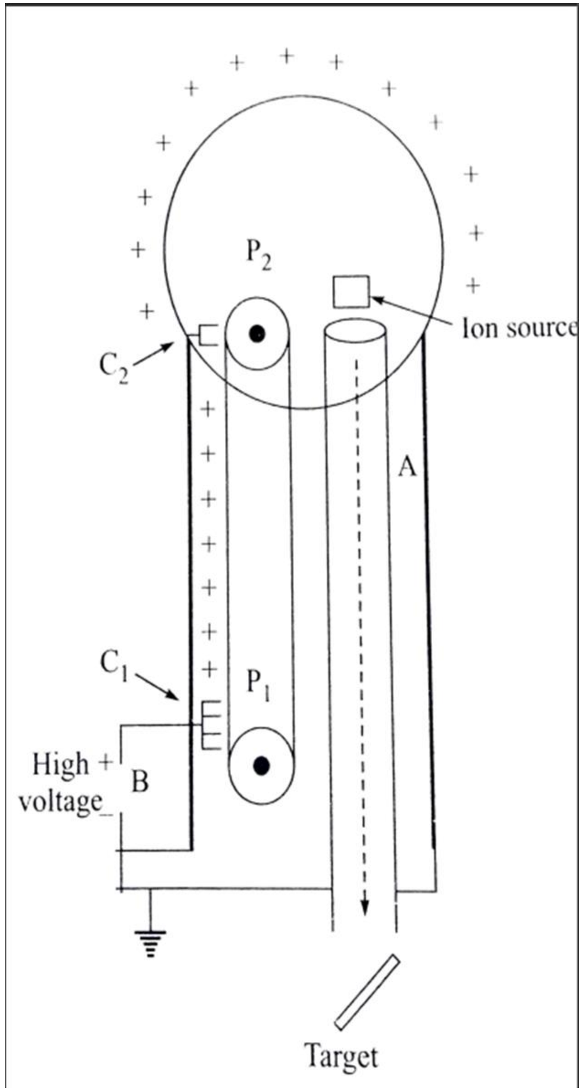
6.3.2 Construction

- In the steel pressure tank SF_6 gas is filled at pressure of the order of 10-20 atmospheres.

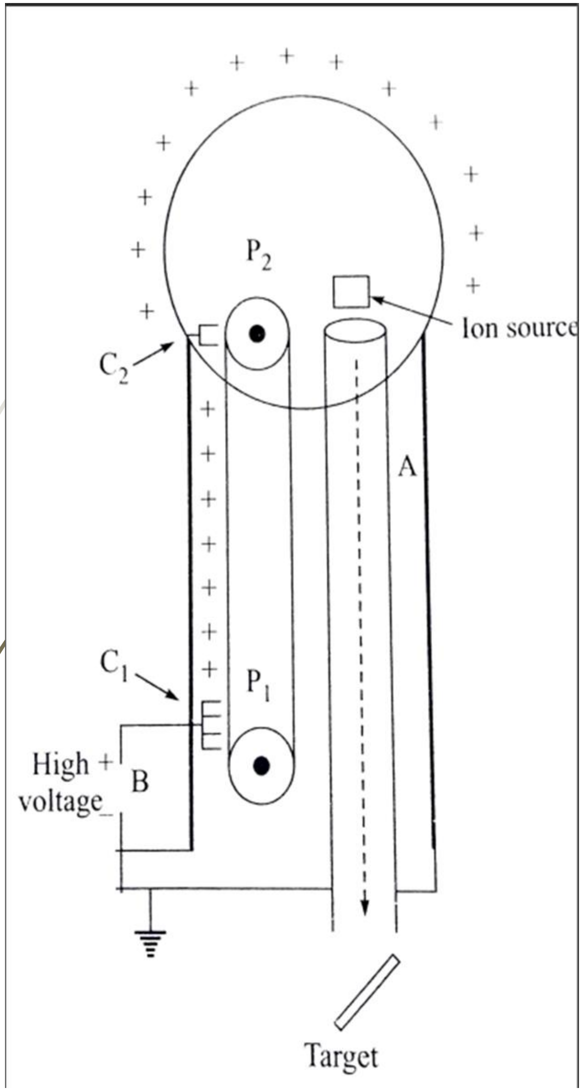


6.3.2 Construction

- SF_6 gas has much higher breakdown voltage.
- With SF_6 gas accelerators have high-voltage terminal can withstand potential differences of the order of **20-30 MV**.

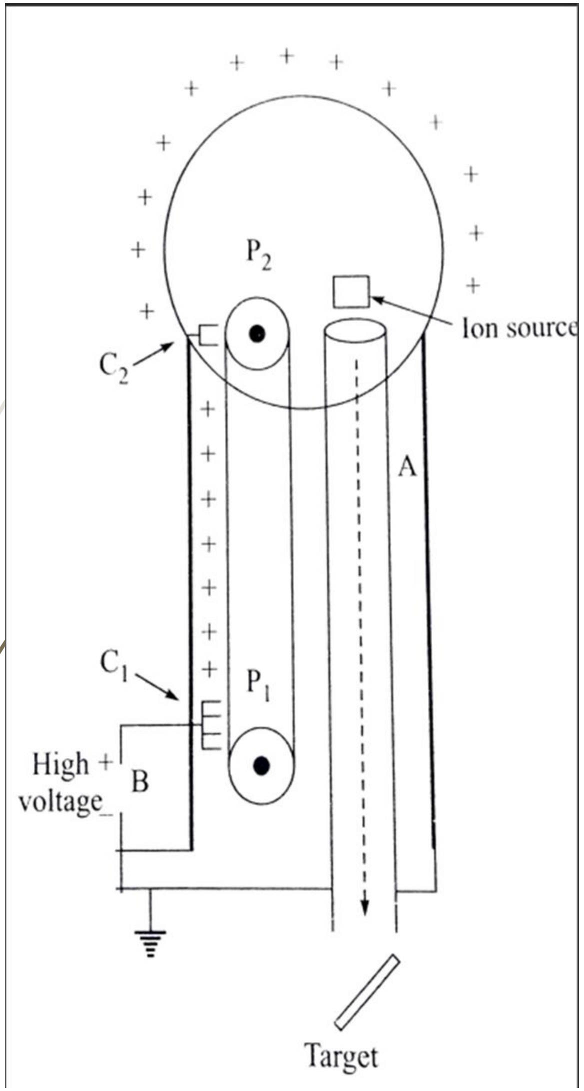


6.3 Van de Graff Accelerator



6.3.3 Working

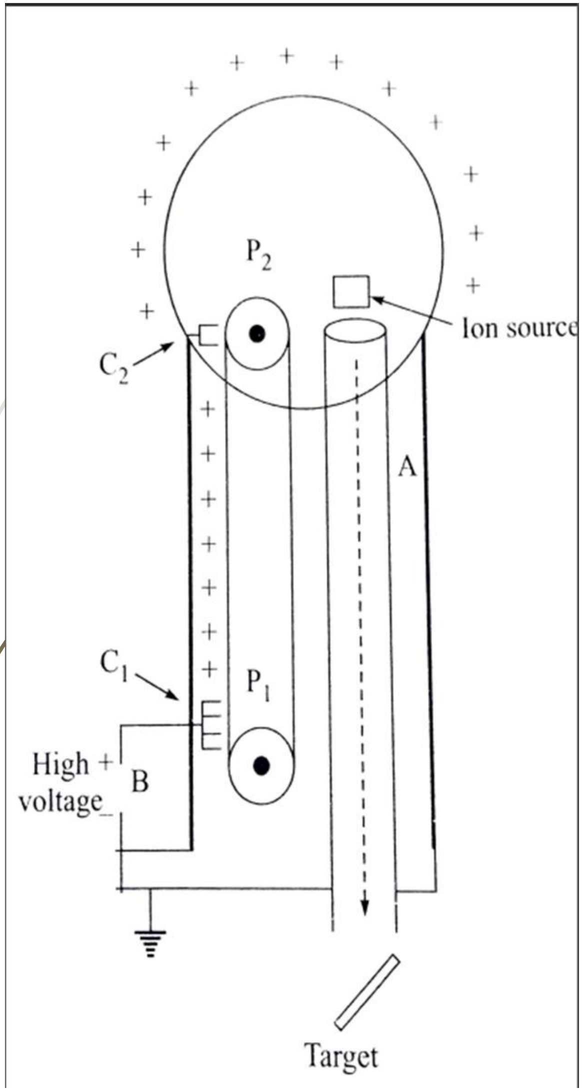
- A dc potential of 5 kV to 50 kV is applied at a point B.
- The positive end is connected to the comb C_1.
- The negative end is grounded.



6.3.3 Working

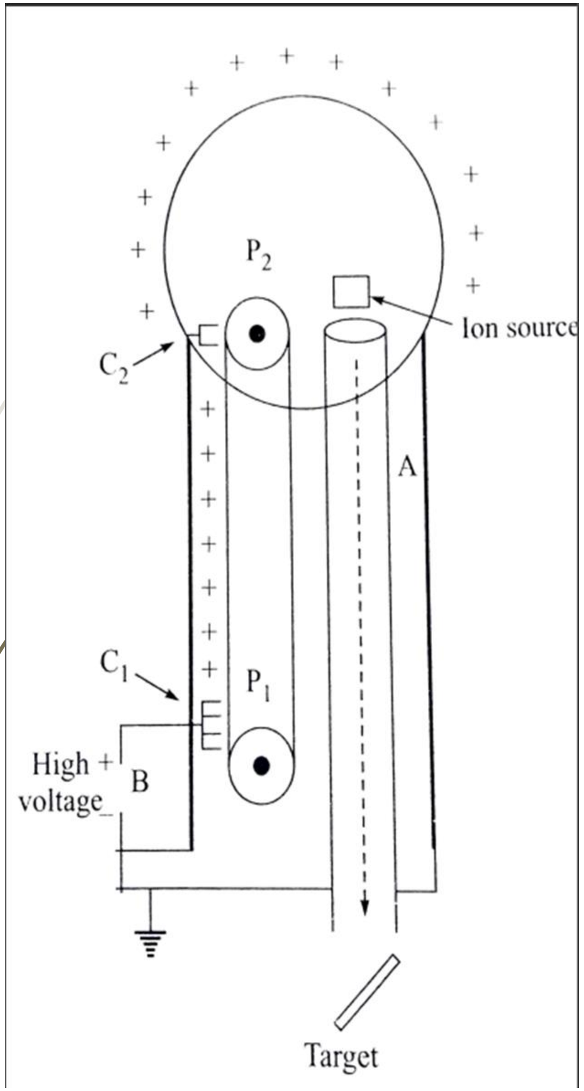
- The belt is run at high speed with the help of motor.
- The comb C_1 is connected to high-voltage supply, an intense electrostatic field is set up near the sharp points of the comb.

6.3 Van de Graff Accelerator



6.3.3 Working

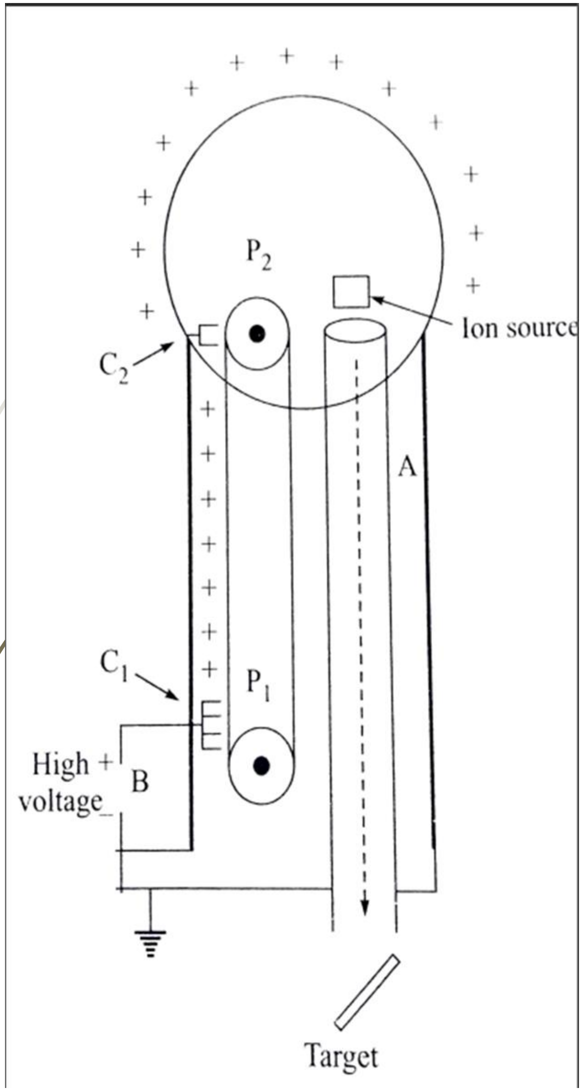
- This field produces positive and negative ions in the air.
- This **discharge of air** is also known as **Corona discharge**.



6.3.3 Working

- Sharp points of the comb **C_1 attracts negative electrons** and **repel positive ions** towards the fast-moving belt.
- The positive ions get deposited on the belt or belt becomes positively charged.

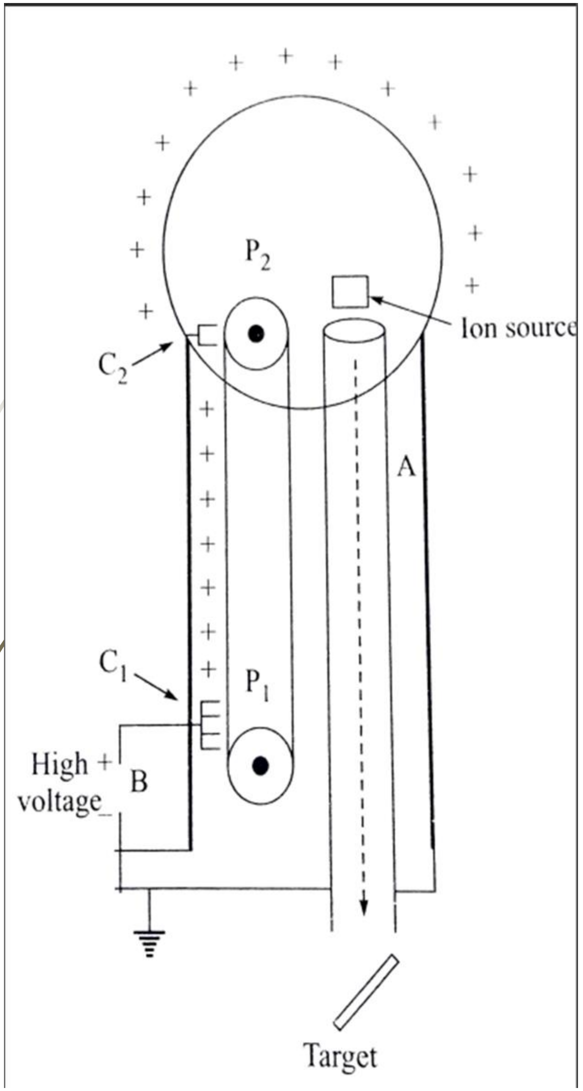
6.3 Van de Graff Accelerator



6.3.3 Working

- As the positively charged belt moves up in the dome, it picks up electrons from the comb C_2 and the positive charge on the belt gets neutralized.

6.3 Van de Graff Accelerator



6.3.3 Working

- As the comb C_2 is connected to the inner side of the dome, the inner side of the dome gets positive charge, which is immediately transferred to outer surface of the dome.

6.3.3 Working

- The resulting **potential V** on the outer conductor can be calculated as

$$V = \frac{Q}{C}.$$

- where C is the total capacity and
- Q is the total charge on the conductor.

6.3.3 Working

- In principle. the potential can be increased without limits as we add more and more charge Q.

- However, in practice a limit is imposed on the potential by the electric breakdown (sparking) of the insulating column that supports the outer conductor or of the surrounding atmosphere.

6.3.3 Working

- When **air** is surrounding the high-voltage dome, it can stand voltages up to about **2-5 MV.**

- However, if the entire accelerator is enclosed in **SF_6 gas**, it can stand voltages up to about **20 MV.**

6.3.3 Working

- **air - 2-5 MV.**
- **SF_6 gas - 20 MV.**
- In small Van de Graff accelerators, the gases used are dry N_2, CO_2 etc.

5.3.4 Advantages (1)

- The Van de Graff accelerator has one enormous advantage over the Cockcroft Walton accelerator.

- The terminal voltage of Van de Graaff accelerator is **highly stable**.

5.3.4 Advantages (1)

- Terminal voltage is constant within ±0.1%.
- This means that the spread in the energy of accelerated particles is from 1 keV to 10 keV.

5.3.4 Advantages (2)

- The energy of the accelerated particles is higher compared to Cockcroft Walton accelerator.

6.3.5 Limitations (1)

- One major limitation of Van de Graaf accelerator is its low-current output.
- The beam current in this accelerator is of the **order of μA**.

6.3.5 Limitations (2)

- The ion source in this accelerator is also in the high-voltage area like that of Cockcroft Walton accelerator.

6.4 Tandem accelerator

6.4 Tandem accelerator

- Modified form of Van de Graaff accelerator which eliminates the problem of placing ion source in high-voltage area, is known as Tandem accelerator.

- Tandem accelerator is **two-stage accelerator** compared to Van de Graaff accelerator, which is a single stage accelerator.

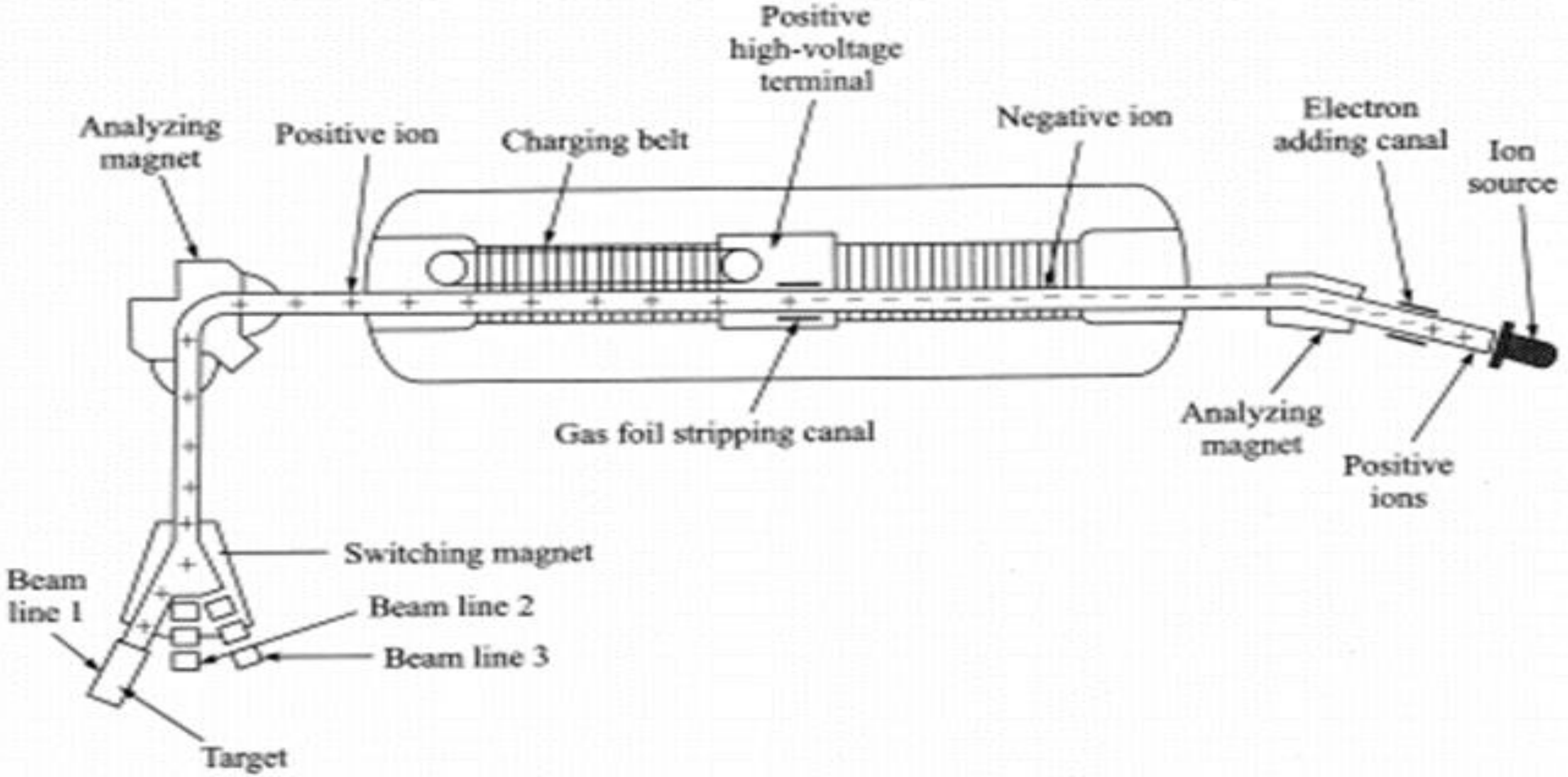
6.4 Tandem accelerator

6.4.1 Principle

- It works on the principle that negatively charged ions are accelerated towards positive potential and in the positive potential region, if we remove few electrons from these negatively charged ions, thus making them positively charged, they will further gets accelerated towards ground potential area.

6.4 Tandem accelerator

6.4.2 Construction and Working



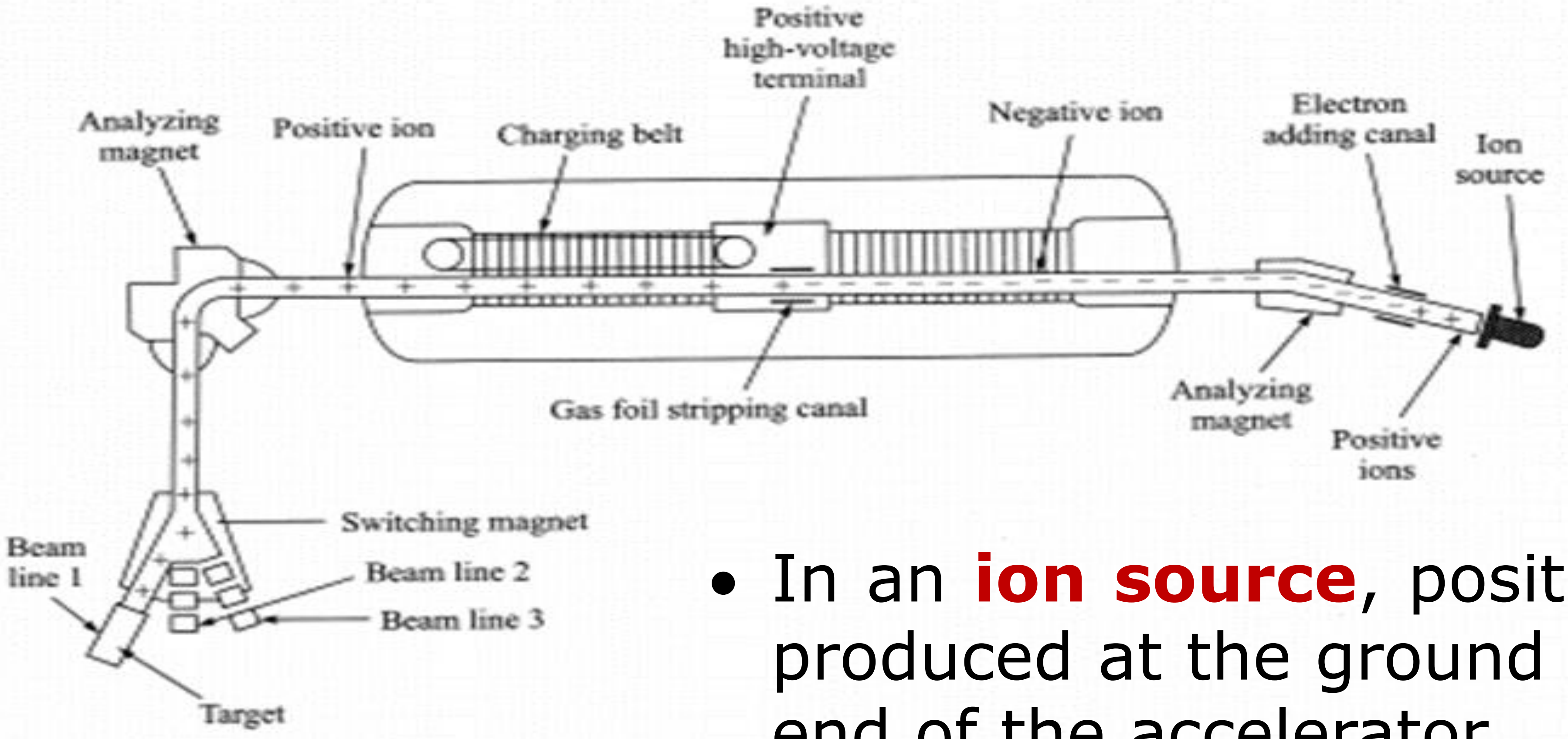
6.4 Tandem accelerator

6.4.2 Construction and Working

- In tandem accelerator, the high-voltage terminal is in the centre of pressure tank, which is filled with SF_6 gas at a pressure of 10-20 atmospheres.

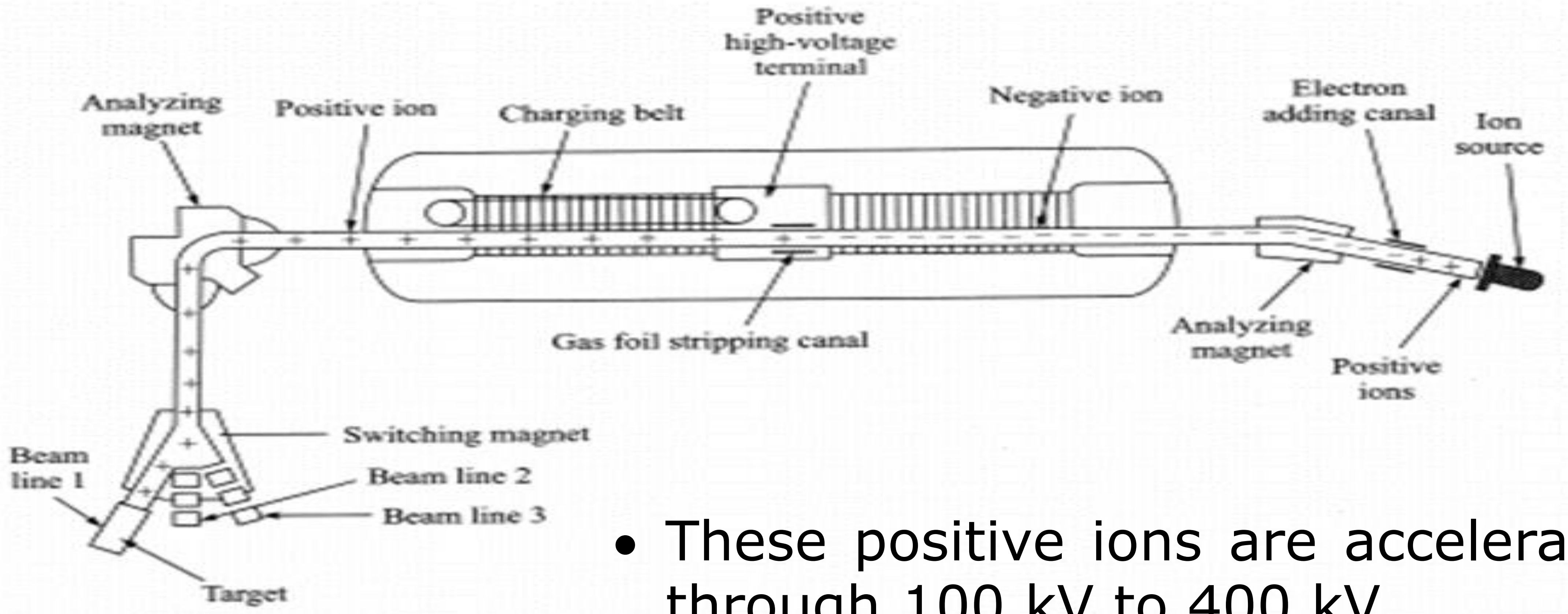
6.4 Tandem accelerator

6.4.2 Construction and Working



- In an **ion source**, positive ions are produced at the ground level at one end of the accelerator.

6.4.2 Construction and Working

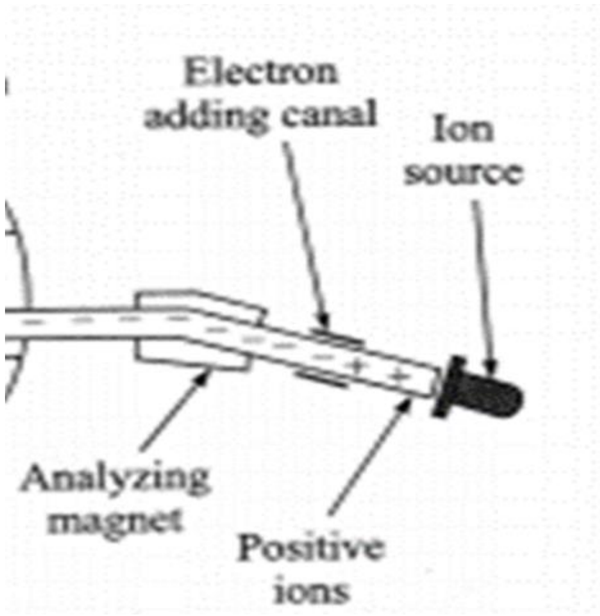


- These positive ions are accelerated through 100 kV to 400 kV.

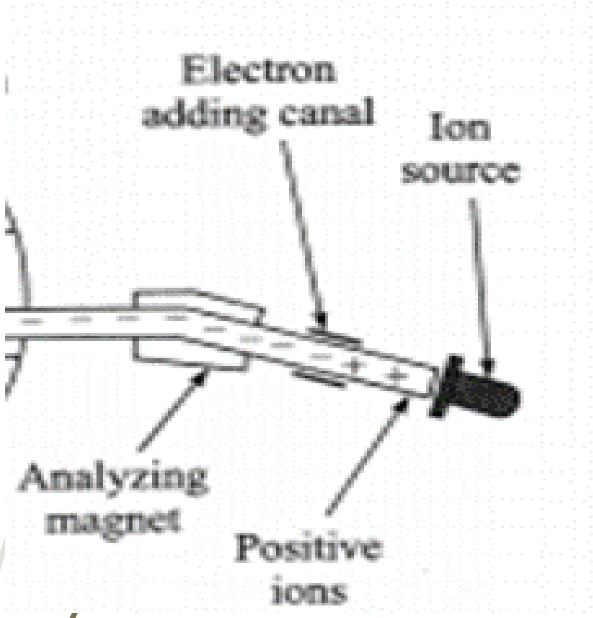
6.4 Tandem accelerator

6.4.2 Construction and Working

- These accelerated ions are allowed to pass through **charge exchange canal** containing vapours of metal (Cs metal contains lot of loosely unbound electrons).



6.4.2 Construction and Working

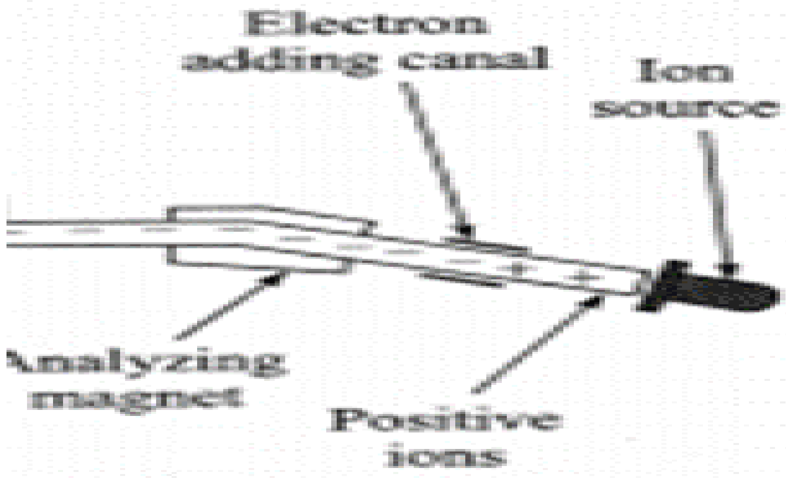


- While passing through charge exchange canal, **1 to 4%** of positive ions picks up two electrons and become negatively charged ions with unit negative charge.
- For example, protons become H^- and O^+ is converted to O^-.

6.4 Tandem accelerator

6.4.2 Construction and Working

- It is highly improbable that positively charged ions pick up **three electrons** to become doubly negatively charged.

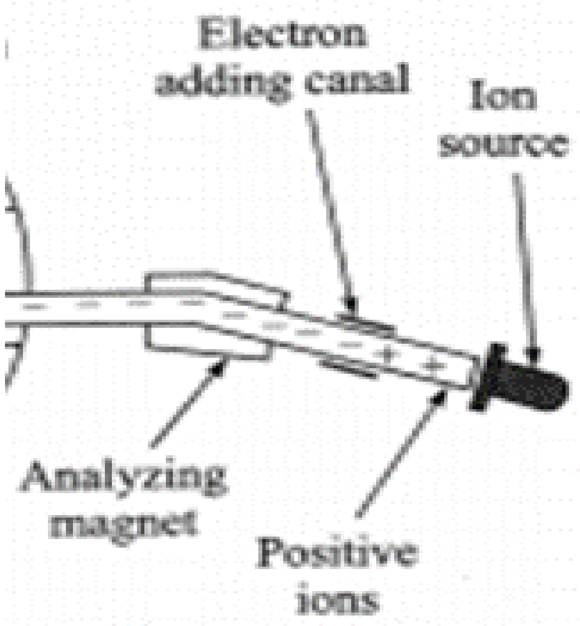


6.4 Tandem accelerator

6.4.2 Construction and Working

- The beam then passes through **first analyzing magnet**.

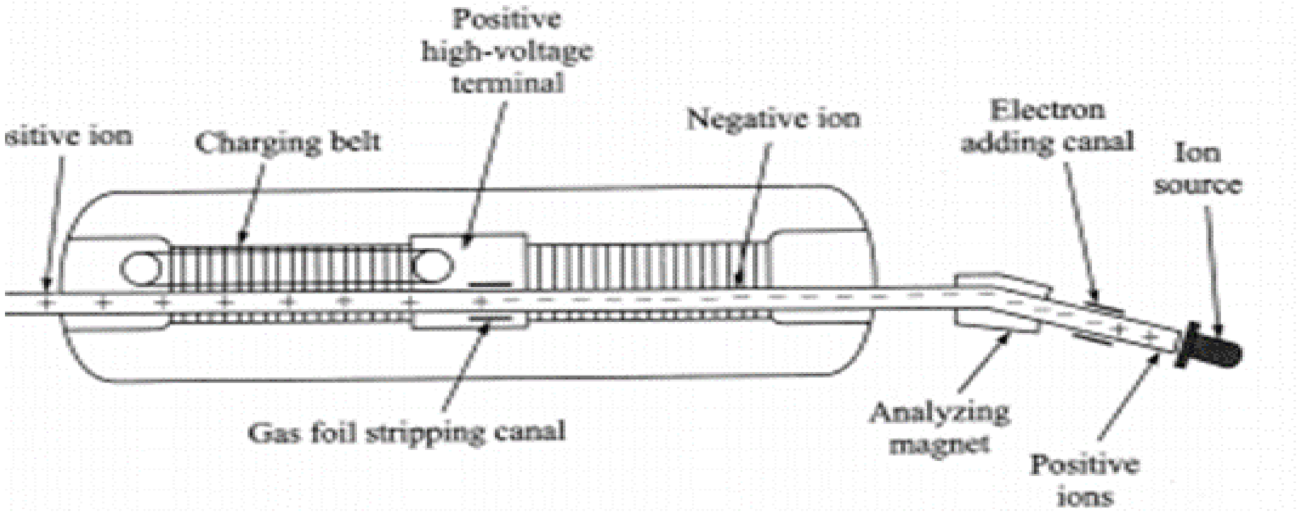
- Here, negative ions are separated and are **injected into the accelerator**.



6.4 Tandem accelerator

6.4.2 Construction and Working

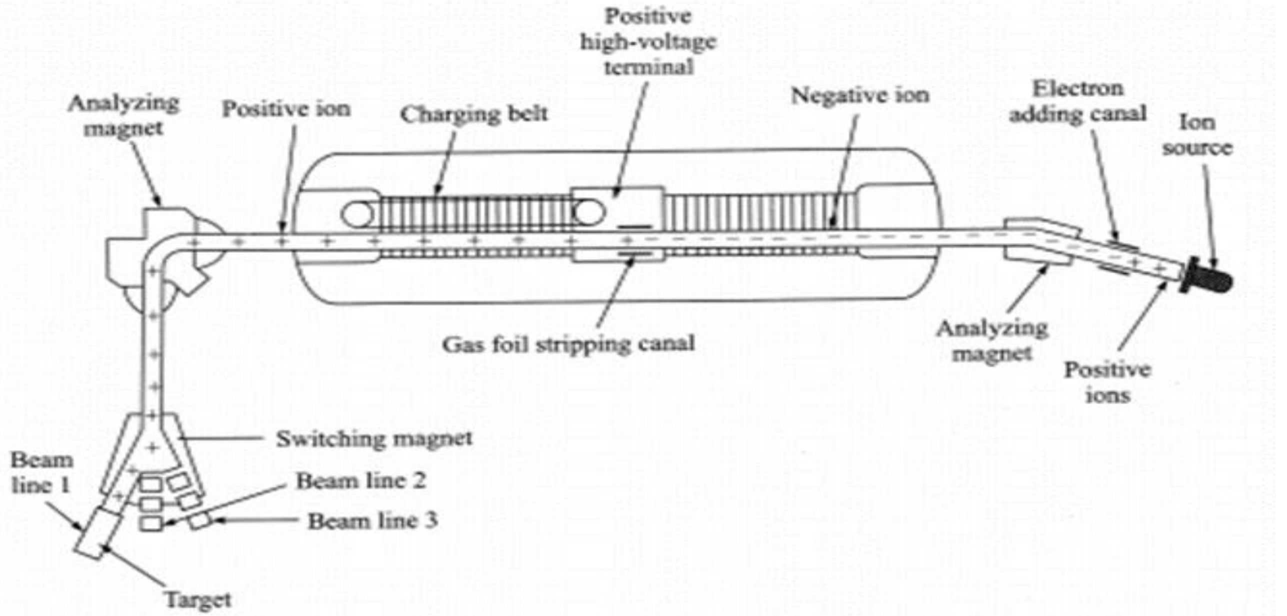
- Negative ions are accelerated towards the positive terminal, which is raised to high potential by a charging belt and when they reach the positive terminal, their kinetic energy becomes V eV, where V is the voltage (in volts) on the terminal.



6.4 Tandem accelerator

6.4.2 Construction and Working

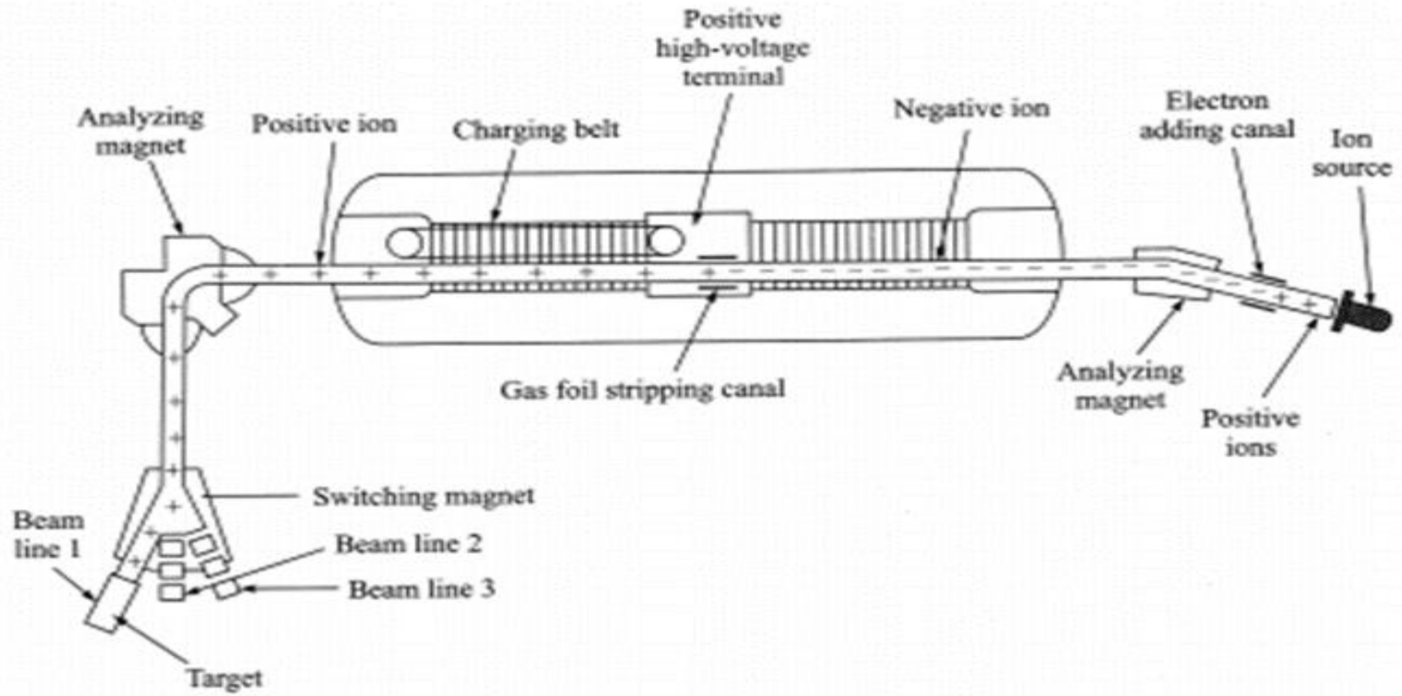
- At the high-voltage terminal, negative ions are allowed to pass through a gas at low pressure (known as ***stripper gas canal***) or through extremely thin carbon foils (known as **stripper foil canal**).



6.4 Tandem accelerator

6.4.2 Construction and Working

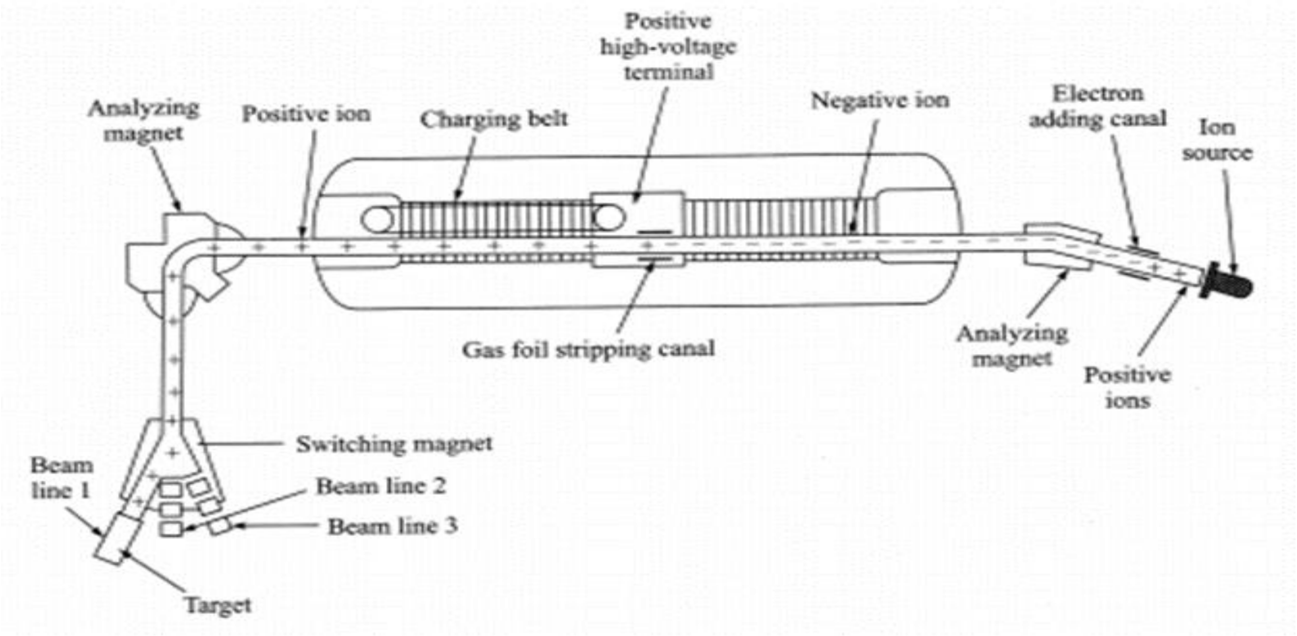
- While passing through stripper, negative ions lose most of the electrons and become positively charged ions.



6.4 Tandem accelerator

6.4.2 Construction and Working

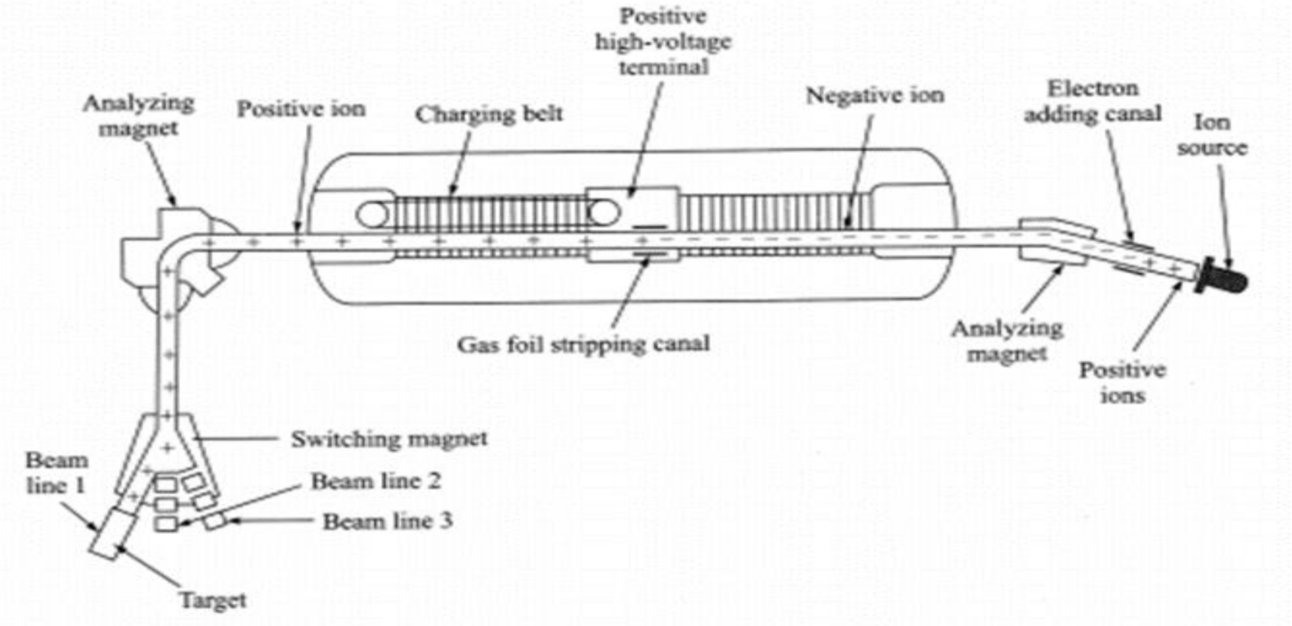
- While passing through stripper, negative ions lose most of the electrons and become positively charged ions. These positively charged ions are repelled by the positive terminal.



6.4 Tandem accelerator

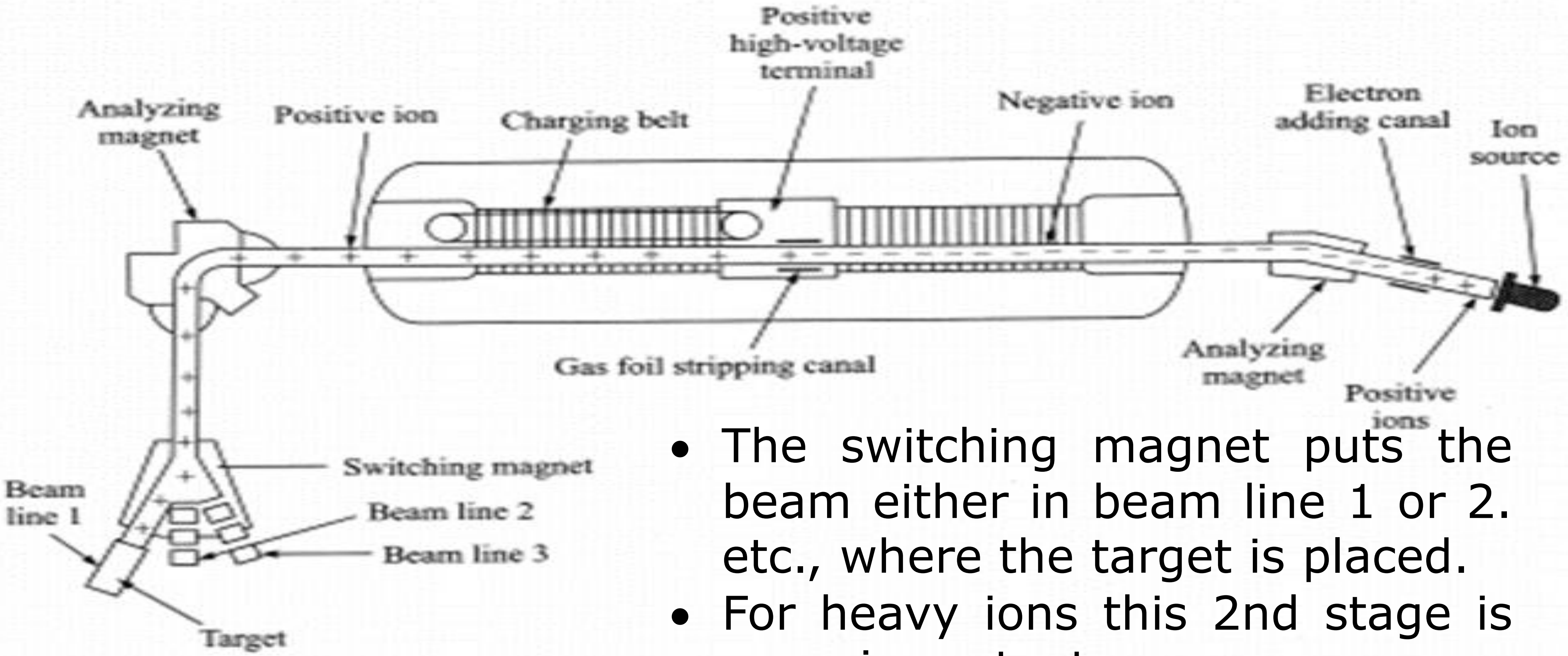
6.4.2 Construction and Working

- After passing through second analyzing magnet which analyze the beam with respect to its energy, or chooses a beam of particular energy only, reaches a switching magnet.



6.4 Tandem accelerator

6.4.2 Construction and Working



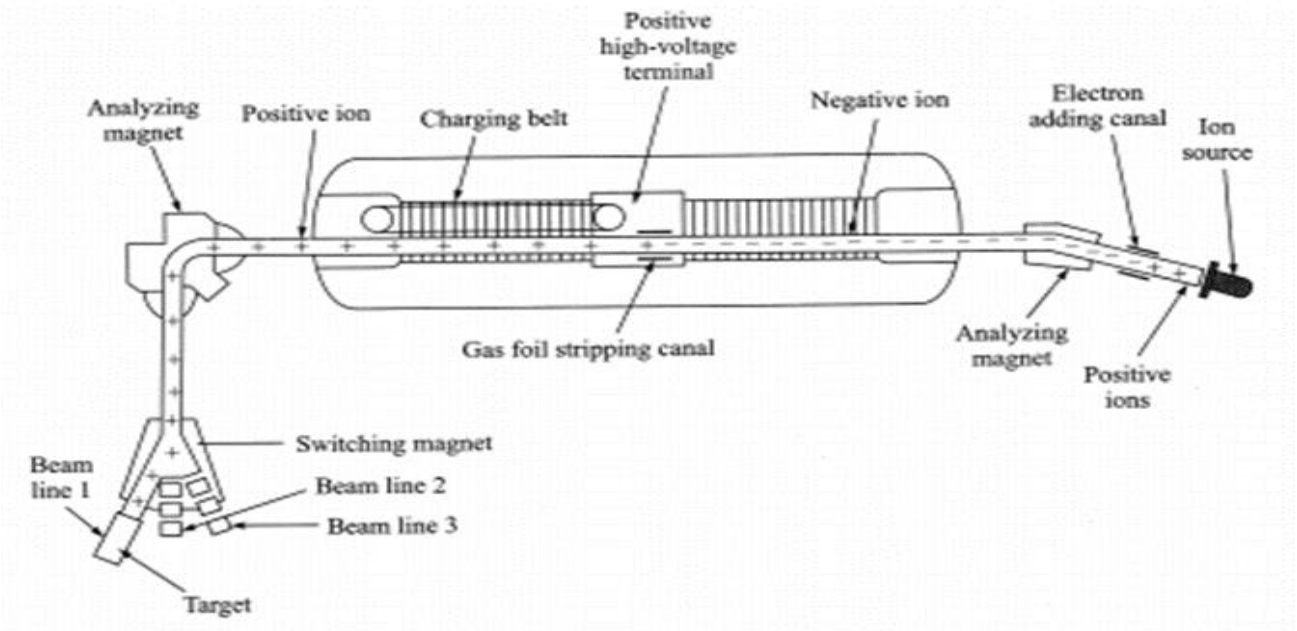
- The switching magnet puts the beam either in beam line 1 or 2. etc., where the target is placed.
- For heavy ions this 2nd stage is more important.

6.4 Tandem accelerator

6.4.2 Construction and Working

For example, if we are accelerating ^{107}Ag ions and assume that the terminal is at 15 MV.

In the first stage, Ag ions are singly charged, and gain energy equal to 15 MeV.

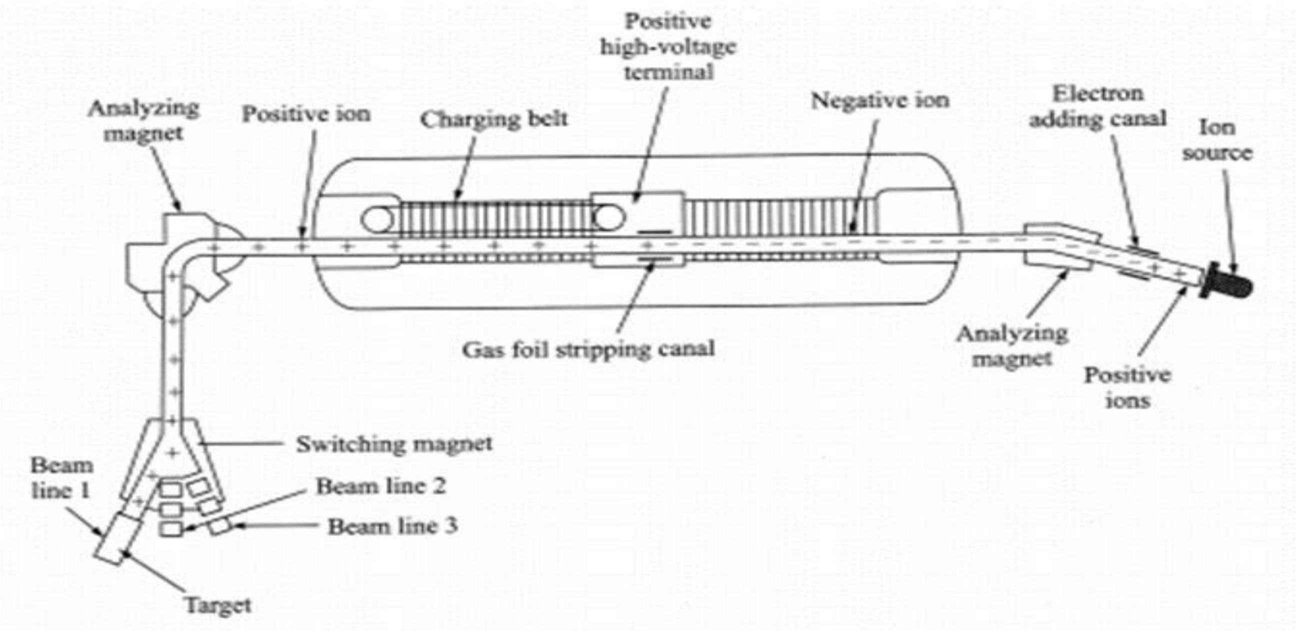


6.4 Tandem accelerator

6.4.2 Construction and Working

- In the stripper foil, suppose 11 electrons are removed from negatively charged Ag ions, so Ag ions acquire 10-unit positive charge.

- These ions in the second stage will gain energy equal to 10 x 15 = 150 MeV.



6.4 Tandem accelerator

6.4.2 Construction and Working

- In the stripper foil, suppose **11** electrons are removed from negatively charged Ag ions, so Ag ions acquire **10-unit positive charge**.
- These ions in the second stage will gain energy equal to **10** x **15** = **150** MeV.
- So, the total energy of Ag ions reaching the target will be **15** + **150** = **165** MeV.

6.4.2 Construction and Working

- However, if we start with negatively charged **hydrogen ions**, in the first stage, they will gain energy **15 MeV** and in the second stage they will further gain energy **15 MeV** only.

- So, the total energy of **protons** will be 15 + 15= **30 MeV**.

6.4 Tandem accelerator

6.4.3 Advantages

1. The ion source is at ground potential so any adjustment in the ion source can easily be made without reducing the terminal voltage.

2. Terminal voltage is used twice for accelerating the particles. For example, protons will gain twice the energy for same terminal voltage as compared to Van de Graaff accelerator

6.4.4 Limitations

1. The **beam current is reduced further compared** to Van de Graaff accelerator. In tandem accelerator beam currents are of the order of few nanoamperes.
2. The total energy gained by the particle is low compared to other accelerators. This limit again comes from the high-voltage on the terminal.

Modification in an accelerator

- The accelerators discussed above cannot be used to accelerate particles to very high energies because of the breakdown in the electrical insulation and sparking in the air.

Modification in an accelerator

- This difficulty was overcome by the discovery of an altogether different principle for accelerating particles.

- Using the **principle of resonance**, particles are accelerated in steps and in each step: particles acquire additional energy by application of a relatively small voltage.

Modification in an accelerator

This technique has led to the development of two types of accelerators:

1. Linear accelerator LINAC or drift tube accelerator), and

2. Cyclic accelerator or cyclotron

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Thanks