Horse pipe and the extraction of the undesired charged particles :-

A horse pipe is a hollow cylindrical pipe that allows the gaseous atoms to pass through it.

The one end (mouth) of the horse pipe is located in the main tokamak at the point $P_2(x_2, y_2, z_2)$ where the confined charged particle(s) reaches while the another end is located outside the main tokamak.

Now as the confined charged particle to follow the circular orbit reaches from point $P_1(0, 0, 0)$ to point $P_2(x_2, y_2, z_2)$ it enters into the mouth of the horse pipe. So, the charged particle at point P_2 inspite of completing its circle strike to the horse pipe. Thus the confined charged particle imparts its all the heat energy to the horse pipe which in turn transfers this heat energy to the tokamak.

The slowed charged particle gets free electron(s) and becomes a gaseous atom.

With the help of Vaccume pumps we can get the undesired gaseous atoms (helion-3 or helium-4 gas) on the another end of the horse pipe which is located at the outside of the main tokamak.

Summary

The confined or deconfined charged particles, the cartesian coordinates of the charged particles and the extraction of the undesired charged particles with the help of horse pipes :-

1. The injected deuteron remains confined within into the tokamak.

(i) The radius of the circular orbit followed by the deuteron is 4.947×10^{-2} m.

(ii) The cartesian coordinates of the deuteron are –

$P_1(0,0,0)$ and $P_2(3.66 \times 10^{-2}, -6.43 \times 10^{-2}, -6.43 \times 10^{-2})$

2. For fusion reaction

$$\underset{(\text{injected})}{{}^{2}_{1}H} + \underset{(\text{Confined})}{{}^{2}_{1}H} \longrightarrow {}^{3}_{2}He + {}^{1}_{0}n$$

(i) For helium-3 nucleus

⇒ The helium-3 nucleus remains confined within into the tokamak.

⇒ The radius of the circular orbit followed by the helium-3 nucleus is 12.218×10^{-2} m.

⇒ The cartesian coordinates attained by the confined helium-3 nucleus are –

$P_1(0,0,0)$ and $P_2(23.94 \times 10^{-2}, 2.68 \times 10^{-2}, 2.68 \times 10^{-2})$

(ii) For neutron :-

The neutron strike to the wall of tokamak.

3. For fusion reaction

$$\underset{(\text{injected})}{{}^{2}_{1}H} + \underset{(\text{Confined})}{{}^{3}_{2}He} \longrightarrow {}^{4}_{2}He + {}^{1}_{1}H$$

1. For proton

⇒ The proton is not confined.

⇒ The radius of the circular orbit to be followed by the proton is 39.3444×10^{-2} m.

⇒ The cartesian coordinates that to be attained by the proton are –

$P_1(0, 0, 0)$ and $P_2(9.4426 \times 10^{-2}, 55.0821 \times 10^{-2}, 55.0821 \times 10^{-2})$

⇒ So, in trying to follow the confined circular orbit, the proton strike to wall of the tokamak [before it attains the above coordinates].

2. For helium-4 nucleus

⇒ The helium-4 nucleus is not confined.

⇒ The radius of the circular orbit to be followed by the helium-4 nucleus is 21.4676×10^{-2} m.

⇒ The cartesian coordinates attained by the helium-4 nucleus are –

$P_1(0, 0, 0)$ and $P_2(9.0163 \times 10^{-2}, -29.6252 \times 10^{-2}, -29.6252 \times 10^{-2})$

⇒ As the helium-4 nucleus reaches at point $P_2(x_2, y_2, z_2)$ it enters into the mouth of the horse pipe and thus be extracted out of the tokamak.

Where,

4. For fusion reaction

$$ {}^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{1}T + {}^{1}_{0}H $$

(injected) (confined) (confined) [Not confined]

(i) For the triton

⇒ The radius of the circular orbit followed by the triton is 26.606×10^{-2} m

⇒ The triton is confined.

⇒ The cartesian coordinates attained by the confined triton are -

$P_1(0,0,0)$ and $P_2(51.61 \times 10^{-2} m, 7.98 \times 10^{-2} m, 7.98 \times 10^{-2} m)$

(ii) For the proton

⇒ The proton is not confined.

⇒ The radius of the circular orbit followed by the proton is 21.66×10^{-2} m.

⇒ The plane of the circular orbit to be followed by the proton lies in the plane made up of negative x-axis, negative y-axis and negative z-axis where the magnetic fields are not applied. So, the proton to undergo to the confined circular orbit, gets rid of the magnetic fields and hence strike to the base wall of the tokamak.

5. For fusion reaction

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

(injected) (Confined) [Not confined] [Not conf.]

(i) For helium-4 nucleus

⇒ The helium-4 nucleus is not confined.

⇒ The radius of the circular orbit to be followed by the helium-4 nucleus is 21.5937×10^{-2} m.

⇒ The cartesian coordinates attained by the helium-4 nucleus are –

$P_1(0,0,0)$ and $P_2(11.6605\times10^{-2}, -28.9355\times10^{-2}, -28.9355\times10^{-2})$

⇒ As the helium-4 nucleus reaches at point P_2, it enters into the mouth of the horse pipe and thus be extracted out of the tokamak.

⇒ The unit of distance is meter.

(ii) For neutron

⇒ The neutron strike to the wall of the tokamak.

For the fusion reaction

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

[injected] [confined] [Not confined]

1. For the helium-4 nucleus

⇒ The helium-4 nucleus is not confined.
⇒ The cartesian coordinates attained by the helium-4 nucleus are –
$P_1(0, 0, 0)$ and $P_2(13.1066 \times 10^{-2} m, -23.0252 \times 10^{-2} m, -23.0252 \times 10^{-2} m)$

⇒ The helium-4 nucleus starts its circular motion from the point $P_1(x_1, y_1, z_1)$ and reaches at point $P_2(x_2, y_2, z_2)$.

As the helium-4 nucleus reaches at point $P_2(x_2, y_2, z_2)$, it enters into the mouth of the horse pipe and thus be extracted out of the tokamak.

Where,

$$P_1(x_1, y_1, z_1) = P_1(0, 0, 0) \quad \text{and}$$

$$P_2(x_2, y_2, z_2) = P_2(13.1066 \times 10^{-2} m, -23.0252 \times 10^{-2} m, -23.0252 \times 10^{-2} m)$$

2. For the gamma rays.

⇒ The gamma rays heats the tokamak.

For fusion Reaction

$$^{3}_{1}T + ^{3}_{2}He \rightarrow ^{5}_{3}Li + ^{1}_{0}n$$

(i) For neutron

⇒ The neutron strike to the wall of the tokamak and hence be absorbed by the boron (The inner liner) of the tokamak.).

(ii) For lithion-5

⇒ The lithion i is produced at point 'F'. The lithion-5 as a homogenous compound nucleus is an unstable isotope of the stable nucleus - the helion-4. So, at point 'F', the produced Li-5 again undergo to the process of formation of lobes within into it and then splits into the helium-4 nucleus and proton.

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

(i) For helion-4

⇒ The produced helium-4 nucleus starts its circular motion from point $P_1(0,0,0)$ and reaches at point $P_2(x_2, y_2, z_2)$ equal to P_2(

$P_2(7.4162\times10^{-2}\,m,\ 25.5860\times10^{-2}\,m,\ 25.5860\times10^{-2}\,m)$.

⇒ As the helium-4 nucleus reaches at point $P_2(x_2, y_2, z_2)$, it enters into the mouth of the horse pipe and thus be extracted out of the tokamak.

⇒ The helium-4 nucleus is not confined.

(ii) For proton

⇒ The Cartesian coordinates to be attained by the proton are - $P_1(0, 0, 0)$ and
$P_2(43.5285 \times 10^{-2} m, -3.0777 \times 10^{-2} m, -3.0777 \times 10^{-2} m)$.

⇒ The produced proton starts its circular motion from point $P_1(0,0,0)$ and before it reaches at point $P_2(x_2, y_2, z_2)$, it strike to the wall of the tokamak.

⇒ Thus the proton is not confined.

For fusion reaction

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

(i) For deuteron :- The deuteron is not confined.

⇒ The cartesian coordinates to be achieved by the deuteron are $P_1(0,0,0)$ and $P_2(26.8306 \times 10^{-2}\,m, -64.2019 \times 10^{-2}\,m, -64.2019 \times 10^{-2}\,m)$.

⇒ The deuteron starts its circular motion from point $P_1(0,0,0)$ and before it reaches at point $P_2(x_2, y_2, z_2)$, it strike to the wall of the tokamak.

(ii) For helium-4 nucleus

⇒ The cartesian coordinates to be achieved by the helium-4 nucleus are $P_1(0,0,0)$ and $P_2(13.1194 \times 10^{-2}\,m, 35.6849 \times 10^{-2}\,m, 35.6849 \times 10^{-2}\,m)$.

⇒ The helium-4 nucleus starts its circular motion from point $P_1(0,0,0)$ and before it reaches at point $P_2(x_2, y_2, z_2)$, it strike to the wall of the tokamak.

⇒ So, the helium-4 nucleus is not confined.

For fusion reaction

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

I. For proton

⇒ The cartesian coordinates to be achived by the proton are $P_1(0, 0, 0)$ and $P_2(14.3564 \times 10^{-2}\,m, -44.3744 \times 10^{-2}\,m, -44.3744 \times 10^{-2}\,m)$.

⇒ The produced proton starts its circular motion from point $P_1(0, 0, 0)$ and before it reaches at point $P_2(x_2, y_2, z_2)$, it strike to the wall of the tokamak.

⇒ So, the proton is not confined.

II. For helium-5 nucleus

⇒ The helium-5 nucleus is produced at point 'F'. The half life of the helium-5 nucleus is . So, the helium-5 nucleus as a homogenous compound nucleus is an unstable isotope of a stable nucleus – the helion-4. So, at point 'F' the produced helion-5 again undergo to the process of formation of lobes within into it and then splits to produced helion-4, the neutron and the reduced mass (Δm).

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

(i) For the helium-4 nucleus

⇒ The helium-4 nucleus is not confined

⇒ The produced helium-4 nucleus starts its circular motion from point $P_1(0,0,0)$ and reaches at point $P_2(10.0531\times10^{-2}\,m, 24.9467\times10^{-2}\,m, 24.9467\times10^{-2}\,m)$.

⇒ As the helium-4 nucleus reaches at point 'P_2', it enters into the mouth of the horse pipe and thus be extracted out of the tokamak.

(ii) For neutron

⇒ The neutron strike to the wall of the tokamak and so the neutron is absorbed by the boron [The inner liner] of the tokamak.

For the fusion reaction

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

[injected] (Left side) (Right side)

I. For the right side propelled helium-4 nucleus :-

⇒ The right side propelled helion-4 is not confined.
⇒ The cartesian coordinates to be attained by the helium-4 nucleus are $P_1(0, 0, 0)$ and $P_2(15.5163 \times 10^{-2}\,m, -62.9780 \times 10^{-2}\,m, -62.9780 \times 10^{-2}\,m)$.

⇒ Before the right side propelled helium-4 nucleus reaches at point P_2, it strike to the wall of the tokamak.

II For the left side propelled helium-4 nucleus

⇒ The left side propelled helium-4 nucleus is not confined.
⇒ The cartesian coordinates to be achieved by the helium-4 nucleas are $P_1(0, 0, 0)$ and $P_2(9.9925 \times 10^{-2}\,m, 63.5892 \times 10^{-2}\,m, 63.5892 \times 10^{-2}\,m)$.

⇒ Before the left side propelled helium-4 nucleus reaches at point P_2, it strike to the wall of the tokamak.

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For the fusion reaction

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

1. For beryllium-7 nucleus

⇒ The beryllium-7 nucleus starts its circular motion from point P_1 (0, 0, 0) and reaches at point P_2 (31.6705×10^{-2} m, -5.8704×10^{-2} m, -5.8704×10^{-2} m)

⇒ As the beryllium-7 reaches at point P_2 (x_2, y_2, z_2) it enters into the mouth of the horse pipe and thus be extracted out of the tokamak.

2. For the gamma rays

⇒ The produced gamma rays heats the tokamak.

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For the fusion reaction

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

[injected] [Confined]

I. For the lithium-7 nucleus

⇒ The lithium-7 nucleus starts its circular motion from point $P_1(0, 0, 0)$ and reaches at point $P_2(33.8797 \times 10^{-2} m, -5.9376 \times 10^{-2} m, -5.9376 \times 10^{-2} m)$

⇒ As the lithium-7 nucleus reaches at point $P_2(x_2, y_2, z_2)$, it enters into the mouth of the horse pipe and thus be extracted out of the tokamak.

II. For the gamma rays

⇒ The produced gamma rays heats the tokamak.

For the fusion reaction

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

[injected] [Confined]

I. For the boron-10 nucleus

⇒ The boron-10 nucleus starts its circular motion from the point $P_1(0,0,0)$ and reaches at point $P_2(35.9199 \times 10^{-2} m, -1.0884 \times 10^{-2} m, -1.0884 \times 10^{-2} m)$

⇒ As the boron-10 nucleus reaches at point $P_2(x_2, y_2, z_2)$, it enters into the mouth of the horse pipe and thus be extracted out of the tokamak.

II. For the gamma rays

⇒ The produced gamma rays heats the tokamak.

The power produced :

To calculate the heat energy produced we will consider the main fusion reactions only. To calculate the heat energy we will consider the increased kinetic energy (E_{inc}) of the each particle that has produced due to fusion reactions.

1. $${}^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{2}He + {}^{1}_{0}n + 3.266\ Mev$$

[0.8187 Mev] [2.4473 Mev]

2. $${}^{2}_{1}H + {}^{3}_{2}He \longrightarrow {}^{4}_{2}He + {}^{1}_{1}p + 18.39\ Mev$$

[3.6980 Mev] [14.6920 Mev]

3. $${}^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{1}H + {}^{1}_{1}H + 4.0314\ Mev$$

[1.0094 Mev] [3.0220 Mev]

4. $${}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n + 17.5896\ Mev$$

[3.5412 Mev] [14.0484 Mev]

$$E_{produced} = 6\ {}^{2}_{1}H \longrightarrow 2\ {}^{4}_{2}He + 2\ {}^{1}_{1}H + 2\ {}^{1}_{0}n + 43.277\ Mev$$

Conclusion : 6 deuterons fuse to produce two helium-4 nuclei, two protons and two neutrons and 43.277 Mev energy.

Total input energy :

⇒ Each deuteron is injected with 102.4 Kev or with 0.1024 Mev energy.

⇒ So, the total input energy that is carried by the 6 injected deuterons is –

$$E_{input} = 6 \times 0.1024 \text{ Mev}$$

$$\Rightarrow E_{input} = 0.6144 \text{ Mev}$$

Net yield energy :

$$\text{Net yield} = E_{produced} - E_{input}$$

$$\Rightarrow \text{Net yield} = 43.277 \text{ Mev} - 0.6144 \text{ Mev}$$

$$\Rightarrow \text{Net yield} = 42.6626 \text{ Mev}$$

⇒ Conclusion : The 6 deuterons fuse and gives us the net yield 42.6626 Mev energy.

VBM fusion reactor and the power produced

⇒ The 6 deuterons fuse to yield 42.6626 MeV.
Or the 6 deuterons fuse to yield $42.6626 \times 1.6 \times 10^{-13}$ J.

⇒ Then, if the 6×10^{18} deuterons fuse per second then the power produced is –

$$P = \frac{42.6626 \times 1.6 \times 10^{-13}}{6} \times 6 \times 10^{18} \ \frac{J}{s}$$

$$\Rightarrow P = 68.2601 \times 10^{5} \ J/s$$

$$\Rightarrow P = 6.8260 \times 10^{6} \ J/s$$

$$\Rightarrow P = 6.8260 \ MW$$

VBM fusion reactor and the lawson criterion

⇒ For a Deuterium - Deuterium fusion reaction the,

$$n_e T_e \geq 10^{22} \ s/m^3$$

⇒ For VBM fusion reactor, the number of particles (n_e) that are taking part in fusion reaction at a time 't' is –

n_e = number of particles available at the center of fusion [or at the point 'F'] at a time 't' per m^3.

or

n_e = The sum of the injected deuterons per bunch (that reach at point 'F' at a time 't') and the confined deuterons per bunch (that pass through the point 'F' at the same time 't') per m^3.

1. The deuterons injected per bunch (n_1) :-

⇒ There the 6×10^{18} deuterons are injected into the tokamak at point 'F' per second.

⇒ The frequency of the Wideroe-type RF linac is 7×10^{6} Hz.

⇒ So, number of deuterons that are injected per bunch are -

$$n_1 = \frac{6 \times 10^{18}}{7 \times 10^{6}} \text{ deuterons per bunch}$$

$$n_1 = 0.8571 \times 10^{12} \text{ deuterons per bunch}$$

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

⇒ So, the number of deuterons (n_1) that are injected per bunch or the number of deuterons that contains an injected bunch are 8.571×10^{11} deuterons.

2. The number of confined deuterons (n_2) per bunch :-

The injected deuteron is confined. or the injected bunch of injected deuterons is confined.

So, the number of confined deuterons per bunch (n_2) is equal to the number of injected deuterons per bunch (n_1).

That is,

$$n_2 = n_1$$

$$\Rightarrow n_2 = n_1 = 8.571 \times 10^{11} \text{ deuterons/bunch}$$

3. Number of total particles (n) that are available at the center of fusion at a time 't' is :-

$$n = \boxed{\text{number of deuterons per injected bunch}} + \boxed{\text{number of deuterons per confined bunch}}$$

$$\Rightarrow n = n_1 + n_2$$

$$n_1 = n_2 = 8.571 \times 10^{11} \text{ deuterons/bunch}$$

$$\Rightarrow n = 2 \times 8.571 \times 10^{11} \text{ deuterons}$$

$$\Rightarrow n = 17.142 \times 10^{11} \text{ deuterons}$$

$\Rightarrow$ There the 17.142×10^{11} deuterons are available at point 'F' at a time 't' where the $t < 10^{-8}$ second.

4. The number of particles (n_e) that are available at point 'F' at a time 't' per m^3 is –

$$n_e = \frac{\text{Number of particles available at center of fusion}}{\text{Volume of any bunch}}$$

$$\Rightarrow n_e = \frac{n}{4/3 \pi r^3}$$

where
r = radius of the bunch
r = 16.5 mm
$n = 17.142 \times 10^{11}$ deuterons

$$\Rightarrow n_e = \frac{17.142 \times 10^{11}}{\frac{4}{3} \times 3.14 \times (16.5 \times 10^{-3})^3 \ m^3}$$

$$\Rightarrow n_e = \frac{17.142 \times 10^{11} \times 3}{4 \times 3.14 \times 4492.125 \times 10^{-9} \quad m^3}$$

$$\Rightarrow n_e = \frac{51.426 \times 10^{11}}{56421.09 \times 10^{-9} \quad m^3}$$

$$\Rightarrow n_e = 0.000911 \times 10^{20} / m^3$$

$$\Rightarrow n_e = 9.11 \times 10^{16} / m^3$$

5. The time of confinement (t_e) of the deuterons :-

The time of confinement of deuterons (t_e) is -

$$t_e = 1.283 \times 10^{11} \text{ Seconds}$$

6. The lawson criterion [$n_e t_e$] for the D-D fusion reaction in the VBM fusion reactor is -

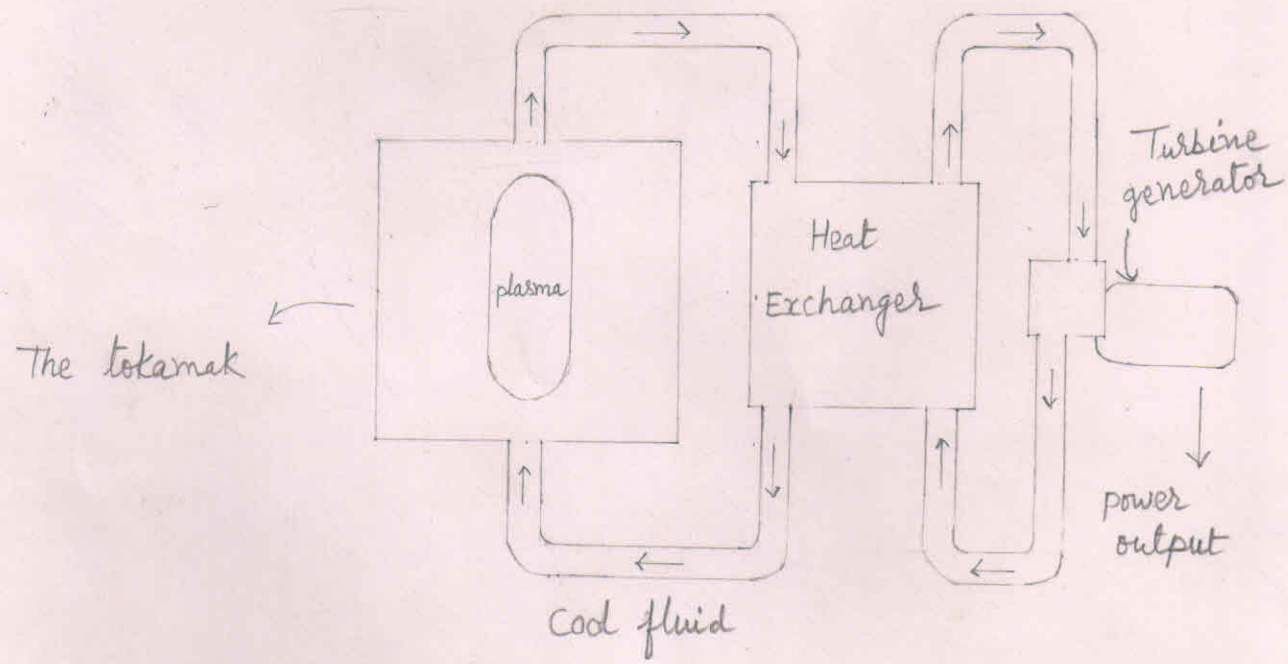
$$n_e t_e = \frac{9.11 \times 10^{16}}{m3} \times 1.283 \times 10^{11} \text{ seconds}$$

$$\Rightarrow n_e t_e = 11.6881 \times 10^{27} \text{ seconds}/m^3$$

$$\Rightarrow n_e t_e = 1.1688 \times 10^{28} \text{ s}/m^3$$

⇒ Decreasing the radius of injected bunch(s) we can increase the value of Lawson's criterion ($n_e t_e$) that we have derived.

Mode of output



⇒

⇒ The heat is transferred by a water-cooling loop from the tokamak to a heat exchanger to make steam.

⇒ The steam will drive electrical turbines to produce electricity.

⇒ The steam will be condensed back into water to absorb more heat from the tokamak.