VBM FUSION REACTOR
D-D CYCLE

Verdict charged particles fuse to form a homogenous compound nucleus. The homogenous compound nucleus is unstable. So, the central group of quarks [that which with gluons and other groups of quarks compose the homogenous compound nucleus] with its surrounding gluons to become a stable and the just lower nucleus [a nucleus having lesser number of groups of quarks and lesser mass (or gluons) than the homogenous nucleus] than the homogenous one, includes the other nearby located groups of quarks with their surrounding gluons and rearrange to form the 'A' lobe of the heterogenous compound nucleus. While the remaining groups of quarks [the groups of quarks that are not involved in the formation of the lobe 'A'] to become a stable nucleus includes their surrounding gluons (or mass) [out of the available mass (or gluons) that is not involved in the formation of the lobe 'A'] and rearrange to form the 'B' lobe of the heterogenous compound nucleus. The remaining gluons [the gluons (or the mass) that are not involved in the formation of any lobe] keeps both the lobes joined them together. Thus, due to formation of two lobes within into the homogenous compound nucleus, the homogenous compound nucleus transforms into the heterogenous compound nucleus.

The heterogenous compound nucleus, due to its instability, splits according to the lines parallel to the direction of the velocity of the compound nucleus ($\vec{V}_{CN}$) into three lobes where the each separated lobe represent a particle. So, the two particles that represent the lobes 'A' and 'B' are stable while the third particle that represent the remaining gluons (or the reduced mass) is unstable. Each particle that has separated from the compound nucleus has an inhereted velocity ($\vec{V}_{inh}$) equal to the velocity of the compound nucleus ($\vec{V}_{CN}$).

Verdict Charged particles with diffrent momentum by charge ratio when injected to a point 'F' where two uniform magnetic fields are perpendicular, the charged particles follow the confined circular paths of diffrent radii passing through the common tangential magnetic field point F (point of injection) by time and again.

Where,

$$r \propto \frac{mv}{q}$$

where radius of the confined circular path followed by the charged particle is directly proportional to the momentum by charge ratio.

or

$$r = \frac{2E_k}{F_r}$$

$\Rightarrow$ E_k = kinetic energy of the particle

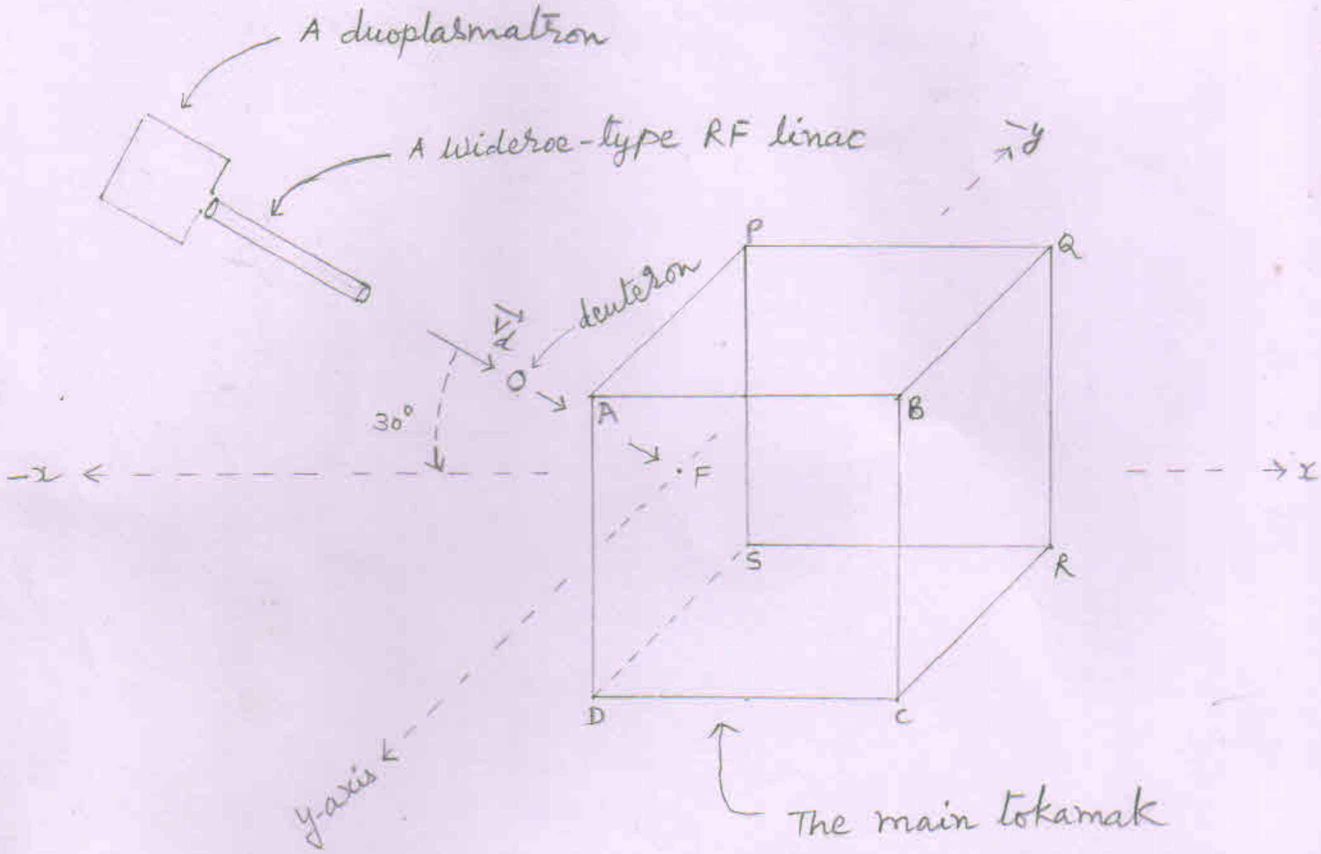
F_R = Resultant force (net force) acting on the charged particle due to the magnetic fields.

By how we can imply the principle :-

1. Injection of bunches of charged particles :-
If the bunches of charged particles of same species (deuterons) are injected to a point F where two magnetic fields are applied, the charged particles (deuterons) of the 1st injected bunch will undergo to a confined circular path and ~~W~~ will pass through the point F (point of injection) by time and again and thus will be available for the deuterons of the later bunch(es) to be fused with at point F.

2. Occurrence of fusion at point F :-
As the deuteron of the n^{th} injected bunch reaches at point F, it fuses with the deuteron of the 1st injected bunch passing through the point F.

Ion Source : Ion source is a duoplasmatron that produce the 6×10^{18} deuterons per second. The produced bunches of deuterons enters into a Wideroe-type RF linac



⇒ Where, the point 'F' is a point of injection. The RF linac acclerate the deuterons. The acclerated deuterons enters into the main tokamak at point 'F' (or the point of injection) where the two perpendicular magnetic fields are applied.

I. Minimum kinetic energy (E_m) required for fusion

1. Tunneling – Tunneling is a consequence of the Heisenberg uncertainity principle which states that the greater certainity we know the velocity of the particle the less we know about its position in the space and vice versa.
The uncertainity in the position is such that when a proton collides with another proton, it may find itself on the other side of the Coloumb barrier and in the attractive potential well of the strong force.

2. Work done to overcome the coulomb barrier

$$U = \frac{k z_1 z_2 q^2}{r_0}$$

So, the kinetic energy of the particle should be equal to

$$E_m = \frac{1}{2} m v^2 = \frac{k z_1 z_2 q^2}{r_0}$$

⇒ Rewriting the kinetic energy of the particle in terms of momentum

$$\frac{1}{2}mv^2 = \frac{p^2}{2m} = \frac{(h/\lambda)^2}{2m}$$

If we require that the nuclei must be closer than the de-broglie wavelength for tunneling to take over and nuclei to fuse. ($r_0 = \lambda$)

$$\frac{kz_1z_2q^2}{r_0} = \frac{kz_1z_2q^2}{\lambda}$$

where,

$$\frac{1}{2}mv^2 = \frac{(h/\lambda)^2}{2m} = \frac{kz_1z_2q^2}{\lambda}$$

so, $$\frac{h^2}{\lambda^2 2m} = \frac{kz_1z_2q^2}{\lambda}$$

or lambda (λ) $= \frac{1}{2}\frac{h^2}{kz_1z_2q^2 m}$

If we use this wavelength as the distance of closest approach, the kinetic energy required for fusion is -

$$E_m = \frac{1}{2}mv^2 = \frac{kz_1z_2q^2}{r_0} = \frac{kz_1z_2q^2}{\lambda} = kz_1z_2q^2 \times \frac{2kz_1z_2q^2m}{h^2}$$

$$\Rightarrow E_m = \frac{2k^2z_1^2z_2^2q^4m}{h^2}$$

where m is the mass of the penetrating (injected) nucleus.

⇒ Minimum kinetic energy required for D-D fusion

$$E_m = \frac{2K^2 z_1^2 z_2^2 q^4 m}{h^2}$$

for D-D fusion

$z_1 = z_2 = 1$

$q = 1.6 \times 10^{-19}$ C

$m = 3.3434 \times 10^{-27}$ kg

$h = 6.62 \times 10^{-34}$ J-s

$K = 9 \times 10^{9}$ Nm^2/C^2

$$\Rightarrow E_{D-D} = \frac{2 \times (9\times10^9)^2 \times 1^2 \times 1^2 \times (1.6\times10^{-19})^4 \times 3.3434\times10^{-27}}{(6.62 \times 10^{-34})^2} \text{ J}$$

$$= \frac{3549.63161088 \times 10^{18} \times 10^{-76} \times 10^{-27}}{43.8244 \times 10^{-68}} \text{ J}$$

$$= 80.9966961528 \times 10^{-17} \text{ J}$$

$$= 50.6229350955 \times 10^{2} \text{ ev}$$

$$E_{D-D} = 5.0622 \text{ kev}$$

$$\simeq 0.005 \text{ Mev}$$

⇒ Minimum kinetic energy required for D-$_2He^3$ fusion

$$E_{D-_2He^3} = E_{D-D} \times z_2^2 \qquad [\because z_2 = 2]$$

$$= 0.0050622 \times 4 \text{ Mev}$$

$$= 0.0202488 \text{ Mev}$$

$$\simeq 20.2488 \text{ Kev}$$

Particle acclerator :

With the help of a Wideroe-type linac we acclerate the deuterons up to 102·4 Kev.

⇒ A Wideroe type linear acclerator

$$K_n = nqV_0 T_{tr} = nqV_{max} \sin\gamma_0$$

Where, $V_0 = V_{max} = 40$ kV and $n = 4$

$\sin\gamma_0 = T_{tr} = 0.64$ and $q = 1.6\times10^{-19}$ C

$$\Rightarrow K_4 = 4\times1.6\times10^{-19}\times40\times0.64 \text{ KJ}$$
$$= 102.4 \text{ Kev} \qquad [\because 1.6\times10^{-19}\text{J} = 1\text{eV}]$$

⇒ Length of the first drift tube

$$l_1 = \frac{\sqrt{n}}{f_{rf}} \times \sqrt{\frac{qV_{max}\sin\gamma_0}{2m}}$$

Where, if

$f_{rf} = 7\times10^6$ Hz , $m = 3.3434\times10^{-27}$ kg

$$l_1 = \frac{\sqrt{1}}{7\times10^6} \times \sqrt{\frac{1.6\times10^{-19}\times40\times10^3\times0.64}{2\times3.3434\times10^{-27}}} \text{ m}$$

$$= \frac{1}{7\times10^6} \times \sqrt{\frac{409.6}{6.6868}\times10^{10}} \text{ m}$$

$$= \frac{1}{7\times10^6} \times \sqrt{61.2550098701\times10^{10}} \text{ m}$$

$$= \frac{1}{7\times10^6} \times 7.8265\times10^5 \text{ m}$$

$$= 1.11807\times10^{-1} \text{ m} = 11.1807\times10^{-2} \text{ m}$$

$$l_2 = \sqrt{2} \times l_1$$
$$= 1.4142 \times 11.1807 \times 10^{-2}\ m$$
$$= 15.8117 \times 10^{-2}\ m$$

$$l_3 = \sqrt{3} \times l_1$$
$$= 1.732 \times 11.1807 \times 10^{-2}\ m$$
$$= 19.3649 \times 10^{-2}\ m$$

$$l_4 = \sqrt{4} \times l_1$$
$$= 2 \times 11.1807 \times 10^{-2}\ m$$
$$= 22.3614 \times 10^{-2}\ m$$

$\Rightarrow$ Total length of the Wideroe-type linac is -

$$L = l_1 + l_2 + l_3 + l_4$$

$$= [11.1807 + 15.8117 + 19.3649 + 22.3614] \times 10^{-2}\ m$$

$$= 68.7187 \times 10^{-2}\ m$$

The tokamak

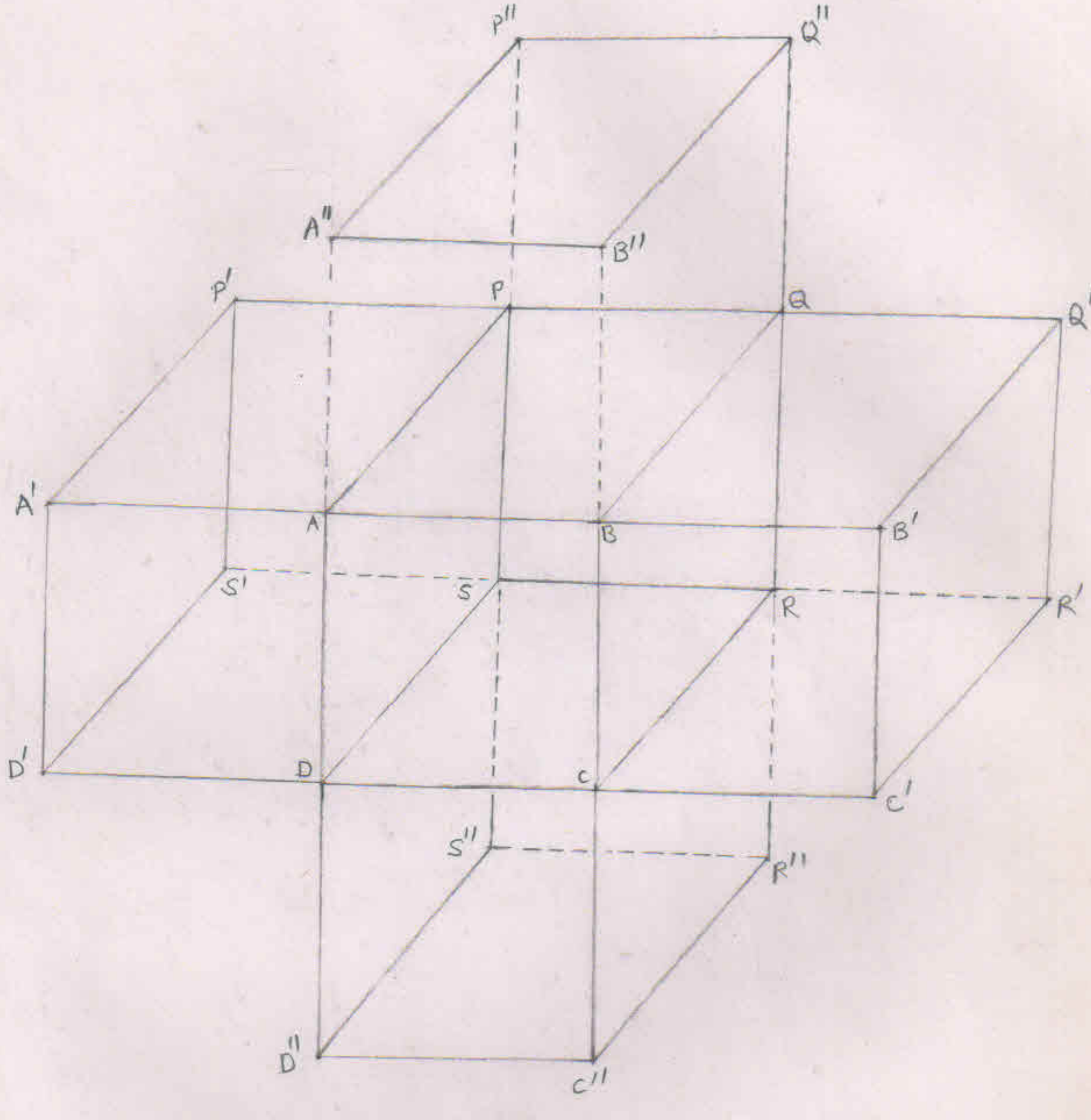
⇒ The tokamak has two parts - one is the main tokamak and the another is the extended tokamak.

⇒ The points A, B, C, D, P, Q, R and S represents the corners of the walls of the main tokamak while all the other remaining points represents the corners of the walls of the extended tokamak.

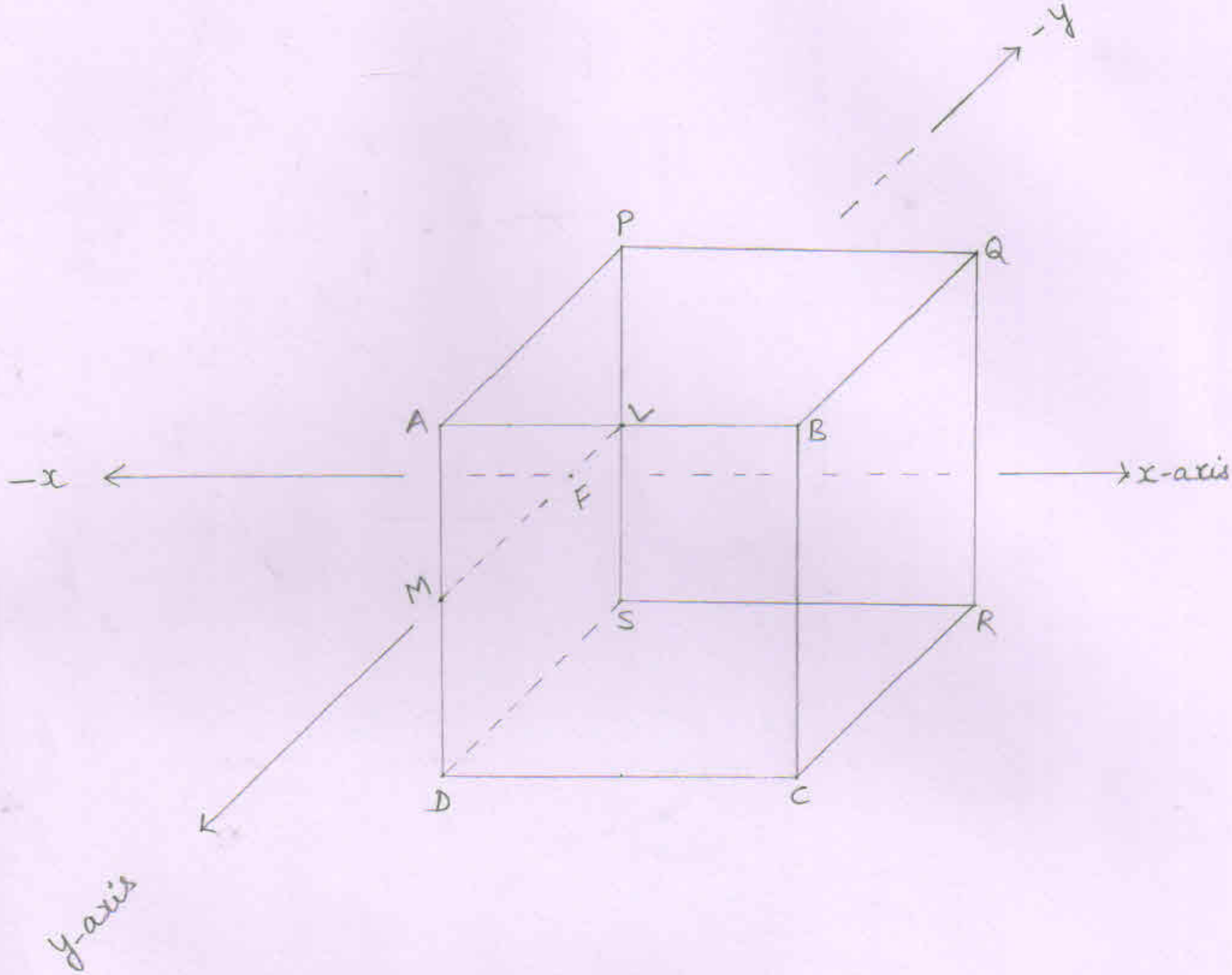
⇒ The tokamak is made up of steel.
⇒ The graphite or the boron is used as the inner liner of the tokamak to absorb the thermal neutrons.

⇒ The location of the point of injection (F) of the charged particles (deuterons) or the location of the centre of fusion (F) within - into the tokamak is —

The main tokamak with its extensions



The location of the point 'F' [or the point of injection or the center of fusion]



⇒ Where, MF = 0.35 m and LF = 0.35 m

AM = 0.35 m and MD = 0.35 m

PL = 0.35 m and LS = 0.35 m

AP = AB = AD = 0.70 m

Total surface area of the tokamak

I. Surface area of the Walls of the main tokamak

⇒ Surface area of the walls

1. ABCD = length × breadth
$= 0.7\,m \times 0.7\,m = 0.49\,m^2$
2. PQRS = $0.7\,m \times 0.7\,m = 0.49\,m^2$
3. APQB = $0.7\,m \times 0.7\,m = 0.49\,m^2$
4. DSRC = $0.7\,m \times 0.7\,m = 0.49\,m^2$
5. BQRC = $0.7\,m \times 0.7\,m = 0.49\,m^2$

⇒ So, the total surface area of the main tokamak = $2.45\,m^2$

⇒ The points APSD do not represent a Wall. It is a blanck place that allows the injected deuterons to enter into the main tokamak (or the region where the magnetic fields are applied.)

II. Surface area of the extended walls of the tokamak.

⇒ The surface area of the each extended wall is = $0.7 \times 0.7\,m^2 = 0.49\,m^2$

⇒ Total no. of extended walls = 20

⇒ Total surface area of the extended walls
= surface area of the extended wall × total no. of extended walls.
$= 0.49\,m^2 \times 20$
$= 9.8\,m^2$

III. Total surface area of the tokamak = surface area of the walls of the main tokamak × total surface area of the extended walls
$= 2.45\,m^2 + 9.8\,m^2$
$= 12.25\,m^2$

Magnetic field coils

VBM fusion reactor has two pairs of semicircular magnetic field coils. out of them, one pair of semicircular magnetic field coils is vertically eracted while another pair of semicircular magnetic field coils is horizontally lying.

1. vertically eracted magnetic field coils :
In a VBM fusion reactor, there are two vertically eracted semicircular magnetic field coils that act as a helmhotz coil.
The distance between the two vertically eracted semicircular coils is equal to the radius of any one of the semicircular magnetic field coil.
i.e. $d = r = 1 \text{ m}$
The vertically eracted semicircular magnetic field coils acting as a helmhotz coil produce a uniform magnetic field ($\vec{B}_y$) parallel to y-axis.

2. Horizontally lying magnetic field coils :
In a VBM fusion reactor, there are two horizontally lying semicircular magnetic field coils that acts as a helmhotz coil.
The distance between the two horizontally lying semicircular magnetic field coils is equal to the radius of any one of the semicircular magnetic field coil.
i.e. $d = r = 0.90 \text{ m}$
The horizontally lying semicircular magnetic field coils acting as a helmhotz coil produce a uniform magnetic field ($\vec{B}_z$) parallel to z-axis.

⇒ Magnetic field due to a semicircular coil at point x is –

$$B_1 = \frac{\mu_0}{4\pi} \times \frac{\pi R^2 n I}{(R^2 + x^2)^{3/2}}$$

⇒ magnetic field due to a semicircular coil at the x, [illegible] if $x = R/2$

$$B_1 = \frac{\mu_0}{4\pi} \times \frac{\pi R^2 n I}{\left(R^2 + \frac{R^2}{4}\right)^{3/2}} \qquad \left[\because x = \frac{R}{2}\right]$$

$$= \frac{8}{5\sqrt{5}} \times \frac{\mu_0 n I}{4R}$$

⇒ So, the magnetic field in the mid plane of the two semicircular coils acting as a helmhotz coil is –

$$B_T = B_1 + B_2$$

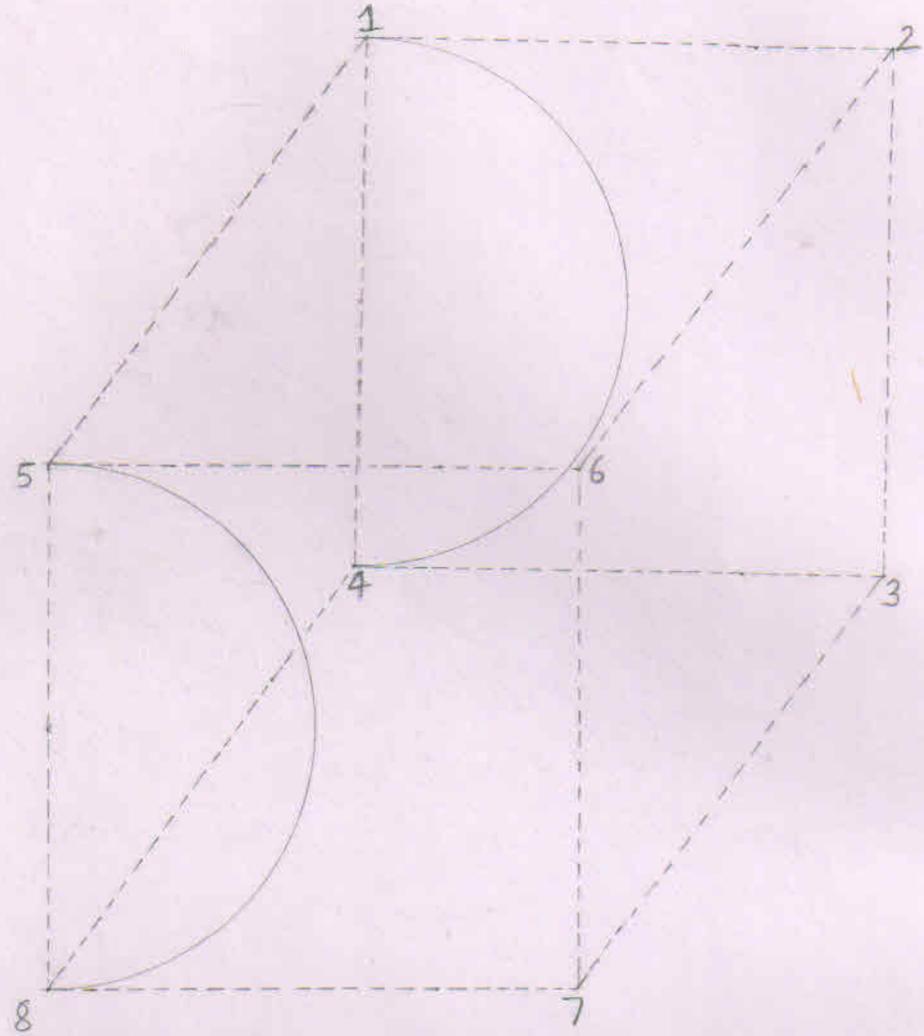
$$= 2B \qquad [\because B_1 = B_2 = B]$$

$$= \frac{16}{5\sqrt{5}} \times \frac{\mu_0 n I}{4R}$$

$$\simeq 1.43 \times \frac{\mu_0 n I}{4R}$$

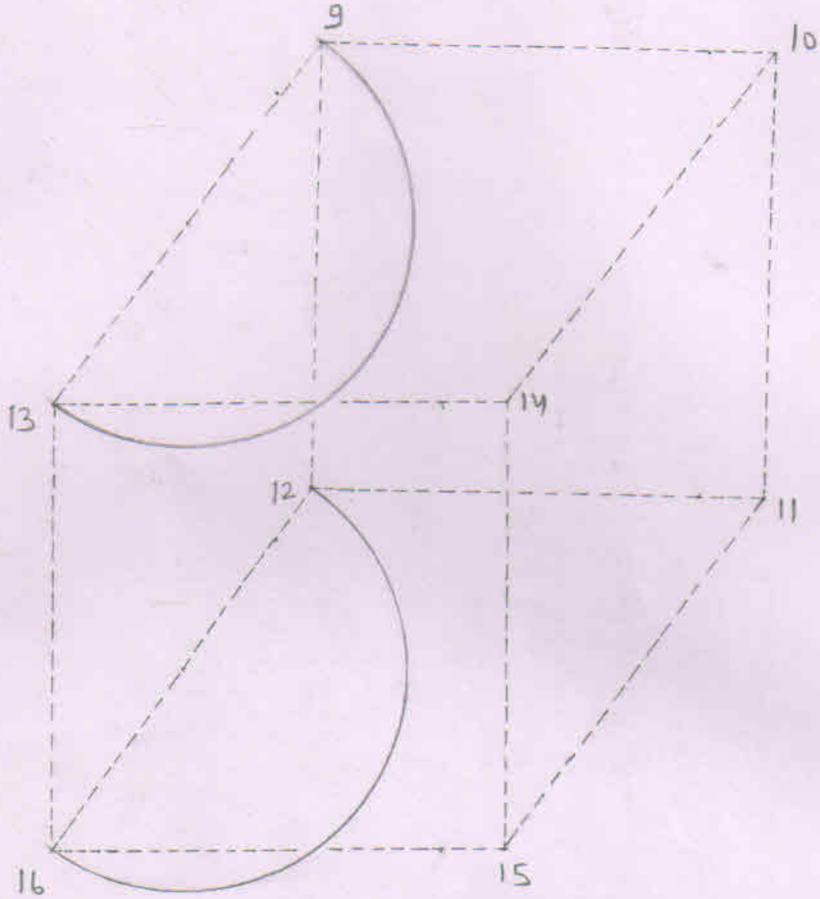
$$\simeq 1.43\, B_{centre} \qquad \left[B_{centre} = \frac{\mu_0 n I}{4R}\right]$$

The vertically eracted magnetic field coils .



∃ The magnetic field coils are exterior to the main tokamak. So, the area covered up by the points 1, 2, 3, 4, 5, 6, 7, 8 is greater than the area covered up by the points P, Q, R, S, A, B, C, D of the main tokamak.

The horizontally lying magnetic field coils



⇒ The horizontally lying semicircular coils are exterior to the main tokamak and interior to the vertically eracted magnetic field coils.

So, the area covered up by the points 9, 10, 11, 12, 13, 14, 15, 16 is less than the area covered up by the points 1, 2, 3, 4, 5, 6, 7, and 8.

1. Magnetic field ($\vec{B}_y$) in the mid plane of the two vertically erected semicircular coils acting as a helmhotz coil is –

$$B_y = 1.43 \; B_{centre}$$

$$B_{centre} = \frac{\mu_0 n I}{4R}$$

Where, $n = 2227$ turns
$I = 1\,KA$ or 10^3 Amperes
$R = 1\,m$

So, $B_{centre} = \dfrac{4 \times 3.14 \times 10^{-7} \times 2227 \times 10^3}{4 \times 1}$ Tesla

$= 0.699278$ Tesla

$\Rightarrow B_y = 1.43 \times B_{centre} = 1.43 \times 0.699278$ Tesla

$= 0.99996754$ Tesla
$\simeq 1$ Tesla

2. Magnetic field ($\vec{B}_z$) in the mid plane of the two horizontally lying semicircular coils acting as a helmhotz coil is –

$$B_z = 1.43 \; B_{centre}$$

$B_{centre} = \dfrac{\mu_0 n I}{4R}$ Where, $n = 2004$ turns
$I = 1\,KA = 10^3$ Amperes
$R = 90\,cm = 0.9\,m$

$B_{centre} = \dfrac{4 \times 3.14 \times 10^{-7} \times 2004 \times 10^3}{4 \times 90 \times 10^{-2}}$ Tesla

The direction of the magnetic field

⇒ The direction of flow of current in the horizontally lying semicircular coils is clockwise so that the direction of the produced magnetic field is according to negative z axis (i.e. downward).

as $B_z = 1$ Tesla

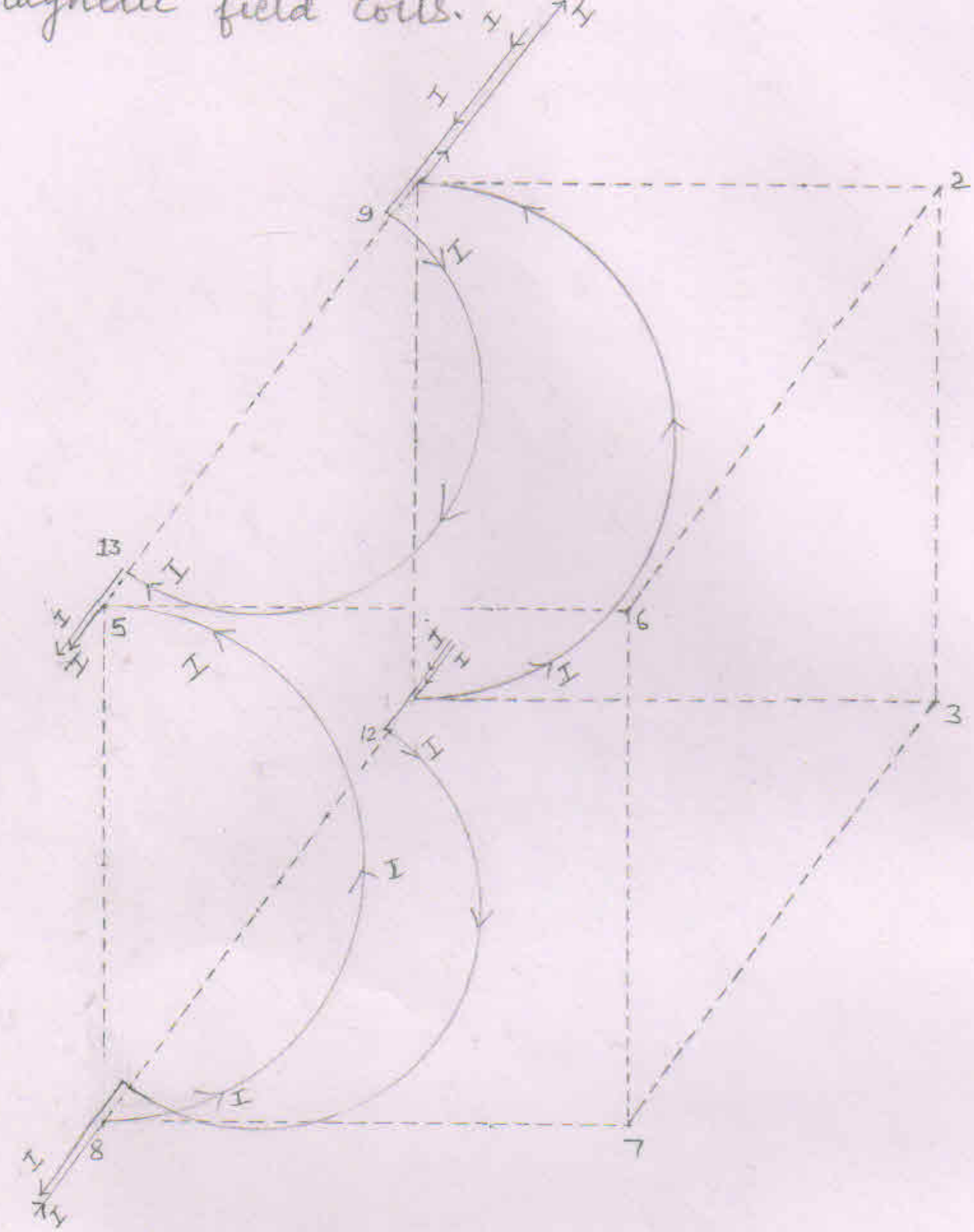
so, $\vec{B}_z = -1$ Tesla

⇒ The direction of flow of current in the vertically eracted magnetic coils is anticlockwise so that the direction of the produced magnetic field ($\vec{B}_y$) is according to y-axis.

As. $B_y = 1$ Tesla

so, $\vec{B}_y = 1$ Tesla

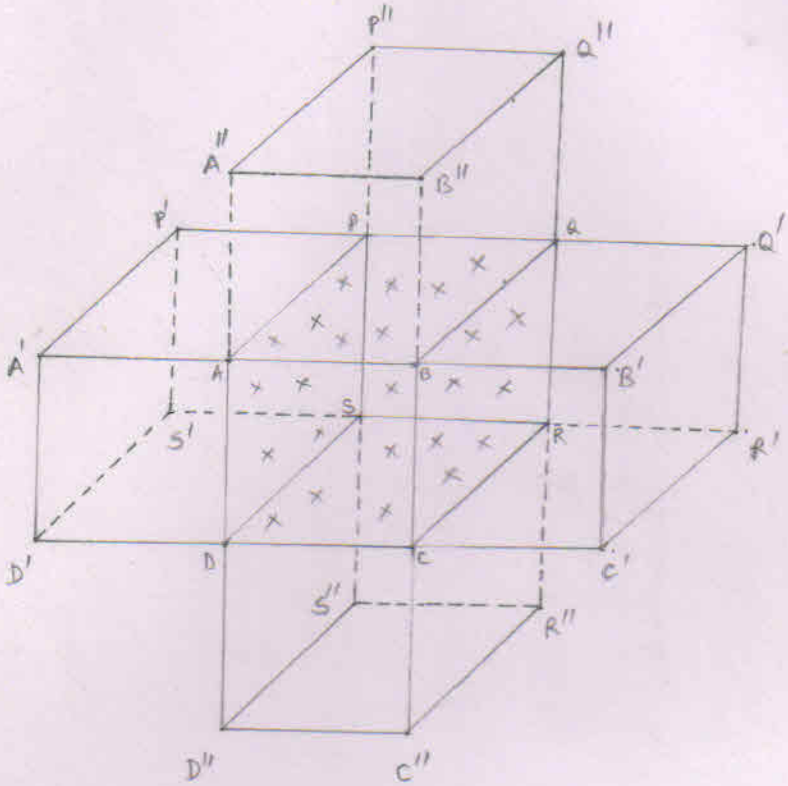
The direction of flow of current in the magnetic field coils.



⇒ In the horizontally lying semicircular coils the current (I) flows in the clockwise direction while in the vertically eracted semicircular coils the current (I) flows in the anticlockwise direction.

⇒ The wire that supply the current (I) in the horizontally lying coils is above to the wire(s) that supply the

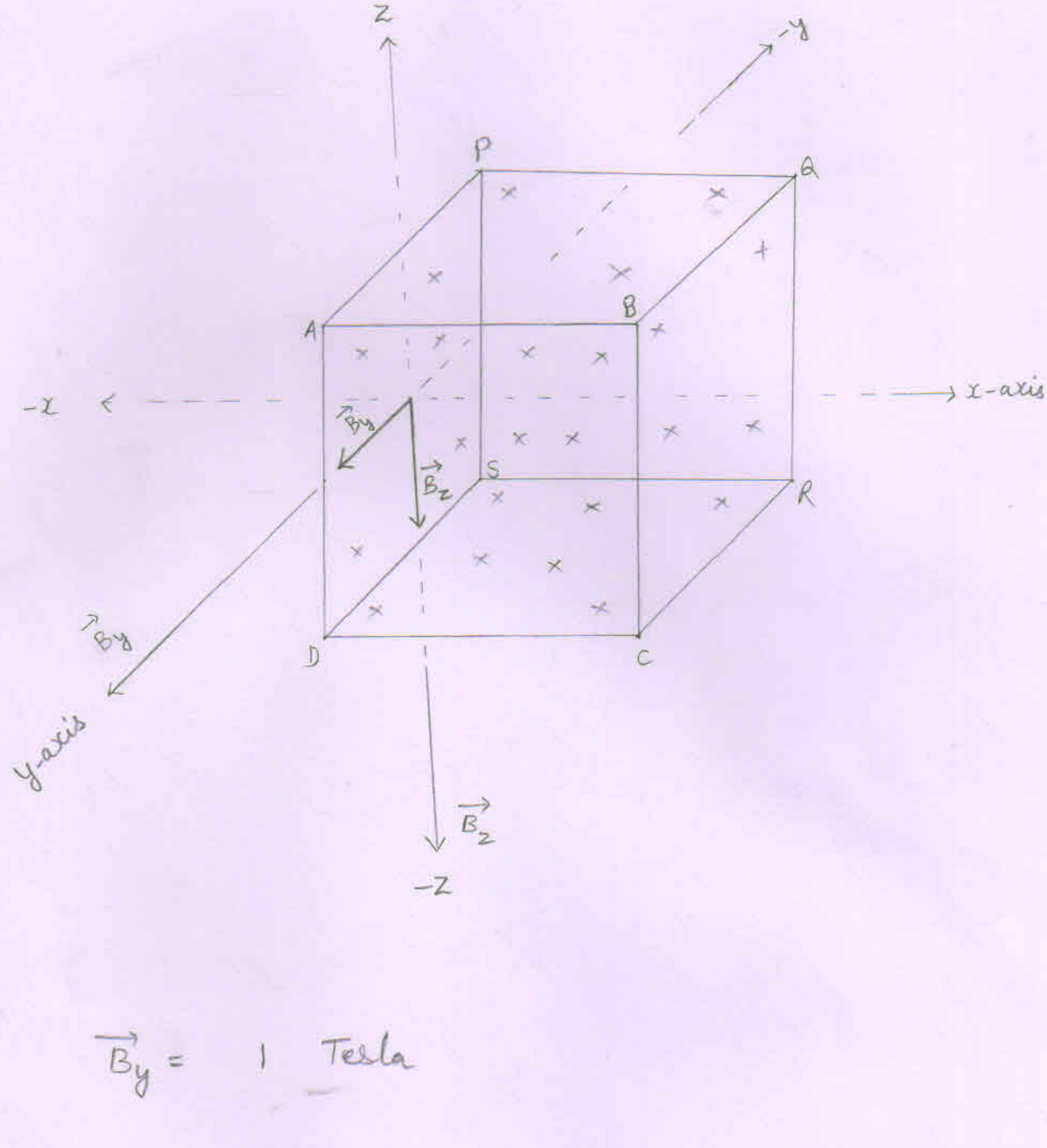
The uniform magnetic fields [$\vec{B_y}$ and $\vec{B_z}$] are applied within into the main tokamak only.



⇒ We have denoted the presence of two uniform magnetic fields by the [×] sign.

Two uniform magnetic field are applied within into the main tokamak.

⇒ The direction of the uniform magnetic fields applied within into the main tokamak.



⇒ Where

$$\vec{B_y} = 1 \text{ Tesla}$$

$$B_z = -1 \text{ Tesla}$$

and $\vec{B_y} \perp \vec{B_z}$

Center of fusion (F) : Center of fusion is actually a point where two charged particles fuses.

For the VBM fusion reactor — the center of fusion is a point from where a charged particle (either it is injected or produced) undergoes to a confined circular path and passes from this point by time and again and thus available for the another injected particle (reaching at this point F) for fusion.

3. Number of centers of fusion (F) : As the point 'F' is acting as a center of fusion, the total no. of deuterons of an injected bunch are $\sim 8 \times 10^{11}$ so the total number of centres of fusion are $\simeq 8 \times 10^{11}$.

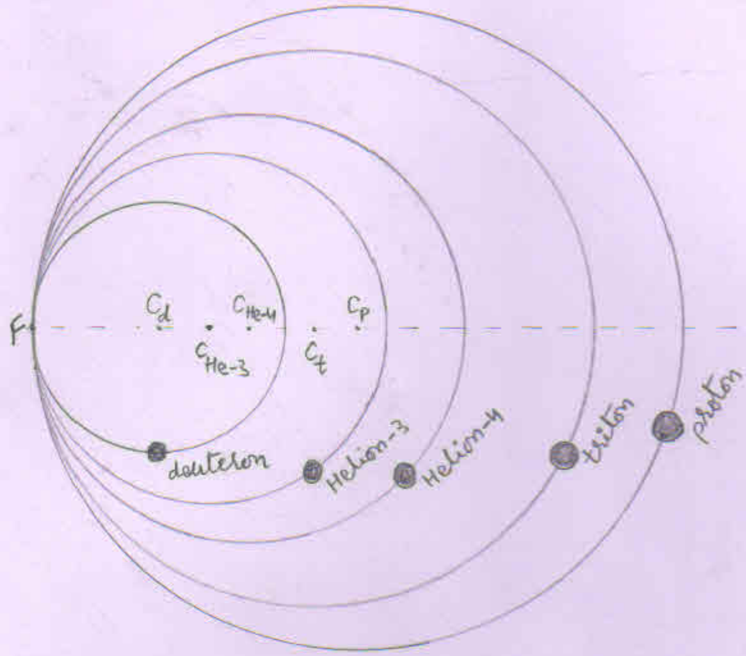
4. Nature of center of fusion : As the magnetic field is tangential in nature so the point F (the center of fusion) that is located within into the magnetic fields is a tangential point of a number of circular orbits (followed or to be followed by the charged particles) of diffrent radii.

* The number of deuterons injected per bunch (n_1) :-

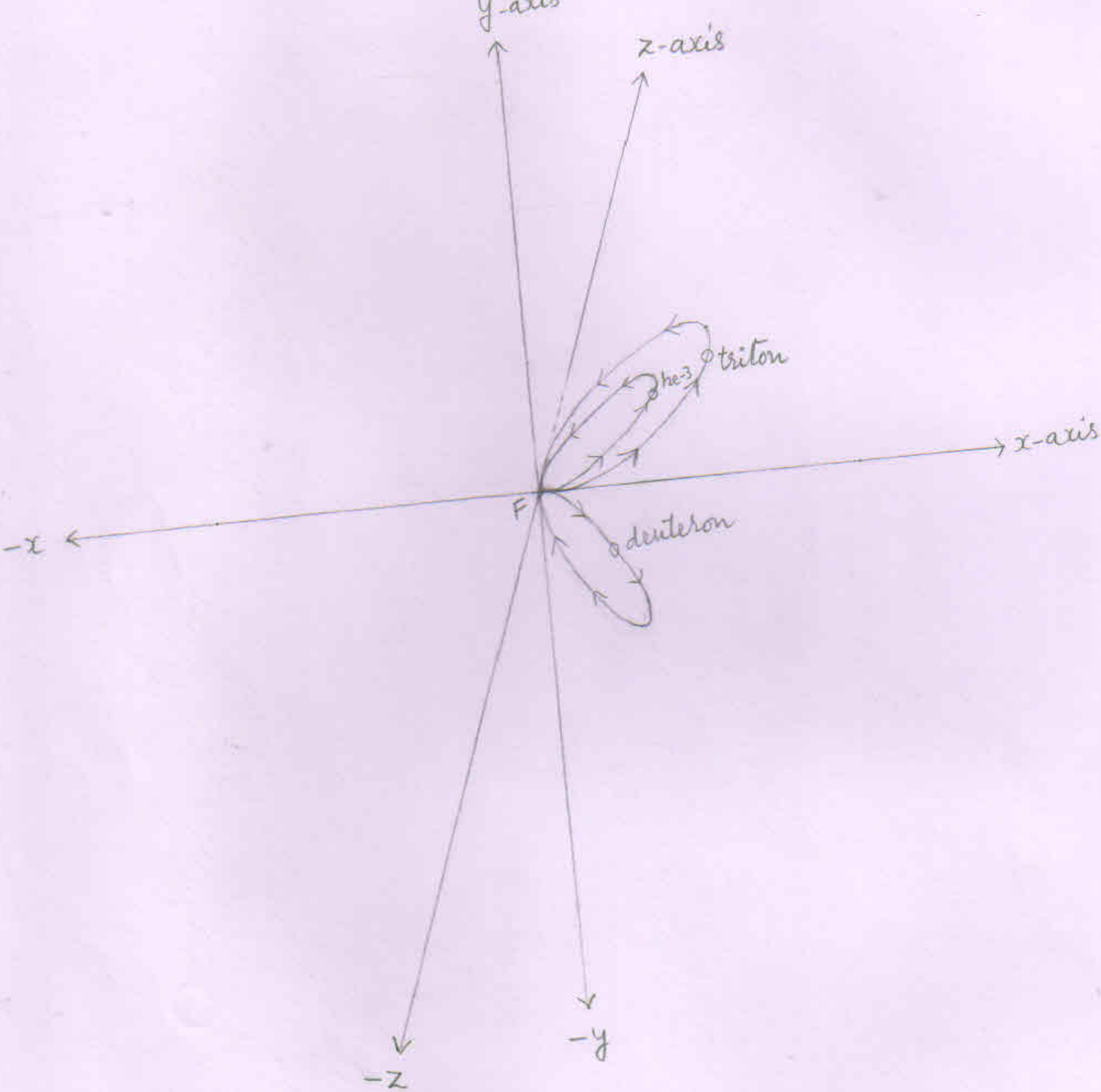
$$n_1 = 8.571 \times 10^{11} \text{ deuterons per bunch}$$

⇒ "The number of deuterons per bunch" is described on the page number 628.

The center of fusion (The point 'F') is the tangential point of all the circular orbits of diffrent radii followed by the Various charged particles.



If we denote the positive x, y and z-axes as shown below then path of the confined particles will lie in the planes as shown below.



⇒ The radius of the circular orbit followed by the confined triton is more than the radius of the circular orbit followed by the confined helion-3.

⇒ 'F' is the centre of fusion or the point of injection

5. Center of fusion (F) is a plateform where the fusion is a certainity :-

From the point F (the center of fusion) the deutoron of earlier bunch will undergo to the confined circular path and will pass through this point by time and again untill it fuses with the deuteron of later bunch.

Similarly, the point 'F' also governs the produced charged particles to pass through it and tends them to be fused with the injected deuterons. thus available us a plateform where the fusion is a certainity.

Or within into the tokamak, the point 'F' (the center of fusion) is the only and only point where the fusion reaction occures.

6. center of fusion in the view of magnetic fields :-

By the view of magnetic fields the center of fusion is the point where the two uniform magnetic fields are perpendicular. But within into the region covered-up by the main tokamak at each and every point the ratio of two perpendicular magnetic fields [$\vec{B_x} / \vec{B_z}$] is constant. So, the each and every point within into the region covered-up by the main tokamak can act as a center of fusion.

Note : That is why. if we use the lithium blanket as an inner liner of the main tokamak then the triton produced due to lithium and neutron reaction will also undergo to a confined circular path and may interrupt the confined path(s) followed by the useful plasma and thus the produced triton may be an obstacle to the steady state VBM-fusion reactor.

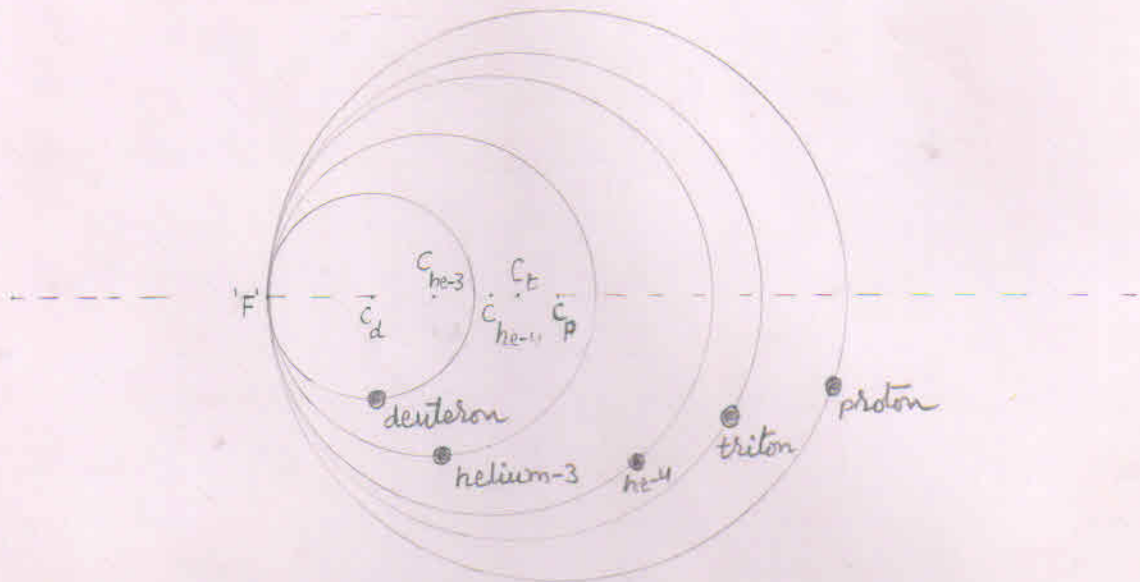
7. Center of plasma :-

center of plasma is the center of the circular orbit followed by the charged particles.

Thus the center of plasma [C_{pm}] differs particle by particle but all the charged particles have a common centre of fusion (the point 'F').

Center of plasma [C_{pm}]:

Center of plasma is the center of the circular orbit followed by the charged particle. So, it differs particle by particle.



$\Rightarrow$ C_d = center of the circular orbit followed by the deuteron.

$\Rightarrow$ C_{he-3} = center of the circular orbit followed by the helium-3 nucleus.

$\Rightarrow$ C_{he-4} = center of the circular orbit followed by the helium-4 nucleus.

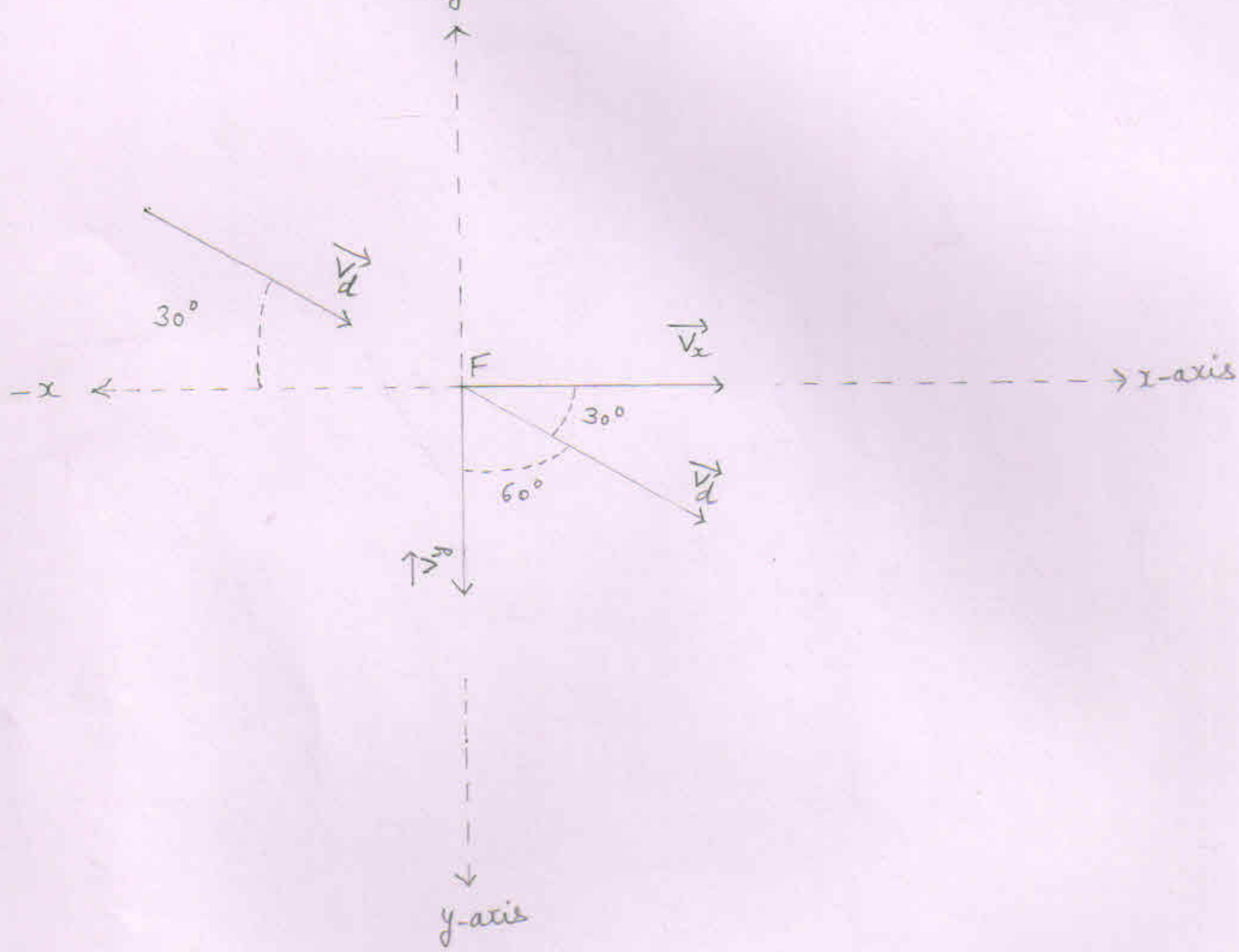
$\Rightarrow$ C_t = center of the circular orbit followed by the triton.

$\Rightarrow$ C_p = center of the circular orbit followed by the proton.

VBM plasma : RF linac injects the bunches of deuterons into the tokamak at point F. Such that each deuteron makes angle 30° with x-axis, 60° angle with y-axis and 90° angle with z-axis. RF linac injects each deuteron with 102.4 kev energy.

Confinement of 1st bunch of deuterons :

As the deuteron(s) of first bunch reaches at point F into the tokamak, it experiences a centripetal force due to magnetic fields and hence it follows a confined circular path passing through the point of injection (F) by time and again.



$\Rightarrow \vec{v}_d =$ velocity of the deuteron

1. Velocity of the injected deuteron

$$K.E = \frac{1}{2} m_d v^2 = 0.1024 \text{ MeV}$$

$$V = \left[\frac{2 \times 0.1024 \times 1.6 \times 10^{-13}}{3.3434 \times 10^{-27}}\right]^{\frac{1}{2}} \text{ m/s}$$

$$= \left[\frac{0.32768 \times 10^{14}}{3.3434}\right]^{\frac{1}{2}} \text{ m/s}$$

$$= [0.09800801579 \times 10^{14}]^{\frac{1}{2}} \text{ m/s}$$

$$= 0.3130 \times 10^{7} \text{ m/s}$$

2. Components of velocity of deuteron at point F

As the deuteron is injected at point F making angle 30° with X-axis, 60° angle with Y-axis and 90° angle with Z-axis, So,

$$\vec{V}_x = V\cos 30^\circ = V \times \frac{\sqrt{3}}{2} = 0.3130 \times \frac{1.732}{2}$$

$$= 0.271 \times 10^{7} \text{ m/s}$$

$$\vec{V}_y = V\cos 60^\circ = \frac{V}{2} = \frac{0.3130 \times 10^{7}}{2} = 0.1565 \times 10^{7} \text{ m/s}$$

$$\vec{V}_z = V\cos 90^\circ = V \times 0 = 0 \text{ m/s}$$

components of momentum of deuteron at point F.

$$\vec{P}_x = mv\cos 30^\circ = 3.3434 \times 10^{-27} \times 0.271 \times 10^{7} \text{ kg m/s}$$

$$= 0.906 \times 10^{-20} \text{ kg m/s}$$

$$\vec{P}_y = mv\cos 60^\circ = 3.3434 \times 10^{-27} \times 0.1565 \times 10^{7} \text{ kg m/s}$$

$$= 0.5232 \times 10^{-20} \text{ kg m/s}$$

$$\vec{P}_z = mv\cos 90^\circ = m \times 0 = 0 \text{ kg m/s}$$

Acting forces on the deuteron

1. $F_y = q V_x B_z \sin\theta$

$V_x = 0.271 \times 10^{7}$ m/s

$B_z = 1$ Tesla

$\sin\theta = \sin 90^\circ = 1$

$F_y = 1.6 \times 10^{-19} \times 0.271 \times 10^{7} \times 1 \times 1$ N

$= 0.4336 \times 10^{-12}$ N

From the right hand palm rule, the direction of force F_y is according to $-y$ axis.

So,

$\overrightarrow{F_y} = -0.4336 \times 10^{-12}$ N

2. $F_z = q V_x B_y \sin\theta$

$B_y = 1$ Tesla

$\sin\theta = \sin 90^\circ = 1$

$F_z = 1.6 \times 10^{-19} \times 0.271 \times 10^{7} \times 1 \times 1$ N

$= 0.4336 \times 10^{-12}$ N

From the right hand palm rule, the direction of force F_z is according to $-Z$ axis.

So,

$\overrightarrow{F_z} = -0.4336 \times 10^{-12}$ N

3. $F_x = q V_y B_z \sin\theta$

$V_y = 0.1565 \times 10^{7}$ m/s

$B_z = 1$ Tesla

$\sin\theta = \sin 90^\circ = 1$

$F_x = 1.6 \times 10^{-19} \times 0.1565 \times 10^{7} \times 1 \times 1$ N

$= 0.2504 \times 10^{-12}$ N

From the right hand palm rule, the direction of force F_x is according to (+) x-axis. So, Resultant force (F_R) :

$$F_R^2 = F_x^2 + F_y^2 + F_z^2$$

$F_x = 0.2504 \times 10^{-12}$ N

$F = F_y = F_z = 0.4336 \times 10^{-12}$ N

$$F_R^2 = F_x^2 + 2F_y^2$$

$$= (0.2504 \times 10^{-12})^2 + 2(0.4336 \times 10^{-12})^2 \ N^2$$

$$= (0.06270016 \times 10^{-24}) + 2(0.18800896 \times 10^{-24}) N^2$$

$$F_R^2 = 0.43871808 \times 10^{-24} \ N^2$$

$$F_R = 0.6623 \times 10^{-12} \ N$$

Radius of the circular path:

Resultant force acts as a Centripetal force on the deuteron. So, the deuteron follows a confined circular path.

The radius of the circular orbit obtained by the deuteron is –

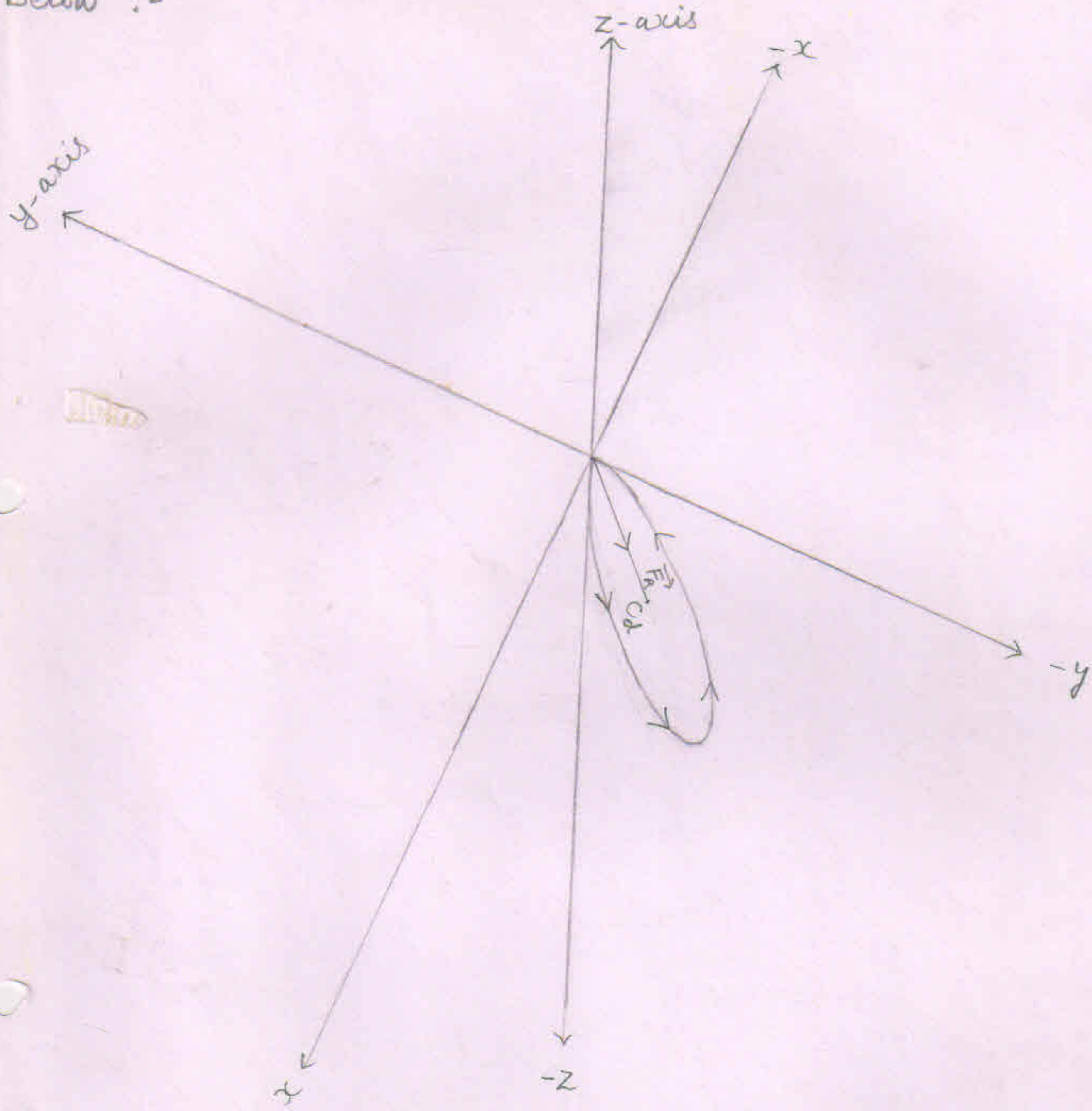
$$r = \frac{mv^2}{F_R}$$

$mv^2 = 0.32768 \times 10^{-13}$ J

$$= \frac{0.32768 \times 10^{-13} \ J}{0.6623 \times 10^{-12} \ N}$$

$$= 0.4947 \times 10^{-1} \ m$$

The confined deuteron follows the circular orbit as shown below :-



⇒ The circular orbit followed by the confined deuteron lies in the IV (down) quadrant or in the plane made up of positive x-axis, negative y-axis and the negative z-axis.

⇒ $\vec{F_R}$ = The resultant force acting on the deuteron when the deuteron is at point 'F'.

⇒ C_d = center of the circular orbit followed by the deuteron.

Angles that make the resultant force ($\vec{F_R}$) [acting on the deuteron when the deuteron is at point 'F'] with positive x, y and z-axes.

1. With x-axis

$$\cos\alpha = \frac{F_R \cos\alpha}{F_R} = \frac{\vec{F_x}}{F_R} = \frac{0.2504 \times 10^{-12}}{0.6623 \times 10^{-12}} \frac{N}{N}$$

$\Rightarrow \cos\alpha = 0.378\dot{0}$

$\Rightarrow \alpha \simeq 67.8$ degree [$\because \cos(67.8) = 0.3778$]

2. With y-axis

$$\cos\beta = \frac{F_R \cos\beta}{F_R} = \frac{\vec{F_y}}{F_R} = \frac{-0.4336 \times 10^{-12}}{0.6623 \times 10^{-12}} \frac{N}{N}$$

$\Rightarrow \cos\beta = -0.6546$

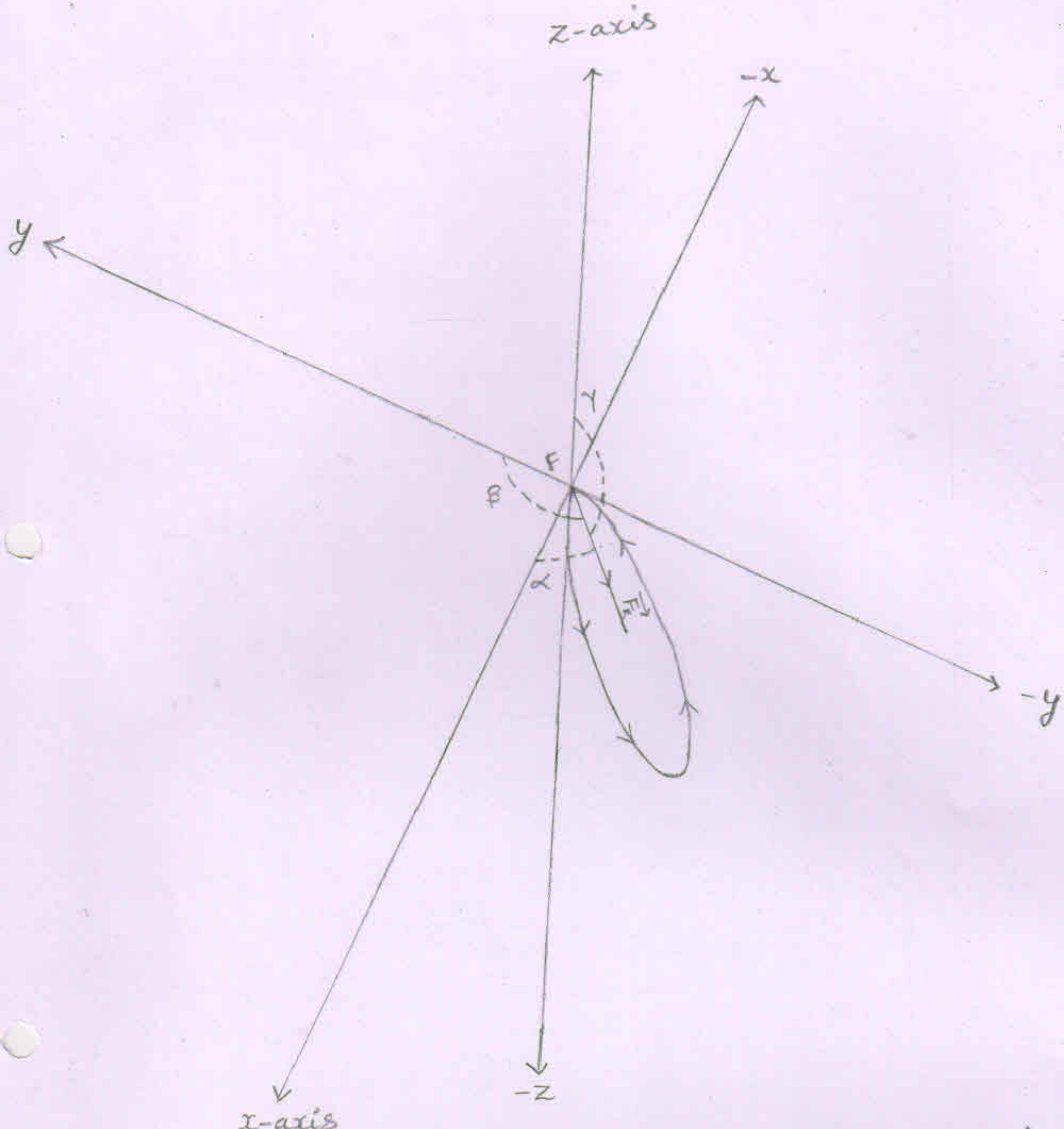
$\Rightarrow \beta \simeq 130.8$ degree [$\because \cos(130.8) = -0.6534$]

3. With z-axis

$$\cos\gamma = \frac{F_R \cos\gamma}{F_R} = \frac{\vec{F_z}}{F_R} = \frac{-0.4336 \times 10^{-12}}{0.6623 \times 10^{-12}} \frac{N}{N}$$

$\Rightarrow \cos\gamma = -0.6546$

$\Rightarrow \gamma \simeq 130.8$ degree



⇒ Angles that make the resultant force ($\vec{F}_R$) acting on the particle when the deuteron is at point 'F'.

where,

$\alpha \simeq 67.8$

$\beta \simeq 130.8$

$\gamma = 130.8$

⇒ All the angles are in degree.

The direction cosines of the line P_1P_2

⇒ The line P_1P_2 is the diameter of the circle followed (or to be followed) by the particle.

⇒ The points $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ make the line P_1P_2.

⇒ The particle starts its circular motion from the point F (– the center of fusion where the particle is either injected or produced).

So, we have denoted the cartesian coordinates for the point F as (0, 0, 0).

⇒ Here the point F(0, 0, 0) and the point $P_1(x_1, y_1, z_1)$ are the same.

⇒ So, the direction cosines of the line P_1P_2 are :–

1. $l = \cos\alpha = \dfrac{x_2 - x_1}{d}$

where,

$d = 2 \times$ radius of the circle

$\cos\alpha$ = cos component of the angle that make the resultant force ($\vec{F}_R$) at point F with the positive x axis.

2. $m = \cos\beta = \dfrac{y_2 - y_1}{d}$

where,
$\cos\beta$ = cos component of the angle that make the resultant force ($\vec{F_R}$) at point F with y-axis.

3. $n = \cos\gamma = \dfrac{z_2 - z_1}{d}$

where,
$\cos\gamma$ = Cos Component of the angle that make the resultant force ($\vec{F_R}$) at point F with positive z-axis.

The cartesian coordinates of the points $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ located on the circumfrence of the circle obtained by the deuteron :-

1. $\cos\alpha = \dfrac{x_2 - x_1}{d}$

$d = 2 \times r$
$= 2 \times 4.947 \times 10^{-2}$ m
$= 9.894 \times 10^{-2}$ m

$\cos\alpha = 0.37$

$\Rightarrow x_2 - x_1 = d \times \cos\alpha$

$\Rightarrow x_2 - x_1 = 9.894 \times 10^{-2} \times 0.37$
$\Rightarrow x_2 - x_1 = 3.6607 \times 10^{-2}$ m
$\Rightarrow x_2 = 3.6607 \times 10^{-2}$ m $\quad [\because x_1 = 0]$

2. $\cos\beta = \dfrac{y_2 - y_1}{d}$

$\Rightarrow y_2 - y_1 = d \times \cos\beta$

$\cos\beta = -0.65$

$\Rightarrow y_2 - y_1 = 9.894 \times 10^{-2} \times (-0.65)$ m
$\Rightarrow y_2 - y_1 = -6.4311 \times 10^{-2}$ m
$\Rightarrow y_2 = -6.4311 \times 10^{-2}$ m $\quad [y_1 = 0]$

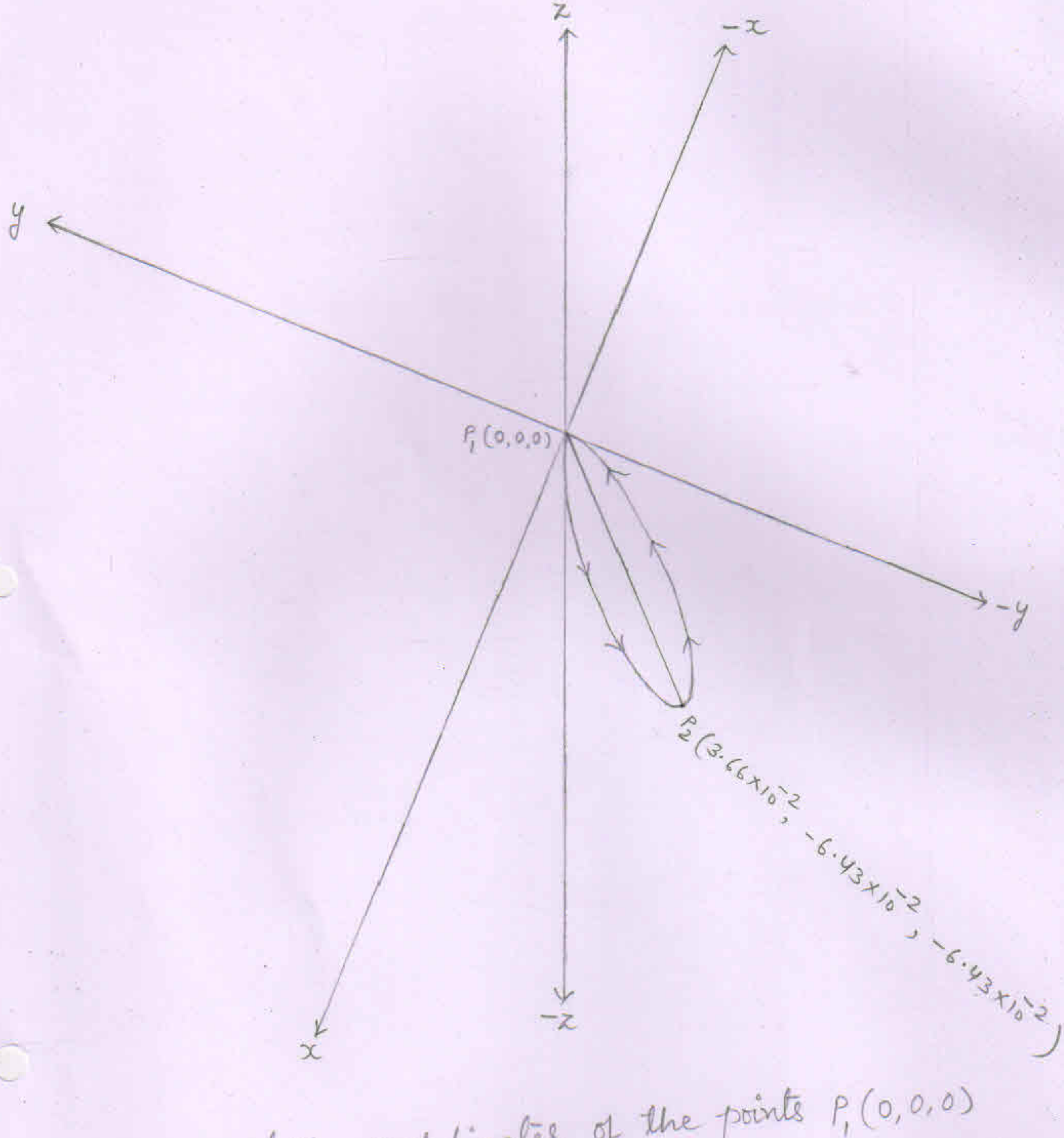
3. $\cos\gamma = \dfrac{z_2 - z_1}{d}$

$\Rightarrow z_2 - z_1 = d \times \cos\gamma$

$\cos\gamma = -0.65$

$\Rightarrow z_2 - z_1 = 9.894 \times 10^{-2} \times (-0.65)$ m
$\Rightarrow z_2 - z_1 = -6.4311 \times 10^{-2}$ m
$\Rightarrow z_2 = -6.4311 \times 10^{-2}$ m $\quad [z_1 = 0]$

The cartesian coordinates of the points $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$



⇒ The cartesian coordinates of the points $P_1(0,0,0)$ and $P_2(3.66\times10^{-2}, -6.43\times10^{-2}, -6.43\times10^{-2})$ where the points $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ are located on the circumfrence of the circle obtained by the deuteron.

⇒ The line $\overline{P_1P_2}$ is the diameter of the circle.

Time period of the confined particles

1. Resultant force

$$F_R^2 = F_x^2 + F_y^2 + F_z^2$$

where, $F_x = q V_y B_z$

$$F_y = q V_x B_z$$

$$F_z = q V_x B_y$$

For the VBM Fusion reactor

$$B_y = B_z = B = 1 \text{ Tesla}$$

so,

$$F_x = q V_y B \quad , \quad F_y = q V_x B$$

and $F_z = q V_x B$

hence $F_y = F_z = F = q V_x B$

putting the values

$$\Rightarrow \quad F_R^2 = F_x^2 + 2F^2$$

$$= q^2 V_y^2 B^2 + 2 q^2 V_x^2 B^2$$

$$F_R^2 = q^2 B^2 (V_y^2 + 2 V_x^2)$$

$$F_R = Bq (V_y^2 + 2 V_x^2)^{\frac{1}{2}}$$

2. Radius of the particle

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

$$= \frac{mv^2}{Bq\,(2v_x^2 + v_y^2)^{\frac{1}{2}}}$$

3. Time period of the particle

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

$$= \frac{2\pi}{v} \times \frac{mv^2}{Bq\,(2v_x^2 + v_y^2)^{\frac{1}{2}}}$$

$$= \frac{2\pi m}{Bq} \times \frac{v}{(2v_x^2 + v_y^2)^{\frac{1}{2}}}$$

where, $v = (v_x^2 + v_y^2 + v_z^2)^{\frac{1}{2}}$

but here, $v_z = 0$

so, $v = (v_x^2 + v_y^2)^{\frac{1}{2}}$

$$\Rightarrow T = \frac{2\pi m}{Bq} \times \left[\frac{v_x^2 + v_y^2}{2v_x^2 + v_y^2}\right]^{\frac{1}{2}}$$

here, $2v_x^2 + v_y^2 > v_x^2 + v_y^2$

So, the time period of the confined particle depends on the x-component of the final velocity of the particle while in the cyclotron it does not depend on the velocity of the particle.

Time period of the particle

1. For deuteron

$$T = \frac{2\pi m}{Bq} \times \frac{v}{(2v_x^2 + v_y^2)^{\frac{1}{2}}}$$

$$\Rightarrow 2v_x^2 + v_y^2 = 2\times(0.271\times10^7)^2 + (0.1565\times10^7)^2 \ m^2/s^2$$

$$= 2\times 0.073441\times10^{14} + 0.02449225\times10^{14} \ m^2/s^2$$

$$= 0.17137425 \ m^2/s^2$$

$$(2v_x^2 + v_y^2)^{\frac{1}{2}} = 0.4139\times10^7 \ m/s$$

put the Value

$v = 0.3130\times10^7$, $B = 1$ Tesla

$q = 1.6\times10^{-19}$ C, $m = 3.3434\times10^{-27}$ kg

$$T = \frac{2\times3.14\times3.3434\times10^{-27}\times0.3130\times10^7}{1\times1.6\times10^{-19}\times0.4139\times10^7} \ s$$

$$= \frac{6.571920776\times10^{-20}}{0.66224\times10^{-12}} \ s$$

$$= 9.92\times10^{-8} \text{ second}$$

or

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

$r = 4.947\times10^{-2}$ m

$v = 0.3130\times10^7$ m/s

$$T = \frac{2\times3.14\times4.947\times10^{-2}}{0.3130\times10^7} \ s$$

$$= \frac{31.06716\times10^{-2}}{0.3130\times10^7} \ s = 9.92\times10^{-8} \text{ second}$$

Time of Confinement of deuteron(s) :-

The time of Confinement of plasma is the time for which the plasma can exist before it radiates away its energy through cyclotron radiations.

⇒ Power loss by cyclotron radiations :

By the Larmor formula, power loss is given as -

$$P = \frac{2e^2a^2}{3c^3}$$

expression for accleration using Lorentz force :

$$ma = \frac{evB}{c}$$

by substitution

$$P = \frac{2e^4v^2B^2}{3c^5m^2}$$

$$\frac{dE}{dt} = \frac{-2e^2v^2B^2}{3c^5m^2} = \frac{-4e^4EB^2}{3c^5m^3} \quad \left[\because \frac{1}{2}mv^2 = E\right]$$

$$\frac{dE}{E} = \frac{-4e^4B^2}{3c^5m^3}\,dt$$

$$E = E_0 e^{-\frac{4e^4B^2}{3c^5m^3}t} = E_0 e^{-\frac{t}{t_0}}$$

$$t_0 = \frac{3c^5m^3}{4e^4B^2} =$$

Time of Confinement of deutron

$$t_e = \frac{3c^5 m^3}{4e^4 B^2}$$

$c = 3\times10^{10}$ cm/s
$m = 3.3434\times10^{-24}$ gram
$e = 4.8\times10^{-10}$ esu
$B \simeq 1$ Tesla $= 10^4$ Gauss

$$t_e = \frac{3\times(3\times10^{10})^5 \times (3.3434\times10^{-24})^3}{4\times(4.8\times10^{-10})^4 \times (10^4)^2}$$

$$= \frac{3\times243\times10^{50}\times37.3736\times10^{-72}}{4\times530.84\times10^{-40}\times10^8} \text{ seconds}$$

$$= \frac{27245.3544\times10^{-22}}{2123.36\times10^{-32}}$$

$$= 12.83\times10^{10} \text{ seconds}$$
$$= 1.283\times10^{11} \text{ seconds}$$

Conclusion : Time of Confinement (t_e) of the deuteron is $\simeq 1.283\times10^{11}$ seconds. Thus we do not expect to see emission from deutrons (plasma). As each and every deuteron injected into the tokamak at the centre of fusion (point F) is with enough energy required for fusion, so, in the VBM fusion reactor there is no need of solenoid (primary transformer) to heat the plasma (secondary transformer) while in the thermonuclear fusion reactors there is a solenoid to heat the plasma.

-: The fusion reactions :-

In the VBM fusion reactor based on D-D cycle, the following fusion reactions occures.

1. $^{2}_{1}H + ^{2}_{1}H \longrightarrow ^{3}_{2}He + ^{1}_{0}n$

[injected] [confined]

2. $^{2}_{1}H + ^{3}_{2}He \longrightarrow ^{4}_{2}He + ^{1}_{1}H$

[injected] [Confined]

3. $^{2}_{1}H + ^{2}_{1}H \longrightarrow ^{3}_{1}H + ^{1}_{1}H$

[injected] [Confined]

4. $^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n$

[injected] [confined]

5. $^{2}_{1}H + ^{2}_{1}H \longrightarrow ^{4}_{2}He + \gamma$ rays

[injected] [Confined]

6.

6(i). $^{3}_{1}H + ^{3}_{2}He \longrightarrow ^{5}_{3}Li + ^{1}_{0}n$

[confined] [confined]

$^{5}_{3}Li \longrightarrow ^{4}_{2}He + ^{1}_{1}H$

6(ii) $^{3}_{1}H + ^{3}_{2}He \longrightarrow ^{4}_{2}He + ^{2}_{1}H$

[Confined] [Confined]

6(iii) $^{3}_{1}H + ^{3}_{2}He \longrightarrow ^{5}_{2}He + ^{1}_{1}H$

[Confined] [Confined]

$^{5}_{2}He \longrightarrow ^{4}_{2}He + ^{1}_{0}n$

7. $^{2}_{1}H + ^{3}_{2}He + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{4}_{2}He$

[injected] [confined] [confined]

8. $^{2}_{1}H + ^{3}_{2}He + ^{2}_{1}H \longrightarrow ^{7}_{4}Be + \gamma$ rays

[injected] [Confined] [confined]

9. $^{2}_{1}H + ^{3}_{1}H + ^{2}_{1}H \longrightarrow ^{7}_{3}Li + \gamma$ rays

[injected] [Confined] [Confined]

10. $^{2}_{1}H + ^{3}_{2}He + ^{3}_{1}H + ^{2}_{1}H \longrightarrow ^{10}_{5}B + \gamma$ rays

[injected] [Confined] [Confined] [Confined]

⇒ How fusion occures

1. Formation of Compound nucleus :-
As the deuteron of n^{th} bunch reaches at point F, it fuses with the deuteron of I^{st} bunch (Confined deuteron passing through the point F) to form a Compound nucleus.

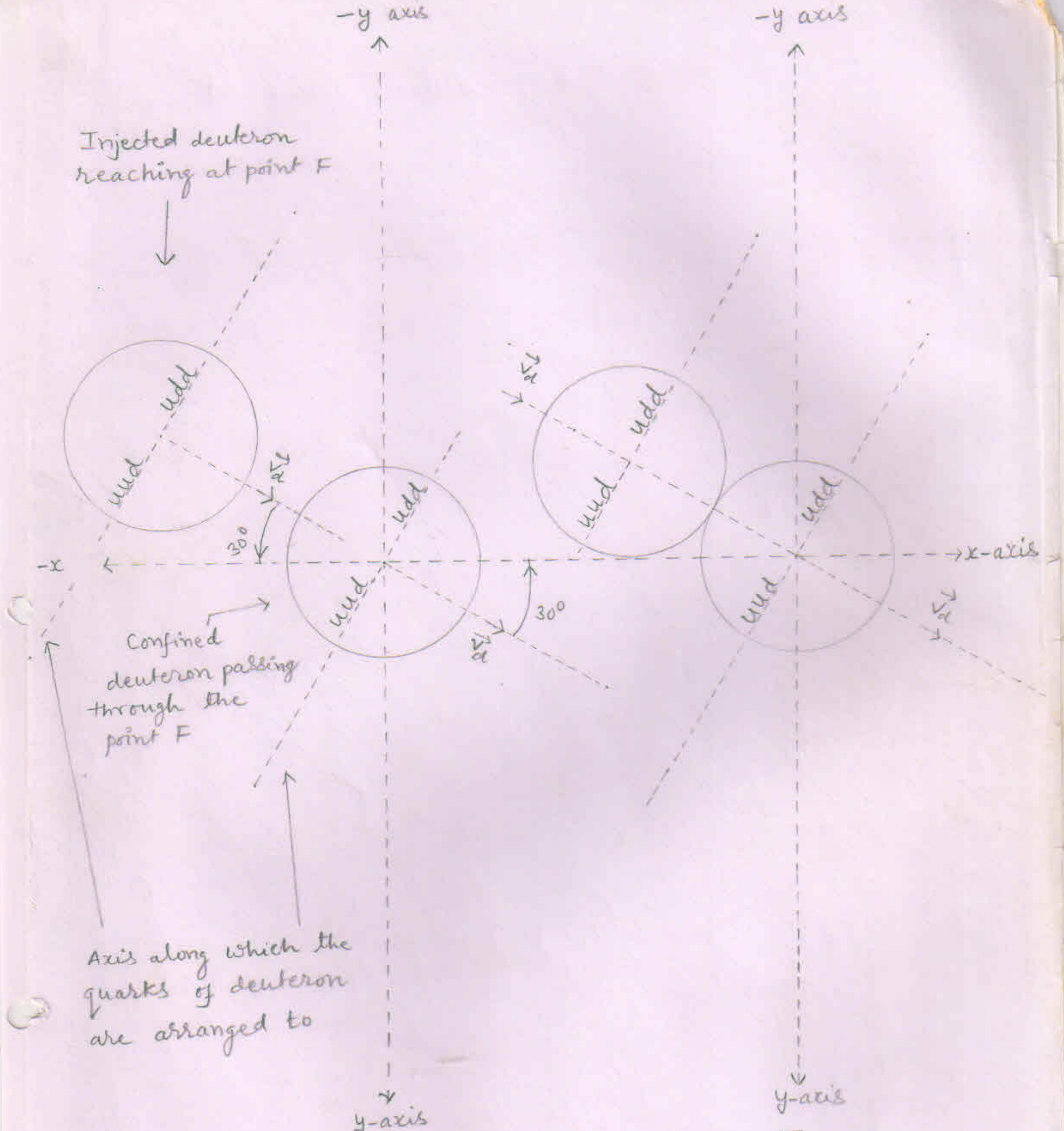
2. Splitting of Compound nucleus :
The Compound nucleus splits into three particles. out of three particles, two are finite nuclei and third one is a reduced mass. Due to spliting of compound nucleus, all the three particles separates from each other with a velocity ($\vec{V}_{CN}$) equal to the velocity of Compound nucleus.

3. Propellation of particles :
Reduced mass converts into energy and acts as a propellant for both the produced final nuclei.

For fusion reaction ${}_{1}^{2}H + {}_{1}^{2}H \rightarrow {}_{2}^{3}He + {}_{0}^{1}n$

1. Interaction of nuclei :-

The injected deuteron reaches at point F and interacts [experiences a repulsive force due to confined deuteron] with the confined deuteron passing through the point F. The injected deuteron overcomes the electrostatic repulsive force and – a like two solid spheres join – the injected deuteron dissimilarly joins with the confined deuteron .

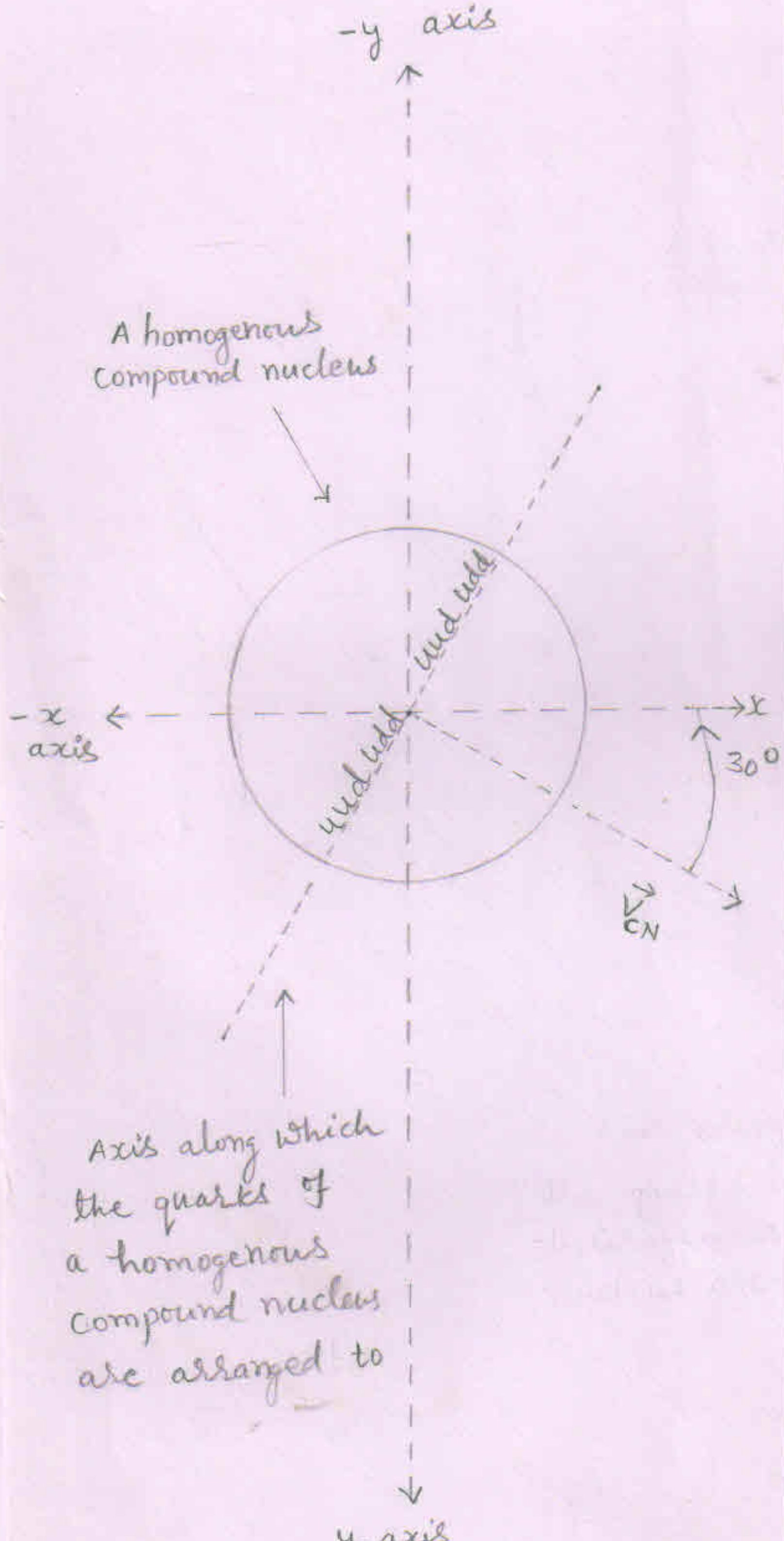


$\boxed{1}$
Injection of deuteron

$\boxed{2}$
Interaction of nuclei

2. Formation of a homogenous compound nucleus :—
The constituents (quarks and gluons) of the dissimilarly joined nuclei (deuterons) behave like a liquid and form a homogenous compound nucleus having similarly distributed groups of quarks with similarly distributed surrounding gluons.

Thus within a homogenous compound nucleus - each group of quarks is surrounded by gluons in equal proportion. So, within a homogenous compound nucleus there are 4 groups of quarks surrounded by gluons.



3

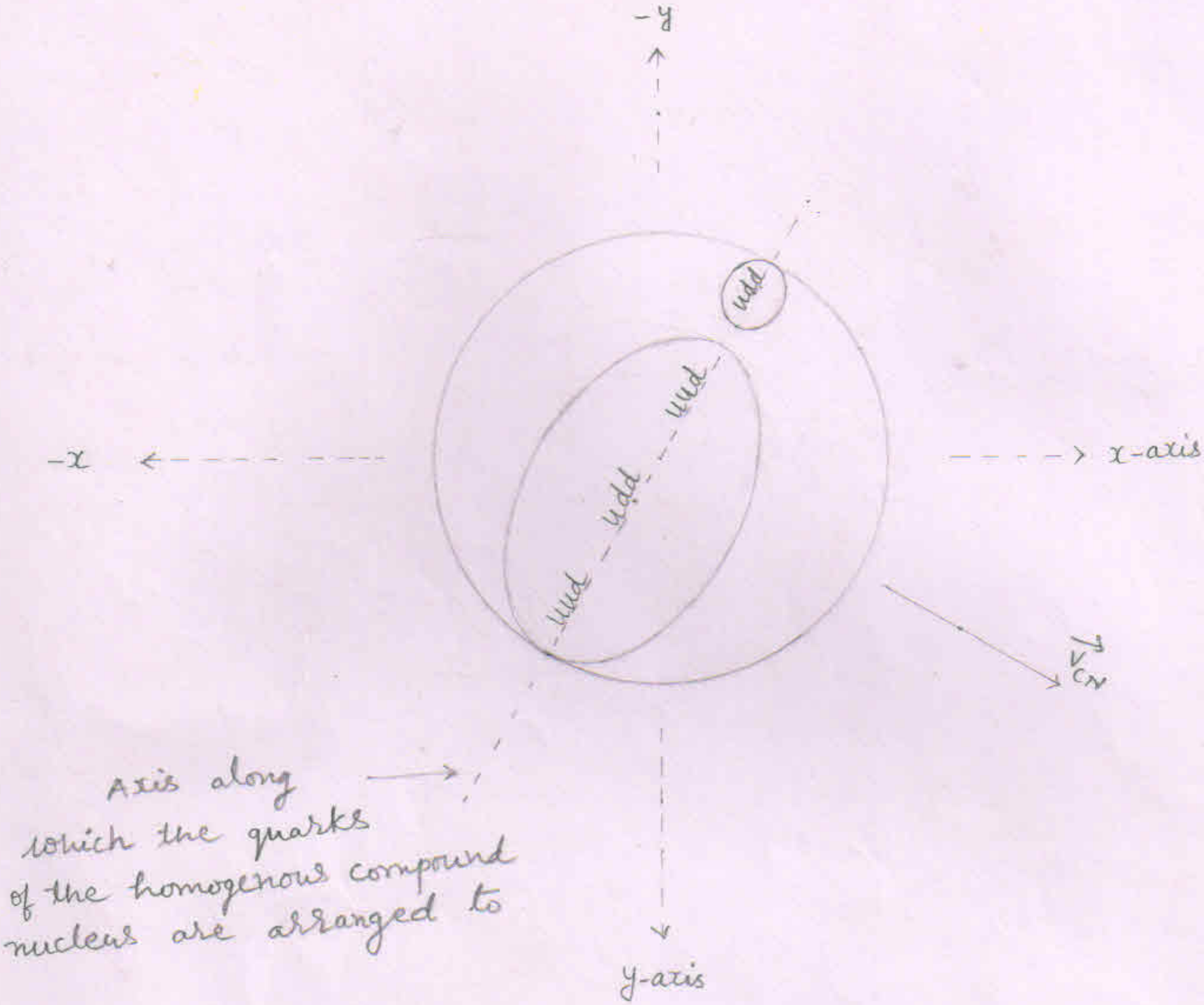
Formation of homogenous Compound nucleus

3. Formation of lobes within into the homogenous compound nucleus or the transformation of the homogenous compound nucleus into the heterogenous compound nucleus :-

The central group of quarks with its surrounding gluons to become a stable and the next higher nucleus (the helion-3) than the reactant one (the deuteron) includes the other two (nearby located) groups of quarks with their surrounding gluons and rearrange to form the 'A' lobe of the heterogenous compound nucleus.

While the remaining groups of quarks to become a stabe nucleus (neutron) includes its surrounding gluons or mass [out of the available mass (or gluons) that is not included in the formation of the lobe 'A'] and rearrange to form the 'B' lobe of the heterogenous compound nucleus.

Thus due to formation of two dissimilar lobes within into the homogenous compound nucleus, the homogenous compound nucleus transforms into the heterogenous compound nucleus.



$\boxed{3}$

Formation of lobes

⇒ Within into the homogenous compound nucleus, the greater nucleus is the helium-3 nucleus and the smaller one is the neutron while the remaining space represents the remaining gluons.

⇒ Within into the homogenous compound nucleus the greater nucleus is the lobe 'A' while the smaller one is the lobe 'B'.

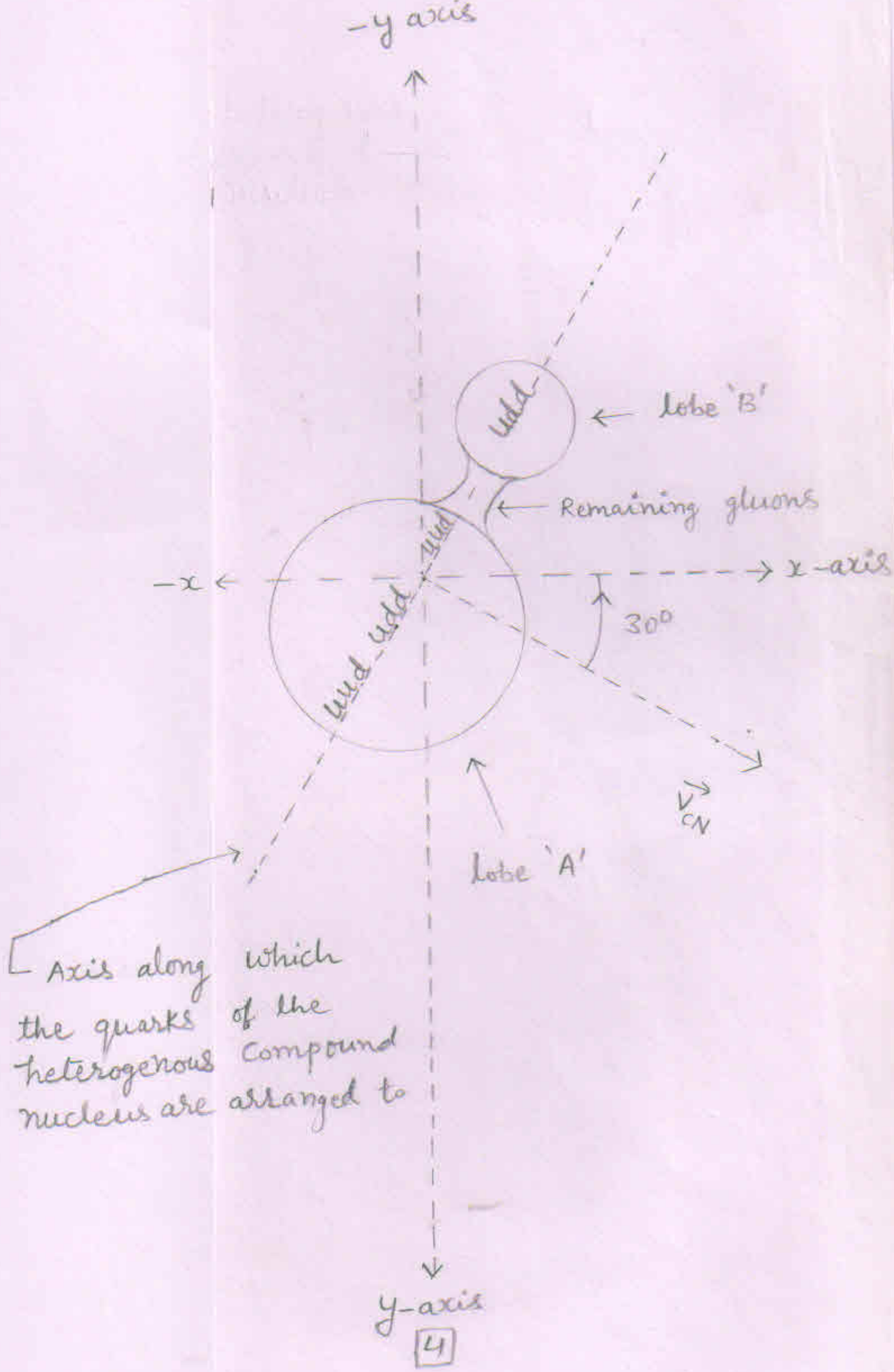
4. Final stage of the heterogenous compound nucleus:-

The process of formation of lobes creates voids between the lobes. So, the remaining gluons [or the mass that is not involved in the formation of any lobe] rearrange to fill the void(s) between the lobes and thus the remaining gluons form a node between the two dissimilar lobes of the heterogenous compound nucleus.

Thus the reduced mass (or the remaining gluons) keeps both the dissimilar lobes - of the heterogenous compound nucles - joined them together.

So, finally, the heterogenous compound nucleus becomes like an abnormal digit eight.

Heterogenous compound nucleus



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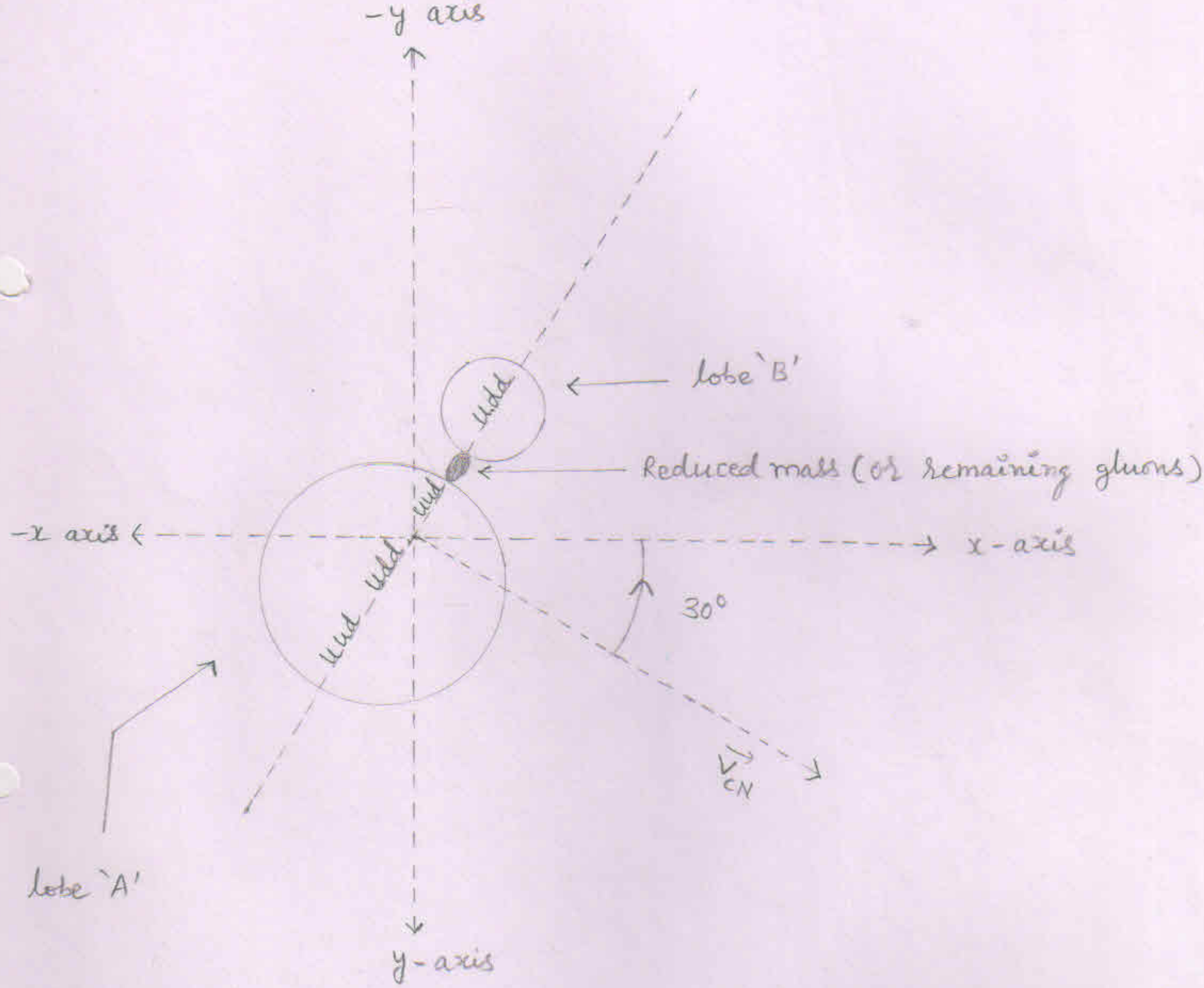

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Final stage of a
heterogenous compound nucleus.

Formation of compound nucleus:

1. As the deuteron of n^{th} bunch reaches at point F, it fuses with the confined deuteron of 1^{st} bunch to form a compound nucleus.

2. Just before fusion, to overcome the electrostatic repulsive force exerted by the deuteron of 1^{st} bunch, the deuteron of n^{th} bunch loses (radiates its energy in the form of electromagnetic waves) its energy equal to 5.0622 kev.

So, just before fusion, the kinetic energy of n^{th} deuteron is –

$$E_b = 102.4 \text{ kev} - 5.0622 \text{ kev}$$
$$= 97.3378 \text{ kev}$$
$$= 0.0973378 \text{ Mev}$$

3. Velocity of n^{th} deuteron just before fusion

$$E_b = \frac{1}{2} m_d v^2 = 0.0973378 \text{ Mev}$$

$$v = \left[\frac{2 \times 0.0973378 \times 1.6 \times 10^{-13} \text{ J}}{3.3434 \times 10^{-27} \text{ kg}}\right]^{\frac{1}{2}} \text{ m/s}$$

$$= \left[\frac{0.31148096 \times 10^{14}}{3.3434}\right]^{\frac{1}{2}} \text{ m/s}$$

$$= \left[0.0931629359 3 \times 10^{14}\right]^{\frac{1}{2}} \text{ m/s}$$

$$= 0.3052 \times 10^{7} \text{ m/s}$$

Components of velocity of n^{th} deuteron just before fusion at point F.

1. $\vec{V}_x = V \cos 30^\circ$

$= 0.3052 \times 10^7 \times \frac{1.732}{2}$ m/s

$= 0.2643 \times 10^7$ m/s

2. $\vec{V}_y = V \cos 60^\circ$

$= 0.3052 \times 10^7 \times \frac{1}{2}$ m/s

$= 0.1526 \times 10^7$ m/s

3. $\vec{V}_z = V \cos 90^\circ = V \times 0 = 0$ m/s

Components of momentum of n^{th} deuteron just before fusion at point F

1. $\vec{P}_x = m\vec{V}_x$

$= 3.3434 \times 10^{-27} \times 0.2643 \times 10^7$ Kg m/s

$= 0.8836 \times 10^{-20}$ Kg m/s

2. $\vec{P}_y = mV_y$

$= 3.3434 \times 10^{-27} \times 0.1526 \times 10^7$ Kg m/s

$= 0.5102 \times 10^{-20}$ Kg m/s

3. $\vec{P}_z = m\vec{V}_z$

$= m \times 0$ Kg m/s

$= 0$ Kg m/s

1. X-Component of momentum of compound nucleus =

$$\begin{bmatrix} \text{X-component of} \\ \text{momentum of confined} \\ \text{deuteron at point F} \end{bmatrix} + \begin{bmatrix} \text{X-Component of} \\ \text{momentum of injected} \\ \text{deuteron (just before} \\ \text{fusion) at point F} \end{bmatrix}$$

$$\vec{P}_x = 0.906 \times 10^{-20} \text{ kg m/s} + 0.8836 \times 10^{-20} \text{ kg m/s}$$

$$= 1.7896 \times 10^{-20} \text{ kg m/s}$$

2. y-component of momentum of compound nucleus =

$$\begin{bmatrix} \text{y-component of} \\ \text{momentum of} \\ \text{Confined deuteron} \\ \text{at point F} \end{bmatrix} + \begin{bmatrix} \text{y-component of} \\ \text{momentum of injected} \\ \text{deuteron (just before} \\ \text{fusion) at point F} \end{bmatrix}$$

$$\vec{P}_y = 0.5232 \times 10^{-20} \text{ kg m/s} + 0.5102 \times 10^{-20} \text{ kg m/s}$$

$$= 1.0334 \times 10^{-20} \text{ kg m/s}$$

3. Z-Component of momentum of Compound nucleus =

$$\begin{bmatrix} \text{z-component of} \\ \text{momentum of confined} \\ \text{deuteron at point F} \end{bmatrix} + \begin{bmatrix} \text{z-Component of} \\ \text{momentum of Injected} \\ \text{deuteron (just before} \\ \text{fusion) at point F} \end{bmatrix}$$

$$\vec{P}_z = 0 \text{ kgm/s} + 0 \text{ kgm/s}$$

4. Mass of the Compound nucleus (M)

$M = 2 \times$ mass of deuteron

$= 2 \times 2.0135$ amu

$= 4.027$ amu

$= 6.6868 \times 10^{-27}$ kg

The components of velocity of compound nucleus :

1. $\vec{V}_x = V_{CN} \cos\alpha = \dfrac{\vec{P}_x}{M} = \dfrac{1.7896 \times 10^{-20}}{6.6868 \times 10^{-27}} \dfrac{kg\,m/s}{kg}$

$\vec{V}_x = 0.2676 \times 10^{7}$ m/s

2. $\vec{V}_y = V_{CN} \cos\beta = \dfrac{\vec{P}_y}{M} = \dfrac{1.0334 \times 10^{-20}}{6.6868 \times 10^{-27}} \dfrac{kg\,m/s}{kg}$

$\vec{V}_y = 0.1545 \times 10^{7}$ m/s

3. $\vec{V}_z = V_{CN} \cos\gamma = \dfrac{\vec{P}_z}{M} = \dfrac{0}{M} = 0$ m/s

4. Velocity of compound nucleus ($\vec{V}_{CN}$) :-

$V_{CN}^2 = V_x^2 + V_y^2 + V_z^2$

$= (0.2676 \times 10^7)^2 + (0.1545 \times 10^7)^2 + (0)^2 \; m^2/s^2$

$= (0.07160976 \times 10^{14}) + (0.02387025 \times 10^{14}) + 0 \; m^2/s^2$.

$V_{CN}^2 = 0.09548001 \times 10^{14} \; m^2/s^2$

$V_{CN} = 0.3089 \times 10^{7}$ m/s

Angles that make the velocity of compound nucleus ($\vec{V}_{CN}$) with axes :-

1 With x - axis

$$\cos\alpha = \frac{V_{CN}\cos\alpha}{V_{CN}} = \frac{\vec{V_x}}{V_{CN}} = \frac{0.2676 \times 10^7}{0.3089 \times 10^7} \frac{m/s}{m/s}$$

$\Rightarrow \cos\alpha = 0.8662$

$\Rightarrow \alpha \simeq 30^\circ$

2. With y-axis

$$\cos\beta = \frac{V_{CN}\cos\beta}{V_{CN}} = \frac{\vec{V_y}}{V_{CN}} = \frac{0.1545 \times 10^7}{0.3089 \times 10^7} \frac{m/s}{m/s}$$

$\Rightarrow \cos\beta = 0.5001$

$\Rightarrow \beta \simeq 60^\circ$

3. With z-axis

$$\cos\gamma = \frac{V_{CN}\cos\gamma}{V_{CN}} = \frac{\vec{V_z}}{V_{CN}} = \frac{0}{0.3089 \times 10^7} \frac{m/s}{m/s}$$

$\Rightarrow \cos\gamma = 0$

$\Rightarrow \gamma = 90^\circ$

Splitting of the heterogenous compound nucleus :-

⇒ The heterogenous compound nucleus, due to its instability, splits according to the lines parallel to the direction of the velocity of the compound nucleus ($\vec{V}_{CN}$) into three particles - helion-3, neutron and the reduced mass (Δm).

out of them, the two particles (the helion-3 and the neutron) are stable while the third one (reduced mass) is unstable.

⇒ According to the law of inertia, each particle that has separated from the compound nucleus, has an inhereted velocity ($\vec{V}_{inh}$) equal to the velocity of the compound nucleus ($\vec{V}_{CN}$).

⇒ So, for conservation of momentum

$$M\vec{V}_{CN} = (m_{He-3} + \Delta m + m_n)\,\vec{V}_{CN}$$

Where,

M = mass of the compound nucleus

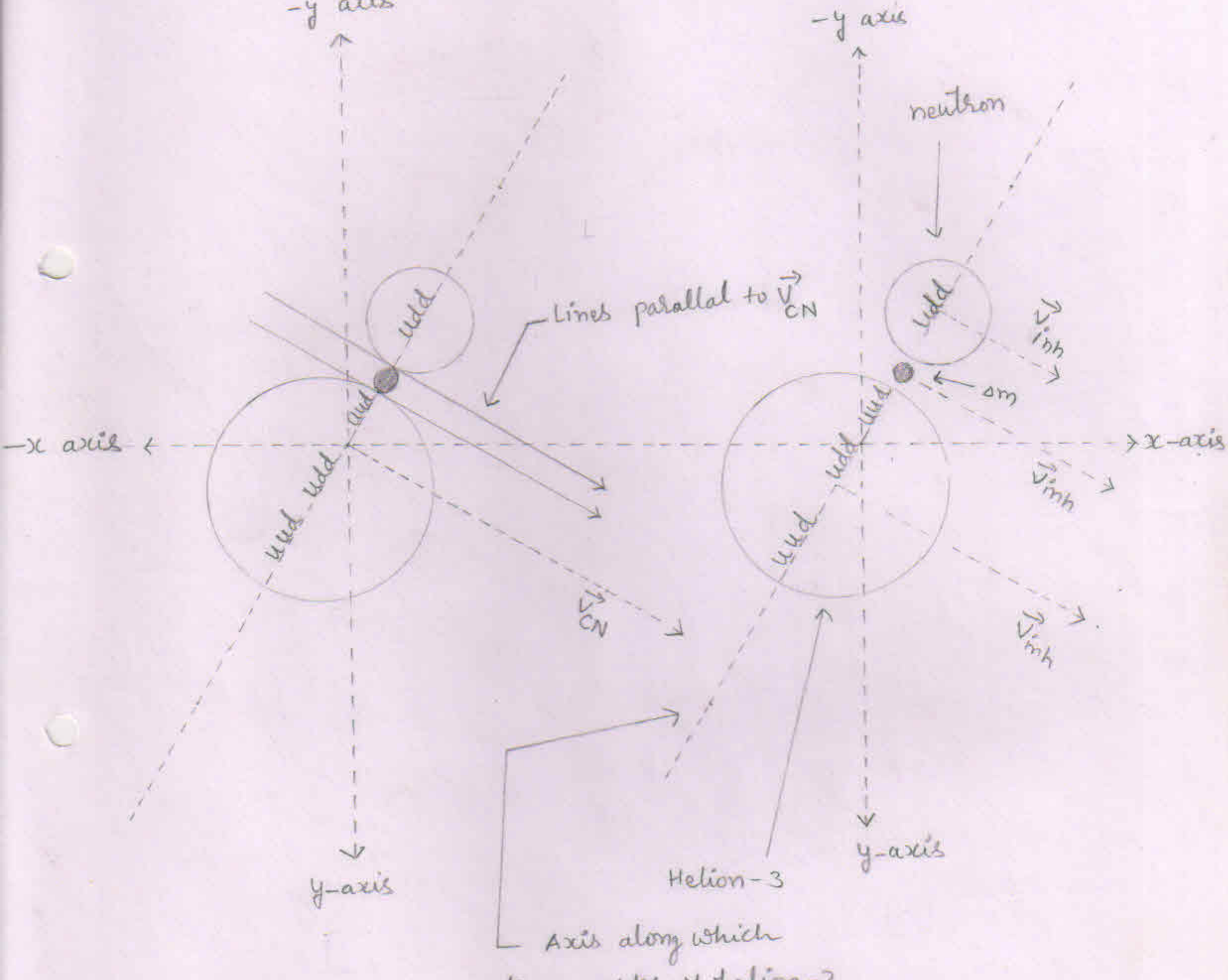
$\vec{V}_{CN}$ = velocity of the compound nucleus

m_{He-3} = mass of the helium-3 nucleus

Δm = reduced mass

m_n = mass of the neutron

The Splitting of the heterogenous compound nucleus



[6]

A heterogenous compound nucleus (showing lines parallal to $\vec{V}_{CN}$)

$\Rightarrow$

[7]

The Splitting of the heterogenous compound nucleus.

Inhereted velocity (v_{inh}) of the particles

⇒ Each particle that has separated from the compound nucleus has an inhereted velocity ($\vec{V}_{inh}$) equal to the velocity of the compound nucleus ($\vec{V}_{CN}$).

I. For helium-3 nucleus

1. $\vec{V}_{inh} = \vec{V}_{CN} = 0.3089 \times 10^7$ m/s

Components of the inhereted velocity of the helion-3

1. $\vec{V}_x = V_{inh} \cos\alpha = V_{CN} \cos\alpha = 0.2676 \times 10^7$ m/s
2. $\vec{V}_y = V_{inh} \cos\beta = V_{CN} \cos\beta = 0.1545 \times 10^7$ m/s
3. $\vec{V}_z = V_{inh} \cos\gamma = V_{CN} \cos\gamma = 0$ m/s

II. Inhereted velocity of the neutron

1. $\vec{V}_{inh} = \vec{V}_{CN} = 0.3089 \times 10^7$ m/s

Components of the inhereted velocity of the neutron

1. $\vec{V}_x = V_{inh} \cos\alpha = V_{CN} \cos\alpha = 0.2676 \times 10^7$ m/s
2. $\vec{V}_y = V_{inh} \cos\beta = V_{CN} \cos\beta = 0.1545 \times 10^7$ m/s
3. $\vec{V}_z = V_{inh} \cos\gamma = V_{CN} \cos\gamma = 0$ m/s

III. Inhereted velocity of the reduced mass

$\vec{V} \quad \vec{V} = 0.3089 \times 10^7$ m/s

Propellation of the particles

Reduced mass converts into energy and thus acts as a propellant for both the particles. (A like, if we put a bowl on the cracker and put the cracker on fire, the bowl and the earth will have equal and opposite momentum.

Similarly, both the particles ${}_2He^3$ and ${}_0n^1$ will have equal and opposite momentum. For this the total energy (E_T) is divided between the particles according to their inverse masses.

1. Reduced mass :

$$\Delta m = [m_d + m_d] - [m_{He-3} + m_n]$$

$$= [2 \times 2.01355] - [3.014932 + 1.00866] \text{ amu}$$

$$= [4.0271 - 4.023592] \text{ amu}$$

$$= 0.003508 \text{ amu}$$

$$= 0.003508 \times 1.6605 \times 10^{-27} \text{ kg}$$

2. Inhereted kinetic energy of reduced mass :

$$E_{inh} = \frac{1}{2} \Delta m V_{CN}^2$$

$$= \frac{1}{2} \times 0.003508 \times 1.6605 \times 10^{-27} \times 0.09548001 \times 10^{14} \text{ J}$$

$$= 0.00027808715 \times 10^{-13} \text{ J}$$

$$= 0.000173 \text{ Mev}$$

3. Released energy (E_R) :

$$E_R = \Delta m c^2 = 0.003508 \times 931 \text{ Mev}$$
$$= 3.265948 \text{ Mev}$$

4. Total energy (E_T)

$$E_T = E_{kin} + E_R$$

$$= 0.000173 \text{ Mev} + 3.265948 \text{ Mev}$$

$$= 3.266121 \text{ Mev}$$

Increament in the energy of the particles :-

The total energy (E_T) is divided between the particles according to their inverse masses. So, the increased energy (E_{inc}) of the particles-

1. For ${}_2He^3$

$$E_{inc} = \frac{m_n}{m_n + m_{He-3}} \times E_T = \frac{1.00866}{1.00866 + 3.014932} \times 3.266121$$

$$= \frac{1.00866}{4.023592} \times 3.266121 \text{ Mev}$$

$$= 0.2506864513 1 \times 3.266121 \text{ Mev}$$

$$= 0.818772 \text{ Mev}$$

2. For ${}_0n^1$

$$E_{inc} = [E_T] - [\text{Increased energy of Helion-3}]$$

$$= [3.266121 - 0.818772] \text{ Mev}$$

$$= 2.447349 \text{ Mev}$$

Increased velocity of the particles

1. For Helion-3

$$E_{inc} = \frac{1}{2} m_{He-3} V_{inc}^2$$

$$V_{inc} = \sqrt{\frac{2 E_{inc}}{m_{He-3}}}$$

$$= \left[\frac{2 \times 0.818772 \times 1.6 \times 10^{-13}}{5.00629 \times 10^{-27}} \right]^{\frac{1}{2}} \ m/s$$

$$= \left[\frac{2.6200704 \times 10^{-13}}{5.00629 \times 10^{-27}} \right]^{\frac{1}{2}}$$

$$= [0.52335569853 \times 10^{14}]^{\frac{1}{2}}$$

$$= 0.7234 \times 10^{7} \ m/s$$

2. For neutron

$$V_{inc} = \left[\frac{2 E_{inc}}{m_n} \right]^{\frac{1}{2}} = \left[\frac{2 \times 2.447349 \times 1.6 \times 10^{-13}}{1.6749 \times 10^{-27}} \right]^{\frac{1}{2}}$$

$$= \left[\frac{7.8315168 \times 10^{-13}}{1.6749 \times 10^{-27}} \right]^{\frac{1}{2}} \ m/s$$

$$= [4.67581157084 \times 10^{14}]^{\frac{1}{2}} \ m/s$$

$$2.1623 \times 10^{7} \ m/s$$

Angle of propellation

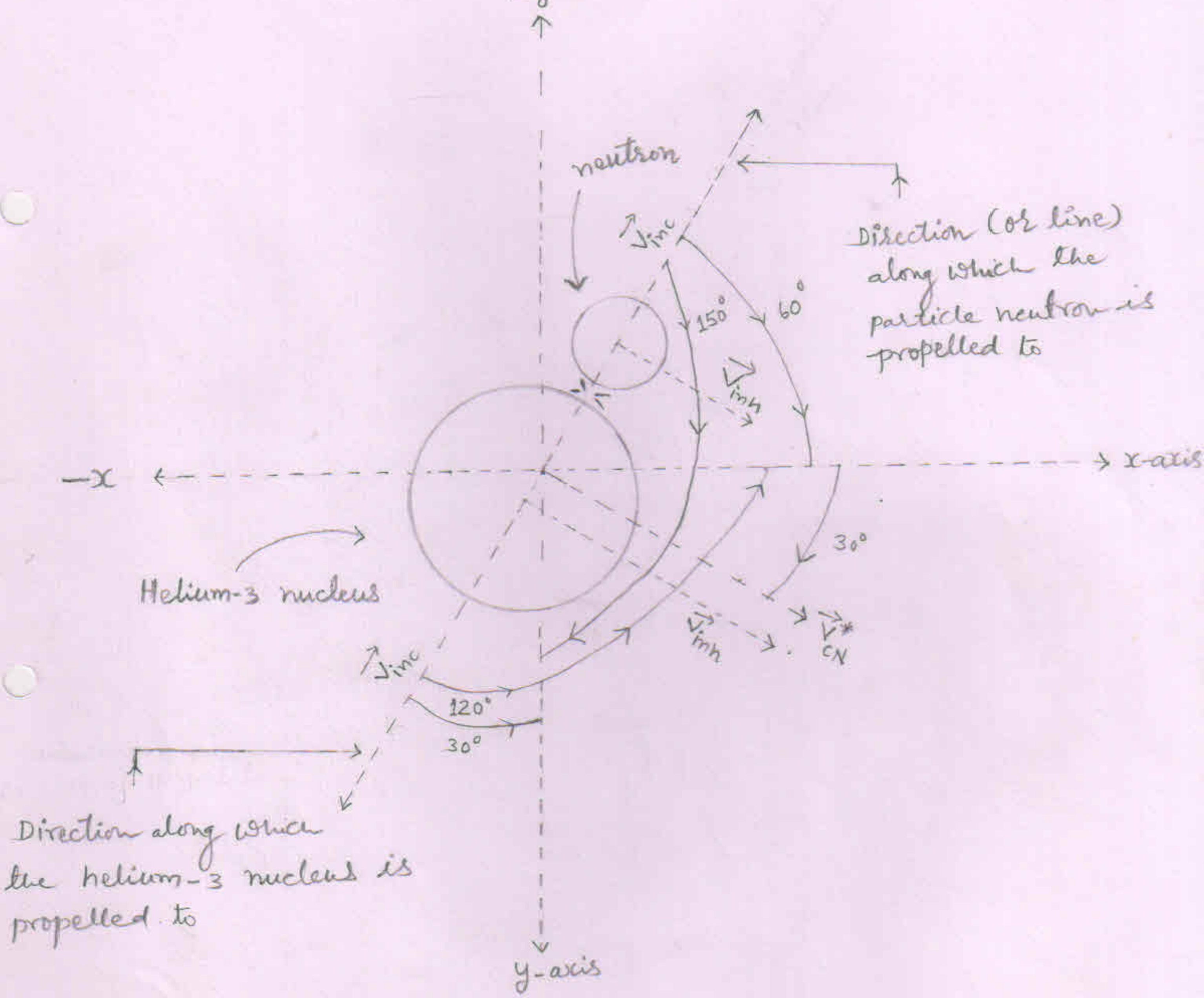
1. As the reduced mass converts into energy, the total energy (E_T) propell both the particles with equal and opposite momentum according to a ray (line) perpendicular to the direction (line) of the velocity of of the compound nucleus ($\vec{V}_{CN}$).

2. We know that when there a fusion process occures, then we find the lighter nucleus in the forward direction [or in the direction of ion beam or in the direction of the velocity of the compound nucleus ($\vec{V}_{CN}$).]

3. At point F, as $\vec{V}_{CN}$ makes 30° angle with x-axis, 60° angle with y-axis and 90° angle with z-axis.

4. So, the neutron is propelled making 60° angle with x-axis, 150° angle with y-axis and 90° angle with z-axis.

5. While the helion-3 is propelled making 120° angle with x-axis, 30°. angle with y-axis and 90° angle with z-axis.



$\Rightarrow$ $\vec{V}^*_{CN}$ = The direction of velocity of heterogenous compound nucleus when it was in existence (Before splitting of compound nucleus).

$\Rightarrow$ $\vec{V}^*_{CN} \perp \vec{V}_{inc}$

$\Rightarrow$ The direction along which the neutron is propelled is perpendicular to the $\vec{V}^*_{CN}$. Similarly, the direction along which the helium-3 nucleus is propelled is perpendicular to the $\vec{V}_{CN}$. While the directions ... 180° with each other.

Components of increased velocity of the particles

I For neutron

1. $\vec{v}_x = v_{inc} \cos\alpha$

$$v_{inc} = 2.1623 \times 10^7 \text{ m/s}$$

$$\cos\alpha = \cos 60^\circ = \frac{1}{2}$$

$$\vec{v}_x = 2.1623 \times 10^7 \times \frac{1}{2} \text{ m/s}$$

$$= 1.0811 \times 10^7 \text{ m/s}$$

2. $\vec{v}_y = v_{inc} \cos\beta$

$$\cos\beta = \cos 150^\circ = -\frac{\sqrt{3}}{2}$$

$$\vec{v}_y = 2.1623 \times 10^7 \times \left(-\frac{\sqrt{3}}{2}\right) \text{ m/s}$$

$$= 2.1623 \times 10^7 \times (-0.866) \text{ m/s}$$

$$= -1.8725 \times 10^7 \text{ m/s}$$

3. $\vec{v}_z = v_{inc} \cos\gamma = v_{inc} \cos 90^\circ =$

$$= v_{inc} \times 0 = 0 \text{ m/s}$$

II For Helium-3 nucleus

1. $\vec{v}_x = v_{inc} \cos\alpha$

$$v_{inc} = 0.7234 \times 10^7 \text{ m/s}$$

$$\cos\alpha = \cos 120^\circ = -\frac{1}{2}$$

$$\vec{v}_x = 0.7234 \times 10^7 \times \left(-\frac{1}{2}\right) \text{ m/s}$$

$$= -0.3617 \times 10^7 \text{ m/s}$$

2. $\vec{v}_y = v_{inc} \cos\beta$

$$\cos\beta = \cos 30^\circ = \frac{\sqrt{3}}{2}$$

$$\vec{v}_y = 0.7234 \times 10^7 \times \frac{\sqrt{3}}{2} \text{ m/s}$$

$$= 0.7234 \times 10^7 \times 0.866 \text{ m/s}$$

$$= 0.6264 \times 10^7 \text{ m/s}$$

3. $\vec{v}_z = v_{inc} \cos\gamma$

$$\vec{v}_z = v_{inc} \cos 90^\circ = v_{inc} \times 0 \text{ m/s}$$

components of final velocity of the particle

1. For neutron

According to	Inhereted Velocity	Increased velocity	Final Velocity (Inh + Inc)
X-axis	$\vec{v}_x = 0.2676 \times 10^7$ m/s	$\vec{v}_x = 1.0811 \times 10^7$ m/s	$\vec{v}_x = 1.3487 \times 10^7$ m/s
Y-axis	$\vec{v}_y = 0.1545 \times 10^7$ m/s	$\vec{v}_y = -1.8725 \times 10^7$ m/s	$\vec{v}_y = -1.718 \times 10^7$ m/s
Z-axis	$\vec{v}_z = 0$ m/s	$\vec{v}_z = 0$ m/s	$\vec{v}_z = 0$ m/s

2. For helium-3 nucleus

According to	Inhereted velocity	Increased velocity	Final Velocity (Inh + Inc)
X-axis	$\vec{v}_x = 0.2676 \times 10^7$ m/s	$\vec{v}_x = -0.3617 \times 10^7$ m/s	$\vec{v}_x = -0.0941 \times 10^7$ m/s
Y-axis	$\vec{v}_y = 0.1545 \times 10^7$ m/s	$\vec{v}_y = 0.6264 \times 10^7$ m/s	$\vec{v}_y = 0.7809 \times 10^7$ m/s
Z-axis	$\vec{v}_z = 0$ m/s	$\vec{v}_z = 0$ m/s	$\vec{v}_z = 0$ m/s

Final Kinetic energy of the particle – neutron

$$V^2 = v_x^2 + v_y^2 + v_z^2$$

$$= (1.3487\times10^7)^2 + (1.718\times10^7)^2 + (0)^2 \ m^2/s^2$$

$$= (1.81899169\times10^{14}) + (2.951524\times10^{14}) + 0 \ m^2/s^2$$

$$\Rightarrow V^2 = 4.77051569\times10^{14} \ m^2/s^2$$

$$\Rightarrow v = 2.1841\times10^7 \ m/s$$

$$\Rightarrow mv^2 = 1.6749\times10^{-27}\times4.77051569\times10^{14} \ J$$
$$= 7.99013672918\times10^{-13} \ J$$

$$\Rightarrow K.E = \frac{1}{2}mv^2 = 3.99506836459\times10^{-13} \ J$$
$$= 2.4969 \ MeV$$

⇒ Angles made by the neutron, when it is at point F, :–

If α, β and γ are the angles made by the neutron with respect to the axes x, y and z respectively. Then

1. $\cos\alpha = \dfrac{v_x}{v} = \dfrac{v\cos\alpha}{v} = \dfrac{1.3487\times10^7 \ m/s}{2.1841\times10^7 \ m/s} = 0.6175$

$\alpha \simeq 51.9$ degree $[\because \cos(51.9) = 0.6170]$

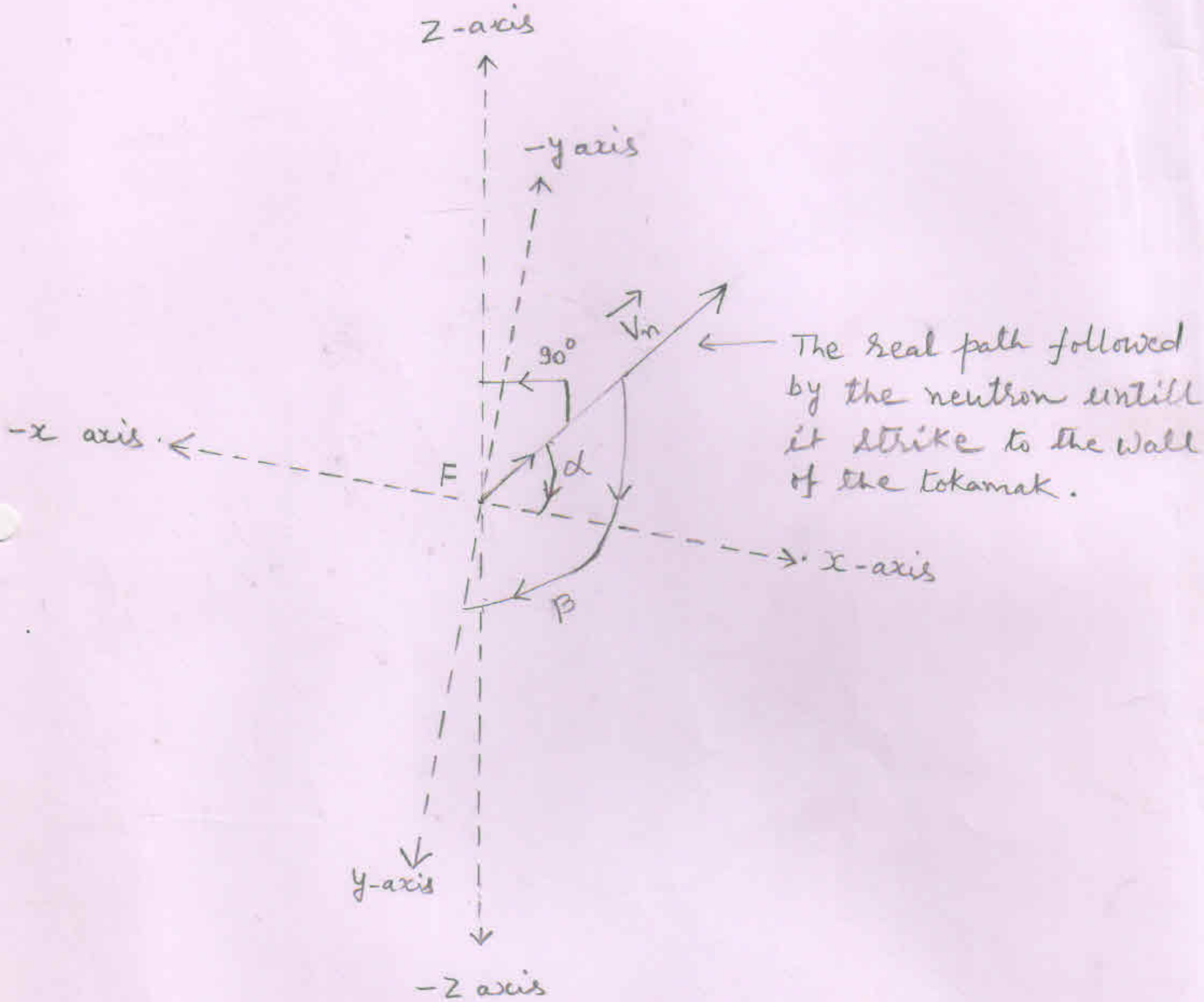
2. $\cos\beta = \dfrac{v_y}{v} = \dfrac{v\cos\beta}{v} = \dfrac{-1.718\times10^7 \ m/s}{2.1841\times10^7 \ m/s} = -0.7865$

$\beta = 141.9$ degree $[\because \cos(141.9) = -0.7869]$

3. $\cos\gamma = \dfrac{v_z}{v} = \dfrac{0}{v} = 0$

$\gamma = 90^\circ$

The real path followed by the neutron:



Where,

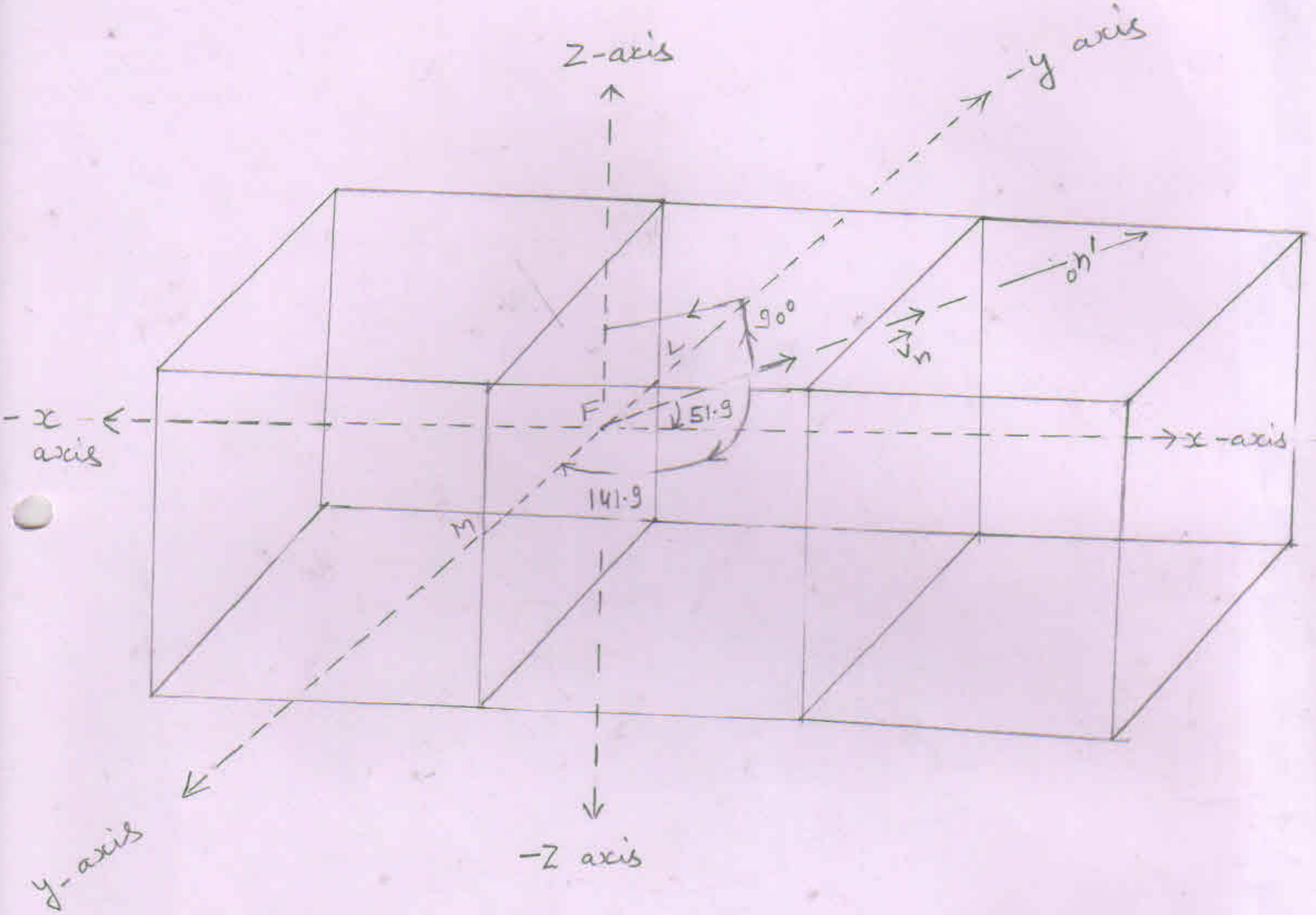
$\alpha \simeq 51.9$ degree

$\beta \simeq 141.9$ degree

$\gamma = 90^\circ$

$\Rightarrow$ α, β and γ are as usual used.

The angles that make the final velocity of the neutron with positive x, y and z-axes.



components of final momentum of helium-3 nucleus

1. $\vec{P}_x = m_{He-3} \vec{V}_x$

$= 5.00629 \times 10^{-27} \times (-0.0941 \times 10^{7})$ kg m/s

$= -0.4710 \times 10^{-20}$ kg m/s

2. $\vec{P}_y = m_{He-3} \vec{V}_y$

$= 5.00629 \times 10^{-27} \times 0.7809 \times 10^{7}$ kg m/s

$= 3.9094 \times 10^{-20}$ kg m/s

3. $\vec{P}_z = m_{He-3} \vec{V}_z$

$= m_{He-3} \times 0$ kg m/s

$= 0$ kg m/s

Final kinetic energy of the particle – He-3 nucleus

$$v^2 = v_x^2 + v_y^2 + v_z^2$$

$$= (0.0941 \times 10^{7})^2 + (0.7809 \times 10^{7})^2 + (0)^2 \ m^2/s^2$$

$$= (0.00885481 \times 10^{14}) + (0.60980481 \times 10^{14}) + 0 \ m^2/s^2$$

$$\Rightarrow v^2 = 0.61865962 \times 10^{14} \ m^2/s^2$$

$$\Rightarrow v = 0.7865 \times 10^{7} \ m/s$$

$$\Rightarrow mv^2 = 5.00629 \times 10^{-27} \times 0.61865962 \times 10^{14} \ J$$

$$= 3.097189469 \times 10^{-13} \ J$$

$$K.E = \frac{1}{2} mv^2 = 1.5485947345 \times 10^{-13} \ J$$

$$= 0.9678 \ MeV$$

$\Rightarrow$ Angles made by the He-3 nucleus with respect to point F. :—

The He-3 nucleus is produced at point F. If α, β, and γ are the angles made by the He-3 nucleus with respect to axes x, y and z respectively. then

1. $\cos\alpha = \dfrac{v_x}{v} = \dfrac{-0.0941 \times 10^{7}}{0.7865} = -0.11$

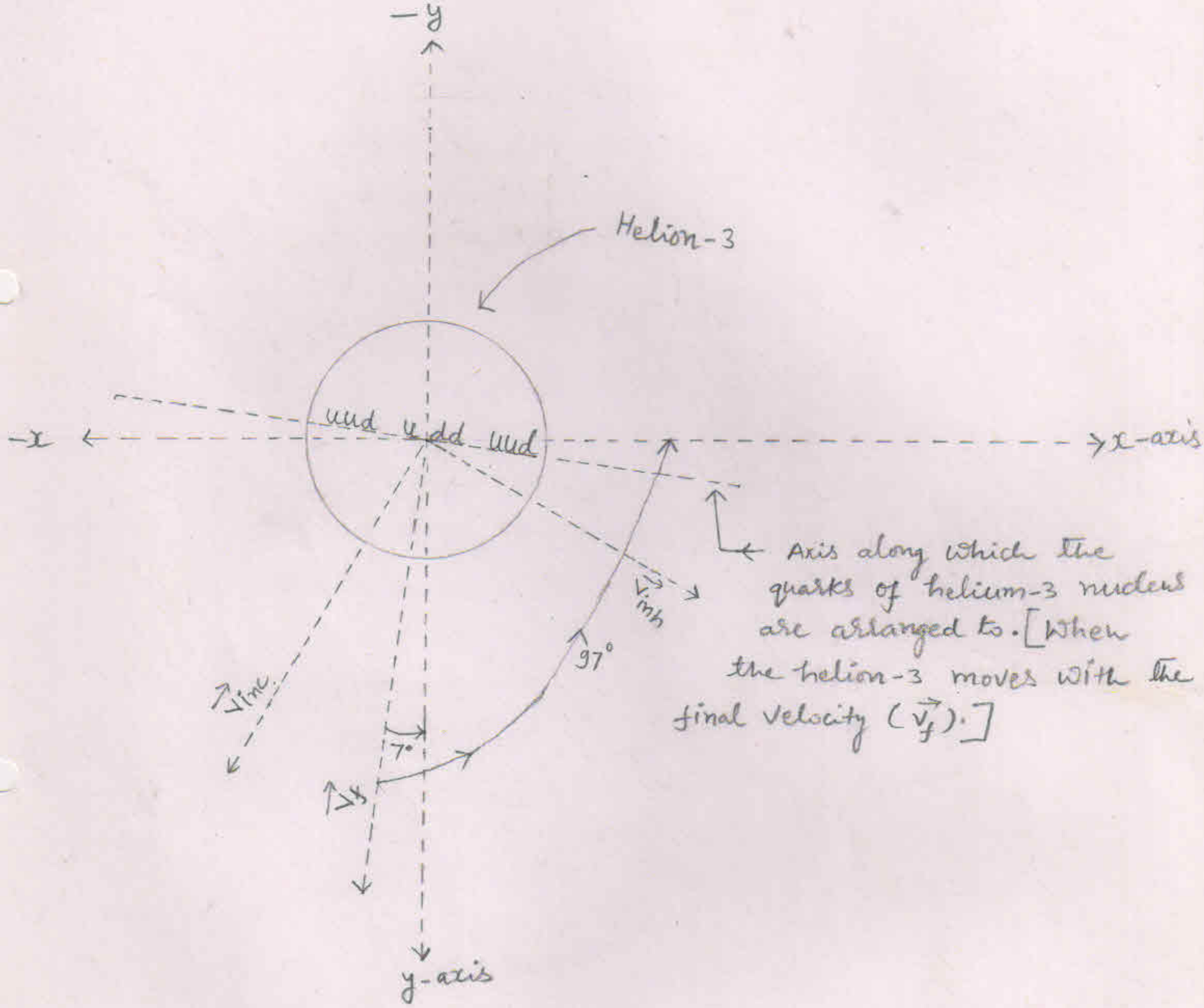
$\alpha \simeq 97^\circ$

2. $\cos\beta = \dfrac{v_y}{v} = \dfrac{0.7809}{0.7865} = 0.9928$

$\beta \simeq 7^\circ$

3. $\cos\gamma = \dfrac{v_z}{v} = \dfrac{0}{0.7865} = 0$

$\gamma \simeq 90^\circ$



⇒ z-axis is perpendicular to both the axes − x and y.

⇒ v_f = final velocity of the helion-3 with which it travels

where, $\vec{v}_f = \vec{v}_{inh} + \vec{v}_{inc}$

Acting forces on the helium-3 nucleus

1. $F_y = q V_x B_z \sin\theta$

$q = 2 \times 1.6 \times 10^{-19}$ C
$V_x = 0.0941 \times 10^7$ m/s
$B_z = 1$ Tesla
$\sin\theta = \sin 90° = 1$

$F_y = 2 \times 1.6 \times 10^{-19} \times 0.0941 \times 10^7 \times 1 \times 1$ N
$= 0.3011 \times 10^{-12}$ N

From the right hand palm rule, the direction of force F_y is according to (+) y axis.
So,

$\vec{F}_y = 0.3011 \times 10^{-12}$ N

2. $F_z = q V_x B_y \sin\theta$

$B_y = 1$ Tesla
$\sin\theta = \sin 90° = 1$

$F_z = 2 \times 1.6 \times 10^{-19} \times 0.0941 \times 10^7 \times 1 \times 1$ N
$= 0.3011 \times 10^{-12}$ N

From the right hand palm rule, the direction of force F_z is according to (+) z axis.
So,

$\vec{F}_z = 0.30112 \times 10^{-12}$ N

3. $F_x = q V_y B_z \sin\theta$

$V_y = 0.7809 \times 10^7$
$\sin\theta = \sin 90° = 1$

$F_x = 2 \times 1.6 \times 10^{-19} \times 0.7809 \times 10^7 \times 1 \times 1$ N
$= 2.4988 \times 10^{-12}$ N

From the right hand palm rule, the direction of force F_x is according to (+) x axis.
So,

$\vec{F}_x = 2.4988 \times 10^{-12}$ N

Resultant force (F_R)

$$F_R^2 = F_x^2 + F_y^2 + F_z^2$$

$F_x = 2.4988 \times 10^{-12}$ N

$F = F_y = F_z = 0.3011 \times 10^{-12}$ N

$$F_R^2 = F_x^2 + 2F^2$$

$$= (2.4988 \times 10^{-12})^2 + 2(0.3011 \times 10^{-12})^2 \quad N^2$$

$$= (6.24400144 \times 10^{-24}) + 2(0.09066121 \times 10^{-24}) N^2$$

$$F_R^2 = 6.42532386 \times 10^{-24} \quad N^2$$

$$F_R = 2.5348 \times 10^{-12} \text{ N}$$

Radius of the circular path :

Resultant force acts as a centripetal force on the helium-3 nucleus. So, the helium-3 nucleus follows a ~~co~~ confined circular path.

The radius of the circulal orbit obtained by the helium-3 nucleus is —

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

$mv^2 = 3.0971 \times 10^{-13}$ J

$$= \frac{3.0971 \times 10^{-13}}{2.5348 \times 10^{-12}} \frac{J}{N}$$

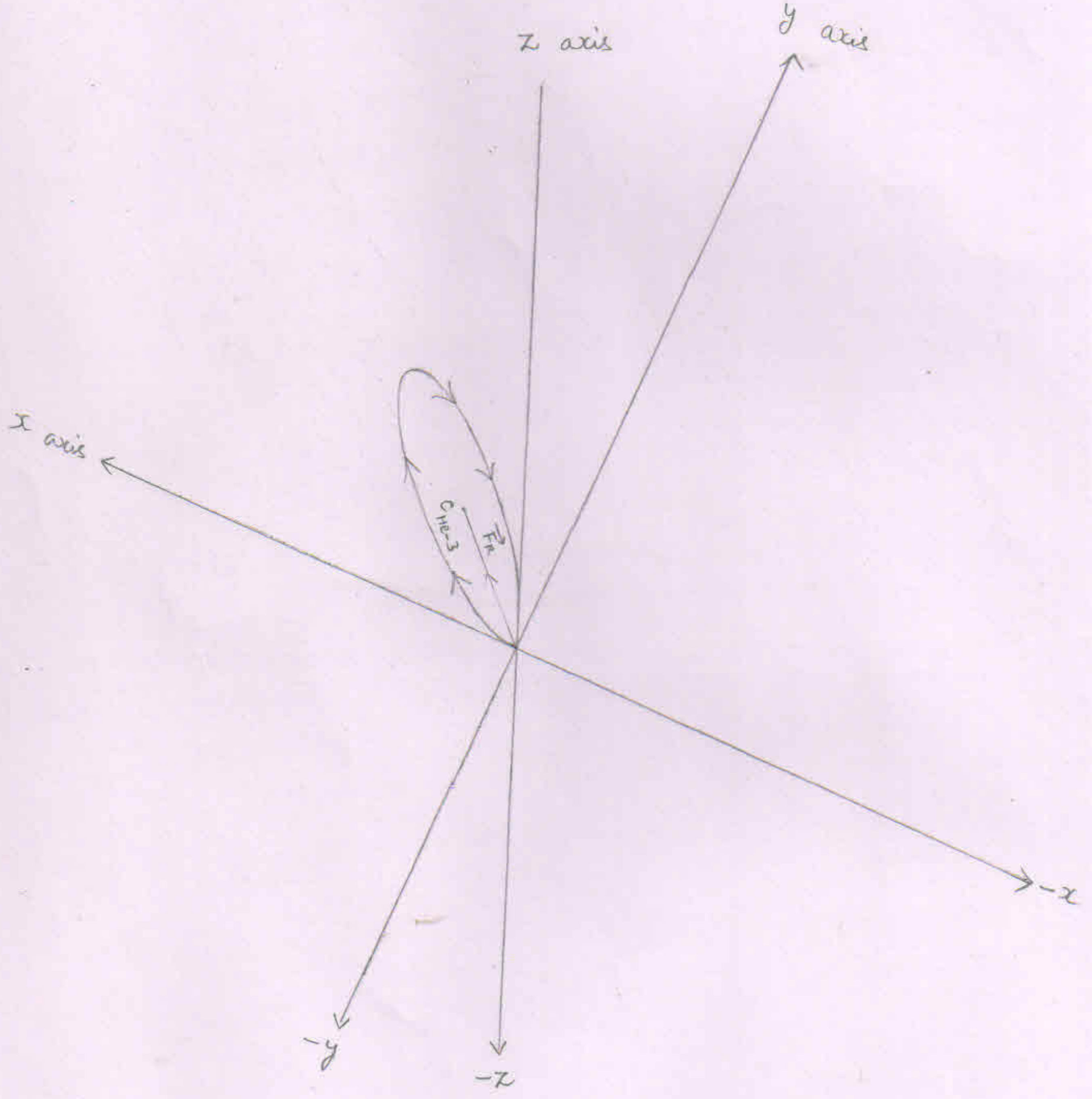
$$= 1.2218 \times 10^{-1} \text{ m}$$

$$= 12.21 \text{ cm}$$

⇒ The circular orbit followed by the confined helion-3 lies in the I (up) quadrant made up of positive x axis, positive y axis and the positive z axis.

⇒ $\overrightarrow{F_R}$ = Resultant force acting on the particle (at point F) towards the centre of the circle.

⇒ C_{He-3} = center of the circle obtained by the helion-3



Angles that make the resultant force ($\vec{F_R}$) acting on the particle at point F with respect to positive x, y and z axes. :-

1. With x-axis

$$\cos\alpha = \frac{F_R \cos\alpha}{F_R} = \frac{\vec{F_x}}{F_R} = \frac{2.4988 \times 10^{-12}}{2.5348 \times 10^{-12}} \frac{N}{N}$$

$\Rightarrow \cos\alpha = 0.9857$

$\Rightarrow \alpha \simeq 9.8$ $\quad [\because \cos(9.8) = 0.9851]$

2. With y-axis

$$\cos\beta = \frac{F_R \cos\beta}{F_R} = \frac{\vec{F_y}}{F_R} = \frac{0.3011 \times 10^{-12}}{2.5348 \times 10^{-12}} \frac{N}{N}$$

$\Rightarrow \cos\beta = 0.1187$

$\Rightarrow \beta \simeq 83.2$ $\quad [\because \cos(83.2) = 0.1184]$

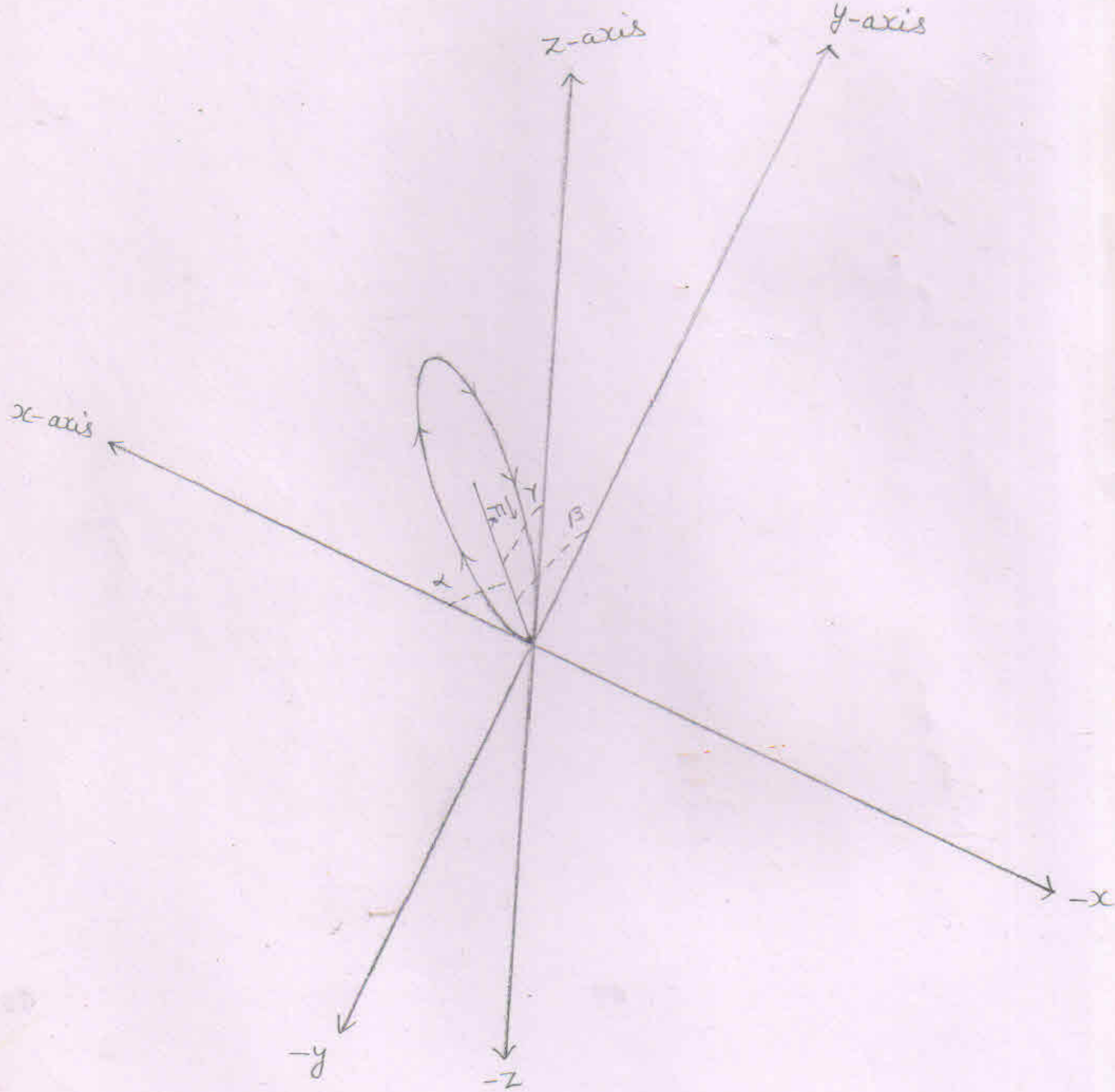
3. With z-axis

$$\cos\gamma = \frac{F_R \cos\gamma}{F_R} = \frac{\vec{F_z}}{F_R} = \frac{0.3011 \times 10^{-12}}{2.5348 \times 10^{-12}} \frac{N}{N}$$

$\Rightarrow \cos\gamma = 0.1187$

$\Rightarrow \gamma \simeq 83.2$

Angles that make the resultant force ($\vec{F_R}$) with respect to positive x, y and z axes at point 'F.'



Where,

$\alpha \simeq 9.8$ degree
$\beta \simeq 83.2$ degree
$\gamma = 83.2$ degree

The Cartesian Coordinates of the points $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ located on the circumfrence of the circle obtained by the helion-3

1. $\cos\alpha = \dfrac{x_2 - x_1}{d}$

$$d = 2 \times R$$
$$= 2 \times 12.218 \times 10^{-2}\, m$$
$$= 24.436 \times 10^{-2}\, m$$
$$\cos\alpha = 0.98$$

$\Rightarrow x_2 - x_1 = d \times \cos\alpha$

$\Rightarrow x_2 - x_1 = 24.436 \times 10^{-2} \times 0.98\ m$

$\Rightarrow x_2 - x_1 = 23.9472 \times 10^{-2}\ m$

$\Rightarrow x_2 = 23.9472 \times 10^{-2}\ m \quad [\because x_1 = 0]$

2. $\cos\beta = \dfrac{y_2 - y_1}{d}$

$$\cos\beta = 0.11$$

$\Rightarrow y_2 - y_1 = d \times \cos\beta$

$\Rightarrow y_2 - y_1 = 24.436 \times 10^{-2} \times 0.11\ m$

$\Rightarrow y_2 - y_1 = 2.68779 \times 10^{-2}\ m$

$\Rightarrow y_2 = 2.6879 \times 10^{-2}\ m \quad [\because y_1 = 0]$

3. $\cos\gamma = \dfrac{z_2 - z_1}{d}$

$$\cos\gamma = 0.11$$

$\Rightarrow z_2 - z_1 = d \times \cos\gamma$

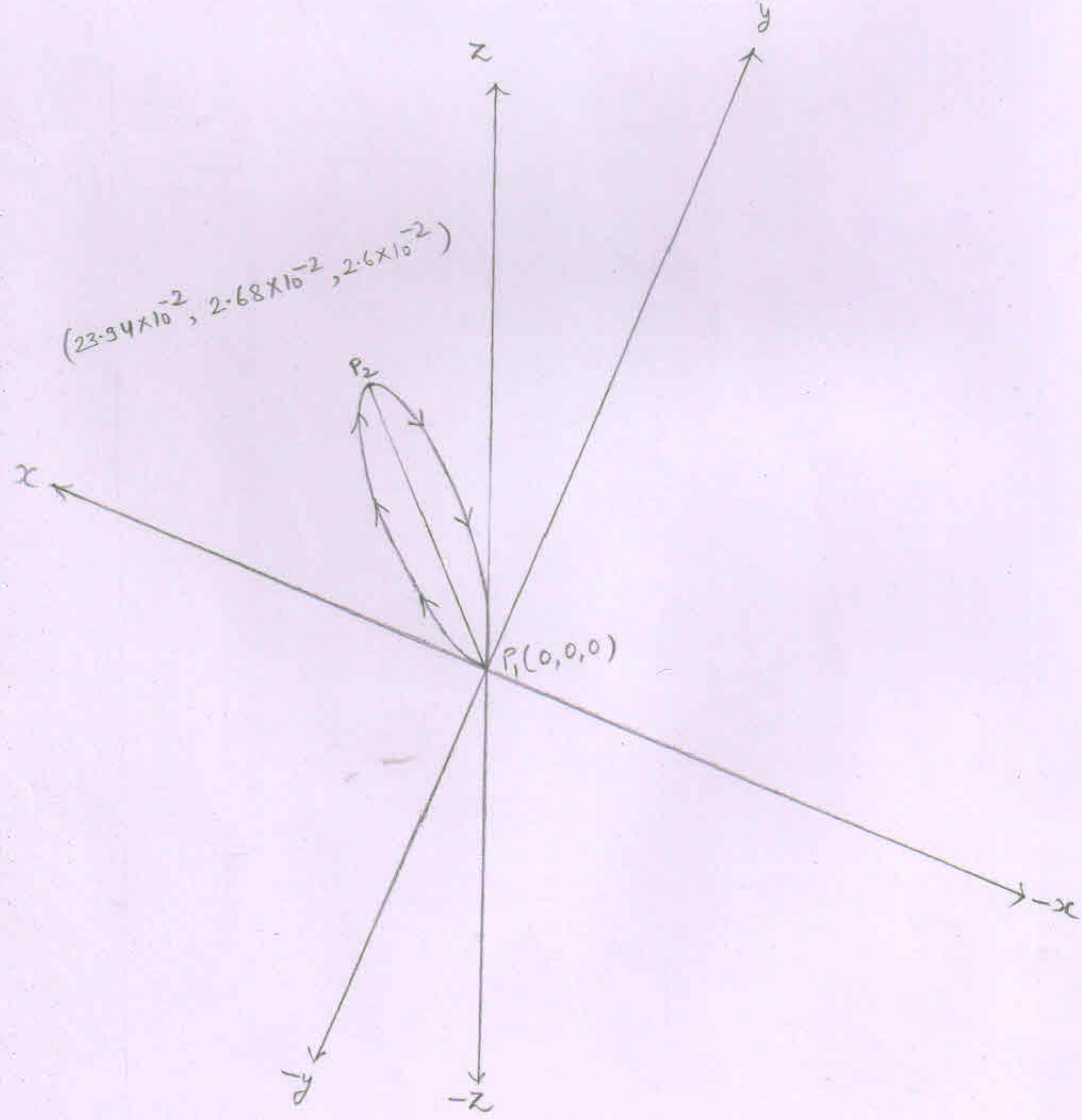
$\Rightarrow z_2 - z_1 = 24.436 \times 10^{-2} \times 0.11\ m$

$\Rightarrow z_2 - z_1 = 2.6879 \times 10^{-2}\ m$

$\Rightarrow z_2 = 2.6879 \times 10^{-2}\ m \quad [\because z_1 = 0]$

The cartesian coordinates of the points $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ located on the circumfrence of the circle obtained by the helium-3 nucleus are as shown below.

$\Rightarrow$ The line $\overline{P_1 P_2}$ is the diameter of the circle.



2. For the particle helium-3 nucleus

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

$$r = 12.21 \times 10^{-2} \text{ m}$$
$$V = 0.7865 \times 10^{7} \text{ m/s}$$

$$T = \frac{2 \times 3.14 \times 12.21 \times 10^{-2}}{0.7865 \times 10^{7}} \text{ s}$$

$$= \frac{76.6788 \times 10^{-2}}{0.7865 \times 10^{7}} \text{ s}$$

$$= 9.7493 \times 10^{-8} \text{ s}$$

Time of confinement of he-3 nucleus

$$\Rightarrow \quad t_e = \frac{3c^5 m^3}{4e^4 B^2}$$

where, $c = 3\times10^{10}$ cm/s
$m = 5.00629\times10^{-24}$ gram
$e = 2\times4.8\times10^{-10}$ esu
$B \simeq 10^4$ Gauss

$$t_e = \frac{3\times(3\times10^{10})^5 \times (5.00629\times10^{-24})^3}{4\times(2\times4.8\times10^{-10})^4 \times (10^4)^2} \text{ seconds}$$

$$= \frac{3\times243\times10^{50}\times125.4723\times10^{-72}}{4\times16\times530.84\times10^{-40}\times10^{8}} \text{ seconds}$$

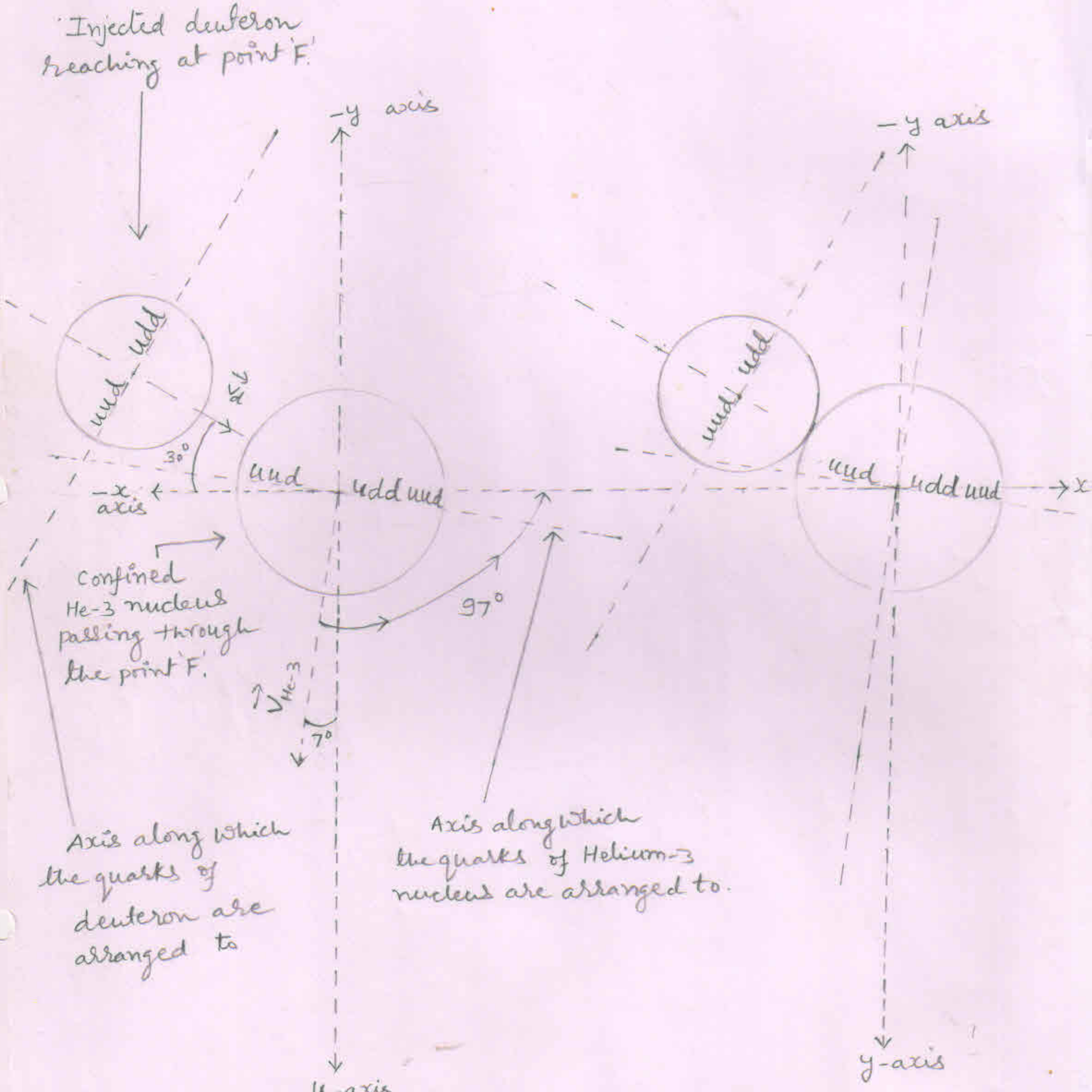
$$= \frac{91469.3067\times10^{-22}}{33973.76\times10^{-32}} \text{ seconds}$$

$$\simeq 2.6923\times10^{10} \text{ seconds}$$

For fusion reaction : ${}^{2}_{1}H + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + {}^{1}_{1}H$

1. The interaction of nuclei :-

The injected deuteron reaches at point 'F' and interacts [experiences a repulsive force due to confined helion-3] with the confined helion-3 passing through the point F. The injected deuteron overcomes the electrostatic repulsive force and - a like two solid spheres join - the injected deuteron dissimilarly joins with confined helion-3.



1

Injection of deuteron

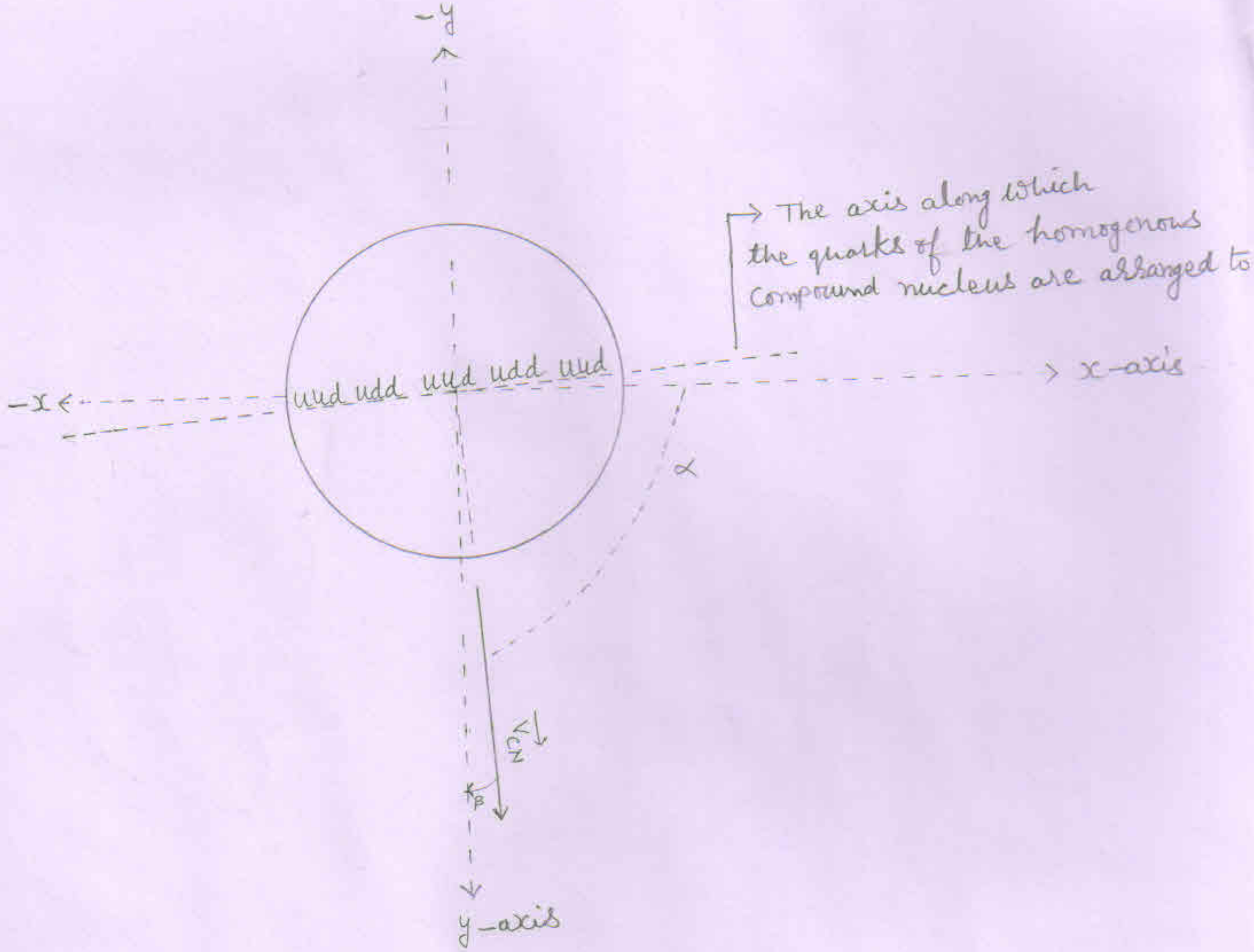
2

Interaction of nuclei

2. Formation of a homogenous Compound nucleus:-
The constituents (quarks and gluons) of the dissimilarly joined nuclei (the deuteron and the he-3 nucleus) behave like a liquid and form a homogenous compound nucleus having similarly distributed groups of quarks with similarly distributed surrounding gluons.

Thus, within a homogenous compound nucleus - each group of quarks is surrounded by the gluons in equal proportion. So, within a homogenous compound nucleus there are 5 groups of quarks surrounded by the gluons.

The homogenous compound nucleus



where

$\alpha \simeq 85.6$

$\beta \simeq 4.4$

3. Formation of lobes within into the homogenous compound nucleus or the transformation of the homogenous compound nucleus into the heterogenous compound nucleus :-

The central group of quarks with its surrounding gluons to become a stable and the next higher nucleus (the helion-4) than the reactant one (the helion-3) includes the other three (nearby located) groups of quarks with their surrounding gluons and rearrange to form the 'A' lobe of the heterogenous compound nucleus.

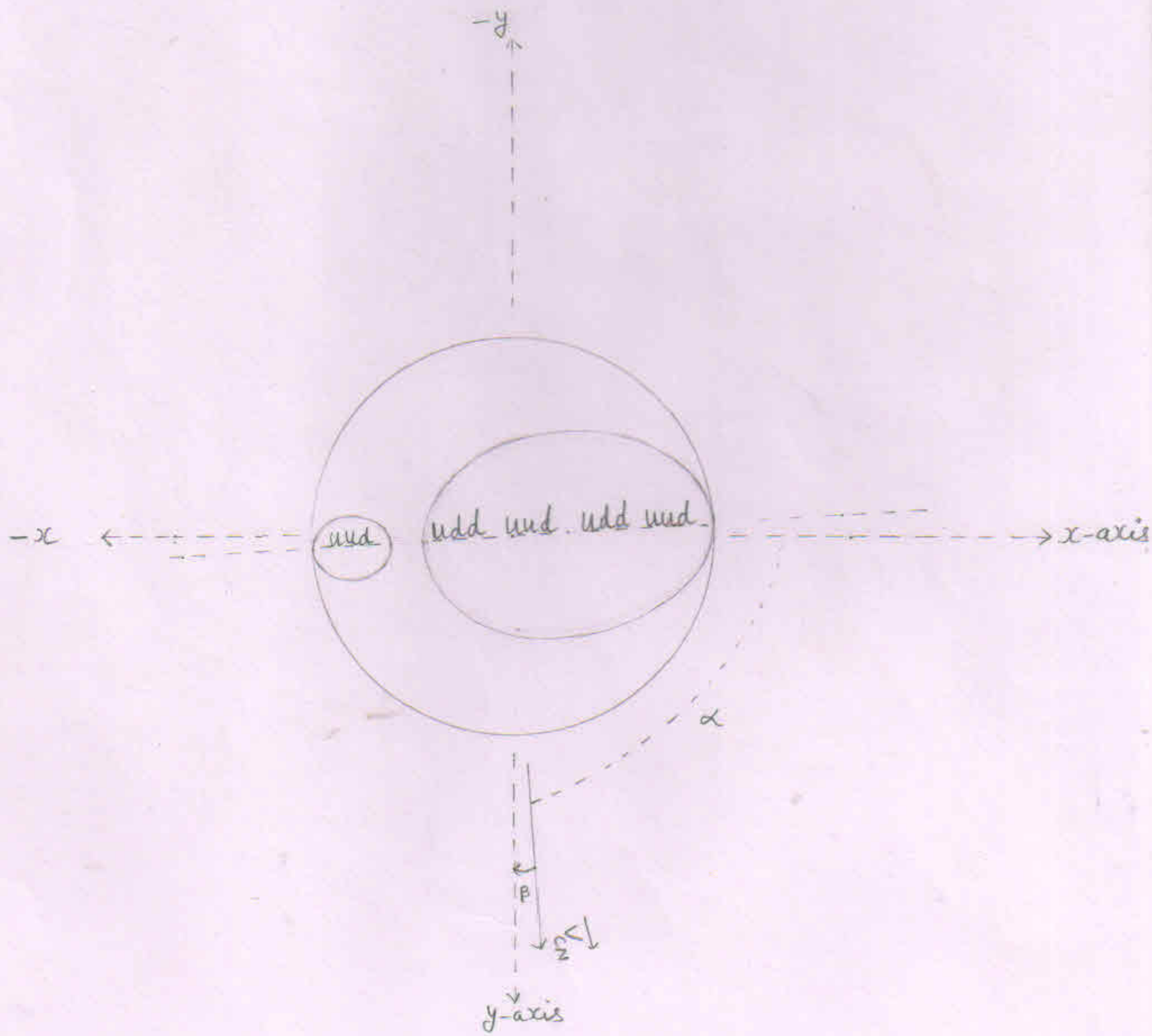
While the remaining group of quarks to become a stable nucleus (the proton) includes its surrounding gluons or mass [out of the available mass (or gluons) that is not included in the formation of the lobe 'A'] and rearrange to form the 'B' lobe of the heterogenous compound nucleus.

Thus, due to formation of two dissimilar lobes within into the homogenous compound nucleus, the homogenous compound nucleus transforms into the heterogenous compound nucleus.

3 Formation of lobes

⇒ Within into the homogenous compound nucleus, the greater nucleus is the helium-4 nucleus and the smaller nucleus is the proton.

⇒ The greater nucleus is the lobe 'A' and the smaller nucleus is the lobe 'B' while the remaining space represent the remaining gluons.



3

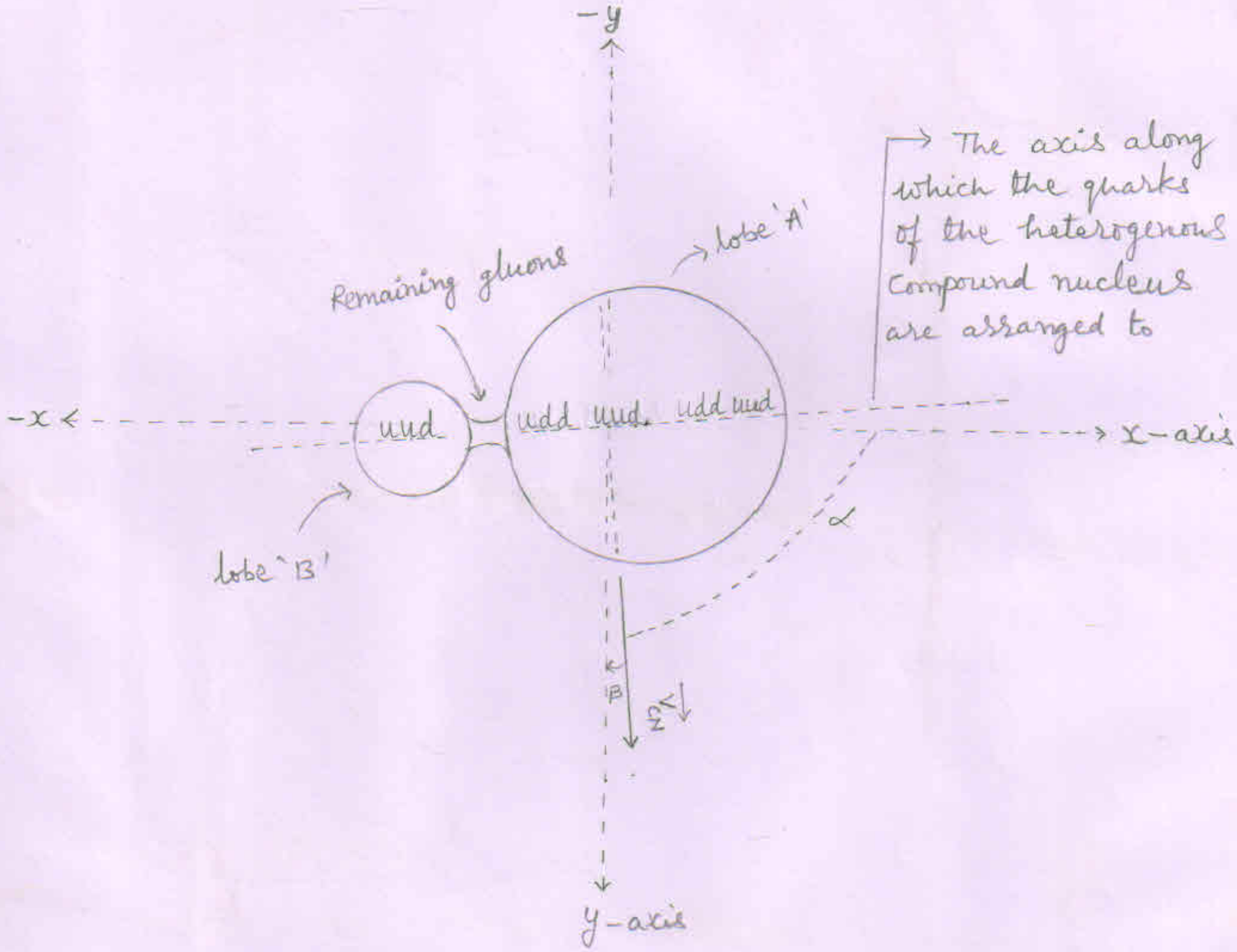
Formation of lobes

4. Final stage of the heterogenous compound nucleus:-

The process of formation of lobes creates voids between the lobes. So, the remaining gluons [or the mass that is not involved in the formation of any lobe] rearrange to fill the voids between the lobes and thus the remaining gluons form a node between the two dissimilar lobes of the heterogenous compound nucleus.

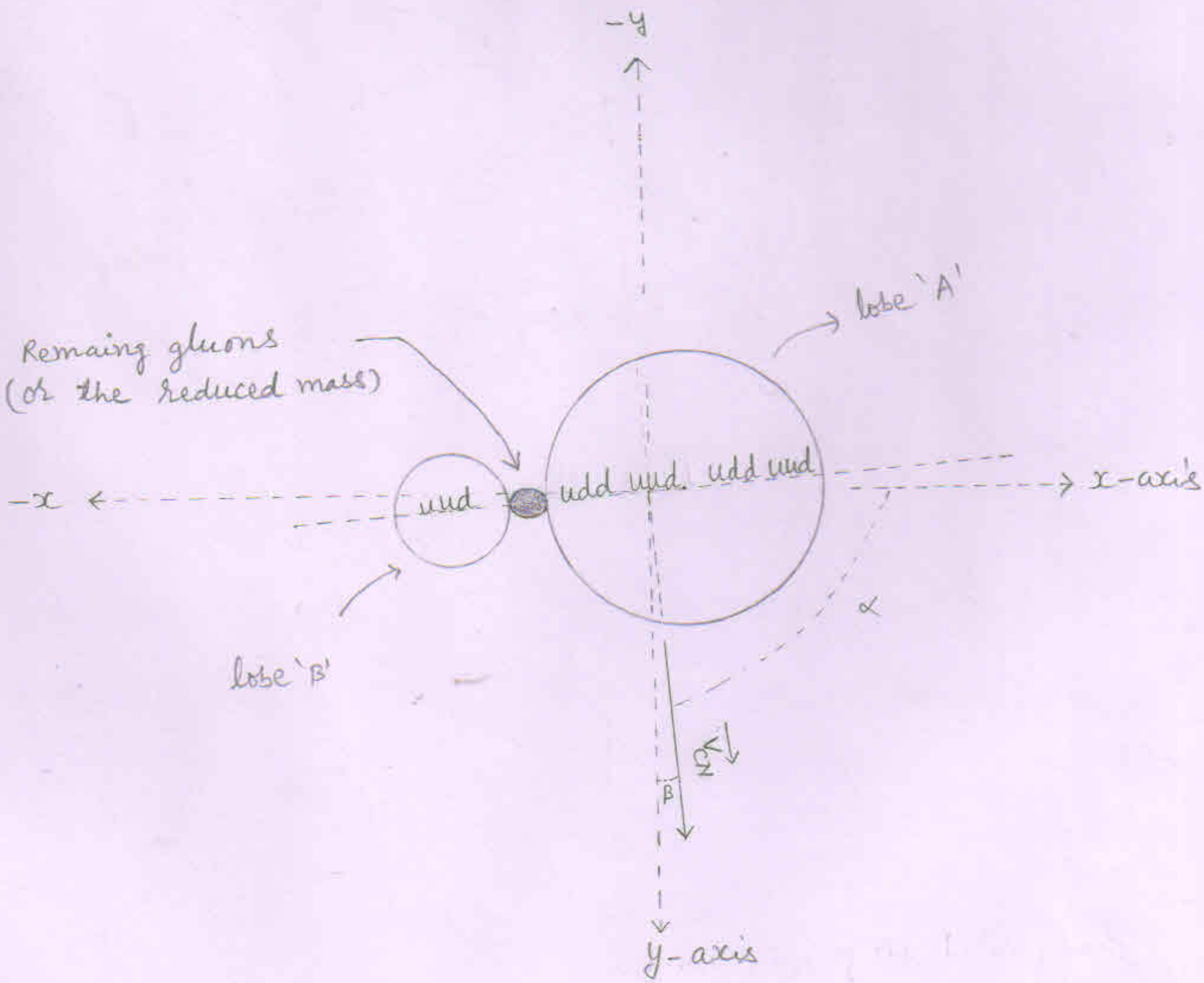
Thus the reduced mass (or the remaining gluons) keeps both the dissimilar lobes - of the heterogenous compound nucleus - joined them together.

So, finally, the heterogenous compound nucleus becomes like an abnormal digit eight or becomes as a dumbbell.



☐ The heterogenous compound nucleus

⇒ for $\alpha \simeq 85.6$ degree
$\beta \simeq 4.4$ degree



Final stage of the heterogenous compound nucleus

Formation of Compound nucleus

1. As the deuteron of $(n+x)^{th}$ bunch reaches at point F, it fuses with the confined helium-3 nucleus (passing from the point F) to form a compound nucleus.

2. Just before fusion, to overcome the electrostatic repulsive force, the injected deuteron loses 20.2488 kev energy. So, just before fusion, the kinetic energy of $(n+x)^{th}$ deuteron is

$$E_b = [102.4 \text{ kev} - 20.2488 \text{ kev}]$$
$$= 82.1512 \text{ kev}$$
$$= 0.0821512 \text{ Mev}$$

3. Momentum of injected deuteron (just before fusion)

$$P = [2 m_d E_b]^{\frac{1}{2}}$$

$$= [2 \times 3.3434 \times 10^{-27} \times 0.0821512 \times 1.6 \times 10^{-13}]^{\frac{1}{2}} \text{ kg m/s}$$

$$= [0.87892583065 \times 10^{-40}]^{\frac{1}{2}} \text{ kg m/s}$$

$$= 0.9375 \times 10^{-20} \text{ kg m/s}$$

Components of momentum of $(n+x)^{th}$ deuteron (just before fusion) at point F :-

⇒ The deuteron is injected making 30° angle with x-axis, 60° angle with y-axis and 90° angle with z-axis.
So, the components of momentum of injected deuteron (that is undergoing fusion reaction with confined He-3 nucleus) just before fusion are -

1. $\vec{P}_x = P\cos\alpha = P\cos 30°$

$= 0.9375 \times 10^{-20} \times \frac{\sqrt{3}}{2}$ kg m/s

$= \frac{1.62375 \times 10^{-20}}{2}$ kg m/s

$= 0.8118 \times 10^{-20}$ kg m/s

2. $\vec{P}_y = P\cos\beta = P\cos 60°$

$= 0.9375 \times 10^{-20} \times \frac{1}{2}$ kg m/s

$= 0.4687 \times 10^{-20}$ kg m/s

3. $\vec{P}_z = P\cos\gamma = P\cos 90°$

$= P \times 0 = 0$ kg m/s

1. x - Component of momentum of Compound nucleus =

[x-component of momentum of Confined he-3 nucleus at point F] + [x-component of momentum of injected deuteron (just before fusion) at point F]

$$\vec{P}_x = [-0.4710 \times 10^{-20} \, kgm/s] + [0.8118 \times 10^{-20} \, kgm/s]$$

$$= 0.3408 \times 10^{-20} \, kgm/s$$

2. y-Component of momentum of Compound nucleus =

[y-component of momentum of Confined he-3 nucleus at point F] + [y-component of momentum of injected deuteron (just before fusion) at point F]

p

$$\vec{P}_y = [3.9094 \times 10^{-20} \, kgm/s] + [0.4687 \times 10^{-20} \, kgm/s]$$

$$= 4.3781 \times 10^{-20} \, kgm/s$$

3. z - Component of momentum of Compound nucleus =

$$\begin{bmatrix} \text{z - Component of} \\ \text{momentum of} \\ \text{Confined He-3 nucleus} \\ \text{at point F} \end{bmatrix} + \begin{bmatrix} \text{z - Component of} \\ \text{momentum of injected} \\ \text{deuteron (just before} \\ \text{fusion) at point F} \end{bmatrix}$$

$$\vec{P}_z = [0 \ kg\,m/s] + [0 \ kg\,m/s]$$

$$= 0 \quad kg\,m/s$$

4. Mass of the Compound nucleus (M) :-

$$M = m_d + m_{He-3}$$

$$= [3 \cdot 3434 \times 10^{-27} + 5 \cdot 00629 \times 10^{-27}] \ kg$$

$$= 8 \cdot 34969 \times 10^{-27} \ kg$$

Components of velocity of compound nucleus ($\vec{v}_{CN}$)

1. $\vec{v}_x = v_{CN} \cos\alpha = \dfrac{\vec{P}_x}{M}$

$= \dfrac{0.3408 \times 10^{-20}}{8.34969 \times 10^{-27}} \dfrac{kg\,m/s}{kg}$

$= 0.0408 \times 10^{7}$ m/s

2. $\vec{v}_y = v_{CN} \cos\beta = \dfrac{\vec{P}_y}{M}$

$= \dfrac{4.3781 \times 10^{-20}}{8.34969 \times 10^{-27}} \dfrac{kg\,m/s}{kg}$

$= 0.5243 \times 10^{7}$ m/s

3. $\vec{v}_z = v_{CN} \cos\gamma = \dfrac{\vec{P}_z}{M} = \dfrac{0}{M} = 0$ m/s

4. Velocity of the compound nucleus ($\vec{v}_{CN}$)

$v_{CN}^2 = v_x^2 + v_y^2 + v_z^2$

$= (0.0408 \times 10^{7})^2 + (0.5243 \times 10^{7})^2 + (0)^2$ m^2/s^2

$= (0.00166464 \times 10^{14}) + (0.27489049 \times 10^{14}) + 0$ m^2/s^2

$v_{CN}^2 = 0.27655513 \times 10^{14}$ m^2/s^2

Angles that make the velocity of Compound nucleus ($\vec{V}_{CN}$) with axes :-

1. With x-axis

$$\cos\alpha = \frac{V_{CN}\cos\alpha}{V_{CN}} = \frac{\vec{V_x}}{V_{CN}} = \frac{0.0408 \times 10^7}{0.5258 \times 10^7} \frac{m/s}{m/s}$$

$\Rightarrow \cos\beta = 0.0775$

$\Rightarrow \alpha \simeq 85.6$

2. With y-axis

$$\cos\beta = \frac{V_{CN}\cos\beta}{V_{CN}} = \frac{\vec{V_y}}{V_{CN}} = \frac{0.5243 \times 10^7}{0.5258 \times 10^7} \frac{m/s}{m/s}$$

$\Rightarrow \cos\beta = 0.9971$

$\Rightarrow \beta = 4.4$

3. With z-axis

$$\cos\gamma = \frac{V_{CN}\cos\gamma}{V_{CN}} = \frac{\vec{V_z}}{V_{CN}} = \frac{0}{0.5258 \times 10^7} \frac{m/s}{m/s}$$

$\Rightarrow \cos\gamma = 0$

$\Rightarrow \gamma = 90^\circ$

The Splitting of the heterogenous compound nucleus:-

⇒ The heterogenous compound nucleus, due to its instability, splits according to the lines parallel to the direction of the velocity of the compound nucleus ($\vec{V}_{CN}$) into three particles – the helion-4, the proton and the reduced mass (Δm).

Out of them, the two particles (the helion-4 and the proton) are stable while the third one (reduced mass) is unstable.

⇒ According to law of inertia, each particle that has separated from the compound nucleus, has an inhereted velocity ($\vec{V}_{inh}$) equal to the velocity of the compound nucleus ($\vec{V}_{CN}$).

⇒ So, for conservation of momentum

$$M\vec{V}_{CN} = (m_{he-4} + \Delta m + m_p)\vec{V}_{CN}$$

Where,

M = mass of the compound nucleus
$\vec{V}_{CN}$ = velocity of the compound nucleus

m_{he-4} = mass of the helium-4 nucleus

Δm = Reduced mass
m_p = mass of the proton